Will Holograms Tame the Data Glut?

A Stanford team has demonstrated the first complete system for storing digital information in these optical inscriptions. It's both a milestone and a measure of how far the technology still has to go

Unlike bacteria, fish, or even humans, which rely on exhaustible food supplies, the bits and bytes of digital information can proliferate without limit. And they don't die unless their creators kill them off. But they do take up space—more and more of it, so that the floppy disk drives in computers have given way to hard disks, then to optical disks, and still the data explosion is straining existing storage technologies. For more than three decades, one answer has shimmered just over the horizon: holograms, subtle optical inscriptions created by the play of laser beams in an optical material. In theory a compact holographic system could store whole libraries of data for quick retrieval. But in practice holographic data storage has remained little more than a tantalizing promise.

"This business has been forever troubled by 'this is what we might do,'" says Robert Hellwarth, an optics researcher and professor of electrical engineering at the University of Southern California in Los Angeles. "As a result," he says, "some of us get a little jaded." Standing between the theoretical promise and a working holographic storage system have been a host of problems, including poorly performing optical crystals and the difficulty of linking light-based holographic media with electron-based computers. But evidence that those problems aren't insurmountable appears on page 749 of this issue, where physicist Lambertus Hesselink of Stanford University and his colleagues John Heanue and Matthew Bashaw report the first demonstration of a holographic storage system that reads and writes digital information while connected to a computer's hard drive.

The Stanford team is "the first to actually build the system that surrounds the holographic medium," coming in ahead of several companies that are also trying to develop digital holographic technology, notes Robert Boyd, a professor of optics at the University of Rochester in New York. "It's quite impressive." Not, perhaps, to an aficionado of hard drives or optical disks: The Stanford system recorded less than a fifth as much data as a floppy disk can hold and took an hour to do it. But the demonstration helps pinpoint what remains to be done to build a practical version, says Hellwarth. Among other things, he says, "it gives the first experimental check on what kind of error rates you can achieve" in optical crystals and shows how digital correction techniques can improve data accuracy—at the cost of storage capacity.

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Beaming in. Team leader Hesselink adjusts the holographic storage apparatus.

A light touch

The ideas behind holography were developed in the 1940s by the British physicist Dennis Gabor. Gabor showed that when a beam of coherent light (light in which the waves all travel in step) scatters off an object and intersects with another coherent beam, the interference pattern created where the beams cross harbors a three-dimensional image of the object. If the interference pattern is recorded in some medium, Gabor showed, the image will reappear when this "hologram" is probed with a third beam of coherent light. When ready sources of coherent light—in the form of lasers—hit the street in the early 1960s, holography took off, with most of its developers following Gabor's lead and using it as a kind of high-tech 3D photography.

But others saw the potential for storing a different kind of pattern: the 0's and 1's of digital data represented as bright and dark pixels. Glenn Sincerbox of IBM's Almaden Research Center in San Jose, California, recalls that he and other researchers saw several key advantages over other technologies. One is storage capacity. The researchers knew that holograms—recorded by light in a transparent medium—should make it possible to pack information throughout a volume of material, instead of simply painting it onto a surface. Another advantage is speed. While most storage technologies handle bits of data one at a time, a holographic system could write or read an entire "page" of digital data in a single flash of a laser beam.

Early efforts to test this promise, recalls Sincerbox, relied on crude masks to imprint the data pattern on a laser beam and on detector arrays "that we glued onto a board" for reading the data. The first recording media were similarly crude: flat emulsions that captured the bright and dark "fringes" of the interference pattern photographically. Such emulsions still serve as a medium for image holograms, but like ordinary photographic film, they have to be developed, and they can store only a few holographic patterns at once—too few to be useful for digital data.

Recently, researchers have developed more powerful tools for encoding information in beams of light and reading it out again. Liquid crystal arrays called spatial light modulators (SLMs) can imprint a digital data stream on the recording beam as a checkerboard of light and dark spots, and light-sensitive charge-coupled devices (CCDs) can recapture the array of data again when the hologram is read. Holography researchers have also turned to recording media that should be able to deliver more of the promised speed and density: so-called photorefractive crystals.

Photorefractive crystals, such as lithium niobate, are rather like 3D film that never needs developing. Create an interference pattern within such a crystal, and the energy in the bright parts of the pattern dislodges electric charges from dopant atoms—impurities—within the crystal's lattice. The charges gradually migrate to darker regions, setting up electric fields that wrinkle the lattice like a plaid coverlet gathered up by a sleeper's hand. The pattern of wrinkles captures the hologram, and it persists after the beams are turned off. Tilt the reference beam slightly before recording each new hologram, and a series of them can be crammed into a single crystal, where they are accessible to a read-out beam probing the crystal from the same angles. To erase the holograms, simply flood the crystal with a single, intense beam.

Other workers showed that with the help of these new tools and media, thousands of holograms could be packed into a single crystal and readily retrieved again. But it would take more than sheer storage density and speed to make a working holographic memory system, the Stanford team realized. They needed to show that the process could record data faithfully—and there were good reasons for doubt. As University of Southern California physicist Jack Feinberg explains, "There is always a huge amount of [randomly] scattered light in these crystals." This scattered light—optical static, in effect—cuts down on the number of holograms that can be accurately stored by introducing errors. The optics surrounding the crystals often make the problem worse by contributing their own reflected light. Data can also be scrambled by unpredictable fluctuations in storage efficiency from place to place in the crystals. In an especially faint region, for example, all the 1's could erroneously get recorded as 0's.

