Nonlinear conversion of cw radiation in waveguide lasers under conditions of stimulated light scattering

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A proposal is made and a theoretical analysis is given of a method for nonlinear conversion of cw laser radiation in a periodic sequence of high-power short laser pulses on the basis of stimulated Brillouin (STBS) and stimulated Raman (STRS) scattering of light. A study is made of the dynamics of formation, in a waveguide STBS laser, of a steady-state sequence of giant Stokes radiation pulses which accumulate practically the whole of the monochromatic pump radiation energy stored during a resonator period. The duration of these pulses is an order of magnitude less than the relaxation time of a hypersonic wave. The main relationships governing nonlinear conversion of cw laser radiation are discussed for the case of a two-stage (STBS + STRS) waveguide laser where giant STBS pulses formed in the resonator initiate generation of high-power short STRS pulses. It is shown that the qualitatively different nature of the conversion of cw radiation into pulses in lasers as a result of stimulated scattering of light is governed by the ratio of the gain increments of the Stokes STRS and STBS pulses, and also by the inertia of the process of excitation of a hypersonic vibration wave in a Raman-active medium.

The range of applications of fiber waveguides in nonlinear optics and in quantum electronics is growing continuously. This has been due to the practical solution of such problems as generation of femtosecond pulses, generation of optical solitons, and construction of waveguide lasers.[1,2]

Stimulated Brillouin scattering (STBS) in fiber waveguides is the dominant nonlinear effect in the propagation of nanosecond light pulses in these waveguides. The low STBS threshold of optical fibers, due to the high power densities of the guided radiation and long nonlinear interaction lengths, makes it possible to utilize this effect for the development of new waveguide lasers utilizing stimulated scattering. In a laser of this type the waveguide performs two functions: that of a resonator and of a distributed active medium. There are optical systems for waveguide STBS lasers in which the waveguide is closed either by a ring or placed in an optical resonator.[3–5]

The thresholds of waveguide STBS lasers are extremely low and can amount to just hundreds or even tens of milliwatts.[4,5]

An experimental investigation[3] of a waveguide STBS laser showed that it was possible to generate a steady-state sequence of Stokes pulses when the pump radiation was provided by an argon laser. In fact, the authors of Ref. 3 attempted for the first time to convert cw radiation into pulses in a fiber waveguide of sufficient length placed inside an optical resonator. However, in the experiments of Ref. 3 the operation of a waveguide STBS laser was found to be unstable and an acoustooptic modulator was used to stabilize the sequence of pulses in the optical system of the laser.

The purpose of our investigation will be to analyze the possibility of using waveguide lasers for nonlinear conversion of cw radiation into a periodic sequence of high-power short light pulses.

The basic idea behind each nonlinear conversion of laser radiation is as follows. Let us assume that in the resonator of a waveguide laser there is already a short "priming" Stokes STBS pulse of duration less than the transit time of light across the resonator. The waveguide, which is a distributed STBS active medium, receives continuous pump radiation from an external source. The remarkable properties of single-mode fiber waveguides used as Raman-active media are the constancy of the spatial structure of the beam throughout the length of the nonlinear interaction of a Stokes pulse with the pump radiation and the ability to achieve high gain increments per trip. When a seed STBS pulse travels in such a waveguide under strong amplification (e^{10} or more) conditions, a nonlinear amplification of a Stokes pulse is possible to the extent that each pass through the waveguide in the laser resonator ensures that the Stokes STBS pulse accumulates ("rakes up") all the pump energy delivered in one resonator period. Therefore, in the case of a waveguide laser we can expect formation of a sequence of high-power short Stokes radiation pulses representing giant STBS pulses.

If, moreover, the Q factor of the resonator of a waveguide STBS laser is sufficiently high also at the Stokes frequencies of stimulated Raman scattering (STRS), then the process of formation of giant STBS pulses may be combined with the next stage of conversion into pulses of concurrent Stokes STRS components traveling also opposite to the pump radiation and acquiring energy from it. In this case a giant STBS pulse triggers a waveguide STRS laser and Stokes STRS pulses are additionally compressed and peaked in the process of generation of higher Stokes components of Raman radiation. Therefore, if the two-stage (STBS + STRS) generation regime is realized in the waveguide laser in such a way that giant STBS pulses are genera-

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ted and then they initiate generation of short STRS pulses, we can achieve nonlinear conversion of cw radiation into pulses. Wide spontaneous Raman scattering pulses in glasses could then in principle be used to generate subpicosecond pulses.

