Efficient phase conjugation under parametric-feedback conditions

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A new method is proposed for exciting stimulated Brillouin scattering under generation conditions in a system with parametric feedback. Phase conjugation of the pump beam can be achieved at a considerably lower threshold intensity by this new method.

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The relatively high excitation threshold seriously limits the use of the phase conjugation accompanying stimulated Brillouin scattering[1] (or "stimulated Mandel'shtam-Brillouin scattering"). In the present experiments, phase conjugation has been achieved for the first time through the excitation of stimulated Brillouin scattering under generation conditions; the result is a significant lowering of the threshold pump intensity. These experiments make use of a new principle: the creation of feedback through a parametrically excited Stokes wave. For the "parametric resonator," in contrast with an ordinary resonator, there is no difficulty in coupling in the pump beam, and the pump frequency can be tuned through a coarse adjustment of the resonator length. This new phase-conjugation method does not require the formation of reference waves at a shifted frequency (such waves are required in Ref. 2), and it can be used to produce phase-conjugating mirrors in low-power lasers.

The method is illustrated by the schematic diagram in Fig. 1a. A spatially inhomogeneous pump beam, $L\,1$, propagates through nonlinear medium 1 and is returned to it as beam $L\,2$ by mirrors 2–4. A stimulated-Brillouin-scattering beam, the phase conjugate of the pump beam, propagates along the same path but in the opposite direction (beams $S\,1$ and $S\,2$). The angle between pump beams $L\,1$ and $L\,2$ is kept small so that the frequency shift of the stimulated Brillouin scattering can be assumed to remain constant within this angle. With the two pump beams $L\,1$ and $L\,2$ and the Stokes beam $S\,1$, another Stokes beam, $S\,2$, is parametrically excited in the medium.

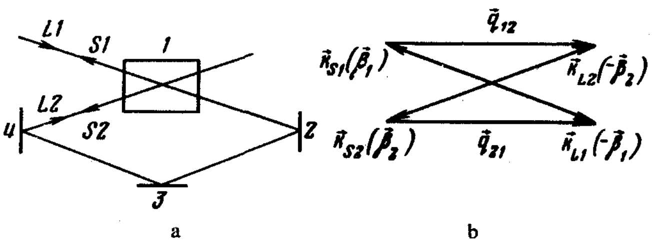

FIG. 1. a—Schematic diagram of a stimulated-Brillouin-scattering generator with parametric feedback; b—wave-vector diagram.

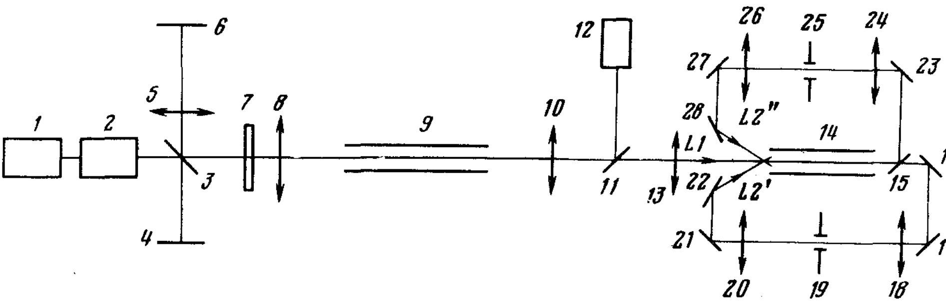

FIG. 2. The experimental apparatus. 1—Single-mode ruby laser; 2—laser amplifiers; 3, 11—glass beam splitters; 4, 16, 17, 21, 22, 23, 27, 28—total-reflection mirrors; 5, 8, 10, 13, 18, 20, 24, 26—lenses; 6—photographic plate; 7—phase plate; 9—glass lightguide; 12—thermocouple; 14—acetone-filled metal lightguide; 15—beam splitter ($R = 0.5$); 19,25—diaphragms.

After reflection from the mirrors, this beam is sent into the cell at the right, where it is converted into beam $S\,1$, creating the feedback.

