Optical Phase Conjugation

In everyday experience time always moves forward. The situation is qualitatively different, however, in the case of wave motion: light waves can be "time-reversed" and made to retrace their trajectories

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Imagine a sportswoman standing on a springboard, preparing to make a high dive. A quick run, a flight—but because of a small technical mistake her body enters the water at a wrong angle, making a big splash and causing waves to spread from the point of contact. How wonderful it would be to reverse time in order to correct the mistake and get a high score! Sprays of water would come together, waves would run backward to the point of contact, the diver would be thrown out of the water and onto the springboard and the surface would become as smooth as it had been before the dive. Unfortunately, although such a scenario can easily be portrayed with the help of a motion-picture projector, the time-reversed process contradicts our everyday experience, and for good reason: the sequence of events violates the second law of thermodynamics (the law that states that systems tend toward maximum entropy).

The scenario can be played successfully, however, if the actor is the wave motion of light or some other electromagnetic radiation. Such a phenomenon is possible because of a remarkable property of light rays that has been known for a long time, namely the reversibility of their propagation. For every light beam that has an arbitrary structure of rays there exists a possible "time-reversed" beam whose rays run along the same trajectories but in the opposite direction, as when a film is run backward. The success in the reversal of wave motion is due to an extreme simplification of the problem: the quantum-mechanical and thermal motions of atoms and electrons that radiate and refract light do not need to be reversed. It is sufficient, for practical purposes, to reverse the temporal behavior of macroscopic parameters describing the averaged motion of a large number of particles.

The existence of reversed beams has important consequences. It is evident, for example, that an ideal beam, or one that is free of distortion and has minimum divergence, can be degraded by transmitting it through inhomogeneities, such as a glass plate of nonuniform thickness. The property of reversibility means it is possible to create an "antidistorted" beam that becomes ideal after being transmitted backward through the inhomogeneities. The technology by which such beams are created and manipulated is called optical phase conjugation. The waves making up such a beam are called phase-conjugate waves.

To describe the properties of a phase-conjugate wave we must first discuss some of the basic concepts of wave motion. As a set of waves moves through space its oscillations arrive at different points at different times. Points at which oscillations are synchronous are said to be in phase. A phase is a stage of a period in relation to some starting position. The surfaces connecting points that have the same phase are known as wave fronts. An important feature of the wave-front surface is that it is perpendicular to the direction of wave propagation. Wave fronts of plane waves are planes and wave fronts of spherical waves are concentric spheres. The wave fronts of actual light beams may have rather complicated shapes and topologies.

The concept of a wave front can be utilized to understand the properties of a phase-conjugate wave. Suppose a photograph of a light wave is made in which the beam is propagating from left to right [*see top illustration on page 57*]. Owing to the reversibility of wave propagation, someone examining the photograph would not be able to tell whether the direction of propagation is from left to right or from right to left. If the beam were propagating from right to left (that is, if the beam were reversed), however, the wave fronts would be reversed with respect to the direction of the beam. That is why in the Russian language the process of generating a reversed wave is called wave-front reversal.

The relation between the wave fronts of two mutually reversed waves is analogous to the relation between the positions of two opposing armies on a military map. The front line of each army coincides with that of the other, and the directions of desirable movement are opposite. One can say that the front lines are mutually reversed: a convex part of one army's front corresponds to a concave part of the other.

Expressed in different language, the phase difference between any two points of the reversed beam has a sign opposite to that of the phase difference between the same points of the original beam. The mathematical operation of changing a phase sign is known as conjugation, and that is why the term optical phase conjugation was coined and subsequently adopted in the English-language scientific literature.

How does one conjugate (that is, reverse) a wave? It is easy to generate the phase conjugate of a plane wave: one simply mounts a plane mirror so that the wave is reflected precisely backward. It is not much more difficult to conjugate a wave that has a spherical wave front. A concave mirror in the shape of a section of a sphere would be mounted so that the center of the mirror corresponds to the source of the wave. Then at every point on the mirror the rays would be incident perpendicularly to the surface and would be reflected precisely backward.