We shall report the numerical solution of a system of nonlinear equations expressed in terms of partial derivatives and describing the kinetics of operation of a waveguide laser beginning with seed noise fields in the Stokes part of the spectrum, as well as a detailed analysis, based on this solution, of the process of formation of STBS and STRS pulses as a result of pumping with cw laser radiation. We shall show that limitation of the pedestal of Stokes STBS pulses, which is due to the inertia of the response of a wave of hypersonic vibrations, can result in nonlinear conversion of cw radiation in a waveguide laser into a periodic sequence of high-power short light pulses. The duration of these pulses is an order of magnitude less than the relaxation time of a hypersonic wave and the intensity two orders of magnitude higher than the pump radiation intensity. Numerical experiments will be reported in which a detailed study is made of the two-stage operation of a waveguide (STBS + STRS) laser. We shall determine the range of the main parameters of the laser system which ensure two-stage nonlinear conversion of giant STBS pulses formed in such a laser into pulses of the first Stokes component of STRS. We shall show that the relationships governing the operation of STBS lasers are general and we shall find the conditions for the experimental implementation of such lasers.

§1. FORMULATION OF THE PROBLEM. MODEL AND SYSTEM OF KINETIC EQUATIONS

We shall consider kinetics of the operation of a waveguide STBS laser with a ring resonator. We shall assume that this laser is pumped by cw radiation coupled into the waveguide via one of the resonator windows. We shall also assume that all the components of the optical system of the laser are transparent to the pump radiation. Moreover, we shall assume that only unidirectional waves are excited in the laser and we shall confine our analysis to the most interesting possibility when waves of two types only are excited in the resonator: the first Stokes component of STBS and the first Stokes component of STRS.

The interaction of the radiation field with natural vibrations of the medium (hypersound and a wave of molecular vibrations) will be described by the following system of equations for slowly varying complex amplitudes of the pump waves $E_L(z,t)$ and of the first Stokes components of STBS and STRS, represented by $E_{sB}(z,t)$ and $E_{sR}(z,t)$:

$$\frac{\partial E_L}{\partial z}+\frac{1}{v_L}\frac{\partial E_L}{\partial t}=-g_{MB}^{\text{eff}}\rho E_{sB}-g_R^{\text{eff}}|E_{sR}|^2E_{sB}, \quad (1)$$

$$\frac{\partial E_{\text{sBB}}}{\partial z}-\frac{1}{v_{\text{sB}}}\frac{\partial E_{\text{sB}}}{\partial t}=-g_{sB}^{\text{eff}}\rho^*E_L+g_R^{\text{eff}}|E_{sR}|^2E_{sB}, \quad (2)$$

$$\frac{\partial E_{sR}}{\partial z}-\frac{1}{v_{sR}}\frac{\partial E_{sR}}{\partial t}=-g_R^{\text{eff}}(|E_L|^2+|E_{sB}|^2)E_{sR}, \quad (3)$$

$$\frac{1}{\Gamma}\frac{\partial\rho}{\partial t}+\rho=E_LE_{sB}^*. \quad (4)$$

Here, Eq. (4) describes the behavior of a slowly varying complex amplitude of a hypersonic wave with a characteristic decay time $T_2=1/\Gamma$ (Γ is the half-width of a spontaneous Brillouin scattering line). Within the framework of the system of equations (1)–(4) the interaction of waves with a Raman-active transition is described in the quasistatic approximation. The validity of this approximation is limited to the transverse relaxation time of molecular vibrations T_{2R}. The value of T_{2R} for glasses is of the order of 10^{-13} sec (Ref. 2).

The system of equations (1)–(4) includes the effective STBS and STRS gains in the waveguide g_B^{eff} and g_R^{eff}; the following comments should be made about these values of the gain.

In the derivation of the system (1)–(4) it is assumed that the fields of the waves interacting in the waveguide can be written as follows:

$$E(r_\perp,z,t)=\tfrac{1}{2}\{E_L(z,t)f_L(r_\perp)\exp[i(\beta_Lz-\omega_Lt)]+\text{c.c.}\}$$
$$+\tfrac{1}{2}\{E_{sB}(z,t)f_{sB}(r_\perp)\exp[i(-\beta_{sB}z-\omega_{sB}t)]+\text{c.c}\}$$
$$+\tfrac{1}{2}\{E_{sR}(z,t)f_{sR}(r_\perp)\exp[i(-\beta_{sR}z-\omega_{sR}t)]+\text{c.c.}\}, \quad (5)$$

where $E(z,t)$ is the complex amplitude of the electric field vector in the core of the waveguide; $f(r_\perp)$ is the transverse distribution of the field amplitude of the main guided mode; β is the propagation constant of the mode.

The function $f(r_\perp)$ can be regarded as identical for all three interacting light waves, because the relative frequency shift $\Delta\omega/\omega$ in the case of STBS and STRS is slight (10^{-5} for STBS and 10^{-2} for STRS). For this reason we shall calculate the effective STBS and STRS gains assuming that the ratios of the frequencies ω_{sB}/ω_L and ω_{sR}/ω_L to be equal to unity.