In the experiments, which will be described in detail later, a rectangular lightguide 14 was used to increase the interaction distance (Fig. 2). In an effort to fill the lightguide uniformly with the pump light, we directed beam $L\,1$ along the lightguide axis, and instead of the single beam $L\,2$ we used two beams, $L\,2'$ and $L\,2''$, of equal intensity and positioned symmetrically with respect to the lightguide axis. These two beams were produced by splitting beam $L\,1$, incident on the lightguide, with a beam splitter 15. Two pairs of confocal lenses (18, 20 and 24, 26) imaged the exit and entrance ends of the lightguide onto each other. Diaphragms 19 and 25, in the focal planes of the lenses, cut out beams $L\,2'$ and $L\,2''$ as they emerged from the lightguide.

Let us examine this arrangement with a rectangular lightguide theoretically. We write the field of beam, $L\,1$, $E_{L\,1}$, and the resultant field of beams $L\,2'$ and $L\,2''$, $E_{L\,2}$, in the lightguide as follows:

$$E_{Lj}(\mathbf{r}) = \sum_{\vec{\alpha} \in (\vec{\alpha})_j} \epsilon_{Lj}(\vec{\alpha}) \exp[-i\mathbf{k}_L(\vec{\alpha})\,\mathbf{r}], \text{ where } j = 1, 2, \ |\mathbf{k}_L(\vec{\alpha})| = \omega_L n_L / c,$$

where ω_L is the pump frequency, $n_L = n(\omega_L)$ is the refractive index of the medium, $\vec{\alpha} = \mathbf{k}_L(\vec{\alpha})_\perp$ is the wave-vector component perpendicular to the z axis (which is along the lightguide axis), and $(\vec{\alpha})_j$ are the intervals of $\vec{\alpha}$ values for beams $L\,1$ and $L\,2 = L\,2' + L\,2''$. It is assumed here that the width of the angular spectrum of each of the beams $L\,1$, $L\,2'$, $L\,2''$ is large enough that the gain over the longitudinal correlation length is much less than unity.

We seek the Stokes field in the lightguide at the frequency ω_s as the field which is the conjugate of the pump field:

$$E_{Sj}(\mathbf{r}) = f_j(z) \sum_{-\beta \in (\alpha)_j} \epsilon^*_{Lj}(-\vec{\beta}) \exp[-i\,\mathbf{k}_S(\vec{\beta})\mathbf{r}],$$

where $j = 1, 2$; $|\mathbf{k}_S(\vec{\beta})| = \omega_S n_S / c$; and $\mathbf{k}_S(\vec{\beta})_\perp = \vec{\beta}$. Ignoring the incoherent oscillatory part of the parametric amplification, as usual, we find equations for the functions $f_{1,2}$:

$$\frac{df_1}{dz} = -(2\kappa_1 + \kappa_2)f_1 - \kappa_2 f_2 ,$$
$$\frac{df_2}{dz} = -(2\kappa_2 + \kappa_1)f_2 - \kappa_1 f_1 , \tag{1}$$

where $\kappa_j = \frac{1}{2} g_j (1 + i\rho)/(1 + \rho^2)$, $\rho = 2(\Omega - \overline{\Omega})/\Delta\Omega$, $\Omega = \omega_L - \omega_S$, $\overline{\Omega}$ is the resonant frequency of the phonon wave, $\Delta\Omega$ is the width of the thermal-scattering line, $g_j = bI_{Lj}$, b is the specific gain at the frequency $\overline{\omega}_S = \omega_L - \Omega$ in the monochromatic plane pump wave, I_{Lj} is the pump intensity averaged over the cross section, and the positive z direction is the pump propagation direction in the lightguide.

The parametric interaction between beams $L\,1$, $S\,1$, on the one hand, and $L\,2$, $S\,2$, on the other, results from a phase matching of the phonon waves with wave vectors $\mathbf{q}_{12}$ and $\mathbf{q}_{21}$ (Fig. 1b) which are excited by the pairs of angular components with the wave vectors $\mathbf{k}_{S1}(\vec{\beta}_1)$, $\mathbf{k}_{L2}(-\vec{\beta}_2)$ and $\mathbf{k}_{S2}(\vec{\beta}_2)$, $\mathbf{k}_{L1}(-\vec{\beta}_1)$, where $-\vec{\beta}_{1,2} \in (\vec{\alpha})_{1,2}$. Similarly, there is parametric interaction in each pair of beams $L\,1$, $S\,1$, and $L\,2$, $S\,2$.

