Generation of picosecond pulses of stimulated Raman scattering of light in an external cavity

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The temporal and spectral characteristics of stimulated scattering of light in an external cavity in carbon disulfide is investigated. Generation of trains of solitary picosecond pulses of stimulated Raman scattering is obtained. The pulse repetition period is equal to the time of two passes of the light through the cavity. A possible explanation of the phenomenon is offered.

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I. INTRODUCTION

Following the discovery in 1962 of stimulated Raman scattering (SRS) this phenomenon was thoroughly investigated, and the result was an understanding of its physical nature and realization of many scientific and practical applications. In particular, SRS is being successfully used to control various characteristics of laser radiation.[1] Promising for this purpose is the use of an SRS laser, which comprises an external cavity filled with a medium in which a laser beam excites SRS. Until recently, however, there were no studies in which single picosecond pulses could be shaped with the aid of an SRS laser. As a rule, the duration of the generated pulses was of the same order as the duration of the laser pulse—only a slight shortening of the pulses was observed because of the SRS excitation threshold. Mode locking of the external cavity within the gain band of the first SRS Stokes component, accompanied by generation of trains of nanosecond pulses, could be realized heretofore only by active modulation of the cavity losses.[2] Yet typical values of the SRS gain-band width in Raman active media permit in principle generation of picosecond and even subpicosecond radiation pulses.

We investigate here the temporal and spectral characteristics of SRS in an external cavity in carbon disulfide. We have produced trains of single picosecond pulses spaced by intervals equal to double the time of light passage over the lengths of the cavity. A possible explanation of the observed phenomenon is offered.

2. EXPERIMENTAL SETUP

In our experiments the stimulated emission was excited in an external cavity in carbon disulfide by a giant pulse from a ruby laser. The choice of carbon disulfide as the scattering liquid was governed by the fact that carbon disulfide has a large SRS growth rate $G^{SRS} = 2\times10^{-2}$ cm/MW (Ref. 3). The main parameters of the ruby-laser emission were the following: energy up to 3 J, pulse duration at half maximum 30 nsec, spectral width less than 0.02 cm^{-1} (one longitudinal mode), and divergence 5×10^{-3} rad.

The external resonator was made up of a spherical mirror M_1 of curvature radius 0.5 m and a flat mirror M_2. The mirror reflection coefficients at the wavelengths 0.69 μm were $R_1 = R_2 = 99.8\%$. The optical axis of the external resonator made an angle 90° with the optical axis of the pump laser.

The ruby-laser radiation, polarized in the vertical plane and elongated by a cylindrical lens L_2 along the axis of the outer cavity to the size of the entrance window of the cell C with carbon disulfide, is focused by cylindrical lens L_1 (focal length $f = 6$ cm) into cell C. The generatrix of the cylindrical lens L_2 is perpendicular and that of lens L_1 parallel to the horizontal plane. The scattering plane is specified by the direction of the generatrix of the cylindrical lens L_1 and the direction of the pump wave vector. The cavity axis M_1M_2 was aligned with the focal line of cylindrical lens L_1 by the procedure of Ref. 4.

The scattered radiation spectrum was analyzed with a prism spectrograph and a Fabry Perot interferometer with a free spectral range 1.25 cm^{-1}. The temporal characteristics of the radiation were investigated with the aid of an FÉK-17 coaxial photocell connected to an I2-7 oscilloscope (the system time resolution was not worse than 0.5 nsec), and also with an electron-optical camera EOK-2MR with a time-resolution limit approximately 20 psec.

The temporal characteristics of the SRS radiation were analyzed mainly at the frequency of the second Stokes component of the SRS. The stimulated Brillouin scattering (SBS) radiation as well as that of the first SRS component was cut off with the aid of a stack of three filters, FS-6, FS-7, and

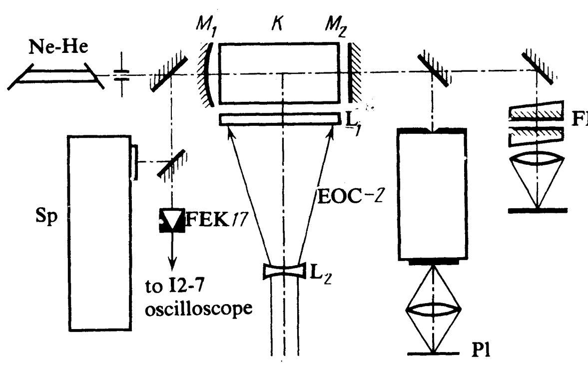

FIG. 1. Experimental setup, K—cell with carbon disulfide, M_1 and M_2—dielectric mirrors, L_1 and L_2—dielectric lenses, FP—Fabry-Perot interferometer, Sp—prism spectrograph, EOC—electron-optical camera.

