Quantum Electronics **41** (3) 207 – 211 (2011)

PACS numbers: 42.55.Rz; 42.55.Xi; 42.60.By; 42.60.Da; 42.65.Hw
DOI: 10.1070/QE2011v041n03ABEH014491

Loop laser cavities with self-pumped phase-conjugate mirrors in low-gain active media for phase-locked multichannel laser systems

T.T. Basiev, A.V. Gavrilov, M.N. Ershkov, S.N. Smetanin, A.V. Fedin, K.A. Bel'kov, A.S. Boreisho, V.F. Lebedev

***Abstract*.** **It is proved that lasers with different loop cavities with self-pumped phase-conjugate mirrors in low-gain active media can operate under injection of external laser radiation and can be used for the development of diode-pumped phase-locked multichannel neodymium laser systems operating both on the fundamental laser transition with the wavelength $\lambda = 1.06$ μm and on the transition with $\lambda = 1.34$ μm. The phase-conjugate oscillation thresholds in the case of injection of an external signal are determined for a multiloop cavity configuration and an increased number of active elements in the cavity. It is shown that phase-conjugate oscillation can occur even if the single-pass gain of the active element is as low as only ~ 2. Under high-power side diode pumping of a multiloop Nd : YAG laser, single-mode output radiation was achieved at $\lambda = 1.064$ μm with a pulse energy up to 0.75 J, a pulse repetition rate up to 25 Hz, an average power up to 18.3 W, and an efficiency up to 20 %. In a multiloop Nd : YAG laser with three active elements in the cavity, single-mode radiation at $\lambda = 1.34$ μm was obtained with a pulse energy up to 0.96 J, a pulse repetition rate up to 10 Hz, and an average power up to 8.5 W.**

Keywords: *multichannel laser system, loop cavity, self-pumped phase-conjugate mirror, holographic gain grating.*

1. Introduction

Multichannel laser systems are of great interest due to the possibility of improving the energy characteristics of laser radiation by summing the output laser beams. The coherent summation of the beams of individual optically coupled lasers allows one not only to increase the laser radiation energy and power, but also to considerably increase the intensity and decrease the divergence of the composed laser beam. This summation requires single-mode lasing and precise matching of the lengths of laser cavities to equalise the resonance frequencies [1]. In [2 – 5], we solved these problems by using loop cavities with self-pumped phase-conjugate mirrors in the active laser media [6 – 12] as the separate channels of a multichannel laser system, which allowed us to obtain phase locking and coherent summation of all the channels. The distinguishing feature of these laser cavities is the dependence of their Q-factors on the active medium gain, since the diffraction efficiency of a phase-conjugate mirror written in the active medium depends on the gain. This significantly increases the oscillation threshold of the laser system and restricts the applicability of low-gain laser media.

In this work, we study different schemes of loop cavities with low-gain active laser elements, which can be used for the development of diode-pumped phase-locked multichannel neodymium laser systems operating not only on the fundamental laser transition at the wavelength $\lambda = 1.064$ μm, but also on the transition at $\lambda = 1.34$ μm.

2. Oscillation threshold for a laser cavity with self-pumped phase-conjugate mirrors and with injection of an external signal from a master oscillator

Let us determine the active element (AE) gain needed to overcome the lasing threshold in a loop cavity. The lowest lasing threshold of a phase-conjugate laser is observed in the case of injection of an external signal from the controlling laser channel in the multichannel scheme. The injected beam writes the most efficient phase-conjugate mirror, which leads to a fast development of lasing in the channel itself. The maximum diffraction efficiency of the gain grating written by an external laser radiation is estimated by the formula [5, 10]

$$\eta \approx G(bLV)^2, \qquad (1)$$

where $G = \exp(\alpha L)$ is the single-pass unsaturated gain of the AE; αL is the unsaturated absorption increment; α is unsaturated gain; L is the AE length; $b = \alpha/4$ is the maximum diffraction coupling coefficient [13] achieved in the case of writing by a high-power external radiation; and V is the interference contrast of writing beams, which is smaller than unity due to a difference in the intensity of interfering beams in the loop cavity. Note that this estimate takes into account the four-wave mixing on the nonlinearity of the gain saturation and neglects the other weaker nonlinearities.

