УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

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Наставном већу Института за физику Београд

Београд, 30. мај 2025.

Предмет:

Молба за покретање поступка за реизбор у звање научни сарадник

МОЛБА

С обзиром да испуњавам критеријуме прописане од стране Министарства науке, технолошког развоја и иновација Републике Србије за звање научни сарадник, молим Научно веће Института за физику у Београду да покрене поступак за мој реизбор у наведено звање.

У прикогу достављам:

1. Мишљење руководиоца лабораторије са предлогом чланова комисије за реизбор у наведено звање:
2. Стручну биографију;
3. Преглед научне активности;
4. Елементе за квалитативну и квантитативну оцену научног доприноса са доказима;
5. Списак и копије објављених радова и других публикација;
6. Податке о цитираности;
7. Копија решења о претхоном избору у звање;
8. Додатне прилоге који документују наводе.

С поштовањем

Васиљевић

Др Јадранка Васиљевић

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Датум 30-05-2025

–Наставном већу Института за физику Београд

Београд, мај 2025.

Предмет:

Мишљење руководиоца лабораторије за реизбор др Јадранке Васиљевић у звање научни сарадник

Др Јадранка Васиљевић запослена је у Лабораторији за теоријску оптику у оквиру Центра за фотонику, Националног центра изузетних вредности Института за физику у Београду. У свом истраживачком раду бави се формирањем апериодичних фотонских решетки формираних коришћењем недифрагујућих зрака као и испитивање феномена простирања светлости у њима. Осим тога истражује нове начине реализације неуређених решетки и изучавање појаве Андерсонове локализације у њима.

С обзиром да др Васиљевић испуњава све предвиђене услове у складу са Правилником о поступку вредновања и квантитативног исказивања научноистраживачких резултата Министарства науке, технолошког развоја и иновација Републике Србије, сагласан сам са покретањем поступка за реизбор Др Јадранке Васиљевић у звање научни сарадник.

За састав комисије за избор др Јадранке Васиљевић у звање научни сарадник предлажем:

1. др Драгана Јовић Савић, научни саветник, Институт за физику у Београду
2. др Дејан Тимотијевић, научни саветник, Институт за мултидисциплинарна истраживања Универзитета у Београду
3. др Душан Аресновић, научни саветни, Институт за физику у Београду.

Душан Арсеновић

Др Душан Арсеновић

Научни саветник

Институт за физику у Београду

2. Стручна биографија кандидата

Јадранка Васиљевић рођена је у Краљеву 1990. године, где је завршила основну и средњу школу. Основне академске студије на Природно-математичком факултету Универзитета у Крагујевцу, смер Физика, уписала је 2009. године, а завршила их 2013. године са просечном оценом 9,51. Исте године уписала је мастер академске студије на истом факултету, смер Физика, које је завршила 2014. године са просечном оценом 9,5. Завршни рад под називом: „*Простирање и локализација светлости у квазипериодичним фотонским решеткама*“, чији је експериментални део урадила на Институту за физику у Лабораторији за нелинеарну фотонику под менторством др Драгане Јовић Савић, одбранила је 2014. године на Природно-математичком факултету Универзитета у Крагујевцу.

Докторске академске студије на Физичком факултету Универзитета у Београду, студијски програм Квантна оптика и ласери, уписала је школске 2014/2015. године. Докторска дисертација под називом ***„Propagation, localization, and control of light in Mathieu lattices“ („Простирање, локализација и контрола светлости у Матјеовим решеткама“)*** урађена је под менторством др Драгане Јовић Савић и коменторством др Дејана Тимотијевића у Лабораторији за нелинеарну фотонику на Институту за физику и одбрањена је 30. септембра 2020. године на Физичком факултету Универзитета у Београду. Докторска дисертација награђена је Студентском наградом Института за физику у Београду за најбољу докторску тезу одбрањену током 2021. године

Од априла 2015. до новембра 2017. године била је стипендиста Министарства просвете, науке и технолошког развоја. Од новембра 2017. године запослена је на Институту за физику у Београду као истраживач приправник у Лабораторији за нелинеарну фотонику, где је била ангажована на пројекту основних истраживања ОИ171036 *„Нелинеарна фотоника нехомогених средина и површина“* Министарства просвете, науке и технолошког развоја Републике Србије, чији је руководилац др Драгана Јовић Савић. У звање научног сарадника изабрана је 20. јануара 2021. године.

Учествовала је на билатералном пројекту између Републике Србије и Републике Немачке *„Контрола светлости помоћу детерминистичких апериодичних и комплексних фотонских решетки“* 2016. и 2017. године, у оквиру ког је више пута посетила Институт за примењену физику Универзитета у Минстеру, Немачка. Сарадњу је наставила и након завршетка пројекта.

Од јануара 2022. до децембра 2024. године учествовала је на пројекту Фонда за науку Републике Србије *„Control and manipulation of light in complex photonic systems“* (**CompsLight**). На том пројекту руководи радним пакетом који се бави изучавањем простирања светлости у неуређеним детерминистичким апериодичним решеткама. Сарадњу је наставила и након завршетка билатералног пројекта.

Од школске 2022/2023. године ангажована је на Природно-математичком факултету Универзитета у Крагујевцу на докторским академским студијама физике, за потребе одржавања наставе на предметима Оптоелектроника и Физика ласера.

Њена област истраживања је оптика и нелинеарна фотоника. Резултате свог истраживања публиковала је у девет радова који су цитирани 32 пута без аутоцитата, уз Хиршов индекс 5 (подаци из базе Web of Science на дан 30.05.2025.): један рад у међународном часопису изузетних вредности (категорија М21а), седам радова у три врхунска међународна часописа (категорија М21) и један рад у истакнутом међународном часопису (категорија М22), три конференцијска рада, једно предавање по позиву са међународног скупа штампано у изводу (М32), као и 10 саопштења са међународних скупова штампана у изводу или целини (М34 и М33).

3. ПРЕГЛЕД НАУЧНЕ АКТИВНОСТИ КАНДИДАТА

Др Јадранка Васиљевић бави се истраживањима у области нелинеарне фотонике: испитивање феномена који се односе на процес интеракције ласерског зрачења са нелинеарном оптичком средином, испитивање ефеката пропагације светлости као што су дискретна дифракција и/или Андерсонова локализације у различитим фотонским решеткам, полазећи од простих периодчних ка све сложенијим апериодичним и неуређеним структурама, испитивање особина недифрагујућох зрака у различитим оптичким срединама и њихова примена за формирање фотонских решетки са подесивим каратеристикама. Њен рад се може поделити у две целине, од чега свака целина има теоријска истраживања која су реализована преко нумеричких симулација и експериментална истраживања. Најпре је део експерименталних резултата кандидаткиња добила у оквиру билатералне сарадње између Републике Србије и Републике Немачке. Након тога је у оквиру пројекта Идеје у Србији покренула експеримент за оптички индуковану технику у форорефрактивним материјалима, с потенцијалном применом и на друге средине. Осим калибрација појединих експерименталних сегмената или појединачних уређаја, надоградила је иницијалну експерименталну поставку, која сада има доста нових могућности и самим тим отвара нове правце истраживања.

Први део истраживања односи се на формирање апериодичних фотонских решетки са подесивим особинама коришћењем недифрагујућих зрака у фоторефративним нелинеарним оптчким срединам и испитивање феномена простирања светлости у таквим фотонским решеткама. Ова истраживања везана су за пројекат на коме је кандидаткиња била укључена "Control and manipulation of light in complex photonic systems"(CompsLight), програм Идеје Фонда за науку РС (2022 – 2024). Истраживање обухвата експерименталну реализацију фотонских решетки са подесивим особинама у фоторефрактивном кристалу уз помоћ оптички индуковане технике, коју прате одговарајуће нумеричке симулације. Нумерички и експериментално такође је испитана и пропагација уске пробе у таквим решеткама. Кандидаткиња је учествовала у покретању експерименталне поставке за формирање фотонских решетки у фоторефрактивном кристалу, унапређењу поставке како би се прилагодла за испитавање линеарне и нелинеарне пороапгације пробног зрака.

Недифрагујући зраци су монохроматска оптичка поља чији профил попречног интензитета остаје непромењен током простирања, а добијају се као решења хомогене Хелмхолцове једначине сепарацијом у различитим координатним системима. Деле се у 4 главне фамилије: Декартови (равни талас и збир равних таласа), Беселови, Матјеови и параболични (Ејри и Веберови) зраци. Карактерише их особина самореконструкције односно могућност регенерације у оригинални профил интензитета након проласка кроз нетранспарентне препреке. Имају примену у бројним областима као што су атомска оптика, оптичке пинцете (енг. tweezer), нелинеарна оптика, фотоника итд. Захваљујући робусности ових зрака, они представљају добре кандидате за формирање фотонских решетки у фоторефрактивним метеријалима. Фотонске решетке су једна од реализација фотонских кристала, а разлика у односу на класичне фотонске кристале је та што поседују мању промену индекса преламања што заправо отвара могућност да се у њима могу испитивати колективни феномени, као што су дискретна дифракција или Андерсонова локализација.

Др Васиљевић се у овом истраживању базирала на недифрагујуће Матјове зраке који су решења Хелмхолцове једначине у елиптичком координатном систему, јер варијација параметара Матјевих зрака (ред, елиптичност и величина) омогућава конституисање различитих просторних дискретних конфигурација са подесивим особинама и као и могућност расподеле попречне дистрибуције дискретних структура по различитим кривим (круг, елипса или хипербола). Фокусирала се на фотонским структурама у елиптично-радијалној геометрији са апериодичном дискретном расподелом интензитета, јер оне нуде широк спектар облика, укључујући елиптичност као додатни степен слободе. Нумерички је формирала различите Матјеове фотонске решетке тако да су таласоводи распоређени на кругу, елипси и хиперболи, променом одговарајућих параметара Матјеових зрака. Матјеови зраци омогућавају једнопролазну експерименталну реализацију, техником опричке индукције и употребом просоторног модулатора светлости, Захваљујући свом облику, формирају се природно ограничене (енг. truncated) апериодичне фотонске решетке, у којим је погодно испитивање појаве површинских стања као и дискретну дифракцију на површини и ивици. Оне такође омогућавају да се анализира димензионалности остварене дискретне дифракције.

У првом кораку истрживања нумерички и експериментално је испитала услове стабилности таквих структура у фоторефрактивном кристалу Стрнoцијум баријум ниобату допирано церијумом (SBN), односно параметара за реализацију Матјеових фотонских решетки у SBN кристалu. Како би експериментало извела ово истраживање др Васиљевић је покренула експеримнталну поставку за технику оптичке индукције која укључује коришћење просторног модулатора светлости уз помоћ својих колега, користећи претходно стечено експериментално знање и вештине. У другом кораку истраживања, експериментално и нумерички је испитивала линеарно простирање уског пробног зрака у тако формираним фотонским решеткама. Како би урадила други део екпрерименталног истраживања, кандидаткиња је унапредила и прилагодила претходно урђену поставку тако да је могуће реализовати фотонске решетке помоћ оптички индуковане технике али и испитивати линеарно и нелинеарно простирање пробног зрака. Урађена је калибрација експерименталне поставке и експерименталних параметара како би се ускладили са нумеричким симулацијама.

За разлику од аперидичних решетки, у периодичним фотонским решеткама постоје само два параметра која утичу на дискретну дифракцију: период решетке и дубина модулације индекса преламања, и они су униформни по целој решетки. Период решетке и модулација индекса преламања Матјеових фотонских решетки нису независни параметри; они су повезани преко параметара Матјеовог зрака (ред, величина и елиптичност). Због апериодичности Матјеових решетки, постоје различита локална окружења пробног зрака која подржавају дискретну дифракцију под утицајем најближих суседа. Током простирања, проба дифрагује кроз различит локална окружења што узрокује додатне варијације у ефектима дискретне дифракције.

У овом истраживању експериментално и нумерички показана је елиптично-радијална дискретна дифракцију у фотонским решеткама реализованих коришћењем једног Матјеовог зрака. Променом реда, величине и елиптичности Матјеовог зрака, показано је да је могуће контролисати дискретну дифракцију у радијалном правцу, као и облик њихових расподела у попречним правцима: кружним, елиптичним или хиперболичким. Променом положаја улазног пробног зрака, показан је прелазак са 1Д на 2Д дискретну дифракцију. Коришћени фоторефрактивни двопреламајућем SBN кристал омогућава испитивање утицаја анизотропије кристала на појаву дискретне дифракције. У овом истраживању показано је да кристална анизотропија игра важну улогу у феномену дискретне дифракције: најизраженија 2Д дискретна дифракција добијена је дуж правца кристалне анизотропије.

Описани резултати објављени су у једном раду у врхунском међународним часописима:

1. **Jadranka M. Vasiljević**, Vladimir P. Jovanović, Aleksandar Ž. Tomović, Dejan V. Timotijević, Radomir Žikic, Milivoj R. Belić, and Dragana M. Jović Savić, “Interdimensional radial discrete diffraction in Mathieu photonic lattices”
Optics Express 31 (18), 28946 (2023).
https://doi.org/10.1364/OE.497795
(M21, IF= 3.4).

Др Васиљевић је презентовала добијене резултате у оквиру међународне конфернције - ***SPIE Photonics Europe, 7 – 11 April 2024 Strasbourg, France*** и објављен је конференцијски рад:

1. **Jadranka M. Vasiljević**, Vladimir P. Jovanović, Aleksandar Ž. Tomović, Dejan V. Timotijević, Radomir Žikic, Milivoj R. Belić, Dragana M. Jović Savić,
“Dimensionality crossover of radial discrete diffraction in optically induced Mathieu photonic lattices“
SPIE Photonics Europe 2024, Strasbourg France, Proceedings Volume 13004, Nonlinear Optics and its Applications 2024; 130040J (2024).
https://doi.org/10.1117/12.3017229
(M33).

Други део истраживања кандидаткиње састоји се од предлога нових нумеричких приступа за реализацију 2Д неуређених решетки, поређење и утицаја различитих метода на транспорт светлости и локализацију у таквим решеткама дуж правца простирања а у зависности од снаге (процента) неуређености. Предложена су два приступа за реализацију неуређених решетки која би одговарала различитим експеримнталним реализацијама. Оба приступа су примењана на реализацију неуређених апериодичних решетки и неуређених периодичних решетки. Кандидаткиња је нумерички испитала и анализирала пропагацију уске пробе у једном типу неуређених апериодичних решетки и резултате поредила са одговарајућим резултатима пропагације исте пробе у неуређеним периодичним решеткама. Додатно је један од предложених нумеричких модела релизације неуређености искористила како би нумерички и експериментално реализовала неуређене апериодичне фотонске решетки формиране од недифрагујућих Матјеових зрака користећи технику оптичке индукције у фоторефрактивном SBN кристалу.

И овај део истраживања има две етепе:

1. Формирање сложених фотонских решетки
2. Испитивање и анализа ефеката простирања светлости у тако формираним решеткама.

Кандидаткиња је прво нумерички испитала параметаре стабилности новоформљених структура у фоторефрактивном SBN кристалу што представља нумеричку симулацију експеримерталне реализације фотонских решетки техником оптичке индукције, да би у наредном кораку нумерички и експериментално испитивала утицај неуређености на простирање уске пробе у неуређеним фотонским решеткама.

Др Васиљевић формирала је сложене структура интерфернцијом више Матјеових зрака који су даље умножавани дуж x и y праваца. Добијене дистрибуције интензитетата сложених структура погодне су за формирање различитих апериодичних фотонски решетки. Сложени оптички системи, као што су детерминистичке апериодичне Матјеове решетке, за разлику од периодичних ометају дифракцију светлости на начин упоредив са неуређеним оптичким системима. Кандидаткиња је додатно систематски укључила случајност у тако већ сложене оптичке систем, мерећи њен релативни допринос случајности како би анализирала везу између неуређености и сложености. Предложила је два метода за реализацију неуређених апериодичних Матјеових решетки са нумерички контролисаним степеном неуређености, који се базирају на различитој варијацији интезитета решетке са променом процента неуређености. Методе је додатно описала а потом разлике анализирала преко линеарне пропагацију пробеног зрака.

За разлику од периодичних решетки, где су растојања и јачине таласовода униформна и хомогена код апериодичних и неуређених решетки окружење побуде игра важну улогу (растојања су неуниформна уједнно и јачине таласовода су нехомогене). За описивање и карактеризацију ефеката пропагације светлоти у таквим структурама неопходно је исптати већи број различитих позиција проба како би се укључио што већи број различитих окружења. Кандидаткиња је зато урадила свеобухватна статистичка анализа великог броја различитих позиција побуде за различите јачине неуређености, урадила усредњавање резултата, додатно је анализиала утицај дужине пропагације, интензитета решетке (еквивалент промени индекса премања), ширине и позиција пробе (униформно и на таласоводу) на добијене резултате.

Показано је да неуређене решетке формиране предложеним методама доводе до појачања транспорта светлости за све проценте неуређености у односу на апериодичну решетку (неуређеност = 0%) - транспорт појачан неуређеношћу (енг. disorder-enhanced transport), За веће степене неуређености добијено је опадање транспорта светлости у односу на мање проценте неуређености. Са ниже проценте неуређености транспорт светлости је је сличан дифузном („diffusive-like“) док за највеће проценте неуређености долази до појаве Андерсонове локалзације. Нумеричко испитивање на већим растојањима пропагације показује да је праг детекције Андерсонове локализације померен ка нижим степенима неуређености.

Додатно, како би се описали и квантификовала ефекте, кандидаткиња је рачунала ефективну ширину зрака која се користи да покаже број побуђених таласовода али њено понашање током пропагације је корисно да се опише тип транспорта светлости (балистички, „diffusive-like, локлаизација). Ефективна ширина је израчуната за нумеричке али и експерименталне резултате где су добијена јако добра поклапања вредности. Како је Андерсонова локализација добијена у одређеном региону процента неуређености у том региону је израчуната локализациона дужина (и за ексерименталне и нумеричке резултате), као мера јачине Андерсонове локализације. Локализациона дужина коришћена је и као мера за поређење различитих предложених метода. Резултати добијени у анизотропном дволомном SBN показују да се Андерсонова локализација јавља у различитим опсезима дуж различитих праваца, што је додатно потврђено измереним локализационим дужинама.

Урађена је анализа усредњених резултата за различите позиције пробе које су померане по решетки у оба правца униформно за једнака растојања тако да су у статистику ушле позиције пробе на таласоводима али и између таласовода, што је упоређено са резултатима статистике која је укључивала позиције проба само на таласоводима, што није показало значајну разлику у локализационим ефектима. Ипак показано је да ширина пробе значајно утиче на појаву локализације, где за широку гаусијанску пробу локализацију није могуће добити у таквим решеткам. Нумеричко испитивање на већим растојањима пропагације показује да је праг детекције Андерсонове локализације померен ка нижим степенима неуређености.

Описани резултати објављени су у два раду у врхунском међународним часописима:

1. D. V. Timotijević, **J. M. Vasiljević**, and D. M. Jović Savić,
   "Numerical methods for generation and characterization of disordered aperiodic photonic lattices"
   Optics Express 30 (5), 7210 (2022).
   https://doi.org/10.1364/OE.447572
   (M21, IF= 3.8).

2. **J. M. Vasiljević**, A. Zannotti, D. V. Timotijević, C. Denz, and D. M. Jović Savić,
   "Light transport and localization in disordered aperiodic Mathieu lattices"
   Optics Letters 47 (3), 702 (2022)
   https://doi.org/10.1364/OL.445779
   (M21, IF= 3.5).

Др Васиљевић је презентовала добијене резултате у оквиру међународне конфернције - ***SPIE Photonics Europe, 3 – 7. April 2022*** Strasbourg, France и објављен је конференцијски рад:

- **Jadranka M. Vasiljević**, Dejan V. Timotijević, Dragana M. Jović Savić
  "Light propagation in disordered aperiodic Mathieu lattices generated with two different randomization methods"
  Proc. SPIE 12143, Nonlinear Optics and its Applications 2022, 121430A (25 May 2022).
  https://doi.org/10.1117/12.2621228
  (M33)

и у оквиру међународне конфернције - ***European Optical Society Annual Meeting (EOSAM) 2022, Porto, Portugal, 12-16. 9. 2022***.

2. **Jadranka M. Vasiljević**, Dejan V. Timotijević, Dragana M. Jović Savić
   "Light propagation in disordered aperiodic Mathieu photonic lattices",
   European Optical Society Annual Meeting (EOSAM) 2022, Porto, Portugal, 12-16. 9. 2022.
   https://doi.org/10.1051/epjconf/202226608015
   (M33).

Досадашњи научно истраживачки рад Јадранке Васиљевић, може се класификовати у следеће основне правце:

1. Предлог нових метода за реализацију неуређених решетки са нумерички контролисаним степеном неуређености који је погодан за примену на различитим решеткама: периодичним, квазипериодичним, апериодичним,
2. Реализација радијално-елиптичних природно ограничених апериодичних дискретних фотонских решетки помоћу недифрагујућих Матјеових зрака са подесивом просторном расподелом.
3. Проучавање, анализа и карактеризација ефеката пропагације светлости у неуређеним решеткам и исптивање услова за настанак Андерсонове локализације и/или појачан транспорт у таквим структурама.
4. Испитивање и карактеризација ефеката пропагације светлости у радијално-елиптичним дискретним апериодичним решеткама са подесивим растојањима и просторном расподело. Контрола облика и димензионалности дискретне дифракције у комбинацији радијалног правца са кружним, елиптичним и хиперболичним.
5. Испитивање и анализа утицаја анизотропије дволомног SBN кристала на интеракцију светлости и материје.

4. ЕЛЕМЕНТИ ЗА КВАЛИТАТИВНУ АНАЛИЗУ РАДА КАНДИДАТА

4.1 Квалитет научних радова

4.1.1 Значај научних радова

Др Јадранка Васиљевић има укупно 9 објављених радова који су цитирани 32 пута без аутоцитата уз Хиршов индекс 5 (подаци из базе Web of Science на дан 30.05.2025.). Од тога 1 рад у категорији M21a, 7 радова у категорији M21 и један рад у категорији M22.

Након одлуке Научног већа о утврђеном предлогу за претходни избор у звање научни сарадник, др Васиљевићје била аутор 3 рецензирана научна рада објављена у међународним часописима. Сва три рада су категорије M21. Одржала је више предавања на међународним конференцијама, од којих једно предавање по позиву.

1. D. V. Timotijević, J. M. Vasiljević, and D. M. Jović Savić,
   "Numerical methods for generation and characterization of disordered aperiodic photonic lattices"
   Optics Express 30 (5), 7210 (2022).
   https://doi.org/10.1364/OE.447572
   (M21, IF= 3.8).
2. J. M. Vasiljević, A. Zannotti, D. V. Timotijević, C. Denz, and D. M. Jović Savić,
   "Light transport and localization in disordered aperiodic Mathieu lattices"
   Optics Letters 47 (3), 702 (2022)
   https://doi.org/10.1364/OL.445779
3. Jadranka M. Vasiljević, Vladimir P. Jovanović, Aleksandar Ž. Tomović, Dejan V. Timotijević, Radomir Žikic, Milivoj R. Belić, and Dragana M. Jović Savić,
   "Interdimensional radial discrete diffraction in Mathieu photonic lattices"
   Optics Express 31 (18), 28946 (2023).
   https://doi.org/10.1364/OE.497795
   (M21, IF= 3.4).

Од претходног избора у звање кандидаткиња је први аутор на 2 рада, а на сва три рада Др Васиљевић је имала главни допринос. Допринос се саастоји на конципирању истраживања кроз развоју и каратеризаји нових нумеричких метода, укључивање нових предложених метода у већ постојећи нумерички модел, покретање и унапређење експерименталне поставке за реализацију нумерички симулираних, калибрацију експерименталних услова са нумеричким, прикупљање и анализа експерименталних и нумеричких резултата, додатни нумерички прорачуни за анализу резултата, припрему и писање радова, комуникацију са уредницима и рецензентима.

Први рад састоји се од предлога нових нумеричких метода за реализацију неуређених решетки са нумерички подесивим степеном неуређености који би одговарали двема експерименталним реализацијама и анализе и поређења два метода кроз истраживање простирања светлосне пробе кроз тако формиране фотонске решетке. Др Васиљевић предложила је два метода за реализацију неуређених апериодични решетки са нумерички подесивим степеном неуређености користећи Матјеове недифрагујуће зраке, тако добијене структуре имплементирала је у своје постојеће нумеричке кодове који симулирају експерименталну реализацију фотонских решетки техником оптичке индукције у фоторефрактивном кристалу или експерименталну реализацију простирања пробе у фотонским решеткама. Упредила је два нумеричка метода испитивањем ефеката при пропагацији пробног зрака. Анализирала је ефекте транспорта светлости и појаве Андерсонове локализације у таквим решеткам у зависноси од степена неуређености, које је додатно квантификовала додатним нумеричким рачуном ефективне и локализационе ширине. Одрадила је већи број нумеричких симулација, усреднјила и анализирала резултате. Испитала је како проценат неуређености, ширина и позиција пробе, интензитет решетке и дужина простирања утичу на ефекте при простирању светлости у таквим фотонским решеткама. Главни циљ је био да истакне утицај неуређености на простирање светлости, фокусирајући се на ефекте локализације и транспорта светлости дуж простирања.

За оба метода је добијено да порастом процента неуређености, транспорт светлости се повећава у односу на 0%. Са повећањем процента неуређености добијен је прелаз са дифузног транспорт на Андерсонову локализацију. Показано је да интензитет решетке смањује транспорт светлоти, дужина пропагације доводи до израженије локализације и на нижим процентима неуређености, ширина пробе има важну улогу да ли ће доћи до појаве Андерсонове локализације. Показано је различито понашање (дифузни транспорт и Андерсонова локализација) дуж различитих праваца у односу на оптичку осу SBN кристала. Један од метода је показао да доводи до израженије локализације што је потврђено додатним одређивањем локализационе дужине.

Након анализе и описа модела и ефеката проапгације, кандидаткиња је уочила везу усреднјеног интензитета решетке (повезан са усреднјеним индексом преламања) и ефеката локализације и транспорта са променом процента неуређености, за оба модела. Директно уочљив поређењем зависности инверзног усреднјеног интензитеа и ефективне шитине у зависности од процента неуређености. Показано је да усреднјени интензитет решетке опада са порастом процента неуређености до неког процента након чега расте али не достиже вредност усреднјеног интензитета решетке без неуређенсти. Код једног од модела разлика усреднјних интензитета је више израженија са променом процента неуређености, што доводи до појаве израженије локализације за тај метод. Сва претходна анализа показује да укључивањем неуређености у апериодичну решетке долази до опадања усреднјеног интензитета што за последиву има појачан транспорт светлости, али је за исте проценте неуређености могуће истовремено имати и транспорт појачан неуређеношћу и Андерсонову локализацију.

Главни допринос ове свеобухватне анализе два метода је и то што предложене методе реализације неуређених решетки нису ограничене само на апериодичне решетке већ се могу применити и на бројне друге простије или комплексније решетке. Такође рад отвара могућност за даља истраживања али и идеју за нове методе реализација неуређених решетки. Поред тога, истиче значај интензитета и анизотропије у појавама као што су локализација и дифракција.

Други рад нумерички и експериментално испитује ефекте транспорта светлости и услова за појаву Андерсонове локализације у неуређеним апериодичним Матјеовим решеткама. Кандидаткиња је предложила формирање аперидичних решетки користећи умножавање збир више недифрагујућих Матјових зрака. Како комплесни оптички системи, као што су апериодичне Матјове решетке сузбијају дифракцију светлости слично као неуређени оптички системи, кандидаткиња је анализирала додатно систематично укључивање нуређености у такве системе са идејом разумевања везе компексности и неуређености. Генерисана је серија 2Д неуређених аперодичних Матијеових решетки у SBN кристалу са нумерички контролисаним степеном неуређености. Уски пробни зрак коришћен је за испитивање ефеката ширења кроз структуре.

Допринос кандидата у овом реду састоји се од екеперименталне реализације неуређених апериодчних Матијових решетки и испитивања феномена при пропагације уске пробе у њима, коју прате одговарајуће нумеричке симуалције и додатни прорачуни, прикупљање резултата, сумирање главних закњучака, припрема и писање рада, комуиникација са уредницима и рецензентима.

Нумерички и експериментално је испитала велики број позиција пробе у неуређеним апериодичним Матјеовим решеткама формираних у SBN кристалу, користећи технику оптичке индукције. Урадила је усредњавање нумеричких и експерименталних резултата уз додатна мерења ефективне и локализационе ширин и добила јако добра поклапања резултата.

Испитан је утицај промене процента неуређености, а показано је да у оваквим системима постоји транспорт светлости појачан неуређеношћу, а за велике неуређености доалзи до појаве Андерсонове локализације. Како екепериментални услови ограничавају анализу на 2cm, кандидаткиња је нумерички симулирала веће дужине простирања (до 5cm) и показано је да на већим дужинама Андерсонова локализације се појављује на мањим процентима неуређености.

Главни допринос овог рада и кандидаткиње је прилагођавање екпериментaлне поставке за реализацију неуређених апериичних решетки користећи оптички индуковану технику у SBN кристалу. Дводимензинална неуређена аперидична Матјеова решетка реализована је у само једном процесу оптичке индукције помоћу просторног модулатора светлости и нумерички преречунатих неуређених структура са подесивим процентом неуређености. Нумерички метод и експериментална конфигурација, коју је кандидаткиња користила, за разлику од претходно коришћених експерименталних техника омогућава директну контролу процента неуређености решетке и паралелно уписивање читаве структуре кроз фоторефрактивни кристал.

Трећи рад, који је најважнији рад кандитаткиње јер укључује покретање нове експерименталне поставке за реализају фотонских решетки у фоторефрактивном кристслу дужине 2cm, али и надоградњу те поставке за испитивања линеарне и нелинеарне пропагације уске пробе у фотонским решеткама, користећи претходно стечено знање и вештине у екеперименталном раду. У претходном научном раду кандидаткиња је научила о техници оптичке индукције која је погодна за реализацију фотонских решетки користећи фоторефрактивни ефекат у фоторефрактивном кристалу. Кандидаткиња је учестовала у планирању и набавци потребне опреме (ласер, просторни модулатор светлости, извор напајања, камера, различити опрички елементи) са чановима своје групе.

Након анализе особина фоторефрактивних кристала, познавања резултата у области, претходног искуста и понуде, кандидаткиња и чланови групе закључили су да је најпогодније користити нелинеарни фоторефрактивни кристал Стронцијум баријум ниобат допиран церијумом (SBN). Како би се иницирао фотрефрактивни ефекат у SBN кристалу неопходна је применити хомогено спољашње електрично поље у правцу оптичке осе. Кристал припада групи кристала са два лома који спада у групу позитивних кристала са једном оптичком осом, што значи да кристал има особину анизотропије - способност материјала да различито прелама светлост у различитим правцима. Због тога, различито поларизована светлост се другачије простире у кристалу. Та особина SBN кристала, корисна је у нелинеарној фотоници јер омогућава паралелено реализацију фотонских решетки техником оптичке индукције и ипситивање простирања пробног зрака, коришћењем различито поларизованих зрака (линерно пларизовани – нормално и ванредно). Такође, кристал је користан и за испитивање нелинерних ефеката простирање светлости.

Како би експериемнтална поставка била погодна за реализацију бројних различитих фотонских структура у поставку је имплементиран просторни модулатор светлости који користи унапред нумерички прерачунате холограме који садржи потребне информације о жељеној структури (интензитет и фаза). Када ласерски зрак обасја просторни модулатор светлости рефлектована светлост је просторно структуирана и на даље се путем оптичких елемената води до кристала. Кандидаткиња је направила неопходне нумеричке кодове за израду нумеричких холограма структура које су или ће се испитивати.

Након прве поставке експеримента, за потребе реализације фотонских решетки, тестиране су различите структуре које су доведене до кристала. Др Васиљевић је урадила анализу параметара потребних да би се формирала решетка која се не мења у унутрашњости кристала. Тестирани су услови у лабораторији да би се спречила нестабилност експерименталне поставке и рада. Предност кристала је што мозе да се користи небројанао пута, процес формирања решетке је релативно брз (од 10s до неколико минута), структура ће остати „записана“ у кристалу док се не изложи белом светлу што потпуно „брише“ записану структуру. Када су постигнути оптимални услови, кандидаткиња је унапредила поставку тако да је погодна и за формирање пробних зракова, чије простирање би се испитивала у формираним фотонским решеткама. Испитани су услови да простирања пробе не утиче на претходно реализовану решетку.

Када је подешавање и калибрација експеримента завршена, др Васиљевић је прешла на испитивање ефеката линеарне пропагације уске пробе у фотонским решеткама користећи Матјеове зраке, са циљем контроле дискретне дифракције унутар фотонске решетке у елиптичној геометрији.

Матијеови зраци, као попречна монохроматска оптичка поља која се не мењају током простирања погодни су за реализацију фотонских решетки техником оптичке индукције. Кандидаткиња је претходно нумерички тестирала параметре Матјеових зрака како би формирала 2D дискретне структуре чији су дискретни фрагменти распоређени на кругу, елипси или хиперболи. Затим је нумерички и експериемнтални испитивала ефекте пропагацију уске пробе у различитим Матијеовим решеткама. Тестирана је утицај променае облика расподеле решетки, димензије и растојања таласовода решетки, као и позиције пробе.

Нумерички је добијена а експериментално потврђена вишедимензионална радијална дискретна дифракција испитујући ефекте линерне пропагације уске пробе у оптички индукованим Матијевоим фотонским решеткама. Дифракција у овим решеткам одвија се радијално (од центра ка споља), као и дуж таласовода распоређених дуж кружних, елиптичних или хиперболичких путања, у зависности од облика Матјеових решетке, што се постиже променом параметара коришћених Матјеоих зрака (ред, елиптичност и величина). Положај улазног зрака утиче на димензионалност добијене дифракције у овим решеткама: 2D дифракције када је позиција пробе на ивици решетке, прелаз са 2D на 1D дифракцију како се позиција пробе помера од ивице. Поред тога показано је да повећањем реда и смањењем величине коришћеног Матјеовог зрака доводи до пораста дифракције.

Овај рад представља нов начин управљања светлошћу у оптичким решеткама са променљивом димензионалношћу, што је важно за потенцијалан дизајн нових фотонских уређаја, управљање преносом информација светлошћу, или развој нових таласовода и фотонских структура.

4.1.2. Параметри квалитета часописа

Кандидаткиња др Јадранка је објавила укупно 3 рада у међународним часописима (у периоду од претходног избора у звање научни сарадник) и то:

2 рад у међународном часопису изузетних вредности (М21) Optics Express (IF = 3,4 SNIP = 1.267 (2023) и IF = 3,8 SNIP = 1.63 (2022)),

1 рад у међународном часопису изузетних вредности (М21) Optics Letters (IF = 3.5 SNIP = 1.55).

Укупан импакт фактор објављених радова др Јадранке Васиљевић је **10.25.**

Додатни библиометријски показатељи према упутству о начину писања извештаја о изборима у звања које је усвојио Матични научни одбор за физику су:

	ИФ	М	СНИП
Укупно	10.25	24	4.447
Укупно по чланку	3.5	8	1.480
Укупно по аитору	2.45	5.41	1.034

4.1.3 Цитираност научних радова кандидата

Према подацима из базе Web of Science на дан 30.05.2025, радови др Васиљевић су цитирани укупно 54 пута, од чега 32 пута без аутоцитата. Према подацима из исте базе, Хиршов индекс кандидаткиње је 5 када се узму у обзир сви цитати.

Прилог: подаци преузети из базе Web of Science дана 30.05.2025. године.

4.1.4 Награде

Др Јадранка Васиљевић је награђена Студентском наградом Института за физику у Београду за најбољу докторску тезу одбрањену током 2021. године

Прилог: доказ о Студентској награди.

4.2. Нормирање броја коауторских радова, патената и техничких решења

Према Правилнику о стицању истраживачких и научнихи звања, радови др Јадранке Васиљевић признају се са пуним бројем поена.

Број коаутора на једном раду из категорије М21 је 3. Рад се бави нумеричким рачунарским симулацијама где се са пуном тежином признаје број коаутора до 5. Друга два рад из категорије М21 имају 7 односно 5 коаутора и баве се експерименталним мерењима и моделовањем, где се пун број поена прихвата до 7 коаутора.

Укупан нормиран број М бодова је непромењен и износи 29,5 што је више од захтеваних 16 бодова за реизбор у звање научног сарадника.