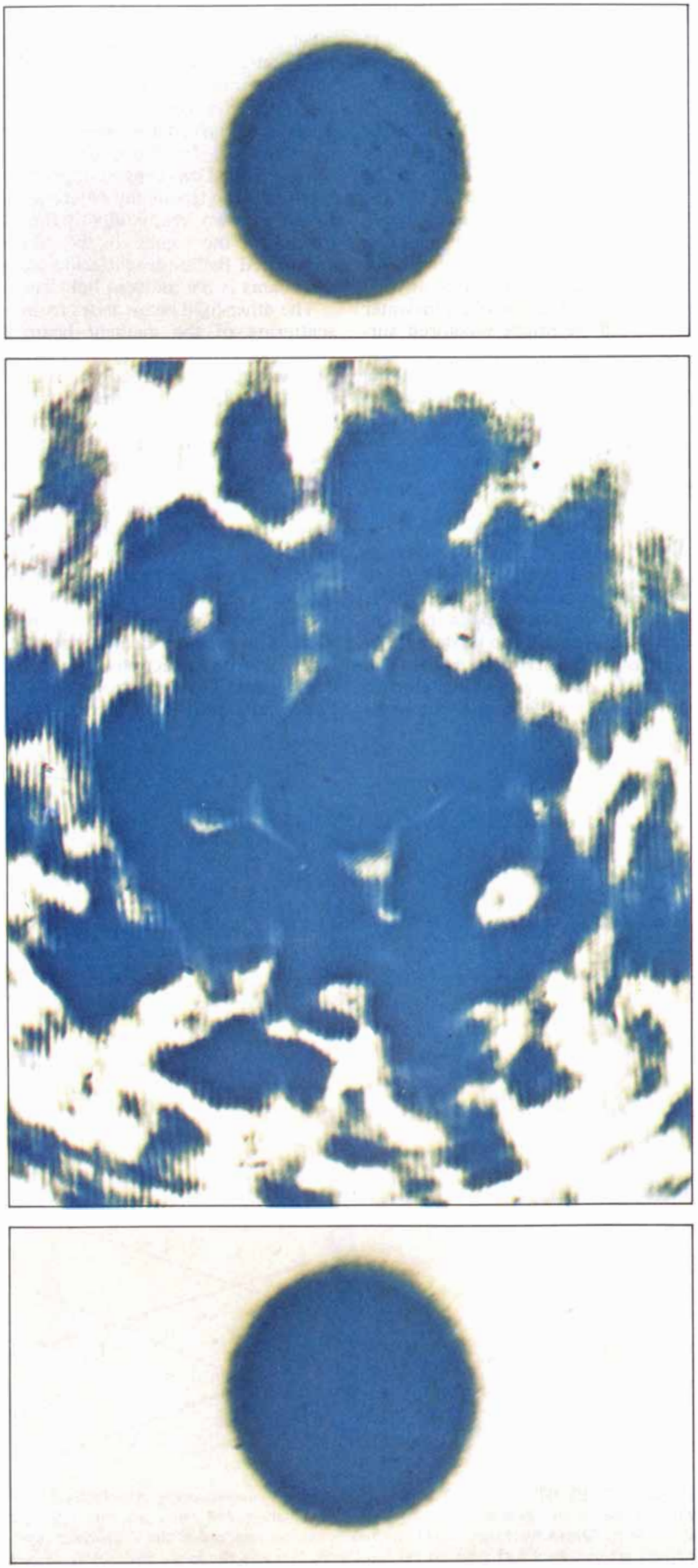
To conjugate a beam that has an arbitrary wave front one could in theory position a mirror whose profile coincides with that of the wave front. Unfortunately such a method is difficult to realize in practice. First, one would have to make a new mirror for each particular incident beam. Second, even the shape of a wave front of a laser beam can change during a brief pulse; one would therefore have to change the shape of the mirror continuously to match the changing shape of the wave. Finally, the precision required to prepare and position such a mirror would be extremely high.

To produce a phase-conjugate wave a medium or surface is required whose properties are affected by the characteristics of waves that are incident on it. That dependence allows the medium or surface to adjust itself with such delicate correspondence to the structure of the incoming beam that a reflected phase-conjugate beam is produced under certain conditions. Fortunately such materials exist. They are termed optically nonlinear.

Two widely used methods of phase conjugation that rely on such materials are stimulated Brillouin scattering and four-wave mixing. Stimulated Brillouin scattering, which is one of the most beautiful effects in nonlinear optics, was discovered in 1964 by Raymond Y. Chiao, Boris P. Stoicheff and Charles H. Townes, who were then working at the Massachusetts Institute of Technology. The effect involves directing a beam of light into a transparent medium such as liquid, compressed gas, glass or crystal. Light of low intensity passes through such a sample with virtually no attenuation. The behavior of a high-intensity light beam, however, is astonishing. Beginning at a threshold power of roughly a million watts the beam is reflected backward almost completely. Although such a power is rather high, it is easily attainable with a laboratory pulsed laser.

The reflected beam is a consequence of events that produce Brillouin scattering (named after the French physicist Louis Marcel Brillouin). In Brillouin scattering a sound wave is directed into a solid, a liquid or a gas. A sound wave causes the density of the material in which it is traveling to change in a periodic way. The resulting pattern, which moves with the wave through the material, consists of alternating zones of compression and rarefaction.

