Non-frequency-shifted, high-fidelity phase conjugation with aberrated pump waves by Brillouin-enhanced four-wave mixing

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The results of an experimental investigation of a new geometry for producing phase conjugation by Brillouin-enhanced four-wave mixing are presented. In this geometry, the four-wave mixing medium is carbon disulfide, and the backward-going pump wave is created from the transmitted forward-going pump wave by stimulated Brillouin scattering (SBS) in glycerol. The two pump waves are hence phase conjugates of each other, and the quality of the phase-conjugation process is not degraded even by the use of an aberrated pump wave. The probe wave is created by SBS in carbon disulfide, which has a Brillouin frequency half that of glycerol, and the conjugate wave is therefore generated at the same frequency as the probe. Since the pump and signal waves differ in frequency by the Brillouin frequency of the carbon disulfide four-wave mixing medium, high reflectivities (approximately 2000%) are obtained as a result of Brillouin resonance enhancement.

In order to obtain high-fidelity phase conjugation in the usual geometry of phase conjugation by four-wave mixing,[1,2] it is necessary that the pump waves be unaberrated or, if they are aberrated, that they be phase conjugates of each other. In this Letter we describe the results of an experimental investigation of a new configuration for phase conjugation by four-wave mixing in which the pump waves are automatically phase conjugates of each other, and we demonstrate experimentally that the fidelity of the phase conjugation is not degraded through the use of aberrated pump waves. Furthermore, in our experimental configuration the input frequencies are chosen in such a manner that there is no frequency shift between the signal and phase-conjugate waves and also such that high reflectivity is obtained through Brillouin enhancement of the four-wave mixing process. Brillouin-enhanced four-wave mixing was studied previously[3-9] but for different choices of input frequencies that lead to a frequency shift between the signal and phase-conjugate waves.

The geometry used in our experimental investigation is shown in Fig. 1. The four-wave mixing takes place in a cell of carbon disulfide whose Brillouin frequency we denote as Ω. After passing through the four-wave mixing cell, the forward-going pump wave of frequency ω is focused into a cell containing glycerol, whose Brillouin frequency shift is twice that of carbon disulfide. The backward-going pump wave is created by stimulated Brillouin scattering (SBS) in this cell, and its frequency is hence equal to $\omega - 2\Omega$. Because of the well-known[10,11] properties of SBS with a focused, aberrated input beam, the output wave from the glycerol cell is to a good approximation the phase conjugate of the input wave. For the same reason, this wave is generated in a direction precisely opposite that of the incoming pump wave, and therefore alignment of the pump waves is automatically achieved. The use of SBS to ensure that the backward-going pump wave is the phase conjugate of the forward-going pump wave has been discussed (but not studied experimentally) for a different configuration by Basov and Zubarev.[12] The probe wave in our configuration at frequency $\omega - \Omega$ is created by SBS in an additional cell containing carbon disulfide. Since this frequency is midway between that of the two pump waves, the conjugate wave generated by the four-wave mixing process is at the same frequency as the probe, which for certain applications is a desirable property of our configuration.

A recent theoretical study[13] of four-wave mixing in this geometry has shown that large reflectivities are achievable. This geometry leads to high reflectivity because the E_1 and E_4 and the E_2 and E_3 fields differ in frequency by the Brillouin frequency of the medium. The beating between each pair of waves thus drives an intense acoustic wave in the medium through the process of electrostriction, and phase conjugation occurs because of a four-wave mixing process mediated by this acoustic wave. For example, the probe and backward pump waves beat together to drive an intense acoustic wave that modifies the refractive index of the medium. The forward-going pump wave scatters off this grating to form the conjugate wave. Furthermore, since the conjugate wave is at the Stokes frequency of the forward-going pump, it is amplified by the normal SBS process as it propagates through the interaction region. Both because of the large nonlin-

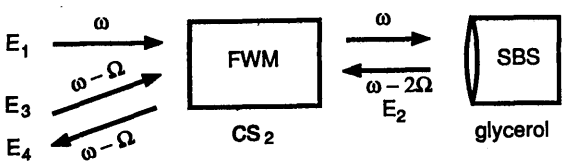

Fig. 1. Geometry of the Brillouin-enhanced four-wave mixing process considered here. The fidelity of the phase conjugation is not affected by aberrations of the pump wave front E_1.

