Circularly Polarized Color Reflection in the Beetle *Plusiotis boucardi*

Sharon A. Jewell, P. Vukusic and N. Roberts

We discovered a naturally occurring microstructure for controlling the polarization and wavelength of reflected light that may pave the way for new tuneable, self-assembled micro-mirrors. We found the microstructure when conducting extensive optical studies on the outer shell of a *Plusiotis boucardi* beetle. We uncovered a previously unreported honeycomb structure that extended across the entire body of the beetle.

It is well understood that highly metallic-looking members of the *Plusiotis* genus are able to control circularly polarized light with a much simpler structure.[2,3] However, until now, this plainer, lime green and faintly iridescent member of the genus had been neglected.

An examination of the shell of a *P. boucardi* specimen under an optical microscope revealed a brightly colored hexagonal array across the entire beetle. Each green hexagonal "cell" was around 8 µm in diameter, with an intensely bright orange spot 4 µm in diameter at the center, surrounded by a 5 µm red ring. Further investigation using transmission electron microscopy (TEM) revealed that this effect was due to "bowl-shaped" recesses underneath the waxy outer layer of the shell.

The beetle shell itself is composed of fibrous chitin embedded in a protein matrix. The TEM images showed that the fibers formed a helicoidal microstructure that was analogous to the structure in a cholesteric liquid crystal. The molecules in each plane of a cholesteric liquid crystal are aligned in roughly the same direction, with the molecular direction in each successive plane rotated slightly with respect to the previous plane.

The thickness over which the molecules rotate through 360° is defined as the pitch of the material. This determines the wavelength of the light reflected from the sample. The TEM images taken from the shell showed that two distinct pitches were formed by the chitin fibers; the upper layers of the shell had a pitch of 319 nm, corresponding to the reflection of green light and the lower layers were of a longer pitch of 370 nm, which strongly reflected the red.

Measurements of the reflected intensity versus wavelength for light incident on the sample at normal incidence showed that peaks occurred at the green and red wavelengths, along with a third distinct peak corresponding to the orange color seen in the images. Using theoretical data produced using a multi-layer optics model for modeling the optics of chiral, birefringent media, we found that this third color was produced by an interference effect between the reflection of light from the two pitches in the microstructure. Synthetic replication of this naturally occurring structure through the use of liquid crystalline materials may lead to the fabrication of these self-assembled microstructures for optical applications. ◮

[Sharon A. Jewell (s.a.jewell@exeter.ac.uk), and P. Vukusic are with the University of Exeter and N. Roberts is with the University of Manchester, United Kingdom.]

References

1. S.A. Jewell et al. "Circularly polarised colour reflection from helicoidal structures in the beetle *Plusiotis boucardi*," New J. Phys. **9**, 99 (2007).

2. A.C. Neville and S. Caveney. "Scarabeid beetle exocuticle as an optical analogue of cholesteric liquid crystals," Biol. Rev. **44**, 531-62 (1969).

3. M. Mitov and N. Dessaud. "Going beyond the reflectance limit of cholesteric liquid crystals" Nature Mater. **5**, 361-4 (2006).
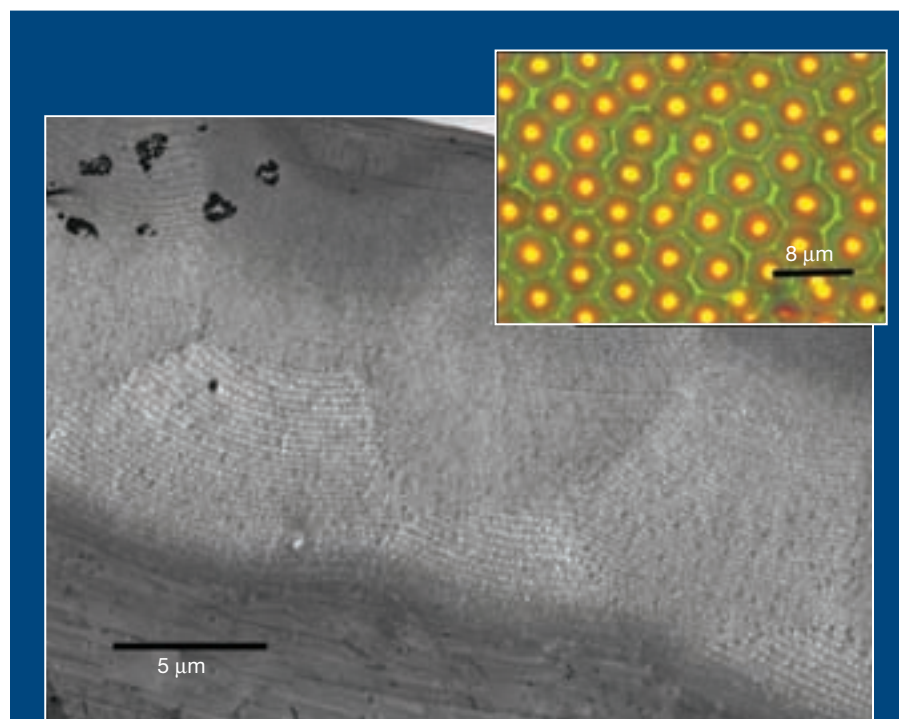
Transmission electron microscopy image collected from a cross-section through the shell of a *Plusiotis boucardi* specimen showing the curved, concentric layered micro-structure. (Inset) Optical microscope image collected from the shell under 100× magnification.

