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Experimental investigation of the feasibility of application of the wavefront reversal phenomenon in stimulated Mandel'shtam-Brillouin scattering

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The possibilities of applying stimulated Mandel'shtam-Brillouin scattering (SMBS) to laser-mediated thermonuclear fusion problems and, in particular, to the decoupling of amplifier stages, shaping of pulse profiles, etc., are considered. The stimulated Mandel'shtam-Brillouin scattering is obtained experimentally under nonstationary conditions by exciting the system with radiation from a photodissociation iodine laser. A stationary scattering regime is also attained with a pump pulse of 5–10 μsec duration. Under these conditions, the operation of an amplifier with a SMBS mirror is studied experimentally in the case of weak input signals ($I_{in} \sim 10^{-3}$ W/cm^2) and a gain per pass of $\sim 10^6$ is attained. Particular attention is paid to the quantitative determination of the characteristics of the degree of pump-beam reproducibility and of the compensation of the optical inhomogeneities of the laser medium, and also to the clarification of the conditions under which they are observed. The range of pump intensities in which complete reproduction of the angular spectrum is observed is found experimentally. The dependence of the compensation accuracy on the degree of reproduction of the angular spectrum is obtained.

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INTRODUCTION

In recent years there has been an ever broadening interest in the phenomenon of wave front reversal in nonlinear processes. High directivity of the scattered radiation was apparently first observed in Refs. 1–3 for stimulated Mandel'shtam Brillouin scattering (SMBS) and in Refs. 4 and 5 for stimulated Raman scattering (SRS). However, only publication of Ref. 6 has made it clear that the field of the scattered radiation is, under certain circumstances, the complex conjugate of the pump field, and that this effect can be used for the compensation of phase distortions of laser emission. In particular, this phenomenon was used in Ref. 7 for compensation of optical inhomogeneities in a ruby amplifier. The publication of these works stimulated theoretical and experimental investigations of the phenomenon of wave front reversal and consideration of the feasibility of its application (see, for example, Refs. 8–20).

The present work is devoted to the study of the possibility of application of this phenomenon to the excitation of SMBS by the emission of photodissociation lasers (PL), which have been developed[21-24] along with others for the solution of laser-mediated thermonuclear fusion (LTF) problems. The experimental investigations were conducted principally in a stationary scattering regime, in which the pulse length of the laser radiation was significantly greater than the lifetime of the acoustical phonons. In this regime, the phenomenon of wave front reversal should be accomplished in the purest form. Special attention was paid to the experimental investigation of the quantitative characteristics of the degree of reproducibility and of the compensation, and the limiting conditions under which they are observed were determined. The results are of interest not only in LTF but also for problems of optical communication[14] and the acceleration of macro- and micro-bodies.[25-29]

1. SOME POSSIBILITIES OF THE APPLICATION OF SMBS TO THE PROBLEM OF LTF

As is known, elements of interstage decoupling and a system of decoupling of the output stages from the target are necessary in LTF systems.

For these purposes, it is expedient to consider, in addition to Kerr and Faraday shutters and phototropic shutters, also shutters that operate on stimulated scattering (SMBS or SRS). Figure 1 shows one of the possible schemes of decoupling amplifiers from a target with the use of SMBS. The radiation of the amplifier by means of a beam-splitting mirror ($R \approx 0.5$) is fed to two SMBS cells. The reflected Stokes radiation is focused on the target. Under conditions in which the spontaneous radia-

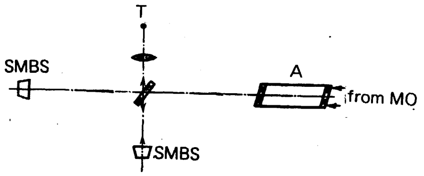

FIG. 1. Scheme of decoupling the amplifier from the target.

tion of the amplifier stages does not exceed the SMBS threshold, the amplifier turns out to be completely decoupled from the target.

It is essential that a contraction of the length and an increase in the curvature of the front of the laser pulse take place in the SMBS process.[30] From this viewpoint, it is expedient to use the system of interstage decoupling shown in Fig. 2. In this scheme, the radiation of the amplifier A_1 is fed to the SMBS cell by means of the beam-splitting mirror and then to the amplifier A_2[1)] and amplified in it.

It should be noted that, in the given system, partial compensation of phase distortions of the beam acquired in the amplifier A_1 can occur in amplifier A_2 if the optical inhomogeneities in them are sufficiently similar.

