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Raman laser with intracavity conversion of 1.34-μm laser radiation in a $BaWO_4$ crystal

A.V. Gavrilov, M.N. Ershkov, A.V. Fedin

Abstract. **Intracavity Raman conversion of 1.34-μm radiation of a Nd : YAG laser by a $BaWO_4$ crystal into the 1.53-μm first-Stokes component is studied in different operation regimes. In the case of passive *Q*-switching of the Nd : YAG laser, the SRS radiation has an average power of 0.28 W with a pulse train energy up to 5 mJ, an individual pulse duration of 19 ns, and a pump pulse repetition rate of 15 Hz. In the case of active *Q*-switching, the average SRS power is 0.85 W at a pulse energy up to 28 mJ, a pulse duration of 20 ns, and a pump pulse repetition rate of 30 Hz.**

Keywords: *stimulated Raman scattering, BaWO₄ crystal, Nd: YAG laser, Q-switching.*

Creation of compact and reliable lasers emitting at the wavelength $\lambda = 1.5$ μm and longer is an important problem of laser physics [1 – 9], because this radiation is eye-safe and propagates through the atmosphere and optical fibres with low losses. One of the promising ways to obtain laser radiation in this region is the frequency conversion of radiation of widely spread commercially available neodymium lasers using stimulated Raman scattering (SRS) in crystals [10 – 15]. Optical pumping of $Ba(NO_3)_2$ crystals at 1.064 μm allowed one to obtain the third-Stokes component of Raman scattering at 1.598 μm with an average power of 0.22 W and a pulse repetition rate of 20 Hz [11]. The poor thermophysical parameters of $Ba(NO_3)_2$ crystals restrict their application in high-average-power laser systems. The average power of SRS radiation can be considerably increased by using Raman media with better thermooptical properties and by conversion to lower Stokes components. Two-stage SRS conversion of 1.064-μm Nd : YAG laser radiation in synthetic diamond was studied in [12]. There, the second Stokes component at 1.485 μm had an average power of 1.63 W at a pulse repetition rate of 5 kHz. The energy of an individual pulse with a duration of ~10 ns was ~0.33 mJ. The main drawback of multistage conversion schemes is the existence of losses at each conversion stage, because of which the one-stage conversion seems to be more promising [13 – 15]. In this case, the radiation at the nonfundamental $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition of Nd^{3+} ions at $\lambda \approx 1.3$ μm is used for pumping.

In [13], laser trains of three approximately 40-ns pulses with the train energy up to 40 mJ at 1.53 μm were obtained using SRS of Nd : YAG radiation in an external cavity. The use of an intracavity scheme allows one to use most efficiently the pump radiation and achieve SRS with the maximum energy efficiency. Intracavity SRS self-conversion of Nd^{3+} : KGW laser radiation at 1.351 μm was obtained in [14]. The energy of individual output pulses at 1.538 μm was 8 – 14 mJ at a duration of 15 – 25 ns. The intracavity Raman conversion of Nd : YVO_4 laser radiation in a $BaWO_4$ crystal was studied in [15]. In this work, the fundamental (λ = 1.342 μm) radiation of a Nd : YVO_4 laser with 20-kHz diode pumping and acousto-optic *Q*-switching was converted to radiation at 1.536 nm with an average power of 0.6 W. At a pulse repetition rate of 15 kHz, the energy of 10-ns SRS pulses was 35 mJ.

In the present work, we experimentally study the intracavity SRS conversion of 1.34-μm radiation of a passively and electro-optically *Q*-switched Nd:YAG laser into the first-Stokes component at 1.53 μm using a $BaWO_4$ crystal.

First, we studied the SRS radiation parameters in the case of passive *Q*-switching of the laser with $\lambda = 1.34$ μm. The optical scheme of the experimental setup is shown in Fig. 1.

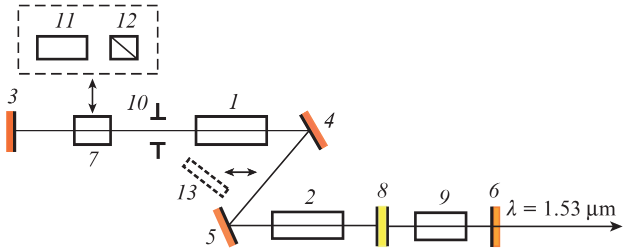

Figure 1. Optical scheme of an intracavity Raman laser: (*1*, *2*) Nd : YAG active elements; (*3*, *4*, *5*) highly reflecting mirrors; (*6*, *8*) Raman cavity mirrors; (*7*) PQS; (*9*) $BaWO_4$ crystal; (*10*) aperture; (11) electro-optic *Q*-switch; (*12*) Glan prism; (*13*) intracavity mirror.

