

One-Way Road in a Photonic Crystal

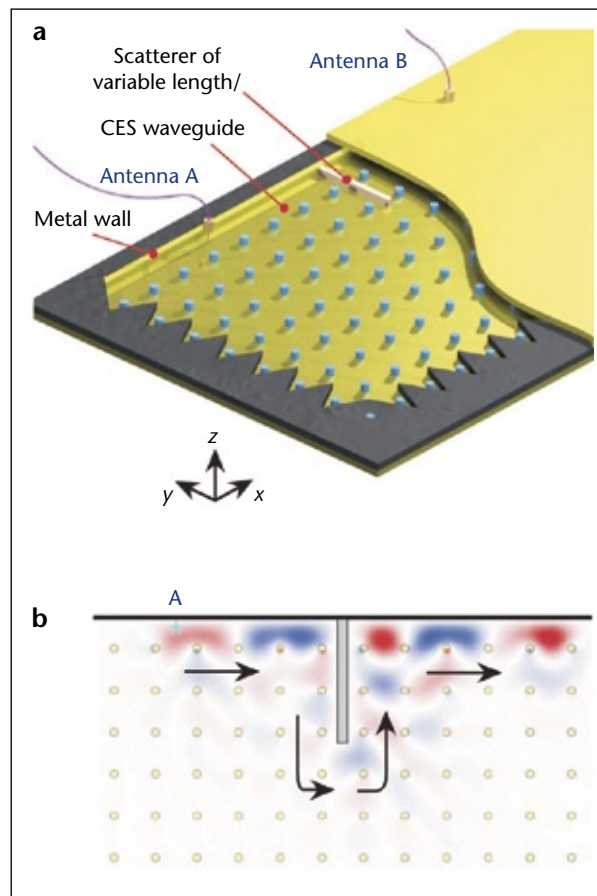
Chiral edge states channel light waves in one direction, like electrons in the quantum Hall effect

Light waves in a photonic crystal behave like electronic waves in an atomic crystal. The periodic crystal structure forces the waves into frequency bands. A wave cannot propagate through the crystal if its frequency falls in the gap between two bands. Normally, crystals don't have a preferential direction: Waves propagate equally well in opposite ways. But in the quantum Hall effect particular edge states occur, that allow electrons to travel only in one direction. Edge states have now also been seen in photonic crystals with magnetic microstructure.

In the quantum Hall effect a magnetic field acts on a two-dimensional electron gas and breaks the time-reversal invariance of the electronic motions. This gives rise to electronic edge states at the one-dimensional boundary of the electron gas. The edge states have a sense of rotation, they are chiral: The electrons can travel along the edge only in one direction, which prevents them from being backscattered by impurities or obstacles. Chiral edge states are a consequence of the non-trivial topology of the energy bands, which stabilizes these states against perturbations. Duncan Haldane and S. Raghu from Princeton had predicted that chiral edge states can also occur for light waves in photonic crystals.

Now, Marin Soljačić from MIT and his colleagues have verified Haldane's prediction experimentally. They have built a two-dimensional photonic crystal for microwaves consisting of a square lattice of ferrite rods in air. This microwave cavity had a bottom, a top and a side wall made from copper plates, while the other side walls consisted of microwave-absorbing foams. From a dipole antenna near the copper wall microwaves were radiated into the cavity. Eight lattice constants away there was a second antenna near the copper wall to measure the transmitted microwave intensity.

The magnetic ferrite rods of the photonic crystal induced a magneto-optical effect, which broke the time-reversal symmetry of the microwave dynamics. Numerical calculations of the crystal's band structure showed that there was a chiral edge state in a band gap around 4.5 GHz. This state allowed the microwaves to travel along the copper wall only in one direction, which was essentially confirmed by the experiments. The transmission in the back direction was damped by 50 dB compared to the transmission in forward direction.



(a) A model of the photonic crystal. The distance between the ferrite rods is 4 cm.

(b) Numerical calculations and experiments show that the microwaves travel around an obstacle without being scattered.

(Courtesy of Zheng Wang *et al.*, Nature)

This photonic one-way street prevented the propagating microwaves from being backscattered by obstacles. Soljačić and his colleagues showed this by inserting a metal plate into the photonic crystal. The plate blocked the direct path along the wall from one antenna to the other. In a normal waveguide such an obstacle would lead to strong backscattering and substantially reduced transmission intensity. But the chiral edge state in the photonic crystal allowed the microwaves to travel around the obstacle and reach the receiver only slightly attenuated.