4.3 Учешће у пројектима, потпројектима и пројектним задацима

Од јануара 2022. до децембра 2024. године учествовала је на пројекту Фонда за науку Републике Србије *„Control and manipulation of light in complex photonic systems“* (**CompsLight**). На том пројекту руководи радним пакетом који се бави изучавањем простирања светлости у неуређеним детерминистичким апериодичним решеткама. Сарадњу је наставила и након завршетка билатералног пројекта.

Прилог: потврда руководиоца пројекта о руковођењу пројектним задатком.

4.4. Ангажованост у формирању научних кадрова

Од школске 2022/2023. године др Јадранка Васиљевић ангажована је на Природно-математичком факултету Универзитета у Крагујевцу на докторским академским студијама физике, за потребе одржавања наставе на предметима ***Оптоелектроника*** и ***Физика ласера***.

Прилог сагласност о ангажовању.

4.5 Организација научних скупова

Кандидаткиња је била члан локалног организационог одбора на Осмој међународној школи и конференцији о фотоници PHOTONICA 2021 & HEMMAGINERO workshop, која се одржала у августу 2021. године.

Потврда копија књиге апстракта.

4.6. Активност у научним и научно-стручним друштвима

Др Васиљевић рецензира научне радове у часописима Journal of the Optical Society of America A, Optics Letters, Optics Express, Nature Communications, Journal of Low Temperature Physics.

Прилози: потврде о рецензијама преузете из рецензентских база часописа, повезаност на ORCID налогу или захтев уредника за рецензију.

4.7. Утицај научних резултата

Утицај научних резултата се види кроз податке о цитираности наведене у секцији 4.1.3. Др Васиљевић је у изборном периоду одржала једно предавање по позиву на Четвртој међународној конференцији, Laser, Optics and Photonics, 2023.

Прилог Позивно писмо.

4.8. Конкретан допринос кандидата у реализацији радова у научним центрима у земљи и иностранству

Др Васиљевић је суштински допринео сваком раду у чијој изради је учествовао. У свим радовима у којима је први аутор (2 од укупно 3 радова објављених у изборном периоду) али и у раду где је други аутор, допринос др Васиљевић је био кључни и одлучујући, као што је описано у секцији 4.1.1. која даје преглед три рада из изборног периода.

У раду у којем је други аутор, допринос др Васиљевић је био кључан и одлучујући јер је кандидаткиња предложила нове нумеричке метода за реализацију неуређених решетки са нумерички подесивим степеном неуређености који би одговарали двема експерименталним реализацијама и анализе и поређења два метода кроз истраживање простирања светлосне пробе кроз тако формиране фотонске решетке. За те потребе др Васиљевић је допунила постојеће нумеричке кодове и обавила нумеричке симулације, које су дале резултате који су утицали на закључке изведене у том раду. Такође је припремила нацрт рукописа, учестовала у дискусији резултат процесу рецензије рада, комунуицирала са уредницима и резензетима.

Др Васиљевић је своје истраживачке активности реализовао у Институту за физику и Институту за мултидисциплинарна истарживања у Београду и Институт за примењену физику и Центар за нелинеарну науку (CeNoS), Универзитет у Минстеру, Немачка.

Највећи део резултата остварених у изборном периоду је у целости реализован у Институту за физику у Београду, док је 1 рад делимично реализован Институт за примењену физику и Центар за нелинеарну науку (CeNoS), Универзитет у Минстеру.

Током својих мастер и докторских студија и билатералне сарадње са Немачком, Др Васиљевић је стекла експериментално знање и вештине, које је искористила да током изборног периода покрене и подеси нову експерименталну поставку.

4.9. Уводна предавања на конференцијама, друга предавања и активности

Др Васиљевић је у изборном периоду одржала једно предавање по позиву на Четвртој међународној конференцији, Laser, Optics and Photonics, 2023 Предавање је било у главној сесији (keynote).

Прилог Позивно писмо.

Такође своје резултате је презентовала на више међународник конференција и webinar, и једној постер сесији.

Прилог сетификати о учешћу и програми скупова.

5. ЕЛЕМЕНТИ ЗА КВАНТИТАТИВНУ ОЦЕНУ НАУЧНОГ ДОПРИНОСА КАНДИДАТА

Остварени резултати у периоду након одлуке Научног већа о предлогу за стицање научног звања научни сарадник:

Категорија	М бодова по раду	Број радова	Укупан М бодова	Норирани број бодова
M21	8	3	24	24
M32	1.5	1	1.5	1.5
M33	1	3	3	3
M34	0.5	2	1	1

Поређење са минималним квантитативним условима за избор у звање научни сарадник:

Минимални број М бодова	Неопходно	Остварено, број М бодова без нормирања	Остварено, нормирани број М бодова
Укупно	16	29.5	29.5
M10+M20+M31+M32+M33+M41+M42	10	29.5	29.5
M11+M12+M21+M22+M23	6	24	24

5. Списак радова кандидата др Јадранке Васиљевић

Радови објављени НАКОН избора у звање научни сарадник

5.1. Радови у врхунским међународним часописима (М21)

1. **Jadranka M. Vasiljević**, Vladimir P. Jovanović, Aleksandar Ž. Tomović, Dejan V. Timotijević, Radomir Žikic, Milivoj R. Belić, and Dragana M. Jović Savić, "Interdimensional radial discrete diffraction in Mathieu photonic lattices"
   Optics Express 31 (18), 28946 (2023).
   https://doi.org/10.1364/OE.497795
   (M21, IF= 3.4).

2. D. V. Timotijević, **J. M. Vasiljević**, and D. M. Jović Savić,
   "Numerical methods for generation and characterization of disordered aperiodic photonic lattices"
   Optics Express 30 (5), 7210 (2022).
   https://doi.org/10.1364/OE.447572
   (M21, IF= 3.8).

3. **J. M. Vasiljević**, A. Zannotti, D. V. Timotijević, C. Denz, and D. M. Jović Savić,
   "Light transport and localization in disordered aperiodic Mathieu lattices"
   Optics Letters 47 (3), 702 (2022)
   https://doi.org/10.1364/OL.445779
   (M21, IF= 3.5).

5.2. Пленарно или уводно предавање по позиву са међународног скупа штампано у изводу (М32)

1. **J. M. Vasiljević**, D. V. Timotijević, D. M. Jović Savić
   "Composite photonic structures: generation and light propagation in them"
   4Th Edition of Laser, Optics and Photonics, February 10, 2023

5.3. Саопштења са међународних скупова штампана у целини (М33)

1. **Jadranka M. Vasiljević**, Vladimir P. Jovanović, Aleksandar Ž. Tomović, Dejan V. Timotijević, Radomir Žikic, Milivoj R. Belić, Dragana M. Jović Savić,
   "Dimensionality crossover of radial discrete diffraction in optically induced Mathieu photonic lattices"

SPIE Photonics Europe 2024, Strasbourg France, Proceedings Volume 13004, Nonlinear Optics and its Applications 2024; 130040J (2024).
https://doi.org/10.1117/12.3017229

2. **Jadranka M. Vasiljević**, Dejan V. Timotijević, Dragana M. Jović Savić
"Light propagation in disordered aperiodic Mathieu photonic lattices",
European Optical Society Annual Meeting (EOSAM) 2022, Porto, Portugal, 12-16. 9. 2022.
https://doi.org/10.1051/epjconf/202226608015

3. **Jadranka M. Vasiljević**, Dejan V. Timotijević, Dragana M. Jović Savić
"Light propagation in disordered aperiodic Mathieu lattices generated with two different randomization methods"
Proc. SPIE 12143, Nonlinear Optics and its Applications 2022, 121430A (25 May 2022).
https://doi.org/10.1117/12.2621228

5.4. Саопштења са међународних скупова штампана у изводу (M34)

1. **J. M. Vasiljević**, Alessandro Zannotti, D. V. Timotijević, Cornelia Denz, D. M. Jović Savić, Experimental realization of chiral photonic lattices, 3rd edition of Advancements on Laser, Optics and Photonics (2021) Conference.

2. **J. M Vasiljevic**, A. Zannotti, D. V Timotijevic, C. Denz, and D. M Jovic Savić, "Twisted Photonic Lattices Created by Elliptical Mathieu Beams", 29th Annual International Laser Physics Workshop 2021 - LPHYS' 21.

Радови објављени ПРЕ избора у звање научни сарадник

5.1. Радови у међународним часописима изузетних вредности (М21а)

1. Alessandro Zannotti, **J. M. Vasiljević**, D. V. Timotijević, D. M. Jović Savić and Cornelia Denz,”*Visualizing the Energy Flow of Tailored Light”*, Advanced Optical Materials 6(8), 1701355-1 – 1701355-6 (2018). Цитиран 1 пут, **M21a, IF=7.430, SNIP = 1.60, Optics: 7/95.**

5.2. Радови у врхунским међународним часописима (М21)

1. **J. M. Vasiljević**, Alessandro Zannotti, D. V. Timotijević, Cornelia Denz and D. M. Jović Savić, *“Light propagation in aperiodic photonic lattices created by synthesized Mathieu–Gauss beams “*, Appl. Phys. Lett. **117**, 041102-1 - 041102-5 (2020). Цитиран 0 пут, **M21, IF=3.597, SNIP = 1.25, Physics, Applied: 37/154.**
2. Alessandro Zannotti, **J. M. Vasiljević**, D. V. Timotijević, D. M. Jović Savić, and Cornelia Denz, *“Morphing discrete diffraction in nonlinear Mathieu lattices”*, Optics Letters, Vol. 44(7), 1592 - 1595, (2019). Цитиран 0 пут, **M21, IF= 3.714, SNIP = 1.61, Optics: 20/97.**
3. **J. M. Vasiljević,** Alessandro Zannotti, D. V. Timotijević, Cornelia Denz and D. M. Jović Savić, *"Elliptical vortex necklaces in Mathieu lattices“*, Phys. Rev. A 97, 033848-1 - 033848-5 (2018). Цитиран 2 пут, **M21, IF= 2.909, SNIP = 0.94, Optics (2017): 23/94.**
4. **J. M. Vasiljević,** Alessandro Zannotti, D. V. Timotijević, Cornelia Denz and D. M. Jović Savić, *" Creating aperiodic photonic structures by synthesized Mathieu-Gauss beams “*,Phys. Rev. A 96, 023840-1 – 023840-5 (2017). Цитиран 3 пут, **M21, IF= 2.909, SNIP = 0.94, Optics (2017): 23/94.**

5.3. Радови у истакнутим међународним часописима (М22)

1. N. M. Lučić, D. M. Jović Savić, A. Piper, D. Ž. Grujić, **J. M. Vasiljević**, D. V. Pantelić, B. M. Jelenković, and D. V. Timotijević, *“Light propagation in quasi-periodic Fibonacci waveguide arrays”*, Journal of the Optical Society of America B 32, 1510 -1513 (2015). Цитиран 5 пут, **M22, IF= 1.731, SNIP = 0.89, Optics (2015): 41/90.**

5.4. Предавање по позиву са међународног скупа штампано у изводу (М32)

1. Jadranka M. Vasiljević, *„**Localization of Light in Mathieu Aperiodic Photonic Lattices**“*, Book of abstracts of Webinar on Laser, Optics & Photonics October 21-22, pp 21, (2020).

5.5. Саопштења са међународних скупова штампана у изводу (М34)

1. **J. M. Vasiljević**, Alessandro Zannotti, D. V. Timotijević, Cornelia Denz and D. M. Jović Savić, *„Waveguiding in Mathieu photonic lattices“,* VII International School and Conference of Photonics, Belgrade, Serbia, August 26-30 (2019). ISBN 978-86-7306-153-5. **(M34)**

2. Marius Rimmler, Alessandro Zannotti, **J. M. Vasiljević**, D. V. Timotijevic, D. M. Jović Savić, Cornelia Denz, *„Chirality and discrete diffraction in nonlinear Mathieu lattices“,* SPIE Photonics Europe, Strasbourg, France, April 22-26, pp 75 (2018). **(M34)**

3. **J. M. Vasiljević**, Alessandro Zannotti, D. V. Timotijević, Cornelia Denz and D. M. Jović Savić, *„Realizing aperiodic photonic lattices by synthesized Mathieu-Gauss beams“,* VI International School and Conference of Photonics, Belgrade, Serbia, August 28-September 1 (2017). ISBN 978-86-82441-46-5 **(M34)**

4. **J. M. Vasiljević**, N. M. Lučić, D. V. Timotijević, A. Piper, D. Ž. Grujić, D. V. Pantelić, B. M. Jelenković and D. M. Jović Savić, „*Light propagation in deterministic aperiodic Fibonacci waveguide arrays*“, V International School and Conference on Photonics, Belgrade, Serbia, August 24-28 (2015). ISBN 978-86-7306-131-3 **(M34)**

5.5. Одбрањена докторска дисертација (М70)

1. Јадранка М. Васиљевић, „Простирање, локализација и контрола светлости у Матјеовим решеткама“ (енг. “Propagation, localization and control of light in Mathieu lattices”), Универзитет у Београду, Физички факултет (2020).

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Numerical methods for generation and characterization of disordered aperiodic photonic lattices

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Abstract: We introduce numerical modeling of two different methods for the deterministic randomization of two-dimensional aperiodic photonic lattices based on Mathieu beams, optically induced in a photorefractive media. For both methods we compare light transport and localization in such lattices along the propagation, for various disorder strengths. A disorder-enhanced light transport is observed for all disorder strengths. With increasing disorder strength light transport becomes diffusive-like and with further increase of disorder strength the Anderson localization is observed. This trend is more noticeable for longer propagation distances. The influence of input lattice intensity on the localization effects is studied. The difference in light transport between two randomization methods is attributed to various levels of input lattice intensity. We observe more pronounced localization for one of the methods. Localization lengths differ along different directions, due to the crystal and lattice anisotropy. We analyze localization effects comparing uniform and on-site probe beam excitation positions and different probe beam widths.

1. Introduction

The phenomenon of Anderson localization (AL) originally discovered a few decades ago is one of the basic prominent phenomena in solid-state physics [1,2]. Originally introduced to explain the localization of electronic wave functions in disordered crystals, it has found growing applications in a variety of classical and quantum systems [3–5], including light waves in different materials [6–8]. AL of light has achieved renewed interest due to the potential for the realization of localization of optical waves in random media, especially in discrete systems [9], laser-written waveguide arrays [10–13], and/or optically induced randomized potential [14]. It is in the focus of investigations, especially in nonlinear optics and photonics, due to the development of new optical technologies and media, such as disordered photonic crystals and photonic lattices, in which the presence of AL appreciably changes the propagation of light [15–17]. Owing to the analogy of paraxial photonic systems to solid-state systems, where the wave function evolution corresponds to propagation of light and thanks to the fact that longitudinally invariant disorder can be effectively realized in lattices, experimental activities in AL of light started to attract the attention of optical community [8].

Up to now, periodic photonic structures have led to light control by photonic band gaps in space and time, whereas random photonic structures give rise to localization [6,8,18]. Dynamical control and manipulation of light by deterministic aperiodic or complex photonic structures [19–21] at the intersection between periodic and random crystal structures, especially the randomization of aperiodic structures, have not yet been fully understood nor exploited for applications. Two-dimensional aperiodic photonic lattices were experimentally realized by the optical induction technique in photorefractive crystal by different combinations of nondiffracting

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Mathieu beams [22], combining them in metastructures by splicing in both transverse dimensions with different offsets, thus allowing for the tunable optical response. Nondiffracting beams are convenient for the generation of photonic lattices by optical induction technique since they have propagation invariant property that is retained under the condition of week nonlinearity [23]. There are four nondiffracting beam families that are exact solutions of the Helmholtz equation in different coordinate systems [24,25]: plane waves in Cartesian, Bessel beams in circular cylindrical [26], Mathieu beams in elliptic cylindrical [27], and parabolic beams in parabolic cylindrical coordinates [28].

Aperiodic lattices in contrast to periodic lattices contain non-uniform distances between the lattice sites with non-homogeneous intensity depths distributions, therefore light propagation strongly depends on the probe beam excitation position local environments [29–31]. Such lattices including quasiperiodic Penrose and Fibonacci, and aperiodic Mathieu lattice, are shown to hamper diffraction of linear light [30,31] which can be explained by excitation of highly localized linear modes [32]. Such lattices also support nonlinear light localization [29,31]. Disordering periodic lattices can lead to AL [7,8] or its suppression [33], referred therein as inverse Anderson transition. AL is enhanced by self-focusing nonlinearity in disordered periodic lattice [7,8]. Disordered quasiperiodic Penrose lattice can support AL and disorder-enhanced transport (DET) which is associated with broadening of eigenfunctions with the disorder. Instead of a singular pattern of quasiperiodic structures such as Penrose or Fibonacci with limited variation in probing local environments, we are proposing consideration of a whole class of aperiodic structures based on Mathieu beams [22] with the adjustable spatial and intensity distribution, thus providing different probing local environments, as well as introducing structure anisotropy variability. A further step is randomization of such class of aperiodic structures in order to create an appropriate platform for investigation of light propagation effects and study their possible transition to AL or DET, which is still an unexplored topic. Exhaustive theoretical or experimental analysis of light propagation in such a large class of aperiodic structures is difficult to implement, therefore, in this paper, we focused on one exemplary aperiodic Mathieu structure and numerically model their possible randomizations and probing of resulting disordered lattices.

In this article, we introduce the modeling of two different methods for the generation of two-dimensional propagation invariant disordered aperiodic Mathieu lattices, corresponding to two different experimental realizations using optical induction technique in a photorefractive crystal. One of the methods corresponds to the already known randomization method [32] with potentially simpler experimental realization such as we use in our previous studies. But for the first time, we suggest a substantially different randomization method and compare them with the previous method, with additional improvement. We present a comprehensive numerical study of transverse light localization in such waveguides arrays. We aim at elucidating the effect of disorder on light propagation considering localization effects along propagation. The influence of lattice intensity on the diffraction rate is also analyzed; specifically differences in the localization while varying a nominal lattice intensity, as well as investigating the averaged lattice intensity. We discuss the effect of different choices for input excitation sites on the disorder-induced localization in such a system. Finally, the effect of the probe beam width on the localization effects is studied.

By gradually adding disorder to the lattice we demonstrate enhanced light transport of the probe beams for all disorder strengths, as well as show the transition from diffusive-like transport to the AL for higher disorder levels. More pronounced localization is observed for longer propagation distances even for lower disorder levels. We attribute effective beam width difference between two randomization methods to varying levels of lattice intensities. We observe more pronounced localization for one of the methods; shorter localization length decreases indicating more pronounced localization. It is shown that localization length differs along different directions, which we attribute to the lattice and crystal anisotropy. There is no noticeable difference in

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localization effects when probe beam excitation positions are distributed only on-site instead of uniformly. For broad Gaussian probe beams localization is not observed in such lattices.

2. Numerical modeling of light propagation in disordered lattices

By solving the coupled nonlocal system of two equations: the nonlinear Schrödinger equation, as propagation equation and a potential equation [34], we numerically simulate the weak nonlinear propagation of probe beam in the photorefractive cerium-doped strontium barium niobate (SBN) crystal with disordered aperiodic Mathieu lattices modeled as propagation invariant potential. Both propagation and potential equations are initial values problems with absorbing boundaries numerically solved by the symmetrized spectral split-step beam propagation method [35]. The propagation equation for an initial extraordinary polarized scalar electric field A (probe beam) with longitudinal wave vector k_z is

$$\mathrm{i}\partial_z A + \frac{1}{2k_z}\Delta_\perp A + \frac{k_z}{2n_{\mathrm{o,e}}^2}\delta n^2\left(|A|^2\right)A = 0. \tag{1}$$

The wave number $k = 2\pi/\lambda = \sqrt{(k_\perp^2 + k_z^2)}$ is defined by the wavelength $\lambda = 532\,\mathrm{nm}$. The potential in this equation is given by nonlinear refractive index $\delta n^2\left(|A|^2\right) = -n_{\mathrm{o,e}}^4 r_{13,33}E$, where $n_\mathrm{e} = 2.325$ and $n_\mathrm{o} = 2.358$ are the extraordinary and ordinary indices, and $r_{13} = 47\,\mathrm{pm/V}$, $r_{33} = 237\,\mathrm{pm/V}$ are corresponding electro-optic coefficients of photorefractive birefringent SBN crystal, respectively. The electric field $E = E_\mathrm{ext} + E_\mathrm{sc}$ that builds up inside the SBN crystal is a superposition of an external electric field $E_\mathrm{ext} = 2000\,\mathrm{V/cm}$ and an internal space charge field E_sc that is determined by the intensity distribution $I = |A|^2$ with a potential equation. The external electric field E_ext is aligned with the optical $c = x$-axis, perpendicular to the $z-$ axis, the direction of propagation, that is parallel to the long axis of the crystal.

In order to take photorefractive material response as well as the electric bias of the SBN crystal into account, we deploy the anisotropic, diffusive potential equation for the spatial evolution of the electrostatic potential ϕ_{sc} of the optically induced space-charge field E_sc,

$$\Delta_\perp\phi_\mathrm{sc} + \nabla_\perp \ln\left(1 + I + I_{DL}\right)\cdot\nabla_\perp\phi_\mathrm{sc} = E_\mathrm{ext}\partial_x \ln\left(1 + I + I_{DL}\right), \tag{2}$$

where I is obtained from Eq. (1) and subsequently Eq. (1) is updated with $E_\mathrm{sc} = \partial_x\phi_{sc}$, iteratively. Disordered lattice intensity distribution $I_{DL} = |A_{DL}|^2$, with input lattice intensity I_in, modeling transverse intensity distribution of nondiffracting pattern homogeneous in the propagation direction, is persistent through iterations. Experimental laser power P is connected with I_{DL} via I_in. Intensity and spatial distribution of I_{DL} determine $\delta n^2\left(|A|^2\right)$ in Eq. (1) through iterations. In this way, instead of modeling refractive index modulation $\delta n^2\left(|A|^2\right)$ directly, we model its underlying cause. Potential $I_{DL} = |A_{DL}|^2$ of disordered lattices $\boldsymbol{DL}$ is formed by coherently adding the two-dimensional original structure $\boldsymbol{L}$ and disorder pattern $\boldsymbol{D}$ with same maximum structure intensity according to the relation

$$A_{DL} = (1-p) * A_L + p * A_D, \tag{3}$$

where A stands for field amplitude. Parameter p is the relative contribution of the original structure and disorder pattern, which we identify as disorder strength (disorder level). By varying p $(0 \leq p \leq 1)$, considering it a uniform measure of disorder strength, we gradually adjust the level of lattice disorder relative to the original, undisturbed structure.

The whole process of writing propagation invariant disordered lattice is here abstracted and modeled through potential I_{DL} in Eq. (2), which we will further refer as a writing lattice pattern.

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Justification of substitution of the writing process with model potential I_{DL} is based on numerically simulation of writing process and the experimental realization of propagation invariant photonic lattices in SBN crystal as in our previous publication [22]. The same writing simulation is carried out as part of our preparation procedure to find a range of input lattice intensities I_{in} for which aperiodic Mathieu lattice stays stable and propagation invariant through the SBN crystal.

3. Two methods for the generation of disordered lattices

Here, we present two methods for the realization of two-dimensional propagation invariant disordered photonic lattices with adjustable disorder strength. We calculated the complex light field of disordered lattice for any disorder strength according to Eq. (3). Such calculated complex light fields of disordered lattices can be used as the writing light patterns for the generation of waveguide lattice by optical induction in the SBN crystal. Previous studies that applied the optical induction technique for realization of photonic lattices in birefringent SBN crystal, externally biased with an electric field aligned along the optical $c = x$-axis, and perpendicular to the propagation direction (z-axis), used the ordinary polarized writing beam with a laser power P, considered to be fairly linear in SBN crystal.

For each disorder strength, when the maximum lattice intensity of the resulting disordered lattice is left unscaled, we will refer to that case as the first method (*M1*), and laser power for experimental realization will vary with change disorder strength. The second method (*M2*) is characterized with scaling I_{DL} with I_{in} for each disorder strength, which effectively keeps the experimental lesser power constant. This distinction in methods results is the result of differences in potential experimental realizations.

For the proposed fabrication of the disordered lattices by the optical induction technique, which corresponds to M1 and M2 we can use our experimental setup from our previous study [22] using one spatial light modulator (SLM) which modulated writing beam, producing computer generating hologram. Another way for experimental realization of M1 based on experimental setup presented in Ref. [32] is to split the structure beam into two parts with controllable powers. The complex light field of the original structure would modify one part of the structure beam by the first SLM, while the complex light field of the disorder pattern addressed on the second SLM would modify the other part of the structure beam. Afterward, those two structure beams, which spectra in the transverse Fourier space are set to be located on the same circle with radius k to ensure the same propagation constant, coherently interfere to create propagation invariant disordered aperiodic lattice. In this way, a relative disorder strength would be indirectly deduced from structure beam powers.

In this paper, as the original undisturbed structure $\boldsymbol{L}$, we use aperiodic Mathieu structure designed by Mathieu Gauss beams, introduced in our previously paper [22]. Disorder pattern $\boldsymbol{D}$ is numerically calculated by interfering plane waves with constant amplitude and random phases, to generate the propagation invariant structure with random pattern in transverse dimension. We generate the disorder pattern whose spectrum in the transverse Fourier space is located on the same circle with radius k as the original undisturbed structure [36], to crate propagation invariant structures with the same propagation constant. The disorder pattern's mean grain size $2\pi/k$ is equal to the characteristic structure size $a = 25\mu m$ of Mathieu Gauss beams, used for the realization of the aperiodic structure. Transverse intensity distributions of the original aperiodic Mathieu structure and disorder pattern, that constitute disordered lattice $\boldsymbol{DL}$ created according to Eq. (3), are shown in Figs. 1 (A1) and (B1), respectively. By increasing disorder strength we change the geometry of the original structure until we completely substitute the original structure with a disorder pattern. As the difference in methods causes two choices of intensity scaling, we will investigate and compare the consequences of such scaling options. For both methods, variation of disorder strength p leads to the variation of writing lattice intensity, effectively correlating disorder strength with writing lattice intensity and indirectly with optically induced

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refractive index modulation inside the crystal. For the same disorder levels averaged lattice intensities differ for M1 and M2, causing differentiation in propagation characteristics under these method's conditions. Transverse intensity distributions of disordered aperiodic lattices with 40% disorder for these two methods are presented in Fig. 1 (C1) and Fig. 1 (D1). Their displayed area is less than 3% of the whole transversal computational space.

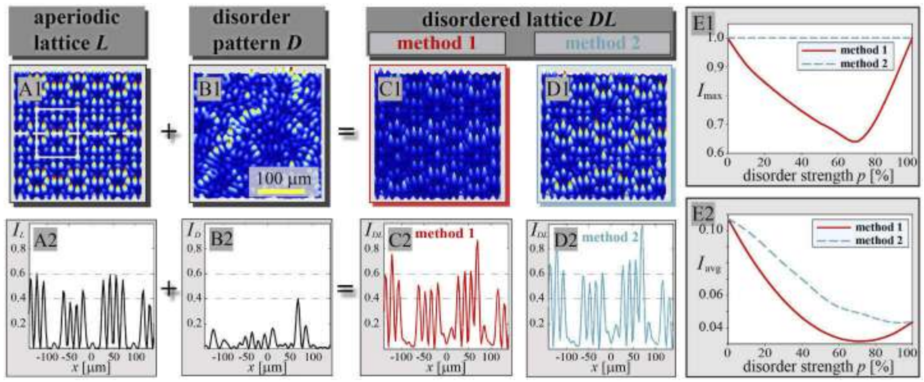

Fig. 1. Two methods of modeling disordered lattices. The transverse intensity distribution of: (A1) aperiodic lattice, with white box indicating typical pattern; (B1) disorder pattern; (C1) and (D1) disordered aperiodic lattices with 40% disorder for M1 and M2, respectively. (A2) - (D2) Corresponding representative lattice intensity cross-section taken along the x-axis marked with a white dashed line in (A1); dashed lines indicate maximum intensities of original lattice and disorder pattern. The maximum lattice intensity (E1) and the averaged lattice intensities (E2) versus disorder strength for different methods.

As an illustration of Eq. (3) in Figs. 1 (A2) - (D2) we present a single typical intensity cross-section along the x-axis (y-position indicated with a dashed line in Fig. 1 (A1)) for aperiodic lattice, disorder pattern, and resulting disordered aperiodic lattices with 40% disorder for two different methods. Levels for $p = 0.4$ and $1 - p = 0.6$ are dashed and coincide with maximum intensities of disorder and aperiodic structure, respectively. Unlike the periodic lattice, our aperiodic lattice is not uniform in the waveguide's distances and their depths vary. For M1 and M2 spatial distribution of the disordered aperiodic lattices are the same, but they differ in waveguides depths as M2 intensity values are greater than M1 intensity values (red and blue plots in Figs. 1 (C2) and (D2)).

We noted that the disorder strength p changes the lattice intensity, hence in addition to maximum lattice intensity I_{max}, we calculate averaged lattice intensity $I_{\text{avg}} = \sum_r I_{DL}(\mathbf{r}) = \sum_{\mathbf{r}} |A_{DL}(\mathbf{r})|^2$, representing the level of influence of potential term in Eq. (2). The resulting differentiation of our methods in I_{max} and I_{avg} dependence on disorder strength is shown in Figs. 1 (E1) and (E2), respectively. In the first method disordered aperiodic maximum lattice intensity and the averaged lattice intensity decrease from 0% to 70% disorder, afterward increase. For 100% disorder, only maximum lattice intensity returns to an input value. In the second method, the maximum lattice intensity of disordered aperiodic lattice is equal to I_{in} for all disorder strengths, but averaged lattice intensity always decreases with increasing disorder strength. Both the maximum lattice intensity and the averaged lattice intensity for M1 are lower than for M2, except for 0% and 100% disorder. Assuming the same disorder pattern, both methods produce the same lattices for 0% and 100% disorder strengths we will exclude these two endpoints when we discuss method differences.

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4. Quantitative description of localization phenomenon

To investigate the transverse light localization in disordered lattices, we statistically analyzed probe beam propagation for different excitation positions selected to involve various local environments. For probe beam excitation positions we use an equidistant 8×8 grid covering one complete typical pattern depicted in Fig. 1 (A1). We performed such analysis, averaging 64 various probe beam intensity distributions at the different propagation distances, for several disorder levels. For each disorder level, we have different realizations of the disordered lattice that are spatially similar due to fixed deterministic disorder pattern with statistical sampling spanning excitation probe positions only (N=64). In the preliminary investigations, we perform statistics with several different fixed disorder patterns and concluded that the statistical quantities and their dependence of disorder we want to report are not significantly influenced by the choice of disorder pattern. Due to the aperiodicity of our lattice, not each typical pattern is the same so we perform N=64 statistics on several of them, again finding no significant variation in statistical quantities of interest. Based on this preliminary analysis we did not vary the disorder pattern between different realizations of disordered lattices.

For comparison, in addition to sampling equidistant excitation positions (uniform), we also perform the statistical analysis sampling on-site positions, exciting only positions of waveguides. On-site excitation positions are chosen according to the positions of aperiodic lattice waveguides, which implies that for higher disorder strengths these positions become less accurate as waveguide's positions and depths are modified by randomization. The process of defining and numerically detecting waveguides positions modified by disorder is time-consuming and we did not pursue it, therefore we abstained from giving strong conclusions regarding on-site positioning at higher disorder levels.

In order to characterize light propagation and localization, we calculate the effective beam width along the propagation distance z according to the relation

$$W_{eff}(z) = P(z)^{-1/2}, \tag{4}$$

where $\mathrm{P}(z) = (\int |A(x,y,z)|^4 dxdy)/(\int |A(x,y,z)|^2 dxdy)^2$ is the inverse participation ratio [8]. We present scaled averaged effective beam width $\langle \omega_{\mathrm{eff}} \rangle = W_{\mathrm{eff}}(z)/(W_{\mathrm{eff}}(0)/FWHM)$ where $FWHM$ is probe beam full width at half maximum. In addition to averaged transverse output intensity distribution, we consider the log-plot profiles of such output intensity distributions to further describe light propagation. Parabolic log-plot fit indicates diffusive-like transport. The exponential decay of the transverse intensity distribution profile determines light localization, hence the linear fit of log-plots of such intensity profiles around the center demonstrates AL. In the region of disorder strength where AL occurs, we obtain localization length ξ_x along the x-axis by fitting intensity profiles $\mathrm{I}(x, y_0)$ with the exponential function

$$I(x, y_0) = \exp\left(-2\frac{|x - x_0|}{\xi_x}\right), \tag{5}$$

where x_0, y_0 denote the position of the beam center. The analogous procedure is applied along the y-direction. In some intermediate cases, when the linear fit is not obvious we compare the goodness of fit of parabolic and linear fits, where higher goodness of fit (closer to 1) indicates preferable fitting of the log plots. Hence, we use the goodness of fit to confirm a suitable fit, linear, or parabolic i.e. to discern the diffusive-like transport or AL. By shrinking the domain where we fit log-plots we notice an increase of the goodness of fit, indicating that localization occurs in a finite central domain, not in whole computation space.

5. Light transport and localization in disordered aperiodic lattices

We compare effects along light propagation in disordered aperiodic lattices generated with two different randomization methods. Figure 2 summarizes the difference between the two methods

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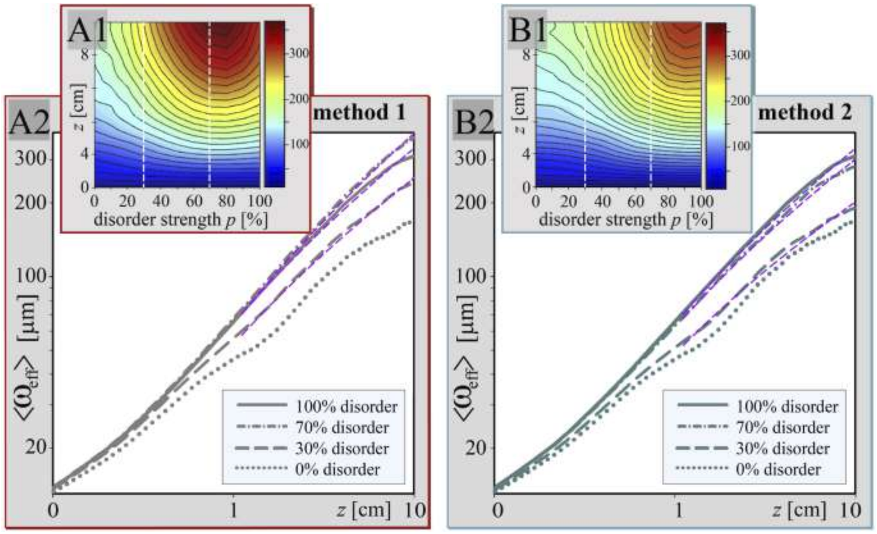

Fig. 2. Comparison of diffraction dependence on disorder strength and propagation distance for two methods. $\langle\omega_{\text{eff}}\rangle$ for various disorder strengths along the propagation distance for: (A1) M1, and (B1) M2; the colormaps display $\langle\omega_{\text{eff}}\rangle$ [μm]. $\langle\omega_{\text{eff}}\rangle$ along the propagation distance for 0%, 30%, 70%, 100% disorder strengths on a double logarithmic scale for: (A2) M1, and (B2) M2. Parameters: input Gaussian probe beam *FWHM* is 8 μm and $I_{\text{in}} = 0.7$.

considering scaled averaged effective beam width $\langle\omega_{\text{eff}}\rangle$. Figures 2 (A1), (B1) display the difference between the two methods presenting $\langle\omega_{\text{eff}}\rangle$ along the propagation distance for various disorder strengths. $\langle\omega_{\text{eff}}\rangle$ during the propagation increases for all disorder strengths. Beam expansion is maximal in the region of 60% to 80% disorder strength for M1 (Fig. 2 (A1)), and in the region of 80% to 90% disorder strength for M2 (Fig. 2 (B1)) indicated with a distribution of points where black isolines cross vertical sections. Examining the horizontal cross-sections from Figs. 2 (A1) and (B1) for each propagation length we confirm DET occurrence. For both methods during the propagation when disorder strengths deviate from that region, we observe the deceleration of $\langle\omega_{\text{eff}}\rangle$ increase. For deviation from disorder strength with maximal beam expansion toward lower disorder strengths, we observe a reduction of DET while for deviation toward higher disorder strengths reduction of DET could be attributed to AL. But, in the case of our lattice, this process is strongly mediated with variation in aggregate lattice intensity, so that we could not identify AL as the sole cause. To confirm that AL of light occurs, and for which disorder levels, we will investigate where the log-plots of the averaged intensity distributions are linearly fitted near the center.

