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High-average-power SRS conversion of radiation in a $BaWO_4$ crystal

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***Abstract*. The SRS conversion of high-repetition-rate trains of self-phase-conjugated giant pulses of a Nd : YAG laser is studied in a $BaWO_4$ crystal. The SRS radiation with the average power up to 7.5 W and the single-pulse energy in a train of 30 mJ was obtained at the SRS conversion efficiency of 20 % – 30 %. The optical power of a thermal lens produced in the $BaWO_4$ crystal pumped by the 30-W laser radiation was 0.12 m^{-1}, which is an order of magnitude lower than in the known $Ba(NO_3)_2$ crystal.**

Keywords: *stimulated Raman scattering (SRS), conversion efficiency, Stokes radiation component, thermal lens.*

The development of high-power solid-state lasers emitting in different spectral regions is of current interest for laser physics. One of the ways to solve this problem is the SRS conversion of radiation from near-IR lasers. Among the known and sufficiently well-studied SRS-active media, the most efficient are barium nitrate $Ba(NO_3)_2$ and potassium – gadolinium tungstate $KGd(WO_4)_2$ crystals [1 – 10]. These crystals have a high SRS gain g, amounting to 6 and 11 cm GW^{-1} in the $KGd(WO_4)_2$ and $Ba(NO_3)_2$ crystals, respectively, pumped at a wavelength of 1.06 μm.

We have studied in [11] the SRS conversion of trains of single-mode, single-frequency, self-phase-conjugated pulses from a Nd : YAG laser in a $Ba(NO_3)_2$ crystal and have demonstrated the generation of the first Stokes component of SRS radiation with the average power and pulse energy up to 5 W and ~ 30 mJ, respectively, at the SRS conversion efficiency of 15 % – 30 %.

However, $Ba(NO_3)_2$ crystals are hygroscopic and have poor mechanical and thermal parameters [7]. Thus, the optical power of a thermal lens produced in these crystals pumped by radiation with an average power density of 0.7 kW cm^{-2} achieves 8 m^{-1} [9]. Although $KGd(WO_4)_2$ crystals have no such disadvantages, their radiation resistance is low and they have a low cross section for the SRS transitions [7]. These limitations severely prevent the development of high-power solid-state Raman lasers. Therefore, the search for new SRS-active media with good mechanical and thermal properties and a high radiation resistance becomes urgent. These media should not be second to a $Ba(NO_3)_2$ crystal in the SRS gain, allowing the generation of a higher-power SRS radiation. Recent studies resulted in the synthesis of new highly efficient crystals [8], one of which is a barium tungstate $BaWO_4$ crystal ($g \geqslant 8.5$ cm GW^{-1}) [9]. Although the Raman linewidth $\Delta\nu_{BaWO_4} = 1.63$ cm^{-1} of this crystal is larger than the Raman linewidth $\Delta\nu_{Ba(NO_3)_2} = 0.4$ cm^{-1} of a $Ba(NO_3)_2$ crystal, the peak value of the Raman cross section for the $BaWO_4$ crystal is almost the same as for the $Ba(NO_3)_2$ crystal [7 – 9], which is provided by a substantially higher integrated Raman cross section.

In this paper, we studied the possibility of generation of SRS radiation with a high average power in a promising $BaWO_4$ crystal pumped by the same Nd : YAG laser as in Ref. [11].

The optical scheme of the experimental setup is shown in Fig. 1. The pump laser consists of two Nd : YAG active elements (*1*) and (*2*) of size ∅6.3 × 100 mm placed in single-lamp quantrons, passive F_2^- : LiF-laser Q-switch (*3*), four deflecting mirrors (*4 – 7*), and an end reflector based on a Sagnac interferometer formed by beamsplitter (*8*) and mirrors (*9*) and (*10*). Phase $\lambda/2$ plate (*11*) is placed in the Sagnac interferometer to separate linearly polarised radiation. During the development of lasing in the active elements and a F_2^- : LiF crystal, the intracavity intersecting beams write dynamic holographic gratings forming the self-adjust-

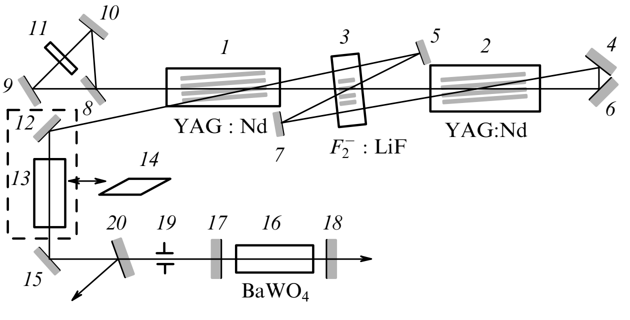

Figure 1. Optical scheme of the laser: (*1, 2*) Nd : YAG active elements; (*3*) F_2^- : LiF passive Q-switch; (*4 – 7, 12, 15*) deflecting mirrors; (*8 – 10*) end reflector based on a Sagnac interferometer; (*11*) $\lambda/2$ phase plate; (*13*) Faraday rotator; (*14*) Fresnel rhomb; (*16*) $BaWO_4$ SRS medium; (*17, 18*) input and output SRS resonator mirrors; (*19*) diaphragm; (*20*) beamsplitter.