Since the result of scattering into the fundamental mode of the Stokes wave is governed by the projection of the transverse distribution of the pump field on the profile of the transverse distribution of a nonlinear polarization wave, the effective stimulated scattering gain can be described by the following expression:

$$g=g_{\text{STS}}\left[\int f_{\text{nl}}(\bar r_\perp)f_L(\bar r_\perp)f_s(\bar r_\perp)d^2\bar r_\perp\right]\left[\int f_s^2(\bar r_\perp)d^2\bar r_\perp\right]^{-1}. \quad (6)$$

In the case of STRS, we have $f_{\text{nl}}(\bar r_\perp)=f_L(\bar r_\perp)f_{sR}(\bar r_\perp)=f^2(\bar r_\perp)$. The situation is more complex in the case of STBS, because the transverse distribution of hypersound may be influenced by the diffraction of the acoustic wave.

We shall assume that the waveguide is a homogeneous medium for a hypersonic wave. We shall also assume that the following condition is satisfied: $l_{\text{d}}\gtrsim l_{\text{a}}$, where $l_{\text{d}}=qa^2$ is the diffraction length and $l_{\text{a}}=v_{\text{ac}}/\Gamma$ is the damping length of hypersound. Under these assumptions the transverse distribution of a hypersonic wave corresponds to the transverse distribution of a striction force pumping this wave, i.e., $f_{\text{nl}}(\bar r_\perp)=f_L(\bar r_\perp)f_s(\bar r_\perp)$. Consequently, the effective STBS gain is described, as in the case of STRS, by the expression

$$g=g_{\text{STS}}\left[\int f^4(\bar r_\perp)d^2\bar r_\perp\right]\left[\int f^2(\bar r_\perp)d^2\bar r_\perp\right]^{-1}. \quad (7)$$

Hence, in the approximation of a Gaussian mode $g=\tfrac{1}{2}g_{\text{STS}}$, where g_{STS} is the steady-state stimulated scattering gain of a Stokes wave in a homogeneous three-dimensional medium which is not bounded along the transverse coordinate. It should be pointed out that the results obtained in the present study are also qualitatively valid in the case when the hypersound does not satisfy the condition $l_d > l_a$. The system of equations (1)–(4) describes correctly the process of STBS amplifcation of a high-intensity Stokes pulse as long as its duration t_p satisfies the following condition:

$$t_p < l_d / v_{ac} = T_2 l_d / l_a . \quad (8)$$

This inequality means that in the region of interaction between the pump radiation and STBS (governed by the duration of a Stokes pulse) the super sound is not diffracted in the available time and its transverse distribution can change significantly.

The boundary conditions for the pump and Stokes waves in the laser resonator are as follows

$$E_L(z=0, t) = E_{L0},$$
$$E_{sB}(z=l, t) = R^{1/2} E_{sB}(z=0, t-T_D), \quad (9)$$
$$E_{sR}(z=l, t) = R^{1/2} E_{sR}(z=0, t-T_D),$$

where R is the effective reflection coefficient of the resonator mirrors. It should be pointed out that whereas in the discussion of conventional laser systems the boundary conditions are usually specified at the front face or at the boundary of the active medium, in the case of an STBS laser the boundary conditions for the Stokes wave should be specified on the boundary opposite to the point of entry of the pump wave. This makes it necessary to introduce into the boundary conditions of Eq. (9) a characteristic delay time T_D ouside the active medium (fiber waveguide).

The system of equations (1)–(4) with the boundary conditions of Eq. (9) and the initial conditions specified at the moment $t = 0$ (spontaneous noise) describes completely the kinetics of operation of a waveguide laser during the subsequent moment and this is true of the first Stokes frequency of STBS and the Stokes frequency of STRS.

§2. NONLINEAR KINETICS OF OPERATION OF A WAVEGUIDE STIMULATED BRILLOUIN SCATTERING LASER

We shall assume that at the moment $t = 0$ a rectangular pump pulse of infinite duration is applied to the investigated laser resonator. In general, the radiation due to STBS is created from spontaneous noise transmitted along the waveguide. In numerical experiments it is convenient to specify a Stokes of STBS "priming" signal distributed over the length of the waveguide and applied at $t = 0$. In our calculations we used a multimode model of Gaussian noise to simulate spontaneous noise at the Stokes frequency of STBS with a characteristic fluctuation correlation time $\tau_{fl} \approx T_2$.

In the case of self-excitation of STBS it is assumed that the intensity of the Stokes STBS and STRS radiation is equal to the intensity of the spontaneous noise: $I_{sB} \sim I_{sR} \sim (10^{-10}–10^{-12}) I_{L0}$, where I_{L0} is the pump intensity at the entry to the waveguide.

