Extraction of the Information Component of the Autodyne Signal in Pulsed-periodic CO₂ Lasers for Doppler Diagnostics of the Surgical Process

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Abstract The creation of laser surgical systems with feedback, which allows performance of high-precision low-trauma operations, is the current trend of modern surgery. CO₂ lasers with pulse-periodic pumping which generate radiation at a wavelength of 10.6 μm and modulated at a frequency of 5–20 kHz are widely used in medical practice. This paper reports the possibility of creating feedback based on the autodyne effect that occurs in such surgical CO₂ lasers during laser dissection/evaporation of biotissues. The algorithm for extracting the information component (Doppler signal) of the autodyne signal for such CO₂ lasers has been developed. We showed that application of this algorithm permits extraction of the Doppler component spectrum in the autodyne signal that occurs when dissecting biotissues. Doppler signals were obtained when dissecting pig tissues in vitro, with a signal-to-noise ratio in the range of 5–15. The results obtained can be used in the development of smart laser surgical systems with feedback.

Keywords: CO₂ laser, laser surgery, autodyne reception, signal-to-noise ratio, signal extraction, laser evaporation, biotissues, feedback.

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1. Introduction

The current trend in the development of laser medicine is the creation and application of smart laser medical systems for performing low-trauma high-precision operations [1–4]. The key problem of creating such systems is the organization of feedback, which would allow in real time not only visualization of and remote manipulation in the operating field (which is quite achievable by existing modern methods of receiving and transmitting images and corresponding technical devices), but also acquisition of objective information about the course of the surgical process and making automated decision on changes of the operation conditions.

Currently, when performing laser operations with feedback system, the “peripheral sensors” and “database” are the surgeon’s vision and experience. Feedback of this kind does not always ensure complete removal of affected tissues and minimal trauma to healthy tissues, and does not exclude the risks of human factors or allow objective assessment of the quality of the operation. Advantages of the laser scalpel such as high speed removal of the affected tissue, precision, as well as low trauma and invasiveness will be most fully manifested when feedback systems are included in laser surgical systems to control and manage the laser intervention process in real time.

To create an optical information feedback channel in such surgical lasers, we have proposed a method for Doppler diagnostics of the process of laser action on biotissues in real time [5, 6]. In the process of surgical radiation exposure to biotissues, various mass-transfer processes occur in the zone of laser radiation exposure: removal of vapor-drop mixture and particles and movement of the tissue surface. The initial laser radiation is scattered in the zone where mass transfer processes occur, and is shifted in frequency due to the Doppler effect. Thus, the amplitude and frequency characteristics of scattered radiation carry information about the processes occurring in the zone of laser radiation exposure to biotissue. The proposed method of Doppler diagnostics consists of rapid registration of the Doppler backscattering signal arisen from the laser exposure zone, and subse-
quent analysis of the characteristic features of this signal in real time depending on the radiation exposure to different types of tissue. According to the characteristics of the autodyne signal, the instant of transition of the laser beam from one tissue to another can be detected; thus, a feedback command can be generated to control the laser radiation. For example, the power level of laser radiation can be quickly lowered or laser generation can be stopped to prevent unwanted damage to a particular biological tissue.

The autodyne reception method is a relatively promising and well-established recording technique of the Doppler backscattering signal. This method of detecting backscattered radiation is based on the autodyne effect (or self-heterodination effect) that occurs in lasers [6]. The mechanism of this effect is as follows: radiation backscattered from an external moving object falls into the laser resonator and initiates modulation of the output power of radiation (an autodyne signal) at the Doppler frequency. At a low level of backscattering, which is realized during scattering by biological tissues, the power spectrum of an autodyne signal is uniquely related by a proportional relationship [6] to the spectrum of backscattered radiation. When this method is applied to laser surgery, the operating laser radiation is at the same time diagnostic. Similar to the well-known method of optical heterodyning, the autodyne effect in various lasers has been utilized in numerous applications: Doppler velocimetry [7], vibrometry [8, 9] and lidars [10–12]. In the literature, use of the autodyne effect in various fields is mainly associated with stable continuous-wave (CW) lasers. This self-heterodyning process is well studied for various types of CW-pumped lasers [6, 9, 10, 14].

