Phase conjugate mirrors

Mirrors that reflect time

from Malcolm Gower

AFTER a decade of being a laboratory curiosity, the first practical applications are now materializing[1] of mirrors which have remarkably different properties from those used in our everyday lives. For example, light reflected from these mirrors, irrespective of their tilt, always retraces its path back to its source — sometimes with increased intensity. Even more remarkable is that transparent objects appear invisible when looked at in such a mirror, called a 'phase conjugate' mirror.

The secret is that the reflected wave is the complex conjugate of the incident wave. Thus as well as reversing the direction of light, a phase conjugate mirror also reverses its phase. Unlike a normal mirror, a diverging beam is reflected from a phase conjugate mirror as a converging beam back to its source (Fig. 1). Furthermore, if a completely transparent phase-distorting object, such as a bottle, is placed in front of the mirror, then its form, which is recognizable solely by the phase information imprinted on the transmitted wave, becomes reversed following reflection. As this reversed wave passes back through the bottle, regions of advanced phase are correspondingly retarded (and vice versa) so that the phase structure of the bottle on the emergent wave is lost, making the bottle appear invisible (Fig. 2). An observer looking into such a mirror would see absolutely nothing.

Because the wave emergent from the bottle is an exact replica of the incident wave, phase conjugate mirrors can be regarded as running the picture backwards in time for the light which falls upon them. Although phase conjugation has become one of the most active areas of optics research in the past few years, many of the fundamental ideas are not new but go back to the holographic or wavefront reconstruction methods first discussed by Gabor[2]. However, it took several years before it was realized that if a hologram made by the superposition of a reference wave and a coherent wave reflected from a subject is illuminated from the back by a reference wave in the opposite direction (conjugate) to the original reference wave, a single real image is produced which is the complex conjugate of the beam originally reflected from the subject[3]. With this type of geometry, it became possible to use holography to perform the phase aberration correction type of experiment shown pictorially in Fig. 2 (ref. 4). But because recording and reading of the hologram are quite separate and different stages of the process, the use of this technique in aberration correction or image projection is limited.

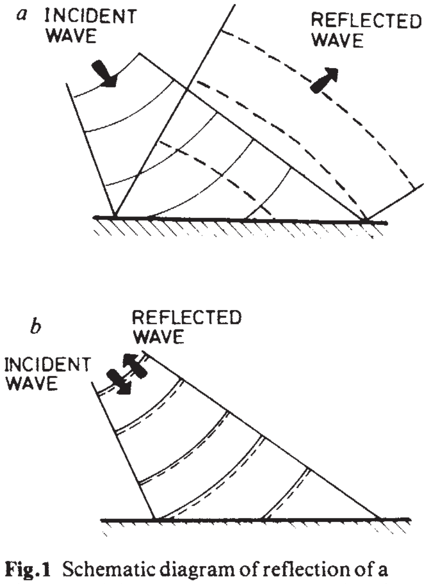

Fig. 1 Schematic diagram of reflection of a divergent light beam from a conventional (*a*) and a phase conjugate (*b*) mirror.

Only with the advent of holography in real time[5] has the true potential of the technique been realized. In an experiment first described by Soviet scientists, a pulsed ruby laser was used simultaneously to write and read a hologram in a cell containing a dye in solution (ref. 6 and Fig. 3). Because the refractive index of the solution is modified by the local light intensity, the pattern of refractive index within the cell becomes a hologram constructed (or written) by the interference of the reference wave E_1 and the subject wave E_3. This is then simultaneously read out by the reference wave E_2 to produce E_4, which is the phase-conjugate of the subject wave. As far as the medium is concerned, the counter-propagating reference waves are indistinguishable, so that E_2 and E_3 can also write a (different) hologram which is read out by E_1 to produce an additional contribution to the phase conjugate wave E_4. The result is a three-dimensional optical device (not a planar surface) which nevertheless returns the phase-conjugate of an incident wave.

This type of real-time holography is more completely and correctly described in nonlinear optical terms as four-wave mixing[7]. Within this framework, when three coherent optical beams are mixed together in a medium whose refractive index changes with light intensity, it is possible to generate a fourth coherent wave whose wavelength and direction depend upon the relative angles of the beams. Waves E_1, E_2 and E_3 may be regarded as inducing in the medium an electrical polarization which oscillates with a frequency of $\omega_4 = (\omega_1 + \omega_2 - \omega_3)$. This polarization radiates a wave at the same frequency ω_4, with a phase $\phi_4 = (\phi_1 + \phi_2 - \phi_3)$ and in the direction of the wave vector $\mathbf{k}_4 = (\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3)$. For the setup depicted in Fig. 3, all three frequencies are chosen identical (degenerate) and the counter-propagating pump waves are conjugates of each other (so that $\mathbf{k}_2 = -\mathbf{k}_1$ and $\phi_2 = -\phi_1$). Thus the generated wave travels in the direction $\mathbf{k}_4 = -\mathbf{k}_3$ with a phase $\phi_4 = -\phi_3$ and so is the conjugate of E_3.