Such systems, as also the system from Ref. 18, are suitable for irradiation of targets of the "ball and disk" type[31] and a conical target.[32] For symmetrical compression of a spherical target[33] the system shown in Fig. 3 is effective. Power amplifiers, SMBS mirrors and master oscillators are placed radially around the target.[2)] The radiation of the master oscillator (MO) passes through the SMBS cell (which is not excited by it) and through the amplifier and its incident on the target T. The radiation scattered by the target, after passing through the amplifier, passes through the focusing system into the cell and excites the SMBS. The reflected Stokes signal is fed again to the amplifier and causes the energy stored in it to be radiated to the target.[18]

An important circumstance having a significant effect on the efficiency of operation of the systems described above (as also on the system of Refs. 7 and 18), is the limitation on the Stokes shift in the SMBS—it should be much less than the width of the gain line of the active medium of the amplifier (this does not apply to the system of Fig. 1). For an iodine laser, this requirement is essential, since its active medium has a comparatively narrow gain band ($\Delta\nu \sim 0.1$ cm^{-1} at $P \sim 1$ atm).[34,24] Therefore as active media for the SMBS in this case, it is best to use compressed gases with small sound velocities and, as a consequence, with small Stokes shifts (for example, $\Delta\nu_s \approx 0.0075$ cm^{-1} in xenon at $P \approx 50$ atm

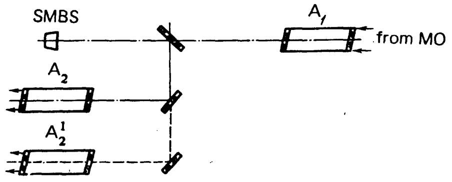

FIG. 2. Scheme of interstage decoupling of amplifiers.

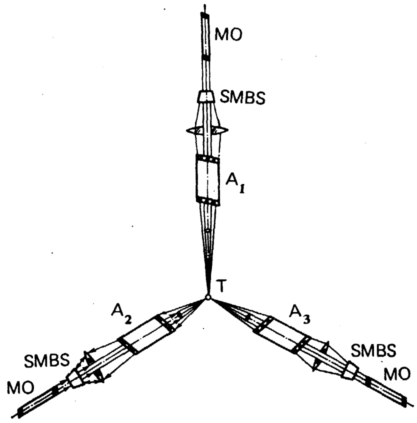

FIG. 3. Scheme of symmetric compression of a target by laser radiation.

and $\lambda \approx 1315\mu$, Ref. 35).

The first experiments on the excitation of SMBS in compressed xenon pumped by a P L operating in a single-pulse regime ($\tau_{gen} = 20-40$ nsec, $E_{gen} = 1-8$ J) $\Delta\nu_{gen} \approx (3-4)10^{-3}$ cm^{-1}, showed (see Table I, where typical results are shown), that the energy reflection coefficient of SMBS amounted to $R_E \approx 4-8\%$ only at an intensity of the pump in the focal plane $I_p \gtrsim 6$ GW/cm^2 in the case of sharp focusing and $I_p \gtrsim 0.06$ GW/cm^2 in a waveguide. In this case, the efficiency of the scattering depends significantly on the transparency of the gas in the SMBS cell (on the presence of and optical breakdown in the gas). In the experiments that have been carried out, the scattering regime is nonstationary, since the lifetime of the acoustical phonons in xenon compressed to 50 atm at $\lambda = 1.3\mu$ amounts to 65 nsec, which is significantly greater than the duration of the pump pulse $\tau_p \approx 20-40$ nsec.

To determine the physical laws and the conditions under which reproducibility and compensation are observed, it is necessary to bring about scattering in a stationary regime, in which reversal of the wave front is manifest in purest form. As shown in Ref. 36, to achieve a stationary regime, pump pulses are needed with a length 20–30 times greater than the lifetime of the phonons.

2. EXPERIMENTS OF EXCITATION OF SMBS IN A STATIONARY REGIME

The possibility of obtaining SMBS in a stationary regime was investigated with a photodissociation iodine laser with pulse duration $\tau_p \approx 5-10$ μsec, output energy $E_p \approx 100$ J, divergence $\theta_p \approx 3 \times 10^{-3}$ rad, and $\Delta\nu_p \approx 0.02-0.03$ cm^{-1}. The pump radiation was focused by a spherical lens into a cell with compressed gas. The scattering efficiency was studied in Xe, N_2 and SF_6. Typical experimental conditions and results are given in Table II and in Fig. 4.

It is seen from the experimental results that the largest power reflection coefficient of the SMBS mirror is obtained in nitrogen, $R_w \approx 45\%$. The maximum intensity in the cell reached $I_p \sim 1$ GW/cm^2, and no breakdown of

TABLE I.

I_p, MW/cm²	τ_p, nanosec	R_E, %	Transparency, %	Presence of breakdown of the gas in the SMBS cell	I_p, MW/cm²	τ_p, nanosec	R_E, %	Transparency, %	Presence of breakdown of the gas in the SMBS cell
$2\cdot10^4$	40	6	30	yes	$5\cdot10^3$	40	3	40	yes
$8\cdot10^3$	20	8	83	no	$3\cdot10^3$	20	0	95	no
$7.5\cdot10^3$	20	5	70	no	$2.6\cdot10^2$ *	40	2	20	yes
$7.5\cdot10^3$	20	0	40	yes	$6\cdot10^1$ *	40	5	70	no
$6\cdot10^3$	20	4	83	no					

*The experiments were carried out in the presence of a waveguide in the cell.

the medium was observed. The reflector coefficient in xenon did not exceed 20%, inasmuch as advanced optical breakdown occurred in the xenon already at $I_p = 170$ MW/cm².

In experiments with SF_6, we succeeded in obtaining $R_w \approx 35\%$ at 1 GW/cm² (no breakdown occurred). The advantages of this medium are the possibility of obtaining efficient scattering at a comparatively low pressure ($P_{SF_6} \approx 15$ atm, $P_{N_2} \approx 70$ atm) and the small Stokes shift (approximately one third the value in nitrogen).

