At the forefront of laser technology
Part I. Optical phase conjugation

by Robert Gallagher

On Dec. 14, 1983, presidential science advisor George Keyworth told the New York Wings Club that recent developments in laser technology confirm the feasibility of the Strategic Defense Initiative or beam-weapons program, "very recent advances that permit us to compensate for atmospheric break-up of laser beams." Keyworth is right. Kosta Tsipis, Richard Garwin, and Hans Bethe are wrong. These recent developments prove that their "proofs," such as Tsipis's December 1981 *Scientific American* article, "Laser Weapons," that lasers will not be able to propagate through the atmosphere to militarily useful distances, are incompetent.

Dr. Keyworth's office has not provided background information on his remarks. This service, however, has recently concluded from unclassified literature the nature of the developments he alluded to. This report—focusing on optical phase conjugation—is the first in a series on these developments.

Keyworth's optimism is apparently informed by progress announced at the May 1983 Conference on Lasers and Electro-Optics (CLEO). R. C. Lind and G. J. Dunning of Hughes Research Laboratories (HRL) reported the first demonstration of the dynamic correction capability of optical phase conjugation in the face of severe distortions produced by atmospheric turbulence. More recently, *Science Digest* magazine reported in its June 1984 issue that scientists at HRL had told them that conjugated laser beams can propagate 60 miles through the atmosphere—in other words, a distance sufficient to reach space-based orbiting mirrors that can redirect such a beam onto a ballistic missile target. Of particular concern, however, is the fact that the field of optical phase conjugation was founded by Soviet, not Western, scientists, and that the field of investigation continues to be dominated by Soviet investigators. In a recent review paper, approximately one-half of the 183 references were to Soviet journals (see reference 2).

Lind and Dunning double-passed a beam produced by a 20 milliwatt dye laser through a 100-meter range of turbulent atmosphere. After the first pass through the range, the probe beam displayed high frequency phase errors, severe wander, and intensity nulls on its axis. The beam was then directed into the conjugator and conjugated. The conjugated beam returned over the range and the corrected beam was picked off at the transmitter. The corrected beam was nearly identical to the 1×2 centimeter elliptical profile of the original probe beam.

This report will discuss possible use of optical phase conjugation in a directed-energy weapons system.

What is optical phase conjugation?

Optical phase conjugation involves the use of non-linear optical effects to precisely reverse the direction of propagation of each plane wave in an arbitrary beam of light, thereby

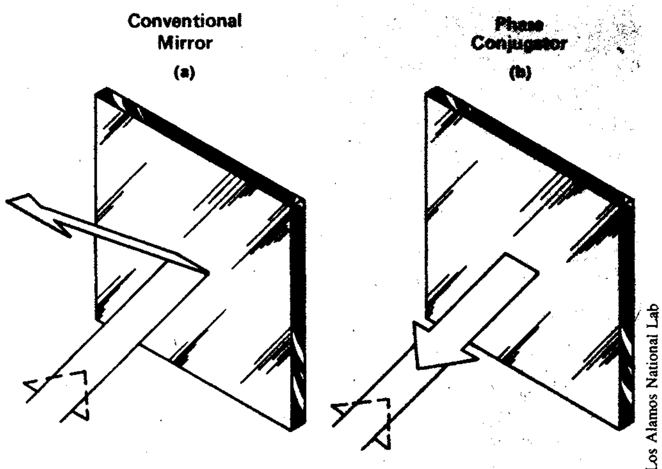


FIGURE 1. *When a conventional mirror (illustrated on the left) reflects a beam, the angle of reflection is the complement of the angle of incidence; a diverging beam continues to diverge after reflection. When a phase conjugate mirror (PCM, shown on right) reflects a beam, it sends it back in the same direction it came from, and makes a divergent beam convergent, or focusing.*

causing the return beam to exactly retrace the path of the incident beam. The process is also known as wavefront reversal or time-reversal reflection. Phase conjugators, also called phase conjugate "mirrors," do not reflect a beam the same way as a conventional mirror (Figure 1). When a beam is reflected from a conventional mirror, its angle of reflection is the complement of its angle of incidence, and if the beam is at all divergent, it continues to diverge following reflection. Since a conjugator sends the beam right back where it came from, the angle of reflection equals the angle of incidence and a diverging beam becomes convergent upon reflection.

This effect occurs despite the beam interference from an aberrator (such as a broken piece of glass, or turbulent atmosphere). In other words, conjugation can enable a designer to get around imperfections in an optical system, or turbulence in the atmosphere. For beam conjugation to be helpful in producing a focused beam on target, it is necessary for the response time of the conjugator to be faster than that of the aberrator. In other words, if the atmosphere has time to change during conjugation, the conjugated beam may not emerge from it focused. Lind and Dunning found atomic sodium to be a successful conjugator because of its rapid 10 nanosecond response time.

