Researchers confine light to crystal surface, design transparent display using nanoparticles

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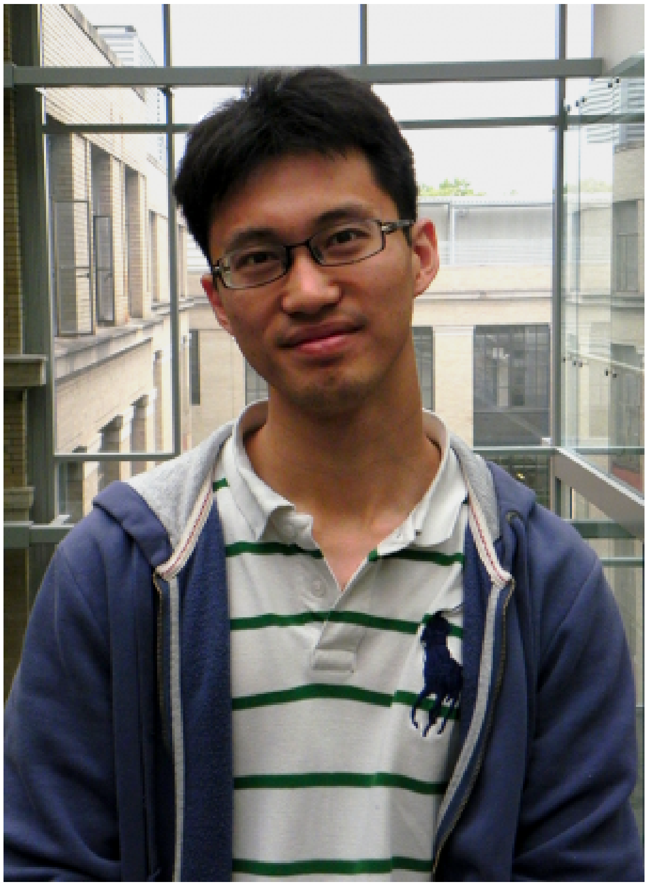

Chia Wei (Wade) Hsu Credit: Courtesy of the Materials Processing Center

Light is a slippery fellow. Stand in a darkened hallway and close a door to a lighted room: Light will sneak through any cracks—it doesn't want to be confined. "Typically, in free space, light will go everywhere," graduate student Chia Wei (Wade) Hsu says. "If you want to confine light, you usually need some special mechanism."

Last summer, Hsu demonstrated a new way to confine light on the surface of a photonic crystal slab. "We were the first ones to experimentally demonstrate this new way to confine light," says Hsu, a graduate student in physics who is conducting research under Marin Soljacic, a professor of physics as MIT.

The photonic crystal is a thin slab whose structure has a periodicity, or repeating pattern, that is comparable in size to the wavelength of light—extremely short distances measured in nanometers (billionths of a meter). "Light can interact with the structure in a non-trivial way. Typically one observes modes called 'guided resonance,' where light is semi-confined in the slab but it can radiate outside. It's not perfectly confined; it still leaks out," Hsu explains.

However, at a certain angle (35 degrees in the study), light stays bound to the surface, oscillating indefinitely. Hsu, Soljacic, co-author and MIT graduate student Bo Zhen, and others reported these findings recently in *Nature*. This phenomenon is called an embedded eigenstate, also known as a "Bound State in the Continuum." The bound state affects just one wavelength of light that reaches the slab. The particular wavelength that is bound is related to the structure of the photonic crystal slab. So for a different structure, the bound state will appear at a different wavelength and wavevector, or angle of propagation. By manipulating the structure, researchers can manipulate the wavelength and the angle of this special state. Separately, Hsu and colleagues detailed their physical and mathematical analysis of the bound state in a theoretical paper in *Light: Science and Application*.

One way to visualize the bound state effect, Hsu says, is to think of the difference between dropping a stone into a lake—where the waves ripple out without being confined—and using a drum stick to hit a drum membrane—which vibrates back and forth, but does not spread because it's blocked by the boundary of the drum. "Eigenstate or eigenvalue refers to a sustained oscillation," Hsu explains.