5 µm

8 µm

Imaging the Wavefront Curvature Reversal in Photonic Crystals

Ethan Schonbrun, Qi Wu, Wounjhang Park, Maxim Abashin, Yeshaiahu Fainman, Tsuyhoshi Yamashita, and Christopher J. Summers

Tightly focused optical waves are ubiquitous in modern technology. Understanding and controlling the behavior of focused light is critical for many applications, including optical data storage, scanning microscopy and laser machining. The exact distribution of a converging field is essentially determined by the frequency and the material in which the wave travels. In isotropic materials where the momentum is parallel to the energy flow, the wavefronts converge when the intensity distribution converges. In metamaterials and photonic crystals (PCs), however, the anisotropy of the dispersion surface results in anomalous focusing properties.

We investigated the wavefronts in a PC fabricated on a silicon-on-insulator wafer. The PC is designed in such a way that 1,550 nm light excites the top of the first photonic band, where negative refraction is known to occur.[1] The excitation is created by allowing a ridge waveguide mode to diffract through an unpatterned silicon slab.[2] We then studied the field distribution at the interface between the slab and the PC region. In the figure, (a) and (d) show the field amplitude, and (b) and (e) show the phase at the slab to PC interface.

Experimental data obtained by heterodyne near-field scanning optical microscopy (HNSOM)[3] are shown in (a-c), and (d-f) show numerical modeling. A diverging beam is incident from the unpatterned silicon slab and negatively refracts at the PC interface, forming an internal focus 3 μm behind the interface. On inspection, the wavefronts shown in the phase plots do not change curvature across the interface, even though the intensity distribution changes from diverging to converging. The wavefronts do change curvature at the internal focus, where they progress from diverging to

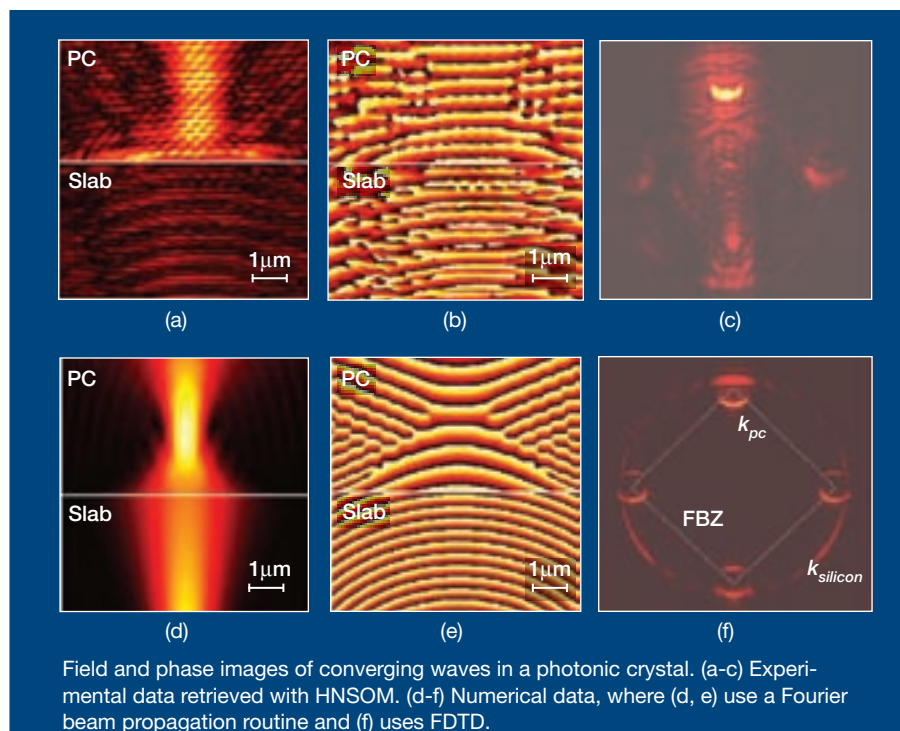converging, contradicting once again the intensity distribution.

