
KathiGeoffrionParker

Through the Looking Glass

with phase conjugation

"I don't understand . . .," said Alice. "It's dreadfully confusing!"
"That's the effect of living backwards," the Queen said kindly: "it always makes one a little giddy at first—"
"Living backwards!" Alice repeated in great astonishment. "I never heard of such a thing!"

—Lewis Carroll

by Barry J. Feldman, Irving J. Bigio, Robert A. Fisher, Claude R. Phipps, Jr., David E. Watkins, and Scott J. Thomas

Imagine a mirror that reflects more light than was incident, that reflects a beam into the same direction regardless of the mirror's tilt, that eliminates image distortions by causing light rays to retrace their paths as if running backward in time, and that when looked at allows the observer to see absolutely nothing. Science fiction, you say? Well, such mirrors have been the subject of intense investigation both here at Los Alamos and at other research laboratories around the world. Not only do they exist, but their practical applications may be far-reaching.

At left. A whimsical look at four aspects of phase-conjugate reflection. These are (clockwise from upper left) backward-traveling wavefronts, light returning to its point of origin, time reversal, and restoration of beam quality.

The mirrors we refer to are called phase conjugators, and they reflect light in a manner radically different from conventional mirrors. Consider a beam of light incident on a conventional mirror (Fig. 1a). The incoming rays can be characterized by a wave vector **k** pointing along the direction of propagation. When a ray is reflected by a conventional mirror, only $k_{\perp}$, the component of the wave vector normal to the mirror surface, is inverted. Thus a light beam can be arbitrarily redirected by adjusting the orientation of the conventional mirror. In contrast, a phase conjugator (Fig. 1b) inverts all components of **k** and thus causes the wave vector to change sign, that is, to be reversed in direction. In this case, regardless of the orientation of the conjugator, the reflected beam exactly retraces the path of the incident beam. Surprising, perhaps, but there is more.

In addition to propagation direction, a complete description of a light beam requires information concerning its intensity and phase. The spatial and temporal dependences of a beam's electric field E are separable, and typically the spatial component (at an instant in time) is described mathematically as the sum of many plane waves, each with a complex amplitude $\mathcal{E}_n$ and with an oscillatory factor $e^{i(\mathbf{k}_n \cdot \mathbf{r})}$ containing the phase information as a function of the spatial coordinate r. The electric field of an incoming beam, E_{in}, can be written as

$$E_{\text{in}} = \sum_n \mathcal{E}_n e^{i(\mathbf{k}_n \cdot \mathbf{r})} .$$

The intensity of the incoming beam, I_{in}, is then given by

$$I_{\text{in}} = |E_{\text{in}}|^2 = \sum_n \mathcal{E}_n \mathcal{E}_n^* ,$$

where $\mathcal{E}_n^*$ is the complex conjugate of $\mathcal{E}_n$. After reflection by a phase conjugator of amplitude reflectivity $\mathcal{R}$, the electric field of the outgoing beam, E_{out}, becomes

$$E_{\text{out}} = \mathcal{R} \sum_n \mathcal{E}_n^* e^{-i(\mathbf{k}_n \cdot \mathbf{r})} .$$

The components of the outgoing beam correspond to the components of the incoming beam, only with the amplitudes replaced by their complex conjugates and with the signs of the wave vectors reversed. This simple relationship between the incident and reflected beams should make it clear why the process is called phase-conjugate reflection.

So far we have ignored the temporal dependence of the electric field. To be complete, other oscillatory factors $e^{i\omega_n t}$ that depend on the frequencies ω_n of the component waves must be included in the equations for the incident and reflected beams. Taking these oscillatory factors into account, we have

$$E_{\text{in}} = \sum_n \mathcal{E}_n e^{i(\omega_n t + \mathbf{k}_n \cdot \mathbf{r})}$$

and

$$E_{\text{out}} = \mathcal{R} \sum_n \mathcal{E}_n^* e^{i(\omega_n t - \mathbf{k}_n \cdot \mathbf{r})} .$$

The fact that the sign reverses for the $\mathbf{k}_n \cdot \mathbf{r}$ term but does not reverse for the $\omega_n t$ term

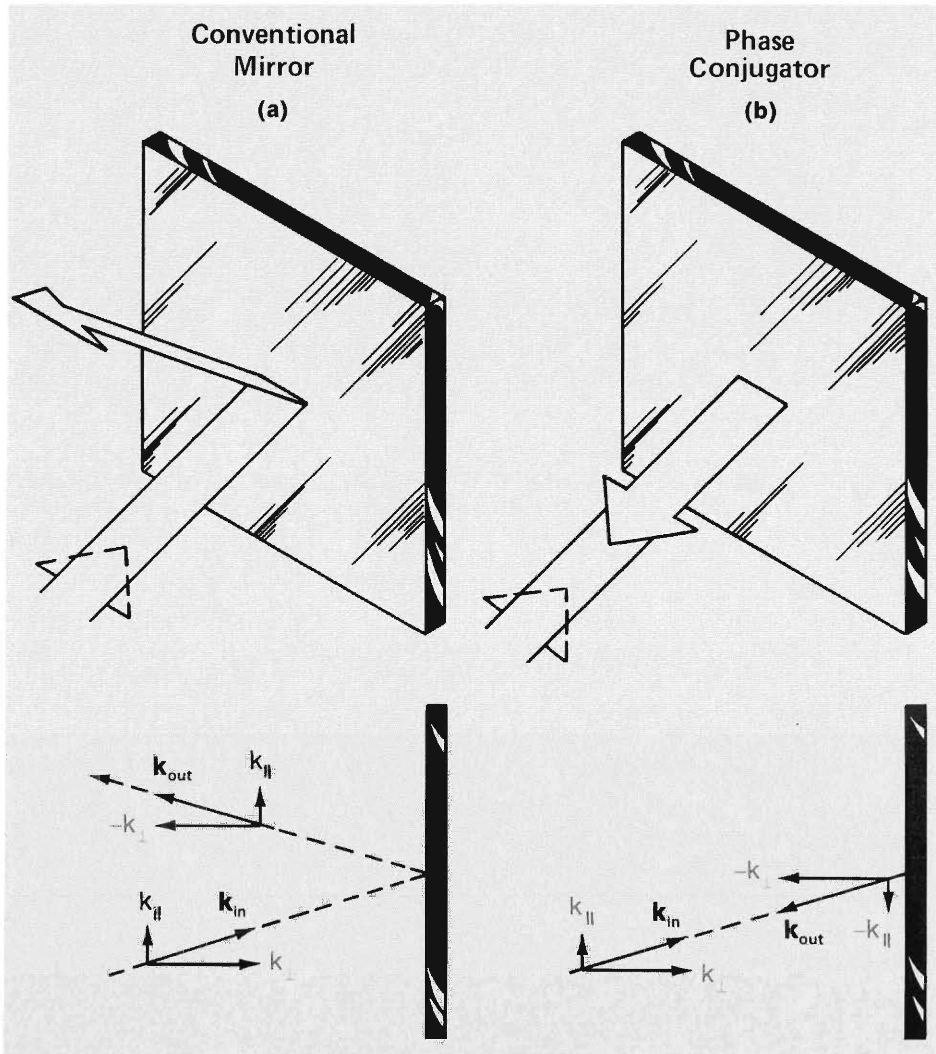

Fig. 1. (a) A conventional mirror reflects light by inverting only the normal component $\mathbf{k}_\perp$ *of the beam's propagation vector* k. *This process leads to the law that the angle of incidence equals the angle of reflection and allows the direction of the reflected beam to be altered by changing the tilt of the mirror. (b) A phase conjugator reflects light by inverting all components so that the propagation vector changes sign* ($\mathbf{k}_{\text{out}} = -\mathbf{k}_{\text{in}}$). *In this case, regardless of the tilt of the mirror, the reflected light exactly retraces the path of the incoming beam.*

indicates that E_{out} is propagating opposite to the direction of E_{in}. Moreover, the complex conjugation of the amplitudes reverses the constant-phase wavefronts with respect to the propagation direction (for example, a lag in phase for E_{in} becomes an advance in phase for E_{out}, and so forth). Regardless of the value of the reflectivity, E_{out} can be thought of as having wavefronts that are everywhere in space coincident with those of E_{in} but that are traveling backward. It is as if time had been reversed: the reflected wave replicates—in reverse—the phase behavior of the incident wave.

Now we can understand one of the most important implications of this kind of reflection. Consider the situation in which a beam passes through an aberrator, or phase-dis-