The results given above were obtained under conditions in which the excitation of the SMBS took place by means of an oscillator having a reflection coefficient of the output mirror $R \approx 10-20\%$. Here, as is seen in Fig. 4, the pulse of scattered radiation had a smooth shape and a duration close to that of the pump.

A calculation-theoretical investigation of the dynamics of generation in such systems, carried out within the framework of a one-dimensional many-particle model, and taking into account the spectral dependence of the amplification cross section of the active laser medium and the Stokes shift in reflection from the SMBS mirror, showed that in the case of a weak effect of the SMBS mirror the generation takes place without spikes at a frequency corresponding to the maximum of the gain line.

The next set of experiments was conducted during operation of the laser in the amplification mode according to the scheme of Fig. 5a. In this case, when there were no cells with the scattering medium, the pulse of the output radiation of the amplifier has a smooth shape (Fig. 5b). Upon excitation of SMBS in xenon (pressure 50 atm) the operating regime of the laser changed considerably (Fig. 5c): the system began to operate as a unit and went into a lasing mode generating trains of short pulses.[3)] Each train consisted of 3–4 pulses as a rule, with length 20–40 nanosec; the time interval between these was equal to the time of two passes of the light over the distance between the total-reflection mirror of the MO and the SMBS mirror. Here, as spectral measurements have shown, the number of Stokes components of successive SMBS corresponds to the number of pulses in the train (Fig. 5d). The number of trains decreased upon decrease in the intensity of the exciting radiation.

The radiation power in the spikes exceeded by a factor of 3–4 the level of power in the free generation mode; the total energy at the output of the amplifier hardly differed from the output energy of free generation, and the reflection coefficient of the SMBS mirror reached 20–30%.

Calculations have shown that in the case of strong feedback from the PL to the SMBS mirror, the generation bears a clearly expressed non-stationary character. The bulk of the energy is emitted, as in the experiments, in the form of a sequence of narrow pulses with the interval between them equal to the time of passage of twice the length of the system (see Fig. 5e, where the results of the calculations are plotted). Consequently, the scattering regime turns out to be nonstationary under these conditions.

A similar transition to a nonstationary regime of operation was also observed in the scheme represented in Fig. 6a,[4)] which does not differ from those described above and essentially simulates the schemes of Refs. 18 and 40. In the experiments, the intensity of the signal scattered by the target at the input of the amplifier varied in the range $I_{in} \approx 0.1-0.003$ W/cm², which is about 10^6-10^8 times smaller than the saturation intensity.

TABLE II.

Medium	P, atm	g, cm/MW	I_p, MW/cm²	Coefficient of reflection, %	Shift $\Delta\nu_s$, cm⁻¹
Xe	53	0.06	40	9	0.007
Xe	43	0.05	170	21	
N_2	70	0.017	525	20	0.018
N_2	70		1060	45	
SF_6	17.5	0.028	1000	36	0.006
SF_6	15.5	0.025	700	22	

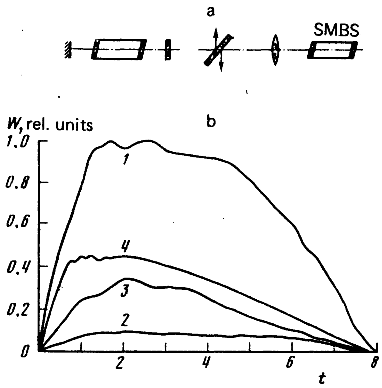

FIG. 4. Results of experiments on the excitation of SMBS by PL radiation, operating in the regime of free oscillation: 2) diagram of setup; b) oscillograms of the pulses; 1—PL pulse, 2—scattered radiation in Xe, 3—scattered radiation in SF_6, 4—scattered radiation in N_2; t in microseconds.