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able phase-conjugate cavity of the laser [11]. This provides the generation of single-mode (the beam quality parameter $M^2 < 1.2$) linearly polarised single-frequency radiation with the average power as high as 35 W in the form of trains containing different numbers of pulses (2 – 10) of duration 20 – 100 ns and energy up to 360 mJ with a train repetition rate of up to 30 Hz.

A BaWO$_4$ crystal of size $6 \times 8 \times 95$ mm grown by the Czochralski technique at the Department of Laser Technologies of the Laser Materials and Technology Research Center, A.M. Prokhorov General Physics Institute, RAS [9] was used as SRS medium (*16*). The BaWO$_4$ crystal was mounted inside the external resonator formed by the input ($R_{1.064} = 15\,\%$, $R_{1.18-1.40} = 100\,\%$) and output ($R_{1.064} = 77\,\%$, $R_{1.18-1.40} = 45\,\%$) plane dichroic mirrors. The negative influence of radiation reflected from the SRS resonator on the pump laser oscillation development was eliminated by a nonreciprocal element. When the repetition rate of pump pulse trains was lower than 10 Hz, polarisation mirror (*12*) and Faraday rotator (*13*) were used; for the repetition rate above 10 Hz, the Faraday rotator was replaced by Fresnel rhomb (*14*) serving as a $\lambda/4$ plate.

Due to its high spectral, spatial, and energy parameters, the Nd : YAG laser could be used for SRS conversion without any additional focusing to a nonlinear crystal. The apertures of the Nd : YAG laser (4.2 mm) and the SRS resonator (3.2 mm) were matched by limiting the pump beam diameter by aperture (*19*) of diameter 3.2 mm (Fig. 1).

The radiation power was measured with an IMO-2N power meter. The temporal characteristics of radiation were recorded with an Agilent 54641A oscilloscope using an LFD-2A avalanche photodiode. The energy and temporal parameters of the pump radiation were measured in front of the input mirror of the SRS resonator. The pump pulse energy directed into the resonator was varied by interchangeable optical filters (*20*). The SRS radiation was recorded using spectral prisms which decomposed the output radiation into spectral components: the pump radiation at $\lambda_0 = 1.064$ μm, and the first ($\lambda_1 = 1.18$ μm), second ($\lambda_2 = 1.325$ μm), and third ($\lambda_3 = 1.51$ μm) Stokes components.

The SRS conversion was studied by gradually increasing the number of pulses in a train, their energy and repetition rate, which provided an increase in the average pump power. We studied first the conversion of trains consisting of two pump laser pulses with a train repetition rate of 10 Hz. For this purpose, the transmission of the F_2^- : LiF crystal was set equal to 30 %; the optical pumping of active elements was 40 J per each quantron. The pulse energy and duration were 60 mJ and 20 ns, respectively.

Figure 2 shows the results of the experiment, which demonstrate that the energy of the SRS components gradually increases up to 8 mJ with increasing the pump pulse energy to 50 mJ, whereas the conversion efficiency to the first Stokes component achieves its maximum equal to 30 % when the pump pulse energy is 25 mJ.

A decrease in the conversion efficiency at higher pump energies is explained by a noticeable increase in the second Stokes SRS component (thresholds for the appearance of the first and second Stokes components are close to each other due to the use of a nonselective high-Q SRS resonator), whose energy achieves the value comparable to the energy ~ 8 mJ of the first Stokes SRS component when the pump energy is equal to 50 mJ. The efficiency of conversion to each of the Stokes components is $\sim 17\,\%$ in this case. The maximum total SRS conversion efficiency is 34 % (the dashed curve in Fig. 2), corresponding to the quantum efficiency of 39 %.

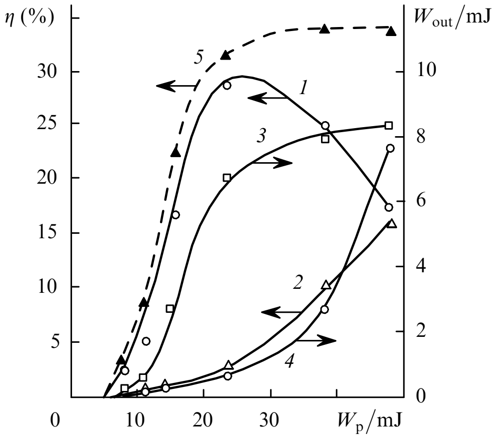

Figure 2. Dependences of the SRS conversion efficiency η, the pulse energy W_{out} of the first (*1*, *3*) and second (*2*, *4*) Stokes components, and the total SRS radiation (*5*) on the pump pulse energy W_{p} upon pumping by trains consisting of two radiation pulses.

To study the SRS conversion at higher average pump laser powers, a greater number of pulses in a train, and a higher pulse repetition rate, we increased the initial transmission of the F_2^- : LiF crystal up to $\sim 50\,\%$ and the pump energy of active elements up to ~ 60 J. In this case, the number of pulses in a train increased up to eight, the pulse energy increased up to 145 mJ, and the pulse duration increased up to 50 ns. The train repetition rate was increased up to 30 Hz. The average power of the pump radiation was 35 W.

