BRINGING LIGHT TO HEEL AND HEAL

TWO PROJECTS — A NEW WAY TO STOP LIGHT IN ITS TRACKS AND A NEW FIBER FOR LASER SURGERY — EXEMPLIFY HOW COMPUTATIONAL SIMULATION DRIVES DISCOVERY
Photonic crystals — not new age amulets, these fascinating materials may nevertheless herald a new age. They hold the promise of a technological revolution — computing and communications at the speed of light.

Tiny, crafted from semiconductor materials — usually silicon — they have unique abilities to trap, guide and control light. Their promise is to shift information technology from electronics to photonics — to use photons, the smallest lumps of energy in light, rather than electrons as the markers of digital 0s and 1s.

One of the most immediate applications is fiber optics. The ability to send multiple wavelengths at high speeds within fibers has transformed communications, but light could do better, much better, if it weren’t hobbled by the electronic switches, routers and other devices of current optical communications technology.

Since they operate by converting optical signals to electronics and back again, these devices considerably reduce the efficiency of current optical networks. Is it possible to create all-optical circuitry — something analogous to the microcircuitry of “chips” but that doesn’t require converting light to electrical current? It’s a challenge many scientists worldwide are addressing, and photonic crystals loom large as an answer within reach.

A key to this work, driving it forward, has been computational simulations that predict — successfully and precisely — how photonic crystals will work in advance of actually making them. “Computation,” says John Joannopoulos of MIT, a pioneer in this nascent field, “has played a dominant role in the study of photonic crystals.” Photons simulations in Joannopoulos’ group recently led directly to a striking advance in the optical fibers used in laser surgery (see “Healing Light”).

The beauty of photonics simulations, says physicist Shanhui Fan of Stanford, is the ability to use the full form of Maxwell’s equations. This set of equations, named for James Clerk Maxwell, a 19th century Scottish physicist, governs most optical and electromagnetic phenomena. Not so long ago, limitations in computing technology required clever approximations to apply these equations. Systems like LeMieux, PSC’s terascale system, however, have written a new script.

“With LeMieux,” says Fan, “we have the ability to solve the entire set exactly.” This means that computational experiments precisely mimic physical reality and give the researchers high confidence that their predictions can be realized in the laboratory.

Fan and graduate student Mehmet Faith Yanik used LeMieux to simulate a new device that can stop light and hold it captured until a subtle shift in optical features releases it. They’ve teamed with a laboratory group at Stanford to build and demonstrate their device, which suggests it may be possible to corral complicated light pulses and, moreover, do it in a way that integrates easily with existing chip technology.
Optical Resonance Chambers

It made news in 2001 when researchers brought light to a standstill for the first time. Two groups at Harvard demonstrated a technique that captured light in clouds of gaseous atoms. But these systems of atomic gases are impractical for an all-optical circuit. Because the Stanford team’s approach relies on photonic crystals, rather than gases, their device could operate at room temperature and be only microns in length, allowing it to easily integrate with traditional microcircuitry.

By careful design of irregularities within patterns of tiny cavities, photonic crystals can allow — or forbid — the passage of certain wavelengths of light on prescribed paths. Exactly which wavelength, or band of wavelengths, can travel through or not depends on the properties of the crystal.

Yanik stumbled on the light-stopping mechanism while using LeMieux to simulate the impact of changing one property of a crystal, the index of refraction — the ratio of light’s speed in a vacuum (well established at 186,000 miles per second) to its speed in a medium, where it travels more slowly. His original goal was a tunable switch — a crystal that could be prompted, by small changes in the refractive index, to allow safe passage to different wavelengths of light.

For one possible design of such a switch, the simulations indicated the effect could be quite strong. Small changes in refractive index allowed a large change in the bandwidth of allowed wavelengths. And that wasn’t all. “I saw an optical signature very similar to the ones observed in atomic media,” says Yanik. “So the question became, could we use the cavities in the crystal to store electromagnetic pulses, just as they were stored in atomic media? If somehow we could get light into this structure, and then change the properties of the entire structure while the light was inside, we could change the properties of light as well and trap it.”

The idea depends on a phenomenon called optical resonance, which is similar to why long and short pipes in an organ produce notes of different frequency. In an organ, each pipe is cut to the length required to amplify sound waves of a desired frequency. The sound energy bounces back and forth inside the pipe and establishes an unmoving wave pattern, or resonance, at the desired frequency. In the Stanford team’s approach, the role of the organ pipe is played by a waveguide — either an empty channel or closely spaced cavities inside the crystal that allow light to propagate. Prior to this work, many groups had used optical resonators to trap light of a single wavelength. Optical communication, however, uses light pulses to encode and transmit information, with each pulse composed of many wavelengths. Trapping such a multi-wavelength pulse in a single resonator would lose the information carried by the pulse.

