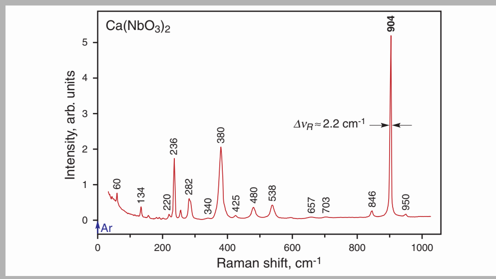
Laser Phys. Lett. **6**, No. 11, 782–787 (2009) / **DOI** 10.1002/lapl.200910077

Abstract: A passively Q-switched nanosecond Nd^{3+}:$Ca(NbO_3)_2$ self-Raman laser with 0.808-μm laser-diode pumping has been demonstrated, operating by nonlinear cascaded scheme at converted wavelength of Nd^{3+} one-micron stimulated emission.



The room-temperature first-order spontaneous Raman scattering spectrum (A-modes) of orthorhombic undoped $Ca(NbO_3)_2$ single crystal

Q-switched nanosecond Nd^{3+}:$Ca(NbO_3)_2$ crystalline self-Raman laser with single-step cascade SE ($\lambda_{SE} = 1.0615\,\mu$m of $^4F_{3/2} \rightarrow {}^4I_{11/2}$ channel) $\rightarrow$ SRS ($\lambda_{St1} = 1.1741\,\mu$m of $\omega_{SRS} \approx 904$ cm^{-1} promotion vibration mode) wavelength conversion

A.A. Kaminskii, [1,*] *J. Dong,* [2,**] *K. Ueda,* [3] *M. Bettinelli,* [4] *M. Grinberg,* [5] *and D. Jaque* [6]

[1] Institute of Crystallography, Russian Academy of Sciences, Moscow 119333, Russia
[2] Department of Electronic Engineering, School of Information Science and Technology of Xiamen University, Xiamen 361005, China
[3] Institute for Laser Science, University of Electro-Communications, 182-8585 Tokyo, Japan
[4] Laboratorio di Chimica dello Stato Solido, DB, Università di Verona and INSTM, Verona 37134, Italy
[5] Institute of Experimental Physics, University of Gdańsk, 80-952-Gdańsk, Poland
[6] Departamento de Física de Materiales C-IV, Universidad Autónoma de Madrid, Madrid 28049, Spain

Received: 5 July 2009, Revised: 7 July 2009, Accepted: 10 July 2009
Published online: 3 August 2009

Key words: self-Raman laser; $Ca(NbO_3)_2$:Nd^{3+} laser crystal; cascaded nonlinear lasing; passive Q-switching; laser-diode pumping

PACS: 42.55.Xi, 42.55.Rz, 42.60.Lh, 42.55.Ye, 43.65.Dr, 42.60.Gd, 42.70.Hj

1. Introduction

Investigations in the last decade convincingly evidenced that one of the efficient ways to generate new wavelengths is the development of the so-called self-Raman or self-SRS laser converters (here SRS is the stimulated Raman scattering) on the base of strongly $\chi^{(3)}$-active insulating crystals doped with trivalent lanthanide lasants (Ln^{3+}), in particular Nd^{3+} ions [1]. The distinctive features of this type of wavelength (frequency) converters are that in these crystals stimulated emission (SE) generation and $\chi^{(3)}$-nonlinear conversion processes can occur simultaneously, simplified the design of laser devices with very attractive practical potential. Some of them are commercially

