High-peak-power diode-pumped actively Q-switched Nd:YAG intracavity Raman laser with an undoped YVO_4 crystal

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ABSTRACT

The efficient stimulated Raman scattering conversion in a diode-pumped actively Q-switched Nd:YAG laser was achieved with an undoped YVO_4 crystal as a Raman shifter. With an incident pump power of 16.2 W, 1176-nm first Stokes average output power of 2.97 W was generated at a pulse repetition rate of 50 kHz. The maximum pulse energy is higher than 83 μJ at both 20 kHz and 30 kHz. With mode-locked modulation, the effective pulse width far above threshold is usually below 5 ns. With an incident pump power of 7.62 W, the peak-power of 43.5 kW was demonstrated at 20 kHz.

Keywords: Raman laser; diode-pumped laser; actively Q-switched

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1. Introduction

Neodymium-doped yttrium aluminum garnet and yttrium vanadate (Nd:YAG and Nd:YVO_4) are the most widely used materials of solid-state laser gain medium [1,2]. The Nd:YVO_4 crystal has a strong broadband absorption and an effective stimulated emission cross section which is five times larger than Nd:YAG [1]. These properties imply that a Nd:YVO_4 laser usually has the higher efficiency and broader operating temperature than a Nd:YAG laser. In the field of Raman laser, the availability of self-Raman process also made the study of diode-pumped passively Q-switched (PQS) and actively Q-switched (AQS) Nd:YVO_4 Raman lasers attractive [3,4]. However, the Nd:YAG crystal has other advantages such as better thermal property and much longer fluorescence life time. Especially the long life time can raise the output pulse energy of a fundamental AQS laser, and should be able to raise the output pulse energy of a AQS Raman laser at the Stokes wavelength. This means that the conversion efficiency of the intracavity stimulated Raman scattering (SRS) might be increased in an AQS Nd:YAG solid-state laser.

With the development of the crystals as Raman shifters, intracavity Raman lasers are realized as an efficient and practical scheme for extending lasing spectrum [2,5-8]. $Ba(NO_3)_2$ [9], $LiIO_3$ [10], $KGd(WO_4)_2$ [11], $PbWO_4$ [12], and $BaWO_4$ [13-19] are well known materials for SRS. Further more, YVO_4 and $GdVO_4$ were found to be the efficient $\chi^{(3)}$-materials for Raman laser [20]. Recently, we have exhibited the AQS Nd:YVO_4 Raman laser with an undoped YVO_4 crystal which was demonstrated as a potential Raman shifter [21]. However, Q-switched Nd:YAG intracavity Raman lasers based on YVO_4 crystals have not been reported to our knowledge.

In this letter, we report the high-pulse-energy and high-peak-power intracavity YVO_4 SRS generation in a compact diode-pumped AQS Nd:YAG laser. At an incident pump power of 16.2 W, 1176-nm first Stokes average output power of 2.97 W is efficiently generated at a pulse repetition frequency (PRF) of 50 kHz. The maximum output pulse energy is higher than 83 μJ. Then, the overall conversion efficiency were up to 21.3-18.3%. The output pulses display a mode-locking phenomenon that leads the narrow effective pulse width and the maximum peak power to be 43.5 kW.

