LIGHT **FANTASTIC**

> “When something is said to be impossible, there are two points for researchers to initially clarify: whether it really is forbidden by the laws of Nature; or whether it is simply that no material that currently exists in Nature can do that”

PROF CHE TING CHAN
Daniel CK Yu Professor of Science, Executive Director, HKUST Jockey Club Institute for Advanced Study

Originally an electronic physicist working at Ames Laboratory in the US, Prof Che Ting Chan moved into exploration of materials with unusual light and sound functionalities when he joined HKUST in the mid-1990s. It was the perfect area for a scientist who had spent his childhood pondering such questions as why the sun appeared white at noon yet red in the evening and how the ocean can be green or grey while water itself is colorless.

The Quest to Know

Starting from functionality, for example, a material that can absorb light more efficiently, Prof Chan and his team first explore the theory behind what they seek to achieve. At the material design stage, the team uses mainly numerical computation to design samples. Then comes fabrication. Prof Chan’s experimental physics colleagues, including Prof WY Tam, Prof KS Wong and Prof HB Chan, make actual samples of the new materials, utilizing the advanced equipment in the University’s central Materials Characterization & Preparation Facility and Nanosystem Fabrication Facility, including electron-beam lithography and focused ion-beam lithography. Characterization, which can probe, measure, and analyze a material’s structure and properties, may involve use of electron microscopes as well as the construction of innovative in-house equipment, not commercially available. An integrated Metamaterials Lab opened in 2016.

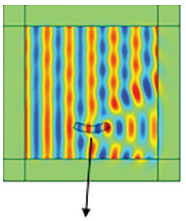
Setting the Pace

The groundbreaking research in new materials has been supported by a large-scale Collaborative Research Fund grant from Hong Kong Research Grants Council (RGC) since early 2000. Such exciting, cutting-edge discovery has encouraged a stream of outstanding research students and post-doctoral researchers from Mainland China to take the plunge and move into the new research area. In 2013, Prof Chan received an Area of Excellence grant of HK$46.5 million from the RGC to lead exploration into novel wave functional materials for manipulating light and sound in collaboration with several other universities in Hong Kong.

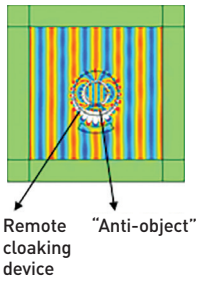
Some of the key discoveries that HKUST research has produced are featured in the following pages.

Cloaking Device

In science fiction, such as HG Wells' *The Invisible Man*, a person could become invisible by drinking a chemical. In reality, no such substance has been made. How about wrapping a material around an object to make it invisible to the human eye? Yes, theoretically, now it could be done, thanks to advanced physics techniques that change the path of light, not the object. In 2006, UK scientists designed man-made materials ("metamaterials") that could provide invisibility by guiding light around an object, and the concept was soon proved experimentally in the US. Instead of creating a cloak to hide an object embedded inside, Prof Chan's group has designed metamaterials with optical properties that are the exact opposite of the material to be cloaked so that light scattered by an object is compensated by the cloak. An observer thus sees neither the object nor the cloak. This method of invisibility has the advantage that the hidden objects can still see the outside world. In conventional cloaks, the objects are blinded because no light enters the cloaked region. Such "remote cloaking" currently works for a narrow band of frequencies. Whether such cloaking strategies can work for a broad range of frequencies remains an open question.



Light coming from the left is scattered by an object, therefore we see the object.



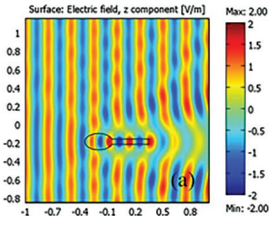
A "remote cloaking" device (the circle) is put next to the object. The device is designed to cancel the light scattering by the object so that the light wave passes through as if nothing is there.

Both the cloaking device and the object become invisible to outside observers. The principle behind is to use a metamaterial "anti-object" to cancel the light scattering by the object you want to hide.

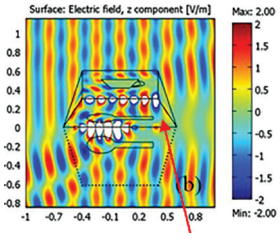
Physical Review Letters, 093901 (2009)

Illusion Optics

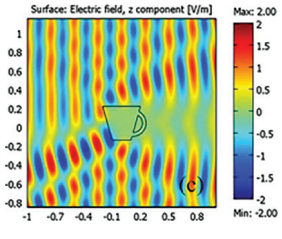
Platform 9¾ at King's Cross Station where students travel to Hogwarts in the world of Harry Potter appears to the eye to be a wall. In the fictional story, it is actually an open channel that the body can pass through. Using the novel notion of "illusion optics", HKUST researchers have demonstrated for the first time that such a phenomenon is possible and, in principle, an apple can be made to look like an orange, or a spoon like a cup. This is achieved by changing the light-scattering pattern of an object to that of another object, making it appear like the second object, with the assistance of "negative index" metamaterials specially designed at HKUST. The illusion device requires very complex man-made materials. Prof Chan's team is now working to realize such novel effects with less complex materials.



