APPLIED PHYSICS

How to Build a Superlens

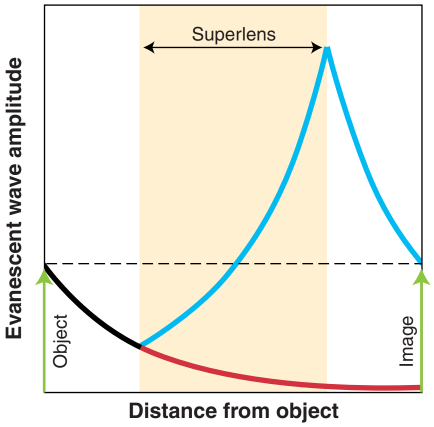
David R. Smith

In 1968, Veselago conceived of a material whose index of refraction, unlike that of any known material, could be negative (*1*). He suggested that this negative-index material would reverse nearly all known optical phenomena. Amid considerable initial skepticism, negative refraction was experimentally confirmed in an artificially structured material at microwave frequencies in 2001 (*2*). The work prompted a flurry of activity by researchers to further explore and demonstrate the properties of negative-index materials.

One of the most dramatic—and controversial (*3*)—predictions to emerge from this activity was a speculation by Pendry (*4*) that a thin negative-index film should function as a "superlens," providing image detail with a resolution beyond the diffraction limit to which all positive-index lenses are subject. On page 534 of this issue, Fang *et al.* (*5*) confirm the theoretical predictions of Veselago and Pendry. They show that a planar negative-index lens can indeed produce a sharp image by virtue of a new mechanism: evanescent wave refocusing.

Conventional positive–refractive index lenses require curved surfaces to bend the rays emanating from an object to form an image. Yet, Veselago noted that negative–refractive index lenses are not subject to the same constraint. He found that a planar slab of material with a refractive index of –1 could also produce an image (*1*). For this lens, diverging rays from a nearby object are negatively refracted at the first surface of the slab, reversing their trajectories so as to converge at a focus within the material. The rays diverge from this focus and are again negatively refracted at the second surface, finally converging to form a second image just outside the slab. Although it produces an image, the planar lens differs from conventional curved-surface lenses in that it does not have an optical axis, does not focus parallel rays, and has a magnification that is always unity.

On careful reexamination of this planar lens, Pendry found that the ray picture applied by Veselago did not tell the whole story (*4*). The electromagnetic field of an object includes not only propagating waves, but also near-field "evanescent" waves that decay exponentially as a function of distance away from the object. The evanescent waves carry the finest details of the object, but cannot be recovered by conventional positive-index lenses, which can therefore resolve objects to no better than roughly one-half of the illuminating wavelength—the diffraction limit.



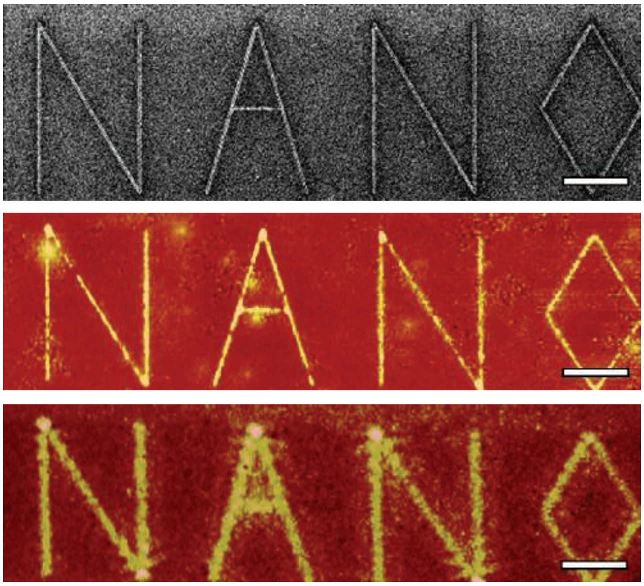
The principle of evanescent wave refocusing. The exponentially decaying wave from the object on the left grows exponentially within the planar negative-index lens (blue curve). On the other side of the lens, it decays again until it has reached its original value at the image plane. These components of the object are lost in the absence of the negative-index lens (red curve).

Pendry found that a planar negative-index slab should refocus the evanescent waves, at least to some extent. An evanescent wave decaying away from an object grows exponentially across the planar negative-index lens (see the first figure). On exiting the lens, the wave decays again until it reaches the image plane, where it has the same amplitude with which it started. Unlike any other lens, the resolution limit of the planar negative-index lens is determined by how many evanescent waves from the object can be recovered, rather than by the diffraction limit.

There is no theoretical limit on the resolution of the superlens, but for a reasonable amount of evanescent wave refocusing to occur, the distances between the object, its image, and the slab surfaces—and the thickness of the slab itself—must all be small relative to the wavelength. If these conditions are not met, the evanescent waves from the object decay to the extent that their recovery becomes impractical owing to material losses and other material imperfections of the lens.

This constraint, as it turns out, also hides a virtue. A negative-index material requires both the electric permittivity ε and the magnetic permeability μ to be less than zero. At optical wavelengths, there are no known materials that have a negative μ; this would appear to rule out a superlens at optical wavelengths. However, over scales much less than a wavelength, electric and magnetic effects decouple, and only one of the two parameters has to be negative. Because $\varepsilon < 0$ occurs naturally in silver and other metals at visible wavelengths, a thin metallic film can act as an optical superlens.