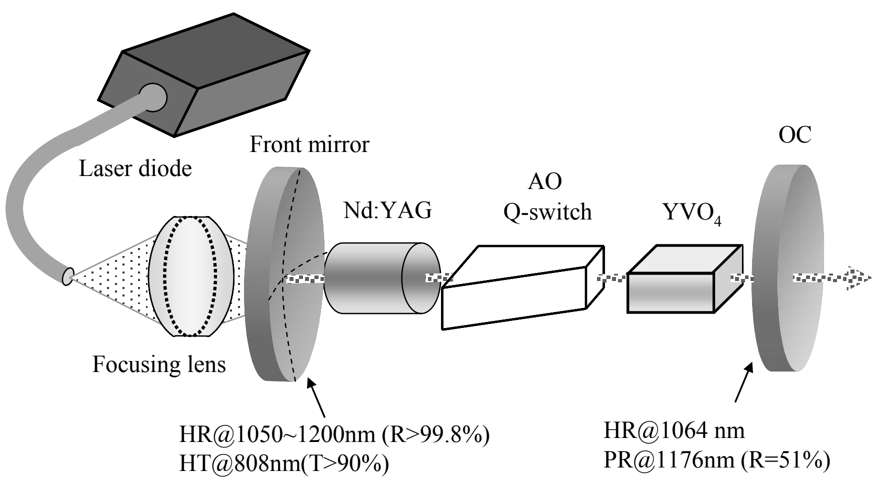

Fig. 1. Scheme of a diode-pumped actively Q-switched Nd:YAG/YVO_4 Raman laser.

2. Experimental setup

Figure 1 depicts the experimental configuration for the diode-pumped AQS Nd:YAG/YVO_4 Raman laser. The cavity mirrors which have special dichroic coating for efficient conversion at the first Stokes component form a plano-concave configuration. The input mirror is a 500-mm radius-of-curvature concave mirror with antireflection coating at 808 nm on the entrance face (R<0.2%), high-reflection coating at 1050-1200 nm (R>99.8%) and high-transmission coating at 808 nm on the other surface (T>90%). The output coupler is a flat mirror with high-reflection coating at 1064 nm (R>99.8%) and partial-reflection coating at 1176 nm (R=51%). Note that the output coupler reflectivity is not optimized and it is limited in availability.

The pump source was an 808-nm fiber-coupled laser diode with a core diameter of 800 μm, a numerical aperture of 0.16 and a maximum output power of 25 W. A focusing lens system with a 85% coupling efficiency was used to re-image the pump beam into the laser crystal. The waist radius of the pump beam was approximately 400 μm. The laser medium was a 0.8-at.% Nd^{3+}:YAG crystal with a length of 10 mm. Both sides of this laser crystal were coated for antireflection (AR) at 1.06 μm (R<0.2%). The Raman crystal was an a-cut undoped YVO_4 crystal with a length of 9.6 mm. These two crystals were both wrapped with indium foil and mounted in water-cooled copper blocks individually. The water temperature was maintained at 20 ℃. The 30-mm-long acousto-optic Q-switch (NEOS Technologies) had antireflection coatings at 1064 nm on both faces and was driven at a 27.12 MHz center frequency with 15 W of RF power. The overall laser cavity length was around 9 cm and depended on pumping power.

3. Experimental results and discussion

The AQS Nd:YAG laser performance at 1064 nm was firstly studied for evaluating the conversion efficiency of the intracavity SRS. For this investigation, an output coupler with partial reflection at 1064 nm was used instead of the above-mentioned Raman cavity output coupler. The optimum reflectivity of the output coupler was found to be approximately 80%. Figure 2 shows the average output power at the fundamental wavelength of 1064 nm with respect to the incident pump power at different pulse repetition rate from 20 kHz to 50 kHz. The threshold for 1064-nm oscillation was below 2.5 W and insensitive to the PRF. With an incident pump power of 8.63, 13.3, and 16.2 W, the average output powers at 1064 nm were 2.6-2.9, 4.7-5.0, and 5.8-6.3 W for PRFs in the range of 20-50 kHz.

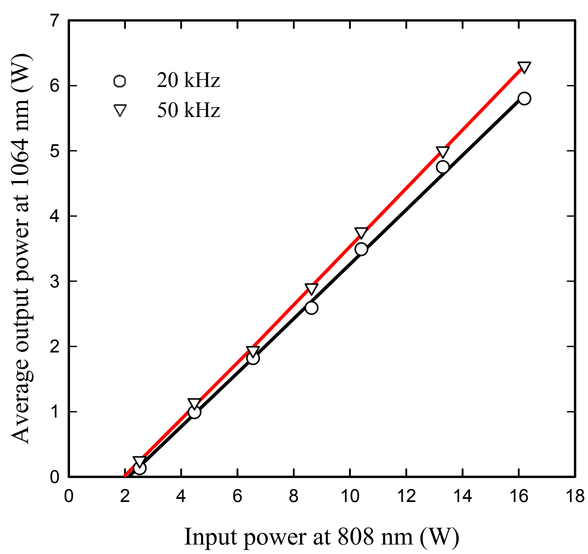

Fig. 2. The average output power at the fundamental wavelength of 1064 nm with respect to the incident pump power at different pulse repetition rate from 20 kHz to 50 kHz.

