Optical materials that exhibit a vanishing refractive index have recently moved from the realm of mathematical curiosity into the practical domain of functional photonic devices. As the refractive index is reduced to zero, both the phase velocity and the wavelength of propagating lightwaves stretch to infinity. Light can then propagate without any phase accumulation, leaping through the medium as if it were completely invisible. Such materials can be created by arranging subwavelength constituents into composite lattices, and offer applications such as directional light sources, innovative lenses and waveguides, insulators, optical cloaks and so on.

To assign an effective index value to a composite metamaterial, it should be possible to treat the material as a homogeneous medium. Although homogeneity is often associated with translational invariance, Jian-Wen Dong and colleagues demonstrate that artificial structures that lack translational periodicity yet exhibit long-range order — known as quasicrystals — can behave as zero-refractive-index materials. This demonstration opens new opportunities for the development of all-dielectric zero-refractive-index metamaterials by extending the concept to a wider class of photonic lattices other than periodic ones.

Not long ago, quasicrystals themselves were considered a curiosity and deemed impossible, as long-range order — which is a hallmark of crystallinity — was assumed to be inextricably linked to translational periodicity. This view has been shattered by the discovery by Shechtman et al. of an ‘impossible material’ with 10-fold rotational symmetry, which spurred a lot of debate, starting with ridicule and ending with the Nobel Prize in Chemistry. The discovery of quasicrystals was so controversial because local rotational symmetries other than 2-, 3-, 4- and 6-fold ones are incompatible with translational symmetry, as illustrated in Fig. 1a,b. Once accepted, however, it led to a new definition of a crystal as any solid having an essentially discrete diffraction pattern, such as those shown in Fig. 1d,e for a periodic and a 5-fold quasicrystal lattice, respectively.

Photonic analogues of crystals and quasicrystals — artificial arrangements of two or more materials with different refractive indices — now find applications across a wide range of light-based technologies. They are capable of moulding the flow of light in many ways, from forbidding the light propagation to enhancing and shaping light emission. Interestingly, owing to their higher rotational symmetries, photonic quasicrystals are more ‘homogeneous’ than their periodic counterparts for light propagating at different angles. As a result, they allow the formation of isotropic and complete bandgaps (for both light polarizations) by using low-refractive-index materials, which is not possible with periodic photonic crystals. Furthermore, quasicrystals are not limited by strict constraints on the positions of Bragg peaks in their diffraction patterns, making them well-suited for phase-matching for nonlinear optical effects such as frequency conversion. The rich spectrum of optical modes with various degrees of spatial localization also makes quasicrystals useful platforms for multimode lasing and multicolour optical sensing.

Periodic photonic crystals can act as homogeneous materials, with...
effective refractive indices ranging from positive — typical for conventional materials — to negative, which make materials capable of bending light the ‘wrong’ way. By tuning their parameters to yield a zero effective index, photonic crystals can even be made ‘invisible’ for lightwaves\(^5\) (Fig. 2a). Importantly, photonic crystals can act as ‘double-zero’ materials, with effectively zero permittivity (\(\varepsilon\)) and permeability (\(\mu\)) if they are tuned to exhibit Dirac cone dispersion at the Brillouin zone centre (\(k = 0\), where \(k\) is the wavevector) at a non-zero frequency\(^{11}\). Double-zero materials provide impedance matching in addition to the phase invariance achievable in ‘single-zero’ materials with either \(\varepsilon = 0\) or \(\mu = 0\).

Dong and co-workers\(^5\) now demonstrate that photonic quasicrystals may also behave as double-zero materials, and this unique property stems from the existence of Dirac points at \(k = 0\) in their dispersion (Fig. 2b,c).