Because the zones of compression are denser than the zones of rarefac-



A PHASE-CONJUGATE, or "time-reversed," light beam can compensate for distortions introduced by an optically inhomogeneous medium (such as frosted glass). A highly directed laser beam (*top*) was distorted, resulting in a degraded beam (*middle*). The degraded beam was then reversed by optical phase conjugation. The backward transmission of the phase-conjugate beam through the inhomogeneous medium restored the quality of the beam (*bottom*).

tion, the behavior of a light wave directed into the material is different in the two zones. Specifically, the index of refraction of the first kind of zone is slightly different from the index of refraction of the second. (The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in the material.) If the separation between the zones is exactly half the wavelength of the incoming light, the light will be reflected. This kind of reflection is familiar to anyone who has seen a thin film of oil on water and noticed its rainbow-colored surface. At each point on the film one color is reflected better than it is at all the others, and it is that color whose corresponding wavelength is half the thickness of the film layer there. Since the thickness of the layer varies, different colors are reflected at different points.

In stimulated Brillouin scattering the sound wave, or pressure-density variation, is not applied externally to the material; it is stimulated internally by pairs of counterpropagating light waves. Just as sound can be thought of as a pressure-density wave, so light can be thought of as a moving electric field. An electric field can compress materials, a phenomenon known as the electrostrictive effect. If an electric field pattern moved at the speed of sound through a material, it could therefore give rise to a sound wave. Such an electric field pattern can be generated by the interference of two optical beams traveling in opposite directions if the frequency difference between the two beams equals the frequency of the sound. In the case of stimulated Brillouin scattering one of the beams is the incident light beam.

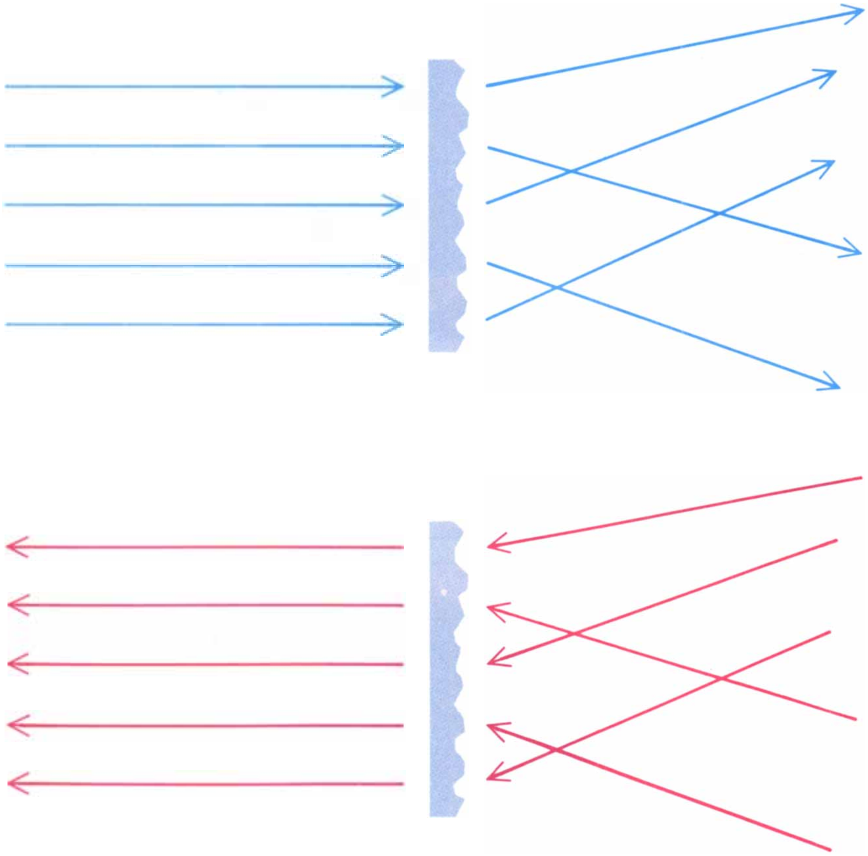
The other light beam arises from the scattering of the incident beam by small, statistically distributed density fluctuations in the medium (that is, thermally fluctuating sound waves). When the frequency and direction of a scattered wave are just right, the wave will interfere with the incident beam and amplify the pressure-density variations in the material. The variations subsequently lead to the reflection of a minute portion of the incident beam. The reflected portion interferes in turn with the incident beam, generating more pressure-density variations. The pressure-density variations lead to more reflections of the incident beam. The reflections build exponentially as distance increases, until a reflected beam emerges from the material. Since the amplification depends on the intensity of the incident beam, however, a prerequisite for producing the reflected beam is that the power of the incident beam must exceed a certain threshold.

