Brillouin-enhanced four-wave-mixing vector phase-conjugate mirror with beam-combining capability

Mark W. Bowers

Institute of Optics, University of Rochester, Rochester, New York 14627, and Lawrence Livermore National Laboratory, L-154, 7000 East Avenue, Livermore, California 94551

Robert W. Boyd

Institute of Optics, University of Rochester, Rochester, New York 14627

Allen K. Hankla*

Lawrence Livermore National Laboratory, L-154, 7000 East Avenue, Livermore, California 94551

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It is often desirable to remove both wave front and polarization aberrations from an optical beam. Scalar phase conjugation, such as ordinary stimulated Brillouin scattering, can correct only for wave-front aberrations. We have developed a new geometry for Brillouin-enhanced four-wave mixing that performs vector phase conjugation to correct for both wave-front and polarization distortions. Results show a reduction in the depolarization losses from 50% to less than 2% of the total output energy. Coherent, variable, multiple-beam combination is achieved without need of nonreciprocal devices such as Faraday rotators.

Laser systems contain optical components that can reduce the degree of polarization of the beam as well as aberrate the optical wave front. Many of the phase-conjugation techniques used, such as stimulated Brillouin scattering in a focused geometry, are scalar by nature and cannot compensate for distortions in the polarization.[1–3] Basov *et al.* were able to achieve vector phase conjugation by making the beam appear as one highly aberrated beam of one linear polarization.[4] Another method of achieving vector phase conjugation is by using four-wave mixing with counterrotating pump beams. This method was first described theoretically by Zel'dovich *et al.*[5] and was analyzed for the specific case of Brillouin-enhanced four-wave mixing[6–8] (BEFWM). It has been found that at high power this method does not produce the same reflectivity for both polarizations and that it exhibits an instability when one of the polarizations is absent.[8] Another method of compensating for polarization distortions is to rotate the polarization between passes through similar laser rods. This method is most useful when the depolarization is not too large and the other distortions are not severe.[9,10]

BEFWM has been shown to achieve scalar phase conjugation with high fidelity and reflectivity.[11] In this Letter we focus on a BEFWM geometry in which the pump and the probe beams are at the same frequency and the conjugate of each is shifted by the Brillouin resonance frequency. To begin our analysis we define the electric field, $\mathbf{E}_m$, and field amplitudes, $\mathbf{A}_m$, as

$$\mathbf{E}_m(z,t) = \mathbf{A}_m(z,t)\exp[i(k_m z - \omega_m t)] + \text{c.c.} \qquad (1)$$

We have defined fields $\mathbf{E}_1$ and $\mathbf{E}_2$ as the pump and its conjugate and the fields $\mathbf{E}_3$ and $\mathbf{E}_4$ as the probe beam and its conjugate. The BEFWM interactions are described to a good approximation by the following set of coupled amplitude equations:

$$\frac{\mathrm{d}\mathbf{A}_1}{\mathrm{d}z} = \frac{-gc}{4\pi}[(\mathbf{A}_1\cdot\mathbf{A}_2^*)\mathbf{A}_2 + (\mathbf{A}_1\cdot\mathbf{A}_4^*)\mathbf{A}_4 + (\mathbf{A}_2^*\cdot\mathbf{A}_3)\mathbf{A}_4], \qquad (2)$$

$$\frac{\mathrm{d}\mathbf{A}_2}{\mathrm{d}z} = \frac{-gc}{4\pi}[(\mathbf{A}_1^*\cdot\mathbf{A}_2)\mathbf{A}_2 + (\mathbf{A}_1^*\cdot\mathbf{A}_4)\mathbf{A}_3 + (\mathbf{A}_3^*\cdot\mathbf{A}_2)\mathbf{A}_3], \qquad (3)$$

$$\frac{\mathrm{d}\mathbf{A}_3}{\mathrm{d}z} = \frac{-gc}{4\pi}[\mathbf{A}_2(\mathbf{A}_1\cdot\mathbf{A}_4^*) + (\mathbf{A}_2^*\cdot\mathbf{A}_3)\mathbf{A}_2 + (\mathbf{A}_3\cdot\mathbf{A}_4^*)\mathbf{A}_4], \qquad (4)$$

$$\frac{\mathrm{d}\mathbf{A}_4}{\mathrm{d}z} = \frac{-gc}{4\pi}[(\mathbf{A}_1^*\cdot\mathbf{A}_4)\mathbf{A}_1 + \mathbf{A}_1(\mathbf{A}_2\cdot\mathbf{A}_3^*) + (\mathbf{A}_3^*\cdot\mathbf{A}_4)\mathbf{A}_3]. \qquad (5)$$