The relation between the Dirac cone and zero refractive index may not be immediately obvious. However, it is easy to understand that if \(c = \mu = 0\) at a non-zero frequency, \(\omega_0\), the photon dispersion near this frequency is a linear function: \(\omega = \omega_0 + v_\gamma k\), where \(v_\gamma\) is the photon group velocity. Linear dispersion is of course a characteristic feature of the Dirac point, which yields many unique transport characteristics of graphene and its photonic analogues. However, the mere existence of the Dirac cone in the bandstructure is not sufficient for the photonic lattice to have zero effective index. Dong et al.\(^5\) explain that not only is a Dirac cone at \(k = 0\) required but also that it should be formed by a crossing of monopole and dipole branches in the dispersion diagram, and not higher-order multipoles. The latter condition guarantees applicability of the effective medium approximation, whereas the former ensures that the effective index is local (that is, it does not depend on the wavevector).

Dong and colleagues provide a recipe for the Dirac cone formation, which is based on tuning the quasicrystal parameters to achieve ‘accidental degeneracy’ of its modes. This is different from the familiar Dirac cones in graphene, which form at the Brillouin zone edge, whereas non-degenerate bands at the zone centre are required by symmetry to be parabolic. The accidental modal degeneracy, which only occurs for certain parameters of the photonic lattice, results in the formation of a Dirac cone accompanied by a flat band that crosses the cone at the Dirac point (Fig. 2b,c).

The same research group has previously used this recipe to design and experimentally demonstrate a double-zero material with a periodic photonic crystal lattice\(^{11}\), and they have now extended this concept to a much broader range of materials. The conical dispersions are protected by the lattice symmetry, and Dong et al.\(^5\) convincingly demonstrate that quasicrystals possess enough rotational symmetry to provide such protection. Furthermore, they show that quasicrystal approximants of different sizes feature Dirac cones, albeit at different optimal parameters of the lattice. This is an important finding as quasicrystals of increased size feature a higher level of structural complexity and long-range correlations, which sets them apart from their periodic counterparts.

To probe if quasicrystals can indeed act as double-zero effective media, Dong and colleagues\(^5\) designed lattices with 12-fold and 8-fold symmetries for operation at frequencies of around 10.5 GHz and fabricated them from alumina rods sandwiched between metal plates. They showed that quasicrystal modes at the Dirac point have almost constant field intensity and phase throughout the whole lattice. They also demonstrated zero refraction of plane waves propagating through a prism constructed from a quasicrystal material (Fig. 2d). Experimental observation of the cloaking of an obstacle (a metal rod) inside the quasicrystal (Fig. 2e) was also consistent with the zero-refractive-index behaviour of the material. Finally, another proof that the quasicrystals had zero effective indices was delivered by measuring asymmetric wave transport through an inversion-symmetry-breaking prism with a quasicrystal lattice.

Dong et al.\(^5\) explain that the conditions for achieving zero-refractive-index behaviour in quasicrystals are more stringent than for opening up photonic bandgaps or even than for realizing negative refractive index. A high level of symmetry is required to protect conical dispersion, and whereas 8-fold and 12-fold quasicrystals were shown to form Dirac cones, the same feature was not observed.

**Figure 2** | Quasicrystals with Dirac cone dispersion at \(k = 0\) act as zero-effective-index materials. \(a\), Lightwaves maintain spatially uniform phase distribution across zero-refractive-index materials, in striking contrast to both positive- and negative-index media, as illustrated for plane-wave refraction at an interface. \(b, c\), Quasicrystals with high rotational symmetry, like the 8-fold lattice shown in the inset, provide enough symmetry to protect Dirac cones (\(b\)). A Dirac point caused by accidental degeneracy is formed by intersecting bands with linear dispersion as well as an additional flat band (\(c\)). \(d\), A plane wave propagating through a prism constructed from a quasicrystal material undergoes zero refraction at interfaces. \(e\), ‘Invisible’ zero-refractive-index materials can make embedded objects invisible to light, as demonstrated by the cloaking of an obstacle inside the quasicrystal developed by Dong and colleagues\(^5\). The inset image in \(b\) and panel \(c\) are modified from ref. S, APS.
in the 5-fold Penrose lattices shown in Fig. 1c. Other limitations of this approach include failure of the effective index approximation for low-index structures as well as for vein rather than discrete-rod lattices. Despite these challenges, this research significantly expands the range of geometries for the design of double-zero materials. It is intriguing if aperiodic structures with long-range order other than quasicrystals\(^*\) can provide the symmetry protection required to achieve zero refractive index. Interesting future directions also include extension to the visible band and to the third dimension, which may unveil new opportunities.

