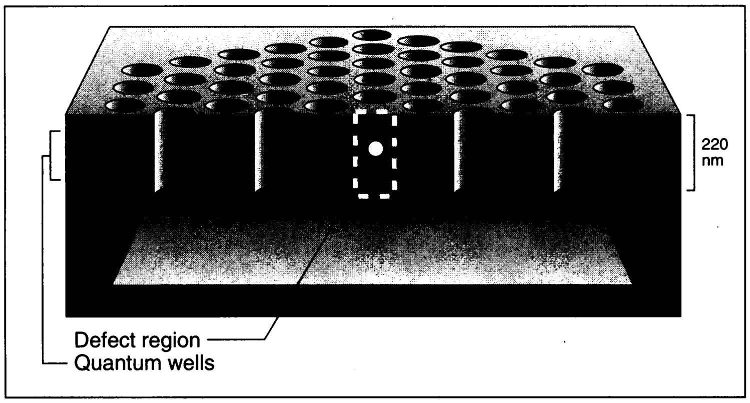
traveling along a thin layer of light-emitting material, then relying on other optical effects, such as internal reflection, to trap the photons in the third direction and keep them from escaping. Working with colleagues at the University of Southern California in Los Angeles, Scherer's group created a slab of indium gallium arsenic phosphide. Like an elaborate club sandwich, the slab included four thin horizontal regions having slightly different electronic properties—so-called quantum wells, where photons would be generated. The group also pierced the slab with a pattern of vertical air holes, creating a 2D photonic crystal that would prevent light from traveling in the plane of the slab. But they omitted one hole to create a defect.



Littlest laser. Light emitted from thin layers called quantum wells cannot propagate through a thicker slab of optical material because it meets a photonic bandgap created by an array of holes. Trapped in a volume of just a fraction of a cubic micrometer, it builds up to laser intensity.

When they pumped energy into the slab with another laser, photons emitted in the quantum wells were trapped at the site of the missing hole, confined horizontally by the 2D photonic crystal and vertically by the reflective air-film interface at the top and bottom of the slab. The result was the world's smallest laser, which trapped and amplified light within a volume of 0.03 cubic micrometer, two orders of magnitude smaller than in vertical cavity lasers. "This allows you to integrate [the structures] in large numbers," says Scherer.

Scherer envisions arrays of these light emitters fabricated within a single photonic crystal and interconnected by waveguides that would carry light signals from one cavity to another. Because the light wouldn't leave the photonic crystal, the scheme would avoid the diffraction losses that mount up when light is sent from one device to another, he says.

Such devices could form the heart of optical routers for communications networks and even serve as logic gates in optical computers—if researchers can develop one final element: a photonic-crystal switch that would control the flow of photons, as a transistor controls the flow of electrons. Scherer envisions two light sources (which could also be lasers) adjacent to one of his lasers. The lasing threshold would be set so that a stream of photons coming from just one of the light sources would not be enough to initiate lasing—the switch would be "off." But photons coming from both sources would trigger lasing, turning the switch "on" and sending an optical signal to the next device in the circuit. "That gives you the equivalent of a [logic] gate," Scherer says. "But this is very far away from where we are now."

Lin is also working on switching but is taking a different approach that harnesses both electrical and optical effects. Photonic crystals are designed to block a given wavelength or range of wavelengths. A defect in the crystal allows the forbidden wavelength to pass through. But an electric field can change the defect's electromagnetic properties, shifting the transmitted wavelength. The effect turns the defect into a shutter, opening or closing for a specific wavelength of light in response to an electric field.

And there's much more to come, as these tiny honeycombs inspire a buzz of experimental activity. Some groups are now coaxing photonic crystals to grow themselves, using polymers that naturally self-organize into complex structures while in solution. Others are making photonic crystals from colloids, natural or engineered particles suspended in a liquid that pack themselves into a regular lattice like marbles in a jar as the liquid is removed.

Yablonovitch's 1987 paper has proved a blockbuster after all. "It just took a lot longer to catch on than I expected," he says.

—DENNIS NORMILE

NEWS

Holograms Can Store Terabytes, But Where?

Finding the right material to store these optical inscriptions is the key to making this optical data storage technology work

Five years ago, a group at Stanford University demonstrated a pioneering data storage system based on holograms, patterns written in a material by the play of lasers (*Science*, 5 August 1994, pp. 736 and 749). To the optimists, the prototype heralded full-fledged systems that might store hundreds of gigabytes of data—the contents of tens of hard drives—in a cubic centimeter of material, while also reading and writing the data almost instantly. New companies sprang up, and IBM, Lucent Technologies, and others stepped into the field. Some optimists predicted that such systems might hit the market within 2 or 3 years.