T.T. Basiev A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: basiev@lst.gpi.ru;
A.V. Gavrilov, M.N. Ershkov, , S.N. Smetanin, A.V. Fedin V.A. Degtyarev Kovrov State Technological Academy, ul. Mayakovskogo 19, 601910 Kovrov, Vladimir region, Russia; e-mail: ssmetanin@bk.ru;
K.A. Bel'kov, A.S. Boreisho, V.F. Lebedev Laser Systems Ltd., ul. 1-ya Krasnoarmeiskaya 1, 190005 St. Petersburg, Russia; e-mail: Boreysho@lsystems.ru

Received 19 November 2010; revision received 2 February 2011
Kvantovaya Elektronika **41** (3) 207 – 211 (2011)
Translated by M.N. Basieva

Previously [2 – 5], we studied multichannel laser systems in which each channel consisted of a loop cavity designed according to the scheme shown in Fig. 1a, which includes a holographic AE (HAE) with a written self-pumped phase-conjugate mirror and can additionally include an amplifying AE (AAE) to increase the output power. In the multichannel laser system, the controlling laser channel injects radiation into the other channels through a reference mirror RM and beam-splitting mirrors [2 – 5]. The injected radiation with the intensity I_0 only once self-crosses in the HAE and writes in it a holographic gain grating with the interference contrast

$$V = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} = \frac{2\sqrt{G}}{1+G} \tag{2}$$

in the absence of the AAE or

$$V = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} = \frac{2\sqrt{G}}{1+G^2} \tag{3}$$

in the presence of an AAE, where I_1 and I_2 are the gain-dependent intensities of waves writing the holographic grating ($I_1 = I_0$ and $I_2 = I_0 G$ or $I_0 G^2$ in the absence or presence of the AAE, respectively). Expressions (2) and (3) can be substituted into formula (1). In this case, the oscillation threshold condition for the scheme shown in Fig. 1a in the absence of AAE can be written in the form

$$\eta = 1, \tag{4}$$

and, in the presence of the AAE, this condition has the form

$$\eta G = 1. \tag{5}$$

Then, for this scheme, we obtain the threshold gain increment

$$\alpha L \approx 2.218, \tag{6}$$

in the absence of the AAE and

$$\alpha L \approx 2.035. \tag{7}$$

in the presence of the AAE.

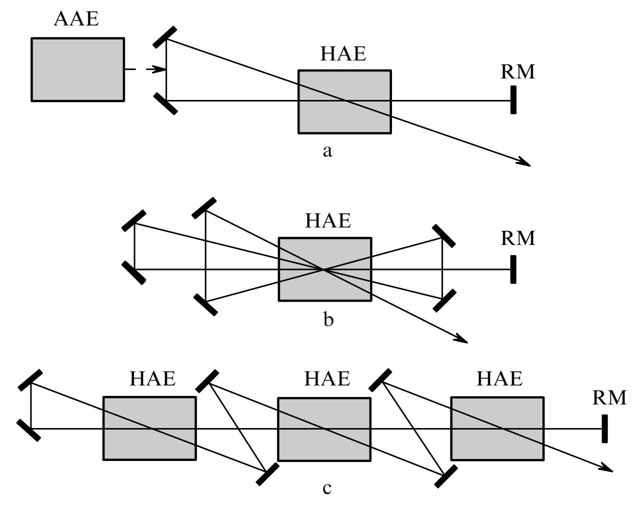

Figure 1. Three optical schemes of loop laser cavities: (HAE) holographic active element; (AAE) amplifying active element; (RM) reference mirror of the phase-conjugate cavity.

The threshold gain increment was found to be rather high: the corresponding single-pass gain of the AE should exceed 9.2, and the use of the additional AAE decreases the required HAE gain only by 20 % (to ~ 7.7). Note that, in the absence of injected external radiation, the threshold gain is considerably higher, because the initial grating is written by the very weak seed radiation of the channel itself.

The threshold gain can be considerably decreased by writing several holographic gratings in the HAE if the cavity has a multiloop configuration; in this case, as we found, it is not necessary to use an additional AAE, which simplifies the laser system. Figure 1b shows a three-loop cavity scheme with only one HAE; a beam with an intensity I_0 injected into this scheme from the reference mirror passes the cavity four times, interfering with itself at preceding passes. As a result, six holographic gratings are written, among which it is necessary to select three most contrast, which are written with participation of the wave with the maximum intensity $I_0 G^3$ (the other gratings are erased). For gratings 1, 2, and 3 written by the waves with intensities $I_0 G^2$ and $I_0 G^3$, $I_0 G$ and $I_0 G^3$, I_0 and $I_0 G^3$, respectively, we have the interference contrasts

