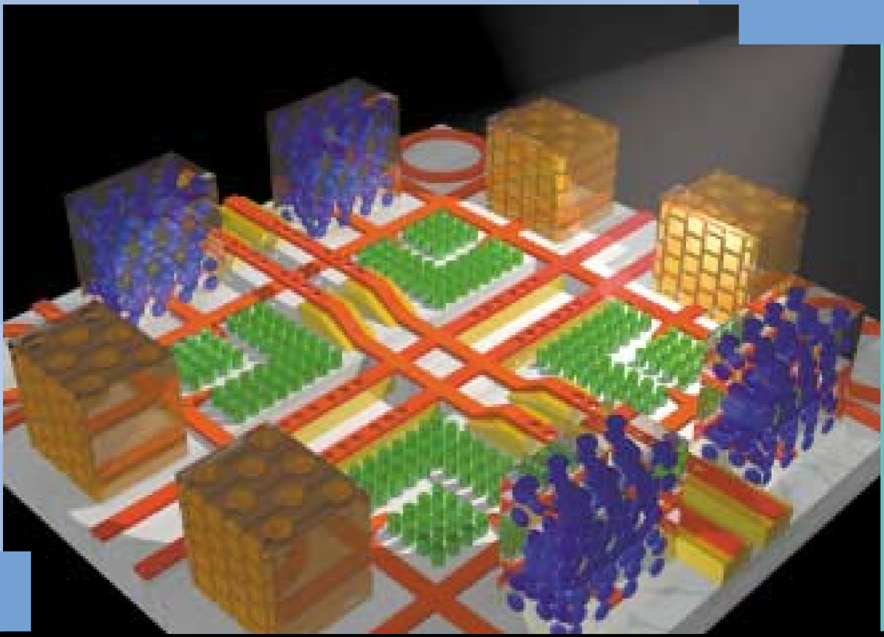
Institute of Physics

Novel microstructures that steer light in the same way as semiconductor devices manipulate electrons may soon transform telecommunications

Photonics



Photonic Micropolis – a vision of the all-photonic chip

John Joannopoulos/MIT

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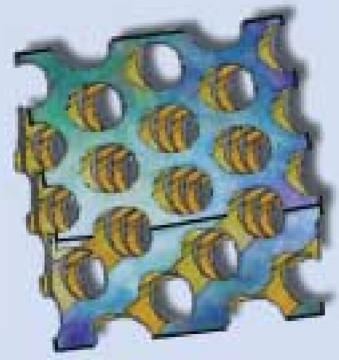
Photonic crystal materials

Futuristic fictional scenarios often depict information stored not on disks and tapes but in some kind of transparent ‘crystal.’ The inference is that photons of light rather than electrons are the signal carriers. Indeed creating ultrafast all-optical computers and communications have been a physicist’s dream for many years. Light has several advantages over electrons as an information carrier: it’s very much faster and has the potential to convey vast amounts of data with lower power losses.


‘Yablonovite’, Eli Yablonovitch’s first photonic band-gap structure

Eli Yablonovitch/UCLA

Telecommunications already employ pulses of light in optical fibres but manipulating light beams is difficult, and routing optical communications is still done using slow, bulky electronic devices.

That may all soon change. Physicists have been working on new optical materials that behave in an exactly analogous way to semiconductors in electronic devices. Both electrons and photons can behave like waves. In crystalline semiconductors like silicon, electron waves of certain energies, or frequencies, scatter off the regular array of atoms and interfere with one another such that they cancel out. This results in a characteristic range of energies forbidden to the electrons called the ‘band-gap’. Electronic band-gaps can be changed by adding ‘defects’ to the crystal such as different atoms. In this way it is possible to manipulate how and where the electrons move. Band-gap engineering is the basis of today’s semiconductor devices.