Although real-time holography is analogous to this method of degenerate four-wave mixing (DFWM)[8], the pictures are not completely equivalent. For example, it has been observed, and DFWM theory predicts, that it is also possible to generate phase conjugate reflections by scattering of the probe wave E_3 from a grating formed by the interaction of the pump waves with each other. This grating is uniform in space and its amplitude oscillates with a frequency of 2ω as a result of coherent oscillations in the excitation of the atoms or molecules in the medium. It has no holographic analogy.

Effects such as light-induced heating, saturable stimulated emission and absorption, molecular orientation (or the optical Kerr effect), electrostriction, surface deformation, charge migration and photorefraction all produce changes in refractive index with light intensity. Each of these mechanisms has been used to produce phase conjugate reflections from media as

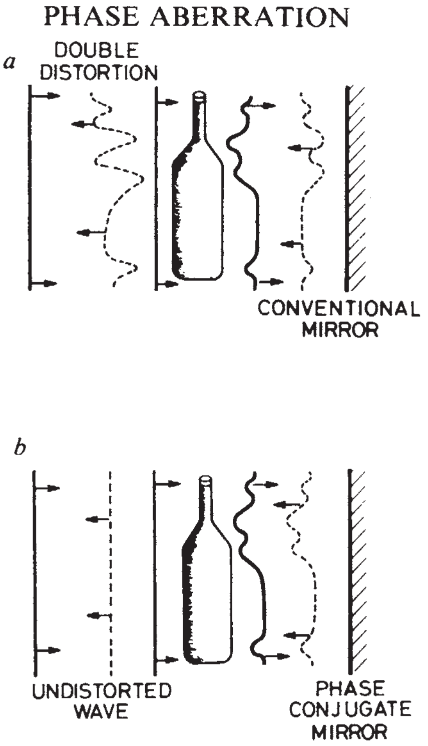

Fig. 2 Schematic diagram of correction of phase aberration by phase conjugate reflection. The phase-distribution across the wave-front returned from the conventional mirror (*a*) is the sum of two refractions by the transparent bottle, but these cancel out (*b*) after reflection from a plane phase conjugate mirror.

diverse as solids, liquids, gases, plasmas, aerosols and liquid crystals. For some of the mechanisms, lasers with continuous powers of only a few microwatts can be used to form the mirror, while for others high-powered pulsed lasers generating millions of watts are necessary. Conjugate reflections have been observed from lasers operating in the ultraviolet to the infrared. Furthermore, conjugate image size-reduction can be produced by simultaneously reading the hologram with a shorter wavelength than that used in writing it. The magnitude of the phase conjugate reflectivity depends upon the relative intensities of the three beams as well as on the characteristics of the non-linear mechanism which couples the light to the medium. The possibility that power can be transferred from the pump waves to the conjugate wave means that conjugate mirrors can exhibit gain, and reflectivities as high as 10,000 per cent have been observed.

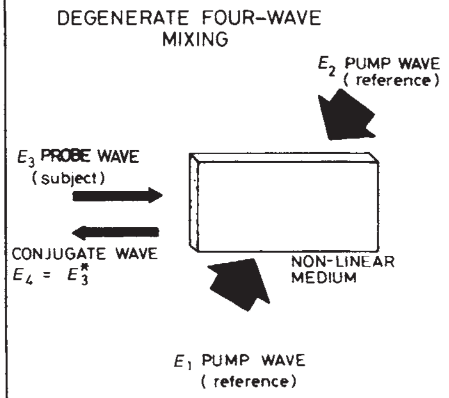

Fig.3 Phase conjugate reflection from a cell in which refractive index varies with light intensity. If E_1 and E_2 are oppositely directed reference waves with frequency identical with the incident wave E_3, the output wave E_4 is the complex conjugate (E_3^*) of E_3 (see text).

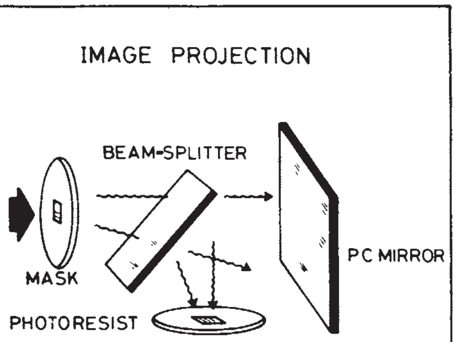

Fig.5 Phase conjugate image projection as may be used for high-resolution photolithography.

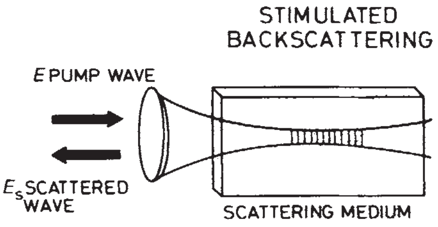

Fig.4 Phase conjugate reflection by stimulated back-scattering.

