Applications of Optical Phase Conjugation

"Time-reversed" light waves can be used to improve laser-beam quality, compensate for atmospheric turbulence, track a moving satellite, encode and decode messages and compare image patterns

by David M. Pepper

Boris Ya. Zel'dovich and his colleagues observed a curious phenomenon as they did an experiment at the P. N. Lebedev Physical Institute in Moscow in 1972. The investigators intentionally distorted an intense beam of red light from a pulsed ruby laser by directing it through a frosted glass plate. Then they aimed the smeared beam down a long tube containing high-pressure methane gas. In accordance with a well-known effect called stimulated Brillouin scattering the beam interacted with the molecules of the gas and was reflected backward; the gas acted as if it were a mirror, but a very unusual one. What surprised the investigators was that after the reflected wave passed back through the same piece of frosted glass a nearly perfect, undistorted optical beam emerged. In other words, the distortions introduced during the first passage through the glass had been undone. (Reflection from a conventional flat mirror, in contrast, would have increased the distortions.) The backward-traveling wave could therefore be loosely thought of as the "time-reversed" replica of the incident wave.

The phrase "time-reversed" is intended to imply that the beam reflected back by the gas faithfully carried all the distortions introduced by the frosted glass plate, but in a reversed sense. When the beam returned through the glass, the distorting properties of the plate therefore canceled the effects they had originally produced. In other words, if it were possible to make a motion picture of the incident beam, the "time-reversed" beam would be portrayed by playing the same film backward. "Time-reversed" waves are more accurately known as phase-conjugate waves, or wave-front-reversed replicas. The technology by which they are generated is known as optical phase conjugation [see "Optical Phase Conjugation," by Vladimir V. Shkunov and Boris Ya. Zel'dovich; SCIENTIFIC AMERICAN, December, 1985].

Phase-conjugate-wave technology has many intriguing applications. A high-quality optical beam can, for instance, be transmitted through a turbulent atmosphere and, after generation of its phase-conjugate beam, be made to retrace its path exactly. When the beam returns to its point of origin, it will therefore be free of degradation. Such beams can be used in the pointing and tracking of moving objects, the processing of images, optical computing, interferometry, laser gyroscopes, fiber and satellite communication systems, laser weapon systems and photolithography. The "mirrors" that generate phase-conjugate beams also make possible novel laser resonators.

Generating "Time-reversed" Light

Two standard methods of producing phase-conjugate waves are stimulated Brillouin scattering and four-wave mixing. In the years following the landmark experiment by Zel'dovich investigators have found that phase conjugation by stimulated Brillouin scattering can occur in a variety of substances other than compressed gas. Such substances are called nonlinear mediums. The term is used here in a special sense: the optical properties of a nonlinear medium, in contrast to those of a linear medium, are affected by light. Examples of nonlinear mediums include semiconductors, crystals, liquids, plasmas, liquid crystals, aerosols and atomic vapors.

Nonlinear mediums are also utilized in four-wave mixing, a scheme that was proposed in 1977 by Robert W. Hellwarth of the University of Southern California, followed by studies by Amnon Yariv of the California Institute of Technology and me (then at Caltech), and by David M. Bloom, Gary C. Bjorklund and Paul F. Liao of the AT&T Bell Laboratories. The technique involves the interaction in a nonlinear medium of four optical beams: three input beams and one output beam. The three input beams consist of a probe beam, whose "time-reversed" replica is sought, and two counterpropagating pump beams that are necessary to "sensitize" the nonlinear medium. The steps leading to the production of the fourth beam, the phase-conjugate output beam, are analogous to those of conventional holography. In holography a photographic emulsion is illuminated with light from an object and a reference beam. The reference beam and the light from the object interact to produce a hologram, or three-dimensional interference pattern, in the emulsion. After the film is developed the fixed, or static, hologram can be read by illuminating it with the same reference beam. The result is a three-dimensional reconstruction of the object's image.

In four-wave mixing the nonlinear medium acts as the photographic emulsion. The interaction of the probe, or object, beam with one of the pump, or reference, beams produces a wave pattern of reinforcement and cancellation (constructive and destructive interference) in the medium that amounts to a real-time, or dynamic, hologram. The phase-conjugate output beam is generated when the other counterpropagating pump beam is reflected from the hologram. Actually two holograms are created: each pump beam, in conjunction with the probe beam, yields a hologram from which the other reference beam is reflected.

Although each method—stimulated Brillouin scattering and four-wave

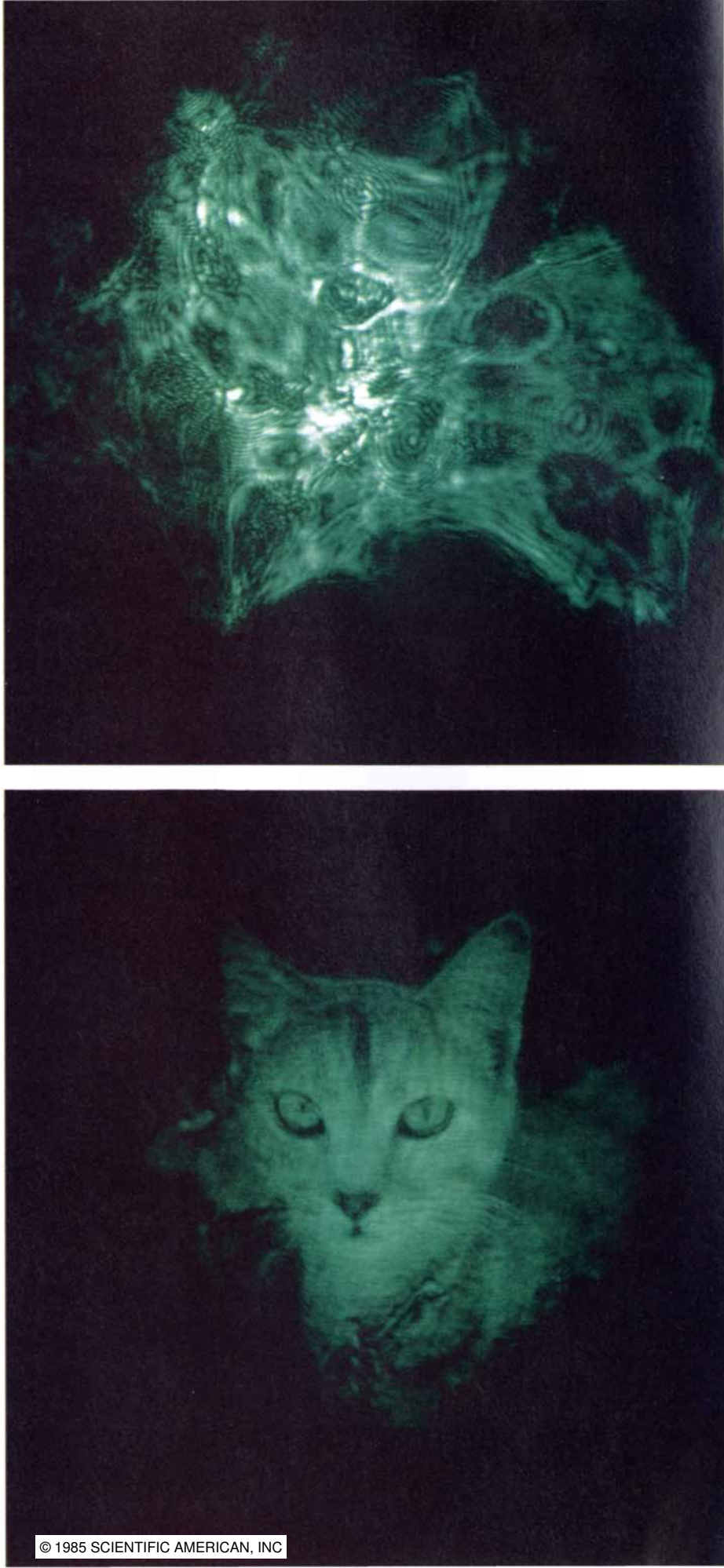
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mixing—has advantages and disadvantages, the end result of both is a phase-conjugate mirror, a peculiar mirror that exists in three dimensions and returns a "reflection" of the initial beam that exactly retraces the path of the initial beam. In both cases the dynamic aspect of the nonlinear medium enables the phase-conjugate mirror to respond to time-varying input beams. The reader is challenged to imagine while reading the article what he or she might see while gazing into such a mirror. (The answer is given at the conclusion of this article.)