Besides, the partially polarized laser beam with a polarization ratio of 3:1 should be excited by the acousto-optic Q-switch and nonlinear Raman crystal. However, when the intracavity Raman laser was used, the relatively random polarization compared to $Nd:YVO_4/YVO_4$ Raman laser may benefit the robustness of the Raman crystal. Therefore, our experimental results revealed that the same Raman crystals can sustain higher peak power per unit area in Nd:YAG laser.

The experimental result for optical spectrum of the Raman laser was monitored by an optical spectrum analyzer (Advantest Q8381A, including a diffraction grating monochromator) with a resolution of 0.1 nm. The Raman scattering spectrum of an YVO_4 crystal is showed in Fig. 3. The first Stokes wavelength of 1176 nm was converted from the fundamental wavelength at 1064 nm by Raman shift at 890 cm^{-1} came from the YVO_4 crystal [20,21]. There is no second Stokes wavelength observed for all pumping power.

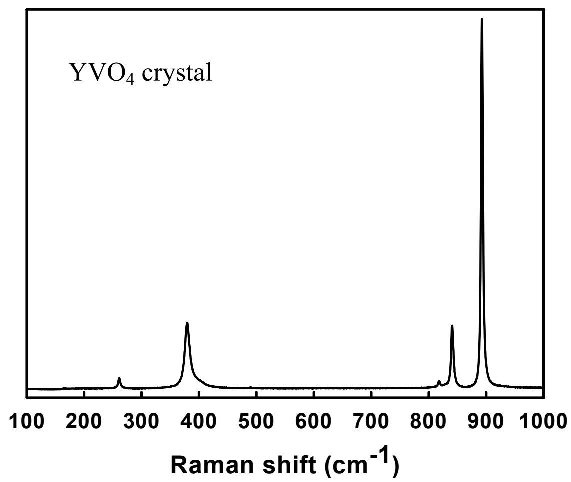

Fig. 3 (a). The Raman scattering spectrum of an YVO_4 crystal, which is almost the same as it of Nd:YVO_4 crystal.

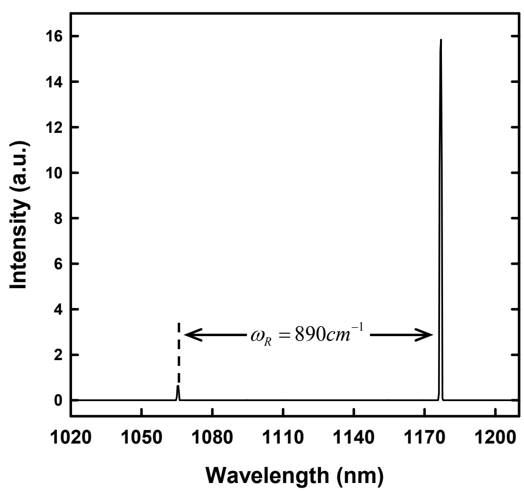

Fig. 3 (b). Optical spectrum of the actively Q-switched Raman output. The fundamental and Raman component are at 1064.5 nm and 1175.9 nm.

