Stimulated Mandel'shtam-Brillouin scattering in a "traveling" regime

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A theory is derived for stimulated Mandel'shtam-Brillouin scattering in a "traveling" regime; numerical simulations have been carried out; and the effect has been observed experimentally in a glass optical fiber and in water (in each case, this is the first such study). The gain, the spectral width, and the broadening of the Stokes pulse are all estimated. The spectrum of the Stokes signal is predicted to change in a medium with an inhomogeneous refractive index.

Stimulated Mandel'shtam-Brillouin scattering (or "stimulated Mandel'shtam-Brillouin scattering") has been studied in many laboratories in a variety of media, including glass optical fibers,[1–3] primarily in the saturation regime. In the present letter we report a study of a stimulated-Brillouin-scattering regime which we call a "traveling" regime and in which the generation of the Stokes wave occurs in a given pump field throughout the propagation of a light pulse in a scattering medium of length L satisfying $2L/c \gg \tau_p$, where c is the velocity of light in the medium, and τ_p is the length of the pump pulse. The conditions required for this scattering regime can be arranged in optical fibers; with an appropriate focusing, they can also be arranged in long liquid-filled cells.

The traveling regime of stimulated Brillouin scattering attracts interest because it might prove useful for remote studies of inhomogeneities along the length of a scattering medium through the use of the particular features of both the time evolution itself of the intensity of the Stokes pulse (its length $\tau_s \cong 2L/c \gg \tau_p$ and the frequency spectrum of this pulse.

Our theoretical analysis of this regime of stimulated Brillouin scattering reveals the following:

1) The gain for the Stokes amplitude in this regime is

$$g = (\Gamma \tau_p / 2)\left(\sqrt{1 + GI_L c/\Gamma} - 1\right), \tag{1}$$

where $\Gamma = \alpha v$(v and α are the velocity and damping of hypersound), and GI_L is the steady-state gain of the stimulated Brillouin scattering (I_L is the pump intensity).

2) The width ($\delta\Omega$) of the angular-frequency spectrum of the Stokes pulse in a homogeneous medium is

$$\delta\Omega = (\pi/2)\Gamma \sqrt[4]{GI_L c/\Gamma} \,/\, (\Gamma \tau_p)^{1/2}\,[1 - (2g)^{-1}]\ . \tag{2}$$

3) Distinctive features arise in the Stokes spectrum when there are steady-state inhomogeneities in the medium which can change GI_L and the refractive index n along the wave propagation direction (z). Changes in the refractive index $n = n_0 + \delta n(z)$ cause the attenuation to become complex: $\tilde{\Gamma} = \Gamma(1 + ik\delta n(z)/\alpha)$, $k = 2\pi/\lambda$. The z dependence of the inhomogeneities gives rise to corresponding dependences of Γ, GI_L, and thus g on $ct/2$ (t is the time) because of the traveling regime of the stimulated Brillouin scattering. In the case of a harmonic law, $n = n_0 + \tilde{n}\cos Kz$, for example, additional peaks appear in the spectrum of the stimulated Brillouin scattering at frequencies which are multiples of $cK/2$.

Figure 1 shows the results of numerical calculations of the time evolution of the Stokes intensity, $I_s(t)$, for homogeneous (a) and inhomogeneous (c) media, along with results calculated on the frequency spectra $|E_s(\omega)|^2$ for the constant and harmonic coefficients of GI_L (b) and the constant and harmonic coefficients of n(d) for the case of a Gaussian pump pulse. Figures 1b and 1d clearly reveal maxima caused by the harmonic modulation of the inhomogeneities.

We have carried out experiments to observe the traveling regime in distilled water and in an optical fiber. In the case of the water, we used the laser apparatus described in Ref. 4. Light with $\lambda = 0.53\ \mu$m and a pulse length $\tau_p = 20$ ns is focused by a mirror telescope into a water-filled cell 6.5 m long. The set of mirrors used for the telescope makes it possible to produce a laser-beam diameter on the order of 2–3 mm at the entrance to the medium. The position of the laser focus is varied from the entrance to the cell to the rear output mirror in the course of the experiments. The results of these experiments show that the onset of stimulated Brillouin scattering in the traveling regime depends strongly on the sharpness of the focusing and on the energy of the laser beam. The traveling regime arises when the beam is focused near the rear end of the cell and at pump intensities which are higher than the intensity of the Stokes wave by a significant factor (10 to 20).

Figure 2 shows a trace of the stimulated Brillouin scattering for water in the traveling regime. We see the typical significant fluctuations in the intensity of the Stokes wave.

