Nonlinear Competition Heats Up

Four materials that transform light in unusual ways are going head to head in the race to build the fastest devices—such as switches—for optical communications systems

The revolutionary process has already begun of trading in the current vehicles of information transfer—electrons, which are shunted around at relatively plodding rates—for racy, high-speed photons. Long-distance fiber-optic roadways have been laid down to whisk these optical vehicles between computer and telecommunications systems separated by continents and oceans. But fully light-based communications systems will require not only interstate highways but also optical on-ramps, off-ramps, and interchanges to direct the photons to their destinations, as well as devices to generate and decipher the flashes of light that carry the messages.

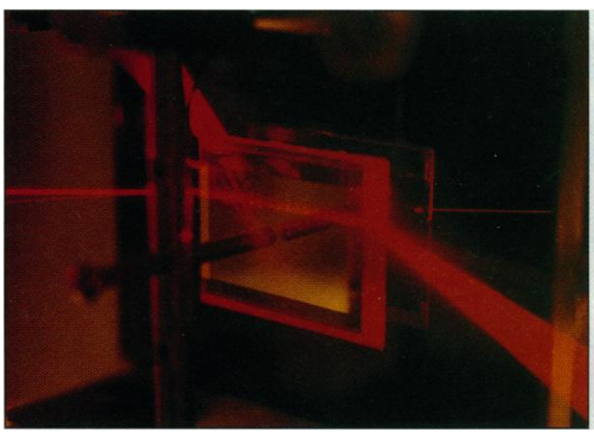
Central to the construction of these new devices are substances known as nonlinear optical (NLO) materials. Unlike most other materials, nonlinear forms undergo intriguing changes when light or other energy passes through them, which in turn can alter light as it moves through. Pass an infrared laser beam through an NLO inorganic crystal, for example, and it may come out green. Or the crystal may act as a switch, jumping the beam from one fiber-optic line to another.

Normal linear materials are like a road that doesn't alter the behavior of cars that drive along its surface, explains Mohammed Islam, a professor of electrical engineering at the University of Michigan, Ann Arbor. "But nonlinear materials are akin to water," he says. "When one boat goes through, it creates a wake that affects those in the vicinity."

Such behavior has been known for decades, and materials scientists have been putting it to use for nearly that long. For the last 30 years, the NLO materials that have occupied center stage have been inorganic crystals, such as lithium niobate or quartz. But these inorganic crystals have a number of drawbacks: They are expensive, fragile, and difficult to integrate with the materials that make up today's communications devices, such as optical fibers and semiconductors. So more recently researchers have been exploring NLO effects in other materials. And three other candidates—polymers, semiconductors, and glass optical fibers—are showing exceptional promise. Indeed, these substances "are beginning to challenge the supremacy of the inorganics," says Larry Dalton, a professor of chemistry and engineering at the University of Southern California (USC).

The value of order—and disorder—in materials is explored in this special news section. Ordered crystals and semi-ordered glass, among other substances, are competing for use in various optical communications devices; the race is described in our first story. A change in the internal order of plastic optical fibers—the topic of the next story—may finally bring fiber optics into the home. The third story looks at how drug and biotech companies, taking their cues from embryonic brine shrimp, are exploiting new ideas about glassy states to preserve their products. **Related Articles begin on p. 1924.**

The battle for supremacy is getting particularly hot around two applications. NLO polymers are rapidly approaching commercialization in electro-optic modulators, devices that encode information in a stream of laser pulses (a capacity that has long been the sole domain of crystals). In addition, glass fibers and semiconductor NLO materials are competing to be used as all-optical switches—equivalent to the transistor—because both can use one light beam to change the direction of another.



ANDREW KOSTRZEWSKI AND HUEY LU

Making the code. A nonlinear polymer-based modulator can chop a laser beam into pulses coded for data transmission.

These races, and competitions for a host of other applications, are creating a climate of intense excitement. "The field is exploding right now," says Daniel Chemla, a solid-state physicist and nonlinear-optics specialist with joint appointments at the University of California, Berkeley, and the Lawrence Berkeley Laboratory. "I don't know if you can even call this a single field anymore."

