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Eye-safe Nd:YVO_4 laser with intracavity SRS in a $BaWO_4$ crystal

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Abstract. **A compact diode-pumped eye-safe Nd:YVO_4 laser with an acousto-optic *Q*-switch and an intracavity $BaWO_4$ Raman converter is developed. The laser power at a wavelength of 1536 nm with a pulse repetition rate of 20 kHz is 0.6 W, the diode-to-Stokes slope conversion efficiency reaches 44%. Laser pulses with an energy of 35 μJ and a duration of 10 ns are achieved at a repetition rate of 15 kHz.**

Keywords: *stimulated Raman scattering, SRS laser, eye-safe spectral region, Nd:YVO_4 laser, $BaWO_4$ crystal.*

1. Introduction

Stimulated Raman scattering is an efficient third-order nonlinear optical process converting laser radiation wavelength [1–3]. In recent years, significant interest is attracted to the creation of solid-state SRS lasers, which is explained by the development of new highly efficient nonlinear crystals [4, 5]. Crystalline Raman media are more advantageous than gaseous media due to a high concentration of scattering centres and good thermal and mechanical properties, which allows one to use them for development of compact, reliable, and all-solid-state laser systems operating at desired wavelengths. Laser diodes (LDs) are often used for pumping active media in modern lasers; diode pumping increases efficiency and considerably decreases dimensions of such lasers in comparison with flash-lamp-pumped lasers. Diode-pumped SRS lasers studied previously were designed using an additional SRS cavity [6, 7] or an intracavity scheme [8–11]. The main distinguishing features of intracavity SRS conversion are a high pump power density in the laser and multiple passes of the pump and Stokes radiation through the cavity, which leads to a decrease in the Raman threshold and an increase in the optical conversion efficiency.

The $BaWO_4$ crystal is known as one of the most efficient SRS materials, which has a high stationary and nonstationary SRS gains. The SRS active mode has a frequency of 925 cm^{-1} and a width of 1.6 cm^{-1} at room temperature. The stationary SRS gain at a wavelength of 1064 nm is 8.5 cm GW^{-1} [12]. This value is somewhat lower than in the $Ba(NO_3)_2$ crystal, but higher than in the other tungstate and molybdate crystals [13]. The $BaWO_4$ crystal is nonhygroscopic and has a high breakdown threshold and good thermophysical characteristics. Its thermal conductivity is 2.7 W m K^{-1}, which is higher than in $Ba(NO_3)_2$ but slightly lower than in $KGd(WO_4)_2$ [14].

Eye-safe lasers are required for various medical and lidar applications. The problem of development of such lasers is that the SRS gain decreases with increasing wavelength and, hence, it is necessary to use high pump powers, which may lead to optical breakdown of the crystal. The SRS gain at 1300 nm estimated by the data from [15] is 5.8 cm GW^{-1}. Recently, the authors of [16] reported on SRS conversion of a Nd:YAG laser radiation (1 Hz, 8 ns, 1319 nm) into the eye-safe region using a $BaWO_4$ crystal. The energy of pulses at a wavelength of 1502 nm was 8.5 mJ, and the conversion efficiency was 47%. In work [17], a SRS converter based on a $BaWO_4$ crystal with an external cavity demonstrated a power of 0.6 W with a conversion efficiency of 14.5%. For pumping, a flash-lamp-pumped Nd:YAG laser (1319 nm) with an acousto-optic *Q*-switch (pulse repetition rate 1.7 kHz) was used. In [18], intracavity SRS conversion was studied in a flash-lamp-pumped Nd:YAG laser with a pulse repetition rate of 3 Hz. The authors obtained radiation at a wavelength of 1.5 μm with a conversion efficiency up to 60% and a pulse energy up to 40 mJ.

In the present paper, we report (as far as we know, for the first time) on the development of a compact diode-pumped Nd:YVO_4 laser with an acousto-optic *Q*-switch and an intracavity SRS converter based on a $BaWO_4$ crystal, which operates at 1536 nm with a low threshold and a high conversion efficiency. The maximum laser power was 0.6 W, while the diode-to-Stokes slope conversion efficiency reached 44%.

