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Autodyne effect in a single-mode Er fibre laser and the possibility of its usage for recognising the evaporated biotissue type

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Abstract. **The autodyne signal arising in an Er fibre laser in the course of evaporating biological models of different types is studied and the possibility of recognising the biotissue type using the method of autodyne detection of the backscattered Doppler signal is assessed. In the experiments we modelled the process of surgical intervention using the contact (hole perforation with the Er laser fibre) and noncontact (surface evaporation with the focused radiation) regimes of impact on different biological models. The amplitude – frequency characteristic of the autodyne detection for the Er fibre laser is measured and the initial spectra of the backscattered Doppler signal arising under the action of laser radiation on the samples of biological models are obtained. The experiments have shown that the spectra of the backscattered Doppler signal, arising in the course of the contact and noncontact action of the Er fibre laser on different biological models, demonstrate clear-cut distinctions.**

Keywords: *fibre laser, self-heterodyning effect, autodyne effect, Doppler spectroscopy, surgical laser with feedback, biotissues.*

1. Introduction

One of the modern trends in the development of surgery is the design and application of robotised automated surgical systems [1, 2] aimed at conducting low-traumatic organ-saving operations. The most important component of a robotised surgical complex is the instrument for high-precision manipulations in the operative site. Fibre lasers possessing flexibility and small transverse dimensions of the optical fibre are a promising instrument for conducting abdominal operations. These lasers have found wide application in abdominal operations using the modern endoscopic instrumentation [3].

One of the key problems in designing robotised surgical systems for abdominal operations is the organisation of the feedback that could in real time not only visualise the operative site (which is easily provided by the available methods of imaging and image transmission), but also collect the information in the process of surgical intervention and promptly make decisions on changing the conditions of impact on the biotissue in the automated regime. A specific feature of abdominal operations is the difficulty of access to the site of surgical intervention and, therefore, the difficulty of acquiring information about the impact on the organ or tissue in real time.

Earlier we proposed a method for the operative control of the process of evaporating biotissues with the radiation of a CO_2 laser. The method is based on the autodyne effect (self-heterodyne effect) that arises in the CO_2 laser when its radiation destroys a condensed medium, in particular, a biological tissue [4][*]. Using this effect we designed an intellectual system that allows one to recognise the type of the biotissue evaporated by the CO_2 laser radiation using the spectral characteristics of the autodyne signal, i.e., to differentiate the tissues in the process of laser evaporation. One can expect the same approach to the organisation of feedback to be valid using fibre lasers, too. Earlier we have shown that in the multi-frequency single-mode Er fibre laser having the power up to 5 W the autodyne effect arises in the presence of an external moving scattering object in the field of the output beam, and that this effect can be used for Doppler spectroscopy and velocity measurements [5]. However, the use of such lasers in the autodyne scheme of tissue evaporation diagnostics still requires additional studies because of the specific features of the autodyne effect in these radiation sources and the peculiarities of their application in surgery. First, the fibre lasers can be extremely sensitive to the backscattered radiation [5], due to which in the course of the biotissue treatment the continuous-wave operation of the laser may fail and switch to the pulsed one. Second, the amplitude – frequency characteristic of the autodyne amplification in fibre lasers may have resonance shape with a narrow enough (10 – 20 kHz) bandwidth, which strongly restricts the band of the detected Doppler frequency shift in the backscattered signal. Third, for this type of lasers the urgent problem is the possibility to detect the Doppler backscattered signal by means of the autodyne detection method using different ways of the radiation delivery to the biotissue and different impact of the radiation on it. As a rule, for the radiation delivery they use multimode fibres with various attachments at the distal end [3]. One can distinguish between two basic regimes of evaporation, namely, the contact regime, when the fibre output face touches the biotissue, and the noncontact regime, when the biotissue is separated by a certain distance from the fibre or the focusing system. In the contact regime, the fibre face becomes charry [6] that may

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[*] The autodyne effect in lasers is universal and manifests itself in the influence of the radiation backscattered from a moving external object on the laser oscillation. In particular, the backscattered radiation causes the modulation of the laser output power (autodyne signal) at the Doppler frequency. This autodyne signal can be used as a source of operative information about the process of the laser radiation impact on the biotissue.

change the backscattered signal, arriving from the zone of the radiation impact on the biotissue.