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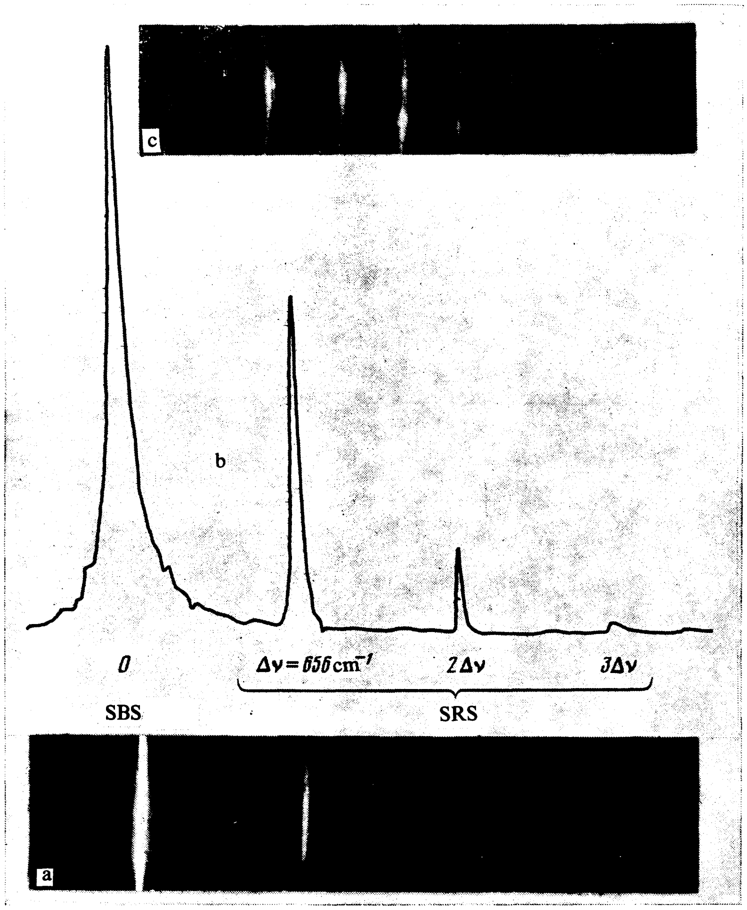

FIG. 2. Scattered-light spectrum obtained with the aid of the prism spectrograph (a) and the corresponding microphotograph of the spectrum (b); c—interference pattern of SBS radiation.

SZS-20. When it was necessary to analyze the SBS radiation, the SRS radiation was cut off with an interference filter.

3. EXPERIMENTAL RESULTS

At a pump energy 0.3 J, intense SBS radiation (first Stokes component) was excited in the cavity and its growth rate in carbon disulfide was larger by an order than the growth rate of the SRS, $G^B = 1.6\times10^{-1}$ cm/W (Ref. 5). Also excited were three Stokes SRS components (Fig. 2). An increase of the pump energy to 0.8 J lead to an increase in the number of excited SBS components to four. The number of the excited SRS components did not change in this case, owing to the great deterioration of the cavity Q (due to a decrease of the reflection coefficients of the mirrors) at the frequency of the fourth SRS component.

The pump pulse had a smooth bell-shaped form (Fig. 3a) but the SRS radiation oscillograms (Fig. 3, b–d) showed a regular spike structure with a period equal to time of two passes of the light along the cavity (3 nsec). At the start of the lasing on the axial period of the time structure of the SRS radiation there were observed one (Fig. 3b) or two (Fig. 3c) single pulses. With further evolution of the lasing, after 10–15 nsec, as well as when the pump energy was increased, the intervals between the spikes increased. In addition, when the energy was raised to 1.2 J, radiation that was not modulated in time appeared and its share increased with increasing pump energy (Fig. 3d). Under the conditions indicated above, at a pump energy 0.3 J, a pulse with a short rise time (less than 1 nsec) appeared on the SBS oscillogram (Fig. 3e). The SBS intensity decreased smoothly past the leading front.