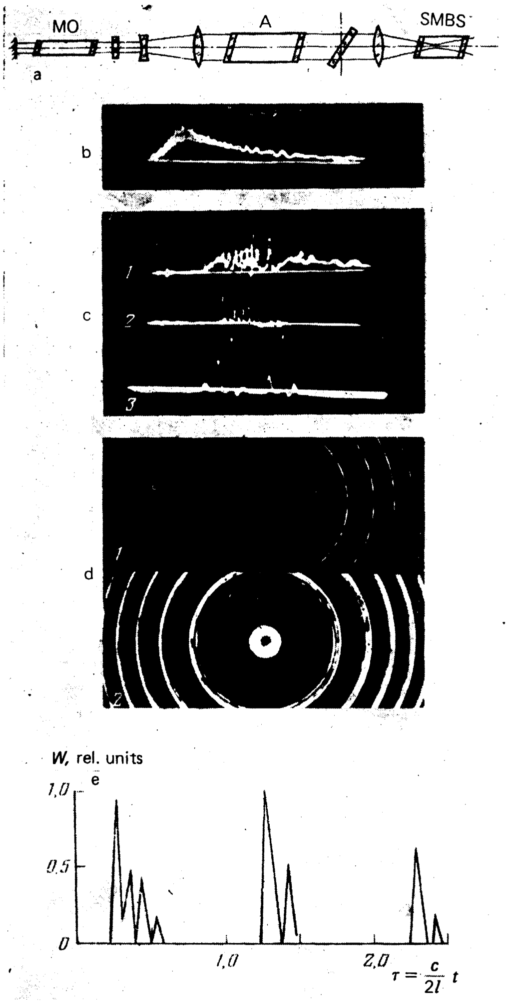

FIG. 5. Results of experiments on the excitation of SMBS by radiation of a photodissociation amplifier; a) diagram of setup; b) pulse of the amplifier in the absence of SMBS; c) radiation pulse under SMBS excitation; 1—amplifier pulse, 2—SMBS pulse, 3—scan of an individual train of radiation pulses; d) spectrograms of radiation of the amplifier free spectral range of the Fabry-Perot etalon $\Delta\nu = 0.05$ cm^{-1}): 1—in the absence of SMBS, 2—under SMBS excitation; e) calculated pulse of the amplifier under SMBS excitation.

The efficiency of operation of the system was investigated in different regimes. Typical oscillograms of the radiation pulse show (Fig. 6b) that powerful spikes of radiation of the amplifier are superposed on the smooth envelope of the radiation pulse of the oscillator. The period between these spikes was determined in our case by the rate of growth of inversion in the amplifier. The radiation pulse exciting the SMBS also has a spiked structure correlating with the structure of the spikes at the target (Fig. 6c). This indicates establishment of a coupling between the SMBS mirror and the target. A self-maintained operating regime sets in upon appearance of this coupling. It exists also in the case in which the pulse length from the oscillator is less than the time of existence of inversion in the amplifier.

Experimental investigation of the self-maintained regime showed that the coefficient of energy transfer to the

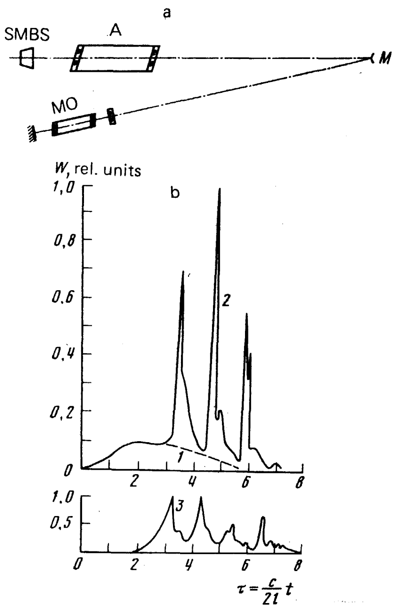

FIG. 6. Results of experiments in the case of weak input signal of the amplifier; a) diagram of setup; b) oscillograms of the MO (1) and amplifier (2) pulses; c) oscillogram of the pulse of radiation exciting the SMBS.

target, i.e., the ratio of the energy at the target to the output energy of the amplifier, turned out in both cases to be the same and to amount to $\frac{3}{4}-\frac{1}{3}$ in the investigated range of intensities of the input signal to the amplifier. We call attention to the fact that the radiation pulses of the amplifier were observed in the experiments also after the end of the operation of the master oscillator (Fig. 6b).

In individual spikes, the coefficient of energy transfer turned out to be close to unity. This indicates that under certain conditions the degree of reversal of the wavefront and of the compensation of aberrations by means of SMBS as rather high.

Thus the investigations that were carried out showed the possibility of obtaining a stationary scattering regime only in the absence of strong feedback from the laser to the SMBS mirror. In this case, the efficiency of the scattering reached ~40%, which enabled us (see below) to carry out a quantitative investigation of the degree of reproducibility and of dynamic compensation in the SMBS process.

3. EXPERIMENTAL DETERMINATION OF THE ACCURACY OF REPRODUCIBILITY OF THE WAVEFRONT IN THE SMBS PROCESS

An important circumstance, having a significant effect on the efficiency of operation of the apparatus described, is the degree of reproducibility of the wavefront of the radiation and of the compensation of the phase distortions of the beam in SMBS.

The results are given below of the study of the quantitative characteristics of the degree of reproducibility of the wavefront in SMBS excitation in nitrogen compressed to ~70 atm by PL radiation with nonresonant feedback and an angular selector.[39] The laser operated in an essentially multimode regime (the number of transverse modes $m \gtrsim 10$). The divergence of the radiation varied in the range ~$(2-10)\times10^{-4}$ rad. The accuracy of reproducibility was determined from a comparison of the angular distribution of the energy and the intensity of the radiation of the pump and the SMBS.[5)] For a control of the accuracy of the wavefront reversal of the radiation, we placed on the end face of the PL a nonsymmetric mask whose non-inverted image in the scattered radiation could be obtained only in the presence of reversal of the wavefront (see, for example, Ref. 41).

The intensity distributions of the radiation of the pump and the SMBS in the "near" and "far" fields, obtained in the case of focusing of the radiation in the cell by means of a spherical lens, are shown in Fig. 7. It is seen that the scattered radiation forms a sufficiently sharp, real image of the end of the PL with the mask placed on it. This means that the front of the reflected SMBS radiation when focused by the spherical lens (without use of a phase plate and waveguide) is reversed relative to the incident wave.