The aim of the present work is to study the autodyne effect in the Er fibre laser, arising in the course of laser destruction of biotissues, and to analyse the possibility of using this effect for the recognition of the type of the biotissue, evaporated in the process of its laser perforation and cutting in contact and noncontact regimes.

2. Experimental setup

The source of laser radiation was a fibre single-mode multifrequency Er laser emitting at a wavelength of 1.54 μm with a power up to 5 W. To transfer the radiation to the object we used a multimode fibre with a core diameter 400 ± 20 μm. This scheme of delivery allows significant reduction of the backscattered signal, arriving at the fibre laser cavity [5]. This attenuation is necessary to prevent the transition of the laser from the continuous-wave regime of oscillation to the regime of chaotic pulsation that can occur due to its extremely high sensitivity to the backscattered radiation.

We modelled the process of surgical intervention using the regimes of both contact (Fig. 1a) and noncontact (Fig. 1b) impact. In the first case the perforation of a hole was implemented by moving the distal end of the fibre and inserting it into the depth of the tissue. In the second case the laser evaporation of biological models was performed in the cutting regime with the laser radiation focused onto the sample surface using a lens with the focal length 3 cm. The samples were moved perpendicular to the laser beam with a given velocity by means of a motorised linear translation stage.

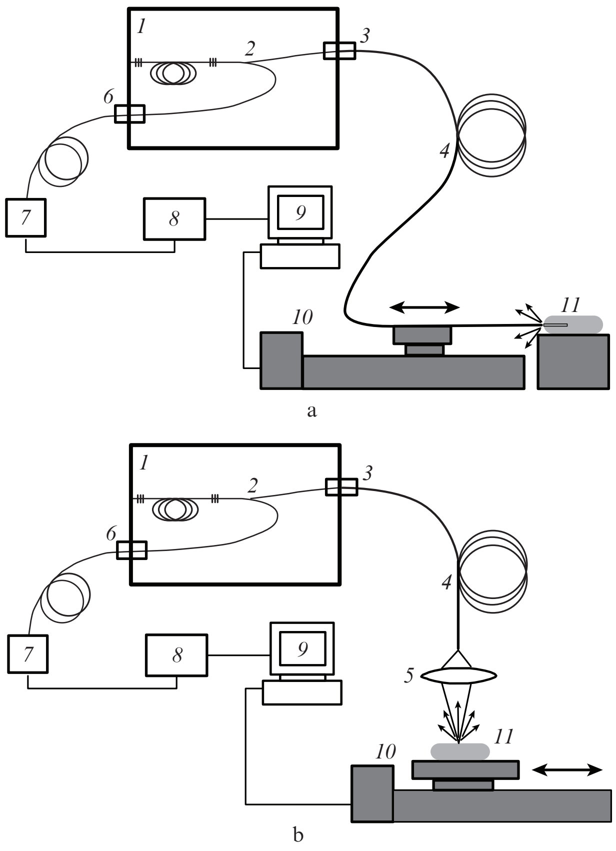

Figure 1. Schematic of the experimental setup for contact (a) and noncontact (b) treatment of a biotissue: (*1*) Er fibre laser; (*2*) Y-coupler; (*3, 6*) optical fibre connector; (*4*) multimode fibre; (*5*) lens; (*7*) photodetector; (*8*) ADC; (*9*) computer; (*10*) motorised linear translation stage; (*11*) biological model.

