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Ablation of Biological Tissues by Radiation of Strontium Vapor Laser

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Abstract. A two-stage laser system consisting of a master oscillator and a power amplifier based on sources of self-contained transitions in pairs SrI and SrII has been developed. The radiation spectrum contains 8 laser lines generating in the range of 1 – 6.45 μm, with a generation pulse length of 50 – 150 ns, and pulse energy of ~ 2.5 mJ. The divergence of the output beam was close to the diffraction and did not exceed 0.5 mrad. The control range of the laser pulse repetition rate varied from 10 to 15 000 Hz. The given laser system has allowed to perform ablation of bone tissue samples without visible thermal damage.

INTRODUCTION

Today, the study of laser impact processes on biological tissues is still of great interest. This is caused by the widespread use of lasers in various fields of medicine such as surgery, orthopedics, dermatology, dentistry, ophthalmology, etc. The applied in practice various methods and techniques for removal of biomaterials determine the main characteristics of laser processing and, mainly, the material removal rate (formation rate of cavities, cuts, holes, etc.). The most effective and least energy-consuming method for a dimensional processing of biotissues (bone, muscle, brain, etc.) is the laser ablation method [1-3]. The term "ablation" is an interdisciplinary and implies a complex of physical and chemical processes occurring under the action of laser radiation, leading to an explosive removal of a certain amount of material from the exposure area. Laser ablation mechanisms are largely determined by laser radiation parameters, in particular the wavelength. Studies show that laser radiation of the mid IR-range is most suitable for minimally invasive surgery of biotissues. This is primarily due to the fact that radiation of the specified range is well absorbed by tissue chromophores, which greatly contributes to minimization of the collateral thermal injury zone [4].

Absorption spectra of a cornea, neural tissue, and dermis may be considered as an example (Fig. 1). A characteristic feature is the position of the mode OH-band of water near 3300 cm^{-1} (3 μm). Two modes can be allocated as well: Amide I - protein vibrational mode at 1665 cm^{-1} (6 μm) and Amide II - protein vibrational mode at 1550 cm^{-1}(6.45 μm).

The works of American scientists from Vanderbilt University [6] show that throughout the entire spectral region from 2.9 up to 9.2 μm the radiation with a wavelength in the range of 6.1 - 6.45 μm is the most optimal in ablation of bone tissues. Figure 2 shows cross-sections of cuts in a cortical bone made by a free electron laser (FEL). The cut depth is clearly wavelength-dependent, with the deepest cuts occurring at λ = 6.1 – 6.45 μm.

The used in these studies FEL generated trains of microsecond macropulses that contained a series of 1-2 ps pulses. The macropulse repetition rate of the given laser was 30 Hz, the macropulse energy - 22.5 mJ; where in the energy density at the sample surface reached the value of 72 J/cm^2 (the diameter of the focal spot size was ~ 200 μm). Critical flaws of the free electron laser are complexity of design, high cost, and extremely large size, which complicates its widespread use in technological research and in medical practice.

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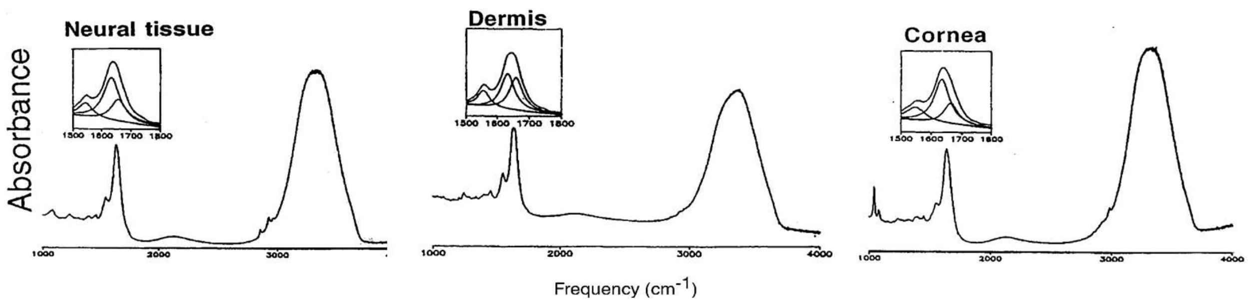

FIGURE 1. Absorption IR-spectra of a cornea, neural tissue, and dermis [5]

