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# Light propagation in disordered aperiodic Mathieu photonic lattices

*Jadranka M.* Vasiljević[1,*], *Dejan V.* Timotijević[2], and *Dragana M.* Jović Savić[1]

[1]Institute of Physics, University of Belgrade, P.O. Box 68, 11001 Belgrade, Serbia
[2]Institute for Multidisciplinary Research, University of Belgrade, Kneza Višeslava 1, 11030, Belgrade, Serbia

**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.

*e-mail: jadranka@ipb.ac.rs

## 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 $I_{\mathrm{m}}$ 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 $I_{\mathrm{in}}$ 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, $I_{\mathrm{m}}$ 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, $I_{\mathrm{avg}}$s are lower for DA than for DP lattices. For M1, $I_{\mathrm{m}}$ and $I_{\mathrm{avg}}$ 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

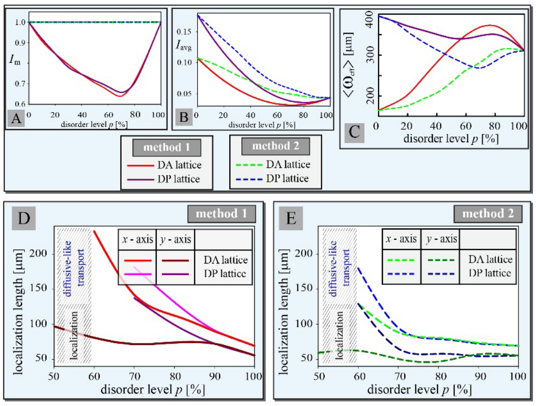


**Figure 1.** Methods differences of realization and light propagation in DA and DP lattices. (A) $I_{\mathrm{m}}$, (B) $I_{\mathrm{avg}}$ of DA and DP lattices versus DL for different methods. (C) $\langle\omega_{\mathrm{eff}}\rangle$ and (D)-(E) localization lengths along the $x$- and $y$-axis for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