The entry of a long pump pulse with a steep leading edge initiates the linear stage of the generation of radiation at the Stokes frequency of STBS. During the initial (linear) stage when the intensity of STBS pulses is still $I_{sB} \ll I_{L0}$, the spontaneous noise is filtered in a frequency band $\Delta\omega = \Delta\omega(t=0)(g_B |F_{L0}|^2 l)^{-1/2}$ per pass in the resonator and fluctuations of the intensity of the Stokes wave are smoothed out: $\tau_{fl} = \tau_{fl}(t=0)(g_B |E_{L0}|^2 l)^{1/2}$. As the intensity of the STBS radiation grows, the nonlinear regime of saturation of the gain corresponding to $I_{sB} \approx I_{L0}$ begins and a decreasing proportion of the pump radiation penetrates into the waveguide. Consequently, the effective Stokes gain of the radiation per pass depends on time: it is maximal at the leading edge of an STBS pulse and minimal at the trailing edge of this pulse. Preferential amplification of the leading edge of a Stokes pulse has the effect that in the saturation regime when the leading edge of a pump pulse is sufficiently steep, a single Stokes STBS pulse is generated in one resonator period. It should be stressed that this separation of a pulse at the Stokes frequency of STBS is essentially due to the same physical mechanism as the amplitude modulation of the pump radiation and of the reflected Stokes wave with a period equal to twice the transit time in active medium.[6,7] Figure 1 shows a detailed picture of the process of formation of a Stokes pulse in the resonator of an STBS laser when generation begins from the spontaneous noise: the results in

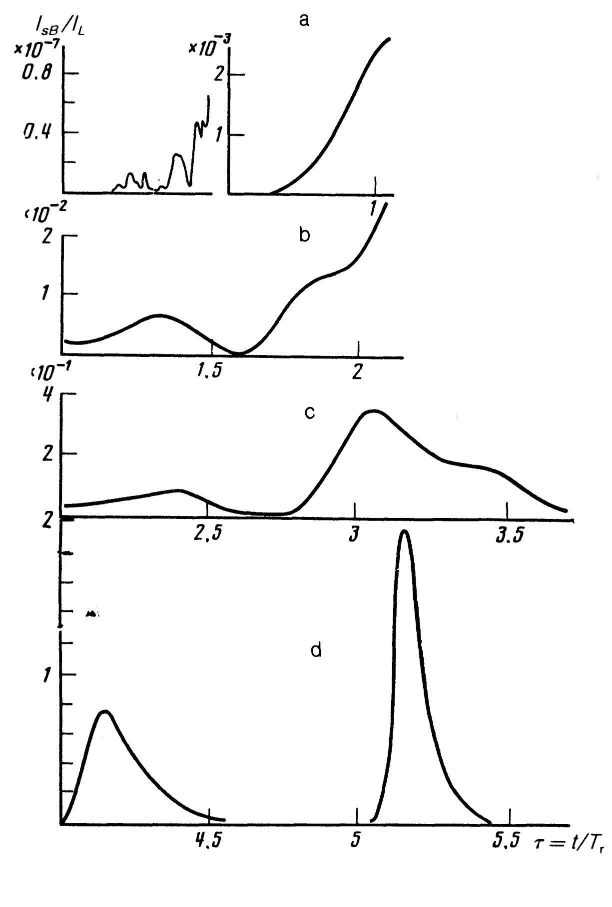

FIG. 1. Process of formation of a single Stokes STBS pulse in a resonator after triggering of the laser by a rectangular pump pulse of infinite duration. The time in the figure is given in resonator periods T_r.

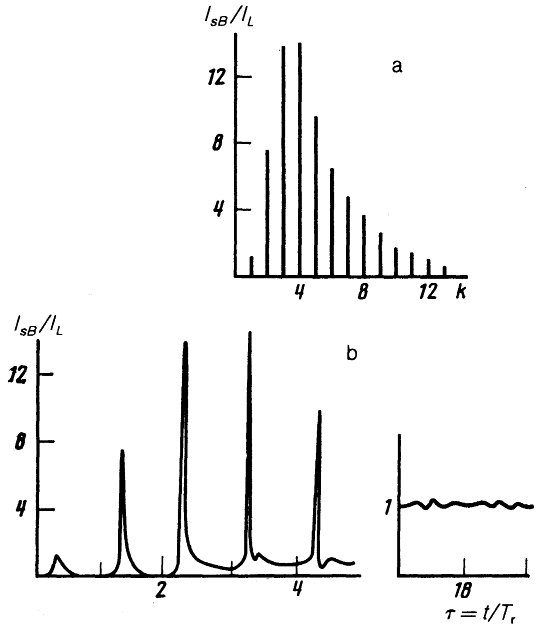

FIG. 2. a) Train of generated pulses (k is the number of passes in the resonator). b) Time dependence of the intensity of STBS radiation (in resonator periods T_r).

this figure were calculated on a computer using the system of equations (1)–(4) and the following values of the principal parameters of the laser: $T_2 = 10$ nsec, $l = 20$ m, $R_{\text{eff}} = 0.5$, $T_r = 200$ nsec, $I_{L0}\, g_B l = 10$. We can see how in the exponential amplification regime the time oscillations of the field are smoothed out at the Stokes frequency (Figs. 1a and 1b); the process of separation of a single Stokes pulse in the gain saturation regime is also demonstrated (Figs. 1c and 1d).