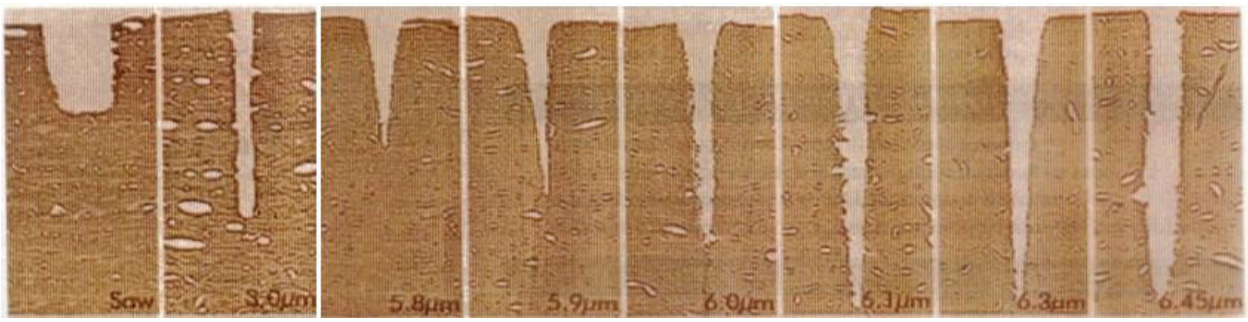

FIGURE 2. Histologic sections of a bone saw cut and laser cuts of a cortical bone made by using FEL wavelengths (λ = 2.9 – 9.2 μm), and an equivalent of 30 individual macropulses with a total of 2.150 J/cm^2 delivered for each ablation [6]

In order to carry out the studies on the effect of laser ablation in the mid IR-range, with a possibility of its further implementation and the use in medical treatment facilities, it is necessary to have a rather powerful, but at the same time relatively cheap and compact, laser source with a high beam quality, radiating at wavelengths in the range of 1, 3 and 6 μm. A nanosecond strontium vapor laser with low divergence of the output radiation can be used as such a source [7].

The strontium vapor laser generating in the range of 1, 3 μm and 6.45 μm perfectly satisfies the requirement of the maximum (resonance) absorption by biotissues. First experiments on laser ablation of tissues with a strontium vapor laser implied the use of a laser with an average power of 2.4 W, operating at pulse repetition rates up to 20 kHz, and the pulse energy not exceeding 0.1 mJ [8]. Ablation of a tissue (achievement of the ablation threshold) occurred only under the multi-pulse exposure, which led to formation of an extensive charring zone.

EXPERIMENTAL SETUP

To improve power characteristics, as well as to improve the quality of laser radiation, an experimental setup has been developed; the diagram is shown in Fig. 3. The basis of the setup is two strontium vapor laser sources united under the classical scheme "master oscillator – power amplifier" [9]. The cascade of the master oscillator was composed of a gas-discharge tube (GDT) (*1*) with a diameter and a length of the working channel equal to 26 and 800 mm, respectively, placed in a telescopic unstable resonator (M = 35) composed of two spherical mirrors, a concave (*2*) and a convex (*3*), with the curvature radius of 3500 mm and 100 mm, respectively. The aperture of the output radiation was ~ 24 mm. The spatial filter-collimator (SF-C) (M = 1.5) included two concave spherical mirrors (*4, 5*) with an aluminum coating, with a curvature radius of 2000 mm and 3000 mm, and a spatial filter with a hole diameter of 0.3 mm placed into a common mirror focus (*6*), which allowed to allocate from the oscillator radiation a spatial component with the divergence close to the diffraction (~ 0.5 mrad). The amplifier GDT (*7*) had large (as compared to the oscillator GDT) dimensions of the active channel: 35 mm in diameter and 1000 mm in length. Windows of both GDT were made of CaF_2, an optical material with low absorption in the mid IR-range and good performance characteristics. Excitation pulses were fed to GDT electrodes from the output of high voltage power supply (*8, 9*), executed on the basis of transducers on powerful transistors with a pulse charging of operating capacities and hydrogen thyratrons TGI-1 1000/25 as switches, followed by a two-stage compression executed by ferromagnetic compression cells. The synchronization block (*10*) consisted of a master oscillator (*10a*), a delay module (*10b*), and allowed to adjust the relative delay time of pumping pulses for the oscillator and the amplifier, making it possible for the laser system to operate at low pulse repetition rates (up to ten and ones of Hz, even in the single-pulse mode). The repetition rate of excitation pulses remained in the range of 15 - 20 kHz. This mode provided an increased stability of the laser pulse energy because the thermal operation mode of active elements did not change.

