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1.5 μm Solid-state Lasers with Diode Pumping

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More robust 1.5 μm compact lasers are found. The results of experimental studies of the conditions of generation of the pulse laser with KGW:Nd^{3+}crystal with transverse pumping are presented. Compact highly efficient 1.531 μm Raman laser emitter is modeled. New crystals for 1.5 μm erbium and Raman neodymium lasers with diode pumping are considered.

Keywords: 1.5 μm range, Erbium laser, Stimulated Raman scattering, SRS self-conversion, Passive crystal Q-switch, Laser resonator.

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1. INTRODUCTION

It is known [1] that the emission wavelengths in the range between 1.5 of 1.8 microns are included into the transparency window of the atmosphere, that is critical in the transmission of radiation over long distances for applications such as communications and lidar. In addition, the lasers with radiation wavelengths in this range are considered safe for the eyes. Eye damage by laser radiation may arise either in consequence of overexposure of the retina or in consequence of excessive absorption of laser energy in the cornea and / or lens. Threshold of retinal lesion by pulsed laser operating in the band between 1.5 of 1.6 microns is higher by orders of magnitude than in the wavelength region of 1 micron.

The wavelengths above 1.6 micron continue to be less dangerous to the retina. In addition, radiation with these longer wavelengths is more and more strongly absorbed by the cornea, that facilitates to reducing retinal exposure. However, the laser radiation with some wavelengths (namely, 3 microns and about 10 microns) is absorbed very strongly, that leads in most cases to the fact that energy is absorbed in a very thin layer of the cornea (less than 100 microns), thereby significantly lowering the lesion threshold.

In view of these considerations, lasers operating in the band between 1.5 of 1.8 micron are beneficial because of their general safety for the eye in combination with good atmospheric transmittance.

Furthermore, the specified spectral range coincides with regions of maximum transparency of silica optical fibers used in optical fiber communications and with maximum sensitivity of common uncooled photodetectors: Germanium and InGaAs photodiodes [2].

Currently, the most convenient in the production and operation half-micron lasers are lasers with emitters on stimulated Raman scattering (SRS-emitters) [3] and erbium lasers. In connection with this there is the issue of improving the optical elements of erbium and Raman lasers.

Raman scattering (RS) of light (Raman effect) is inelastic scattering of optical radiation on the molecules of matter (solid, liquid or gaseous), accompanied by a noticeable change in the frequency of the radiation [4].

2. CONSTRUCTION OF LASER RAMAN EMITTER

In [3] established the benefits of solid-state laser emitters with SRS self-conversion, passive Q-switching by crystal of YAG:V^{3+}, diode transverse pumping and plane-parallel resonator relative to other sources of monochromatic radiation working in the safe for the eyes spectral region of radiation. The perspective crystal of $PbMoO_4$:Nd^{3+}, cut along the axis (010), in the application of lasers with SRS self-conversion is noticed.

The basis of the developed laser Raman emitter is known fully solid-state design, which includes a prism of total internal reflection and adjustment wedges, since it can be easily modified to selected emitter, it provides a stable generation of the fundamental transverse mode of laser radiation in a wide range of ambient temperatures, it is compact and manufacturing of most of its parts is adjusted in Ukraine.

SRS is most effective for the first Stokes component, that is, for the first discrete shifting of the main wavelength to longer wavelengths at a frequency that depends on the Raman medium. In chosen crystal of $PbMoO_4$:Nd^{3+} during pumping neodymium ions emit few emission lines of radiation with the second highest intensity at $\lambda_{excite} = 1.351$ μm (corresponding to the transition ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$ of neodymium ions), which in the matrix crystal of $PbMoO_4$ with frequency of Raman modes of $\nu_R = 871$ cm^{-1} [5] with sufficient intensity is converted to the desired radiation with $\lambda_{signal} = 1.531$ μm:

$$\nu_R = \frac{1}{\lambda_{excite}} - \frac{1}{\lambda_{signal}}$$

due to SRS.