The autodyne signal was recorded with a PDA400 photodetecting device (Thorlabs) with the operation wavelength range 700 – 1700 nm and the radio frequency range 0 – 10 MHz. The signal from the photodetector was applied to the ADC connected to the computer. In the experiments the radiation of the Er fibre laser affected the samples of biological models of different types and simultaneously the autodyne signal was recorded for the further analysis.

The objects were samples of different biological models, simulating the properties of real biotissues:

1. An agar sample 15 × 15 × 10 mm with the mass fractions of water 95%, 90% and 85%. The impact of the laser radiation on these samples modelled the evaporation of soft biotissues with different water contents.
2. A stripped apple and apple skin. These samples modelled the impact of laser radiation on the tissues with strongly differing physical properties.
3. Different porcine tissues *in vitro* (fat, myocardium, liver, kidney, muscle).

The power of laser radiation in the experiments was 5 ± 0.15 W, the power at the output from the multimode fibre was 3.7 ± 0.1 W. Therefore, in the case of a contact laser impact, the intensity of radiation at the biological model equalled 2.9 ± 0.1 kW cm^{-2}. In the noncontact regime the radiation was focused at the sample surface into a spot with a diameter 730 ± 40 μm [measured at the 1/e level using a Laser Scope UFF 100 device (PROMETEC, Germany)]. The radiation power after the focusing amounted to 3.4 W. Thus, the radiation intensity in the noncontact regime equalled 0.81 ± 0.06 kW cm^{-2}.

3. Results and discussion

Figure 2 presents an example of a typical autodyne signal, arising in the contact regime of Er fibre laser impact on the myocardium, the fibre moving with the velocity 1.4 mm s^{-1}. One can see that the amplitude of the autodyne signal (the variable component of the output power) is sufficiently large. We determined the mean value (during the time 50 ms) of the modulation depth of the laser power during the impact on biological models. The typical value of the mean modulation depth amounted to 5% – 15%, depending on the impact conditions and the biological model parameters. During short

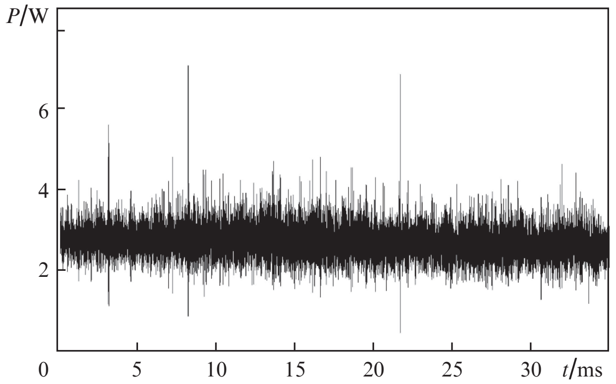

Figure 2. Autodyne signal in the case of contact impact of the radiation of the Er fibre laser on the myocardium sample.

time intervals (up to 0.5 ms) the modulation depth varied within 1%–10%.

According to the results of the studies [7], the autodyne reception of the backscattered radiation can be considered linear with sufficient accuracy (nonlinearity less than 5%), when the modulation depth of the laser radiation power does not exceed 50%. Thus, we can conclude that under the conditions of our experiments at time intervals of tens of milliseconds the implemented regime of autodyne reception of backscattered radiation was close to a linear one.

We studied specific features of the autodyne signal formation and its correlation with the biological model type. The motion of the fibre into the sample or of the sample with respect to the laser beam was performed with the velocity 1.4 mm s^{-1}. Then, the averaged power spectrum of the autodyne signal during the time $T_{\mathrm{avr}} = T_{\mathrm{adc}}N = 2.2$ s was determined, where $T_{\mathrm{adc}} = 0.44$ s is the duration of a single ADC write/read cycle, during which 262144 signal values (the capacity of the ADC buffer memory) are digitised with the discretisation rate 2.5 MHz and transmitted into the computer memory; and $N = 5$ is the number of write/read cycles for averaging. The above time of averaging was chosen because during this time the depth of the channel or the length of the cut (1.4 mm s^{-1} × 2.2 s ≈ 3 mm) were significantly larger than the fibre diameter (400 μm) and the diameter of the focused laser beam (800 μm). The aim of these experiments was to clarify the differences in the power spectra of the backscattered signal, formed in the process of evaporation of biological models of different types. Such differences may serve as a basis for developing a method of recognising the type of the evaporated biotissue and designing the feedback communication channel in surgical systems based on fibre lasers.