Here g is the Brillouin intensity gain coefficient and c is the speed of light. In deriving these equations, we did not assume that any of the amplitudes were necessarily small compared with any other. We dropped some terms that can have a measurable contribution to the system under certain circumstances but have a negligible contribution under our experimental conditions. We did assume that the angle between the pump and the probe was sufficiently small and that the interaction was essentially phase matched, that is, $\Delta k \equiv |\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}_4| \cong 0$. In Eqs. (2)–(5), $\mathbf{A}_m$ is allowed to be complex, so we can write $\mathbf{A}_m = |A_{mx}|\hat{x}\exp(i\phi_{mx}) + |A_{my}|\hat{y}\exp(i\phi_{my})$. In our BEFWM geometry shown in Fig. 1, the probe beam is divided into two spatially separated beams with orthogonal polarizations. Since we are working in a domain where g is real and the initial value of $\mathbf{A}_4$ is zero, we can see that the initial phase of beam A_{4x} will be given by

$$\phi_{4x} = \phi_{1x} + \phi_{2x} - \phi_{3x}, \qquad (6)$$

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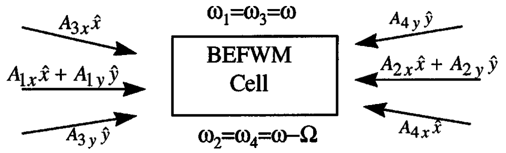

Fig. 1. Brillouin-enhanced four-wave mixing geometry of our experiments. The pump beams are A_1 and A_2, and the probe beams and their conjugates are A_3 and A_4, respectively.

and likewise for A_{4y}. Numerical simulations using Eqs. (2)–(5) show that each of the phases ϕ_1 through ϕ_4 is essentially constant through the interaction region.

It has been shown[12] that phase locking of this type will occur when $I_1 I_2 > I_3^2 \exp(-25)$ in the interaction region. Of interest to us are the phases of the beams when they are recombined after conjugation, as shown in Fig. 2(a). Note that we can always choose a polarization basis that will achieve equal reflectivity in both polarizations. Basov *et al.*[13] first showed that the phase difference on recombination of the $\hat{x}$ and the $\hat{y}$ components is $\Delta\phi = \Omega \Delta L / c$, where Ω is the Brillouin frequency shift and ΔL is the optical path length difference between the two probe beam paths. In our four-wave mixing geometry we find that we will still have a phase shift even for $\Delta L = 0$. To calculate this phase shift we need to find the phase difference between the two output probe conjugate polarizations and the conjugate of the two input probe polarizations. This phase shift will be defined by $\Delta\beta \equiv \phi_{4x} - \phi_{4y} + \phi_{3x} - \phi_{3y}$. It can be determined by substitution of Eq. (6) into $\Delta\beta$ for each of the polarization components to be

$$\Delta\beta = \phi_{1x} - \phi_{1y} + \phi_{2x} - \phi_{2y} . \qquad (7)$$

The end result is a phase shift of

$$(\Delta\phi)_{xy} \equiv \phi_{4x} - \phi_{4y} + \phi_{3x} - \phi_{3y} = \frac{\Omega \Delta L}{c} + \Delta\beta . \qquad (8)$$

For the case in which the beam splitter in Fig. 2(a) is a polarizing beam splitter (PBS), one finds that when $(\Delta\phi)_{xy} = 2M\pi$, where M is any integer, perfect vector phase conjugation occurs. This condition is achieved by variation of the optical path difference between the probe beams, the polarization ellipticities of the pump beams, or the Brillouin resonance frequency Ω. In our system we use a combination of the first two methods while maintaining constant temperature in the Brillouin-active medium.