3. METHOD OF CALCULATING RESONATOR MIRRORS AND ANTIREFLECTIVE COATINGS OF OPTICAL ELEMENTS OF EMITTER

For most effective SRS and, consequently, the high-

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est output peak power of Raman radiation out coupling and nontransmitting mirrors of the resonator should have maximum reflection coefficients for primary (excitation) radiation with $\lambda = 1.351$ μm but for the first Stokes component (signal radiation) with $\lambda = 1.531$ μm resonator mirrors should have classic reflection coefficients: nontransmitting mirror should have maximum reflection coefficient and outcoupling mirror should be translucent [6]. Antireflective coatings of the optical elements inside the resonator should have minimum reflection coefficient for the excitation radiation and for signal radiation with $\lambda = 1.351$ μm and $\lambda = 1.531$ μm, respectively, and antireflective coatings of the optical elements outside the resonator should have minimum reflection coefficient only for signal radiation with $\lambda = 1.531$ μm.

To calculate resonator mirrors and antireflection coatings of the optical elements of the emitter the matrix method of calculating the multilayer dielectric coatings, which are also called interference coatings, multilayers or one-dimensional photonic crystals, was used. Let's consider this method to the case of normal incidence of the radiation on the surface of the interference coating consisting of non-absorbent materials and bordering on non-absorbing semi-infinite homogeneous media. The basic structure for the study of multi-layer systems is a homogeneous dielectric layer (magneto-dielectric film). The characteristic matrix of a homogeneous dielectric layer can be represented as follows:

$$\mathbf{m} = \begin{pmatrix} \cos(\frac{2\cdot\pi}{\lambda_0}\cdot n\cdot d) & -\frac{i}{n}\cdot\sin(\frac{2\cdot\pi}{\lambda_0}\cdot n\cdot d) \\ -i\cdot n\cdot\sin(\frac{2\cdot\pi}{\lambda_0}\cdot n\cdot d) & \cos(\frac{2\cdot\pi}{\lambda_0}\cdot n\cdot d) \end{pmatrix},$$

Wherein λ_0 is the radiation wavelength in a vacuum, n is refraction index of light with λ_0 by material of the current layer, d is geometrical thickness of the layer, i is imaginary unit.

If we consider a multi-layered medium consisting of N layers with known characteristic matrix, $\mathbf{m}_j$ (j is layer number in the path of the radiation propagation), the matrix of the entire medium can be represented as matrix of the individual layers product:

$$\mathbf{M} = \prod_{j=1}^{N} \mathbf{m}_j,$$

$$\mathbf{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}.$$

The coefficients of transmission and reflection of light with λ_0 for the layered medium, bordering on both sides with semi-infinite homogeneous media, are expressed in terms of the elements of the characteristic matrix of the entire layered medium:

$$T = \frac{4}{2 + (|M_{11}|)^2\cdot\frac{n_m}{n_s} + (|M_{12}|)^2\cdot n_m\cdot n_s + (|M_{21}|)^2\cdot\frac{1}{n_m\cdot n_s} + (|M_{22}|)^2\cdot\frac{n_s}{n_m}},$$

$$R = 1 - T,$$

where in n_m and n_s are refractive indices of light with λ_0 by materials making up the first (from which radiation propagates) and the second (into which radiation goes) semi-infinite medium, limiting the layered structure, respectively.

To speed up the process of calculation and selection of the most technologically advanced interference coatings with preset coefficients of reflection the computer application in the «C++» programming language with «Qt» class library in the free «Qt Creator» IDE with open source code and with cross-platform «MinGW» compiler was written. The refractive indices of light by materials, of which optical elements of Raman emitter and theirs interference coatings are produced, for radiation wavelengths we are interested were taken from [7]. As the material for the active element was taken crystal $PbMoO_4$, for the passive Q-switch – crystal of $Y_3Al_5O_{12}$ (YAG), for the remaining optical elements – radiation resistant optical glass, K108, the refractive index of which is close to the refractive index of light by optical glass, K8, antireflective coating of the active element – thin film of SiO_2, antireflection coating of passive Q-switch – MgF_2, mirrors and anti-reflective coatings of glass optical elements – alternating layers of thin films of SiO_2 and ZrO_2. The calculated coefficients of emission reflection with $\lambda = 1.351$ μm and $\lambda = 1.531$ μm on the end faces of the optical elements of the laser emitter are presented in Table 1.