> **"Materials have always been the Achilles' heel of holographic storage."**
>
> **—Glenn Sincerbox**

After 5 years, the world is still waiting. The promise of holographic storage remains bright: By storing data in a three-dimensional (3D) volume of material rather than writing it on the surface of a disk, the scheme should achieve vastly greater storage densities than current magnetic and optical disk technology offer. And because it transfers data to and from the storage medium in entire pages rather than bit by bit, the scheme promises readout speeds of up to a gigabit per second. But holographic storage is still a method without an ideal medium.

"Materials have always been the Achilles' heel of holographic storage," says Glenn Sincerbox of the University of Arizona, Tucson. "We have always lacked one or two very important properties."

Most parts of the technology have made good progress since that early demonstration, by Stanford's Lambertus Hesselink and his colleagues. In 1995, Stanford, IBM's Almaden Research Center, and several universities and industries formed the Holographic Data Storage System (HDSS) consortium, with a 5-year budget of $32 million, half of it from the participants and half from the U.S. Defense Department's Advanced Research Projects Agency (DARPA). The consortium has

SOURCE: SCHERER *ET AL.*

developed most of the electronics, optics, and lasers needed for working systems, says Sincerbox: "We have been able to pull together the enabling technologies that you need for a holographic data system to work." Indeed, several companies may soon introduce read-only holographic archiving systems, which would store vast amounts of data and serve it up in a flash.

But turning holographic storage into the equivalent of a super–disk drive, able to speedily write as well as retrieve vast amounts of data, will take optical materials with an elusive combination of properties. They will have to record holograms quickly, preserve them faithfully, and erase old data to make room for new. For now, materials that can preserve holograms for long periods are often slow to record them or can't be erased; materials that record data quickly often lose the optical traces over time.

The dilemma has spurred materials researchers at companies and in a consortium called PRISM, formed by DARPA, Stanford, and several companies in 1994 to develop optical recording media. They are working with existing materials, looking for ways to preserve holograms longer or capture them faster, and they are also searching for completely new materials with ideal combinations of properties. Hans Coufal, who heads IBM's research in holographic data systems and whose lab is testing potential materials, is optimistic. "Several materials look very encouraging," he says.

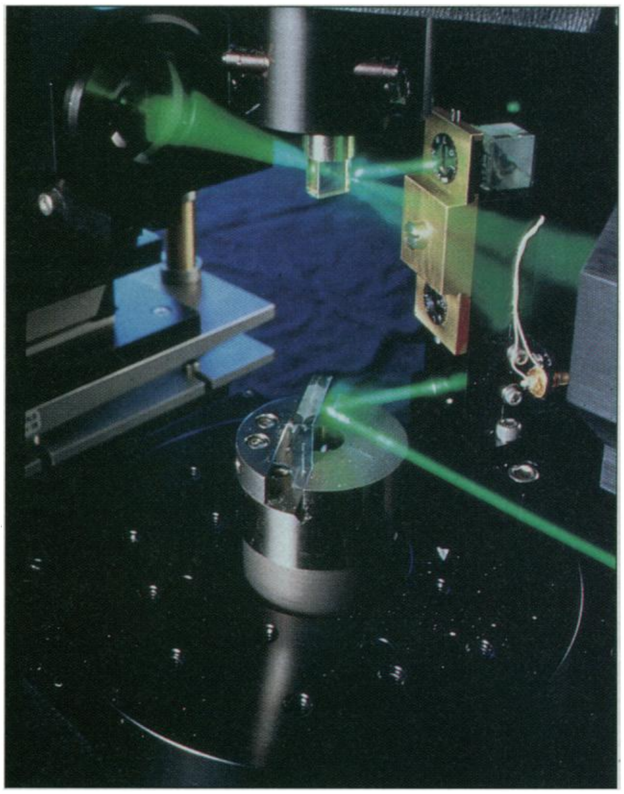
The light touch

Materials problems may be slowing developments now, but, ironically, it was a materials problem that kicked off the field of holographic storage in the first place. More than 3 decades ago, researchers found that bright light changes the optical properties of lithium niobate, a material they were studying as a possible optical switch because its refractive index changes in response to an electric field. The discovery that light itself has the same effect came as an unpleasant surprise. "When it was discovered at Bell Labs in 1966, people thought of it as a nuisance." says Stephen Zilker of Bayreuth University in Germany. But he adds: "Only 2 or 3 years later, people realized that you can use it for writing holograms."

