second characteristic length ℓ_{d2} appears when we require that $\Delta\varphi$ does not fluctuate from one pair of paths to another by more than 2π: $\langle\Delta\varphi^2\rangle \sim \Delta k^2\langle\Delta s^2\rangle < 2\pi$, leading to $\langle\Delta s^2\rangle \sim Dt \sim \ell_t s < 2\pi/\Delta k^2$ and $s < \ell_{d2} \sim 1/\ell_t\Delta k^2$, where angular brackets <…> denote averaging over all paths with the same length s, D is the diffusion coefficient and t is the time that a photon takes to propagate along a path of length $s = ct$ (with c the speed of light). Here, we used the fact that wave propagation is diffusive on average, so that the photons perform random walks with a diffusion coefficient equal to $D = c\ell_t/3$. In the experiment, the values of ℓ_{d1} and ℓ_{d2} are in the ranges 2–6 µm and 4–80 µm, respectively[6].

At this point, it is crucial to recall that one cannot isolate a single pair of counterpropagating waves in an experiment, and that the measured CBS cone is therefore a sum of contributions due to the waves following all possible paths with various lengths s and corresponding to different $\Delta s < s$. Given the slow decay of the path length distribution in reflection (the weight for paths of length s is proportional to $s^{-3/2}$) and the oscillating character of the interference signal as a function of $\Delta s/\ell_{d1}$, one may expect that integrations over s and Δs suppress CBS considerably. However, this argument does not take into account other inelastic processes — such as absorption — that penalize long paths and limit the integration over s to a bound below some inelastic scattering length ℓ_i. Fazio *et al.* show that significant CBS enhancement factors can only be obtained when $\ell_{d1} > \ell_i$ and only relatively short paths contribute to the CBS signal[6].

It is surprising and unexpected that the short coherence time of Raman scattered light, which can be safely assumed to be negligible in standard Raman scattering experiments, turns out to be so important that it leads to observable phenomena in a disordered medium. Naively, one would expect disorder to destroy any residual coherence and suppress interference — yet the experiment carried out by Fazio and collaborators supports exactly the opposite conclusion. The key to understanding why this is the case lies in the close relation between the CBS phenomenon and the reciprocity principle that implies the equality of amplitudes and phases for two waves following the same paths in opposite directions. Reciprocity is preserved by Raman scattering for wave paths that are sufficiently short. Ensemble averaging over different realizations of disorder suppresses intensity fluctuations (speckle) at large scattering angles, and makes the CBS signal emerge as the sole surviving interference effect. Hence a disordered medium can be thought of as a highly efficient, self-adjusting interferometer where the equality of optical paths for interfering waves is guaranteed by construction.

The work of Fazio and co-workers[6] also opens the way to interesting extensions. One can imagine, for example, a technique of Raman spectroscopy for disordered media in which statistical properties of disordered materials would be estimated from the Raman CBS cone. Indeed, parameters such as ℓ_{d1} and ℓ_{d2} — which the authors use as free variables for their fits — should actually depend on the characteristics of the scattering medium, suggesting that they could be used to obtain information about the structure of a given material. Another natural extension would be a time-dependent Raman CBS experiment where the angular profile of Raman backscattering is tracked as a function of time (or, equivalently, of path length s) for a short-pulse illumination of the disordered sample. Finally, it would be extremely interesting to understand if other interference phenomena occurring for waves in disordered media (such as short- and long-range mesoscopic correlations or universal conductance fluctuations)[1] can be identified in scattering experiments with Raman light. ❐

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VIEW FROM... NANOMETA 2017

A question of topology

The mathematics of manifolds is providing inspiration for creating exotic states of light with unique properties such as robustness against disorder and unidirectional propagation.

Oliver Graydon

At the start of the year on the snowy slopes of Seefeld, near Innsbruck in Austria, the question as to how topological effects can be implemented and exploited in photonics was one of the topics being discussed in earnest. Over 200 photonics researchers had gathered to attend the 6th International Topical Meeting on Nanophotonics and Metamaterials (NANOMETA) from 4–7 January.

Put simply, topology is the branch of mathematics describing the equivalence of seemingly different shaped objects and the invariance of certain properties when an object is stretched, twisted and deformed. It recently came under the spotlight in the world of physics, with the 2016 Nobel Prize for Physics being awarded to David Thouless, F. Duncan Haldane and J. Michael Kosterlitz “for theoretical discoveries of topological phase transitions and topological phases of matter.” In particular, the prize acknowledged the discovery of various topological effects governing the physics of thin films of electrical conductors, superconductors and magnets — perhaps the most famous example being the topological insulator that only conducts electricity on its surface but not its interior.