In medical practice, surgical devices based on single-mode CO2 lasers with a radiation wavelength of 10.6 µm are widely used [15, 16]. Despite the more than 60-year history of the use of CO2 lasers in medicine, they remain one of the most demanded laser medical instruments. This is due to the wide range of medical applications of this type of lasers [16].

However, in surgical devices CO2 lasers pumped by trains of radio frequency (RF) (in the frequency range from tens to hundreds of MHz) pulses with variable pulse ratios [hereinafter, pulse-periodic (PP) pumping] are widely used [17, 18]. In these lasers, “continuous” radiation is a sequence of pulses with a repetitive frequency of 5–20 kHz, and change in the radiation power is achieved by changing the duration of the pumping pulses [19]. CO2 lasers with PP pumping are significantly less stable than CO2 lasers pumped by a direct current (DC) discharge or other lasers with continuous pumping of the active medium. However, DC discharge-pumped CO2 lasers are not used in medical devices due to their high cost and large dimensions at the same laser power range. The compactness and low cost of PP pumping CO2 lasers have been the determinants of its widespread use in medicine, despite the instability of laser radiation.

However, there is no information about the features of using PP-pumped CO2 lasers as a source of Doppler measurement tasks. Use of the autodyne effect in CO2 lasers is found in the literature only for lasers with continuous pumping in relation to the problems of velocity measurement [7] and atmospheric sounding with lidars [10–12]. The standard and most commonly used Doppler signal processing procedure for CW lasers is spectral analysis [13, 20]. In particular, the signal spectrum is used to determine the speed of movement of the scattering centers in the laser radiation field.

The question arises of how to can process the autodyne signal arising in PP-pumped CO2 lasers during exposure to biological tissues. The initial radiation for such lasers has already been modulated in the frequency range of 5–20 kHz, and the task is to extract the Doppler signal against the background of such modulated radiation. This problem is relevant not only for the development of feedback for smart surgical devices, but also for broader issues related to Doppler measurements using such CO2 lasers.

This paper presents the results of algorithms development for processing autodyne signal in single-mode CO2 lasers with PP pumping of the active medium, in order to extract the Doppler signal that carries information about mass transfer processes in the zone of radiation exposure on biotissues.

2. Materials, Methods and Tools

A medical-surgical device of the Lancet series (RIK LLC, Russia) based on a waveguide CO2 laser with an output power up to 25 W, generated at a wavelength of 10.6 µm [10], was used as a PP pumped CO2 laser.

To study the features of the autodyne signal arising in this laser, we used the setup shown in Fig. 1. Laser radiation was focused using a lens with a focal length of 125 mm from ZnSe (the diameter of the laser beam in focus is 400 microns) on the surface of the object of study (a rotating metal disk or a sample of biotissue). Part of the laser radiation (approximately 4%) was diverted to the receiving area of the IR photodetector using a beam-splitting plate. An uncooled fast-response HgCdTe sensor (bandwidth 30 Hz to 3 MHz) with an integrated amplifier (gain factor kamp = 25) and specific detection ability D’ (10.6 µm) = 2.9•10^6 cm^2 Hz^1/2 mW^-1 was used as an IR photodetector. The signal from the photodetector was fed to the first channel of the high-speed analog-to-digital converter (ADC) ADM212 × 60M (JSC InSys, Russia). The synchronization pulses...
from the laser control system were fed to the second ADC channel.

AMAESTRO power and energy measurement system with UP19k-30H5-D0 (Gentec-EO) thermocouple power detector was used to measure the output laser power. To generate frequency-shifted scattered radiation, a standard method was used - a rotating metal disk positioned at an angle to the axis of the laser beam. In this case, the velocity component \( V \) of the disk surface moving towards the laser beam is not zero.

Radiation falling on the surface of the disk is scattered and forms a backscattered signal shifted by the value
\[
\frac{f_D}{\lambda} = 2 \frac{V}{\lambda}
\]
This backscattered radiation falls back into the laser resonator and initiates additional beats of the output laser radiation at the frequency \( f_D - \text{autodyne signal} \).

The Mathcad.13.1 software and Delphi 2009 application development tool were used to analyze the autodyne signal, extract it, and develop processing algorithms. Spectral analysis based on the Fast Fourier Transform (FFT) algorithm was used as the main signal processing tool.

