Simultaneous wave-front and polarization conjugation of picosecond optical pulses by stimulated Rayleigh-wing scattering

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Using phase conjugation by stimulated Rayleigh-wing scattering (SRWS) in carbon disulfide, we have observed simultaneous correction of wave-front and polarization distortions. SRWS was excited by pulses of 20-psec duration containing as much as 15 μJ of energy at a wavelength of 0.53 μm and produced phase-conjugate reflectivities as large as 10%.

Optical phase conjugation is a nonlinear-optical process that is useful for removing aberrations from optical systems. Stimulated Brillouin scattering (SBS) is the process most commonly used for generating the phase conjugate of a high-peak-power laser pulse. Phase conjugation by SBS was first demonstrated by Zel'dovich *et al.* in 1972.[1] They found that when the output of a Q-switched laser was focused into a cell containing compressed methane, SBS was excited, resulting in the generation of a phase-conjugate signal in the backward direction. However, phase conjugation is not peculiar to SBS. In fact, any stimulated scattering process that returns a scattered wave with a sufficiently small frequency shift can lead to phase conjugation.[2]

In this Letter we describe the results of an experimental investigation of phase conjugation by stimulated Rayleigh-wing scattering (SRWS) in carbon disulfide (CS_2). SRWS is the stimulated scattering process resulting from the tendency of anisotropic molecules to become aligned along the electric field direction of an applied optical wave. SRWS leads to the generation of a wave shifted in frequency by approximately the inverse of the orientational relaxation time of the anisotropic molecules.[3] In the limit of no pump depletion, the generated wave experiences exponential growth in accordance with the equation

$$I_s(z) = I_s(0)\exp(gI_L z), \tag{1}$$

where g is the SRWS gain factor (3×10^{-3} cm/MW for CS_2) and I_L denotes the laser intensity. As the process leading to phase conjugation, SRWS possesses two distinct advantages over SBS. First, the response time for SRWS is of the order of the orientational relaxation time (2 psec for CS_2), which is much shorter than the response time for SBS (the phonon lifetime for CS_2 is 2.5 nsec at $\lambda = 0.53$ μm). Therefore SRWS can be efficiently excited by picosecond laser pulses. Second, SRWS is sensitive to the state of polarization of the incident laser beam. In fact, it has been shown theoretically that SRWS can lead to vector phase conjugation, that is, the simultaneous conjugation of the optical wave front and state of polarization.[4] In particular, if the incident laser field is represented as

$$\mathbf{E}(\mathbf{r}, t) = A(\mathbf{r})\hat{\epsilon}(\mathbf{r})\exp[i(kz - \omega t)] + \text{c.c.}, \tag{2}$$

where $A(r)$ represents the complex field amplitude and $\hat{\epsilon}(r)$ denotes the polarization unit vector, SRWS leads to the generation of the field

$$\mathbf{E}_{pc}(\mathbf{r}, t) = A(\mathbf{r})^*\hat{\epsilon}(\mathbf{r})^* \exp[i(-kz - \omega t)] + \text{c.c.} \tag{3}$$

Vector phase conjugation has proved useful in removing distortions in both the phase and the polarization of a laser beam.[5]

The first reported observation of SRWS was that of Mash *et al.*[6] in 1965. Later, Foltz *et al.*[7] observed that, when SRWS is excited by circularly polarized laser light, the scattered radiation is also circularly polarized but with the opposite sense of rotation. This result suggests that polarization conjugation perhaps can be achieved by SRWS. However, a detailed theoretical analysis by Chiao and Godine[3] showed that the light scattered into the backward direction by SRWS excited by a uniformly polarized laser beam is nearly, but not exactly, the polarization conjugate of the incident laser beam. Zel'dovich and Yakovleva[4] have analyzed the situation in which SRWS is excited by partially polarized laser light and predict that perfect vector phase conjugation will be obtained if the incident laser beam is completely depolarized. The wave-front reconstruction properties of SRWS have been studied by Rivoire *et al.*[8]

Although the prediction of Zel'dovich and Yakovleva that SRWS can return the vector phase conjugate of the input signal was made nearly 10 years ago, no explicit experimental verification of these properties was previously reported to our knowledge. In this Letter we present results that demonstrate conjugation of both the wave front and the polarization of picosecond laser pulses by SRWS.

