Flirting with invisibility: New materials can bend some wavelengths of light around an object.

**Light Fantastic**

The cloaking device, a cylinder designed to bend microwaves of a specific wavelength.

**By KENNETH CHANG**

Increasingly, physicists are constructing materials that bend light the "wrong" way, an optical trick that could lead to sharper-than-ever lenses or maybe even make objects disappear.

Last October, scientists at Duke demonstrated a working cloaking device, hiding whatever was placed inside, although it worked only for microwaves.

In the experiment, a beam of microwave light split in two as it flowed around a specially designed cylinder and then almost seamlessly merged back together on the other side. That meant that an object placed inside the cylinder was effectively invisible. No light waves bounced off the object, and someone looking at it would have seen only what was behind it.

The cloak was not perfect. An alien with microwave vision would not have seen the object, but might have noticed something odd. "You'd see a darkened spot," said David R. Smith, a professor of electrical and computer engineering at Duke. "You'd see some distortion, and you'd see some shadowing, and you would see some reflection."

A much greater limitation was that this particular cloak worked for just one particular "color," or wavelength, of microwave light, limiting its usefulness as a hiding device.

NOW YOU SEE IT: Duke researchers built a simplified version of their cloaking device out of copper rings and wings patterned onto fiberglass sheets and demonstrated that it successfully diverted microwaves.
Light Fantastic

Some wavelengths of light around an object (as in this idealized simulation) to make it vanish.

A wavefront entering the cloaking device is bent and diverted.

The wavefront, flowing around the cloaked area and reforming almost seamlessly.

Since the device does not significantly reflect or distort the wave, it is effectively invisible.

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The method is not magic, nor are the materials novel. Physicists are taking ordinary substances like fiberglass and copper to build metamaterials that look like mosaics of repeating tiles. The metamaterials interact with the electric and magnetic fields in light waves, manipulating a quantity known as the index of refraction to bend the light in a way that no natural material does.

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Continued on Page 4
Bending Wavelengths of Light to Flirt With Invisible

The Bending of Light

When rays of light cross a boundary from air to another material, they bend according to the material's index of refraction. Below, how water and two hypothetical liquids bend light.

![Diagram of light bending](image)

The Irresistible Fantasy of the Invisible Man, and Machine

Humans have always dreamed of invisibility. Persuas, in Greek mythology, had a cape to make him disappear. Leprechauns and other magical creatures did it on their own.

In more recent times, invisibility has been a theme in fiction from H. G. Wells to Harry Potter. In "The Invisible Man," Wells had a scientist change the refractive index of his own body. In Harry Potter, a cloak does the trick. In "The Lord of the Rings," it's, of course, a ring that makes the wearer vanish, with some rather unpleasant side effects.

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The New York Times, 3D model by Christoph Bormann and Gunar Lobing, Karlsruhe University
Wavelengths of Light to Flirt With Invisibility

The Bending of Light

When rays of light cross a boundary from air to another material, they bend according to the medium's index of refraction. Below, three liquids bend light:

<table>
<thead>
<tr>
<th>Index of Refraction</th>
<th>Positive Refraction</th>
<th>No Refraction</th>
<th>Negative Refraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>With a refraction index of 1.3, water bends light inward, closer to the perpendicular.</td>
<td>The same as the surrounding air, would not distort light.</td>
<td>A hypothetical liquid with a negative refraction index would bend light the “wrong” way.</td>
</tr>
<tr>
<td>1</td>
<td>An observer looking down at a 45-degree angle (orange line) toward a point on the rod would see a point farther down, making the rod and class bottom appear closer to the surface than they are.</td>
<td>An observer looking into the class would not see any distortion.</td>
<td></td>
</tr>
<tr>
<td>-1.3</td>
<td>An observer looking down at a point on the rod would see severe distortion and countereffective magnification effects, as the line of sight was refracted down and backward.</td>
<td></td>
<td></td>
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Both Wonder Woman and the Romulan of “Star Trek” managed to fly their racing car invisible, and in the movie “Predator,” an alien hunter used high technology to cloak itself, while Arnold Schwarzenegger, prey for once, went low-tech. He used a real coat to mask his body heat, making himself invisible to the alien in the infrared spectrum.

