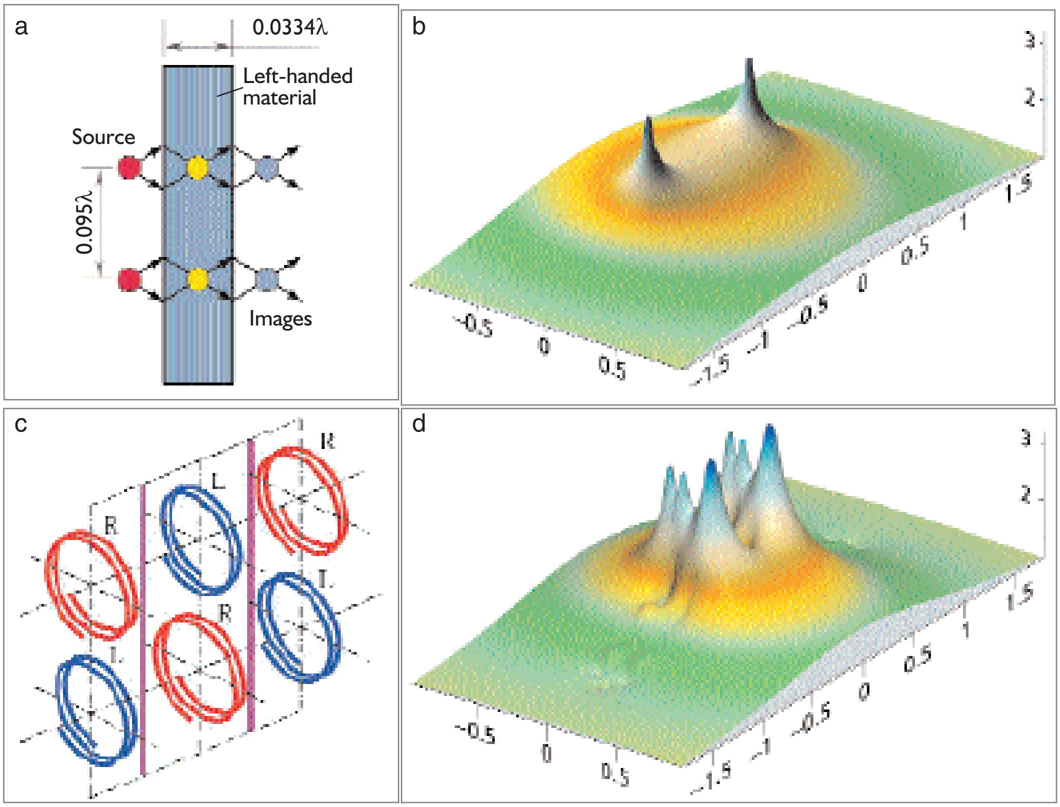
Superlenses

Left-handed materials are those with a negative refractive index. They are left-handed because the normal right-handed rule relating magnetic fields and current direction is reversed in them (see *The Industrial Physicist*, June 2000, pp. 11–13). One of the peculiar capabilities predicted for such materials is the formation of perfect images with solid, flat, ultrathin layers of material. A. Lagarkov and V. N. Kissel of the Institute for Theoretical and Applied Electromagnetics (Moscow) have now experimentally demonstrated the reality—and the limitations—of such perfect imagers or superlenses (*Phys. Rev. Lett.* 2004, 92, 077401-1).



Institute for Theoretical and Applied Electromagnetics
Russian Academy of Sciences, Moscow

An image of two antennas (a) separated by only a fraction of a wavelength of emitted microwave radiation is possible (b) when focused by a left-handed material that includes an array of wires (c), but not possible without it (d).

In normal lenses, diffraction of electromagnetic radiation—whether it be light, microwaves, or infrared (IR)—sets a limit on the resolution of an image. Generally, sources can be resolved only if they are more than a wavelength apart from each other. In theory, however, in a left-handed material, the direction of radiation changes at the surface of a material with a negative index of refraction in such a way as to form a perfect focus on the other side of the solid plate. This occurs, however, only if the distance between the plate and the object to be imaged is less than the thickness of the plate.

