*Quantum Electronics* **31** (8) 709–712 (2001) 

PACS numbers: 42.60.By; 42.60.Lh; 42.65.Es
DOI: 10.1070/QE2001v031n08ABEH002031

# Efficient multistage SBS amplifier

I M Bel'dyugin, V V Davydov, V K Demkin, V F Efimkov, I G Zubarev, S I Mikhailov, V B Sobolev

***Abstract*****. A two-stage weak-signal SBS amplifier scheme with an independent pumping of both amplification stages is proposed and implemented. This scheme is devoid of the disadvantages inherent in a single-stage amplifier because the competitive influence of pump-correlated noise components is suppressed in it due to their amlification either only in the first stage or only in the second one. It is experimentally shown that this system allows amplifying weak signals by a factor of $10^6 - 10^9$ for a bandwidth determined by the type of SBS-active material involved and its gain increment ($10^{-2}$–$10^{-4}$ cm$^{-1}$). The gain of $\sim 10^8$ is obtained with retention of the spatial characteristics of the signal being amplified.**

***Keywords***: *SBS amplifier, two-stage amplification, small-signal gain.*

## 1. Limitations on the SBS-amplifier gain

Despite the apparent simplicity of realising large gains [$\sim \exp(25-30)$], which are determined by the threshold of the lasing onset from spontaneous noise, and despite the possibility of operation throughout the visible and near-IR ranges, SBS amplifiers have not yet found applications in practical laser devices for image reception and processing. Here, the main negative factors are: the competitive influence of lasing from spontaneous noise; the presence of non-zero correlation of the spatial structures of the pump and the Stokes signal, responsible for the generation of spatial Stokes components phase-conjugated relative to the pump [1]; and a significant reduction in the gain in the saturation regime due to the pump depletion in the counterpropagating interacting waves [2].

To overcome the latter factor, a two-stage SBS amplifier was proposed and realised in Ref. [2], the pump radiation first being fed to the first amplification stage and then to the second one. This technique allowed a sharp increase in the pump conversion coefficient, and the parameters of this amplifier approached the corresponding parameters of a co-propagation scattering amplifier. In this paper, we study a two-stage SBS amplifier with an independent pumping of each of the amplification stages. This allowed us, on the one hand, to retain the advantages of a two-stage scheme [2] and on the other hand to weaken significantly the influence of the first two factors, because the components with a structure conjugate relative to the pump are amplified either only in the first stage or only in the second one.

We will assume that SBS is stationarity in the case of interaction of monochromatic waves. Then, the spatial components of the pump and Stokes wave radiation can be represented as Fourier expansions in terms of plane waves [3–5]:

$$E_{\mathrm{p}} = \sum_n A_n(z)\exp(\mathrm{i}k_n r), \quad E_{\mathrm{s}} = \sum_m a_m(z)\exp(-\mathrm{i}k_m r). \qquad (1)$$

Using expressions (1), it is possible to obtain [6] the equations for the average pump intensity $I_{\mathrm{p}}(z) = \sum_n |A_n|^2$, the Stokes signal correlated with the pump, $a_n^{\mathrm{c}} = A_n^* \sum_m A_m a_m / I_{\mathrm{p}}$, and the Stokes signal uncorrelated with the pump, $a_n^{\mathrm{nc}} = a_n - A_n^* \sum_m A_m a_m / I_{\mathrm{p}}$:

$$\frac{\mathrm{d}I_{\mathrm{s}}^{\mathrm{c}}}{\mathrm{d}z} = 2gI_{\mathrm{p}}I_{\mathrm{s}}^{\mathrm{c}} + gI_{\mathrm{s}}^{\mathrm{c}}I_{\mathrm{s}}^{\mathrm{nc}},$$

$$\frac{\mathrm{d}I_{\mathrm{s}}^{\mathrm{nc}}}{\mathrm{d}z} = gI_{\mathrm{p}}I_{\mathrm{s}}^{\mathrm{nc}} - gI_{\mathrm{s}}^{\mathrm{c}}I_{\mathrm{s}}^{\mathrm{nc}}, \qquad (2)$$

$$\frac{\mathrm{d}I_{\mathrm{p}}}{\mathrm{d}z} = 2gI_{\mathrm{p}}I_{\mathrm{s}}^{\mathrm{c}} + gI_{\mathrm{p}}I_{\mathrm{s}}^{\mathrm{nc}},$$