Table 1 – The coefficients of reflection of radiation with $\lambda = 1.351$ μm and $\lambda = 1.531$ μm on the end faces of the optical elements of the laser emitter

Element	The coefficients of reflection of radiation on element, %	
	with $\lambda = 1.351$ μm	with $\lambda = 1.531$ μm
Outcoupling mirror	99.81	54.19
The end faces of the active element	0.28	0.24
The end face of the prism of total internal reflection and of two adjusting wedges	0.31	0.33
The end faces of the Q-switch	0.14	0.11
Nontransmitting mirror	99.76	99.76
The outer end face of the glass plate, on the inner end face of which the mirrors are applied	–	0.001

4. METHOD OF CALCULATING ANGULAR DIVERGENCE OF ZERO TRANSVERSE MODE

The angular divergence of zero (main) transverse mode is defined in [8] as follows:

$$\theta = \sqrt{\frac{\lambda_0}{L_n}},$$

wherein λ_0 is the radiation wavelength in a vacuum, L_n is optical length of the resonator.

For radiation with $\lambda = 1.351$ μm for the selected emitter the angular divergence of zero transverse mode is 7'31" and for radiation with $\lambda = 1.531$ μm is 8'.

5. Q SWITCH

The non-linear absorber of YAG:V^{3+} is promising for using in a Raman laser, which generates relatively eye-safe radiation, because such absorber is a saturable absorber for the primary radiation and practically transparent in the unsaturated condition for Stokes components [9]. For a wavelength of 1.34 microns, its refractive index $n = 1.82$, the absorption cross section of the ground level $\sigma_{gsa} = 72 \cdot 10^{-18}$ cm^2, the absorption cross section of the excited level $\sigma_{esa} = 7.4 \cdot 10^{-18}$ cm^2.

In [10] it is noted that the characteristics of the laser depends on the orientation of the crystallographic axes of the Q-switch of V^{3+}: YAG relatively to the crystallographic axes of the active element. The threshold energy of laser pumping does not depend on the crystallographic orientation of the Q-switch. The energy of the laser varies according to the angle of rotation of the Q-switch around the optical axis and is maximum at the crystal of V^{3+}: YAG, grown along the [100] direction and cut out so that the optical axis of the Q-switch is perpendicular to the crystallographic (100) plane.

According [11] the initial density of the normalized inverse population depends on the parameters of passive Q-switch and resonator:

$$N = \frac{1 + \dfrac{\ln(\frac{1}{T_0^2})}{\ln(\frac{1}{R}) + L}}{1 + (\dfrac{\sigma_{esa}}{\sigma_{gsa}}) \cdot \dfrac{\ln(\frac{1}{T_0^2})}{\ln(\frac{1}{R}) + L}},$$

wherein T_0 is the initial transmission of passive Q-switch for the primary radiation, R is outcoupling mirror reflection coefficient for the primary radiation, L is monotreme dissipative optical losses of the primary radiation in the resonator, σ_{esa} is absorption cross section of the excited state of passive Q-switch, σ_{gsa} is absorption cross-section of the ground state of passive Q-switch.

We have proposed to use a laser with a passive Q-switch with $T_0 = 50$ %, because it provides a high normalized initial inverse population density at a moderate pump power of the active element.

6. SYSTEM OF PUMPING ACTIVE ELEMENT AND CONCENTRATION OF ITS ACTIVATORS

One of the peaks of the absorption of radiation by the Nd^{3+} ions in the laser crystals [12] coincides with a wavelength of industrial high-power laser diode bars with $\lambda = 808$ nm.

At selected transverse pumping the active element by laser diode bars it is proposed to use diffuse reflectors to increase the efficiency and uniformity of the pumping [13] and hence to increase output energy of pulses generated by the developed laser emitter and to reduce the thermal effects in the active element.

Initially we proposed to use an active element in the form of 50 mm long and 4 mm in diameter rod of $PbMoO_4$:Nd^{3+}crystal with maximum achievable concentration of neodymium ions (with a mass fraction of $Nd^{3+}$of 3 %) [14] to achieve maximum power density of the excitation radiation with $\lambda = 1.351$ μm to exceed the Raman threshold. In the process of manufacturing the Raman emitter, probably it will be needed to optimize the concentration of the activator and the thickness of the selected active element, since at too much magnitudes of these values the active element could not be completely pumped by selected pump system and, therefore, there would be too non-uniform pumping and low output energy of pulses generated by developed laser emitter.

