PACS numbers: 42.65.Es; 42.70.Nq; 42.40.Eq
DOI: 10.1070/QE2009v039n12ABEH014079

Loop SBS oscillator on a stationary nonlinear refractive index grating

I.M. Bel'dyugin, A.A. Gordeeev, V.F. Efimkov, I.G. Zubarev, S.I. Mikhailov, V.B. Sobolev

***Abstract*. A loop SBS oscillator is studied, in which pump radiation coupled out from a nonlinear medium is directed backward to the medium. To increase the interaction length, a light guide is used. The feedback is obtained on a stationary nonlinear refractive index grating produced by the pump waves. The signal generated at the Stokes frequency in the loop propagates in the direction opposite to the pump and is amplified due to the classical backward SBS. Such an oscillator can be treated as a distributed feedback oscillator produced by the pump waves themselves.**

Keywords: *loop scheme, SBS oscillator, nonlinear refractive index grating, threshold amplification increment*.

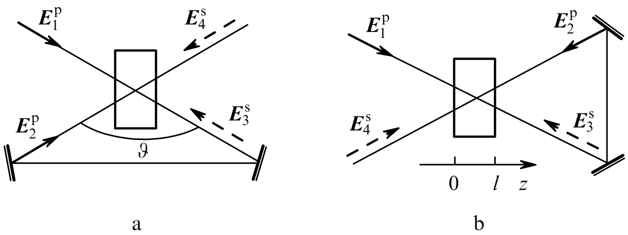

Figure 1. Loop oscillators on reflection (a) and transmission (b) nonlinear refractive index gratings; $\boldsymbol{E}_{1,2}^{p}$ are the pump waves; $\boldsymbol{E}_{3,4}^{s}$ are the signal waves generated in the loop; rectangles show the active nonlinear medium.

Loop parametric-feedback oscillators have a number of features useful for practical applications, which still attract the attention of researchers to them [1 – 3]. As is known, such oscillators can be produced both on reflection and transmission nonlinear refractive index gratings [4]. In the first case, the pump beam with the amplitude E_2^{p}, after a passage through a loop, is coupled into the active medium through the same cell window as the input pump beam with the amplitude E_1^{p} (Fig. 1a). In the case of transmission gratings, these beams are coupled into the active medium from the opposite sides (Fig. 1b). In this case, the nonlinear refractive index gratings providing the parametric feedback are produced by the interference of the pump waves $E_{1,2}^{p}$ and signal waves $E_{3,4}^{s}$ spontaneously scattered in the required directions (Fig. 1):

$$\delta n \sim E_1^{p} E_4^{s*} + E_2^{p} E_3^{s*}. \quad (1)$$

Experiments performed using the scheme in Fig. 1b and active SBS media are described in literature [5]. As a generation mechanism, the authors of [5] considered the forward SBS. The direct evidence of this could be detection of a significantly smaller Stokes shift of laser radiation compared to backward SBS; however, such measurements have not been performed so far. Below, we propose a different physical mechanism of lasing in the loop. The aim of this paper is to obtain lasing in such a scheme and to estimate the threshold gain increments.

If scattering occurs without a frequency shift as, for example, in the case of photorefractive crystals or Nd : YAG amplifiers, interference gratings (1) are stationary in space. In the experimental scheme in Fig. 1a, the angles ϑ between the wave vectors of the pump and the signal wave (i.e. the angles between the vectors $\boldsymbol{E}_1^{p}$ and $\boldsymbol{E}_4^{s}$ and vectors $\boldsymbol{E}_2^{p}$ and $\boldsymbol{E}_3^{s}$) are close to π. Therefore, the period of the corresponding nonlinear refractive index grating is $\Lambda = \lambda[2\sin(\vartheta/2)]^{-1} \approx \lambda/2$, where λ is the wavelength of the pump wave in the medium.