Coding pulses

What does unite all NLO materials is their unique light-changing abilities. Underlying that behavior is the fact that the electronic charges of NLO materials are exceptionally easy to polarize, or displace along the molecule, under the influence of a passing wave of energy. This wave can either be the original beam of light itself, an additional control beam, or even an applied electric voltage. The electric field of the incoming wave can cause negatively charged electrons and positively charged ions in the material to vibrate. If that vibration is strong enough, it can affect the frequency of the original wave, overlapping and reinforcing it like the overtones of a musical note. This can have any number of consequences: It can change the speed with which light moves through a material (the refractive index), change the material's transparency, or alter the frequency of the output beam.

While this ability to shift the frequency of laser light continues to be one of the most lucrative properties of NLO materials (see box on p. 1920), it's their ability to change their refractive index that's likely to prove essential to the future of optical information networks. This property forms the basis for electro-optic modulators, which can transform a single beam of light into a series of discrete pulses, suitable for transmitting information. NLO researchers routinely disagree about whether such devices are truly nonlinear, as they control a beam of light with an electric field instead of another optical beam or just the original beam itself. "But what is light besides an electromagnetic wave?" asks Chemla rhetorically. "So it's artificial to separate the two."

The most common design for such modulators, called a Mach-Zehnder interferometer, works by controlling the interference between two beams of light. The interference patterns determine whether the two beams merge to produce a single, stronger beam or cancel each other out. Photons in these beams behave like waves which, just like waves in the ocean, have a repeating series of peaks and troughs. When a light beam enters this device, it is split into two separate pulses whose peaks and troughs are perfectly aligned. These pulses then enter parallel channels carved in an NLO material. As long as the NLO material in both channels has the same refractive index, the waves move at the same speed and their peaks and troughs remain in synch. When the two waves recombine in a single channel at the end of the device, the original beam is restored.

When a voltage is applied across one of the channels, however, it produces electrical waves that travel alongside the photons in the channel. These traveling electric waves boost the index of refraction of the material, slowing the light enough that its peaks now line up with the troughs of the unaffected beam, a change known as a pi phase shift. When these out-of-phase waves meet at the single channel, they cancel each other out, and the pulse is stopped. Thus by varying the applied electric field, devicemakers can chop a single beam of laser light into separate pulses.

"But different NLO materials produce this change in index of refraction, and therefore the change in phase, by different mechanisms," says Dalton. Lithium niobate crystals—the current mainstay of commercial electro-optic modulators—change their index of refraction partly by moving relatively heavy ions back and forth in the material. Commercial lithium niobate modulators switch light pulses on and off at a rate of 20 billion times per second, or 20 gigahertz. And experimental NLO crystal devices made last year by researchers at NTT in Yokosuka, Japan, have even pushed such modulators to a blinding 75 gigahertz.

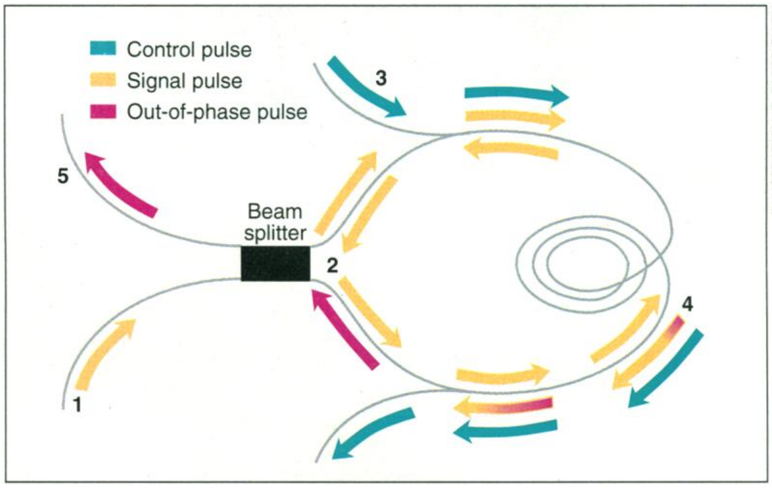


ILLUSTRATION: C. FABER SMITH

Loopy idea. Glass fiber-optical switches can route beams of light by changing their properties. In this design, a signal pulse (1) is split into two beams that travel in opposite directions around a fiber loop (2). A control pulse is added (3) so it travels alongside one signal pulse, altering its phase (4). The changed phase causes the beam splitter to route the reunited signal pulses down a particular fiber (5). With no control pulse added, the signal pulses are sent down another fiber.

