Oblique-angle deposition, an industrial workhorse technique, has been used to deposit silver thin films that should refract negatively in the visible regime.

By virtue of their microstructure, artificial composite materials called metamaterials show properties not exhibited by their component materials. Negatively refracting metamaterials are typically made by embedding in a homogeneous host material an array of metallic, subwavelength elements that simulate electric and magnetic dipoles (electric dipoles are pairs of opposite charges separated by a small distance, whereas dipoles are small loops of current). These materials have an unusual ability to manipulate electromagnetic waves because, in them, an electromagnetic wave propagates with the direction of its energy flow opposed to its phase velocity. This phenomenon is indicated by the real part of the complex-valued refractive index being negative. The imaginary part of the refractive index indicates attenuation of light intensity. (A complex-valued quantity is a pair of two numbers, one of which is its real part and the other its imaginary part.)

Theoretical analyses have shown that negative refraction will enable the emergence of planar lenses instead of curved lenses, that would produce high-fidelity images and would therefore advance optical read and write operations with high-density CDs and DVDs. Moreover, these planar lenses could be integrated with semiconductor technology, which is based on planar interfaces between dissimilar materials. Another possible use is in making cloaks to hide objects from optical inspection, or to reduce interaction between two neighboring optical devices. The elements in a metamaterial that refracts negatively in the microwave and terahertz regimes comprise incomplete loops and straight wires. In the near-infrared part of the spectrum, parallel pairs of metal rods in a dielectric (insulating) host material and parallel pairs of dielectric rods in a metal have been used. Recently, a 2D periodic array of parallel silver nanowires embedded in alumina was shown to negatively refract visible light.

Optical applications of negative refraction would be greatly facilitated by a simple technique that allows fabrication of thin-film samples with a large transverse area. Such a method would reduce unit production costs significantly and promote commercial exploitation of the technology. With that goal in mind, we decided to use oblique angle deposition (OAD), which emerged as far back as the 1860s and is now considered a workhorse technique in the optical-thin-films industry. In an evacuated chamber, vapor from a solid is directed at an angle (deposition angle) to the normal to a flat substrate. The vapor is either thermally generated by heating the solid or by directing an energetic beam of electrons, ions, or photons toward it. Deposition conditions can be chosen so that nanorods grow preferentially toward the incoming vapor, with the resulting thin film having long been recognized to be optically anisotropic (a directional property

Figure 1. Scanning electron microscope image of a silver thin film prepared by the oblique-angle-deposition technique.
that is exploited in devices such as antiglare sunglasses and polarization filters for cameras).

We deposited a thin film comprising parallel, tilted silver nanorods on square substrates of fused silica by electron-beam evaporation. Figure 1 shows a scanning electron microscope image of this 240-nm-thick film. The nanorods are tilted with respect to the substrate normal at an angle of 66° ± 5°. A silver thin film, when considered as a continuum at sufficiently large wavelengths, must possess a kind of anisotropy classified as orthorhombic. We assumed that it has linear dielectric and magnetic properties. In general, the effective relative permittivity tensor \( \tilde{\varepsilon} \) of the film then must have three distinct eigenvalues, and so must the effective relative permeability tensor \( \tilde{\mu} \). But both will have the same set of three eigenvectors. When the film is illuminated normally, different combinations of the eigenvalues of these two tensors appear for the two linear polarization states when the wave vector of the incident light lies wholly in the deposition plane. We label the combinations \( \varepsilon_p, \mu_s \) for p-polarization, and \( \varepsilon_s, \mu_p \) for s-polarization. This distinction in the properties of the thin film on normal illumination is due to the thin film’s anisotropy.

The two reflection coefficients \( r_p \) and the two transmission coefficients \( t_p \) were measured at specific wavelengths using an ellipsometer and a walk-off interferometer. From these data, the refractive indexes \( n_{p,s}, n_{p,s}^2 = \varepsilon_{p,s},\mu_{p,s} \) were obtained. We found that the real part of \( n_p > 0 \), but the real part of \( n_s < 0 \) at wavelengths ranging from 532 to 690 nm. Thus, the silver thin film will negatively refract p-polarized light in a large part of the visible regime. However, because significant attenuation also occurs, optimization of deposition parameters and infiltration of the void regions of the silver thin film by a gain medium are topics for further research.

In summary, we have fabricated a thin film that has two different complex-valued refractive indexes for normally incident light of different linear polarization states. The real part of one of the two refractive indexes is negative over a wide range of wavelengths of visible light. Hence, this thin film will negatively refract light of many colors. Thin films of this kind can be deposited over continuous, transparent, flexible substrates that are tens of centimeters in width. Integration with semiconductor technology is also possible. We are now working on optimizing deposition conditions to both achieve negative refraction over the widest range of visible-light wavelengths and minimize attenuation.

**References**


**Author Information**

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**Akhlesh Lakhtakia**  
Engineering Science and Mechanics  
Pennsylvania State University  
University Park, PA  
http://www.esm.psu.edu/~axl4/

Akhlesh Lakhtakia is the Charles Godfrey Binder Professor of Engineering Science and Mechanics. He obtained his BTech and DSc from the Institute of Technology, Banaras Hindu University, India, and his MS and PhD from the University of Utah. His research interests include complex materials, metamaterials, and sculptured thin films.

**Yi-Jun Jen**  
Department of Electro-Optical Engineering  
National Taipei University of Technology  
Taipei, Taiwan  

Yi-Jun Jen is professor and chairman of the Department of Electro-optical Engineering, which he joined in 2002. He received his MS and PhD from the Institute of Optical Sciences at National Central University, Taiwan, in 1994 and 2001, respectively. His current research interests include anisotropic optical analysis, fabricating nanosculptured thin films, developing novel optical devices with multilayer design, and measuring nanoscale composite materials.