$$V_1 = 2G^{1/2}/(1+G),$$
$$V_2 = 2G/(1+G^2), \tag{8}$$
$$V_3 = 2G^{3/2}/(1+G^3),$$

which are substituted into (1) to find the diffraction efficiencies $\eta_{1,2,3}$ of these gratings. The lasing threshold condition for these holographic gratings can be written as

$$\eta_1 + \eta_2 G + \eta_3 G^2 = 1, \tag{9}$$

from which we obtain the threshold gain increment for the scheme of Fig. 1b

$$\alpha L \approx 1.283, \tag{10}$$

which is considerably smaller than in the previous case even with the use of an AAE [see formula (7)], and, correspondingly, the required single-pass gain of the AE decreases more than twice (to ~ 3.6).

A drawback of the scheme shown in Fig. 1b can be a small output power due to the absence of an AAE inside the cavity, although this insignificantly affects the lasing threshold. A decrease in the lasing threshold simultaneously with an increase in the output power can be achieved by increasing the HAE length or by using several HAEs in the schemes shown in Fig. 1. Figure 1c presents a scheme with three HAEs, which is equivalent to the scheme in Fig. 1a with a threefold longer HAE. The threshold gain for the scheme in Fig. 1c is determined by expression (6), where the AE length L must be changed by the triple length $3L$, which yields the threshold gain increment

$$\alpha L \approx 0.739, \tag{11}$$

which is lower than in all the other cases (the required single-pass gain of the AE is ~ 2.09).

3. Experimental studies of a transversely diode-pumped multiloop Nd : YAG laser

Usually, a high AE gain in the case of diode pumping is achieved by strong focusing of the pump beam [14], which considerably restricts the active medium volume involved into lasing and decreases the output power. The authors of [12] describe a laser with a self-pumped phase-conjugate loop cavity, which was pumped by a laser diode array whose beam was sharply focused into the AE in order to increase its gain, because of which phase-conjugate lasing occurred in a very small volume of the active medium and the pulse energy was lower than 1 mJ. To increase the output energy and the pumped AE volume retaining a high gain, it is necessary to considerably increase the pump pulse energy. We designed a pump cavity for a Nd : YAG AE (1 at % Nd^{3+}) $5 \times 6 \times 110$ mm in size with repetitively pulsed pumping through the opposite 6×110-mm sides of the AE by six SLM-3 laser diode arrays with dimensions of 5×25 mm and a peak power of 2.1 kW each. The measured unsaturated single-pass gain of the AE at a pump pulse energy of 3.7 J and a pump pulse duration of 300 μs was ~ 5, which exceeded the threshold value required for phase-conjugate lasing in the scheme shown in Fig. 1b ($G \approx 3.6$).

We performed experiments with a cavity shown in Fig. 1b based on our pump cavity with diode pumping. Instead of an external injector of laser radiation, we used in the same laser channel an auxiliary cavity whose output beam preliminarily wrote a phase-conjugate mirror in the AE, which ensured subsequent phase-conjugate lasing. As an output mirror at the laser exit, we used an optical wedge with a reflectance of 4 %. For comparison, we also assembled a compact linear two-mirror Fabry – Perot cavity using the same pump cavity and an output mirror with a reflectance of 62 %.

The output loop laser beam had a low divergence and a Gaussian transverse intensity distribution in both near- and far-field zones. Under diode pumping with a pulse energy of 2.9 J and a pulse duration of 300 μs, the measured angular divergence of the output laser beam was 0.34 mrad in the horizontal and 0.29 mrad in the vertical directions, which exceeds the diffraction limit by no more than 30 %. This occurs because the distortions and inhomogeneity of the gain caused by the side diode pumping are self-compensated due to the phase conjugation. At the same time, the divergence of the output beam of the compact Fabry – Perot cavity exceeded 4 mrad, and the transverse intensity distribution of the beam significantly changed with its propagation, i.e., we obtained a substantially multimode beam. The output energy was 0.51 J for the loop cavity and 0.72 J for the Fabry – Perot cavity, i.e., differed by only 40 % (although the loop cavity was an order of magnitude longer than the Fabry – Perot cavity), which is also explained by the adaptive properties of the loop cavity. It should also be noted that the space parameters of the loop cavity radiation did not change as the pump pulse repetition rate increased from 7 to 25 Hz, while the laser beam divergence in the case of the Fabry – Perot cavity increased to 6 mrad.