Yanik and Fan’s idea, however, goes a crucial step further by tuning all of the wavelengths within a pulse to the same frequency and, at the same time, adjusting the crystal to resonate at that frequency. They do this by adjusting the index of refraction once the pulse has entered the crystal. As all the frequency components are collapsed to a single frequency, the information becomes encoded by the phase and intensity of light along the waveguide.

Changing the resonance of the crystal, Yanik explains, is like adjusting the spacing of stepping stones across a river. Shifting the crystal’s index of refraction is similar to spreading the stones out, so that photons — the tiniest energy chunks of light — of a particular frequency can no longer hop from stone to stone. They have been trapped. When the pulse needs to be released, the index of refraction is shifted back, the stones move closer together, and the photons zip away.
A Dynamic Duo: Maxwell & LeMieux

“The entire idea,” says Yanik, “from refractive-index switches to light-trapping devices, was first realized on a supercomputer.” Once he and Fan identified the light-stopping possibility, Yanik adapted software he’d already written to simulate it. Using almost every one of LeMieux’s 3,000 processors, they simulated a series of possibilities until arriving at a 100-micron waveguide with 120 side-cavities. “A hundred microns,” says Fan, “fits on a chip, a small distance in practice, but a long distance to simulate.”

To exploit the large-scale parallelism of LeMieux’s 3,000 processors, Yanik’s software parceled separate parts of the crystal waveguide to separate processors. It took 10 simulations to describe the light-trapping behavior, with each simulation of a light pulse entering the waveguide requiring two hours, which Yanik estimates as a year’s worth of computing on a desktop PC.

The simulations showed that shifting the index of refraction around the pulse forces the wavelengths to adopt a single frequency, and traps the pulse in and between cavities. In the 100 micron, 120 side-cavity waveguide, a 1/10,000th shift in the index of refraction is enough to capture the information in commonly used pulses of light.

Another surprising result of the simulations, says Fan, is that if the index of refraction were tuned beyond the point where the light pulse screeches to a halt, the pulse would not merely stop, but reverse in its tracks, backing out of the crystal as though it were a train reversing direction to re-emerge, caboose first, from a tunnel. This time reversal effect, he says, might prove useful in repairing signal degradation.

Efforts to build the device in the lab, in collaboration with Stanford colleagues Martin Fejer and James Harris, are now running parallel to more simulations. “What we’ve done so far is a two-dimensional simulation,” says Fan, “as a proof of principle. We are now extending it to a three-dimensional simulation to arrive at the exact structure the device needs to take.”

For optical networks, a device that can catch and hold light for an arbitrary length of time offers promise to alleviate the congestion that happens when too many pulses arrive simultaneously at a network junction. Beyond that, there’s the promise of quantum computing, the vision of transistors that manipulate single photons rather than electrons. It’s a future, perhaps sooner than we think, in which circuits will be a thousand times smaller and faster. Yanik and Fan’s simulations with LeMieux bring us a step closer. (KG)

HEALING LIGHT

In November 2004, a woman in North Carolina with potentially suffocating growths in her larynx and trachea had them removed by a high-power laser and went home the same day. This condition had never before been treated without anesthesia and operating-room surgery. Six years earlier, John Joannopoulos’ team of physicists at MIT used supercomputers to learn something no one knew about mirrors.

The two events are linked. A new laser technology, developed from a startling insight into the physics of light, may have saved the woman’s life and, at the least, promises huge savings in the treatment of her disease — recurrent respiratory papillomatosis — one that affects tens of thousands of people in the United States alone.

It’s a success, furthermore, that exemplifies how supercomputing is no longer merely a supporting character, but with increasing frequency plays a lead role in scientific discovery. In 1998, John Joannopoulos and his team of researchers at MIT discovered what has come to be called a “perfect mirror.” Their eureka moment came not in the laboratory or with pencil and paper working out of mathematical theory. It happened because a computational model produced results no one expected.

The Perfect Mirror

It may be the most significant advance in mirror technology, said the New York Times, since Narcissus fell in love with his own image in a pool of water. The perfect mirror is so called because it reflects light at any angle with virtually no loss of energy. As a result it makes possible a number of applications in optical technology, the most significant to date being flexible optical fiber that can transmit the high-powered CO₂ lasers used in endoscopic surgery.