* Corresponding author: e-mail: kaminalex@mail.ru, ** jdong@xmu.edu.cn

Crystal	Generation of stimulated emission			Stimulated Raman scattering			Ref. [a)]
	SE channel	λ_{SE}, μm	Mode [b)]	λ_{SRS}, μm	Line [c)]	ω_{SRS}, cm^{-1}	
$\alpha-KY(WO_4)_2$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	$\approx$ 1.0688	ps	$\approx$ 0.975	ASt_1	$\approx$ 905	[4]
				$\approx$ 1.183	St_1		
				$\approx$ 1.325	St_2		
$\alpha-KGd(WO_4)_2$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	$\approx$ 1.0672	ps, ns	$\approx$ 0.974	ASt_1	$\approx$ 901	[2,4,5]
				$\approx$ 1.181	St_1		
				$\approx$ 1.321	St_2		
			ns	$\approx$ 1.162	St_1	$\approx$ 768	[2,6]
				$\approx$ 1.276	St_2		
			CW	$\approx$ 1.181	St_1	$\approx$ 901	[7]
	$^4F_{3/2} \rightarrow {}^4I_{13/2}$	$\approx$ 1.351	ns	$\approx$ 1.538	St_1	$\approx$ 901	[2,8,9]
$\alpha-KLu(WO_4)_2$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0702	ns	1.1852	St_1	$\approx$ 907	[10]
$KY(MoO_4)_2$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0669	ns	1.1758	St_1	$\approx$ 868	[10]
				1.1868	St_1	$\approx$ 947	
$NaLa(MoO_4)_2$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0653	ns	$\approx$ 1.177	St_1	$\approx$ 988	[11]
$Ca(NbO_3)_2$	**$^4F_{3/2} \rightarrow {}^4I_{11/2}$**	**1.0615**	**ns**	**1.1741**	**St_1**	**$\approx$ 904**	**[this work]**
$CaMoO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0573	ns	1.1656	St_1	$\approx$ 880	[12]
$SrMoO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0577	ns	1.1671	St_1	$\approx$ 980	[12]
$SrWO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0699	ns	1.1561	St_1	$\approx$ 922	[12,13]
YVO_4	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0641	ns	1.1754	St_1	$\approx$ 890 [d)]	[14]
	$^4F_{3/2} \rightarrow {}^4I_{13/2}$	$\approx$ 1.342	ns	$\approx$ 1.525	St_1		[15]
$\beta-LaBGeO_5$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0482	ns	0.8972	ASt_2	$\approx$ 803	[10]
				0.9668	ASt_1		
				1.1446	St_1		
$GdVO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0633 [e)]	ns	1.1733	St_1	$\approx$ 882 [d)]	[16]
	$^4F_{3/2} \rightarrow {}^4I_{13/2}$	$\approx$ 1.341	ns, ps	$\approx$ 1.521	St_1		[17]
$LuVO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0658	ns	1.1788	St_1	$\approx$ 900 [f)]	[18]
$BaWO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	$\approx$ 1.055	ns	$\approx$ 1.169	St_1	$\approx$ 926	[19]
$PbMoO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0594	ns	1.1668	St_1	$\approx$ 869	[20]
$PbWO_4$	$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0580	ns	1.1695	St_1	$\approx$ 901 [g)]	[10,20,21]

[a)] Were used articles only in refereed journals.

[b)] Nonlinear cascade lasing under nanosecond (ns) and picosecond (ps) pulse emission, and continuous-wave (CW) generation.

[c)] Stokes (St) and ant-Stokes (ASt) nonlinear lasing.

[d)] SRS-promoting mode was established in [22].

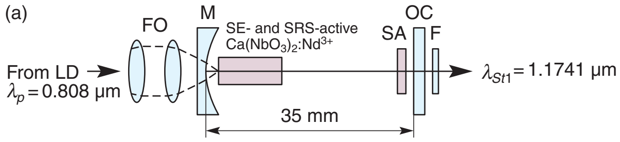
[e)] SE wavelengths given in [23] have some discrepancy with the room-temperature Stark level energies of $GdVO_4$:Nd^{3+} crystal (see note (c) for Table 1 in [18]). The author of [23] measured SE at fundamental wavelength 1.0651 μm and SRS lasing at three wavelengths 1.1756, 1.1652, and 1.0950 μm, which related to different SRS promoting vibration mode of $GdVO_4$ crystal.

[f)] SRS-promoting mode was established in [24].

[g)] SRS-promoting mode was established in [25].

