 

*NONLINEAR OPTICAL PHENOMENA*

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# Optimisation of phase conjugation by SBS in a capillary

O V Kulagin, V I Rodchenkov

***Abstract*. Phase conjugation of laser radiation is studied by SBS in a capillary filled with $TiCl_4$. A combination of a relatively low SBS threshold for spatially inhomogeneous radiation, a high quality of phase conjugation, and a wide dynamic range of the phase conjugated radiation energy was obtained. $PBr_3$ is proposed and investigated as a nonlinear optical medium for further decreasing the SBS threshold.**

***Keywords***: *stimulated Brillouin scattering, phase conjugation, fibre.*

Owing to the simplicity of its realisation, phase conjugation (PC) by stimulated Brillouin scattering (SBS) remains one of the most widely used methods for optimisation of the output radiation parameters in various laser systems. To decrease the threshold energy of SBS mirrors, the waveguide geometry of SBS excitation is often used, especially in the case of PC of spatially inhomogeneous radiation. For this purpose, a number of authors [1 – 7] used multimode fibres which lower the SBS threshold to a few tens of watt for a submicrosecond pulse duration [1, 3].

In later papers [5 – 7], the SBS threshold for nanosecond pulses was lowered to 17 μJ [6], and the possibility of PC by SBS of continuous radiation was demonstrated. In this case, the SBS threshold was 70 mW [7]. Moreover, it was shown experimentally that PC of a low-mode radiation (for example, compensation of large-scale aberrations) is characterised by a rather high quality [5, 6].

However, the quality of PC in a fibre depends significantly on the conditions under which the radiation is coupled into the fibre, as well as on the parameters of the fibre itself [8]. In Ref. [8] and the literature cited therein, the reasons behind the deterioration of the quality of PC by SBS in a fibre are studied in detail. They include the broadening of the phase conjugated radiation spectrum, the difference in the wave vectors of the pump and the PC waves, and depolarisation. The spectrum is broadened due to the need for a sharp focusing of the PC radiation upon its coupling into the fibre, its divergence is comparatively large ($\theta \approx 0.1$ rad), so that the variations $\delta\nu \sim \nu\theta^2/2$ (where $\nu$ is the frequency shift upon SBS) in the frequency shift for PC radiation increase. If these variations (which are approximately equal to $2.6 \times 10^{-3}$ cm$^{-1}$ for fused quartz at an incident radiation wavelength of 1.06 μm [9]) become comparable with the SBS line width $\Delta\nu \approx 1/(\pi\tau\sqrt{M})$ (where $\tau$ is the hypersound relaxation time, and $M \approx 20$ is the gain increment for SBS, which means that $\Delta\nu \approx 2.4 \times 10^{-4}$ cm$^{-1}$ in fused quartz), the PC quality deteriorates. Such a broadening of the PC radiation spectrum was studied experimentally in Ref. [10] where the agreement between the measured broadening and the theoretical estimates was demonstrated.

Another factor limiting the possibilities of PC by SBS in a fibre is the mismatch between the wave fronts of the incident and PC waves due to a difference in their wave vectors. The length of such a mismatch is estimated from the expression $l \approx k_s/[(k_i - k_s)k_i\theta^2]$, where $k_i$ and $k_s$ are the wave vectors of the incident and the scattered wave, respectively, and $l \approx 20$ cm for a quartz fibre. If the gain increment $M(l)$ for SBS is comparatively small at this length ($M(l) \sim 1$), the mismatch of the wave fronts lowers the preferential amplification of the PC component in the Stokes wave, resulting in a deterioration of the PC quality [8]. Thus, we find that the limiting length of the fibre beyond which the quality of PC by SBS deteriorates is defined by the expression $lM \approx 4$ m. These constraints, as well as several others, are much less stringent in liquids used for SBS, since both the frequency shift due to SBS and the hypersound relaxation time in them are at least five times smaller [9].

The aim of this paper is to study PC by SBS in a two-cell system consisting of an SBS amplifier (a cell containing $TiCl_4$) and an SBS generator, representing a quartz capillary filled with $TiCl_4$ (Fig. 1). Apart from lowering the SBS threshold compared to the threshold upon conventional focusing into the bulk, such an arrangement also allows PC of spatially inhomogeneous laser radiation in a wider dyna-

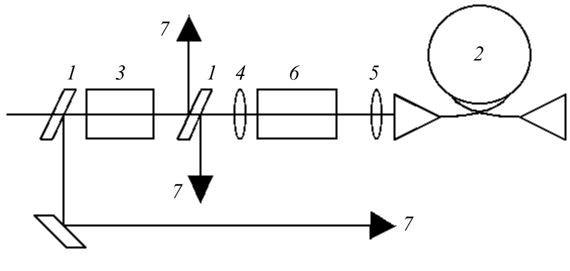


**Figure 1.** Experimental setup: (*1*) interference polarisers; (*2*) capillary cell with $TiCl_4$; (*3*) Faraday rotator; (*4*, *5*) projecting objectives; (*6*) cell with $TiCl_4$; (*7*) power meters.

