Disorder-Enhanced Transport in Photonic Quasicrystals

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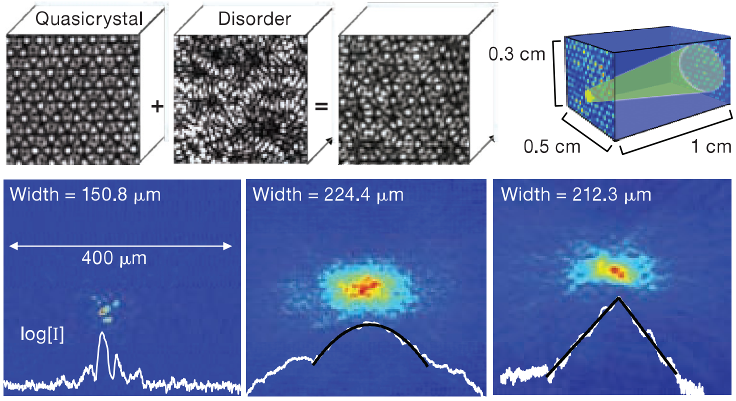
Optics is at the forefront of research into one of the most beguiling problems of the day: What is the effect of disorder on materials properties? In 1958, P.W. Anderson developed a theory of wave localization due to disorder in solids, for which he won the Nobel Prize in 1977. He showed that disorder acts to inhibit electron transport. Three decades later, Sajeev John suggested that, since Anderson localization is a general wave phenomenon (not specific to electrons), localization effects could be observed with electromagnetic waves.

Following this idea, Lagendijk's group has proposed the "transverse localization scheme," where the temporal evolution of a wavepacket in a disordered medium is mapped onto the paraxial propagation of an optical beam going through a transversely disordered dielectric.[1] This concept culminated in a direct experimental observation of Anderson localization in any periodic system containing disorder.[2]

Numerous experiments followed, including detailed studies of Anderson-localized modes in photonic lattices,[3] and localization experiments with cold atoms (in the groups of Alain Aspect and Massimo Inguscio). With these experiments now becoming accessible, optics has become perhaps the best context for delving into the fascinating surprises that disordered systems can present, as manifested, for example, by the recent experimental demonstration of amorphous photonic lattices exhibiting a bandgap.[4]

One of the most intriguing unanswered questions is how disorder affects the transport of waves in quasicrystals. In our recent paper,[5] we demonstrated disorder-enhanced transport in quasicrystals. Discovered by Dan Schechtman in 1982 and explained by Levine and Steinhardt two years later, quasicrystals are structures that are ordered but not periodic. They contain long-range order with symmetries that are forbidden to periodic systems (e.g., fivefold rotational symmetry). The observed enhancement of transport by disorder[5] is opposite to what happens in periodic crystals where transport is inhibited due to the presence of disorder.[2] Disorder-enhanced transport is highly counterintuitive and has been debated for two decades. Our observation provides proof for what was argued in solid-state quasicrystals (which are found in certain metal alloys): When these materials are more disordered (more defects), their conductivity is actually higher.



Transport in a clean quasicrystal — Enhanced transport in a slightly disordered quasicrystal — Anderson localization in a highly disordered quasicrystal

Our experiments employ a photorefractive crystal and five interfering laser beams to induce a photonic lattice structured as a fivefold rotationally symmetric quasicrystal. The interference pattern in the crystal induces a refractive index change that acts on light in the same way that nuclei in solid-state quasicrystals act on electrons. We introduce controllable disorder by passing a beam through a diffuser, thus introducing a random speckle pattern superimposed on the quasicrystal. By launching a probe beam into the lattice, we can track the diffraction of the beam as it propagates, thus giving a direct measure of the conductivity of light as it travels through.

We find that when the probe beam excites eigenstates associated with a region of low density-of-states (near the pseudogap), disorder actually increases the rate of diffraction, thus experimentally proving the hypothesis of disorder-enhanced transport. This is because the eigenstates near the pseudogap in a pure quasicrystal are spaced out from one another and thus do not resonantly tunnel between one another to form broader states; they are highly localized. When disorder is introduced, the probability of tunneling between these highly localized states increases, hence the states become broader, thereby enhancing transport. This work makes many ideas experimentally accessible, ranging from the combined action of disorder and nonlinearity to quantum correlations of photons in photonic quasicrystals. ▲

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