2. Experimental setup

The scheme of the experimental setup is shown in Fig. 1. The laser was based on a Nd:YVO_4 active element 3 × 3 × 17 mm in size with a composite structure consisting of a central part of a Nd:YVO_4 crystal (0.3 at %, *a*-cut) and 3-mm-thick edges made of pure YVO_4 in order to decrease the thermal lens. As SRS elements, we used $BaWO_4$ crystals 30 and 45 mm long. The active element and the nonlinear crystal wrapped into indium foil were mounted into water-cooled copper heat sinks whose temperature was stabilised at about 20 °C. The wavelength of the first Stokes component under excitation at a wavelength of 1342 nm is 1536 nm. The faces of the active element and SRS crystals were antireflection coated for the laser and Stokes wavelengths (reflection coefficient $R_{1342,\,1536}$ < 0.5%). A concave dichroic input mirror with a curvature radius of 1000 mm, which was transparent for the LD wavelength (transmittance T_{808} > 94%), reflected the laser radia-

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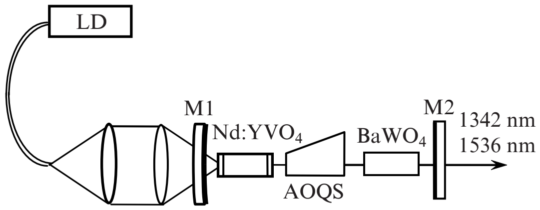

Figure 1. Optical scheme of a Nd:YVO_4 laser with laser diode (LD) pumping, an acousto-optic Q-switch (AOQS), and an intracavity $BaWO_4$ SRS converter; M1 and M2 are the input and output mirrors, respectively.

tion ($R_{1342,\,1536}$ > 99%). Two plane mirrors with R_{1342} > 98% and R_{1536} = 86% and 70% were used as output mirrors.

For pumping, we used a fibre-coupled (fibre diameter 600 μm, numerical aperture 0.22) laser diode (wavelength 808 nm, power up to 25 W). A two-lens optical system focused the pump radiation into the laser element, the excitation region diameter being about 600 μm. For Q-switching, we used a QS041-1H/J-AP5 acousto-optic Q-switch 35 mm long driven at a 41-MHz carrier frequency with a rf power of 15 W. We used Q-switching rates of 15, 20, and 25 kHz. All optical elements of the laser were antireflection coated for a wavelength of 1064 nm and positioned at the minimum distance from each other, which allowed us to decrease the cavity length to 110 mm.

For spectral selection of SRS radiation, we used a dichroic mirror which reflected the pump radiation (R_{1342} > 99.8%) and partially transmitted the Stokes radiation (T_{1536} = 30%). Energy characteristics were measured using a Molectron EPM2000 energy/power meter. The temporal pulse profile was recorded by a germanium PIN photodiode and a Tektronix TDS-5052 oscilloscope with a time resolution of about 0.5 ns.

3. Experimental results and discussion

An intracavity SRS converter completely locking the pump radiation inside the cavity allows one to obtain a high conversion efficiency. To determine the maximum laser power achievable at the fundamental wavelength 1342 nm, in the scheme of Fig. 1 we used an output mirror with the reflection coefficient R_{1342} = 90%, which was close to optimal. In this case, SRS conversion in the laser was absent. In a Q-switching regime with a pulse repetition rate of 20 KHz and 10-W cw diode pumping, the average power of the laser at a wavelength of 1342 nm was 1.5 W [Fig. 2, curve (*1*)]. The laser slope efficiency reached 20%. The laser pulses had a smooth temporal profile with a half-height duration of about 80 ns.

When using output mirrors reflecting at 1342 nm, we observed intense output Stokes radiation. Figure 2 presents the dependences of the Stokes radiation power on the diode pump power for a laser with a $BaWO_4$ crystal 45 mm long at a pulse repetition rate of 20 kHz for two output mirrors. The use of the output mirror with a higher reflection coefficient at a wavelength of 1536 nm leads to a decrease in the Raman oscillation threshold from 7 W (R_{1536} = 70%) to 5.2 W (86%). The maximum average power of 0.6 W at a pump power of 9 W (which corresponds to a 46% energy efficiency and a 53% quantum conversion efficiency with respect to the power at 1342 nm) was achieved using an output mirror with R_{1536} =

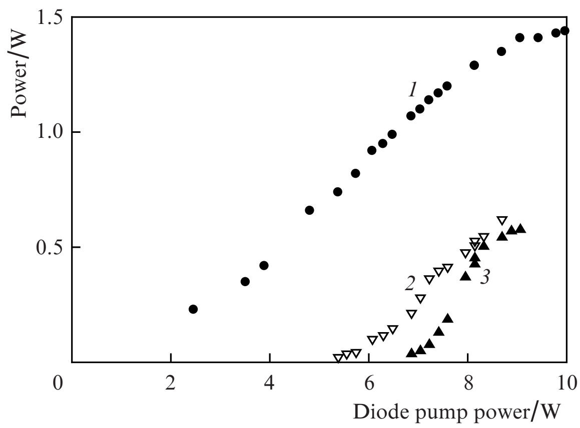

Figure 2. Power of a laser with a 45-mm-long $BaWO_4$ crystal and an output mirror with R_{1342} = 90% (pulse repetition rate 20 kHz) (*1*) and power of 1542-nm Stokes obtained using output mirrors with R_{1536} = 86% (*2*) and 70% (*3*) versus the diode pump power.

