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Dependence of the threshold increment of an SBS amplifier on geometrical parameters

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Abstract. **The influence of parameters of the active medium of an SBS amplifier on the SBS threshold is studied. It is shown that the expression for the threshold gain increment is universal and is valid in a broad range of parameters. The threshold gain increment is measured in a light guide where the spontaneous noise can be amplified within a large solid angle. Experiments on the SBS amplification of weak images in a light guide are performed. The gain $\sim 10^6$ is obtained without considerable distortions of the image quality.**

Keywords: *SBS amplifier, light guide, gain increment.*

1. Introduction

SBS amplifiers offer a unique set of parameters such as the gain band and the gain [1, 2]. In particular, the brightest natural source of visible light – the sun emits less than one noise quantum in a single spatiotemporal mode within the band of a standard SBS amplifier. Therefore, these amplifiers are undoubtedly of interest both for optical radars and detectors of object images illuminated by lasers.

It is easy to understand that the maximum linear gains (in the weak saturation regime) are achieved at the pump radiation intensities close to the SBS threshold. As the pump intensity is further increased, the intrinsic noise of the SBS amplifier increases drastically and the gain begins to saturate [1, 2]. Thus, the maximum linear gain is $K^{\max} \approx \exp G^{\text{th}}$, where $G^{\text{th}} = gI_{\text{p}}^{\text{th}} l$ is the threshold gain increment; g is the specific gain per unit length of the amplifier and per intensity unit of the pump radiation; I_{p}^{th} is the pump threshold intensity; and l is the amplifier length. It is commonly accepted that the threshold increment is $G^{\text{th}} \approx 25$. This gives the maximum gain for the SBS amplifier $K^{\max} \leqslant \exp 25 \simeq 7 \times 10^{10}$. For pulsed signals, this value determines the power gain. The study is performed in the plane wave approximation, and amplification is assumed stationary. The presence of the transverse Gaussian structure of the pump beam and the Stokes beam being amplified, the nonstationary amplification and the time dependence of the gain – all these factors reduce the measured maximum gain [1, 2].

The threshold gain increment $G^{\text{th}} \simeq 25$ is reported virtually in all books and papers devoted to different types of stimulated scattering (SS). This quantity proved to be adequate to the experimental conditions under which a variety of SS processes were observed from the spontaneous noise level. However, it is not absolute and depends on the geometrical parameters of the active region. Therefore, the maximum gain, in particular, for the SBS amplifier also depends on the experimental geometry. This dependence is studied in the present paper.

2. Calculation of the SBS amplifier parameters

The equation describing the amplification of a Stokes signal of intensity I_{S} in the stationary regime in an SBS amplifier in the presence of spontaneous noise in the plane wave approximation and the fixed-pump-intensity approximation [i.e. $I_{\text{p}}(z) = I_{\text{p}}(0) = I_{\text{p}}$] has the form [3, 4]

$$\frac{\mathrm{d}I_{\text{S}}}{\mathrm{d}z} = \frac{\partial R}{\partial o}\delta o I_{\text{p}} + gI_{\text{p}}I_{\text{S}}. \qquad (1)$$

Here, $\partial R/\partial o$ is the differential coefficient of pump radiation scattering (R in cm^{-1}) into the unit solid angle o; δo is the solid angle of the SBS amplifier; and the Stokes signal propagates in the positive direction along the z axis. The solid angle δo considered in all the SBS studies is the angle within which the Stokes radiation propagates within the pump beam over the entire length l of the active medium. As for any optical system, the quantity $\sqrt{\delta o}$ is the angular aperture of the SBS amplifier. In the simplest SBS amplifier scheme, in which the active region is formed by the pump beam itself with diameter d and for which the angular aperture is $2d/l$, the solid angle is $\delta o \simeq (d/l)^2$.

We solve Eqn (1) by using the boundary condition $I_{\text{S}}(z=0) = I_{\text{S}}(0)$, where $I_{\text{S}}(0)$ in the intensity of the external input Stokes signal being amplified. In this case, the solution of Eqn (1) has the form

$$I_{\text{S}}(l) = \frac{\partial R}{\partial o}\frac{\delta o}{g}\left[\exp(gI_{\text{p}}l) - 1\right] + I_{\text{S}}(0)\exp(gI_{\text{p}}l). \qquad (2)$$

Because very high gains are required in practice, we have $\exp(gI_{\text{p}}l) \gg 1$ in expression (2) and it can be written in the form

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$$I_S(l) = \left[\frac{\partial R}{\partial o}\frac{\delta o}{g} + I_S(0)\right]\exp(gI_p l). \quad (2a)$$

It follows from (2a) that, even if the external Stokes signal is absent at the amplifier input [$I_S(0) = 0$], the Stokes radiation is nevertheless present at the amplifier output. In this case, the quantity

$$I_{SN}(0) = \frac{\partial R}{\partial o}\frac{\delta o}{g} \quad (3)$$

can be considered as the intensity of the SBS amplifier noise reduced to the input ($z = 0$). This noise is independent of the pump radiation intensity and is determined only by the parameters (in particular, geometry) of the active medium.