Figure 3 shows the dependences of the average power and energy of the total radiation pulse and the SRS components on the average pump power. We observed three SRS components with the average powers equal to 5, 2.4, and 0.25 W for the first, second, and third Stokes components, respectively, and the pulse energy of the SRS

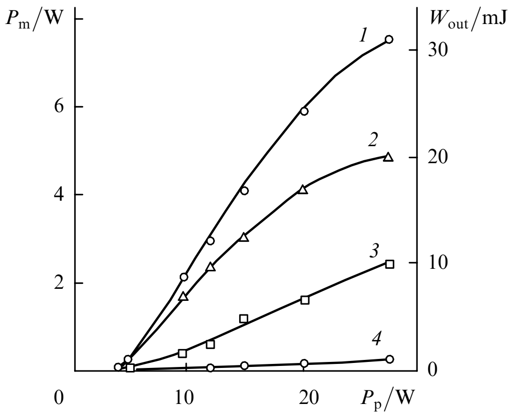

Figure 3. Dependences of the average power P_{m} and pulse energy W_{out} of the total SRS radiation (*1*), and the first (*2*), second (*3*), and third (*4*) Stokes components of the output radiation on the average pump power P_{p} upon pumping by trains consisting of eight radiation pulses.

component equal to 20, 10, and 1 mJ, respectively. The maximum SRS conversion efficiency was 18.4 %, 8.8 %, and 1 % for the first, second and third Stokes components, respectively. The average power of the total SRS radiation exceeded 7.5 W. Therefore, the maximum total SRS conversion efficiency at a high average power achieved 28.2 %, while the quantum efficiency was 31.5 %.

Note that no radiation damage was observed in the $BaWO_4$ crystal exposed to prolonged pumping by radiation with the power density up to 40 kW cm^{-2}. This value proved to be comparable with the admissible power density of 38 kW cm^{-2} that we have obtained for a $Ba(NO_3)_2$ crystal. Note that the divergence of the output SRS radiation obtained from the $BaWO_4$ crystal was substantially lower than that for the $Ba(NO_3)_2$ crystal. We attempted to estimate the thermooptics of the $BaWO_4$ crystal by a change in the refractive index and the optical power of a thermal lens induced in the crystal by the pump radiation with the average power of up to 30 W and the laser beam diameter of 3.2 mm. The change in the refractive index Δn was determined by the number N of displacements of fringes of the interference pattern produced by radiation from an auxiliary He – Ne laser reflected from the front and rear ends of the SRS crystal: $\Delta n = 0.5N\lambda/L$, where L is the SRS crystal length and λ is the wavelength of auxiliary laser radiation. By assuming that the refractive index changes quadratically over the cross section of the SRS crystal (from $n + \Delta n$ in its axial region to n near its boundary; $n = 1.84$ is the refractive index of $BaWO_4$), we estimated from above the optical power of the induced thermal lens [12] as $1/f = 8\Delta nL/a^2$, where $a = 6$ mm is the minimum transverse size of the SRS crystal.

The dependence of the optical power of the thermal lens of the $BaWO_4$ crystal on the average pump power density is presented in Fig. 4. One can see that, as the average pump power is increased up to 30 W in a beam of diameter 3.2 mm, the optical power $1/f$ of the lens linearly increases up to 0.12 m^{-1} (the focal distance of the thermal lens is $f \geqslant 7$ m) at a rate of 0.012 m^{-1} per 1 W cm^{-2} of the average power density, which is an order of magnitude lower than for the barium nitrate crystal [10].

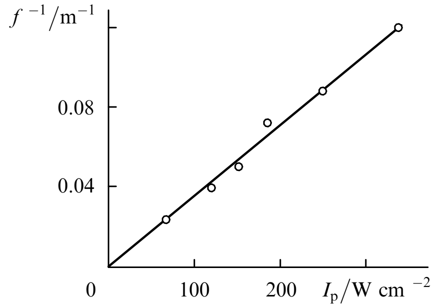

Figure 4. Dependence of the optical power $1/f$ of the thermal lens in the $BaWO_4$ crystal on the average pump power I_p.

Therefore, our investigation has shown that the $BaWO_4$ crystal possesses a number of advantages as a SRS converter over one of the best SRS converters to which the $Ba(NO_3)_2$ crystal belongs. Apart from a high radiation resistance, the slope efficiency and the energy and quantum SRS conversion efficiencies of the $BaWO_4$ crystal pumped by radiation with the high average power are nearly twice as large as those for the $Ba(NO_3)_2$ crystal [11]. Due to its better thermooptical characteristics, the barium tungstate crystal allows one to increase the average pump power by increasing the number of pulses in a train or the repetition rate of pump trains approximately by a factor of eight to achieve the admissible focal distance of the thermal lens (no less than 1 m). This shows that the $BaWO_4$ crystal is a promising nonlinear medium for the development of high-average-power Raman lasers.

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