NANOPHOTONICS

Optical time reversal with graphene

Would you ever guess that a microscopic flake of graphite could reverse the diffraction of light? An experiment that demonstrates just such an effect highlights the exciting optical applications of graphene — an atomic layer of carbon with a two-dimensional honeycomb lattice.

Yaroslav Urzhumov, Cristian Ciracì and David R. Smith

Diffraction of light is as unavoidable and unstoppable as the expansion of our Universe and the growth of entropy in a closed system. It originates from the wave nature of photons and the Heisenberg uncertainty principle: once confined to a finite aperture, photons acquire a spread in their momentum that is inversely proportional to the size of the aperture. When the aperture is as small as the wavelength, the spread in photon directions grows so large that it is no longer easy to tell what the original beam looked like.

Not easy does not mean impossible, however. The photons still carry information about their origin and the aperture through which they passed. If one could carefully collect all information about the intensity and phase of photon waves on a closed surface or a plane — for example, with a massive array of sensors — it would be possible to reconstruct the temporal evolution of the fields and, of course, predict their fate in the future. This would be a prescription for a perfect imaging apparatus that could resolve sub-wavelength features of the source.

Whether or not such a measurement can be taken even in principle is debatable[1,2]; however, the cost of an enormously large array of sub-wavelength sensors is undoubtedly high. It is, therefore, an exciting discovery that atomic lattices can be tricked into acting like a sensor array. Hayk Harutyunyan and colleagues, reporting in *Nature Physics*, demonstrate that just a few layers of graphene can serve as a highly efficient phase-conjugating surface, which they prove by showing controllable negative refraction of a light beam[3].

The extraordinary electronic, optical and mechanical properties of graphene, the first truly two-dimensional crystal to be isolated, have been much lauded since the discovery of this carbon allotrope in 2004[4]. The unusual electronic band structure of graphene — a zero-overlap semi-metal and a zero-bandgap semiconductor — is such that electrons and holes have zero effective mass. Thus, electronic excitations in graphene can model the behaviour of a massless fermion with

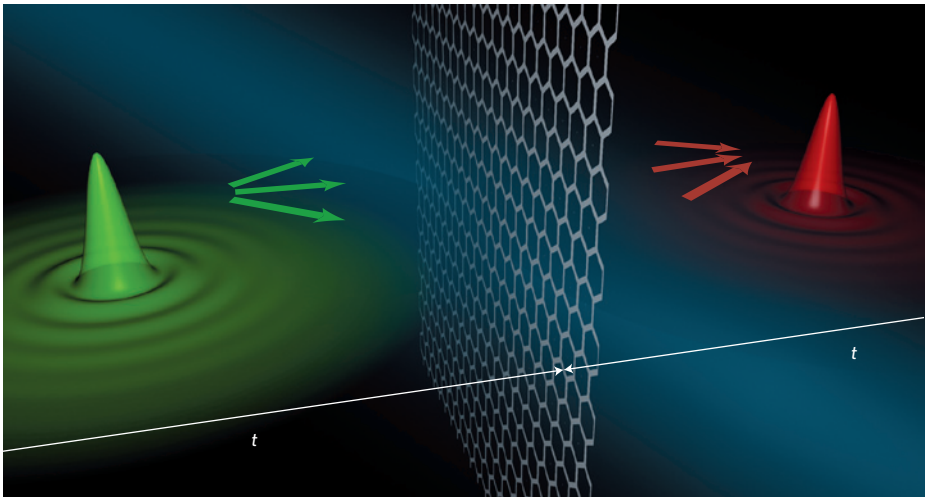

Figure 1 | A phase-conjugating graphene sheet. The transmitted field on the right is the exact time-reversed replica of the field incident from the left. The field profiles are thus reconstructed with sub-wavelength accuracy.

electric charge — a quasiparticle with no analogue in the standard model. It is believed that these super-light electrons and holes are responsible for graphene's unexpectedly strong interaction with light[5]. These exotic band structures, however, persist only in single- and double-layer graphene; thicker stacks rapidly attain the properties of three-dimensional graphite, which is a metal.

Diffraction imposes a fundamental constraint on the resolution of conventional imaging systems, known as the Abbe diffraction limit. Roughly speaking, the minimum resolvable feature size is about half of the wavelength of light in the medium where the image is formed. Going beyond this limit requires doing something extraordinary to the imaging concept. One such revolutionary idea is based on collecting and amplifying evanescent waves — the Fourier components of the image encoding the sub-wavelength details of the image.

This concept became widely known thanks to John Pendry and his 'perfect lens' article[6] in 2000. His idea was to use a medium with a negative index of refraction; a simple slab of such a material enables both negative refraction of propagating waves and amplification of evanescent waves. As negative-index media are not found in nature, scientists were quick to propose artificial nanostructured 'metamaterials' to fill the gap[7]. The catch with the perfect-lens concept was that the quality of the image degrades exponentially as a function of loss in the material. In practice, this limits the imaging distance to about one wavelength or even less. In addition, the lattice constant of metamaterials — typically greater than 100 nm — sets another limit. Consequently, successful implementations of the perfect lens have been based on natural materials, and so far limited to near-field imaging[8,9].