Figure 2 shows the dependences of the output energy of the Nd : YAG loop laser W_L on the pump pulse energy W_p for the pump pulse duration $\tau = 300$ μs and different repetition rates. One can see that the increase in the output laser energy with increasing pump pulse energy is linear with a large inclination angle, which determines the slope efficiency of the laser (exceeding 30 %). The dependences corresponding to different pump pulse repetition rates almost overlap with each other, which means that the energy (as well as the spatial) parameters of laser radiation do not depend on the pump pulse repetition rate. At the maximum pump pulse energy of 3.63 J, the output energy of single-mode laser radiation reaches 0.73 J and the maximum average power is 18.3 W at the pump pulse repletion rate of 25 Hz, which corresponds to the optical efficiency of 20%.

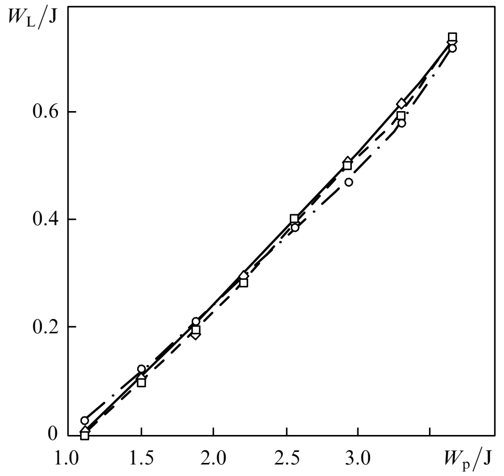

Figure 2. Dependences of the output energy W_L of the diode-pumped multiloop Nd : YAG laser on the pump pulse energy W_p at the pump pulse duration of 300 μs and pulse repetition rates of 7 (◇), 10 (□), and 25 Hz (○).

Figure 3 present the dependences of the output laser energy W_L on the pump pulse duration τ at a pump pulse repetition rate of 10 Hz and different peak pump powers P. As is seen, as τ increases by a factor of 2.7 (form 150 to 400 μs), which corresponds to the same increase in the pump

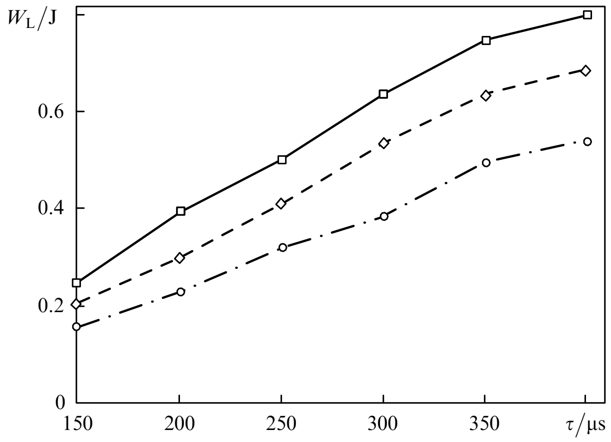

Figure 3. Dependences of the output energy W_L of the diode-pumped Nd : YAG multiloop laser on the pump pulse duration τ at the pump pulse repetition rate of 10 Hz and the peak pump power $P = 11$ (◇), 9.7 (□) and 8.5 (○) kW.

pulse energy W_p ($W_p = P\tau$), the output pulse energy increases by a factor of 3.3 (faster than the pump energy), i.e., the laser efficiency increases by a factor of 1.22. This can be explained by an increase in the diffraction efficiency of the phase-conjugate mirror due to an increase in the AE gain with increasing pump pulse duration, which leads to an increase in the output laser energy. We previously observed a similar effect (increase in the laser energy efficiency with the pump pulse duration) in a loop laser with lamp pumping [11].