It follows from (2) that the SBS process from the spontaneous noise level described by the first term in the right-hand side of (2), generally speaking, has no the threshold. For any arbitrarily low pump intensity I_p, the output scattered radiation is observed at the Stokes frequency. However, there exists the so-called experimentally observed SS threshold. It is determined by the passage from the exponential amplification of the Stokes noise, described by expression (2a) for $I_S(0) = 0$, to its amplification in the pump saturation regime. The pump intensity I_p^{th} at which the intensity of the amplified spontaneous noise $I_{SN}(l)$ comprise a certain, noticeable part of the pump intensity:

$$I_{SN}(l) = \frac{I_p^{th}}{\eta} \quad (4)$$

is treated as the threshold intensity. Of course, the value of η depends on the sensitivity of measurements. However, it is commonly accepted that $\eta = 10^2$ (small saturation regime), and it is for this value that the threshold increment is $G^{th} \simeq 25$.

Let us find the threshold gain increment. By using expressions (4), (2a) [for $I_S(0) = 0$] and (3), we obtain the expression

$$I_{SN}(l) = \frac{I_p^{th}}{\eta} = \frac{\partial R}{\partial o}\frac{\delta o}{g}\exp(gI_p^{th} l). \quad (5)$$

By multiplying both sides of equality (5) by gl, introducing the notation $\Lambda = \eta l(\partial R/\partial o)\delta o$, and taking into account that $G^{th} = gI_p^{th} l$, we obtain after transformations

$$G^{th} - \ln G^{th} = \ln\frac{1}{\Lambda}. \quad (6)$$

The differential scattering coefficient $\partial R/\partial o$ for various media changes in a rather broad range from $\sim 10^{-8}$ to $\sim 10^{-6}$ cm^{-1} sr^{-1} (for $\lambda \approx 1$ μm) [3]. For most of the media used in experiments, this coefficient is $\sim 10^{-7}$ cm^{-1} sr^{-1}. The experimental conditions under which SBS is observed also change in a broad range. The solid angle δo within which spontaneous radiation can propagate and can be amplified changed, as a rule, between $\sim 10^{-6}$ and 10^{-4} sr. Let us take the standard values of the parameters: $\eta = 10^2$, $l = 10$ cm, $\partial R/\partial o = 10^{-7}$ cm^{-1} sr^{-1}, and $\delta o = 10^{-5}$ sr. For these values, we have

$$\Lambda = \eta l \frac{\partial R}{\partial o}\delta o = 10^{-9}. \quad (7)$$

Then, by solving Eqn (6), we obtain $G^{th} \simeq 25$. As mentioned above, it is this threshold increment value that is most often used in the literature for different types of SS. Note that this value changes only by ± 10 % when Λ changes by an order ± 1 of magnitude.

On the other hand, according to (2), the decrease in the pump intensity (increment G) by 10 % with respect to its threshold $G^{th} \simeq 25$ will reduce the intensity of the output Stokes radiation more than by an order of magnitude. However, the increase in the pump intensity with respect to its threshold by the same amount will result in such an increase in $I_S(l)$ that the pump depletion should be already taken into account. That is why the pump threshold I_p^{th} measured experimentally by the method described above is a good characteristic of the SBS process and is reproduced in experiments of many authors.

Nevertheless, the quantity Λ depends on the two parameters, the length l and solid angle δo, which can be varied in a very broad range (by many orders of magnitude). Note here that upon scattering in a 'free' space (i.e. in the simplest geometry), these parameters are mutually dependent (the solid angle decreases with increasing length). On the contrary, when a light guide is used, these parameters become obviously independent. This will result in a substantial change in the threshold increment G^{th}. The dependence $G^{th}(\Lambda)$ obtained by solving numerically Eqn (6) is presented in Fig. 1.