For both methods, in Figs. 2 (A2), (B2) we present $\langle\omega_{\text{eff}}\rangle$ as a function of propagation distance z (on a double logarithmic scale), for four disorder strengths. A purple dashed lines define fits of $\langle\omega_{\text{eff}}\rangle$ by power-law $\langle\omega_{\text{eff}}\rangle(z) \propto z^{\nu}$, for M1 and M2, respectively. ν corresponds to beam expansion rate: $\nu = 1$ signifying ballistic transport and $\nu = 0.5$ characterize diffusive-like transport. For a short propagation distance (z<1 cm), beam expansion is almost linear ($\nu = 1$ i.e. ballistic transport). For a longer propagation distance (from 1 cm to 10 cm), the beam expansion rate is closest to $\nu = 0.5$ i.e. diffusive-like transport. For M1 is maximal for 70% $\nu = 0.52$ and lower $\nu = 0.48$ for both 30% and 100%. For M2 the beam expansion rate is maximal for 100% $\nu = 0.48$ and lower for 70% and 30%, $\nu = 0.47$ and $\nu = 0.45$, respectively.

For both methods in the disordered aperiodic lattice with any percent of disorder $\langle\omega_{\text{eff}}\rangle$ is greater than in the lattice without disorder indicating DET, which could be explained that disorder spreads linear modes [32] (Fig. 3 (A)). At the shorter propagation distance ($z = 2$ cm), $\langle\omega_{\text{eff}}\rangle$s

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are increasing with increasing disorder strength. A broadening of the beam is more pronounced for longer propagation distances ($z = 6$ cm and 10 cm). There we notice that $\langle\omega_{\text{eff}}\rangle$s at the fixed propagation distances are increasing up to the maximum values which occur at disorder strength 80% for M1 and 90% for M2, indicating maximum of DET. With the further increase of disorder strength, $\langle\omega_{\text{eff}}\rangle$s are decreasing indicating the possibility of AL occurrence. Corresponding $\langle\omega_{\text{eff}}\rangle$s have greater values for M1 than for M2, which is easily discerned from Fig. 3 (A).

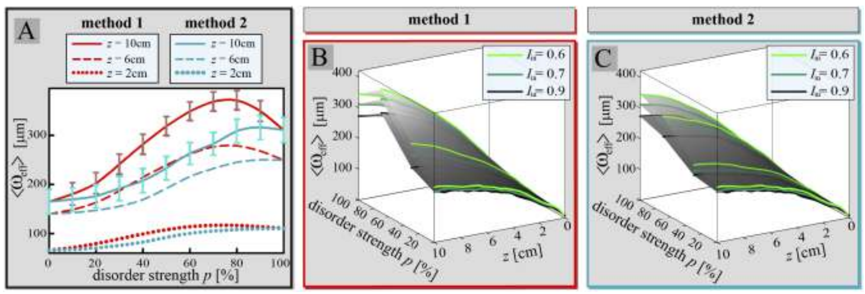

Fig. 3. Influence of disorder strength p and input lattice intensity I_{in} on the light diffraction. (A) $\langle\omega_{\text{eff}}\rangle$ versus disorder strength after 2 cm, 6 cm, and 10 cm of propagation for $I_{\text{in}} = 0.7$ for both methods. The error bars are the statistical standard deviations of $\langle\omega_{\text{eff}}\rangle$. (B) M1 and (C) M2: interpolated surfaces of $\langle\omega_{\text{eff}}\rangle$ along the propagation distance for 0%, 30%, 70%, 100% disorder strengths and for various I_{in}. Other parameters are as in Fig. 2.

The following study is the independent verification of the influence of input lattice intensity I_{in} on diffraction. We compare $\langle\omega_{\text{eff}}\rangle$s in dependence of disorder strength along propagation distance for 3 different values of the input lattice intensity I_{in}. Figures 3 (B), (C) summarize $\langle\omega_{\text{eff}}\rangle$ for two methods where we highlight lines of constant disorder strength along the propagation distance. By observing slopes of highlighted lines for each I_{in}, we illustrate the beam expansion explained in the description of Fig. 2. For all disorder strengths and propagation distances, we observe the direct influence of lattice intensity on diffraction, for both methods, where lowering I_{in} causes an increase in $\langle\omega_{\text{eff}}\rangle$. Since the explicit independent increase in lattice intensity leads to a similar effect as the inclusion of weak nonlinearity in disordered lattices, indirect change in intensity due to correlation with variation of disorder strength can also influence AL [7,8]. This effect will especially be visible in Figs. 6 and 7, where comparing log-plots of average intensity distributions for two methods for the same higher disorder strengths, observing that M1 which has lower lattice intensity than M2, produces lover central picks and higher tails, similar to Refs. [7,8].

The main difference in our methods is caused by the difference in the maximum lattice intensity I_{max}, which is varying with change of disorder strength for the first method, while it is constant for the second method, as well as different variations of the averaged lattice intensities I_{avg} with the change of disorder strength for different methods (Figs. 1 (E1), (E2)). For both methods, $\langle\omega_{\text{eff}}\rangle$ variation versus disorder strength is different for different propagation distances (Fig. 3 (A)). We notice that $\langle\omega_{\text{eff}}\rangle$s after a longer propagation distance (10 cm), have a dependence on disorder strength similar to I_{avg} (Fig. 1 (E2)). Hence, to investigate this connection, we normalize $\langle\omega_{\text{eff}}\rangle$ and reciprocal averaged lattice intensity $(I_{\text{avg}})^{-1}$ according to relation $F(p)/(F(1) - F(0)) - F(0)$, where F is $\langle\omega_{\text{eff}}\rangle$ or $(I_{\text{avg}})^{-1}$, and p is disorder strength. We present them, as well as their differences in Fig. 4 for both methods. For both methods, variations of normalized $\langle\omega_{\text{eff}}\rangle$ closely follow $(I_{\text{avg}})^{-1}$. Therefore, we conclude that $\langle\omega_{\text{eff}}\rangle$ is strongly influenced with the variation in $(I_{\text{avg}})^{-1}$ versus disorder strength for longer propagation distances, for narrow probe beam width.

Deviation of $\langle\omega_{\text{eff}}\rangle$ and $(I_{\text{avg}})^{-1}$ graphs is quantified with their difference, quantity that contains the influence of parameters not directly connected to the lattice intensity, such as lattice and beam shapes. For M2 where the dependence of $(I_{\text{avg}})^{-1}$ on p is monotonous, distributions of $\langle\omega_{\text{eff}}\rangle$ and

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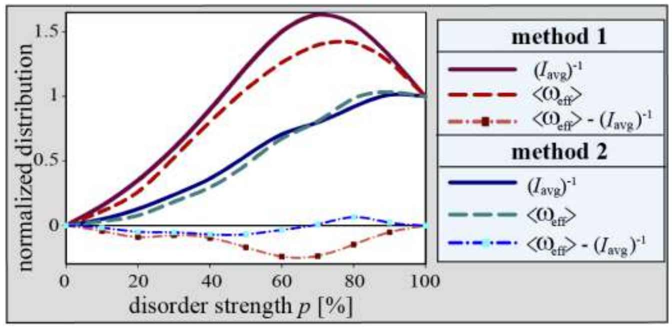

Fig. 4. Comparison of methods via $\langle\omega_{\rm eff}\rangle$ and $(I_{\rm avg})^{-1}$. Normalized $\langle\omega_{\rm eff}\rangle$, $(I_{\rm avg})^{-1}$ and their differences for both methods as a function of disorder strength. Other parameters are as in Fig. 2.

$(I_{\rm avg})^{-1}$ and $(I_{\rm avg})^{-1}$ vs. p closely overlap. We associate a dip of deviation for M1 in Fig. 4 with a sharp minimum in dependence of the maximum lattice intensity $I_{\rm max}$ versus p (Fig. 1 (E1)) and also with a minimum in $I_{\rm avg}$ versus p (Fig. 1 (E2)), occurring at the same disorder level. As we demonstrate in Fig. 3, light diffraction is reverse proportional to input lattice intensity. Hence, for the minimum of the maximum lattice intensity in M1, we have the highest $\langle\omega_{\rm eff}\rangle$ (maximal DET). The narrow probe beam for low lattice intensity diffracts the most, but at longer propagation distances $\langle\omega_{\rm eff}\rangle$ does not reach the variation of $I_{\rm avg}$ as at minimal lattice intensities beam already rapidly expanded early in propagation. Further in this section, we will independently study probe beam width influence on diffraction in our lattice.

We analyze the averaged transverse intensity distributions of probe beam along the propagation distance by using the log-plot cross sections of averaged intensity distributions and localization lengths. Figures 5 (A) - (D) summarize the averaged transverse intensity distributions of probe beam for some disorder strengths and some propagation distances. Parallelly, we investigate a suitable log-plot cross section along the x-axis (gray/red/cyan plots) and y-axis (black/dark red/dark cyan plots) in Fig. 6.

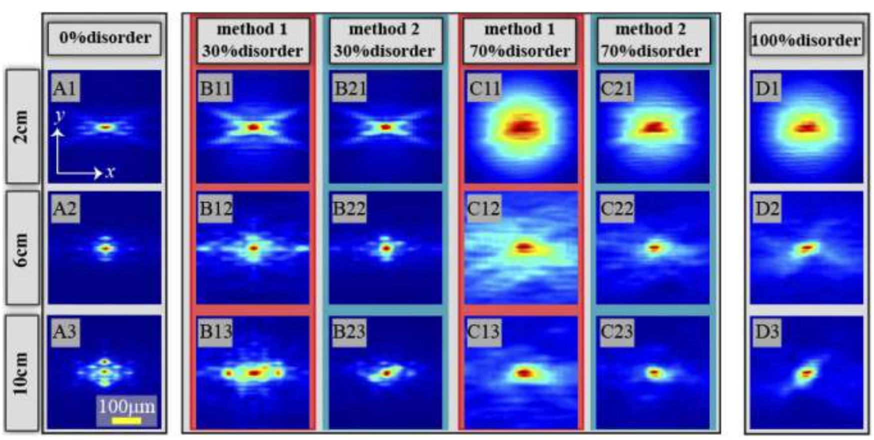

Fig. 5. Disorder-induced light transport and localization in aperiodic Mathieu lattice. Numerically averaged intensity distributions at the lattice output for different disorder strengths at different propagation distances. Other parameters are as in Fig. 2.

Figure 5 (A) depicts averaged intensity distribution in aperiodic lattice without the disorder, for 3 different propagation distances (2 cm, 6 cm, and 10 cm), demonstrating discrete diffraction of light, also visible in Fig. 6 (A). Figures 5 (B), (C) present averaged intensity distributions for two values of disorder strength (30% and 70%) after 3 propagation distances for both methods; suitable log-plot cross section along the x-axis (red and cyan plots) and y-axis (dark red and dark cyan plots) are presented in Figs. 6 (B), (C). For 30% disorder averaged intensity distributions and the log-plot cross sections near the center are broader for M1 than for M2. More pronounced diffraction, i.e. DET for M1 is evident (Figs. 5 (B), Fig. 6 (B)). Also, the less pronounced diffraction of light along the y-direction, for both methods, is noticeable due to the crystal ($r_{33}>>r_{13}$) and lattice anisotropy (Fig. 1 (A1)).

With further increasing disorder strength (>30%), averaged intensity distributions and the log-plot cross sections near the center are broadened, indicating DET. Additionally, the diffraction and localization effects are more noticeable along the y-transverse direction, for both methods, due to the crystal and lattice anisotropy: as visible for 70% disorder strength at $z = 2$ cm (Figs. 6 (C11), and (C21)). The interplay of lattice and crystal anisotropy influence is evident for shorter propagation distances in the log-plot cross sections near the center for M1 (Figs. 6 (C11)), where the log-plot along the x-axis is fitted with parabola, indicating diffusive-like transport, while the log-plot along the y-axis is linearly fitted indicating light localization. At the same time, as the influence of lattice anisotropy is mediated with lattice intensity, for M2 the log-plots cross sections near the center along the x- and y-axis are linearly fitted (Fig. 6 (C21)). The localization length is shorter along the y-axis, indicating that localization is still stronger in this direction. The influence of the lattice and crystal anisotropy persists for longer propagation distances (Figs. 6 (C12), (C22), (C13), (C23)), which will be illustrated with different localization lengths along the x- and y-direction in Fig. 8. Also, localization lengths in both directions for M2 are shorter than for M1, which shows that stronger localization occurs for M2.

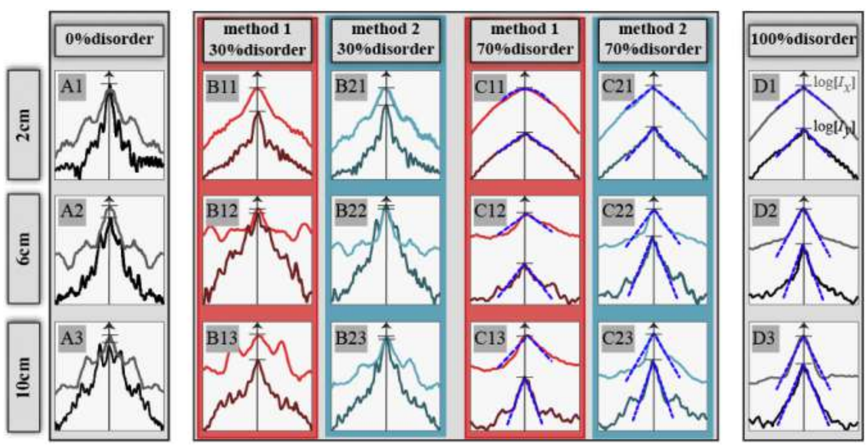

Fig. 6. Comparison of light localization along different directions. Log-plot cross sections of averaged intensity distributions along the x-axis (gray/red/cyan plots) and y-axis (black/dark red/ dark cyan plots), for different disorder strengths: (A) 0% , (B1), (B2) 30%, (C1), (C2) 70% and (D) 100%; blue dashed lines are corresponding linear fits. The horizontal axes span 400 µm in the x- and the y-direction. For each plot, there are two stacked vertical axes, where short horizontal bars are set on 1's. Other parameters are as in Fig. 2.

For 100% disorder, we notice even more pronounced localization with a longer propagation distance (Fig. 5 (D), and Fig. 6 (D)). Also, more pronounced localization is along the y-axis than the x-axis. Since, for 100% disorder, the original lattice does not contribute to anisotropy and the disorder pattern, we use in our study, does not have clear x-y anisotropy preference, we conclude that the direction of crystal anisotropy is primarily cause of more pronounced localization in the y-direction. On the other hand, the asymmetry of log plots (along any axis and arbitrary disorder level) is due to the specific occurrence of the used disorder pattern. The influence of the disorder pattern anisotropy (not along x-y-direction) is noticeable at some probe beam transverse intensity distributions, as can be discerned comparing Figs. 5 (D2) - (D3) with Fig. 1 (B1).

To mitigate asymmetry of the log-plot cross-sections of averaged intensity distributions we use the average of the left and right sides of such profiles along the x-axis from the center. We fit such averaged log-plots cross sections and calculate the localization length according to Eq. (5) for disorder levels where the log-plot cross sections are linearly fitted. Figure 7 depicts a comparison of localization along the x-axis in our two methods for various disorder strengths and two propagation distances (4 cm and 8 cm). For lower disorder strengths we do not fit the log-plots (Figs. 7 (A1) and (B1)), where significant features of aperiodic lattices are remaining. However, we notice the spreading of the log-plots simultaneous with increased $\langle \omega_{\text{eff}} \rangle$, indicating that DET occurs. For both methods, at disorder strength between 50-60% at the shorter propagation distance (4 cm) light diffraction is closest to diffusive-like transport where the parabolic fits of the log-plots near the center could be attempted with low confidence (goodness of fit lower than 0.85). But, this tendency is further weakened at a longer propagation distance, so after 8 cm of propagation for 60% disorder log-plots are linearly fitted near the center indicating light localization (Fig. 7 (B2)). For higher disorder strength (80% and 100%) light localization is visible for the shorter propagation distance (4 cm, Fig. 7 (A2)), but more pronounced localization is evident for longer propagation distances also proved by linear fits of log-plots. One can see more pronounced localization for M2 than M1: log-plot fits for the same disorder level are steeper for M2, the slopes of the fits determine localization lengths.

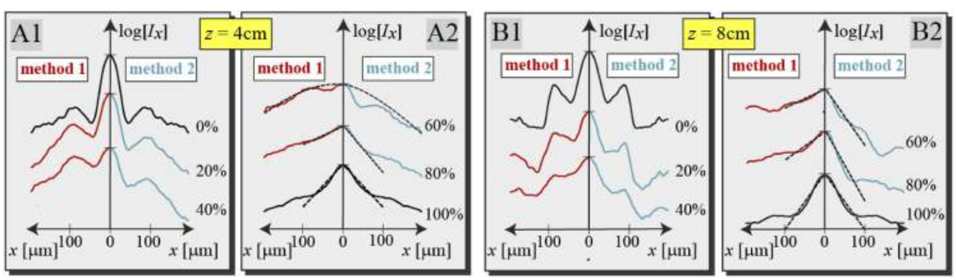

Fig. 7. Comparison of light localization in two methods for various disorder strengths and two propagation distances. Log-plot cross sections of intensity distributions symmetrized over left and right side of the x-direction, for M1 (left), M2 (right), and different disorder strengths after (A1)-(A2) 4 cm, and (B1)-(B2) 8 cm of propagation. The y-axes stacked similarly as in Fig. 6 and the other parameters are as in Fig. 2.

We characterize light localization by comparing the localization length (Eq. (5)) of linearly fitted log-plots along the x- and y-direction (Fig. 8) after 10 cm of propagation. The localization lengths in either direction are greater for M1 than for M2 indicating more pronounced localization for M2, qualitatively connecting lattice intensity with AL strength. For both methods, more pronounced localization is visible along the y-axis where the localization lengths have lower values comparing to the x-axis, due to the crystal and lattice anisotropy. One can see that differences between localization lengths are larger for lower disorder strengths, while their values converge to each other as disorder strength increases, meeting at 100% disorder strength; a similar conclusion stands for $\langle \omega_{\text{eff}} \rangle$s (Fig. 2 (A)). We notice that AL occurs at different disorder levels along different directions. Along the y-axis, localization appears for lower disorder strengths than along the x-axis. Figure 8 illustrates diffusive-like transport along the x-axis and light localization along the y-axis for the same 50%-60% disorder region.

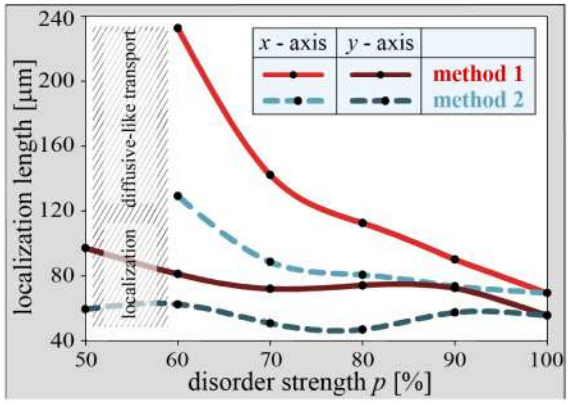

Fig. 8. Comparison of localization lengths after 10 cm of propagation distances for various disorder strengths for both methods and both the x- and y-directions. Other parameters are as in Fig. 2.

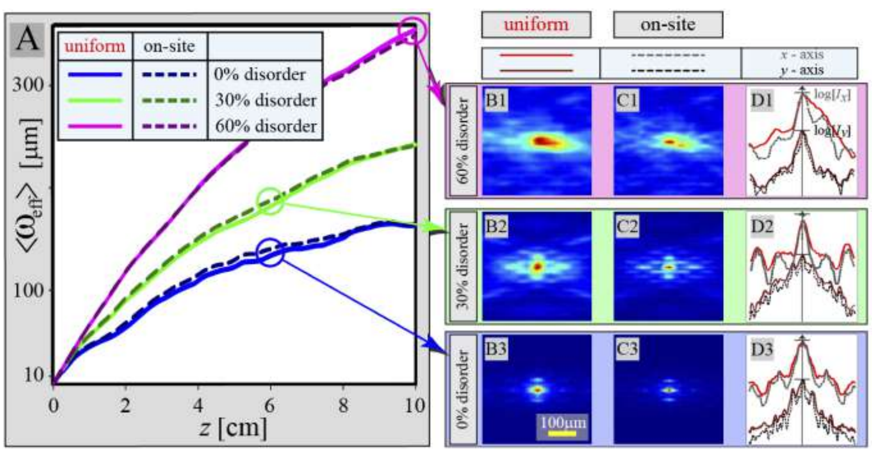

Fig. 9. Influence of probe beam excitation positions on the diffraction and localization (for M1). (A) $\langle \omega_{\text{eff}} \rangle$ versus propagation distances for uniform excitation positions and only on-site positions for different disorder strengths. (B) and (C) Appropriate averaged intensity distributions at the lattice output. (D) Log-plot cross sections of averaged intensity distributions along the x-axis (red/gray plots) and y-axis (dark red/black plots) for uniform and on-site positions for different disorder strengths. Other parameters are as in Fig. 2.

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Moreover, we study the consequences of the choice of excitation probe beam positions distribution on the beam propagation. Statistics presented up to this point was based on the uniform distribution of probe beam excitations regardless of waveguide positions. Further, we investigate if the choice of only on-site excitation positions significantly changes the diffraction and localization characteristics. Figure 9 summarizes such results for M1. We compare $\langle\omega_{\text{eff}}\rangle$s for three disorder levels (Fig. 9 (A)) and observe slight differences between uniform and on-site excitation. Appropriate averaged intensity distributions are presented in Figs. 9 (B), (C) as well as their log-plots along the x- and y-axis (Fig. 9 (D)). We notice dissimilarity in $\langle\omega_{\text{eff}}\rangle$s for uniform one and on-site cases, at the different propagation distances for 0% and 30% disorder than for 60% disorder. $\langle\omega_{\text{eff}}\rangle$ has higher values for on-site excitation cases than for uniform, especially for lower disorder strengths (0% and 30%) after 6 cm propagation distance. However, for higher disorder strength (60%) $\langle\omega_{\text{eff}}\rangle$ is greater for uniform excitation case after 10 cm propagation distance. Such difference is caused by different computational spaces: the effective beam width is calculated for the whole computation space, with the significant contribution of tails in calculations, while the transverse intensity distributions and the log-plots are shown for the shorter (central domain), where tails contributions are discounted. Also, discrete diffraction is more pronounced for lower disorder strength for on-site excitation cases than for uniform cases, as is visible from intensity distributions and log-plots (Figs. 9 (B2) - (D2), and (B3) - (D3)). For 60% disorder, discrete diffraction is not observed for the on-site case, due to the diminished accuracy of on-site positions for higher disorder strengths. For all disorder strengths, the weaker difference is in log-plots along the y-direction. Asymmetry of log-plots is due to the specific occurrence of the used disorder pattern. However, the consequence of this choice is unsubstantial on statistical quantities.

In this research, we observe that dependence of light diffraction on various parameters is more noticeable for longer propagation. However, the question remains if the wider beams that are consequences of longer propagation distance lose their sensitivity to the local environment and thus hinder the accuracy of diffraction properties investigation. We observed different rates of increase of averaged effective beam width during propagation in our disordered lattices and consequently a variety of beam widths and shapes. Hence, we investigate the independent influence of probe beam width on light transport and localization in our disordered lattices in comparison to the free space propagation of the Gaussian beam. Figure 10 summarizes such results.

We choose three various input probe beam widths (8μm, 20μm, and 50μm). Averaged effective beam widths are considered along the propagation distance for different disorder strengths: 0%, 70%, and 100% (Fig. 10 (A)). More pronounced light transport is observed for narrower probe beam widths. Strong correlation of $\langle\omega_{\text{eff}}\rangle$ with I^{-1}_{avg} for input probe beam of 8μm presenting in Fig. 4, gradually diminish for wider probe beams. Also, wider probe beam reduces their sensitivity on disorder strength p and propagation distance, making wider beams less suitable for our investigation. Appropriate averaged intensity distributions after 4 cm propagation are presented in Figs. 10 (B), (C), (F). For 70% disorder, the log-plots along the different domains of the x-axis are shown in Fig. 10 (D) for different input probe beam widths, while Fig. 10 (E) present only their central domain along the x-axis of 400μm. We show that for all probe beam widths, along the x-axis in our disorder lattices light is spreading to the same degree as the Gaussian in free space propagation. Different domains along the x-axis represent the degree of diffraction for different probe beam widths (Fig. 10 (D)). However, a significant difference between the log-plots in our disordered lattice and the log-plots of Gaussian free space propagation is noticeable only in a limited central domain after the same propagation distance (Fig. 10 (E)). For narrow probe beam widths (8μm and 20μm), Figs. 10 (E1) (E2), localization occurs in the central domain with a size comparable to the size of the typical lattice pattern. In contrast, a wide probe beam (50μm)

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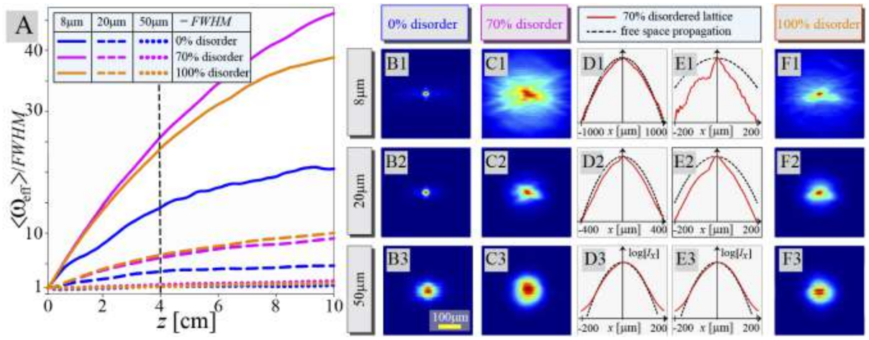

Fig. 10. Influence of probe beam width on the localization effects for M1. (A) Normalized $\langle\omega_{\mathrm{eff}}\rangle$s versus propagation distances for three probe beam widths and different disorder strengths. Appropriate averaged intensity distributions after 4 cm (the dashed line in (A)) propagation distance for various disorder strengths: (B) 0%, (C) 70%, (F) 100%. (D) Log-plots of averaged intensity distributions along the x-axis in disordered lattice with 70% disorder strength compared with corresponding log-plots of Gaussian free space propagation. (E) The same log-plots along the x-axis as in (D) for narrow central domain from -200 to 200 μm. Other parameters are as in Fig. 2.

barely diffracts, i.e. propagates almost the same as a wide Gaussian beam in free space, limiting suitable widths of the probe beam for lattice excitation.

6. Conclusion

In this article, we presented two different theoretical methods for the realization of disordered two-dimensional photonic lattices optically induced in a photorefractive media. We numerically model light propagation in disordered aperiodic Mathieu lattices. We observed enhanced light transport for all disorder strengths but AL of light for higher disorder strengths in both methods. Localization effects are more pronounced for longer propagation distances. More pronounced localization is observed for M2 than M1: we attributed the difference between the two methods to various levels of lattice intensity. When studying the dependence of AL and DET on disorder level, to mitigate the influence of lattice intensity, we suggest further modification of our M2 in which averaged intensity levels are equalized for every disorder strength used. Localization length differs along different directions, due to the crystal and lattice anisotropy. There is no noticeable difference in localization effects if we choose only on-site probe beam excitation positions, as compared to uniform position distribution. For broad probe Gaussian beams localization is not observed in such lattices.

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Optics Letters

Light transport and localization in disordered aperiodic Mathieu lattices

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Complex optical systems such as deterministic aperiodic Mathieu lattices are known to hinder light diffraction in a manner comparable to randomized optical systems. We systematically incorporate randomness in our complex optical system, measuring its relative contribution of randomness, to understand the relationship between randomness and complexity. We introduce an experimental method for the realization of disordered aperiodic Mathieu lattices with numerically controlled disorder degree. Added disorder always enhances light transport. For lower disorder degrees, we observe diffusive-like transport, and in the range of highest light transport, we detect Anderson localization. With further increase of disorder degree, light transport is slowly decreasing and localization length decreases indicating more pronounced Anderson localization. Numerical investigation at longer propagation distances indicates that the threshold of Anderson localization detection is shifted to lower disorder degrees.

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Localization of light has drawn considerable attention in many areas of light–matter interaction owing to the evident potential for the realization in disordered media [1–4]. In contrast, Anderson localization (AL) is a well-known effect in condensed-matter physics, which predicts that electrons may become immobile in a disordered crystal. This concept of waves in disordered media has been subsequently transferred to many other areas, such as matter waves, ultracold atoms, and light or sound waves [2]. Realizing that AL is a wave phenomenon relying on interference, these concepts were extended to optics and photonics. The AL of light has been successfully demonstrated in various customized configurations, when the disorder degree (DD) is increased [5–10]. In optically induced disordered photonic quasicrystals with weak disorder, it is observed that weak disorder enhances light transport. When increasing disorder finite-time, diffusive-like transport appears, while a further increase of disorder leads first to coherent backscattering [11] and for the strong disorder to AL. Thereby, the spatial extent of the probe beam decreases and its central part of the log-plot intensity profile displays an exponential decay [9,12,13].

In nature, perfect periodicity, in contrast to disorder or aperiodicity, is not very often encountered. Deviation from periodicity results in higher complexity. In optics, the properties of various photonic quasicrystals and aperiodic systems have been studied [13–18]. Considering localization characteristics, such structures lie between periodic and random structures. Numerous aperiodic and quasiperiodic photonic structures have been realized artificially [19–21]. Non-diffracting beams, with propagation invariant transverse intensity distributions, are applicable in modern photonic research e.g. numerous two-dimensional aperiodic photonic lattices have been optically induced in photosensitive media using them [21–23]. Aperiodic lattices contain non-uniform distances between the lattice sites with non-homogeneous intensity depth distributions, and hence light propagation crucially depends on the nature of the local environment of the probe beam positions. In contrast that occurring in periodic systems, light diffraction is hampered owing to the aperiodicity [12,21,22,24]. Still, light localization in aperiodic lattices is an unexplored area of research, especially in randomized aperiodic lattices. In our previous studies, we introduced a method for the creation of various two-dimensional aperiodic photonic structures by the interference of Mathieu beams, experimentally realized in a single optical induction process in parallel [23]. We showed that such obtained aperiodic Mathieu photonic lattice (AML) hinders linear light expansion in comparison to periodic lattice and supports nonlinear light localization[24].

In this Letter, we introduce a numerical method for controllable randomization of AMLs to investigate if they support AL. We construct an experimental system for the realization of disordered lattices by a single optical induction process in parallel using a spatial light modulator (SLM) and numerically precalculated disordered patterns with adjustable DDs. This numerical method and experimental configuration, in comparison to the previous one [5,12], enable us direct control of the lattice DD and parallel optical induction of the corresponding light intensity in the whole volume of the photorefractive crystal.

Here, we investigate the light propagation in disordered AMLs numerically and experimentally. We study the conditions for light localization in such lattices as well as the effects of disorder during the propagation. For all DDs, we experimentally obtain and numerically confirm disorder-enhanced transport in

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such lattices. For lower DDs, we observe diffusive-like transport. In contrast, for strongly disordered lattices, AL is verified. We demonstrate that the localization length differs along different transverse directions owing to the crystal and lattice anisotropy. We also confirm numerically a more pronounced localization for longer propagation distances, while for lower DDs, the AL prevails over diffusive-like transport for longer propagation distances.

To realized disordered aperiodic lattices with an adjustable DD, we generate numerically a two-dimensional disordered aperiodic Mathieu structure ***DS*** by combining the original aperiodic Mathieu structure ***S*** with disorder pattern ***D*** according to the relation:

$$A_{\mathrm{DS}} = (1-p) * A_{\mathrm{S}} + p * A_{\mathrm{D}}, \tag{1}$$

where A stands for the field amplitude and the parameter p ($0 \le p \le 1$) denotes the DD as the relative contribution of the original structure and disorder pattern. We experimentally generate the aperiodic Mathieu structure as a combination of the spatially shifted patterns from Fig. 3(e1) of Ref. [23] with the x and y shifts of 144 and 152 μm, respectively. Such a structure has an invariant transverse intensity profile during propagation, with Fourier components located on a circle with radius $k_\perp$ [23,25]. A two-dimensional disorder pattern is numerically created by interfering plane waves with constant amplitude and random phases [9]. We generate a propagation invariant disorder pattern whose spectra are located on the same circle in the transverse Fourier space as the original aperiodic structure. The grain size of the disorder pattern plays a significant role in the propagation behavior [9], and we specify it to be equal to the characteristic structure size of the Mathieu–Gauss beams used for the realization of the original aperiodic structure.

We use the experimental configuration presented in Fig. 1 to fabricate and probe two-dimensional disordered AMLs. The laser source is a frequency-doubled Nd:YVO_4 laser that emits continuous wave laser light at a wavelength of $\lambda = 532$ nm and a maximum power of 5 W. The expanded and subsequently collimated laser beam is divided into two separate beams – the writing beam being ordinary polarized and an extraordinary polarized probe beam. The writing beam optically induces a refractive index modulation in a photorefractive birefringent cerium-doped strontium barium niobate (SBN) crystal (Altechna), addressing the weaker electro-optic coefficient $r_{13} = 47$ pm/V. Probing the artificial photonic structure with extraordinarily polarized probe beams addresses the stronger electro-optic coefficient $r_{33} = 237$ pm/V. The SBN crystal with dimensions of $5 \times 5 \times 20\,\mathrm{mm}^3$ has refractive indices of $n_o = 2.325$ and $n_e = 2.358$. We use an imaging system formed by a microscope objective (MO) and a 16-bit camera with 0.32 μm per pixel to detect the transverse intensity distribution of the writing and/or probing beam at the back face of the crystal.

For our experimental realization of disordered lattices, we first calculate numerically the respective complex light fields we are using as digital holograms that we image onto the optical system by a phase-only SLM [26]. The entire field information of the desired structure is encoded in elaborate diffraction gratings displayed by the SLM1. The diffraction pattern of the disordered lattice is bandpass filtered in Fourier space (FF_1) [26]. In this way, an ordinarily polarized beam is spatially modulated. We expand it to illuminate the SBN crystal. The crystal is externally biased with an electric field of $E_{\mathrm{ext}} = 2000$ V/cm aligned along the optical $c = x$ axis, perpendicular to the direction of propagation, the z axis, and parallel to the long axis of the crystal. As a result, the ordinarily polarized beam optically induces a refractive index modulation, which corresponds to the numerically calculated disordered aperiodic structure.

We demonstrate a powerful approach for the experimental creation of two-dimensional disordered photonic lattices (periodic, quasiperiodic, or aperiodic) in a single writing process. For the experimental induction, it is sufficient to numerically precalculate the light field of desired structures with any DD according to Eq. 1, and encode by SLM, thus generating in a single step a corresponding light intensity distribution in the volume of the SBN crystal. One example of disordered AML is presented in Fig. 2.

After fabrication of the lattice, the writing beam and the external electric field are switched off, and a narrow Gaussian probe beam illuminates the lattice. Because the probe beam power of $\approx 10\,\mu$W keeps propagation in the linear regime, the modulation of the lattice refractive index stays near unmodified until active deletion. The probe beam of a full width at half maximum of 8 μm is directly positioned in front of the crystal and its transverse position defines the input center, and the beam size is adequate to illuminate one lattice site. Simulation of the light propagation along the z axis in optically induced disordered aperiodic Mathieu lattices in a photorefractive SBN crystal is numerically described by solving a system of equations as explained in Ref. [24].