During the first few passes across the resonator the Stokes STBS pulse is amplifed and compressed but it leaves behind a strong hypersonic wave near the front edge of a waveguide and this wave reflects back some of the pump radiation and thus creates an extended trailing edge of the Stokes pulse. This residual hypersonic wave has the effect that an ever decreasing intensity of the pump radiation penetrates the waveguide during each pass through the resonator. Eventually, the strong acoustic wave at the front of the waveguide reflects practically all the pump radiation and this smooths out the structure of the pump radiation pulse emerging from the laser and stabilizes it at the level $I_{sB} = I_{L0}$. The process is shown in detail in Fig. 2. Therefore, a numerical experiment allows us to draw the conclusion that in the case of conversion of cw pump radiation into a steady-state sequence of pulses in a stimulated scattering laser it is necessary to introduce into the resonator some additional device which "truncates" the trailing edge of an STBS pulse. In view of this we have suggested earlier[8] the use of the effect of nonlinear bleaching of a resonantly absorbing medium[9] introduced into the laser resonator. A bleachable filter makes it posssible to limit the pedestal of the Stokes pulses and to achieve generation of a sequence of STBS pulses of duration considerably less than the relaxation time of a hypersonic wave and with an intensity two orders of magnitude higher than the pump intensity. A typical picture of the operation of the proposed waveguide STBS laser is shown in Fig. 3.

We shall now give the parameters of a laser system in which these effects may be observed.

In the numerical experiments the pump wavelength was $\lambda = 1.06\,\mu$, whereas the relaxation time of hypersound T_2 at this wavelength was $T_1 = 1/\Gamma = 10$ nsec. The waveguide length was taken to be $l = 20$ m and the resonator period $T_r = 200$ nsec; the effective reflection coefficient of the mirros was assumed to be $R = 0.5$. A nonlinearly bleachable filter converted the radiation in accordance with the law

$$I_{s1}=I_{s0}\exp\left[-\varkappa_0(1+I_{s0}/I_0)^{-1}\right], \qquad (10)$$

where $\varkappa_0$ is the initial absorption of the filter. The operating threshold of a waveguide STBS laser is found from the following simple expression:

$$I_{L\,\text{th}}=(\varkappa_0-\ln R)/g_B l. \qquad (11)$$

The intensity of cw pump radiation reaching the "input" of an STBS laser is limited by the following condition:

$$I_L g_B l<25. \qquad (12)$$

This means that a Stokes pulse amplified from the spontaneous level noise should not grow to a amplitude comparable

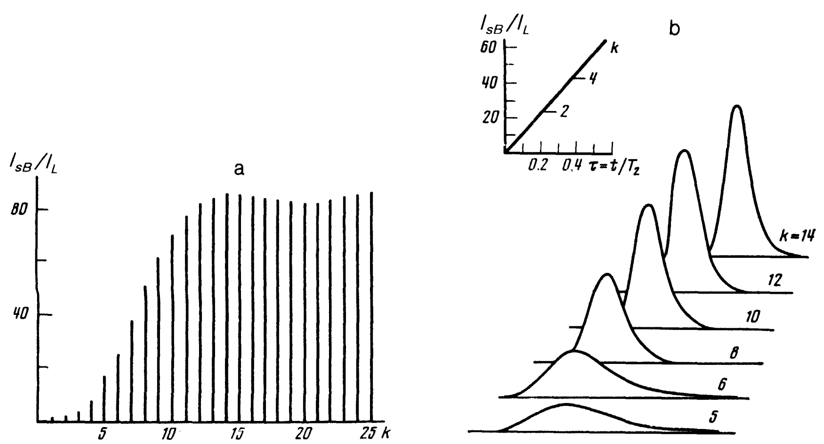

FIG. 3. a) Train of pulses generated in an STBS laser with a nonlinearly bleachable filter. b) Compression and amplification of a Stokes STBS pulse during the development of the process (k is the number of passes in the resonator).

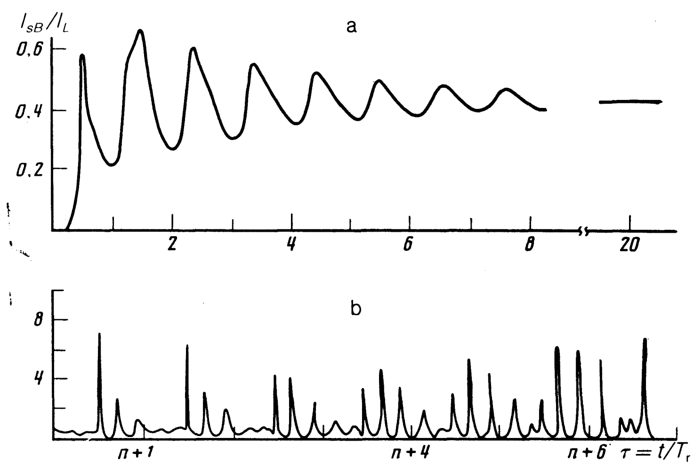

FIG. 4. a) Transient process and stabilization of the intensity of Stokes STBS radiation in the case when $g_B I_L l > 25$ and $\varkappa_0 = 8$. b) Formation of an irregular sequence of Stokes STBS pulses when $g_B I_L l = 10$ and $\varkappa_0 = 4$.