A hologram is generated when one laser beam—the "reference" beam—intersects a second beam carrying an image or data. The result is an interference pattern, a pattern of dark and bright spots that can be recorded on film or in some other medium. The original data or image can be resurrected later by shining a third laser beam on the hologram.

The pesky refractive index change—the so-called photorefractive effect—looked like just the thing for recording holograms, because it is long-lasting. In regions where the light is intense, electrons are excited to higher energy levels, enabling them to migrate though the material. The displaced electrons generate local electric fields that distort the crystal lattice, in effect creating a pattern of minute optical flaws in the material.

Lithium niobate went on to become the mainstay of holographic data storage efforts—it was the material Hesselink's group relied on initially, for example. But it has big shortcomings. Niobate crystals are expensive and have to be grown individually. And the light that reads out holograms from lithium niobate and other photorefractive materials also erases them.



The right stuff? IBM experiment to determine how a candidate optical storage material responds to light.

CREDIT: IBM

One way to record holograms more permanently in lithium niobate is to "fix" them, as a photographer in a darkroom fixes a print. Heating the material or exposing it to an electric field can make the lattice distortions persist, but those methods can be cumbersome. A more promising process for fixing holograms in niobate crystals has recently been demonstrated by Karsten Buse of Osnabrück University in Germany and Demetri Psaltis and Ali Adibi at the California Institute of Technology in Pasadena.

Their technique relies on crystals doped with two elements—iron and manganese—and exposed to two wavelengths of light: ultraviolet (UV) to prepare the material and red to actually write the hologram. "The UV sensitizes the material for red recording by transferring electrons from manganese to the red-sensitive iron," explains Buse. The red light then excites the iron ions to dump these extra electrons, which migrate through the lattice and get trapped on manganese ions, preserving the hologram. The hologram can later be read with red light, which has too little energy to wrest the displaced electrons from manganese, keeping the hologram intact.

These fixing processes don't address another of lithium niobate's failings: its lack of sensitivity. "You cannot write very fast on it, and you might have to use a strong laser or put up with a slow writing rate," says Psaltis. It can take a few minutes to store a hologram, although he adds that for long-term data archiving that may not be a concern.

Given niobate's shortcomings, some researchers are studying a different set of photorefractive materials for larger scale applications: photorefractive polymers. These organic materials can capture a hologram much faster—in a matter of milliseconds—and at lower light intensities than lithium niobate can. But the images last only as long as the polymers are exposed to an electric field. Once the field is switched off, says Zilker, "the electron-hole pattern will erase itself by thermal re-excitation" within a few minutes. "Organic photorefractive materials will not become a long-term storage system," he says, although they could work well for temporarily storing large amounts of data during image processing.

Lasting inscriptions

Although changes in a photorefractive material's charge distribution can be fleeting, other materials offer more permanence, because light triggers drastic changes in their properties. Zilker, for example, is exploring photochromic materials, polymers that darken when exposed to light. When two polarized lasers interfere to create a bright spot in a photochromic material, the light's electric field orients some of the polymer's side chains. At each spot where these side chains line up, they darken the polymer and also change its refractive index.

The process is slow; like lithium niobate, photochromic materials can take minutes to store data. But Zilker notes that "this reorientation is extremely stable." His team roasted a material containing stored data at 160°C for 4 weeks, and the stored information did not degrade. "For permanent long-term storage, these are my materials of choice," says Zilker. He adds that they might also be viable for read-write memories. They can be erased with circularly polarized light, which scrambles the side-chain orientations. And he sees a way around the slow recording times: Because the refractive index changes that these materials undergo as the side chains align are so large, he says, systems could be designed to work with the smaller changes that result from a writing time of a few milliseconds.

Another class of materials that promises durable holographic storage is photopolymers. In these materials, the laser light triggers molecules to link up in chains, or polymerize. The polymerization is most extensive at the bright spots in the hologram, and it also changes the refractive index locally. Photopolymers are the equivalent of fast film, says Hesselink. "If you absorb a photon, a chemical reaction takes place and maybe 100 events could take place, and this makes the materials two to three orders more sensitive than the photochromic materials or photorefractive materials." The transformation, however, is permanent, making photopolymers a promising basis for read-only memories but not for read-write systems.

Another drawback of these materials is that they shrink during the writing process, as the molecules polymerize. The shrinkage shifts the angle of each hologram and alters the distance between its features. This makes it hard for the system to find stored holograms when it reads data. But researchers at Lucent are addressing the problem with a so-called "two chemistry" system, which is still under wraps. By separating the chemical events that record the hologram from the chemistry of the material as a whole, they say, it reduces shrinkage drastically.