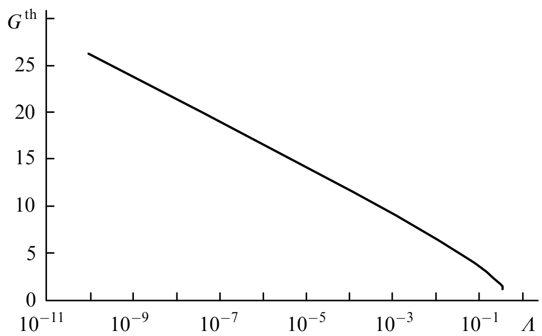

Figure 1. Calculated dependence of the threshold gain increment G^{th} on Λ.

The length of the active medium of the SBS amplifier can be considerably changed only by using an optical fibre. In this case, the coherence length of the pump radiation should not be smaller than the fibre length. And if the fibre length is 1 km and the rest of the parameters in (7) are the same, the threshold increment will be ~ 14, as follows from Fig. 1. The maximum gain will be only $\exp 14 = 1.2 \times 10^6$.

3. Formulation of the problem

Because we are interested in amplifiers of pulsed signals, we cannot change considerably the active medium length. We studied in [1, 2] the SBS amplifier of spatially single-mode signals. The values of the parameters of the active medium were close to the values in (7). The SBS energy gain was $\sim 2 \times 10^9$, which is somewhat lower than the theoretical limit. Such an amplifier is quite suitable for optical radars. However, if we want to intensify the image of objects illuminated by laser radiation, it is necessary to increase the angular aperture of the amplifier. The gain region in the simplest optical scheme of the SBS amplifier is determined by the pump beam diameter d and the active medium length l. The pump field should be homogeneous because the gain increment in the inhomogeneous field for the Stokes signal reversed with respect to the pump is doubled. A spatially homogeneous pump beam is ideal from this point of view. The Stokes beam in this SBS amplifier should propagate in the direction virtually opposite to the pump beam direction because the inequality $d \ll l$ was fulfilled in most of the experiments. This circumstance prevents the use of the SBS amplifier in laser systems with a high gain because the possibilities of optical isolators preventing the penetration of the pump radiation to the laser amplifier channel are limited.

The use of a light guide seems to be quite attractive. The Stokes beam in our studies [5, 6] was directed along the light-guide axis, whereas pump beams formed by a prism raster were reflected from the light-guide walls. Because the spatially homogeneous pump field is ideal for the SBS amplification, it is expedient to direct the pump beam along the light-guide axis and to make the Stokes beam be reflected from the walls. This reflection (of course, total) is possible if the refractive index of the active medium exceeds the reflection coefficient of the light-guide walls. In this case, the angular separation of the pump and Stokes beams is performed, which allows one to abandon optical isolators. To eliminate the restriction of the Stokes beam at the input and output ends of the light guide, the Stokes-beam axis should pass through the centres of the light-guide ends. This determines the discrete angles of propagation of the Stokes beams, which are counted from the light-guide axis in two mutually perpendicular planes parallel to the walls: $\alpha_i = \arctan(di/l)$, where $i = 1, 2, 3, ...$ is the number of reflections from the walls. The maximum value of α_i inside the light guide is limited by the angle of total internal reflection. Outside the light guide, the angles increase according to the laws of refraction. Thus, by using a light guide, it is possible to amplify simultaneously many Stokes beams (multiplication).

Despite many studies devoted to SBS in light guides, the noise parameters of such a device have not been adequately investigated so far. In this paper, we analyse the possibility of amplifying weak signals (images) in a light guide and the influence of spontaneous noise on this process.

4. SBS amplifier with a light guide pumped by single-mode radiation

Figure 2 shows the block-diagram of the pump radiation I_p of the SBS amplifier and the input Stokes signal I_S channels (the complete scheme of these channels is presented in Fig. 1 in [2]). Master oscillator (*1*), shown schematically in Fig. 3, is a passively Q-switched Nd : glass laser with the selection of the frequency and transverse modes. The laser emitted 40-ns, 20-mJ pulses in the single-frequency and single-mode regime. Radiation from the master oscillator is divided into two channels in which neodymium amplifiers and optical isolations are used. The master-oscillator frequency was shifted in the Stokes-signal channel in the SBS active medium (carbon disulfide CS_2). The output elements of the Stokes-signal channel are sensor (*2*) for recording the energy and shape of the Stokes beam and optical attenuator (*3*). The scheme of the latter is described in [2].