Phase conjugation by stimulated Brillouin scattering was first achieved by Valery V. Ragul'skii, Vladimir I. Popovichev, Fuad S. Faizullov and one of us (Zel'dovich) at the P. N. Lebedev Physical Institute in Moscow in 1972. The main trick that allowed phase conjugation to take place was the use of a special glass plate that had been made nonuniform by etching with hydrofluoric acid. A beam of red light from a pulsed ruby laser was distorted by being passed through the plate. The distorted beam was directed into a pipe one meter long, four millimeters wide and four millimeters high that had been filled with gaseous methane at a pressure of 140 atmospheres. Stimulated Brillouin scattering occurred in the pipe, and the reflected beam, when it was passed backward through the same etched plate, emerged undistorted. That is to say, its structure was identical with that of the incident beam.

Phase conjugation by stimulated scattering has now been realized in a large number of scattering mediums and many types of lasers. The main advantage of the technique is that it only requires a cell filled with an appropriate gas, liquid or solid. The simplicity of the setup has prompted Robert W. Hellwarth of the University of Southern California to comment that in stimulated scattering "Nature surely loves the phase-conjugate beam." It is interesting that in 1977 Hellwarth proposed another way to conjugate waves: four-wave mixing.

Four-wave mixing is now the other popular method of phase conjugation. It involves the interference of four light beams in a nonlinear medium. Three of the beams are input beams: one is the object beam whose phase conjugate is sought and the other two are reference beams. The reference beams, which travel in opposite directions with respect to each other and are usually plane waves, have the same frequency as the object beam itself. The object beam may enter the medium from any direction. The fourth beam, an output beam, is the phase conjugate of the object beam and emerges along the same line as that of the object beam, although its direction of propagation is reversed.

The conjugate beam is produced by perturbations in the medium due to the interference of the object beam with



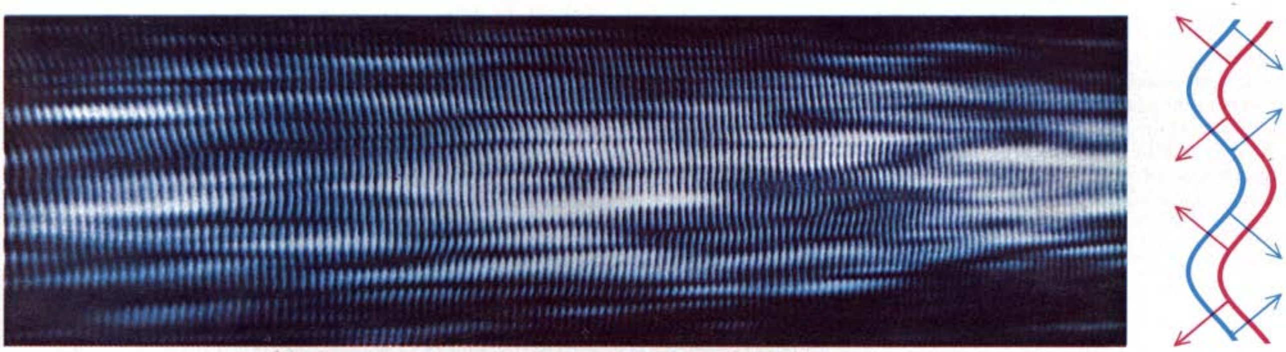
REVERSIBILITY OF LIGHT WAVES has important consequences. An ideally directed beam (one that is free of distortion and divergence) is degraded when sent through a glass plate of nonuniform thickness (*top*). The beam can be restored if the individual rays of the beam are reversed and transmitted backward through the same glass plate (*bottom*).

one of the reference beams. Wherever the electric fields of the waves oscillate with the same phase, the fields are added and the local intensity of light is high. Where the fields oscillate with the opposite phase, the fields are subtracted and the local intensity of light is low. The zones of high intensity are sandwiched between the zones of low intensity. The size, shape and orientation of all the zones are determined by the characteristics of the interfering fields. All the information about the phase of the object beam is therefore stored in what is known as an interference pattern, which manifests itself in the medium as a series of zones that have different refractive indexes.

