ANDERSON LOCALIZATION OF LIGHT

A little disorder is just right

As with most things in life, some disorder can cause unexpected new phenomena. But when it comes to disorder-induced Anderson localization of light in a photonic crystal, simulations suggest that moderation may be the best policy.

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This year marks the fiftieth anniversary of Philip Anderson's seminal work suggesting that when a certain critical amount of disorder is added to an otherwise periodic semiconducting crystal, the interference of multiply scattered electrons can cause them to come to an effective standstill and their wavefunctions to become strongly localized[1]. Such behaviour, known as Anderson localization, is an inherently wave-like phenomenon, and its signatures have been observed in many different contexts, including sound waves[2] and even matter waves[3]. But achieving Anderson localization of light in three dimensions[4] has proved elusive and often controversial. Probing the exponential spatial localization of light necessary for a definitive demonstration of Anderson localization is particularly challenging, and such experimental investigations are scarce. On page 794 of this issue[5], Conti and Fratalocchi attempt to circumvent such difficulties by performing massively parallel numerical calculations of the effect of disorder on the optical fields within an archetypal example of a 3D photonic crystal, the inverted opal. Their results suggest that the key to realizing 3D Anderson localization of light is to ensure that the amount of disorder introduced in such a system is not too little, and not too much, but just right.

Electrons and photons are analogous in most important respects when it comes to their propagation through a medium. In mathematical terms, the Schrödinger equation is for electrons in a quantum well what the wave equation is for light in a dielectric structure. The wave equation can be cast in a form similar to the Schrödinger equation by separating the dielectric function into its spatial average and fluctuation components[4]. The potential term in the Schrödinger equation is then represented by the (frequency-scaled) fluctuations in dielectric function ($\varepsilon_{\text{fluct}}\omega^2/c^2$) whereas its eigenvalues come out as the (frequency-scaled) average dielectric function ($\varepsilon_0\omega^2/c^2$). For most optical systems, the dielectric function is real and positive at all points in space. This means that fluctuations in the dielectric function are usually much smaller than its average. Consequently, the size of the potential wells corresponding to these fluctuations is usually much smaller than the energy states of the system, which, in turn, means that no bound states can arise.

The upshot of all this is that it is impossible to trap light in the same way as one might trap a conventional particle. Unlike electrons, whose electrostatic nature can be used to create trapping potentials with walls much larger than their kinetic energy (regardless of order or periodicity), photons can only be localized through interference, which often involves order. This is one reason that, in the absence of periodicity, 3D localization has been so elusive[6]. Yet it was through an understanding of this fact that the very idea of the photonic crystal[4], which provides a powerful platform for exploring such phenomena[7], was prompted.

Like a semiconducting crystal, a photonic crystal can have an energy gap within which propagation is forbidden. Moreover, the introduction of impurities and other defects into the crystal's structure can generate spatially localized states within this gap. Owing to the way in which photonic crystals are grown, the occurrence of some disorder is unavoidable. But although researchers usually do their best to minimize this, in the context of producing and studying localization effects, disorder is indispensable.

When a pulse of light passes through a photonic crystal without scattering, it will generally emerge from the crystal in much the same shape (but for some broadening of the pulse owing to dispersion). But if the pulse encounters defects in the crystal's structure, they will cause its photons to scatter, much like the steel balls in a pinball machine. This can cause a transition on the propagation of light through the crystal from a predominantly ballistic

