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Generation of a broad-area laser diode in an asymmetrical V-cavity possessing a spectrally nonselective feedback mirror

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Abstract. **Generation of a broad-area laser diode is experimentally studied in an external asymmetrical V-cavity comprising an inclined output feedback mirror (FBM) that is nonselective with respect to spectrum and phase. The study is aimed at finding the ranges of a pump current and FBM inclination angles, in which the laser beam is narrow-directed. Laser radiation spectra are measured and FBM angles are juxtaposed with the angles of the output laser beam and the average period of filament positions in the laser diode.**

Keywords: *broad-area laser diode, narrow-directed laser beam, asymmetrical V-cavity, filaments, mode selection.*

1. Introduction

Broad-area laser diodes (BALDs) are now highly needed and actively developing class of laser emitters. The growing interest to high-energy laser systems is explained by their numerous applications in modern technologies. It is a common knowledge that under high pump currents, channels of increased brightness (filaments) arise in the emission zone of the BALD [1–6]. Due to a phase mismatch between filaments, the laser structure has many nonphased transverse modes, which results in a high beam divergence and local intensity maxima arising in certain propagation directions. Suppression of the transverse multimode emission and formation of a single mode require the matching of all the emitting channels.

An array of uniformly spaced waveguides with a period Λ_a is matched with field antinodes of two converging beams with a wavelength λ incident onto a system of waveguides at angles $+\varphi$ and $-\varphi$ relative to the longitudinal axis if the angle φ satisfies the Bragg condition (Fig. 1):

$$\sin\varphi = \frac{\lambda}{2\Lambda_a}. \quad (1)$$

Note that in this case the phases of fields in neighbouring nodes differ by the value of π. Hence, by using two converging beams one can produce a phase-matched periodic distribution of nodes on a face of a laser diode (LD).

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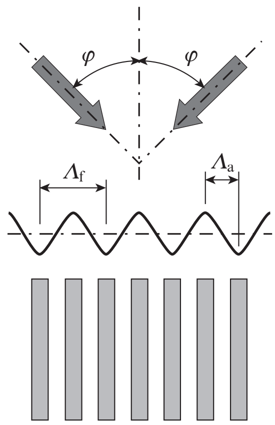

Figure 1. Matching an array of uniformly distributed waveguides with antinodes of two interfering converging beams.

If the filaments are distributed in accordance with these nodes then a high-order transverse mode will be formed with the period $\Lambda_p = 2\Lambda_a$, which occupies the whole cross section of a laser diode emitting domain. Obviously, the periodical filament positions and their phase matching in the case of an isolated laser diode not affected from outside are determined by filamentation mechanisms. In this view, actual is the degree of the influence of the distribution of interference intensity and phase across the LD face produced by a feedback (FB) radiation on the formation of the phase-matched filament structure.

The laser cavities, in which the phase-matched field distribution along the laser diode face is realised due to FB beams, are called the cavities with off-axis FB or V-cavities [7–12]. The latter may comprise two FB mirrors (symmetrical V-cavity) or consist of a single mirror (asymmetrical V-cavity). In the latter case, the cavity Q-factor is maximal for the transverse mode, for which the direction of one of the beams is normal to the FB mirror (FBM) [7].

We have studied the possibilities and conditions of formation for a phase-matched filament spot distribution on a LD face by using a broad-area laser diode. It was placed in an asymmetrical V-cavity (Fig. 2) which is the simplest and most efficient one for selecting high-order transverse modes. In experiments, as a FBM we used a spectrally nonselective reflector with the reflection coefficient R = 7%. Such a choice of spectrally nonselective mirror is explained by intention to exclude a possible influence of FB signal spectral filtering on selection of laser transverse modes.

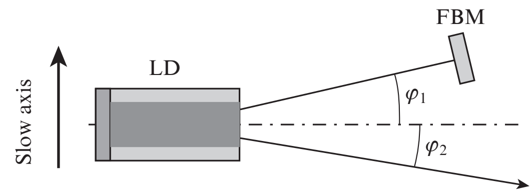

Figure 2. External asymmetrical V-cavity: (LD) laser diode; (FBM) feedback mirror.

2. Study of generation in a cavity formed by the LD faces

The output face of the BALD (with a stripe width of 100 μm) used in experiments had a strong antireflection coating, which provided laser operation in the luminescence regime up to the nominal pump current $I_{\text{nom}} = 2$ A. A similar commercial laser diode available without such a coating operated at a wavelength $\lambda \approx 1.064$ μm had the spectral FWHM $\Delta\lambda = 4-5$ nm (Fig. 3) and provided the output power $P = 2$ W at the nominal current of 2 A.

