PHOTONIC CRYSTALS

Disorder sets light straight

Photonic crystals can control the flow of light but they are extremely sensitive to structural disorder. Although this often degrades performance, disorder can actually be used to enhance light collimation.

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Some fundamental physical processes go largely unnoticed in our macroscopic world. A good example is diffraction — the spreading of light beams as they propagate. Macroscopic objects and light sources are much larger than the wavelength of light, which means the distances needed to observe diffraction effects are vastly larger than the length scales present in our daily life. At small scales however, diffraction effects can dominate, and are critical hurdles for controlling the flow of light at distances smaller than the wavelength. As they report in *Nature Physics*, Pin-Chun Hsieh and colleagues[1] demonstrate how disorder can enhance the collimation of light through Anderson localization — a wave phenomenon that only emerges in disordered systems[2].

When low-loss dielectric materials are periodically patterned at subwavelength scales, the flow of light mimics electron propagation in crystalline potentials, with analogues to solid-state concepts such as energy bandgaps or wavefunction localization near defects. The highly controllable environment of photonic crystals[3] has also produced completely new routes for the control of light propagation that do not have a direct analogue in conventional electronic systems. One such example is the apparent propagation of light without diffraction, known as supercollimation[4]. The remarkable dispersion-engineering versatility of photonic crystals allows for the creation of systems in which all Fourier components of an optical beam propagate in the same direction. This enables diffraction-free light propagation without any waveguiding mechanism or self-guiding nonlinear optical effect[5].

Although crucially important in its own right, non-diffractive light propagation based on perfectly periodic structures has one fundamental drawback: it only works within a narrow frequency bandwidth, which makes supercollimation effects very sensitive to frequency variations of the propagating beam. Hsieh *et al.*[1] now demonstrate that disorder can become an unexpected ally for tackling this problem.

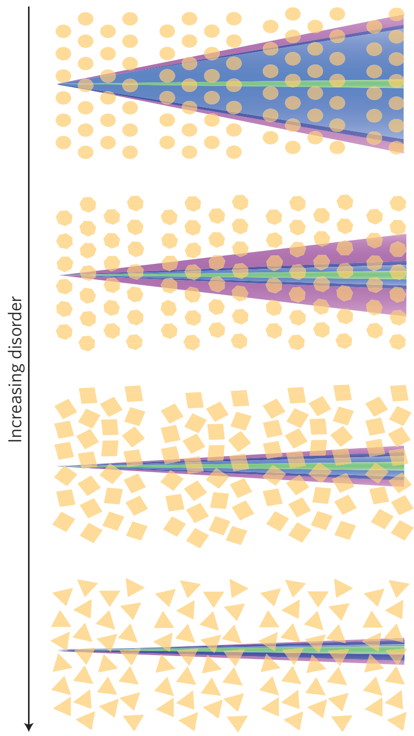

Figure 1 | Anderson-assisted light-beam supercollimation. The schematic shows how a focused polychromatic light beam spreads as it propagates (from left to right) through different photonic crystal superlattices. Each superlattice consists of alternating layers of photonic crystal slabs and homogeneous dielectric stripes. Structural disorder is introduced by replacing the circular holes of a perfectly periodic superlattice (top panel) with randomly rotated polygonal-shaped apertures. The amount of disorder increases when going from heptagonal (second panel from top) to squared (third panel from top) and then to triangular-shaped apertures (bottom panel). The emergence of transverse Anderson localization for light in the disordered cases increases both the collimation bandwidth and the degree of collimation of the propagating beam. As disorder grows in the system, the collimation enhancement also increases.

At first sight the approach of Hsieh *et al.*[1] could seem counterintuitive. It is well known that structural disorder is detrimental to any optical functionality of a periodic photonic structure. But instead of battling disorder, they discovered a fundamental way to leverage it. Their approach builds on the concept of Anderson localization, which is a universal wave phenomenon introduced almost six decades ago in the context of electronic transport in disordered solids[2]. The effects of Anderson localization emerge as the result of the destructive interference of the multiple scattering paths of a wave traveling through an environment with enough disorder. Disordered photonic structures were soon identified as ideal platforms for exploring this unique class of phenomena due to their intrinsic advantages in this context[6,7].

The idea of transverse Anderson localization of light is especially interesting[8,9]. The same physics that enables full three-dimensional Anderson localization allows a system featuring a random refractive index distribution in two dimensions to display diffraction-free light propagation along a third (transverse) direction. Using this idea, Hsieh *et al.*[1] created a technologically significant platform — a chip-scale photonic crystal superlattice — in which the role of disorder is twofold: it significantly broadens the operating bandwidth of diffractionless propagation while enabling the observation of transverse Anderson localization.

The nanofabricated silicon-on-insulator structures are superlattices of alternating layers consisting of photonic crystal slabs and homogeneous dielectric stripes (Fig. 1). In such systems, 1.55 μm light is transmitted via cascaded electromagnetic tunnelling through the leaky guided resonances supported by the homogeneous stripes. Controllable disorder is cleverly introduced by creating photonic crystals with randomly rotated polygonal-shaped apertures — the smaller the number of sides these polygonal shapes have, the larger the amount of disorder introduced in the system. Using near- and far-field infrared measurements, together with detailed numerical simulations, Hsieh *et al.*[1] showed that, as the amount of disorder grows in the system, both the collimation bandwidth and degree of collimation are significantly enhanced with respect to the perfectly periodic case.

These enhanced collimation effects can be explained in terms of the inhomogeneous spectral broadening of the guided resonances and the subsequent increase in the frequency dispersion of the cascaded resonant tunnelling process, which is induced by disorder. But that's not all. Careful analysis of the collimated beam width and its intensity profile revealed that, in the very same spectral interval in which collimation is enhanced, light transport displays two key characteristics of transverse Anderson localization: a near-zero value of the exponent appearing in the power-law relation that links the beam width to the propagation distance and an asymmetric transverse intensity profile. This is in stark contrast to the canonical Gaussian profile observed in most disordered photonic systems that operate in the diffusive regime.

The ubiquity of photonic crystals in a variety of research areas, combined with the extraordinary appeal of Anderson localization phenomena, means these discoveries will certainly stimulate novel fundamental breakthroughs. One could envision, for example, new physics emerging from the incorporation of optical nonlinear materials to such superlattice structures. Other potential developments could arise from the study of quantum optical effects that take advantage of the unique nature of Anderson light-localization properties. But the implications go beyond fundamental importance. Supercollimation assisted by Anderson localization in on-chip dielectric platforms brings Anderson localization to the centre of the integrated photonics stage. Although a number of technological hurdles will need to be overcome along the way, these findings could have a particularly important impact on the development of a new class of optical interconnects. ❒

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