A dielectric spoon



Illusion device



A metallic cup

Left and far left: Light-scattering patterns of a cup and a spoon. The scattering patterns are different, and the different patterns allow our eyes to detect different objects.

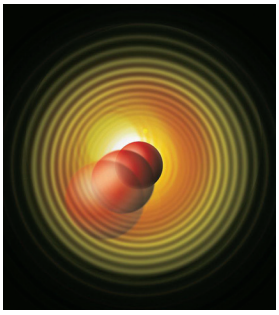
Center: By using a negative index metamaterial, the scattering pattern of a spoon can be changed to that of the cup. An observer in the far field will see a cup, although the object is actually a spoon.

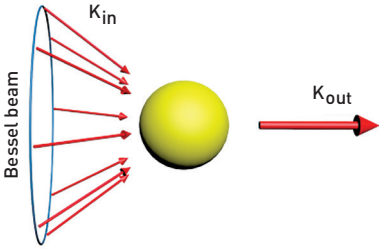
Physical Review Letters, 102, 253902 (2009)

Tractor Beam

It is commonly believed that light carries momentum and as such, light always pushes objects away. "Tractor beams" of light that pull objects toward them only exist in movies and science fiction. However, in 2011, Prof Chan and his collaborators solved the problem of making light attract an object, finally bringing the futuristic possibilities envisioned in the popular 1960s television series *Star Trek* closer to reality. The "tractor beam" breakthrough was published as a cover story in *Nature Photonics* journal and drew substantial media interest. Prof Chan and his student showed subsequently in an article in *Nature Communications* how light could push an object sideways. The tractor beam concept is different from the so-called "optical tweezers" commonly used to manipulate small particles. Optical tweezers, relatively easy to realize with today's technology, act to grab a particle while the tractor beam pulls a particle, offering the possibility of manipulation with zero contamination. The tractor beam is very selective in the properties of the particles it pulls, so it can be useful for the optical sorting of micro-particles in an inexpensive device.

The Starship Enterprise using its tractor beam to pull an object without touching it in an episode of *Star Trek: The Next Generation.*





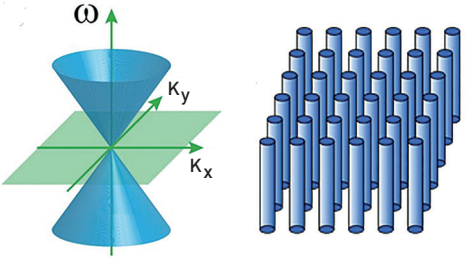
Left: In some special optical beams, the projection of the photon momentum on the beam axis is less than the total momentum. Some particles can have multiple excitations that can interfere to form a forward directed beam. Under such circumstances, the scattered light can have more momentum on the beam axis than the incoming light, allowing for light to "pull" without violating the conservation of momentum.

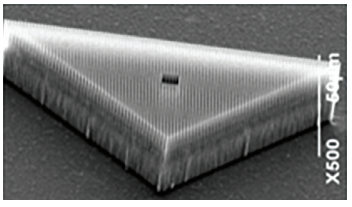
Far left: A schematic picture showing a beam of light pulling a spherical particle toward the light source.

Nature Photonics 5, 531 (2011)

Zero Refractive Index

Physics textbooks teach that a vacuum has a refractive index of one. Since a vacuum is already "empty space", does it mean its refractive index cannot be less than one? The amazing versatility of man-made materials means that some artificial materials can, in principle, have refractive indices of less than one. Prof Chan's team recently designed and made photonic crystals with a refractive index approaching zero, which is optically emptier than a vacuum. Such zero index materials have unusual and interesting properties, including an infinite phase velocity. In addition, light travels inside such materials without any phase change, as if space does not exist. Interestingly, Prof Chan discovered a hidden mathematical relationship between the "Dirac cone physics" in graphene (a new electronic material) and a metamaterial with a zero refractive index.





Top left: Some photonic crystals can be specifically designed so that they have a conical frequency-momentum relationship called a "Dirac cone". Theory shows that these photonic crystals behave as if the effective refractive index is zero at some specific frequency.

Top right: A "photonic crystal" composed of an ordered array of dielectric (e.g. Si) cylinders.

Bottom: A prism of "zero index" photonic crystals, made experimentally in Prof WY Tam's laboratory as a realization of the blueprint shown in the top right diagram.

Nature Materials, 10, 582 (2011)