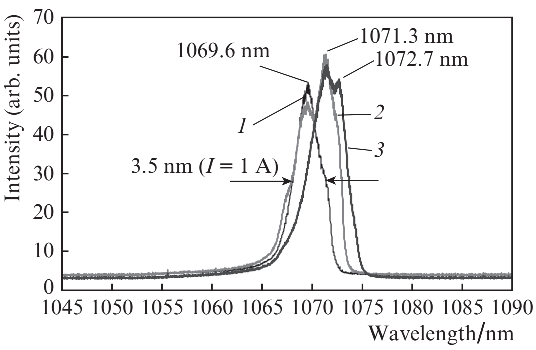

Figure 3. Generation spectrum of the LD at the pump current I = (*1*) 1, (*2*) 1.5, and (*3*) 2 A.

A picture of output face radiation of a commercial LD (without deep antireflection) under various pump currents had the structure traditional for broad-area diode lasers that comprised a number of bright domains (Fig. 4). By assuming that the brightness profile of the output LD face is formed by many nonphased filaments with a Gaussian intensity distribution one can present the array of such emitters which form the total intensity profile mentioned at the output face (Fig. 5). In this view, the period of positions of independent radiation sources along the face of studied LD varies from 7 to 11 μm at the filament FWHM changing from 6.6 to 8.5 μm, the filaments being more concentrated near the ends of the LD active domain.

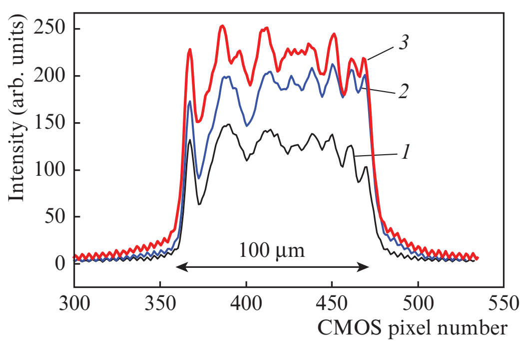

Figure 4. Intensity distribution at the LD output face under pump currents of (*1*) 0.4, (*2*) 0.7, and (*3*) 1 A; $T = 25\,^{\circ}$C.

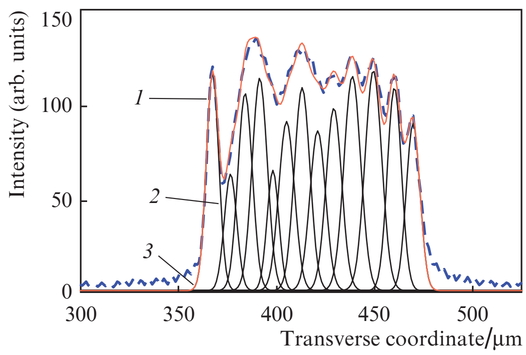

Figure 5. (Colour online) Luminescence intensity distribution at the LD output face under pumping current $I = 0.4$ A (*1*) and the set of filament Gaussian intensity distributions [curves (*2*)], the sum of which yields the distribution (*3*); $T = 25\,^{\circ}$C.

Study of the angular distribution of laser radiation intensity in the far zone in the plane of p–n transition reveals its dependence on the pump current: at a current $I = 0.4$ A the angular FWHM is $\Delta\theta = 5^{\circ}$, at $I = 0.7$ A it is $\Delta\theta = 5.4^{\circ}$, and at $I = 2$ A we have $\Delta\theta = 6.5^{\circ}$ (Fig. 6). The angular width $\Delta\theta = 5^{\circ}$ corresponds to a coherent source with $\lambda \approx 1$ μm and the emitting zone width of about 15 μm. By juxtaposing this value with filament dimensions and positions obtained earlier (Fig. 5) one can conclude that this corresponds to two neighbouring phased filaments. Thus, the radiation of the LD output face is formed by a number of filaments with the phase matching limited by two neighbouring ones.

In the asymmetrical V-cavity used (Fig. 2), the feedback is realised through an inclined position of the external FBM, which increases the Q-factor of the transverse mode that possesses the period

$$\Lambda = \frac{\lambda}{\sin\varphi_1}, \tag{2}$$

where φ_1 is the angle between the LD axis and normal to the FBM.