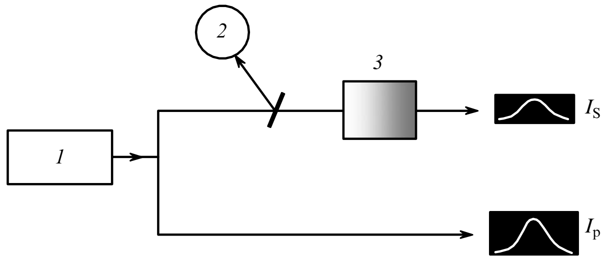

Figure 2. Block-diagram of the pump and Stokes radiation channels: (*1*) master oscillator; (*2*) detector of the energy and shape of Stokes pulses; (*3*) optical attenuator; I_p and I_S are the pump and Stokes beam intensities, respectively.

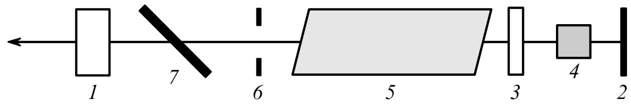

Figure 3. Optical scheme of the master oscillator: (*1*) and (*2*) output and highly reflecting resonator mirrors, respectively; (*3*) auxiliary mirror [mirrors (*1*) and (*3*) are plane–parallel glass plates]; (*4*) passive F^{2+} : LiF Q switch; (*5*) Nd : glass active element; (*6*) aperture of diameter 2.5 mm for transverse-mode selection; (*7*) dielectric polariser; the resonator length is 1.2 m, the pulse FWHM is 50 ns.

Figure 4 presents the scheme of the experiment on the image intensification. The horizontally polarised pump beam of intensity I_p is expanded with twofold Galilean telescope (*1*) and transmitted through a soft square aperture with the square side of 7.5 mm. Lenses (*3*) and (*4*) form an adjusted Kepler telescope. Polariser (*5*), Faraday rotator (*6*), and quartz 45° plate (*7*), behind which the polarisation plane remains horizontal, serve for optical isolation. Then, the pump beam is directed with two deflecting prisms to a Nd : silicate glass amplifier. The beam reflected in roof prism (*11*) propagates again through the amplifying rod and is directed to SBS amplifier (*12*) representing a cell with carbon disulfide CS_2 with the reflection coefficient $n_1 = 1.62$. In the cell a 1×1-cm square light guide of length 20 cm is placed. The light-guide walls are made of optically polished CaF_2 plates with the refractive index $n_2 = 1.43$. The SBS amplifier is located near the image plane of soft aperture (*2*) formed by the Kepler telescope [lenses (*3*) and (*4*)]. The image size was 10.5×10.5 mm. The pump-beam axis coincides with the light-guide axis. The pump beam emerging from the SBS amplifier is directed by prism (*13*) to IKT-1N calorimeter (*14*), and radiation reflected from the prism face is directed to photodiode (*15*) for measuring the shape of the pump pulse propagated through the SBS amplifier. Det10A photodiode (*15*) is connected to a 200-MHz Rigol DS 5205CA digital storage oscilloscope.

The Stokes beam of intensity I_S propagates through object aperture (*16*) and enters the light guide of the SBS amplifier virtually simultaneously with the pump radiation. The beam passes through the centre of the left (in the scheme) end of the light guide, experiences two reflections from the walls and emerges from the centre of the right end. The Stokes beam emerged from the light guide was directed by two deflecting prisms to screen (*20*) on which the image of object aperture (*16*) is formed by lens (*18*). Radiation reflected from faces of prism (*17*) was directed to power