Table 1 Selected self-Raman lasers based on crystals doped with Nd^{3+} ions

available now (see note in [2]). The self-Raman crystalline lasers offer certain advantages (for example, compactness and functional simplicity) compared to usual solid-state Raman lasers in which two separate media – lasing crystal (or glass) and $\chi^{(3)}$-converting crystal are used. The list of known "neodymium" crystalline self-Raman lasers operated at room-temperature with different pumping sources and mode generation is reported in Table 1. Presently, numerous developments of the last-mentioned type of Raman lasers rank among the scientific and applied aims of many groups of researchers (see, e.g. [3]). The results of the productive investigations mentioned above indicate conclusively that the search of new SRS-active Ln^{3+}-ion doped crystals is currently a topical problem because it gives birth to laser sources at new wavelengths.



(b)

Reflection (R), transmission (T)

Wavelength, μm	R_M	T_M	R_{OC}	T_{OC}
λ_{SE} = 1.0615	≈ 99.8	a)	≈ 99.8	a)
λ_{St1} = 1.0615	≈ 99.8	a)	≈ 65	≈ 35
λ_p = 0.808	≈ 15	≈ 85	b)	b)

a) Minor.
b) Lasing crystal absorb ≈ 100% of pump radiation.

Figure 1 (online color at www.lphys.org) (a) - schematic diagram of LD pumped passively Q-switched Nd^{3+}:$Ca(NbO_3)_2$ self Raman laser; (b) – optical reflection and transmission of cavity components at pumping and lasing wavelengths (see also text)

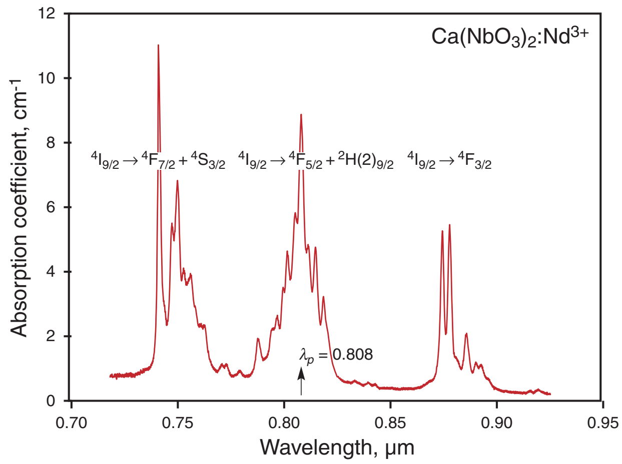


Figure 2 (online color at www.lphys.org) The fragment of room-temperature absorption spectrum of the orthorhombic $Ca(NbO_3)_2$:Nd^{3+} crystal ($C_{Nd} \approx 2$ at.%, c-cut ≈ 3-mm plate) in the spectral range from ≈ 0.72 to ≈ 0.93 μm with the identification of its inter-manifold $^4I_{9/2} \rightarrow {}^{2S+1}L_{J'}$ band-areas, including the pumping channel $^4I_{9/2} \rightarrow {}^4F_{5/2} + {}^2H(2)_{9/2}$ (see also text)

In this letter, we present results on the first performance of a laser-diode (LD) pumped self-Raman laser on the base of the $\chi^{(3)}$-active Nd^{3+}:$Ca(NbO_3)_2$ crystal with passively Q-switched nanosecond room-temperature operation at single-step cascade conversion of SE wavelength deriving from the main generation $^4F_{3/2} \rightarrow {}^4I_{11/2}$ channel of Nd^{3+} lasants. The research dates back to our recent study of efficient SRS activity in this undoped orthorhombic calcium niobate [26] and our old comprehensive spectroscopic and SE investigations of $Ca(NbO_3)_2$:Nd^{3+} single crystals [27]. It should be emphasized here that $Ca(NbO_3)_2$ was the seventh host-crystals for Ln^{3+} lasants [28].