where $z$ is the longitudinal coordinate of the signal propagation; $I_{\mathrm{s}}^{\mathrm{c}} = \sum_n |a_n^{\mathrm{c}}|^2$ and $I_{\mathrm{s}}^{\mathrm{nc}} = \sum_n |a_n^{\mathrm{nc}}|^2$ are the average intensities of the parts of the Stokes signal correlated and uncorrelated with the pump. In the absence of saturation, the system (2) transforms to the system

$$\frac{\mathrm{d}I_{\mathrm{s}}^{\mathrm{c}}}{\mathrm{d}z} = 2gI_{\mathrm{p}}I_{\mathrm{s}}^{\mathrm{c}}, \quad \frac{\mathrm{d}I_{\mathrm{s}}^{\mathrm{nc}}}{\mathrm{d}z} = gI_{\mathrm{p}}I_{\mathrm{s}}^{\mathrm{nc}}, \qquad (3)$$

which illustrates the amplification of the correlated component with a double increment and that of the uncorrelated component with a single increment.

The possibility of employing equations of the type (2) follows directly from simple estimates of the number of spatial pump components ($n \gg 1$) and the characteristic

**I M Bel'dyugin, V V Davydov, V K Demkin** 'Astrofizika' State Unitary Research and Production Association, Volokolamskoe shosse 95, 123424 Moscow, Russia
**V F Efimkov, I G Zubarev, S I Mikhailov, V B Sobolev** P N Lebedev Physics Institute, Russian Academy of Sciences, Leninskii prospekt 53, 119991 Moscow, Russia

Received 3 April 2001
*Kvantovaya Elektronika* **31** (8) 709–712 (2001)
Translated by E N Ragozin

gains over the longitudinal correlation length ($\Gamma_c \ll 1$), which we made using a specific experiment geometry. Since the spatial structure of the input Stokes signal is not related to that of the pump, the input signal represents an uncorrelated component. The criterion for a proper operation of the SBS amplifier may be formulated as follows: $I_s^{nc}(L) \gg I_s^c(L)$.

One can see directly from Eqns (3) that the second equation describes the amplification in the average pump field, while the first one, describes the well-known phase conjugation. It is obvious that in the case of an SBS amplifier, it is phase conjugation that causes, on the one hand, distortions of the spatial structure of the amplified signal and, on the other hand, restricts the gain due to saturation, because phase conjugation can make a significant contribution to the overall Stokes signal at the amplifier output. The parasitic effect of phase conjugation cannot be eliminated completely, because the contribution to the non-zero correlation of the fields is made by the intrinsic spontaneous amplifier noise, the possible overlap of radiation patterns of the pump and the Stokes signal due to diffraction by the receiving aperture and the inhomogeneities of the optical elements of the SBS amplifier, and also by the nonlinear processes of the 'forward' four-wave mixing type [1]. As noted above, a two-stage SBS amplifier is largely devoid of such disadvantages because the parasitic phase-conjugation component of the Stokes signal is in fact amplified only throughout half the total gain length. The mechanism of operation of such a correlation isolation is shown in Fig. 1.

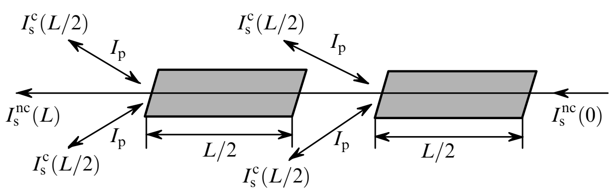


**Figure 1.** Schematic of a two-stage SBS amplifier.

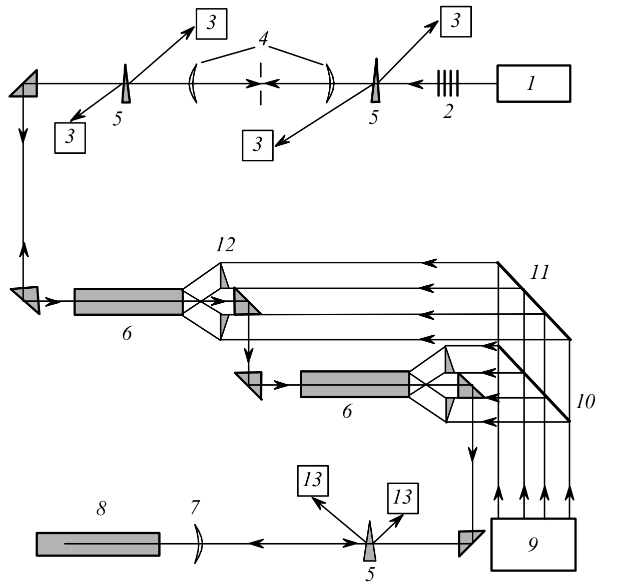


**Figure 2.** Experimental arrangement: (*1*) source of the Stokes signal; (*2*) calibrated filters; (*3*) calorimeters of the system for recording the nonlinear distortions in amplification; (*4*) telescope with a spatial filter; (*5*) deflection wedges; (*6*) SBS-amplifier stages; (*7*) lens which focuses the output Stokes radiation into the PC mirror; (*8*) PC mirror; (*9*) pump source for the SBS amplifier; (*10*) semitransparent mirror; (*11*) $R = 100$ % mirror; (*12*) prism rasters; (*13*) calorimeters of the output and reflected radiation.

