RANDOM PHOTONICS

True Anderson localization

In three-dimensional disordered media, light localization can occur when the disorder is above a certain threshold. Researchers now report experimental evidence of this transition from light diffusion to trapping.

Claudio Conti

Anderson localization is a fundamental concept of condensed matter physics. After more than 50 years[1], the fact that disorder induces energy localization — and thus hampers its propagation — is still driving a variety of new ideas and research directions. In photonics, the quest to observe the Anderson localization of light has fuelled much of our modern research, such as photonic crystals and nanostructured devices[2]. However, the direct observation of this phenomenon has proved elusive; various evidence has been reported, but questioned. It is largely recognized that disorder-induced localizations can sustain coherent laser emission and act as optical cavities[3,4]; however, their ability to be excited in the absence of gain has been debated[5,6].

Now, writing in *Nature Photonics*[7], Sperling *et al.* provide evidence for the transition from diffusive light propagation to localization. Importantly, they employed observables that are intrinsically independent of losses, thus settling the issue with superior unambiguity with respect to former reports.

The key point in Anderson localization is its dimensionality; that is, the number of spatial dimensions where localization occurs. In three dimensions, there is a transition from diffusion to localization when the amount of disorder is above a critical threshold. In optics, this means that below the critical point (for small disorder; that is, a low-scattering sample), light is able to fill all the space in the random medium, as it does in fog. Conversely, for strong disorder, as in the pigments of white paint used by Sperling *et al.*, light gets trapped in three-dimensional (3D) spatial regions. In other words, light can freely propagate in a transparent medium such as water, whereas in disordered media, which are commonly formed by alternating materials such as air and liquid in foams, either diffusion or localization may occur, depending of the strength of disorder.

In a given sample, the strength of disorder is determined by a number of different parameters. Sperling *et al.* used tightly packed dielectric grains of titanium dioxide (Fig. 1), in which the level of scattering and randomness resulted from the value of their refractive index (about 2.8), the size of the grains (hundreds of nanometres) and their packing fraction (around 0.4). Tiny statistical variations in the parameters and the composition of the samples may affect the strength of disorder. Sperling *et al.* quantified this by measuring the transport mean-free path, l^*; the sample with the smallest value of l^* has the strongest disorder.

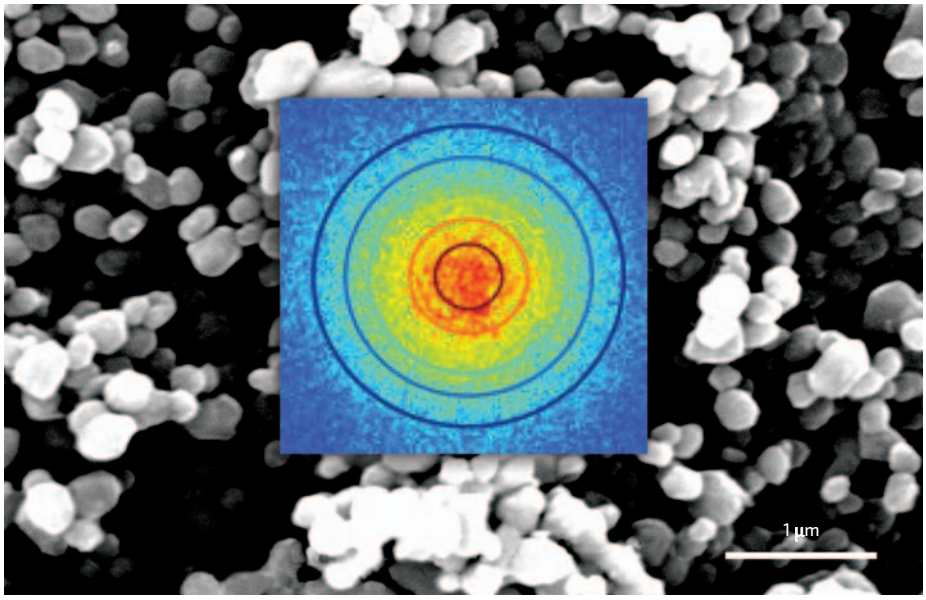

Figure 1 | Light at the onset of the Anderson localization superimposed over a scanning electron microscopy image of a disordered sample.