Until the Joannopoulos team’s 1998 finding, reported with a paper in Science, mirrors were understood to come in two basic flavors, both with inherent limitations. Everyone knows about metallic mirrors. They work all too well for seeing your own face in the morning, but they don’t work for optical fiber because a large portion of the light leaks away, absorbed by the metal, rather than reflected.

For optical fiber and other applications where energy loss matters, the choice has been mirrors made from dielectrics — materials that don’t conduct electricity well. Dielectrics generally don’t reflect light well either, but scientists found ways to alternate thin dielectric layers of different reflective properties to achieve reflection without energy loss. The drawback has been that these dielectric mirrors reflect light only from certain angles, and their application depends on being able to use light at a limited range of angles and frequencies.

This limitation was thought to be a law of nature, like gravity — no way to get around it — until 1998, when Joannopoulos’ team noticed anomalous results from a computational model of a photonic crystal mirror they were running at the San Diego Supercomputer Center. The light seemed to reflect at a much larger angle than was thought possible. “We saw some interesting results in the computation,” says Joannopoulos. “Then came the theory to explain the computation, and then came a real experiment making something like this and testing it.”

The result: a multi-layered dielectric mirror that reflects light from all angles without energy loss. Within a few years, the perfect mirror proved to be the solution for delivering a high-powered laser via flexible optical fiber.

A DREAM COME TRUE FOR ENDOSCOPIC SURGERY PROMISES LARGE COST SAVINGS
Open Wide for a High-Power Laser

Fiber optics to transmit visible light, based on conventional dielectric mirror technology, has been around for years, but high-power lasers — such as CO₂ lasers used in endoscopic surgery — will melt conventional optical fiber. Joannopoulos and his MIT colleague Yoel Fink realized that the perfect mirror offered a potential solution. With further computations and pioneering laboratory work by Fink, the team developed a hollow-core fiber — essentially a dielectric perfect mirror rolled up into a tube — designed in such a way, based on photonics, to transmit high-power lasers.

To take this idea beyond the laboratory into useful applications, Joannopoulos and Fink in 2000 helped to found a company, OmniGuide Communications, to develop and market the new hollow-core fiber. Further computations over the next few years — at San Diego, Illinois and Pittsburgh — explored other fundamental issues and phenomena of this new class of cylindrical photonic-crystal fiber.

In endoscopic surgery, the lack of a fiber for high-power transmission has meant that the laser had to be delivered via an apparatus with an articulated arm and large handpiece — precluding use of these precise lasers for many minimally invasive procedures. For this reason, the surgery to treat RRP required dislocating the patient’s jaw and general anesthesia, so that the laser could be brought close enough to the affected area.

UNTIL NOW, THIS SURGERY REQUIRED DISLOCATING THE PATIENT’S JAW

A test case for the OmniGuide hollow-core fiber came last year. In serious cases of RRP, the surgery often must be repeated to keep the breathing passage open. Dr. Jamie Koufman, director of the Center for Voice and Swallowing Disorders of Wake Forest University Baptist Medical Center, had a woman patient who had undergone several previous RRP surgeries, but once again had developed near-total obstruction of the larynx and trachea.

Koufman obtained FDA approval to use the prototype fiber. With a numbing topical spray in the throat and trachea, no anesthesia, and a CO₂ laser delivered via an OmniGuide fiber, she cleared the RRP growths. The patient, who went home that day, is doing fine.

"Unsedated, laryngeal laser surgery with the OmniGuide fiber is a dream come true for me as an endoscopic surgeon," said Koufman, "and the patient loved it because it was easy for her." Typical cost of RRP operating-room surgery with general anesthesia is $25,000. With expected FDA approval, the new procedure promises very large cost savings nationally. (MS)


HOLLOW FIBER TO GUIDE LIGHT

These two cross-sectional images represent a schematic (left) of a model OmniGuide hollow core fiber and the first visualization (right) from a computational simulation by Joannopoulos of the same fiber. The “perfect mirror” photonic reflector consists of alternating concentric layers (green and blue) of dielectric with differing indices of refraction. The visualization shows boundaries between the dielectric shells (blue circles) and power density (increasing from red to yellow) of a light beam contained within the hollow core.

TOOLS OF DISCOVERY

"These novel optical fibers, based on photonic crystals," says Joannopoulos, “offer a new approach for medical lasers, making it possible to guide a CO₂ laser beam, which can cut tissue with high precision, into a patient’s body through a very small incision. It will likely prove itself useful for many procedures.”

"Computational science has come a long way over the past 20 years. Even well known equations can have remarkable unexpected consequences that we would never learn about without these powerful computational engines, such as LeMieux. This is just one advance that highlights how these machines are invaluable tools of discovery.”