Property	
Space group	$D^{14}_{2h} - Pcan\,(Pbcn)$, No. 60
Unit cell parameters, Å [29] $^{a,b)}$	$a = 5.757$; $b = 14.97$; $c = 5.225$
Number of formula per unit cell	$Z = 4$
Density, g/cm$^{3\ a)}$	≈ 4.77
Melting temperature, °C	≈ 1560
Thermal conductivity, W/m/K $^{c)}$ [30]	$\kappa_a \approx 6.08$; $\kappa_b \approx 5.71$; $\kappa_c \approx 8.24$
Optical transparency range, μm $^{d)}$	≈ 0.3 – ≈ 5.5
Hardness (Mohs scale)	4.5 – 5.5
SE effective peak cross-section, 10^{-19} cm^2	$\sigma^p_e \approx 1.2$ $^{e)}$
SRS-promoting vibration mode, cm^{-1}	$\omega_{SRS} \approx 904$ $^{f)}$
First Stokes steady-state Raman gain coefficient, cm/GW	$g^{St1}_{ssR} \approx 2.8$ $^{g)}$

a) For undoped crystal.
b) According to a recent refinement within $Pbcn$ setting [31]: $c = 5.22202$; $a = 14.96976$; $b = 5.74724$ Å.
c) For $Ca(NbO_3)_2$:Nd^{3+} single crystal ($C_{Nd} = 0.894 \times 10^{20}$ cm^{-3}).
d) For ≈ 1-mm-thick plate.
e) For $^4F_{3/2} \rightarrow {}^4I_{11/2}$ luminescence transition at 1.0615 μm wavelength related to SE generation line.
f) Related to stretching and bending A_g-modes of NbO_6 distorted octahedral (Fig. 3).
g) For the first Stokes SRS line at 1.1741 μm wavelength.

Table 2 Some known room-temperature physical properties of the orthorhombic $Ca(NbO_3)_2$ and Nd^{3+}:$Ca(NbO_3)_2$ single crystals

2. Crystals and experimental setup

Both undoped and neodymium activated calcium niobate crystals were grown by the usual Czochralski technique. Good optical quality $Ca(NbO_3)_2$ crystals doped with ≈ 2% Nd^{3+} lasants by weight in the melt were obtained with the stoichiometric amounts of Ti^{4+} charge compensators. All calcium niobates were pulled (rate ≈ 6 mm/h and rotation ≈ 30 min^{-1}) in air using an Ir crucible. These crystals were used to fabricate polished samples for nonlinear-laser and spectroscopic measurements.

The performance of Q-switched nanosecond generation regime in self-Raman laser based on the orthorhombic $Ca(NbO_3)_2$:Nd^{3+} ($C_{Nd} \approx 2$ at.% with charge Ti^{4+}-compensators) niobate was carried out using a "black garnet" ($Y_3Al_5O_{12}$ crystal co-doped with Cr_2O_3 and CaO) as a saturable absorber (SA) and widely used simple scheme for compact laser design with laser-diode (LD) pumping. It was practically the same as for $LuVO_4$:Nd^{3+} self-Raman laser recently described in [18]. As shown in Fig. 1, it is composed of a 35-mm long laser cavity with a 40-mm cur-

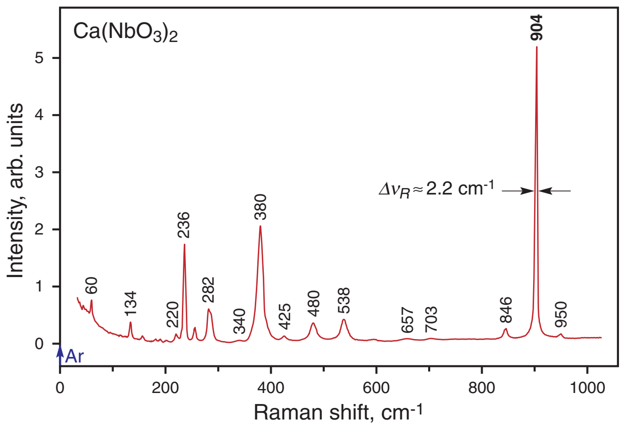


Figure 3 (online color at www.lphys.org) The room-temperature first-order spontaneous Raman scattering spectrum (A-modes) of orthorhombic undoped $Ca(NbO_3)_2$ single crystal recorded in back scattering geometry $\approx c\,(bb) \approx c$ (notation is used by analogy to [32]) under Ar-ion laser 0.488 μm wavelength excitation (indicated by arrow). Raman shift