However, the angle spectrum of the pump radiation is far from completely reproduced (Fig. 7b)—the divergence of the SMBS radiation is approximately half the divergence of the pump radiation (a similar effect was also observed in Ref. 3).

The interpretation of the narrowing in the case of a focused single-model beam is given in Ref. 10. By analogy with Ref. 10, we can give the following qualitative explanation of this effect for a multimode beam (see also Ref. 13). The Stokes radiation, in the case of sharp focusing, is mainly amplified in the immediate vicinity of the focus. The intensity of the pump in the focal plane is maximal on the axis and falls off toward the periphery, and the wings of this distribution are produced predominantly by the modes of high order. The amplification coefficient of the Stokes modes of low order turns out to be higher, since they are localized near the optic axis, where the pump is more intense.

In order that the angular spectra of the SMBS and the pump coincide, it is necessary to use such an input system in which equalization of amplification in the SMBS medium takes place for all components of the angular spectrum. An optical waveguide is usually used for these purposes.[35] As our experiments have shown, an analogous effect is obtained with the help of a two-lens input system, constructed in such fashion that the equivalent focus of it is located in the SMBS cell behind the plane of the image of the end face of the PL (Fig. 8a).[6)]

In the case of a two-lens input system, reversal of the wavefront is also observed in the experiments, and the intensity distribution of the radiation was reproduced under certain conditions in both the near and the far zones. In separate experiments, artificial asymmetry of the directivity diagram of the FL radiation was used as a check on the reversal of the wavefront. In this case, the reversal of the wavefront should appear in the turning of the image of the far-zone SMBS radiation "from bottom to top" and "from right to left" relative to the image of the far-field radiation of the pump. It is seen from Fig. 8b that the angular distributions of the pump and SMBS radiation are practically identical; here the far-field radiation of the SMBS turned out to be inverted. The angular distribution are reproduced not only in intensity but also in energy—the difference in the angular distributions of the energy of the SMBS and pump radiations did not exceed the accuracy of the measurements—10–15%.

Under these same conditions (a "two-lens" system of input of the radiation), the degree of reproducibility of the angular spectrum as a function of the pump intensity was investigated. The results of the investigations are shown in Fig. 9.

At a pump intensity of $I_p \approx 400-800$ MW/cm^2, which significantly exceeds the threshold in the case of SMBS ($I_{\rm thres}$ ~200 MW/cm^2), practically complete reproducibility of the angular spectrum is observed, both in the intensity and in the energy of the radiation. Upon increase in the pump intensity in the focal plane of the input system, above some threshold level ($I_p > 800$ MW/cm^2), a decrease is observed in the intensity at the center of the spot of the far-field of the scattered radiation, although the intensity at the center of the spot in the PL radiation is a maximum.[7)] Here, as energy measurements have

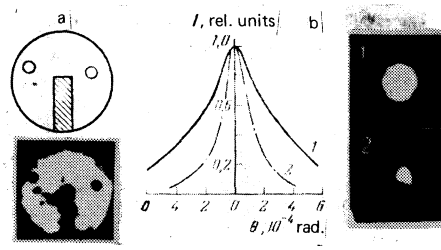

FIG. 7. Results of experiments on the reproducibility of the wave front by the SMBS mirror for sharp focusing of the pump radiation: a) mask on the end face of the PL and its image in the scattered radiation; b) dimensions of the spots and the intensity distributions of the exciting (1) and scattered (2) radiation at the focus of the lens.

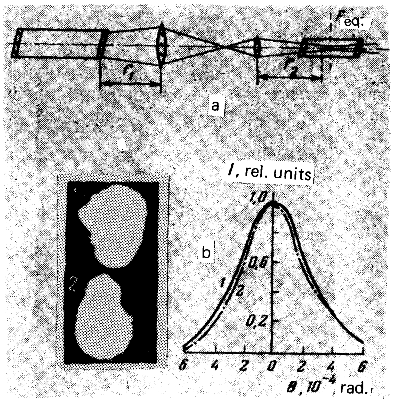

FIG. 8. Results of experiments on the reproducibility of the wave front by the SMBS mirror in the case of a two-lens input of the pump radiation: a) scheme for the input of the pump radiation into the medium active for SMBS; b) sizes of the spots and intensity distributions of the exciting (1) and scattered (2) radiations at the focus of the lens.