In the case of Fig. 1b, the angles ϑ between the same pairs of vectors lie in the range from 10^{-2} to 10^{-1} rad; therefore, the periods of spatial nonlinear gratings usually lie in the range $\Lambda = \lambda/[2\sin(\vartheta/2)] \approx \lambda/\vartheta \approx (10 - 100)\lambda$. Therefore, transmission gratings used in experiments are larger than reflection gratings, and, hence, they are less sensitive to the motion and diffusion of particles in gases and to the thermal conductivity in solids.

If scattering occurs with the frequency shift, as in the case of SBS, nonlinear refractive index gratings move in space from the side of the wave with a smaller wave vector to the side of the wave with a larger wave vector. As for the periods of the nonlinear refractive index gratings, their ratio remains invariable – transmission gratings are larger than the reflection gratings. The SBS process requires some establishment time, which is proportional to the gain increment and the lifetime τ of acoustic phonons. This process is of the resonance type and involves phonons with the wave vectors $|\boldsymbol{q}| = 2|\boldsymbol{k}|\sin(\vartheta/2)$, where $\boldsymbol{k}$ is the wave vector of the pump wave and ϑ is the scattering angle. In this

I.M. Bel'dyugin 'Astrofizika' Research and Production Association, Volokolamskoe shosse 95, 125424 Moscow, Russia;
A.A. Gordeeev, V.F. Efimkov, I.G. Zubarev, S.I. Mikhailov, V.B. Sobolev P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: efimkov@sci.lebedev.ru, zubarev@sci.lebedev.ru, sergmihailov@tochka.ru

Received 17 February 2009
Kvantovaya Elektronika **39** (12) 1148 – 1152 (2009)
Translated by I.A. Ulitkin

case, the lifetime of acoustic photons is $\tau = 2/(\Gamma q^2)$ [6], where Γ is the medium viscosity coefficient. The values of τ are usually presented in the literature for backward SBS, when $\vartheta = \pi$ and q has a maximum value. In this case, $\tau \sim 1 - 10$ ns for most of the used media; hence, it is almost impossible, in the case of conventional Q-switched lasers with pulse durations of the order of tens of nanoseconds, to observe forward SBS when $\vartheta \approx 10^{-2}$–$10^{-1}$ rad and τ increases by $10^2 - 10^4$ times. In this connection, in the scheme in Fig. 1b, a classical parametric mirror, which could close the feedback loop, which is necessary for realisation of a loop SBS oscillator, is not formed during the SBS. Note also the obvious necessity of a more adequate analysis of forward SBS, which should take into account the relaxation mechanism of the volume viscosity, and rejection of the method of slow amplitudes in deriving material equations.

Nevertheless, as in the case of Fig. 1b, there exist refractive index gratings though which the feedback loop can be closed. First of all, this is the stationary density grating produced by the interference of two almost counter-propagating pump waves ($E_1^{\rm p}$ and $E_2^{\rm p}$) due to the electrostriction phenomenon. Then, spontaneous Stokes radiation propagating opposite to pump radiation will be partially reflected from this grating to the feedback loop. And although the period of this stationary grating is not consistent with the Stokes radiation wavelength, the threshold condition for this loop SBS oscillator can be fulfilled at a large enough gain for backward SBS. Such an oscillator can be treated as a distributed feedback oscillator.

Active SBS media have also a cubic nonlinearity for which the medium polarisation is $P^{(3)} = \varepsilon_0\chi^{(3)}E^3$, where $\chi^{(3)}$ is the third-order nonlinear susceptibility; ε_0 is the permittivity of vacuum. The establishment times of these nonlinearities in such media as carbon bisulphide CS_2, which was used in our experiments, are determined by the relaxation rate of anisotropic molecules in liquids and are equal to $\sim 10^{-12}$ s. In this case, the frequency shift Ω of the Stokes component during backward SBS is $\sim 10^{10}$ s^{-1}. Therefore, the wave interference (1) will generate, at this nonlinearity, a travelling refractive index grating (phase grating) on which the pump waves will be re-scattered into the feedback loop with the required frequency shift. At a sufficient SBS gain, this can lead to self-excitation of this loop SBS oscillator. However, we should note that in such media as CS_2, the electrostriction nonlinearity is almost an order of magnitude larger than the cubic nonlinearity.