The Stanford team's approach "was to say, 'Okay, we have materials that are not really optimal, so let's think about ways of encoding the information'" to minimize the loss of data from these effects, explains Feinberg, who studies applications of photorefractive materials. To get around fluctuations in the crystal's storage efficiency, the Stanford group decided to encode each bit in two pixels, a bright-dark sequence standing for a 1 and a dark-bright sequence for a 0. That way the information would depend only on the relative difference between the bright and dark pixels and would be indifferent to the overall intensity of the signal. For every set of eight information-carrying bits, the group also included four error-correcting bits, chosen so that a mathematical comparison with the information-carrying bits would reveal mistakes and how to correct them.

The team chose the enigmatic smile of the Mona Lisa as the subject of its first crack at digital holographic storage. The portrait, and later a 10-frame video, was stored in a computer's hard drive in digital form. From the disk drive, it was sent to the SLM, encoded in a laser beam as a checkerboard of bright and dark pixels, and holographically written inside the thin slice of lithium niobate, a centimeter square and a millimeter thick. "The important thing is not to think about it in terms of storing pictures," says Heanue, but simply as a string of bits representing 0's and 1's. "We put a bunch on each page"—each checkerboard of bright and dark pixels—"and go until we've stored them all." Then, to prove they really had stored the image, the team scanned the medium with a probe beam, read the data from the beam via the CCD, and displayed the images again.

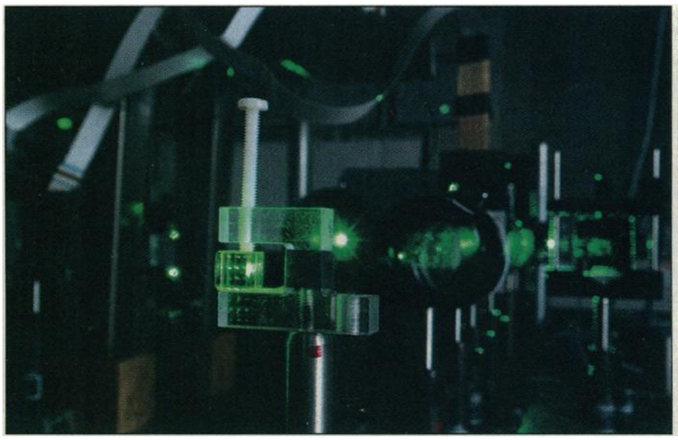
"This business has been forever troubled by 'this is what we might do.'"
—Robert Hellwarth

That proof-of-principle was a milestone, but it showed how far the technology still falls short. Because the crystal responded slowly to light, the collection of holograms took an hour to write. Moreover, the images weren't "fixed," so they could only be read a few times before the read-out beam would erase them. The error correction techniques, the limitations of the material, and problems with the SLM combined to limit the storage capacity to just 163 kilobytes of data. And when Hesselink and his colleagues analyzed the results, they found that they had achieved an error rate of about one bit in a million, still many orders of magnitude less accurate than the disk drive in your personal computer.

But the numbers, though modest, are a first: "I don't know of anyone else who has put together a system that works," says Gaylord Moss, a consultant in Los Angeles who holds several patents in holographic optics. And for team leader Hesselink, the results are just the beginning.

Could it be a contender?

Hesselink believes that the group can push the error rate down "by several orders of magnitude" by making the error correction more sophisticated and taking straightforward measures like coating the optics with anti-reflection films. With the help of better SLMs and laser systems, they should also be able to boost the information density, to as much as 10 to 100 gigabytes—the equivalent of several hundred hard disks—per cubic centimeter of crystal. Hesselink and his colleagues think they can speed data read-out as well, by steering the read-out beam electronically instead of keeping the beam fixed and rotating the crystal, as they did for this first demonstration.



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Crystal power. Holograms written by lasers in a centimeter-square wafer of lithium niobate stored a digital version of the Mona Lisa.

Other researchers caution, however, that a bigger hurdle still stands in the way of a competitive holographic storage system: the need for better materials—ones that respond faster to light and retain holograms longer but can still be erased and rewritten. Tinkering with dopants and crystal structures should help, says Marvin Klein, a materials researcher at the Hughes Research Laboratories in Malibu, California, but "one shouldn't expect major improvements overnight. It could take years." Mark Kryder, director of the Data Storage Systems Center at Carnegie-Mellon University in Pittsburgh, Pennsylvania, agrees: "I don't believe you will see a product within 5 years. My feeling is that it will be at least 10." And by that time, Kryder adds, more established storage technologies will have advanced by orders of magnitude, and a crowd of new techniques already further along in development will have made their debuts as well. Holography, he says, may never manage to leapfrog its competitors.

But Hesselink, buoyed by the success of his demonstration, has started his own spin-off company, called Optitek Inc., with the goal of bringing a product to market in 2 to 3 years. One reason for the haste is competition; several other companies are working feverishly toward similar goals, although none has yet published results comparable to the Stanford group's. And Hesselink is eyeing what may be an early niche for holographic storage: the futuristic service known as video-on-demand, in which customers could download videos from a central library over fiber-optic links. Video-on-demand would require a way to retrieve torrents of data quickly, but it could tolerate fairly high error rates. And it would require only a read-only memory (ROM), for which Hesselink thinks present materials could suffice.

He's confident, however, though, that holographic storage will eventually answer a broader need. And that's why he thinks "it would be a real shame if we stopped at this point and just let holographic storage die." For Hesselink and others gambling on the technology, the one sure thing is that the digital population explosion—and the need for technologies to cope with it—is just beginning.

–James Glanz

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