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TECHNOLOGY REVIEW 2006

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Fresh perspectives propel advances

Somewhere between pure science and pure hard-won experience lies technological success. This year's rich variety of achievements in photonics and optoelectronics extends to both extremes of the range.

The well-worn term "paradigm shift"—sometimes preceded by the phrase "nothing less than a"—has, for many who have spent time in the corporate world, become not merely empty of meaning, but a symbol of hyperbole. Contrary to what some may think, though, the term was not invented by a motivational consultant. Instead, it was coined by science historian Thomas Kuhn, and popularized in his 1962 book *The Structure of Scientific Revolution*; the term arose from his views on science and how it progressed—which, he believed, was erratically.

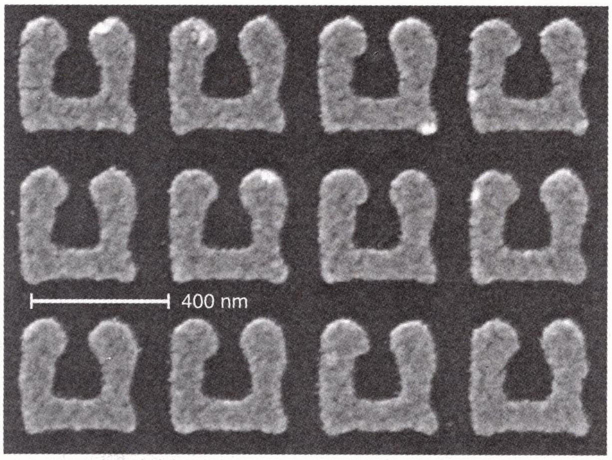

FIGURE 1. A metamaterial with nanoscale feature sizes has a magnetic resonance for 3-μm light—an important step toward the fabrication of a negative-refractive-index material at that wavelength.

Kuhn maintained that scientists typically (in times of what he called "normal science") act as puzzle solvers, adding to or tweaking the existing theoretical base, or paradigm. Every once in a while, however, a combination of new data and scientific brilliance can cause a fundamental change in outlook, causing a deep restructuring, or shift, of the paradigm. One example is the change from a Ptolomaic to a Copernican view of the solar system.

While more-mundane acts of restructuring—such as the relocation of an engineering department nearer to the manufacturing area—may be termed paradigm shifts by a company exec, they are most likely not. However, a slight broadening of the term's original meaning to include radical shifts in thinking relative to technology may not be unwarranted. In the past few years, and especially this past year, the field of optics has been approaching what could be such a shift—that involving the design, development, and possibly the eventual practical use of negative-refractive-index materials in optical systems.

In technology, just as in science, however, fundamental changes in approach mean nothing without the rest of the creative and difficult work needed to make devices suitable for the real world. The

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ers at the University of Edinburgh (Edinburgh, Scotland) and Pennsylvania State University (University Park, PA) have postulated that a homogeneous mixture of two hypothetical isotropic dielectric-magnetic materials, each pulverized to tenth-wavelength-size (or smaller) grains, could form a negative-index metamaterial (see *Laser Focus World*, November 2005, p. 53). The researchers have no idea yet what these two substances might be, however.

Many research efforts are under way around the world to create metamaterials that operate at shorter wavelengths and show clearer negative-index effects. Improved photolithographic techniques and more-refined nanostructures will eventually lead to a metamaterial that exhibits a negative refractive index in the visible region. In addition, metamaterials showing nonlinear effects (such as frequency doubling) or gain (leading to optics that could not only focus but amplify light) will be developed. Conquering the practical problems of light absorption, difficulty of fabrication, and performance, however, is what will bring metamaterials out from the lab and into your cell-phone camera.

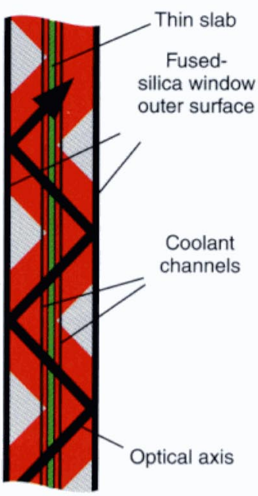


FIGURE 3. A Thin (4.5-mm) Nd:YAG slab is suspended between two fused-silica windows; cooling fluid flows between the windows and the slab. The laser light is totally internally reflected off the outer surfaces of the windows.

Silicon photonics

Decades of research and development have brought silicon electronic chips from their original single-transistor form all the way to integrated circuits that contain a billion transistors with nanoscale features. Just as important, the associated semiconductor-processing technology has turned silicon into a versatile medium for precision mass-producible devices that include not only electronics, but MEMS (microelectromechanical systems) devices as well.

This year, integrated silicon photonics has moved closer to reality. Silicon's poor light emission has traditionally frustrated efforts to create integrated optoelectronic circuits based on the material. But in February, researchers at Intel (Santa Clara, CA) revealed the first all-silicon laser on a chip, an S-shaped waveguide Raman laser that, when pumped with pulsed light at 1536-nm, lased at 1669.5 nm (see *Laser Focus World*, February 2005, p. 9). The group soon demonstrated a continuous-wave (CW) version, in which a reverse-biased *p-i-n* diode in the waveguide reduced the optical loss caused by two-photon-absorption-induced free-carrier absorption to the point at which CW operation was achieved. A silicon Raman laser developed by researchers at the University of California at Los Angeles, though optically pumped by pulsed light, can be directly modulated with an electrical signal to a *p-n* junction diode on the gain chip (see *Laser Focus World*, April 2005, p. 21).

