Capabilities of Autodyne Reception in Medical CO_2 Laser Devices

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Abstract. The generation characteristics and the capabilities of autodyne reception in single mode CO_2 lasers with pulse-periodic pumping of the active medium used in medical laser devices are investigated. It has been demonstrated that medical laser device based on CO_2 laser model DIAMOND C-30A (Coherent Co.) has the best long-term laser power stability ((2–3)%), while the setup with CO_2 laser model 48–2W (Synrad Co.) has the best short-term stability (0.62%). Amplitude-frequency characteristics of autodyne reception were studied for lasers of these devices. Power spectra of the autodyne signal appearing during evaporation of fat and muscle tissues under CO_2 laser radiation of the three types of laser devices were recorded. It has been shown that all these laser devices allow to detect the autodyne signal during evaporation of biological tissues. The medical laser setup with CO_2 laser model 48–2W has the highest signal-to-noise ratio during detection of laser backscattered radiation. This is due to the fact that this laser has larger autodyne amplification and better short-term power stability. The results can be used in the development of smart laser surgical systems with feedback. © 2019 Journal of Biomedical Photonics & Engineering.

Keywords: medical laser device; CO2 laser; laser power stability; autodyne reception; signal-to-noise ratio; laser evaporation; biotissues.

Paper #3321 received 29 Mar 2019; revised manuscript received 10 Jun 2019; accepted for publication 10 Jul 2019; published online 1 Aug 2019. doi: 10.18287/JBPE19.05.030301.

1 Introduction

The creation of the so-called smart laser medical systems is a modern development trend of laser medicine. Setting up feedback is the key problem in creation of such systems. The feedback should not only allow to visualize the surgical area and to remotely manipulate in it (this can be done using the existing modern methods of image acquisition and transfer and the corresponding technical equipment), but also to receive objective information about the process of surgical intervention and to make automated decisions on changing the conditions of operation [1, 2].

Currently, the vision and experience of the surgeon play the role of "peripheral sensors" and "database" in the feedback system when laser operations are conducted. Such feedback does not always guarantee the full removal of diseased tissues and minimum damage of healthy tissues, does not exclude human factor risks and does not allow to evaluate objectively the quality of the operation performed. Such advantages of the laser scalpel as high speed of removal of diseased tissues, precision, low invasiveness will be most fully realized if feedback is introduced into the composition of laser surgical systems for the purpose of real-time supervision and control over the process of laser intervention.

Surgical devices based on single-mode CO_2 lasers with a radiation wavelength of 10.6 μm are widely used [3] in medical practice. In order to diagnose and control the process of laser surgical intervention in real time, we have suggested [4–7] an approach based on the self-heterodyne method for such devices, wherein the operating laser radiation is simultaneously a diagnostic one, creating an optical information feedback channel. The essence of the method is that the backscatter from the moving exterior object reaches the laser cavity and initiates a modulation of the laser output power (autodyne signal) at the Doppler frequency. This process is called the autodyne effect in lasers [8]. The modulation of the laser power arises due to the mixing in the laser cavity of the main radiation and backscattered frequency-shifted radiation. This is similar to optical heterodyning. Therefore, this effect is sometimes called self-heterodyning and self-mixing [4, 6]. The operational diagnostics of processes of laser evaporation of biological tissues in accordance with this method consists in discovering discrepancies and distinctive features of amplitude and frequency characteristics of the signal for different types of evaporated biological tissues and correcting the parameters of applied laser radiation [4–7]. This self-heterodyne process has been well studied for continuous CO_2 lasers [6]. The paper [6] presents a theoretical model of the autodyne effect in CO_2 lasers of this type, describing the amplitude-frequency characteristics (AFC) of autodyne amplification, modulation depth and non-linear signal distortions of the autodyne signal at high levels of backscatter/reflection. It has been shown that the original spectrum of the Doppler backscattering signal can be reconstructed from the autodyne signal spectrum when the “weak” backscattered signal is realized. It is demonstrated that a weak Doppler backscattering signal is formed during CO_2 laser radiation interaction with organic materials, which does not introduce nonlinear distortions into the autodyne signal [6]. Thus, this method can be used to receive real-time information and diagnose the process of laser evaporation/dissection of biological tissues. In our proposed approach to creating an optical information feedback channel, a surgical CO_2 laser is simultaneously a diagnostic one. In this regard, as for any laser Doppler diagnostic methods, the corresponding requirements for mode structure and radiation stability are imposed on this laser. At the same time, CO_2 lasers pumped with trains of radio frequency (RF) pulses (with frequency ranging from tens to hundreds of MHz) with variable pulse ratio (hereinafter – pulse-periodic (PP) pumping) are often used in surgical devices. These lasers are characterized by compactness, long-term stability of operating characteristics and long life-cycle. In these lasers, the “continuous” laser radiation is a pulse train with a frequency of 5–20 kHz, where laser power is modified by changing the pump pulse duration [9]. A computational model of the self-heterodyne effect in such lasers has earlier been proposed [4]. However, there is no information about the features of use of real surgical devices with this type of lasers as feedback sensors.