The Moscow researchers showed theoretically, however, that inevitable energy losses within a left-handed material prevent the formation of a perfect image—that is, one that brings to a point all the photons that leave from a given point. But a near-perfect image that significantly exceeds the diffraction limit is possible if the plate thickness is only about 1/30th of a wavelength (or at least a small fraction of a wavelength), which limits energy losses. To test this theoretical result, the researchers fabricated a material that had the requisite negative refractive index at a frequency of 1.6 GHz. The material consisted of an array of horizontal 5-mm-diam spiral wires and vertical wires aligned in parallel. The team created images of two wires, separated by one-sixth of a wavelength and emitting microwave radiation at the 1.6-GHz frequency. The experiments showed that the plate created images that clearly separated the two wires. Without the plate, the wires blurred into a single peak.

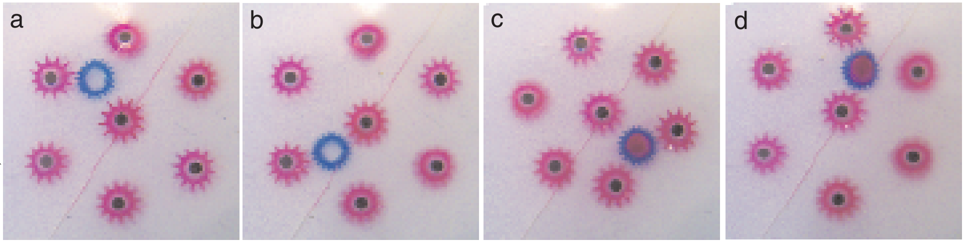
Superlensing is unlikely to show up in new microscopes, however. For one thing, left-handed materials appear difficult to develop for optical or IR frequencies. More fundamentally, such superlensing occurs only when the object is within the near-field of the plate. Near-field imaging using ultrasmall apertures is already a developing microscope technology.

However, Kissel believes that near-term applications will be realized in microwave engineering. “New microwave components [such as frequency and spatial filters, phase shifters, and nonlinear devices] and resolution enhancement in the fields of microwave medical imaging and nondestructive inspection seem to be the most likely developments,” he says.

Self-organizing device

Machines normally operate in a state close to equilibrium, in which flows of energy are minimized. This condition ensures maximum stability and predictability of operation. Living organisms, in contrast, operate far from equilibrium. As thermodynamicist Ilya Prigogine first showed 30 years ago, large energy flows allow living things to self-organize themselves, a process that also occurs with inanimate systems far from equilibrium.

Can small machines self-assemble on the basis of the same principles of dynamic



ProChimia, Poland

In this application, seven electromagnetic gears form a carousel that entrains an empty floating nonmagnetic container (blue in a), rotates it around (b) to a filling point (c), and continues the rotation to a point where it can be ejected (d).

self-organization? Bartosz Grzybowski at Northwestern University, together with colleagues at Harvard University and ProChimia (Sopot, Poland), has demonstrated that they can, at least on a basic level. The team found that simple processing devices can self-assemble themselves in a fluid from simple parts that are guided into place by electromagnetic fields and the vortex flows created by their own rotation (*Appl. Phys. Lett.* 2004, *84*, 1798).

Grzybowski and his colleagues used the old idea of mixing and pumping fluids by rotating a magnet in the fluid with a rotating external magnetic field. But their approach differs from conventional methods in that they can easily reconfigure their machinery to meet the needs of a variety of applications.

The machine consists of a liquid-filled tub with a rotating magnet and a switchable array of small electromagnets outside it. Atop the liquid, the researchers float conical magnetic rotors 750 μm in diameter and 3.6-mm-diam nonmagnetic rings with spokes or teeth on the outside. In addition, a small vibrating aluminum foil creates an initial fluid flow.

When the rotating external magnet is at rest, no energy flows through the machine and the magnetic rotors and nonmagnetic rings self-assemble randomly into rotor–ring pairs. When that magnet is turned on, several events occur. The conical magnetic rotors start spinning at about 1,000 rpm, creating tiny vortices that center themselves inside the rings. The rings, in turn, are propelled by the vortices at 33 rpm and create their own slower and wider vortices around them. The rotor–ring pairs are attracted to the fixed external electromagnets, but the vortices set up by the rings repel other rings, and so the rotor–ring pairs settle in a stable array, one pair over each switched-on electromagnet. The machine is now ready to function.

Depending on the arrangement of the external electromagnets, the machine can perform simple mechanical operations such as sorting small particles by size or manipulating small containers so they can be filled with reagents. Another application is as a highly efficient mixer. Friction in the rotors is essentially eliminated because the rotors have no axles. (In the overall system, of course, frictional losses do occur in the rotating external magnet and in the fluid itself.)