Figure 4 illustrates the average output power and output pulse energy at 1176 nm with respect to the incident pump power for PRF of 20, 30, and 50 kHz. Reducing the PRF leads to a lower threshold for stimulated Raman output, but it leads to a smaller maximum output power due to the increasing thermal loading of the end-pumped Q-switched Nd-doped laser [22]. Moreover, the self-focusing-induced damage on YVO_4 crystal usually occurred especially at low PRF while the pump power is been over driving. Nevertheless, the efficient average output powers at 1176 nm were separately 1.62, 2.49, and 2.97 W at PRFs of 20, 30, and 50 kHz with the incident pump power of 7.62, 13.3, and 16.2 W. As a consequence, the maximum SRS conversion efficiency of 62-47% with respect to the output power available from the fundamental laser of 1064 nm was demonstrated at the PRF of 20-50 kHz. Then, the maximum optical-to-optical conversion efficiency from 808-nm pump were as high as 21.3-18.3% at the PRF of 20-50 kHz. The overall conversion efficiency is the highest one for Raman lasers until now to our knowledge [2]. The efficiency could be improved if we can use a c-cut YVO_4 crystal [23] with properly antireflection coating and an optimized output coupler. The maximum pulse energies, E_{max}, at PRFs of 20, 30 and 50 kHz were 84.5, 83.1 and 59.4 μJ. The E_{max} were higher than 83 μJ at PRFs below 30 kHz. Therefore, the E_{max} of this Nd:YAG/YVO_4 Raman laser was almost two times the E_{max} of the Nd:YVO_4/YVO_4 Raman laser in almost the same AQS scheme [21].

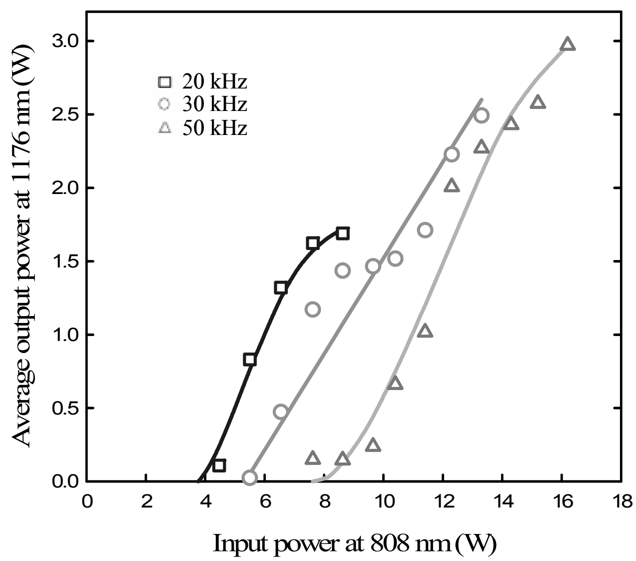

Fig. 4. The average output power at the Stokes wavelength of 1176 nm with respect to the incident pump power at different pulse repetition rate from 20 kHz to 50 kHz.

The temporal behaviors were recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 GS/s, 1-GHz bandwidth) with two fast p-i-n photodiode and an interference filter allowing transmission only at 1064 nm. Figure 5 and 6 show the typical pulse train and pulse shape for the fundamental and Raman components. The pulse-to-pulse amplitude fluctuation was not more than ±10% in optimized cavity. With the pulse energy of 81.2 μJ at 1176 nm, the pulse width of the pulse envelop in Fig. 6. is 2.2 ns. Because the mode-locked phenomenon cause the Raman pulse a deeply modulated shape, the peak power can not be approximated as the pulse energy divided by envelope's pulse width. After numerical computing, the peak power of the Raman pulse in Fig. 6. is 43.5 kW corresponding to an effective pulse width, W_{eff}, of 1.87 ns. Here we defined the W_{eff} as the pulse energy divided by peak power [21]. Consequently, the W_{eff} for Raman pulses far above threshold are distributed among 3.6-1.8, 5.0-3.5, and 5.0-3.0 ns at the PRFs of 20, 30, and 50 kHz. For example, Fig. 7. depicts the typical evolvement of pulse shapes dependent on pump power at 50 kHz. With a pump power of 8.63 W which was near threshold of SRS, broad envelope and deep mode-locked modulation was observed with a W_{eff} of 5.17 ns showed in Fig. 7 (a). While pump power was increased to 12.3 W, the W_{eff} was narrowed to 3.07 ns showed in Fig. 7 (b). Then, W_{eff} was become broader due to growing pulse tail. With a pump power of 14.8 W, the pulse was observed with a W_{eff} of 3.33 ns showed in Fig. 7 (c). Comparing to results of the

$Nd:YVO_4/YVO_4$ Raman laser in almost the same AQS scheme, this $Nd:YAG/YVO_4$ Raman laser raised maximum ouput pulse energy and peak power from 43 μJ to 83 μJ and 14 kW to 43.5 kW [21].

