Fun with light and matter
Metamaterial “atoms” absorb and re-radiate light like real atoms, allowing unique capabilities for imaging and communications.

Los Alamos scientist Hou-Tong Chen tests his metamaterial inventions in an anechoic chamber. The chamber is designed to absorb electromagnetic waves and prevent reflections to simulate a wide empty space — effectively, a room with no walls.

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Barbaric though it may seem by modern standards, there was something pleasantly straightforward about the whole thing. One could readily see that it had all the proper components for pulling video content from the air. The knob selected the frequency, and those rod and loop antennas grabbed the electric and magnetic components, respectively, of the electromagnetic waves that carried the video stream. You could even see little red, green, and blue pixels on the screen if you looked closely enough.

In his research into advanced electromagnetic-transmission technology, Hou-Tong Chen, of the Los Alamos Center for Integrated Nanotechnologies, pursues the new with a nod to the old. He’s inventing a new generation of ultrathin “metamaterial” devices for manipulating electromagnetic waves in the microwave, terahertz, and infrared bands, with the promise of enabling flat, light-weight, and low-cost components for important communication and imaging applications. And at the heart of each device are a bunch of tiny metallic rod and loop antennas.

Fresh take on freshman physics

Every student of physical science or engineering takes a year of introductory physics, which includes a semester on electricity, magnetism, and their joint appearance as electromagnetic waves. It’s all 19th-century science, but Chen, and others in his field, are giving it a dramatic facelift for the 21st century.

Electromagnetic waves are comprised of perpendicular, oscillating electric and magnetic fields. Electric fields push and pull on charged particles directly, so electrons in a conducting antenna move back and forth along the antenna as an oscillating electric field passes by. Magnetic fields drive electrons to circulate around a conducting loop antenna when the oscillating field is directed through it. The electrical currents thus formed in the antennas can then be interpreted by an electronic device, such as a television.

But Chen has a different objective. Rather than using antennas and electronics to make and receive transmissions, he creates arrays of small antenna-like structures to act as resonators, absorbing the energy of passing electromagnetic waves and then re-radiating them—forward, backward, or some other direction—with altered properties. Essentially the same thing routinely happens at the atomic scale, with atoms and molecules acting as resonators, deep inside a thick, bulk material, as when light rays are bent by a glass lens. But his devices are flat and constructed from repeating metallic resonators large enough to be seen with the naked eye, or nearly so. Each resonator is effectively “painted” onto a thin-film substrate, creating a metamaterial surface, or metasurface, to play the same role that atoms and molecules play in normal, bulk-material lenses and other optical devices.

“My ‘meta-atom’ resonators need to be at least ten times smaller than the wavelength of light I’m using,” says Chen. “It’s difficult to make them for visible light, with wavelengths less than a millionth of a meter. But for centimeter-sized microwaves or submillimeter terahertz waves, packing thin-film surfaces with resonators is much more practical.”

Metasurface monocle

One of the first practical applications Chen pursued with his metasurface resonators was an anti-reflective (anti-glare) film, similar in function to coatings added to prescription eyeglasses. He found that his resonators could be used to alter the phase of electromagnetic waves, such that one wave could be made to have its electric field point downward at the same time and place as another wave’s electric field points upward, producing a cancellation. If the system is structured so that this cancellation occurs upon reflection, then viola, the reflection vanishes, and the glare is gone.

Chen experimented with different arrangements of resonators and found that the best results could be obtained by layering two sheets of resonators, with resonators of different shapes on each sheet. At each of the metasurfaces,
Several technologies may permit the construction of an actively controlled metasurface lens capable of altering its own pattern of resonator shapes when needed. Here, resonators (pairs of copper rectangles) fitted with diodes (bridging the rectangles) change their properties with the application of a voltage from an external circuit.

CREDIT: Michael Pierce/LANL

Electromagnetic waves, such as radio waves and visible light, are comprised of perpendicular, oscillating electric and magnetic fields. An old television antenna captures both, using straight conducting rods to obtain an electrical current from the electric-field component of the wave and a conducting loop to obtain a current from the magnetic-field component.

A dense, repeating pattern of conducting electromagnetic resonators, roughly resembling a blend of rod and loop shapes, can be used to manipulate many kinds of electromagnetic waves, as long as the wavelength is at least about ten times larger than an individual resonator.

A phase adjustment occurs, producing some waves moving back and forth between the two layers. On the side where the light enters, the system is engineered to produce phase cancellation so little or no light reflects; on the opposite side, phases are tuned to produce nearly 100 percent transmission through the sheets.

Crucially, the anti-reflective metasurface films can be made exceedingly thin. With previous anti-reflective coatings, the phase change is produced while the wave travels through the coating—a miniscule distance for visible light, but an impractically large distance for longer-wavelength signals. With metasurfaces, the phase change is produced directly by the resonators, so no travel distance is needed.

Different resonator shapes produce different results. Square- and circle-shaped resonators, for example, proved anti-reflective only for a fairly narrow frequency of incoming light; that is, they produced a narrow-band anti-reflective effect. With a “+” shaped resonator, however, Chen was able to achieve a much broader-band anti-reflective effect. Other shapes allowed for interesting multi-band effects—anti-reflective for a few distinct frequencies only.