Figure 3 presents a logarithmic plot of the averaged power spectrum of the autodyne signal, arising during the contact impact of the Er fibre laser radiation on the myocardium sample. The typical spectra of the autodyne signal arising in the process of the biological model exposure possess two components, one in the low-frequency region below 100 kHz, and the other with a peak at the frequency 340 kHz. The peak at the frequency 340 kHz is determined by the resonance amplitude–frequency characteristic (AFC) of the autodyne reception for this laser [5]. Note that at the frequency 680 kHz a small peak is also present. This peak is the second harmonic of the fundamental resonance peak of the autodyne signal. The amplitude of the second harmonic signal equals less than 1% of the fundamental signal. This fact also confirms the statement that in the experiments carried out the linear regime was implemented in the autodyne reception of backscattered radiation.

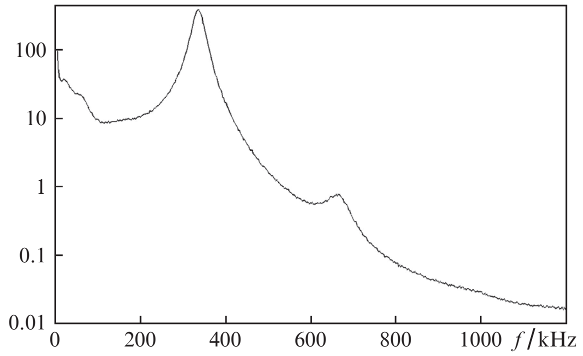

Figure 3. Power spectrum of the autodyne signal, arising in the Er fibre laser in the course of the contact impact on the myocardium sample.

Note that the fundamental peak at the frequency 340 kHz contains nearly 90% of the total autodyne signal energy. Due to this fact the differences in the autodyne signal spectra, related to different types of biological models, were insignificant, since the shape of this peak is determined by the narrow resonance of the autodyne gain in the Er fibre laser. It was interesting to find the initial spectrum of the backscattering Doppler signal. It was shown [7] that for the linear regime of the autodyne reception one can find the initial spectrum of the backscattering Doppler signal dividing the spectrum of the autodyne signal by the AFC of the autodyne reception. To find the 'true' backscattering spectrum, arising in the process of radiation impact on the biological models, we measured the AFC of the autodyne reception (Fig. 4). The AFC was measured using the standard technique with a rotating disc as a source of scattering [7].

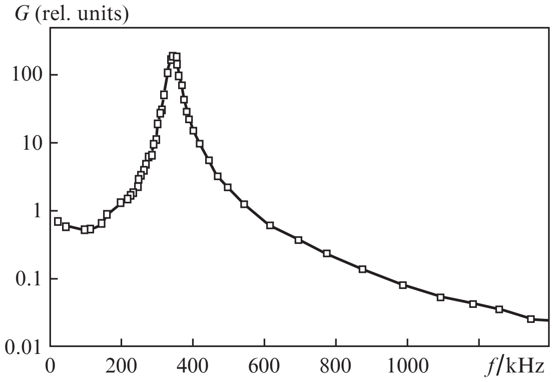

Figure 4. Amplitude–frequency characteristic of the autodyne gain in the Er fibre laser.

Based on the measured AFC we obtained the initial spectra of the backscattering Doppler signal, induced by the impact of the Er laser radiation on the biological models of different type.