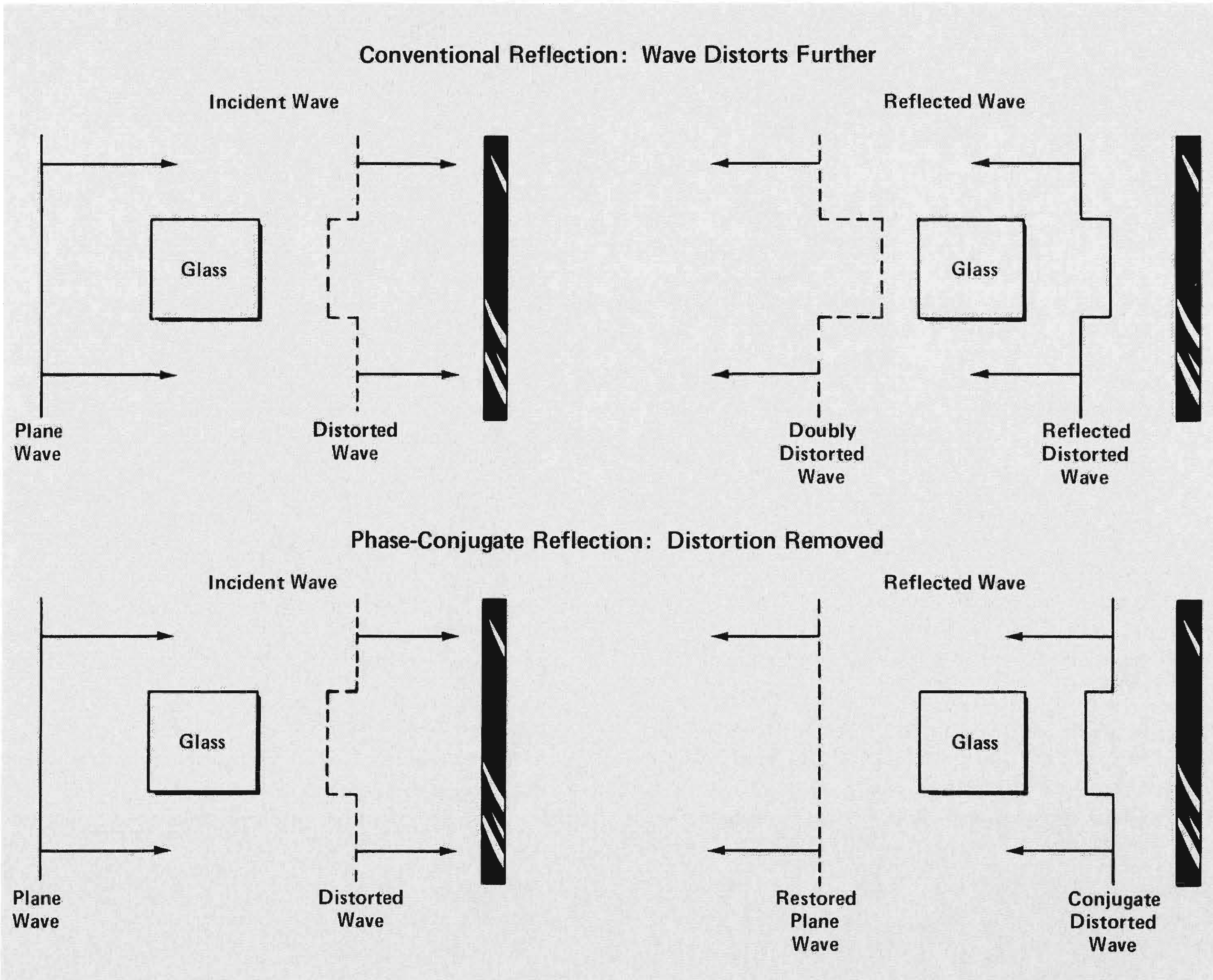

Fig. 2. Phase distortion with conventional and phase-conjugate reflection. In both cases the incoming plane wave (left side) encounters a block of glass, and a distorted wave is formed because the glass, with a different refractive index, retards the phase of the wave's central region. Conventional reflection (top right) retains this lag in phase so that the return trip through the glass doubles the distortion. On the other hand, phase-conjugate reflection (bottom right) changes the lag in phase to an advance in phase so that the return trip removes the distortion and a plane wave emerges, as if the wave had traveled backward in time.

torting medium, and then reflects from a phase conjugator (Fig. 2). The aberrator changes the beam into a distribution given by E_{in} that contains information about all of the phase distortions introduced by the medium. The phase conjugator then converts E_{in} into a new distribution E_{out} (by complex-conjugating all amplitudes and by reversing all wave vectors).This reflected beam is *exactly* programmed so that after passing backward through the aberrator it becomes a backward propagating replica of the original beam. The emerging beam does not contain any evidence that the aberrator existed! Thus, a high-quality optical beam can be double passed through a poor-quality optical system with no overall loss in beam quality. This double-passing technique can be applied to many problems in which a distorting medium, such as the turbulent atmosphere or a multi-mode optical fiber, would be

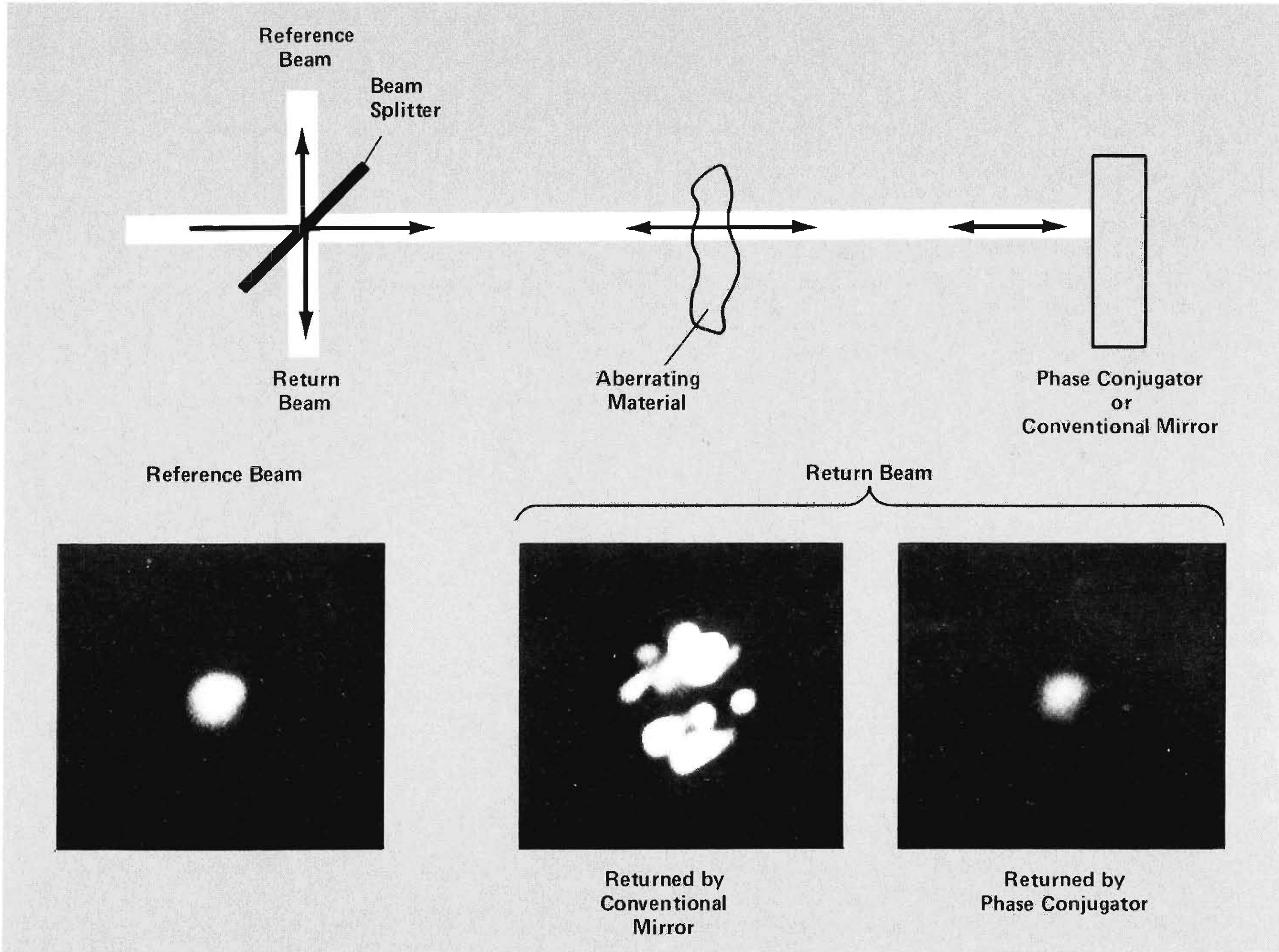

Fig. 3. Experimental demonstration of phase-conjugate reflection. An undistorted laser beam (left photograph) is double passed through an aberrating material. Conventional reflection for the return trip results in a highly distorted beam (middle photograph), whereas phase-conjugate reflection removes the distortions and only a uniform intensity change is obvious (right photograph).

detrimental to effective beam transport.

Figure 3 shows an experimental demonstration, with the aberrator pictured in Fig. 4, of this amazing feature of phase-conjugate reflection. Only two conditions are required to insure repair of the distorted beam. First, the phase-distorting aberrator must not undergo any changes during the time it takes for the beam to strike the phase conjugator and return; second, the light itself must not affect the physical properties of the aberrator.

It should now be clear why, when one looks at an ideal phase conjugator, one sees "nothing." All the light impinging on an ideal phase conjugator returns exactly on the path from where it came. Light glancing off one's nose, for example, is reflected directly back to one's nose, not into one's eyes. The only light an observer has a chance of seeing is that reflected off one's eyeball to the mirror and back. This is perhaps not quite nothing, but not much either. For those who believe that the eye is the "window to the soul," the phase conjugator allows the possibility of soul searching (patent pending), at least in the technical sense.

How Does One Make Such a Mirror?

In principle, if the phase distortions in a beam of light were known in advance, then one could design a mirror with a compensating surface to perform as a phase conjugator. Indeed, this is the principle behind the field of adaptive optics, in which a mirror surface is controlled and modified in such a manner as to reverse the phase front of an incoming beam (Fig. 5). Typically, the elements used for the shaping of this "rubber" mirror are piezoelectric crystals whose lengths change precisely when the voltages across their faces are changed. Such mirrors have been built, and research on improving their properties is proceeding in a number of laboratories. However, these mirrors suffer from slow response time (about 1 millisecond), imperfect correction due to the finite spatial resolution of each piezoelectric element, and expense in the construction and computer control of the large number of piezoelectric elements generally involved. In contrast, the phase conjugators discussed in this article (which invoke nonlinear optical techniques) need not suffer from such limitations.

NONLINEAR OPTICS. The methods to be discussed henceforth invoke processes en-

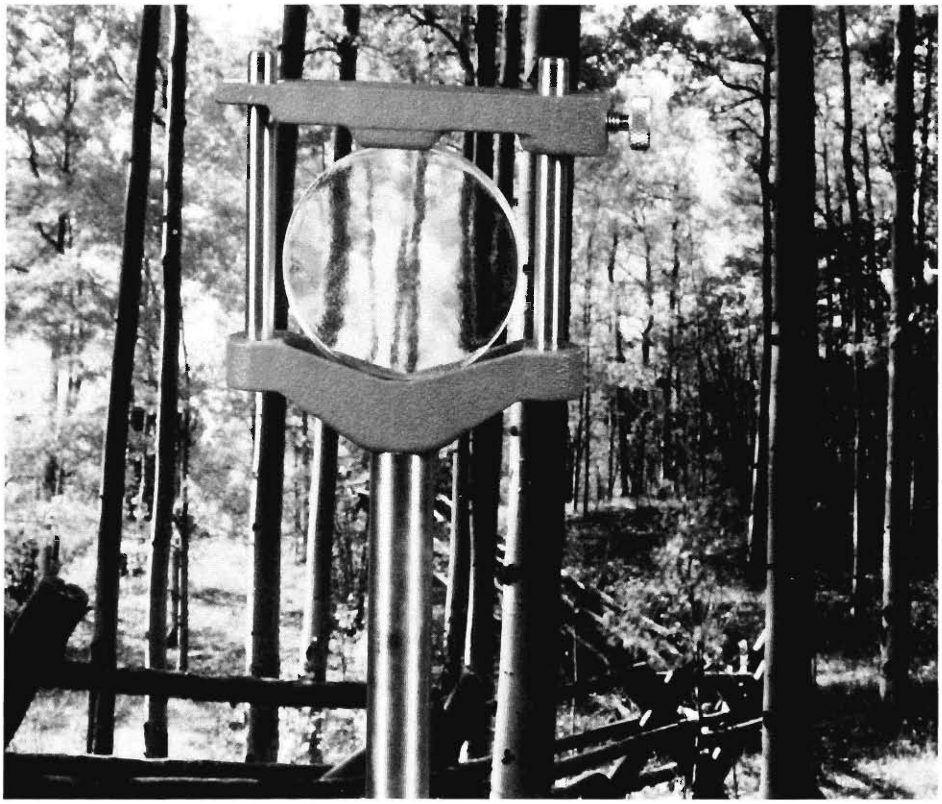

Fig. 4. Is this optical element useful? The distorted sodium chloride window in this picture was used as an aberrator in the experiment of Fig. 3 to illustrate the healing properties of phase-conjugate reflection. This technique becomes an attractive option when the quality of key optical components is limited by expense or technical considerations.