At a particular angle, or wavevector, as light tries to escape, outgoing waves of the same amplitude, but opposite phase, cancel each other—which is known as destructive interference. "All of the outgoing waves are cancelled, so light becomes confined," Hsu says. "There are no outgoing waves anymore and then it becomes perfectly confined in the slab."

Unexpected finding

In 1929, scientists John von Neumann and Eugene Wigner theoretically predicted such a state, known as an embedded eigenvalue. The trapped state is in contrast to what typically happens when light resonates on the surface for a time, but then escapes or decays.

"This bound state was certainly an unexpected discovery. We happened upon it when we were looking for something else," Soljacic explains.

The researchers are looking for a practical use of this finding. "The same mechanism we described about this interference cancellation mechanism can also be applied to a structure that's similar to a fiber, so it may have potential use in optical communication too," Hsu says. Although light does not escape the typical optical fiber because of its total internal reflection, the fiber confines all angles of light above a critical angle. "All the light above some cut off will be confined. In our mechanism, cancellation only happens at one particular angle. Only light at that particular angle is confined, so it has some more selectivity," Hsu explains.

Breakthrough from simplicity

Prior examples of theoretically predicted embedded eigenstates were too complicated to realize. "Here we found a structure that is very simple to realize," Hsu says. Fellow graduate student in Soljacic's group, Jeongwon Lee, fabricated the photonic crystal structure, using a structure which the group had already studied.

Lee fabricated the photonic crystal on silicon nitride slab, using interference photolithography to etch the periodic structure or repeating pattern. Hsu and Zhen measured the sample in the lab and analyzed the data to confirm the phenomenon. "In this simple structure, we found this phenomenon of this new type of light confinement. Since the structure is simple, we were able to demonstrate it, which other people were not able to because their systems are more complicated," Hsu explains.

Hsu is working toward a deeper understanding of why this phenomenon occurs where light gets confined, as well as exploring potential applications in photonic crystal lasers. "We are investigating where this new type of light confinement can give rise to different behaviors of lasers," he adds.

Creating transparent displays

Besides his light confinement work, Hsu led the demonstration of a blue transparent display composed of a clear polymer coating with embedded resonant nanoparticles made of silver.

Such displays work because the wavelength of blue light is strongly scattered by interaction with silver. "In this case, we only want to scatter the particular wavelengths of our projector light. We don't want to scatter other wavelengths because we will need it to be transparent," he says.

"We can take a piece of glass which is originally transparent and put in nanoparticles that only scatter a particular, narrow bandwidth of light. Light in the visible spectrum is made of many different wavelengths from 300 nanometers to 750 nanometers. If we have such a structure, then most of the light can pass through, so it is still transparent, but if we project light of that particular narrow bandwidth, light can be scattered strongly as if it were hitting a regular screen," Hsu explains. The results were published in a *Nature Communications* article, "Transparent displays enabled by resonant nano particle scattering," in January.

Hsu's theoretical design consisted of a nanoparticle with a silica (silicon dioxide) core and a silver shell, but the experiment was done using purely silver particles. "Silver-only is good enough if we want to scatter only blue light," he says. A very tiny amount of silver, just six-thousandths of a milligram, produced the effect in the demonstration, making it a potential economical approach.

Silver has conducting electrons, and when the particular blue wavelength interacts with them, those conducting electrons will oscillate back and forth strongly. "It's a resonance phenomenon. At that point, you'll get very strong light scattering," Hsu explains. The phenomenon is called a localized surface plasmon resonance.

One advantage of this approach is that the projected image has a broad viewing angle. "Nanoparticle scattering will send light in all different directions, so you will be able to see the image no matter which angle you look at. So it will be useful for applications where you would want people to see it from all different directions," Hsu says.

Hsu received his bachelor's in physics and mathematics at Wesleyan University in 2010. His doctoral thesis will be split between the nanoparticle display work and the confinement of light work.

More information: "Observation of trapped light within the radiation continuum." Chia Wei Hsu, et al. *Nature* 499, 188–191 (11 July 2013) DOI: 10.1038/nature12289. Received 25 February 2013 Accepted 13 May 2013 Published online 10 July 2013

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