Figure 5 presents the power spectra of the backscattering signal arising under the noncontact evaporation of agar samples with different water contents. Figure 6 shows the power

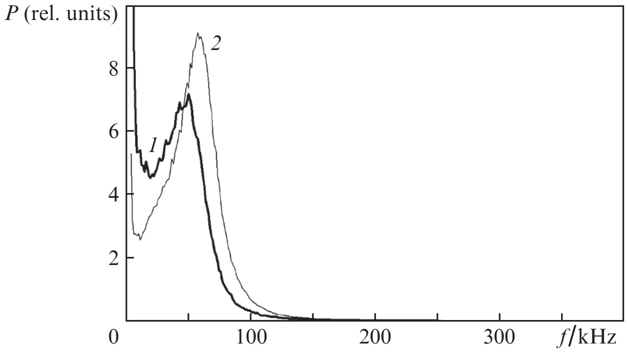

Figure 5. Power spectra of the backscattering signal, arising in the course of noncontact evaporation of agar biological models by the radiation of the Er fibre laser for the mass fractions of agar (*1*) 10% and (*2*) 5%.

spectra of the backscattered signal for the noncontact laser evaporation of a stripped apple and the apple skin. This is an example of biological models that possess a strong difference only in the power of the backscattered signal. The power-normalised spectra of the signals are almost identical (Fig. 7). Figure 8 presents the averaged normalised backscattering spectra of different biological models for the contact regime of the laser impact.

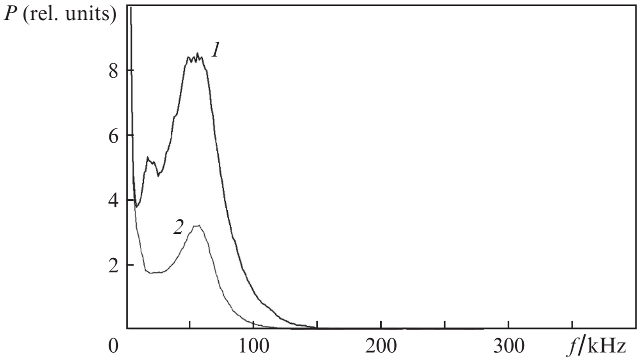

Figure 6. Power spectra of backscattering signal arising in the course of noncontact evaporation of (*1*) apple skin and (*2*) apple.

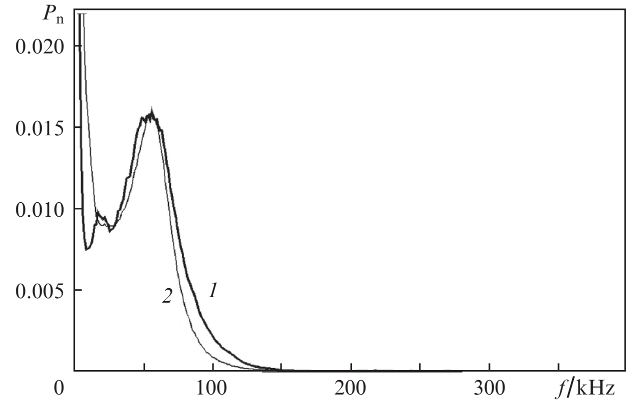

Figure 7. Normalised power spectra of the backscattering signal, arising in the course of noncontact evaporation of (*1*) apple skin and (*2*) apple.

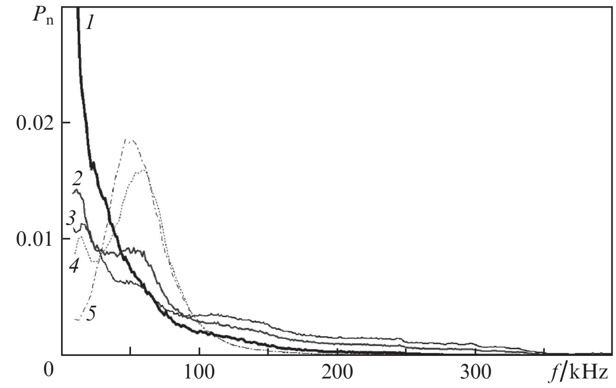

Figure 8. Normalised power spectra of the backscattering signal, arising in the course of noncontact evaporation of porcine tissues using the radiation of the Er fibre laser: (*1*) fat; (*2*) myocardium; (*3*) liver; (*4*) kidney; (*5*) muscle.