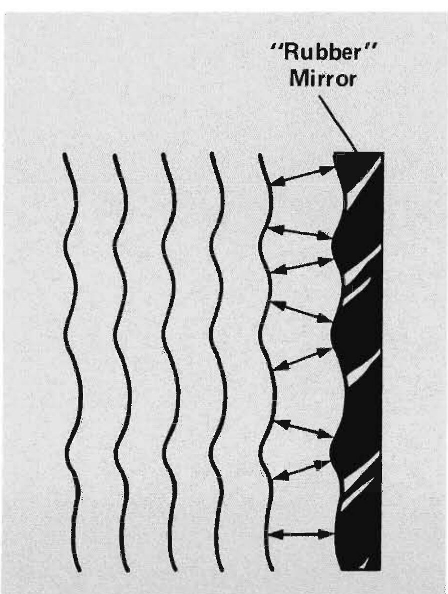

Fig. 5. Adaptive optics. If the phase distortions of the wavefront of an optical beam are known, a mirror surface can be shaped such that its surface is normal to the wave's propagation vector at every point. The reflected beam would then be the phase conjugate of the incoming beam because conventional reflection normal to the surface reverses the sign of the propagation vector.

tirely different from those of the flexible mirror described above, although the desired end result, formation of the conjugate wave, is the same. The research carried out at Los Alamos addresses the field that has become known as *nonlinear* phase conjugation. In this approach the processes that generate a phase-conjugate reflection depend upon the nonlinear response of matter to an optical field. (Generally, the nonlinearity of the response attains a useful magnitude only at the field intensities available from a laser beam.) There exists a plethora of these effects. In general, if a nonlinear response causes the refractive index of a medium to change with optical intensity, then the interference pattern formed by two or more laser beams can produce a volumetric index-of-refraction grating in the medium. Such gratings are the key to the magic of phase conjugators. But what is a refractive-index grating and why is it important?

First, it should be remembered that the refractive index is a relative measure of the speed of light through a material. As a result, the refractive index appears as a factor in the propagation vector ($|\mathbf{k}| = 2\pi n/\lambda$, where n is the refractive index and λ is the wavelength of the light in vacuum). The refractive index thus directly influences the oscillatory factor containing the phase information. Any physical process that alters the refractive index in a region of a material will, in turn, alter the phase of any light passing through that region. The trick, of course, is to alter the refractive index in just the right way so that the material scatters the light wave into its conjugate.

To further understand refractive-index gratings, we turn momentarily to holography. In fact, the true father of phase conjugation may well be the person who developed the notion of the hologram, Dennis Gabor (with help from W. L. Bragg). We say this because there are important similarities between holography and optical phase conjugation. One of the most important optical phase-conjugation techniques, which will be discussed later, is called degenerate four-wave mixing and is essentially real-time optical holography.

Consider the making of a holographic image (Fig. 6a). Typically, the light from a laser is split into two plane-wave beams. One, the reference beam, remains undistorted. The second is reflected diffusely off the object, causing the optical phase front to be distorted. The reference beam and the distorted beam are then directed from different angles onto a photographic film where they meet to form an interference pattern. All the phase information implicit in the interference is recorded as a fine pattern of silver grains in the developed film emulsion; the interference pattern has been "written" permanently into the film. Later, the pattern is "read" by directing at the film from the rear an undistorted plane wave (Fig. 6b). In this case, the grains of silver act as a grating and scatter the light to generate a distorted beam with the same phase relationships of the original distorted beam (when viewed from the same angle). This scattered beam is seen by the eye as a virtual image of the object.

The key to holography, of course, is the

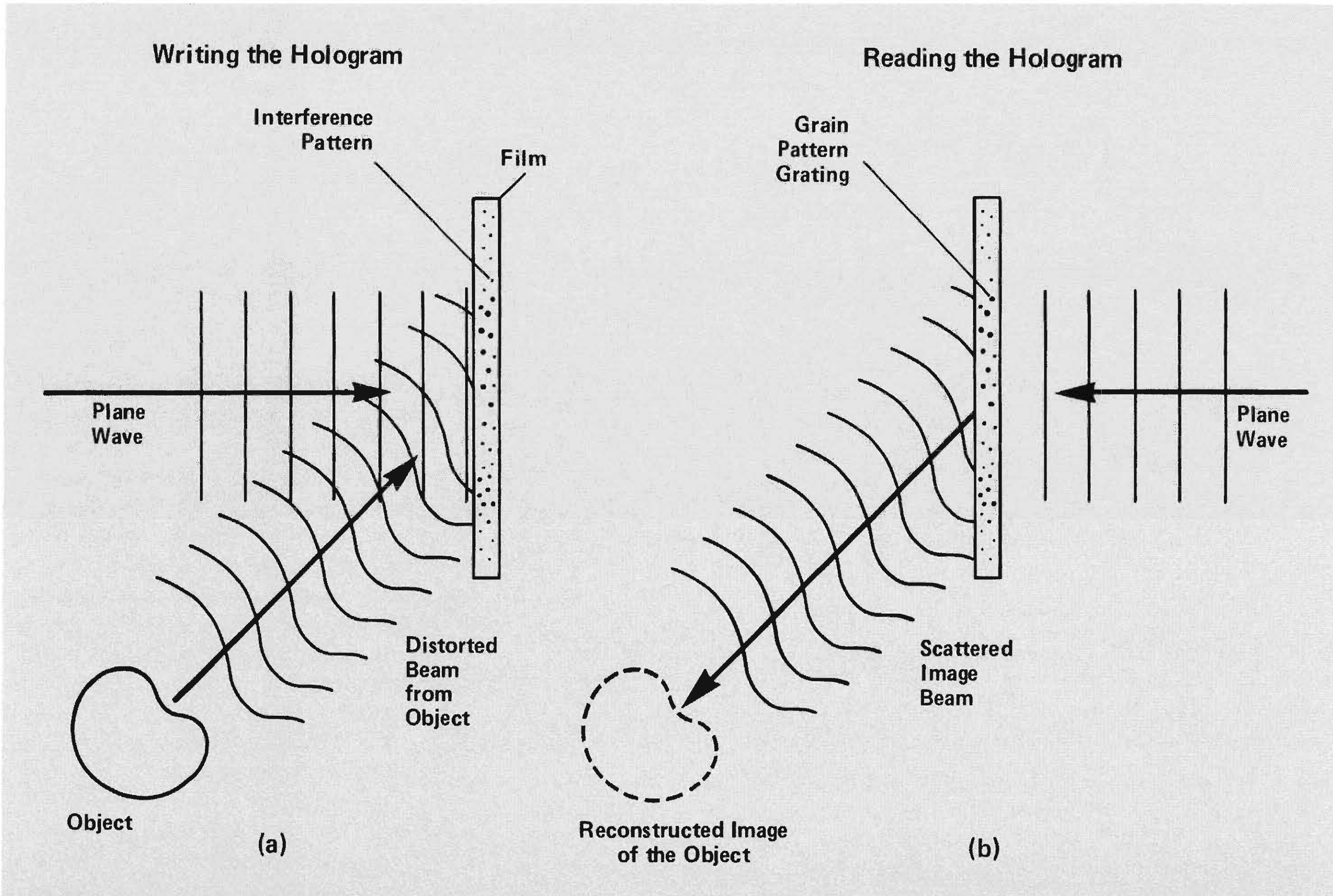

Fig. 6. Conventional holography consists of two distinct "write" and "read" steps. (a) First, the film is exposed to the interference pattern formed by an undistorted reference beam with a distorted beam reflected off the object. The result, after development of the film, is the hologram, a grain pattern in the emulsion. (b) A second undistorted reference beam, here traveling in the exact opposite direction, reads the hologram by scattering off the pattern of grains. Because the various scattered waves interfere with each other, these grains act as a heterogeneous grating. When viewed at the original angle, the phase relationships of the distorted beam will have been reconstructed, creating an image of the object.

pattern formed in the film emulsion. But this is a permanent grating. What is needed for phase-conjugate reflection is some medium in which a grating is written and read simultaneously; that is, the incident distorted beam generates a grating pattern that immediately scatters the reflected beam in the opposite direction with the conjugate phase relationships of the original. To set up such a grating we invoke nonlinear optics.

The nature and effectiveness of a refractive-index grating depend strongly on the nonlinear mechanism coupling the light and the material. Many such mechanisms are available. For example, if the optical wavelength corresponds to an absorption wavelength in the material, then the absorbed energy will give rise to heating of the material and a corresponding modification of the refractive index at that wavelength. If the absorption is bleachable (that is, if the material becomes more transparent as more energy is absorbed), then the index of refraction will change with intensity. However, if the material is nominally transparent, then other effects typical of nonlinear optics (such as those called stimulated Brillouin scattering, the optical Kerr effect, stimulated Raman scattering, and multiple-photon absorption) can be used to produce a refractive-index grating. The material itself can be a solid, liquid, gas, or plasma or more exotic systems such as liquid crystals, dielectric particles within a liquid, gaseous bubbles, or bulk plasma within a solid.

In this article we will discuss two types of nonlinear mechanisms for phase conjugators: those involving elastic photon scattering, in which the conjugating medium is left essentially unchanged by the process, and those involving inelastic photon scattering, in which the incident photons deposit some of their energy in the medium. We will treat an important example of each.

