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# Photonic waveguides shed their cladding

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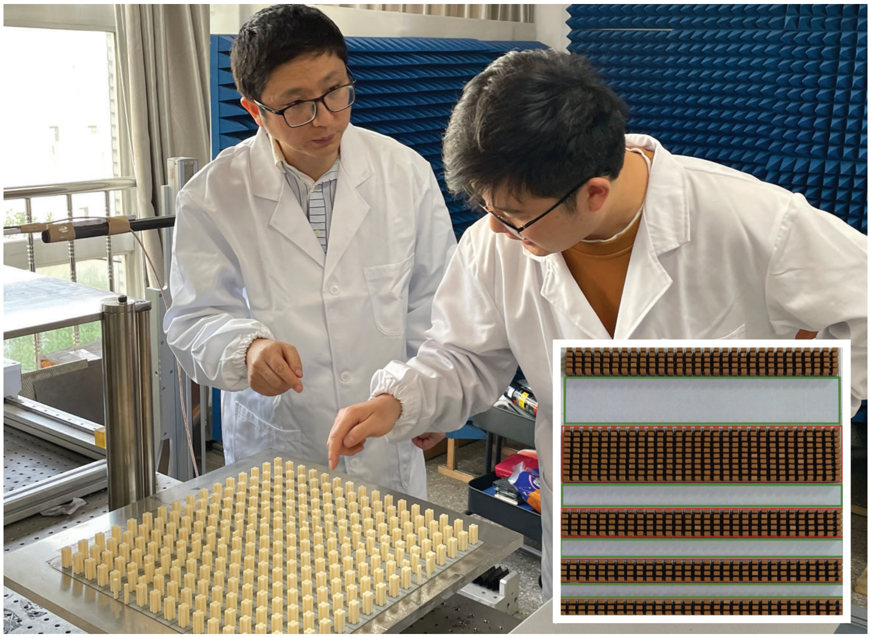

**FIGURE 1. A PHOTONIC CRYSTAL** made of dielectric posts surrounded by air transmits different wave modes than either material alone. Yun Lai (left) and his postdoc Hongchen Chu (right) are shown here with one such metamaterial. Alternating regions of air and photonic crystal forms a waveguide array with no separation between adjacent channels (inset). The photonic crystal, which has 3.6 × 2.4 mm posts, and the air host disjoint sets of wave modes, so light doesn't cross the boundary between them. (Photo courtesy of Cong Wang; inset adapted from ref. 1.)

Fiber-optic cables form the backbone of worldwide communication systems. By carrying light rather than electrical pulses, the cables transmit information faster and more efficiently than copper wires. The devices those cables connect still use electrical wires, though, so optical signals have to be converted at either end of their journey. Replacing device electronics with photonic analogues would both improve information-transfer capabilities and avoid resistive heating.

In a traditional fiber-optic cable, a core—usually a glass fiber about 10–100 $\mu$m wide—is surrounded by cladding that has a lower refractive index than the core and confines light using total internal reflection. That's fine for long-distance travel, where space isn't at a premium. But if photonic circuits are to replace electronic ones, cables will have to be shrunk down and packed onto chips to make integrated photonic circuits. The cladding is wasted space, and it places a fundamental limit on how tightly packed the cores can be: Light leaks through if the separating layer is thinner than $\lambda/2$, where $\lambda$ is the wavelength of the light.

A team of researchers led by Yun Lai, Ruwen Peng, and Mu Wang at Nanjing University in China has now devised a waveguide array whose light-carrying channels don't require a separation layer.[1] Experiments and simulations demonstrate that the zero-separation waveguide array (ZSWA) confines light to individual channels and efficiently directs it around sharp corners—a critical capability for use in integrated photonic circuits.

## Setting boundaries

Fiber optics based on total internal reflection are just one of the existing methods for guiding light along a desired path. But the various options all involve surrounding a light-carrying channel with a material that excludes transport: a photonic-bandgap crystal, a topological insulator, or even a metal. Researchers have worked toward shrinking the excluding layer to make increasingly compact photonic circuits, but some sort of barrier between conduits has remained necessary.