But the high price of growing the crystals can drive the cost of the lithium niobate modulators as high as $50,000, says Rick Lytel, a device physicist at Akzo Nobel Electronic Products in Redwood City, California. Another drawback of inorganic NLO crystals is that they are difficult to grow on semiconductor materials, adds USC electrical engineer William Steier, and this makes them very difficult to integrate with semiconductor-based microelectronics devices.

Polymers as pulsemakers

NLO polymers, on the other hand, may be able to sidestep these pitfalls. Not only are polymers far cheaper to make because they can be engineered using common organic synthesis techniques, but they can easily be layered on semiconductors, says Steier. What's more, he adds, the polymer-based modulators have the potential to pulse light beams at even higher speeds than inorganics. The movement of ions in the lithium niobate, he explains, slows high-speed electric waves, causing them to fall behind some of the racing photons, which then cannot be phase-shifted. The polymers, on the other hand, change their refractive index by whisking electrons around. Electrons don't slow down the traveling electric waves, and, as a result, these devices have the potential to increase their top speeds. "The higher the speed, the more information you can put in the optical beam," says Steier.

Over the last few years, researchers have been tailoring new NLO polymers and steadily improving their effects. And although polymer-based electro-optic modulators have yet to make it to the market, they are beginning to post impressive research results. In a forthcoming paper in the journal *Chemistry of Materials*, for example, Dalton, Steier, and their colleague Harold Fetterman at the University of California, Los Angeles, report using a polymer called polyurethane-Disperse Red 19 (PUR-DR19) to make an electro-optic modulator that operates at up to 60 gigahertz. And, says Dalton, "theory tells us that polymers will get us to 200 gigahertz."

But polymers have their downside, notes Lytel. Although fast, polymers are not as robust as the inorganics, typically breaking down with continued exposure to high temperatures. Dalton says his group's device has proved it can last up to 1000 hours at 100 degrees Celsius. Of course, that's not the multiyear life-span that telecommunications companies will be looking for. But based on the current pace of development, Lytel predicts that polymer-based modulators will make it to the market within 2 years, where they will go head-to-head with their crystalline competition.

Ultimate light switches

Two different NLO materials—glass optical fibers and semiconductors—are also going head-to-head in the effort to commercialize all-optical switches. No matter which is successful, if all-optical switches could be made practical, they would break an irksome bottleneck in telecommunications.

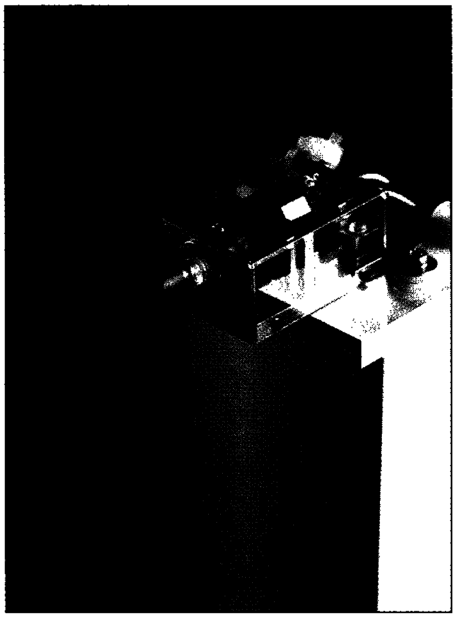
"At the moment, all fiber-optic communications systems are limited by electronic components" that can detect and retransmit signals at a top speed of around 10 gigabits per second, says Erich Ippen, a professor of electrical engineering and computer science at the Massachusetts Institute of Technology in Cambridge. "To break this bottleneck, you'd like to be able to do that all optically," he says. But although nonlinear-optics researchers have been producing prototype optical switches since the mid-1980s, transferring these achievements to the market remains "at least one 'eureka' away," according to MIT electrical engineer Kristin Rauschenbach.