This paper presents the results of study of lasing characteristics and the possibilities of autodyne reception in single mode CO_2 lasers with pulse-periodic pumping of the active medium, used in medical laser devices.

2 Materials and Methods

The following medical laser devices were used in order to measure the lasing characteristics and autodyne reception in single mode CO_2 lasers with PP pumping of the active medium:

1. “Lantset” series device (OOO “RIK”, Russia) based on a waveguide laser with output up to 25 W [10] (hereinafter as LD-1);
2. “L`med. ” series device (OOO “RIK”, Russia) [11] based on a CO_2 laser model DIAMOND C-30A [12] produced by Coherent Co. USA (hereinafter as LD-2). Laser output up to 30 W;
3. Medical laser setup based on a CO_2 laser model 48-2W [13] produced by Synrad Co. USA (hereinafter as LD-3). Laser output up to 25 W. UC-2000 Laser Controller from Synrad Co. and MCS20-230/24 power supply from MURR Elektronik Co. were used in this setup.

Studies of the characteristics of CO_2 lasers in these devices were carried out in accordance with the scheme shown in Fig. 1. Laser radiation was focused through a ZnSe lens (focal length of 125 mm, focused laser beam diameter of 400 µm) on the surface of the object of study (a rotating metallic disc or a sample of biological tissue). A part of the radiation (2%) was directed by means of beam splitter to the receiving area of the IR photodetector. A non-cooled fast-response HgCdTe sensor with an integrated preamplifier was used as the photodetector. An electric signal is formed on the photodetector’s output in the form of beats at the difference frequency, the spectrum of which is uniquely determined by the spectrum of the scattered light. The signal from the photodetector is directed to the 1-st channel of the fast-response analog-to-digital converter (ADC) ADM212x60M (AO “Instrument systems”, Russia). The synchronization pulses from the laser control system were fed to the second ADC channel. Precision power supply device GPC-303DQ was used to provide the laser radiation photodetector with constant current within the (0.5–30) V voltage range and (0.005–3) A current with pulsation below 1 mW. MAESTRO laser power/energy meter with UP19K-30H5-D0 (Gentec-EO, Canada) thermopile power detector was used to measure the output laser power and its long-term stability.