Adaptive Optics

Optical phase conjugation has many applications because there is often a need to compensate for static and dynamic distortions encountered in optical systems. High-power lasers, tracking systems, atmospheric communication networks and photolithographic systems are all hampered by such noise, which can also hamper the effectiveness of a weapon system. Either four-wave mixing or stimulated Brillouin scattering can help.

Many of these applications depend on a so-called double-pass geometry: an arrangement in which a laser beam is phase-conjugated and reflected in such a way that it passes through the same medium twice. Such a reflected beam exactly retraces the path of the incident beam in a "time-reversed" sense. In one example of such a geometry a low-power seed laser injects a highly directed light beam into an amplifier that is typically made up of a solid or a gas of highly excited atoms or molecules. As the beam passes through the amplifier it "tickles" the molecules into releasing their energy as radiation. A powerful beam is produced, but at the cost of directivity: inhomogeneities in the amplifying medium distort the beam so that it diverg-



PHASE-CONJUGATE MIRROR is able to compensate for distortions imposed on an image of a cat. In both photographs the image was distorted by transmitting it through a piece of frosted glass. Reflection of the image back through the same piece of glass by an ordinary mirror yielded an unrecognizable image (*top photograph*). Reflection of the image back through the frosted glass by a phase-conjugate mirror, on the other hand, corrected the distorted image (*bottom photograph*). It did so because a phase-conjugate mirror produces a beam that propagates back through the distorting glass in a "time-reversed" sense: its trajectory retraces that of the original beam and thereby undoes the distortions. Jack Feinberg of the University of Southern California performed the experiment using an argon laser.

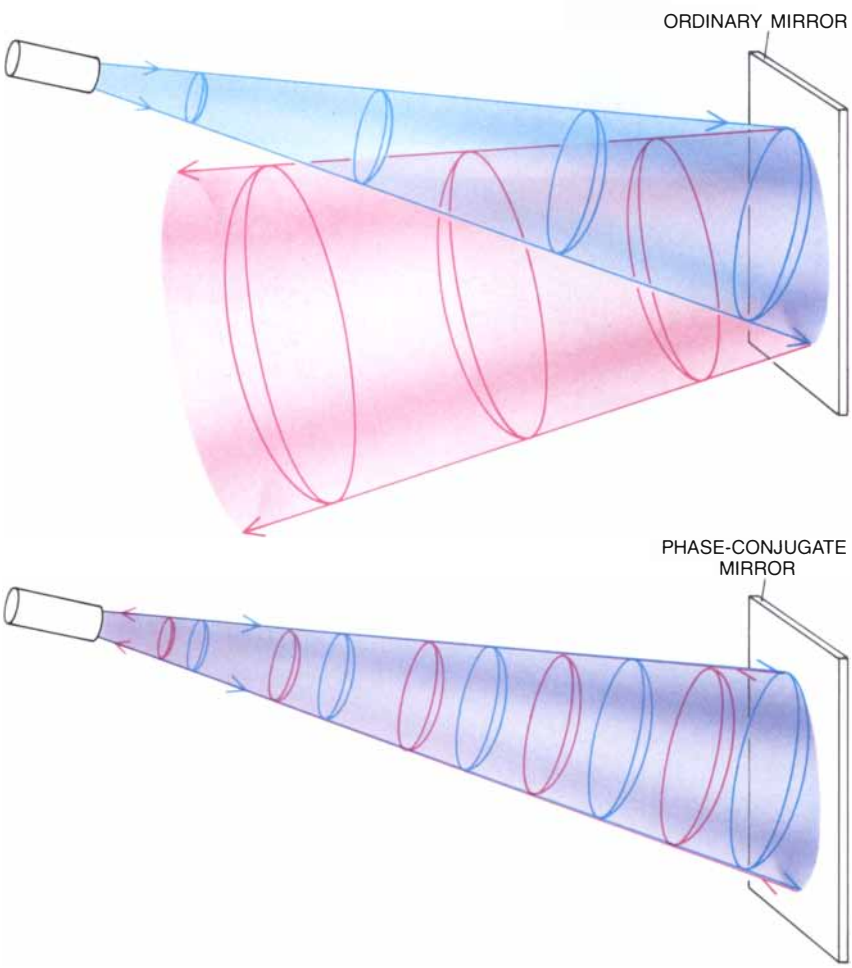
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es. The distortions can be removed if a phase-conjugate mirror placed at the end of the amplifier receives the beam. When the phase-conjugate beam from the phase-conjugate mirror travels back through the amplifier, its motion, which is the reverse of the original beam, undoes the degrading effects of the medium. The double-passed beam that emerges is both powerful and highly directed.

As a consequence of fundamental and practical considerations there are limits on the physical size of a single amplifier and hence on the output power it can produce. By using a set of amplifiers in a parallel arrangement and a phase-conjugate mirror one can both compensate for optical distortions within each amplifier and "phase up," or synchronize, an entire ensemble of amplifiers. Since the ensemble acts as an optical phased array of amplifying elements, the peak intensity of the output beam is proportional to the square of the number of amplifiers. The peak intensity produced by an array of amplifiers in which the phase of the radiation is random is merely proportional to the number of amplifiers. The basic scheme, proposed by Nikolay G. Basov and his colleagues at the Lebedev Physical Institute and by Thomas R. O'Meara and his colleagues at the Hughes Research Laboratories, has been recently demonstrated by David A. Rockwell and Concetto R. Giuliano, also at Hughes.

Another example of a double-pass geometry is the self-targeting of radiation, which also relies on a beam from a low-power seed laser. In this case, however, the seed laser directly illuminates a target, such as a fusion pellet containing a mixture of deuterium and tritium (isotopes of hydrogen). Some of the light scattered by the pellet passes through a nearby amplifier. As the beam passes through the amplifier its power is increased. A phase-conjugate mirror at the end of the amplifier produces an intense "time-reversed" beam that is directed back to the target. If the beam were powerful enough, the nuclei in the pellet would fuse, releasing useful energy.

Self-targeting can be applied to other situations as well: the fusion pellet can be replaced by an orbiting satellite. On illumination any scattered light returning from the satellite and collected by a phase-conjugate laser system can be amplified and sent back to the satellite. To the extent that the intervening atmosphere and satellite position do not appreciably change during the round-trip optical transit time, the phase-conjugate mirror not only will compensate for atmospheric turbulence (the phenomenon that causes the "twinkling" of stars) but also will make it possible to track the satellite by maintaining a continuous beam of illumination on it. The satellite could subsequently direct the amplified laser beam to a missile and, if the radiation were sufficiently intense, destroy it. Such schemes have been proposed and extensively evaluated for laser weapon systems since the early 1970's.



PROPERTIES OF A PHASE-CONJUGATE MIRROR are compared with those of an ordinary mirror. As shown here, a beam of light illuminates both mirrors. The ordinary mirror (*top*) merely reflects the beam. The phase-conjugate mirror (*bottom*) redirects the diverging beam so that a converging, "time-reversed" beam is formed, independent of angle.

Lensless Imaging

Many optical systems rely on large numbers of lenses that are difficult to control and adjust. Phase-conjugate schemes have been proposed that could eliminate such difficulty. They could, for instance, be used to transfer a given two-dimensional pattern from one plane in space to another. That is precisely the goal of photolithography, the technique by which a mask pattern containing a microelectronic circuit layout is transferred to a semiconducting chip that is coated with a photographic emulsion. (Direct physical contact of the mask with the substrate may be undesirable.)