DEGENERATE FOUR-WAVE MIXING. An example of an elastic photon-scattering process in nonlinear optics is degenerate four-wave mixing, the phase-conjugation technique that corresponds to real-time holography. In this case the light and the material couple through a nonlinearity in the material's polarizability. When a light beam travels through a transparent material, its oscillating electric field generates a corresponding polarization wave by altering a number of properties (for example, the average position of the material's electrons). At low intensities the polarization can be taken to be directly proportional to the electric field ($P = \alpha E$). As a result, the induced polarization wave oscillates at the same frequency as the radiation but radiates its energy with a

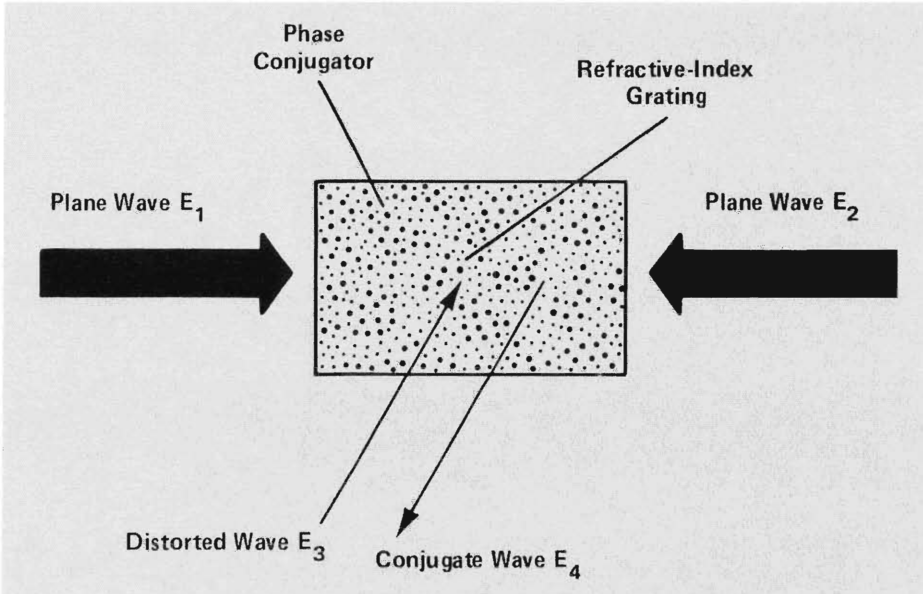

Fig. 7. In degenerate four-wave mixing the write and read steps of holography take place simultaneously. Interference of the intense plane wave E_1 and the distorted wave E_3 generates a refractive-index grating in the nonlinear optical material of the phase conjugator. The intense counterpropagating plane wave E_2 immediately scatters off this grating to form the reflected wave E_4 that is the phase conjugate of E_3. Because the roles of E_1 and E_2 can be exchanged, a second wave, indistinguishable from E_4, is also produced. The intensity of the reflected wave is a function of the three incident fields (E_1, E_2, and E_3) and of the material properties of the phase conjugator (such as the magnitude of its nonlinear optical effect).

time lag that retards the phase of the light beam (giving rise to the material's normal refractive index). At high enough intensities, however, the polarization becomes nonlinear and can be expressed as

$$P = \alpha_0 + \alpha_1 E + \alpha_2 E^2 + \alpha_3 E^3 + \dots \ .$$

If the electric field is oscillatory ($E = Ae^{i\omega t}$), the higher-order terms in this equation cause the polarization wave to have a variety of frequency components that can radiate in new directions and at new frequencies and that alter the material's refractive index. The third-order term consists of a number of components, one of which is responsible for the polarizability changes used to generate the refractive-index grating in degenerate four-wave mixing.

In this process three fields of the same frequency impinge on a transparent or semi-transparent material with a large third-order polarizability (Fig. 7). Two of the fields (E_1 and E_2) are counterpropagating, high-intensity plane waves (a reference field to help write the grating, another to read it), and the third (E_3) is the field one wishes to "reflect," or phase conjugate. In this environment the interference of the reference field E_1 with the field of interest E_3 generates a refractive-index grating. The other reference field E_2 experiences this bulk grating within the material and is partially scattered back along the direction of E_3. We refer to this scattered wave as E_4. However, the roles of E_1 and E_2 can be interchanged. Thus E_2 and E_3 establish a different refractive-index grating that partially scatters E_1 back along the direction of E_4. In general, the fields scattered from the two gratings are indistinguishable and both contribute to the phase-conjugate field E_4. Here we see that the sequential steps of normal holography—the formation of a grating and the subsequent scattering from it—are, indeed, accomplished simultaneously. It should be evident from this discussion, however, that in degenerate four-wave mixing E_4 is not really a reflection of E_3 but rather a scattering of E_1 and E_2.

Is the scattered field the conjugate of the incident field? The phase of a scattered beam is determined by the phase variations within the refractive-index gratings. Because of the unique phase relationships between the reference beam and the grating, the scattered field E_4 should be proportional to the complex conjugate of E_3. In fact, with the nonlinear polarization appropriate to degenerate four-wave mixing, Maxwell's equations give E_4 as everywhere *strictly* proportional to the phase conjugate of E_3. In degenerate four-wave mixing experiments it is crucial that E_1 and E_2 approximate plane waves within the interaction volume and that they be precisely counterpropagating; otherwise, the scattered radiation will not be exactly the conjugate of E_3.

Although degenerate four-wave mixing is a nonlinear optical effect generated by the interaction of three fields, the effect is nevertheless linear with respect to the field E_3 that is being phase conjugated. This means that a superposition of E_3 fields will generate a corresponding superposition of E_4 fields. Thus, accurate reconstruction of the original field (only propagating in the opposite direction) is possible.

If E_1 and E_2 are sufficiently intense and E_3 is weak, it is conceivable that E_4 will be more intense than E_3. Hence the phase-conjugate scattering can actually lead to a "reflectivity" greater than 100 per cent ($\mathcal{R} > 1$). This is accomplished, of course, not by generating light out of thin air but by scattering light from the intense fields E_1 and E_2 back into the direction of E_3, giving the appearance of amplification. Alas, energy is always conserved.

The origins of the concept of nonlinear optical phase conjugation are somewhat obscure owing to confused terminology and various incomplete demonstrations. Generally, B. I. Stepanov, E. V. Ivakin, and A. S. Rubanov of the Soviet Union are credited with the first demonstration in 1970 of distortion correction by degenerate four-wave mixing (similar work by J. P. Woerdman was nearly concurrent), and there is little doubt that the early pioneering in the field was by Soviet researchers. In particular, B. Ya. Zel'dovich, V. I. Popovichev, V. V. Ragul'skii, and F. S. Faizullov stand out as the first to recognize that nonlinear optical phase conjugation would also occur via stimulated processes such as our next example.

STIMULATED BRILLOUIN SCATTERING. This technique is an example of an inelastic photon scattering process. An intense laser beam is focused into a nearly transparent optical material where it Brillouin scatters off acoustic phonons (Fig. 8). As a result, the beam loses energy to the acoustic wave in the medium and is slightly reduced in frequency as it scatters back in the opposite direction. The high intensity of the focused laser beam literally drives the process to high efficiency by stimulating the scattering. Zel'dovich and coworkers were the first to demonstrate that this scattered beam was the phase conjugate of the incident beam. Here's how it works.

Intense optical radiation can interact with transparent media to produce material-density gradients by an effect called electrostriction. Electrostriction refers to the phenomenon in which a dielectric in an electric-field gradient experiences a force in the direction of increasing electric field. An analysis of this effect shows that the mechanical pressures in a liquid at the focal volume of commonly available lasers can exceed 100 atmospheres.

Now consider a strong incoming beam E_{in}, of frequency ω_{in}, moving through a material that exhibits electrostriction. Assume that the beam scatters off a sound wave (some acoustic noise always exists; for example, the laser beam itself can create such noise) to travel in the backward direction as E_{out} with lower frequency ω_{out}. The frequency shift of the light, $\omega_{in} - \omega_{out}$, is equal to the sound-wave frequency ω_s. Alternatively, assume that the incoming beam interferes with *optical* noise. If some of the optical noise happens to have the frequency ω_{out} and is propagating opposite to E_{in}, the two will interfere and produce a moving intensity grating. Because of electrostriction the intensity grating generates a sound wave, or density grating, of spacing $\lambda_s = v_s/\omega_s$, where v_s is the sound velocity.

Thus, there are two concurrent processes being described here. In one E_{in} interacts with a sound wave to produce E_{out}. In the other E_{in} interacts with E_{out} to produce a sound wave. For exactly the right set of frequencies and wave vectors, these two processes will reinforce each other by positive feedback and E_{out} will grow exponentially (until E_{in} is significantly depleted). Exponential growth will be fastest when E_{out} is precisely the phase conjugate of E_{in}, and thus non-phase-conjugate scattering is suppressed.

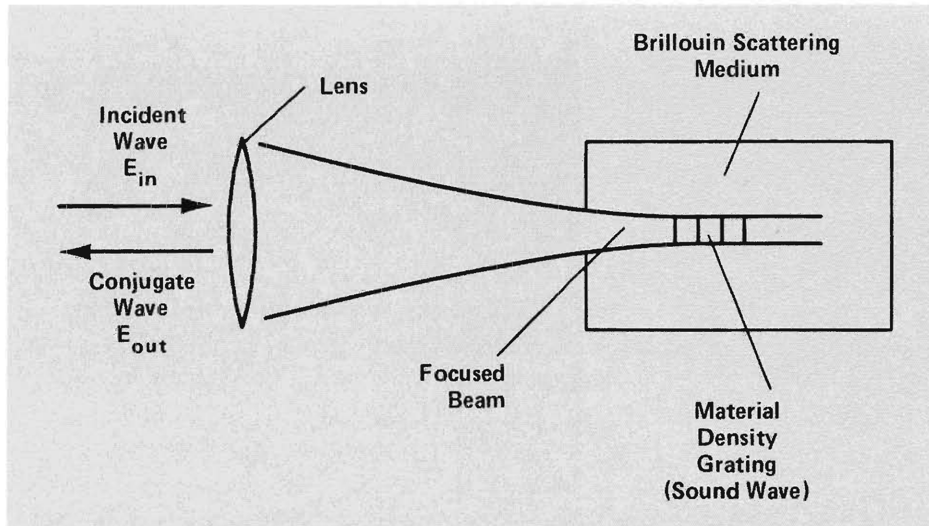

Fig. 8. Backward stimulated Brillouin scattering. The incoming field E_{in} *interacts with an acoustic wave to produce a backward scattered wave* E_{out} *and also interacts with* E_{out} *(through the medium) to produce an acoustic wave. The two processes positively reinforce each other only when* E_{out} *is the phase conjugate of* E_{in}.

The acoustic wave generated in this process travels in the same direction and, most important, with the right phase fronts to conjugate the incident wave E_{in}. In essence, a "rubber grating" has been created in the conjugating medium whose scattering planes are always correctly aligned to reflect the conjugate wave.

Of course, the effectiveness of stimulated Brillouin scattering as a phase conjugating process is also dependent on the phase coherence of the incident beam, the extent of its phase disturbances, and the depth of the established grating. The details of these dependences are only now beginning to be appreciated.

Infrared Phase Conjugators

Work on nonlinear optical phase conjugation received a late start in this country, and it wasn't until the work on this phenomenon in 1976 by R. W. Hellwarth and in 1977 by A. Yariv and D. M. Pepper that phase-conjugation studies began in earnest in the United States. Not long thereafter, work began at Los Alamos in the laser fusion effort when it became apparent that nonlinear optical phase conjugation held promise not only for improvement of the beam quality of large-aperture lasers but also for improved target sighting and tracking of the tiny fusion pellets. (More will be discussed about applications later.)