vature concave "pump" mirror (M) and a flat output coupler (OC) having the required dichroic dielectric coatings. The crystalline active $Ca(NbO_3)_2{:}Nd^{3+}$ element (for SE and SRS) in the form of a rod oriented along the c-axis ($l = 5$ mm with $\varnothing = 3$ mm) with wide-band antireflection coatings of its plane-parallel ends was positioned near the "pump" mirror. On the other side of the compact cavity near its OC a commercial 2-mm thick antireflection coated SA-plate (with cross-section 10×10 mm^2) was placed. The initial transmission of the SA at ≈ 1.1 μm wavelength was about 90%. The pump source was a CW fiber-coupled LD (LIMO GmbH) with a core diameter of 100 μm and a maximum output power of 5 W at 0.808 μm wavelength. Its radiation was directed through two-lens focusing optics (FO) with 20-mm focal length and high coupling efficiency into the lasing $Ca(NbO_3)_2{:}Nd^{3+}$ crystal. As shown in Fig. 2, the LD wavelength is not matched with the maximum of absorption peak of pump region of Nd^{3+} lasants in the title calcium niobate. The lasing crystalline rod was wrapped in an In foil and mounted tightly in a water-cooled Cu holder, which was kept at a stable temperature of 20°C. Some crystallographic and physical properties of the niobates studied are given in Table 2.

3. Nonlinear laser $^4F_{3/2} \rightarrow {}^4I_{11/2} \rightarrow$ SRS cascading

The spectral composition, pulse temporal behaviour of cascaded generation and its average output power of $Nd^{3+}{:}Ca(NbO_3)_2$ self-Raman laser were measured by universally accepted methods using a spectral analyzer AQ-type, a fast InGaAs PIN photodiode together with a narrowband filter (F) for the first Stokes emission and

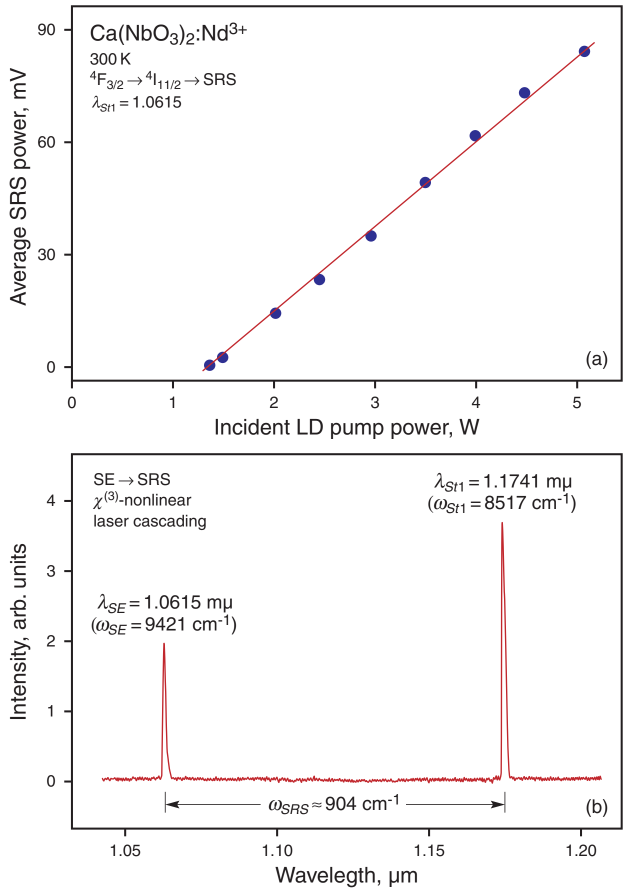


Figure 4 (online color at www.lphys.org) Generation characteristics of nanosecond $Nd^{3+}{:}Ca(NbO_3)_2$ self-Raman laser: (a) – the dependence of the average output power at $\lambda_{St1} = 1.1741$ μm wavelength as a function of incident LD-pump power at $\lambda_p = 0.808$ μm; (b) – the lasing spectrum with SE and SRS lines

a wideband digital Textronix oscilloscope, as well as a Molectron-PM3 power meter. Some of obtained results are given in Fig. 4. As seen, the "threshold" pump power of cascade ($^4F_{3/2} \rightarrow {}^4I_{11/2} \rightarrow$ SRS) lasing at $\lambda_{St1} = 1.1741$ wavelength was found to be 1.3 W. With increasing pump power up to 5 W, the average output power of nanosecond (with 2.5-ns pulse duration at ≈ 15-kHz repetition rate) nonlinear-laser generation reached ≈ 85 mW with absolute conversion efficiency of about 2%.