The threshold power of pumping the main radiation is determined by the expression from [15]:

$$P_{pumpth} = \eta \cdot (\omega_p^2 + \omega_L^2) \cdot \frac{\ln(\frac{1}{R}) + \ln(\frac{1}{T_0^2}) + L + 2 \cdot \sigma \cdot n_{a0} \cdot l}{2 \cdot \sigma \cdot l}, \quad (1)$$

Wherein η is the parameter related to the efficiency of the pumping, which is determined experimentally, ω_p is the mean radius of the pump beam in the gain medium, ω_L is the radius of the laser mode of primary radiation, R is outcoupling mirror reflection coefficient for the primary radiation, T_0 is initial transmission of passive Q-switch for the primary radiation, L is monotreme dissipative optical losses of the primary radiation in the resonator, σ is the cross section of the stimulated emission of the gain medium, n_{a0} is the initial density of the populations of the lower laser level, l is the geometric length of the gain medium.

In our case of transverse pumping ω_p and ω_L are equal to the radius of the active element. Since in (8) there are several variables that are determined experimentally for a particular manufactured laser, we were able to estimate the threshold power of the pumping main radiation only approximately: it is assumed that it will be less than 400 watts.

The threshold pump power and the corresponding energy of the pulse generated by laser emitter should be increased with increasing mass fraction of Nd^{3+} in the active element and with decreasing the initial transmission of the passive Q-switch for the primary radiation [16].

There are ranges of pump powers and durations, which provide monopulse mode of laser emitter operation [6, 16]. To provide single-pulse mode of laser emitter operation with significant increased pump power it is necessary to reduce the duration and vice versa.

The studies of [16] have shown that the minimum threshold pump power is provided at a position of the polarization plane of the active element relative to the axis of rotation of 13 °, providing that the counting starts from a plane passing through the rotation axis of the active element and the axes of radiation of pump diodes. When changing the plane of polarization of the active element relative to the axis of rotation in the range between 8 ° of 18 ° threshold pump power varies slightly.

It was found that when there is the misalignment of the active element and the resonator the pump power range, which provide single-pulse mode operation of the laser, is reduced down to zero at significant misalignment. Therefore, when the laser is assembled it is necessary to control the position of the active element relative to the resonator axis.

7. PROPOSED CONSTRUCTION OF LASER RAMAN EMITTER

The laser structure provided that the resonator alignment is performed using the adjustment wedges which adjust the direction of radiation propagation in the resonator. Therefore, there is a range of positions of adjustment wedges, whereby minimum losses are set in the resonator, thereby it is providing the necessary energy in a pulse of laser radiation and it is not exceeding the maximum threshold pump power. In the course of the experiments [16] the positions of the wedges were fixed about the middle of the range, within which the generation was provided, that ensures stable operation of the laser when the ambient temperature changes.

Fig. 1 presents the proposed construction of the laser Raman emitter: 1 are bars of the pump laser diodes with each bar power of 100 watts and with radiation wavelength of 808 nm; 2 is active element with antireflection coatings, 3, at the end faces in the sleeves; 4 is out coupling mirror disposed on the glass plate, 11; 6 is prism of total internal reflection with antireflection coatings, 5, in the path of the laser radiation propagation; 7 a read just ment wedges with antireflection coating, 5, at the end faces in the sleeves; 9 is laser passive Q-switch with antireflection coating, 8, at the end faces in the sleeve; 10 is non transmitting mirror deposited on a glass plate, 11; 12 is AR coating; 13 are sleeves, in which wedges and Q-switch can be rotated and which are fixed with fixators, 14; 15 are diffuse reflectors made of milk glass. Sleeves are proposed to be made of titanium, since its thermal expansion coefficient is close to the thermal expansion coefficients of the materials of which are made adjacent optical parts.