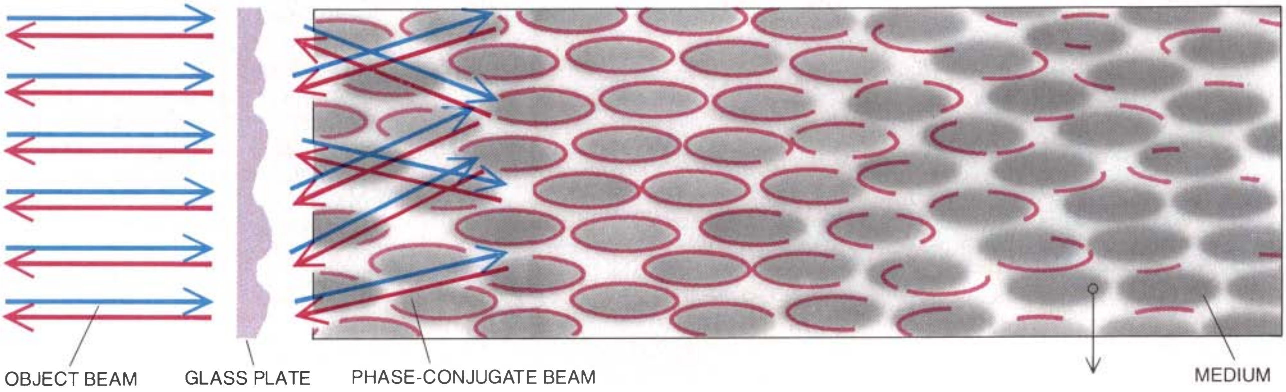
The second reference beam is reflected by the zones of the interference pattern, that is, the beam reads out the information about the phase structure stored in the pattern. Since the second reference beam comes from a direction opposite to that of the first one, the reflected beam is the phase conjugate of the object beam. Although the reflection from each zone of the pattern is weak, the sum of all such reflections is large and a considerable amount of energy can be transferred from the reference beam to the conjugate beam.

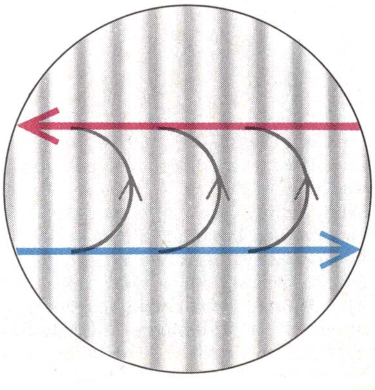
The symmetry in the arrangement of the reference beams suggests that the interference pattern could just as well be created with the second reference beam and the object beam and be read out with the first reference beam. In reality two interference patterns are formed in the nonlinear medium: each reference beam generates a pattern from which the other reference beam is reflected.

What we have just described is, in fact, the recording and reading out of a "dynamic" hologram. A hologram is an interference pattern, made with laser beams and stored in photographic film, that enables one to produce a three-dimensional image. Traditional "static" holography consists of the following three distinct steps: a hologram is recorded by illuminating a photographic transparency with a two-wave interference pattern resulting from an object beam and a reference beam; the film is developed, and the hologram is

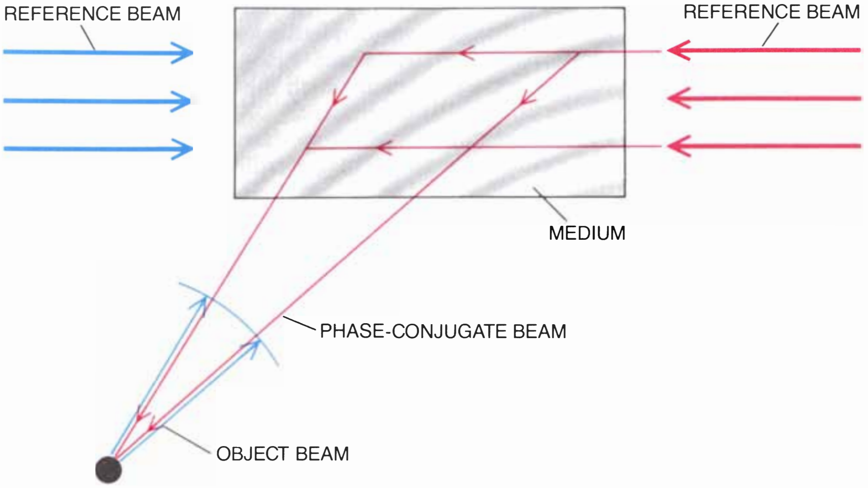


PHOTOGRAPH OF A LASER BEAM suggests the reversibility of light waves: on the basis of the image alone it is impossible to tell whether the beam travels from the left of the page to the right or from the right to the left. (The direction is from left to right.) The series of vertical dark bands resulted from the interference of the laser beam with a "reference" beam; they indicate wave-front surfaces, or places of synchronous oscillation. The wave-front surfaces of two mutually conjugated waves (in this hypothetical scenario the leftward-traveling wave and the rightward-traveling wave) are reversed with respect to the directions of propagation (*right*).