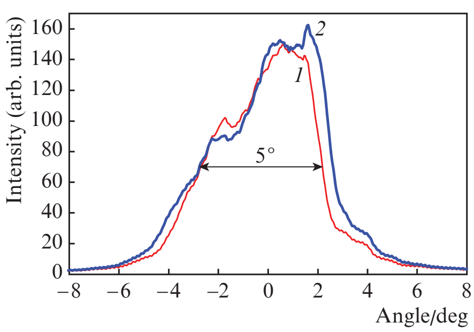

Figure 6. Intensity distribution of the far-field laser radiation at currents I = (*1*) 0.4 and (*2*) 0.7 A; $\Delta\theta$ = (*1*) 5° and (*2*) 5.4°.

In order to form a transverse mode on periodical filaments the latter should be synchronised in such a way that the phases of neighbouring filaments differed by π. Then at the period of filament positions Λ_f one may expect a transverse mode with the period $\Lambda_m = 2\Lambda_f$. For the measured periods of filament positions $\Lambda_f = 7-11$ μm, the period of the transverse mode Λ_m fits the range of 14–22 μm. From this period values and in view of Eqn (2) one may expect transverse mode selection in the range of FBM angles $\theta = 2.8°-4.3°$; the least angle corresponds to the longest mode period.

A principal schematic diagram of the experimental setup with an external cavity is presented in Fig. 7. In the experiment, the angle of FBM turn relative to the LD axis was varied. Generation parameters were recorded by a spectrometer and a CMOS camera. The latter was used for measuring intensity distributions in the far-zone laser radiation, images of which were formed on an opaque screen. In order to reduce optical losses, a collimating cylindrical lens with an antireflection coating was placed directly in front of the LD output face. This substantially weakened the dependence of the generation threshold pump current on a distance between the FBM and LD output face. The antireflection coating on the collimating lens excluded laser emission up to the nominal pump current of the LD.

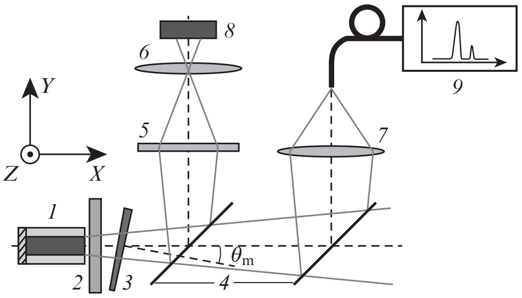

Figure 7. Scheme of measuring the parameters of LD radiation in an external V-cavity:
(*1*) laser diode; (*2*) cylindrical lens; (*3*) FBM; (*4*) beam splitters; (*5*) opaque screen; (*6*, *7*) focusing objectives; (*8*) CMOS matrix; (*9*) spectrometer.

3. Experimental study of LD generation in an external asymmetrical V-cavity

In experiments with an external FBM, the threshold current was $I_{th} = 300$ mA. At an angular position of the FBM relative to the LD output face, the laser emission substantially differed in the spectrum and far-field intensity distribution from that of LD without external cavity and from the emission when the FBM was placed perpendicular to the LD output face. The angular profile of the laser radiation intensity distribution depended on the pump current and angle of FBM turn. At pump currents of up to 500 mA, the laser generation at inclined FBM position exhibited a stable spectrum and stable far-field intensity distribution. Under higher currents, the number of emitting beams sharply increased, the ratio of their intensities became unstable, and the generation spectrum broadened and was also unstable. In this view, lasing was only studied in the operation current range of 400–500 mA.

In the case of the FBM arranged normally to the LD axis, the generated radiation at small currents ($I = 1.3I_{th}$) consists of one or two high-intensity beams with several satellites of lower intensity at the total angular width θ of approximately 7°. In all the cases, no strong coincidence of the LD axis and beam propagation direction was observed. The average angular deviation of the highest-intensity laser beam from the LD axis was 0.2°; the laser emission spectrum was unstable varying within the limits of 10 nm at negligibly small variations of FBM inclination angles. Generally, such characteristics of laser radiation testify that there are many competing modes in LD radiation, which are sensitive to small variations of the FB signal. At a higher pump current, the parameters of laser radiation became similar to those of LD without external cavity.

Variation of the FBM turn angle demonstrated laser generation in discrete angles (Fig. 8). Note that at small FBM turn angles, the angle of output beam did not coincide with the FB angle (the beam, whose direction coincides with normal to the FBM). The angle difference reduced at higher FBM turn angles, and at angles greater than 2° these angles actually coincided.

