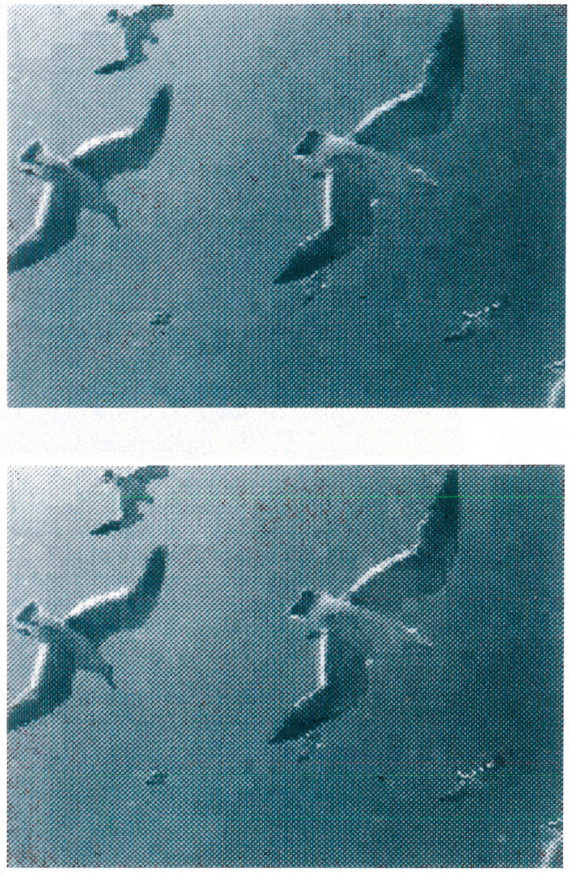
NEW COMPOUND BRIGHTENS OUTLOOK FOR PHOTOREFRACTIVE POLYMERS

A picture is worth a thousand—no, hundreds of thousands—of bits of information. If that picture can be optically stored and retrieved, with the data bits moving in and out in parallel, one has a very fast way to transfer information. So goes one of the motivations for research on optical holography: One can record data as a pattern of 0's and 1's on a page and rapidly store an image of that page.

Central to the scheme is a photorefractive material to record and store the optical image over long time periods or through repeated read operations. The first candidate materials were photorefractive inorganic crystals such as lithium niobate and barium titanate, but since 1991 photorefractive polymers have become viable alternatives. This fall polymers drew the spotlight when a research team from the University of Arizona reported a material with a diffraction efficiency of nearly 100% as well as high optical gain.[1] While the finding was a big step forward, polymer materials still face a long road ahead, and it's not certain that they will reach their ultimate destination—commercialization.



Before and after a digital journey undertaken to demonstrate a fully digital optical storage system. Top: Digitized photograph of birds in flight. After being stored in a computer the image was converted to an optical signal and written as a hologram in a photorefractive crystal. Bottom: The holographic image, read out by a laser beam, was transmitted error-free. (Courtesy of Lambertus Hesselink, Stanford University.)

Optical storage

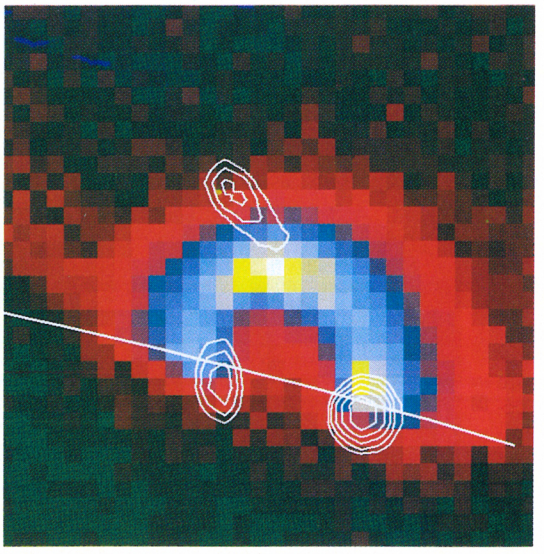
In photorefractive materials the index of refraction depends on the local electric field. This property enables you to imprint an interference pattern on the material as follows: Suppose you shine two coherent laser beams—a signal beam and a reference beam—onto a piece of photorefractive material. The interference of the two beams creates a pattern in the material, with regions of high and low intensity. In the regions where the light is most intense, absorption can generate both positive and negative charges, which separate and rearrange themselves, sometimes aided by the application of an external electric field. As the charges separate, they give rise to an internal electric field. The field in turn causes changes in the index of refraction. The net result is the creation of a refractive-index grating in the material (a hologram), with the periodicity of the grating reflecting the interference pattern of the laser beams.

Once you have removed the signal and reference beams that created the hologram, you can retrieve the signal beam by shining a laser beam of the same frequency—the reading beam—along the path followed by the original reference beam. The refractive-index grating will diffract the light in such a way as to regenerate the signal, just as in static holography.