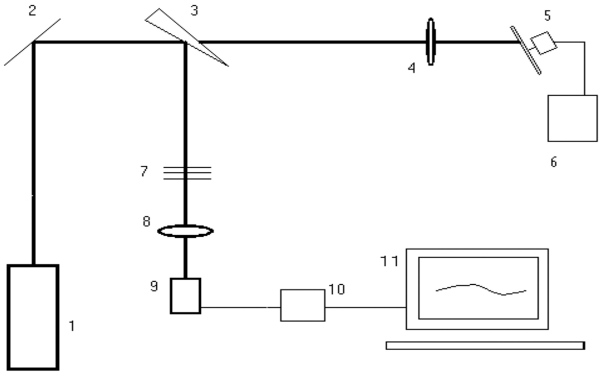


Fig. 1 Schematic diagram of the experimental setup. 1 – CO_2 LD; 2 – copper mirror; 3 – beam splitter; 4 – lens; 5 – rotating metallic disc; 6 – power supply; 7 – teflon attenuators; 8 – lens; 9 – HgCdTe photodetector; 10 – ADC; 11 – PC.

The following studies were performed on the test bench:

- lasing characteristics of undisturbed radiation, including: the shape and amplitude of laser pulses, their repeatability within a short time period (so-called “short-term stability”); the long-term-stability of the laser power; The long-term laser power stability was measured for 10 min, which corresponds to the average time of a laser operation [14]. Long-term stability Δ_{long} was determined using the formula: $\Delta_{long} = \left(P_{\max} - P_{\min}\right)/2 < P >$, where $P_{\max}$ and $P_{\min}$ are the maximum and minimum lasing power during 10 min of the laser’s activity, $<P>$ is the average lasing power during 10 min. Short-term laser power stability was determined as deviation of laser power from the power of the average pulse shape. A special algorithm described in the “Results and Discussion” section was developed to characterize the short-term laser power stability;
- amplitude-frequency characteristics (AFC) of autodyne reception of selected CO$_2$ lasers using the surface of a rotating disk as a source of backscattered radiation;
- biological models *in vitro* were used to model the process of laser dissection of biological tissues. In surgical practice, this process is performed by moving the focused laser beam along the surface of the biological tissue at a speed of 0.1–10 mm/s. We used a motorized linear translator in our experiments to model the dissection of biological models. Fresh pig tissue samples containing muscle and fat components were placed on it. The samples were steadily moved in relation to the laser beam focused on the samples’ surface. Simultaneously, autodyne signal from the products of laser destruction of biological tissues was registered at an average power level of 6.5–7 W for all three laser devices.

All measurements were conducted using the following ADC settings: sampling frequency 7.5 MHz; buffer size – 32768 points. The main method for analyzing an autodyne signal is spectral analysis based on the Fast Fourier Transform (FFT) algorithm.

3 Results and Discussion

The radiation of studied lasers is a sequence of pulses with a repetition frequency of around 10 kHz. Average laser power is regulated by the duration of its pumping pulses. Fig. 2 demonstrates the dynamics of the laser radiation of the LD-2 at average output power of 5 W. The long-term stability of the radiation power of the lasers under study has been measured within 10 min after the laser was switched on.

As an example, the dependency of laser power of LD-3 on time at different relative pulse duration (different average output power) is demonstrated in Fig. 3. Table 1 shows the results of measurement of long-term stability of the laser devices under study.

As follows from Table 1, the best long-term laser power stability (2–3%) was shown by laser model DIAMOND C-30A, being a component of LD-2. The long-term laser power instability in CO$_2$ laser devices, in general, depends on the design features of the lasers and the lasing conditions at different pumping levels of the lasing medium. These features may include: composition of the working mixture, thermal conditions forming within the laser during long-term activity, possible changes during transition from one lasing line to another (CO$_2$ laser signature [14]), etc.

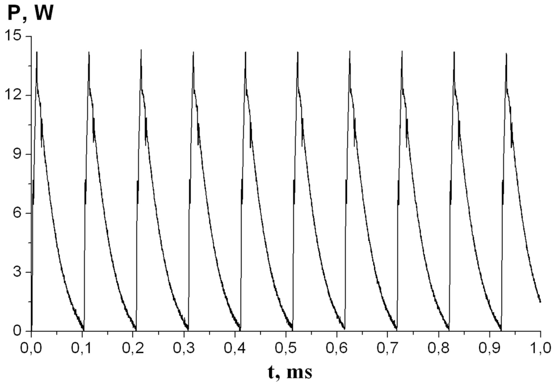


Fig. 2 The dynamics of the laser radiation of the LD-2 at average output power of 5 W.