For a distributed feedback oscillator constructed according to the scheme in Fig. 1b, from Maxwell's equations in the fixed pump field approximation and under the assumption of interaction of plane waves, we can obtain the system of equations for the slowly varying amplitudes $E_{3,4}^{\rm s}$:

$$\frac{dE_3}{dz} = -\frac{gI_1}{2}E_3 + iK^*E_4\exp(-i\Delta kz),$$
$$\frac{dE_4}{dz} = \frac{gI_2}{2}E_4 - iKE_3\exp(i\Delta kz), \tag{2}$$

where g is the specific gain during SBS (in cm MW^{-1}); $I_{1,2} = |E_{1,2}^{\rm p}|^2$; K is the coupling coefficient of the Stokes waves on a stationary density grating produced by the interference of the pump waves (in cm^{-1}); Δk is the wave detuning due to the difference between the wavelengths of the pump and Stokes radiation. If the feedback is produced by the phase grating resulting from the cubic nonlinearity, the coefficient K in (2) should be replaced by $^1/_2\gamma E_1E_2^* = {}^1/_2\gamma(I_1I_2)^{1/2}\exp(ik_{\rm p}L)$, where $\gamma = k\chi^{(3)}/n^2$, k is the wave vector, and n is the refractive index of the medium. The boundary conditions have the form:

$$E_4(0) = 0, \quad E_3(l) = \sqrt{R}E_4(l)\exp(ik_{\rm s}L),$$
$$E_2 = \sqrt{R}E_1\exp(ik_{\rm p}L), \tag{3}$$

where $\sqrt{R}$ is the reflection coefficient for the radiation fields in the feedback loop; $k_{\rm s}$, $k_{\rm p}$ are the corresponding wave vectors; L is the length of the external part of the loop.

After the replacement

$$E_3(z) = a_1(z)\exp\left(-i\frac{\Delta kz}{2}\right),$$
$$E_4(z) = a_2(z)\exp\left(i\frac{\Delta kz}{2}\right) \tag{4}$$

system (2) is reduced to a system of equations with constant coefficients

$$\frac{da_1}{dz} = -\left(\frac{gI_1}{2} - i\frac{\Delta k}{2}\right)a_1 + iK^*a_2,$$
$$\frac{da_2}{dz} = \left(\frac{gI_2}{2} - i\frac{\Delta k}{2}\right)a_2 - iKa_1. \tag{5}$$

Solving this system and using boundary conditions (3), we find the threshold condition for the self-excitation of the loop oscillator in the scheme in Fig. 1b:

$$\left(\frac{gI}{4} - i\frac{\Delta k}{2}\right)\cosh(\beta l) - \beta\sinh(\beta l) = iK\sqrt{R}\exp(i\Delta kl)\sinh(\beta l). \tag{6}$$

Here

$$I = I_1 + I_2; \quad \beta = \left[\left(\frac{gI}{4} - i\frac{\Delta k}{2}\right)^2 + |K|^2\right]^{1/2}.$$

The system of equations (2) implicitly suggests that amplification occurs at the SBS gain line centre; then, g is a real quantity. In oscillators, as a rule, it is not so: lasing occurs at the shifted frequency. Therefore, g, in fact, is a complex quantity and $g = g' + ig''$ should be substituted in (6). Here, the real part of (6) will determine the threshold amplification increment, while the imaginary part – the laser frequency. To simplify the expression for the lasing threshold, system (2) was solved, taking into account the fact that in the experiment $gI \gg |K|$ and $R \sim 1$. Then, for the minimal threshold increment $G_{\rm th} = gI_{\rm th}l$ we can obtain the estimate:

$$\exp G_{\rm th} \approx \frac{g}{\gamma}\left[1 + \frac{(2\Delta kl)^2}{G_{\rm th}^2}\right]^{1/2}. \tag{7}$$