Researchers have studied the photorefractive behavior of inorganic crystals for many years. (See, for example, the article by Jack Feinberg in PHYSICS TODAY, October 1988, page 46.) But photorefractive polymers did not surface until 1991, when Stephen Ducharme, J. Campbell Scott, Robert Twieg and W. E. Moerner of the IBM Almaden Research Center, in San Jose, California, doped a nonlinear optical polymer with a charge-transporting molecule to make the resulting material photoconductive.[2] However, the diffraction efficiency, defined as the power of the diffracted beam divided by the power of the reading beam, was woefully small. Over the next few years researchers began to develop new approaches to designing and fabricating suitable polymeric materials,[3] and the measured diffraction efficiency crept up to a few percent.

Yohkoh Reveals Site of Solar Flare Energy Release

It may look like a Volkswagen Beetle on a hill, but the surprising observation[1] shown here—specifically the uppermost set of white contours—has solar physicists cruising toward one of their primary goals: unraveling the mysteries of solar flares. This image of a flare was made by a team of Japanese researchers using the Yohkoh satellite (see PHYSICS TODAY, May 1992, page 19), and the emission represented by those contours is closely related to the origin of the flare's energy.



The photo shows a flare extending beyond the visible edge of the Sun (the long white line). The colors represent the intensities of soft x rays with integrated energies from 1 to 4 keV. In the thousands of flares imaged to date in soft x rays, relatively low-energy emissions of this sort are almost always confined within loop-like structures, presumably by magnetic fields, and are usually interpreted as thermal bremsstrahlung from plasma at 10–20 million kelvins. The contours show three distinct sources of hard x rays at 33–53 keV. Although hard x rays with energies less than about 20 keV often coincide with the soft x rays, more energetic hard x rays, like those shown here, typically occur in localized patches where the soft x-ray loop connects to the solar surface. Such "footpoint emissions" are usually interpreted as thick-target bremsstrahlung emitted by electrons that were accelerated high in the corona, streamed down the magnetic field lines and were stopped by the denser regions of the Sun. The event shown here conforms to all expectations—except for the patch of hard x rays above the loop.

It is this patch of emission, first found by Satoshi Masuda in his thesis work at the University of Tokyo, that has the solar community buzzing. The absence of a "thick target" so high (about 20 000 km) above the surface should rule out nonthermal emission from this region—but a thermal interpretation implies a temperature of 200 million kelvins. "*Something* energetic is going on *above* the soft x-ray loop," says Takeo Kosugi (National Astronomical Observatory, Japan). Because this emission varied in concert with the lower, thick-target hard x rays throughout the four-minute event, "this something must be directly related to particle acceleration," he says.

The Sun's atmosphere is permeated with a tangled web of magnetic fields, often not derivable from a potential. Solar researchers have long supposed that flares are powered by the magnetic free energy available in such nonpotential fields. The observation shown here, and several others made and analyzed by Masuda, Kosugi and others, fits the expectation of an energy release site high in the Sun's highly magnetic corona.

The next step is to unravel the physics. The Japanese group favors an interpretation based on magnetic reconnection, in which oppositely directed magnetic fields still higher in the atmosphere are annihilated and in the process create a jet of plasma that subsequently collides with the lower soft x-ray loop, heating the plasma to hundreds of millions of kelvins. This is very similar to a picture developed theoretically by Terry Forbes (University of New Hampshire, Durham) and Jean-Marie Malherbe (Meudon Observatory, Paris).[2] It may be that as observations like this one continue to roll off the Yohkoh data tapes, other interpretations will emerge.

—STEPHEN G. BENKA

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(See the article by Anthony Garito, Rui Fang Shi and Marvin Wu in PHYSICS TODAY, May 1994, page 51.) But the new compound reported this fall jumps that efficiency to nearly 100%.

Designing the polymer

Photorefractive polymers offer several potential advantages over their inorganic crystalline cousins, chiefly lower costs, structural flexibility and ease of processing. One can also tailor a polymer by mixing in a combination of molecules with the right properties, whereas it is difficult to optimize separately the performance characteristics of a crystal.

To make the high-efficiency material announced this fall, the University of Arizona researchers blended together four materials. The team consisted of Klaus Meerholz, Boris Volodin, Sandalphon, Nasser Peyghambarian, Hanh Hall, Anne Padias, Scott Lyon and Bernard Kippelen (who is also with CNRS in Strasbourg, France). They started with a common photoconductive polymer, PVK (poly(*N*-vinylcarbazole)). They added a strong electron acceptor, TNF (2,4,7-trinitro-9-fluorenone), to increase the photosensitivity in the visible. Essentially TNF forms a charge-transfer complex with PVK that absorbs photons to create mobile charges. The next ingredient was an electro-optic chromophore (a molecule or portion thereof that absorbs light) called DMNPAA (2,5-dimethyl-4-(*p*-nitrophenylazo)anisole), which has a large permanent dipole moment and can align with the external electric field. The chromophore provides optical nonlinearity, which is required for the photorefractive effect. The final touch was ECZ (*N*-ethylcarbazole), a plasticizer that enables the chromophores to align more easily with the applied field. Effectively, ECZ lowers the glass transition temperature. The percentages by weight of DMNPAA, PVK, ECZ and TNF in the new material are, respectively, 50, 33, 16 and 1.