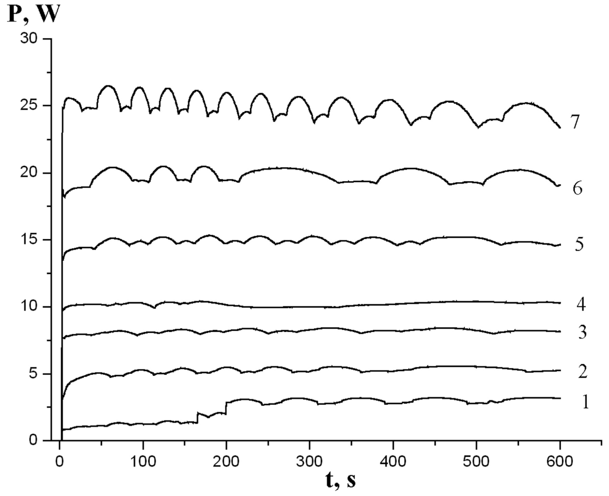


Fig. 3 Long-term instability of the radiation power of the LD-3. 1) P = 3 W; 2) P = 5 W; 3) P = 8 W; 4) P = 10 W; 5) P = 15 W; 6) P = 10 W; 7) P = 25 W.

It is known that the noise characteristics of the laser source are an important parameter for the task of Doppler measurements using CW lasers [15]. These characteristics describe the instability of laser radiation at time intervals during which the signal is registered. This parameter is characterized either by the laser’s spectral noise density or the short-term instability. In our case, laser radiation is already modulated at a frequency of around 10 kHz. This is why we cannot directly implement the approaches used for continuous pumping lasers. In this case, the change of the laser pulse shape should be regarded as the laser’s noise.

Table 1 Long-term power stability of CO2 lasers of laser devices under study.

Power, W	**Long-term laser power stability, +/- SP, %**		
	LD-1	**LD-2**	**LD-3**
5	2.7	2.6	4.9
10	3.3	2.1	1.3
15	3.1	2.7	3.3
20	10.0	3.0	4.6

Table 2 Short-term instability of CO$_2$ laser pulses at average output power of 5 W.

Laser device	**dPpulse, %**		**M, %**	
	5 W	**15 W**	**5 W**	**15 W**
LD-1	1.5±1	0.42±0.05	2.45±0.1	0.87±0.05
LD-2	0.77±0.2	0.4±0.05	1.52±0.05	0.75±0.05
LD-3	0.62±0.1	0.36±0.05	1.58±0.05	0.66±0.05

For example, Fig. 4 shows the dynamics of laser power during 35 µs for several laser pulses N (the 10th, the 20th, the 40th) and the average pulse shape (averaging over 40 pulses) for LD-1, at average output power of 5 W. As demonstrated, a notable instability can be observed in LD-1's laser at the initial time of the pulse and at time interval of 15–25 µs.

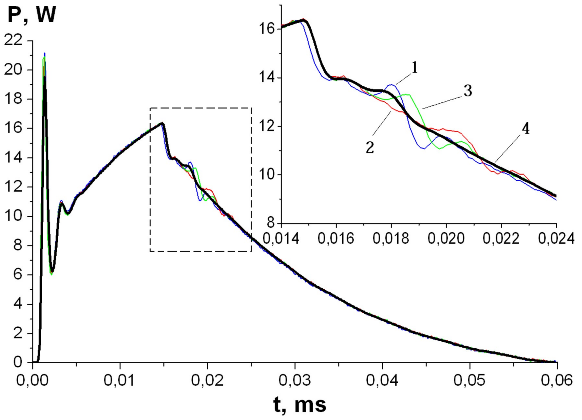


Fig. 4 Dynamics of laser power during 60 µs for several laser pulses of LD-1 radiation. Average radiation power 5W. 1) blue – the 10th pulse; 2) red – the 20th pulse; 3) green – the 40th pulse; 4) black, bold – the average pulse shape.