The laser contains two active Nd:YAG elements (*1*) and (*2*), each of them being 6.3 mm in diameter and 130 mm long. Optical pumping was performed by DNP-6/90A lamps placed together with the active elements in a pump cavity with diffuse reflectors and connected to a GND-13 power supply. Initially, the capacity of storage capacitors for each pump cavity was 75 μF. The pump pulse duration was 250 μs. The pump pulse repetition rate was varied from 1 to 30 Hz. To suppress lasing at 1.064 μm, we used a Z-shaped cavity scheme with plane selective mirrors (*4*) and (*5*) (reflection coefficients $R_{1.34} > 98\%$ at $\lambda = 1.34$ μm and $R_{1.064} < 2\%$ at λ = 1.064 μm). Plane end mirrors (*3*) and (*6*) had high reflection

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coefficients ($\sim$99%) at 1.34 μm. For passive *Q*-switching, we used a passive *Q*-switch (PQS) (*7*) based on a V : YAG crystal 6.3 mm in diameter and 4 mm long. The faces of the active elements and PQS were antireflection coated for the wavelength 1.064 μm. The SRS cavity with a 8-cm-long $BaWO_4$ crystal (*9*) was formed by plane mirrors (*6*) ($R_{1.34} > 98\%$, $R_{1.53} = 55\%$) and (*8*) ($R_{1.34} = 30\%$, $R_{1.53} > 99\%$). The reflection coefficient of the SRS cavity mirrors at the second Stokes wavelength (1.78 μm) did not exceed 5%, which almost completely excluded the second Stokes generation. An aperture diaphragm (*10*) with a diameter of 5 mm was placed between the active element (*1*) and the PQS. The energy characteristics of the SRS radiation were measured by an Ophir laser power/energy meter. The temporal parameters were measured by an LFD-2A avalanche photodiode connected to an Agilent oscilloscope with a frequency bandwidth of 350 MHz.

In this cavity scheme, the maximum electric pump energy was limited to 75 J by the radiation resistance of antireflection coatings of the PQS; optical breakdown of the $BaWO_4$ crystal at these energies did not occur. The dependence of the average SRS power on the pump pulse repetition rate was studied for the initial PQS transmittance $T_0 = 47\%$, 59%, and 74% (Fig. 2). It was found that, in the case of a PQS with $T_0 =$ 59%, the average SRS power linearly increases with increasing pulse repetition rate from 2 to 5 Hz and reaches 0.2 W, which corresponds to the maximum energy (40 mJ) recorded for a four-pulse train at 1.53 μm. With a further increase in the pump pulse repetition rate, we observe a saturation of the average SRS power, which is explained by considerable residual losses in the V : YAG crystal, which lead to a strong heating of the used PQSs and to a visually observed sharp deterioration of the laser beam quality. The maximum average SRS power (0.28 W) was observed in the case of a PQS with $T_0 = 59\%$ and a pulse repetition rate of 15 Hz. The corresponding dependences of the time characteristics of radiation on the pump pulse energy are presented in Fig. 3. At the maximum pump pulse energy of 75 mJ and a repetition rate of 15 Hz, the laser emitted a train of four pulses at 1.53 μm with a total energy up to 19 mJ, a repetition period of 20 μs, and an individual pulse duration of $\sim$19 ns.

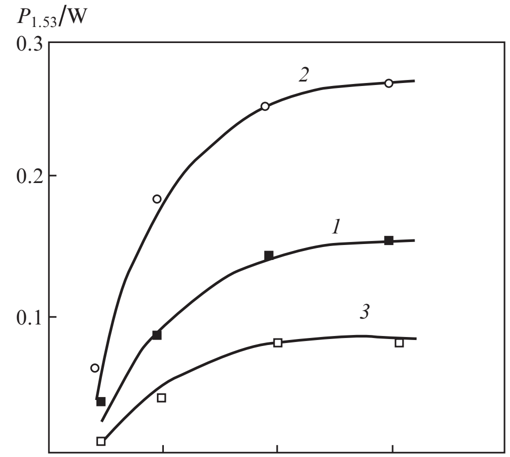

Figure 2. Dependences of the Raman power $P_{1.53}$ at 1.53 μm on the pump pulse repetition rate *f* at the initial PQS transmittance $T_0 = 47\%$ (*1*), 59% (*2*), and 74% (*3*).