To investigate the transverse localization of light in disordered lattices, we statistically analyze the probe beam propagation for different excitation positions selected to involve various local environments [12,21,24]. We performed such an analysis for each disordered lattices at various DDs using only one disorder pattern, averaging 100 different intensity distributions at the output face of the crystal, after a propagation distance of 2 cm. In addition to the averaged transverse output intensity distribution, we consider the log-plot profiles of such output intensity

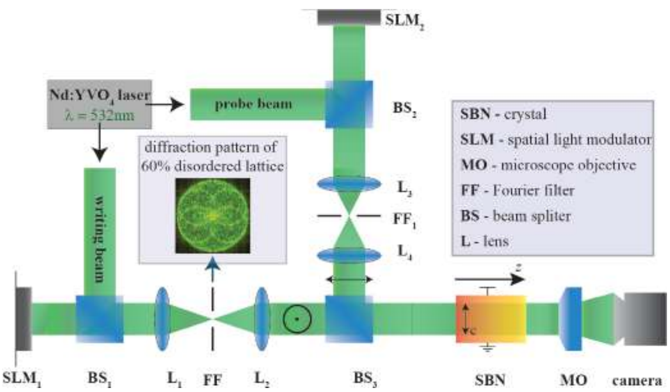

Fig. 1. Experimental configuration for investigating light propagation in two-dimensional disordered aperiodic lattices.

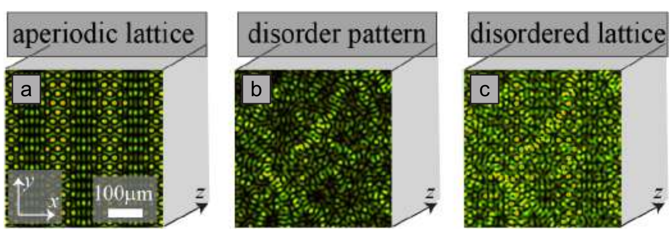

Fig. 2. Transition from aperiodic to disordered lattice: (a) original AML; (b) disorder pattern; (c) disordered AML with 60% DD.

distributions to further analyze the light propagation. To characterize the light localization, we consider the averaged effective beam widths at the output of the crystal and along the propagation distance. We calculate the effective beam width according to the relation $\omega_{\rm eff} = P(z)^{-1/2}$, where $P(z)$ is the inverse participation ratio [5]. Considering the averaged $\omega_{\rm eff}s$ and log-plot intensity profiles, we determine the DD range for the light localization. The parabolic fit (a Gaussian shape) of the log-plots of the averaged transverse intensity distribution profiles indicate diffusive-like transport [22]. However, the exponential decay of the transverse intensity distribution profile characterizes the light localization [22]. When the log-plots of such intensity profiles can be linearly fitted around the center, we consider AL to be confirmed. Owing to the crystal and lattice anisotropy, we obtain the localization lengths ξ along the x and y axes separately. ξ along the x axis is determined by fitting the intensity profiles $I(x)$ with the exponential function $I(x) = \exp[-2|x - x_0|/\xi]$, where x_0 denotes the position of the beam center. The same functional form applies to the y axis.

Figures 3(a1)–3(f1) represent experimental results for averaged intensity distributions at the output crystal face for six values of DD and their experimental log-plot cross-section along the x axis (white plots). Corresponding numerical log-plots (red line) are depicted in Figs. 3(a2)–3(f2). Comparing experimental and numerical log-plots and their linear and parabolic fits of the central areas (shown in black), we notice a good agreement between experimental and numerical results. Figure 3(a1) depicts the experimental averaged intensity distribution in the original AML [24], which demonstrates discrete diffraction of light. Next, we introduce disorder in this aperiodic lattice. For 10% DD, the averaged intensity distribution is broader than without disorder, as is shown in Fig. 3(b1). With further increase of DD, the averaged intensity distributions are broadened, while the log-plot cross-sections near the center can be fitted by a parabola, indicating diffusive-like transport, presented in Figs. 3(c)–3(d). However, an even stronger DD narrows the averaged intensity distributions, and the log-plot cross-sections near the center can be linearly fitted, as depicted in Figs. 3(e)–3(f), demonstrating AL in such a disordered aperiodic lattice.

To quantify the amount of beam expansion, we calculate the average $\omega_{\rm eff}se$ of the output intensity distributions from experiment and numerics (2 cm) for different DDs; Fig. 4(a) summarizes such results with a very good agreement between numerics and experiment. Figure 4(b) presents a log-plot cross-section along the x axis of the experimental averaged intensity distributions. Comparing the $\omega_{\rm eff}s$ and log-plots, we find regions of diffusive-like transport and light localization in our disordered aperiodic lattices. The averaged $\omega_{\rm eff}$ in the disordered aperiodic lattice with any DD is larger than in a corresponding lattice without disorder. We notice that the averaged $\omega_{\rm eff}s$ increase up to 60% DD indicating disorder-enhanced transport and decrease with further increase of the DD indicating light localization. Additionally, for lower DDs, log-plots are parabolically fitted near the center, characterizing diffusive-like transport [Fig. 4(b)]. AL of light is obtained for the highest DDs (80%–100%) where the log-plots are linearly fitted near the center [Fig. 4(c)]. In addition to this characterization, we also describe the light localization using ξ for DDs where linear fits of the log-plot are obtained. We notice that ξ decreases as DD increases. For 100% DD, we find the lowest $\xi = (107.3 \pm 7.2)\,\mu$m, while for 90% and 80% DD, ξs increase by 15% and 30%, respectively. Diffraction in disordered AMLs along different directions (x axis and y axis) is different owing to the crystal and lattice anisotropy, as noticeable from Fig. 3. With increasing DD, even as the log-plots along the y axis exhibit the same tendency as the log-plots along the x axis, transition to AL does not necessarily occur at the same DD. In the region of AL, ξs along the x axis are lower in comparison to ξs along the y axis. With the further increase of DD, ξs along the x direction are lower for 30% to 70% than in the y direction as noticeable from Fig. 4(c).

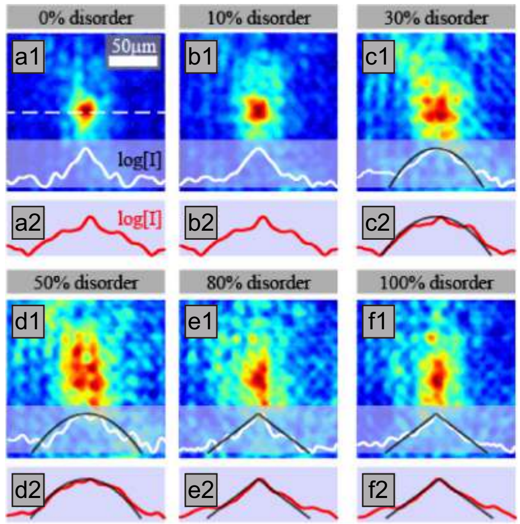

Fig. 3. Disorder-induced light transport and localization in AMLs. (a1)–(f1) Experimentally obtained averaged intensity distributions at the crystal output for different DDs, with their experimental log-plot cross-section along the x axis [marked with a white dashed line in panel (a1)]. We clean the experimental noise (caused by the rapid multiple experimental realizations of disordered lattices and subsequent probing) by removing 10% of the overall intensity for every intensity distribution. (a2)–(f2) Corresponding log-plots of numerically simulated averaged intensity distributions. Black lines represent the corresponding fits near the center. In the experiment, a laser writing beam power of 50 μW corresponds to the input maximum lattice intensity of 0.7 a.u. in simulations.

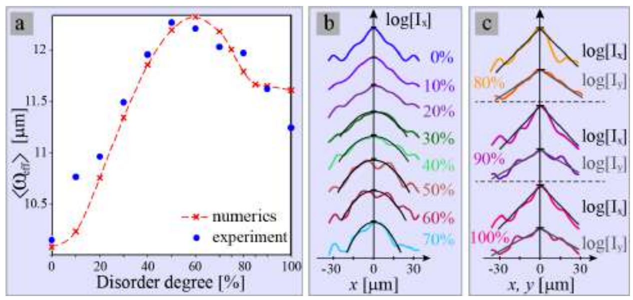

Fig. 4. Light localization dependence on DD. (a) Numerically simulated and experimentally obtained averaged $\omega_{\rm eff}s$ at crystal back face versus DD after 2 cm of propagation. (b) Experimental log-plot cross-sections along the x axis of averaged intensity distributions from the back face of the crystal. (c) Experimental log-plots of averaged intensity distributions at the back face of the crystal along different directions (the x and y axes). Experimental log-plot cross-sections in panels (b), (c) are shown for all DDs (dots) from panel (a).

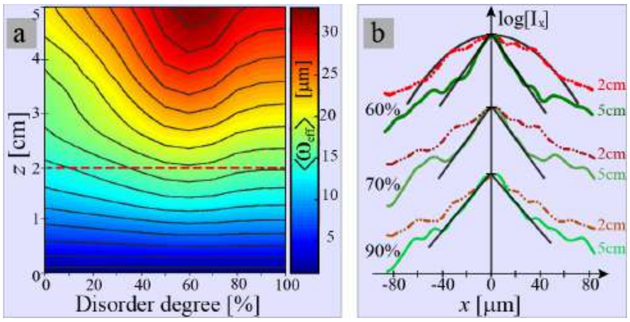

Fig. 5. Light localization dependence on the propagation distance. (a) Numerically simulated averaged ω_{eff} along with the propagation distance for different DDs. The red dashed line indicates the experimental propagation distance. (b) Numerical log-plot cross-section taken along the horizontal direction of averaged intensity distributions after propagation distances of 2 and 5 cm.

To understand if localization also occurs for lower DDs, we investigate the effects of disorder along the propagation distance. Numerically we choose a propagation length longer than the experimental crystal length. We calculate the averaged ω_{eff} along the propagation (for a 5 cm long crystal) for different DDs [Fig. 5(a)]. ω_{eff} increases during propagation for all DDs. The beam expansion is minimal for the original AML and maximal in the region of 50% to 70% DD, which is indicated by a distribution of points where black isolines cross vertical sections. For non-zero DDs up to 60%, ω_{eff} increases at a higher rate during the propagation indicating disorder-enhanced light transport. For DDs larger than 60%, ω_{eff}s increase at a lower rate during the propagation (for all propagation distances) simultaneously with the occurrence of light localization. However, AL is more evident from intensity distribution log-plots for the longer propagation distances. Figure 5(b) depicts log-plots along the x axis of the averaged intensity distributions after propagation lengths of 2 and 5 cm for different DDs. For 60% DD after 2 cm of propagation, the log-plot is fitted with a parabola near the center indicating diffusive-like transport. In contrast, after 5 cm of propagation, the log-plot is linearly fitted near the center indicating light localization. For higher DD, light localization is visible for a shorter propagation distance (2 cm), but more pronounced localization is evident for longer propagation distances also proved by the linear fits of the log-plots. Notwithstanding that we have a higher expansion at 5 cm than at 2 cm (higher ω_{eff}), we observe that the localization is more pronounced at 5 cm than at 2 cm. At longer propagation, it is easier to see that regions of AL and maximum expansion overlap. We further quantify light localization by comparing ξ of such linear fitted log-plots after propagation distances of 2 and 5 cm. ξs we obtain after 2 cm are approximately 30% larger than ξs after 5 cm, which indicates more pronounced AL as the propagation distance increases.

To conclude, we have introduced an advanced experimental approach with the numerical controllable DDs for the realization of disordered AMLs by one parallel induction process. By introducing different DDs, we have realized controllable media for the investigation of light localization effects. Experimentally and numerically, we have investigated linear propagation of the narrow Gaussian probe beam in such disordered aperiodic Mathieu lattices. For all DDs, we have demonstrated disorder-enhanced light transport. AL of light in disordered AMLs is observed for the highest DD. Localization lengths along the x axis are lower than the corresponding localization lengths along the y axis, according to crystal and lattice anisotropy. Nevertheless, for the longer propagation distances, a more pronounced AL is demonstrated. The results we obtained in disordered aperiodic Mathieu lattices are similar to those in disordered quasicrystals and in contrast to those in disordered periodic lattices. In general, our approach can be applied to other kinds of photonic lattices using the presented ideas and methods.

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Data availability. Data underlying the results presented in this Letter are not publicly available at this time but may be obtained from the authors upon reasonable request.

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Interdimensional radial discrete diffraction in Mathieu photonic lattices

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Abstract: We demonstrate transitional dimensionality of discrete diffraction in radial-elliptical photonic lattices. Varying the order, characteristic structure size, and ellipticity of the Mathieu beams used for the photonic lattices generation, we control the shape of discrete diffraction distribution over the combination of the radial direction with the circular, elliptic, or hyperbolic. We also investigate the transition from one-dimensional to two-dimensional discrete diffraction by varying the input probe beam position. The most pronounced discrete diffraction is observed along the crystal anisotropy direction.

1. Introduction

The ability to tailor and manipulate light in photonic lattices is an important topic of scientific investigations and practical applications in optics [1]. Photonic lattices or arrays of evanescently coupled waveguides are typical examples of structures where discrete effects and dynamics can be investigated. Light focused into one waveguide that linearly propagates along the waveguide array will tunnel to neighboring sites, exhibiting a characteristic diffraction pattern with the intensity mainly focused in the outer lobes. This phenomenon, called the discrete diffraction of light [2] was theoretically and experimentally observed in one-dimensional (1D) waveguide arrays [3] and two-dimensional (2D) photonic lattices [4]. It is also investigated in aperiodic photonic lattices [5–8] as well as in other systems, such as atomic photonic lattices [9–11].

The truncation of periodic photonic lattice causes an additional distortion in the periodicity and results in the formation of optical surface states that are analogous to the surface states in the electronic theory of periodic systems [12,13]. Optical self-trapped discrete surface waves - surface solitons - have been demonstrated in 1D waveguide arrays [14,15] and in 2D photonic lattices [16]. Physical systems with dimensionality crossover have attracted huge attention, for example, the continuous transformation of photonic lattice from one dimension to two dimensions [17]. In such systems, intermediate states can occur that do not exist in either 1D or 2D geometries. For these structures, there are still open questions: How, when and why does a system cross over from one to two dimensions?

Nondiffracting beams are convenient for the generation of 2D photonic lattices, since they can retain propagation-invariant structure even under weak nonlinearity [18]. There are four major nondiffracting beam families that are exact solutions of the Helmholtz equation in different coordinate systems [19,20]: plane waves in Cartesian, Bessel beams in circular cylindrical [21], Mathieu beams in elliptic cylindrical [22], and parabolic beams in parabolic cylindrical coordinates [23]. We opt for Mathieu beams, since they are used for optical lattice-writing that allows solitons or even elliptically shaped vortex solitons [24]. They are also used for the creation

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of different aperiodic photonic lattices by the optical induction technique in photorefractive crystals [8,25], as well as for particle manipulation [26].

In this paper, we investigate the conditions for discrete diffraction occurrence and its properties in the aperiodic Mathieu photonic lattices, both experimentally and theoretically. Owing to their shape, Mathieu beams enable one-pass experimental realization of naturally *truncated aperiodic* photonic lattices, supporting *surface states* as well as discrete diffraction on the surface. We focus on the aperiodic photonic structures in elliptical-radial geometries, since they offer a broad range of shapes, including ellipticity as an additional degree of freedom. They also allow to raise the question on the dimensionality of discrete diffraction. For difference, in periodic photonic lattices there are only two parameters affecting discrete diffraction: the lattice period and the refractive index modulation depth, and they are uniform over the whole lattice. However, the lattice period and the refractive index modulation of Mathieu lattices are not independent parameters; they are connected via Mathieu beam parameters (the beam order, characteristic structural size, and the ellipticity of the beam). Due to the aperiodicity of Mathieu lattice, there are various probing local environments supporting discrete diffraction influenced by the nearest neighbors. During the propagation, diffracting probe can pass through changed local enviroments, unlike in the periodic lattice, causing additional variations in the discrete diffraction effects.

Here, we demonstrate elliptical-radial discrete diffraction in photonic lattices realized by a single Mathieu beam. By changing the order, characteristic structure size, and ellipticity of the Mathieu beam, we are able to control discrete diffraction in the radial direction, as well as the shape of their distributions in the perpendicular directions: circular, elliptic, or hyperbolic. By changing the input probe beam position, we observe switching from the 1D to the 2D discrete diffraction. In our medium - the photorefractive birefringent cerium-doped strontium barium niobate (SBN61:Ce) - the crystal anisotropy plays an important role in the discrete diffraction phenomenon: we observe the most pronounced 2D discrete diffraction along the crystal anisotropy direction.

2. Numerical modeling and experimental realization of light propagation in Mathieu photonic lattices

We investigate the light propagation in Mathieu photonic lattices in the photorefractive medium and study the conditions for the discrete diffraction of light in such lattices. We model linear light propagation in a photonic lattice by solving the coupled system of two equations: the nonlinear Schrödinger equation for the scalar electric field, as the propagation equation, and the diffusion equation for the electrostatic potential as the potential equation [27,28]. We solve both equations numerically, by employing a spectral split-step beam propagation method [29]. The propagation equation of the scalar electric field A with longitudinal wave vector k_z is given by:

$$\mathrm{i}\partial_z A + \frac{1}{2k_z}\Delta_\perp A + \frac{k_z}{2n_{\mathrm{o,e}}^2}\delta n^2 A = 0, \qquad (1)$$

where the wave number $k = 2\pi/\lambda = \sqrt{(k_\perp^2 + k_z^2)}$ is defined by the laser wavelength $\lambda = 532$nm. The potential in the propagation equation is specified by $\delta n^2 = -n_{\mathrm{o,e}}^4 r_{13,33} E$, where $n_\mathrm{e} = 2.325$ and $n_\mathrm{o} = 2.358$ are the extraordinary and ordinary indices, and $r_{13} = 47$pm/V and $r_{33} = 237$pm/V are the corresponding electro-optic coefficients of the birefringent SBN61:Ce crystal. The total electric field $E = E_\mathrm{ext} + E_\mathrm{sc}$ that builds up inside the crystal is a superposition of an external electric field $E_\mathrm{ext} = 2000$V/cm aligned with the optical $c = x$ axis and an internal space charge field E_sc that results from the incident intensity distribution within the potential equation.

In order to take the electric bias of the crystal into account and the photorefractive material response, we implement an anisotropic potential equation for the spatial evolution of the

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electrostatic potential ϕ_{sc} of the optically-induced space-charge field $E_{\rm sc}$

$$\Delta_\perp \phi_{\rm sc} + \nabla_\perp \ln(1+I) \cdot \nabla_\perp \phi_{\rm sc} = E_{\rm ext} \partial_x \ln(1+I), \tag{2}$$

where $I = |A|^2$ is obtained from Eq. 1. Subsequently, Eq. 1 is updated with the optically induced space-charge field

$$E_{\rm sc} = \partial_x \phi_{sc}, \tag{3}$$

obtained by solving Eq. 2. This procedure is iteratively repeated along the propagation direction.

The process of generation of the propagation-invariant Mathieu photonic lattice is modeled through the distribution $I = I_{latt}$ from Eq. (2), which we refer to as the writing lattice pattern in the experiment [25]. Thus, we obtain first the spatial distribution of I_{latt} in a separate numerical simulation of Eqs. (1) and (2), by propagating an ordinary Mathieu beam in the weak nonlinear case. Then we use such a nearly diffractionless lattice distribution as a lattice potential, to simulate an extraordinary Gaussian probe beam propagation. For this, we use the same equations but with the modified total intensity distribution $I = I_p + I_{latt}$, where the Gaussian probe beam intensity $I_p = |A|^2$ is obtained from Eq. 1. In our simulations with the probe beam, I_p is kept sufficiently weak, so as not to cause an excessive nonlinear modification.

To experimentally investigate the linear light propagation of narrow probe Gaussian beam in Mathieu photonic lattices, we use the experimental setup shown in Fig. 1. As a light source, we use a frequency-doubled Nd:YVO_4 laser that emits continuous wave laser light at a wavelength of $\lambda = 532$nm. The expanded and collimated laser beam (telescope L1-L2) illuminates as a plane wave the phase-only spatial light modulator (SLM). Both the amplitude and phase of the reflected light field are modulated. This is accomplished by addressing to the SLM a precalculated hologram containing the information on the complex light field of the Mathieu lattice, encoded with an additional blazed grating [25,30]. In this way, an ordinary polarized beam is spatially modulated and we use it as the writing beam. We demagnify it by a telescope (L3-L4), to illuminate a crystal. The diffraction pattern of the Mathieu lattice is bandpass filtered in Fourier space (FF) [30]. The SBN61:Ce crystal with dimensions of $5 \times 5 \times 20\text{mm}^3$ is externally biased with an electric field of $E_{\rm ext}$ aligned with the optical $c = x$ axis, perpendicular to the direction of propagation, z axis, and parallel to the long axis of the crystal. As a result, the ordinary polarized beam optically induces a refractive index modulation, using the lattice writing beam power P, corresponding to the numerically calculated Mathieu lattice. After the fabrication of the Mathieu lattice, the writing beam and the external electric field are switched off. Then an extraordinary polarized narrow Gaussian probe beam illuminates the specified lattice position and we observe linear light propagation in the Mathieu photonic lattice. A half-wave plate rotates the probe beam's linear polarization by 90° relative to the writing beam's polarization, addressing the

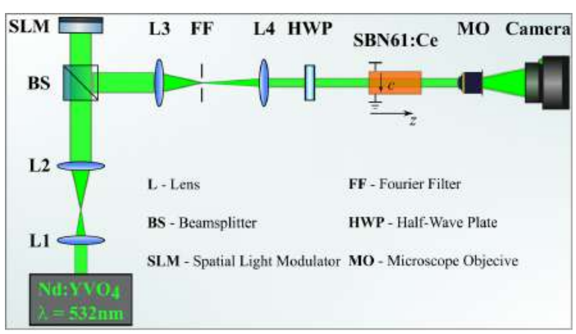

Fig. 1. Experimental setup for the light beam propagation investigation in the two-dimensional Mathieu photonic lattice.

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stronger electro-optic coefficient. We use an imaging system formed by a microscope objective (MO) with the camera to detect the transverse intensity distribution of the writing and/or probing beam at the back face of the crystal. A low probe beam's power keeps the propagation in a linear regime, and the lattice refractive index modulation remains unmodified (until erased by white light). The probe beam of full-width-at-half-maximum of 8μm is directly positioned in front of the crystal and its transverse position defines the input center. We determine the beam size to be adequate to illuminate one lattice site.

3. Transition from 1D to 2D discrete diffraction

Mathieu beams are a class of nondiffracting beams suitable for the realization of photonic lattices. We base our study on even Mathieu beams $M_m(\xi, \eta)$ of order m, which are mathematically described as a product of the radial c_{em} and angular J_{em} Mathieu functions of order m: $M_m(\xi, \eta) = C_m(q)J_{em}(\xi; q)c_{em}(\eta; q)$. Here, $C_m(q)$ is a weighting constant that depends on the ellipticity parameter $q = f^2k_t^2/4$ that is related to the positions of the two foci f and the transverse wave number $k_t = 2\pi/a$, where a is the characteristic structure size. Elliptical coordinates (ξ, η) are related to the Cartesian coordinates (x, y) by $x + iy = fcosh(\xi + i\eta)$. Mathieu beams M_m are used for generating lattice intensity distribution I_{latt} by numerical simulation of Eq. 1 and Eq. 2. By changing some of the main characteristics of Mathieu beams, defined by the parameters: beam order m, ellipticity q, and characteristic structure size a, we are capable of managing various spatial intensity distributions of Mathieu lattices [25]. The refractive index change and the lattice period of such a lattice are not independent parameters, but are connected via Mathieu beam parameters m, q, and a. Various probing local environments in Mathieu lattices support the formation of different discrete diffraction patterns. By changing the ellipticity of the Mathieu lattice, one changes the curvature of the lines connecting nearest neighbour sites (which is zero in the periodic lattice), thus influencing discrete diffraction patterns. Similarly, the anisotropy of our medium (SBN61:Ce crystal) enables the conditions for supporting discrete diffraction in certain directions.

We start by using Mathieu lattice with zero ellipticity ($q = 0$), where the waveguide arrays are distributed along the circles, as well as along the radial spikes. Three input probe beam positions are chosen, shown in Fig. 2(a1), (1, 2, and 3) marked with yellow arrows for the sites at the first, second, and fourth circle waveguide arrays, respectively. All 3 positions belong to the same radial spike, while positions 4 and 5 (the green arrows) belong to the most intense first circular waveguide. We compare the numerical and experimental results of the probe beam intensity distributions at the crystal back face after 2 cm propagation. For the first input probe beam position on the lattice edge (marked as position 1 in Fig. 2(a1)), we observe behavior similar to the 2D discrete diffraction. We will refer to it as the radial 2D discrete diffraction in the truncated elliptical-radial lattice (Fig. 2(b1),(b2)). On the same circular waveguide array, but on the opposite side of the input probe beam position, we notice out-of-order appearance of intensive spots collecting evanescent leakage of the waveguides from the opposite side.

Following the geometrical distribution of the lattice, we show the projection of the probe beam intensity distributions on the circle and spike waveguide arrays (the corresponding circles and spikes are marked in Fig. 3(a)) along the propagation distance. In the circular direction, we cut the first four circles opposite to the excitation position and show flattened probe intensity distributions in Fig. 3(b), presenting discrete diffraction along circles. On the edges of Fig. 3(b) distribution, corresponding to the cut point, we can follow the dynamics of the previously mentioned opposite intensive spot. In the radial direction, we notice discrete edge diffraction along some of the truncated spike waveguide arrays (Fig. 3(c)). When we shift the probe beam input position away from the lattice edge (position 2 in Fig. 2(a1)), the two-dimensionality of discrete diffraction is less pronounced, but at the expense of separate circular and radial 1D discrete diffractions. For the third probe beam position (position 3 in Fig. 2(a1)), we notice separate circular and radial

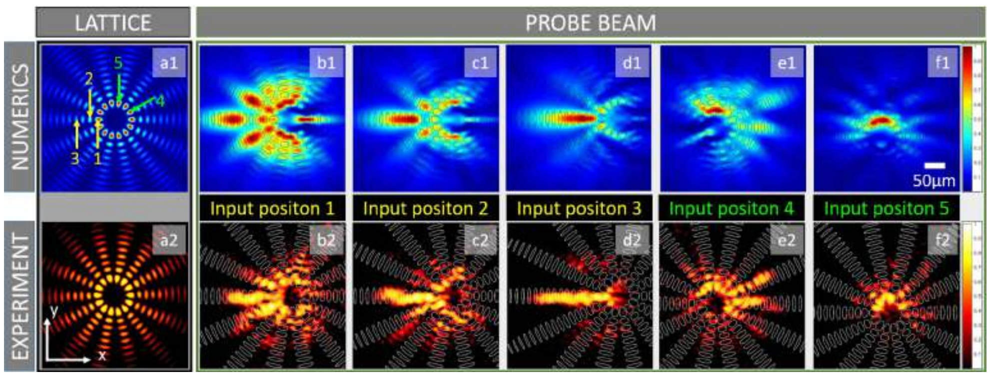

Fig. 2. Influence of various probe beam input positions on the discrete diffraction in Mathieu lattice. The intensity distribution of the Mathieu lattice at the exit crystal face observed numerically (a1) and experimentally (a2), with yellow arrows in (a1) indicating various input probe beam positions. Intensity distributions of the probe beam at the exit crystal face obtained numerically (the first row) for the input probe beam positions: 1 (b1), 2 (c1), 3 (d1), 4 (e1), and 5 (f1), taken from Visualization 1, Visualization 2, Visualization 3, Visualization 4 and Visualization 5, respectively, representing the numerical intensity distributions of the probe beam along the propagation direction. Experimentally obtained intensity distributions at the crystal exit face (the second row) for input probe beam positions: 1 (b2), 2 (c2), 3 (d2), 4 (e2), and 5 (f2). Parameters are: Mathieu lattice order m = 7, ellipticity $q = 0$, and characteristic structure size $a = 30\mu m$, $I_{latt} = 1$, experimental lattice writing beam power $P = 0.5mW$.

discrete diffractions. Hence, we observe the switching from 2D to 1D discrete diffraction in truncated elliptical-radial lattice, by changing the input probe beam position.

Additionally, we investigate the influence of crystal anisotropy on light diffraction in such a lattice (Fig. 2). We consider various input probe beam positions, depicted as positions 1, 4, and 5 in Fig. 2(a1): All input beam positions are on the same circular waveguide array and would be equivalent, apart from the relative orientation to the crystal anisotropy. As one can see, in such lattices 2D discrete diffraction is possible to observe *only* for input probe beam positions along the crystal anisotropy direction (c-axis) (Fig. 2(b)).

With increasing Mathieu lattice order m, the number of spike waveguide arrays is increased, favoring 2D discrete diffraction (Fig. 4(a-c)). We study the probe beam propagation for three

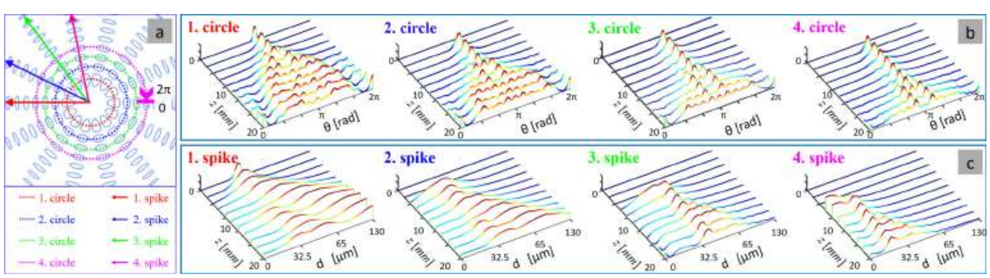

Fig. 3. Discrete diffraction along the circular and spike waveguide arrays. Projections of intensity distributions along circles (b), and spikes (c) corresponding to (a). For each circle, the circumference is measured in the angular coordinate θ starting from the cut point, and the radial coordinate d from the common center of the circles. The parameters are as in Fig. 2(b1).

lattice orders: $m = 7, 9$, and 12, and obtain more pronounced 2D discrete diffraction for higher lattice order. Also, we study how the variation of the Mathieu lattice characteristic structure size a influences the propagation of the probe beam: Increasing the characteristic structure size a uniformly increases the distance between neighboring sites (Fig. 4(c-e)). We are able to control optimal conditions for 2D or more 1D discrete diffractions in certain regions, and with the variation of structure size a, we are able to move those regions. We investigate Mathieu lattices for three characteristic structure sizes: $a = 30, 35$, and $40\mu m$. 2D discrete diffraction becomes less pronounced with the increase of a, which is caused by the increasing order separation in each concentric elliptical waveguide array.

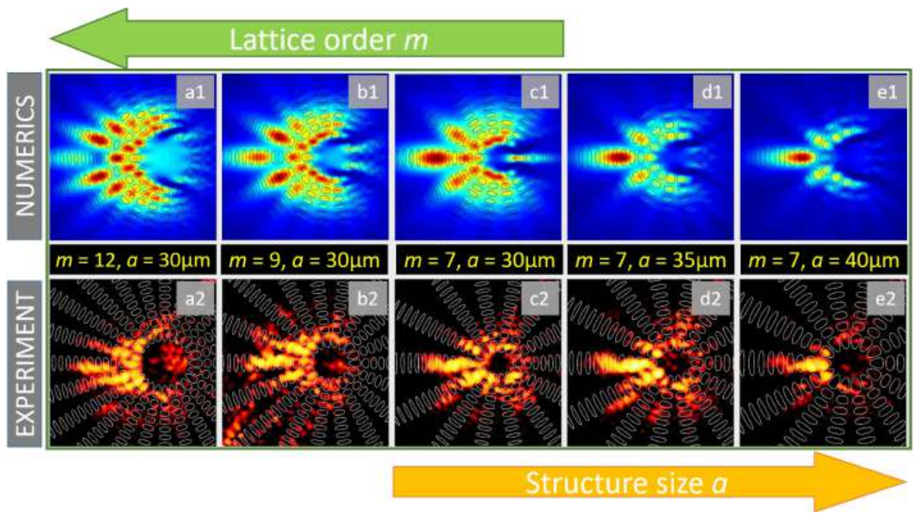

Fig. 4. Influence of Mathieu lattices order m and structural size a on the discrete diffraction patterns. (a1-e1) Numerically observed intensity distributions of the probe beam at the exit crystal face for different parameters m, a, marked in each panel, and $q = 5$, taken from Visualization 6, Visualization 7, Visualization 8, Visualization 9, Visualization 10, respectively. The second row presents the corresponding experimental exit face intensity distributions (a2-e2). Other parameters are as in Fig. 2.

At the end, we study how the variation of Mathieu lattice ellipticity q influences the discrete diffraction of light (Fig. 5). We perform our investigation by probing Mathieu lattices with various ellipticities: $q = 0, 10, 125$, and 625. Probe beam input positions are marked with the yellow arrows depicted in Fig. 5 (the first row). For ellipticity $q = 0$, we notice 2D radial discrete diffraction, in contrast to the ellipticity of $q = 10$, where one notices the splitting to 1D radial discrete diffractions along the inner ellipse and the left spike waveguide array. With further increasing q, due to modulation depth distributions - i.e., nonuniform distributions, favorable conditions for discrete diffraction appear for high q, where we have hyperbolic lattices. For ellipticity $q = 125$, we obtain 2D discrete diffraction across hyperbolas, while for $q = 625$, we observe more 1D discrete diffraction along the edge hyperbola, mostly due to the sharp decrease of array intensity distribution away from the edge hyperbola. As stated, the distribution is rapidly decaying away from the edge row, which in the absence of anisotropy would result in dominantly 1D discrete diffraction (not shown).

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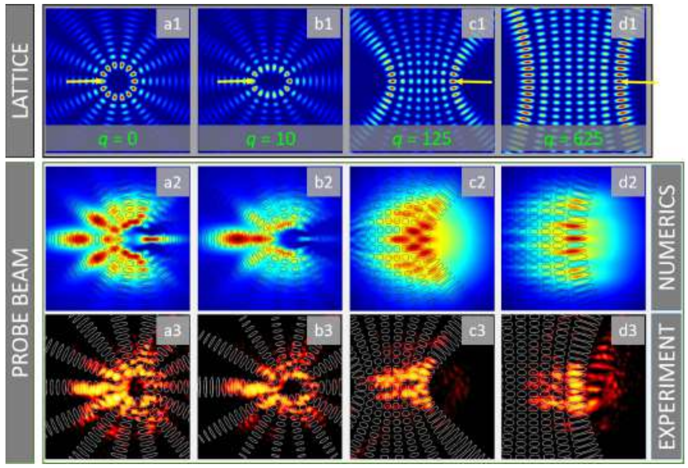

Fig. 5. Lattice ellipticity q influence on the discrete diffraction of light. First row: Intensity distributions of Mathieu lattice. Second row: probe beam intensity distributions at the exit face of the crystal, obtained numerically (a2- d2), taken from the corresponding numerical intensity distributions of the probe beam along the propagation direction: Visualization 1, Visualization 11, Visualization 12, Visualization 13, respectively. The third row: Experimental intensity distributions of the probe beam at the crystal exit face (a3-d3). Other parameters are as in Fig. 2.