**O V Kulagin, V I Rodchenkov** Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia; e-mail: ok@appl.sci-nnov.ru

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mic energy range. The role of the limiter protecting capillary (*2*) from an extremely intense pump beam entering the capillary is played by the SBS amplifier (cell *6*) operating in the focused beam.

Note Refs [11, 12] devoted to SBS studies in capillaries. A 1000-fold decrease in the SBS threshold (to 13 W) in a capillary of diameter 10 μm and length 1 m filled with $CS_2$ was reported in Ref. [11]. However, in a device with such a small aperture, PC of spatially inhomogeneous radiation is not possible and the dynamic energy range is small. A similar two-cell sceme was studied in Ref. [12] for phasing of radiation from multichannel lasers. However, the SBS threshold could not be lowered because of the capillary size (diameter 5 mm, length 1 m). In addition, the construction used in both cases (placement of the capillary inside the liquid-filled cell) restricted a further increase in the length of the active medium.

Note also that apart from possessing the advantages mentioned above, a scheme with a nonlinear liquid medium is less prone to the laser-induced breakdown of the active medium (breakdown in the fibre causes its damage) and introduces smaller polarisation distortions. To verify this, we will use the expression, obtained from Fresnel formulas, for the phase difference $\delta$ between two polarisation components of the pump wave introduced upon total internal reflection of the pumping radiation:

$$\tan\frac{\delta}{2} = \frac{\cos\theta\left(\sin^2\theta - n^2\right)^{1/2}}{\sin^2\theta},$$

where $n$ is the ratio of the refractive indices of the contacting media. Estimates made for the fibre geometry chosen for the experiments ($\theta \approx 0.08$ rad) show that the phase difference achieves the value $\pi/4$ in a capillary segment of length 13 cm, while the corresponding value for a quartz fibre is 5.9 cm. Thus, the depolarisation constraint imposed on the limiting length of the amplifying PC medium is more stringent for a quartz fibre. In other words, if the SBS gain increment at lengths of such a scale is small ($M \leqslant 1$), depolarisation leads to instability and a deterioration of the PC quality. A detailed analysis of the effect of depolarisation on the PC quality in the case of induced scattering in a fibre is given in Ref. [13].

The experimental setup is shown in Fig. 1. The SBS amplifier represented a $TiCl_4$-filled metal cell having a length 40 cm and an aperture 32 mm. In this setup, a quartz capillary of length 330 cm and aperture 0.85 mm, which is also filled with $TiCl_4$, serves as the generator. For the sake of convenience of operation, the capillary was hermetically mated with the input cells and enclosed in a metal casing of size 40 cm × 40 cm.

A laser with the following parameters was used in the experiment: wavelength 1.054 μm, pulse duration about 30 ns, beam divergence close to the diffraction limit, beam diameter in front of lens (*4*) approximately 8 mm, and pulse energy 1 mJ – 1.5 J. By mounting appropriate phase plates in front of lens (*4*), the divergence of the laser beam was increased by a factor of about 24 (to 2 mrad) and 100 (to 8 mrad). The focal length of lens (*4*) was 12 cm. The focal waist of the beam was projected from the amplifier cell to the entrance of the capillary cell by objective (*5*) placed at a distance of 40 – 50 cm from lens (*4*). This objective had a focal length of about 5 cm and consisted of two lenses with a focal length 10 cm each in order to reduce aberration. The working surfaces of all optical components and cell windows were covered with an antireflection coating.

The energy was measured with IMO – 2N and IMO – 3 calorimeters, and FD – 24K photodiodes with a S8 – 17 storage oscillograph. During the passage of the laser beam in the forward direction, a few percent of the radiation relected from the right polariser (*1*) were used for measuring the incident energy. During the backward passage of the radiation reflected from the SBS mirror, the fraction of the depolarised radiation, reflection coefficient, and the quality of PC were measured. To measure the PC quality, the reflected beam was focused by a lens of focal length 5 m, and a diaphragm of diameter 0.5 mm was placed in front of the calorimeter in the focal waist.