70%. In this case, the maximum diode-to-Stokes conversion slope efficiency reached 44%. In all the cases, the radiation was polarised horizontally (in the plane of Fig. 1), which corresponded to the minimal losses in the acousto-optic Q-switch.

The use of a $BaWO_4$ crystal 30 mm long in the laser with a pulse repetition rate of 20 kHz and a mirror with R_{1536} = 70% lead to an increase in the Raman oscillation threshold and a decrease in the conversion efficiency (Fig. 3). This is explained by a smaller SRS gain, which is linearly proportional to the crystal length. The use of longer SRS crystals can lead to a further increase in efficiency, but the synthesis of such crystals is a difficult technological problem.

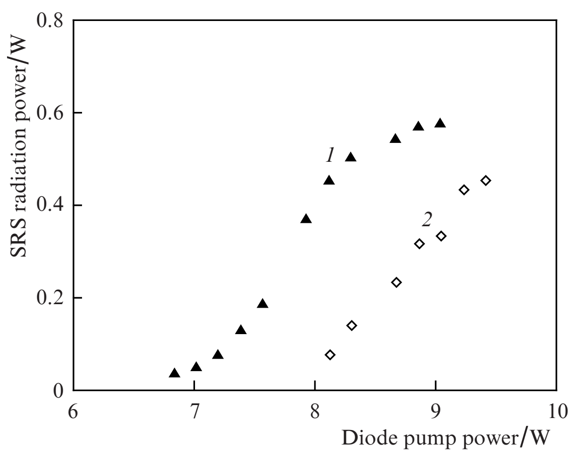

Figure 3. Dependences of the Stokes radiation power of a laser with intracavity SRS (output mirror with R_{1536} = 70%, pulse repetition rate 20 kHz) on the diode pump power for $BaWO_4$ crystals with lengths of 45 (*1*) and 30 mm (*2*).

The dependences of the Stokes energy for pulse repetition rates of 15, 20, and 25 kHz and for output mirrors with R_{1536} = 86% and 70% are presented in Fig. 4. As is seen from the figure, at the lowest pulse repetition rate (15 kHz), the pulse energy reaches 35 μJ at a pump power of 8 W. The long interval between pulses makes it possible to accumulate a higher

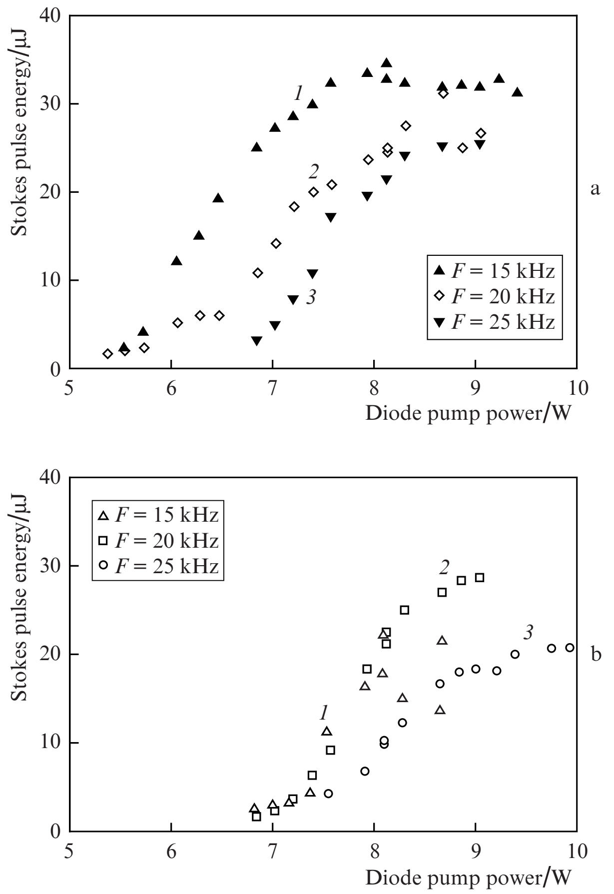

Figure 4. Dependences of the Stokes radiation energy of a laser with a $BaWO_4$ SRS crystal 45 mm long on the diode pump power for pulse repetition rates of 15 (*1*), 20 (*2*), and 25 kHz (*3*) and output mirrors with R_{1536} = 86% (a) and 70% (b).