Variable output coupling can be achieved simultaneously with vector phase conjugation by using the slight modifications shown in Figs. 2(b) and 2(c). The fraction of the outcoupled energy to total conjugate energy is given by[12]

$$\eta = \frac{1}{2}\left\{1 + \frac{2\sqrt{I_{4a} I_{4b}}}{I_{4a} + I_{4b}} \cos[(\Delta\phi)_{ab}]\right\} . \qquad (9)$$

A benefit of this type of output coupling in a vector phase conjugation system is that there is no need for additional active or passive unidirectional devices. Here we can also have smaller amplifiers in our amplifier chain and still be able to increase the beam size before recombination to prevent optical damage to the components.

Figure 3 displays an experimental realization of the BEFWM vector phase conjugation with beam combining that we have studied extensively. The pump and probe beams are 10 ns in duration and originate from the same Nd:YAG single-longitudinal-mode oscillator. In the BEFWM region the pump beam is circularly polarized and contains 100 mJ in a diameter of 5 mm, and each of the four probe beams has 150 mJ in a diameter of 100 μm. The probe beam is split with either a beam splitter or a combination consisting of a polarizer, a half-wave plate, and a second polarizer. The polarizer combination is useful in separating the conjugated beams into a main output directed toward detector D1, a depolarized component toward detector D2, and a residual component toward detector D3. The

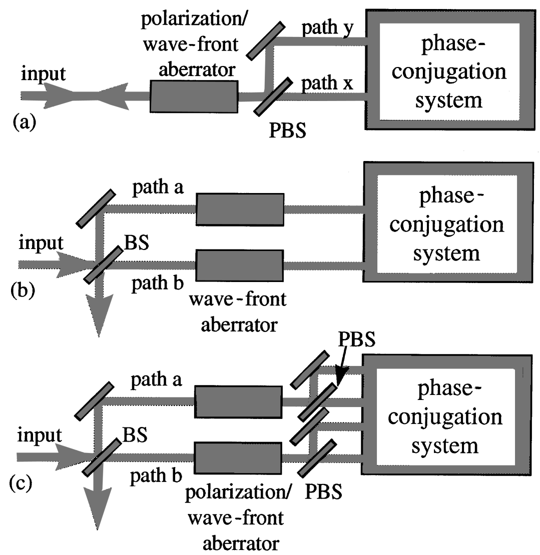

Fig. 2. Several applications of this BEFWM phase-conjugate mirror. For simplicity the pump beams are not explicitly shown. (a) Vector phase conjugation is obtained through use of a polarizing beam splitter (PBS). (b) Beam combining can be implemented as shown, with an ordinary beam splitter (BS). (c) Vector phase conjugation and beam combining are simultaneously produced.

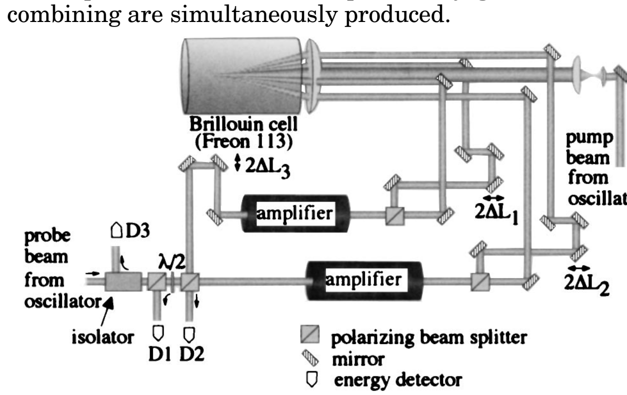

Fig. 3. Laser amplifier system based on the geometry shown in Fig. 2(c). Detector D2 is used to measure the amount of depolarized light, and detector D3 measures the amount of light that is coupled back toward the oscillator. The path lengths ΔL_1 and ΔL_2 can be adjusted to control the degree of depolarization while ΔL_3 is used to adjust the fraction of the output coupled to detector D1.