When we asked Peyghambarian why he thought this particular compound worked so much better than the lower efficiency materials, he speculated that the reason might be

the particularly high concentration of the chromophore. There's a limit to how dense you can pack the chromophores before they start to crystallize and the material becomes opaque. At a concentration of 50% DMNPAA, the Arizona group is pushing the limit. Few other research groups have been able to make optically clear composite mixtures with such high fractions of chromophores. Perhaps his group succeeded, Peyghambarian said, because they had such a uniform compound, largely free of impurities that could cause crystallization.

To read and write holograms into their polymer device, Peyghambarian and his colleagues used small diode lasers, operating at a power of just 1–2 milliwatts. The cover of this issue is a photograph of a three-dimensional image of a penny that was retrieved from holographic storage in the new material; the red color reflects the 675-nm wavelength used to read and write the image.

Photorefractive materials can be used for other types of optical processing besides storing holograms. For example, if you send two beams through a sample, the weaker beam can exchange energy with the stronger one, growing in intensity. The Arizona researchers measured a net optical gain coefficient of about 210 cm^{-1} in their compound. For a sample with a thickness of about 100 microns, this coefficient enables the image to be amplified by a factor of 10 or so. A typical value for the gain coefficient in an inorganic crystal is 20–50 cm^{-1}, although the smaller gain coefficient is offset by the larger thicknesses available in crystals.

Limitations and hurdles

Diffraction efficiency is only one of many properties required of a photorefractive material to be used in a practical optical storage device. Another is the lifetime of the image—both during storage in the dark and, more critically, during multiple read operations. The image in a photorefractive device tends to fade a bit each time one shines a light on it to retrieve information. For the inorganic crystals, procedures have been developed to "fix" the image, by either thermal or electrical means, but the procedures are by no means perfect. So far there are no techniques for fixing the refractive grating in the newer, polymeric materials, although IBM researchers have been able to decrease the erasure rate by lowering the reading-beam intensity.[4] Peyghambarian told us that the data storage time for his group's new material is now limited to a matter of hours, because the charges do not remain trapped for long.

Yet another property of an optical storage device is its thickness. One would like to be able to store many images at once within a volume of photorefractive material. To retrieve each image one would rotate the storage medium (or the readout beam) to a particular angle. This technique works fine for inorganic crystals, which can be a few centimeters thick. By contrast, a typical photorefractive polymer is only about 100 microns thick. The Almaden group has demonstrated, however, that one can still make a large volume of the photorefractive polymeric materials by stacking many thin layers, each with its own electrodes.[5]

One possible disadvantage of polymers compared with crystals is that the former require the application of an applied field, on the order of tens of volts per micron.

The development of suitable photorefractives is not the only thing standing in the way of a complete system for holographic storage. There are significant hurdles to overcome with the other components as well. In the complete system envisioned, information starts as digital data stored in a computer. These data are impressed upon an array of liquid crystals known as a spatial light modulator such that the information gets coded as a pattern of light and dark spots on a light beam passing through the modulator. The image beam is then combined with a reference beam to form a hologram in a photorefractive medium. The retrieved image can then be recaptured with an array of photodetectors, which convert the optical signal back to digital data for deposition once more into a computer.

Moving the Mona Lisa

Until last spring no one had put all the components together in this way. So the field got a boost, if only psychological, when John F. Heanue, Matthew C. Bashaw and Lambertus Hesselink of Stanford University successfully implemented a fully digitized system: They took the Mona Lisa from her resting spot as digitized data in a computer, beamed her up through a spatial light modulator, stored her in a lithium niobate crystal and reconstituted her holographically.[6] (See the photo on page 17 of a flock of birds treated in the same manner.) The lady was very little the worse for the wear (or had her smile faded?).

The experiment was an important feasibility demonstration, showing that there are no fundamental limitations to the technology. To deal with problems that had plagued earlier attempts at a digital system—the cross talk between adjacent pixels in the spatial light modulator and the variations in the intensity of the recalled data "pages"—the Stanford researchers adopted a differential encoding technique. The experiment also demonstrated the need for further improvements to the materials and components. For example, the spatial light modulator used by the Stanford experimenters was less than optimal for their application, so they had to use an array of 8 by 8 pixels for every transmitted bit. As a result, the image transfer time was long—about one hour—and the amount of data stored was small—163 kilobytes. The group also incurred an error rate of one per million, unacceptably high for commercial purposes. Hesselink points out, however, that the raw bit error rate is comparable to that for existing optical storage devices and that proper signal processing can improve this error rate.

—Barbara Goss Levi

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CONVINCING EVIDENCE SEEN FOR ISOTOPES OF ELEMENT 110

On 9 November a group of researchers led by Peter Armbruster and Sigurd Hofmann at the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany, observed a sequence of four alpha particles emitted from selected reaction products of a thin piece of ^{208}Pb under bombardment from a beam of 311-MeV ^{62}Ni ions. The alphas clearly represented a decay chain, being essentially coincident in position and