4. Conclusion

As is shown in our research, the Nd^{3+}-ion doped niobates are also attractive crystals for self-SRS conversion processes. We believe that the achieved modest efficiency of one-micron nanosecond cascaded nonlinear-laser generation in the $Nd^{3+}{:}Ca(NbO_3)_2$ self-Raman laser can be increased by optimizing the spectral pumping condition, setup arrangements, and the enhancement of the optical quality of title crystal.

Acknowledgements The authors note that the conducted research was considerably enhanced through scientific cooperation with the "Joint Open Laboratory for Laser Crystals and Precise Laser Systems" and supported in part by the Russian Foundation for Basic Research, the Xiamen University, the University of Electro-Communications, the University of Verona, the University of Gdansk, as well as the Autonomous University of Madrid.

References

[1] A.A. Kaminskii, Crystalline Lasers: Physical Processes and Operating Schemes (CRC Press, Inc., Boca Raton, FL, 1996); J. Hulliger, A.A. Kaminskii, and H.J. Eichler, Adv. Funct. Mater. **11**, 243 (2001).

[2] A.A. Kaminskii, N.S. Ustimenko, A.V. Gulin, S.N. Bagaev, and A.A. Pavlyuk, Doklady Phys. **43**, 148 (1998).

[3] S.N. Karpukhin and A.I. Stepanov, Sov. J. Quantum Electron. **16**, 1027 (1986); G.G. Grigoryan and S.B. Sogomonyan, Sov. J. Quantum Electron. **19**, 1402 (1989); J.T. Murray, R.C. Powell, N. Peyghambarian, D. Smith, W. Austin, and R.A. Stolzenberger, Opt. Lett. **20**, 1017 (1995); L.J. Qin, X.L. Meng, C.L. Du, Z.S. Shao, L. Zhu, B.C. Xu, and H.J. Zhang, Jpn. J. Appl. Phys. **41**, 6018 (2002); A.Z. Grasiuk, S.V. Kurbasov, and L.L. Losev, Opt. Commun. **240**, 239 (2004); P. Černý, H. Jelínková, P.G. Zverev, and T.T. Basiev, Prog. Quantum Electron. **28**, 113 (2004); V.A. Orlovich, V.N. Burakevich, A.S. Grabtchikov, V.A. Lisinetskii, A.A. Demidovich, H.J. Eichler, and P.-Y. Turpin, Laser Phys. Lett. **3**, 71 (2005); Y.F. Chen, Opt. Lett. **30**, 400 (2005); J.A. Piper and H.M. Pask, IEEE J. Sel. Top. Quantum Electron. **13**, 692 (2007); H.M. Pask, P. Dekker, R.P. Mildren, D.J. Spence, and J.A. Piper, Prog. Quantum Electron. **32**, 121 (2008); L. Fan, Y.X. Fan, Y.H. Duan, Q. Wang, H.T. Wang, G.H. Jia, and C.Y. Tu, Appl. Phys. B **94**, 553 (2009).

[4] K. Andryunas, Yu. Vishchakas, V. Kabelka, I.V. Mochalov, A.A. Pavlyuk, G.T. Petrovskiĭ, and V. Syrus, JETP Lett. **42**, 410 (1985); K. Andryunas, Yu.K. Vishchakas, V.I. Kabelka, I.V. Mochalov, A.A. Pavlyuk, and V.P. Syrus, Quantum Electron. **15**, 1144 (1985); K. Andryunas, A. Barila, Yu. Vishchakas, I.V. Mochalov, G.T. Petrovskii, and V. Syrus, Opt. Spectrosc. **64**, 235 (1988).