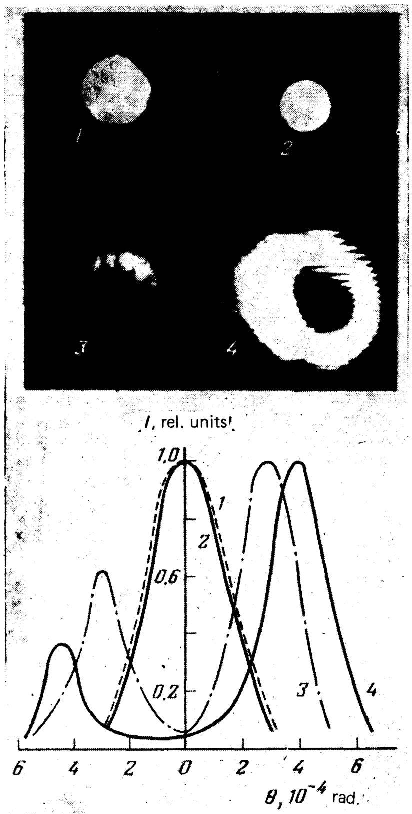

FIG. 9. Intensity distributions of the MO and SMBS radiation at different pump intensities; 1—far-field radiation of the MO; 2, 3, 4–far-field of the scattered radiation at pump intensities of 770, 1000 and 2000 MW/cm^2, respectively.

shown, the angle at which ~90% of the energy is propagated remains practically the same for FL and SMBS radiation, although the character of the angular distribution is notably different.

The experimental data that have been obtained can be explained qualitatively if we the spatial structure of the pump radiation in the cell with the scattering medium, is taken into account in the geometric-optics approximation (Fig. 10). The intensity distribution of the laser radiation in the near field and in its image plane has a dip in the paraxial region. The shape of the phase front of the output radiation is such that the profile of the intensity in the focal plane has a maximum on the axis, and this character of the intensity distribution is preserved also on some portion of the propagation of the beam in the transfocal region. The wings of the angular distribution are formed by radiation emerging from the near-field region with the largest intensity.

At a pump intensity at the focus I_p ~200–400 MW/cm^2, when $R_w \ll 1$, the structure of the scattered radiation is formed basically in the neighborhood of the focus, where the intensity distribution has a maximum on the axis, and the amplification for the rays $0-0'$ is greater than for the rays $1-1'$ (Fig. 10). In this regime, as in a single-lens input system only the radiation which corresponds to the core of the directivity diagram of the pump beam is reproduced. The intensity distribution of the Stokes signal is identical in shape with the intensity

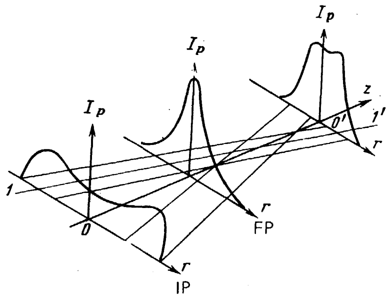

FIG. 10. Intensity distribution of the pump in the cell with the scattering medium.

distribution of the pump only in the paraxial region of the PL near field (Fig. 11a).

At higher levels of the pump (I_p ~400–88 MW/cm^2) the amplification coefficient for the rays $1-1'$ increases and becomes sufficient for excitation of scattering, which leads to practically complete reproducibility of the near and far fields of the pump beam (Fig. 11b).

Upon further increase in the pump power $I_p > 800$ MW/cm^2, its intensity in the vicinity of the focus is greatly weakened, due to the conversion into a Stokes component of the SMBS; therefore, the near-focus region has practically no effect on the amplification of the Stokes signal. Such saturation of the pump shows up in the paraxial rays $0-0'$ more strongly than in the peripheral rays, so that a dip appears in the intensity distributions of the scattered radiation both in the near and the far field near the axis (Fig. 11c).

At high pump levels, certain other effects can also contribute in principle to the worsening of the reproducibility. These include the appearance of a pre-breakdown state in the nitrogen. The ensuing vibrational excitation of the nitrogen occurring leads to the appearance of fine-grained inhomogeneities of the index of refraction and to self-focusing of the radiation which, as is well known,[43] hinders stimulated scattering.

Thus, the investigations have shown that for the effect of reproducibility of the envelope of the intensity distribution in SMBS with reflection coefficient $R_w \gtrsim 0.1$ there exists a limitation of the pump radiation from both above and below. In the experiments, the reversal in nitrogen ($P \approx 70$ atm) takes place under the condition

$$400\ \mathrm{MW/cm^2} \leqslant I_p \leqslant 800\ \mathrm{MW/cm^2} \quad (1)$$

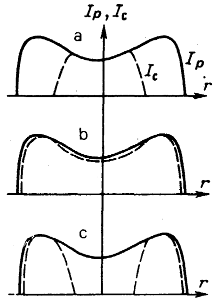

FIG. 11. Intensity distribution of the pump and Stokes radiation in the near field of the PL at various pump intensities: 2) $-I_p = 200–400$ MW/cm^2, b) $I_p = 400–800$ MW/cm^2, c) $I_p > 800$ MW/cm^2.

4. USE OF THE SMBS MIRROR FOR DYNAMIC COMPENSATION OF OPTICAL INHOMOGENEITIES OF AN IODINE LASER

Compensation of phase distortions of a beam, due to the optical inhomogeneities of the active medium, was accomplished first in a two-pass ruby amplifier[7] at a duration of pulse radiation ~100 nsec. The optical inhomogeneities in the rod were practically unchanged during this time, so that the compensation was static in this sense.

Another possibility of compensation of the inhomogeneities was noted above, i.e., that the radiation passing through the amplifier A_1 and reflected by the SMBS mirror is fed to one or several other amplifiers with the same profile of index of refraction as in A_1 (see Fig. 2). In such schemes, there are limitations on the accuracy of the compensation, due to the change in the profile of the inhomogeneities of the index of refraction of the active medium during the time of passage of the radiation through the system.