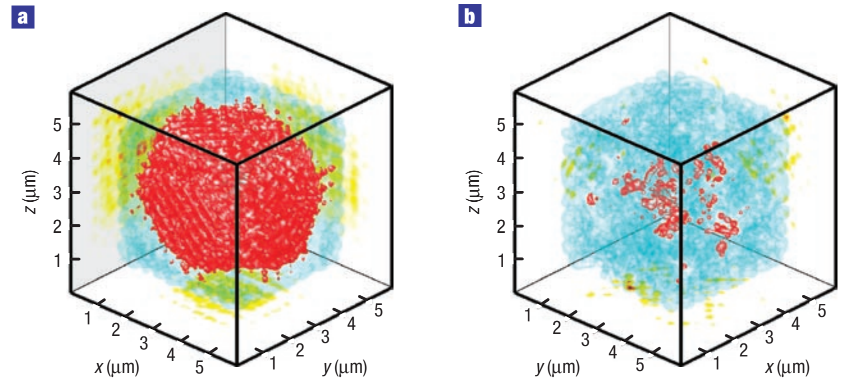

Figure 1 Transition from Bloch-mode lasing to Anderson lasing with increasing disorder in a photonic crystal. **a**, When a laser gain medium is injected into the voids of a perfect (or nearly perfect) photonic crystal, it undergoes lasing from states at the edge of the bandgap that extend throughout the crystal. **b**, With increasing disorder, however, increased scattering and narrowing of the bandgap extinguishes these modes. Instead, lasing occurs from 'Anderson states' — localized states further into the bandgap that correspond to spatially localized modes within the crystal.

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to a diffusive regime. In this regime, the photons entering the crystal as a short pulse will leave as a drawn-out exponential. The duration of this exponential (characteristic time) is directly linked to the diffusion constant. But localization can change it and bring about a critical slowing of photons because they dwell for longer times in these localized states.

From their simulations, Conti and Fratalocchi find that, for moderate amounts of disorder above a certain value, the decay strongly deviates from a single exponential and the distribution of characteristic times of the emerging light splits into separate components with two different time constants. The first component results from the expected delays induced by scattering. The second component corresponds to a more pronounced critical slowing down of photons arising from the population of localized states. But perhaps surprisingly, they find that this critical component only arises within a certain range of disorder, with the localization length reaching a minimum at some optimal value and then increasing once more with increasing disorder. This happens because as well as generating localized states in a crystal's bandgap, disorder also causes the gap to get smaller. Eventually the localized states, merging with the extended states either side of the ever-shrinking gap, close it, at which point the system reverts to full disorder and ceases to localize. This trade off between the need to generate enough disorder but not too much, and the difficulty in finding and measuring a magnitude, such as of localization length, that constitutes a faithful signature of the phenomenon, provides another explanation for why Anderson localization has been so difficult to realize experimentally.

The authors also investigate the implications of such phenomena for lasing. Laser action from states at the edge of a photonic crystal's bandgap can be induced by introducing an appropriate medium into the crystal's structure and exciting it with sufficiently intense pump light. This arises from the fact that states at the band edge correspond to stationary waves that concentrate electromagnetic field, which promotes population inversion and, eventually, so-called Bloch-mode lasing. Conti and Fratalocchi find that as the disorder in such a system increases, narrowing of the bandgap extinguishes lasing from the edge states, which can then only occur via localized states further into the gap — in a peculiar form of random lasing that they refer to as Anderson lasing (see Fig. 1). This behaviour is not only intriguing from a fundamental point of view, but it can be the basis of new types of lasers. Although making a laser based on Anderson localization might seem much easier than one based on photonic crystal modes, it is unclear whether the precise degree of disorder needed to induce it would be any easier to achieve than the high degree of perfection required to make ordinary lasers.

Although the insights that the authors obtain are likely to be relevant to many different photonic crystal systems, certain limitations of their model should be mentioned. The system modelled is a silicon inverted opal. The type of disorder considered is that introduced by a distribution of sizes with no topological disorder. That is, each air sphere has a random size with a Gaussian distribution, but each is centred on the sites of the lattice of the opal, and to make findings independent of a particular configuration of spheres, all magnitudes are obtained by averaging over many realizations. This assumption limits which structures this can be generalized for, because different distributions of sizes may yield different results. Furthermore, it is well known that in this particular system many other defects are present, such as, for instance, dislocations and stacking faults.

Such issues notwithstanding, the results of Conti and Fratalocchi's simulations should certainly cause a stir in the field, and hopefully stimulate new ideas in the design of systems to test present theories of optical localization. At the very least, it should enable researchers to better determine if it is even possible to realize and measure true Anderson localization in currently available 3D photonic crystals.

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