When l^* is greater than the optical wavelength λ (600 nm), light can propagate through the sample, albeit randomly scattered and diffused. In contrast, when l^* is comparable to λ, a localized regime is expected. This critical transition can be taken as the definition of Anderson localization, and is absent when considering 2D or 1D disordered systems. Indeed, although various researchers have previously reported the transverse Anderson localization of light — that is, the observation of disorder-induced light localization in 1D[8] and 2D[9] — an indisputable demonstration of the 3D Anderson transition for light has been lacking.

Previous experimental techniques were not able to discern the effects of material losses, which, for a variety of technical reasons, can mask or even mimic the onset of Anderson localization, thus hampering an unequivocal proof. In their experiment, Sperling *et al.* directly observed the time evolution of the beam size at the output of the disordered medium. Simple reasoning shows that this observable is indeed independent of losses[10]. This experiment comprised a low-noise camera and a time-gated intensifier, thus providing a sophisticated set-up for measuring the fast evolution of the limited number of photons transmitted by a disordered sample when illuminated by a laser beam.

Within certain simplifications, the observed phenomenology of Anderson localization can be described as follows: assume that light can be imagined as a fluid, and light propagation in a random medium can be described as a fluid percolating in a sponge. If we observe the size of the stain on the sponge, we see that it grows with time — this is known as the diffusive regime. However, if there is localization, the stain stops increasing at some point and its size

acquires a time-independent characteristic value, which confers the spatial extent of the Anderson localization. Roughly speaking, at the localization transition, the porous structure of the sponge becomes so tiny that the fluid cannot penetrate it, and the fluid, originally infiltrated in the sponge, gets trapped and stays localized in a 3D region. A standard fluid does not exhibit this behaviour, but the 'light fluid' does, owing to subtle interference effects occurring when the transport mean free path l^* is comparable to the wavelength λ.

One exciting result provided by the work of Sperling *et al.* is the clear determination of the ratio between λ and l^* at which the transition occurs. Well-known theoretical investigations state that the condition for localization is $\lambda/l^* = 2\pi$, which is known as the Ioffe–Regel criterion. However, the fact that the ratio λ/l^* must be 2π (or larger) is based on general theoretical arguments; until now, the precise experimental value was unknown. The novel results of Sperling *et al.* demonstrate that $\lambda/l^* = n$, where n is the spatially averaged refracting index of the sample.

Sperling *et al.* found that the critical value of the refractive index n is around 1.7, which is in agreement with previously reported numerical investigations based on full simulations of Maxwell's equations[11]. However, for computational reasons, the simulations were limited to very small samples (a thousand times smaller than those adopted in the experiments of Sperling *et al.*). More work is therefore required to establish a definite agreement regarding this 'magic' value of the refractive index at which the 3D disorder induced localization of light is observed.

The key challenge is to assess both the unique characteristics and the value of the Anderson localization of light, with respect, for example, to the same effect for sound waves or matter waves in ultracold gases. This effect could allow us to build disorder-based laser sources that will be widely tuned and very versatile[12]. Light can also sustain relevant nonlinear effects even in absence of active optical media. The physics of the nonlinear Anderson localization of light, and in particular the 3D case, is an important research frontier. This field can also be related to modern techniques[13] for transmitting light through disordered media by proper engineering of the beam's wavefront; the way this can be related to Anderson localization, and exploited to sustain nonlinear effects in the presence of relevant randomness, is yet unexplored. In addition, the quantum properties of light at the Anderson transition are, in many respects, unknown.