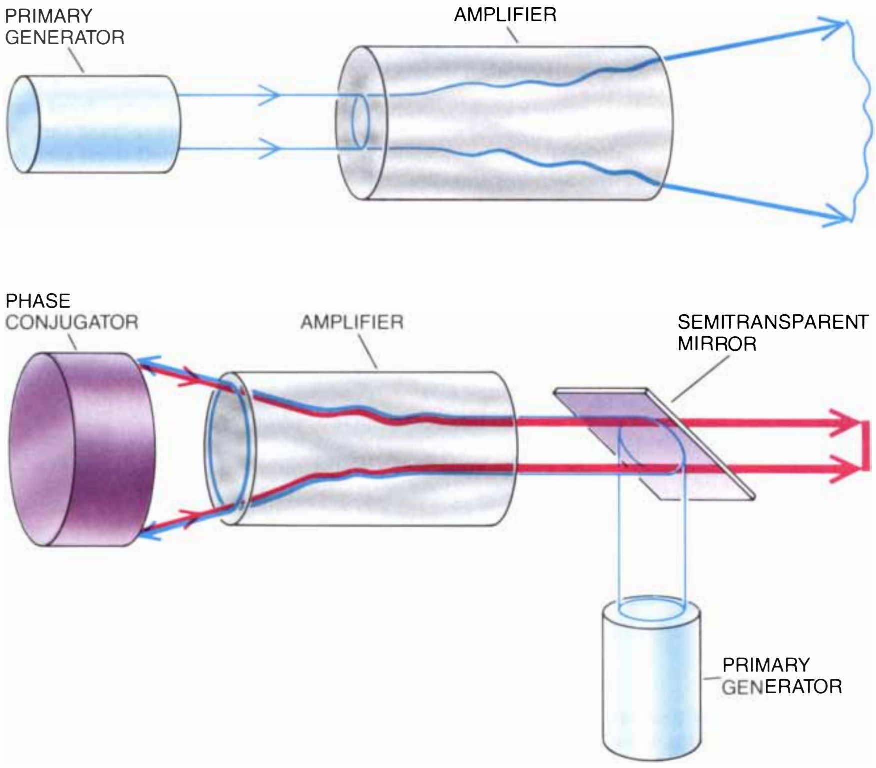




STIMULATED BRILLOUIN SCATTERING is one method of generating phase-conjugate light beams. A powerful, highly directed beam of light (*blue*) is distorted by transmission through a glass plate of inhomogeneous thickness. The distorted beam enters a transparent medium such as crystal, glass, liquid or compressed gas. It scatters from small, statistically distributed density fluctuations (thermally fluctuating sound waves) at the far end of the medium, giving rise to waves of varying spatial configurations (*curved red fragments*). When the frequency and direction of a scattered wave are just right, the wave will interfere with the incident beam and generate more pressure-density variations in the medium (*gray bars in magnified region at right*). The variations subsequently lead to the reflection of a minute portion of the incident beam. The reflected portion interferes in turn with the incident beam, generating more pressure-density variations. The pressure-density variations generate more reflections of the incident beam. The reflections build exponentially until a powerful phase-conjugate beam (*red*) emerges from the material. The high quality of the beam is restored on backward transmission of the conjugate beam through the glass plate.



FOUR-WAVE MIXING is another way of producing phase-conjugate beams. It involves the interference of four light beams in a crystal, glass, liquid or compressed-gas medium. Three of the beams are input beams: one is the object beam (*shown here as a spherical wave*) whose phase conjugate is sought and the other two are reference beams. The fourth beam, an output beam, is the desired phase conjugate of the object beam. The interaction of the object beam with one of the reference beams (*blue*) produces an interference pattern in the medium. The second reference beam (*red*) is reflected by the interference pattern. Since the second reference beam comes from a direction opposite to that of the first reference beam, the reflected beam is the phase conjugate of the object beam. In reality all the processes occur simultaneously. Moreover, two interference patterns are formed in the medium: each reference beam generates a pattern from which the other reference beam is reflected.



DIRECTIVITY OF LASER BEAMS is improved by employing optical phase conjugation. Most lasers designed to generate powerful beams are constructed according to the illustration at the top. A "local oscillator," or primary generator, produces a highly directed beam at the expense of output power. The power is increased by passing the beam through an amplifier. Inhomogeneities in the amplifying medium introduce distortions in the beam, however. The illustration at the bottom shows how to compensate for such distortions. Light from a primary generator is reflected by a semitransparent mirror through an amplifier. The distorted beam emerging from the amplifier is phase-conjugated and sent back through the amplifier. The phase-conjugate beam propagates backward with respect to the original beam through the same inhomogeneities of the laser medium, so that its motion is reversed. The resulting "double-passed" beam is both highly powerful and free of distortions.