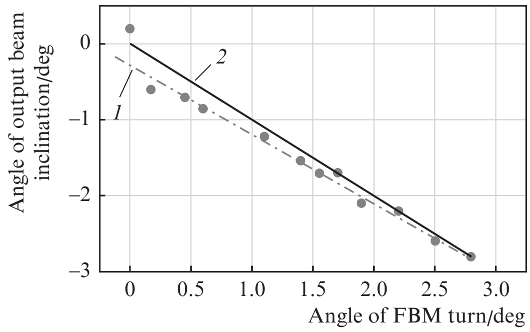

Figure 8. Dependence of the output beam angle (the angle relative to the LD axis) on the angle of FBM turn: positions corresponding to laser generation (points), linear approximation of experimental results (*1*), and the line of equal angles of the output beam and FBM turn (*2*).

At FBM turn angles $\theta > 0.2°$, generation became double-beam with strongly different beam intensities (Fig. 9a). Interestingly, there was no beam in the FBM direction with an intensity comparable to that of the output beam. In the angle range $\theta = 0.2°-1°$ the emission spectrum is unstable, it varies within 11 nm.

Further turn of the FBM in the angle range $\theta = 1.1°-2.5°$ results in an unstable double-beam generation with no addition satellites (Fig. 9a). The laser generation spectrum has a single line with the FWHM value of about 1 nm (Fig. 9b), in some cases the spectrum had additional side satellites with the intensity of at most 20% relative to the main line. The spread of spectral intensity peak positions in various tests was within the limits of 3 nm.

Turn of the FBM by an angle $\theta = 2.8°$ and more results in the third beam arising in a laser generation (Fig. 10a), whose direction coincides with the LD axis. The angular width of the central beam $\Delta\theta$ was approximately 2°. Appearance of this beam in the spectrum of transverse modes testifies that a zero-order supermode arises, which is a parasitic one in this case. The emission spectrum in this case is comprised of a relatively wide main base and the narrow peak having the FWHM of at most 1 nm (Fig. 10b); instability of the maximal peak position in various tests was approximately 10 nm. At FBM turn ang-

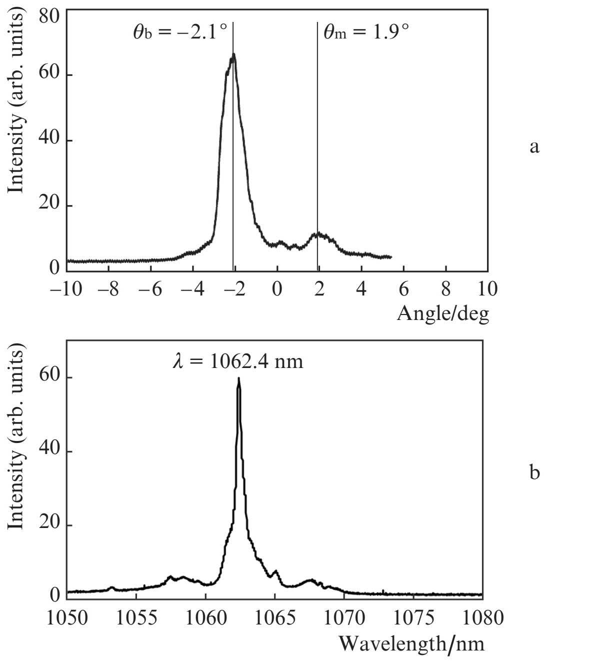

Figure 9. (a) Distribution of the far-field laser radiation intensity and (b) laser generation spectrum at the FBM angle $\theta_m = 1.9°$; $I = 500$ mA, $T = 26$°C.