The scheme of the experimental setup is shown in Fig. 2. Single-mode and single-frequency pump radiation $I_{\rm p}$ with the polarisation in the horizontal plane propagates through dielectric polariser (*1*), quartz plate (*2*) rotating the polarisation plane by 45°, and Faraday rotator rod (*3*). After it, the polarisation plane of pump radiation becomes vertical. Then, radiation passes through a 20-cm-long, 1×1-cm lightguide (*4*), filled with the active medium (carbon bisulphide CS_2). Pump radiation incident on the cell is reflected from its window to photodetector (*7*) measuring the pump energy. After the light guide, prisms (*5*) and (*6*) return the pump beam into the light guide, where it is reflected twice from its light guide walls. In this case, the beam axis passes through the centres of both light guide ends, and the angle between the beams is determined by the expression $\vartheta = \arctan(2d/l) \approx 5.7^{\circ}$. Pump radiation I_{out} coupled out from the light guide is reflected by glass wedge (*8*) to photodetector (*9*). Radiation generated in the loop at the Stokes frequency I_s propagates towards the pump, is reflected from the magnitooptical rod end (*3*) and is directed by mirror (*10*) to photodetector (*11*). After passing through rod (*3*) and 45° quartz plate (*2*), radiation remains vertically polarised and is reflected from polariser (*1*).

To measure the spectra of pump radiation I_{out} and generaton I_s, these beams were directed to light diffuser (*13*) by mirrors (*12*) and (*15*), respectively, thereby illuminating on the light diffuser the regions not intersecting due to nontransparent plane and thin screen (*14*). The light diffuser is in the focus of lens (*16*) (the focal distance is 16 cm). Then, there was placed Fabry–Perot etalon (*17*) with a gap $d = 1$ cm, objective (*18*) (the focal distance is 200 mm), and photosensitive WinCamD-UCM matrix (*19*) mounted in the objective focus and connected to the PC. In this scheme measuring the spectrum in the focus of objective (*18*), an etalonogram with two separate regions is produced, one of which belongs to the pump beam I_{out}, and the other – to the generation beams I_s. The shape of the pump and laser pulses was measured with a high-speed Det 10A photodiode and a 200-MHz digital Rigol DS 5202CA oscilloscope. Near-field laser radiation was recorded on photographic plate (*20*), which was introduced into the beam I_s reflected from polariser (*1*). Far-field radiation was recorded using lens (*21*) with the focal distance 105 cm and photographic plate (*22*), which were introduced into the beam I_s reflected from mirror (*15*). In this case, the photographic plate was located in the lens focus. Pulse energies were measured with photodetectors (*7*, *9*, *11*) with integrating circuits. The output signals of photodetectors were fed to 25-MHz digital Rigol DS 5022M oscilloscopes.

Usually, in studying loop SBS oscillators shown in the scheme of Fig. 1a, no question arises whether we observe generation in a loop or simply backward SBS from the level of spontaneous noises. This is caused by the large difference between the threshold increments for these processes, ~ 1 in the first case and ~ 25 in the second. In the scheme (Fig. 2) studied by us, this difference is not so large and explanations are necessary to prove that it is generation that we observe in the loop.

In our paper [7], for the cell used in the experiment we measured the threshold value of the amplification increment for the backward SBS from the level of spontaneous noises $G_{th} = gI_{th}l \approx 10$. In a loop oscillator (Fig. 2), pump radiation, coupled out from the cell after the first passage, returns to the cell. In this case, there arises a question about the value of the threshold increment for the backward SBS from the level of spontaneous noises. The threshold increment depends on the geometrical parameters of the active medium [7]:

$$G_{th} - \ln G_{th} = \ln \frac{1}{\Lambda}, \quad \Lambda = \eta l \frac{\partial R}{\partial o} \delta o, \tag{8}$$