The feasibility of such image transfer has been demonstrated by Marc D. Levenson and his colleagues at the IBM Research Laboratory in San Jose and more recently by Malcolm C. Gower of the Rutherford Appleton Laboratory in England. Light from a laser passes through the mask pattern, a semitransparent mirror and then an amplifier. The intensity of the beam increases at the expense of introducing distortions into the beam. The resulting image is sent back through the amplifier by a phase-conjugate mirror. The "time-reversed" beam is both powerful and free of distortions, so that when it reflects from the semitransparent mirror, it exposes the emulsion with the pattern. The phase-conjugate system has advantages in relation to conventional methods such as compensating for optical aberrations.

Lensless-imaging schemes involving optical phase conjugation are useful in other ways. One is the removal of dis-

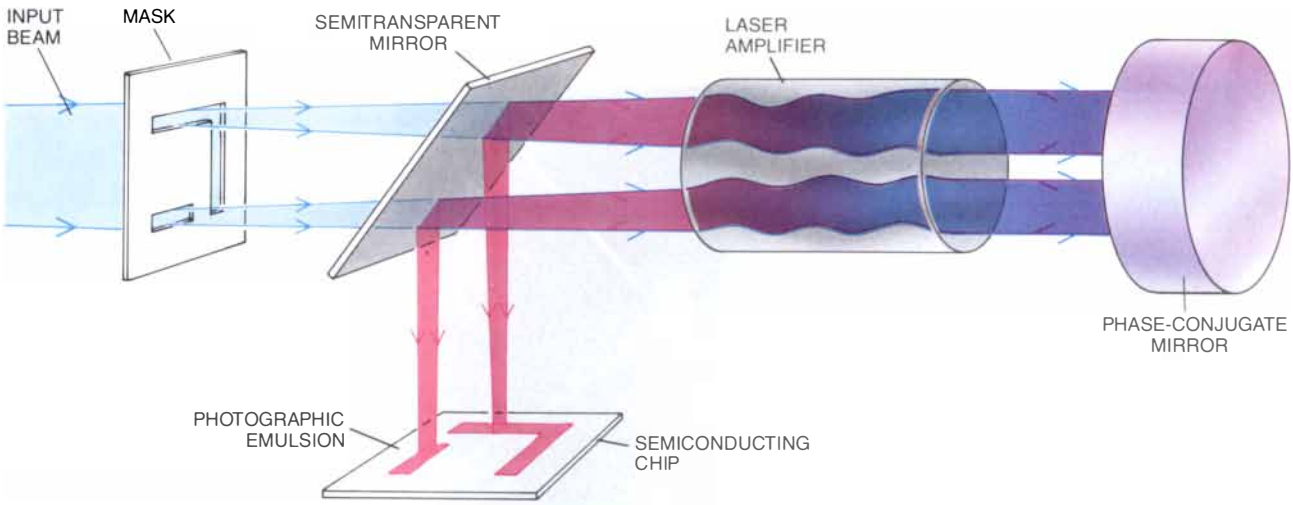
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tortions introduced by fiber-optic cables. Such distortions arise as follows. Imagine sending a three-dimensional image (say of a tree) through a plate-glass window. The window does not degrade to any serious degree the quality of the image. If the same glass window is replaced by a long optical fiber, the image will be unrecognizable after traveling only a few centimeters. The reason is that the image of the tree travels in many optical modes, each of which corresponds to a given ray that zigzags down the fiber. Since all the modes traverse different paths, they are out of step by the time they reach the end of the fiber. (They no longer have the same phase relation to each other as they did at the beginning of the fiber.) In other words, just as a piece of frosted glass scrambles an image, so does an optical fiber.

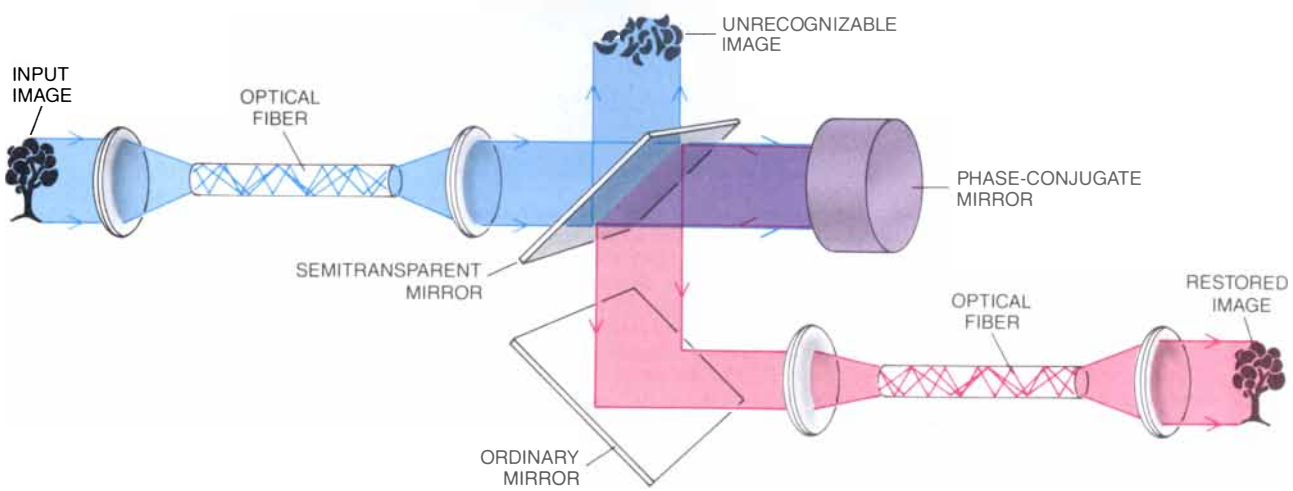
The image can be unscrambled if it is phase-conjugated and sent back through the same fiber, or through another, identical fiber link. This concept, initially pointed out by Yariv, has been successfully demonstrated by Gilmore J. Dunning and Richard C. Lind of Hughes, and more recently by Baruch Fischer and Shmule Sternklar of the Technion–Israel Institute of Technology in Israel. Even though they worked with two-dimensional images, the scheme can in principle also allow for the transmission of three-dimensional images through fibers.

Phase-Conjugate Resonators

How might the performance of a laser change were one or both of its cavity mirrors to be replaced by a phase-conjugate mirror, forming a so-called phase-conjugate resonator? A resonator is a hollow cavity for reinforcing a sound wave or an electromagnetic wave. Typically it consists of a long tube filled with an amplifying medium (a solid or a gas), capped at each end with a highly polished semitransparent



PHOTOLITHOGRAPHY, the transfer of a two-dimensional pattern from one plane in space to another, can be done without optical lenses by employing a phase-conjugate mirror. The process can be used to transfer a mask pattern containing a microelectronic circuit layout onto a semiconducting chip coated with a photographic emulsion. A beam of light (*blue*) from a laser passes through the mask, a semitransparent mirror and then a laser amplifier. Although the amplifier increases the power of the beam, inhomogeneities in the amplifying medium distort its quality. After the beam is phase-conjugated (*red*) it propagates back through the amplifier, undoing the distortions and emerging with the original beam information restored. On reflection from the semitransparent mirror, an intensified image of the mask pattern exposes the emulsion. The system compensates for optical aberrations, has high resolution over a large field of view, eliminates laser speckle, minimizes beam spreading and avoids physical contact with the substrate.



DISTORTIONS DUE TO FIBER-OPTIC CABLES can be removed by a phase-conjugate mirror. The distortions arise because a spatial image (*left*) sent down a cable travels in many optical modes: each mode corresponds to a given ray that zigzags down the fiber (*blue*). Since all the modes traverse different paths, by the time they reach the end of the fiber they are out of step, producing a scrambled image (*center*). The image can be unscrambled if it is phase-conjugated (*red*) and sent down an identical cable (*right*).