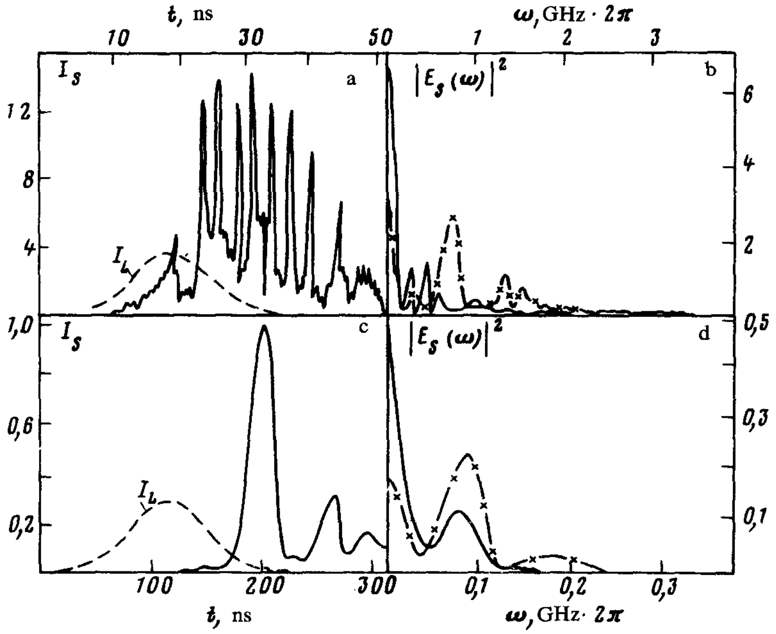

FIG. 1. a, c: Time evolution of I_s, in units of 10^{-5} W/cm^2. a—in a homogeneous medium, $L = 600$ cm, $\Gamma = 2\times 10^9$ s^{-1}, $\tau_p = 16$ ns, $I_{L_{\max}} = 4\times 10^6$ W/cm^2, $c = 2.3\times 10^{10}$ cm/s; c—in an inhomogeneous medium, $L = 3000$ cm, $\Gamma = 10^8$ s^{-1}, $\tau_p = 100$ ns, $I_{L_{\max}} = 3\times 10^6$ W/cm^2, $c = 1.95$ cm/s. b, d: Spectrum of $|E_s(\omega)|^2$, in units of 10^{-14} W · s/cm^2. b—For the conditions of part a (solid line) $g = \text{const}$; (crosses) $GI_L = GI_L \cdot [1 + 0.5\ \sin(2\pi z/75)]$; d—for the conditions of part c (solid line) $g = \text{const}$; (crosses) $n = n_0 + 8\times 10^{-4}\ \sin(2\pi z/670)$.

In the experiments with the optical fiber we use a single-mode fused quartz fiber (SiO_2 + 3% GeO_2 by weight) with a length $L = 200$ m and an attenuation $\beta = 2$ dB/km. The pump source is a single-frequency, single-mode Nd:YAG laser ($\lambda = 1.06\ \mu$m) in periodic-pulse operation with $\tau_p = 90$ ns. Figure 3 shows an oscilloscope trace of the stimulated Brillouin scattering from an experiment; the length of the Stokes pulse is $\tau_s = 2\ \mu$s, corresponding to stimulated scattering over the entire length of the fiber. At the end of the trace, we see the undistorted pump pulse reflected from the rear end of the fiber. The behavior of the intensity of the Stokes wave, as in the case of scattering in water, is fluctuational, with a spike having an average duration $\tau_{\text{spike}} \cong 25$–$30$ ns. This spike structure of the stimulated Brillouin scattering is random over the length of the fiber and also from one occurrence to another. This random time dependence

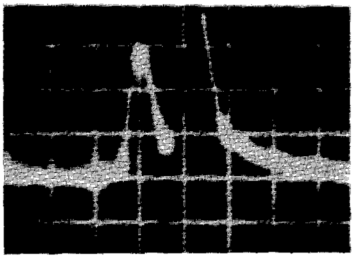

FIG. 2. Oscilloscope trace of an experiment with stimulated Brillouin scattering in the "traveling" regime for a cell $L = 6.5$ m long filled with distilled water. The time division is 20 ns.

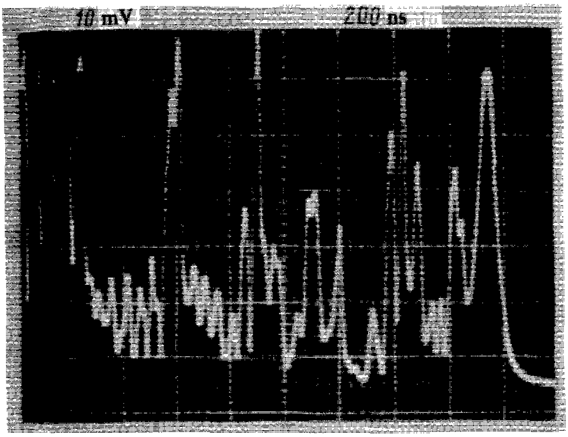

FIG. 3. Oscilloscope trace of an experiment with stimulated Brillouin scattering in the traveling regime in an optical fiber $L = 200$ m long. The time scale is 200 ns/div. Visible at the end of the pulse of the stimulated Brillouin scattering is the undistorted pump pulse reflected from the rear end of the optical fiber ($\tau_p = 90$ ns).

stems from the random distribution of thermal hypersonic perturbations which nucleate the stimulated Brillouin scattering, as is confirmed by the results of our numerical simulation. In particular, we find an agreement in terms of the spike length τ_{spike}. It should be noted that as the pump power is reduced by a factor of nearly three, we find no significant change in τ_{spike}.

Despite the random nature of the stimulated Brillouin scattering in the traveling regime from one pump pulse to another, we see from Fig. 3 that there are at least four regions in which the stimulated Brillouin scattering is most intense. This result can be explained in terms of small changes in the pump intensity over the length of the fiber due to variations in the fiber diameter and also a difference between the refractive indices of the core and the cladding.

The results of this study show that the traveling regime of stimulated Brillouin scattering can be used for remote probing of both random (e.g., technological) and regular (e.g., due to the presence of acoustic fields) inhomogeneities of a medium.

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