Another glare-control technology ready for a metamaterial upgrade is the polarizer. Polarizers use thin conducting lines to absorb electromagnetic waves oriented in a particular direction (e.g., electric up-down and magnetic left-right) and transmit waves only with the perpendicular polarization. The most familiar application might be as a glare-reduction coating on sunglasses (in this case, for fighting glares produced by the world at large, not by the glasses themselves). Most nuisance glares tend to be caused by light bouncing off of flat surfaces, such as roads and lakes; the light becomes polarized in the same direction every time by the bounce. Polarizing sunglasses filter out the bounced component and let the remaining unpolarized light through, giving the wearer a view of the scene without the glare.
Metasurface polarizers, with repeating resonators shaped like thin lines, accomplish roughly the same effect, but can be combined with phase adjustment to produce useful elements of control. By layering two or three polarizing metasurfaces, with resonators rotated by different angles, Chen was able to create a device that fully rotates the polarization of terahertz waves by 90 degrees—useful for materials characterization and polarization-sensitive sensing and imaging applications—both as a transmission device (cross-polarized light is what goes through) and as a reflection device (cross-polarized light is what bounces back). A similar effect can be produced with a thick stack of conventional polarizers, each rotating the wave's polarization by a very small angle until it adds up to 90 degrees, but with metasurfaces, three ultrathin layers stacked together can control phase and polarization with minimal losses.

Chen’s lens

“Polarizers and anti-reflective surfaces are great, and anything that can be controlled with thin films has the potential to be a technological game-changer,” says Chen. “But my favorite application so far is the metasurface lens.”

Light can be focused by thick glass lenses or curved reflective dishes. For some applications, these are problematic because lenses and dishes are large and heavy. They generally can’t be integrated into lightweight field equipment, and they come at an enormous premium on satellites and spacecraft.

“To beam a signal from, say, Jupiter back to Earth requires a large and heavy high-gain antenna,” says Chen. “But if a thin film could do the job, just imagine how much size and weight that would free up for additional systems and instruments on the spacecraft—and how much more we could learn from it.” Indeed, after more than a decade of engineering and construction, NASA’s 1989-launched Galileo spacecraft suffered a malfunction, with its high-gain dish antenna failing to fully deploy. Because of its size and weight, it had to be packaged and self-assembled in space from smaller segments supported by metal ribs, similar to an umbrella, but some of those metal ribs did not unfurl. The problem was ultimately traced to the lubricant that allows the metal ribs to open. A thin-film sheet, however, has no moving parts (and no need for lubricant) and would be immune to this type of problem.

Chen, together with his Los Alamos colleague Abul Azad, set out to build a complex array of resonator shapes sandwiched between two opposite-orientation polarizer metasurfaces. Each shape was designed to interact with the polarizers and produce a different phase change. Chen and Azad arranged the different shapes in concentric rings to behave like a simple, conventional lens—but without any of the thickness or heft.

A conventional lens focuses (or beams) light because light waves travel more slowly through glass than through empty space, interacting along the way with atoms that act like tiny resonators. The thickness of the lens diminishes outward from its center, producing less of a slowdown farther out. The effect is to manipulate the incoming wave front, focusing light inward toward a focal point (or making parallel the light radiating outward from a focal point in the case of beaming). The metasurface lens brings about the same controlled phase changes varying outward from the center: different resonator shapes act like different thicknesses of glass.
And like a deliberately misshapen lens that sends light off to the side, it can focus or beam electromagnetic waves in any direction he chooses, simply by adjusting the arrangement of resonator shapes.

**Intention and invention**

The ability to control beaming with thin, lightweight components got Chen thinking about what else his metasurfaces might be able to do.

“That’s how science and invention work,” he says.

“With each new thing you discover, you ask what else that new discovery might allow you to do that you couldn’t do before.”

In the case of the metasurface lens, Chen immediately recognized the potential for steering beams and transmissions in different directions by adjusting the resonator pattern on the fly. If he could create resonators able to respond to some kind of command to change shape, he could then aim transmissions in different directions with a single thin-film lens and no moving parts—no active pointing, no motor drive. The beam goes off in different directions as desired, but the lens stays fixed. This is what he’s working on now, and he already has some promising leads. Initial experiments suggest he can rearrange resonator shapes with externally applied electrical signals or laser light. This capability may have a serious technological impact, yet even robust, lightweight, steerable metasurface lenses are probably far from the end of the story.

“With research into novel phenomena like these, some applications seem to jump right off the page, while others only emerge later after we’ve had more time to reflect,” says Chen. One of the jump-off-the-page applications he cites is miniaturization of optical systems. A typical handheld camera lens contains lots of complex and expensive optical components. Something similar goes for transmission and imaging devices at longer wavelengths (e.g., microwave or infrared). Indeed, microwave lenses, for example, are neither glass nor thin; rather, they are extremely large plastic spheres. These and other components should be amenable to replacement with one or more thin-film metasurfaces, at once reducing complexity, weight, size, and cost.

Another readily evident application is terahertz screening, like at airport security checkpoints. Terahertz waves penetrate most materials but are not dangerous the way x-rays are. Metasurface films controlling terahertz waves could make for simple, inexpensive screening systems that could be easily deployed all over the world. Indeed, terahertz systems of all kinds show promise for future technologies and are limited only by the current lack of available components for controlling them—components such as lenses, polarizers, and even anti-reflective films. Chen is working with colleagues across organizational boundaries to expand the Lab’s already-extensive portfolio of metamaterial components and technologies.

But what about the more-time-to-reflect applications of the future—what might those be? Chen points to the fact that Mother Nature provides a variety of materials with useful properties, but very often they are limited. The index of refraction, for instance, is always positive, meaning that natural materials bend light only in particular ways. But metamaterial refraction of light, such as that from Chen’s metasurface lens, doesn’t operate by changing the index of refraction of a medium; its resonators are governed by a different principle, allowing it to do things nature’s materials can’t. As such, the ultimate capabilities of metamaterials and metasurfaces may depend only on human creativity and imagination. What doors might that open?

“I don’t know yet,” Chen admits. “But the exotic discoveries in metamaterials and metasurfaces so far feed into many, perhaps most, aspects of electrodynamics and optics. That’s got to mean something.”

—Craig Tyler