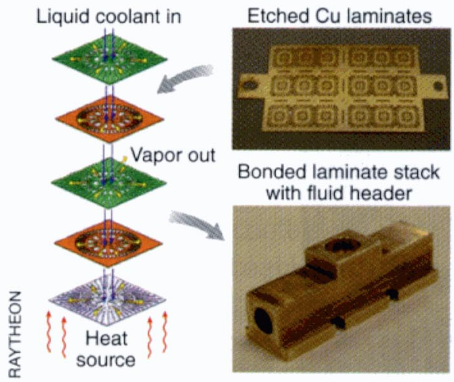
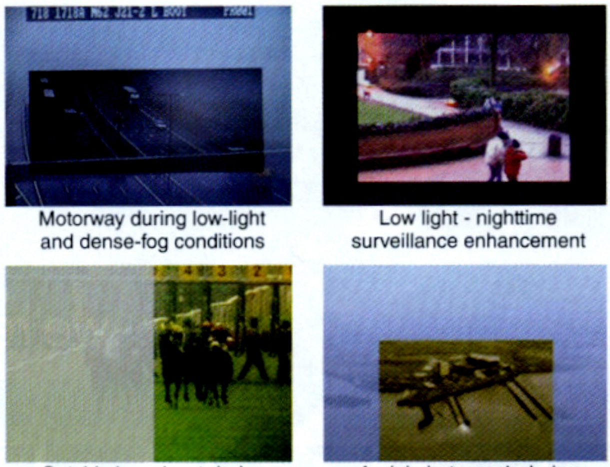


FIGURE 4. In the two-phase ECHIC and the single-phase CHIC, diffusion-bonded copper laminates create a maze of coolant flow passages and fins to increase the removal of heat from high-power laser-diode arrays.

Scientists at Intel have also created a second essential element of a practical silicon photonic circuit (or at least one that would rely on CW lasers): a high-speed silicon optical modulator. Last year, they



Motorway during low-light and dense-fog conditions

Low light - nighttime surveillance enhancement

Outside broadcast during heavy rain and fog

Aerial photograph during poor weather conditions

DMIST

FIGURE 5. Real-time pixel-by-pixel image enhancement cuts through fog and haze; the distance-based scattering-compensation algorithm operates on each color (red, blue, and green) separately.

reached 1-Gbit/s optical modulation for a silicon device in which the refractive index of a silicon waveguide was modulated by a metal-oxide-semiconductor capacitor. The device trounced the previous record by a factor of 50; however, even this is not considered truly high-speed. This year, the researchers revealed a refined version that reaches 10-GHz (see Fig. 2).[4] Redesigning the silicon waveguide—for example, changing the top layer from polysilicon to crystalline silicon—and improving other elements such as the driver circuitry allows the device to transmit 10 Gbit/s with a 3.8-dB extinction ratio and 10 dB of on-chip loss.

All these silicon devices operate at or close to a wavelength of 1.5 μm. An alternative approach to silicon photonics, which can operate at shorter wavelengths, is heterogeneous integration. In this case, a light-emitting material other than silicon is layered onto a silicon chip and can potentially be integrated with silica waveguides and ordinary silicon detectors. Andrew Steckl and Jeong Ho Park of the Nanoelectronics Laboratory at the University of Cincinnati (Cincinnati, OH) have fabricated visible lasers on silicon that consist of a 0.5-μm active layer of europium-doped gallium nitride (GaN); when pumped by pulsed 337-nm light, the lasers emit at 620 nm with a threshold of 117 kW/cm^2 (see p. 13). Modal gain and loss were 100 and 46 cm^{-1} respectively. Doping GaN with other rare-earth elements could produce other laser wavelengths in the visible, UV, and IR regions.

High-power light

As the optical output of a solid-state laser is boosted, the standard laser-rod geometry becomes less and less practical—a result of beam nonuniformities and other problems caused by the long thermal path in the rod. To shorten the thermal path, a laser rod can be made either long and thin (a fiber) or short and fat (a disk or slab). Both approaches have their strong points.

In the past couple of years, fiber lasers have undergone an unprecedented growth in power (see *Laser Focus World*, August 2005, p. 66). The record optical output for a single-fiber laser is currently held by IPG Photonics; in a paper presented at SPIE's Photonics West 2005 (Jan. 24–27; San Jose, CA), IPG researchers revealed that they had achieved a 1960-W output from a 1075-nm-emitting ytterbium-doped fiber that produced a beam with a quality M^2 of 1.2 at an electrical-to-optical (wall-plug) efficiency of greater than 20%. Engineers and researchers from around the world are aiming to push this number higher, though; for example, also at Photonics West 2005, David Payne from the University of Southampton (Southampton, England) discussed techniques for scaling single fibers to 10-kW power levels (see *Laser Focus World*, April 2005, p. 29).

For multiple-fiber lasers, in which the outputs of many single-fiber lasers are combined in a passive multimode fiber, IPG Photonics again holds the record; in addition to installing a 20-kW fiber laser at the Bundesanstalt für Materialforschung und-prüfung (BAM; Berlin, Germany), the company has also installed a 36-kW laser for an unnamed customer. The laser's output is delivered by an optical fiber with a diameter of 200 μm, resulting in a beam-parameter product of 11 mm × mrad.

Fiber lasers are limited by the fact