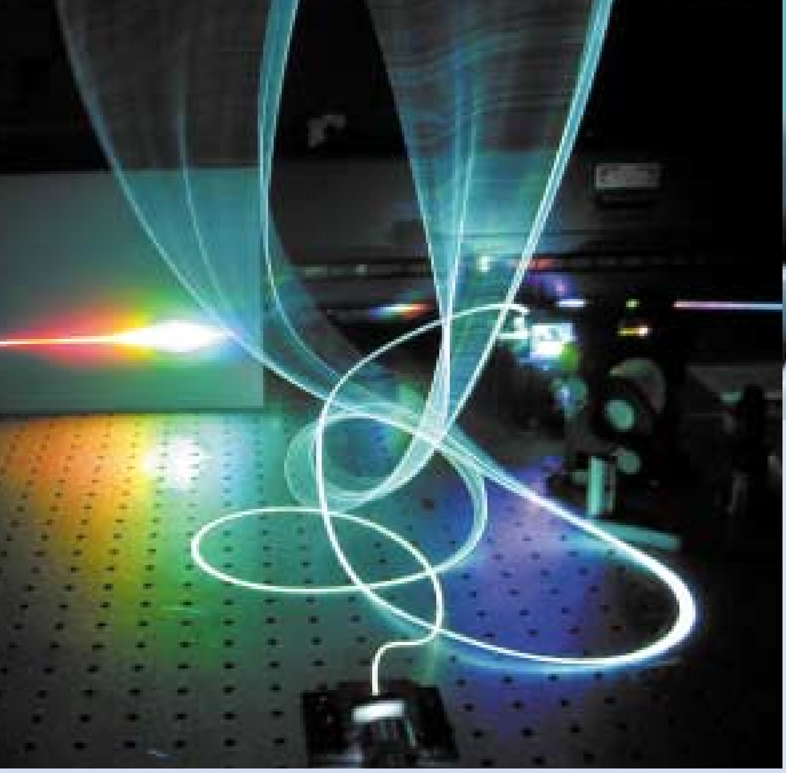
Photonic band-gaps

Now researchers in North America, Europe and Japan are developing structures that generate photonic band-gaps. A range of wavelengths of light is similarly blocked by interference as they reflect off repeating geometrical structures (such as air holes) in a transparent material. Unlike semiconductors these ‘photonic crystals’ are made artificially because the repeat pattern must match the wavelength of, say, infrared light used in telecommunications – about half a micrometre or one-hundredth the thickness of a human hair. Again, light can be manipulated by introducing defects (by filling up one of the air holes, for instance) into the regularity of the photonic structure. The concept of photonic crystals is poised to revolutionise optoelectronics, allowing the creation of miniaturised waveguides to steer light, or tiny lasers and other devices that emit light without loss. They offer the first practical prospect of the optical computer.

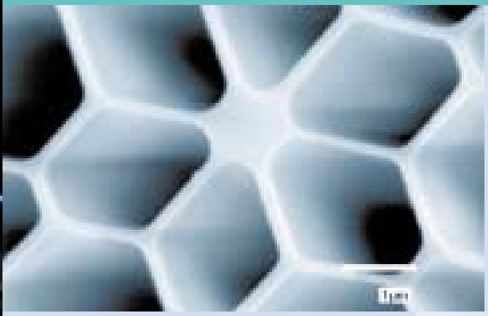
Early work on photonic crystals was done by Remigius Zengerle and Philip Russell in Hamburg in the late 1970s and early 1980s but they didn’t think of creating a photonic band-gap. It was Eli Yablonovitch who made the first photonic band-gap structure in 1991 when at Bell Communications in New Jersey (see left). His team mechanically drilled a complex diamond-like 3D array of millimetre-sized air holes into a transparent material; it blocked frequencies in the microwave region. Since then, researchers have been incredibly inventive in devising all kinds of techniques to generate band-gaps at shorter wavelengths in a wide range of materials from silicon to plastics. These include building up structures with similar but smaller-scale geometries layer by layer – by stacking rods, or wafers cut into strips, criss-crossed like a pile of logs (see back cover).

These approaches often rely on various forms of patterning whereby the required shapes are sputtered on or chemically etched using masks. One innovative method developed by Andrew Turberfield and Bob Denning at the University of Oxford uses four laser beams to create a 3D interference pattern, with the right geometry for a photonic crystal, on a light-reactive polymer. After the laser-induced chemical reaction, the unreacted parts are washed away.