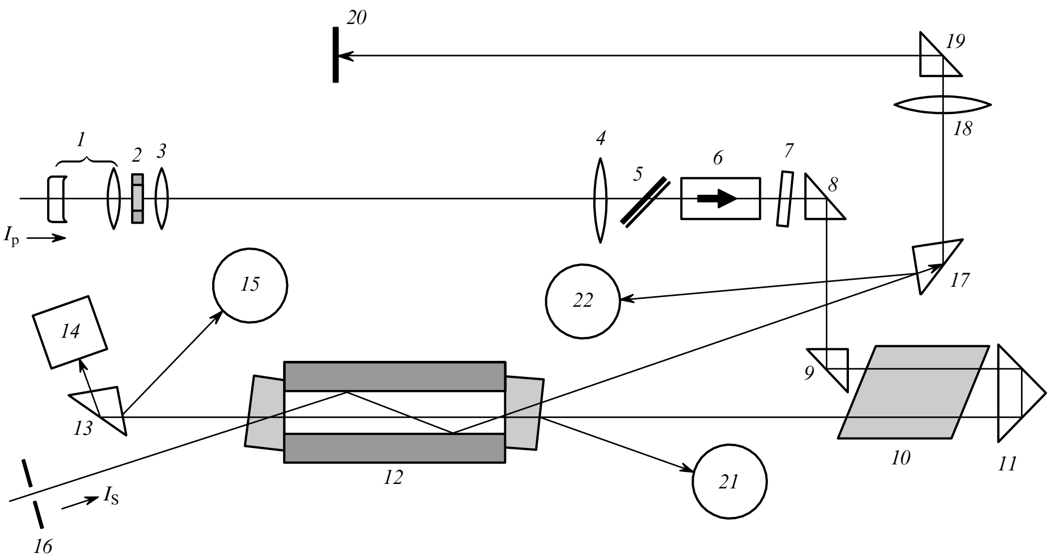

Figure 4. Scheme of the experimental setup for image intensification: (*1*) Galilean telescope; (*2*) soft square aperture; (*3*) lens with the focal distance $F = 100$ cm; (*4*) lens with $F = 150$ cm; (*5*) polariser; (*6*) Faraday rotator; (*7*) 45° quartz plate; (*8, 9, 13, 17, 19*) deflecting prisms; (*10*) $\varnothing 45 \times 580$-mm amplifying neodymium rod; (*11*) roof prism; (*12*) $1 \times 1 \times 20$-cm light guide with the CS_2 active medium; (*14*) calorimeter; (*15*) photodiode; (*16*) object aperture; (*18*) lens with $F = 100$ cm; (*20*) screen in the image plane; (*21*) and (*22*) power meters.

meter (*22*). Power meter (*21*) controls the pump energy of the SBS amplifier by detecting radiation reflected from the glass window of the cell. Power meters (*21*), (*22*) [and (*2*) in Fig. 2) are photodiodes with an integrating chain, whose output pulses were fed to 25-MHz Rigol DS 5022M digital storage oscilloscopes. The power meters were calibrated by using an IKT-1N calorimeter. Object aperture (*16*) was a circular aperture of diameter 3.5 mm, which was partially covered by two opaque plates with rectangular angles so that the object had the shape of a mushroom.

5. Experimental results

First of all, we measured the dependence of the radiation energy transmitted through the light guide on the input energy in the absence of the Stokes signal. Figure 5 presents the three dependences: experimental, in the absence of losses, and calculated. One can see that energy losses appear at the input pump energy ~0.4 J. This demonstrates the achievement of the generation threshold of the noise Stokes radiation.

Let us use expression (7) by substituting the values $\eta \approx 10^2$, $\partial R/\partial o \approx 10^{-7}$ cm^{-1} sr^{-1} and $l \approx 20$ cm into it. As for the solid angle δo, it is equal to a cone with the apex angle, which is equal to the double angle being additional to the total internal reflection one. The latter is ~29° for $n_1 = 1.62$ and $n_2 = 1.43$, i.e. $\delta o \sim 1$ sr. As a result, we obtain $G^{\rm th} \approx 10.5$. At the same time, the gain increment $G = gI_{\rm p}l$ is equal to 10 for the 0.4-J, 40-ns pump pulse. Here, $g = 5 \times 10^{-2}$ cm MW^{-1}, $I_{\rm p} = 10$ MW cm^{-2}, and $l = 20$ cm. The close values of $G^{\rm th}$ and G demonstrate good agreement between the calculated and experimental data.

Figure 6 presents the oscillograms of the input and output pump pulses. This figure is obtained by the overlap of two oscillograms recorded with photodiode (*15*). First we recorded the oscillogram of the output pump pulse by selecting proper filters mounted in front of the photodiode. Then, upon the same pumping, a 300-fold filter was removed from the filter set and placed in front of the cell. In this case, the output pump energy is equal to the

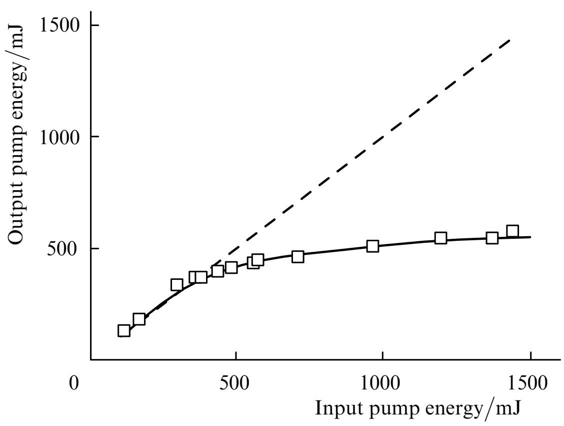

Figure 5. Dependences of the pump energy at the light-guide output on the input energy: experimental (squares), in the absence of losses (the output energy is equal to the input energy) (dashed straight line), and calculated (solid curve).