## 2. Two-stage SBS amplifier

To perform experimental investigations, we built a neodymium-glass laser setup. The setup included a passively $Q$-switched, single-mode, single-frequency master oscillator, a preamplification system, a SBS oscillator to generate Stokes radiation based on a carbon tetrachloride cell into which part of the radiation was focused, a Faraday optical isolator, a two-stage SBS amplifier, and a pump production channel containing a GOS-1000 two-pass amplifier head. The 60-ns pump pulses were synchronised with the input Stokes radiation to an accuracy of 4 ns. The main elements of the optical arrangement are shown in Fig. 2.

The single-mode, single-frequency Stokes radiation passed through a system of calibrated filters (*2*), optical wedges (*5*), and a telescope with a spatial filter (*4*) to be injected in a two-stage amplifier. After amplification, the Stokes radiation was directed to the phase-conjugate (PC) mirror with the help of lens (*7*). The pump beam of diameter $\sim 45$ mm was formed with the help of a semitransparent mirror and a totally reflecting mirror and injected in SBS-amplifier stages (*6*) employing focusing rasters (*12*) [7] with a focal length of $\sim 25$ cm and a dimension of each cell of 10 mm $\times$10 mm. The amplification stage was a 20-cm long light guide of square 10 mm $\times$10 mm section filled with carbon tetrachloride. The characteristic lifetime of acoustic phonons at the wavelength of a neodymium laser was $\tau \sim 1$ ns, which ensured a stationary SBS regime and the amplification bandwidth $\Delta\nu = 1/\pi\tau c\Gamma^{0.5}$ of the order of $10^{-2} - 10^{-3}$ cm$^{-1}$, where $c$ is the velocity of light and $\Gamma$ the overall gain increment of the two amplification stages. A system of calorimeters (*3*) served to determine the degree of nonlinear signal distortion upon amplification. To eliminate the effect of four-wave mixing, the PC mirror was placed at a distance of $\sim 12$ m from the SBS amplifiers, and the radiation reflected by the PC mirror passed through the amplifiers in the backward direction at the end of amplification.

We measured the dependences of the amplification efficiency gain increment for different energies of the input Stokes signal, determined nonlinear signal distortions upon amplification, and recorded oscillograms of the input and output pulses of the Stokes radiation and the pump. The temporal behaviour of the signals was recorded with the aid of FK50KP photocells and fast C7-19 oscilloscopes (not shown in Fig. 2).

## 3. Experimental results and discussion

Fig. 3 shows the gain of a two-stage SBS amplifier as a function of the overall gain increment for an energy of the input Stokes signal of $\sim 8 \times 10^{-8}$ J. The theoretical gain was obtained by the numerical solution of stationary equations (2) with the inclusion of losses by the Fresnel

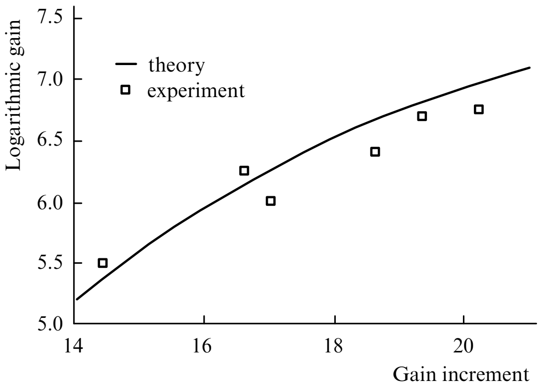


**Figure 3.** Theoretical and experimental dependences of the gain of the two-stage SBS amplifier on the overall gain increment for an energy of the input Stokes signal of $\sim 8 \times 10^{-8}$ J.

reflection from the optical elements of the amplifier and considering that $I_s^c \sim 0$. For an input signal energy of $\sim 10^{-7}$ J, the output signal was as high as $\Gamma \sim 0.5$ J. Note that the self-excitation of a single-stage SBS amplifier with an equivalent gain increment commenced at $\Gamma \sim 10$.