where $\eta = 10^2$ is the empirical coefficient; l is the length of the active SBS medium; $\partial R / \partial o \sim 10^{-7}$ cm^{-1} sr^{-1} is the spontaneous scattering cross section; δo is the solid angle within which spontaneous radiation propagates in the active medium. Calculations by expression (8) for our cell filled with CS_2 gives $G_{th} \approx 10.5$, which well agrees with the experiment. From the point of view of the backward SBS from the level of spontaneous noises, the loop can be considered as two analogous cells placed at a distance L from each other. Then, in expression (8), we should replace l by $2l = 40$ cm and $\delta o \approx 1$ sr by $\delta o = S/(L/2)^2 = 1/(45)^2 \approx 5 \times 10^{-3}$ sr; finally, we obtain $G_{th} \approx 17.5$, i.e.

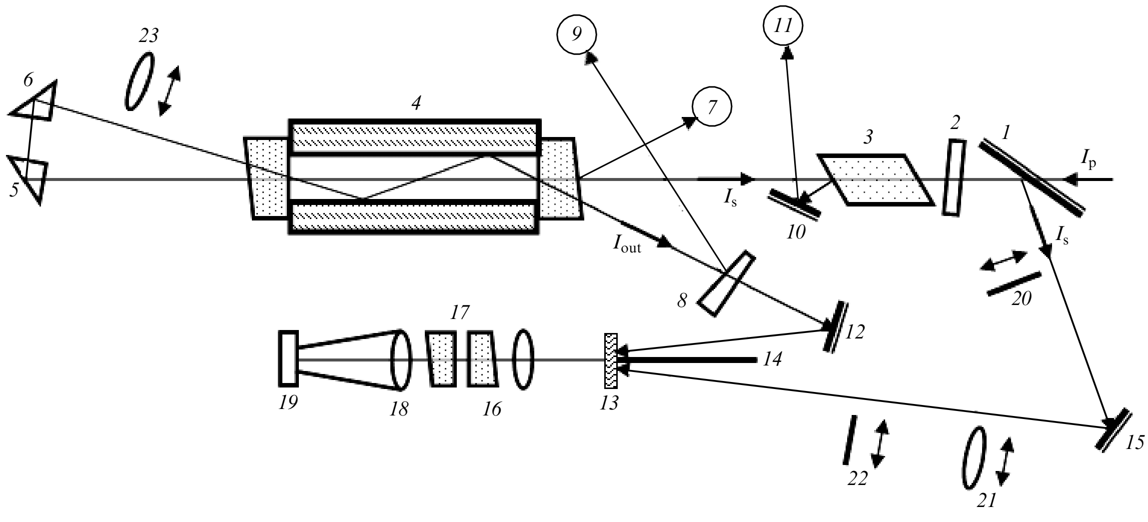

Figure 2. Scheme of the experiment: (*1*) polariser; (*2*) 45° quartz plate; (*3*) magnitooptic glass rod; (*4*) light guide with the active substance; (*5*, *6*) folding prisms; (*7*, *9*, *11*) energy photodetectors; (*8*) glass wedge; (*10*, *12*, *15*) dense mirrors; (*13*) light diffuser; (*14*) screen; (*16*) lens; (*17*) Fabry–Perot etalon; (*18*) objective; (*19*) photosensitive matrix; (*20*, *22*) photographic plates; (*21*, *23*) lenses.

organization of a loop in our case does not lead to a decrease in the threshold SBS increment from the level of spontaneous noises.

The experimental dependence of the output energy of the loop SBS oscillator on the pump pulse energy is presented in Fig. 3. Taking into account the pump pulse duration $\tau =$ 40 ns, the gain in CS_2 $g = 5 \times 10^{-2}$ cm MW^{-1}, and the light guide dimensions $1 \times 1 \times 20$ cm, we obtain the experimental value of the threshold increment $G_{th} = gI_{th}l \approx 5$. The estimate of the threshold amplification increment by expression (7) gives a close value. The oscillograms of the pump pulses and the loop SBS oscillator are shown in Fig. 4. Figure 5 demonstrates the spectra of pump radiation and the loop SBS oscillator. The Fabry–Perot interferometer had a gap $d =$ 1 cm, which, during the processing of interferograms, gives a shift $\Omega = 0.125$ cm^{-1} corresponding to the Stokes shift in CS_2 during the backward SBS. Note that we obtained similar results when carbon tetrachloride was used as an active medium.