In the course of the experiment, the relative dependence of the reflection coefficient of the SBS mirror on the incident energy was measured for three different divergences of the input radiation ($8.3 \times 10^{-2}$, 2 and 8 mrad). Measurements were made each time in two positions, with open and closed capillary. In other words, the ordinary PC by SBS of a focused beam was compared with the PC by SBS in a two-cell system.

In the case of SBS of a single-mode radiation, the thresholds for the one- and two-cell regimes did not differ significantly (this is in accord with the estimates made by taking the capillary geometry into consideration). For an incident energy of 1.2 mJ in the single-cell regime, about 10% of the energy was reflected, while the threshold of the process for a two-cell regime dropped by a factor of about 1.25, i.e., the threshold energy was $W_{th} \approx 0.9$ mJ.

In the case of multimode radiation, the SBS threshold in the single-cell mode increases in proportion to the divergence of the input radiation, while for the two-cell mode, the threshold increased insignificantly, i.e., by no more than 20 % – 25 % for the maximum divergence, which may be attributed to the aperture losses in the part of the incident radiation scattered at large angles by the phase plate.

The results of measurements of the reflection coefficient for multimode radiation are presented in Fig. 2. Apparently, a considerable part of the reflected radiation diverged at quite large angles and was not received by the calorimeter during the reflection coefficient measurements. This led to comparatively small values of the reflection coefficient and a slight decrease in its value upon an increase in the energy. The fraction of the inverse radiation, i.e., the radiation having the initial diffraction-limited divergence, was as high as 60 % – 80 % even for a 1.5 – 2-fold increase in the threshold (which was determined at the level of 10 % reflection). Upon a further rise of the pump energy over the threshold, the PC quality was found to lie in the interval 70 % – 90 %. It should be noted that in spite of an increase in the depolarisation of the reflected radiation in a two-cell mode (compared to the depolarisation in a single-cell mode), its value did not exceed 20 %.

The PC threshold can be lowered further by varying the capillary geometry as well as by changing the nonlinear-optical medium used in the measurements. Estimates presented here show that a decrease in aperture and an increase in the length of the capillary are undesirable. The liquid used as the SBS medium in the capillary must have a refractive index larger than for fused quartz, and a low absorption at the working wavelength. These requirements are met by $PBr_3$ which has a high refractive index (1.697) and no significant absorption in the visible and near IR

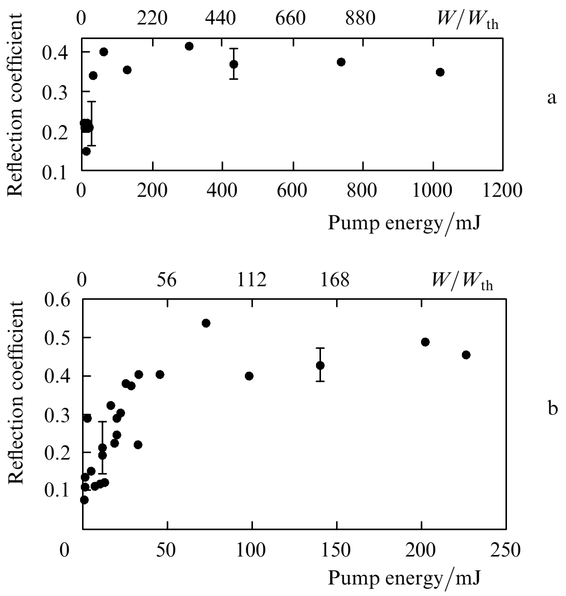


**Figure 2.** Dependences of the reflection coefficient of a PC mirror on the pump energy $W$ and on the excess of the pump energy over the SBS threshold $W/W_{th}$ for a pump beam divergence 8 (a) and 2 mrad (b).

range. For the sake of experimental verification, measurements of absorption by the thermal defocusing technique [14] carried out in a cell containing high-purity $PBr_3$ gave the value $\sim 10^{-6}$ cm$^{-1}$ at a wavelength 1.06 μm. The SBS threshold in $PBr_3$ was found to be 1.27 times lower than the SBS threshold in $TiCl_4$. Consequently, a replacement of the working medium allows a further decrease in the activation threshold for the PC mirror under consideration.

The two-cell PC mirror scheme (consisting of a generator capillary and an amplifier cell) allows a lowering of the threshold of PC by SBS of spatially inhomogeneous radiation to the SBS threshold for a single-mode beam while maintaining the high quality of PC (0.7 – 0.9) and a wide dynamic range (more than $10^3$).

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