Analysis of the temporal structure of the SRS, carried out with an ÉOK-2MR electron-optical camera, has shown that the temporal structure of the SRS constitutes under our experimental conditions a sequence of single picosecond pulses with a repetition period 3 nsec; the duration of each single pulse did not exceed 50 psec (Fig. 4, a and b). With further evolution of the lasing and with increasing pump energy the number of spikes per axial period increases (Fig. 4c), and this explains the described observed decrease of the intervals between the spikes and the presence of the unmodulated component on the SRS oscillograms (see Fig., 3d). It was observed that with increasing pump, besides the increase in the number of spikes per axial period, a decrease takes place in the duration of each pulse, down to 14 psec (Fig. 5).

It was not our aim to optimize the output energy parameters of the SRS laser. The transmission coefficient of the first SRS Stokes component was 0.6% in our case, and since the exit windows of the cell C (Fig. 1) were not cut at the Brewster angle to the cavity axis, the radiation loss per pass due to parasitic reflections was about 8%, which exceeds by more than one order the fraction of the recorded wave energy. The efficiency of conversion of the pump energy into scattered light was measured when one of the mirrors of the

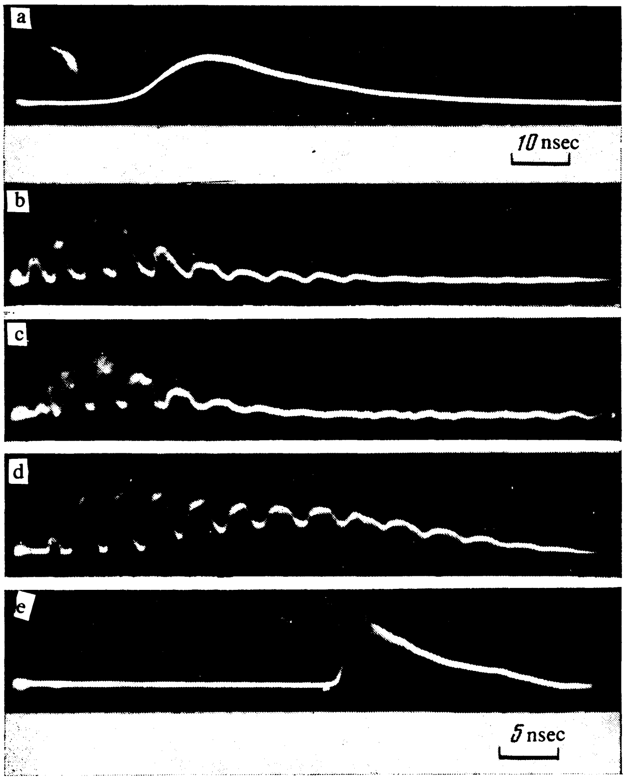

FIG. 3. Oscillograms of the pump radiation (a) as well as of the SRS radiation (b–d) and of the SBS (e) excited in the external cavity.

outer cavity was removed. In this case, at a pump energy 2.8 J, the energy of the scattered light was 0.4 J, corresponding to an approximate conversion efficiency 15%. Obviously, the conversion efficiency in the cavity was substantially higher. However, to assess the efficiency of converison of the pump radiation into short SRS pulses additional optimization of the lasing conditions is necessary.

Besides the spectral and temporal characteristics of the SRS radiation, data were obtained on the beam divergence of the output beam divergence of our SRS laser. It was found that in the vertical plane the SRS beam divergence is 3×10^{-3} rad, which agrees with the diffraction divergence in the vertical plane if it is assumed that the transverse dimension of the region of the nonlinear interaction is $\alpha f = 3\times10^{-3}$ cm, where α is the pump radiation divergence and f is the focal length of the cylindrical lens L. The SRS radiation divergence in the horizontal plane was 6×10^{-3} rad and was substantially larger than the diffraction divergence. This is due to the possibility of exciting a large number of angular modes in the horizontal plane because the region of the nonlinear interaction has in our case a unique profile.

4. CONCLUSION

The generation of picosecond SRS radiation pulses under the experimental conditions indicated above is probably due to the fact that intense SBS radiation is excited in the cavity and it is in the field of this radiation that the short SRS pulses are formed. If it is assumed that the efficiency of pump-radiation conversion into SBS radiation in the cavity is 10%, the gain per pass in the cavity at a pump energy 0.3 J, an SBS pulse radiation 5 psec amounts to exp(30–40) for SRS in an SBS radiation field. As a result of the propagation of so intense an SBS radiation with a steep leading pulse in an SRS-active medium, under conditions of saturation of the SRS gain, formation of a short RS pulse becomes possible, and this in fact takes place in our case.