The experiment opens very interesting possibilities. Photonic crystals can now be used as a model to study the physical properties of systems with interesting nontrivial topological features e.g. of the band structure. With photonic one-way roads for infrared or visible light one could improve the transmission properties of photonic fibers substantially: it would provide a way for immunity against e.g. back scattering.

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Further information:

- Zheng Wang *et al.*: Observation of unidirectional backscattering-immune topological electromagnetic states. *Nature* 461, 772 (2009) <http://dx.doi.org/10.1038/nature08293>
- Group of Marin Soljačić at MIT: <http://www.mit.edu/~soljadic/>
- F. D. M. Haldane, S. Raghu: Possible Realization of Directional Optical Waveguides in Photonic Crystals with Broken Time-Reversal Symmetry. *Phys. Rev. Lett.* 100, 013904 (2008) <http://dx.doi.org/10.1103/PhysRevLett.100.013904>
- Eli Yablonovitch: One-way road for light. *Nature* 461, 744 (2009) <http://dx.doi.org/10.1038/461744a>

Mantis Shrimp Boasts High-Tech Eye

A unique quarter-wave retarder enables the marine crustacean to see the circular polarization of light

Nature's inventions are often superior to high-tech devices. This is particularly true for optical materials and components, which are structured on the nanometer scale – something, that nature still can do much better than us. An amazing example is the eye of the mantis shrimp *Odontodactylus scyllarus*. It is equipped with a quarter-wave retarder to transform circularly into linearly polarized light. In contrast to its man-made analogs this natural device works perfectly for the whole visible spectrum.

It is well known that mantis shrimps can sense the polarization direction of linearly polarized light. Their eyes contain countless bundles of light-sensitive cells, seven per bundle. Each cell has a tiny slit in front of it, which light can only pass if it has the right polarization direction. Last year it was discovered that these shrimps can also distinguish between right and left handed circularly polarized light. In order to achieve this they have to convert circularly into linearly polarized light. Nicholas Roberts from the University of Bristol and his colleagues figured out how the shrimps manage to do this.

Circularly polarized light can be converted into linearly polarized one by a quarter-wave retarder. This optical device separates the circularly polarized light into two linearly polarized components, whose phases differ by 90 degrees. The retarder delays the components differently until their phases match. The two components then add up to linearly polarized light. As the phase shift of light in a material depends on the wavelength, quarter-wave retarders usually work only in a narrow wavelength interval. The eye of the mantis shrimp however can convert circularly into linearly polarized light over the whole visible spectrum. Thus, it contains a virtually achromatic quarter-wave retarder.

Roberts and his colleagues report that in front of each cell bundle there sits an eighth cell, being 150 μm long. This cell transmits the incoming light to the other seven cells.



The mantis shrimp, *Odontodactylus scyllarus*.

(Courtesy of Roy Caldwell, University of California, Berkeley)

The long length of the light path and the low effective birefringence as a function of wavelength make the eighth cell a nearly achromatic quarter-wave retarder. For wavelengths between 400 nm und 700 nm the conversion from circularly to linearly polarized light was nearly perfect. The phase shift of this crustacean quarter-wave retarder differed at most by 2.7 degrees from its optimal value of 90 degrees. High-tech retarders made from artificial nanostructures show deviations of up to 9.1 degrees.

An optimized computer model of the shrimp's eye cells has reproduced their unusual optical properties. The researchers propose to build an artificial quarter-wave retarder that mimics the shrimp's retarder by using liquid crystals. This broad-band optical component inspired by nature could be used to improve existing optical technologies like blue ray.

Further information:

- N. W. Roberts *et al.*: A biological quarter-wave retarder with excellent achromaticity in the visible wavelength region. *Nature Photonics* (online October 25th 2009)
<http://dx.doi.org/10.1038/nphoton.2009.189>
- Ed Yong: Mantis shrimp eyes outclass DVD players, inspire new technology. (October, 25th 2009)
http://scienceblogs.com/notrocketscience/2009/10/mantis_shrimp_eyes_outclass_dvd_players_inspire_new_technolo.php
- Press release of the University of Bristol:
<http://www.bristol.ac.uk/biology/news/2009/30.html>

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Seeing Previously Invisible Molecules for the First Time

New microscopic technique reveals previously unseen molecules in color

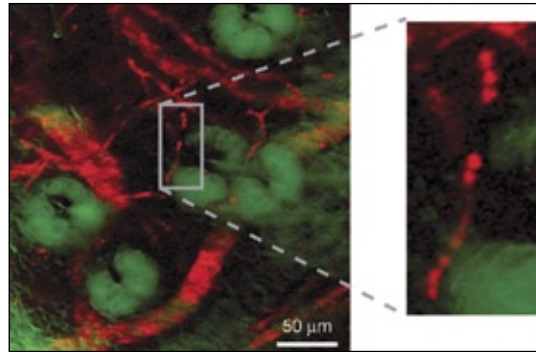
A team of Harvard chemists led by Xiouliang Sunney Xie from the Department of Chemistry and Chemical Biology has developed a new microscopic technique. It is based on stimulated emission for seeing, in color, molecules with undetectable fluorescence. The room-temperature technique allows researchers to identify previously unseen molecules in living organisms and offers broad applications in biomedical imaging and research.