In spite of these hurdles, companies are pushing ahead. "The most crucial aspect now is to find the right niche, the right market," says Psaltis. And several companies are betting that read-only systems for archiving and quickly retrieving large amounts of data will turn out to be the right niche. Because holographic systems handle information as entire "data pages," they can search stored information rapidly by looking for telltale patterns, rather than examining it bit by bit. "Holographic storage stands to be a real winner as a search engine for associative retrieval of information," says Sincerbox.

Optostor AG, a company near Düsseldorf, Germany, expects to have a holographic read-only memory system for long-term archiving on the market in about 2 years. Its heart will be a photorefractive crystal measuring 50 millimeters by 50 millimeters by 4 millimeters, containing a terabyte of data stored in holograms that have been "fixed" by heating. "You can put it in a normal PC, and the dimensions are only a little bigger than a typical disk," says Theo Woike of the University of Cologne in Germany, whose research group has a contract with the company.

Others are also at work on read-only holographic storage based on photorefractive crystals and photopolymers, although some researchers speak coyly of having read-write systems in the works, while refusing to divulge proprietary information. One is Hesselink, who was a founder of Siros Technologies, formerly Optitek. "We have spent a lot of effort on [storage in] photopolymers—a read-only material. But in the Siros implementation, there is also a possibility of making that a read-write system," he says.

The wait has been longer than he and others expected 5 years ago. But their optimism hasn't dimmed. When will the first commercial holographic storage system appear on the market? "Within a year, I think," says Sincerbox.

–ALEXANDER HELLEMANS

Alexander Hellemans is a science writer in Naples, Italy.

NEWS

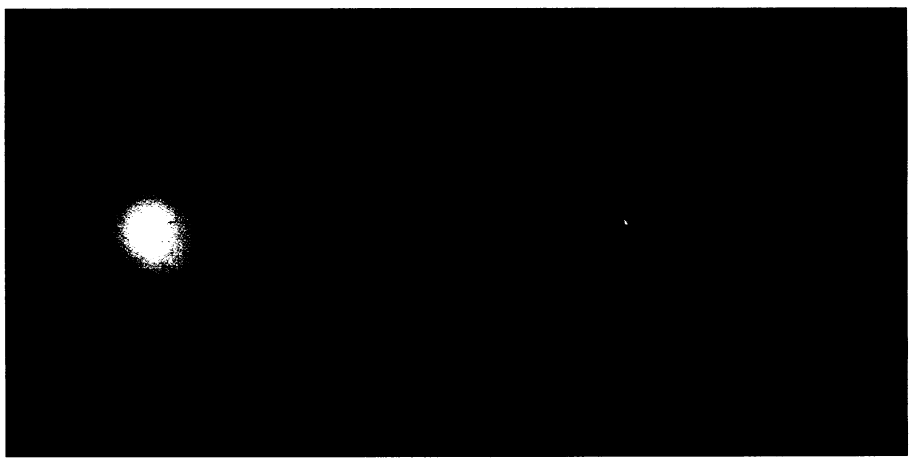
Technique for Unblurring The Stars Comes of Age

Adaptive optics technology, which can undo the effects of atmospheric turbulence, is expanding its reach to fainter stars and larger swaths of sky

For millions or billions of years, the light from distant stars rushes toward Earth relatively undisturbed, but in the last few microseconds it gets scrambled. Turbulence in Earth's atmosphere distorts wavefronts and blurs details, placing what once looked like an ironclad limit on the resolution of even the largest ground-based telescopes. Although the 10-meter Keck telescopes on Mauna Kea, Hawaii, can detect light from vanishingly faint objects in the distant universe, they can't see these objects—or anything else—in much more detail than a large amateur backyard instrument can capture.

For the past few years, however, technologically minded astronomers have been working on a solution, called adaptive optics (AO). The concept is daring: Measure the changing distortions in the light waves and compensate for them hundreds of times per second by flexing a deformable mirror in the light path, using tens or even hundreds of tiny piezoelectric actuators. But what at first looked like technological hubris gradually became a working technology, albeit limited to a few telescopes and able to make observations only near bright stars, used as probes of atmospheric distortion. "We had the concepts available back in the 1980s," says Laird Close of the European Southern Observatory (ESO), "but it took longer than expected" to make AO a practical tool for astronomers.

Now astronomers are fitting AO systems to many more telescopes; soon, most of the



CREDIT: KECK OBSERVATORY

Look sharp. A star comes into focus in images made this year at the Keck II telescope, one of the world's largest, before (left) and after the adaptive optics system was activated.