4. Lasing in a Nd : YAG loop laser at $\lambda = 1.34$ μm

In [4, 5], we proposed a multichannel design of Nd : YAG laser systems with self-pumped phase-conjugate mirrors formed on the population gratings of not only the fundamental but also of other laser transitions, which have a low gain. In particular, the unsaturated gain increment of Nd : YAG crystals at $\lambda = 1.34$ μm is calculated by the formula $\alpha_{1.34}L = (\alpha_{1.06}L)\sigma_{1.34}/\sigma_{1.06}$, where $\alpha_{1.06}L$ is the unsaturated gain increment at $\lambda = 1.06$ μm and $\sigma_{1.34}/\sigma_{1.06} \approx 0.22$ is the ratio of the gain cross sections at $\lambda = 1.34$ and 1.06 μm [15]. At the gain increment $\alpha_{1.06}L \approx 4.6$, which can be realised for Nd : YAG rods with the length $L = 10 - 13$ cm under high-power lamp pumping, we obtain $\alpha_{1.34}L \approx 1.0$, which exceeds the required value for the scheme in Fig. 1c [see formula (11)]. In this case, it is also necessary to introduce selective losses between neighbouring AEs to suppress lasing at $\lambda = 1.06$ μm, which, at $\alpha_{1.06}L \approx 4.6$, starts as soon as after two passes through the AE. This can be easily done using selectively reflecting mirrors in the Z-shaped cavity [16]. Such a modified scheme is shown in Fig. 4 and was experimentally tested with large (∅6.3 × 130 mm) Nd : YAG AEs under lamp pumping with a pulse energy of 72 J and a pulse duration of 300 μs.

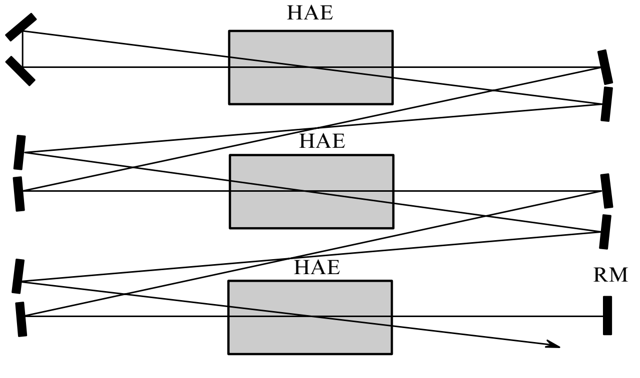

Figure 4. Optical scheme of the Nd : YAG loop laser operating at a wavelength of 1.34 μm.

Instead of an external injector, we again used an auxiliary cavity in the same laser channel, which generated a radiation for preliminary writing of phase-conjugate mirrors in the AE, which ensured successive phase-conjugate lasing. In this case, as an output mirror at the laser exit, we placed a glass plate, which was antireflection coated at $\lambda = 1.06$ μm and had a reflectance of 6 % at $\lambda = 1.34$ μm.

The laser emitted single-mode radiation at a wavelength of 1.34 μm with a low divergence, close to the diffraction limit, and with a Gaussian transverse intensity distribution in both near- and far-field zones at pump pulse repetition rates of 2 and 10 Hz, which confirms efficient operation of the phase-conjugate mirrors of the cavity. Figure 5 shows the dependences of the output laser energy W_L at $\lambda = 1.34$ μm on the pump pulse energy W_p for one HAE at the pulse duration $\tau = 300$ μs and repetition rates of 2 and 10 Hz. One can see that the single-mode radiation energy increases linearly, slightly slower in the case of the higher pulse repetition rate. At the maximum pump pulse energy (72 J) for one AE, the output laser energy reaches 0.96 J, which corresponds to the lasing efficiency of 0.45 %. The highest average power of the single-mode laser radiation at $\lambda = 1.34$ μm was 8.5 W at the pump pulse repetition rate of 10 Hz.

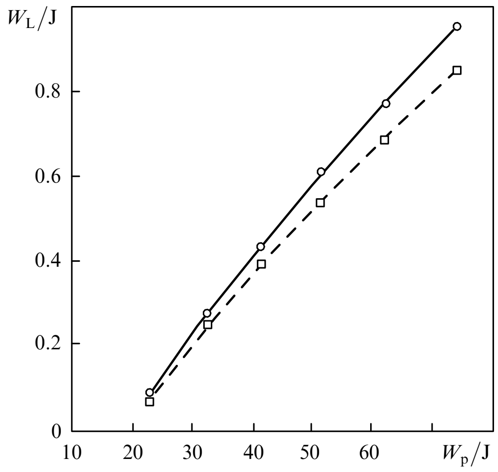

Figure 5. Dependences of the output energy W_L of the lamp-pumped Nd : YAG loop laser operating at a wavelength of 1.34 μm on the pump pulse energy W_p at a pump pulse duration of 300 μs and pulse repetition rates of 2 (○) and 10 (□) Hz.

5. Conclusions

Thus, we studied the possibility of using low-gain active laser elements in different schemes of loop cavities for diode-pumped phase-locked multichannel neodymium laser systems operating not only on the fundamental laser transition at $\lambda = 1.06$ μm, but also on the transition at $\lambda = 1.34$ μm.