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mirror. Laser output results when light passes through one of the mirrors.

In 1978 a team at Caltech headed by Yariv that included John C. AuYeung, Dan Fekete and me explored this question. In the course of our work we successfully developed the first pulsed phase-conjugate laser. In our experiment a ruby rod served as the amplifying medium. We placed a conventional mirror at one end of the rod and a phase-conjugate mirror at the other end. The phase-conjugate mirror, in this case a four-wave mixer, consisted of a cell filled with carbon disulfide; the pump beams were obtained from another pulsed ruby laser.

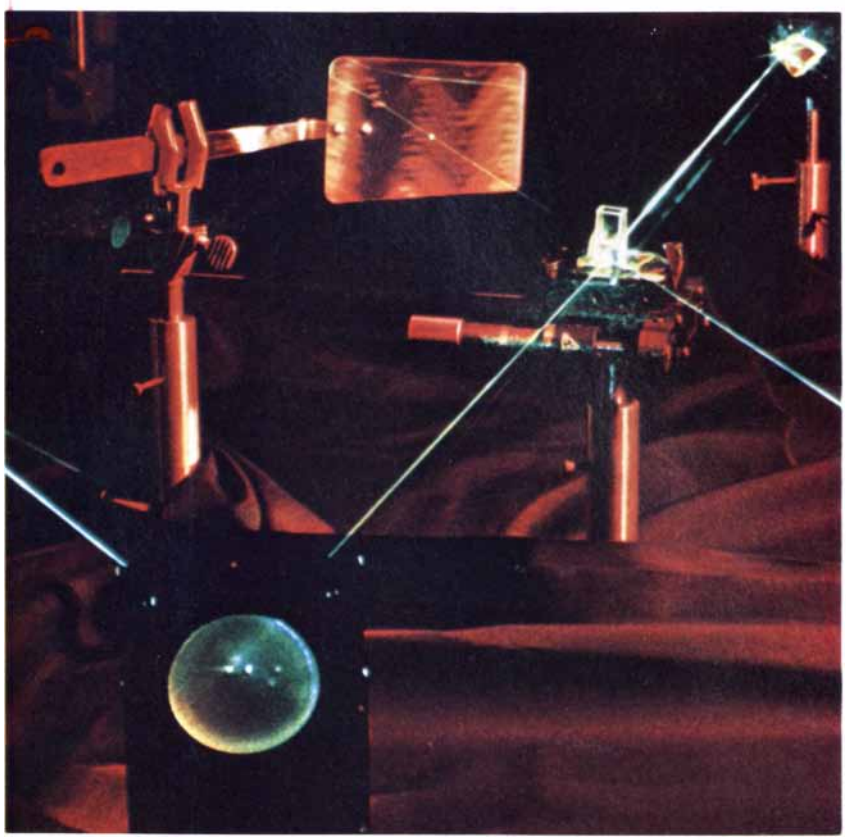
We found that a phase-conjugate resonator has unique properties. Perhaps the most obvious property is that the phase-conjugate mirror can compensate for static and dynamic aberrations in the cavity due to, for instance, imperfect optical components, as well as dynamic thermal and mechanical perturbations. A phase-conjugate resonator is therefore highly efficient at extracting the optical energy stored in the laser medium. A more subtle effect relates to what is called "resonator stability." The ability of a conventional resonator to store energy is dependent on the relation between the radiation, the cavity length and the mirror curvature. A phase-conjugate resonator is free from such constraints.

The properties of the phase-conjugate resonator occupy the attention of a number of research groups including those at Hughes, Caltech and Stanford University and in the Soviet Union, France, Great Britain and Canada. Devices based on four-wave mixing and stimulated Brillouin scattering have both been employed.

Lind and Duncan G. Steel (then at Hughes) have, for instance, recently constructed the first continuously lasing phase-conjugate resonator. The phase-conjugate mirror they used consisted of a one-centimeter cell filled with atomic sodium vapor, pumped by a dye laser. Inserting a frosted glass sheet within the laser cavity had virtually no effect on the system: it continued to produce a reasonably good beam, even as the plate was moved into the cavity. The same frosted plate prevented a conventional version of the same dye laser from producing any beam at all.

A phase-conjugate resonator of particular interest can be built using a four-wave mixer. Since two pump beams are employed, the intensity of the output phase-conjugate beam can exceed the intensity of the input probe beam. In other words, a four-wave mixer can be made to have optical gain. Such a four-wave mixer is said to be an amplifying phase-conjugate mirror. Even an "empty" laser resonator, consisting of only an amplifying phase-conjugate mirror and a conventional mirror, can therefore be made to lase; no internal amplifying medium is necessary. Since the phase-conjugate mirror also reflects any light striking it back to the point of origin, lasing will still occur even if the conventional mirror is moved about. Yariv and I proposed such a device and with the assistance of Fekete have tested it; it has also been demonstrated by Bloom, Liao and N. P. Economou of the AT&T Bell Laboratories.

Perhaps the most novel laser resonator was built by Jack Feinberg of the University of Southern California and Hellwarth. They merely positioned a kitchen spatula in the vicinity of a phase-conjugate mirror (a barium titanate crystal pumped by a laser). The amplifying properties of the phase-conjugate mirror created a phase-conjugate resonator, with the crystal and the reflective surface of the spatula forming the cavity mirrors. An intense beam of light was then seen between the spatula and the crystal. The phase-conjugate mirror tracked any motion of the spatula by maintaining the beam on its surface. Moral: Do not wear anything reflective near an amplifying phase-conjugate mirror!

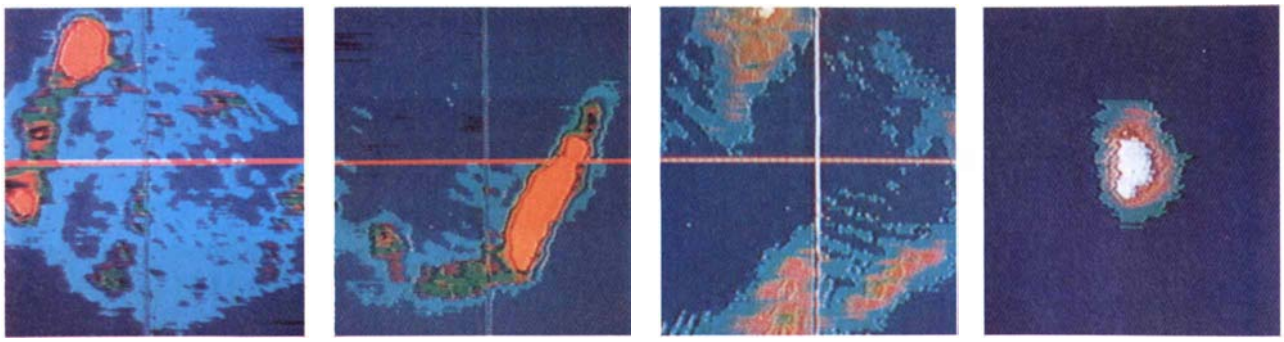


"SPATULA LASER" consists of a reflecting mirror (*spatula*) and a phase-conjugate mirror (*crystal at beam intersection*). A conventional laser consists of a long tube capped at each end with a highly polished mirror. The tube is typically filled with an amplifying medium (a highly excited solid or gas). The spatula laser requires no amplifying medium because the phase-conjugate mirror provides the necessary gain. The amplification is achieved by pumping, or exciting, the rectangular crystal with two laser beams known as pump, or reference, beams. One of the pump beams enters the photograph from the corner at the lower left and is reflected by a mirror (*green disk*) to the phase-conjugate mirror. Some of the laser beam is absorbed by the crystal; most of the beam continues on to the wedge-shaped mirror in the upper-right corner. The beam reflected by that mirror becomes the other pump beam. After the crystal has absorbed sufficient energy from the two counterpropagating pump beams it will begin to lase with any shiny surface in its vicinity, as if the region between the crystal and the shiny surface were filled with an amplifying medium. The laser beam lying along the line between the spatula and the crystal is thereby generated. If the spatula were moved, the phase-conjugate mirror would track it by maintaining the beam on its surface. The laser beam emerges through the crystal (*right*). The experiment was done by Feinberg and Robert W. Hellwarth of the University of Southern California.