While the search for negligible-loss negative-index metamaterials continued, in 2008 the very same John Pendry exploited an alternative idea for a perfect imaging system: time-reversed propagation induced by phase conjugation[10]. Although optical phase-conjugation is an old concept dating back to the inventor of holography, Dennis Gabor, credit should be given to Pendry for suggesting a physical mechanism

capable of breaking the diffraction limit using a dynamic form of phase conjugation. Phase conjugation — and consequent time-reversed propagation — occurs as an interaction between four mutually coherent beams mediated by the third-order optical nonlinearity of the medium. In essence, two coherent pump beams write a virtual phase hologram into the medium, and the third beam diffracts off this hologram, creating the fourth. This fourth beam is still coherent with the third one, and it happens to be its exact time-reversed replica. This wave-reconstruction process is cheap, sustainable, and supposedly extremely fast; the carbon atoms act here as the aforementioned field sensors, assembled by nature into a perfect gigantic array.

Pendry's proposal[10] brings metals and semi-metals such as graphene back into the perfect-imaging business, this time with a hope of achieving it in the far-field. All metals are good sources of optical nonlinearities[11], but the third-order susceptibility of graphene is two orders of magnitude higher[12]. Combine this with its atomically smooth natural surface, and you will understand why graphene is the innate champion of optical phase-conjugation.

Separation between carbon atoms in graphene is only 1.4 Å. Potentially, this means that graphene-based imaging will happen — Harutyunyan *et al.* show negative refraction of a beam unambiguously, yet do not go as far as demonstrating super-resolved imaging. But the big leap forward has now been made. ❐

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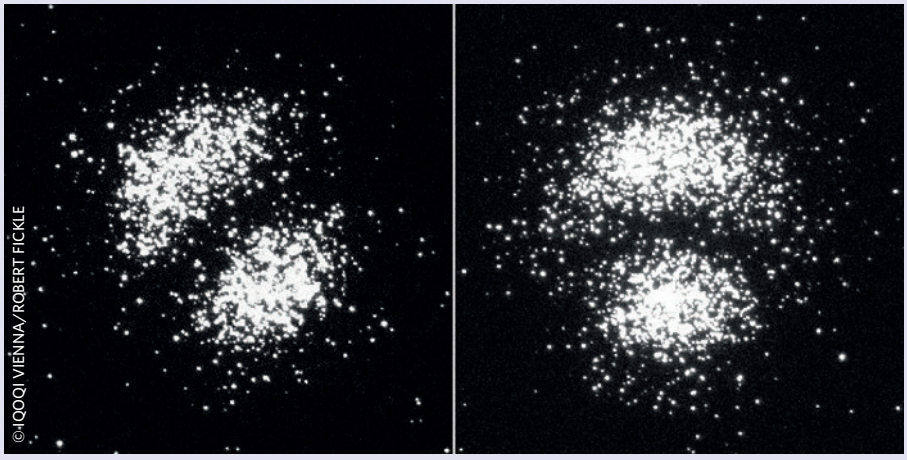
QUANTUM ENTANGLEMENT

Now you see it

We cannot 'see' magnetic fields and yet nobody seems to find magnetism particularly mysterious. That is because we can see its effects, we have all played with fridge magnets and iron filings. It is true that we trust what we can see more. So what about more elusive phenomena, such as quantum entanglement? Would it be less spooky if you could actually see it with your own eyes?

Well, now you can. In the entanglement equivalent of an 'iron filings' demonstration, Robert Fickler and colleagues have used state-of-the-art cameras to image — in real time — the effect of measurement on a pair of entangled photons (*Sci. Rep.* **3,** 1914; 2013. Movie available via http://go.nature.com/84ppZp).

The experiment starts with two polarization-entangled photons. The polarization of one photon is measured directly, whereas the second photon travels through an interferometric set-up that transfers its polarization to a selected spatial optical mode. These modes have clear visual signatures (the first-order Laguerre–Gauss mode is pictured), although their structures become more complex for higher modes. The speed and sensitivity of the ICCD cameras used allow the effect of polarization measurements on the first photon to become visible in the changing pattern of the second photon's spatial mode. In this way it is possible to monitor the probability distribution of the spatial modes while scanning the polarization states of the first photon.



Visualizing the effect of measurement on one photon of an entangled pair is fascinating, but for multiparticle entanglement things become more complicated. The complexity of entangled states scales exponentially with the number of particles, so testing entanglement in these conditions becomes prohibitively difficult. Nevertheless, significant effort has been devoted to characterizing and quantifying multiparticle entanglement, as well as building understanding through the use of mathematical tools.

In line with this, Michael Walter and colleagues have now found that different classes of entangled states can be associated with geometric objects known as polytopes, which contain all possible local eigenvalues of states in the corresponding entanglement class (*Science* **340,** 1205–1208; 2013). Local information alone can therefore be used to determine whether a pure multiparticle state belongs to that polytope. This approach provides a visual and more practical characterization of entanglement, and more importantly, a local witness of global entanglement.

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