4. Conclusion

In summary, we have presented a method for radial and angular discrete diffraction generation in various Mathieu lattices, experimentally and numerically. Such photonic lattices are optically induced in a photorefractive crystal, using one-pass creation in the experiment. They are also a kind of truncated lattices that could support surface states. Mathieu photonic structures offer an extensive variation of shapes as well as ellipticity, as the additional degree of freedom, with the waveguides deployed along circles, ellipses, and hyperbolas, as well as radial spikes. We have controlled radial discrete diffraction by changing the order, characteristic structure size, and ellipticity of Mathieu beams used for the optical induction of photonic lattices. Shifting the input probe beam position, we have observed a transition from 1D to 2D discrete diffraction. We have found the most pronounced 2D discrete diffraction along the crystal anisotropy direction. Note that the discrete diffraction created by our approach exhibits branching 1D discrete diffraction along circle/ellipse and spike waveguide arrays, while predominantly 1D discrete diffraction occurs in hyperbolic lattices. Our results pave the way for exploiting light propagation in a novel class of optical lattices, but they are not limited to these particular lattices: They can readily be generalized in other kinds of optically induced lattices. Adaptivity and reconfigurability of the light-guiding structures play an important role in enabling functionality, displaying a significant advance in modern photonics and providing an important step towards novel innovative wave-guiding applications and light routing approaches. They will hopefully find useful applications in the capacity-enhanced optical information processing.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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2022 TECHNICAL PROGRAMME

AND

EXHIBITION GUIDE

SPIE. PHOTONICS EUROPE

3–7 APRIL 2022 | PALAIS DE LA MUSIQUE ET DES CONGRÈS | STRASBOURG, FRANCE

SESSION 5

LOCATION: SALON 9, NIVEAU/LEVEL 0 . . . . TUE 10:50 TO 12:30

Multimode Dynamics I

Session Chair: **Peter Horak,** Optoelectronics Research Ctr. (United Kingdom)

10:50: **Spatiotemporal complexity: multimode fiber light sources and their applications** *(Invited Paper)*, Katarzyna Krupa, Institute of Physical Chemistry PAS (Poland). . . . . [12143-19]

11:20: **Towards a new understanding of optical poling efficiency in multimode fibers**, Maxime Jonard, XLIM Institut de Recherche (France); Maggy Colas, Institut de Recherche sur les Céramiques, Univ. de Limoges (France); Yann Leventoux, Tigran Mansuryan, XLIM Institut de Recherche (France); Julie Cornette, Institut de Recherche sur les Céramiques (France); Alessandro Tonello, XLIM Institut de Recherche (France); Stefan Wabnitz, Mario Zitelli, Sapienza Univ. di Roma (Italy); Fabio Mangini, Univ. degli Studi di Brescia (Italy); Mario Ferraaro, Yifan Sun, Sapienza Univ. di Roma (Italy); Vincent Couderc, Claire Lefort, XLIM Institut de Recherche (France) . [12143-21]

11:40: **Dissipative solitons and frequency combs in a ring quantum cascade laser** *(Invited Paper)*, Lorenzo Luigi L. Columbo, Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino (Italy); Marco Piccardo, Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge (USA) and Center for Nano Science, Fondazione Istituto Italiano di Tecnologia and Technology, Milano (Italy); Franco Prati, Luigi Lugiato, Dipartimento di Scienza e Alta Tecnologia, Università dell'Insubria, Como (Italy); Massimo Brambilla, Dipartimento di Fisica Interateneo and CNR-IFN, Università e Politecnico di Bari (Italy); Alessandra Gatti, Dipartimento di Scienza e Alta Tecnologia, Università dell'Insubria, Como (Italy) and Istituto di Fotonica e Nanotecnologie IFN-CNR (Italy); Carlo Silvestri, Mariangela Gioannini, Dipartimento di Elettronica e Telecomunicazioni,Politecnico di Torino (Italy); Nikola Opacak, Institute of Solid State Electronics, TU Wien (Austria); Benedikt Schwarz, Institute of Solid State Electronics (Austria); Federico Capasso, Harvard John A. Paulson School of Engineering and Applied Sciences, Cambridge (USA). . . . . [12143-8]

12:10: **Discretized X-wave in a multimode optical fiber**, Karolina Stefanska, Lab. Interdisciplinaire Carnot de Bourgogne (France) and Wroclaw Univ. of Science and Technology (Poland); Pierre Béjot, Lab. Interdisciplinaire Carnot de Bourgogne (France); Karol Tarnowski, Wroclaw Univ. of Science and Technology (Poland); Bertrand Kibler, Lab. Interdisciplinaire Carnot de Bourgogne (France) . . . . [12143-23]

Lunch/Exhibition Break . . . . .Tue 12:30 to 13:50

SESSION 6

LOCATION: SALON 9, NIVEAU/LEVEL 0 . . . . .TUE 13:50 TO 17:10

Nonlinear Material Systems I

Session Chair: **Thibaut Sylvestre,** FEMTO-ST (France)

13:50: **Nonlinear topological photonics** *(Invited Paper)*, Hrvoje Buljan, Univ. of Zagreb (Croatia) . . . . [12143-24]

14:20: **Time-varying optical nonlinearities near an epsilon-near-zero condition**, Anton Bykov, King's College London (United Kingdom); Guixin Li, Institute for Quantum Science and Engineering, Southern Univ. of Science and Technology (China); Anatoly V. Zayats, King's College London (United Kingdom). . . . . [12143-25]

14:40: **Turbulence control by time-symmetry breaking**, Salim Benadouda Ivars, Muriel Botey, Ramon Herrero, Univ. Politècnica de Catalunya (Spain); Kestutis Staliunas, Univ. Politècnica de Catalunya (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain) . . . . [12143-28]

15:00: **All-optical Fredkin gate using silicon nitride microring resonator**, Menglong He, Kambiz Jamshidi, TU Dresden (Germany) . . . . [12143-29]

15:20: **Second harmonic generation in silicon oxynitride thin films**, Jakub Lukeš, Karel Zidek, Institute of Plasma Physics of the CAS, v.v.i. (Czech Republic). . . . . [12143-70]

Coffee Break. . . . . Tue 16:00 to 16:30

LOCATION: SCHWEITZER AUDITORIUM, NIVEAU/LEVEL 0 . . . . . . 16:30 TO 18:05

Hot Topics II

Francis Berghmans, Vrije Univ. Brussel (Belgium)
2022 Symposium Chair

16:30: **Welcome and opening remarks**

16:35: **Enhancing optical contrast for cancer detection and therapy guidance** *(Plenary)*, Brian W. Pogue, Thayer School of Engineering at Dartmouth (USA) . . . . [12146-500]

17:20: **Cell by lens: arguments and divagations for next visionary challenges in biophotonics and beyond** *(Plenary)*, Pietro Ferraro, Istituto di Scienze Applicate e Sistemi Intelligenti "Eduardo Caianiello" (Italy) . [12144-500]

WEDNESDAY 6 APRIL

SESSION 7

LOCATION: SALON 9, NIVEAU/LEVEL 0 . . . . .WED 8:30 TO 10:20

Nonlinear Material Systems II

Session Chair: **Hrvoje Buljan,** Univ. of Zagreb (Croatia)

8:30: **Parametric phase-sensitive amplification in silicon nitride waveguides** *(Invited Paper)*, Victor Torres-Company, Peter Andrekson, Magnus Karlsson, ping Zhao, Zhichao Ye, Chalmers Univ. of Technology (Sweden) . . . . . [12143-30]

9:00: **Polyvinylcarbazole: a new material for passive optical limiting**, Olivier Muller, Morgane Guerchoux, Silke Braun, Théo Jean, Manon Dandois, Lionel Merlat, Institut Franco-Allemand de Recherches de Saint-Louis (France). [12143-31]

9:20: **Experimental and theoretical study of second and third harmonic generation in amorphous silicon**, Laura Rodríguez-Suné, Univ. Politècnica de Catalunya (Spain); Michael Scalora, U.S. Army Combat Capabilities Development Command (USA); Crina M. Cojocaru, Univ. Politècnica de Catalunya (Spain); Neset Akozbek, US Army (USA); Ramon Vilaseca, Jose F. Trull, Univ. Politècnica de Catalunya (Spain) . . . . [12143-32]

9:40: **Electric-field poling of silicon nitride waveguides for the linear phase modulation**, Boris Zabelich, Edgars Nitiss, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Anton Stroganov, LIGENTEC SA (Switzerland); Camille-Sophie Brès, Ecole Polytechnique Fédérale de Lausanne (Switzerland) . . . . [12143-33]

10:00: **Investigation of LBO and BBO subnanosecond optical parametric amplifiers operating in the visible spectrum range**, Julius Vengelis, Gabrielė Stanionytė, Eglė Vėjalytė, Viktorija Tamulienė, Vygandas Jarutis, Vilnius Univ. (Lithuania) . . . . [12143-34]

Coffee Break. . . . . .Wed 10:20 to 10:50

SESSION 8

LOCATION: SALON 9, NIVEAU/LEVEL 0 . . . . .WED 10:50 TO 12:20

Nonlinear Sources and Dynamics

Session Chair: **Victor Torres Company,** Chalmers Univ. of Technology (Sweden)

10:50: **Pulse dynamics in microlasers** *(Invited Paper)*, Soizic Terrien, The Univ. of Auckland (New Zealand). . . . . [12143-35]

11:20: **Polarization symmetry breaking of regenerative pulses in excitable microlasers with delayed optical feedback**, Stefan Ruschel, The Univ. of Auckland (New Zealand); Venkata Anirudh Pammi, Ctr. de Nanosciences et de Nanotechnologies (France); Bernd Krauskopf, Neil G. R. Broderick, The Univ. of Auckland (New Zealand); Sylvain Barbay, Ctr. de Nanosciences et de Nanotechnologies (France) . . . . [12143-36]

11:40: **Investigation of optical parametric generator pumped by subnanosecond passively Q-switched micro-laser pulses**, Jonas Banys, Justina Savickytė, Ona Balachninaitė, Simona Armalytė, Viktorija Tamulienė, Vygandas Jarutis, Julius Vengelis, Vilnius Univ. (Lithuania) . . . . [12143-37]

12:00: **Computation of Kerr lensing effect in laser amplifiers**, Christoph Pflaum, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) . . . [12143-38]

Lunch/Exhibition Break . . . . .Wed 12:20 to 13:50

SESSION 9

LOCATION: SALON 9, NIVEAU/LEVEL 0 . . . . .WED 13:50 TO 15:20

Multimode Dynamics II

Session Chair: **Katarzyna Krupa,** Institute of Physical Chemistry PAS (Poland)

13:50: **Multimode effects in nonlinear fibre optics: from telecommunications to high-harmonic generation** *(Invited Paper)*, Peter Horak, Optoelectronics Research Ctr. (United Kingdom) . . . . [12143-39]

14:20: **Fast nonlinear integration of the nonlinear Schrödinger equation using a neural network**, Lauri Salmela, Tampere Univ. (Finland); Mathilde Hary, Tampere Univ. (Finland) and Institut FEMTO-ST, Univ. Bourgogne Franche-Comté (France); Mehdi Mabed, John M. Dudley, Institut FEMTO-ST, Univ. Bourgogne Franche-Comté (France); Goëry Genty, Tampere Univ. (Finland) . . . . [12143-40]

14:40: **Light propagation in disordered aperiodic Mathieu lattices generated with two different randomization methods**, Jadranka Vasiljević, Institute of Physics Belgrade (Serbia); Dejan V. Timotijević, Institute for Multidisciplinary Research, Univ. of Belgrade (Serbia); Dragana M. Jović Savić, Institute of Physics Belgrade (Serbia) . . . . [12143-41]

Light transport and localization in disordered aperiodic Mathieu lattices

J. M. Vasiljevic[1], D. V. Timotijevic[2], and D. M. Jovic Savic[1]

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Complex systems may be governed by just a few simple rules, not unlike highly ordered systems such as periodic, still, they produce patterns that can be compared to random systems. Complex photonic lattices are suitable for the investigation of many physical phenomena from solid-state to atomic physics with easier experimental realization. Light transport in complex optical systems is a rich and fascinating topic of research. From the investigation of light propagation in aperiodic and disordered media plentiful interesting optical phenomena are obtained, such as Anderson localization.

Nondiffracting beams are highly relevant in optics and atom physics, particularly because their transverse intensity distributions propagate unchanged for hundreds of diffraction lengths [1]. They have potential applications in free-space wireless communications, optical interconnections, long-distance laser machining, and surgery. Four different fundamental families of propagation invariant light fields, distinguish in the underlying real space coordinate system, exist: Discrete, Bessel, Mathieu, and Weber nondiffracting beams [2-4], also, suitable for generation of photonic lattices [5-8].

We realized deterministic aperiodic photonic lattices with controllable complexity, using Mathieu beams combined in metastructures and spliced in both transverse dimensions with different offsets [7], and shown that such lattices hinder light diffraction in comparison to periodic lattices [9]. A further step of randomization of these structures allows for an additional level of diffraction control. Also, the propagation of light in such structures is an unexplored topic, hence will be one of the topics of investigation in this paper. The aim is to involve the fundamental concepts of structured dielectric materials, photonic crystals, as promising candidates for advanced information processing with the unique property of light localization as a nonlinear light-mater interaction phenomenon. We focus our research on the generation of randomized aperiodic lattices with gradually controlled disorder degree in various systems with the investigation of the relationship between complexity and randomness.

We present a comprehensive numerical study of the transverse localization of light in disordered aperiodic Mathieu photonic lattices comparing disorder degree differentiation. A disorder-enhanced light transport is observed for all disorder degrees. With increasing disorder strength light transport becomes diffusive-like and with further increase of disorder degree the Anderson localization is observed. Furthermore, the influence of lattice intensity on the localization effects is studied. The difference in light transport is attributed to various levels of lattice intensity managed by disorder degree. Additionally, we show that localization length differs along different directions, due to the crystal and lattice anisotropy.

References:

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[8]J. M. Vasiljević, A. Zannotti, D. V. Timotijević, C. Denz, and D. M. Jović Savić, Phys. Rev. A 97, 033848 (2018).
[9] J. M. Vasiljević, A. Zannotti, D. V. Timotijević, C. Denz, and D. M. Jović Savić, Appl. Phys. Lett.117, 041102 (2020)

Summary for the program

Light transport and localization in disordered aperiodic Mathieu lattices

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Complex photonic lattices are suitable for the investigation of many physical phenomena from solid-state to atomic physics with easier experimental realization. Light transport in complex optical systems is a rich and fascinating topic of research. Nondiffracting beams are highly relevant in optics and atom physics, particularly because their transverse intensity distributions propagate unchanged for hundreds of diffraction lengths, moreover, suitable for the generation of photonic lattices. Four different fundamental families of propagation invariant light fields, distinguish in the underlying real space coordinate system, exist: Discrete, Bessel, Mathieu, and Weber nondiffracting beams. We realized deterministic aperiodic photonic lattices with controllable complexity, using Mathieu beams combined in metastructures and spliced in both transverse dimensions with different offsets, and shown that such lattices suppress light diffraction comparing with periodic lattices. A further step of randomization of these structures permits an additional level of diffraction control. The propagation of light in such structures is an unexplored topic, hence it is one topic of investigation in this paper. The aim is to involve the fundamental concepts of structured dielectric materials, photonic crystals, as promising candidates for advanced information processing with the unique property of light localization as a nonlinear light-mater interaction phenomenon. We generate randomized aperiodic lattices with gradually controlled disorder degree in various systems to investigate the relationship between complexity and randomness. We present a comprehensive numerical study of the transverse localization of light in disordered aperiodic Mathieu lattices comparing disorder degree differentiation. A disorder-enhanced light transport is observed for all disorder degrees. With increasing disorder strength light transport becomes diffusive-like and with further increase of disorder degree, the Anderson localization is observed. Furthermore, the influence of lattice intensity on the localization effects is studied. The difference in light transport is attributed to various levels of lattice intensity managed by disorder degree.

Light propagation in disordered aperiodic Mathieu lattices generated with two different randomization methods

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ABSTRACT

We present the numerical modeling of two different randomization methods of two-dimensional aperiodic photonic lattices based on Mathieu beams, optically induced in a photorefractive media. We numerically study light propagation in such lattices. For both methods, we compare light transport and localization in such lattices along the propagation and for various disorder strengths. For all disorder strengths, a disorder-enhanced light transport is observed. With increasing disorder strength light transport becomes diffusive-like while with further increase of disorder strength, the Anderson localization is observed. For longer propagation distances this transition is more pronounced. The influence of input lattice intensity on the localization effects is studied. We observe more pronounced localization for one of the methods, and different diffraction and localization along different directions, due to the crystal and lattice anisotropy. The difference in light transport and localization between two randomization methods is attributed to various levels of input lattice intensity.

Keywords: light propagation, disordered lattices, Mathieu beams, Anderson localization, disorder-enhanced light transport, diffusive-like transport

1. INTRODUCTION

Some of the fascinating effects observed when light propagation through different types of periodic photonic structures was studied are light discrete diffraction or discrete spatial solitons.[1–3] It was demonstrated that periodic lattices have essential characteristics of photonic crystal structures (Brillouin zones, band structure, etc.) leading to light control by photonic band gaps in space and time. Also, light localization in disordered media was investiagted.[4,5] Anderson localization (AL), a basic phenomenon from solid-state physics has found applications for light waves in different materials,[6–8] Bose-Einstein condensates,[9] and sound waves.[10] It was demonstrated an appreciable change of light propagation in the presence of disorder, the transition from the diffraction of light to spatial AL is observed by increasing disorder strength in different customized configurations.[8,11–14]

Deterministic aperiodic structures are at the intersection between periodic and disorder crystal structures. Various aperiodic and quasiperiodic photonic structures were realized artificially,[15,16] their properties have been studied for light control and manipulation.[17,18] Aperiodic lattices contain non-uniform distances between the lattice waveguides with unequal waveguides intensity depths. Therefore in such lattices in contrast to periodic, light propagation strongly depends on local environments of the probe beam excitation position,[15,19] and linear light diffraction is hampered owing to the aperiodicity.[15,19] Also, aperiodic lattices support nonlinear light localization.[19,20] Still, numerous aperiodic structures exist and have not yet been fully explained or exploited for applications. For instance, Penrose or Fibonacci structures have limited variation in probing local environments, however aperiodic Mathieu lattices[21] with the adjustable spatial and intensity distribution allow the tunable optical response which is provided with numerous different probing local environments, as well as introducing structure anisotropy variability. For the experimental realization of photonic lattices by optical induction technique in general, nondiffracting beams are convenient since they are propagation invariant for weak nonlinearity.[22] Two-dimensional aperiodic photonic lattices based on multiplexing of nondiffracting beams were experimentally realized by the optical induction technique in photorefractive crystal.[21,23]

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Besides nonlinear localization, an additional step of light control was the randomization of periodic or quasiperiodic photonic lattices.[7,8,24] Disordering periodic lattices can lead to AL[7,8] or its suppression, referred to as inverse Anderson transition.[25] Disordered quasiperiodic Penrose lattice can support AL and disorder-enhanced transport (DET) which is related to the broadening of eigenfunctions with the disorder.[24] However, an unexplored topic is the control and manipulation of light in other disordered aperiodic lattices. In order to create an appropriate platform for investigation of light propagation effects in disordered aperiodic lattices and study their possible transition to AL or DET, we propose considering randomization of a whole class of aperiodic structures based on Mathieu beams.[21] Since in such a large class of aperiodic structures is difficult to implement an exhaustive theoretical or experimental analysis of light propagation, in this paper, we are focusing on one aperiodic Mathieu structure and numerically model their possible randomizations and probing of resulting disordered lattices.

In this contribution, we introduce the modeling of two different methods for the generation of two-dimensional propagation invariant disordered aperiodic Mathieu lattices with adjustable disorder strength, corresponding to two different experimental realizations using optical induction technique in a photorefractive crystal.[26] We numerically investigate a transverse light localization in such lattices and compare the effects of disorder on light propagation considering two different randomization methods. We examine the influence of propagation distance, for both methods, as well as the lattice intensity influence on the diffraction rate. We demonstrate disorder-enhanced light transport of the probe beams, for all disorder strengths, by gradually adding disorder to the aperiodic Mathieu lattice. Also, we show the conversion from diffusive-like transport to AL for higher disorder strengths. More pronounced localization is demonstrated for longer propagation distances even for lower disorder strengths. We attribute the difference of effective beam width for two randomization methods to varying levels of lattice intensities. We observe more pronounced localization for one of the methods, which is related to shorter localization length for one of the methods. Also, it is shown that localization length differs along different directions, which we attribute to the lattice and crystal anisotropy.

2. TWO NUMERICAL METHODS FOR FORMATION OF DISORDERED APERIODIC LATTICES

Here, we present two methods for the generation of two-dimensional propagation invariant disordered aperiodic photonic lattices with adjustable disorder strength. We formed complex light filed of disordered lattices $\boldsymbol{DL}$ by coherently adding the two-dimensional original structure $\boldsymbol{L}$ and disorder pattern $\boldsymbol{D}$ with same maximum structure intensity according to the relation

$$\varphi_{DL} = (1-p) * \ \varphi_L + p * \ \varphi_D, \tag{1}$$

where φ stands for field amplitude, while intensity distribution of such complex light field display transverse intensity distribution of disordered aperiodic lattice $I_{DL} = |\varphi_{DL}|^2$ with input intensity I_{in}. Parameter p is the relative contribution of the original structure and disorder pattern, which we identify as disorder strength. By varying disorder strength ($0 \leq p \leq 1$) we gradually adjust the level of lattice disorder relative to the original structure. Calculated complex light fields of disordered lattices can be used as the writing light patterns for the generation of two-dimensional photonic lattice by optical induction in the cerium-doped strontium barium niobate (SBN) crystal.[21] Previous studies that applied the optical induction technique for realization of photonic lattices in birefringent SBN crystal, externally biased with an electric field aligned along the optical $c = x$-axis, and perpendicular to the propagation direction (z-axis), used the ordinary polarized writing beam with a laser power P, considered to be fairly linear in SBN crystal.

When the maximum lattice intensity of the resulting disordered lattice for each disorder strength is unscaled, we will refer to that case as the first method (*M1*). The second method (*M2*) is characterized by scaling I_{DL} with I_{in} for each disorder strength. A consequence of distinction in methods accompanies differences in potential experimental realizations. For the proposed fabrication of the disordered aperiodic lattices by the optical induction technique, which corresponds to both methods we can use experimental setup from our previous study[21] using a spatial light modulator to modulated writing beam, producing computer generating hologram. For prospective experimental realization of such disordered aperiodic lattice according to our suggest M1, laser power of an ordinary polarized writing beam will vary with change of disorder strength, while for M2 it will be constant for each disorder strength.

As the original undisturbed structure $\boldsymbol{L}$ in this paper, we use an aperiodic Mathieu structure designed with combinations of Mathieu-Gauss beams spliced in both transverse dimensions with different offsets, as introduced in our previous paper.[21] Numerically by interfering plane waves with constant amplitude and random phases, we calculated propagation invariant structure with random pattern in transverse dimension, disorder pattern $\boldsymbol{D}$. Also, we adjusted his spectrum in the transverse Fourier space to be located on the same circle with radius k as the original structure,[27] to provide propagation invariant structures with the same propagation constant. The disorder pattern's mean grain size $2\pi/k$ is equal to the characteristic structure size $a = 25\mu m$ of Mathieu Gauss beams, used for the realization of the aperiodic structure.[21]

For both methods, by increasing disorder strength we change the geometry of the original structure shown in Fig. 1 (A) until we completely substitute the original structure with a disorder pattern display in Fig. 1 (B). Transverse intensity distributions of disordered aperiodic lattices with 40% disorder for these two methods are presented in Figs. 1 (C) and (D). As an illustration of Eq. (1) in Fig. 1 (E) we present a single typical intensity cross-section along the x-axis (y-position indicated with a dashed line in Fig. 1 (D)) for disordered aperiodic lattices with 40% disorder for two different methods. In contrast to the periodic lattice, our aperiodic lattice is not uniform in the waveguide's distances and their depths vary. For M1 and M2 spatial intensity distribution of the disordered aperiodic lattices are the same, but they differ in waveguides depths as M2 intensity values are greater than M1 intensity values, as noticeable from red and green plots in Fig. 1 (E).

The difference in methods is caused by choices of intensity scaling, hence, we will investigate and compare the consequences of such scaling options. For both methods, variation of disorder strength p leads to the variation of lattice intensity, effectively correlating disorder strength with lattice intensity and indirectly with optically induced refractive index modulation inside the crystal. For the same disorder strength, lattice intensities differ for M1 and M2, causing a distinction in light propagation characteristics in such disordered lattices. As we mentioned, the disorder strength p changes the lattice intensity, hence in addition to maximum lattice intensity $I_{\max}$, we calculate averaged lattice intensity $I_{\text{avg}} = \sum_{\mathbf{r}} I_{DL}(\mathbf{r}) = \sum_{\mathbf{r}} |\varphi_{DL}(\mathbf{r})|^2$. The resulting differentiation of our methods in $I_{\max}$ and I_{avg} dependence on disorder strength is shown in Figs. 1 (F) and (G), respectively. For M1, the maximum lattice intensity and the averaged lattice intensity of disordered aperiodic decrease from 0% to 70% disorder, afterward increase. For 100% disorder, only the maximum lattice intensity returns to an input value. For M2, the maximum lattice intensity of disordered aperiodic lattice is constant and equal to I_{in} for all disorder strengths, but the averaged lattice intensity always decreases with increasing disorder strength. Both the maximum lattice intensity and the averaged lattice intensity for M1 are lower than for M2, except for 0% and 100% disorder. Assuming the same disorder pattern, both methods produce the same lattices for 0% and 100% disorder strengths we will exclude these two endpoints when we discuss method differences.

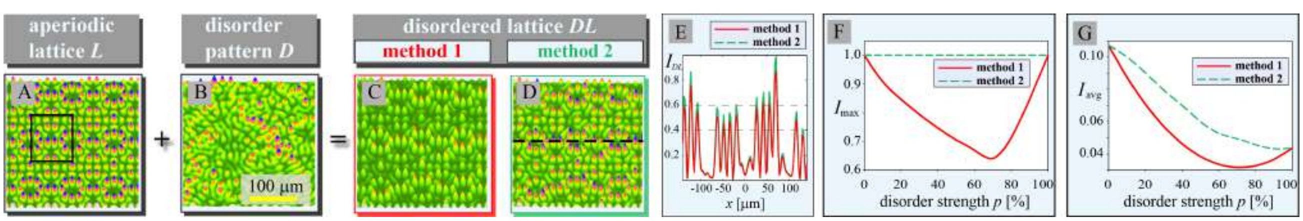

Figure 1. Two methods for generation of disordered aperiodic lattices. The transverse intensity distribution of: (A) aperiodic lattice, an typical pattern marked with black rectangle; (B) disorder pattern; (C) and (D) disordered aperiodic lattices with 40% disorder for M1 and M2, respectively. The displayed area is less than 3% of the whole transverse computational space. (E) Intensity cross-section taken along the x-axis marked with a black dashed line in (D) for disordered aperiodic lattices with 40% disorder for M1 and M2; dashed lines indicate maximum intensities of original lattice and disorder pattern. (F) The maximum lattice intensity and (G) the averaged lattice intensities versus disorder strength p for different methods.

3. NUMERICAL MODELING OF LIGHT PROPAGATION IN OPTICALLY INDUCED DISORDERED APERIODIC MATHIEU LATTICES

In this paper we consider numerically simulations of the weak nonlinear propagation of probe beam in the nolinear photorefractive SBN crystal with disordered aperiodic Mathieu lattices modeled as propagation invariant potential by solving the coupled nonlocal system of two equations: the nonlinear Schrödinger equation as propagation equation and a potential equation,[28] using a spectral split-step beam propagation method.[29] The propagation equation for an initial extraordinary polarized scalar monochromatic electric field ψ (probe beam) with longitudinal wave vector k_z is

$$\mathrm{i}\partial_z \psi + \frac{1}{2k_z}\Delta_\perp \psi + \frac{k_z}{2n_{\mathrm{o,e}}^2}\delta n^2\left(|\psi|^2\right)\psi = 0. \tag{2}$$

The wave number is defined by the wavelength $\lambda = 532\,\mathrm{nm}$ as $k = 2\pi/\lambda = \sqrt{(k_\perp^2 + k_z^2)}$. The potential in propagation equation is given by nonlinear refractive index $\delta n^2\left(|\psi|^2\right) = -n_{\mathrm{o,e}}^4 r_{13,33} E$, where $n_{\mathrm{e}} = 2.325$ and $n_{\mathrm{o}} = 2.358$ are the extraordinary and ordinary refractive indices, and $r_{13} = 47\,\mathrm{pm/V}$, $r_{33} = 237\,\mathrm{pm/V}$ are corresponding electro-optic coefficients of photorefractive birefringent SBN crystal, respectively. The electric field $E = E_{\mathrm{ext}} + E_{\mathrm{sc}}$ that builds up inside the crystal is a superposition of an external electric field E_{ext} and an internal space charge field E_{sc}. The external electric field $E_{\mathrm{ext}} = 2000\,\mathrm{V/cm}$ is aligned with the optical $c = x$-axis, perpendicular to the $z-$axis, the direction of propagation, that is parallel to the long axis of the crystal while the internal space charge field E_{sc} is determine by the intensity distribution $I = |\psi|^2$ with a potential equation.

Photorefractive material response, as well as the electric bias of the SBN crystal, are taken into account by deploying the anisotropic, diffusive potential equation for the spatial evolution of the electrostatic potential ϕ_{sc} of the optically induced space-charge field E_{sc},

$$\Delta_\perp \phi_{\mathrm{sc}} + \nabla_\perp \ln\left(1 + I + I_{DL}\right) \cdot \nabla_\perp \phi_{\mathrm{sc}} = E_{\mathrm{ext}} \partial_x \ln\left(1 + I + I_{DL}\right), \tag{3}$$

where I is obtained from Eq. (2) and subsequently Eq. (2) is updated with $E_{\mathrm{sc}} = \partial_x \phi_{sc}$, iteratively. Disordered aperiodic lattice intensity distribution I_{DL}, with input lattice intensity I_{in}, modeling transverse intensity distribution of nondiffracting pattern homogeneous in the propagation direction, is persistent through iterations. Intensity and spatial distribution of I_{DL} determine $\delta n^2\left(|\psi|^2\right)$ in Eq. (2) through iterations. Potential I_{DL} of disordered lattices $\boldsymbol{DL}$ is formed according to Eq. (1). Here we abstracted and modeled the whole process of writing propagation invariant disordered lattice through potential I_{DL} in Eq. (3), based on numerical simulation of the writing process and the experimental realization of propagation invariant photonic lattices as in our previous publication.[21] We applied such numerical simulation to find a range of input lattice intensities I_{in} for which aperiodic Mathieu lattice stays stable and propagation invariant through the SBN crystal.

4. DISORDER-ENHANCED LIGHT TRANSPORT AND LOCALIZATION IN APERIODIC MATHIEU LATTICES

Here, we compare effects along light propagation in disordered aperiodic lattices with adjustable disorder strength generated with two different randomization methods. In order to study the transverse light localization in such lattices we statistically analyzed the propagation of narrow probe beam for different excitation positions, selected to involve various local environments. The probe beam excitation positions are selected from an equidistant 8×8 grid within one complete typical pattern depicted in Fig. 1 (A1). For several disorder strengths, we study averaged transverse intensity distributions, which we averaged over 64 various probe beam intensity distributions and at different propagation distances. We use the same disorder pattern for both methods and all disorder strengths. Hence, we produce the same lattices for 0% and 100% disorder strengths, consequently, we will exclude these two endpoints when we discuss method differences. To further describe light propagation we consider the log-plot profiles of such averaged intensity distributions. The parabolic log-plot fit of the log-plot profiles of averaged intensity distributions indicates diffusive-like transport. The exponential decay determines light localization, or in another word the linear fit of log-plots of such averaged transverse intensity distribution around the center demonstrates AL. In the region of disorder strength where AL occurs, we obtain localization length ξ_x along the x-axis by fitting intensity profiles $\mathrm{I}(x, y_0)$ with the exponential function $\mathrm{I}(x, y_0) = \exp\left[-2|x - x_0|/\xi_x\right]$, where x_0, y_0 denote the beam center position. The analogous procedure is applied along the y-direction. Furthermore, in order to characterize light propagation and localization, we calculate the effective beam width along the propagation distance z according to the relation $W_{\text{eff}}(z) = \mathrm{P}(z)^{-1/2}$, where $\mathrm{P}(z)$ is the inverse participation ratio.[8] We present scaled averaged effective beam width $\langle\omega_{\text{eff}}\rangle = W_{\text{eff}}(z)/(W_{\text{eff}}(0)/FWHM)$ where $FWHM$ is probe beam full width at half maximum.

First, we study the influence of disorder strength p on light diffraction after various propagation distances. For both methods in the disordered aperiodic lattice with any percent of disorder, scaled averaged effective beam widths $\langle\omega_{\text{eff}}\rangle$ is greater than in the lattice without disorder indicating DET (Fig. 2 (A)). At the shorter propagation distance ($z = 2\,\text{cm}$), $\langle\omega_{\text{eff}}\rangle$s are increasing with increasing disorder strength for both methods. However, a broadening of the beam is more pronounced for longer propagation distances ($z = 10\,\text{cm}$). Hence, we notice that $\langle\omega_{\text{eff}}\rangle$s at the fixed propagation distances are increasing up to the maximum values which occur at disorder strength 80% for M1 and 90% for M2, indicating maximum of DET. With the further increase of disorder strength, $\langle\omega_{\text{eff}}\rangle$s are decreasing indicating the possibility of AL occurrence. Corresponding $\langle\omega_{\text{eff}}\rangle$s have greater values for M1 than for M2, signifying more pronounced DET for M1, which is easily discerned from Fig. 2 (A).

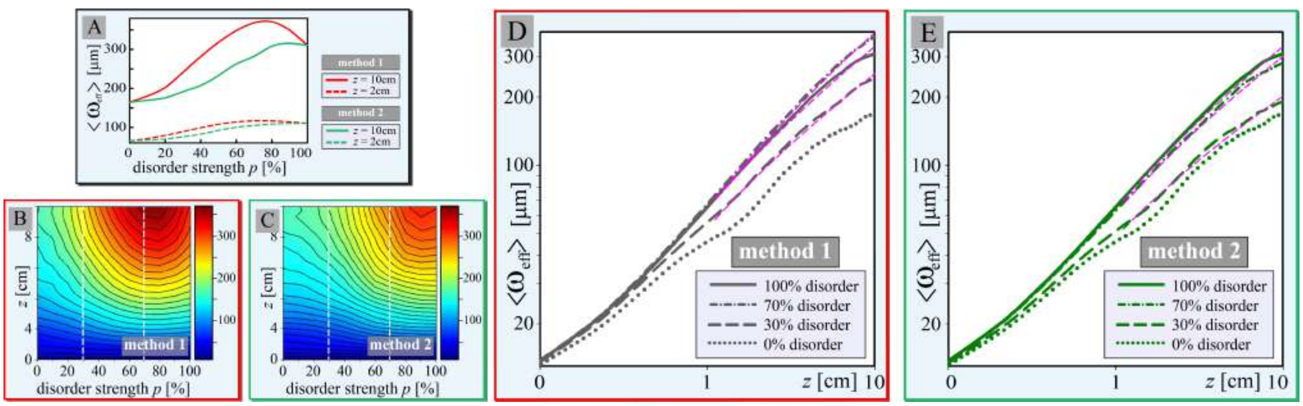

Figure 2. Diffraction dependence on disorder strength and propagation distance for two methods. (A) $\langle\omega_{\text{eff}}\rangle$ versus disorder strength p, for both methods, after 2 cm and 10 cm of propagation. (B)-(C) $\langle\omega_{\text{eff}}\rangle$ for various disorder strengths along the propagation distance for M1 and M2, respectively; the colormaps display $\langle\omega_{\text{eff}}\rangle$ in µm. $\langle\omega_{\text{eff}}\rangle$ along the propagation distance for 0%, 30%, 70%, 100% disorder strengths on a double logarithmic scale for: (D) M1, and (E) M2. Parameters: input Gaussian probe beam $FWHM$ is $8\,\mu\text{m}$ and $I_{\text{in}} = 0.7$.

In order to compare distinction of light propagation between methods we present $\langle\omega_{\text{eff}}\rangle$ along the propagation distance for various disorder strengths for M1 and M2 in Figs. 2 (B), (C) respectively. Maximal beam expansion, noticeable from the distribution of points where black isolines cross vertical sections, is in different regions for different methods. For M1 it is in the region of 60% to 80% disorder strength (Fig. 2 (B)), and in the region of 80% to 90% disorder strength for M2 (Fig. 2 (C)). For both methods, during the propagation $\langle\omega_{\text{eff}}\rangle$ increases for all disorder strengths. To quantify beam expansion rate ν, we examine $\langle\omega_{\text{eff}}\rangle$ as a function of propagation distance z (on a double logarithmic scale) for 4 disorder strengths, display in Figs. 2 (D), (E) for M1 and M2, respectively. We fit $\langle\omega_{\text{eff}}\rangle$ for some disorder strengths by power-law $\langle\omega_{\text{eff}}\rangle(z) \propto z^{\nu}$ (indicated with a pink dashed lines in Figs. 2 (D), (E)). Only for a short propagation distance ($z < 1\,\text{cm}$), beam expansion is almost linear i.e. ballistic transport, designate with $\nu = 1$. For a longer propagation distance (from 1 cm to 10 cm), the beam expansion rate is closest to $\nu = 0.5$ indicating to diffusive-like transport. For M1 the beam expansion rate is maximal for 70% $\nu = 0.52$ and lower $\nu = 0.48$ for both 30% and 100%, while for M2 is maximal for 100% $\nu = 0.48$ and lower for 70% and 30%, $\nu = 0.47$ and $\nu = 0.45$, respectively.

