Platform enables tunable photonic crystals with integrated spin-orbit coupling and controlled laser emission

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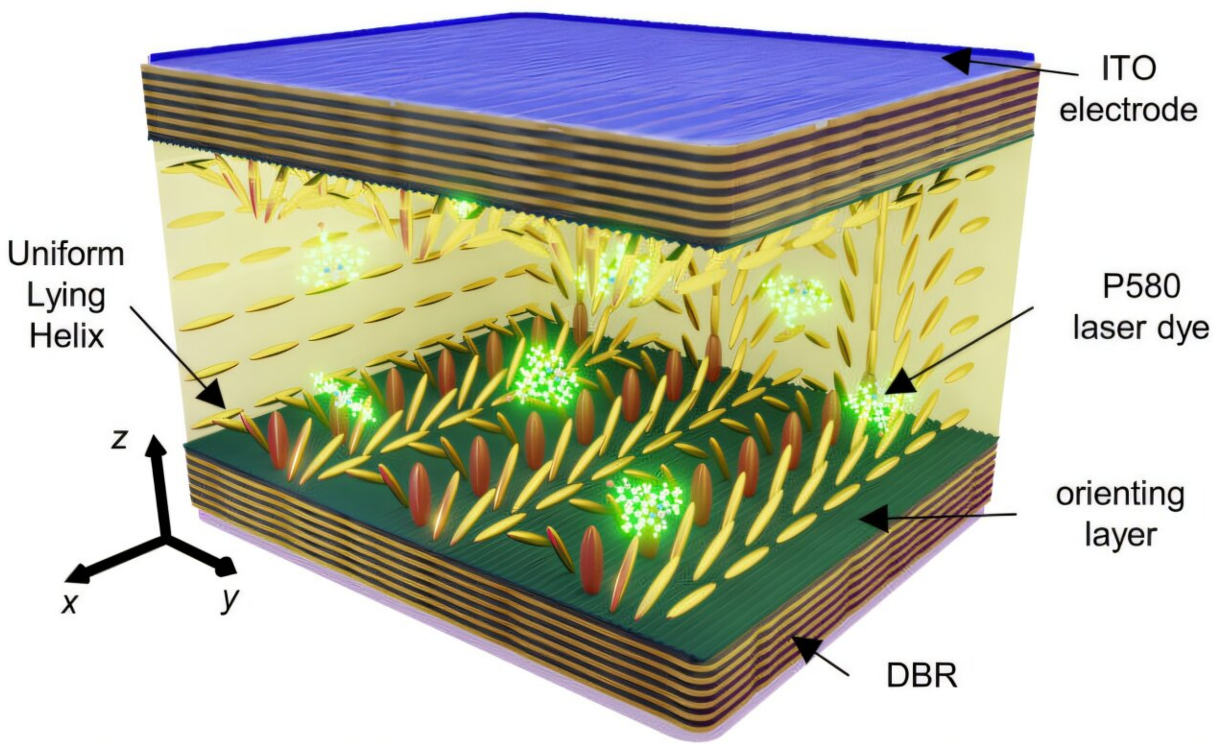


Tunable photonic crystal based on a self-organizing liquid crystal structure in an optical microcavity. Credit: Marcin Muszyński, Faculty of Physics, University of Warsaw

A team of researchers has developed a novel method for using cholesteric liquid crystals in optical microcavities. The platform created by the researchers enables the formation and dynamic tuning of photonic crystals with integrated spin-orbit coupling (SOC) and controlled laser emission. The results of this research have been published in the journal *Laser & Photonics Reviews*. The team is from the Faculty of Physics at the University of Warsaw, the Military University of Technology, and the Institut Pascal at Université Clermont Auvergne.

"A uniform lying helix (ULH) structure of a cholesteric phase liquid crystal is arranged in the optical cavity. The self-organized helix structure with the axis lying in the plane of the cavity acts as a one-dimensional periodic photonic lattice. This is possible due to the unique properties of liquid crystals, which are elongated molecules that resemble a pencil," explains Prof. Jacek Szczytko from the Faculty of Physics at the University of Warsaw, where research on novel optical microcavities is being conducted.

"A cholesteric structure is a spiral structure made up of layers of almost parallel oriented molecules lying in a single plane. From layer to layer, the orientation of the molecules is gently twisted, which altogether builds up a helical structure reminiscent of DNA helixes or 'piggyback' noodles. The direction perpendicular to the layers of molecules determines the axis of the helix formed.