We shall regard the deviation of laser power from the average pulse shape as the level of short-term laser power instability. We have elaborated an algorithm to characterize this short-term instability of CO$_2$ lasers with PP pumping. For this we established the average pulse shape $P_0(t)$ during 4.37 ms (ADC selection of 32768 points at sampling frequency of 7.5 MHz). This time interval comprises around 40 pulses produced by CO$_2$ lasers. After determining the average laser pulse shape we determined the root-mean-square deviation of laser power $P(t)$ from the average pulse shape $P_0(t)$. The short-term laser power instability for these lasers was determined as a ratio of the root-mean-square power deviation from the power of the average pulse shape $P_0(t)$ to the average laser power $<P(t)>$:

$$dP_{pulse} = \frac{\sqrt{\left\langle \left(P(t)-P_0(t)\right)^2 \right\rangle}}{\left\langle P(t) \right\rangle}. \tag{1}$$

Here the angle brackets "< >" mean averaging over the duration of the laser pulse period. Herewith, the dP_{pulse} value may vary from pulse to pulse (Fig. 5). Table 2 shows the results of calculation of short-term instability for the three laser devices at average output power of 5 W and 15 W, averaged across 40 laser pulses.

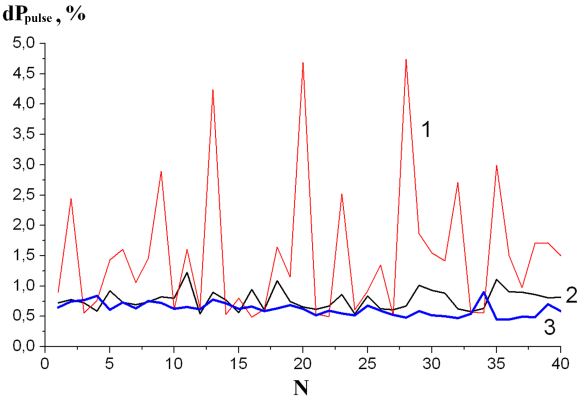


Fig. 5 Short-term laser power instability dP_{pulse}. 1) red – LD-1; 2) black – LD-2; 3) blue – LD-3. Average output power is 5 W.

Note that the larger the short-term stability of laser radiation, the more repetitive are the pulse shapes, and, therefore, smaller autodyne signals, appearing due to backscatter laser radiation, can be revealed. The level of short-term instability determines the minimum autodyne signal that can be detected. Experiments have shown that the LD-3 has the maximum short-term stability. Therefore we suppose that this LD will demonstrate an autodyne signal with a higher signal/noise ratio. It should be mentioned that when laser power is increased, the short-term instability parameter falls. Moreover, short-term instability is almost similar for LD-1, LD-2 and LD-3 at laser power of 15 W. This is due to two factors. First, when power is increased, laser impulses become smoother. Second, the modulation depth of laser radiation decreases as <*P*> grows. Table 1 shows the modulation depth, determined using the formula $M = \langle (P_{\max} - P_{\min}) \rangle / 2 < P >$, where $P_{\max}$ and $P_{\min}$ are the maximum and minimum pulse power, respectively.

When backscatter radiation from a moving object reaches the laser cavity, an additional modulation of laser output power appears at the Doppler frequency. Fig. 6 shows the one laser pulse with autodyne signal on LD-1, received when radiation was scattered by the rotating disk at laser power of 7 W. The level of autodyne signal depends both on the backscatter coefficient and the autodyne amplification [4, 6].