The obtained spectra of the backscattering Doppler signal have characteristic frequencies f_d in the range from 10 to 100 kHz for both contact and noncontact methods. These frequencies correspond to the velocity of the products of the biotissue evaporation ($\lambda f_d/2$) from 7.8 to 78 mm s^{-1}. The velocity of the fibre motion with respect to the biological model was 1.4 mm s^{-1} in all experiments. Thus, the observed spectra are determined by the scattering of radiation at the moving products of destruction and at the crater surface in the biological model. Note that in spite of the small width of the resonance band of autodyne reception (Fig. 4), the backscattering Doppler signal was registered in the frequency range far beyond the resonance band and had a sufficiently high signal-to-noise ratio (100–300).

The studies have shown that the biological models can be distinguished by the power of the backscattering signal, as well as by the shape of its spectrum. Some models have clear differences by only one of these criteria (either by the power, or by the spectral shape), while others differ by both.

To evaluate the degree of spectral shape difference for different biological models we used the quantity:

$$\eta = \int_{\nu_1}^{\nu_2} | P_{n1}(\nu) - P_{n2}(\nu) | d\nu, \qquad (1)$$

where $P_{n1}(\nu)$ and $P_{n2}(\nu)$ are the compared spectra, normalised within the frequency range from ν_1 to ν_2. Using the same relation, we evaluated the reproducibility of the averaged spectra, obtained for the same biological model. The experiments have shown that the coefficient η varied within the interval 0.03–0.07 in estimating the reproducibility, while in comparing the spectra for different models it varied within the interval 0.17–0.35. This fact shows that the proposed method allows the differentiation of the type of the tissue, evaporated by the radiation of the Er laser, since the degree of difference between the spectra essentially exceeds their irreproducibility.

One should note that under the contact impact the fibre face becomes black because of the burning products. We experimentally assessed the coefficient of absorption of the output radiation by the layer of soot stick to the fibre face; it was within 0.2–0.4. Therefore, 60%–80% of the radiation passes through the blackened face, and this is quite enough to record the backscattered radiation. From the good reproducibility (small coefficient η) of the obtained spectra it follows that the blackening is sufficiently stable and does not essentially affect the capability to recognise the type of the evaporated biotissue using the backscattering signal.

A specific feature of the noncontact spectra is the presence of a strong component at low (up to 10 kHz) frequencies (see Figs 5–7), while in the contact regime these components were not observed for most biological models. In our opinion, the strong low-frequency component in the backscattering Doppler spectra is caused by the scattering from the surface of the crater in the biological model. A similar effect was observed in [8], where the backscattering Doppler signal was studied in the process of perforating biological models with the radiation of a CO_2 laser. This result also agrees with the theoretical model presented in Ref. [9].

In our experiments with the contact regime a small crater was produced near the fibre output face with the depth up to 3 mm, depending on the impact conditions. It was observed at the moment of through perforation of the biological model. A few seconds before the through perforation a hole appeared at the back side of the biological model, and then in 1–2 s the face of the fibre appeared from the hole. Since in this case there is no radiation focusing, the level of scattered radiation arriving from the crater bottom is much lower than that from the destruction products that move in this crater and can be located at the very face of the fibre. Note that for the noncontact regime only the fat tissue spectrum contained a characteristic strong low-frequency component. This is because in this tissue the distinct channel near the fibre face does not appear, since it is immediately filled with melted fat. In the course of noncontact impact, the laser radiation is focused at the surface of the sample. In this case, the signals scattered both from the crater bottom and from the moving products of destruction will return to the fibre.