"It turns out that when such a structure is observed in the direction perpendicular to the axis of the helix under appropriate illumination, distinct stripes with a width equal to the helix pitch are noticed. The use of liquid crystals that respond to an electric field enables precise control of this pitch, and thus of the structure of the photonic bands, opening up new perspectives in photonic engineering," adds Prof Szczytko.

The effects described are made possible by the use of optical microcavity, which restricts the movement of light in one dimension, giving it properties similar to particles endowed with mass. In the cavity, photons that have no rest mass start to behave like massive particles. Adding a photonic potential in space with a given period associated with a helix jump extends this analogy and allows further manipulation of these properties.

"The goal of our research is to discover how light can acquire properties normally attributed to matter while retaining its unique characteristics. In our group, using liquid crystal optical microcavities fabricated in collaboration with a team from the Military University of Technology, we have been studying optical analogs of effects previously known from solid-state physics," adds Prof Szczytko.

The optical microcavities were fabricated by researchers from the Military University of Technology, in Prof. Wiktor Piecek's group, using helical structures created by Prof Eva Oton in cavities fabricated by Dr. Przemysław Morawiak and Dr. Rafał Mazur.

"The development of a suitable liquid crystalline mixture and conditions that allow the formation of a well-ordered homogeneous helix over a large area of an optical cavity is a complex challenge in materials engineering and liquid crystalline technology. Our team has many years of experience in controlling self-organized liquid crystal structures," emphasizes Prof Piecek from WAT.

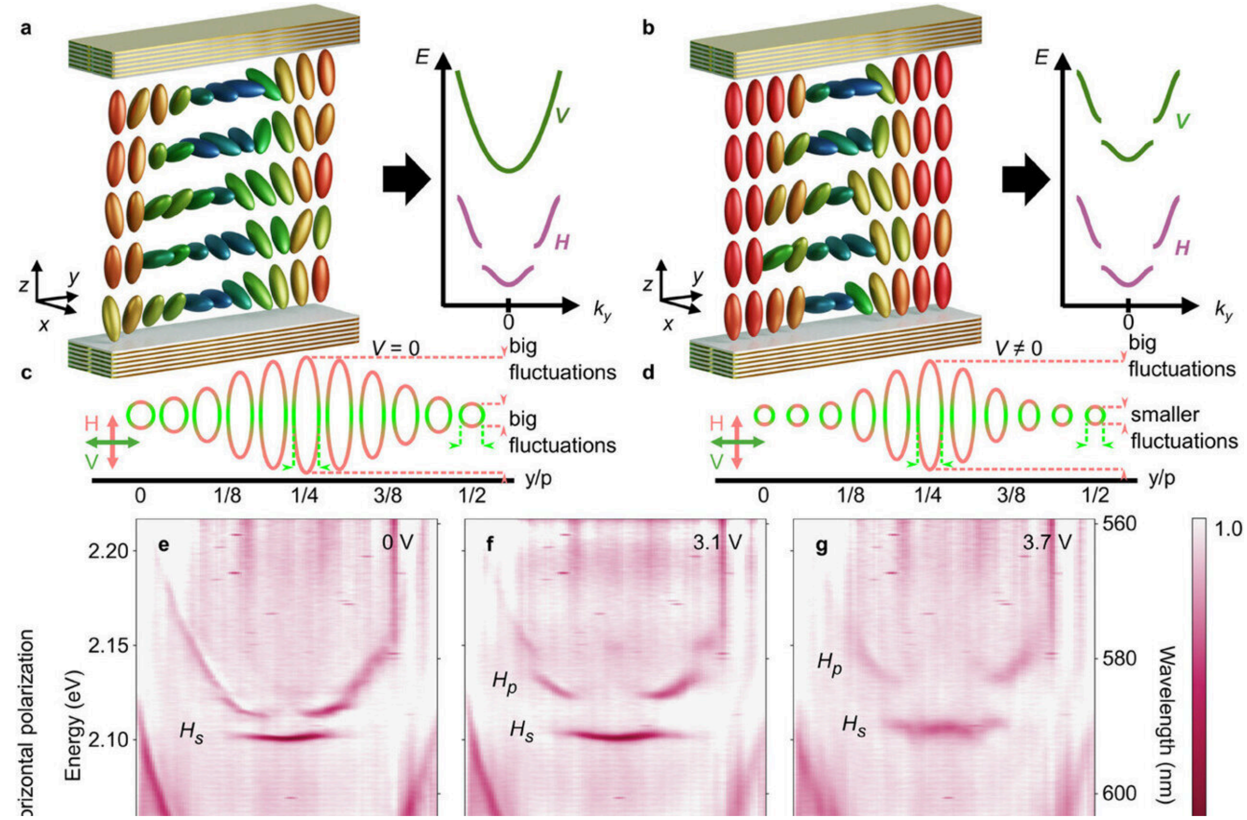
"For years, scientists have been developing nano- and microstructures that modulate the properties of the light that interacts with them. Photonic crystals—repeatable structures with periods comparable to the wavelength of light, which lead to the formation of band structures and band gaps that prevent photons possessing specific energies, similarly to what happens in the case of electrons in semiconductors—are of particular interest here," explains Marcin Muszyński, first author of the paper and a doctoral student carrying out research at the Faculty of