Because the Los Alamos candidate in the laser fusion derby was the carbon dioxide (CO_2) gas laser operating in the infrared at a wavelength of 10 micrometers, the challenge was to find efficient nonlinear optical phase-

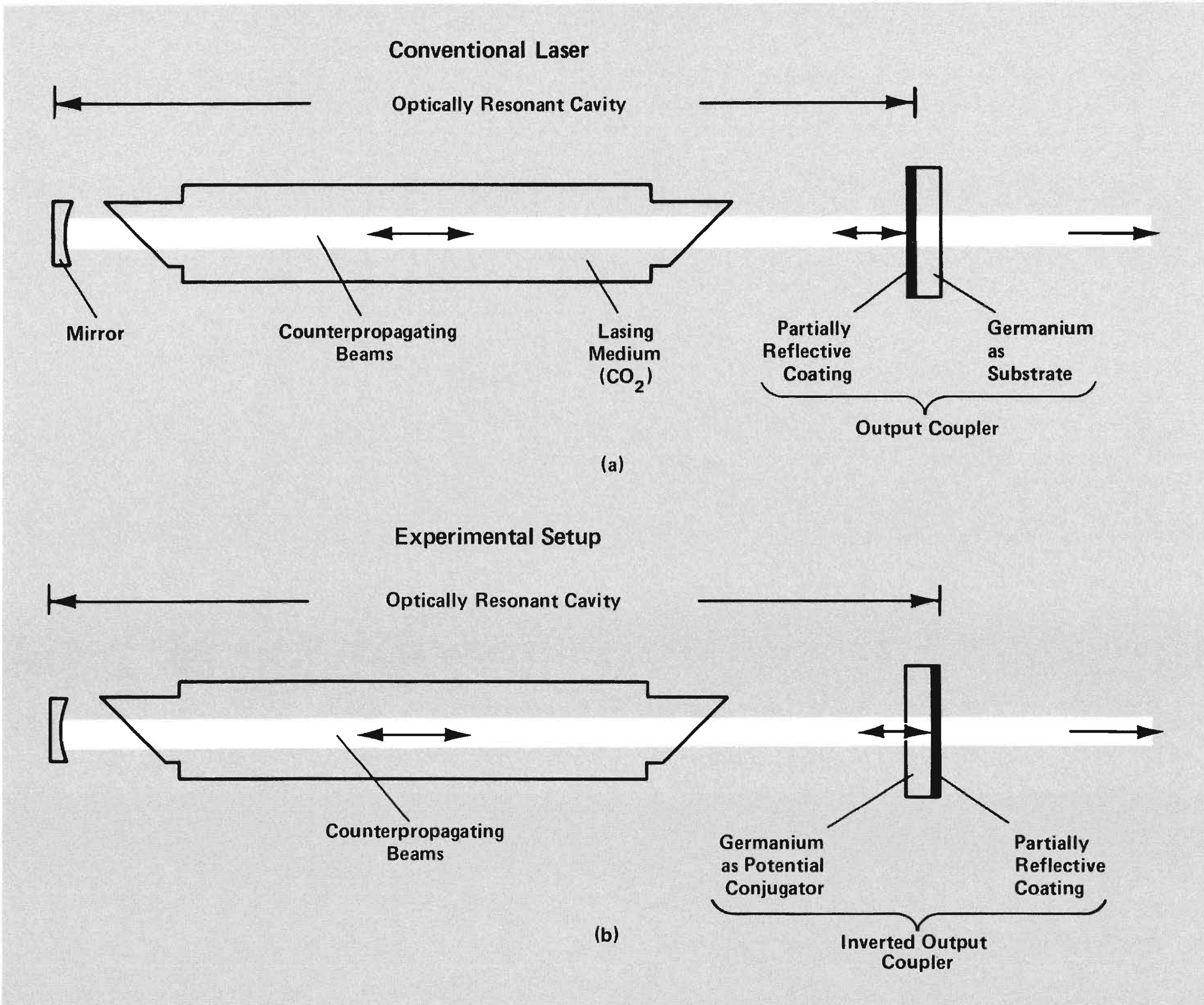

Fig. 9. Reconfiguring the carbon dioxide (CO_2) laser cavity for the degenerate four-wave mixing experiment. (a) The conventional CO_2 laser uses germanium as the substrate for the partially reflective coating on the output coupler. (b) Flipping the output coupler places the germanium, a highly nonlinear optical material, on the inside of the optically resonant cavity and thus within the intense, almost perfectly counterpropagating fields that constitute the laser cavity's standing wave.

conjugating materials at this wavelength. In March 1978, Ernest Bergmann, Irving Bigio, Barry Feldman, and Robert Fisher successfully produced the first demonstration of infrared optical phase conjugation with a CO_2 laser utilizing germanium as the nonlinear material.

Germanium had played an important role in CO_2 laser technology for many years. As an easy to grow, easy to polish, optically transparent material in the infrared, it had long been used as the substrate material that is coated with a partially reflecting, partially transmitting film to make it into a CO_2 laser mirror. Figure 9a shows the material in use as the substrate for a laser "output coupler" with the reflective coating toward the inside of the laser cavity. This device transmits part of the beam out of the laser and reflects the rest back into the optically resonant cavity where the counterpropagating beams form a standing wave. Note that the germanium material itself is outside the laser cavity.

With one of those welcome flashes of recognition, it was realized that a simple reversal of the output coupler (Fig. 9b) would immediately satisfy many of the requirements for degenerate four-wave mixing. This trivial operation placed the germanium substrate, which has a rather large nonlinear optical coefficient, inside the cavity, where it was exposed to the high-intensity intracavity electromagnetic field. Moreover, the two beams making up the standing wave inside an optical resonator are almost perfectly counterpropagating plane waves by design; the problems of misaligned and converging or diverging beams were thus readily avoided. All that was needed to complete the experiment was to redirect at an oblique angle the output of the laser back into the illuminated portion of the germanium substrate (Fig. 10). Lo and behold, phase conjugation occurred in the germanium. The reflectivity measured in that first experiment was only 2 per cent, but the work represented a breakthrough in CO_2 laser development and demonstrated that optical phase

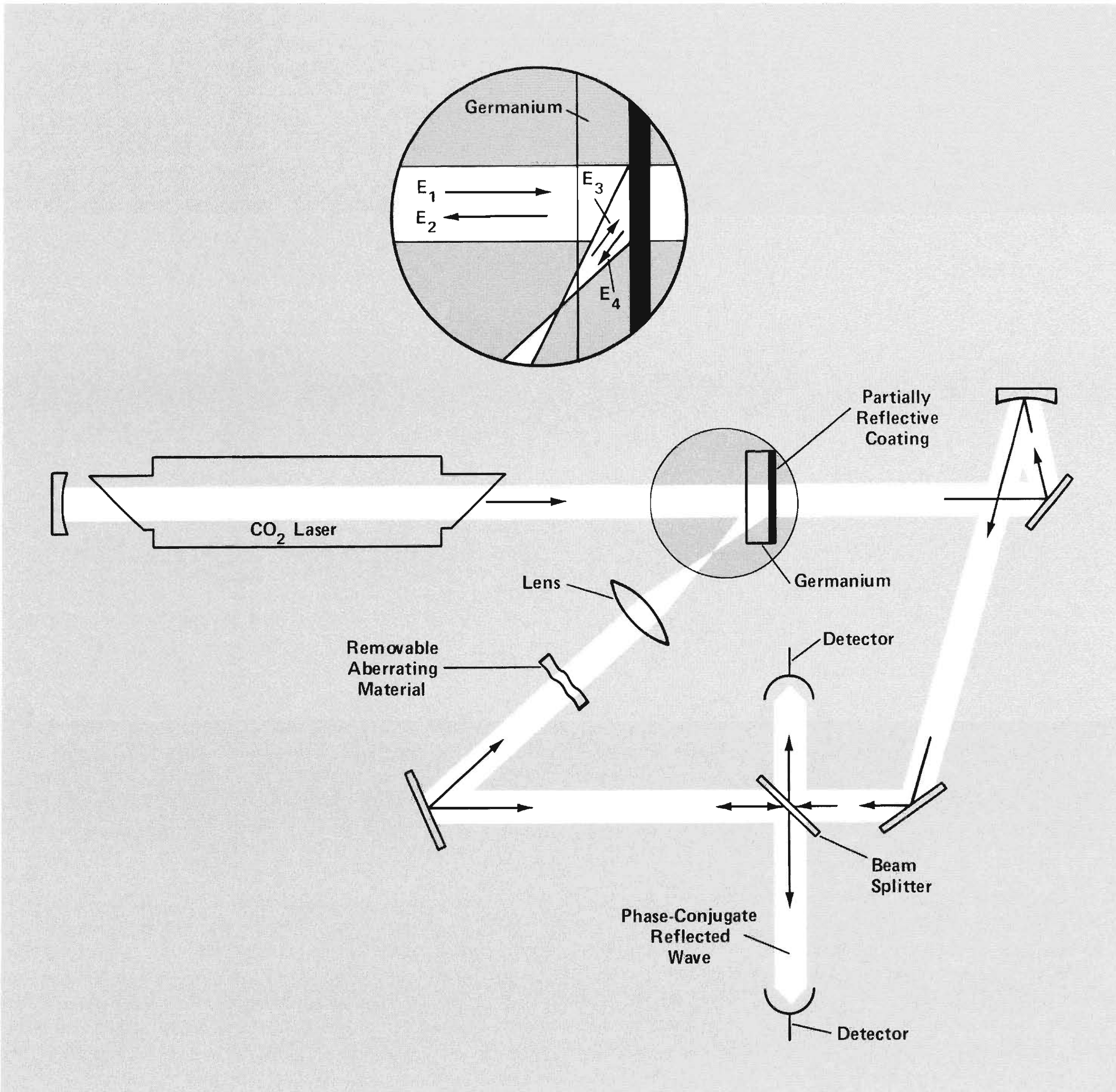

Fig. 10. Degenerate four-wave mixing in the infrared. Here the CO_2 laser shown in Fig. 9b with counterpropagating fields E_1 and E_2 has part of its output directed at an angle back into the germanium to form the field E_3. Since this arrangement provides the proper conditions for degenerate four-wave mixing (Fig. 7), the phase-conjugate wave E_4 is generated. The beam splitter allows both the original laser output beam and the reflected conjugate beam to be monitored by infrared-sensitive detectors. An aberrator can be placed in the beam to check the phase-conjugate properties of the reflected wave. The CO_2 laser has been simplified here for the sake of clarity.