We measured nonlinear distortions of a signal during its amplification. Initially, a balance was set between the readings of the calorimeters (*3*) that measured the signal energy in front of and behind the telescope with a spatial filter. Then, similar measurements in the amplification regime were made with the amplified signal reflected from the PC mirror (*8*). The spatial filter of the telescope (*4*) was so adjusted that its transmission in the forward direction was equal to 0.9. The ratio between the calorimeter readings for a signal amplified and reflected from the PC mirror ranged from 1 to 0.8. This is indicative of relatively small nonlinear signal distortions for the gain $\sim 10^6$.

When the energy of the input Stokes signal was reduced to less than $10^{-9}$ J and the overall peak gain increment was $\Gamma_{\max} < 20$, the system passed into the regime of linear amplification, at which the maximum amplification is possible. The energy efficiency can be estimated from a simple analytic formula obtained assuming the interaction of synchronous triangular pulses:

$$K \approx \frac{\exp \Gamma_{\max}}{\Gamma_{\max}/2}, \quad \Gamma_{\max} = g I_{\max} L.$$

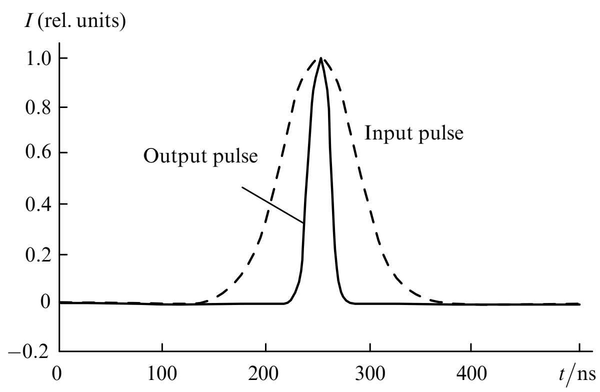


**Figure 4.** Shortening of the Stokes pulse in the unsaturated amplification regime.

In this regime, the Stokes pulse significantly shortens during its propagation through the SBS amplifier. This is illustrated in Fig. 4, which depicts the results of numerical simulation.

The energy ($\sim 4 \times 10^7$) and intensity ($\sim 3.5 \times 10^8$) gains obtained experimentally for $\Gamma_{\max} \sim 20$ and an input signal energy of $\sim 10^{-9}$ J are in good agreement with the calculations. Fig. 5 shows oscillograms of the output Stokes pulses obtained in the regimes of linear amplification and saturation. A significant shortening of the output Stokes pulse in the regime of linear amplification is clearly visible.

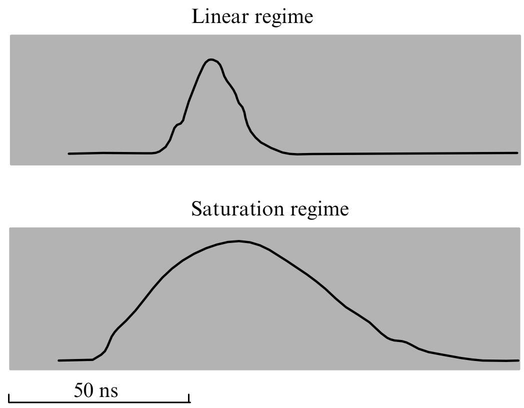


**Figure 5.** Oscillograms of the output Stokes pulses in the unsaturated amplification and saturation regimes.

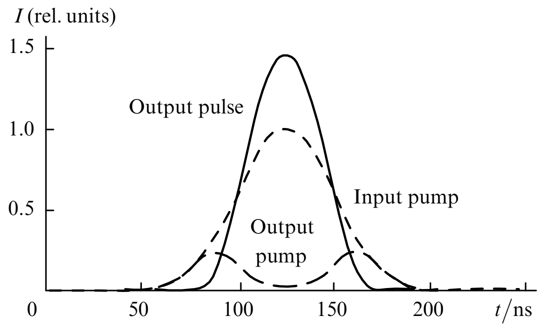


**Figure 6.** Calculated pulse shapes in the saturation regime

Of great interest is the variant of amplification in the regime of deep saturation, which is commonly referred to as the beam combining and is the inverse variant of that considered above. Fig. 6 shows the theoretical time shapes of the interacting pulses for an input signal energy of $\sim 10^{-1}$ J, Gaussian input pulses, and a peak overall increment $\Gamma_{\max} = 12$. In this case, the energy of the output Stokes pulse is comparable with the pump energy of the second stage, while the peak intensity exceeds that of the pump. For comparison, Fig. 7 also presents oscillograms of the pump and the Stokes signal obtained experimentally under the conditions specified above. The results of energy measurements in the regime of strong saturation are presented in Table 1.