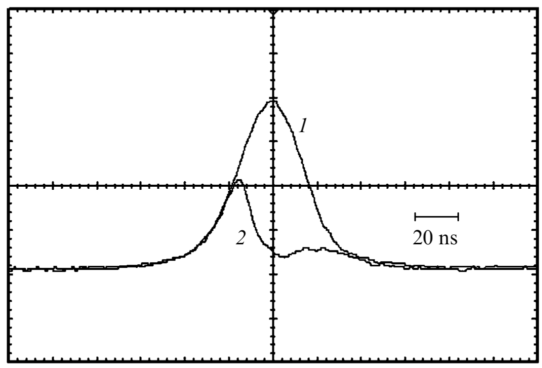

Figure 6. Oscillograms of the input (*1*) and output (2) pump pulses.

input pump energy, and the shape of the output pulse repeats the shape of the input pulse due to the absence of SBS. The input energy measured with detector (*21*) was 1.3 J, and the output energy measured with calorimeter (*14*) was 0.5 J. Figure 7 shows the time dependences of the input and output pump pulses calculated by using the MathCAD13 software package taking into account the phonon lifetime $\tau_{ph} = 7$ ns for carbon disulfide. The input pump energy used in calculations was 1.3 J. One can see from Figs 6 and 7 that the experimental and calculated data are in good agreement.

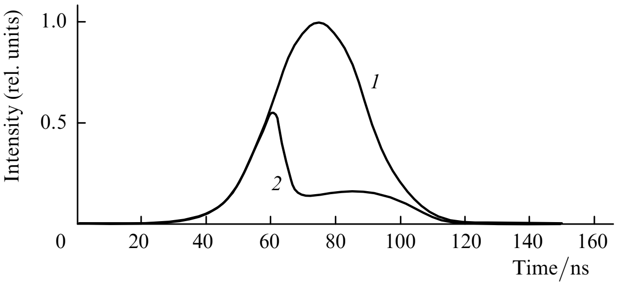

Figure 7. Calculated time dependences of the input (*1*) and output (*2*) pulses.

The intensification of weak images was studied in the following way. First, without the Stokes-beam attenuation [in optical attenuator (*3*) in Fig. 2] and without pumping the SBS amplifier, the readings of power meters (*2*) in Fig. 2 and (*22*) in Fig. 4 were connected. Simultaneously, the object image was obtained on screen (*20*) (Fig. 4). Then, the signal was attenuated by 10^6 times and the pump energy was increased to the value at which the signal was amplified by 10^6 times as well. In this case, the pump energy was 1.7 J and the gain increment was $G = gI_pl \sim 40$. The object image was again obtained on the screen. Figure 8 presents the results of this study demonstrating the absence of strong distortions upon signal amplification by 10^6 times. The intensified image exhibits only a more pronounced interference structure.

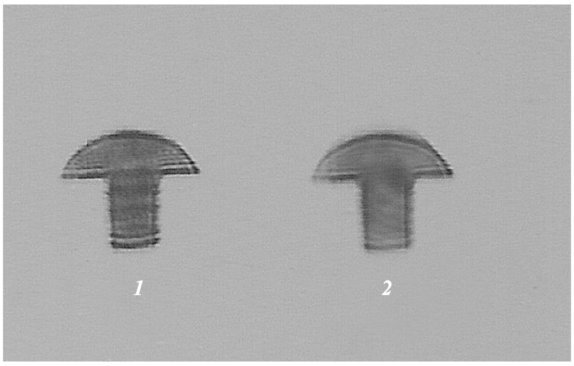

Figure 8. Object images obtained after the 10^6-fold attenuation of the Stokes signal and the 10^6-fold energy amplification (*1*) and without signal attenuation and energy amplification (*2*).

6. Conclusions

We have shown that the maximum linear SBS gains determined by the threshold pump intensity depend on the geometrical parameters of the SBS amplifier and, first of all, of the solid angle δo determined in our experiments by the angle of total internal reflection from the light-guide walls. Therefore, to achieve the maximum gain during the reception and image intensification of objects illuminated by laser radiation, it is necessary to match the angular apertures of the received image and SBS amplifier and also to use special schemes of the latter.

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