Stimulated Mandel'shtam–Brillouin scattering excited by radiation with a broad spectrum

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It is established experimentally that the efficiency of the stimulated scattering does not depend on the width of the exciting-radiation spectrum if the interaction length is shorter than the coherence length of this radiation. The spectral and angular characteristics of the scattered light are investigated in the case of broad-band pumping.

D'yakov has shown in his theoretical paper[1] that stimulated Mandel'shtam—Brillouin scattering (SMBS) and stimulated Raman scattering (SRS) can be produced just as effectively by broad-band pumping1) as by narrow-band pumping. Effective forward SRS was observed using radiation with a broad spectrum, [2–4] but the gain for backward SRS was practically zero. [4] It was also reported that the use of broad-band radiation leads to a sharp decrease of the intensity of SMBS. [5,6] Thus, on the basis of all the published experimental results, the prevailing opinion was that effective backward scattering is impossible in the case of broad-band pumping, although the theory[1] leads to the opposite conclusion.

To check on this theory, we have compared the SMBS threshold powers at different widths of the spectrum of the exciting light and different lengths of the scattering medium. The diagram of the setup is shown in Fig. 1. The beam from a ruby laser enters a cell filled with methane gas at a pressure 150 atm. 2) A light pipe placed in the cell ensures uniform illumination over its entire length. The illumination is made uniform over the cross section of the scattering region by using an

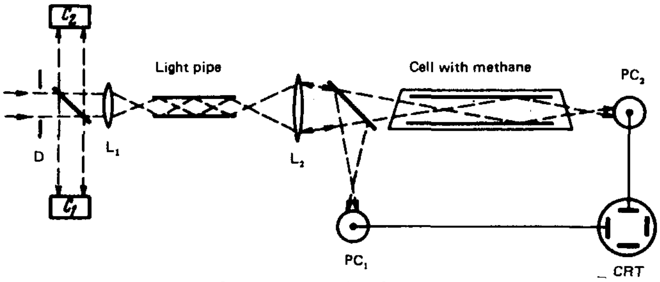

FIG. 1. Experimental setup: D—diaphragm, 4 ×4 mm; L_1—lens with $f = 14$ cm; the light pipe (length 23 cm, cross section 2 ×2 mm) is made up of organic-glass plates; L_2—lens with $f = 30$ cm or 50 cm if the cell length is 24 cm or 99 cm, respectively; the cell windows are inclined 11°; the short cell contains a hollow glass light pipe 23 cm long and 2 ×2 mm in cross section, while the long cell contains a light pipe 97 cm long and 4 ×4 mm in cross section; the light-pipe losses are ~14%; PC_1 and PC_2—coaxial photocells FEK-0.9; CRT—cathode ray tube of I2-7 oscilloscope; the time constant of the recording apparatus is ≈10 nsec; C_1 and C_2—systems used to vary the parameters of the exciting and scattered light.

external light pipe. At the entrance to this light pipe, the lens L_1 produces the image of a diaphragm illuminated by the laser beam. The rays passing at different distances from the optical axis of the system strike the light-pipe walls at different angles. The exit end of the light pipe is therefore uniformly illuminated regardless of the distribution of the radiation at its entrance. The lens L_2 projects the image of the exit end onto the entrance to the cell.

The laser operated in the single-mode or multimode regime. In the former case the width of its spectrum at half-height was $\delta\nu < 5\times10^{-4}$ cm^{-1}, i.e., smaller than $\delta\nu_0$. In the case of multimode generation, the radiation oscillogram (Fig. 2a) takes the form of periodically repeating fluctuations with an average duration that agrees with the width of the spectrum. The light intensity, averaged over the period, had a nearly Gaussian variation. The intensity in single-mode generation had a similar variation. The pulse duration at half-height was ~180 nsec. Owing to the use of a Faraday cell (to decouple the laser from the cell), one component of the SMBS is observed in the spectrum of the scattered light. The structure of this component duplicates in its details the spectral distribution of the exciting radiation (Figs. 2b and 2c), and the frequency shift ($\approx 4.9 \times 10^2$ cm^{-1}) does not depend on the width of the pump spectrum.

