Reentrant delocalization transition in one-dimensional photonic quasicrystals

Kyle Linn1,*, Sachin Vaidya1, Christina Jörg1, Megan Goh2, Mikael C. Rechtsman1
1Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA
2Department of Physics, Amherst College, Amherst, Massachusetts 01002, USA
*kyelen11@gmail.com

Abstract: We theoretically predict and experimentally observe that the localization of light in one-dimensional photonic quasicrystals is followed by a second delocalization transition on increasing quasiperiodic modulation strength - an example of a reentrant transition. © 2023 The Author(s)

Anderson localization is a generic phenomenon of wave localization and the cessation of all wave transport in disordered media [1]. Localization in the context of photonics can be employed for various photonic applications, such as for random nanolasing, formation of photonic pseudogaps, formation of high Q/V nanocavities and for reducing crosstalk between waveguides in fiber arrays for telecommunications [2].

It is known that in one and two dimensions, an infinitesimal amount of random disorder causes Anderson localization but in three dimensions, a sharp transition occurs between extended and localized regimes at a finite value of disorder strength. Such a sharp transition can also occur in one dimension when the random disorder of lattice potentials is replaced by quasiperiodicity. The well-known Aubry and André model is an example of a quasiperiodic lattice that exhibits such a sharp transition for the entire energy spectrum [3], which is associated with a duality relation between the different sides of the mobility edge. Extensions of the Aubry-André model with long-range couplings were previously investigated theoretically and found to possess mobility edges where both extended and localized states co-exist. Moreover, some dimerized tight-binding models were recently found to exhibit a second reentrant transition of some states back to the same localization regime [4].

In this work, we experimentally demonstrate a surprising localization behavior in multi-layer structures with quasiperiodic thickness modulation, i.e., one-dimensional photonic quasicrystals (1D PhQCs). In particular, we observe that in addition to the complete inhibition of transmission corresponding to a sharp localization transition, there is a second transition to an extended regime upon increasing the quasiperiodic modulation strength.

The system considered here consists of a set of multi-layer structures made out of two materials, silicon and silica (SiO₂), with refractive indices n_{Si} = 3.5 and n_{SiO₂} = 1.5, respectively. These layers are stacked along the $z$-direction and we consider propagation purely along the stacking direction. Motivated by the Aubry-André model, we modulate the thicknesses of each layer in a unit cell, defined as a pair of neighboring Si and SiO₂ layers, according to $t_n = t_0 [1 + A \cos(2\pi \beta n)]$, where $n \in \{1, 2, \ldots, N\}$ identifies a pair of layers, $2N$ is the total number of layers, $A$ is the strength of the spatial modulation and $\beta$ is the closest Diophantine (rational) approximation to the golden mean, $\phi = (1 + \sqrt{5})/2$, for a given value of system size, $N$. For $A = 0$, the system is a one-dimensional photonic crystal whereas for $A \neq 0$, the system is a 1D PhQC.

We obtain the states of our PhQCs using the plane-wave expansion method, as implemented in MIT Photonic Bands (MPB) package [5], and calculate their inverse participation ratios (IPR) given by $\text{IPR}_p = \frac{\int |\mathcal{H}_p(z)|^4 dz}{(\int |\mathcal{H}_p(z)|^2 dz)^2}$, where $\mathcal{H}_p$ is the scalar magnetic field corresponding to the $p$-th state and the integral is taken over the entire finite system. IPR is a measure of localization of states, where small (large) values of IPR indicate extended (localized) states.

Fig. 1 (a) shows a plot of the frequency spectrum of the PhQC states as a function of $A$ and their corresponding IPR. Here, the frequency eigenvalues have been converted to dimensionless wavelength $\lambda/(\langle a \rangle)$, where $\langle a \rangle = 2t_0$ is the average lattice constant. For small values of $A$ ($A < 0.3$), the states are extended since the structure may be thought of as being crystalline with a small quasicrystalline perturbation. For larger values of $A$, the states undergo transitions to a localized regime, as indicated by a sharp increase in their IPR. We observe that not all transitions occur for the same value of $A$, which is reminiscent of mobility edges in complex models. Moreover, for some states around $\lambda/(\langle a \rangle) = 3.2$ and $A = 0.8$, we observe a sharp reduction in IPR on further increasing $A$, marking a reentrant transition to a second extended regime for these states. In Fig. 1 (c), we also examine the $\mathcal{H}(z)$-field profile for one such state that undergoes a reentrant transition, marked by the arrow in Fig. 1 (a). The field profiles show the transition from extended to localized and back to extended as $A$ is increased.

We examine the transmission spectrum of the PhQCs in detail numerically and experimentally. Fig. 1 (b) shows a plot of the transmission spectrum of the PhQCs as a function of $A$, calculated using a transfer matrix approach.
We see that the localization transitions from Fig. 1 (a) correspond to the vanishing of transmission through the structures. Furthermore, we also see a recovery of transmission around $\lambda / \langle a \rangle = 3.2$, which corresponds to the reentrant transition of some states to an extended regime.

For the experiment, we fabricate the PhQCs using plasma-enhanced chemical vapor deposition (PECVD), alternating between Si and SiO$_2$ deposition on a glass substrate. We fabricate a total of ten samples with $\langle a \rangle = 0.25$ $\mu$m, $t_0 = 0.125$ $\mu$m, $N = 13$, $\beta = 21/13$ and varying values of $A$. A scanning electron microscope (SEM) image of a typical sample is shown in Fig. 1 (d). To characterize our samples, we measure the transmission spectrum of each sample as a function of wavelength using a supercontinuum laser and filter.

The measured transmission spectrum is shown in Fig. 1 (e), along with the simulation results for comparison in Fig. 1 (f). We find that despite the relatively small system size, the localization transitions for states near $\lambda = 0.85$ $\mu$m and 0.75 $\mu$m are clearly observed as the sharp inhibition of transmission. Furthermore, the reentrant transition to an extended regime near $\lambda = 0.78$ $\mu$m is observed as a sharp recovery of transmission for $A > 0.8$.

To conclude, we have observed localization transitions and a reentrant delocalization transition in 1D PhQCs with an Aubry-André-type quasiperiodic modulation by measuring their transmission spectra. These PhQCs generically exhibit mobility edges and reentrant transitions and therefore provide a potentially useful platform for exploring the rich localization physics in complex models.

References

1. P. W. Anderson, “Absence of diffusion in certain random lattices,” Phys. review 109, 1492 (1958).
2. M. Segev, Y. Silberberg, and D. N. Christodoulides, “Anderson localization of light,” Nat. Photonics 7, 197–204 (2013).
3. S. Aubry and G. André, “Analyticity breaking and anderson localization in incommensurate lattices,” Ann. Isr. Phys. Soc 3, 18 (1980).
4. S. Roy, T. Mishra, B. Tanatar, and S. Basu, “Reentrant localization transition in a quasiperiodic chain,” Phys. Rev. Lett. 126, 106803 (2021).
5. S. G. Johnson and J. D. Joannopoulos, “Block-iterative frequency-domain methods for maxwell’s equations in a planewave basis,” Opt. Express 8, 173–190 (2001).