This anomalous behavior is due to the dispersion surface near the band edge. Isotropic materials have a circular dispersion surface that is concave. This ensures that the phase and group velocities are always parallel and thus the intensity distribution is always consistent with the curvature of wavefronts. In PCs, the dispersion surface becomes convex, leading to a large angle between phase and group velocities. Consequently, the phase velocity, which dictates the wavefronts, refracts positively. However, the group velocity, which determines the intensity distribution, refracts negatively. Since HNSOM provides both the amplitude and phase information simultaneously, we can resolve the convex dispersion surface of the PC by performing the two-dimensional Fourier transform of the complex field, as shown in (c, f).

This study shows a surprising result of focusing using a PC, namely that the evolution of the intensity distribution is counter to the curvature of the wavefronts. The effect has been traced to the curvature of the dispersion surface, which has also been evaluated experimentally. Direct measurements of optical fields in a complex media provide a powerful tool for better understanding the optical properties of complex media and designing novel optical devices based on them. ▲

[E. Schonbrun (schonbru@deas.harvard.edu), Q. Wu and W. Park are with the department of electrical engineering at the University of Colorado, Boulder. M. Abashin and Y. Fainman are with the department of electrical engineering at the University of California, San Diego. T. Yamashita and C.J. Summers are at the School of Material Science and Engineering at Georgia Institute of Technology in Atlanta.]

References
1. C. Luo et al. Phys. Rev. B **65**, 201104 (2002).
2. E. Schonbrun et al. Appl. Phys. Lett. **90**, 041113 (2007).
3. P. Tortora et al. Opt. Lett. **30**, 2885 (2005).

Field and phase images of converging waves in a photonic crystal. (a-c) Experimental data retrieved with HNSOM. (d-f) Numerical data, where (d, e) use a Fourier beam propagation routine and (f) uses FDTD.

Localization of Light in Disordered Lattices

Tal Schwartz, Guy Bartal, Shmuel Fishman and Mordechai Segev

In basic solid-state physics, it is often assumed that solid materials, such as metals and semiconductors, are periodic arrays of atoms, where electrons are described by Bloch functions extended all over the lattice. In reality, however, the picture is more complex: Disorder always exists, and no material is perfectly periodic. In 1958, Philip Anderson predicted that interference effects may alter the eigenmodes of a disordered lattice from extended states into localized ones.[1] Consequently, when an electron is initially placed on one atom, it cannot diffuse to cover the whole crystal, but will rather remain localized around its initial position, and therefore the material will not conduct electric current (at zero temperature). Anderson's prediction had rewarded him with the Nobel Prize in 1977. Today, the phenomenon of Anderson localization is a basic concept in solid-state physics. However, phonons, which are always present at non-vanishing temperatures, and interactions among the electrons themselves, have prohibited the observation of Anderson localization in atomic crystals. Consequently, Anderson localization (strong localization)—namely, exponential suppression of transport—has never been observed in atomic lattices.

In recent years, several experiments demonstrated strong localization effects in highly scattering media—powders or suspensions of dielectric material.[2,3,4] Nevertheless, the medium in these experiments was completely random, lacking the underlying periodic structure of Anderson's model describing localization in disordered lattices.