In our everyday lives, we are more used to dealing with disordered systems than ordered ones. The reason is to be found in the richness and large number of degrees of freedom that disorder provides. One can think, for example, about the many ways a group of beads can be stacked in a random fashion, in contrast with the limited number of possibilities for an ordered packing. We are just beginning to learn how to control disorder. The applicative possibilities offered by random photonics are still to be imagined, ranging from microscopy and laser-assisted surgery to telecommunications, solar energy harvesting and astrophysical investigations. ❐

Claudio Conti is at the Department of Physics, University Sapienza, Piazzale Aldo Moro 5, 00185, Rome, Italy.
e-mail: claudio.conti@uniroma1.it

References

1. Anderson, P. W. *Phys. Rev.* **109,** 1492–1505 (1958).
2. John, S. *Phys. Rev. Lett.* **58,** 2486–2489 (1987).
3. Cao, H. J. *Phys. A* **38,** 10497–10535 (2005).
4. Wiersma, D. S. *Nature Phys.* **4,** 359–367 (2008).
5. Wiersma, D. S., Bartolini, P., Lagendijk, A. & Righini, R. *Nature* **390,** 671–673 (1997).
6. Sheffold, F., Lenke, R., Tweer, R. & Maret, G. *Nature* **398,** 206–207 (1998).
7. Sperling, T., Bührer, W., Aegerter, C. M. & Maret, G. *Nature Photon.* **7,** 48–52 (2013).
8. Lahini, Y. *et al. Phys. Rev. Lett.* **100,** 013906 (2008).
9. Schwartz, T., Bartal, G., Fishman, S. & Segev, M. *Nature* **446,** 52–55 (2007).
10. Cherroret, N., Skipetrov, S. E. & Van Tiggelen, B. A. *Phys. Rev. E* **82,** 056603 (2010).
11. Gentilini, S., Fratalocchi, A., Angelani, L., Ruocco, G. & Conti, C. *Opt. Lett.* **34,** 130–132 (2009).
12. Leonetti, M., Conti, C. & Lopez, C. *Nature Photon.* **5,** 615–617 (2011).
13. Vellekoop, I. M., Lagendijk, A. & Mosk, A. P. *Nature Photon.* **4,** 320–322 (2010).

FREQUENCY COMBS

Spatial coherent control

Combining concepts from Doppler-free spectroscopy, coherent quantum control and frequency comb spectroscopy leads to new opportunities for the precision excitation of atomic species with high resolution, both spectrally and spatially.

Andrew M. Weiner

Many powerful and sophisticated tools have been developed for optical spectroscopy since the advent of the laser. Within the field of nonlinear spectroscopy, counter-propagating beam geometries that cancel out Doppler shifts in gas-phase atomic samples provide natural linewidth resolutions deep within Doppler-broadened inhomogeneous lines[1]. Usually such studies are performed using tunable continuous-wave lasers. On the other hand, ultrashort pulses can also be exploited despite their very large bandwidths. In approaches based on the concept of quantum control, femtosecond pulses that are shaped temporally and spectrally coherently excite two photon or Raman transitions. Spectral resolution is achieved at the level of the finest features tailored to the optical spectrum[2]. Another ultrashort pulse approach employs frequency combs[3]. Here, the long-term coherence associated with a periodic train of mode-locked pulses with a stabilized pulse-to-pulse phase relationship carves the broadband optical spectrum into a series of precisely spaced delta functions with stabilized absolute frequencies. Such combs have revolutionized the precision and accuracy with which different optical transition frequencies can be measured and compared.

Now, reporting in *Nature Photonics*, Itan Barmes and co-workers beautifully combine these concepts to control and shape the spatial excitation of alkali gases, at the same time furthering the accuracy at which we can determine spectroscopic constants[4].

The experimental apparatus starts with femtosecond pulses from a Ti:sapphire frequency comb laser, which are spectrally shaped in a grating-based pulse shaper equipped with a programmable liquid-crystal modulator[5]. Shaped pulses are directed into a heated vapour cell containing either pure rubidium or a rubidium–caesium mixture, where they excite resonant two-photon absorption. After passing through the cell, the pulses are reflected back for nonlinear interaction in the Doppler-free,