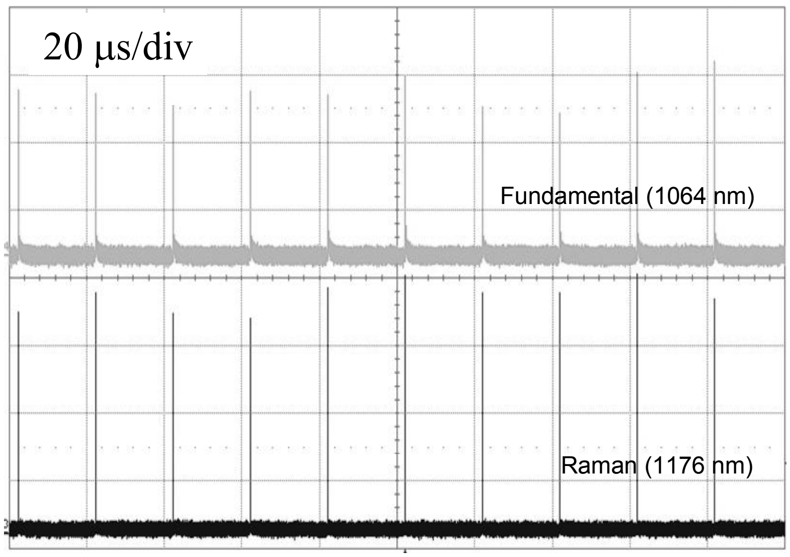

Fig. 5. Typical oscilloscope trace of a train for fundamental and Raman pulses.

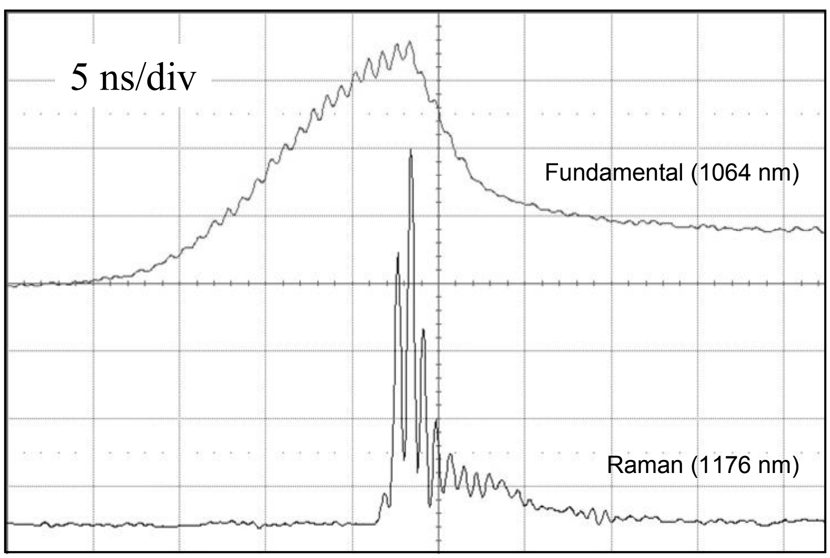

Fig. 6. Oscilloscope trace with mode-locking effect for fundamental and Raman pulses at a pulse repetition rate of 20 kHz.