Generically, there are two forms of optical phase conjugation investigated today: backward stimulated Brillouin (or Raman) scattering (BSBS or BSRS) and degenerate four-wave mixing (DFWM). In 1972 B. Ya. Zel'dovich with a team of the Soviet Academy of Sciences demonstrated phase conjugation with Brillouin scattering. In backward stimulated Brillouin scattering, an intense laser beam in a fluid produces a sound wave. The shock front of this wave backscatters the incoming beam as its conjugate. This outgoing laser beam has a frequency downshifted from the incoming laser beam by an amount equal to the frequency of the sound wave created—an approximately 0.01% change in frequency.

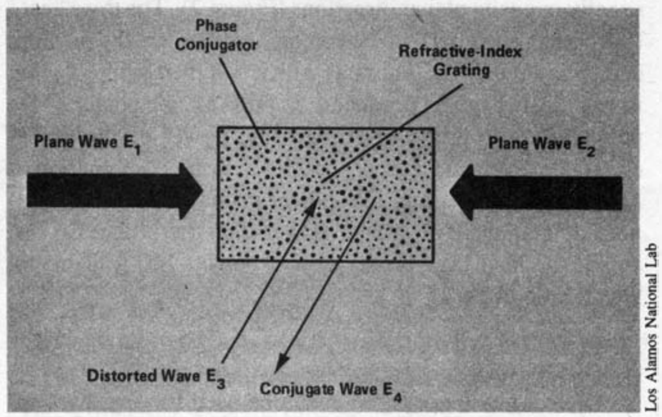


FIGURE 2. *In degenerate four-wave mixing, two pump beams (E(1) and E(2)) interact with a distorted probe beam (E(3)) in a nonlinear material or conjugator to produce, for example, the convergent conjugate of an originally divergent probe beam (E(4)).*

B. I. Stepanov with other Soviet scientists first demonstrated distortion correction by degenerate four-wave mixing in 1970. Lind and Dunning's experiment used a DFWM conjugator. In degenerate four-wave mixing, three beams of the same frequency interact in a nonlinear medium to produce a fourth beam, also of the same frequency, the conjugate of

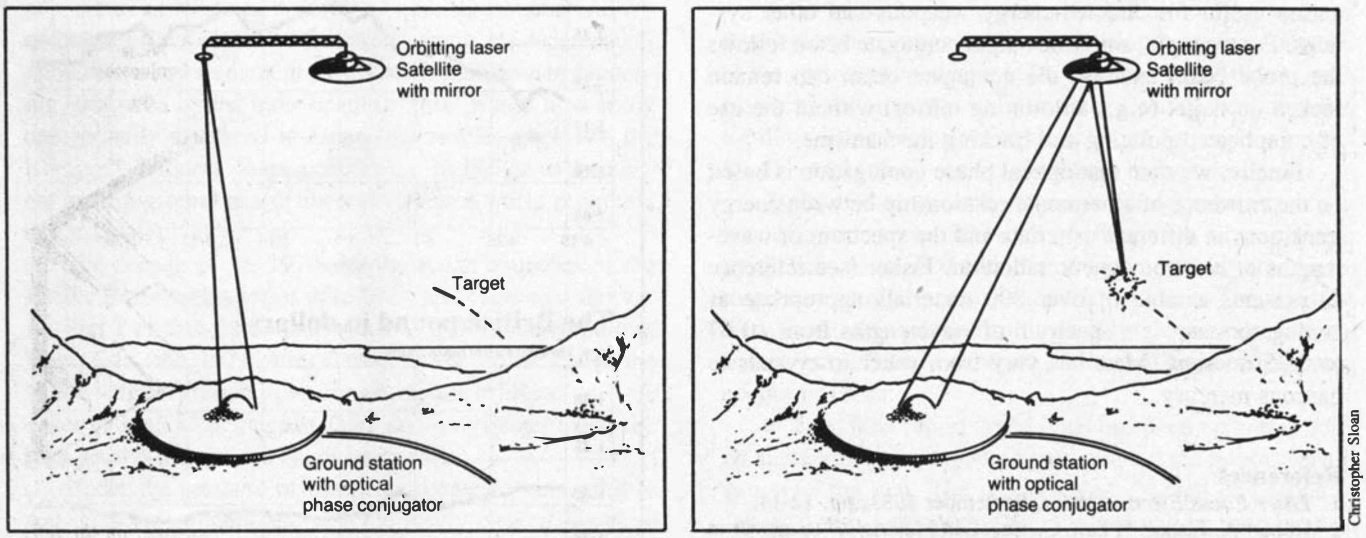


FIGURE 3. *The Fusion Energy Foundation proposes an application of phase conjugators (shown above) that eliminates any need to orbit large laser amplifiers in a space-based laser defense system. Upon deployment to destroy a ballistic missile target, a satellite equipped with a mirror and a small laser directs its beam towards the laser amplifier/phase conjugator facility on earth. The ground-based facility conjugates the beam and amplifies it to the power required to destroy the target. The amplified beam is then reflected off the orbiting mirror to the target.*