Next, for some disorder strengths and some propagation distances (2 cm and 10 cm), we analyze the averaged transverse intensity distributions and corresponding log-plot cross section along the x-axis (gray/red/green plots) and y-axis (black/dark red/dark green plots) summarized in Fig. 3. For aperiodic lattice without disorder, discrete diffraction of light is demonstrated, also visible from log-plot cross sections. Then we increase disorder

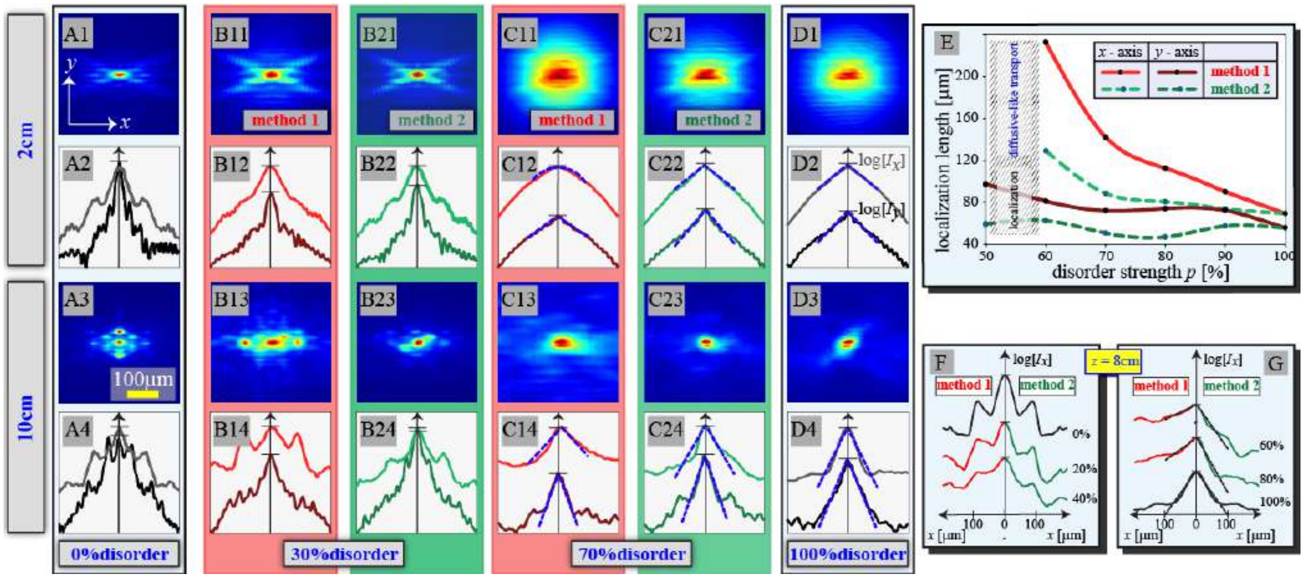

Figure 3. Light transport and localization in disorder aperiodic Mathieu lattice. Numerically averaged intensity distributions at the lattice output and corresponding log-plot cross sections of averaged intensity distributions along the x-axis (gray/red/green plots) and y-axis (black/dark red/dark green plots) (A1) - (D1) and (A2) - (D2), after 2 cm propagation distance and (A3) - (D3) and (A4) - (D24) after 10 cm propagation distance, for different disorder strengths. Blue dashed lines are corresponding linear fits. The horizontal axes span 400 μm in the x- and the y-direction. For each plot, there are two stacked vertical axes, where short horizontal bars are set on 1's. (E) Localization lengths after 10 cm of propagation distances for various disorder strengths along the x- and y-directions. Log-plot cross sections of intensity distributions symmetrical over left and right side of the x-direction, for M1 (left), M2 (right) at different disorder strengths: (F) 0%, 20% and 40% and (G) 60%, 80% and 100% disorder. Other parameters are as in Fig. 2.

strength. For 30% disorder for both methods, more pronounced diffraction i.e. DET, is noticeable from averaged intensity distributions and the log-plot cross sections Figs. 3 (B). More pronounced DET is evident for M1 than for M2. With further increasing disorder strength ($> 30\%$), averaged intensity distributions and the log-plot cross sections are more broadened, still showing DET. Also, for 70% disorder we notice DET for both methods, and at the same time, for longer propagation distance 10 cm, the log-plots cross sections are linearly fitted (Figs. 3 (C14), (C24)), demonstrating AL. The slopes of the fits determine localization lengths ξ. Since they are sharper for M2 than for M1, we conclude we have stronger localization for M2 at 70% disorder. For 100% disorder for all propagation distances (Figs. 3 (D)), we notice even more pronounced localization than for 70% disorder, mark with sharper slope of linear fits.

For both methods we examine light diffraction and localization along the x- and y- directions. For all disorder strengths, the less pronounced light diffraction along the y-direction is noticeable due to the crystal ($r_{33} >> r_{13}$) and lattice anisotropy (Fig. 1 (A)). The interplay of lattice and crystal anisotropy influence is evident for 70% disorder for shorter propagation distances from the log-plot cross sections for M1 (Fig. 3 (C12)). The log-plot along the x-axis is fitted with parabola, showing diffusive-like transport, while the log-plot along the y-axis is linearly fitted, indicating light AL. However, for M2 the log-plots along both directions are linearly fitted, therefore, AL is observed along both directions (Fig. 3 (C22)). For 70% disorder at longer propagation distances for both methods (Figs. 3 (C14), (C24)), and for 100% disorder for all propagation distances (Figs. 3 (D)) we notice liner fits of log plots along the both directions, with sharper slope of linear fits along the y-axis, indicating that AL is stronger in this direction. Since, for 100% disorder, the original lattice does not contribute to anisotropy and the disorder pattern, we use in our study, does not have clear x-y anisotropy preference, we conclude that the direction of crystal anisotropy is primarily cause of more pronounced localization in the y-direction.

For disorder strengths where we observed localization (linearly fitts of log-plot cross sections) we characterize light localization by comparing the localization length along the x- and y-direction. Such localization lengths after 10 cm of propagation are depicted in Fig. 3 (E). For both methods, more pronounced localization is visible along the y-axis where the localization lengths have lower values compared to the x-axis, due to the crystal and lattice anisotropy. Also, it is noticeable that localization lengths are larger for lower disorder strengths, while their values converge to each other as disorder strength increases, meeting at 100% disorder strength; a similar conclusion stands for $\langle\omega_{\mathrm{eff}}\rangle$s (Fig. 2 (C)). Even more, we notice that AL occurs at different disorder strengths along different directions. Along the y-axis, localization appears for lower disorder strengths than along the x-axis. Figure 3 (E) illustrates diffusive-like transport along the x-axis and light localization along the y-axis for the same 50%-60% disorder region.

The asymmetry of log plots cross-sections of averaged intensity distributions, along any axis and arbitrary disorder strength, is due to the specific occurrence of the used disorder pattern. The influence of the disorder pattern anisotropy (not along x-y-direction) is visible at some probe beam averaged transverse intensity distributions, as can be discerned comparing Figs. 3 (D3) with Fig. 1 (B). To mitigate asymmetry of the log-plot cross-sections we average the left and right sides of such profiles along the x-axis from the center, and we fit them with parabola or linearly. Figures 3 (F) - (G) depict a comparison of localization along the x-axis in our two methods for various disorder strengths after 8 cm) propagation distance. Since for lower disorder strengths significant features of original aperiodic lattices are remaining, the log-plots are not fitted (Fig. 3 (F)). Still, we notice the spreading of the log-plots simultaneous with increased $\langle\omega_{\mathrm{eff}}\rangle$ along the propagation, shown in Figs. 2, indicating DET. For both methods, at disorder strength between 50-60% light diffraction is closest to diffusive-like transport, however the parabolic fits of the log-plots could be attempted with low confidence (goodness of fit < 0.85). After 8 cm of propagation for 60% disorder log-plots are linearly fitted near the center indicating light localization (Fig. 3 (G)). For higher disorder strength (80% and 100%) light localization is noticed also confirmed by linear fits of log-plots. Since the slopes of the fits determine localization lengths, one can see that log-plot fits for the same disorder strength are steeper for M2 showing more pronounced localization for M2 than M1.

In the following, we are studying the independent input lattice intensity I_{in} influence on light diffraction for both methods. We compare $\langle\omega_{\mathrm{eff}}\rangle$s in dependence of disorder strength along propagation distance for 3 different values of I_{in}. Figures 4 (A), (B) summarize $\langle\omega_{\mathrm{eff}}\rangle$ for M1 and M2, respectively. By observing slopes of highlighted lines for constant disorder strength along the propagation distance for each I_{in}, we emphasize the beam expansion. For all disorder strengths and propagation distances, we observe the direct influence of lattice intensity on diffraction, for both methods, where lowering I_{in} causes an increase in $\langle\omega_{\mathrm{eff}}\rangle$.

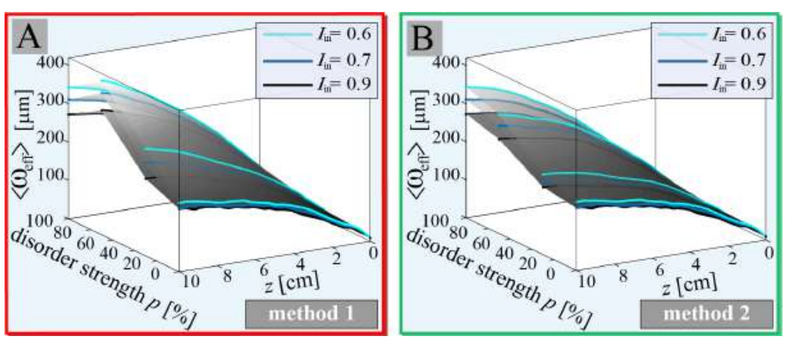

Figure 4. Input lattice intensity I_{in} influence on the light diffraction. (B) M1 and (C) M2: interpolated surfaces of $\langle\omega_{\mathrm{eff}}\rangle$ along the propagation distance for 0%, 30%, 70%, 100% disorder strengths and for various I_{in}. Other parameters are as in Fig. 2.

In previous examinations, we notice differences in methods comparing corresponding averaged transverse intensity distributions, the log-plot cross section along the x-axis and y-axis or quantities $\langle\omega_{\mathrm{eff}}\rangle(z,p)$ and localization lengths. As we describe in Section 2, the main difference in our methods is caused by the difference in the maximum lattice intensity $I_{\max}$ with the change of disorder strength p (Fig. 1 (F)). As a consequence, a different variation of the averaged lattice intensities I_{avg} with p for different methods is noticeable from Fig. 1 (G). For both methods, we observed that influence of disorder strength p to $\langle\omega_{\mathrm{eff}}\rangle$ variate with increases of propagation distances (Fig. 4 (A)). After a longer propagation distance (10 cm) we noticed that $\langle\omega_{\mathrm{eff}}\rangle$s dependence on disorder strength p is similar to reciprocal I_{avg}.

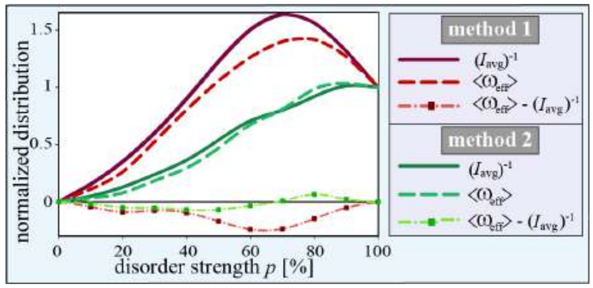

Figure 5. Methods differentiation via $\langle\omega_{\text{eff}}\rangle$ and $(I_{\text{avg}})^{-1}$. Normalized $\langle\omega_{\text{eff}}\rangle$, $(I_{\text{avg}})^{-1}$ and their differences for both methods as a function of disorder strength. Other parameters are as in Fig. 2.

To investigate $\langle\omega_{\text{eff}}\rangle$ and reciprocal averaged lattice intensity $(I_{\text{avg}})^{-1}$ connection we normalize them according to relation $F(p)/(F(1)-F(0))-F(0)$, where F is $\langle\omega_{\text{eff}}\rangle$ or $(I_{\text{avg}})^{-1}$. For both methods, we display such normalized values, as well as their differences in Fig. 5. We conclude that $\langle\omega_{\text{eff}}\rangle$ is strongly influenced with the variation of $(I_{\text{avg}})^{-1}$ with disorder strength for longer propagation distances and for narrow probe beam width, since variations of normalized $\langle\omega_{\text{eff}}\rangle$ closely follow $(I_{\text{avg}})^{-1}$ for both methods. M2 has a minor deviation of $\langle\omega_{\text{eff}}\rangle$ from $(I_{\text{avg}})^{-1}$ versus p, while for M1 a slightly more prominent deviation is visible. Also, for M2 we noticed more pronounced localization in both directions in comparison to M1, hence, we can connect lattice intensity with AL strength. Additionally for M1, a dip of deviation of $\langle\omega_{\text{eff}}\rangle$ from $(I_{\text{avg}})^{-1}$ versus p we can associate with a sharp minimum of I_{max} and I_{avg} versus p (Figs. 1 (F) - (G)) which occur at the same disorder strength. As we prove in Fig. 4, light diffraction is reverse proportional to input lattice intensity. Hence, for the minimum of the maximum lattice intensity in M1, we have the highest $\langle\omega_{\text{eff}}\rangle$ (maximal DET). The narrow probe beam for low lattice intensity diffracts the most, but at longer propagation distances $\langle\omega_{\text{eff}}\rangle$ does not reach the variation of I_{avg} as at minimal lattice intensities beam already rapidly expanded early in propagation. By a difference of $\langle\omega_{\text{eff}}\rangle$ and $(I_{\text{avg}})^{-1}$ a deviation of these two quantities that contain the influence of parameters not directly connected to the lattice intensity, such as lattice and beam shapes, can be quantified.

5. CONCLUSION

In summary, we presented two different theoretical methods for the realization of two-dimensional disordered aperiodic photonic lattices with adjustable disorder strength optically induced in a photorefractive media. We numerically investigate light propagation in disordered aperiodic Mathieu lattices. Comparing the effective beam width along the propagation distance for various disorder strengths, averaged transverse intensity distributions, the log-plot profiles of such averaged intensity distributions, and localization lengths along different directions we characterize light transport and localization for two methods. For both methods, we observed enhanced light transport for all disorder strengths but AL of light for higher disorder strengths. Localization effects are more pronounced for longer propagation distances. More pronounced localization is observed for M2 than M1, and we attributed the difference between the two methods to various levels of lattice intensity. We observe that localization length differs along different directions, due to the crystal and lattice anisotropy. According to the investigation we present in this study we suggest diminishing the influence of lattice intensity for studying the dependence of AL and DET on disorder strength. We propose a further modification of our M2 in which averaged intensity levels would be equalized for every disorder strength used.

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TOM 5 Resonant Nanophotonics

Controlling chromaticity by lamellar gratings

Hiroyuki Ichikawa, Naoki Arita, Keigo Shikimi, Ryunosuke Tani

Ehime University, Japan

Fundamental numerical study on controlling chromaticity with the simplest diffractive structure is carried out. Observed various characteristics on transmission/reflection and dielectric/metal will be useful guidelines for practical optimisation of device structures.

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TOM 8 Non-linear and Quantum Optics

Light propagation in disordered aperiodic Mathieu photonic lattices

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We present the numerical modeling of two different randomization methods of photonic lattices. We compare the results of light propagation in disordered aperiodic and disordered periodic lattices. In disordered aperiodic lattice disorder always enhances light transport for both methods, contrary to the disordered periodic lattice. For the highest disorder levels, we detect Anderson localization for both methods and both disordered lattices. More pronounced localization is observed for disordered aperiodic lattice.

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TOM 13 Advances and Applications of Optics and Photonics

Chip integrated photonics for ion based quantum computing

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Ion traps are a promising platform for the realisation of high-performance quantum computers. To enable the future scalability of these systems, integrated photonic solutions for guiding and manipulating the laser light at chip level are a major step. Such passive optical components offer the great advantage of providing beam radii in the µm range at the location of the ions without increasing the number of bulk optics. Different wavelengths, from UV to NIR, as well as laser beam properties, such as angle or polarisation, are required for different cooling and readout processes of ions. We present

Light propagation in disordered aperiodic Mathieu photonic lattices

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Abstract. We present the numerical modeling of two different randomization methods of photonic lattices. We compare the results of light propagation in disordered aperiodic and disordered periodic lattices. In disordered aperiodic lattice disorder always enhances light transport for both methods, contrary to the disordered periodic lattice. For the highest disorder levels, we detect Anderson localization for both methods and both disordered lattices. More pronounced localization is observed for disordered aperiodic lattice.

1 Introduction

Anderson localization (AL), a well-known phenomenon in solid-state physics [1] is transferred to other fields like ultracold atoms, matter, light or sound waves [2], and demonstrated in various customized configurations [3–6]. The physics of periodic photonic systems has fundamental importance. Still, deviations from periodicity are significant as they may result in higher complexity, like the realization of photonic quasicrystals, the structures that are between periodic and disordered ones. Heretofore, light propagation properties have been studied in periodic photonic lattices [7, 8], as well as in disordered ones [3, 9, 10]. However, the quasiperiodic and aperiodic photonic lattices are merged as a further attractive research field for light propagation.

In our previous studies, we introduced aperiodic Mathieu structures with controllable complexity [11] and we studied light localization in them [12]. In such lattice, light expansion is hindered in comparison to periodic lattice and nonlinear light localization is demonstrated [12]. Randomization of periodic lattices can lead to AL [3, 9] or its suppression [13], while disordered quasiperiodic Penrose lattice can support AL and disorder-enhanced transport (DET) [14].

In this paper, we present two numerical methods for controllable randomization of photonic lattices and study disorder level (DL) influence on light propagation. For both methods, we numerically investigate the linear light propagation in disordered aperiodic Mathieu (DA) and disordered periodic (DP) lattices. For all DLs, we observe DET and AL is verified for higher DLs in DA lattices, for both methods. In contrast, in DP lattices disorder suppress diffraction and AL is observed for higher DLs. Localization length differs along different transverse directions owing to the crystal and lattice anisotropy. We confirm a more pronounced localization for DA lattices in both directions and both methods.

2 Light propagation in DA and DP lattics

Two-dimensional disordered structures $\boldsymbol{DS}$, with an adjustable DL, are numerically realized by combining an original structure $\boldsymbol{S}$ with a disorder pattern $\boldsymbol{D}$ according to the relation $A_{DS} = (1-p) * A_S + p * A_D$, where A is the field amplitude, and parameter p is the relative contribution of the original structure and disorder pattern, i.e. DL. To ensure propagation invariant structures with the same propagation constant, we preset the Fourier spectrum of the disorder pattern, numerically calculated by interfering plane waves with constant amplitude and random phases, to be located on the same circle with radius k as the original structure [15]. As the original structure we use an aperiodic Mathieu structure created as in our paper [11], or square lattice with period d equal to the characteristic structure size $a = 25\,\mu$m of Mathieu beams used for the creation of the aperiodic structure. Disorder pattern's mean grain size $2\pi/k$ is equal to a of Mathieu beams. A case when the maximum lattice intensity I_{m} of the disordered lattice $I_{DL} = |A_{DS}|^2$ for each DL is unscaled, we will refer as M1, and M2 is the case when I_{DL} is scaled with I_{in} for each DL. For both methods, an increase of DL modifies the transverse intensity distribution of the original structure until completely substitutes it with the disorder pattern. For the same DL, the spatial intensity distributions of the disordered lattices are the same for both methods, but they differ in waveguides depths. For both methods, I_{m} dependencies of DL for DA and DP lattices are almost the same (Fig. 1 (A)). Opposite to the periodic lattice, our aperiodic lattice is not uniform in waveguide's distances, and their depths vary. We calculate averaged lattice intensity $I_{\mathrm{avg}} = \sum_{\mathbf{r}} I_{DL}(\mathbf{r})$ of DA and DP lattices for both methods (Fig. 1 (B)). For both methods, I_{avg}s are lower for DA than for DP lattices. For M1, I_{m} and I_{avg} are lower than for M2.

We study the difference in light propagation in DA and DP lattices realized with these methods. We use intensity distributions of disordered structures I_{DL} in numerical simulation of the light propagation along the z-axis in disordered lattices in a photorefractive crystal, numerically

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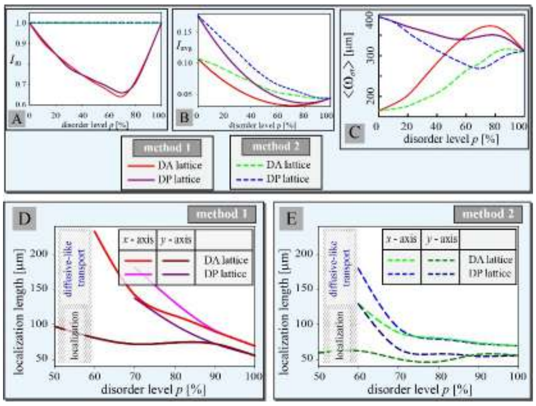

Figure 1. Methods differences of realization and light propagation in DA and DP lattices. (A) I_{m}, (B) I_{avg} of DA and DP lattices versus DL for different methods. (C) $\langle \omega_{\mathrm{eff}} \rangle$ and (D)-(E) localization lengths along the x- and y-axis for M1 and M2, respectively versus DLs after 10 cm of propagation.

described by solving a system of equations as explained in Ref. [12]. We statistically analyze the propagation of a narrow Gaussian probe beam, of an FWHM of 8 μm, for different excitation positions selected to involve various local environments of the disordered lattice [14]. We realize such analysis for various DLs, using only one disorder pattern, averaging 64 different intensity distributions after 10 cm propagation distance.

According to relation $W_{\mathrm{eff}} = \sqrt{\mathrm{IPR}(z)}$, where $\mathrm{IPR}(z)$ is the inverse participation ratio [3], we calculate the effective beam width W_{eff} and determine a range of DL where DET and light localization are obtained. In Fig. 1 (C) we show scaled averaged effective beam widths $\langle \omega_{\mathrm{eff}} \rangle = W_{\mathrm{eff}}(z)/(W_{\mathrm{eff}}(0)/FWHM)$. In the DA lattice with any percent of disorder, $\langle \omega_{\mathrm{eff}} \rangle$ is greater than in the lattice without disorder, specifying DET for both methods. A maximum DET is indicated with $\langle \omega_{\mathrm{eff}} \rangle$ highest value noticed at 80% for M1 and 90% for M2. Further increase of DL decreases $\langle \omega_{\mathrm{eff}} \rangle$, indicating the possibility of AL occurrence. $\langle \omega_{\mathrm{eff}} \rangle$ has a greater value for M1 than for M2, denoting a more pronounced DET for M1. Opposite in the DP lattice, $\langle \omega_{\mathrm{eff}} \rangle$ decreases up to the minimum values which occur at 60% for M1 and 70% for M2. With the further increase of DL, $\langle \omega_{\mathrm{eff}} \rangle$ increases for M2, while for M1 fluctuates. We examine the averaged transverse intensity distributions and corresponding log-plots of such averaged intensity distributions (not shown here). When the log-plots intensity profiles are linearly fitted around the center, we consider AL is confirmed [10]. In the region of DL where AL occurs, we obtain localization length by fitting intensity profiles with the exponential function [10], along the x and y-axis. For DA and DP lattices, in Figs. 1 (D)-(E) we show localization lengths for M1 and M2, respectively. For both methods, more pronounced localization is visible along the y-axis where localization lengths have lower values compared to the x-axis, due to the crystal and lattice anisotropy. AL occurs at different DLs along different directions, along the y-axis appears for lower DL than along the x-axis.

3 Conclusion

We presented two different methods for the creation of disordered photonic lattices with adjustable DL. We numerically studied light propagation in DA and DP lattices. For both methods, we observed enhanced light transport for all DLs but AL of light for higher DLs in DA lattice, contrary in DP lattice, we only observed AL for higher DLs. More pronounced localization is demonstrated in DA lattices for both methods and for M2 in both DA and DP lattices. Due to the crystal and lattice anisotropy, localization lengths differ in different directions.

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Presentation + Paper

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Hide Abstract -

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Read Abstract +

Dimensionality crossover of radial discrete diffraction in optically induced Mathieu photonic lattices

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ABSTRACT

We demonstrate transitional dimensionality crossover of radial discrete diffraction in optically induced radial-elliptical Mathieu photonic lattices. Varying the order, characteristic structure size, and ellipticity of the Mathieu beams used for the photonic lattices generation, we control the shape of discrete diffraction distribution over the combination of the radial direction with the circular or elliptic. We also investigate the transition from one-dimensional to two-dimensional discrete diffraction by varying the input probe beam position. Discrete diffraction is the most pronounced along the crystal anisotropy direction.

Keywords: Dimensionality crossover, radial discrete diffraction, photonic lattices, discrete diffraction, Mathieu beams, optical induction, strontium barium niobate crystal

1. INTRODUCTION

One of the main areas of research and applications in optics is the control and manipulation of light in photonic lattices.[1] Arrays of evanescently coupled waveguides or photonic lattices are common structures for discrete effects and dynamics studies. When light is focused into one single waveguide and propagates linearly along the array, it will tunnel to the neighboring waveguide and display a distinctive diffraction pattern, with the intensity mainly concentrated in the outer lobes. The discrete diffraction of light[2] was observed in one-dimensional (1D) waveguide arrays[3]and two-dimensional (2D) photonic lattices,[4] both theoretically and experimentally. It is also studied in other systems, like atomic[5,6] and aperiodic[7–10] photonic lattices.

An additional periodicity distortion is produced by the truncation of the periodic photonic lattice, leading to the development of optical surface states that are analogous to the surface states in the electrical theory of periodic systems.[11,12] Surface solitons (optical self-trapped discrete surface waves) have been found in 2D photonic lattices[13] and 1D waveguide arrays.[14,15] Physical systems that exhibit dimensionality crossover have gained significant interest; one such example is the continuous transformation of 1D into a 2D photonic lattice.[16] One can observe intermediate states that do not have 1D or 2D geometry in such systems. An unanswered question regarding these structures remains: How, when, and why does a system transition from one to two dimensions?

Nondiffracting beams are practical for 2D photonic lattice creation as they retain their propagation-invariant structure even with weak nonlinearity.[17] Four principal nondiffracting beam families are exact solutions of the Helmholtz equation in different coordinate systems:[18,19] plane waves in Cartesian, Bessel beams in circular cylindrical,[20] Mathieu beams in elliptic cylindrical,[21] and parabolic beams in parabolic cylindrical coordinates.[22] Mathieu beams are utilized for optical lattice writing, even allowing the development of elliptically formed vortex solitons.[23] They are additionally used for different aperiodic photonic lattices generation by the optical induction technique in photorefractive crystals[10,24] and for particle manipulation.[25]

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Both experimental and theoretical methods are used in this work to investigate the requirements for discrete diffraction occurrence and its properties in the aperiodic Mathieu photonic lattices. Mathieu beam shape enables the one-pass experimental realization of naturally *truncated aperiodic* photonic lattices, allowing both surface states and discrete diffraction on the surface. We focus on the aperiodic photonic structures in elliptical-radial geometries because they provide a diverse range of shapes, including ellipticity as an additional degree of freedom. They also allow us to consider the dimensionality of discrete diffraction. The lattice period and the refractive index modulation in periodic photonic lattices are uniform over the whole lattice. Contrarily, they are not independent parameters in Mathieu lattices since they are both related to beam characteristics (beam order, characteristic structural size, and beam ellipticity). Due to the aperiodicity of the Mathieu lattice, several probing local settings permit discrete diffraction impacted by the nearest neighbors. Unlike the periodic lattice, during the propagation, the diffracting probe might pass through several local environments, resulting in additional variations in the discrete diffraction effects.

Here, we demonstrate elliptical-radial discrete diffraction in photonic lattices realized by using a single Mathieu beam and a dimensionality crossover of radial discrete diffraction. We can control discrete diffraction in the radial direction and the shape of their distributions in the perpendicular directions by varying the order and characteristic structure size of the used Mathieu beam. By shifting the position of the input probe beam, we observe the transition from 1D to 2D discrete diffraction. In our medium - the photorefractive birefringent cerium-doped strontium barium niobate (SBN61:Ce) - the crystal anisotropy plays a significant role in the discrete diffraction phenomenon. Hence, we observe the most pronounced 2D discrete diffraction along the crystal anisotropy direction.

2. NUMERICAL MODELING AND EXPERIMENTAL REALIZATION OF LINEAR LIGHT PROPAGATION IN MATHIEU PHOTONIC LATTICES

We examine the conditions for discrete diffraction of light by investigating its linear propagation in Mathieu photonic lattices made in the photorefractive medium, SBN61:Ce crystal. By solving the coupled system of two equations, the nonlinear Schrödinger equation of the scalar electric field (propagation equation) and the diffusion equation for the electrostatic potential (potential equation),[26,27] we model linear light propagation in a photonic lattice. Using a spectral split-step beam propagation method,[28] we numerically solve both equations. The following is the propagation equation of the scalar electric field Ψ with longitudinal wave vector k_z:

$$\mathrm{i}\partial_z \Psi + \frac{1}{2k_z}\Delta_\perp \Psi + \frac{k_z}{2n_{\mathrm{o,e}}^2}\delta n^2 \Psi = 0, \tag{1}$$

where the wave number $k = 2\pi/\lambda = \sqrt{(k_\perp^2 + k_z^2)}$ is defined by the laser wavelength $\lambda = 532\,\mathrm{nm}$. The potential in the propagation equation is specified by $\delta n^2 = -n_{\mathrm{o,e}}^4 r_{13,33} E$, where $n_\mathrm{e} = 2.325$ and $n_\mathrm{o} = 2.358$ are the extraordinary and ordinary indices, and $r_{13} = 47\,\mathrm{pm/V}$ and $r_{33} = 237\,\mathrm{pm/V}$ are the corresponding electro-optic coefficients of the crystal. The total electric field $E = E_{\mathrm{ext}} + E_{\mathrm{sc}}$ that builds up inside the crystal is a superposition of an external electric field $E_{\mathrm{ext}} = 2000\,\mathrm{V/cm}$ aligned with the optical $c = x$ axis (perpendicular to the propagation direction $z-$axis) and an internal space charge field E_{sc} that results from the incident intensity distribution within the potential equation. Taking into account the electric bias of the crystal and the photorefractive material response, we solve an anisotropic potential equation for the spatial evolution of the electrostatic potential ϕ_{sc} of the optically-induced space-charge field E_{sc}

$$\Delta_\perp \phi_{\mathrm{sc}} + \nabla_\perp \ln(1+I) \cdot \nabla_\perp \phi_{\mathrm{sc}} = E_{\mathrm{ext}} \partial_x \ln(1+I), \tag{2}$$

where $I = |\Psi|^2$ is obtained from Eq. (1). Subsequently, Eq. (1) is updated with the optically induced space-charge field

$$E_{\mathrm{sc}} = \partial_x \phi_{sc}, \tag{3}$$

obtained by solving Eq. (2). This procedure is iteratively repeated along the propagation direction z.

The propagation-invariant Mathieu photonic lattice is numerically generated using the distribution $I = I_{latt}$ from Eq. (1), which we reference as the writing lattice pattern in the experiment.[24] Thus, in distinct numerical simulations of Eqs. (1) and (2), we first obtain the spatial distribution of I_{latt} by propagating an ordinary Mathieu beam in the weak nonlinear case. Then, we use such a nearly propagation-invariant lattice distribution as a lattice potential, to simulate an extraordinary Gaussian probe beam propagation. In this case, we use the same equations yet modify total intensity distribution $I = I_p + I_{latt}$, where the Gaussian probe beam intensity $I_p = |\Psi|^2$ is obtained from Eq. (1). Not to cause an excessive nonlinear modification in our simulations with the probe beam, I_p is kept sufficiently weak.

To experimentally investigate the linear light propagation of narrow probe Gaussian beam in Mathieu photonic lattices generated in photorefractive SBN61:Ce crystal, we use the experimental setup shown in Fig. 1. As a light source, we use the continuous frequency-doubled Nd:YVO$_4$ laser that emits at a wavelength of $\lambda = 532\,\mathrm{nm}$. The collimated and expanded laser beam (telescope L1-L2) illuminates as a plane wave the phase-only reflected spatial light modulator (SLM). In this fashion, both the amplitude and phase of the reflected light field are modulated. That is accomplished by addressing to the SLM a precalculated hologram containing the information on the complex light field of the Mathieu lattice, additionally encoded with a blazed grating.[24,29] In this way, an ordinary polarized beam is spatially modulated, and we use it as the writing beam. The second telescope (L3-L4) demagnifies the writing beam to illuminate the crystal. The diffraction pattern of the Mathieu lattice is bandpass filtered in Fourier space (FF).[29] The SBN61:Ce crystal with dimensions of $5 \times 5 \times 20\,\mathrm{mm}^3$ is externally biased with an electric field E_{ext}, aligned with the optical $c = x$ axis, perpendicular to the direction of propagation, z axis, and parallel to the long axis of the crystal. As a result, the ordinary polarized beam, with power P, optically induces a refractive index modulation, writing the lattice in the crystal whose nodes conform with the numerically calculated Mathieu lattice.

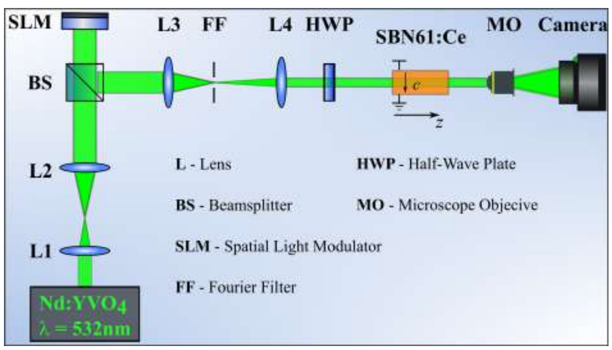

Figure 1. Experimental setup for investigating the light beam propagation in the two-dimensional Mathieu photonic lattice.

After the fabrication of the Mathieu lattice, the writing beam and the external electric field are switched off. Subsequently, an extraordinarily polarized narrow Gaussian probe beam illuminated the specified lattice position, and we observed linear light propagation in the Mathieu photonic lattice. A half-wave plate rotates the probe beam's linear polarization by 90° relative to the writing beam's polarization, addressing the higher electro-optic coefficient. We use an imaging system formed by a microscope objective (MO) with the camera to detect the transverse intensity distribution of the writing and/or probing beam at the back face of the crystal. A probe beam's low power keeps the propagation in a linear regime, and the lattice refractive index modulation remains unmodified (until erased by homogeneous white light). The probe beam, whose full-width-at-half-maximum is $8\,\mu\mathrm{m}$, is directly positioned in front of the crystal, and its transverse position defines the input center. The probe beam size is adequate to illuminate only one lattice site.

3. DIMENSIONALITY CROSSOVER OF RADIAL DISCRETE DIFFRACTION IN MATHIEU PHOTONIC LATTICES

Mathieu beams, as a class of nondiffracting beams, are suitable for the photonic lattices generation. We base our study on even Mathieu beams $M_m(\xi, \eta)$ of order m, which are mathematically described as a product of the angular J_{em} and radial c_{em} Mathieu functions of order m: $M_m(\xi, \eta) = C_m(q) J_{em}(\xi; q) c_{em}(\eta; q)$. A weighting constant $C_m(q)$ depends on the ellipticity parameter $q = f^2 k_t^2/4$, related to the positions of the two foci f and the transverse wave number $k_t = 2\pi/a$, where a is the characteristic structure size. Elliptical coordinates (ξ, η) are related to the Cartesian coordinates (x, y) by $x + iy = f cosh(\xi + i\eta)$. Mathieu beams M_m, whose intensity distribution I_{latt} is numerically calculated from Eqs. (1) and (2), generate lattices in photorefractive crystal. By changing Mathieu beams parameters, i.e., beam order m, characteristic structure size a, and ellipticity q, we can realize different spatial intensity distributions of Mathieu lattices.[24] The refractive index change and the period of such lattice are not independent but linked via Mathieu beam parameters m, q, and a. Various probing local environments in Mathieu lattices support the formation of different discrete diffraction patterns. By varying the Mathieu lattice ellipticity, the curvature (equal to zero in the periodic lattice) of the lines connecting nearest neighbor sites, and thus the discrete diffraction pattern, changes.