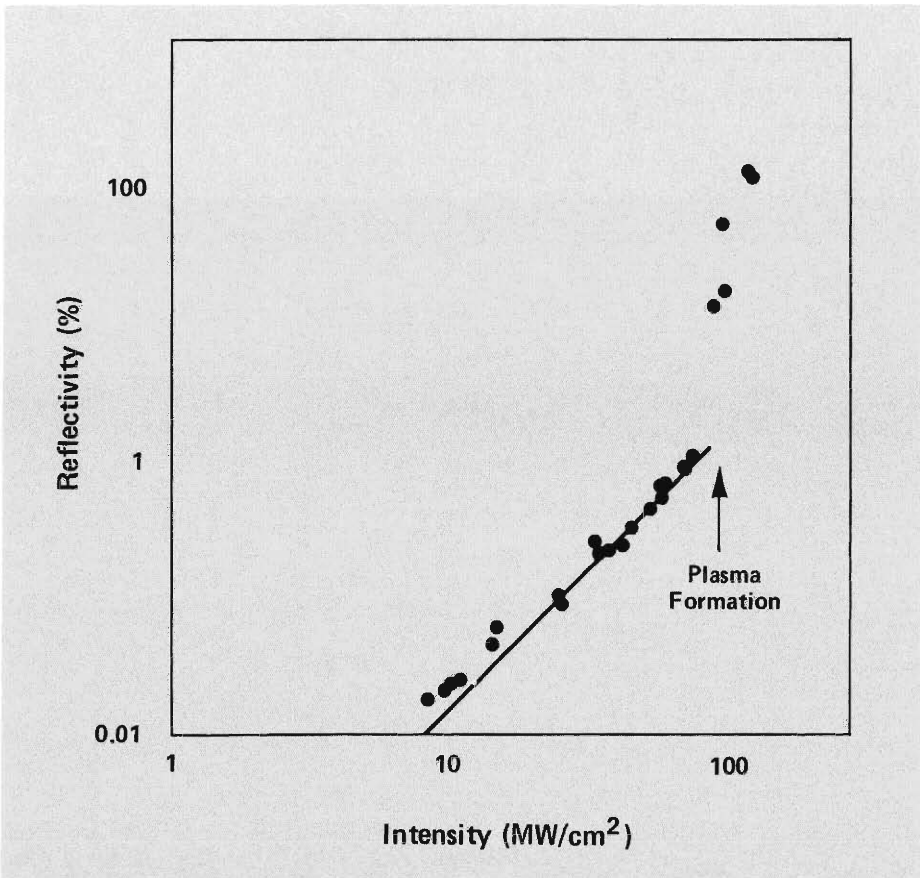

Fig. 11. Phase-conjugate reflectivity of germanium as a function of intensity. High field intensities in germanium give rise to a high-density electron plasma within that material. This creates large optical nonlinearities and phase-conjugate reflectivities of 200 per cent or greater.

conjugation was both possible and simple to achieve with materials already on hand in most laboratories involved in research on CO_2 lasers.

After these initial experiments, continued work on germanium by Claude Phipps and David Watkins revealed more surprises from this innocent looking material. In a carefully controlled experiment with germanium outside the laser cavity, they demonstrated, for field intensities of 100 megawatts per square centimeter and greater, that the phase-conjugate reflectivity increased dramatically. Apparently, at these high intensities free electrons were generated by multiple-photon absorption across the 0.6-electron-volt indirect band gap of germanium. This rapidly gave rise to a high-density electron plasma (2×10^{15} electrons per cubic centimeter) within the bulk germanium. Such a highly nonlinear process produced a dramatic increase in the phase-conjugate reflectivity of the material. Reflectivities greater than 200 per cent were demonstrated for germanium samples (Fig. 11).

Concurrently, Fisher and Feldman used the CO_2 gain medium itself as an optical phase conjugator by using the saturation properties of the excited CO_2 gas mixture to establish a field-dependent population grating. Because of larger interaction volumes and favorable gain conditions, effective phase-conjugate reflectivities greater than 400 per cent were obtained. At this same time, Fisher, Feldman, and Bergen Suydam carried out theoretical work on the pulse characteristics of optical phase conjugation.

Further CO_2 laser research was done by Watkins on a saturable absorber consisting of potassium chloride doped with rhenium tetroxide. This work confirmed many of the theoretical predictions about phase conjugation by ideal saturable absorbers.

Ultraviolet Phase Conjugators

Throughout 1979 substantial developments in the field continued worldwide for both the infrared and visible portions of the spectrum; there were, however, no observations of phase conjugation in the ultraviolet. Because of the increasing importance of ultraviolet lasers in photochemical and fusion research, Los Alamos researchers focused their attention on this part of the spectrum. Using pulses of 20-picosecond duration from a Nd:YAG laser whose emission had been quadrupled in frequency to yield light at a wavelength of 266 nanometers, Feldman, Fisher, and Stanley Shapiro set up the degenerate four-wave mixing experiment shown in Fig. 12. The increased complexity (when compared with the previously described experiment of Figs. 9 and 10) was required because great care had to be taken to insure temporal overlap of the very short pulses within the phase-conjugating medium by making the optical path lengths of each of the three interacting beams equal to within about 1 millimeter.

Liquid carbon disulfide (CS_2) was one of the most attractive conjugator candidates because of its large nonlinear optical coefficient. Although CS_2 is strongly absorbing in the ultraviolet, dilution with hexane produced a "window" between the two strong absorption peaks centered at 230 and 330

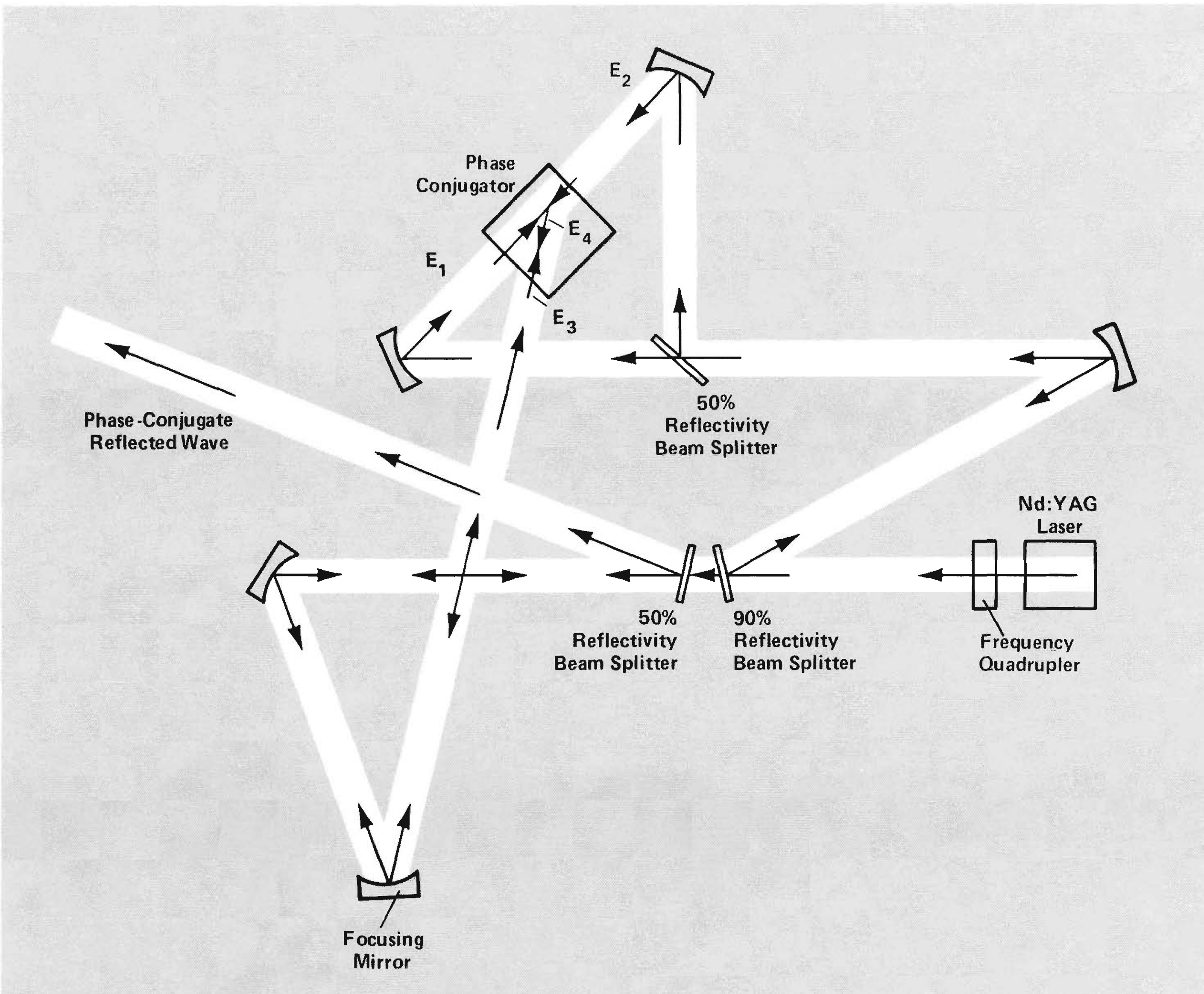

Fig. 12. Degenerate four-wave mixing in the ultraviolet. The frequency-quadrupled output (266-nanometer wavelength) of a Nd:YAG laser is split so that 90 per cent of the beam is directed to the phase conjugator as two counterpropagating beams (E_1 and E_2). Part of the remaining 10 per cent arrives as E_3 at the conjugator from a different angle and is phase-conjugate reflected (E_4).

nanometers. The transmission window had the remarkable property of being tunable as a function of CS_2 concentration in hexane (Fig. 13). A 40-per cent (by volume) mixture of CS_2 in hexane was chosen to optimize the nonlinear interaction at 266 nanometers. Although conjugate reflectivities of only 0.1 per cent and less were observed from the CS_2-hexane mixture and from several other materials, these observations represented the first demonstration of nonlinear optical phase conjugation in the ultraviolet and gave impetus for further development.