The algorithms were tested both by numerical simulation of a real autodyne signal at a Doppler frequency, and by using a rotating disk as a source of scattered radiation at a selected Doppler frequency. The developed algorithms were also tested in conditions close to the actual surgical process. In this case, in vitro pig tissue was used as the object of laser exposure and the source of scattering. To do this, freshly prepared samples of pig tissue containing muscle and fat components were placed on a movable coordinate table and moved uniformly (at a speed of 1.0 mm/s) in the focus of the laser beam. At the same time, an autodyne signal occurring during backscattering was registered from the products of laser destruction of biological tissue with an average power level of 7 W for all three lasers.

3. Results

3.1 Autodyne effect in PP-pumped CO\(_2\) lasers

The radiation of the CO\(_2\) laser used is a pulse with a repetition frequency of 10 kHz. The average radiation power is regulated by the duty cycle of the pump pulses. For example, Figure 2 shows the dynamics of the signal from a photodetector when generating a laser with an average output power of 10 W. Also, Figure 2 schematically shows the dynamics of the RF pumping current for this CO\(_2\) laser. When the RF pump current is turned on, the output power gradually increases. When the RF discharge is stopped, there is a gradual decline in laser generation. When the average output power of the CO\(_2\) laser changes, the duty cycle of the laser pulses and their shape change.

Figure 3 shows the shapes of laser pulses for different output powers. For each value of the radiation power, 4 pulses are superimposed on each other, taken at an interval of 200 \( \mu \text{s} \). It can be seen that at a time interval of approximately 1 ms, the shape of the pulses remains almost unchanged.

When the average generation power of such lasers changes, the modulation depth also changes. Figure 4 shows the signal from the photodetector at different levels of power generation and additional power modulation by mechanical interruption of the laser beam. Additional modulation (200 Hz interrupt frequency) was provided by a mechanical laser beam chopper in the form of a disk with holes, installed in front of the photodetector.

When backscattered radiation, shifted in frequency...
due to the Doppler effect, enters the laser, additional modulation of the initial radiation at the Doppler frequency $f_D$ occurs. Figure 5 shows an example of laser pulses with additional modulation arising from scattering by the surface of a rotating disk.

The laser radiation power $P(t)$ at low backscattering coefficients $\beta^2$ (by power) can be represented as a small perturbation $p(t)$ to the initial power $P_0$ [6]:

$$P(t) = P_0 + p(t) = P_0 + P_0M\sin(f_Dt)$$

$$= P_0 + 2P_0\sqrt{G(f_D)\beta^2}\sin(f_Dt)$$

where $P_0$ is the power of the laser radiation in the absence of backscattering, $p(t)$ is the autodyne signal at the Doppler frequency $\Omega$, $M = 2(G(f_D)\beta^2)^{1/2}$ is the depth of modulation, and $G(f_D)$ is the autodyne gain.

Accordingly, a signal arises on the photodetector:

$$i(t) = SP(t),$$

where $S$ is a parameter that depends on the sensitivity of the photodetector.

3.2 Extraction of the information component of the autodyne signal in CO2 laser with PP pumping

For CW lasers, the power spectrum of the signal $i(t)$ that arises on the photodetector is directly related to the backscattered radiation spectrum [6]. Since waveguide CO2 lasers with RF pumping of the active medium are pulsed, the direct spectral approach to the photodetector signal $i(t)$ is not applicable. For such lasers, the power $P_0$ in the formula (1) is a function of the time $P_0(t)$, and therefore it is not possible to directly obtain information about the Doppler backscattering spectrum. Moreover, the shape of the function $P_0(t)$ depends on the average output power of the laser. The power spectrum of such radiation will be a series of discrete components located at frequencies $f_0, 2f_0, 3f_0, \ldots$. Their amplitudes will fall with a frequency $f$ as $\sim 1/f^2$. From the point of view of Doppler signal recording, such components are parasitic noise. Signal recording will only be possible for high Doppler frequencies $f_D$, at which the components are already significantly weak.