In Table 1, $E_{\text{out}}$ is the energy of the output Stokes signal and $E_{\text{p}}$ is the pump energy of the second amplification stage. The theoretical ratio between these quantities is close to unity. The uncertainty of absolute measurements involving

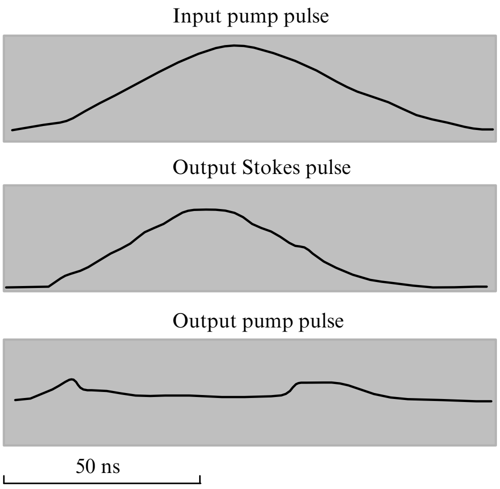


**Figure 7.** Oscillograms of the pump pulses at the SBS-amplifier input and output and also oscillograms of the output Stokes pulse in the regime of strong saturation.

**Table 1.**

| $E_{in}/mJ$ | $E_{out}/J$ | $E_p/J$ | $E_{out}/E_p$ |
|---|---|---|---|
| 80 | 6.1 | 7.3 | 0.84 |
| 80 | 6.7 | 8.3 | 0.8 |
| 90 | 6.6 | 7.4 | 0.9 |
| 100 | 5.0 | 5.2 | 0.9 |

the IKT-1N calorimeters used in our experiments was $\sim 10\,\%$. The uncertainty of relative calibration was determined in a conventional way – by simultaneous energy measurements of the same beam – and did not exceed 2 % – 3 %. Hence, it follows that the accuracy of determination of this ratio for $E_{out}/E_p \sim 1$ is 3 % – 4 %. The scatter in the experimental data may be attributed to uncontrollable shot-to-shot variations in the pump pulse duration and possible abrupt jumps of the Stokes signal phase [8], resulting in a partial loss in monochromaticity and, as a consequence, in the reduction in the conversion efficiency.

Therefore, the two-stage SBS amplifier proposed and implemented in this work has parameters which are relatively easy to calculate neglecting the parasitic oscillation with phase conjugation in the pump channels. This amplifier offers small nonlinear distortions and can be used as a narrow-band amplifying filter for the reception of images of remote objects with the gain of $\sim 10^6 - 10^9$. If combined with laser amplifiers, it permits attaining the gain of $\sim 10^{12}$.

## References


1. Gordeev A A, Efimkov V F, Zubarev I G, Mikhailov S I, Sobolev V B *Kvantovaya Elektron.* **20** 1005 (1993) [*Quantum Electron.* **23** 875 (1993)]
2. Efimkov V F, Zubarev I G, Mikhailov S I, Sobolev V B *Kvantovaya Elektron.* **20** 1021 (1993) [*Quantum Electron.* **23** 890 (1993)]
3. Bel'dyugin I M, Galushkin M G, Zemskov E M *Kvantovaya Elektron.* **3** 2467 (1976) [*Sov. J. Quantum Electron.* **6** 1349 (1976)]
4. Sidorovich V G *Zh. Tekh. Fiz.* **46** 2168 (1976)
5. Basov N G, Efimkov V F, Zubarev I G, Mikhailov S I *Tr. Fiz. Inst. Akad. Nauk SSSR* (Proc. P N Lebedev Physics Institute) **172** 14 (1986)
6. Anikeev I Yu, Zubarev I G, Mikhailov S I *Kvantovaya Elektron.* **13** 142 (1986) [*Sov. J. Quantum Electron.* **16** 88 (1986)]
7. Grasyuk A Z, Efimkov V F, Zubarev I G, Kotov A V, Smirnov V G *Tr. Fiz. Inst. Akad. Nauk SSSR* (Proc. P N Lebedev Physics Institute) **91** 131 (1977)
8. Basov N G, Zubarev I G, Mironov A B, Mikhailov S I, Okulov A Yu *Pis'ma Zh. Eksp. Teor. Fiz.* **31** 685 (1980)