Many biologically important colored molecules such as hemoglobin absorb light but do not fluoresce. Instead, the electrons in these molecules release their additional but transient energy by converting it to heat. „Since these molecules do not fluoresce, they have literally been overlooked by modern optical microscopes,“ Xie said.

The researchers' new microscopic technique generates and records a stimulated emission signal by using two carefully timed excitation ($\lambda = 590$ nm) and stimulation ($\lambda = 660$ nm) pulse trains. Each train has incredibly short pulse duration of approximately 200 femtoseconds and a repetition rate of 76 MHz. A modulator switches the intensity of the excitation pulses on and off at five MHz. The modulation creates a stimulated emission signal at the same frequency. The signal produced by the non-fluorescent molecules provides a highly sensitive image of previously „invisible“ molecules.

One application of the scientists' invention is mapping in color the delivery of non-fluorescent drugs to their target cells. Another possible use is imaging tiny structures such as blood vessels including individual red blood cells and single capillaries (see image). The structure and hemoglobin-dynamics of blood vessels play a major role in many biomedical processes. Two example processes are the transition of tumors from a dormant to malignant state and oxygen delivery in the brain. Current established imaging technologies like MRIs and CT scans either lack the spatial resolution needed to resolve individual capillaries or require external contrast agents.

Fluorescent labels such as the green fluorescent protein, or GFP, are extensively used for observing the activity of biomolecules and distinguishing target molecules in a cell. The GFP labeling technique provides well-defined images. However, the bulky



Stimulated emission image of the microvascular network in a mouse's ear. The sample shows in red the blood vessel network surrounding green-colored sebaceous glands. In the zoomed-in image, individual red blood cells are lined up within a single capillary approximately five micrometers in diameter.

(Courtesy of Wei Min and Sijia Lu, Department of Chemistry and Chemical Biology, Harvard University)

protein can disturb delicate biological pathways, especially when it is larger than the biomolecules it is illuminating. Xie's team mapped the delivery of a non-fluorescent drug molecule and imaged blood vessels without fluorescent labels. Their new technique is also capable of imaging non-fluorescent proteins in cells of live *Escherichia coli* bacteria.

„While earlier studies made use of similar pump-probe experiments to provide images of fluorescent molecules with spatial resolution comparable to that of confocal fluorescence microscopy and high temporal resolution, this study, for the first time, makes use of stimulated emission microscopy to image non-fluorescent molecules,“ said Zeev Rosenzweig, a program director in the National Science Foundation Division of Chemistry, one of the funding agencies of the project.

Although potential photo-damage, and the complexity and cost of the system still need to be addressed for the technique to gain wide applicability, „there is no doubt that the study provides a unique way to image a wide range of molecules currently inaccessible to today's state-of-the-art optical microscopes,“ notes Rosenzweig.

Stefan W. Hell and Eva Rittweger from the Max Planck Institute for Biophysical Chemistry, Göttingen, Germany commented in *Nature*, that it would be an intriguing possibility for the future to design a set of laser pulses that fulfill both roles of stimulated emission – switching off molecular signals (like in STED microscopy) and stimulating photon emission – to provide images of unlabelled, non-fluorescent molecules at sub-diffraction (nanoscale) resolution for the first time. Hell and Rittweger also sta-

ted, that for many reasons, Min and colleagues' method is a bold step towards unveiling details of live cells and tissues that would otherwise be left uncharted.

NSF/KP

Further information:

- W. Min *et al.*: Imaging chromophores with undetectable fluorescence by stimulated emission microscopy. *Nature* 461, 1105-1108 (2009) <http://dx.doi.org/10.1038/nature08438>
- Comment by Stefan W. Hell und Eva Rittweger: Light from the dark. *Nature* 461, 1069 (2009) <http://www.nature.com/nature/journal/v461/n7267/full/4611069a.html>
- Research group Xiaoliang Sunney Xie: <http://bernstein.harvard.edu/XieHome.html>
- NSF Home Page: <http://www.nsf.gov>