The need for the eureka, explains Nassar Peyghambarian, a professor of optical sciences at the University of Arizona, Tucson, is that optical switching relies on more complex behavior of the NLO material, which "takes much higher fields to begin to generate." Ironically, up to now the most successful materials used in optical switches have been glass optical fibers, which have a vanishingly small NLO effect. But in their favor, such fibers are nearly perfectly transparent. That allows control and signal light pulses to travel in tandem through kilometers of fiber with little energy loss, allowing the nonlinear effect produced by the control pulse to build to the needed levels.

One of the most common optical switches utilizing glass fibers is known as the nonlinear optical loop mirror (NOLM). These devices are similar to Mach-Zehnder interferometers in that they exploit the same principal of changing the refractive index of the NLO material to generate interference between two light waves. And like the interferometers, NOLMs begin by splitting a single light pulse into two. But there the devices depart in design and function. In the loop mirror switch, the two pulses, once split, travel in opposite directions through a long loop of fiber, passing each other briefly in the middle

Blue-Light Special

Laser manufacturers have long wanted to sing the blues—and with nonlinear optics they may soon get their wish. A blue-light semiconductor laser—a device much like the cheap, compact infrared lasers found in CD players but with shorter wavelengths—has topped their wish list. Short wavelengths mean information could be more tightly packed on optical disks, increasing their storage capacity. "The demand for blue lasers is here now. There are huge potential markets for this," says Derek Nam, an electrical engineer at SDL Inc., a laser diode manufacturer in San Jose, California.



DUPONT

Mo' better blues. Firing an infrared semiconductor laser through a nonlinear crystal produces a blue light beam.

But demand is far ahead of supply. Laser makers have had real trouble getting blue light from semiconductors. Materials that emit blue light when they're jolted with electricity, such as zinc selenide, are not very durable, and the emitted light is often too dim (*Science*, 24 February, p. 1093). So researchers are trying to enter the blue-light marketplace via a back door known as nonlinear "frequency doubling."

Specific frequencies of light entering a nonlinear material set in motion a complex interaction among electrons that affects the frequency of the light leaving the substance, doubling it and cutting its wavelength in half (see main text). That means light from a conventional, durable infrared semiconductor laser with a wavelength of 860 nanometers can be shot through a nonlinear crystal and generate light at 430 nanometers—comfortably in the blue part of the spectrum.

But in nonlinear optics, things are rarely comfortable or straightforward, particularly solutions. "The problem," says Nam, "is power." Stamp-size semiconductor lasers don't generate a beam with much power, and at low intensities only a fraction of the beam actually converts into blue light. But over the last few years advances in the power of small lasers combined with efficiency-boosting nonlinear techniques have made the blue picture brighter.

The laser group at Coherent Inc. in Santa Clara, California, for example, has used a technique codeveloped with the IBM Almaden Research Center known as "resonant doubling." Laser light is shot through a nonlinear crystal called potassium niobate, and any light not converted to blue is captured by a mirrored "resonant chamber" and sent through again. "It allows you to build up power at a particular frequency," explains John Trail, an optical engineer heading the project. With efficiency rates of 30% even a small, 100-milliwatt infrared laser can generate nearly 30 milliwatts of blue light—plenty of illumination for reading and writing optical disks. Coherent's blue laser will be on the market this spring, but at $25,000 it's destined for high-end computer systems with massive storage needs. Despite the cost it is something of a landmark: the first solid-state blue laser on the market. "People have wanted to do this for a long while," says Trail.

At DuPont, physicist John Bierlein has taken a different route. Instead of recycling the unconverted light, his group confines the original infrared beam in a "wave guide," a thin channel of nonlinear material that doubles the frequency of the infrared photons and keeps the laser beam tightly focused, maintaining its intensity. The device is still only about 10% efficient, but starting with a typical infrared laser the final output is well over 2 milliwatts—still the minimum needed to read an optical disk. Japan's Pioneer Electronic Corp. has licensed the technology from DuPont and built a prototype system which packs an entire movie's worth of high-quality video on a laser disk the size of today's audio CDs.