The phase-conjugate oscillation thresholds are determined for a multiloop cavity configuration and for an increased number of AEs in the loop cavity. It is shown that the phase-conjugate oscillation in the case of injection of an external signal can occur even when the single-pass gain of the AE is as low as ~ 2.

Under a high-power side diode pumping, we obtained single-mode radiation of a multiloop Nd : YAG laser at $\lambda = 1.064$ μm with a pulse energy up to 0.75 J, a pulse repetition rate up to 25 Hz, an average power up to 18.3 W, and a lasing efficiency up to 20 %. Using three AE inside the cavity, we obtained single-mode radiation of a Nd : YAG loop laser at $\lambda = 1.34$ μm with a pulse energy up to 0.96 J, a pulse repetition rate up to 10 Hz, and an average power up to 8.5 W.

Our results promise the possibility of creating solid-state phase-locked multichannel laser systems operating at different laser transitions of neodymium under high-power diode pumping.

Acknowledgements. This work was partly supported by the Analytical Departmental Targeted Program 'Development of Scientific Potential of Higher School' (Grant No. RNP.2.1.1/3838), by the Federal Targeted Program 'Scientific and Scientific-Pedagogical Personnel of Innovative Russia' (State Contract Nos 02.740.11.0020 and 02.740.11.0480), and by the Russian Foundation for Basic Research (Grant No. 09-02-99023).

References

1. Likhanskii V.V., Napartovich A.P. *Usp. Fiz. Nauk*, **160**, 101 (1990) [*Sov. Phys. Usp.*, **33**, 228 (1990)].
2. Basiev T.T., Gavrilov A.V., Osiko V.V., Smetanin S.N., Fedin A.V. *Kvantovaya Elektron.*, **33**, 659 (2003) [*Quantum Electron.*, **33**, 659 (2003)].
3. Basiev T.T., Gavrilov A.V., Osiko V.V., Smetanin S.N., Fedin A.V. *Kvantovaya Elektron.*, **37**, 143 (2007) [*Quantum Electron.*, **37**, 143 (2007)].
4. Basiev T.T., Gavrilov A.V., Osiko V.V., Smetanin S.N., Fedin A.V. *Kvantovaya Elektron.*, **39**, 31 (2009) [*Quantum Electron.*, **39**, 31 (2009)].
5. Basiev T.T., Gavrilov A.V., Smetanin S.N., Fedin A.V. *Dokl. Ross. Akad. Nauk*, **430**, 321 (2010) [*Doklady Phys.*, **55**, 13 (2010)].
6. Bel'dugin I.M., Galushkin M.G., Zemskov E.M. *Kvantovaya Elektron.*, **11**, 887 (1984) [*Sov. J. Quantum Electron.*, **14**, 602 (1984)].
7. Bel'dugin I.M., Berenberg V.A., Vasil'ev A.E., et al. *Kvantovaya Eektron.*, **16**, 1142 (1989) [*Sov. J. Quantum Electron.*, **19**, 740 (1989).
8. Damzen M.J., Green R.P.M., Syed K.S. *Opt. Lett.*, **20**, 1704 (1995).
9. Fedin A.V., Gavrilov A.V., Basiev T.T., Antipov O.L., Kuzhelev A.S., Smetanin S.N. *Laser Phys.*, **9**, 433 (1999).
10. Basiev T.T., Fedin A.V., Osiko V.V., Smetanin S.N. *Laser Phys.*, **13**, 903 (2003).
11. Basiev T.T., Gavrilov A.V., Smetanin S.N., Fedin A.V. *Doklady Ross. Akad. Nauk*, **408**, 614 (2006) [*Doklady Phys.*, **51**, 296 (2006)].
12. Smith G., Damzen M.J. *Opt. Express*, **15**, 6458 (2007).
13. Kogelnik H. *Bell Syst. Techn. J.*, **48**, 2909 (1969).
14. Grechin S.G., Nikolaev P.P. *Kvantovaya Elektron.*, **39**, 1 (2009) [*Quantum Electron.*, **39**, 1 (2009)].
15. Zverev G.M., Golyaev Yu.D., Shalaev E.A., Shokin A.A. *Lazery na alyumoittrievom granate s neodimom* (Lasers Based on Neodymium-doped Aluminum Yttrium Garnet) (Moscow: Radio i Svyaz', 1985).
16. 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**, 710 (2010) [*Quantum Electron.*, **40**, 710 (2010)].