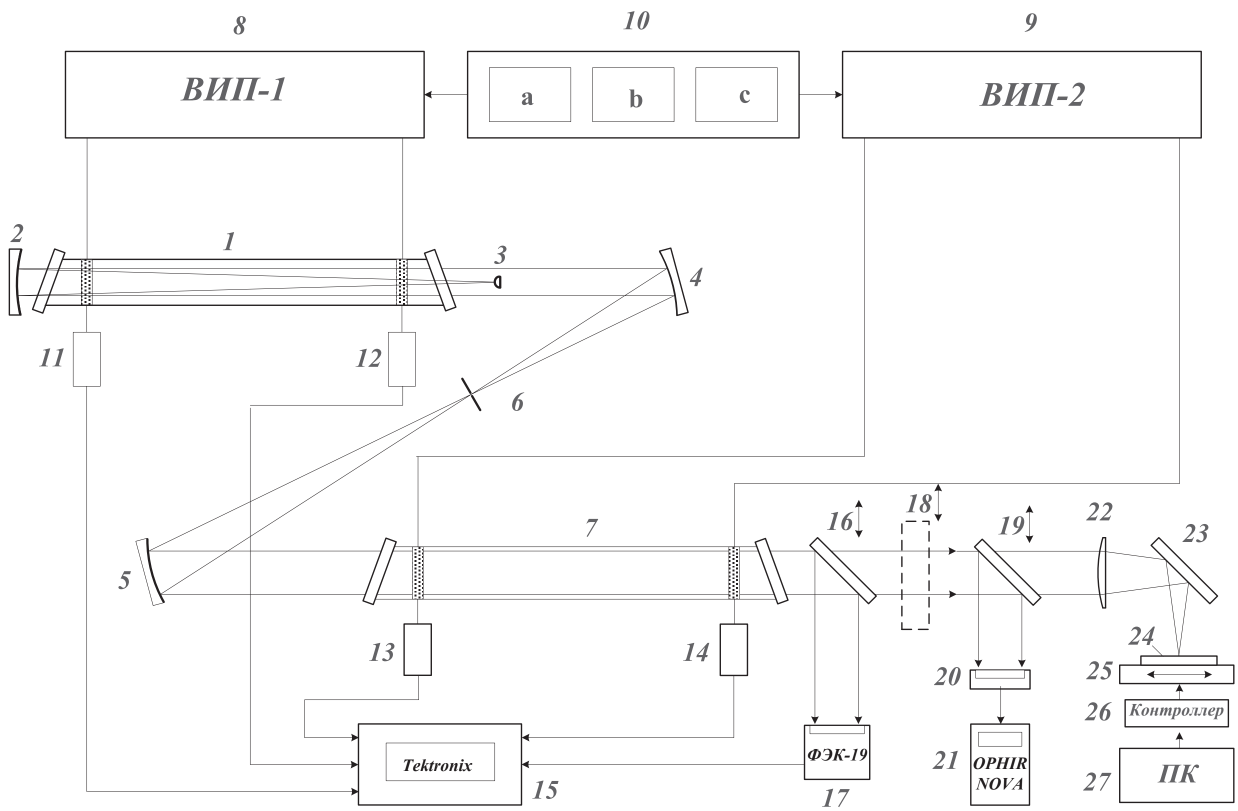

FIGURE 3. The diagram of the experimental setup: *1* – GDT-1; *2* - rear mirror, R = 3500 mm; *3* - output mirror, R = 100 mm; 4 - input mirror SF-C, R = 2000 mm; *5* - output mirror SF-C, R = 3000 mm; *6* – spatial filter, D = 0.5 mm; *7* - GDT-2; *8, 9* - high voltage power sources; *10* - control unit and synchronization (CUS); *11, 13* - voltage dividers; *12, 14* - low-resistance shunts; *15* - multi-channel oscilloscope "Tektronix"; *16, 19, 23* - rotary mirrors; *17* – Photoelectric Multiplier-19; *18* - block of spectral filters; *20* - gauge "OPHIR-NOVA"; *21* - indicator "OPHIR-NOVA"; *22* - spherical lens, CaF_2, F = 100 mm; *24* - target; *25* - coordinate table; *26* - controller; *27* - computer

The measurement system of laser parameters allowed to control the amplitude and the shape of high-voltage pumping pulses (voltages on GDT and the current through the tube) with the use ofvoltage dividers (*11, 13*) and low-resistance shunts (*12, 14*), and the amplitude and the shape of laser pulses at different wavelengths with the use of a spectral filter block (*18*) and a photodetector Photoelectric Multiplier-29 (*17*). Excitation and laser pulses were recorded using an oscilloscope "Tektronix". A power meter "NOVA-OPHIR" was used to control the output capacity oflaser radiation. To perform ablation of bone tissue samples, rotary mirrors*16, 19* and a filter block *18* were outputted outside the optical path. The main technical characteristics of the developed system are given in Tab. 1.

