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MATERIALS SCIENCE

Round the bend with microwaves

Simulations reveal that microwaves propagating through a waveguide can travel around sharp bends in the device without being reflected. The finding might open the way to technologies that exploit this uncommon phenomenon.

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Like any synthetic structure, photonic systems do not always perform according to expectations. Fabrication errors can give rise to defects that affect the propagation of electromagnetic waves — from radio to optical wavelengths — through the wave-carrying medium, causing undesired effects. For example, structural defects introduce noise in the medium's properties that can, in extreme cases, completely block photon transmission. Efforts are therefore under way to engineer systems whose topology (rather than shape) governs photon transport, making them immune to such effects. These efforts rely on results[1,2] showing that, as photonic systems undergo a certain type of continuous deformation, their properties remain intact and photon transport becomes topologically protected. Writing in *Physical Review Letters*, Ma *et al.*[3] demonstrate this theoretically for a waveguide design. Their system could enable the topologically protected transport of microwave photons, which would be able to travel around sharp corners without being reflected backwards.

In the early 1980s, physicists realized that certain physical properties of electronic systems are entirely dictated by the topology of the material concerned[4]. A hallmark discovery was that, in the presence of a strong magnetic field, the transverse electrical conductance of a material becomes quantized (the quantum Hall effect). In materials that exhibit this phenomenon, conduction is remarkably robust against defects and disorder.

The electronic states in the interior of such systems become localized so that the bulk of the material becomes an insulator. By contrast, the boundary of the material supports extended one-way circulating electronic states, known as chiral edge states, that mediate conduction. The system's topology determines whether edge states occur; materials that allow them are called topological insulators. A remarkable property of edge states is that they allow electrical current to route around disorders, with no backscattering of electrons.

It was initially thought that topological insulators could be generated only in the presence of a magnetic field, which specifically breaks the time-reversal symmetry of the system. However, in 2005, Charles Kane and Eugene Mele showed[5] that similar topologically robust properties can be achieved through spin–orbit coupling of electrons — that is, coupling of the electrons' orbital angular momentum with their spin angular momentum — while preserving the system's time-reversal symmetry. This opened up a wider range of systems that can have topologically protected states. Since then, topological insulators have attracted great interest, both for their intriguing fundamental properties and for their potential application in quantum computation.

Photonic systems can exhibit topological features analogous to those of electronic systems[6–8]. Ma *et al.* simulate a system that acts like a topological insulator for microwave radiation. The authors consider a device called a parallel-plate metawaveguide, which consists of an array of centimetre-scale metallic cylinders arranged in a hexagonal lattice, bounded on either side by metal plates (Fig. 1). For microwaves that have wavelengths of about 15 cm, this array constitutes a 'metamaterial' in which the refractive index varies on a scale comparable to the wavelengths of microwaves.

The metawaveguide supports two decoupled polarization modes of the microwaves' electromagnetic fields — the transverse electric (TE) and transverse magnetic (TM) modes. These can propagate only in a plane perpendicular to the cylinder axis. The hexagonal geometry of the cylinder lattice causes the emergence of Dirac cones in the metawaveguide's energy-band structure — cone-shaped bands that meet at their tips. At the tips of the Dirac cones, the TE and TM modes have the same energy, and the velocity with which the wave envelopes propagate is constant near this point.

Ma and colleagues show that introducing an asymmetry in the metawaveguide's geometry, in the form of a gap between the cylinder array and one of the enclosing plates, couples the TE and TM modes. This change in the array's configuration modifies the energy-band structure of the device, causing a bandgap to open up between the Dirac cones. The resulting bandgap has non-trivial topological properties analogous to those described by the electronic Kane–Mele model. In other words, the metawaveguide becomes a photonic analogue of a topological insulator. Here, symmetric and antisymmetric combinations of the TE and TM modes, which are time-reversed counterparts,

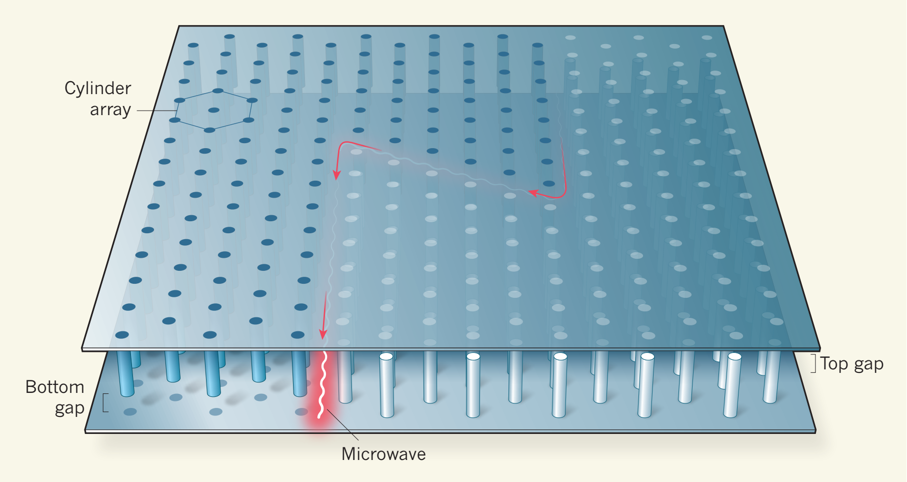

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Figure 1 | Reflection-free microwave propagation in a waveguide. Ma *et al.*[3] have simulated the propagation of microwaves in a metawaveguide. The proposed device contains a hexagonal array of metal cylinders displaying an asymmetry along the cylinder axis — a gap between one end of the cylinders and the enclosing metal plate. The two sections shown are joined together such that the position of the gap is inverted between them (on the left the gap is at the bottom, whereas on the right it is at the top). This configuration allows microwaves to travel along the bent interface between the two sections with negligible backward reflection at the two 120° turns.

constitute a pseudo-spin, and the asymmetry induces spin–orbit interaction.

In further simulations, Ma *et al.* show that if two such metawaveguides are coupled to each other in a configuration of opposing topological indices — for example, such that the position of the gap at the tips of the metal cylinders is inverted between the two devices — the interface between them displays intriguing properties. Specifically, the authors observe topologically protected edge states of opposing chirality (handedness), which propagate in opposite directions along the interface. They show how these states can be excited by placing a suitably polarized electric or magnetic dipole inside the gap of the metawaveguide that is adjacent to the interface. For example, a left-polarized dipole excites microwaves that always propagate in the backward direction, whereas a right-polarized dipole excites forward-only waves. These waves are immune to backscattering and can take sharp turns along the interface. The authors' simulations demonstrate this for an interface bent by 120°.

However, these edge states are not robust against all types of disorder. For example, a disorder that flips the pseudo-spin of a state can couple a forward-propagating state to a backward-propagating one, destroying the edge states' protection against backscattering. This is analogous to the effect of magnetic impurities in materials exhibiting the 'quantum spin Hall effect' against which edge states are not protected. In the wavelength domain applicable to telecommunications (about 1,550 nm), the effects of such pseudo-spin flips are negligible[9], but it is not known whether the effect is also small in the microwave domain. Future work may clarify this.

An experimental realization of the effects modelled in Ma and colleagues' work would open up new ways to engineer electromagnetic structures that would benefit from topological protection[10,11]. For example, one could explore designs for microwave devices such as waveguides, filters, antennas and amplifiers that would make the devices insensitive to design defects and that could have applications in telecommunications technology. ■

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