"The main advantage of such machines is that they are reconfigurable in real time simply by moving the external electromagnets," Grzybowski explains. "This is because they are metastable systems, not stable ones." The basic design could be shrunk to the scale of tens of micrometers, although at smaller scales, the importance of capillary forces on the liquid surfaces might necessitate major changes. Grzybowski believes that three-dimensional arrays operating within the fluid rather than at the surface are possible on smaller scales, and the team is looking at such arrays in ongoing research.

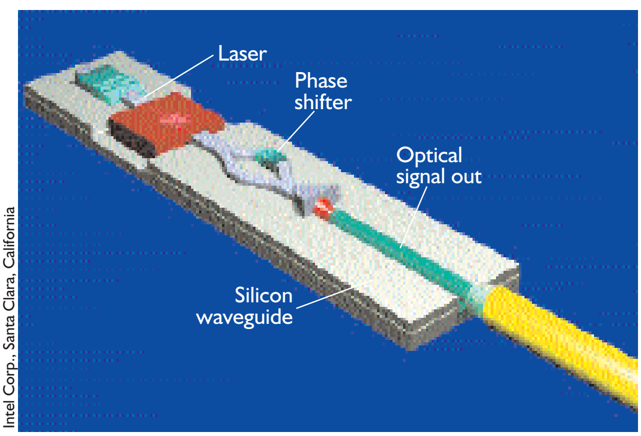
Silicon photonics

Silicon is the inexpensive basis for all electronics; photonics generally uses more costly materials. A long-term goal of photonics researchers is to use all-silicon elements for photonics, thus cutting the costs of these elements and allowing their integration into ordinary microcircuits. However, a major barrier to this goal until now has been the relatively slow speed of silicon-based modulation of light, which had only reached about 20 MHz.

An Intel Corp. team (Santa Clara, CA, and Jerusalem, Israel) has now eliminated this speed limit by developing a complementary metal oxide semiconductor capacitor that achieves light modulation rates as high as 2.5 GHz (*Nature* 2004, *427*, 615). The approach uses the well-known change in refractive index that occurs in silicon as the density of free carrier electrons or holes varies. Conventional approaches of injecting electrons into a silicon p-i-n (positive-insulator-negative) diode have been limited in speed. The Intel team instead used a capacitance effect to achieve greater speed.

The modulator consists of a negatively doped crystalline silicon slab and a positively doped polysilicon (amorphous silicon) layer, with a gate oxide sandwiched between them and aluminum electrodes deposited atop the polysilicon layer. The light travels through the polysilicon layer.

With a positive voltage applied to the electrodes, a thin layer of charge quickly accumulates on the outer layers of the gate oxide



Intel Corp., Santa Clara, California

A silicon-based capacitor modulates light at high speed by shifting the phase of the light, splitting the beam, and allowing the two beams to interfere with each other.

layer that lies next to the polysilicon. This charge is sufficient to slightly change the index of refraction and shift the phase of the transmitted light. To convert a shift in phase to a modulation in amplitude only requires splitting the light into two parts, which are then interfered against each other. When the phase shift causes destructive interference, the transmitted light amplitude decreases, modulating the light.

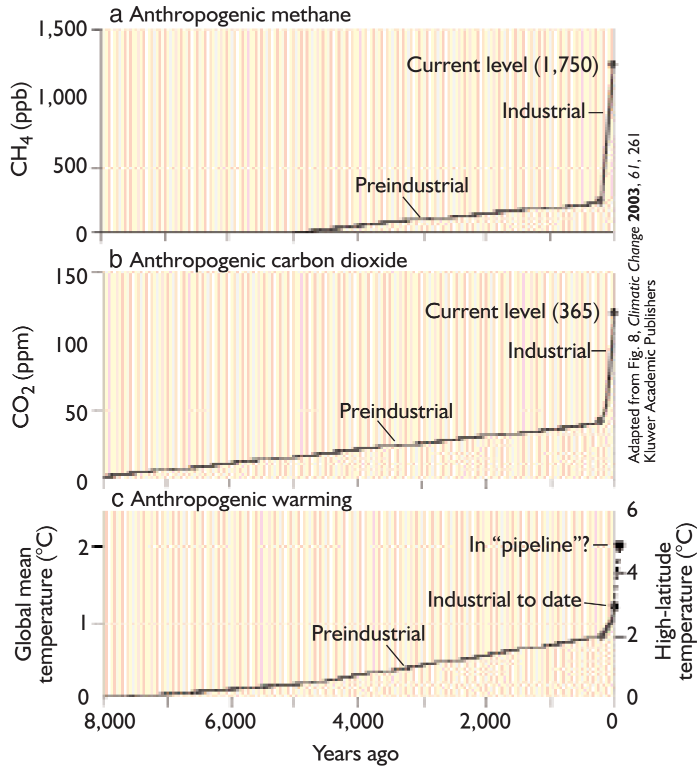
"Experiments performed so far indicate we can reach at least 2.5 GHz," said Ansheng Liu, one of the team researchers. Inexpensive, all-silicon photonics could ease the use of optical links at the chip level and reduce bottlenecks in data transfer in computers, among other applications.