We performed three experiments to examine the vector phase-conjugation capabilities of SRWS. These experiments used the output of a frequency-doubled, Q-switched, and mode-locked Nd:YAG laser to excite SRWS. The second-harmonic pulses at a wavelength of 0.53 μm had a duration of $T = 20$ psec and contained as much as 15 μJ of energy. The beam was spatially filtered and collimated before being fo-

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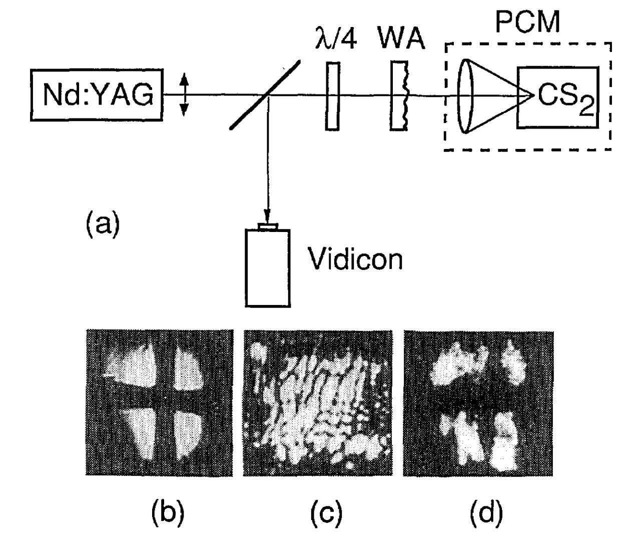

Fig. 1. Wave-front correction by SRWS. (a) Experimental setup. (b) Incident laser beam. (c) Laser beam after a double pass through the wave-front aberrator (WA) on reflection by a normal mirror. (d) The corrected beam after a double pass through the phase aberrator on reflection by SRWS.

cused at $f/2.5$ into a 10-cm-long cell containing CS_2 (see Fig. 1). The focusing lens and the CS_2 cell constitute the phase-conjugate mirror (PCM). Stimulated backscattering was observed for input energies Q greater than 2 μJ. Note that the single-pass gain parameter $gI_LL \approx gQ/2\lambda T$, where λ is the wavelength in the medium, is equal to approximately 20 at this energy, in agreement with the usual value of gI_LL at threshold.[2] To verify further that the return signal was generated by SRWS, we measured its spectrum with a 0.75-m spectrometer. Near threshold, the return signal was found to be slightly shifted (less than 50 GHz) to the Stokes (low-frequency) side of the laser frequency, consistent with previously reported results for SRWS.[9]

Our first experiment demonstrates the ability of SRWS to remove wave-front distortions in the standard double-pass geometry.[2,5] A phase aberrator (a microscope slide etched with hydrofluoric acid) was introduced into the laser beam. The effects of the phase aberrator can be seen in Fig. 1(c), where the PCM was replaced by a normal mirror. After the beam passed twice through the phase aberrator, the spatial profile of the return beam was found to be severely degraded [compare Figs. 1(b) and 1(c)]. However, when the laser beam was returned through the phase aberrator through the use of the PCM, the wave-front distortions were removed [see Fig. 1(d)], and the spatial profile of the input beam was restored. Similar results were obtained for both linearly and circularly polarized input beams, although the best performance of SRWS as a PCM was obtained by using a circularly polarized input beam.

Removal of distortions of the state of polarization of the incident beam by SRWS was observed in a similar fashion. Here the aberrator consisted of a glass plate stressed by overtightening the set screws of an optical mount. The stressed-induced birefringence scrambled the polarization state of the transmitted laser beam. A linearly polarized laser beam passed through this polarization aberrator, was reflected from either the PCM or the normal mirror (see Fig. 2), and passed through the aberrator a second time. The return signal was then decomposed through use of a polarizing beam splitter into polarization components parallel and perpendicular to that of the input laser. Since a perfect vector phase-conjugate signal would be composed of only the parallel component, these two components are referred to as the "good" and the "bad" components, respectively. When a normal mirror was used to reflect the beam back to the polarization aberrator, the return signal was no longer linearly polarized, as evidenced by the nearly equal energies in both the good and the bad components [Fig. 2(c)]. However, when the normal mirror was replaced by the PCM, the initial state of polarization was restored, and all the energy was found to be in the good component [Fig. 2(d)].

To obtain a quantitative measurement of the performance of SRWS as a PCM, we introduced a known polarization aberrator, namely, a quarter-wave plate, into the beam [see Fig. 3(a)]. The axes of the wave plate were oriented at 45 deg with respect to the polarization direction of the linearly polarized incident beam. When the quarter-wave plate was double passed by means of a normal mirror, the polarization state of the return beam was rendered orthogonal to