Promising as these developments now seem, some blue-laser specialists see frequency-doubling devices as little more than stopgaps."It's an engineering package very much for 1995," says Brown University's Arto Nurmikko, "but no one can argue that real blue lasers won't replace them." Such devices, he argues, will ultimately be more efficient, smaller, and cheaper than the nonlinear variety. But Nurmikko admits that "ultimately" is probably 5 to 10 years down the line. And that "is a fairly big window of opportunity [for] a temporary solution," Trail says.

–Antonio Regalado

and returning eventually to the point where they were split, where they reunite. The channels of the splitter are designed so that if the pulses are in phase at this point, they are sent off in one direction; if they're out of phase, they are routed down a different fiber.

In order to change the phase of one of the signal pulses coursing through the fiber loop, a control pulse of light is injected at the beginning of the loop so that it travels alongside one signal pulse. As it travels the loop, it "deforms electron clouds" in the glass, says Islam, causing a slight polarization of the glass molecules and increasing the material's refractive index, slowing the progress of the signal photon. But this reduction is so slight that the two pulses must travel together for several kilometers before the signal pulse is fully out of phase with its counterpart traveling in the opposite direction.

The advantage of such fiber-optic–based systems, says Islam, is that they can change the index of refraction extremely quickly, because the electron manipulation is so fast. That, Ippen adds, enables them to "switch very short pulses in very rapid succession." Last year, for example, Masatoshi Saruwatari and his colleagues at NTT showed that they could get such devices to switch light pulses at a speed of 100 gigabits per second.

But the size of the devices—the kilometers of coiled fiber pack into a container the size of a shoe box—remains a real obstacle. The transistors that form present-day switches, in contrast, can be packed by the millions onto a microchip. In an effort to shrink the optical devices, researchers around the world have been working to replace the long fiber component of the NOLMs with a tiny chip-based device made of semiconductor.

Switching phases, switching materials

Last year, the first true semiconductor analog to the NOLM, the terahertz optical asymmetric demultiplexer (TOAD), was built by Paul Prucnal and his colleagues at Princeton University. The device retains the loop construction but replaces the long central fiber coil with a circuit etched onto a semiconductor chip made from an alloy of indium, gallium, arsenide, and phosphide. The wavelength of the control pulse is tailored so that it excites negatively charged electrons and oppositely charged "holes" in the material to combine and give off photons. This elimination of charged particles changes the polarization of the material over a much shorter distance than the stretch needed by light to exert a similar effect in glass fibers. This in turn increases the semiconductor's index of refraction and slows the signal pulse.

This fast index of refraction change allows the device to switch extremely short pulses. But because the device can't switch again until the depleted electrons and holes are replaced—a comparatively slow process—it must wait longer than the fiber devices before it is ready to switch the next pulse coming down the line. The first device, for example, was able to switch light pulses at a rate of only 3 gigabits per second, says Prucnal. Since then, however, researchers led by Julian Lucek and David Cotter at British Telecom in Suffolk, U.K., have boosted the speed to 40 gigabits per second.

But instead of switching each pulse as it comes down the fiber, these devices can also be used to switch every 250th pulse, for example, in a common telecommunications task called demultiplexing. Such systems are currently used to reconstruct large signals that have been divided up into smaller chunks for ease of transmission; chunks from 250 of these large signals can be sent down a fiber in quick succession, and a TOAD can grab every 250th chunk, re-forming one original signal. In addition, Prucnal says, TOADs can pluck these chunks out at record speeds, when the main stream of data is moving at 250 gigabits per second. And semiconductor-based demultiplexers have the advantage over fiber-based systems, as they are smaller and should be easier to integrate with current semiconductor communications devices, says Prucnal. But before TOADs and their ilk make it to market, they will need to be integrated with other demultiplexing components on a single chip; Prucnal and others are currently pursuing this goal.

The performance of both the fiber-optic and semiconductor devices continues to improve, which is good, says Keith Blow, a physicist at British Telecom, because "the continued demand for bandwidth is not slowing." With electronics, he says, "you're probably going to run out of steam" to meet this demand. And that means the pull from the market, not only for optical switches but all the other NLO devices needed to create the information roadways of the future, is likely to get much stronger over time.