Earlier this year, we reported the experimental observation of Anderson localization in a disordered photonic lattice—the localization of light in a periodic structure with disorder superimposed upon it. The experiment used the transverse localization scheme, which can be mapped directly to the original Anderson model.[6] We imprinted a two-dimensional periodic pattern with a controlled degree of disorder in a dielectric medium, and propagated a probe beam in the induced structure.

The evolution of the beam along its propagation direction has a complete equivalence to the time-evolution of a wave packet in a two-dimensional lattice, and we recorded the intensity cross-section of the outcoming beam. We repeated the measurements with hundreds of different realizations of disorder, obtaining the statistical (ensemble-average) transport properties of the perturbed photonic lattice. The experiments demonstrated a clear crossover from diffusive transport to Anderson localization (see figure).
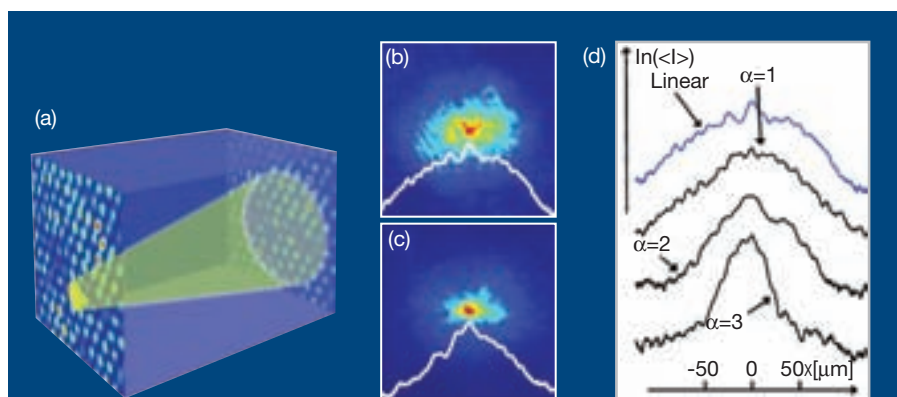
We then proceeded to study nonlinear propagation in disordered lattices and its effect on the localization process. Theoretically, there are many open questions regarding the combined action of nonlinearity and disorder, and our system can serve as a well-controlled tool to answer such questions. We find that, under self-focusing, nonlinearity localization is enhanced, as the beam narrows down when we increase the strength of nonlinearity, and the characteristic exponentially decaying intensity profile appears at a lower level of disorder, where the transport was still diffusive in the linear case.

In conclusion, we have presented the first experimental observation of Anderson localization in periodic structures containing disorder and a study of the effects of nonlinearity on localization. We foresee that our system would become a standard tool in future study of the Anderson localization of light, and that it will provide the experimental avenue for gaining deeper understanding of localization, in optics as well as in other physical systems. ▲

[Tal Schwartz, Guy Bartal, Shmuel Fishman and Mordechai Segev (msegev@tx.technion.ac.il) are with the physics department at Technion, the Israel Institute of Technology, Haifa, Israel.]

(a) A probe beam propagates in a photonic lattice of hexagonal symmetry, periodicity of 11 μm, and a controlled level of disorder, where the index of refraction is invariant along the propagation direction. The beam width at the input face is about 9 μm, and the transport properties of the disordered lattice are studied by monitoring the intensity profile at the output face of the lattice. (b) Intensity cross-section of the probe beam, ensemble-averaged at the lattice output, under moderate disorder, exhibiting diffusive broadening. The white curve corresponds to the logarithm of the intensity profile, and shows the Gaussian profile characteristic to diffusion. (c) Same as (b), but with stronger disorder. Here the intensity profile is exponentially decaying, revealing Anderson localization. (d) Averaged intensity profiles (in log scale) at the lattice output, showing the transition from diffusion in linear propagation (blue curve) to localization with an exponential decay in nonlinear propagation (black curve).

References
1. P.W. Anderson. Phys. Rev. **109**, 1492 (1958).
2. D. S. Wiersma et al. Nature **390**, 671 (1997).
3. A.A. Chabanov et al. Nature **404**, 850 (2000).
4. M. Störzer et al. Phys. Rev. Lett. **96**, 063904 (2006).
5. T. Schwartz et al. Nature **446**, 52 (2007).
6. De Raedt et al. Phys. Rev. Lett. **62**, 47 (1989).