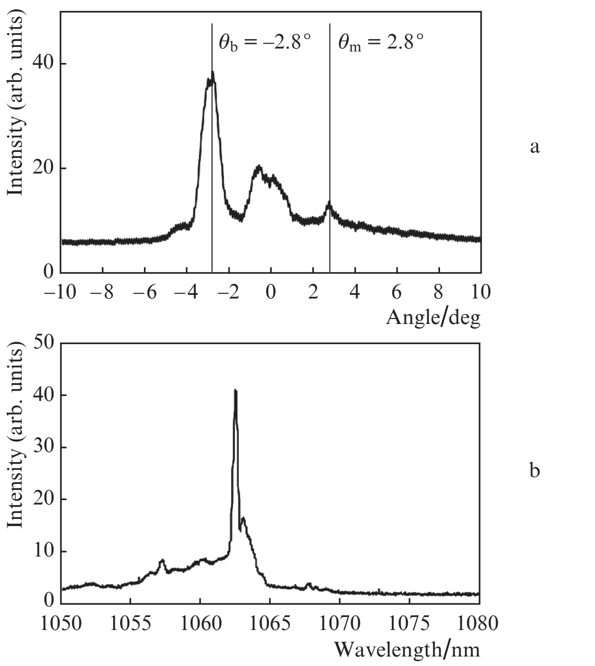

Figure 10. (a) Distribution of the far-field laser radiation intensity and (b) laser generation spectrum at the FBM angle $\theta_m = 2.8°$; $I = 500$ mA, $T = 26$°C.

les greater than 2.8°, no lasing was observed; the LD switched to the luminescence regime.

4. Discussion

The employment of an asymmetrical V-cavity without spectrally selective elements in the feedback circuit of the BALD revealed a strongly pronounced effect of transverse mode selection only at the pump currents not exceeding double the threshold current $2I_{th}$. In the case of normal FBM position with respect to the LD axis, no narrow-directed radiation was observed. This testifies that in-phase emission of all or a part of active channels is impossible in such a cavity geometry. A narrowed angular divergence was only observed with inclined positions of the FBM, at small mirror inclination angles the positions of the output beam and FB beam being clearly asymmetric, which testifies inclination of the phase front of the supermode generated in the transverse cross section of the laser diode. This agrees with the results of filament observation from [13]. The effect of transverse mode selection in the LD was mostly pronounced when the FBM was inclined at the angles of $\theta_m = 1.9°$ and 2.5°, which corresponds to the transverse mode phase periods $\Lambda_m = 32$ and 24 μm, respectively. Expected selection of modes with Λ_m in the range 14–22 μm was not observed. Hence, the experiments realised selection of transverse modes with the phase period approximately three times greater than the period of filament positions in the LD without external cavity.

For interpreting these experimental results, consider a waveguide of a laser diode with filaments as a limited system of single-mode waveguides with a period Λ. It was shown [14], that light beams may propagate in such a waveguide system without diffraction if the pump radiation falls to the waveguide system at the angles that provide the phase difference of $\pi/2$ between the phases of excited waves in neighbouring waveguides. These angles of incidence are determined by the relation

$$\sin\theta = \frac{2m+1}{4}\frac{\lambda}{\Lambda}. \qquad (3)$$

One can see that the excitations of nondiffraction beams are discrete and the minimal angle of incidence (at $m = 0$) is half the Bragg angle θ_{Br} for the waveguide grating with the period Λ_a determined by relation (1).

If we consider an LD as an array of periodically placed channel waveguides with the axes normal to the laser output face then the nondiffraction beam will be matched with this array and will propagate in it in the case where the period of waveguide positions in the array is related to the converging angles of the interfering beams in air by Eqn (3). Thus, for $m = 0$ this relation takes the form

$$\Lambda_0 = \frac{1}{4}\frac{\lambda}{\sin\theta_0}. \qquad (4)$$

In the limits of such channel waveguide system, a light beam excited by a plane wave incident onto the LD faces at an angle θ_0 will propagate without diffraction after reflection from the rear LD face as well. The interaction between the incident and reflected beams results in an interference grating of intensity having the period Λ_{Br} determined by condition (1).

By comparing Eqns (1) and (4) we obtain:

$$\Lambda_{Br} = 2\Lambda_0. \qquad (5)$$

Hence, the intracavity intensity Bragg grating with the period Λ_{Br} is superposed on the initial waveguide array with period Λ_0 in such a way that every second waveguide from the array occurs in the domain of zero intensity of the interference grating formed by the converging beams. Since the initial array is formed by the variation of the refractive index due to the intensity gradient, zero radiation intensity should actually make this waveguide disappear from the waveguide structure, which, in turn, will remove the condition for exciting the non-diffraction beam. This contradiction can be resolved under the condition that the dynamic Bragg grating is formed in the structure, in which the intensity maxima and minima periodically change places in such a short time that the variation of refractive index induced thermally does not change. As applied to laser filaments, this means their pulse-periodical glow where a channel emits light for a certain time and then emission starts in a neighbouring channel. Existence of such a dynamic grating is directly confirmed by the limited lifetime (emission time) of filament, which is a fraction of picosecond [15].