To simulate the autodyne signal and then develop a method for extracting and processing the desired component at the Doppler frequency, we used the following function:

$$Y(t) = (a_1 + b_1\exp(-t/\tau_1))$$

$$\ast (1 + M\sin(2\pi fDt)) \text{ for } t < \tau_0$$

$$Y(t) = (a_2 + b_2\exp(-t/\tau_2))$$

$$\ast (1 + M\sin(2\pi fDt)) \text{ for } t > \tau_0$$

(3)

where $a_1, b_1, a_2, b_2, \tau_1, \tau_2$ are constants that determine the shape of the laser pulse at the front and back edges, respectively; $f_D$ – Doppler frequency; $M$ – Doppler modulation depth; $\tau_0$ – duration of the leading rising edge of
the pulse.

Function (3) at $M = 0$ describes the shape of the laser pulse quite well (Fig. 6). In particular, for an average output power of 10 W, the coefficients in (3) have the following values: $a_1 = 174$, $b_1 = 164$, $\tau_1 = 34.8 \mu s$ at $t < \tau_0$ and $a_1 = -7$, $b_1 = 179$, $\tau_1 = 35 \mu s$ at $t < \tau_0$.

Figure 7a shows the power spectra of the signal $Y(t)$ at Doppler frequency shifts $f_D = 0.5 \text{ MHz}$ and $f_D = 0.1 \text{ MHz}$ for the modulation depth $M = 0.03$. The spectra are shown for a signal with a duration of 1.31 ms. As expected, the Doppler signal is extracted at a frequency of 0.5 MHz, whereas the signal is almost invisible at a frequency of 0.1 MHz.

It is clear that in order to extract the Doppler component $p(t)$ (formula (1)), it is necessary to subtract the signal of the original undisturbed laser pulses from the signal recorded by the photodetector. For example, Fig. 7b shows the spectra that are obtained by subtracting the undisturbed signal obtained at $M = 0$ from the model autodyne signal $Y(t)$. In this case, signals at the Doppler frequencies of 0.1 MHz and 0.5 MHz are extracted quite clearly.

It should be noted that this approach cannot be applied to a real laser signal obtained using a CO$_2$ laser with PP pumping. This is due to the fact that even at a fixed average output power, the shape of the laser pulses may change slightly, which is due to short-term instability of the laser radiation.

For CW lasers, short-term instability is manifested as the noise of laser radiation. For PP-pumped lasers, this instability manifests as the non-reproducibility of the shape of the laser pulses (for more information, see reference [19]). In this regard, when subtracting some fixed shape from the real signal, additional spectral components will occur.

Study has shown in that the period-averaged instability of the laser pulse shape (calculated from 40 consecutive pulses) for such CO$_2$ lasers is 0.4–2.0% [19]. Moreover, the maximum instability (greater than 1%) is usually observed at the front edge (the power rising edge) and on the section near the transition of the rising front to the power decline section. In this regard, we have proposed and investigated an algorithm for extracting an information component of the autodyne signal at the Doppler frequency in CO$_2$ lasers with PP pumping, which is described below.

When processing signals, we are dealing with a limited period of time. Therefore, we are not dealing with the original signal itself registered by the photodetector, but a signal multiplied by a certain time “window” $\Pi(t)$.  

![Fig. 6](image-url) Laser pulse shape for an average output power of 10 W. The gray line is the experimental pulse, the black line is the approximation curve according to the formula $Y(t)$ (2).

![Fig. 7](image-url) (a) - Power spectrum of the model autodyne signal $Y(t)$. (b) - Power spectrum $Y(t)$ after subtracting undisturbed laser radiation ($Y(t)$ at $M = 0$). The black line is for $f_D = 0.1 \text{ MHz}$, the red line is for $f_D = 0.5 \text{ MHz}$. Modulation depth $M = 0.03$.  

