Disorder-Enhanced Transport in Photonic Quasi-Crystals: Anderson Localization and Delocalization

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Abstract: We demonstrate experimentally that disorder enhances transport of waves in Penrose-type photonic quasicrystals. Increasing disorder gives rise to a transition from "bumpy ride" to diffusive transport.

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Anderson Localization is a well-known concept in solid-state physics predicted by Philip Anderson in 1958 [1] and which led to the 1977 Nobel Prize. Realizing that Anderson localization is a universal wave phenomenon relying on interference, these concepts were introduced into to optics. In 2007, our group used the transverse localization scheme [2] and made the first demonstration of Anderson localization [3] in its original context, where random fluctuations superimposed upon a periodic structure bring transport to a halt. This was the first experimental observation of Anderson localization in any periodic system containing disorder, just as Anderson predicted it. Numerous experimental works have followed, in optics [4,5] and matter-waves [6].

Here, we experiment with localization in photonic quasicrystals, and show that disorder enhances transport – opposite to Anderson localization effects in crystals and in fully random media. In that respect, what we observe here is "Anderson delocalization": a novel phenomenon unique to quasicrystals.

Quasicrystals (QCs) are structures with no unit cell, exhibiting no reflection or translation symmetries, but having long-range order. They were discovered in 1984 [7] when a sharp diffraction pattern was observed from an aluminum alloy, providing evidence that the alloy has a 5-fold rotational symmetry, which, according to belief at that time, was crystallographically forbidden. Such long-range order without periodicity gives rise to unique properties [5,8]. For example, the band structure of a quasi-periodic potential is fractal-like, and the eigenmodes are critical states best described as having polynomially-decaying envelope functions (unlike the periodic Bloch modes of a lattice). The question of what disorder would do to transport in QCs has thus far hardly been addressed, and even the few theory papers on this subject [9] heavily rely on tight-binding models, whose ability to model QCs, especially in the presence of disorder, is very limited. It is therefore of fundamental interest to find out how disorder affects transport in QCs and whether it ever leads to localization, bringing transport to a complete halt.

We work with photonic lattices, employing the transverse localization scheme [2,3], which is represented by the paraxial wave equation for monochromatic light, in complete analogy to Anderson's model:

$$i\frac{\partial\Psi}{\partial z}=-\frac{1}{2k}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\Psi-\frac{k\Delta n}{n_0}\Psi \qquad (1)$$

Here z is the propagation coordinate, x and y are the transverse dimensions, Ψ is the field envelope, k is the wave number, n_0 is the bulk refractive index, and Δn is the local change in the refractive index (lattice + disorder). The equivalence to solid-state physics emerges when $z\rightarrow t$ and $-\Delta n\rightarrow V$, implying that the evolution of a light beam behaves like the wavepacket of a quantum particle in a 2D potential, but with the coordinate z replacing time.

Figure 1 shows the experimental scheme described by Eq. (1). We use the induction technique [2,3] to transform an optical intensity pattern into a refractive index structure $\Delta n(x,y,z)$, which includes both the QC lattice and the disorder. A "frozen" potential (as required in the Anderson scheme) is achieved by constructing the interference pattern (QC lattice + disorder) from a ring in (k_x, k_y) (momentum) space, on which the transverse k components of the induction waves are overlaid. In this way all induction waves have the same propagation constant k_z, and accumulate the same phase during propagation in z, hence the interference pattern and the index change $\Delta n(x,y)$ induced by it do not vary with z either. Five plane waves are used to create a ten-fold Penrose quasi-lattice on which the disorder is superimposed. To make the disorder propagation-invariant, we pass a beam through a conical lens, which creates a narrow ring of light at the Fourier plane of a 4f system, where a diffuser is placed. When the thickness of the ring is considerably narrower than the typical size of a scatterer upon the diffuser, the pattern (lattice + speckles) formed at the output of the 4F system does not vary while propagating even for large distances. We launch a weak probe beam through the structure, and monitor the exiting beam. In optics, the propagation distance is always finite (equivalent to finite time), hence transport must be studied through ensemble-averaging over many realizations of the disorder (under same parameters), as appropriate for an expectation-value problem. The different realizations of the disorder are created by passing the beam through different locations upon the diffuser.