with the pump intensity in one trip across an STBS-active medium. Otherwise ($I_L g_B l > 25$) the operation pattern will be in the form of damped relaxation oscillations and the intensity of the STBS radiation will be established at a constant level (Fig. 4a). It follows that the conditions of Eqs. (11) and (12) limit the initial absorption in the filter $\varkappa_0$. Moreover, if the value of $\varkappa_0$ is sufficiently high, the energy losses of the Stokes radiation in the laser resonator increase considerably and this reduces the efficiency of conversion of the pump energy acquired in one laser resonator period into the energy of a Stokes STBS pulse. When the initial absorption in the filter $\varkappa_0$ is reduced, the nonlinearity of the process of bleaching this filter by the Stokes radiation is insufficient to limit the pedestal of the Stokes STBS pulses. For example, numerical experiments carried out for $\varkappa_0 \leqslant 4$ indicate than an irregular sequence of Stokes pulses with a low radiation contrast (Fig. 4b) is then formed. A steady-state sequence of giant STBS pulses of intensity considerably higher than the pump radiation intensity appears in the range $4 \lesssim \varkappa_0 \lesssim 8$. It should be pointed out that in these calculations the intensity needed to bleach the filter is assumed to be equal to the intensity of the cw pump radiation.

For $\varkappa_0 = 8$ and $I_L g_B l = 10$ ($g_B = 4.5 \times 10^{-9}$ cm/W) the pump intensity is $I_L = 1.13 \cdot 10^6$ W/cm^2, which in the case of an effective area of the waveguide mode $S = 20 \times 10^{-18}$ cm^2 gives the following power of cw laser pump radiation: $P = I_L S = 226$ mW. In numerical experiments the intensity needed for bleaching the filter does not exceed 10^6 W/cm^2, so that we can use widely available filters of the kind employed for the locking of modes in lasers.[9] When the initial absorption of the filter is $\varkappa_0 = 8$, the threshold value of the pump intensity given by Eq. (11) is $I_{L\,\mathrm{th}} = 0.97 \times 10^6$ W/cm^2.

The efficiency of conversion of the energy of the pump radiation into a Stokes wave

$$\eta = \int_0^{T_r} I_s\, dt \Big/ \int_0^{T_r} I_L\, dt$$

is calculated to be up to 75% for the Stokes pulse radiation of 1.5 nsec.

§3. COMPRESSION OF STOKES PULSES IN THE CASE OF TWO-STAGE GENERATION OF STIMULATED RAMAN SCATTERING PULSES IN A WAVEGUIDE STIMULATED-BRILLOUIN-SCATTERING LASER

It follows from our calculations that a waveguide STBS laser is capable of nonlinear conversion of cw pump radiation into a periodic sequence of short giant STBS pulses of duration an order of magnitude less than the relaxation time of hypersound. We can have an experimental situation in which STBS pulses initiate generation of pulses of the first Stokes component of the concurrent STRS and these pulses also propagate opposite to the pump radiation and acquire the energy from this radiation. Such a regime of two-stage conversion of STBS pulses as a result of concurrent STRS may be realized if the following threshold condition for the self-excitation of STRS is satisfield:

$$I_{sB} = -\ln R_R / g_R l, \tag{13}$$

where I_{sB} is the maximum intensity of STBS pulses in a laser resonator and R_R is the effective reflection coefficient of the mirror at the combined generation frequency.

It follows from numerical experiments that the decisive factor that governs the nature of the process of combined generation of STBS and STRS pulses in a stimulated scattering laser is the ratio of the steady-state STRS and STBS gains $\theta = g_R / g_B$.