Work in the ultraviolet continued at Los Alamos with several other notable achievements. This work was motivated by the development in the late '70s of a new class of lasers, the rare-gas halide excimers. The excimer lasers offered for the first time the possibility of high-power, high-efficiency emission at various wavelengths in the ultra-

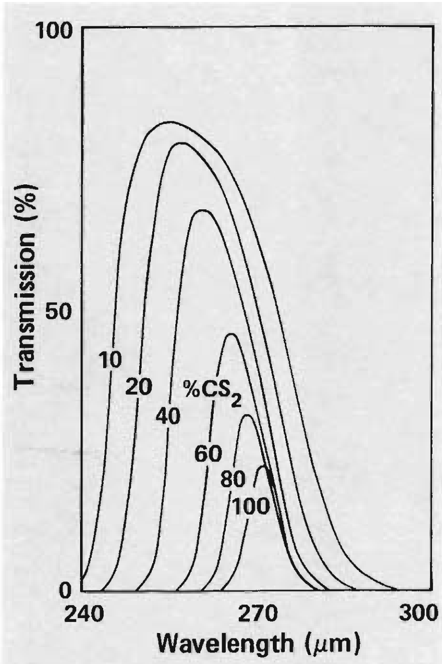

Fig. 13. The transmission spectra of various CS_2-hexane solutions. The transmission increases, broadens, and shifts as the percentage of CS_2 in the mixture decreases. These curves are for 1-millimeter path lengths through the sample.

violet. Using a high-power spectrally narrowed krypton fluoride laser at a wavelength of 248.6 nanometers, Bigio, Michael Slatkine, Feldman, and Fisher successfully demonstrated optical phase conjugation, again based on degenerate four-wave mixing in various liquid solutions. Similar successes were achieved with a xenon fluoride laser at 351 nanometers using backward stimulated Brillouin scattering in various organic liquids (Fig.14). In the latter case phase-conjugate reflectivities of over 70 per cent were clearly demonstrated. In another experiment nearly phase-conjugate reflectivities of about 30 per cent were observed using backward stimulated Raman scattering in liquid nitrogen. This process is, in essence, the same as stimulated Brillouin scattering except that rather than coupling with sound waves, energy from the incident beam is deposited into the vibrational energy levels of the nitrogen molecules. One of the remarkable features of this experiment, and of stimulated Raman scattering in general, is the large wavelength shift of the scattered beam with respect to the incoming beam. In this case the phase-conjugate beam at 382 nanometers was visible whereas the incoming beam at 351 nanometers was not. This wavelength shift precisely equals the difference between energy levels of the vibrational mode of the nitrogen molecule, a relatively large energy change.

In all cases involving these excimer lasers, whose emission is normally broad in frequency, phase conjugation could be observed only when the laser was constrained to operate within a narrow frequency bandwidth. Put simply, a broad range of frequencies results in a "smeared" interference pattern and a nondistinct refractive-index grating that fails to scatter the beam efficiently. The necessary bandwidth reduction was achieved by a process called injection locking in which a much weaker laser at the same frequency but with a narrow bandwidth controls the laser of interest. This technique was perfected at Los Alamos by Bigio and Slatkine. For example, the xenon fluoride laser was successfully injection locked using a weak, narrow-bandwidth argon-ion laser operating at a wavelength coincident with one of those of the xenon fluoride laser. As little as one watt from the argon-ion laser was sufficient to control the

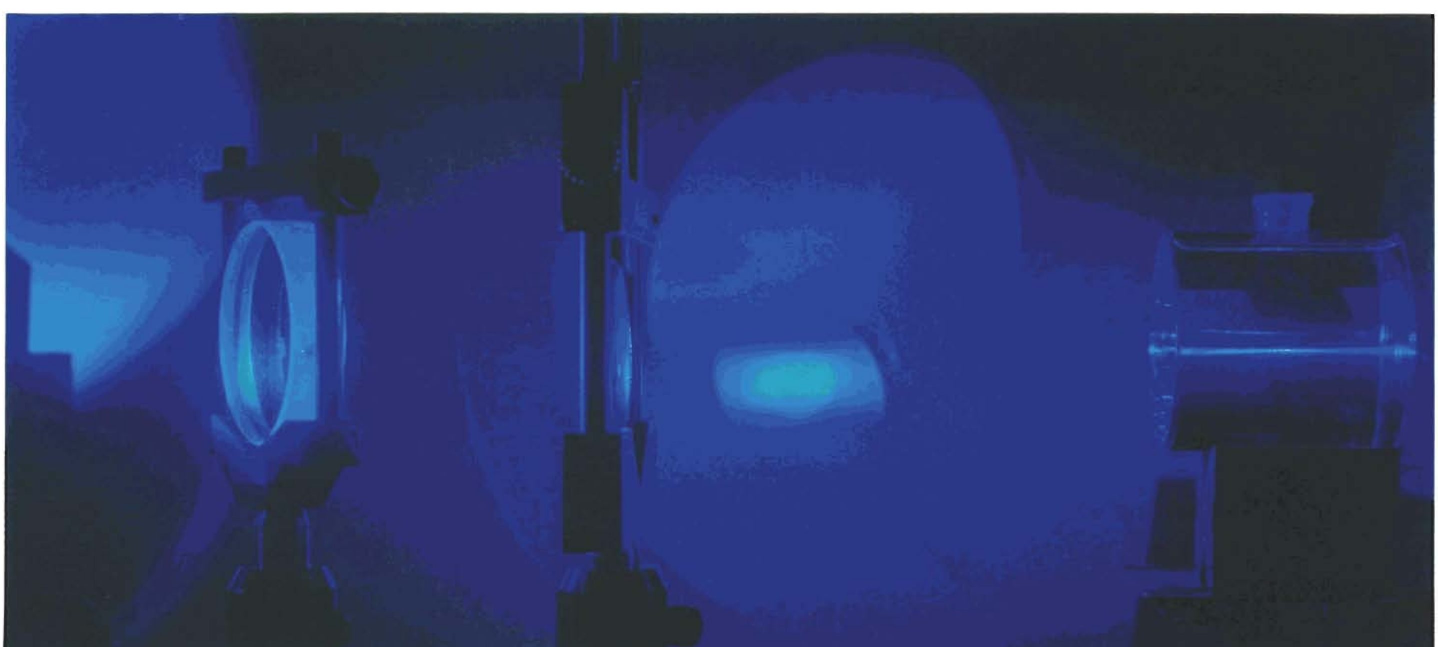

Fig. 14. In this photograph an ultraviolet light beam from a xenon fluoride laser passes through the optics from left to right and is phase-conjugate reflected by liquid hexane in the cell on the right via stimulated Brillouin scattering. The visible light beam in the cell is due to fluorescence. Part of the phase-conjugated return beam is diverted by the beam splitter on the left and appears as the spot in the background.

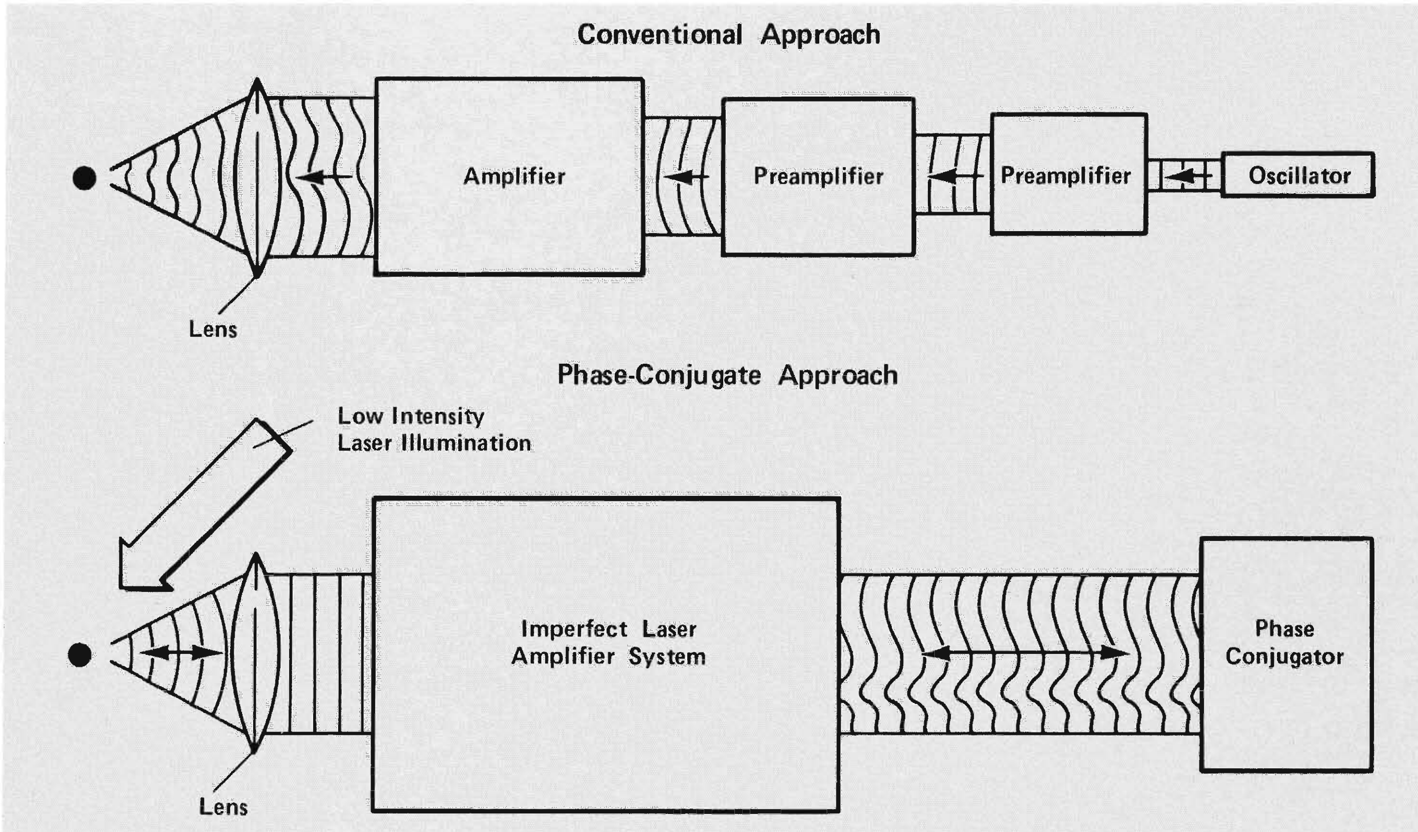

Fig. 15. Laser fusion systems. The conventional system (top) uses a long chain of laser amplifiers that may gradually introduce distortions in the beam arriving at the fusion target. In the phase-conjugate laser fusion system (bottom), a spatially broad, low-intensity laser illuminates the target. A small fraction of this illumination is reflected off the fusion target into the solid angle of the focusing optics and is amplified, phase-conjugate reflected, and further amplified on its return. Because the phase-conjugate beam exactly retraces its path, the amplified beam automatically hits the tiny fusion target. In addition, any phase distortions imparted to the beam by the complex amplification system will be removed on the return pass.

output bandwidth of the ten-million-watt xenon fluoride laser.