Another limitation is connected with the fact that light propagation in an inhomogeneous amplifying medium is not completely reversible.

Actually, the amplification of the radiation is described by the equations

$$\begin{aligned} &\frac{\partial E_1}{\partial z}+\frac{i}{2k}(\Delta_\perp+k^2\delta\varepsilon(\mathbf{r}))E_1=\frac{\sigma\Delta(r)}{2}E_1,\\ &-\frac{\partial E_2}{\partial z}+\frac{i}{2k}(\Delta_\perp+k^2\delta\varepsilon(\mathbf{r}))E_2=\frac{\sigma\Delta(r)}{2}E_2, \end{aligned} \tag{2}$$

where

$$E_1(z,r)=E_0,\ E_2(l,r)=E_1^*(l,r)$$

are the complex amplitudes of the direct and reverse waves, k is the wave number, $\Delta_\perp$ is the Laplace operator with respect to the transverse coordinates, $\frac{1}{2}\delta\varepsilon(r) = \delta n(r)$ is a function describing the profile of the index of refraction, σ is the amplification cross section, and $\Delta(r)$ is the inverted population.

If the inversion distribution in the amplifier is homogeneous $\Delta(r)\equiv\Delta_0$, then, after the substituion of the variables $\bar{E}_{1,2}=E_{1,2}\exp\{\sigma\Delta_0 z/r\}$, these equations become complex conjugates, which ensures ideal reproducibility of the characteristics of the input signal. The presence of inhomogeneities of the amplification coefficient leads to irreversibility of the propagation of the light beam and, as a consequence, to inaccuracy of the reproducibility.

Let a be the characteristics spatial scale of the change of the inversion $\Delta(r)$. In the case in which the displacements of the ray is in the transverse direction over the length of the amplifier is small ($\Delta r \ll a$) and the medium can be regarded as a thin lens, broadening of the angular spectrum of the input signal takes place by an amount

$$\Delta\theta\approx 4(\sigma\Delta_{max}l)^{1/2}/ka. \tag{3}$$

This corresponds to an intensity-distribution narrowing due to inhomogeneities of the inversion in an equivalent amplifier with $\delta\varepsilon\equiv 0$ and length $2l$.

If the amplifier is sufficiently long, and it is not possible to regard it as a thin lens ($\Delta r \gtrsim a$), then the radiation at the output of the amplifier is insensitive to the field distribution of the input signal and also to the signal reflected from the SMBS mirror. This amplifier length $l_a \sim a(2\Delta n)^{1/2}$ corresponds to the distance at which fundamental mode of the waveguide is isolated by the inhomogeneities of the index of refraction of the active medium. It is clear that if the length of the amplifier exceeds a certain limit then the phase distortions of the beam are not compensated.

Experimental investigations of dynamic compensation were carried out on the PL described above, the optical inhomogeneities in which during the time of pulse generation (~5–10 μsec) changed within the limits $\delta n \approx 10^{-7} - 10^{-6}$.[39,44] The amplifier length was less than the limiting value.

The degree of dynamic compensation was estimated from the narrowing of the directivity diagram of the SMBS radiation after passage through an inhomogeneous amplifying medium. In the case of complete compensation, the decrease in the divergence should amount to

$$\Delta\theta\approx 2l(\mathrm{grad}\, n)_{max}, \tag{4}$$

where $(\mathrm{grad} n)_{max}$ is the maximum gradient of the index of refraction and l is the amplifier length.

In experiments with a two-pass compensation system, in which radiation constituted by a series of pulses with amplitude changing from spike to spike of the amplitude, the accuracy of reproducibility in SMBS with different spikes was different. Under these conditions, the fraction of energy of the output radiation (~50%) was emitted at angles significantly greater than the divergence of the input signal ($\theta_{out}\sim 10^{-2}$ rad, $\theta_{in}\sim 2\times 10^{-4}$ rad), although a narrowing of the core of the directivity diagram was observed for the reverse passage of the radiation through the amplifying medium. Evidently this is connected with the fact that condition (1), necessary for reproducibility of the angular spectrum of the pump radiation, was not satisfied in the experiment.

Experiments with a one-pass system allowed us to establish a quasi-stationary mode of operation of the SMBS mirror when pumped with a smooth pulse, and to investigate the dependence of the degree of compensation on the completeness of the reproduction of the angular spectrum in SMBS: 1) for the case of complete reproduction (two-lens input, 2) for the case of non-reproduction of the higher components of the angular spectrum (single-lens input), 3) for nonreproduction of the lower components of the angular spectrum (two-lens input at high pump intensities).

In the first case, we obtained practically total dynamic compensation of the inhomgeneities of the amplifier. The divergence of the output radiation of the amplifier A_2 amounted to $\theta_{0.51}\approx 2\times 10^{-4}$ rad in the case of a divergence $\theta_{0.51}\approx 7\times 10^{-4}$ rad of the radiation reflected by the SMBS mirror (Fig. 12a). The recorded narrowing of the directivity diagram agrees well with the estimate by formula (4).