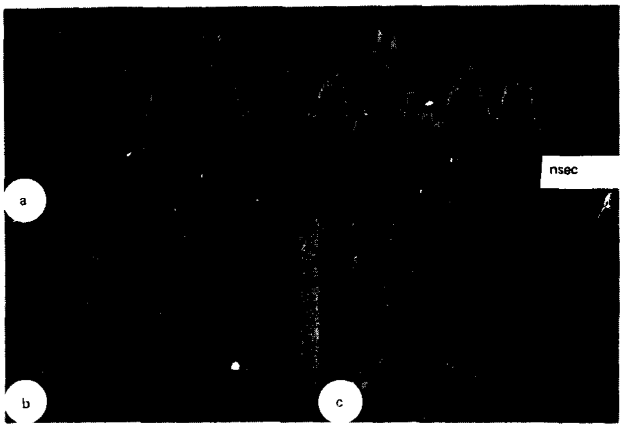

FIG. 2. Characteristics of the exciting and scattered light for broad-band pumping: a- oscillogram of part of the laser pulse; b- spectrograms of the exciting light (top) and of the light scattered in the short cell (bottom), obtained simultaneously with a Fabry-Perot etalon with dispersion 1.667×10^{-1} cm^{-1}; c- analogous spectrograms obtained with an etalon with dispersion 1.085×10^{-2} cm^{-1}, the interval between lines is equal to the distance between the axial modes of the laser (2.17×10^{-3} cm^{-1}).

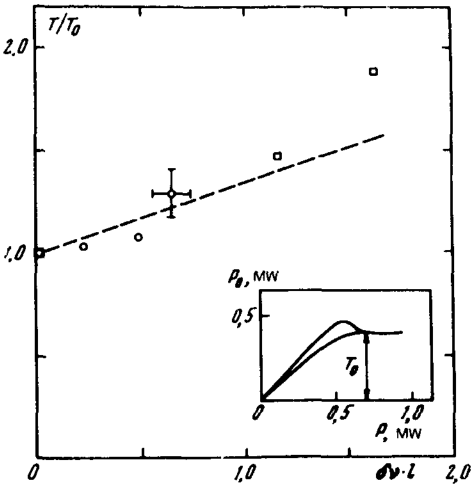

FIG. 3. SMBS threshold vs width of pump spectrum ($\delta\nu$) and length (l) of scattering medium. Circles—experimental results at $l = 24$ cm; squares—at 99 cm. Dashed line—calculation from formula (2). Lower right—experimental oscillogram. Here P is the instantaneous pump power, P_0 is the instantaneous power of the radiation passing through the scattering medium, and T_0 is the threshold power.

The gain in the SMBS is proportional to e^G, where $G = Ig_0l$ in the case of narrow-band excitation. Here I (MW/cm^2) is the pump intensity and l is the interaction length. If the pump intensity exceeds the threshold I_{thr}, with $G(I_{\text{thr}}) \approx 25$, then an appreciable fraction$^{3)}$ of the pump is converted into scattered light, and the intensity of the light passing through the medium becomes stabilized at the indicated threshold level.$^{4)}$ The threshold was determined with the aid of two photocells that registered the power of the exciting radiation at the entrance to and the exit from the cell. The signal from the photocells was fed simultaneously to the horizontal and vertical deflecting system of a cathode-ray tube, and the oscillogram determined the dependence of the instantaneous radiation power passing through the scattering medium on the pump power. After measuring the threshold power (T_0) under narrow-band excitation (Fig. 3). We calculated the threshold intensity $I_{0\,\text{thr}}$ and then found that $G(I_{0\,\text{thr}}) \approx 24$. The measured values of the SMBS threshold at various widths $\delta\nu$ of the pump spectrum and at various interaction lengths l are shown in Fig. 3 as functions of the parameter $\delta\nu l$. This parameter has a simple physical meaning, viz., $\delta\nu(\text{cm}^{-1})\cdot l \equiv l/l_{\text{coh}}$, where l_{coh} is the coherence length of the exciting light.[9] To compare the results with the theory, we consider two cases, $\delta\nu l \ll 1$ and $\delta\nu l \gtrsim 1$.