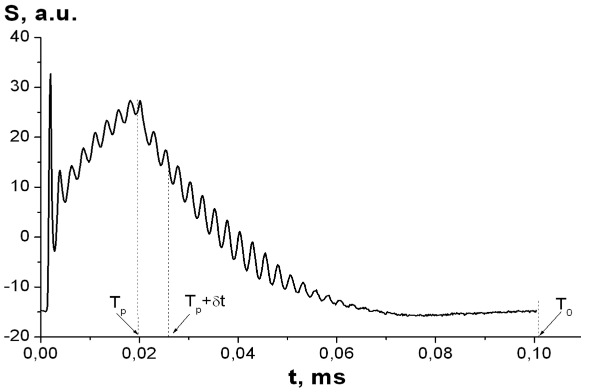


Fig. 6 Autodyne signal on LD-1, received when radiation was scattered by the rotating disk. Average output power is 7 W.

In order to measure the amplitude-frequency characteristics (AFC) of autodyne amplification of the lasers, we used an algorithm that allowed to extract the variable component from the laser pulses due to the autodyne effect. The algorithm suggests subtracting the average laser pulse, recorded in the absence of the rotating disk, from the registered signal. Thus, the newly obtained signal only contains the variable component at the Doppler frequency, as well as a component caused by the irreproducibility of the laser pulse shapes (short-term instability). The latter was mostly observed at the initial stage of the pulse and near the part of the beginning of the decline (see Fig.4). We further determined a time slot $t_p + \delta t < t < T_0 - \delta t$ (T_0 is the time period of the laser's amplitude modulation, t_p is the pump pulse duration, see Fig. 6) on the rear falling edge of the pulse and found the signal power spectrum within the selected time slot, averaged across 40 periods. Fig. 7 shows the power spectrum of autodyne signal in the CO_2 LD-3 ($P = 6.7$ W) during scattering from the surface of the disk rotating at a constant speed.

We measured the frequency response of the autodyne detection for all CO_2 laser devices, which was determined as the dependence of the area of the power spectrum of autodyne signal on the Doppler frequency shift. The area of the power spectrum was determined in the spectral window $\nu_0 - d\nu < \nu_0 < \nu_0 + d\nu$ (ν_0 is the spectrum peak position, $d\nu = 70$ kHz), which obviously exceeds the width of the carrier frequency of the Doppler signal in the whole range of measured frequencies. The results of these measurements are shown in Fig. 8. The measurements for the three CO_2 laser devices were conducted in identical conditions. Laser power during AFC measurements was at 7 W. Herewith, the position of the disk's surface relative to the incident laser beam and the ADC selection parameters were identical.

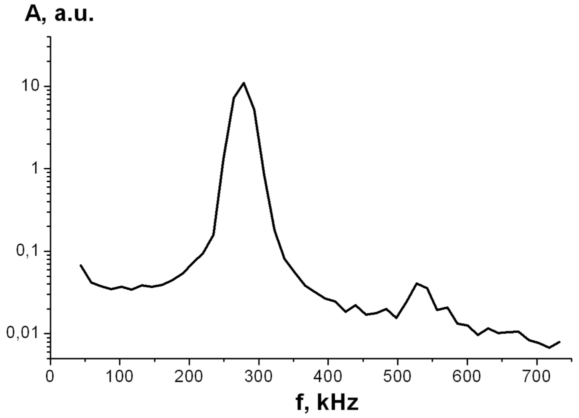


Fig. 7 Power spectrum of autodyne signal in the CO_2 LD-3 during scattering from the surface of the rotating disk. Average output power is 6.7 W.

As follows from Fig. 8, the CO_2 LD-3 has the maximum autodyne amplification. Greater autodyne amplification means that this laser is more sensitive to backscatter. It should also be pointed out that the maximum of the AFC resonance curve for this laser is located at lower frequencies. This is also more optimal from the viewpoint of detecting the autodyne signal appearing during scattering from biological tissues during their laser evaporation. This is due to the fact that the original spectrum of the Doppler backscatter signal during laser evaporation of biological tissues is located near the low frequencies [6, 7].