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VIEW FROM… COMMUNICATION NETWORKS BEYOND THE CAPACITY CRUNCH

Is it crunch time?

As the demand for data transmission escalates and optical fibre capacity approaches its limit, the telecommunications research community is debating if the capacity crunch is nearing and is suggesting ways to be technology-ready.

Rachel Won

The demand for data transmission has grown exponentially during the past few decades. The situation is unfortunately exacerbated by the fundamental limit of optical fibre capacity, the so-called the Shannon limit, that is due to the intensity-dependent Kerr nonlinearity limit in optical fibre and that determines the maximum information that can be packed within a single fibre and within the available optical amplifier band for that fibre. It seems that a capacity crunch is potentially looming. Heated debates and discussion on this topic took place at Communication Networks Beyond the Capacity Crunch, a scientific discussion meeting at The Royal Society in London on 11 and 12 May, followed by a satellite meeting at The Royal Society at Chicheley Hall in Buckinghamshire, UK, on 13 and 14 May.

Andrew Lord from BT kicked off the meeting by giving a talk on the impact of capacity growth on national telecommunications networks. He revealed BT’s ten-year vision for providing 500 Mbps data rates for most homes and 1 Gbps for premium customers who are prepared to pay more, and that BT is technology-ready to meet the demands predicted based on current data usage. According to him, the access technologies seem sound and safe, suggesting that there is no capacity crunch, which spiced up the discussion session following his talk.

“From my perspective, I would not say that we are experiencing a crunch in the true sense of the word at this point in time. Rather, it is something that we need to be concerned about in the future given the traffic growth in core networks and the challenges associated with meeting it at a reasonable cost per bit,” said David Richardson from the University of Southampton, UK, who was an invited speaker at the discussion meeting.

There has been tremendous effort to increase the capacity of fibre optic communication systems by improving the speed and spectral density of single fibre systems. So far the technology has kept up very well with the demand. However, how long this will be sustained is a burning question.

“In the past 25 years, we scaled these fibre optics systems in the lab by over five orders of magnitude in capacity. The crunch is that this trend has reached its end and as a result we need to go parallel, much like the computer processors went from increasing clock rates with each new generation to increasing cores and other parallel approaches,” said Dan Kilper from the University of Arizona, USA, who was also an invited speaker at the meeting.

In the near future, fibre optics communication systems will increase capacity through parallel growth in multi-amplifier bands, multiple fibres and multi-carrier transmission. Because of technological advances that enable continued exponential scaling in these parallel systems, the end user will not notice much difference, Kilper pointed out. “However, it is more difficult to scale these systems and so we may not see the same pace of growth. This will eventually have some effect such as potentially higher costs,” he also warned.

The consensus is that there are three capacity crunches, namely, fibre capacity crunch, wireless capacity crunch and processor off-chip capacity crunch.

Telecommunications research in the past 30 years has been looking at innovative ways of coding and multiplexing optical signals to unlock the maximum practical spectral efficiency (~10 Tbit s\(^{-1}\) Hz\(^{-1}\)) provided by single-mode fibres (SMFs). In the talk given by Richardson, three components that define the fibre capacity were discussed: optical bandwidth that is defined by the gain bandwidth of the erbium-doped fibre amplifier, spectral efficiency that indicates how efficiently we use that bandwidth, and the number of independent spatial channels, of which there are currently just two — one spatial mode and two orthogonal polarizations.

Different configurations and types of optical fibres can be exploited to increase the fibre capacity. Bundling up SMFs, to create what is called a parallel SMF system, can be a solution, but the approach might share common amplifiers to simultaneously amplify multiple fibres within the bundle. On the other hand, multicore fibres — fibres with multiple, say N, cores in the fibre cross-section each operating more or less independently of each other — could increase the fibre capacity. Few-mode fibres — fibres that support a

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