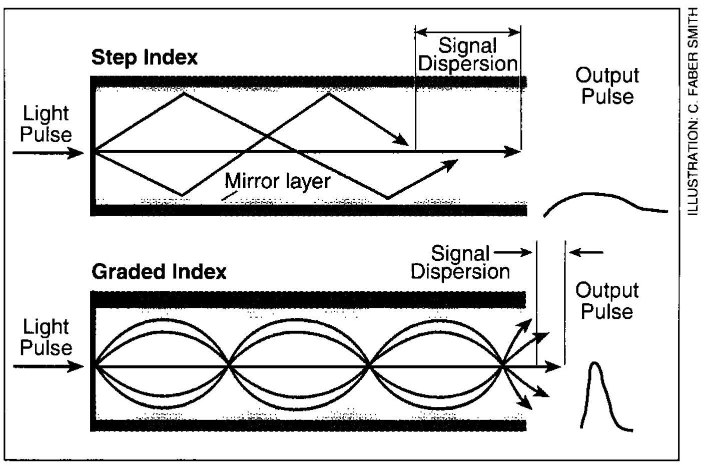
–Robert F. Service

TELECOMMUNICATIONS

Paving the Information Superhighway With Plastic

The deepest oceans and the highest mountains haven't stopped telecommunications companies from wiring the world with the latest in high-performance fiber-optic cables. But taking those fibers from the curb to your house—that's proven to be one tough trip. Now, a team of Japanese scientists has developed a new type of plastic cable that may overcome the roadblock.

While the glass optical fibers currently used for long-distance connections can transmit massive amounts of data in the form of pulses of light—theoretically up to trillions of bits of data, or terabits, per second—they are poorly suited to "short-hop" applications. Each is thinner than a hair, and expensive junction equipment is needed to precisely align an optical beam so it can jump from a "trunk" fiber into a local one. This makes the cost of wiring each and every home in a community prohibitive. In contrast, the copper wires that already feed movies to our televisions are cheap and simple to use. But they can't transmit nearly as much data as fibers do. For the technological visionaries who dream of sending 500 cable channels into each home simultaneously, "that's a bottleneck," says Edward Berman, president of Boston Optical Fiber Inc. in Marlborough, Massachusetts.



Making the grade. Graded-index plastic optical fibers *(bottom)* have faster lanes for photons near their perimeters, ensuring that—unlike step-index fibers—all the photons arrive closer together.

The solution, a group of Japanese researchers now says, can be found in one word: plastics. In a presentation last September at the European Conference on Optical Communication in Florence, Italy, materials scientist Yashuhiro Koike and his colleagues from Keio University in Yokohama described using a new type of plastic optical fiber to transmit light pulses from a red semiconductor laser at a blinding 2.5 billion bits per second—that's a transmission rate, or bandwidth, 25 times greater than that of the fastest copper cable. The performance is more than enough to handle the transmission demands of most short-hop applications for the foreseeable future, says Robert Steele, a plastic-fiber specialist with Delphi Packard Electric in Warren, Ohio. If a manufacturing process for producing large amounts of the plastic can be developed, it is "going to displace a lot of the copper going in," Steele says.

This is not the first time plastic optical fibers have been developed; they have been around for decades and used increasingly over the last 10 years for such applications as carrying information between sensors and processors in robots. And certainly the thought of using them to wire homes had crossed a number of researchers' minds. "Their diameter is larger [than glass fibers], which makes them more user-friendly to connect and install," says Berman.

But the traditional plastic fibers—known as step-index fibers—were not suitable for high-speed data transmission. One problem: Photons in each light pulse traveling down the fiber spread apart as they move. As a result, the pulses must be spaced far apart or they overlap, making it impossible to determine where one signal ends and the next begins. That limits bandwidth to 100 million bits per second over 100 meters of fiber.

The reason photons don't fly along in formation lies in the fiber makeup. Each is composed of a strand of solid plastic surrounded by a thin coating that acts like a mirror. As photons of light travel down these strands, they glance off the reflective walls. But different photons within a single light pulse glance off these walls at different angles. Those that bounce back and forth at steeper angles end up traveling a longer distance from one end of the fiber to the other, and as a result arrive at the other end well