In the range of low values of the parameter $\theta \leqslant 10^{-2}$ (for glasses, we have $\theta \approx 10^{-2}$–10^{-3}) during the initial stage of generation it is found that short and strong STBS pulses are formed and these then excite STRS. Generation of STRS pulses results in partial suppression of the process of generation of a steady-state sequence of STBS pulses (Fig. 5). In view of the low value of STRS gain ($\theta \ll 1$), the threshold condition (13) is satisfied only near the maximum of the envelope of STBS pulses, which results in compression of STRS pulses during generation at the combined frequency (Fig. 5). It should be stressed also that STRS pulses are formed at the leading edge of a strong STBS pulse. The formation of a short STRS pulse at the leading edge of an STBS pulse and the subsequent detachment from it (Fig. 5) is due to a reduction of the group velocity of STBS pulses in the

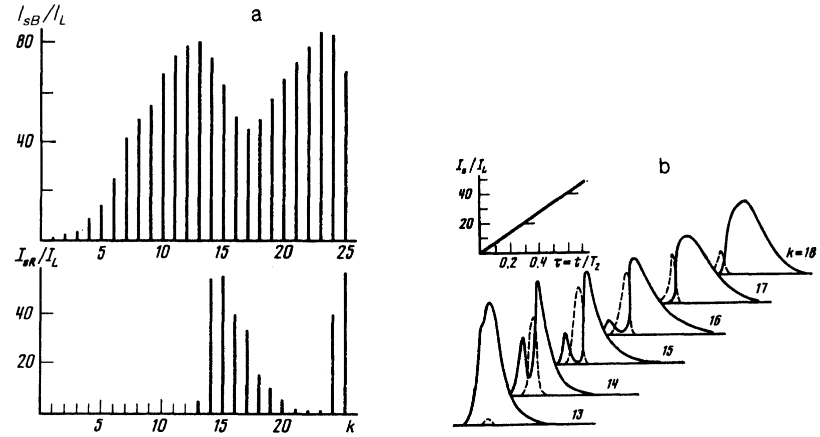

FIG. 5. Trains of STBS and STRS pulses formed for $\theta = 5\times10^{-3}$; $g_B I_L l = 10$, $R = 0.5$. b) Kinetics of two-state conversion of STBS pulses on excitation of concurrent STRS in a waveguide laser.

laser resonator because of the inertia of the excitation of a hypersonic wave (finite width of the STBS gain profile). Moreover, a Stokes STRS pulse becomes detached from the leading edge of an STBS pulse also because in the region of positive dispersion of the group velocity a Stokes STRS pulse overtakes an STBS pulse ($v_{sR} > v_{sB}$ for $k''_{\omega^2} > 0$).

In the case of a strong energy exchange between the waves the intensity of STBS pulses exhibits dips and this results in strong broadening of the spectrum of these pulses with a consequent reduction of the effective gain ($\tau_p^{sB} < T_2$). Therefore, during the next few trips across the resonator the peak intensity of the STBS pulse decreases and its duration increases (Fig. 5). In the course of the further evolution of the generation (when pump radiation is fed continuously to the laser resonator from an external source), the STRS pulses lose some of their energy at the resonator mirrors and the STBS pulses are amplified and compressed, causing generation of a new train of STRS pulses (Fig. 5). This effect—manifested by the formation of pulsating trains of STRS pulses—has been observed in numerical experiments right down to $\theta = g_R/g_B \approx 10^{-2}$.

Therefore, interaction of two coupled STBS and STRS lasers results in a quasiperiodic process of formation of pulsating trains of STRS pulses and partial suppression of the generation of STBS pulses. At low parameters $\theta \sim 10^{-2}$ the high threshold peak intensity of the STBS pulse [Eq. (13)] results in the formation of short and strong STRS pulses. These, however, carry a small fraction of the pump energy delivered during one resonator period. For example, an STRS pulse with the maximum intensity in a train carries 10–15% of the pump energy delivered in one resonator period (Fig. 5).

A numerical experiment makes it possible to study in detail the role of the parameter θ in the process of nonlinear conversion of radiation in the two-stage laser under discussion.

Figure 6 shows the evolution of the operation of a two-stage (STBS + STRS) laser when the ratio of the gains is $\theta = 10^{-1}$. For this ratio of the STBS and STRS gains, the condition (13) imposed on the threshold of STRS-pulse generation is less stringent. Therefore, STRS pulses suppress generation of STBS pulses before the latter reach their maximum values governed by the gain per pass, by the losses in the resonator, and by the line width 2Γ. Consequently, the resultant STRS pulses have a lower intensity and greater duration compared with the case when $\theta = 5\times10^{-3}$ (com-

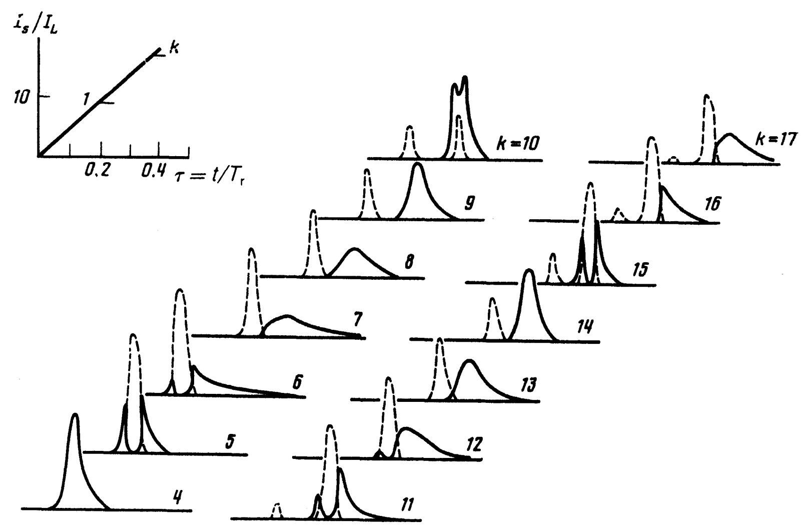

FIG. 6. Kinetics of operation of a two-stage (STBS + STRS) laser when $\theta = 10^{-1}$.