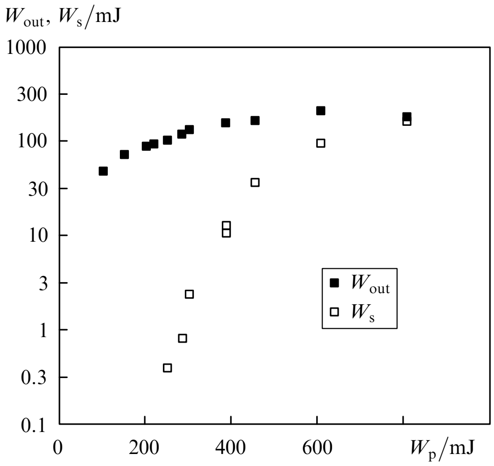

Figure 3. Dependences of the pump energy W_{out} at the light guide output and the output energy W_s on the pump energy W_p.

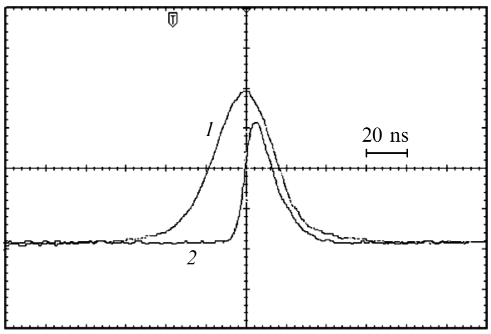

Figure 4. Oscillograms of the pump (*1*) and generation (*2*) powers.

The geometrical parameters of the loop SBS oscillator in our case had such values that the Fresnel number for it was ~ 200. Therefore, lasing had purely a multimode character (Fig. 6); we used this circumstance to estimate the minimal threshold increment. Some decrease in the Fresnel number was achieved by introducing lens (*23*) with $F = 60$ cm in the feedback loop (see Fig. 2); The light guide was placed between the lens and its focal plane so that the pump beam cross section on the cell window farthest from the lens have dimensions 0.4×0.4 cm. This resulted in a decrease in the threshold increment and an increase in the output energy (Fig. 7), as well as in a decrease in the divergence of far-field radiation (Fig. 8).

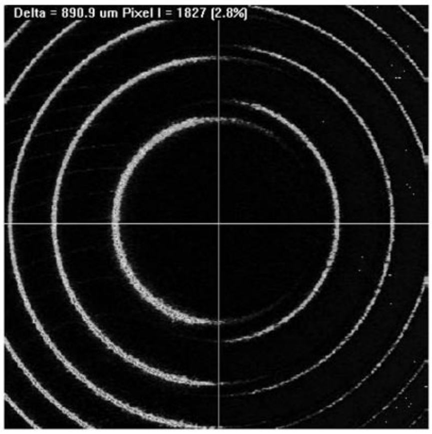

Figure 5. Etalonograms of the spectra of pump radiation I_{out} (on the right from the vertical axis) and output radiation I_s (on the left from the vertical axis).

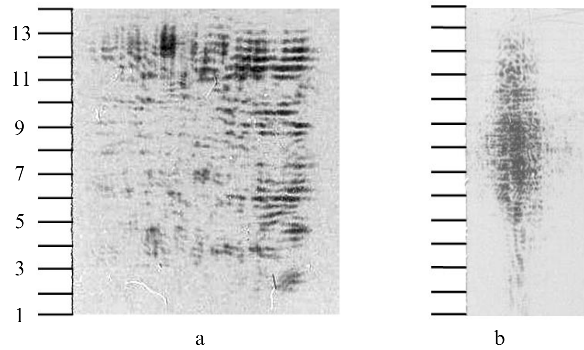

Figure 6. Distribution of the output energy density in the near field (at a distance of ~ 100 cm from the right end of the light guide) (a) and in the far field (in the focus of the lens with $F = 105$ cm) (b); on the left is the millimetre scale.