We conducted studies detecting the autodyne signal that appears during evaporation of fat and muscle tissues by CO_2 lasers devices. The biological tissue samples were placed on the moving stage. It moved the sample within the focal plane of the lens 4 (Fig. 1) in a direction perpendicular to the optical axis. Movement speed V was constant and equaled 0.75 mm/s. Laser power was at 6.7 ± 0.2 W. Fig. 9a shows the averaged power spectra of the autodyne signal formed in the CO_2 LD-3 during evaporation of fat and muscle tissues by laser radiation at output power of 6.7 W. Fig. 9b shows the averaged power spectra of autodyne signals after subtracting the noise power spectrum. As we demonstrated in Ref. [16], the power spectra of the autodyne signal depend on the features of laser induced mass transfer within the area of laser interaction with tissues, as well as the quantity, size and dynamic characteristics of diffusers. In particular, the nature of mass removal during laser evaporation of biological tissues is defined by their structural features and water content (20–40% of water for fat tissues and 70% for muscle tissues [16]), which determine the absorption capacity of the tissue at CO_2 laser wavelength $\lambda = 10.6$ μm. A significant change in water content leads to a change in the tissue destruction mechanisms: from intensive surface evaporation (as in the case of laser dissection of muscle tissue) to volumetric explosive boiling (in fat tissue).

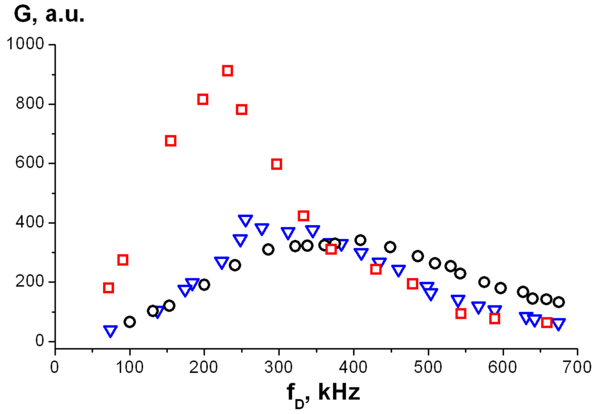
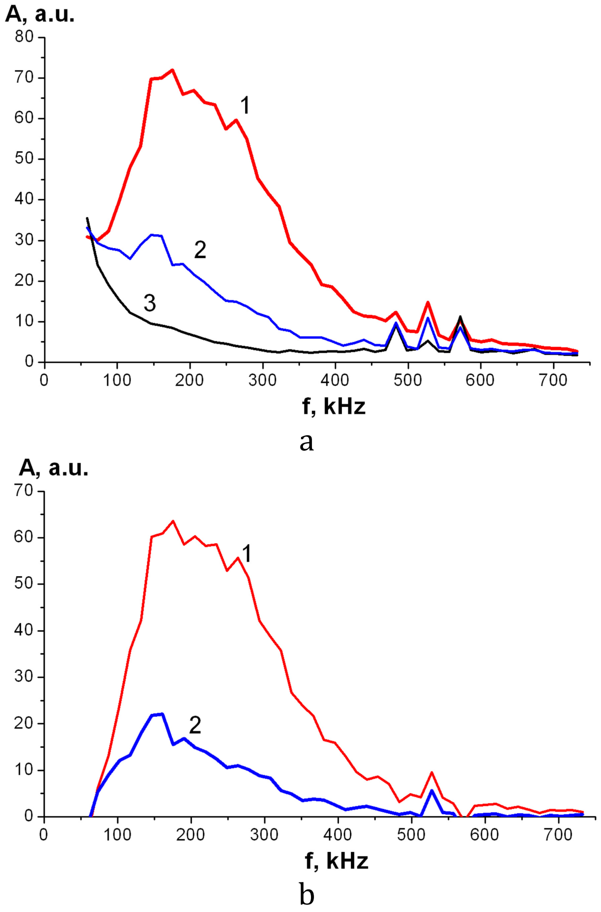


Fig.8 Amplitude-frequency characteristics of autodyne reception. □ (red) – LD-3; O (black) – LD-1; ∇ (blue) – LD-2. Average output power is 7 W.