[5] A.M. Ivanyuk, P.A. Shachverdov, V.D. Belyaev, M.A. Ter-Pogosyan, and V.L. Ermolaev, Opt. Spectrosc. **59**, 573 (1985); A.M. Ivanyuk, M.A. Ter-Pogosyan, P.A. Shachverdov, V.D. Belyaev, V.L. Ermolaev, and N.P. Tichonova, Opt. Spectrosc. **59**, 950 (1985); A.M. Ivanyuk, V.A. Sandulenko, M.A. Ter-Pogosyan, P.A. Shachverdov, V.G. Chervinskii, A.V. Lukin, and V.L. Ermolaev, Opt. Spectrosc. **62**, 961 (1987); A.S. Grabtchikov, A.N. Kuzmin, V.A. Lisinetskii, V.A. Orlovich, G.I. Ryabtsev, and A.A. Demidovich, Appl. Phys. Lett. **75**, 3742 (1999); T. Omatsu, Y. Ojima, H.M. Pask, J.A. Piper, and P. Dekker, Opt. Commun. **232**, 327 (2004); A. Hamano, S. Pleasants, M. Okida, M. Itoh, T. Yatagai, T. Watanabe, M. Fujii, Y. Iketaki, K. Yamamoto, and T. Omatsu, Opt. Commun. **260**, 675 (2006).

[6] A.V. Gulin, G.I. Narkhova, and N.S. Ustimenko, Quantum Electron. **28**, 804 (1998).

[7] A.A. Demidovich, A.S. Grabtchikov, V.A. Lisinetskii, V.N. Burakevich, V.A. Orlovich, and W. Kiefer, Opt. Lett. **30**, 1701 (2005).

[8] N.S. Ustimenko and E.M. Zabotin, Instr. Exp. Technol. **48**, 239 (2005).

[9] N.S. Ustimenko and A.V. Gulin, Instrum. Exp. Technol. **41**, 386 (1998); J.H. Huang, J.P. Lin, R.B. Su, J.L. Li, H. Zheng, C.H. Xu, F. Shi, Z.Z. Lin, J. Zhuang, W.R. Zeng, and W.X. Lin, Opt. Lett. **32**, 1096 (2007).

[10] A.A. Kaminskii, Laser Photon. Rev. **1**, 93 (2007).

[11] A.V. Gulin, V.A. Pashkov, and N.S. Ustimenko, Proc. SPIE **4350**, 36 (2001).

[12] A.A. Kaminskii, S.N. Bagaev, K. Ueda, K. Takaichi, and H. J. Eichler, Crystallogr. Rep. **47**, 653 (2002).

[13] H. Jelínková, J. Šulc, T.T. Basiev, P.G. Zverev, and S.V. Kravtsov, Laser Phys. Lett. **2**, 4 (2005).

[14] Y.F. Chen, Opt. Lett. **29**, 2172 (2004); F.F. Su, X.Y. Zhang, Q.P. Wang, S.H. Ding, P. Jia, S.T. Li, S.Z. Fan, C. Zhang, and B. Liu, J. Phys. D **39**, 2090 (2006); V.N. Burakevich, V.A. Lisinetskii, A.S. Grabtchikov, A.A. Demidovich, V.A. Orlovich, and V.N. Matrosov, Appl. Phys. B **86**, 511 (2007); X.H. Chen, X.Y. Zhang, Q.P. Wang, P. Li, and Z.H. Cong, Laser Phys. Lett. **6**, 26 (2009).

[15] Y.F. Chen, Opt. Lett. **29**, 1915 (2004); Y.T. Chang, K.W. Su, H.L. Chang, and Y.F. Chen, Opt. Express **17**, 4330 (2009).

[16] T.T. Basiev, S.V. Vassiliev, V.A. Konjushkin, V.V. Osiko, A.I. Zagumennyi, Y.D. Zavartsev, S.A. Kutovoi, and I.A. Shcherbakov, Laser Phys. Lett. **1**, 237 (2004); F.F. Su, X.Y. Zhang, Q.P. Wang, P. Jia, S.T. Li, B. Liu, X.L. Zhang, Z.H. Cong, and F.Q. Wu, Opt. Commun. **277**, 379 (2007); P. Dekker, H.M. Pask, D.J. Spence, and J.A. Piper, Opt. Express **15**, 7038 (2007); B.S. Wang, H.M. Tan, J.J. Peng, J.G. Miao, and L.L. Gao, Opt. Mater. **29**, 1817 (2007).