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ear coupling and because of the SBS gain, the Brillouin-enhanced four-wave mixing process leads to large reflectivities. The nature of this interaction is described by the following set of coupled amplitude equations:

$$\frac{\partial E_1^*}{\partial z} = -E_4^*(Q_{14} + Q_{23}e^{i\Delta kz}), \tag{1a}$$

$$\frac{\partial E_2}{\partial z} = -E_3(Q_{23} + Q_{14}e^{-i\Delta kz}), \tag{1b}$$

$$\frac{\partial E_3^*}{\partial z} = -E_2^*(Q_{23} + Q_{14}e^{-i\Delta kz}), \tag{1c}$$

$$\frac{\partial E_4}{\partial z} = -E_1(Q_{14} + Q_{23}e^{i\Delta kz}), \tag{1d}$$

where the coupling coefficients

$$Q_{14} = g\frac{nc}{8\pi}E_1^*E_4 \tag{2a}$$

and

$$Q_{23} = g\frac{nc}{8\pi}E_2E_3^* \tag{2b}$$

are proportional to the amplitudes of the density waves driven by the beating of waves 1 and 4 and the beating of waves 2 and 3, respectively. The strength of the nonlinear coupling is characterized by the coefficient

$$g = \frac{g_0}{1 + i(\Delta_3 - \Delta_2)/\Gamma}, \tag{3}$$

where g_0 is the line-center amplitude gain coefficient for the normal SBS process,[14] which for carbon disulfide is equal to 0.075 cm/MW; $\Delta_2 = \omega_2 - \omega + 2\Omega$ and $\Delta_3 = \omega_3 - \omega + \Omega$ are the detunings from perfect Brillouin resonance for the E_2 and E_3 waves of angular frequencies ω_2 and ω_3, respectively; ω is the frequency of the forward-going pump wave; and Γ is the Brillouin linewidth. The wave-vector mismatch $\Delta k = 2n\Omega/c$ is the intrinsic phase mismatch of Brillouin-enhanced four-wave mixing in the geometry of Fig. 1. These coupled amplitude equations are formally identical to those considered previously for Brillouin-enhanced four-wave mixing in the different geometry in which the two pump waves are at the same frequency and hence in which the probe and the conjugate differ in frequency by twice the Brillouin frequency of the medium.[5] The solution to these equations in the constant-pump limit predicts that in the limit of low pump intensities [more precisely, in the limits $|g(I_1 - I_2)| \ll \Delta k$ and $\Delta k^2 \gg |g|^2 I_1 I_2$] the phase-conjugate intensity reflectivity is given by[5]

$$|r|^2 = \frac{g_0^2 I_1 I_2 L^2}{1 + (\Delta_2 - \Delta_3)^2/\Gamma^2}\,\mathrm{sinc}^2(\Delta kL/2), \tag{4}$$

and in the limit of high-pump intensities {more precisely, in the limits $|g(I_1 - I_2)| \gg \Delta k$ and $\exp[g(I_1 + I_2)L] \gg 1$, I_1/I_2} is given by the ratio of pump beam intensities, i.e.,

$$|r|^2 = I_1/I_2. \tag{5}$$

In these equations I_1 and I_2 are the pump-beam intensities and L is the length of the four-wave mixing medium.

In our experiment we used the frequency-doubled output of a single-longitudinal-mode Nd:YAG laser, yielding 8 mJ of energy in a 10-nsec pulse. The length of the four-wave mixing cell was 3 cm, and the diameters of the input beams were 1.5 mm at the cell. The angle between the pump and probe beams was 6 deg. The carbon disulfide was flowed in series through the four-wave mixing cell and the SBS cell in which the probe beam was generated and was filtered and passed through a heat exchanger to control its temperature before being recirculated. The glycerol was flowed through a separate circulation system that was also temperature stabilized. The glycerol SBS cell was typically operated at a reflectivity of 5%. The maximum steady-state reflectivity as predicted by Eq. (5) is thus equal to 20. In our experiment we observed reflectivities of approximately 20.

In order to demonstrate that the large reflectivity is in fact a consequence of Brillouin resonance enhancement, we have measured the detuning characteristics of the interaction. At room temperature, the Brillouin frequency Ω of the carbon disulfide is 7.6 GHz, and that of the glycerol is 15.4 GHz. However, the velocity of hypersound in glycerol is a strong function of temperature,[15] and the Brillouin frequency changes with temperature at a rate of approximately −40 MHz/°C. Thus by changing the temperature of the glycerol we are able to tune the backward pump wave into exact Brillouin resonance. Figure 2 shows the measured reflectivity plotted as a function of the glycerol temperature. The energies of the incident laser beams were held sufficiently low that the detuning characteristics are accurately predicted by the Lorentzian line shape given by Eq. (4). The solid curve in Fig.

