

visibility cloaks get all the publicity, but they may just be the beginning if the promise of transformation optics can be realized. The discipline could lead to smaller photonic and electronic devices and more cost-competitive solar cells – in addition to those long-sought-after invisibility cloaks.

Achieving these and other advances assumes that the challenges confronting transformation optics can be successfully overcome. Chief among these are dealing with losses and building the tiny structures needed in metamaterials, the composite materials that make the field possible.

Taking the shortest path

Transformation optics work by exploiting how light travels, researcher Vladimir M. Shalaev said. “Light propagates in such a way that it minimizes the optical path, which is a product of the geometrical path and the refractive index.”

Shalaev, a professor of electrical and computer engineering at Purdue University in West Lafayette, Ind., is a key player in the new field. He noted that bulk homogeneous materials have a single refractive index. Thus, the path of light through them is determined by geometry.

Metamaterials, in contrast, can have a varying refractive index. This can be done by building rings and rods, by embedding metallic nanoparticles or by other means.

The key is that the structures must be much smaller than the wavelength of the light of interest and that the structures must interact with the photons.

The result is an apparent refractive index at specific wavelengths that is not restricted to being more than 1, as is the case with bulk materials. Instead, it can be less, with values close to 0 and even negative possible.

Because of this, light then can be made to curve around objects, which is how an invisibility cloak would work. It can be made to disappear into a concentrator, never to re-emerge. It can even be made to reverse direction, all courtesy of metamaterials with the right refractive index value and profile.

For Shalaev, the physics behind this is exciting, but he acknowledges that applications ultimately will drive funding and the field itself. He noted ongoing announcements of advances in invisibility cloaking and pointed out that making an object look like something else has been demonstrated, which is a step toward cloaking. Such mimicry can be beneficial when trying to hide something and is of interest to the military.

But cloaking and mimicry are not where some of the first important uses could arise, Shalaev said. “One of the first key applications of metamaterials and transformation optics I expect to be in the area of

subdiffraction imaging. The most promising thing here is a planar magnifying hyperlens.”

Such a hyperlens would magnify objects that were below the traditional diffraction limit, about a half-wavelength of light, so that they could be imaged with conventional optics. A researcher using a standard microscope equipped with a hyperlens could observe objects currently too small to see.

Just as importantly, a hyperlens would work in the opposite direction, concentrating light into spots smaller than can be achieved with standard optics. That capability could be of critical importance to the semiconductor industry, which manufactures chips using nonlinear optical-based processing. That will be the basis for the 22-nm technology node, expected to debut in 2011, but trouble looms beyond that for the current 193-nm immersion lithography. A hyperlens would allow the extension of current tricks to even smaller features and could be a boon to the chip industry.

Let the sun shine in

Besides a hyperlens, another potential transformation optics application involves solar cells. Most are built using crystalline silicon wafers with a thickness of up to 300 μm . That distance is required to efficiently capture the red part of the

spectrum, which is poorly absorbed by silicon.

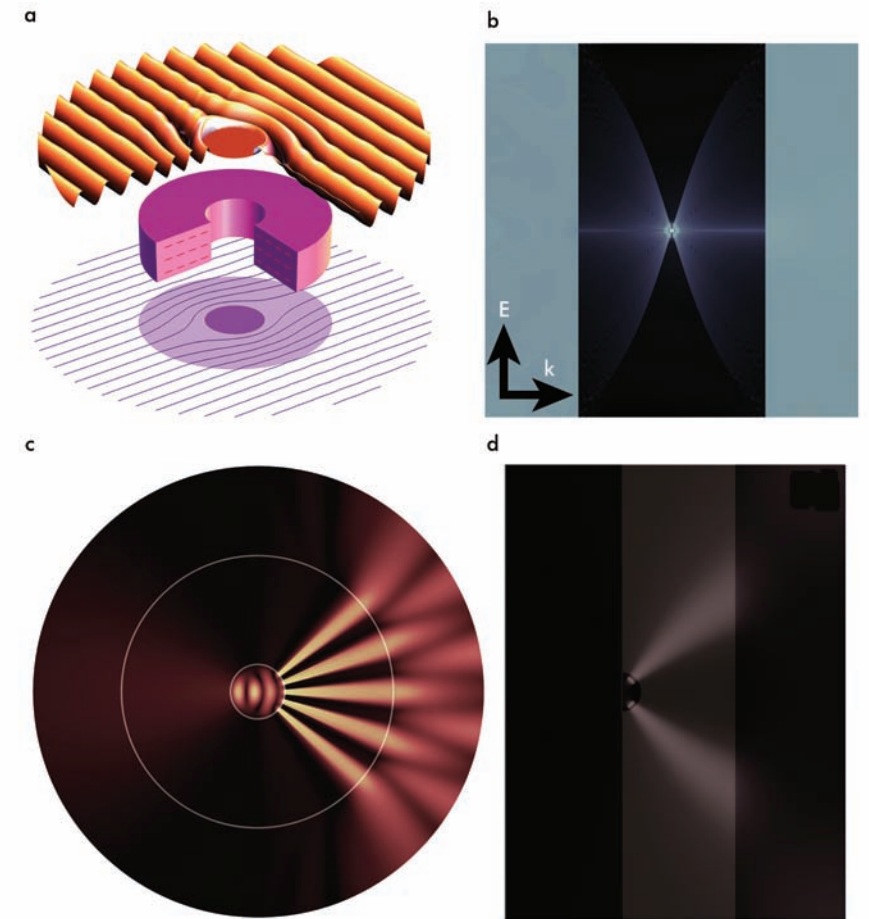
However, silicon adds significantly to the cost of solar cells. It is part of the reason why solar power is anywhere from two to five times as pricey as it would have to be to be cost-competitive.