Millennia of global warming

Scientific, economic, and political discussions about global warming caused by human activity have tended to focus on the emissions of carbon dioxide (CO_2) by the burning of fossil fuels, a process that became significant only 200 years ago. But deforestation, the conversion of forest land to agricultural or pasture land, also increases CO_2 as carbon stored in trees is released to the atmosphere. Indeed, a new study by William F. Ruddiman of the University of Virginia indicates that human agricultural and deforestation activities have been increasing greenhouse gases and inducing global warming for thousands of years (*Climatic Change* **2003**, *61*, 261; *Nature* **2004**, *427*, 582) and may have prevented the return of Ice Age climates.

Ruddiman's analysis begins with the well-accepted theory that the cyclical alternation of Ice Ages with brief interglacial periods, such as the present, is controlled by regular oscillations in Earth's orbit. The amount of sunlight received by the planet in summer and winter varies by as much as ±10% as Earth's orbital eccentricity (ellipticity) changes, as the point in Earth's orbit nearest the sun moves around the orbit, and as Earth's axis wobbles (precesses). This 20% oscillation—a combination of 100,000-, 41,000-, and 23,000-year cycles—sets in motion changes in Earth's climate that amplify the variation in solar radiation. In the end, the oscillation determines the advance and disappearance of the giant ice sheets that have periodically covered much of the northern hemisphere for the last 2.75 million years.

Samples of atmospheric gases trapped in ice in Greenland and Siberia show that the levels of two greenhouse gases, CO_2 and methane, closely track solar-radiation cycles, with the gases increasing as the radiation and temperature rise and declining when they fall. But this close correlation, valid over hundreds of thousands of years, breaks down in the most recent period. Although solar radiation started to decline 10,000 years ago, CO_2 in the atmosphere began to rise 8,000 years ago and methane started to rise 5,000 years ago, rather than falling as expected. The anomaly amounts to a rise of one-sixth in CO_2 and nearly one-half in methane over the levels that would be expected by the radiation cycle alone.



Methane emissions from farming over the last 5,000 years (a) and CO_2 emissions from deforestation over the last 8,000 years (b) have elevated temperatures at high latitudes (c) and may have forestalled a new Ice Age.

After ruling out possible nonhuman causes for the rise in greenhouse gases, Ruddiman showed that deforestation, which began with the development of agriculture in the Eastern Mediterranean some 8,000 years ago, could account for the observed rise of CO_2. Deforestation during the last 8 millennia has resulted in clearing nearly 13 million square kilometers of land and the release of some 320 billion tons of carbon into the atmosphere. This is about twice the carbon released by the burning of fossil fuels. Also, beginning about 5,000 years ago, East Asian farmers began widespread rice farming with irrigated paddies, which would emit roughly enough methane, in Ruddiman's view, to account for the methane anomaly.

The gases released by deforestation and agriculture may have pushed back the onset of a new Ice Age. In the past, ice caps in North America started to form 5,000 years after solar radiation began dropping, which would mean some 3,000 to 6,000 years ago. Ruddiman estimates that the additional CO_2 released by human activities would have elevated temperatures at high latitudes by the 2 °C needed to prevent glaciation. His estimates assumed that the deforestation alone affected climate through CO_2 release, and ignored the effects of reduced cloud cover caused by fewer trees recycling water to the atmosphere.

"Although the conclusion that humans have been warming the climate for thousands of years seems startling, my colleagues have generally been quite supportive," Ruddiman reports. There have been disputes over the possible magnitude of the effect but general acceptance of its reality.

For the present, the knowledge that deforestation has already caused substantial climatic modification serves as a warning because export-driven deforestation in tropical areas is now proceeding at a record pace. Although staving off the growth of Earth's ice sheets is certainly beneficial, melting them clearly would not be.