Putting the origin ($z = 0$) at the right end of the lightguide (of length l), and using $f_2(0) = 0$, we find, for $-l \leqslant z \leqslant 0$,

$$f_1(z) = \frac{f_1(0)}{1+\xi} e^{-\kappa z}(e^{-\kappa z} + \xi), \qquad f_2(z) = \frac{f_1(0)}{1+\xi} e^{-\kappa z}(e^{-\kappa z} - 1), \tag{2}$$

where $\kappa = \kappa_1 + \kappa_2$ and $\xi = I_{L2}/I_{L1}$. The condition for steady-state emission is

$$e^{\kappa l}(e^{\kappa l} - 1)(1 + \xi)^{-1}(\sqrt{\zeta_L' \zeta_S'}\, e^{i\Omega\tau'} + \sqrt{\zeta_L'' \zeta_S''}\, e^{i\Omega\tau''}) = 1. \tag{3}$$

where $\zeta_{L,S}'$ and $\zeta_{L,S}''$ are the factors describing the attenuation of the pump and of the stimulated-Brillouin beams for the two parts of the path outside the medium, without consideration of an interference of the stimulated-Brillouin beams brought together by beam splitter 15 ($\zeta_L' + \zeta_L'' = \xi$; it is assumed that $\zeta_L' \approx \zeta_L''$), and τ' and τ'' are the circular-flight times calculated from the group velocity of the light. Condition (3) determines the resonant frequencies and the threshold pump intensities.

If $\zeta_{L,S}' = \zeta_{L,S}'' = \zeta_{L,S}$ and $\tau' = \tau' = \tau$, the resonator is tuned to the center of the gain band, $\overline{\omega}_S$, when $\tau = (2\pi/\Omega)m$, where $m = 1, 2, \ldots$. The shift of the resonant frequency upon a change in τ is smaller by a factor of $\omega_S/\overline{\Omega} \sim 10^{-5}$ than that for an ordinary resonator. With $\zeta_L = \zeta_S = 0.5$ the threshold value of $G_1 = g_1 l$ is $G_1^{\text{th}} = \ln 2$ or roughly 1/20 of the value regarded for the excitation of stimulated-Brillouin scattering with phase conjugation under ordinary conditions (without the mirrors returning the pump beam to the lightguide).

In the experimental apparatus (Fig. 2), a pump beam 8 mm in diameter passed through a phase plate 7, which increased the angular divergence of the pump beam from 1.5 to 15 mrad. Lens 8 ($f = 25$ cm) directed the pump beam into glass lightguide 9 (cross section of 3.5×3.5 mm^2, length of 80 cm), which flattened the transverse intensity distribution. The exit end of this lightguide was imaged by confocal lenses 10 and 13 onto the entrance end of a metal lightguide 14 (cross section of 3×3 mm^2, $l = 5$

cm) filled with acetone. Decoupling was arranged by increasing the distance between lightguide 14 and laser 1 to 6 m. The pulse length of the pump was 28 ns and its spectral width $\sim 10^{-2}$ cm^{-1}. The optical path lengths of the two paths were chosen to be the same and were adjusted to equality within ~ 3 mm. They were set at $d = 26$ cm, $d = 29$ cm, and $d = 32$ cm, corresponding to $m = 4$, 4.5, and 5. The threshold pump power was determined from the appearance of a stimulated-Brillouin-scattering spot on photographic plate 6, in the focal plane of lens 5 ($f = 1$ m). With $d = 26$ cm and $d = 32$ cm we found $P_{L1}^{\text{th}} = 1.8$ MW. With $d = 29$ cm, P_{L1}^{th} increased to ~ 2.5 MW. The angular divergence of the stimulated-Brillouin beam was determined from the spot diameter on photographic plate 6 and found to agree with the angular divergence of the pump.

Under the assumption that over the circumvention time τ the intensity of the stimulated Brillouin scattering increases by a factor of $4\zeta^2(1 + 2\zeta)^{-2}e^G(e^{(1/2)G} - 1)^2$ $[\zeta = \zeta_{L,S}; G = (g_1 + g_2)l]$, in accordance with (3) with integer m; and using the steady-state value $b = 2.2 \times 10^{-2}$ cm/MW; we find, with $\zeta = 0.3$ and $m = 5$, the theoretical value $P_{L1}^{\text{th}} = 1.2$ MW. This value is slightly lower than the experimental threshold; the discrepancy can be attributed to the time variation of the stimulated Brillouin scattering.

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