Physics of the University.

"However, typical technologies for producing photonic crystals have several drawbacks: their manufacture is technologically complex and therefore expensive and time-consuming. The lattices themselves are limited in size, and the parameters of the fabricated structures, such as the period or 'depth' of a trap once built, are difficult to change.

"Our work solves these problems—the structures created by self-organization have a surface area in the order of hundreds of square micrometers, and thanks to the reorientation of the liquid crystal molecules in an electric field, we can dynamically control the band structure of the light trapped in the microcavity.

"The uniqueness of our system lies in the fact that it is formed by the self-organization of liquid crystal molecules, and the medium itself retains the properties of a liquid. The application of an electric voltage allows us to observe in real time with a camera how the structure evolves, while maintaining a periodic order," adds Muszyński.



The tunable band structure. Illustrative representation of the LC director arrangement inside the microcavity and the corresponding schematic dispersion relations of the horizontal (⍰⍰ , pink) and vertical (⍰⍰ , green) modes for a) zero and b) non-zero voltage. ⍰⍰ and ⍰⍰ polarizations refer to the laboratory frame and correspond to the ⍰⍰ and ⍰⍰ directions of the sample frame, respectively. Effective refractive index ellipses for ⍰⍰ and ⍰⍰ polarizations showing periodical dependence along the ULH axis ⍰⍰ over half pitch ⍰⍰ and obtained by averaging director distributions shown in (a) and (b) along microcavity axis ⍰⍰ for c) zero and d) non-zero voltage, respectively. Reflectivity spectra of e–g) horizontally and h–j) vertically polarized band structures measured for different voltages (indicated in top right corners) applied to the sample A. Credit: *Laser & Photonics Reviews* (2024). DOI: 10.1002/lpor.202400794

"Liquid crystal molecules have the shape of an ellipsoid elongated in one direction. This characteristic feature leads to the formation of a large birefringence, which is crucial for the research being conducted. It allows light of different polarizations to interact differently with the lattice, creating independent energy bands.

"We observed that introducing a tilt of the molecules for the helix axis leads to an interaction between some of the energy subbands for the two lattices. We named this effect interband spin-orbit coupling (ISOC)," says Przemysław Oliwa, second author of the paper and a Ph.D. student carrying out research at the UW Faculty of Physics.

"The interpretation and precise theoretical description of this effect was suggested by Prof Guillaume Malpuech and Prof Dmitry Solishkov, researchers from Institut Pascal, Université Clermont Auvergne, France, who collaborate with our team."

"Based on our experience from previous work, we also introduced an organic dye into this liquid crystal periodic structure. This new system allowed us to observe lasing from two states with different energies, i.e. double lasing. Furthermore, due to the existence of a spin-orbit interaction between the bands in the periodic structure, we observed lasing in both linear and circular polarization.

"These latter results show that our research is both fundamental and applied," adds Dr. Piotr Kapuscinski from the Faculty of Physics at the UW, co-author of the paper.

"Our results open the door to applications in topological photonics and modern laser technologies. We show new possibilities for combining SOC effects with periodic photonic structures, and point to directions for further research into phenomena such as topological phase transitions, the Su-Schrieffer-Heeger model, or non-abelian feature fields," Professor Szczytko concludes.

More information: Marcin Muszyński et al, Electrically Tunable Spin-Orbit Coupled Photonic Lattice in a Liquid Crystal Microcavity, *Laser & Photonics Reviews* (2024). DOI: 10.1002/lpor.202400794

Provided by University of Warsaw