Germany reported making a metamaterial that had a negative index of refraction for a visible wavelength.

Some critics remain unimpressed. Nicole Guarino of the Spanish National Research Council still calls Dr. Pendry’s statements on negative refraction “propaganda” But today, most physicists accept the negative refraction interpretation.

The debate did highlight limits of metamaterials. They are dispersive, meaning the angle of refraction depends very sensitively on the frequency of light, and they are lossy, meaning that they absorb energy from the light as it passes through.

Nonetheless, Dr. Pendry has proposed that negative refraction materials can be used to make a “superlens” because they sidestep a process called diffraction that blurs images taken with conventional optics. Researchers led by Xiang Zhang, a professor at the University of California, Berkeley, have demonstrated that a thin, flat piece of silver can indeed produce such images, able to resolve two thin lines separated by 70 billionths of a meter.

“You put your object on one side and your image will be projected on the other side,” Dr. Zhang said.

The superlens can also preserve detail lost in conventional optics. Light is usually thought of as having undulating waves. But much closer up, light is a much more jumbled mess, with the waves mixed in with more complicated “evanescent waves.”

The evanescent waves quickly dissipate as they travel, and thus are usually not seen. A negative refraction lens actually amplifies the evanescent waves, Dr. Pendry calculated, and that effect was demonstrated by Dr. Zhang’s experiment. A negative refraction could, in theory, lead to an optical microscope that could make our tiny biological structures like viral viruses.

The main limit now is that an object has to be placed very close to the lens, within a fraction of a wavelength of light.

Another possible use would be for a DVD-type recorder. The finer focus could allow more data than high-definition movies to be packed in the same space, perhaps the entire Library of Congress on a platter the size of today’s DVD, Dr. Zhang said.

The metamaterials researchers also look for new problems to solve. “Now it’s sort of fired up our imaginations to do this cloning thing,” Dr. Pendry said, “because we realized we could actually make use of these materials.”

In May 2006, Dr. Pendry and Dr. Smith proposed a design that would block a single microwave frequency. By October, Dr. Smith’s group at Duke demonstrated a working version, although simplified and imperfect. Dr. Smith’s microwave device cannot be adapted to visible light, because the energy absorption problem becomes too great.

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From ordinary objects, metamaterials that manipulate light.

A step in a process called "cloaking" that eludes the conventional eye.

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The evanescent waves quickly dissipate as they travel, and thus are usually not seen. A negative refraction lens acts essentially as the evanescent waves, Dr. Pendry calculated, and that effect was demonstrated by Dr. Zhang's experiment. A negative refraction could someday lead to an optical microscope that could make out tiny biological structures like individual viruses.

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He said he hopes to build the design, which requires tiny rods arrayed around a cylinder, in a few years. Metamaterials could also be used for other novel devices. Dr. Shalaev suggested "an immortal" that would trap light of a certain wavelength. "That could be used as a sensing device," he said.

Whether the cloak could be made big enough to cover a man or wizard or an alien spaceship is another question. "I'm fairly optimistic knowing what I know now," Dr. Smith said.

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The New York Times; 1st made by Christopher: Howards and Glenn Carroll, Kreford, University.
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The cloak was not perfect. An alien with microwave vision would not have seen the object, but might have noticed something odd. “You’d see a darkened spot,” said David R. Smith, a professor of electrical and computer engineering at Duke. “You’d see some distortion, and you’d see some shadowing, and you would see some reflection.”

A much greater limitation was that this particular cloak worked for just one particular “color,” or wavelength, of microwave light, limiting its usefulness as a hiding place. Making a cloak that works at the much shorter wavelengths of visible light or one that works over a wide range of colors is an even harder, perhaps impossible, task.

Nonetheless, the demonstration showed the newfound ability of scientists to manipulate light through structures they call “metamaterials.”