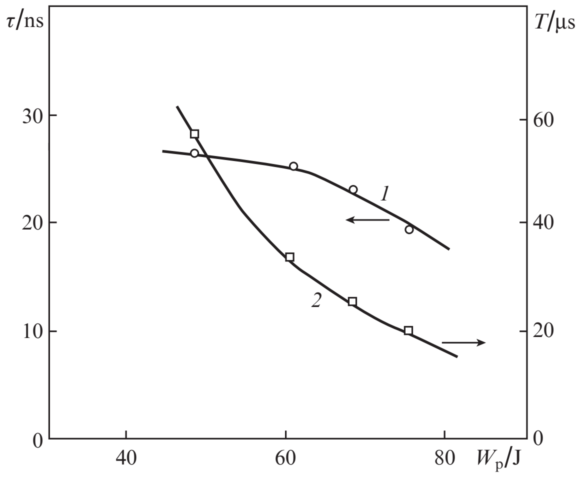

Figure 3. Dependences of the duration τ (*1*) and the repetition period *T* (*2*) of SRS pulses on the pump pulse energy W_p at the pulse repetition rate *f* = 15 Hz and the initial PQS transmittance $T_0 = 59\%$.

The SRS conversion of laser radiation at 1.34 μm in the case of electro-optic *Q*-switching was also studied using the scheme shown in Fig. 1. As a *Q*-switch, we used a $LiNbO_3$ crystal (*11*) and a Glan prism (*12*). In this case, we made some changes in the scheme. To decrease the action of intense intracavity radiation on the $LiNbO_3$ crystal, we introduced a mirror (*13*) ($R_{1.34} = 70\%$, $R_{1.064} < 2\%$) in the cavity. For the same purpose, the capacity of the discharge capacitors for the pump cavity (*1*) was decreased from 75 μF to 50 μF. The maximum electric pump energy in this case was 63 J and was limited by the radiation resistance of the $LiNbO_3$ crystal. At the pulse repetition rate *f* = 5 Hz, the average SRS power was $\sim$0.1 W at a pulse energy of 19.6 mJ. In this scheme, we managed to increase the pump pulse repetition rate to 30 Hz, which corresponded to an electric pump power of 1.9 kW. The average SRS power reached 0.44 W [Fig. 4, curve (*1*)]. An increase in the thermal load on the $LiNbO_3$ crystal with increasing pump power led to a decrease in the SRS pulse energy by 25%, from 19.6 to 14.7 mJ [Fig. 5, curve (*1*)]. The peak SRS pulse power in this case decreased from 0.98 to 0.74 MW at the same pulse duration of 20 ns.

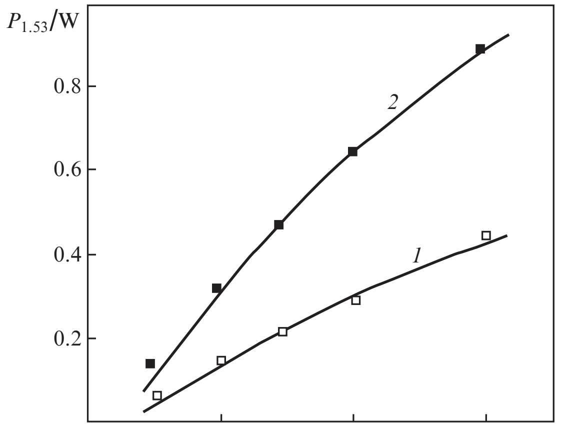

Figure 4. Dependences of the Raman power $P_{1.53}$ on the pump pulse repetition rate *f* for the schemes with $LiNbO_3$ (*1*) and $LiTaO_3$ (*2*).

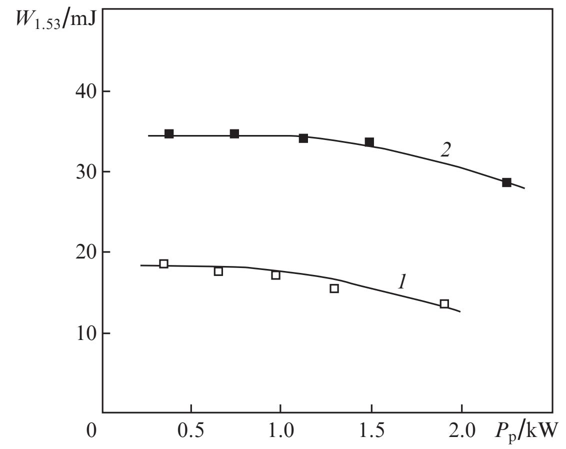

Figure 5. Dependences of the Raman pulse energy $W_{1.53}$ on the electric pump power P_p for the schemes with $LiNbO_3$ (*1*) and $LiTaO_3$ (*2*).