In the ZSWA design, adjacent waveguides are made from different materials (see figure 1 inset). Light can travel in either material, and the interface between the two materials blocks light transmission, keeping it on its intended path. Since every layer serves as a waveguide, no space is wasted on barriers.

To create a reflecting interface, the researchers sought materials with disjoint spatial dispersions. That means if light of a particular frequency has wavevector $\mathbf{k}$ in one material, the possible values for $k_x$—the wavevector's component parallel to the interface—in that material must not overlap with the allowable values $k'_x$ in the other material.

The idea of disjoint spatial dispersions can be understood by considering the equal-frequency contours (EFCs) in figure 2a. Each one shows the allowable wavevectors for light at a given frequency in a particular material. Homogeneous materials, such as the core and cladding used in fiber-optic cables, have isotropic EFCs. The contour radii depend on the materials' refractive indexes. Any light in the core whose wavevector lies to the right of the dashed vertical line is confined to the core because there are no modes in the cladding with the same value of $k_x$; that light undergoes total internal reflection.

Fiber-optic cables produce confinement only in the core—light can't be confined to the cladding. For two materials to exclude light from each other, their EFCs would have to be entirely disjoint, as in figure 2b. With no overlap between the allowable values of $k_x$ for the given frequency, light can't pass between the materials through an interface along the $x$ direction. And because the restriction holds for every $\mathbf{k}$, it's angle independent, unlike total internal reflection, which has a minimum incident angle.

But what materials behave in such a way? Lai came to the project with experience designing materials with unusual EFCs. In 2016, he and his coworkers at

10 December 2024 01:57:36

Soochow University in Suzhou, China, and Hong Kong University of Science and Technology constructed a photonic metamaterial with an EFC shifted such that the material's boundary with air produced no reflection regardless of the incoming wave's direction.[2] When Lai moved to Nanjing University in 2018 and established his own microwave lab, he started brainstorming what other phenomena could be induced by shifted EFCs.