For a number of years scientists in optics have been exploring whether the topologically protected effects seen in other physical systems can be realized in photonics and put to good use. Activity and progress in topological photonics has recently accelerated with a string of high profile papers, and this year's NANOMETA event had two sessions and a breakthrough talk dedicated to the topic.

Gennady Shvets from the University of Texas at Austin started the ball rolling with an invited talk on the subject. He described how topological phases of light could potentially prove to be very beneficial in photonics for eliminating unwanted scatter, as well as offering new opportunities for routing, trapping and storing light.

"When you think of topological insulators, the key property is the existence of edge states that cannot be scattered by perturbation, we want to replicate this in optics," explained Shvets. In essence, the realization of topologically protected edge states of light in a practical manner could potentially yield new designs of unidirectional optical waveguides that are more robust to fabrication imperfections and immune from backscattering losses, for example.

"The interface between regions of topological phase with different Chern numbers [an important parameter describing the topological properties of a system] always has a guided mode that follows the interface no matter what its shape," explained Shvets. "One could also create topological cavities that can trap light and introduce time delays and think about making non-reciprocal interface-based devices such as a compact, broadband, four-way circulator."

One of the big challenges in realizing topologically protected states of light is the requirement to break time-reversal symmetry. While this can be achieved by the presence of a magnetic field, many photonics researchers are exploring alternative options such as the use of spin–orbit coupling and making a topological platform from arrays of ring resonators, an approach pioneered by Mohammed Hafezi from the University of Maryland who give an invited talk on the topological quantum transport in photonic structures.

In addition to discussing topological edge states of light, several talks discussed the interplay of plasmonics and topology in various materials. Deng Pan described theoretical research conducted at Wuhan University in China and The Institute of Photonic Sciences (ICFO) in Spain that predicts that a honeycomb superlattice of doped graphene nanoribbons should support topologically protected unidirectional plasmon edge states when exposed to a magnetic field of a few tesla.


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Snow-covered Seefeld in Austria is home to the NANOMETA conference every two years.

In another talk, Cesare Soci explained how a collaboration between Nanyang Technological University (NTU) in Singapore and the University of Southampton, UK was investigating the behaviour of plasmons in topological insulators made from trichalcogenides that are alloys of sulfur, selenium and tellurium. He explained how topological protection could lead to long plasmon propagation lengths as well as spin-momentum locking and plasmon control by charge injection or magnetic field.

"This brings new opportunities for integration of electronics, plasmonics and spintronics with exotic effects," commented Soci. "The main challenge at visible and ultraviolet frequencies is to isolate the surface state contribution from bulk effects."

Finally, in one of the evening's breakthough sessions, Moti Segev from Technion in Israel described work at Technion, NTU, the University of Central Florida and Penn State University that claims to have resulted in the realization of the first topological insulator laser. "This is a laser in which the lasing mode is topologically protected and it brings topological robustness to lasers," he told the audience. "It's robust against defects and disorder and the use of a topological cavity brings unidirectional energy flux and a high slope efficiency." Although the experimental design of the device was not described in detail, it appears that it was made by optically pumping the edge of a microring array to create a laser cavity from a closed triangular-shaped path for a topological mode.

It will be interesting to see if topology-related research features as strongly in the next NANOMETA conference, which is scheduled to take place in January 2019.

The biannual conference series started in January 2007, coincidently at the same time that *Nature Photonics* launched. According to the conference founder, Nikolay Zheludev from the University of Southampton, the motivation behind its creation was to give "Europe a top international meeting rivalling the famous Winter Colloquium on the Physics of Quantum Electronics (PQE) run by Marlan Scully at the Snowbird ski resort in Utah, USA [http://www.pqeconference.com])."

Zheludev took the proposal to the European Physical Society in 2005 and it became a partner and sponsor of NANOMETA, and has provided the conference management ever since. "The idea was to focus on the emerging fields of nanophotonics and metamaterials, which explains the conference name," commented Zheludev, who co-chairs the event with Harald Giessen from the University of Stuttgart who took over from Ekmel Ozbay from Bilkent University in 2011. ❐

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