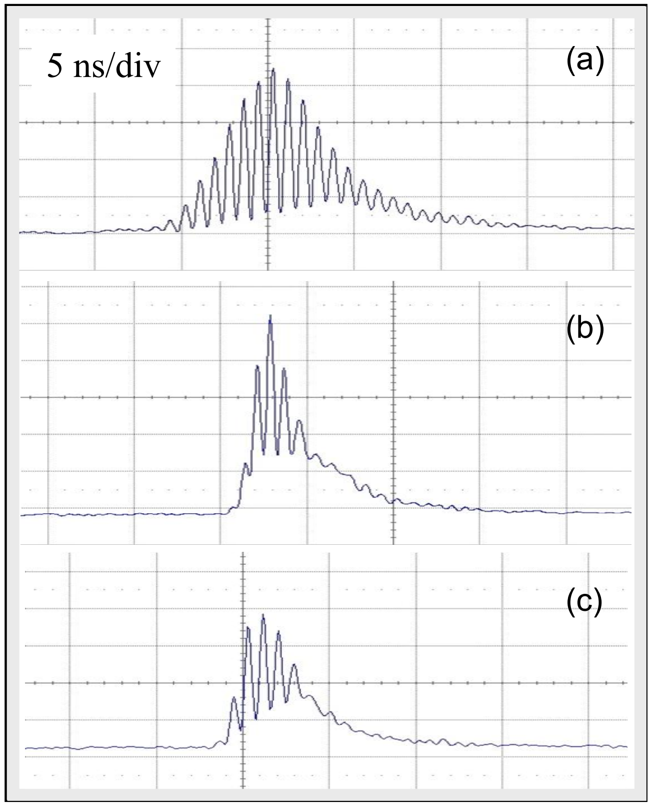

Fig. 7. With input power of 8.6 W, 12.3 W, and 14.8 W at a pulse repetition rate of 50 kHz, the effective pulse width (pulse energy divided by real peak power) of (a), (b), and (c) is 5.17 ns, 3.07 ns, and 3.33 ns. The vertical scales are in alternative units.

4. Conclusions

In summary, an efficient diode-pumped actively Q-switched Nd:YAG/YVO_4 intracavity Raman laser has been demonstrated. 1176-nm average output power of 2.97 W has been generated at a pulse repetition rate of 50 kHz. Further, the maximum optical-to-optical conversion efficiency from 808-nm pump were as high as 21.3-18.3% at the PRF of 20-50 kHz. The maximum pulse energy was higher than 83 μJ at both 20 kHz and 30 kHz. The output pulses displayed a mode-locking phenomenon that leads to narrow effective pulse width compared with envelope's pulse width. With an incident pump power of 7.62 W, the peak-power of 43.5 kW was demonstrated at 20 kHz.

REFERENCES

[1] W. Kochner and M. Bass, chapter 2 in *Solid-State Lasers*, Springer-Verlag (2003)

[2] J.A. Piper and H.M. Pask, "Crystalline Raman Lasers," IEEE J. Selected Topics in Quantum Electron. 13, 3, 692-704 (2007)

[3] Y.F. Chen, "Efficient subnanosecond diode-pumped passively Q-switched Nd : YVO_4 self-stimulated Raman laser", Opt. Lett. 29, 11, 1251 (2004)

[4] Y.F. Chen, "High-power diode-pumped actively Q-switched Nd : YVO4 self-Raman laser: influence of dopant concentration", Opt. Lett. 29, 16, 1915 (2004)

[5] T.T. Basiev, A.A. Sobol, P.G. Zverev, L.I. Iveleva, V.V. Osiko, R.C. Powell, "Raman spectroscopy of crystals for stimulated Raman scattering," Opt. Mater. 11, 4, 307-314 (1999)

[6] P.G. Zverev, T.T. Basiev, and A.M. Prokhorov, "Stimulated Raman scattering of laser radiation in Raman crystals", Opt. Mater. 11, 335 (1999)

[7] H.M. Pask, "The design and operation of solid-state Raman lasers", Prog. Quantum Electron. 27, 3 (2003)

[8] Peter Dekker, Helen M. Pask, David J. Spence and James A. Piper, "All-solid-state 704 mW continuous-wave yellow source based on an intracavity, frequency-doubled crystalline Raman laser," Opt. Lett. 32, 9, 1114-1116 (2007)

[9] A.S. Eremenko, S.N. Karpukhin, and A.I. Stepanov, "Stimulated Raman scattering of the second harmonic of a neodymium laser in nitrate crystals", Sov. J. Quantum Electron. 10, 113 (1980)

[10] E.O. Ammann and C.D. Decker, "0.9-W Raman oscillator", J. Appl. Phys. 48, 1973 (1977)