To increase the average SRS power, instead of $LiNbO_3$ we used a $LiTaO_3$ crystal, which has a higher radiation resistance; the other elements of the scheme remained the same. In this case, it was possible to increase the electric pump energy to 75 J. At a pump pulse repetition rate of 30 Hz, the average SRS power was 0.85 W [Fig. 4, curve (*2*)]. In this scheme, the second Stokes component with $\lambda = 1.78$ μm was also recorded. The maximum average power of this component did not exceed 9% of the first Stokes component and was 75 mW. With increasing electric pump power to 2.3 kW, the energy of SRS pulses at 1.53 μm changed not so strongly (less than by 18%), from 34 to 28 mJ [Fig. 5, curve (*2*)]. The peak power of SRS pulses with a duration of ~20 ns changed from 1.7 to 1.4 MW. These parameters are almost twice as high as the corresponding values obtained in the scheme with a $LiNbO_3$ crystal. Since the average SRS power in the considered case increases almost linearly without saturation, it can be further increased by increasing the pump pulse repetition rate.

Thus, we obtained eye-safe laser radiation at 1.53 μm as a result of the first-Stokes Raman conversion in a $BaWO_4$ crystal. Using intracavity conversion of 1.34-μm radiation of a Nd:YAG laser with passive and electro-optic *Q*-switching, we achieved the SRS power of 0.28 and 0.85 W, respectively, which is promising for practical applications.

References

1. Konovalov V.A., Pavlovich V.L., Raevskii E.V. *Kvantovaya Elektron.*, **32** (3), 192 (2002) [*Quantum Electron.*, **32** (3), 192 (2002)].
2. Bykov V.N., Sadovoi A.G. *Kvantovaya Elektron.*, **32** (3), 202 (2002) [*Quantum Electron.*, **32** (3), 202 (2002)].
3. Abazadze A.Yu., Bykov V.N., Zverev G.M., Pleshkov A.A., Simakov V.A. *Kvantovaya Elektron.*, **32** (3), 210 (2002) [*Quantum Electron.*, **32** (3), 210 (2002)].
4. Naumov V.L., Onishchenko A.M., Podstavkin A.S., Shestakov A.V. *Kvantovaya Elektron.*, **32** (3), 225 (2002) [*Quantum Electron.*, **32** (3), 225 (2002)].
5. Ustimenko N.S., Gulin A.V. *Kvantovaya Elektron.*, **32** (3), 229 (2002) [*Quantum Electron.*, **32** (3), 229 (2002)].
6. Abazadze A.Yu., Zverev G.M., Kolbatskov Yu.M., Ustimenko N.S. *Kvantovaya Elektron.*, **34** (1), 20 (2004) [*Quantum Electron.*, **34** (1), 20 (2004)].
7. Rudnitskii Yu.P., Shachkin L.V., Durmanov S.T., Smirnov G.V. *Kvantovaya Elektron.*, **35** (12), 1113 (2005) [*Quantum Electron.*, **35** (12), 1113 (2005)].
8. Galagan B.I., Denker B.I., Sverchkov S.E., Kuleshov N.V., Kisel V.E., Levchenko V.I. *Kvantovaya Elektron.*, **37** (4), 351 (2007) [*Quantum Electron.*, **37** (4), 351 (2007)].
9. Dashkevich V.I., Orlovich V.A., Shkadarevich A.P. *Zh. Prikl. Spektr.*, **76**, 725 (2009).
10. Basiev T.T., Powell R.C., in *Handbook of Laser Technology and Applications* (Bristol – Philadelphia: Institute of Physics Publishing, 2004).
11. Takei N., Suzuki S., Kannari F. *Appl. Phys. B*, **74** (6), 521 (2002).
12. Sabella A., Piper J.A., Mildren R.P. *Opt. Express*, **19** (23), 23554 (2011).
13. Basiev T.T., Basieva M.N., Gavrilov A.V., Ershkov M.N., Ivleva L.I., Osiko V.V., Smetanin S.N., Fedin A.V. *Kvantovaya Elektron.*, **40** (8), 710 (2010) [*Quantum Electron.*, **40** (8), 710 (2010)].
14. Dashkevich V.I., Orlovich V.A., Shkadarevich A.P. *Zh. Prikl. Spektr.*, **77**, 377 (2010).
15. Zverev P.G., Ivleva L.I. *Kvantovaya Elektron.*, **42** (1), 27 (2012) [*Quantum Electron.*, **42** (1), 27 (2012)].