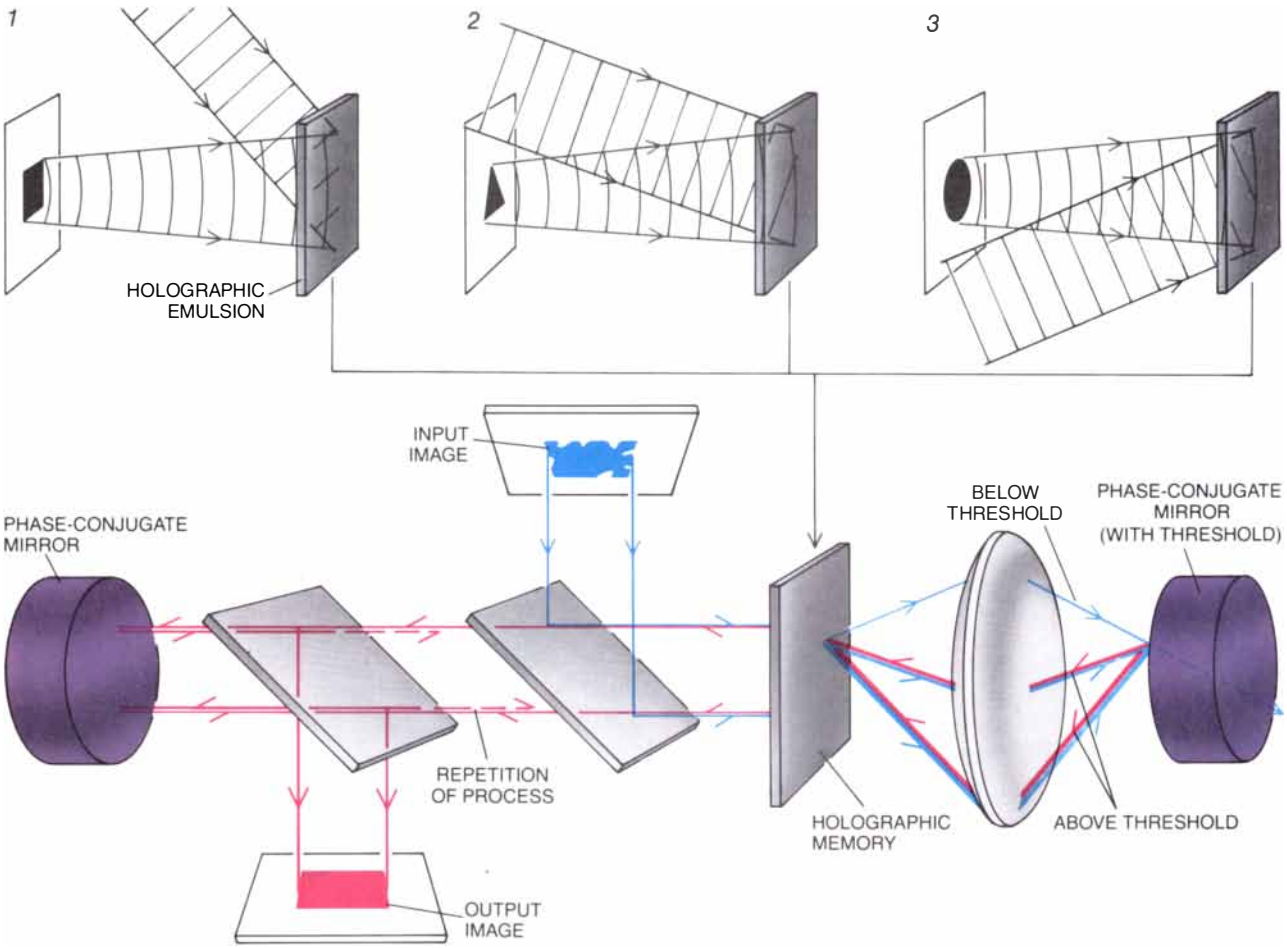
Image Processing

The common element in all four-wave-mixing processors is the optical

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ATMOSPHERIC TURBULENCE is compensated for by optical phase conjugation. Laser light that traversed a 100-meter outdoor range produced highly distorted beam spots (*sequence of three photographs at left*) that vary in space and time. (The turbulence that produced the distortions is also responsible for the twinkling of stars and the apparent undulation of objects viewed over a heater or on a paved road on a hot afternoon.) When the beam was phase-conjugated and sent back through the atmosphere, the near-perfect quality of the beam spot was restored (*right*). The video-processed, color-encoded photographs were made at an exposure of 1/2,000 second. Gilmore J. Dunning and Richard C. Lind of the Hughes Research Laboratories did the experiment with a tunable dye laser.



ASSOCIATIVE MEMORY can recognize two images that share common features with each other. A memory-storage element is formed by illuminating a photographic emulsion with a reference beam and an image of a square (*top left*), creating a hologram, or an interference pattern, in the film. The process is repeated on the same emulsion for a triangle and a circle. The incident angle of the reference beam is changed in each case so that the images can be distinguished. The photographic emulsion—now a holographic memory element—is developed and placed between two phase-conjugate mirrors (*bottom*). The image to be categorized (*imperfect square shown here*) is reflected by a semitransparent mirror onto the emulsion (*blue*). Every time a ray of light from the imperfect square matches a ray from one of the holograms stored in the film a strong output ray is produced (*heavy line*); if the rays do not match, a weaker output is produced (*medium and thin lines*). Strong and medium output rays are reflected by the phase-conjugate mirror at the right (*red*). Weak output rays, however, do not have enough energy to cause conjugation to occur and therefore pass through the phase-conjugate mirror (*blue ray at right*). In this way the qualities of "squareness" are selected. After the strong and medium output rays are conjugated a second time by the phase-conjugate mirror at the left the process is repeated. Successive iterations yield a square as an output. In other words, the system "recognized" that the input image was an imperfect square, not an imperfect circle or triangle.

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interaction of the beams. On a fundamental level the conjugate beam can be thought of as an algebraic product of the three input optical beams (the probe beam and the two counterpropagating pump beams); the nonlinear medium in the four-wave-mixing cell provides for the multiplicative effect through the coupling of the beams. Hence if any or all of the input beams are encoded either in a spatial fashion (by passing the beams through various slides or other optical transparencies) or in a temporal manner (by pulsing them), the conjugate output beam will be encoded in a way proportional to the product of all the information of the interacting beams.

Research groups led by Yariv at Caltech and by Osamu Ikeda at the Tokyo Institute of Technology have shown that by spatially encoding the pump beams, instead of the probe beam, in a four-wave mixer one can transmit images in a "one way" manner, even through a distorting medium. (Remember that the lensless-imaging techniques discussed above involve the double-pass transmission of an image.) Suppose a projectionist wants to send an image or a motion picture (say of a sportswoman diving off a springboard) to a friend some distance away. Owing to atmospheric turbulence, the diver would be unrecognizable.