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of duration $T$:
$$i(t, ∆t) → i(t) \Pi(t - ∆t), \quad (4)$$
Time $∆t$ defines the position of the time window for which the spectrum is defined. In our work, we used a rectangular view of the time window $\Pi(t)$:
$$\Pi(t) = \begin{cases} 1 : 0 \leq t \leq T \\ 0 : t < 0, t > T \end{cases} \quad (5)$$
This algorithm consists of the following steps:
1. The smoothest section in the period of the laser pulse starting from time $t_1$ is extracted (see Fig. 6). Then we get N windows of this section by shifting by a period:
$$i_k(t) = i(t) \Pi(t - t_1 - kT), \quad (6)$$
where $k = 0, 1, 2 \cdots N - 1$
2. Then the averaged form of the laser pulse is found on the selected section of the time window by N sequential pulses:
$$I(t) = \frac{1}{N} \sum_{k=0}^{N-1} i_k(t) \quad (7)$$
3. At each time window of N laser pulses, a desired component is extracted by subtracting the averaged pulse form $I(t)$ from the source signal:
$$I_k(t) = i_k(t) - I(t), \quad (8)$$
4. N power spectra of the extracted desired signals are calculated:
$$S_k(v) = \frac{1}{2\pi} \left| \int I_k(t) e^{2\pi ivt} dt \right|^2 \quad (9)$$
5. The spectrum $S_0(v)$ averaged over N pulses is calculated:
$$S_0(v) = \frac{1}{N} \sum_{k=0}^{N-1} S_k(v) \quad (10)$$

The following notation is used:
- $T_0 = 1/ f_0$ – period of laser pulses
- $f_0$ – frequency of laser pulse repetition
- $T$ – duration of the time window section
- $t_1$ – start time of the time window on the laser pulse
- $i(t)$ – the primary signal recorded by the photodetector

$N$ is the number of windows used for averaging.

Figure 8 shows the power spectra of an autodyne signal averaged over 40 pulses that occur in a CO2 laser with PP pumping when scattered by the surface of a rotating disk (the upper figure is a linear scale, the lower figure is a logarithmic scale.). a – $f_D = 1$ MHz; b – $f_D = 0.15$ MHz. 1 – power spectrum of the selected signal segment with a duration of $T = 60 \ \mu s$, located on the falling edge. 2 – power spectrum of the selected signal area after subtracting the averaged shape of the laser pulse.

| Algorithm | $f_D = 1$ MHz | $f_D = 0.15$ MHz |
|-----------|---------------|-----------------|
| №1        | 7.2           | 0               |
| №2        | 65            | 11              |

The power spectra of an autodyne signal averaged over 40 pulses that occurs in a CO2 laser with PP pumping when scattered by the surface of a rotating disk (the upper figure is a linear scale, the lower figure is a logarithmic scale.). a – $f_D = 1$ MHz; b – $f_D = 0.15$ MHz. 1 – power spectrum of the selected signal segment with a duration of $T = 60 \ \mu s$, located on the falling edge. 2 – power spectrum of the selected signal area after subtracting the averaged shape of the laser pulse.

Table 1 lists the signal-to-noise ratios for these two algorithms: №1 averaged spectrum of the selected signal seg-

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ment, located on the falling edge; \( \Delta \) spectrum of the selected signal area after subtracting the averaged shape of the laser pulse.

Thus, the proposed algorithm for processing the autodyne signal in CO\(_2\) lasers with PP pumping allows us to extract the desired component of the laser radiation beats at the Doppler frequency. This method can be used in a number of applications related to Doppler measurements using such lasers. In particular, the development of smart surgical laser systems with feedback is of particular interest. At the moment, almost all modern surgical CO\(_2\) laser installations use CO\(_2\) lasers with PP pumping. The above result was given for the case when the backscattering source is the surface of a rotating metal disk that gives a fairly narrow spectrum. This allows us to extract a useful Doppler signal with a relatively high S/N ratio. It is interesting to examine how effective the proposed method of signal processing is in extracting the Doppler beat signal that occurs during laser exposure to biotissues. Experiments were conducted to test the developed algorithm for processing the autodyne signal in the case of exposure of CO\(_2\) laser radiation to biotissues. These in vitro experiments used fat and muscle tissues from a pig. These tissues have different physical characteristics (including absorption coefficient and thermal conductivity) and structures, which makes it possible to test the developed method in extracting the information component of the autodyne signal. To do this, freshly prepared samples of pig tissue were placed on a movable coordinate table and moved uniformly (at a speed of 1.0 mm/s) in the focus of the laser beam in the direction perpendicular to the axis of the laser beam with a radiation power of 7 W. At the same time, an autodyne signal was recorded, which occurred when laser radiation was backscattered from the biotissue destruction products.