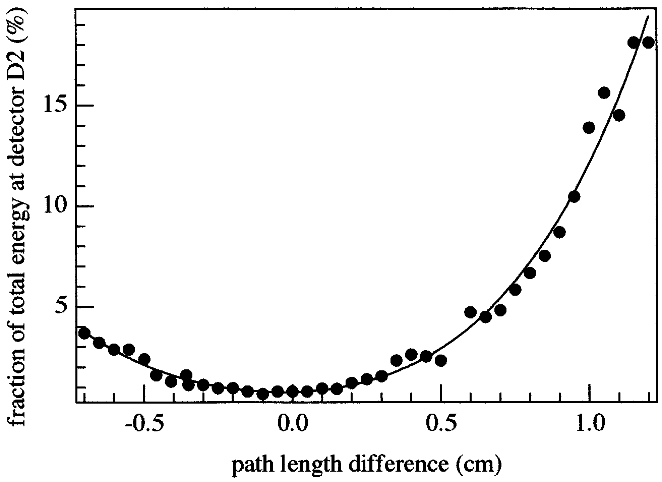

Fig. 4. Fractional depolarization versus the path length difference ΔL_1 (or ΔL_2). The origin of ΔL_3 is arbitrary. Note that the amount of depolarization can be reduced to acceptable levels with only centimeter tolerances on the path length difference.

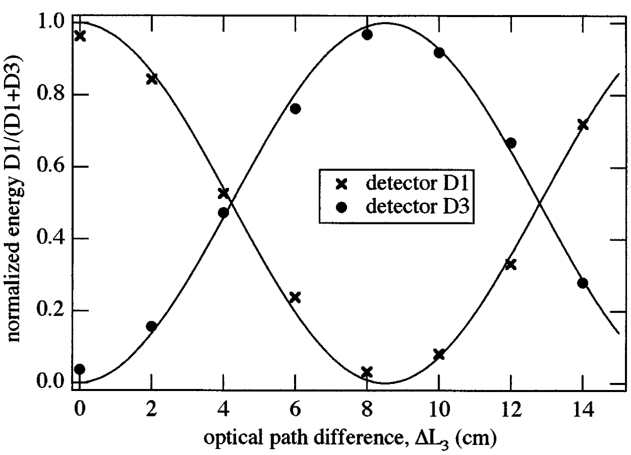

Fig. 5. The return beam can be directed to either D1 or D3 by varying ΔL_3. The path length difference need be regulated only to centimeter scale accuracy for nearly complete energy transfer to occur.

two input probe beams pass through separate amplifiers and are split again into two orthogonal polarizations. All five beams, the pump and the four probe beams, are focused into a cell containing a Brillouin medium. Each of the four probe beams needs to come to a focus anywhere inside the conical volume formed by the pump beam as it converges to a focus inside the Brillouin cell. The phase of each probe beam conjugate at the beam splitter can therefore be calculated by Eq. (8). By adjustment of ΔL_1 or ΔL_2, the path length of one probe beam with respect to the other, it is possible to have $(\Delta\phi)_{xy} = 2M\pi$ and thus to reconstruct the original wave fronts and polarizations as they pass back through the amplifiers. We have demonstrated such a reconstruction with sufficient accuracy that less than 2% of the total output energy resides in the incorrect polarization (see Fig. 4). By comparison, if we replace the phase-conjugate system with a dielectric mirror, the degree of depolarization is nearly 50% of the total output energy.

By adjustment of the path length difference between the two amplifier chains, ΔL_3, it is possible to adjust the relative phase of the two probe beams. If this phase shift is $(2M + 1)\pi$ rad, then the beam polarization is effectively rotated $\pi/2$ rad compared with its input state as it passes back through the $\lambda/2$-wave plate. The beam is then coupled out toward detector D1 as shown in Fig. 5.

In conclusion, we have demonstrated a high-power vector phase-conjugate mirror system that can reduce the fraction of depolarized light from 50% to less than 2%. The system can be used to combine multiple output beams into one coherent beam without need of any unidirectional device. We have also shown that there are several different means by which one can vary the fraction of return energy that is coupled out of the system. We have run the system at more than 5 J of output energy at 10 Hz with better than 1.5 times diffraction-limited performance. The system is inherently insensitive to small changes (~1 cm) in the optical path lengths and has a shot-to-shot variation of less than 5%.

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*Present address, Positive Light, 103 Cooper Court, Los Gatos, California 95030.

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