Thanks go to Philip Russell of Bath University, Richard De La Rue of Glasgow University



Philip Russell/ University of Bath



Philip Russell's remarkable 'holey' photonic fibre (cross-section shown) can be used to create a powerful white-light laser source

A cheaper method explored by other UK research groups involves self-assembling minute spheres of silica or a polymer from a suspension into a 3D periodic shape, which acts as a template. If the particles are first suspended in a solution of titanium dioxide, for example, the oxide can then be chemically reacted to form a solid 3D network, and the particles removed by dissolving or burning them off. Though the idea is clever, it is difficult in practice.

Luckily, photonic band-gaps can be achieved in just two dimensions, and many research groups have been using standard fabrication techniques to build thin films of gallium arsenide and other semiconductors into useful optical structures. For example, Axel Scherer and colleagues at the University of Southern California have trapped and amplified light in a slab of indium gallium arsenic phosphide to create the world's smallest laser in less than 0.03 of a cubic micrometre, while John Joannopoulos' team at MIT has made silicon waveguides that bend light beams at right angles with 100 per cent transmission. Groups led by Richard De La Rue at the University of Glasgow and Thomas Krauss of the University of St Andrews have also been working on photonic crystal waveguides using gallium arsenide and similar materials, and have demonstrated a 2D photonic band-gap.

Holey fibres

One of the most exciting developments has perhaps been the simplest. Philip Russell, now at the University of Bath, has ingeniously stacked together glass tubes in a hexagonal bundle and then stretched it under heat into a hole-filled 'photonic crystal fibre', a hair's breadth across (see diagram). The geometry of the air channels is such that the fundamental mode of light is confined to travelling just through a central solid core of the fibre. The result is that far more light can be squeezed down the fibre – leading to some amazing possibilities. Much more data can be carried over longer distances. Intense light also introduces so-called nonlinear properties (in which the refractive index of the glass changes strongly). Optical nonlinearity can be harnessed to create intense bursts of light with a spectrum of sunlight. This novel light source is already finding use in measuring frequency, medical imaging and spectroscopy.

Russell's team has now gone on to make the 'ultimate communications fibre'. This has a hollow core and could transmit 1000 times more power, say, across the Atlantic without the need for signal-boosting repeaters – a development that could transform the telecommunications market. With this mind, Russell and his colleagues have set up a company, Blazephotonics. It will be one of the first to exploit the burgeoning technology of photonic crystal materials.

NATURE DID IT FIRST

Biology produces complex microstructures and it is not surprising that some have photonic properties. For example, the brilliant blues of tropical butterflies (see front cover), as studied by Roy Sambles of the University of Exeter, are the result of diffracted light from a periodic array of holes in the wing scales. Andrew Parker from the University of Oxford explores the patterned photonic structures in a number of strange animals such as a worm called a sea mouse which has iridescent hairs, and the scales of the ancient coelacanth, with a view to understanding their evolution.

The unusual iridescence of opals is due to a 'soft' photonic band-gap (light can still propagate in some directions) caused by the close-packing of silica spheres a fraction of a micrometre across. Theoretician John Pendry at Imperial College has coined the term 'super opal' for a material that excludes all radiation in a given frequency range.

AND JOHN PENDRY OF IMPERIAL COLLEGE FOR THEIR HELP WITH THIS PAPER

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Department of Higher Education and Research
The Institute of Physics
76 Portland Place, London W1B 1NT, UK
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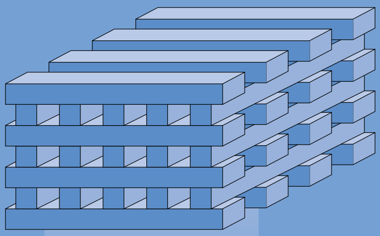

A microscopic 3D 'log-pile' structure that can generate a photonic band-gap

Editor: Nina Hall, Design: Pete Hodkinson.