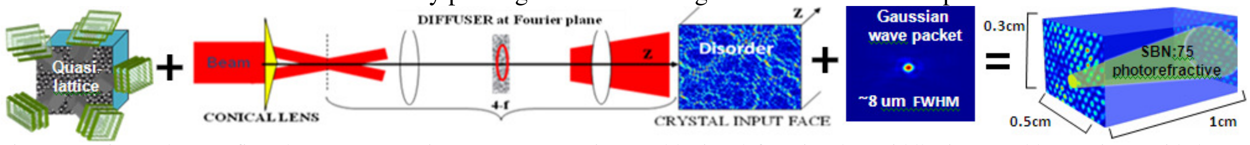

Fig.1. Experimental setup: five plane waves creating a Penrose Quasi-Crystal lattice (left). Disorder (middle) is created by passing a wide beam through a conical lens, and then placing a diffuser at the Fourier plane located in the middle of the 4F system. The disorder and the lattice are then both coherently added and imaged to the input facet of the nonlinear crystal, where the probe is injected right) and monitored at the output

Simulated results, shown in Fig. 2a, display the ensemble-averaged width of the beam propagating through the QC as a function of z, without disorder (lower curve) and with 20% disorder. With no disorder, transport through the QC displays a "bumpy ride", with irregular oscillations occurring as the tunneling from one site to another is never resonant, because the QC potential is never identical for adjacent sites. Such “bumpy ride” is especially pronounced for wavepackets selectively comprised of narrow QC eigenmodes. These are the kind of wavepackets we study here. When disorder is introduced, the band structure is no longer ideally fractal, but rather has piecewise continuous regions. As such, the bands resemble crystalline bands containing disorder, which is why transport is diffusive-like in its characteristic shape. Unlike the traditional role of disorder in reducing transport, here – in disordered QCs – transport is enhanced. Consequently, transport through the QC containing disorder is considerably enhanced (Fig. 2a, upper curve), displaying a Gaussian profile characteristic of diffusive transport. At high disorder levels, the potential becomes completely random, and the system crosses over to Anderson localization.

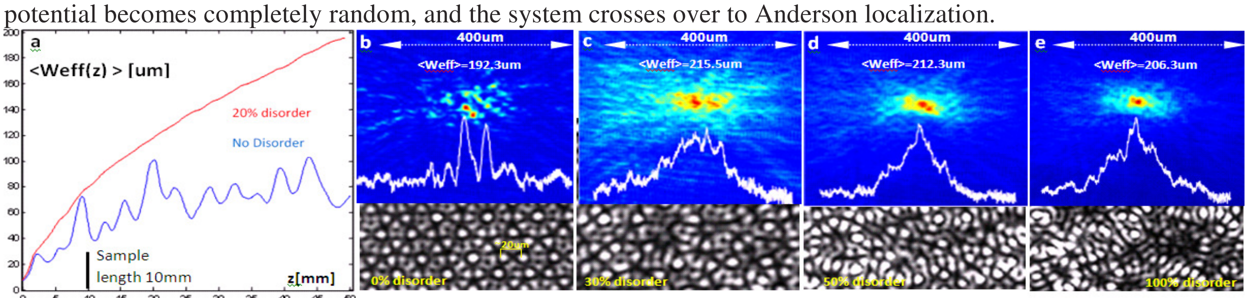

Fig.2. (a) simulation results for a “clean” QC (blue curve) and a disordered quasi-lattice with 20% disorder (red curve). Shown are the average beam width as function of z. The red curve has a positive slope and is always above the blue curve, indicating that transport is higher at all z. (b-e) Experiments - Figures 2b to 2e shows the output intensity and the log of its cross section, for a beam propagating for 10mm in a frozen 2D (QC + disorder), with increasing amount of disorder (samples of which are pictured underneath- disorder value is in yellow), indicating that the average width first increases and only at 30% disorder starts to decrease, where at the same point the log plot shows parabolic tails indicating diffusive-like behavior. At 50% and 100% disorder the beam is exponentially localized showing linear tails in the log plots.

The experimental results are depicted in Fig. 2 (b-e). Figure 2b shows the beam exiting the QC with no disorder superimposed. The exiting beam is always fractured and varies depending on the initial launch point, because the potential in a QC has no translational symmetry. The mean beam width is 192µm. Figures 2(c-e) depict the output beam for increasing strength of disorder ensemble-averaged over 50 realizations of the disorder (same statistics), for each value of disorder strength. As expected from the simulation (Fig. 2a), at 30% disorder transport is diffusive-like (Fig. 2c), with an average beam width of 215um. Increasing the disorder strength makes the beam more and more localized (Fig. 2d), until at 100% disorder it displays the exponential tails characteristic of Anderson localization with an average beam width of 206µm (Fig. 2e). That is, at very high disorder levels the potential becomes fully random – with little trace of the initial quasi-periodic potential, and transport comes to a halt.

The experimental and theoretical results displayed in Fig 2 unequivocally show that disorder enhances transport in QCs for a range of values of disorder strength, making it diffusive-like transport. **This constitutes the first observation of disorder-enhanced transport in any quasi-crystalline structure in nature**. This study raises very many new questions: what happens after very long evolution (say, 10^6 coupling lengths)? How would nonlinearity affect transport in QCs containing disorder? How does the structure of the wavepacket affect transport? These and very many other questions are now within experimental reach, following the experiments displayed here.

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