The performed studies have shown that the backscattering signal, obtained using the method of autodyne detection, carries information about the local processes of mass transfer, developing in the zone affected by the Er fibre laser radiation. For both contact and noncontact treatments all biological models demonstrated clear individual differences either in the power level, or in the spectral shape of the backscattering Doppler signal.

4. Conclusions

The studies of the autodyne signal that appears in the Er fibre laser in the course of evaporating biological models of different types are carried out. It is shown that under the conditions of contact and noncontact regimes of evaporation the implemented regime of the Doppler signal autodyne reception was linear. The amplitude–frequency characteristic of the autodyne reception for this laser and the initial spectra of the backscattering Doppler signal are obtained. It is shown that in spite of the narrow (10 kHz) band of the resonance autodyne amplification of the Er fibre laser, the backscattering signal is registered with a high signal-to-noise ratio (100–300) within the frequency range beyond the resonance band.

The possibility of distinguishing the type of the evaporated biotissue with the help of the method of autodyne detection of the backscattered radiation is studied. It is shown that both for contact and noncontact impacts, all biological models possess distinct differences either in the power or in the shape of the averaged spectrum of the backscattering Doppler signal.

The obtained results offer a perspective of implementing the recognition of the evaporated biotissue and constructing the surgical systems with a feedback, based on the fibre lasers, aimed at low-traumatic organ-saving operations.

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References

1. Takeyoshi O., Degani A., Schwertzman D., et al. *Ann. Thorac. Surg.*, **87** (4), 1253 (2009).
2. Rivera-Serrano C., Johnson P., Zubiate B., Kuenzler R., Choset H., Zenati M., Tully S., Duvvuri U. *Laryngoscope*, **122**, 1067 (2012).
3. Minaev V.P., Zhilin K.M. *Sovremennye lazernye apparaty dlya khirurgii i silovoy terapii na osnove poluprovondikovykh i volokonnykh lazerov* (Modern Laser Instruments for Surgery and Force Therapy Based on Semiconductor and Fibre Lasers) (Moscow: Izdatel' I.V. Balabanov, 2009).
4. Varev G.A., Geinits A.V., Dmitriev A.K., Konovalov A.N., Kortunov V.N., Panchenko V.Ya., Reshetov I.V., Ul'yanov V.A. *Almanakh Klinicheskoy Meditsiny*, **XVII**, Ch. 2, 164 (2008).
5. Dmitriev A.K., Konovalov A.N., Ulianov V.A. *Kvantovaya Elektron.*, **44** (4), 309 (2014) [*Quantum Electron.*, **44** (4), 309 (2014)].
6. Sandler B.I., Sulyandziga L.N., Chudnovskii V.M., Yusupov V.I., Kosareva O.V., Timoshenko V.S. *Perspektivy lecheniya diskogennykh kompressionnykh form poyasnichno-kresttsovykh radikulitov s pomoshchyu punktsionnykh neendoskopicheskikh lazernykh operatsii* (Prospects of Treatment of Diskogenic Compression Forms of Lumbosacral Radiculitis Using Paracentetic Non-Endoscopic Laser Operations) (Vladivostok: Dal'nauka, 2004).
7. Gordienko V.M., Konovalov A.N., Ul'yanov V.A. *Kvantovaya Elektron.*, **41** (5), 433 (2011) [*Quantum Electron.*, **41** (5), 433 (2011)].
8. Vasil'kov V.V., Gordienko V.M., Dmitriev A.K., Konovalov A.N., Kortunov V.N., Panchenko V.Ya., Ul'yanov V.A. *Kvantovaya Elektron.*, **32** (10), 89 (2002) [*Quantum Electron.*, **32** (10), 89 (2002)].
9. Dmitriev A.K., Ivanov S.V., Konovalov A.N., Kortunov V.N., Ul'yanov V.A., Koshcheev A.V. *Phys. Wave Phenom.*, **13** (1), 15 (2005).