Applications of Optical Phase Conjugation

Although still in its infancy, the emerging field of nonlinear phase conjugation shows promise of revolutionizing the design of optical systems. As we have already discussed, the phase-conjugate beam has the remarkable property of emerging undistorted on its return pass through a distorting optical system. The advantages of this property for optical systems such as those involved in laser fusion, optical-fiber communication, and atmospheric propagation are enormous. Already the application of phase-conjugation techniques to the large fusion research lasers has resulted in their increased brightness on target. Moreover, the use of this technique (demonstrated in the Soviet Union) results in the automatic alignment of the beam on the fusion pellets. A schematic of such a phase-conjugating laser fusion system is shown in Fig. 15. Light from a low-intensity illumination laser is scattered off a fusion target. This illumination beam can be spatially broad and need not be critically aligned. Some of the scattered radiation is gathered in by a focusing system and undergoes amplification as it travels through the laser amplifiers. At the far end of the amplifier chain the radiation is returned by a phase conjugator through the laser chain for further amplification to exceedingly high intensities. Regardless of the optical distortions encountered on the first pass, the phase conjugator automatically redirects the beam back to its source, the fusion target. The amplified beam *cannot* miss! This technique allows the use of lower quality optics and eliminates much of the expense of the alignment systems usually required.

We now reconsider the scheme in Fig. 15, but this time with the laser and the target separated from each other by more than several hundred miles. Just as in the laser-fusion application of optical phase conjugation, similar aiming procedures could be used to direct laser light nearly instantaneously and accurately over long distances through the Earth's distorting atmosphere. These procedures could be extremely useful for communications systems.

Other potential applications of phase conjugation abound. The use of a phase conjugator as one of the cavity mirrors of a laser allows automatic cavity alignment and could lead the way to improved beam quality and stability. In fact, if a tunable laser is used to establish the counterpropagating beams for degenerate four-wave mixing, then external frequency control of the laser output is possible.

A phase conjugator has also been used as a fine optical frequency filter. In one of the injection-locking experiments described above, a xenon fluoride laser emitting radiation in roughly equal amounts at 351 and 353 nanometers was Brillouin scattered from a variety of liquids. Because of injection locking by an argon-ion laser, the bandwidth of the radiation at 351 nanometers was much narrower than that of the 353-nanometer radiation. As a result, only the 351-nanometer light could form a distinct grating and only this radiation was efficiently backscattered. Thus all radiation but the narrow-bandwidth phase-conjugate component at 351 nanometers was filtered out by the scattering process.

Applications of phase conjugation have also been proposed in the use of photolithography. Potentially, the use of short-wavelength ultraviolet radiation should yield greater resolution and accuracy in the manufacture of microelectric circuits. However, distortions in the ultraviolet imaging systems have impeded the success of this application. Even with imperfect optics the unique imaging properties of the phase-conjugation process could result in far greater resolution and accuracy than heretofore has been possible.

Finally, a theoretical analysis of the quantum optical properties of a phase-conjugated beam arising from degenerate four-wave mixing indicates that a particular state (the so-called two-photon coherent state) of this radiation field possesses unique properties. These properties may allow substantial signal-to-noise improvements in certain light-detection schemes, improvements that would be especially pertinent to such applications as the detection of gravity waves.

In conclusion, optical phase conjugation is a rapidly expanding field that is radically altering the design of optical systems and their capabilities. Although not all of the proposed applications may prove to be more effective than other more conventional approaches, there is little doubt that some—and indeed many not yet even foreseen—will have a major impact on optical systems of the future. Much remains to be explored in this intriguing wonderland. ■

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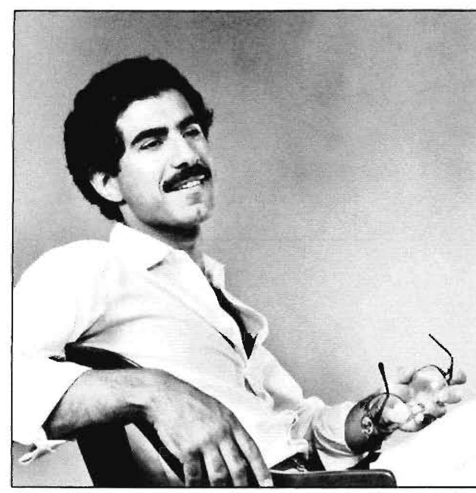
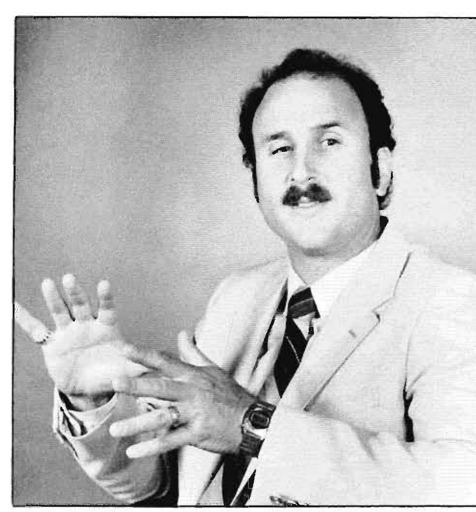
AUTHORS

Barry J. Feldman received his Bachelor of Science from Brown University in 1965 and his Ph.D. in physics from Massachusetts Institute of Technology in 1971. It was at M.I.T., under the tutelage of Drs. Ali Javan and Michael Feld, that he first began his love affair with lasers. Upon graduation he came directly to Los Alamos where for several years he was involved in theoretical efforts related to laser fusion and laser isotope separation programs. His work included theoretical studies of laser coherence phenomena, laser pulse propagation, and Raman scattering. In 1976 he joined the CO_2 Laser Research and Applications Group as Associate Group Leader and was involved in the group's experimental efforts at ultrashort pulse generation, new laser development, optical phase conjugation, and nonlinear optics in the ultraviolet. Currently he has turned his attention to the study of nonlinear optical phenomena in organic and biological systems.

Irving J. Bigio received his B.S., M.S., and Ph.D. degrees in physics from the University of Michigan in 1969, 1970, and 1974, respectively. His doctoral work under John Ward and Peter Franken dealt with nonlinear optics, and he has maintained a broad interest in the field of quantum electronics ever since. He came directly to Los Alamos in April 1974 as a staff member in the laser isotope separation program and has also worked in the laser fusion program. In 1976 he received a Fulbright Senior Scholar Award and spent the 1976-77 academic year as a visiting professor at the Weizmann Institute of Science, Rehovot, Israel. During his tenure at the Weizmann Institute, he taught graduate courses in laser physics and nonlinear optics and helped direct graduate student research. Since returning to Los Alamos he has resumed his research and has taught courses at the University of New Mexico Graduate Center. Currently, he is working on a variety of topics in quantum electronics and has recently taken an interest in the application of laser techniques and nonlinear optics to the solution of biophysics problems.



Robert A. Fisher received all of his schooling at the University of California, Berkeley, obtaining a B.A. in 1965, an M.A. in 1967, and a Ph.D. in 1971. He then joined the laser fusion effort at Lawrence Livermore Laboratory and concurrently taught at the University of California, Davis, before discovering New Mexico in 1974. While at Los Alamos he has worked in the Laser Fusion and Applied Photochemistry divisions. He was vice-chairman of the 1981 Gordon Conference on Lasers and Nonlinear Optics, and he served on the program committees for both the 1982 International Quantum Electronics Conference and the 1981 Annual Meeting of the Optical Society of America. He is the guest editor of a special issue on optical phase conjugation of the *Journal of the Optical Society of America* and is the editor of the soon-to-be-published Academic Press book entitled *Optical Phase Conjugation*. His professional interests include nonlinear optics, laser-related phenomena, optical phase conjugation, and molecular physics.



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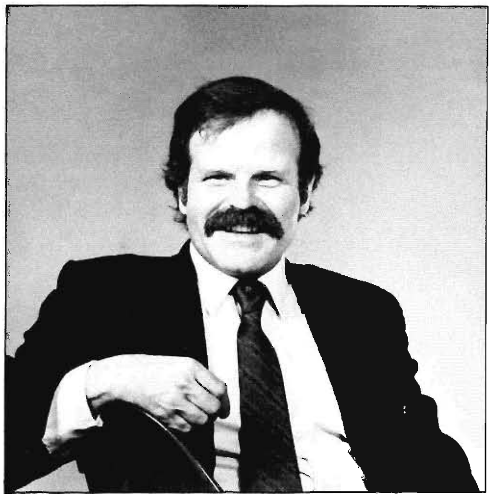
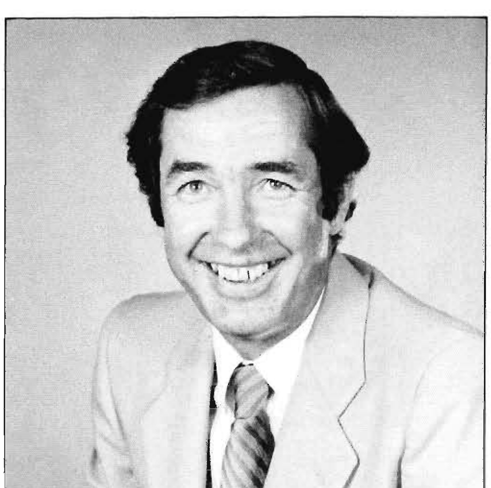


Claude R. Phipps, Jr., ha[redacted]os Alamos since 1974. He received his B.S. and [redacted]ng from the Massachusetts Institute of Technology in [redacted] and his Ph.D. in electrical engineering (plasma physics) from Stanford University in 1972. His research interests have ranged from superconductivity through Thomson scattering in plasmas to nonlinear optics at infrared wavelengths, particularly phase conjugation. He has also played a significant role in the measurement of infrared properties of optical materials. His wife, Lynn, is a commercial artist, and his son, David, is a physics major at Boston University. He is a member of the Society of Photo-Optical Instrumentation Engineers.

David E. Watkins earned his Bachelor of Science in 1975 from New Mexico Institute of Technology and his Master of Science in 1978 and his Ph.D. in 1981 from the University of Washington. He performed the research for his Ph.D. thesis, which involved phase conjugation by degenerate four-wave mixing, at Los Alamos as a graduate research associate. David has worked on high repetition rate CF_4 lasers and Raman conversion for the uranium enrichment program and maintains a strong interest in nonlinear optical phenomena.



Scott J. Thomas was born in Spruce Pine, North Carolina, on November 18, 1934. He joined the U.S. Air Force in 1955 and worked as an aircraft technologist in the Strategic Air Command. From 1961 to 1974 he was employed by Lawrence Livermore Laboratory in the Laser Fusion Division. He came to Los Alamos in 1974 and worked on laser research and development for the laser fusion program until 1981. Since then he has worked in the Applied Photochemistry and Chemistry divisions. He has published work on laser-produced plasmas, laser photochemistry, chemical lasers, dye lasers, gas lasers, nonlinear optical studies, and laser damage to optical surfaces. His present position as a staff member entails work on laser research and development.