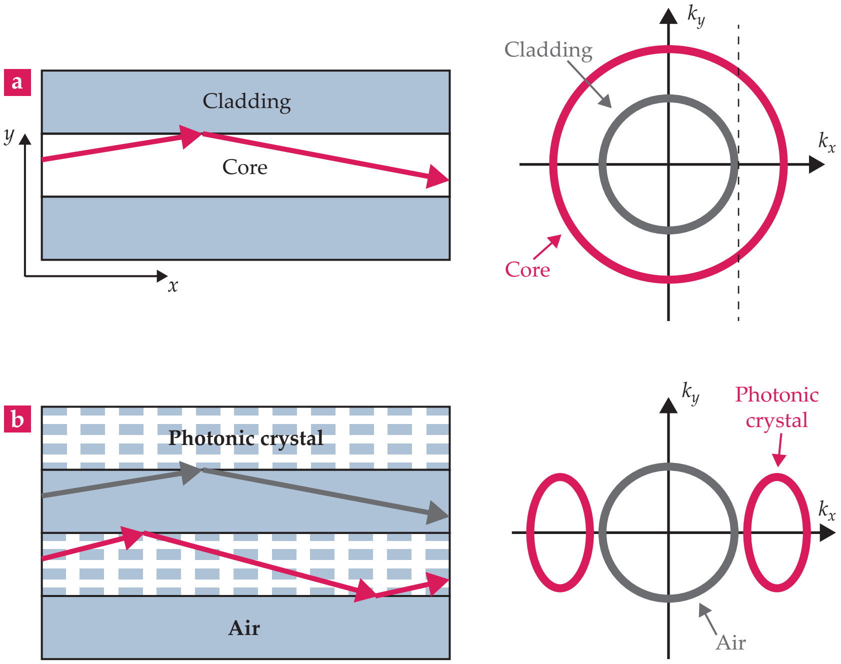

**FIGURE 2. MATERIAL BOUNDARIES** can direct transmitted light. **(a)** The core of a fiber-optic cable confines light by total internal reflection off the boundary with the cladding. The equal-frequency contours on the right, which show the modes ($k_x$, $k_y$) available in each material at a single frequency, illustrate the same restriction: Core modes to the right of the dashed line are confined because their component in the direction of travel, $k_x$, is beyond the maximum allowed in the cladding. **(b)** If the equal-frequency contours for two materials have no common values for $k_x$, which is possible when one of them is an asymmetric photonic crystal, light can't pass between them. (Adapted from ref. 1.)

After his move, Lai started collaborating with new coworkers Peng and Wang, both of whom had experience working with waveguides and plasmonics. Eventually they arrived at the idea of creating cladding-free waveguide systems. "Our collaboration shows that discussions with experts from different backgrounds are very beneficial and could easily generate new inspiration," says Lai. "It was less likely that I would have come up with this counterintuitive idea alone."

## Guiding light

For their two waveguide materials, the researchers used air and a photonic crystal made from a grid of rectangular dielectric rods. Parallel to the waveguide direction, the rods were 3.6 mm long and 2.4 mm apart; perpendicular to it, they were 2.4 mm long and 1.2 mm apart.

The asymmetry was necessary to create the EFC shown in figure 2b. If the photonic crystal was symmetric, its EFC would have two additional ovals, one above and one below the air's circular EFC. The materials would then have available modes with the same values of $k_x$, and light would be able to pass through their boundary. The asymmetric crystal and the air have no shared values of $k_x$, so light can't pass through waveguide interfaces. The materials do have modes with the same value of $k_y$, though, which is necessary for light to enter and exit the waveguides at their ends.

Since Lai's lab is set up for microwave experiments, and because millimeter-scale photonic structures are generally easier to build than nanometer-scale ones, the researchers developed their proof-of-principle device to work at frequencies around 15 GHz. But to underscore that the same principle will apply for frequencies of practical interest, they selected rods with a dielectric constant $\varepsilon$ of 12 to match that of silicon at the 100–300 THz frequencies used for telecommunications.

Hongchen Chu, Lai's postdoc, experimentally tested the ZSWA shown in the figure 1 inset, which had channel widths ranging from 10 mm to 30 mm. He sent waves into each channel and tracked their propagation with a two-dimensional microwave scanner. In each case, the light stayed in its intended waveguide—air or photonic crystal—and exited through that waveguide's output port at the other end.

To be of practical use in photonic circuits, the ZSWA channels must be able to not only confine light to a straight path but also direct it along a defined route. PhD student Tongtong Song realized he could steer the microwaves using arrangements of supercells—three-by-five blocks of the dielectric rods. Each metamaterial supercell had two edges through which waves could enter and exit, akin to the ends of the waveguides in the array, and two edges that blocked light, as at the waveguide boundaries.

Light moving through suitably arranged blocks and areas of empty space was steered around 90° and 180° turns. Initially some of the light leaked out as it turned the corners, but the researchers suppressed the loss by adding dielectric rods at the weak points. The same technique reduced backscatter as the waves traversed 180° turns. Scanner measurements showed overall transmission rates of about 95% through the turning paths, compared with nearly 100% for straight paths.

Challenges to shrinking down ZSWAs remain. When the channels in the device get narrow, for example, modes in next-nearest-neighbor channels begin to couple. Because practical optical chips have additional complications compared with the 2D microwave ones, Lai hopes to bring in collaborators who are more familiar with optical-chip fabrication.

"There's still a lot of work to do," says Lai. "But I don't see any insurmountable obstacles in applying this concept to optical chips and other communication systems, which we plan to achieve in the near future."

**Christine Middleton**

## References

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2. J. Luo et al., *Phys. Rev. Lett.* **117**, 223901 (2016).

10 December 2024 01:57:36