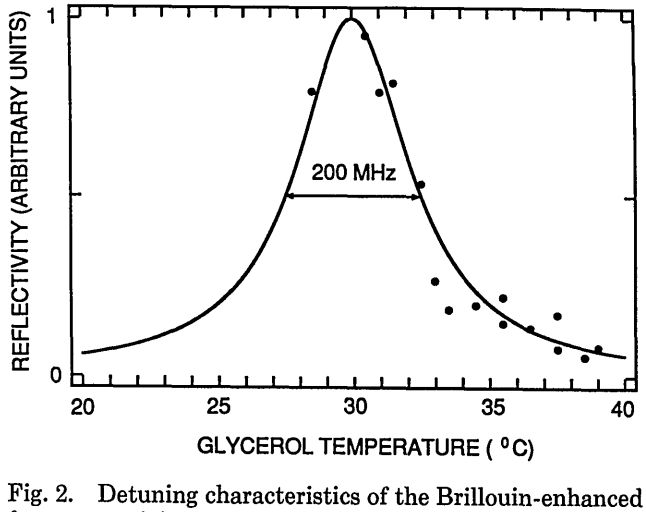
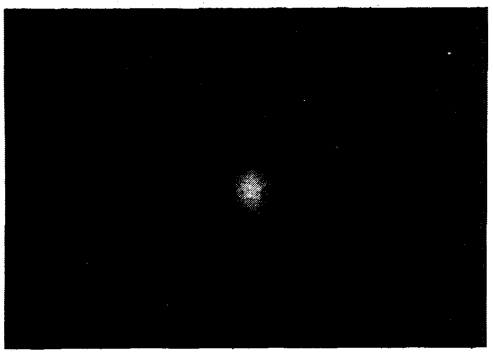
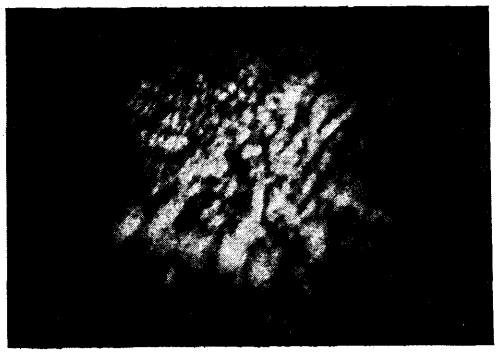


Fig. 2. Detuning characteristics of the Brillouin-enhanced four-wave mixing process, given by the measured reflectivity plotted as a function of the glycerol temperature. The Brillouin frequency of glycerol changes with temperature at a rate of −40 MHz/°C.

(a)



(b)



(c)

Fig. 3. Demonstration of high-fidelity aberration correction with aberrated pump waves. (a) Conjugate-beam intensity distribution when none of the input waves are aberrated. (b) Conjugate-beam intensity distribution when an etched-glass aberrator is placed at the entrance window of the four-wave mixing cell, thus distorting the probe and forward-going pump waves. (c) Intensity distribution of the aberrated pump beam.

2 is a Lorentzian curve that has been fitted to the data. The 200-MHz width of this curve is somewhat larger than the 120-MHz Brillouin linewidth of carbon disulfide, presumably because of the spectral breadth of the input waves.

We have also demonstrated experimentally that the quality of the phase conjugation is insensitive to the pump-beam wave front. Figure 3(a) shows the spot size of the conjugate beam in the far field when none of the input waves are aberrated. Figure 3(b) shows the spot size in the far field when an etched-glass aberrator is placed at the entrance window to the four-wave mixing cell, so that it distorts both the forward-going pump and probe waves. Note that the degradation of the beam quality is negligible. The severity of the aberrations impressed upon the waves is illustrated in Fig. 3(c), which shows the spot size when the four-wave mixing cell is replaced by a normal mirror oriented to reflect the pump wave back upon itself. The degree of aberration impressed upon the probe wave is similar.

In conclusion, we have demonstrated experimentally that a new geometry for phase conjugation by Brillouin-enhanced four-wave mixing produces high phase-conjugate reflectivity and is insensitive to pump-wave-front aberrations.

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