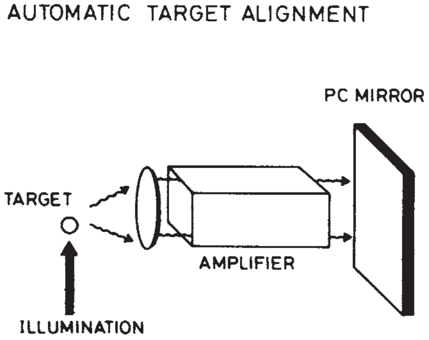

Fig.6 Star wars: automatic target detection and (?) destruction of externally illuminated targets (see text).

There is, however, a much simpler method of producing phase conjugate reflections. Soon after the invention of the laser, it was discovered that if a high-intensity beam is simply focused into a medium, various light-scattering processes (Brillouin, Raman and Rayleigh scattering) can be stimulated to produce gain in the backward direction (Fig. 4), and that backward-travelling waves can be produced with an intensity comparable with the laser intensity. In 1972, Zel'dovich *et al.*[9] found that stimulated Brillouin back-scattered radiation is the phase-conjugate of the (aberrated) pump laser beam. Reflectivities for the process can approach 100 per cent.

To understand this phenomenon we may regard the Brillouin wave, E_s, as being produced by the scattering of the pump light E from noise-generated sound waves which travel in the forward direction. Hence E_s is Doppler down-shifted in frequency by an amount determined by the speed of sound in the medium. Positive feedback and gain occur as more sound waves are created by the electrostrictive forces set up by the (forward-moving) pattern formed by the interference between E and E_s. The intricate coupling between the three waves leads to an exponential growth-rate for the conjugate wave which is nearly twice as great as that for all other Brillouin back-scattered waves. Hence the stimulated conjugate wave will rapidly establish itself and, by depleting the pump intensity, will further inhibit the growth of other back-scattered waves. It is almost as if the sound waves are contoured to form a moving deformable mirror which exactly matches the pump wavefront.

Within the constraints imposed by the small frequency shift of the Brillouin wave (1 part in 10^4–10^5), it is possible to generate almost perfect phase conjugate reflections from solid, liquids, gases and plasmas. Although this is the easiest and most popular method of making phase conjugate mirrors, stimulated backscattering from induced molecular vibrations (Raman), orientational (Rayleigh-wing) and temperature (thermal-Rayleigh) fluctuations have also been used. Because of their growth from noise, stimulated processes are a threshold effect and so usually require a much higher laser intensity ($\gg 10^9$ W cm^{-2}) than needed for generating DFWM mirrors. On the other hand, stimulated Brillouin scattering does not require uniform pump waves for good conjugation, while pump beams of sufficient quality for DFWM mirrors are extremely difficult to produce for use with very high-power lasers. For these applications Brillouin mirrors are usually preferred.

The practical applications of phase conjugate mirrors are still in their infancy. Clearly they will find a use in compensating for optical aberrations of the type depicted in Fig. 2. Already they have been used to correct for aberrations due to imperfect optical elements such as windows or lenses, high-power laser amplifiers and the Earth's atmosphere. Figure 5 shows an arrangement in which a laser beam is projected through a mask pattern and a beam-splitter onto the mirror, so that an image of the mask is projected from the beam-splitter. This technique may be useful for photolithography as used in the production of silicon chips, where extremely complicated patterns are projected with high resolution over relatively large areas. Indeed, using ultraviolet light, Levenson has achieved a resolution of greater than 500 line pairs per millimetre over an area of 0.3 cm^2 with such a phase conjugate lensless image projection scheme. The automatic pointing and tracking of targets can also be achieved using phase conjugate mirrors. A small glint from a target, illuminated by a low-power laser, is sent through a high-power amplifier onto a phase conjugate mirror, which sends the now very intense laser radiation back through the amplifier and onto the target to destroy it (Fig. 6).

Other applications such as mode dispersion correction in optical fibres, information processing and laser resonators with phase conjugate mirrors are all being investigated (see, for example, ref. 10). As a result of the discovery of phase conjugation with its remarkable properties, a great revival of interest in optical physics is now taking place. □

Malcolm Gower is in the Laser Division, SERC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX.

1. Levenson, M.D. *J. appl. Phys.* **54**, 4305 (1983).
2. Gabor, D. *Nature* **161**, 777 (1948).
3. Denisyuk, Yu.N. *Optics Spect.* **15**, 279 (1963).
4. Kogelnik, H. *Bell Syst. tech. J.* **44**, 2451 (1965).
5. Gerritsen, H.J. *Appl. phys. Lett.* **10**, 239 (1967).
6. Stepanov, B.I. *et al. Sov. Phys. Dokl.* **16**, 46 (1971).
7. Hellwarth, R.W. *J. opt. Soc. Am.* **67**, 1 (1977).
8. Yariv, A. *IEEE J. Quant. Electr.* **QE-14**, 650 (1978).
9. Zel'dovich, B.Ya. *et al. JETP Lett.* **15**, 109 (1972).
10. *Optical Phase Conjugation* (ed. Fisher, R.A.) (Academic, New York, 1983).