From the theory developed for the first case ([1], see also[10]), it follows that the SMBS threshold is practically independent of the width of the spectrum. The spectrum of the scattered light has the same shape as the pump spectrum. Our results confirm these conclusions fully. Insofar as we known, this is the first published experimental verification of the indicated SMBS theory.

There is no exact theory for the case $\delta\nu l \gtrsim 1$. There is, however, an estimate of the gain in the case of broad-band pumping.[11] According to this estimate,

$$G(I) = \frac{1}{2} l \Big[g_0 I - 8\delta\nu - 8\delta\nu_0 + \sqrt{(g_0 I - 8\delta\nu - 8\delta\nu_0)^2 + 32\delta\nu_0 g_0 I} \Big]. \tag{1}$$

An analysis of expression (1) shows that G decreases with increasing parameter. Putting $G(I_{\text{thr}}) = 24$ and recognizing that $l \ll (1/\delta\nu_0)$ in our experiments, we obtain from (1)

$$I_{\text{thr}} = \frac{24}{g_0 l}\left(1 + \frac{1}{3}\delta\nu l\right).$$

Hence

$$\frac{I_{\text{thr}}}{I_{0\,\text{thr}}} \equiv \frac{T}{T_0} = 1 + \frac{1}{3}\delta\nu l. \tag{2}$$

The experimental points in Fig. 3 are in satisfactory agreement with (2). We were unable to find published data that could be compared quantitatively with formulas (1) and (2). We note, however, that the difference between the results of[6], where a very low SMBS efficiency was noted, and[12], where this efficiency was high, is apparently due to different values of the parameters l/l_{coh}.

In the case of broad-band excitation of SMBS in the short cell, we compared also the wave fronts of the scattered and exciting light by the procedure used in[13] for narrow-band pumping. The divergence of the laser beam, $\approx 2\times10^{-4}$ rad, was close to the diffraction value. The divergence increased 150 times after passing through lens L_1, the light pipe, and lens L_2. At the same time, the angular distribution of the light scattered in the cell and then passing through the same elements was the same as the distribution of the laser radiation. It follows therefore that the electric field of the scattered wave is the complex-conjugate of the laser field.

Thus, we have established experimentally that the SMBS efficiency is determined by the ratio of the interaction length to the coherence length of the exciting light. If the interaction length is shorter than the coherence length then, in accord with the theory, the SMBS threshold is practically independent of the width of the pump spectrum, and the spectrum and the wave front of the scattered light duplicate the corresponding characteristics of the pump. For larger interaction lengths, there is also agreement between the experiment and the theoretical estimates.

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1) The radiation is considered here to be broad-band if the width of its spectrum exceeds the width $\delta\nu_0$ of the spontaneous-scattering line.

2) $\delta\nu_0 \approx 7\times10^{-4}$ cm^{-1}; the gain is $g_0 \approx 0.094$ cm/MW.[7]

3) This is precisely the threshold that must be overcome to observe stimulated scattering.

4) Experiments with our setup have shown that it is the average light intensity which is stabilized in the case of broad-band pumping.

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Erratum: Stimulated Mandel'shtam-Brillouin scattering excited by radiation with a broad spectrum [JETP Lett. 19, 196 (1974)]

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On p. 197, in the right-hand column, 6th and 7th lines of text should read "($\approx 4.9 \times 10^{-2}$ cm^{-1})," not "($\approx 4.9 \times 10^{2}$ cm^{-1})."