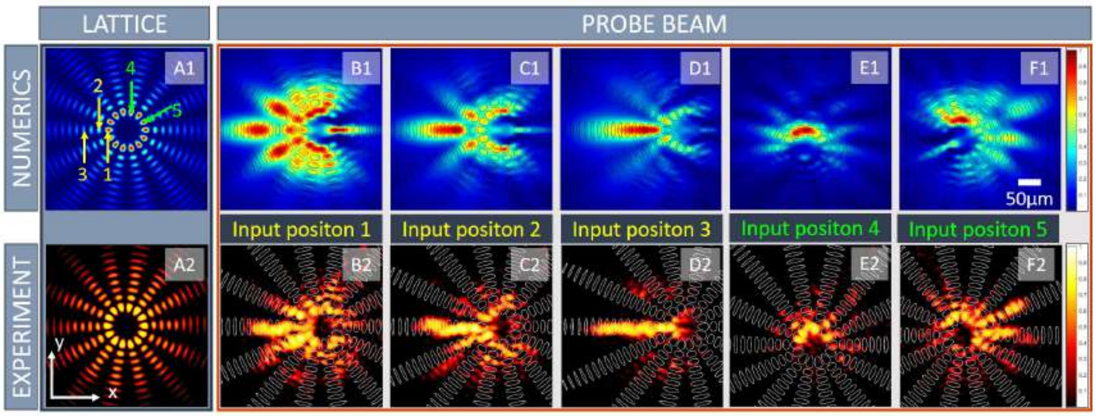

Figure 2. Discrete diffraction in Mathieu lattice for various probe beam input positions. Numerical (A1) and experimental (A2) intensity distribution of the Mathieu lattice at the exit crystal face, with arrows in (A1) indicating various input probe beam positions. The first row shows numerically observed probe beam intensity distributions at the exit crystal face for the input probe beam positions: 1 (B1), 2 (C1), 3 (D1), 4 (E1), and 5 (F1). The second row presents experimentally obtained intensity distributions at the crystal exit face for input probe beam positions: 1 (B2), 2 (C2), 3 (D2), 4 (E2), and 5 (F2). Parameters are: Mathieu lattice order m = 7, ellipticity $q = 0$, and characteristic structure size $a = 30\,\mu m$, $I_{latt} = 1$, experimental lattice writing beam power $P = 0.5mW$.

We first use the Mathieu lattice with zero ellipticity ($q = 0$), where the waveguides are distributed along the ***circles*** and the radial spikes. The input probe beam enters the lattice at the leftmost sites (positions 1, 2, and 3 in Fig. 2 (A1) marked with yellow arrows) of the first, second, and fourth circular waveguide array. All three positions belong to the same radial spike, while positions 4 and 5 (the green arrows in Fig. 2 (A1)) belong to the most intense (inner) circular waveguide array. We compare the numerical and experimental results of the probe beam intensity distributions at the crystal back face after 20 mm propagation. For the first input probe beam position on the lattice edge (marked as position 1 in Fig. 2 (A1)), we observe behavior similar to the 2D discrete diffraction. We will refer to it as the radial 2D discrete diffraction in the truncated elliptical-radial lattice (Fig. 2 (B1), (B2)). On the same circular waveguide array, at the position (right) opposing the entrance of the input probe beam, we notice the out-of-order appearance of intensive spots collecting evanescent leakage of the waveguides from the opposite, left side. When we shift the probe beam input position away from the lattice edge (position 2 in Fig. 2 (A1)), the two-dimensionality of discrete diffraction is less pronounced at the expense of separate circular and radial 1D discrete diffractions. For the third probe beam position (position 3 in Fig. 2 (A1)), one notices separated circular and radial 1D discrete diffractions.

Figure 3 displays the propagation distance dependence of the light intensity of probing beams projected to circles, following the geometry of the lattice. First, we cut the four inner circles (Fig. 3 (A)) at points opposing the excitation positions 1 and 3 (Fig. 2 (A1)) and show flattened probe intensity distributions in Figs. 3 (B) and (C), respectively, exhibiting discrete diffraction along circles. At the cut point (the right-hand side position mentioned in the previous paragraph), i.e., on the edges of distributions in Figs. 3 (B) and (C), the intensity builds up near the exit side of the crystal, an effect predominantly noticeable on the first circles for both input positions. According to probe intensity distributions, for input position 1, discrete diffraction appears along

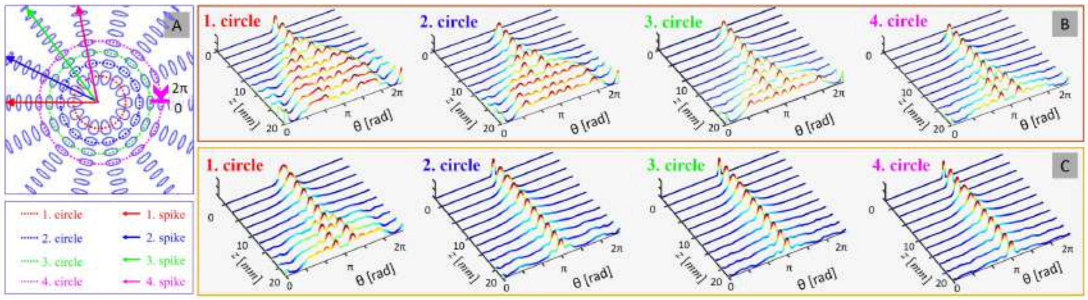

Figure 3. Discrete diffraction along the circular waveguide arrays. Propagation distance (z) dependence of intensity distributions (B) and (C), projected to four circles given in (A), for probing beams entering the lattice at positions 1 and 3 in Fig. 2 (A1), respectively. For each circle, the circumference is measured in the angular coordinate θ starting from the cut point.

the first four circles (Fig. 3 (B)). For input position 3, discrete diffraction is observed only along the first circle (Fig. 3 (C)). The discrete edge diffraction is apparent along some truncated spike waveguide arrays in the radial direction. The transition from 2D to 1D discrete diffraction happens in the truncated elliptical-radial lattice upon changing the input probe beam position.

The anisotropy of our medium (SBN61:Ce crystal) favors the discrete diffraction in some directions. Hence, to investigate the influence of crystal anisotropy on light diffraction in the Mathieu lattice, we consider different input probe beam positions, depicted as positions 1, 4, and 5 in Fig. 2 (A1). Note that all input beam positions lie on one circular waveguide array. If the crystal did not have the anisotropy, the discrete diffraction would have resulted in equal intensity distributions for all three points. However, the crystal possesses anisotropy, and the intensity distributions for the chosen input beams are not identical (Figs. 2(B), (E), and (F)). Therefore, in such lattices, 2D discrete diffraction is observable *only* when the input probe beam enters waveguides that are located at the lattice symmetry axis parallel to the crystal anisotropy direction (c-axis) (Fig. 2(B)).

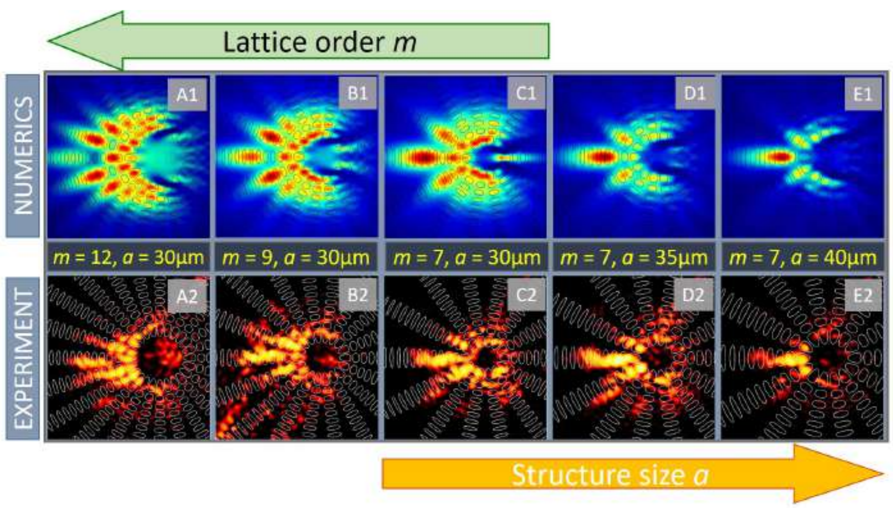

Figure 4. Influence of Mathieu lattice order m and structural size a on the discrete diffraction patterns in elliptical waveguide arrays. Numerically (A1-E1) and experimentally (A2-E2) observed intensity distributions of the probe beam at the exit crystal face for parameters m and a, marked in each panel. The ellipticity $q = 5$, and other parameters are as in Fig. 2.

Finally, we investigate how lattice order m and characteristic structure size a influence discrete diffraction patterns (Fig. 4). Mathieu lattice ellipticity q is set to 5 to observe the effects of discrete diffraction for different curvatures. Hence, the waveguide arrays are distributed along the ***ellipse***, as well as along the radial spikes. We examined the probe beam propagation for three lattice orders, $m = 7,\ 9$, and 12 (Fig. 4 (A-C)). With increasing order m, the number of spike waveguide arrays rises, leading to more pronounced 2D discrete diffraction. The effect of tree characteristic structure sizes, $a = 30,\ 35$, and 40 μm, on descrete diffraction in Mathieu lattices was analyzed (Fig. 4 (C-E)). When characteristic structure size a increases, the distance between neighboring sites grows, lowering the order of discrete diffraction (from 2D to 1D). Controlling m and a, we can maintain optimal conditions for 1D, 2D, or intermediate discrete diffractions in certain regions, and with the structure size a variation, we can move those regions.

4. CONCLUSION

In conclusion, we presented an experimental and numerical method for obtaining radial and angular discrete diffraction in various Mathieu lattices. Mathieu photonic lattices are optically induced in a photorefractive crystal through one-pass creation in the experiment. They are also a kind of truncated lattices that could support surface states. Mathieu photonic structures have a broad spectrum of shapes and ellipticity as an additional degree of freedom, with the waveguides arranged along circles, ellipses, hyperbolas, and radial spikes. We control radial discrete diffraction by varying the order and characteristic structure size of Mathieu beams utilized for photonic lattice induction. We observed a dimensionality crossover of radial discrete diffraction from 1D to 2D discrete diffraction by shifting the position of the input probe beam. The most pronounced 2D discrete diffraction is observed along the crystal anisotropy direction. Our approach provides branching 1D discrete diffraction along circle/ellipse and spike waveguide arrays in truncated photonic lattices. The findings from this work pave the way for exploiting light propagation in novel classes of optical lattices without limitation to the ones studied here. The adaptability and reconfigurability of light-guiding structures are essential in allowing functionality, demonstrating a substantial advancement in photonics nowadays and making an important step towards novel, innovative waveguiding applications and light routing approaches. They should be of great importance in capacity-enhanced optical information processing applications.

ACKNOWLEDGMENTS

This work was supported by funding provided by the Institute of Physics Belgrade through the grants by the Ministry of Science, Technological Development and Innovations of the Republic of Serbia, by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-66/2024-03/200053) and by the Science Fund of the Republic of Serbia, **GRANT No 7714356, IDEAS - CompsLight**.

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Dimensionality crossover of radial discrete diffraction in optically induced Mathieu photonic lattices

Jadranka M. Vasiljević[1], Vladimir P. Jovanović[2], Aleksandar Ž. Tomović[2], Dejan V. Timotijević[2], Radomir Žikic[2], Milivoj R. Belić[3], and Dragana M. Jović Savić[1]

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Light manipulation in photonic lattice (PL) is a prime area of investigation and application in optics [1]. PLs provide a huge platform for investigating discrete light diffraction effects. Discrete diffraction of light was theoretically and experimentally observed in both one-dimensional (1D) and two-dimensional (2D) structures, as well as in aperiodic or other systems. Truncating periodic PLs cause additional distortion of the periodicity, resulting in the formation of optical surface states akin to electronic surface states in periodic systems [2]. The continuous transition from 1D to 2D PLs is an attractive field of study, with a still open question regarding intermediate states that can occur in such physical systems with dimensionality crossover that do not exist in either 1D or 2D geometries [3].

Nondiffracting beams, propagation-invariant fields over hundreds of diffraction lengths even in the presence of weak nonlinearity [4], are ideal for generating 2D PLs and have diverse applications in free-space wireless communications, optical interconnections, long-distance laser machining, and surgery. There are four fundamental families of such propagation-invariant light fields: Discrete, Bessel, Mathieu, and Weber nondiffracting beams [5-7]. Among these, Mathieu beams are preferred for optical lattice writing, enabling solitons, elliptical vortex solitons, and the creation of various aperiodic and disordered PLs through optical induction in photorefractive crystals, as well as for particle manipulation [8-12].

In this paper, experimentally and theoretically we examine conditions for discrete diffraction occurrence in aperiodic Mathieu PLs. The unique shape of Mathieu beams enables the creation of ***naturally truncated aperiodic PLs*** with our advanced one-pass experimental realization by optically induction in the photorefractive crystal using a single Mathieu beam [13]. Such photonic structures in elliptical-radial geometries offer diverse shapes, with circular, elliptical, and hyperbolic waveguide paths and radial spikes, raising questions about discrete diffraction dimensionality. Mathieu lattice period and the refractive index modulation are connected via Mathieu beam parameters (the beam order, characteristic structural size, and the ellipticity of the beam). Different local environments within these lattices during propagation create additional variations in discrete diffraction effects.

We study weak nonlinear light propagation in various aperiodic Mathieu PLs and experimentally and numerically demonstrate radial and angular discrete diffraction in them. We are able to control discrete diffraction in the radial direction and shape their distributions in perpendicular directions: circular, elliptic, or hyperbolic, by modifying the Mathieu beam's order, size, and ellipticity. Additionally, we investigate the transition from 1D to 2D discrete diffraction, highlighting the significant role of crystal anisotropy in our medium, with the most prominent 2D discrete diffraction observed along the crystal anisotropy direction. Our findings lay the groundwork for exploiting light propagation in a novel class of optical lattices, extending beyond these specific lattice configurations, and generalized to diverse types of optically induced lattices. Such adaptivity and reconfigurability of light-guiding structures are vital for advancement in modern photonics with a significant step towards innovative wave-guiding applications and light-routing approaches.

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Summary for the program :

Dimensionality crossover of radial discrete diffraction in optically induced Mathieu photonic lattices

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We focus our experimentally and numerical investigation of weak nonlinear light propagation in various aperiodic Mathieu lattices optically induced in the photorefractive medium using our advanced one-pass experimental setup. We demonstrate the transitional dimensionality of discrete diffraction within such radial-elliptical Mathieu photonic lattices. We control the shape of discrete diffraction distribution over the combination of the radial direction with the circular, elliptic, or hyperbolic through adjustments of beam order, characteristic structure size, and ellipticity of the Mathieu beams used for the photonic lattices generation. By varying the input beam position, we investigated the transition from one-dimensional to two-dimensional diffraction, and we observed the most prominent discrete diffraction along the crystal's anisotropic direction.

LPHYS'21

LPHYS'21. PROGRAM:

Seminar 5: Nonlinear Optics & Spectroscopy

Co-chairs:

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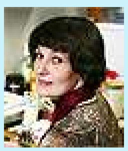

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Monday, 19 July, 2021

***S5.1* (16:00 – 17:30)** **Chair**: Sergey Stremoukhov (Russia)

16:00 – 16:20 J M Vasiljević (Institute of Physics, Belgrade, Serbia), A Zannotti (Institute of Applied Physics and Center for Nonlinear Science (CeNoS), Munster, Germany), D V Timotijević (Institute for Multidisciplinary Research, Belgrade, Serbia), C Denz (Institute of Applied Physics and Center for Nonlinear Science (CeNoS), Munster, Germany), D .M Jović Savić (Institute of Physics, Belgrade, Serbia)
Twisted Photonic Lattices Created by Elliptical Mathieu Beams Abstract

16:20 – 16:35 D H G Espinosa (School of Electrical Engineerig and Computer Science, University of Ottawa, Ottawa, Canada), S R Harrigan (Department of Physics, University of Ottawa, Ottawa, Canada), K M Awan (Stewart Blusson Quantum Matter Institute, University of British Columbia, Vancouver, Canada), P Rasekh (School of Electrical Engineerig and Computer

Science, Ottawa University, Ottawa, Canada), K Dolgaleva (Department of Physics, University of Ottawa, Ottawa, Canada; School of Electrical Engineerig and Computer Science, University of Ottawa, Ottawa, Canada)
Geometry-Dependent Two-Photon Absorption in AlGaAs Waveguides Abstract

16:35 – 16:55 S Yu Stremoukhov (National Research Centre "Kurchatov institute", Moscow, Russia; Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia)
Theory of Harmonics Generation in Perforated Extended Gas Media Interacting with Two-Color Mid-IR Laser Fields (invited talk) Abstract

16:55 – 17:10 L E Semenova (Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia)
The Raman and Hyper-Raman Scatterings of Light by LO-Phonons in a CdS Crystal Under Excitation Near Resonance with the An=2 and Bn=1 Exciton Levels Abstract

17:10 – 17:25 M Martyanov, S Mironov, A Poteomkin (IAP RAS, Nizhny Novgorod, Russia)
Compact Multipass Yb: KGW Amplifier for Photocathode Laser Driver Abstract

Tuesday, 20 July, 2021

***S5.2* (16:00 – 17:30)** **Chair**: Maria Komissarova (Russia)

16:00 – 16:15 K V Lvov (Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia), S Yu Stremoukhov (National Research Center "Kurchatov Institute", Moscow, Russia; Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia), F V Potemkin (Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia)
Anti-Stokes Wing Shift on External Focusing Change Under Mid-IR Filamentation in Dielectrics Abstract

16:15 – 16:30 M V Komissarova (Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia), T M Lysak (Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, Moscow, Russia), I G Zakharova, A A Kalinovich (Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia)
Parametric Gap Solitons in PT-Symmetric Optical Structures Abstract

16:30 – 16:45 K A Barantsev, A N Litvinov (Institute of Physics, Nanotechnology and Telecommunications, Peter the Great St.Petersburg Polytechnic University, St.-Petersburg, Russia)
Peculiarities of Autobalanced Ramsey Spectroscopy of CPT Resonance in Optically Dense Medium Abstract

16:45 – 17:00 M V Ponarina (Oscillation department, Prokhorov General Physics Institute of RAS, Moscow, Russia), A G Okhrimchuk (Fiber Optics Research Center, Prokhorov General Physics Institute of RAS, Moscow, Russia; D. Mendeleyev University of Chemical Technology of Russia, Moscow, Russia), T V Dolmatov, M G Rybin (Oscillation department, Prokhorov General Physics Institute of RAS, Moscow, Russia), E D Obraztsova (Natural Sciences Center, Prokhorov General Physics Institute of RAS, Moscow, Russia), V V Bukin, P A Obraztsov (Oscillation department, Prokhorov General Physics Institute of RAS, Moscow, Russia)
Tunable Multi-Wavelength Mode-Locking in Nd: YAG Waveguide Laser Abstract

Twisted Photonic Lattices Created by Elliptical Mathieu Beams

J M Vasiljević[1], A Zannotti[2], D V Timotijević[3], C Denz[2], and D .M Jović Savić[1]

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Nondiffracting beams are highly applicable in optics, photonics, and atom physics, peculiar because their transverse intensity distributions propagate unchanged for hundreds of diffraction lengths and allow the creation 1D and 2D photonic lattices in photosensitive media[1]. Four different fundamental families of propagation invariant light fields exist, distinguish in the underlying real space coordinate system: Discrete, Bessel, Weber, and Mathieu nondiffracting beams [2-5]. *Mathieu beams* are the solution of the Helmholtz equation in elliptic cylindrical coordinates [5-7], therefore they are the best suited to address physical effects in elliptical coordinates. Mathieu beams are classified according to their symmetry properties as even and odd. Their transverse discrete intensity distributions can be shaped by their order and an ellipticity parameter. These real-valued beams are characterized by only discrete spatial phase distributions. By complex superposition of appropriate even and odd Mathieu beams, *elliptical Mathieu beams* are obtained, with remarkable continuously modulated spatial phase distributions that act as orbital angular momenta, related with transverse energy flow [8].

Experimentally and numerically, we investigated linear and nonlinear self-action of elliptical Mathieu beams in a photorefractive SBN crystal [8]. Linear propagation of elliptic Mathieu beams enables a nondiffracting transverse intensity distribution with transverse energy redistribution along elliptic paths compensated in each point. In contrast, their nonlinear self-action in SBN breaks this sensitive equilibrium and leads to the formation of high-intensity filaments, which rotate in the direction determined by the energy flow. We show that such filamentation depends on the strength of the nonlinearity and the structure size of used Mathieu beams. We investigate the nonlinear propagation of such refractive index formations in SBN crystal and show they are convenient as lattice-writing light to optical induction of two-dimensional chiral twisted photonic refractive index structures with tunable ellipticity. This study provides considerably advancing the field of chiral light and photonic structures since we demonstrated that elliptical Mathieu beams are suitable for the fabrication of two-dimensional photonic lattices with elliptic trajectories by optical induction technique.

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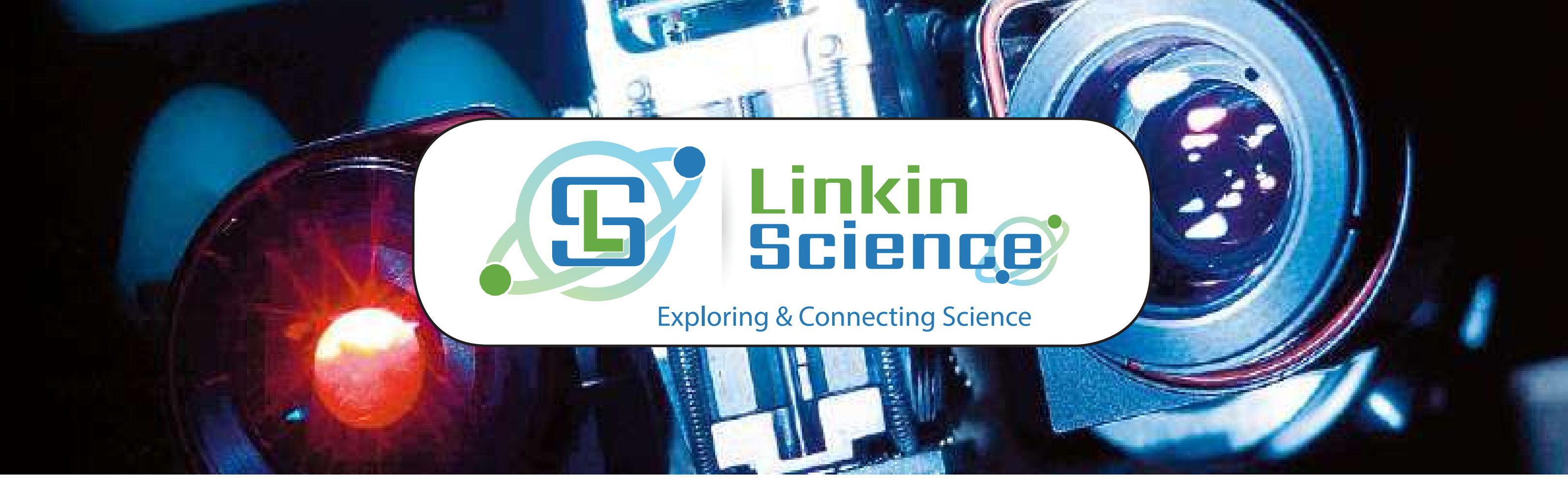

Proceedings of

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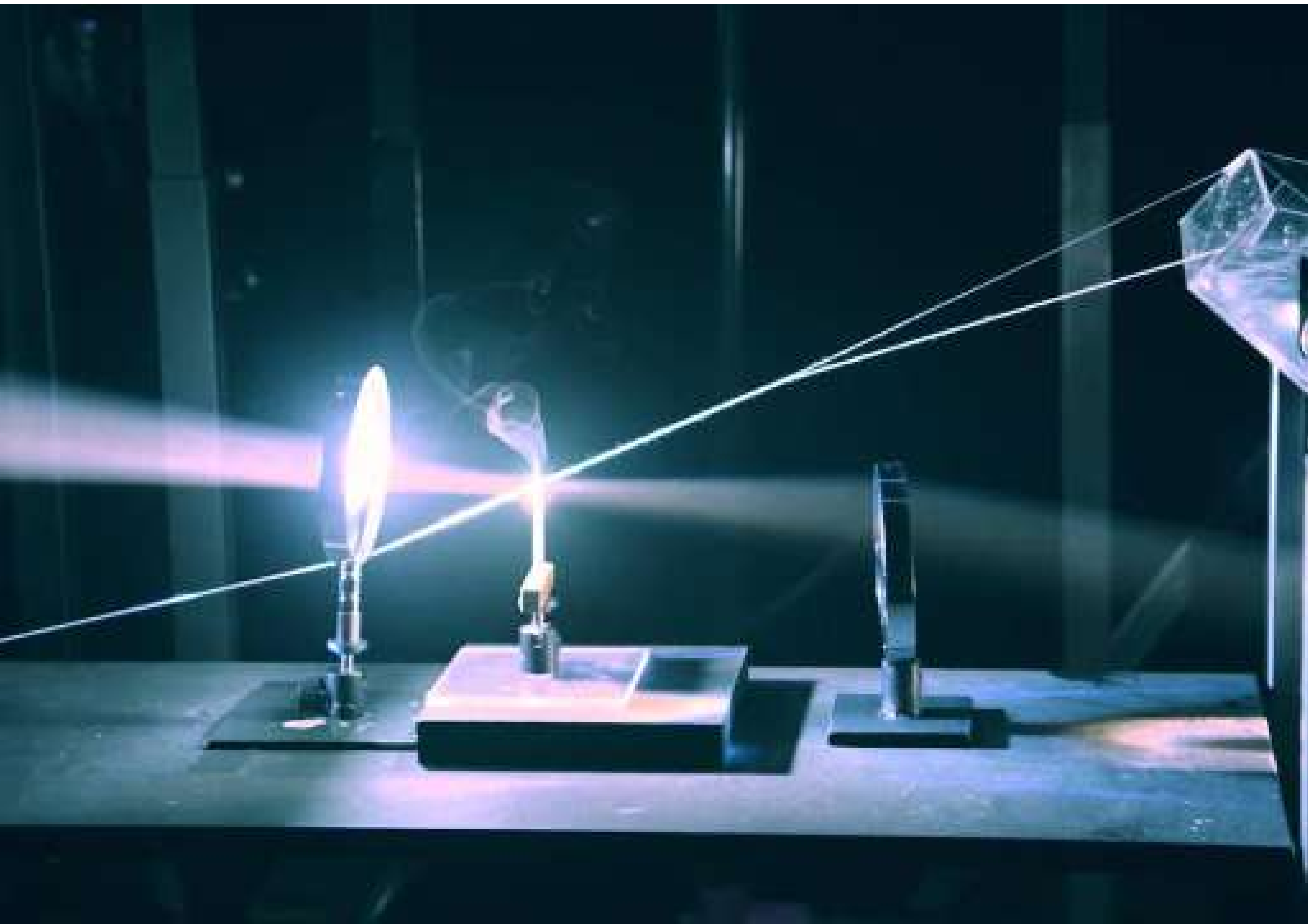

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A team of highly skilled committee members dwell upon the trending topics of research to create a conference theme which can be used to exhibit ideas and research works among the scientific group laying the path for scientific discoveries.

Welcome Message

Linkin Science welcomes you all to the the Virtual Online Conference On Advancements Of Laser, Optics & Photonics to be held during September 01-02, 2021. We anticipate, your participation at Laser, Optics & Photonics 2021 which catalyses ideas and enhance new interdisciplinary collaborations.

Laser, Optics & Photonics 2021 are rapidly expanding by playing a prominent role in many fields. This Conference is a platform to Industry, Academia, Researchers, Innovators to come together to discuss the research activities, advancements, ideas and exhibit laser, optics & photonics products.

Laser, optics & photonics is rapidly gaining traction across a range of industries, from agriculture to water treatment to energy storage. Today, laser, optics & photonics is one of the most innovative, cutting-edge areas of scientific study and it continues to advance at staggering rates. Laser, optics & photonics have made some of the greatest advancements in pediatric optometry & skin laser resurfacing. Scientists in the laser, optics & photonics fields are focused on determining how future drifts in laser, optics & photonics. While laser, optics & photonics are their recent application & trends in it, the benefits are clear with it. Scientists and engineers are focused on applying laser, optics & photonics to resolve these issues. Laser, optics & photonics have been hailed as the next big thing for decades, but it is only now that it is truly becoming a reality in the medical device space.

Our exciting scientific program will be presented over the course of three days in various session types Keynote Presentations, Oral sessions, Young research forum, symposia, Poster sessions and workshops.

Highlights of Conference

- Keynote Talks
- Best Poster Awards
- Outstanding Abstract
- Best Research
- Young research Forum (YRF)

Regards,
Scientific Committee

Experimental realization of chiral photonic lattices

Vasiljević[1*], Alessandro Zannotti[3], D. V. Timotijević[2], Cornelia Denz[3], and D. M. Jović Savić[1]

[1,2]University of Belgrade, Serbia

[3]University of Münster, Germany

Nondiffracting beams find their applications in optics, photonics, and atom physics. Particularly, their transverse intensity distribution propagates unchanged for hundreds of diffraction lengths, consequently allowing the creation of 1D and 2D photonic lattices with nondiffracting beams in photosensitive media. Low diffraction and robustness of nondiffracting beams make them appropriate for deployment in free-space wireless communications, optical interconnections, long-distance laser machining, optical tweezers, biology, surgery, etc. There are four different propagation invariant light fields: Plane waves, Bessel, Weber, and Mathieu nondiffracting beams. Mathieu beams are the solution of the Helmholtz equation in elliptic cylindrical coordinates, therefore being the best suited to address physical effects described in elliptical coordinates. They are classified according to their symmetry properties as even and odd Mathieu beams. Elliptical Mathieu beams are obtained as a complex superposition of appropriate even and odd Mathieu beams, with remarkable continuously-modulated spatial phase distributions that create orbital angular momenta, related with a transverse energy flow. Their transverse intensity distribution can be shaped by their order and the parameter of ellipticity.

We study linear characteristics and nonlinear self-action of elliptical Mathieu beams in a photorefractive crystal experimentally and numerically. Linear propagation of such beams validates a nondiffracting transverse intensity distribution with transverse energy redistribution along elliptic paths compensated in each point. In contrast, their nonlinear self-action breaks this sensitive equilibrium and leads to the formation of high-intensity filaments, which rotate in the direction determined by the energy flow. Our study advances the field of chiral light and photonic structures by pointing to the suitability of Elliptical Mathieu beams as light patterns for optical induction of chirally twisted photonic lattices with elliptic envelopes in the transverse plane. The order of used Elliptical Mathieu beam determines the number of created chiral waveguides, where the waveguides slopes can be manipulated by changing the nonlinearity strength or the structure size of the used beam.

Biography

Dr. Jadranka M. Vasiljević received her Ph.D. degree in 2020 at the Faculty of Physics at Belgrade University, Serbia. Since 2015 she joined the research group of Dr. DraganaJovićSavić at the Institute of Physics, University of Belgrade, Serbia. She is part of the Laboratory for Nonlinear Photonics at the Institute of Physics, University of Belgrade, Serbia. Her research area is Nonlinear Optics and Photonics. Currently, research interests are nondiffracting beams, in particular, based on the family of Mathieu beams. She is studying the realization of two-dimensional dynamical structures in the photorefractive medium by Mathieu beams, aperiodic and complex structures with Mathieu beams, and investigating phenomena correlated with light propagation in Mathieu photonic lattices.

Notes:

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Conference Program

3rd Edition of Virtual Online Conference on Advancements of Lasers, Optics and Photonics

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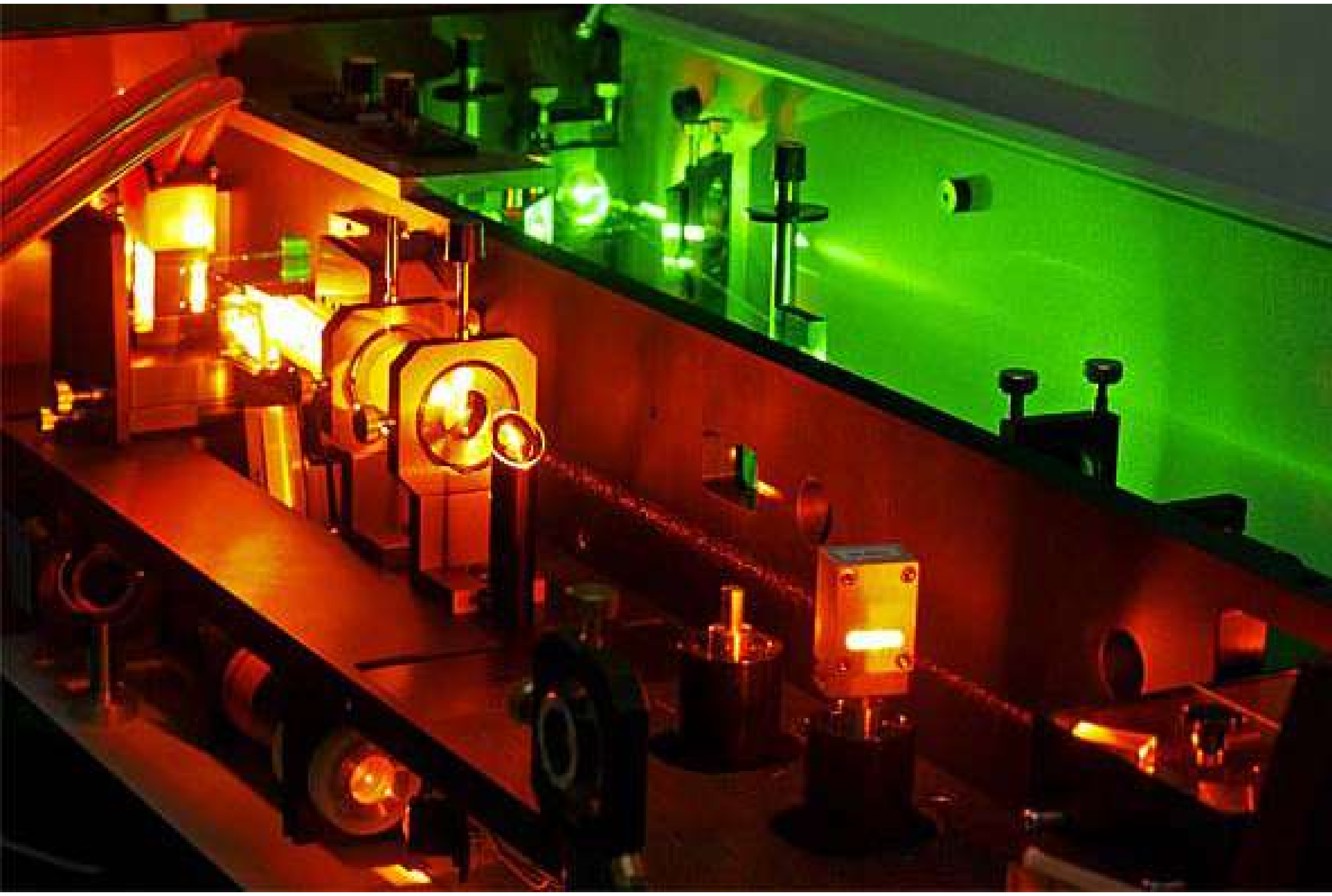

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Conference Program

DAY 1: Wednesday 1st September 2021 EDT Time Zone

09:00-09:30	Opening Session Welcome Address
09:30-10:05 **Keynote**	**Photonics in Radar and LiDAR Systems** Paulo Pereira Monteiro, *University of Aveiro, Portugal* (Local Time: 14:30)
10:05-10:40 **Keynote**	**Creating Materials with a desired Refraction Coefficient** Alexander G. Ramm, *Kansas State University, USA* (Local Time: 09:05)
10:40-11:15 **Keynote**	**Cryogenic Laser Technology** David C Brown, *Fellow of The Optical Society of America, Advanced Pho tonic Sciences, USA* (Local Time: 10:40)
11:15-11:35	**Break Out Session/ Networking Lounge 20 mins**
11:35-12:00 **Oral Session**	**Multi-Electron Trojan Wave Packets in the Circularly Polarized and the Magnetic Fields on the Multi-layer Langmuir Type (1) Trajectories in Helium Atoms and Quantum Dots** Matt Kalinski, *Utah State University, USA* (Local Time: 09:35)
12:00-12:25 **Oral Session**	**Application of lasers in phosphor material development for solid-state lighting** Hisham Menkara, *PhosphorTech Corporation, USA* (Local Time: 12:00)
12:25-12:50 **Oral Session**	**Experimental realization of chiral photonic lattices** Jadranka Vasiljevic, *University of Belgrade, Serbia* (Local Time: 18:25)
12:50-13:15 **Oral Session**	**Application of ultra-short pulse lasers in the restauration of historical stained-glass** Luis A Angurel, *University of Zaragoza, Spain* (Local Time: 18:50)
13:15-13:35	**Break Out Session/ Networking Lounge 20 mins**
13:35-13:50 **Poster Presentation**	**LED Photobiomodulation therapy combined with biomaterial as a scaffold promotes better bone quality in the dental alveolus in an experimental extraction model** Vanessa Dalapria, *UNINOVE- Nove de Julho University, Brazil* (Local Time: 14:35)

Oral

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Wish to thank

Prof/Dr/Ms. Jadranka Vasiljevic

University of Belgrade, Serbia

for phenomenal and worthy Oral presentation on

Experimental realization of chiral photonic lattices

at the 3rd Edition of Virtual Conference On Advancements Of Laser, Optics & Photonics

held during September 01-02, 2021

Laser, Optics & Photonics 2021 Scientific Committee

David C. Brown

David C Brown

Advanced Photonic Sciences, USA

Subject **Share your research on | 10-11 Feb, 2023**
From Laser, optics and photonics
Sender Laser, optics and photonics
To Jadranka
Date 17.10.2022 08:28

Dear Dr. Jadranka M Vasiljević,

Wishes from Sciwide webinars.