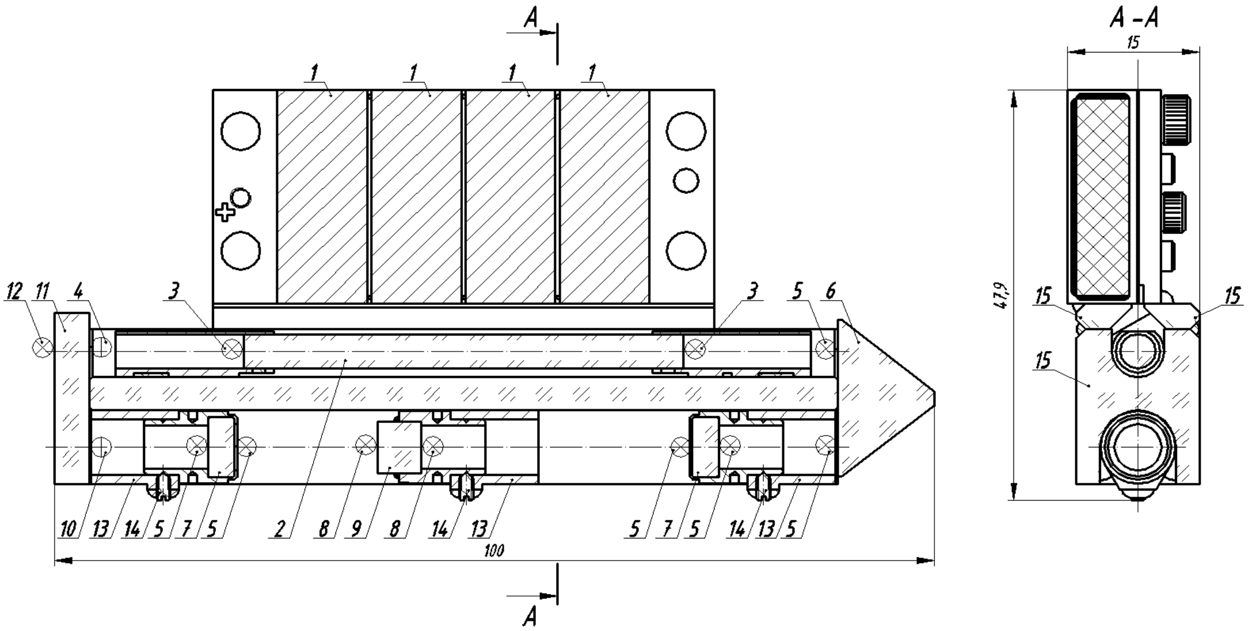

Fig. 1 – Proposed construction of laser Raman emitter

8. 1.5 μM SOLID-STATE ERBIUMLASER WITHOUT YTTERBIUM

Despite the many advantages, Raman lasers have their drawbacks, such as energy losses during SRS and the mechanical fragility of some crystals, of which solid Raman medium are made. Thus, when the length of the active element of the cylindrical crystal of $PbMoO_4$: Nd^{3+} was equal to 79 mm the minimum achievable diameter was equal to 5.85 mm, which can cause some problems when pumping long elements. Therefore, as an alternative the erbium lasers with resonant pumping the active element was also considered.

One of the advantages of the pumping the erbium activator through ytterbium sensitizer is that the phenomenology of this pumping and laser generation can be substantially separated [1]. However, in some materials (especially YAG) absorption band near 980 nm is too narrow (~ 2 nm) to be pumped by conventional diodes and it is necessary to use narrow band diodes.

The obvious drawback of the pumping erbium through ytterbium sensitizer is a low Stokes efficiency (~ 60 %) and a high proportion of thermal losses (~ 40 %). Waste heat is deposited in the gain medium and limits the output power.

In the last decade high-power semiconductor laser diodes emitting near 1.5 microns became reliable and commercially available. This new technology offers resonance (direct) pumping Er^{3+} ions delivering excitation energy directly to the upper state. The key motivation for the resonant pumping is significantly better Stokes efficiency (96 %) and the corresponding reduction in waste heat deposited in the gain medium. As a result, the resonantly pumped erbium-doped gain medium can operate at much higher average power than medium with ytterbium sensitizer.

It is proposed [2] to use saturable absorbers of crystals doped with cobalt-aluminum-magnesium spinel (stoichiometric formula is $MgAl_2O_4$) as passive modulator for 1.5 microns erbium lasers.

In the first lasing experiments (in the lamp-pumped erbium glass laser) by using a crystal with cobalt spinel the mode of passive Q-switching was done with efficiency approaching the efficiency of active modes of modulation. From the combination of the physical and mechanical, technological and laser properties of crystals doped with cobalt-aluminum-magnesium spinel were best among known today passive Q-switches for erbium glass lasers. Also it was shown the applicability (with necessary to use focusing emission of some active elements in the passive Q-switch) of these crystals for passive Q-switching of neodymium lasers generated between 1.32 of 1.44 microns waves of radiation.

For such lasers the active element of the new crystal of $Ca_3Y_2(BO_3)_4$:Er^{3+} having high optical and mechanical characteristics had made at the Institute for Single Crystals NAS of Ukraine.