Transformation optics offers a solution to this problem through the construction of plasmonic solar cells. These use metallic nanostructures that support surface plasmons, excitations of the conduction electrons at the interface between a metal and a dielectric. Properly engineered, these metallic-dielectric structures can concentrate and fold the light into the semiconductor layer, making possible more cost-effective solar cells.

“Plasmonic solar cells have the potential to make solar cells ten to twenty times thinner, while keeping the efficiency the same. Because materials costs constitute a large price of the solar cell, the needed two- to fivefold reduction in price is within reach,” said Albert Polman, scientific group leader at the FOM Institute for Atomic and Molecular Physics in Amsterdam, the Netherlands.

A pioneer in the plasmonic solar cell field, Polman said that research results are encouraging. The addition of the metallic nanoparticles does add to the cost of the solar cell, partly because the material of choice is silver or gold. The cost, however, is minimal because the structures measure in the 100-nm range.

There is also some added cost resulting from additional processing. There are solutions to this issue, however. For example, Polman’s group has developed a technique that allows the nanostructures to be added in a roll-to-roll soft imprinting process to the back of the solar cell.



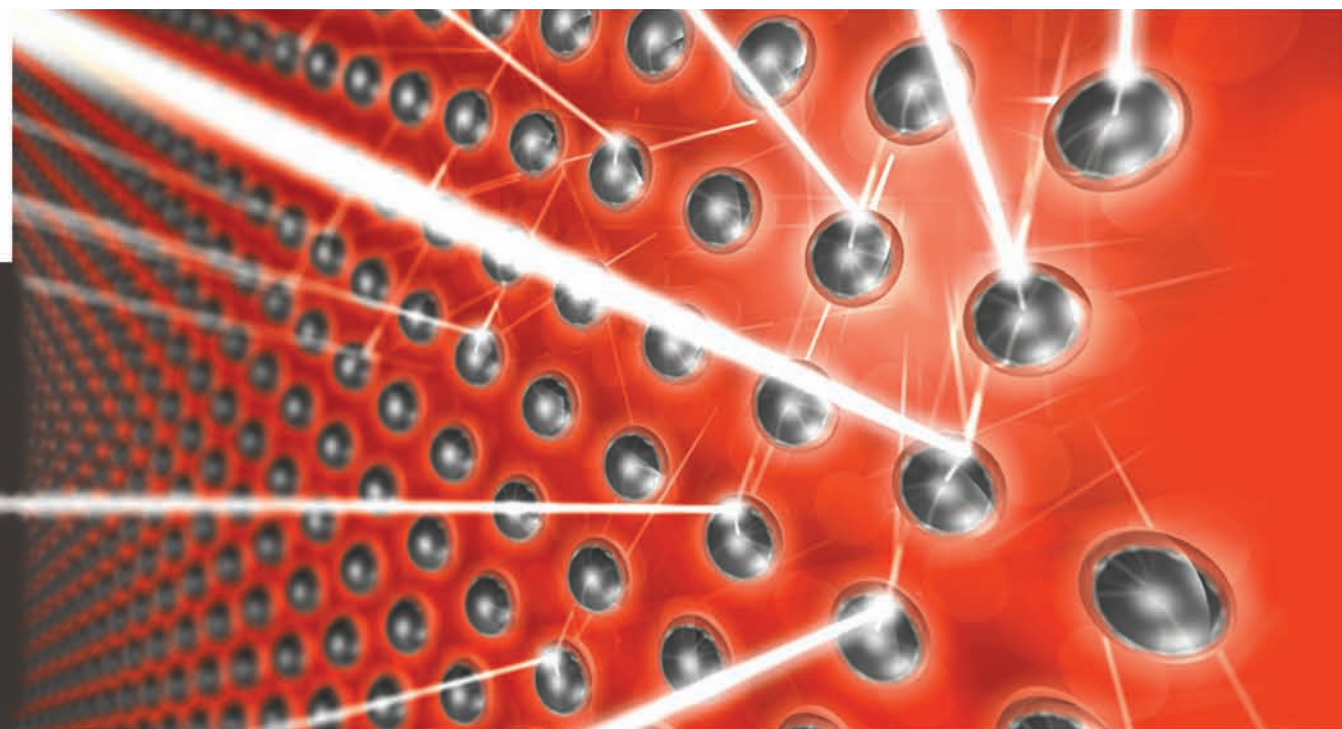
Transformation optics could be used to create (a) an invisibility cloak, (b) a light concentrator or (c and d) a hyperlens. These applications depend on steering light where desired: around an object for invisibility or to a point for a concentrator. Courtesy of Vladimir M. Shalaev, Purdue University.