pare Figs. 5 and 6). Then, an STRS pulse with the maximum intensity converts at 50% of the pump energy delivered during one resonator period. It should be pointed out that as a Stokes STRS pulse becomes detached from the leading edge of an STBS pulse and "suppresses" the latter, new STRS pulses appear at the resonator mirrors during one resonator period and the contrast of the output pattern decreases. Figure 6 shows the process of formation of additional STRS pulses in one resonator period for $\theta = 0.1$. The first STRS pulse "burns out" a Stokes STBS pulse and then loses its energy at the resonator mirrors. In view of the inertia of the response of a wave of hypersonic vibrations, a new STBS pulse appears with a time shift relative to the preceding pulse. Therefore, the next STRS pulse is formed later during the resonator period (Fig. 6). In the interval shown in Fig. 6 such a process of the appearance of additional STRS pulses in one resonator period is repeated twice.

When the gains g_B and g_R are comparable, the competition between the STBS and STRS amplification processes in the active medium of the laser results in the formation of single high-power STRS pulses. According to the proposed mode, STRS pulses are compressed in duration until the limits of validity of the system of equations (1)–(4) are no longer obeyed. A correct estimate of the duration of the pulses formed in this way would require solution of the problem allowing for the finite relaxation time of a wave of molecular vibrations. Such a situation may occur, for example, in compressed gases.[10]

CONCLUSIONS

Formation of single short Stokes radiation pulses in one resonator period of a Brillouin laser on excitation with an external monochromatic beam represents, in the spectral language, the establishment of certain phase relationships between the adjacent resonator modes representing mode self-locking in the resonator. As shown by Lugov and Strel'tsov in Ref. 11, when a large number of Stokes components of STBS is excited in an optical resonator in the presence of a nonlinear absorber, a strong parametric interaction appears between the STBS components and results in locking of the resonator modes and generation of short pulses of duration governed by the number of the output Stokes STBS pulses $\tau_p \sim T/N$ with a period $T = 2\pi/\Omega_B$, where Ω_B is the Brillouin frequency shift. This method of generation of ultrashort pulses was put into practice in Ref. 12. As shown above, the mechanism of formation of short STBS and STRS pulses in a waveguide laser is of fundamentally different physical nature.

Fabelinskiĭ *et al.*[13] were the first to detect experimentally generation of trains of single picosecond STRS pulses on excitation of stimulated scattering in an external resonator in carbon disulfide by giant pulses from a single-mode ruby laser. In spite of the fact that the experimental setup used in Ref. 13 differed considerably from our stimulated scattering laser model, the results of the present paper can nevertheless account qualitatively for the effects reported in Ref. 13. For example, the postulated physical mechanism of the generation of picosecond STRS pulses in the field of a strong STBS pulse proposed by us should indeed be active under the experimental conditions of Ref. 13. The parameter is $\theta = g_R/g_B \approx 0.1$ for carbon disulfide, so that the mechanism of two-stage generation of STRS pulses in the field of a triggering STBS pulse should be efficient (Fig. 6). At the leading edge of an STBS pulse during the development stage a Stokes STRS pulse is formed. The latter pulse utilizes the pump energy per trip and induces generation of higher Stokes components. A reduction in the off-duty factor of the time spike structure in the course of operation of such a system and an increase in the fraction of radiation unmodulated in time on increase in the pump energy, observed in Ref. 13, are clearly due to inertia of the nonlinear response of the medium (Fig. 2).

It therefore follows that the results of the published experiments confirm qualitatively the ideas put forward in the present paper on the main physical mechanisms of operation of a two-stage stimulated scattering laser. In the experimental realization of the proposed method of nonlinear conversion of cw laser radiation into a periodic sequence of high-power short light pulses, the most promising is an optical system of a stimulated scattering laser in which waveguide propagation of radiation in a Raman-active medium is used. This makes it possible to avoid the competition between stimulated scattering and self-focusing effects in the active medium of a laser.

It should also be pointed out that strong compression of light pulses in gases was reported in Ref. 10 and it was due to a similar two-stage (STBS + STRS) process.

Moreover, detection of STBS in fiber waveguides operating in the middle infrared range[14] suggest that the proposed method could be used for intracavity conversion of cw CO_2 laser radiation.

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