TABLE 1. The basic technical data of the experimental setup

Parameter	Value
Laser wavelengths	6.45; 3.01; 3.06;2.92; 2.69; 2.60; 1.03; 1.09 μm
Average total power	1 - 28 W
Laser beam diameter	35 mm
Pulse duration	20 ns 6.45μm 150 ns ~ 3 μm 80 ns ~ 1 μm
Beam divergence	0,5mrad
Pulse repetition rate	15 - 20 kHz
Maximum pulse energy	1.7 mJ
Cooling	water

RESULTS AND DISCUSSION

The result of the carried out studies on the use of the strontium vapor laser system for the implementation of the resonant ablation mode under the exposure of a bone tissue to IR-radiation were incisions of a cortical bone with a depth of up to 100 μm. The width of the cut varied in a range from 20 to 50 μm. There was no charring or carbonization of the tissue adjacent to edges of the cut. Fig. 4 shows photographs of incisions on the surface of bone tissue samples.

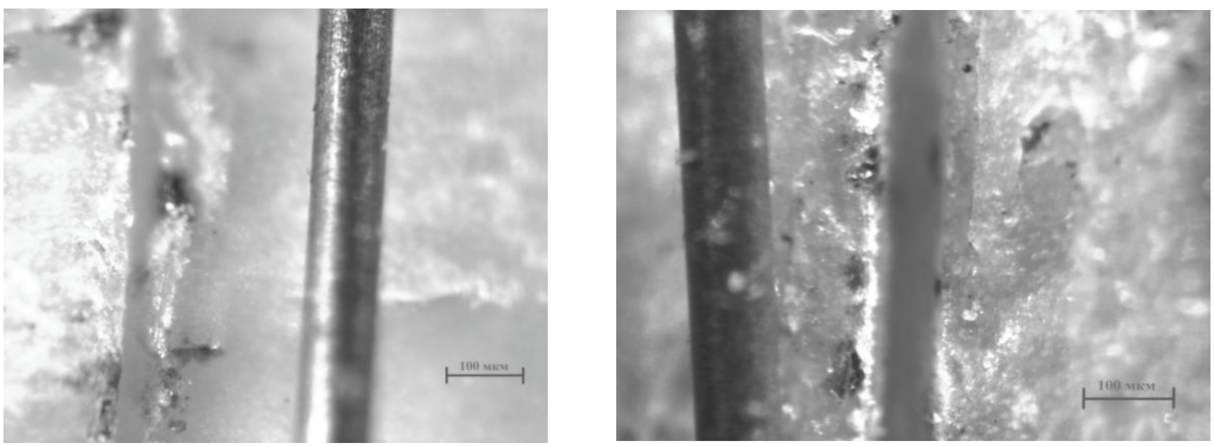

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FIGURE 4. Photographs of ablated areas of the cortical bone: (*a*) – f = 400 Hz, v = 17 mm/s; (*b*) – f = 800 Hz, v = 10 mm/s

IR-spectrum of the bone tissue absorption is a component combination of the corresponding characteristics of water, collagens, and hydroxyapatites. Figure 5 shows the bone tissue absorption spectrum.

The carried out experiments were not aimed at determination of the relationship between the depth of the cut and the absorption of water, collagen, and hydroxyapatites. However, the assumption has been made that the main mechanism inablation of a bone tissue, in this case, is the thermal expansion of overheated liquid in tissues.

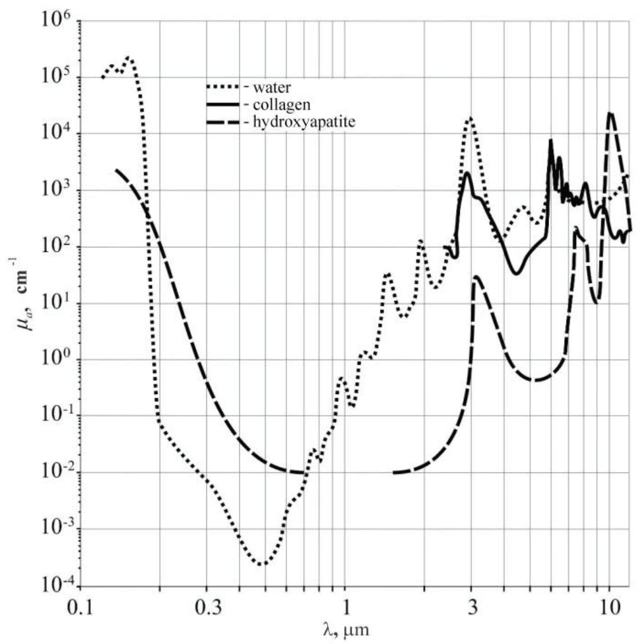

FIGURE 5. The absorption spectra of water, collagen, and hydroxyapatite [10]

CONCLUSION

It has been concluded that the strontium vapor laser with nanosecond pulse duration and generating in the range of 1 – 6.45 μm is a promising laser source for laser ablation. The results of experiments on ablation of solid living tissues, with the use of the developed two-stage laser system consisting of a master oscillator and a power amplifier based on strontium vapor emitters operating on self-limiting transitions SrI and SrII, have been presented.

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