We extend our immense honor to invite you as a Keynote Speaker for the upcoming webinar on "4th Edition of Laser, Optics and Photonics Virtual", which is scheduled during 10-11 Feb 2023 from GMT 07:00 to 12:00.

This virtual conference holds special promise to discuss the future discoveries. The colossal and enthusiastic presence of young and brilliant researchers, scientists, academicians, opticians, laser experts, healthcare professionals, business delegates and exceptional student communities adds to the excitement of the two-days virtual congress which provides an insight

For more information visit: https://sciwideonline.com/v-laser2023/

We look forward meeting you in Virtually.

Thanks & Regards,
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Final Program

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February 10, 2023

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Website: https://sciwideonline.com/v-laser2023/

February 10, 2023 GMT 07:00 – 16:00

Webinar Timings	Speakers Timings	
07:00 – 07:10		Introduction

Keynote Sessions-1

07:10 – 07:45	10:10 – 10:45	Title: Shape Memory Effect and Atomic Scale Aspects of Reversibility in Shape Memory Alloys **Osman Adiguzel, Firat University, Turkey.**
07:45 – 08:20	15:45 – 16:20	Title: Recent advance of laser lipolysis **Bin Chen, Xi'an Jiaotong University, China.**
08:20 – 08:55	17:20 – 17:55	Title: Plasmonics and Plasmonic Metamaterials Using Random Metal Nanostructures for High Efficiency Light-Emitting Devices **Koichi Okamoto, Osaka Metropolitan University, Japan.**
08:55 – 09:30	19:55 – 20:30	Title: Nucleation and Dynamics of Chiral Spin Textures in Topological Materials **Oleg Tretiakov, University of New South Wales, Australia.**
09:30 – 10:05	10:30 – 11:05	Title: Composite photonic structures: generation and light propagation in them **Jadranka Vasiljević, Institute of Physics, Serbia.**
10:05 – 10:40	18:05 – 18:40	Title: Photoalignment and photopatterning based on nanosize azodye layers for new liquid crystal display and photonics devices **Vladimir Chigrinov, Hong Kong University of Science and Technology, Hong Kong.**

Invited Sessions

10:40 – 11:00	18:40 – 19:00	Title: Compressive sensing based imaging spectropolarimetry **Wenyi Ren, Northwest Agriculture & Forestry University, China.**
11:00 – 11:20	13:00 – 13:20	Title: Tunable Tm-Yap based laser for Bio-medical applications **Salman Noach, Jerusalem College of Technology, Israel.**
11:20 – 11:40	12:20 – 12:40	Title: A Polarized Digital Holographic Approach in Biological and Medical Research **Maria Antonietta Ferrara, Institute of Applied Sciences and Intelligent Systems, National Research Council of Italy, Italy.**
11:40 – 12:00	14:40 – 15:00	Title: Quantum-Classical Mechanics: Principles, Applications, and Prospects **Vladimir Valentinovich Egorov, FSRC "Crystallography and Photonics", Russia.**
12:00 – 12:20	17:00 – 17:20	Title: III-V light-emitting diodes and laser diodes **Usman I Muhammad, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan.**
12:20 – 12:40	14:20 – 14:40	Title: Microcavities with embedded quantum dots as an example of polaritonic structure **Konstantin V. Gumennik, A.A. Galkin Donetsk Institute for Physics and Engineering, Russia.**

Keynote Session-2

12:40 – 13:15	20:40 – 21:15	Title: Study on Environmental Factors Impacts to Underwater Wireless Optical Communication **Shien-Kuei Liaw, National Taiwan University of Science and Technology, Taiwan.**

13:15 – 13:50	16:15 – 16:50	Title: Micropores containing quantum dots as an example of a polaritonic structure **Vladimir V Rumyantsev, A.A. Galkin Donetsk Institute for Physics and Engineering, Russia.**
13:50 – 14:50	16:50 – 17:50	Title: Review of the New Unitary Quantum Theory **Leo Georgy Sapogin Technical University (MADI), Russia.**
14:50 – 15:25	06:50 – 07:25	Title: Creation of electro-magnetic assisted “Star-like” formation from cancer cells using a laser trap **Horace Crogman, California State University Dominguez Hills, USA.**
15:25 – 16:00	07:25 – 08:00	Title: Analytical predictive modeling in fiber optics structural analysis **Ephraim Suhir, Portland State University, USA.**

Closing Ceremony

SCIWIDE WEBINARS

V-LASER2023 wish to thank

Prof/Dr/Mr/Ms. ***Jadranka Vasiljević***

Institute of Physics, Serbia

for his/her worthy Keynote presentation at

"4th Edition of Laser, Optics and Photonics Virtual"

held on February 10, 2023

Prof. Bin Chen

Xi'an Jiaotong University, China

Composite photonic structures: generation and light propagation in them

J. M. Vasiljević[1], D. V. Timotijević[2], D. M. Jović Savić[1]

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Phone:
Institute/ Organization: Institute of Physics, Belgrade
Country: Serbia
Presentation Category: Oral Presentation

Abstract: Nondiffracting beams are highly applicable in optics, photonics, and atom physics, because their transverse intensity distributions propagate unchanged for hundreds of diffraction lengths and allow the creation of 1D and 2D photonic lattices in photosensitive media [1]. Depending on coordinate system four fundamental families of propagation invariant light fields exist: Discrete, Bessel, Weber, and Mathieu nondiffracting beams [2-4]. Mathieu beams are the solution of the Helmholtz equation in elliptic cylindrical coordinates [4-6]. According to their symmetry properties they are classified as even and odd. Their order and an ellipticity parameter can shape their transverse discrete intensity distributions.

Deterministic aperiodic or complex photonic structures are at the intersection between periodic and disorder crystal structures. In optics, the properties of such structures have been studied, as appealing structures for the control and manipulation of light. Various aperiodic and quasiperiodic photonic structures are realized artificially and light propagation is investigated in them. We experimentally realized the aperiodic photonic structures with controllable complexity, created by different combinations of Mathieu beams, by splicing them in both transverse dimensions in different offsets [7] and we studied light localization in them. In such lattice, light expansion is hindered in comparison to periodic lattice and nonlinear light localization is demonstrated [8].

Furthermore, we numerically modeled two different randomization methods of photonic lattices [9]. We compare the results of light propagation in disordered aperiodic Mathieu lattices and disordered periodic lattices. In disordered aperiodic lattice disorder always enhances light transport for both methods, contrary to the disordered periodic lattice. For the highest disorder levels, we detect Anderson localization for both methods and both disordered lattices. More pronounced localization is observed for disordered aperiodic lattices.

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[9] D. V. Timotijević, J. M. Vasiljević, and D. M. Jović Savić. Opt. Express 30(5), 7210 (2022).

Biography of Presenting Author:

Dr. Jadranka M. Vasiljević received her Ph.D. degree in 2020 at the Faculty of Physics at Belgrade University, Serbia. Since 2015 she joined Laboratory for Nonlinear Photonics at the Institute of Physics, University of Belgrade, Serbia. Since 2022 Jadranka is member of project supported by the Science Fund of the Republic of Serbia, program IDEAS, 7714356 – **CompsLight**. Her research area is Nonlinear Optics and Photonics. She is studying realization of two-dimensional dynamical structures in the photorefractive medium by Mathieu beams; realization of aperiodic and complex structures with Mathieu beams; investigation of phenomena correlated with light propagation in Mathieu photonic lattices.

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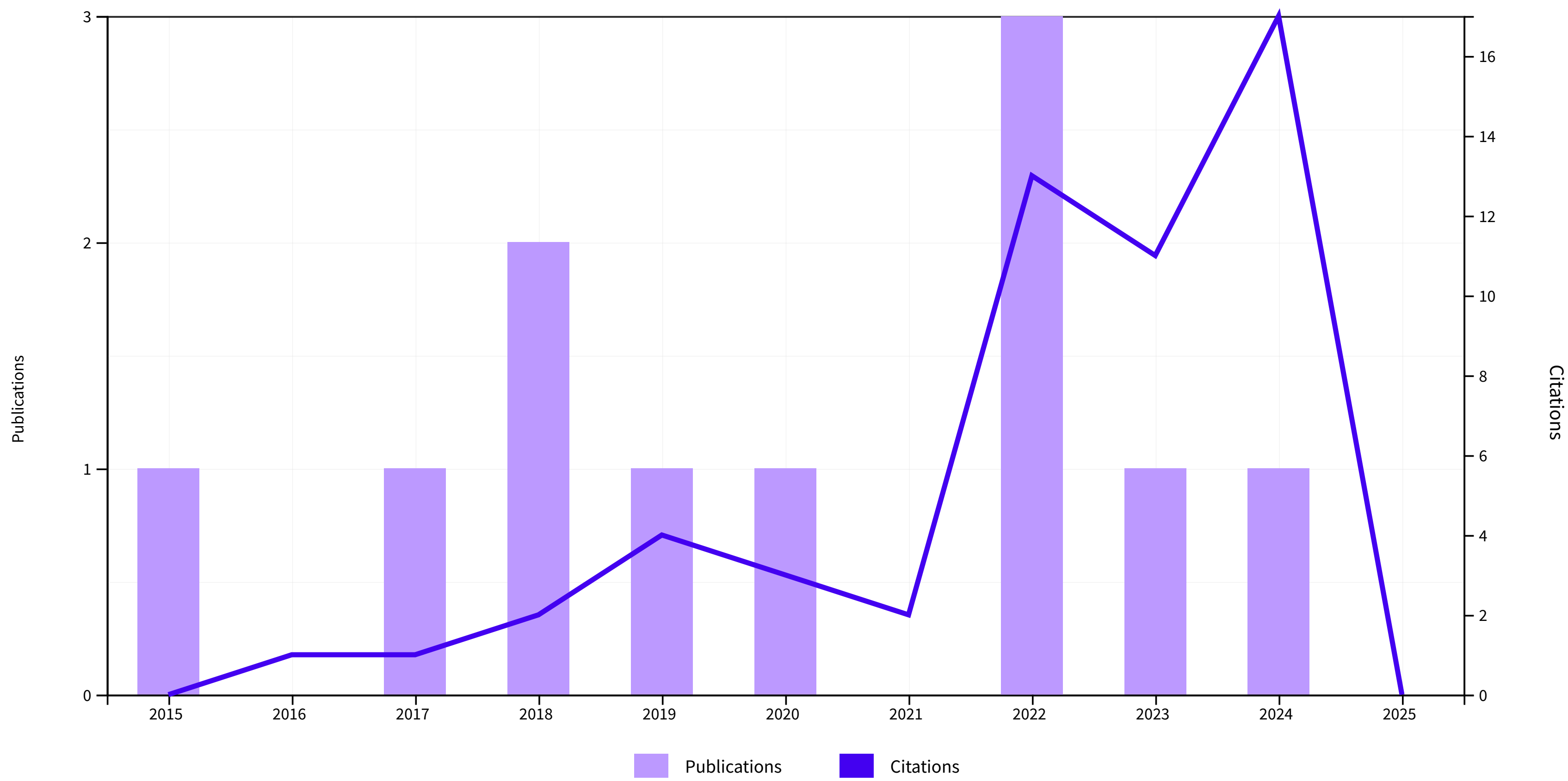

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1 Dimensionality crossover of radial discrete diffraction in optically induced Mathieu photonic lattices Vasiljevic, JM; Jovanovic, VP; (...); Savic, DMJ Conference on Nonlinear Optics and its Applications 2024 | NONLINEAR OPTICS AND ITS APPLICATIONS 2024 13004	0	0	0	0	0	0	0
2 Interdimensional radial discrete diffraction in Mathieu photonic lattices Vasiljevic, JM; Jovanovic, VP; (...); Savic, DMJ Aug 28 2023 | OPTICS EXPRESS 31 (18) , pp.28946-28953 Enriched Cited References	0	0	0	1	0	0.33	1
3 Numerical methods for generation and characterization of disordered aperiodic photonic lattices Timotijevic, DV; Vasiljevic, JM and Savic, DMJ Feb 28 2022 | OPTICS EXPRESS 30 (5) , pp.7210-7224	0	1	1	2	0	1	4
4 Light transport and localization in disordered aperiodic Mathieu lattices Vasiljevi, JM; Zannotti, A; (...); Savid, DMJ Feb 1 2022 | OPTICS LETTERS 47 (3) , pp.702-705	0	1	1	3	0	1.25	5
	0	0	0	0	0	0	0

5 Light propagation in disordered aperiodic Mathieu lattices generated with two different randomization methods Vasiljevic, JM; Timotijevic, DV and Savic, DMJ Conference on Nonlinear Optics and Its Applications 2022 | NONLINEAR OPTICS AND ITS APPLICATIONS 2022 12143							
6 Light propagation in aperiodic photonic lattices created by synthesized Mathieu-Gauss beams Vasiljevic, JM; Zannotti, A; (...); Savic, DMJ Jul 27 2020 | APPLIED PHYSICS LETTERS 117 (4) Enriched Cited References	1	3	1	2	0	1.17	7
7 Morphing discrete diffraction in nonlinear Mathieu lattices Zannotti, A; Vasiljevic, JM; (...); Denz, C Apr 1 2019 | OPTICS LETTERS 44 (7) , pp.1592-1595	0	2	3	3	0	1.14	8
8 Visualizing the Energy Flow of Tailored Light Zannotti, A; Vasiljevic, JM; (...); Denz, C Apr 19 2018 | ADVANCED OPTICAL MATERIALS 6 (8)	0	0	1	3	0	0.75	6

9 [Elliptical vortex necklaces in Mathieu lattices](#) Vasiljevic, JM; Zannotti, A; (...); Savic, DMJ Mar 27 2018 | PHYSICAL REVIEW A 97 (3)	0	0	3	1	0	0.63	5

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Матични научни одбор за физику

Број: 660-01-4/2020-14/38
22.01.2021. године
Б е о г р а д

На основу члана 27. став 1 тачка 1) и члана 76. став 5. Закона о науци и истраживањима („Службени гласник Републике Србије", бр. 49/2019) и Правилника о поступку, начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача („Службени гласник Републике Србије", број 24/16, 21/17 и 38/17) и захтева који је поднео

Институт за физику у Београду

Матични научни одбор за физику на седници одржаној 22.01.2021. године, донео је

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О СТИЦАЊУ НАУЧНОГ ЗВАЊА

Др Јадранка Васиљевић

стиче научно звање
Научни сарадник

у области природно-математичких наука - физика

О Б Р А З Л О Ж Е Њ Е

Институт за физику у Београду

утврдио је предлог број 0801-1175/1 од 16.12.2020. године на седници Научног већа Института за физику у Београду и поднео захтев Матичном научном одбору за физику број 0801-1201/1 од 17.12.2020. године за доношење одлуке о испуњености услова за стицање научног звања **Научни сарадник.**

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Доношењем ове одлуке именована стиче сва права која јој на основу ње по закону припадају.

Одлуку доставити подносиоцу захтева, именованој и архиви Министарства просвете, науке и технолошког развоја у Београду.

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проф. др Милан Дамњановић

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1. 10. 20 20 год.
БЕОГРАД СТУДЕНТСКИ ТРГ

На основу члана 29 Закона о општем управном поступку («Службени гласник РС» број 18/2016 и 95/2018), и члана 149 Статута Универзитета у Београду - Физичког факултета, по захтеву ЈАДРАНКЕ ВАСИЉЕВИЋ, мастер физичара, издаје се следеће

УВЕРЕЊЕ

ЈАДРАНКА ВАСИЉЕВИЋ, мастер физичар, дана 30. септембра 2020. године, одбранила је докторску дисертацију под називом

"ПРОСТИРАЊЕ, ЛОКАЛИЗАЦИЈА И КОНТРОЛА СВЕТЛОСТИ У МАТЈЕОВИМ РЕШЕТКАМА"

пред Комисијом Универзитета у Београду - Физичког факултета и тиме испунила све услове за промоцију у ДОКТОРА НАУКА – ФИЗИЧКЕ НАУКЕ.

Уверење се издаје на лични захтев, а служи ради регулисања права из радног односа и важи до промоције, односно добијања докторске дипломе.

Уверење је ослобођено плаћања таксе.

ДЕКАН ФИЗИЧКОГ ФАКУЛТЕТА

Проф. др Иван Белча

Република Србија
Универзитет у Београду
Физички факултет
Београд

Институт за физику у Београду

на основу одлуке Жирија о додељивању Годишње награде додељује:

СТУДЕНТСКУ НАГРАДУ
ИНСТИТУТА ЗА ФИЗИКУ ЗА 2021. ГОДИНУ

др Јадранки Васиљевић

за докторску тезу под називом
"Propagation, localization and control of light in Mathieu lattices"
("Простирање, локализација и контрола светлости у Матјеовим решеткама")

др Жељка Никитовић
председница
Научног већа

Београд
31. август 2021.

др Александар Богојевић
директор
Института за физику

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Број 0801-869/1
Датум 30-05-2025

Потврда о руковођењу радним пакетом на пројкету

Овим потврђујем да је Др Јадранка Васиљевић, научни сарадник запослен на Институту за физику у Београду, руководилац радног пакета WP4- **Light propagation** in randomized DAPL на пројекту "Control and manipulation of light in complex photonic systems"(CompsLight). Пројекат је финансиран од стране Фонда за науку Републике Србије са буџетом **233.435,86** евра и реализован је у периоду од 1. јануара 2022. до 31. децембра 2024. године.

Београд 30. мај 2025. године

Драгана Јовић Савић

Др Драгана Јовић Савић
Руководилац пројекта CompsLight
Научни саветник
Институт за физику у Беогрдау

УГОВОР О ФИНАНСИРАЊУ
РЕАЛИЗАЦИЈЕ НАУЧНОИСТРАЖИВАЧКОГ ПРОЈЕКТА

Control and manipulation of light in complex photonic systems
CompsLight
7714356
У ОКВИРУ ПРОГРАМА ИДЕЈЕ ФОНДА ЗА НАУКУ РЕПУБЛИКЕ СРБИЈЕ
ИЗВОР ФИНАНСИРАЊА: Споразум о зајму број 9029-YF -SAIGE- Пројекат акцелерације иновација и подстицања раста предузетништва у Републици Србији и средства из буџета Републике Србије.

УГОВОРНЕ СТРАНЕ:

1. ФОНД ЗА НАУКУ РЕПУБЛИКЕ СРБИЈЕ, са регистрованим седиштем у Београду, ул. Немањина 22-26, Београд, матични број 17921410, ПИБ 111343775, број рачуна КЈС 840-670723-30, кога заступа др Милица Ђурић-Јовичић, в.д. директора (у даљем тексту: **Фонд за науку**),

са једне стране,

и

2. Реализатор истраживања/корисник средстава одобрених за финансирање Пројекта (у даљем тексту сваки од наведених појединачно означен као **Корисник средстава**, а сви заједнички означени као **Корисници средстава**):

2.1. Акредитована научноистраживачка организација – НИО Институт за физику Београд, Универзитет у Београду (назив научноистраживачке организације), са седиштем на адреси Прегревица 118, Београд-Земун, ПИБ: 100105980, матични број: 07018029, коју заступа Александар Богојевић (име и презиме особе овлашћене за заступање), директор, која је носилац реализације Пројекта (у даљем тексту: **Носилац Пројекта**);

2.2. Акредитоване научноистраживачке организације – НИО (у даљем тексту: **Учесници Пројекта**):

1) Институт за мултидисциплинарна истраживања, Универзитет у Београду (назив научноистраживачке организације), са седиштем на адреси Кнеза Вишеслава 1, Београд-Чукарица, ПИБ: 101012100, матични број: 07002068, коју заступа Драгица Станковић (име и презиме особе овлашћене за заступање), директор (у даљем тексту: **Учесник Пројекта);**

3. Драгана Јовић Савић (име и презиме руководиоца Пројекта), запослена у НИО Институт за физику Београд, Универзитет у Београду Носиоцу Пројекта (у даљем тексту: **Руководилац Пројекта**),

са друге стране.

3. Implementation Plan

3.1. Credentials of PI and members of Project team

- Describe strong points of credentials of the PI and the members of the Project team.
- Describe the complementarity and synergy of the members of the Project team for the proposed research. How will they match the Project's objectives and bring together the necessary expertise?
- Provide a list of members of the Project team in Table 3.1 and their involvement, as a textual description.

PI Dr. Dragana Jović Savić (maiden name: Dragana Jović) is leading a small, but tremendously successful group focusing on the **theoretical** and **numerical** work that can provide predictions of dynamic and stationary effects in photonic crystals physics as well as their **experimental** realization. She is working for more than 15 years successfully in the field of nonlinear optics and photonics. Starting from the theoretical research of photorefractive spatial solitons, photonic lattices, and counterpropagating beams, her focus shifted gradually toward surface solitons and solid-state phenomena such as Anderson localization of light in photonic lattices. Her experimental experience started with her Alexander von Humboldt Fellowship hosted in the Institute of Applied physics, Münster and carried on with DAAD projects. Dr. Jović Savić established a Nonlinear Photonics laboratory and a team of researches – the primary source for CompsLight project members. In this Lab, they have successfully realized experimental results such as the realization of quasi-periodic Fibonacci waveguide arrays or defect-guiding of Airy beams in optically induced waveguide arrays. The group has extended its research from theoretical and numerical modeling to complete experimental investigations, and in the last ten years, the team has been advancing their experimental experience.

Dr. Dejan Timotijević is an experienced researcher in the field of nonlinear optics and metamaterials for more than 30 years, notably giving a foundation of relaxation method for modeling photorefractive materials. He has extensive applicative experience working in an industrial environment as a developer of major scientific visualization software (OriginLab) and in bioinformatics.

MSc Jadranka Vasiljević has recently started her Ph.D. studies, and her thesis is supervised by Dr. Jović Savić. She was included in the DAAD project and spent a few months at Institute for Applied physics in Muenster, where she got a huge experimental experience working on an experiment with an optical induction technique.

Prof. Dr. Milivoj Belić is a world leader in nonlinear photonics; he played an active role in the development of the key concepts of the field as well as theoretical prediction of many effects. He published more than 600 peer-reviewed papers, with more than 7000 citations and his h-index is 39. He is currently a Full Professor at Texas A&M University in Doha, Qatar. In his previous engagement, as Principal research fellow at the Institute of Physics, Belgrade, he initiated nonlinear optics and photonics research in Serbia. He mentored numerous Ph.D. students in this research field, among them Dr. Jović Savić and Dr. Timotijević. He is an internationally well-known expert in nonlinear optics, nonlinear photonics as well as light propagation in photonic crystals and photonic lattices.

All project tasks require a strong synergy and interaction of the team members and their complementary expertise. The planned research program includes continuous, strong interaction of project members and the synergy effect of their complementary expertise: **theory**, **numerics,** and **experiments** in nonlinear photonics. That in turn will guarantee high-quality execution of the project, strong education of students, and will allow new exciting results. The interaction of the project members during the project will rely on personal meetings, discussions, and continuous exchange of information during the years. Our collaboration **in the past years** has been organized along these lines. It has been very successful and resulted in a number of joint **publications in the leading journals**.

Table 3.1. Members of the Project team

ID	Name and family name	SRO	Person-months	Effective person-months
PI	Dr. Dragana Jović Savić	Institute of Physics Belgrade	12	10.8
P1	Dr. Dejan Timotijević	Institute of Physics Belgrade	12	10.8
P2	MSc Jadranka Vasiljević	Institute of Physics Belgrade	12	10.8
P3	Prof. Dr. Milivoj Belić	Texas A&M University Qatar	12	10.8
			Total Person-months: 48	Total Effective person-months: 43.2

- Involvement and roles of the key members of the Project team, as a textual description. Describe in what way each of them will contribute to the proposed research. Show that each has a valid role and adequate resources in the Project to fulfill that role.

Dr. Jović Savić will coordinate all steps necessary for successful project outcomes. She will directly contribute to all aspects in each phase of the project and take particular care of befitting visibility of the project results via publications in highly-ranked scientific journals and presentations at international conferences.

Dr. Timotijević with his experience helps the team in developing theoretical models and numerical codes for solving complex physical problems. His theoretical and numerical work can provide predictions of dynamical and static physical effects in complex photonic systems and the conditions for their experimental realization. He will work with Dr. Jović Savić on the integration of numerical codes and the estimation of optimal experimental parameters.

MSc Vasiljević will share on the one hand his first-hand experimental experience with the optical induction technique from Nonlinear photonics group in Muenster, Germany, and – on the other hand – benefit from the knowledge in the frame of theoretical modeling such systems in the group. She will design the experimental setup with Dr. Jović Savić and Dr. Timotijević's guidance. Also, she will collect numerical results and compare them with experimental.

Prof. Dr. Belić possesses an extensive teaching and research experience. He demonstrated a leadership role in the fundamental science programs including programs in nonlinear photonics. He is shaping the fundamental science programs and establishing a long-term strategy for aligning the goals of this project with new research directions. His experience and deep understanding of similar research topics will be instrumental in the realization of the CompsLight project. His main contribution will be in designing theoretical models for describing processes that take place in SBN crystal.

All key members have full access to the work environment, literature, communication, computer and laboratory setup.

The first period will be used to test new equipment and to prepare set-up for the fabrication of appropriate photonic structures (Dr. Jović Savić, Dr. Timotijević, MSc Vasiljević). Using numerical simulations we will provide appropriate experimental data with the help of colleagues who have long experience in making numerical codes (Dr. Timotijević). We will also analyze obtained experimental results, explore the problems in depth, discuss the relevant issues, and define the physical models (Dr. Jović Savić, Dr. Timotijević, MSc Vasiljević, Prof. Dr. Belić). We will test and run the numerical codes for simulation of the experiment, and then collect numerical results and compare them with the experimental data (MSc Vasiljević, Dr. Jović Savić, Dr. Timotijević).

3.2. Implementation plan

The Project **implementation plan** includes:

- a brief presentation of the overall structure of the work plan;
- detailed work description:
    - a list of work packages[33] (WP) (table 3.2a);
    - a description of each work package (table 3.2b);
    - a list of major deliverables (table 3.2c);
    - a list of milestones[34] (table 3.2d);
    - a list of budget headings (table 3.2.e);
- timing of the different work packages and their components; fill out a Gantt chart (following the **template** available within Project documentation for this Program and Open call published on http://fondzanauku.gov.rs/) to match the implementation plan of this Project and **upload** it. Please use the template provided.
- Note: Data in Tables 3.2a–3.2d must match the Gantt chart.

[33] "Work package" means a major sub-division of the proposed Project.
[34] "Milestones" are control points in the Project that help to chart progress. Milestones may correspond to the completion of a key deliverable, allowing the next phase of the work to begin. They may also be needed at intermediary points so that, if problems have arisen, corrective measures can be taken.

Table 3.2a: List of work packages (WP)

WP No	WP title	WP Lead SRO's acronym	WP Coordinator - team member's ID	Start month	End month	Total calendar months of WP duration
1	**Generation** of DAPL using non-diffracting beams	IPB	PI	1	12	12
2	**Light propagation effects** in DAPL	IPB	P1	13	24	12
3	Generation of **randomized** DAPL	IPB	P1	25	27	3
4	**Light propagation** in randomized DAPL	IPB	P2	28	36	9

3.2b: Work package description

Work package number	1	Work package title	**Generation** of DAPL using non-diffracting beams
Lead SRO's acronym	IPB		
WP Coordinator - team member's ID	PI		
Team members` IDs	PI, P1, P2, P3		

Objectives

This WP is aimed to establish the method to generate and experimentally realize various kinds of non-diffracting beams and investigate the conditions for their existence and propagation. The aim is to extend these concepts to the mutual interaction of two or more beams for their incorporation into complex photonic systems that will be used for the generation of photonic lattices. These reconfigurable and adaptive photonic lattices will be created by laser light in nonlinear refractive index materials. We aim at designing deterministic aperiodic photonic crystal structures, based on such flexible optical induction technique.

Description of work (where appropriate, broken down into sub-activities), and role of the team members

This WP covers the investigation of complex non-diffracting beam propagation, their interaction in photorefractive media, as well as the application in designing complex **DAPL** with different classes of these beams or such **compound** beams, using the various beam size, relative distance and phase difference between two or more beams or beam couples. This work package contains the following sub-activities:

S1.1 Provide numerical codes for the experimental realization of different classes of non-diffracting beams using spatial light modulator (SLM) (**P1, P2**)

S1.2 Prepare the experimental setup for the generation of such beams, their propagation, and interaction (**P1, P2**)
S1.3 Defining theoretical model and prepare numerical code for finding the best parameters of propagation and interaction of such beams as well as generation of DAPL (**PI, P1, P2, P3**)
S1.4 Modification of the experimental setup and generation of complex DAPL (**P2**)
S1.5 Collecting and comparing experimental and numerical data, writing the research papers (**PI, P1, P2**)

Deliverables of the work package (brief description and month of delivery)

D1.1 Refined theoretical model and corresponding numerical code for DAPL prediction (**6th month**)

D1.2 Experimentally generated optically induced DAPL using multiple non-diffracting beams (**12th month**)

Универзитет у Крагујевцу
ПРИРОДНО-МАТЕМАТИЧКИ ФАКУЛТЕТ

University of Kragujevac
FACULTY OF SCIENCE

Радоја Домановића 12, 34000 Крагујевац, Србија
Radoja Domanovića 12, 34000 Kragujevac, Serbia

Број: 8/562
Датум: 23. 10. 2024.
Крагујевац

**Институту за физику
Универзитет у Београду
Прегревица 118
11080 Београд**

Предмет: **Захтев за давање сагласности на ангажовање наставника на Природно-математичком факултету у Крагујевцу на докторским академским студијама Физике**

Обраћам Вам се са молбом да за потребе Природно-математичког факултета Универзитета у Крагујевцу дате сагласност за рад у допунском радном односу до 30% пуног радног времена **др Јадранки Васиљевић** за потребе одржавања наставе у школској 2024/2025. години на реализацији наставе из предмета:

- **Оптоелектроника**, изборни предмет на Докторским академским студијама Физике са недељним фондом предавања од 5 часова и 2 часа студијског истраживачког рада.
- **Физика ласера**, изборни предмет на Докторским академским студијама Физике са недељним фондом предавања од 5 часова и 2 часа студијског истраживачког рада.

Укупно оптерећење на ДАС физике ПМФ-а у Крагујевцу износи **0,70**, са укупно **30%** радног времена у школској 2024/2025. години..

Замолили би вас да у Сагласности, на основу нових Упустава за припрему документације студијских програма докторских академских студија, наведете следеће:
-оптерећење које др Јадранка Васиљевић има на вашем Институту,
-оптерећење у другим установама где је већ дата сагласност (уколико је др Јадранка Васиљевић још негде ангажована) и
-оптерећење које ће др Јадранке Васиљевић имати на ПМФ-у Крагујевцу и које износи 0,70 часова.

Поред тога, према Упуствима, потребно је и да нам доставите:
-Одлуку о избору др Јадранке Васиљевић на вашем Институту и
-потписану Изјаву др Јадранке Васиљевић којом потврђује податке који су наведени у Сагласности.

С поштовањем,

Декан
Природно-математичког факултета у Крагујевцу

Проф. др Марија Станић

Централа: 034 336 223 Деканат: 034 335 039 • Секретар: 034 300 245 • Студентска служба: 034 300 260 • Факс: 034 335 040
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ПИБ: 100105980, Матични број: 07018029, Текући рачун: 205-66984-23

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Природно-математички факултет

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Број 0801-1759/2
Датум 09.12.2022.

16.12.2022
01 678 — —

Поштовани,

На основу Вашег дописа број 8/422 од 5.12.2022. године достављамо Вам **сагласност** да **др Јадранка Васиљевић,** запослена на Институту за физику у Београду, буде ангажована на Природно-математичком факултету у Крагујевцу за потребе одржавња наставе из предмета **Оптоелектроника** и **Физика ласера** са укупно 30% посто радног времена у школској 2022/23.

Колегиница Васиљевић је ангажована са 100% радног времена на Институту за физику и није ангажована у другим институцијама. Оптерћење које ће др Јадранка Васиљевић имати на ДАС физике ПМФ у Крагујевцу износи 0,70 часова.

С поштовањем,

ДИРЕКТОР ИНСТИТУТА ЗА ФИЗИКУ У БЕОГРАДУ
Института од националног значаја за Републику Србију

др Александар Богојевић

ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ
УНИВЕРЗИТЕТ У БЕОГРАДУ • ИНСТИТУТ ЗА ФИЗИКУ • БЕОГРАД

У Београду,
09.12.2022. године

УНИВЕРЗИТЕТ У БЕОГРАДУ
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Датум 09. 12. 2022

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Природно-математички факултет

ИЗЈАВА

Ја доле потписана, Јадранка Васиљевић, изјављујем да су сви подаци наведени у допису 0801-1759/2 од 09.12.2022. године Института за физику у Београду тачни.

Изјаву дајем ради регулисању мог ангажовања на Природно-математичком факултету у Крагујевцу на докторским академским студијама **Физике** на наставном предмету **Оптоелектроника и Физика ласера** са укупно 30 % посто радног времена у школској 2022/23.

С поштовањем,

др Јадранка Васиљевић

JВасиљевић

У Београду,
09.12.2022. године

ИНСТИТУТ ЗА ФИЗИКУ

ПРИМЉЕНО:	09. 03. 2021		
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МИНИСТАРСТВО ПРОСВЕТЕ, НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА
Матични научни одбор за физику

Број: 660-01-4/2020-14/38
22.01.2021. године
Београд

На основу члана 27. став 1 тачка 1) и члана 76. став 5. Закона о науци и истраживањима („Службени гласник Републике Србије", бр. 49/2019) и Правилника о поступку, начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача („Службени гласник Републике Србије", број 24/16, 21/17 и 38/17) и захтева који је поднео

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О СТИЦАЊУ НАУЧНОГ ЗВАЊА

Др Јадранка Васиљевић

стиче научно звање

Научни сарадник

у области природно-математичких наука - физика

О Б Р А З Л О Ж Е Њ Е

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утврдио је предлог број 0801-1175/1 од 16.12.2020. године на седници Научног већа Института за физику у Београду и поднео захтев Матичном научном одбору за физику број 0801-1201/1 од 17.12.2020. године за доношење одлуке о испуњености услова за стицање научног звања **Научни сарадник.**

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Book of abstracts

PHOTONICA2021

VIII International School and Conference on Photonics

& HEMMAGINERO workshop

23 - 27 August 2021,

Belgrade, Serbia

Editors

Mihailo Rabasović, Marina Lekić and Aleksandar Krmpot

Institute of Physics Belgrade, Serbia

Belgrade, 2021

ABSTRACTS OF TUTORIAL, KEYNOTE, INVITED LECTURES, PROGRESS REPORTS AND CONTRIBUTED PAPERS

of

VIII International School and Conference on Photonics PHOTONICA2021

23 - 27 August 2021

Belgrade Serbia

Editors
Mihailo Rabasović, Marina Lekić and Aleksandar Krmpot

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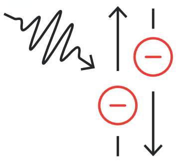

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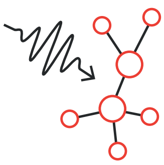

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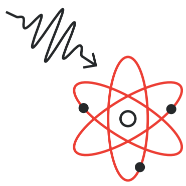

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Date 19.11.2023 21:32

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Other IDs

Scopus Author ID: 57190421714

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Name

Jadranka Vasiljević

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