[17] Y.F. Chen, Opt. Lett. **29**, 2632 (2004).

[18] A.A. Kaminskii, M. Bettinelli, J. Dong, D. Jaque, and K. Ueda, Laser Phys. Lett. **6**, 374 (2009).

[19] M.E. Doroshenko, T.T. Basiev, S.V. Vassiliev, L.I. Ivleva, V.K. Komar, M.B. Kosmyna, H. Jelínková, and J. Šulc, Opt. Mater. **30**, 54 (2007); J. Šulc, H. Jelínková, T.T. Basiev, M.E. Doroschenko, L.I. Ivleva, V.V. Osiko, and P.G. Zverev, Opt. Mater. **30**, 195 (2007).

[20] A.A. Kaminskii, S.N. Bagayev, K. Ueda, H.J. Eichler, J. Garcia-Sole, D. Jaque, J.J. Romero, J. Fernandez, R. Balda, A.V. Butashin, and F. Agullo-Rueda, Laser Phys. **11**, 1142 (2001).

[21] W.B. Chen, Y. Inagawa, T. Omatsu, M. Tateda, N. Takeuchi, and Y. Usuki, Opt. Commun. **194**, 401 (2001).

[22] A.A. Kaminskii, K. Ueda, H.J. Eichler, Y. Kuwano, H. Kouta, S.N. Bagayev, T.H. Chyba, J.C. Barnes, G.M.A. Gad, T. Murai, and J.R. Lu, Opt. Commun. **194**, 201 (2001); A.A. Kaminskii, K. Ueda, H.J. Eichler, Y. Kuwano, H. Kouta, S.N. Bagayev, T.H. Chyba, J.C. Barnes, T. Murai, and J. Lu, Laser Phys. **11**, 1124 (2001).

[23] Y.F. Chen, Appl. Phys. B **78**, 685 (2004).

[24] A.A. Kaminskii, H. Rhee, H.J. Eichler, K. Ueda, K. Oka, and H. Shibata, Appl. Phys. B **93**, 865 (2008).

[25] A.A. Kaminskii, C.L. McCray, H.R. Lee, S.W. Lee, D.A. Temple, T.H. Chyba, W.D. Marsh, J.C. Barnes, A.N. Annanenkov, V.D. Legun, H.J. Eichler, G.M.A. Gad, and K. Ueda, Opt. Commun. **183**, 277 (2000).

[26] A.A. Kaminskii, J. Dong, H.J. Eichler, J. Hanuza, K. Ueda, M. Maczka, H. Rhee, and M. Bettinelli, Laser Phys. Lett., **DOI** 10.1002/lapl.200910078.

[27] A.A. Kaminskii, G.I. Rogov, and Kh.S. Bagdasarov, Phys. Status Solidi (b) **31**, K87 (1969); A.A. Kaminskii, Phys. Status Solidi (a) **1**, 573 (1970); A.A. Kaminskii, G.A. Bogomolova, and L. Li, Inorg. Mater (USSR) **6**, 254 (1970); A.A. Kaminskii, S.E. Sarkisov, and L. Li, Phys. Status Solidi (a) **15**, K141 (1973).

[28] A.A. Ballman, S.P.S. Porto, and A. Yariv, J. Appl. Phys. **34**, 3155 (1963).

[29] K.S. Alexandrov, Dokl. Akad. Nauk SSSR **132**, 660 (1960), in Russian.

[30] Y. Cheng, X.D. Xu, J. Xu, Z. Xin and S.M. Zhou, Appl. Phys. B **96**, 43 (2009).

[31] J. Leitner, K. Růžička, D. Sedmidubský, and P. Svoboda, J. Therm. Anal. Calorim. **95**, 397 (2009).

[32] T.C. Damen, S.P.S. Porto, and B. Tell, Phys. Rev. **142**, 570 (1966).