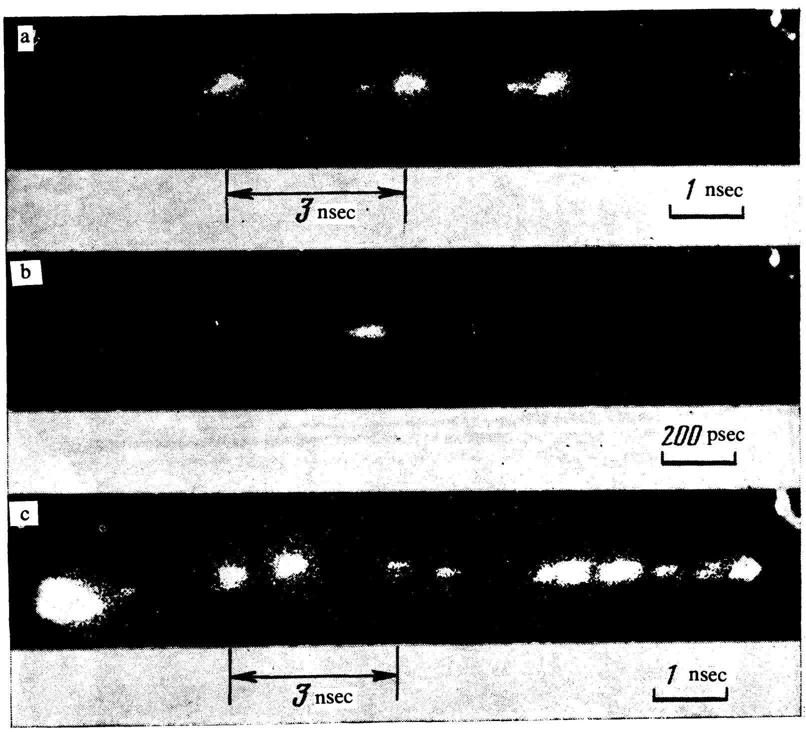

FIG. 4. Time scans of SRS radiation on the EOK-2 camera at pump energies 0.3 J (a, b) and 0.8 J (c).

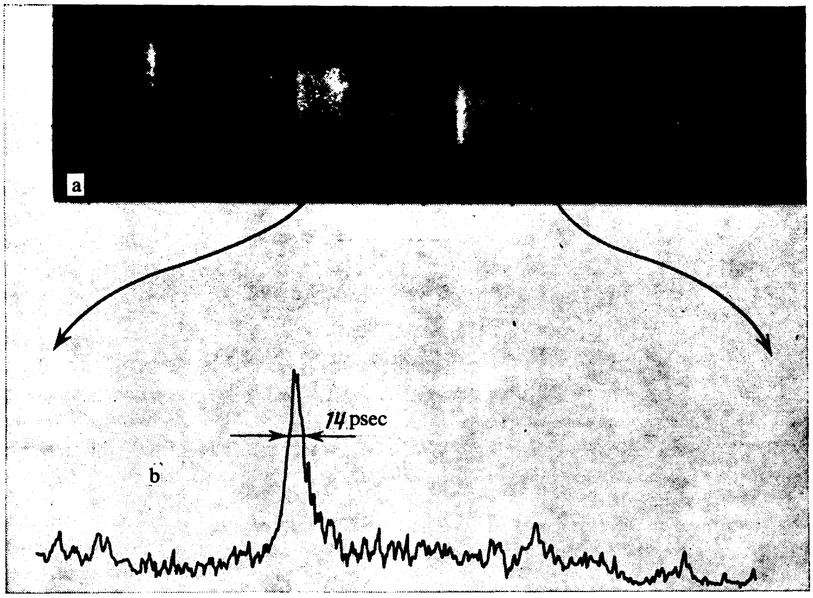

FIG. 5. Time scan of SRS (a) on DEK-2 camera and corresponding photomicrogram (c) obtained at a pump energy 1.5 J.

Favoring such a mechanism of formation of short SRS pulses are the following experimental facts. First, the short pulses appeared in the time scan of the SRS practically immediately, in contrast to generation of short pulses in stimulated scattering of the Rayleigh-line wing light in an external cavity,[7] where continuous radiation was first excited, whose spectrum gradually broadened and shifted in the Stokes direction, and only then did short radiation pulses appear. If the SRS lines observed by us were the result of only the pump radiation, similar temporal dynamics should be expected here, too, but was not observed in experiment. Second, when SBS is suppressed in carbon disulfide in a transversely pumped external cavity,[8] no short pulses were present in the time scan of the SRS radiation.

Thus, SBS excitation plays a decisive role in the cavity mode locking in our experiment.

We note in conclusion that the synchronization of the SRS radiation in an external cavity can be used to produce a discretely tunable picosecond laser.

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