9. CONCLUSION

Investigations of solid-state laser allowed to specify the conditions of improving of its design and operating conditions. Compact, powerful, high-performance laser emitter operating at emission wavelength of 1.531 μm in the single-pulse or quasi-continuous mode was modeled. Methodology of calculating of the parameters of solid-state lasers was developed. Special computer application was written to speed up the calculation and selection processes of the most technologically advanced interference coatings with predetermined reflection coefficients. The set of design and technological documentation for the production of a simulated Raman laser emitter was compiled. New crystals for 1.5 μm erbium and Raman neodymium lasers with diode pumping were fabricated. In the future we plan to complete the production of the described laser.

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1,5 мкм твердотільні лазери з діодним накачуванням

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У цій статті здійснюється пошук більш надійних півторамікронних компактних лазерів Представляються результати експериментальних досліджень умов генерації імпульсного лазера на кристалі KGW:Nd^{3+} з поперечним накачуванням. Моделюється компактний високоефективний лазерний ВКР-випромінювач на 1,531 мкм. Розглядаються нові кристали для півторамікронного ербієвого і неодимового на ВКР лазерів з діодним накачуванням.

Ключові слова: Півторамікронний діапазон, Ербієвий лазер, Вимушене комбінаційне розсіювання, ВКР- самоперетворення, Пасивний кристалічний лазерний затвор, Резонатор лазера.

1,5 мкм твердотельные лазеры с диодной накачкой

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В этой статье осуществляется поиск более надежных полуторамикронных компактных лазеров. Представляются результаты экспериментальных исследований условий генерации импульсного лазера на кристалле KGW:Nd^{3+} с поперечной накачкой. Моделируется компактный высокоэффективный лазерный ВКР-излучатель на 1,531 мкм. Рассматриваются новые кристаллы для полуторамикронных эрбиевого и неодимового на ВКР лазеров с диодной накачкой.

Ключевые слова: Полуторамикронный диапазон, Эрбиевый лазер, Вынужденное комбинационное рассеяние, ВКР-самопреобразование, Пассивный кристаллический лазерный затвор, Резонатор лазера.

REFERENCES

1. J. Vetrovec, D.A. Copeland, A.S. Litt, *SPIE LASE 2012* Conference (San Jose: CA: 2013).
2. G. Karlsson, V. Pasiskevichius, F. Laurell, J.A. Tellefsen, B. Denker, B. Galagan, V. Osiko, S. Sverchkov, *Appl. Opt.* **39**, No 33, 6188 (2000).
3. И.В. Безносенко, Ю.П. Мачехин, *Прикладная радиоэлектроника* **13** No4, 406 (2014).
4. C.V. Raman, K.S. Krishnan, *Nature* **121**, 501 (1928).
5. P.G. Zverev, *phys. status solidi* **1** No 11, 3101 (2004).
6. Y.M. Yashkir, Y.Y. Yashkir, *Numerical modeling of the intra-cavity stimulated Raman scattering as a score of subnanosecond optical pulses* (University of Toronto Optical

Technological Center).
7. https://refractiveindex.info (date of application 05.21.2016).
8. Ю.В. Байбородин, *Основы лазерной техники* (Москва: Высшая школа: 1988).
9. А.А. Сироткин, В.И. Власов, А.И. Загуменный, Ю.Д. Заварцев, С.А. Кутовой, И.А. Щербаков, *Квантовая электроника* **44** №1, 7 (2014).
10. А.Н. Титов, В.Н. Иванов, В.Н. Ветров, Б.А. Игнатенков, О.Б. Сторощук, Л.И. Крутова, К.В. Дукельский, В.В. Медоволкин, Е.В. Урбанович, Д.В. Иванов, *Оптический журнал* **75** No1, 49 (2008).
11. S. Ding, X. Zhang, Q. Wang, J. Zhang, S. Wang, Y. Liu, X. Zhang, *J. Phys. D.: Appl. Phys* **40**, 2736 (2007).
12. http://pracgw.sinp.msu.ru/images/atom/descriptions%20atom/atom18.pdf.
13. С.Г. Гречин,П.П. Николаев, *Квантовая электроника* **39** No1, 1 (2009).
14. M.B. Kosmyna, B.P. Nazarenko, V.M. Puzikov, A.N. Shekhovtsov, *Acta Physica Polonica A* **124** No2, 305 (2013).
15. X. Zhang, A. Brenier, Q. Wang, Z. Wang, J. Chang, P. Li, S. Zhang, S. Ding, S. Li, *Opt. Express* **13** No19, 7708 (2005).
16. И.В. Безносенко, Ю.П. Мачехин, *Прикладная радиоэлектроника* **13** No2, 169 (2014).