[11] A.S. Grabtachikov, A.N. Kuzmin, V.A. Lisinetskii, V.A. Orlovich, G.I. Ryabtsev, and A. A. Demidovich, "All solid-state diode-pumped Raman laser with self-frequency conversion", Appl. Phys. Lett. 75, 3742 (1999)

[12] J. Findeisen, H.J. Eichler, and A.A. Kaminskii, "Efficient picosecond $PbWO_4$ and two-wavelength $KGd(WO_4)_2$ Raman lasers in the IR and visible", IEEE J. Quantum Electron. 35, 173 (1999)

[13] T.T. Basiev, A.A. Sobol, P.G. Zverev, L.I. Iveleva, V.V. Osiko, R.C. Powell, "Raman spectroscopy of crystals for stimulated Raman scattering," Opt. Mater. 11, 4, 307-314 (1999)

[14] P. Cerný, P.G. Zverev, H. Jelínková, T.T. Basiev, "Efficient Raman shifting of picosecond pulses using $BaWO_4$ crystal," Opt. Commun. 177, 397-404 (2000)

[15] T.T. Basiev, A.A. Sobol, P.G. Zverev, L.I. Ivleva, V.V. Osiko, "Laser material for stimulated Raman scattering," Patent of Russian Fedration, 2178938 C1 1, pending 25.04.2000

[16] P.G. Zverev, T.T. Basiev, M.E. Doroshenko, V.V. Osiko, "Barium tungstate Raman laser – a new coherent source for sodium star experiments," Trends in Optics and Photonics 34, Advanced Solid State Lasers, H. Injeyan, U. Keller, and C. Marshall, eds.(OSA Washington D.C.) 348-354 (2000)

[17] P.G. Zverev, T.T. Basiev, L.I. Ivleva, V.V. Osiko, N.M. Polozkov, I.S. Voronina, "Raman laser on strontium tungstate crystal," Trends in Optics and Photonics 68, (OSA Washington D.C.) 70-73 (2002)

[18] P. Cerný, H. Jelínková, T.T. Basiev, and P.G. Zverev, "Highly efficient picosecond Raman generators based on the BaWO4 crystal in the near infrared, visible, and ultraviolet," IEEE J. Quantum Electron. 38, 11, 1471-1478 (2002)

[19] Y. F. Chen, K. W. Su, H. J. Zhang, J. Y. Wang, M. H. Jiang, "Efficient diode-pumped actively Q-switched Nd:YAG/BaWO4 intracavity Raman laser," Opt. Lett. 30 (24), 3335 (2005)

[20] A.A. Kaminskii, K. Ueda, H.J. Eichler, Y. Kuwano, H. Kouta, S.N. Bagaev, T.H. Chyba, J.C. Barnes, G.M. A. Gad, T. Murai, and J. Lu, "Tetragonal vanadates YVO_4 and $GdVO_4$ – new efficient $\chi^{(3)}$-materials for Raman lasers", Opt. Commun. 194, 201 (2001)

[21] K.W. Su, Y.T. Chang, and Y.F. Chen, "Power scale-up of the diode-pumped actively Q-switched Nd:YVO_4 Raman laser with an undoped YVO_4 crystal as a Raman shifter," Appl. Phys. B 88, 47-50(2007)

[22] K. Andryunas, Y. Vishakas, V. Kabelka, I.V. Mochalov, A.A. Pavlyuk, G.T. Petrovskii, V. Syrus, JETP Lett. 42, 333 (1985)

[23] P.G. Zverev, A.Y. Karasik, A.A. Sobol, D.S. Chunaev, T.T. Basiev, A.I. Zagumennyi, Y.D. Zavartsev, S.A. Kutovoi, V.V. Osiko, I.A. Shcherbakov, "Stimulated Raman scattering of picosecond pulses in $GdVO_4$ and YVO_4 crystals," Advanced Solid State Photonics Conference, Technical digest, Feb. 1-4, 2004, Santa Fe, USA, WB9. OSA TOPS ASSL, TuB10, 25-27