Figure 9a shows the averaged power spectrum of the signal received by the photodetector without using any extraction algorithm, in the case of exposure of laser radiation to fat tissue and in the case of no exposure. The spectrum was obtained using 16384 ADC sample values with a duration of 1.31 ms. The spectrum was obtained by averaging the spectra over 10 such ADC samples. As one would expect, no noticeable changes are observed in the resulting spectrum when exposing the radiation to the tissue. Also, no noticeable features are observed in the spectrum when radiation is applied to fat tissue and when the smoothest area is selected on the trailing edge in a laser pulse (Fig. 9b). This figure shows the spectra of the region at the back of the laser pulse averaged over 10 ADC samples of 32568 values. In this case, the spectrum was obtained in the same manner as when radiation was scattered by the surface of a rotating disk (see Fig. 8).

Figure 10 shows the power spectra of the signal emitted by the photodetector, but obtained using the above-described method of extracting the information component of the Doppler signal by subtracting the average shape of the laser pulse. As can be seen from Figure 10, use of the above method of extracting the information component of the signal allows not only extraction of the autodyne signal that occurs during the exposure of radiation to biotissue, but also allows detection of the difference in the autodyne signal when exposing to different tissues - fat and muscle. The difference in the power spectra for muscle and fat tissues is due to the distinct structures of these tissues and the mechanisms of their vaporization at 10.6 \( \mu \)m [21, 22]. The main component of these tissues that absorbs CO\(_2\) laser radiation is water (\( \mu \approx 830 \text{ cm}^{-1} \)). Muscle tissue consists of

![Figure 9a](image-url) Average power spectra of a signal from an IR photodetector. (a) - a sample with a duration of 1.31 ms (16384 ADC sample values); (b) - sample with a duration of 0.06 ms (512 ADC sample values). Black line - no laser radiation; thin gray line - laser radiation power 7 W; thick gray line - when exposing radiation with a power of 7 W to fat tissue.
Parallel muscle fibers - myofibrils. Interstitial water is evenly distributed over the volume of muscle its content is 70%. Fat tissue is a collection of fat cells with a central fatty drop surrounded by cytoplasm.

The water content in fat tissue is approximately 30%. Fat (a combination of fatty acids) is practically transparent for CO₂ laser radiation (approximately 1 cm⁻¹) [22]. In relation to CO₂ laser radiation, fat tissue is a heterogeneous absorbing medium. Vaporization of muscle occurs by surface vaporization with the removal of a vapor-droplet mixture and tissue fragments. At the vaporization of fat, the processes of explosive boiling of tissue water with intensive removal of the vapor-droplet mixture and the contents of fatty globules dominate. We have previously shown [23] that laser evaporation of fat tissue is accompanied by a more intense removal of mass at high speeds compared to muscle tissue. All these listed circumstances lead to the difference in the power spectra of the autodyne signal for the two types of biological tissues.

We present the results for the surgical PP pumping CO₂ laser “Lancet” (Russia), which does not have the best stability compared to other commercial PP pumping CO₂ lasers Coherent and Synrad (USA) [19]. This suggests that the proposed method of obtaining operational information about the type of vaporized biotissue in the process of laser exposure is quite practical and reliable. Also, unlike our previous results obtained for a more stable Coherent laser [19], the algorithm does not need to record the averaged shape of laser pulses every time in the absence of backward radiation.

Our results can serve as a basis for creating laser surgical systems with feedback that allow rapid diagnostics: to receive real-time information about the type of biotissue being vaporized and identify it relative to another; to determine the moment of radiation transition from one type of tissue to another; and to control the process of tissue evaporation when certain conditions are reached (to stop or continue the process of evaporation). In particular, such diagnostics can be used for laser evaporation of pathological tissues without damaging healthy ones while removing benign or malignant neoplasms.

4. Conclusions

An algorithm has been developed for extracting the information component of Doppler signal in the autodyne signal that occurs in surgical CO₂ lasers with PP pumping when backscattered radiation that shifts in frequency due to the Doppler effect hits the laser. We have shown that the developed algorithm based on subtraction of the averaged form of the laser pulse allows reliable extraction of the Doppler component in the autodyne signal for frequencies greater than 50 kHz, whereas the standard method of spectral analysis does not allow extraction of a desirable information component in the spectral range of 50–500 kHz. Averaged spectra of the Doppler component of radiation beats of a medical CO₂ laser were obtained when dissecting biotissues in vitro. The resulting signal-to-noise ratio when exposed to biotissues was 5:15. We found that the desired Doppler component in the autodyne signal extracted by this method has different amplitude-frequency characteristics under laser action on different biotissues.