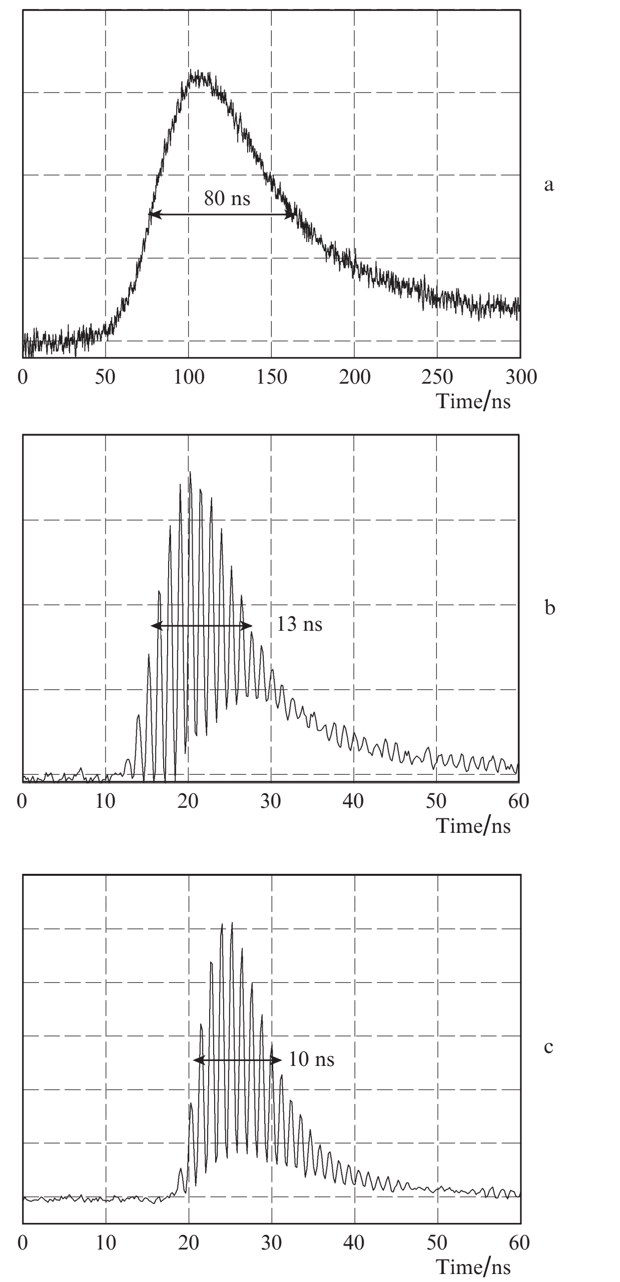

Figure 5. Oscillograms of output pulses of a laser with a 45-mm-long $BaWO_4$ crystal (pulse repetition rate 20 kHz, wavelength 1342 nm, output mirror with R_{1342} = 90%) (a) and Stokes pulses for output mirrors with R_{1536} = 86% (b) and 70% (c).

population inversion in the active medium, which increases the total energy of output pulses.

The compact Nd : YVO_4 laser with an acousto-optic *Q*-switch, cw diode pumping, and an output mirror with R_{1342} = 90% emitted 1342-nm pulses with a smooth temporal structure (Fig. 5a), which points to single-mode lasing. The spectral width of the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ optical transition in the Nd : YVO_4 crystal is approximately threefold larger than in Nd : YAG [19]. The use of a cavity with a high *Q*-factor for the wavelength 1342 nm in the case of intracavity SRS leads to multimode lasing. SRS, as a fast nonlinear process, can modulate laser radiation and thus cause mode locking in the laser, which results in lasing of ultrashort pulses. The oscillograms of laser pulses (Figs 5b and 5c) demonstrate lasing of trains of picosecond Stokes pulses. The duration of trains was 13 and 10 ns in the case of output mirrors with R_{1536} = 86% and 70%. The delay between two consequent pulses was about 0.6 ns, which was determined by the laser cavity length. The time resolution of the recording system was insufficient for measuring the duration of individual pulses, which were shorter than 500 ps. Using an output mirror with a higher transmission at 1536 nm, we obtained shorter output pulse trains and a higher peak intensity. The mode-locking regime did not allow us to measure the peak intensity of the obtained laser radiation. Note that, in the case of solid-state active media with narrower laser transitions, intracavity SRS lasers operate in a single-mode regime and mode locking does not occur [20]. Thus, the use of active laser media with particular spectral parameters, as well as the use of spectrally selective elements inside the cavity, allows one to control the number of generated modes in SRS lasers and to choose mode-locking or *Q*-switching regime.

4. Conclusions

We created a compact diode-pumped 1536-nm Nd : YVO_4 laser with an acousto-optic *Q*-switch and an intracavity SRS converter based on a $BaWO_4$ crystal. The output power at a pulse repetition rate of 20 kHz with a 45-mm-long $BaWO_4$ crystal was 0.6 W with a diode-to-Stokes slope conversion efficiency of 44%. Laser pulses with an energy of 35 μJ and a duration of 10 ns were obtained at a pulse repetition rate of 15 kHz. The laser operated in a mode-locking regime and emitted trains of 20–30 picosecond pulses with a duration shorter than 500 ps.

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