Surface evaporation produces small (10–50 μm) fragments of tissue structures, moving at a speed around 1 m/s, and water steam. Laser heating of fat tissue leads to overheating and explosive boiling of the water located within the tissues, followed by ejection of large (up to 300 μm) drops of water and fat. This is accompanied by an apparent increase of the autodyne signal power, which is well demonstrated in Fig. 9. Herewith, as seen in Fig. 9b, the nature of the form of autodyne signal power spectra during dissection of fat and muscle tissues is similar, with a characteristic maximum at a frequency of 150 kHz. This behavior of spectra in different tissues is explained by the fact that the original spectrum of the Doppler backscattered signal overlaps with the AFC of autodyne reception, which has a resonance form with a maximum at a frequency of 230 kHz. A similar picture was earlier observed during continuous CO_2 laser impact on PMMA [6]. Similar differences of spectra of these types of tissues were found for all the laser devices used for the study (see Table 3).



a

b

Fig. 9 Averaged power spectra of the autodyne signal formed in the CO_2 LD-3 during evaporation of biotissues. a) power spectra of the original autodyne signals; b) averaged power spectra of autodyne signals after subtracting the noise power spectrum. 1 – fat; 2 – muscle. 3 – noise. Average output power is 6.7 W. V = 0.75 mm/sec.

Table 3 Signal/noise ratio of the autodyne signal in CO_2 LD.

Laser device **signal/noise**	LD-1 (6.5 W)	LD-2 (6.8 W)	LD-3 (6.7 W)
Disk, max of AFC	350	120	790
muscle	1.7	1.15	2.0
fat	3.1	1.4	3.8

The results of studies of autodyne reception in the CO_2 lasers of the devices are shown in Table 3. Table 3 demonstrates the signal/noise ratio at maximum sensitivity of AFC during scattering of radiation from the rotating disk and the signal/noise ratio within the (70–520) kHz spectral range during evaporation of biological tissues. As can be seen in Table 3, the CO_2 LD-3 has the highest signal-to-noise ratio. This is due to the fact that the LD-3 has a minimum level of short-term instability (Table 2).

4 Conclusions

Studies of the generation characteristics and the capabilities of autodyne reception in CO_2 lasers with PP pumping of the active medium used in medical laser devices are carried out. The best long-term laser power stability (2–3%) was demonstrated by LD-2 with laser model DIAMOND C-30A, produced by Coherent company, while the best short-term stability (0.62%) was demonstrated by LD-3 with CO_2 laser model 48-2W, produced by Synrad company. The amplitude-frequency characteristic of the autodyne reception for these lasers was measured. Power spectra of the autodyne signal appearing during evaporation of fat and muscle tissues by laser radiation were obtained. The experiments have shown that all the lasers under study make it possible to detect the autodyne signal during the evaporation of biological tissues. CO_2 laser 48-2W installed on LD-3 also has the highest signal/noise ratio when detecting laser backscattered radiation. This is due to the fact that this laser has the largest autodyne amplification and the best short-term stability as compared to the lasers installed on LD-1 and LD-2. The results can be used in the development of smart surgical systems based on CO_2 lasers with feedback.

Disclosures

All authors declare that there is no conflict of interests in this paper.

Acknowledgments

This work was supported by the Ministry of Science and Higher Education within the State assignment FSRC “Crystallography and Photonics” RAS in part of “the dynamics of laser evaporation of biotissues” and Russian Science Foundation (Project No. 18-29-02069-мк) in other parts.

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