Thus, in a laser structure with the observed time-averaged distribution of filaments that has the period Λ_f, the intracavity Bragg grating matched with the filaments may be only formed at the FB beam incident angle equal to half the angle θ_{Br} for the period Λ_f. Due to a small variation of the period of filament positions this angle may also slightly vary. At lower incident angles, the matching conditions for the arising intensity Bragg structure and the filament grating are realised in the case of the corresponding increase in the period Λ_f. At greater angles of FB beam incidence, the matching is possible at closer filament positions. Λ_f reduces only to a certain limit after which the priority transverse (along the slow axis) mode is not excited and, hence, stable generation of narrow-directed laser beam is not observed.

Just such a dependence on the FB beam angle of incidence was observed in experiments, in which the most pronounced effect of transverse mode selection in the LD was found at the FBM angles θ_m = 1.9° and 2.5°, which correspond to the transverse mode phase periods of 32 and 24 μm. At these angles, the least spread of emission spectrum was observed as well, which points to both the transverse mode selection and spectral selection.

When the FB beam was directed onto the LD face at the angle at which the formed transverse mode period was double that of filament placement Λ_f, the character of radiation distribution in the far-zone (Fig. 10) changed. In this case, in the far-zone in addition to side beams, a radiation along the LD axis was observed, which testifies on the one hand the formation of a high-order transverse mode and on the other hand generation of the fundamental supermode.

5. Conclusions

Experimental results show that the employment of the V-cavity without spectrally selective elements demonstrates the well pronounced effect of transverse mode selection only at the pump currents below double the threshold current. At small angles of FBM turn, the output beam and FB beam were not symmetrically disposed, which testifies that the phase front of the mode arising on filaments is inclined.

The effect of LD transverse mode selection was mostly pronounced when the FBM was inclined at the angles θ_m = 1.9° and 2.5°, which correspond to the transverse mode phase periods of 32 and 24 μm. These values approximately equal double the period of bright domain positions on the output face of LD without external FB. Such a transverse mode corresponds to the hypothesis on existence of nondiffraction propagation of beams, which form in the laser medium a grating of intensity with the period twice greater than that of filament positions.

Expected mode selection with the phase period equal to double that of filament positions was only observed simultaneously with the generation of the fundamental supermode, which resulted in a three-beam generation picture in the far-zone.

References

1. Thompson G.H.B. *Opto-Electron.*, **4**, 257 (1972).
2. Bakhert Kh.-Yu., Bogatov A.P., Eliseev P.G. *Sov J. Quantum Electron.*, **8** (3), 346 (1978) [*Kvantovaya Elektron.*, **5** (3), 603 (1978)].
3. Bogatov A.P., Drakin A.E., Stratonnikov A.A., Konyaev V.P. *Quantum Electron.*, **30** (5), 401 (2000) [*Kvantovaya Electron.*, **30** (5), 401 (2000)].
4. Marciante J.R., Agrawal G.P. *Appl. Phys. Lett.*, **69** (5), 593 (1996).
5. Goldberg L., Surette M.R., Mehuys D. *Appl. Phys. Lett.*, **62**, 2304 (1993).
6. Bossert D.J., Marciante J.R., Wright M.W. *IEEE Photon. Technol. Lett.*, **7**, 470 (1995).
7. Raab V., Menzel R. *Opt. Lett.*, **27** (3), 167 (2002).
8. Thestrup B., Chi M., Petersen P.M. *Proc. SPIE*, **5336**, 39 (2004).
9. Jechow A., Raab V., Menzel R., Cenkier M., Stry S., Sacher J. *Opt. Commun.*, **277**, 161 (2007).
10. Chen J. et al. *Appl. Phys. Lett.*, **85** (4), 524 (2004).
11. Lim J.J. et al. *IEEE J. Sel. Top. Quantum Electron.*, **15** (3), 993 (2009).
12. Svetikov V.V., Nurligareev D.Kh. *Quantum Electron.*, **44** (9), 810 (2014) [*Kvantovaya Electron.*, **44** (9), 810 (2014)].
13. Welch D.F. *IEEE J. Sel. Top. Quantum Electron.*, **6** (6), 1470 (2000).
14. Goncharov A.A., Svidzinskii K.K., Sychugov V.A., Usievich B.A. *Quantum Electron.*, **33** (4), 342 (2003) [*Kvantovaya Electron.*, **33** (4), 342 (2003)].
15. Burkhard T., Ziegler M.O., Fisher I., Elsässer W. *Chaos, Solitons & Fractals*, **10** (4-5), 845 (1999).