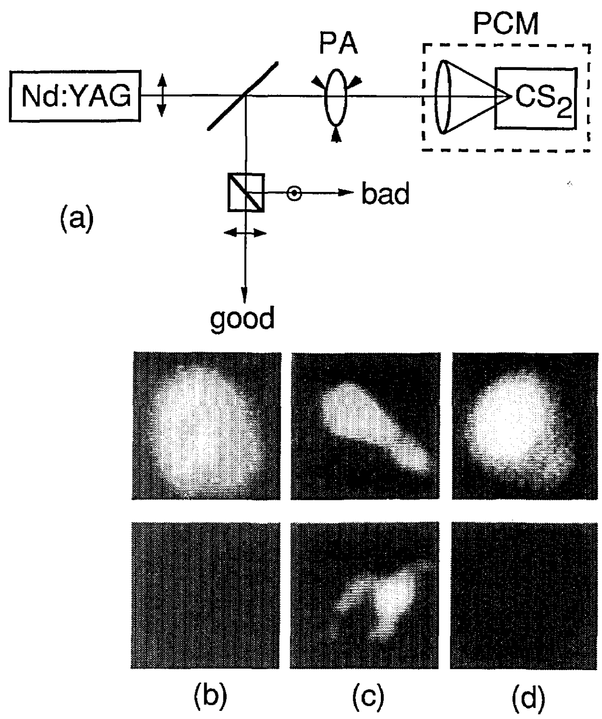

Fig. 2. Polarization correction by SRWS. (a) Experimental setup. (b)–(d) Intensity distributions of the two polarization components of the laser beam: top row, good components; bottom row, bad components. (b) The incident laser beam consisted of only one polarization component. (c) The laser beam after a double pass through the polarization aberrator (PA) on reflection by a normal mirror. The presence of light in the bad component indicates the severity of the polarization distortion. (d) The corrected beam after a double pass through the polarization aberrator on reflection by the PCM.

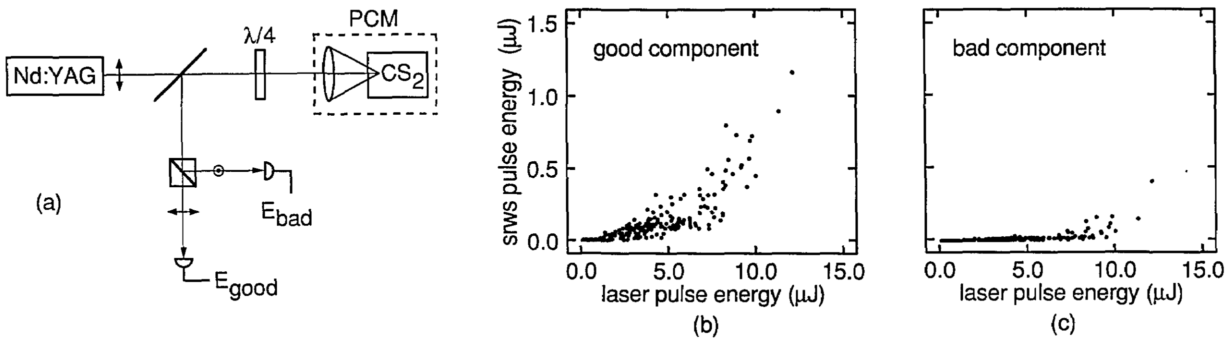

Fig. 3. Fidelity of polarization correction by SRWS. (a) Experimental setup. (b), (c) Energy in the good (b) and bad (c) components of the signal returned by SRWS plotted as functions of the laser pulse energy. For laser pulse energies less than 7 μJ, the polarization correction is essentially perfect.

that of the input beam. However, when a perfect vector phase conjugate of the input beam is produced, the effects of the wave plate are completely removed, and the polarization state of the return signal is identical to the input polarization state. For this reason, the presence of imperfections in the phase-conjugation process can be determined by measuring the energy in the orthogonal, or bad, component. The results of such a measurement are shown in Fig. 3(b). When the input pulse energy exceeds the threshold value of 2 μJ, a signal is observed in the backward direction in the good-polarization component. No signal is observed in the bad component for pulse energies below 7 μJ. Hence, under our experimental conditions, high-quality polarization conjugation occurs for input energies in the range of 2 to 7 μJ. At an input energy of 7 μJ, the phase-conjugate reflectivity is in excess of 10%, which is significantly larger than that of other demonstrated techniques for producing vector phase conjugation.[5]

For input pulse energies larger than 7 μJ, the polarization state of the return signal was found to deviate from that of a perfect vector phase conjugate. This degradation was most likely due to the onset of competing effects, such as self-focusing, self-phase modulation, and stimulated Raman scattering. We observed that filamentation occurred for input laser intensities below those required for observation of a significant broadening of the spectrum of the return signal. Since stimulated Raman scattering and self-phase modulation tend to broaden the spectrum, this observation indicates that self-focusing is the first competing process to occur in our experimental geometry and is hence the primary effect that degrades the fidelity of the PCM. However, by properly choosing the experimental parameters, we were able to reduce the effects of self-focusing. In particular, when SRWS was excited by a circularly polarized input laser beam, higher phase-conjugate reflectivities were obtained than when a linearly polarized input was used. This observation is consistent with the theoretical prediction that the gain factor for SRWS is higher for a circularly polarized pump wave than for a linearly polarized pump wave.[3] We have also observed that aberrations are better corrected when circularly polarized rather than linearly polarized light is used. Since a circularly polarized beam experiences self-focusing less readily than does a linearly polarized beam,[10] these observations are consistent with the conjecture that self-focusing is the process that limits the fidelity of phase conjugation by SRWS.

In conclusion, the results presented here show that SRWS provides an effective means of generating the vector phase conjugate of picosecond laser pulses.

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