Quantum Devices to Thrive on Disorder

It is usually assumed that a greater effort to perfect control and order in a device is rewarded by better results. However, imperfection and disorder could be a state of contentment when it comes to photon trapping.

Disorder is usually considered to be a nuisance: it deteriorates the qualities of a perfect system and is therefore minimized wherever possible. While most researchers strive to make their devices perfect, Luca Sapienza and Peter Lodahl at the DTU Fotonik of the Technical University of Denmark have used disorder to give rise to completely new photonic properties, suddenly making the lack of order a desired ingredient for their system. They used *Anderson Localization*, a phenomenon originating from disorder, to corral photons into specific regions of a disordered photonic crystal. In this way, the team has demonstrated that disorder and imperfection in photonics need not be viewed as a nuisance.

Anderson Localization is one of the most famous disorder-induced phenomena [1,2]. It was originally proposed for electrons by Philip W. Anderson in 1958, to explain why certain conducting materials suddenly turned into insulators in the presence of imperfections. Since then, it has been observed for sound waves, microwaves, light waves and, more recently, matter waves. Fundamentally, Anderson Localization is a wave phenomenon based on the interference of multiple waves scattered off a disordered potential. We can gain some elementary insight into how Anderson Localization of photons works, if we consider the following situation: take a light ball traveling along a large horizontal channel. If the bottom of the channel is smooth, the ball will enter the channel and safely exit at the other end. If there are randomly distributed obstacles along the channel, the ball will bounce off of these scatters. If there are enough obstacles, the ball may never reach the end, but continue to bounce back and forth within a certain length of the channel: the ball has been localized in space due to scattering events affecting its propagation. Of course, in our particular case, the photon would be more of a wave, which gets reflected by multiple scatters at the same time and thus interferes with itself.

The trapping of photons has a lot to offer. For example, if scientists can trap light more efficiently, they can make better solar cells. Trapped photons can be used for sensing applications, for example, to create *optical hot spots*, which are very sensitive to modifications of the refractive index due to the presence of certain molecules in the environment. Moreover, single photons are believed to be an excellent candidate for carrying information in quantum information networks.

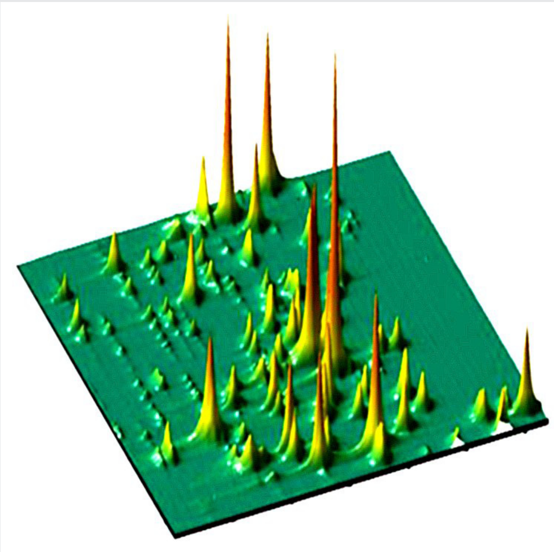

Figure 1: Anderson localized modes of light. The high intensity peaks show the random positions where the light emitted in a disordered photonic crystal waveguide becomes strongly localized. These are signatures of Anderson localization of light.

Lodahl and his team have used Anderson Localization of light to trap photons in disordered photonic crystals. A photonic crystal is a periodic arrangement of materials with different optical properties; because of this periodicity, it features some special properties, different from the ones of the constituting materials. For example, if a periodic array of holes is etched on a slab of semiconductor, only certain frequencies of light can propagate through the slab. Of course, manufacturing such photonic crystals can be very demanding because of the high precision required. Lodahl and his team built innovative photonic crystals with randomly placed holes, which had the advantage of being fabrication-error robust. Their disordered photonic crystals could be effectively used to trap photons without requiring a nanometer scale accuracy in the fabrication. "Relaxing the constraints over the production of a perfect structure, at the advantage of an imperfection-friendly system," Sapienza envisages, "can lead to easier and cheaper production of devices."

Lodahl and his team went a step further by studying the interaction of light with matter at the nanoscale, for example, with single quantum dots. Quantum dots are minutely small globular structures, few nanometers in spatial extent that can be seen, for some of their properties, as artificial atoms. The rates at which a quantum dot absorbs and re-emits photons are extremely sensitive to the local environment. In this way, the photons can be used to probe the material properties at the nanoscale. Such light-matter interfaces provide a very effective way of processing and communicating information. "The idea is," explains Hakan Tureci, from Princeton University (New Jersey, USA), "to use optically active solid state qubits, such as semiconductor quantum dots, to store quantum information that, through photons, is then communicated to other qubits at distant nodes in a quantum network of such stationary qubits." He believes that the application of complex light-confinement mechanisms, such as Anderson Localization, not only extends this initial proposal of a quantum network, but may well also contain the seeds to overcoming important practical limitations inherent in trapping photons in the more traditional photonic crystal cavities.

Photon manipulation is lucrative for information and telecommunication technology, because, unlike electrons, photons are massless and chargeless particles and, therefore, have fewer interaction mechanisms with their surroundings. Photonic crystals are the optical analogues of semiconductors — just like semiconductor materials control electrons, photonic crystals manipulate photons. "This experimental demonstration by Sapienza and his team adds yet another point of similarity between electrons and photons," comments Antonio Badolato of the University of Rochester (New York, USA). Tureci adds: "The past decade has witnessed a remarkable growth in research activity in the exploration and utilization of rather unconventional mechanisms to confine light to tiny volumes, which in many instances draws inspiration from condensed-matter systems e.g. photonic band gap cavities and dielectric resonators. The significance of Sapienza's design is that it relies on one of the most complex wave confinement mechanisms ever studied: Anderson Localization."

[1] P. W. Anderson, *Absence of diffusion in certain random lattices*, Phys Rev **109**, 1492-1505 (1958).

[2] A. Niederberger, *The Disordered Quantum Prison*, Opt. Photon. Focus **1**, 1 . http://www.opfocus.org/index.php?topic=story&v=4&s=1

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Luca Sapienza, Henri Thyrrestrup, Søren Stobbe, Pedro David Garcia, Stephan Smolka & Peter Lodahl, **Cavity Quantum Electrodynamics with Anderson-Localized Modes**, Science (2010) **327**, 1352-1355.