The developed algorithm for extracting the information component of the PP pumped CO₂ laser radiation beats can be used in the development of laser smart surgical systems with feedback, and in various applications related to Doppler measurements. This will allow objective monitoring of laser surgery in real time and improve the safety of laser methods in surgery. Surgical installations with such feedback can be used in the development of new approaches to performing high-precision and low-trauma laser operations.

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Conflict of Interest

We have no conflict of interest with any company or commercial organization.

References

1. Acemoglu A, Ficha L, Kepiro IE, Caldwell DG, Mattos LS: Laser incision depth control in robot-assisted soft tissue microsurgery. J Med Robotics Res. 2(3), 1740006, 2017.
2. Dmitriev AK, Konovalov AN, Kortunov VN, Ulyanov VA: Methods of feedback arrangement for smart surgical systems based on fiber lasers. Biomed Eng. 53(4), 71–75, 2019.
3. Sobol EN, Sviridov AP, Vorobieva N, Svistushkin V: Feedback controlled laser system for safe and efficient reshaping of nasal cartilage. Head Neck Oncol. 2, (Suppl 1): O17, 2010.
4. Deshpande N, Peretti G, Mora F, Guastini L, Lee J, Barresi G, Caldwell DG, Mattos LS: Design and study of a next-generation computer-assisted system for transoral laser microsurgery. OTO Open. 2(2), 2018.
5. Vasil’tsov VV, Gordienko VM, Dmitriev AK, Konovalov AN, Kortunov VN, Panchenko VY, Ulyanov VA: Diagnostics of the laser perforation of biological tissues by the method of autodyne detection of backscattered radiation. Quantum Electron. 32(10), 891–896, 2002.
6. Gordienko VM, Konovalov AN, Ulyanov VA: Self-heterodyne detection of backscattered radiation in single-mode CO2 lasers. Quantum Electron. 41(5), 433–440, 2011.
7. Churnside JH: Laser Doppler velocimetry by modulating a CO2 laser with backscattered light. Appl Opt. 23(1), 61–66, 1984.
8. Giuliani G, Bozzi-Pietra S, Donati S: Self-mixing laser diode vibrometer. Meas Sci Technol. 14(1), 24–32, 2002.
9. Giuliani G, Norgia M, Donati S, Bosch T: Laser diode self-mixing technique for sensing applications. J Opt A: Pure Appl Opt. 4(6), S283–S294, 2002.
10. Koganov GA, Shuker R, Gordov EP: Multimirror autodyne lidar for local detection of hostile gases. Appl Opt. 44(15), 3105–3109, 2005.
11. Gordov EP, Khmelnitskii GS, Fasliev AZ: Multipurpose cw CO2 autodyne lidar. Proc SPIE. 2773, 160, 1995.
12. Burakov SD, Godlevskii AP, Ostanin SA: Determination of the profile of distant objects with the help of a coherent autodyne lidar. Atmos Opt. 3(5), 498–501, 1990.
13. Gordienko VM, Koryabin AV, Kravtsov NV, Firsov VV: Wind Doppler lidar with 1.5 µm fiber laser. Laser Phys Lett. 5, 390–393, 2008.
14. Dmitriev AK, Konovalov AN, Ulyanov VA: Autodyne effect in a single-mode Er fibre laser and the possibility of its usage for recognizing the evaporated biotissue type. Quantum Electron. 45(12), 1132–1136, 2015.
15. Peng Q, Juzeniene A, Chen J, Svaasand LO, Warloe T, Giercksky KE, Moan J: Lasers in medicine. Rep Prog Phys. 71(5), 056701, 2008.
16. Dyer PE, Snelling HV: Gas lasers for medical applications. In: Helena Jelínková. Lasers for Medical Applications. Diagnostics, Therapy and Surgery, Woodhead Publishing, pp. 177–202, 2013.
17. He D, Hall DR: A 30-W radio frequency excited waveguide CO2 laser. Appl Phys Lett. 43, 726–728, 1983.