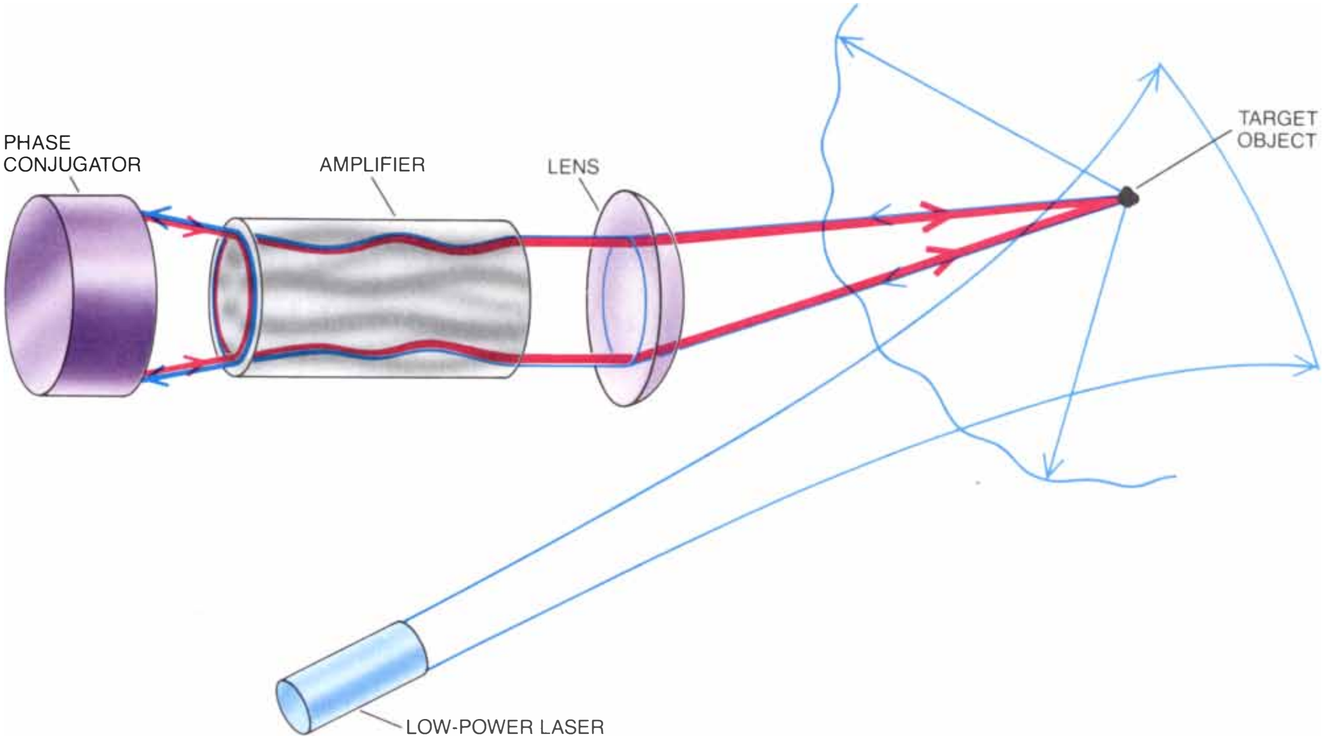
read out with another, or the same, reference beam. Four-wave mixing is an example of dynamic holography because all three processes—recording, developing and reading out—occur simultaneously, the induced variations in the refractive index disappear after the illuminating radiation is switched off, and the hologram is continually changing in response to variations in the object beam.

It is no surprise, therefore, that the idea of four-wave conjugation can be found in the work of the early pioneers of holography such as Dennis Gabor, Yury N. Denisyuk, Emmett N. Leith and Juris Upatnieks. In 1965 Herwig W. Kogelnik of the Bell Telephone Laboratories suggested that the three processes of static holography could be combined in time to yield a dynamic hologram and thereby cause phase conjugation. In 1971 Boris I. Stepanov, Evgeny I. Ivakin and Alexander S. Rubanov of the Institute of Physics in Minsk and J. P. Woerdman of the Philips Research Laboratories in the Netherlands conducted the first tests of dynamic holography employing counterpropagating reference beams. Hellwarth initiated the subsequent intensive study of four-wave mixing. He also successfully described the phenomenon in terms of nonlinear optics. Other investigators who have played an important role in the development of four-wave conjugation include Amnon Yariv and David M. Pepper, then at the California Institute of Technology, and David M. Bloom and Paul F. Liao of AT&T Bell Laboratories.