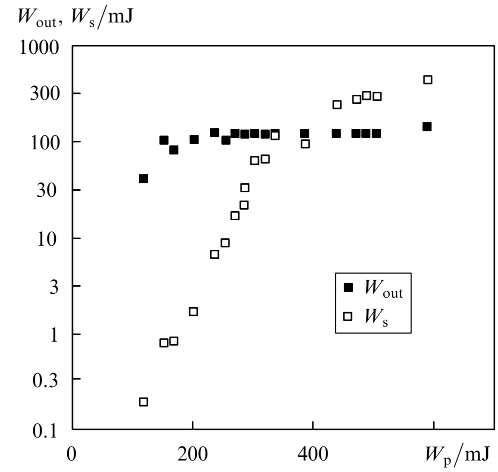

Figure 7. Dependences of the pump energy W_{out} at the light guide output and the output energy W_s on the pump energy W_p for the scheme with lens (*20*) (Fig. 1).

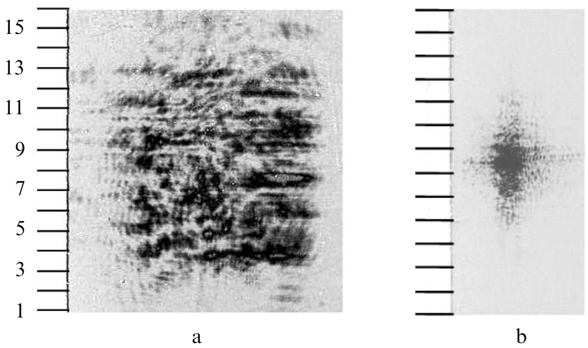

Figure 8. Distribution of the output energy density in the near field (at a distance of $\sim$ 100 cm from the right end of the light guide) (a) and in the far field (in the focus of the lens with $F = 105$ cm) (b) for the scheme with lens (*20*) (Fig. 1) in the backward pump beam; on the left is the millimetre scale.

Thus, we have realised in this paper the loop SBS oscillator in which the feedback is implemented on a stationary nonlinear refractive index grating. In this case, the signal generated in the loop is amplified due to the classical backward SBS. This oscillator can be treated as an oscillator with a distributed feedback produced by the pump waves themselves. This scheme can be useful in some applications, for example, in phasing radiation from several loop oscillators. The matter is that stationary nonlinear refractive index gratings, which provide the feedback, can be produced by one and the same pump wave and, hence, can be phased with each other.

References

1. Basiev T.T., Gavrilov A.V., Osiko V.V., Smetankin S.N., Fedin A.V. *Kvantovaya Elektron.*, **37** (3), 255 (2007) [*Quantum Electron.*, **37** (3), 255 (2007)].
2. Smith G., Damzen M.J. *Opt. Express*, **15** (10), 6458 (2007).
3. Antipov O., Eremeykin O., Ievlev A., Savikin A. *Opt. Express*, **12**, 4314 (2004).
4. Tikhonchuk V.T., Zozulya A.A. *Progr. Quantum Electron.*, **15** (4), 231 (1991).
5. Kulagin O.V., Potlov P.B., Shilov A.A. *Kvantovaya Elektron.*, **19** (11), 1089 (1992) [*Quantum Electron.*, **22** (11), 1012 (1992)].
6. Fabelinskii I.L. *Molecular Scattering of Light* (New York: Plenum Press, 1968; Moscow: Nauka, 1965).
7. Bel'dyugin I.M., Efimkov V.F., Zubarev I.G., Mikhailov S.I. *Kvantovaya Elektron.*, **37** (7), 656 (2007) [*Quantum Electron.*, **37** (7), 656 2007)].