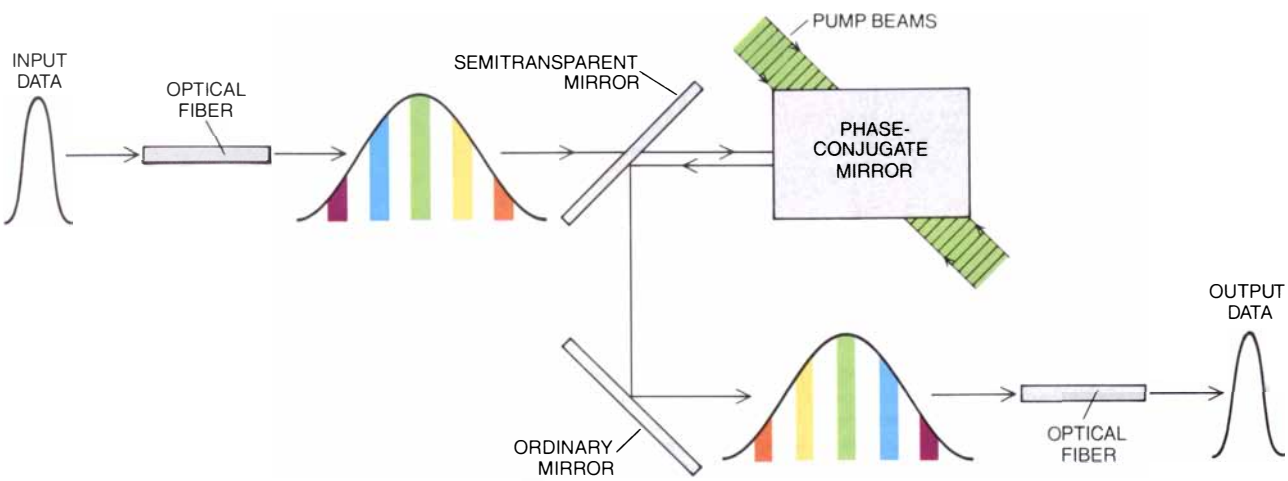
The image can be transmitted by replacing the projector with a four-wave mixer and equipping the friend with a beacon laser. The sequence of events is as follows. The friend aims his beacon laser toward the projectionist. The distorted beam, as seen by the projectionist, in essence samples, or probes, the atmospheric turbulence. If the projectionist allows the light to strike a conventional four-wave mixer, the "time-reversed" beam will undo the atmospheric distortions and make its way back to his friend with no information. By placing a transparency of the diver in the path of one of the pump beams, however, the phase-conjugate mirror can be spatially encoded with the wanted information. In this way the phase-conjugate mirror reflects a predistorted image of the diver. The result is that a unique "time-reversed" beam bearing a distortion-free image reaches the friend at the beacon laser.

Image processing also plays an important role in a variety of fields such as criminology (the comparing of fingerprints), biological sciences and medicine (classification and identification of various classes of cells and their mutations), artificial intelligence, robotics and automation systems. Sophisticated optical systems could facilitate these and other comparison techniques. Conventional holography has, for instance, been employed for some time to perform image-processing functions. The theory was developed in 1963 by Anthony B. Vander Lugt of the University of Michigan, who also demonstrated various classes of image filters and pattern-recognition schemes by means of conventional fixed holograms recorded on film emulsions. Four-wave-mixing technology, since it is a form of real-time, or dynamic, holography, can enhance the power of the technique. Jean-Pierre Huignard of the Thomson-CSF Laboratories in France, Feinberg and Y. H. Ya of the Telecom Research Laboratories in Australia have made significant contributions to this field.

One potential application of four-wave mixing to image processing is a real-time pattern-recognition device. It was proposed by several colleagues and me at Caltech in 1978 and demonstrated by Jeffrey O. White (then at Caltech) and Yariv in 1980 and independently by S. G. Odulov and M. S. Soskin of the Institute of Physics of the Academy of Sciences of the Ukrainian S.S.R. during the same year. The scheme involves a four-wave mixer. The three input beams to the mixer (that is, the two pump beams and the probe beam) pass through respective transparencies whose spatial patterns are to be compared. The pattern formed by the resulting conjugate output beam reveals the overlap, if any, between the patterns of the transparencies. In White and Yariv's experiment, for instance, one slide bore the character string *C-A-L-T-E-C-H* and another slide bore the letter *C*. The output of the system was two bright spots, each of which "pointed" to one of the two occurrences of the letter in the character string.

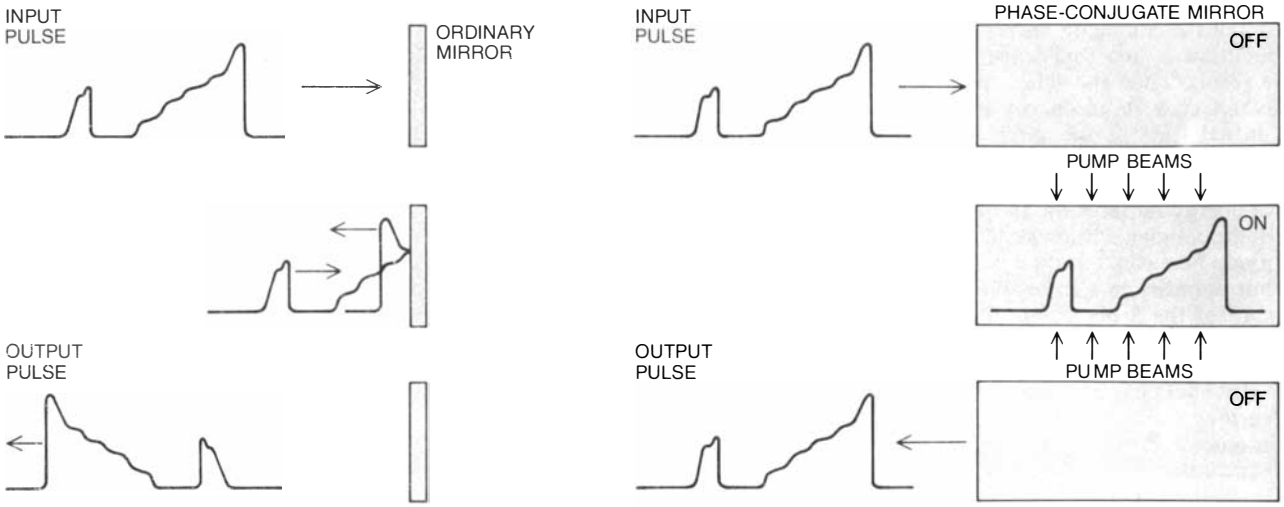
Associative Memory

Implicit in the design of an ideal pattern-recognition device is the assumption that the test letter perfectly matches the key letter in the character string. What if the test letter differs somewhat from the key letter? Suppose, for instance, that the letters are



TEMPORALLY BROADENED PULSE can be reconstituted by a phase-conjugate mirror. The broadening occurs because the various frequency components (*shown here as different colors*) that constitute a pulse propagate at slightly different speeds through space. A four-wave-mixing phase-conjugate mirror (pumped at the central frequency component of the pulse) placed midway along a fiber-optic cable transmitting the pulse will rearrange the pulse in such a way that the slower traveling components enter the second half of the cable first. As the conjugated pulse propagates through the remainder of the cable the faster traveling components will therefore catch up with the leading (that is, slower) part of the pulse: the pulse is renarrowed and the cable can transmit more information.

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TEMPORAL REVERSAL of a pulse sequence is achieved by a phase-conjugate mirror. An ordinary mirror (*left*) preserves the temporal ordering of a pulse sequence on reflection. A phase-conjugate mirror (*right*) will reverse the temporal ordering if the mirror is turned on when the entire pulse is inside the mirror. The mirror is actuated by applying two reference, or pump, beams to the mirror.

set in different typefaces (Gothic and Roman, say) or that one or both are blurred or even have missing areas. These examples are of particular interest because they correspond to daily experience: one recalls an incomplete image through a complicated process known as associative memory.

Teuvo K. Kohonen of the University of Helsinki and more recently John J. Hopfield of Caltech have developed models of associative memory, variations of which can be realized by means of a system containing phase-conjugate mirrors. The model might provide insight into how neural networks within the brain function. The basic idea consists of a mathematical algorithm that, in essence, compares a given input data string with one in memory, generates a new version of the data string and then iterates, or repeats, the procedure with the new version as the input. The comparison, selection and feedback process repeats until the input and output data strings converge, or agree. Many research groups, including those led by H. John Caulfield of the University of Alabama, Demetri Psaltis of Caltech, A. D. Fisher of the U.S. Naval Research Laboratories and A. A. Vedenov of the I. V. Kurchatov Institute of Atomic Energy in the U.S.S.R., have been exploiting electronic techniques (computers) and electro-optical techniques to simulate the process.