Many laboratories throughout the world have successfully made use of four-wave conjugation. A particularly attractive feature of the method is that, unlike phase conjugation by stimulated Brillouin scattering, no threshold power of the object wave is required for conjugation to occur. A number of other interesting methods of phase conjugation are also being studied.

The possible applications of optical phase conjugation are many. Two of the early ones are the production of highly directed laser beams and the self-targeting of radiation. Self-targeting provides a way of heating a small object, whose area may be as small as a millionth of the cross-sectional area of the laser beam used in the method, without recourse to a complicated system of lenses, mirrors and other optical elements. In the future the technique could possibly be exploited to heat a dense plasma and thereby initiate thermonuclear fusion.

Almost all laser setups designed to generate powerful laser beams are built in accordance with the following



SELF-TARGETING OF RADIATION is another application of optical phase conjugation. The technique, which provides a way of heating a small object without recourse to a complicated system of lenses and mirrors, could possibly be exploited to heat a dense plasma and thereby initiate thermonuclear fusion. A broad beam of low-powered light is directed to the vicinity of the object to be heated. The object scatters the radiation in all directions. Some of that radiation passes through an optical lens and strikes an amplifier placed near the object. As the radiation travels through the amplifier its power is magnified. A phase conjugator placed at the end of the amplifier creates an "antidistorted" beam and reflects it back through the amplifier, directing a powerful laser beam on the object.

scheme. First, one builds a so-called primary generator ("local oscillator") that produces a highly directed beam at the expense of output power. To obtain the desired power one then passes the beam through an amplifier. The amplifier consists of a solid or gas of highly excited molecules. As the primary beam travels through the amplifier, it stimulates the molecules and causes them to release their energy as radiation.

An ideally homogeneous amplifier would not distort the directivity of the beam. The constancy of the refractive index of such an amplifier would have to be better than one part per million, however. One can hardly hope to obtain such a high degree of homogeneity, particularly under the conditions of intense excitation of the amplifying medium. The refractive index of glass, for instance, changes by one part per million when the temperature changes by a thirtieth of one degree Celsius.

Fortunately distortions in the directivity of the beam introduced by the amplifier can be corrected by a "double pass" scheme utilizing optical phase conjugation. The idea was suggested and experimentally tested in 1972 by Oleg Yu. Nosatch and Ragul'skii and their colleagues at the Lebedev Physical Institute. They generated an ideally directed beam with a primary pulsed laser made of ruby crystal. The beam then passed through a ruby amplifier; the resulting beam, which was powerful but distorted, was subjected to optical phase conjugation. Finally, they sent the phase-conjugate beam back through the amplifier. They found that during the second pass through the amplifier the beam consumes almost all the energy stored in the excited molecules of the ruby.

The investigators also found something truly remarkable, namely that after the phase-conjugate beam passes through the amplifier it becomes ideally directed. The explanation of the phenomenon lies in the fact that the phase-conjugate beam propagates backward with respect to the original beam through the same inhomogeneities of the laser medium and therefore "reverses" its motion. The phase-conjugate beam compensates not only for static inhomogeneities due to optical elements but also for dynamic inhomogeneities. The reason is that the time it takes light to travel through an amplifier several meters long, roughly a hundred-millionth of a second, is much less than the time required for the excitation and relaxation of optical inhomogeneities in a laser.

Optical phase conjugation has also proved useful in the self-targeting of radiation. The idea was first suggested by Kogelnik. There are several possible ways to carry out the method; we shall describe only a single example. One begins by directing a broad beam from a relatively low-power laser in the vicinity of the object one wishes to heat. The object scatters the radiation in all directions; some of that radiation, after passing through optical lenses, falls on an amplifier placed near the object. As the radiation travels through the amplifier its power is magnified. A phase conjugator placed at the end of the amplifier creates an "antidistorted" beam and reflects it back through the amplifier. The result is that a powerful, directed beam is focused on the object. The focusing of the beam on the target is limited only by the wave nature of light (that is, diffraction effects) and is independent of the orientation of a focusing system. The target appears to "attract" the amplified radiation. Nikolay G. Basov and his colleagues at the Lebedev Physical Institute are studying the feasibility of facilitating laser fusion by self-targeting.

Investigators throughout the world are now exploring numerous other uses of optical phase conjugation. At present the number of applications would seem to be limited only by imagination.