In the second case, the decrease in the divergence of the SMBS radiation after passage through the amplifier

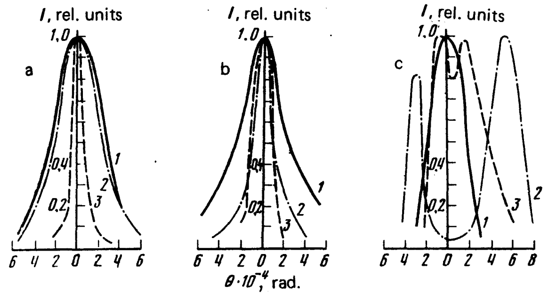

FIG. 12. Angular distributions of the intensity of the exciting (1), scattered (2) and amplified (3) radiations: a) complete reproducibility of the angular spectrum; b) nonproducibility of the higher components of the angular spectrum; c) nonreproducibility of the lower components of the angular spectrum.

was noticeably less than that calculated by formula (4) (Fig. 12b).

In the third case, the narrowing of the directivity diagram, as in the case of complete reproduction, was determined by the maximum values of the gradient of the index of refraction, in correspondence with the estimate (4). The angular distribution of the SMBS radiation, initally in the form of a ring, took a shape with maximum intensity at the center of the distribution after passage through the amplifier (see Fig. 12c).

The results can be explained (see Sec. 3 and Fig. 11) by the fact that in the case of incomplete reproduction the intensity distributions of the Stokes signal and the pump do not coincide, while the phase front of the scattered radiation is reversed.

At low pump intensities $I_p < 400$ MW/cm^2, and also at a single-lens input, the Stokes radiation falls practically entirely in the paraxial region of the PL, where the inhomogeneities of the index of refraction are small (Fig. 11a). Accordingly, the narrowing of the directivity diagram in the case of repeated passage of the Stokes signal through the amplifier is not large (Fig. 12b).

In the case of a two-lens input with $I_p > 800$ MW/cm^2, the intensityof the Stokes signal at the PL input is large in the region with large optical inhomogeneities (Fig. 11c), so that the narrowing of the directivity diagram, as also in the case of complete reproduction, is determined by the maximum gradient of the index of refraction. The intensity of the SMBS radiation is then maximal in those portions of the amplification layer which, in accord with the profile, produce in the radiation an angular spectrum that is conserved in the case of the SMBS components (Fig. 12c). Upon complete reproduction of the angular spectrum, the amplification of the scattered radiation takes place over the entire end face of the amplifier (see Fig. 11b) and the narrowing of the directivity diagram is determined by the expression (4) (Fig. 12a).

Thus, the experiments have shown that coincidence of the entire width of the angular SMBS spectrum and the width of the directivity diagram of the pump radiation has a significant effect on the degree of compensation.

1) The radiating passing through the beam-splitting mirror can be used to "power" other similar stages of amplifiers (see Fig. 2).

2) A single oscillator can be used with distribution of the radiation among all the channels.

3) A mode of automodulation of the radiation upon introduction of the SMBS mirror inside the laser was observed in Refs. 37 and 38.

4) The oscillator used was the iodine PL described in Ref. 39 with nonresonant feedback and an angular selector. The working medium of the SMBS was xenon at 50 atm. A two-lens input system was used (see below).

5) The intensity distribution was recorded on infrared film in the focus of a lens with f_{eq}=40 m.

6) Application of this system is effective for lasers for which the intensity distributions are significantly different in the near and far fields.

7) It should be noted that no advanced breakdown of the gas in the SMBS cell occurs under these conditions, since the energy balance of the radiation is satisfied: $E_p = E_{SMBS} + E_{trans}$.

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The effect of zero points in the modulation of light in a Fabry-Perot interferometer

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The modulation of light by a homogeneous electric field in a Fabry-Perot interferometer filled with a nondispersive dielectric is considered and some features of the modulation are explained. A "zero point" effect is predicted which consists of the disappearance of the modulation of a light wave passing through the interferometer. The effect should occur for a certain number of frequencies p of the modulating field (irrespective of its amplitude) and for certain frequencies ω of the incident light wave, the derivatives of the light-wave modulation parameter with respect to the frequency p or ω being discontinuous at the zero points. It is pointed out that the effect can be used to measure the absolute optical length of the interferometer with an accuracy several orders of magnitude better than the light wavelength (and in some cases better than the thickness of the atomic layer of the substance). It can also be used to measure precisely the refractive-index deviations induced in matter by various external factors (for example, a light field, pressure, magnetic field, etc.).

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If a light wave passes through matter located in a strong, homogeneous electric field that modulates its index of refraction, in the general case the frequency and amplitude of the wave are modulated. Such a modulation was produced by Kaminow[1] and is widely used in condensed dielectrics[2,3] and gases.[4-8] The corresponding theory was proposed both for the case of condensed dielectrics[1-3,9] and for gases.[9-11]

The modulation of light in a Fabry-Perot interferometer filled with a condensed dielectric (located in an inhomogeneous electric field) was considered in Ref. 12. The consideration was limited to the case of spatial synchronism of the modulating microwave frequency with all the frequency components of the modulated light field. According to Gordon and Rigden,[12] because of this synchronism the modulation parameter of the