Obviously the military would be interested in any material that could be used to hide vehicles or other equipment. But such materials could also be useful in new types of microscopes and antennae. So far, scientists have written down the underlying equations, performed computer simulations and conducted some proof-of-principle experiments like the one at Duke. They still need to determine the practical limitations of how far they can bend light to their will.

The method is not magic, nor are the materials novel. Physicists are taking ordinary substances like fiberglass and copper to build metamaterials that look like mosaics of repeating tiles. The metamaterials interact with the electric and magnetic fields in light waves, manipulating a quantity known as the index of refraction to bend the light in a way that no natural material does.

“There are some things that chemistry can’t do on its own,” said John B. Pendry, a physicist at Imperial College London. “The additional design flexibility with introducing structure as well as chemistry into the
equation enables you to reach properties that just haven’t been accessible before.”

When a ray of light crosses a boundary from air to water, glass or other transparent material, it bends, and the degree of bending is determined by the index of refraction.

Air has an index of 1. Water’s index of refraction is about 1.3. That is why rippling water waves distort the view of a pond bottom, for instance. It is refraction that makes a straw in a glass of water look as if it is bending toward the surface, and fish swimming in a pond look closer to the surface than they really are.

Diamonds have a refractive index of 2.4, giving them their sparkling beauty.

For visible light, transparent materials like glass, water and diamonds all have an index of 1 or higher, meaning that when the light enters, its path bends inward, closer to the perpendicular. Because the index is uniform throughout a material, the bending occurs only as the light crosses a boundary.

But with metamaterials, scientists can now also create indexes of refraction from 0 to 1. In the Duke cloaking device, the index actually varies smoothly from 0, at the inside surface of the cylinder, to 1, at the outside surface. That causes the path of light to curve not just at the boundaries, but also as it passes through the metamaterial.

Metamaterials first took center stage in a scientific spat a few years ago over a startling claim that the index of refraction could be not just less than 1, but also negative, less than 0. Light entering such a material would take a sharp turn, almost as if it had bounced off an invisible mirror as it crossed the boundary.

The refractive index depends on the response of a material to electric and magnetic fields. Typically within a material, electrons flow in a way to minimize the effects of an external electric field, producing an internal electrical field in the opposite direction. But that is not universally true. For some metals like silver, an oscillating electric field induces a field in the same, not opposite, direction.

Victor G. Veselago, a Russian physicist, realized in the 1960s that if it were possible to find a material that responded in a contrarian way not just to electric fields and but also magnetic fields, a result would be a negative index of refraction.

Dr. Pendry was among the first to start making metamaterials in the late ’90s, building a structure of thin wires that responded to electrical fields in a way opposite most materials. He also designed one that reacted similarly to magnetic fields.

Dr. Smith, then at the University of California, San Diego, attended a talk by Dr. Pendry at a conference in 1999. He and his colleagues built the first metamaterial to combine electric and magnetic behavior.

The journal Physical Review Letters rejected his scientific paper describing the experiment, considering it simplistic and uninteresting. Only then did Dr. Smith come upon Dr. Veselago’s work on negative refraction and the larger implications of the experiment. “We had it, but we didn’t realize it,” said Dr. Smith, who is now at Duke. “Then I rewrote the abstract, and it was accepted.”

That set off a contentious back and forth that lasted several years between researchers who made and
measured negative-refraction metamaterials and those who said that the experiments showed nothing of the sort, that negative refraction was at best an illusion and violated the laws of physics.

Part of the difficulty in resolving the controversy was that the negative refraction experiments were at microwave wavelengths. Designing metamaterials for shorter wavelengths and higher frequencies like visible light is more difficult, because fewer materials are transparent at the higher frequencies.

“Just look around the room,” Dr. Pendry said. “How many things can you see through? Not many. You’re running out of road.”

This year, researchers at the Ames Laboratory in Iowa and Karlsruhe University in Germany reported making a metamaterial that had a negative index of refraction for a visible wavelength.

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