More recently Bernard H. Soffer, Dunning, Yuri Owechko and Emanuel Marom, all at Hughes, and, independently, Dana Z. Anderson of the Joint Institute for Laboratory Astrophysics in Colorado are developing architectures for all-optical associative memories. The Hughes scheme uses a conventional fixed hologram to store the memory information and phase-conjugate mirrors to provide the necessary image feedback [*see bottom illustration on page 79*]. Physically the device is simply a resonator capped with a phase-conjugate mirror at each end. The holographic memory element is positioned within the resonator cavity. One of the phase-conjugate mirrors has a threshold characteristic that enables it to select the features stored in memory that have the most in common with those of an input image for the next iteration.

Although digital computers can execute image processing and associative-memory functions, they do the job in discrete steps. The optical approach offers an advantage: image information can be processed in a parallel manner. In other words, the entire picture field is processed at the same time.

Frequency Effects

Throughout the discussion of the applications of four-wave mixing the implicit assumption has been made that the three input beams and the one output beam have the same frequency, or optical wavelength. Such a scenario is known as the "degenerate" case. In 1978 Richard L. Abrams of Hughes and I analyzed the case of "nearly degenerate" four-wave mixing, an example of which occurs when the frequency of the incident probe is slightly shifted with respect to the frequency of the two identical pump beams.

There are several situations in which nearly degenerate four-wave mixing occurs: the frequency of a probe beam reflected from a moving satellite would be Doppler-shifted with respect to the pump beams in a ground-based phase-conjugate mirror; two separate lasers (one to provide the pump beams and the other to provide the probe beam) that have slightly different frequencies may be involved in a given system; a pulse of light, which consists of a continuous band of frequencies, could be incident on a phase-conjugate mirror.

As Yariv, Fekete and I suggested in 1979, a phase-conjugate mirror could possibly be exploited to compensate for pulse-spreading effects in fiber-optic cables. Such effects limit the information-handling rate of a cable since densely spaced pulses that spread appreciably can spill into one another, rendering the data string unrecognizable. The spreading occurs because the frequency components of a pulse travel at slightly different speeds through a given material. If a four-wave-mixing phase-conjugate mirror is placed at the midpoint of a fiber-optic cable that is transmitting a pulse, the frequency components will be reordered so that the slower-propagating frequencies leave the mirror before the faster-propagating frequencies do. The faster-propagating ones will therefore catch up with slower ones on transit through the second half of the cable, restoring the quality of the pulse by renarrowing it to its original state.

How does a phase-conjugate mirror reorder the frequency components of a pulse? In the degenerate case the probe beam and one of the two counterpropagating pump beams generate a stationary optical interference pattern within the medium of the four-wave mixer. The other pump beam is reflected from the pattern and produces the phase-conjugate beam. In the nearly degenerate case the frequency shift causes the interference pattern to move through space, creating a mov-

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ing phase-conjugate mirror within the medium of the four-wave mixer. As a result, when the other pump beam is reflected, its frequency is Doppler-shifted (just as the pitch of a train whistle changes when the train passes a stationary observer). Conservation of energy requires the frequency shift of the conjugate beam in relation to the pump beams to be equal in magnitude but opposite in sign to the frequency shift of the probe beam; the frequency distribution of the probe wave is "flipped" symmetrically.

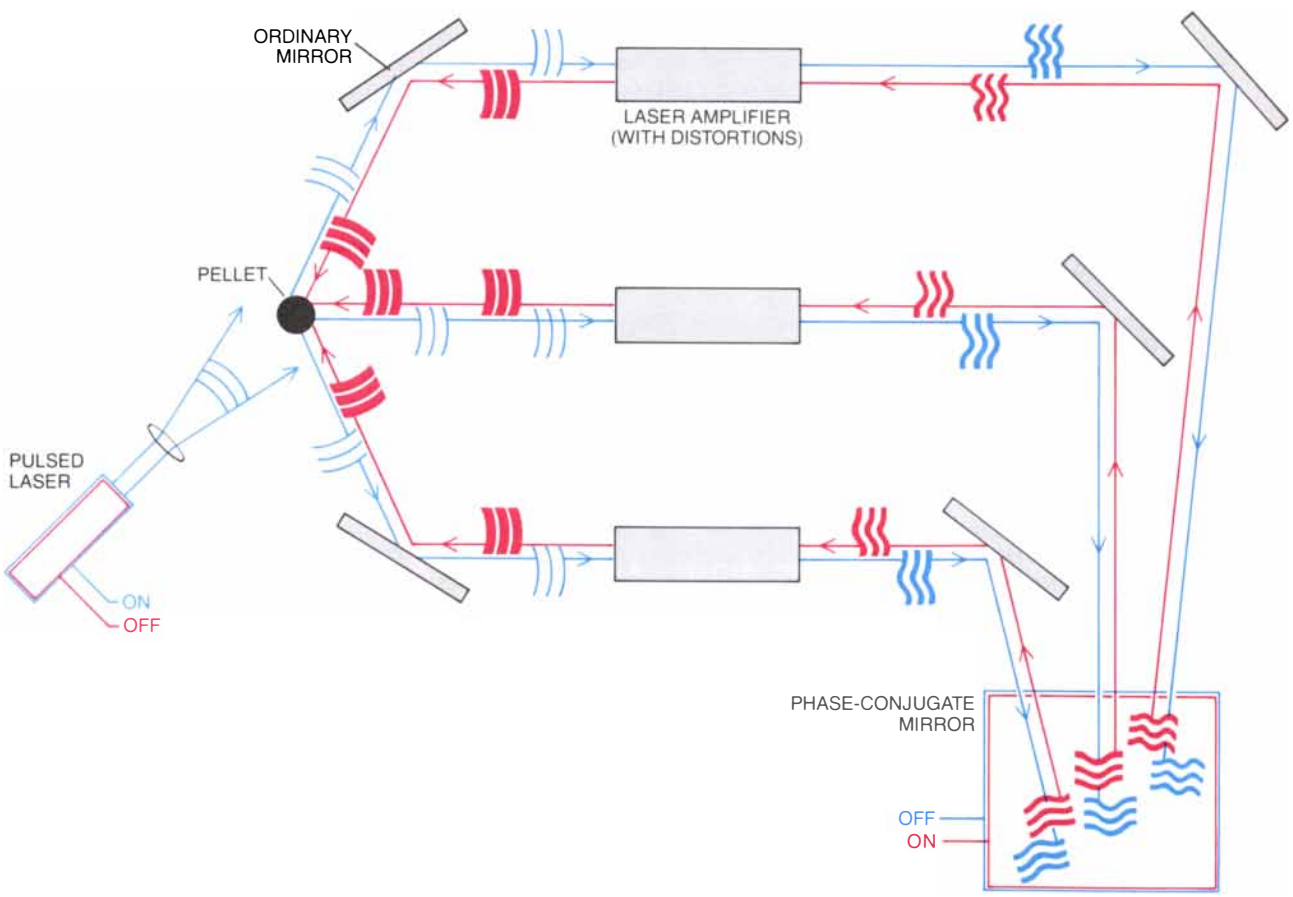
By changing the frequencies of the various beams that interact in a phase-conjugate mirror a so-called narrow-band reflective optical filter can also be realized. Typically such a filter will block (that is, not conjugate or reflect) all frequencies except those within a very narrow band that can be one ten-millionth of the optical frequency. In contrast, a simple piece of colored glass has a relatively coarse band-pass filter: it will pass light having a frequency that is within a band equal to about a hundredth of the optical frequency. The actual properties of the filter depend on the geometry of the phase-conjugate mirror and the specific nonlinear medium employed. The filter will not function, for example, unless the atoms of the medium can respond fast enough to the moving interference pattern. First proposed in 1978 by Abrams and me, phase-conjugate narrow-band filters have now been constructed in various laboratories, using a host of nonlinear mediums and laser sources. Although in the future the filters might replace conventional models in satellite and other communication systems, at present they are merely intriguing devices.