The current state of affairs, Polman explained, is that the concepts have been proved in the lab, and the results agree with what models predict. It is now a question of implementing a solution tailored to a particular solar cell manufacturing process and showing the benefit in a real-world installation. He reported that his group is working with manufacturers to do just that.

Kylie R. Catchpole, a research fellow

at the Canberra-based Australian National University, is an active collaborator of Polman’s. She noted that one knob that researchers can turn to boost performance involves adjusting the plasmon resonance, the wavelength of maximum photon interaction and scattering.

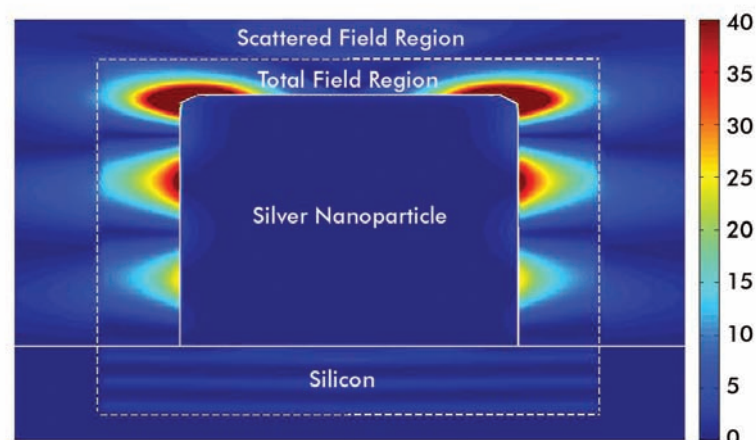
“There is much more scope for tuning the plasmon resonance than we realized. This makes it very easy to make the scat-



bending light at will with transformation optics

BY HANK HOGAN
CONTRIBUTING EDITOR

A plasmonic solar cell, shown in this artist’s rendering, at left, could cut the cost of solar power. Light is scattered and trapped using an array of metal nanoparticles placed either in front or in back of the solar cell. Less silicon is then needed. Courtesy of AMOLF/Tremani.



Standing waves form around a tall silver nanoparticle on a silicon substrate when light comes from above. Such nanoparticles scatter more light into the silicon, making it absorb like a much thicker sample. Courtesy of Kylie R. Catchpole, Australian National University.

tering strongest in the part of the spectrum where absorption most needs improving,” she said.

The overall behavior of the nanoparticles is strongly dependent on their size, shape and arrangement, she added. Thus, fabrication techniques, as well as design and characterization strategies, will be important in producing these plasmonic solar cells.

Dealing with loss

There are some problems to be overcome, however, before a hyperlens, plasmonic solar cell or an invisibility cloak can be built. One is manufacturing. Because the metamaterials must have features well below the wavelength of the light of interest, the structures involved can be quite small.

For the visible range of 400 to 700 nm, the dimensions may have to be much less

than 100 nm. That is one reason why so many demonstrations are done first using microwaves. The longer wavelength means that the structures can be much larger and, therefore, easier to construct.

Progress in this area is being made, however. Shalaev’s group at Purdue, for instance, has made metamaterials with a negative refractive index at 500 nm, well into the visible. Negative refraction is possible for only a relatively narrow spectral window, but Shalaev pointed out that going negative is not necessary for many applications. For these, the refractive index need only be near 0 or vary between 0 and 1. Because of that, broadband use of transformation optics is possible.

Another problem is optical loss. As photons traverse a metamaterial, they can disappear into it. For some applications, that is not an issue. For others, it can be a killer. An invisibility cloak that hides you

but that looks black because of light loss, for instance, wouldn’t be of much use.

There are solutions. One that has been proposed is to compensate for the loss by adding something like dye molecules or quantum dots to the dielectric. These would create optical gain, potentially negating any loss.

Such a scheme would have to be done carefully, cautioned Mikhail A. Noginov, a professor of physics at Norfolk State University in Virginia. Too much gain could lead to nonlinear effects and, with feedback, could result in a laser. The goal would be to balance gain and loss, with the outcome a small loss.

Noginov also has done work in which the loss was reduced without gain by alloying two metals together. In another loss-reducing scheme, he modified the surface of a metal with dye molecules, which led to elongation of the surface plasmon polariton propagation length. Both of these approaches, however, have their own issues. The first, for instance, helps only at some wavelengths and actually makes loss higher at others.

But, in speaking about the future, Noginov predicts that the loss issue will be resolved. He said that silicon today is a nearly perfect material, but this came only after decades of work. That history gives hope for tomorrow’s transformation optics applications and the metamaterials that make them possible.

Speaking of the metamaterials, Noginov said, “Now they’re not as good as we want, but probably after some time and some effort, they may be significantly improved.”

hank.hogan@photonics.com