one of the others. Two beams "pump" the medium from exactly opposite planar directions (Figure 2). The third beam (the probe) is the beam to be conjugated; it enters the medium at the required angle, interacts with it and then pumps so that its conjugate beam is produced. In DFWM, the power of the pumps and the probe determines the power of the output conjugate beam so that it is possible with the combination of high-power pumps and low-power probe to achieve a "reflected" conjugate of greater power than the probe. So far, conjugates have been produced with powers 100-fold greater than their probes.

Applications

Optical phase conjugation can be used for any laser application that requires long-distance transmission through inhomogeneous media, e.g., laser communications with submarines, or directed energy weapons. In an application designed by the Fusion Energy Foundation (Figure 3), the attack sequence against a ballistic missile in its boost phase is initiated by a small laser aboard an orbiting mirror spacecraft:

1) The spacecraft directs its beam downward through the atmosphere to the earth-bound conjugator and amplifier.

2) On the ground, the arriving pulse passes through a laser amplifier enroute to the conjugator. The pulse is conjugated and amplified on its second pass to missile-kill intensities.

3) The pulse travels upwards to deflect off the orbiting mirror at the appropriate angle to intercept the target.

There are other characteristics of optical phase conjugation useful for directed-energy weapons and other systems. For example, since the output conjugate beam follows the probe beam exactly, the conjugate beam can remain locked on target (e.g., an orbiting mirror) without the use of complicated pointing and tracking mechanisms.

Finally, we note that optical phase conjugation is based on the existence of a harmonic relationship between energy transitions in different materials and the spectrum of wavelengths of electromagnetic radiation. Fisher (see reference 2) presents a table of over 300 materials appropriate as conjugators across a spectrum of wavelengths from 10.67 to 0.25 microns. Materials vary from water to crystals to gaseous mercury.

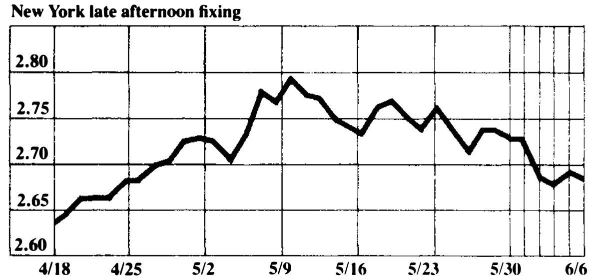
References

1. *Laser Focus/Electro-Optics,* September 1983, pp. 12-14.
2. Robert A. Fisher, "Phase Conjugation Materials," to appear in *CRC Handbook of Lasers.*
3. C. R. Giuliano, "Applications of Optical Phase Conjugation," *Physics Today,* April 1982.
4. Barry J. Feldman, et al., "Through the Looking Glass with Phase Conjugation," *Los Alamos Science,* Fall 1982, p. 9.

Currency Rates

The dollar in deutschemarks

New York late afternoon fixing



The dollar in yen

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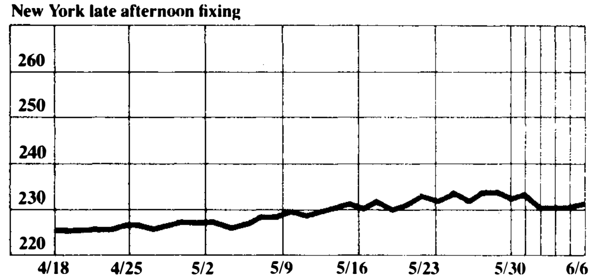
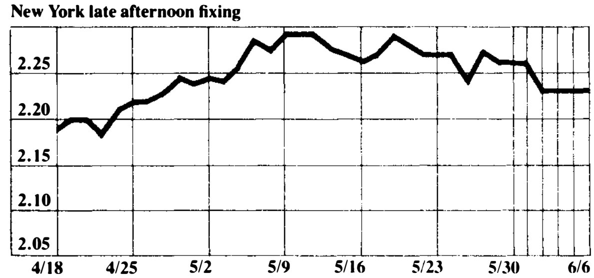


The dollar in Swiss francs

New York late afternoon fixing



The British pound in dollars

New York late afternoon fixing