Following Pendry's suggestion, Fang *et al.* now demonstrate evanescent wave refocusing in the context of optical lithography. In the experiments, a thin film of silver



A demonstration of evanescent wave refocusing. Fang *et al.* show that evanescent wave refocusing can be used to create the optical image (**center**) of a lithographically written object (**top**) with subwavelength resolution. Without the lens, the image resolution is much lower (**bottom**). Scale bar, 2 μm.

CEDIT SECOND FIGURE: FROM (5)

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serves as the superlens that transfers the image of a lithographically written pattern to a nearby layer of photoresist. But coaxing evanescent waves to grow requires two stringent criteria to be satisfied. First, the surface of the film must be extremely smooth; otherwise, surface imperfections scatter the incident light and wash out the finer details carried by the evanescent waves. Second, the thickness of the silver film must be optimized: If it is too thick, material losses dominate over the evanescent wave refocusing, and none of the information carried by the evanescent waves is recovered in the image. The film produced by Fang *et al.* meets both criteria, with an optimal thickness of ~35 nm and a surface roughness of less than 1 nm (*6*).

The demonstration of superlensing requires a subwavelength object. In the experiments of Fang *et al.*, such an object is formed by the light that passes through thin slits (with a width of 40 nm) that have been patterned into an otherwise opaque chromium mask. Because the slits are narrow relative to the wavelength (365 nm), the light is strongly diffracted, with most subwavelength features being contained in the evanescent waves. As a result, the image blurs rapidly as a function of distance away from the mask. The reduction in image quality is noticeable over a distance of tens of nanometers, as can be seen in the second figure.

Fang *et al.* use the light that passes through the chromium mask and the lens to expose a layer of photoresist, where the optical image is converted into a topographic map of peaks and valleys that can be scanned with an atomic force microscope. As an example, the authors patterned the word "NANO" into the mask (see the second figure, top panel). In the absence of the silver superlens, the lines that form the letters are diffuse (bottom panel), with a measured line width of more than 300 nm. With the silver superlens, the evanescent waves are recovered, and markedly better resolution is obtained (middle panel), with an observed line width of less than 90 nm.

The results of Fang *et al.* (*5*) confirm that the predicted phenomenon of evanescent wave refocusing is indeed possible at visible wavelengths. This important advance not only resolves a controversial aspect of negative-index materials, but also opens the door to a variety of possible applications, including higher resolution optical imaging and nanolithography. Optical elements can now be designed to access and exploit the near-field of light.

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NEUROSCIENCE

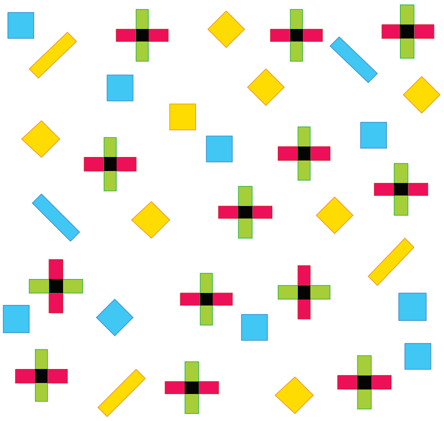
Watching Single Cells Pay Attention

Jeremy M. Wolfe

As visual organisms, we spend much of our time engaged in visual search behavior. We seek to make the current object of our desire into the current object of our visual attention and motor action. You want a sip of coffee. There is the mug. Then you wonder, where is the "%" sign on the keyboard? Next, the ring of the phone redirects your attention to that object. Most searches such as these go by so quickly and effortlessly that we don't notice the search aspect at all. We do notice when the task becomes more difficult: Where is that corkscrew in the kitchen gadget drawer? Ah, there it is, in full view, but somehow not noticed until after a prolonged period of searching. Insights into how area V4 of the visual cortex might participate in these sophisticated search tasks are revealed by Bichot *et al.* (*1*) on page 529 of this issue.

So, how do we carry out these search tasks? Behavioral and physiological experiments conducted over more than a quarter century have emphasized one of two types of mechanism: parallel processing, in which all (or many) objects are analyzed at once (*2*, *3*); and serial processing, in which one (or very few) of the available objects are selected for specialized analysis (*4*, *5*).

You may be able to get a qualitative appreciation for these modes of processing by searching for one of the objects in the figure. Find the blue diamond. You will probably notice that all of the blue items seem to make themselves available to you at the same time. If you now search for the yellow square, the blue items recede into the background, while the yellow ones take center stage. Obviously, the stimulus has not changed. Your search goal has changed your analysis of that stimulus. If you are asked to search for the plus sign with red-vertical and green-horizontal elements, all the red and green plus signs may seem to become salient. But at the same time, you may be aware that some scrutiny of single items is needed before you find the plus sign having red linked to vertical. (If it felt instantaneous, go find the *other* plus sign with a red-vertical element. There are two.) The color and orientation features seem to be present almost immediately, but the binding of a color to an orientation seems to require something more.



Finding a needle in a haystack. Your analysis and experience of this display will change depending on whether you are looking for a blue diamond or for a plus sign with a red-vertical element. Bichot *et al.* reveal how different aspects of attention modulate the response of neurons in area V4 of the visual cortex as monkeys perform similar tasks (*1*).

Here, then, are two rather different types of processing that might be seen to fall into the general category of "attention." First, it seems possible to attend to a distributed set of items based on features like color. And second, it seems possible to select individual items for fixation or to select an item for further analysis even if it is not fixated. In most, if not all, search tasks, these processes interact to produce an effective visual search (*6*, *7*). Parallel information about features will guide your serial selection of individual objects—as you pick your favorite bits out of a fruit salad, for example.

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