Time-Domain Applications

Another major class of information-processing techniques involves pulsing one or more of the interacting optical beams of a four-wave mixer to encode messages. Such a system could be used to effectively communicate with a satellite. A reflected wave can be generated by a phase-conjugate mirror only when the probe beam as well as both pump beams are illuminating the nonlinear medium. Hence by turning on or off one or more beams the reflectivity of the mirror is controlled and a message can be encoded in the output conjugate beam.

Suppose a satellite is equipped with a low-power beacon laser. Assume now that this probe laser is directed to a ground station equipped with a laser amplifier and a four-wave-mixing phase-conjugate mirror. If the conjugator is pulse-encoded, it not only will compensate for atmospheric turbulence and amplifier distortions but also will direct an encoded message back to the satellite. Moreover, under the proper conditions the system can track the spacecraft's motion.

A phase-conjugate mirror can also reverse a pulse sequence in time so that the last part of the sequence to enter the device is the first to leave. Such a pulse-sequence reversal device was proposed independently by David A. B. Miller, then at Heriot-Watt University in Edinburgh, O'Meara and Yariv.



PARALLEL AMPLIFYING SYSTEM could be used to initiate fusion. A fusion pellet is illuminated by a pulsed low-power laser (*blue*). Pulses scattered from the pellet pass through the three parallel laser amplifiers shown here. The intensity of the individual pulses is increased, but at the expense of introducing distortions. The pulses are then directed to a four-wave-mixing phase-conjugate mirror. By the time they reach the mirror they are out of step because they have traveled different distances. When all the pulses are inside the mirror, it is turned on, conjugating each pulse and reversing their temporal order with respect to one another (*red*). On the return trip the distortions are removed and the pulses become synchronized, so that an intense pulse of radiation hits the pellet.

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It could have important consequences in laser-fusion research.

Imagine a phase-conjugate mirror so long that a pulse sequence can spatially fit in the nonlinear medium. (A pulse that has a duration of a billionth of a second would, for example, require a foot-long phase-conjugate mirror.) When all the pulse sequence is contained within the medium, one immediately turns on the phase-conjugate mirror by activating the two counterpropagating pump waves. Once the pump waves are activated, the last part of the pulse sequence to enter the medium will be the first part to leave it.

O'Meara has combined the features of the pulse-sequence reversal device with a double-pass compensation scheme. In this arrangement a phase-conjugate beam propagates backward through a medium to compensate for distortions. He has also proposed a system that could simultaneously synchronize pulses from a chain of laser amplifiers arranged in a parallel configuration. The system could illuminate a fusion pellet and compensate for optical distortions introduced in the process, thereby optimizing performance.

The freedom to encode temporally the various beams in an independent manner can be exploited to realize yet another class of all-optical processors known as time-domain convolvers and correlators. The correlator, as an example (proposed by O'Meara and Yariv), is in essence a temporal analogue to the spatial-domain, real-time pattern-recognition device and so can recognize a given pulse sequence. Other variations of such a processor can rapidly encode and decode temporal messages. These time-domain schemes could be employed in signal processors, radars and optical devices.

Govind P. Agrawal and Christos Flytzanis of QUANTEL in France have suggested that phase conjugation could also be used to sense the state of the optical logic elements forming the heart of potential optical computers. An optical logic element might consist of counterpropagating beams in a nonlinear medium, an arrangement resembling the configuration of the pump beams in a four-wave mixer. A probe beam properly directed into such a logic element would therefore be conjugated and could be read to ascertain the logic state. The probe would not affect the operation or modify the logic state of the memory element.

Fundamental Studies

The emergence of optical phase conjugation has unified many areas of applied and fundamental optical physics. Spectroscopy, the study of the interaction of matter and radiation, has particularly benefited. In this application the experimental picture is turned around: the three input beams (the probe beam and the two pump beams) are now used to investigate the properties of the nonlinear medium itself. One can, for example, explore the physics and spectroscopy of four-wave-mixing processes by measuring the intensity of the phase-conjugate beam as a function of such parameters as the polarization, frequency, intensity and angle of incidence of the pump and probe beams, the pressure of a buffer gas (in the case of a gaseous medium) and the intensity of applied electric and magnetic fields.

The application of these techniques to such nonlinear mediums as atomic vapors, aerosols, photorefractive crystals and various organic species provides another source of detailed information about fundamental atomic and quantum-mechanical processes. Even though the field of laser spectroscopy has existed for many years, the phase-conjugate geometry offers yet another tool for gaining insight into the interaction of light with matter.

In addition the quantum-optical properties of interactions producing phase-conjugate beams may be useful in realizing novel classes of ultrasensitive detectors, which might be sensitive enough to respond to gravitational waves or to tap an optical-fiber telephone line. Although the development is still in its infancy, research is being carried out on an international level.

The concepts, techniques and basic applications of optical phase conjugation can in principle be applied to most other areas of the electromagnetic spectrum. This may open the door to microwave phase conjugation, for instance, with obvious applications in the fields of radar, millimeter-wave imaging systems and high-frequency temporal signal processing, as well as microwave spectroscopy.

Groups in the U.S.S.R. and the U.S. are also considering such candidates as phonons (sound waves) for phase-conjugation experiments. Acoustic-wave signal-processing devices and sonar are two areas that could benefit from such research. The technology might ultimately allow for the detection and tracking of submarines.

Answers and Questions

Now that the reader has been exposed to many of the potential applications of optical phase conjugation, I shall provide the solution to the question posed earlier: What do you see when you look at a phase-conjugate mirror? In an ordinary mirror the viewer obviously sees his or her face. Some of the light scattered from various parts of the face will be reflected by the mirror and find its way into one's eye. The phase-conjugate mirror, on the other hand, would direct any light scattered from the face right back to its point of origin. Light scattered from the nose will therefore be reflected and sent back to the nose. The only light seen by the viewer would be the illumination light that initially scatters from the cornea, strikes the phase-conjugate mirror and returns to the eye. In other words, the viewer would see a uniformly lighted mirror surface with no obvious details. A second person looking at the viewer directly (that is, not by way of the mirror) would, however, see the viewer's face illuminated by the action of the phase-conjugate mirror.

As a rather speculative note on which to conclude, I shall point to an intriguing curiosity. The particle-wave duality of light and matter raises the question of whether the propagation of matter can be reversed. The nonlinear optical interactions leading to phase conjugation involve stimulated effects and are therefore restricted by a law in physics, the Pauli exclusion principle, to particles known as bosons. All bosons are integer-spin particles. (Spin is a parameter of quantum theory.) A photon, or quantum of light, for instance, has a spin of 1 and is therefore a boson. Electrons, protons, neutrons and certain unstable elementary particles, on the other hand, are fermions, or half-integer spin particles, and as such are forbidden by the Pauli exclusion principle to take part in stimulated interactions.

Many classes of bosons such as helium-4 nuclei (composed of two protons and two neutrons), Cooper pairs (electron-positron quasi particles existing in superconductors) and certain short-lived elementary particles (pi and K mesons, for example) can in principle take part in "time-reversed" matter-wave interactions. Superfluids and superconductors may be suitable mediums for such interactions. The actual realization, however, seems a faint possibility because of the weakness of most particle-particle and particle-photon interactions, the requirement of an intense, undistorted beam for observing the effects, and the short lifetime of many bosons. Yet before the invention of the laser the field of nonlinear optics (which is the backbone of optical phase conjugation), although known in principle, was itself a *gedanken,* or thought, experiment and was therefore ruled out as a viable experimental possibility.

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