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Medical instruments based on high-power diode and fibre lasers

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***Abstract*. The characteristics and possible applications of scalpels based on diode and fibre lasers emitting at 0.97, 1.06, 1.56, and 1.9 μm, which are produced and developed by the IRE-Polyus Co., are presented. The advantages of such devices and the possibilities for increasing their output power and extending their spectral range are shown.**

Keywords: *diode lasers, fibre lasers, medical laser instruments.*

1. During the two recent decades, laser techniques for treating various diseases have been developed, and lasers have become a customary and efficient tool for physicians at large medical centres. However, the complexity of such medical facilities, the need of permanent qualified engineering attendance, and the necessity of using specialised operating rooms, which is determined by the presence of bulky equipment and high-power supply units, impeded the wide use of laser instruments in surgery and power therapy in the mass public health.

The advent of high-power semiconductor lasers (laser diodes) in 1990s and a rapid progress in their reliability and output power accompanied by a decrease in their cost are the factors that made it possible to remove the main existing obstacles. Diode lasers and diode-laser-pumped lasers currently replace lasers of other types in medical apparatuses. This is determined by the following advantages of diode and diode-laser-pumped lasers: a small mass, energy consumption, and size; no need of liquid cooling; the high reliability and long service life; ease of handling and no need of frequent maintenance operations and qualified attendance; the high stability of laser parameters and simple control over the radiation parameters (the radiation power, modulation, and, to a certain degree, the wavelength); and the low sensitivity to mechanical and climatic effects.

These advantages and the decreasing costs of the devices and their service have created prerequisites for their wider application in the public health, including ambulatory and polyclinic service and even the first-aid service and mobile field hospitals.

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The use of fibre lasers pumped by diode lasers opens additional opportunities for their application in medicine. New technologies also allow the improvement of medical apparatuses based on diode lasers with fibre outcoupling of radiation.

2. The largest inconvenience in the instruments of previous generations and in numerous modern devices for doctors is the fact that a laser head contains discrete elements that require a precise alignment. In this case, there appear difficulties associated with the maintenance of the alignment under inevitable external mechanical actions, the necessity of restoring the alignment after replacing disabled elements, for example, flash lamps, etc. An additional problem is the protection of optical surfaces from moisture and contamination that lead to a decrease in the output power or a laser failure.

The technologies developed at the IRE-Polus Co. make it possible to design the devices in which the radiation formation, the control over its properties, and the radiation summation (including beams with different wavelengths) occur inside optical fibre elements and require no alignment of discrete elements. This equally concerns fibre lasers and diode laser modules with radiation coupling through a fibre. It is natural that the penetration of moisture and dust into the optical channel as far as the output end of the fibre is excluded in a finished device. This is an advantageous feature of such lasers compared, for example, to lasers on diode-laser-pumped crystals, which have a high efficiency and good weight – size characteristics but possess the aforementioned drawbacks of lasers with discrete elements.

These features make it possible to improve the reliability of medical apparatuses, to reduce their dependence on the environment and mechanical actions, to simplify their operation, and to lower the cost of their service.

3. When biological tissues are exposed to laser light, various components of these tissues have different absorption coefficients for radiation with different wavelengths. Fig. 1 shows the absorption coefficients of laser radiation in melanin, oxyhemoglobin, and water versus wavelength available from the literature. The wavelengths emitted by IRE-Polus diode lasers and fibre laser modules are also presented. The difference in their absorption coefficients in the media mentioned above is clearly seen.

An important fact is that the radiation at each wavelength has a specific effect on a biological tissue, which may be optimal for various medical technologies. For example, radiations at a wavelength of ~ 0.81 μm (a diode laser) and 1.06 μm (a Nd : YAG or Yb fibre laser) penetrating deeply

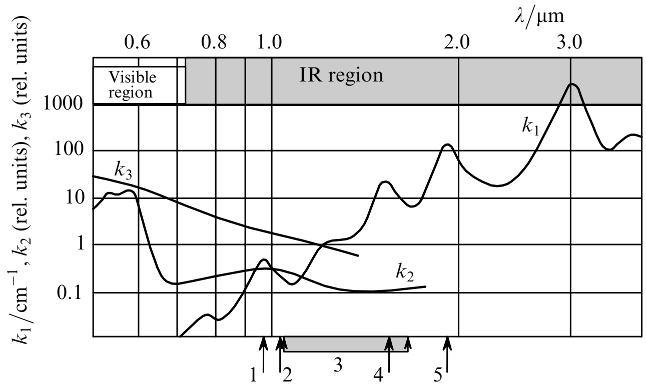

Figure 1. Spectral dependences of the absorption coefficients in water (k_1), oxyhemoglobin (k_2), and melanin (k_3) for radiations from different sources: (*1*) diode laser ($\lambda = 0.97$ μm); (*2*) Yb-doped-fibre laser ($\lambda = 1.03 - 1.12$ μm); (*3*) Raman fibre laser ($\lambda = 1.12 - 1.7$ μm); (*4*) Er-doped-fibre laser ($\lambda = 1.53 - 1.62$ μm); and (*5*) Tm-doped-fibre laser ($\lambda = 1.9 - 2.0$ μm).

into tissues are optimal for laser thermotherapy of tumours [1]. The diode-laser radiation wavelength (0.97 μm) coincides with local peaks of the absorption coefficients for water and oxyhemoglobin and combines well the cutting and hemostatic properties [2]. The use of lasers at a wavelength of 0.97 μm has shown a high efficiency in a least-invasive puncture-assisted treatment of patients with pain syndromes of lumbar osteochondrosis and trifacial neuralgia [3]. The radiation at a wavelength of ~ 1.56 μm (a fibre laser on a fibre activated by Er ions) is weakly absorbed in hemoglobin and melanin, whereas its absorption in water is significant. Therefore, it can be used in laser thermoplastics of cartilages [4] in the correction of the nasal septum shape, when the cartilage should be heated at a minimal action on the blood-containing tissues. Using lasers at a wavelength of 1.56 μm, the data on the regeneration of cartilaginous tissues of intervertebral disks [5] have been obtained. Moreover, this wavelength can be efficient for nonsurgical correction of defects of eyesight [6]. Preliminary investigations [7] have demonstrated a number of attractive features of the action of radiation at a wavelength of 1.9 – 2.0 μm on biological tissues (a Tm-doped-fibre laser).

Hence, physicians can select a wavelength of the working radiation. Table 1 presents the characteristics that were achieved in several types of fibre lasers produced by the IRE-Polus Co. Note that the average service life of high-power laser diodes in such devices is ~ 10^6 h.

More complete information on the devices produced by this company is available at its web-sites [8, 9]. Note that it is possible to develop medical instruments based on Raman fibre lasers operating at an arbitrary wavelength within the range of 1.12 – 1.7 μm.

These devices not only extend the range of wavelengths that can be used in practice but make it possible to combine radiations with different wavelengths in the working fibre without an appreciable complication in the designs and significant loss in the efficiency. In addition, the fraction of each radiation can be varied in accordance with the requirements of a particular medical procedure. The radiation of fibre and diode lasers can be combined with the retention of the aforementioned advantages. Moreover, it becomes possible to continuously change the wavelength of the entire working radiation or its part within certain limits during a medical procedure. Fig. 2 presents the structure of the family of IRE-Polus laser modules, which are basic devices for the production of medical apparatuses.

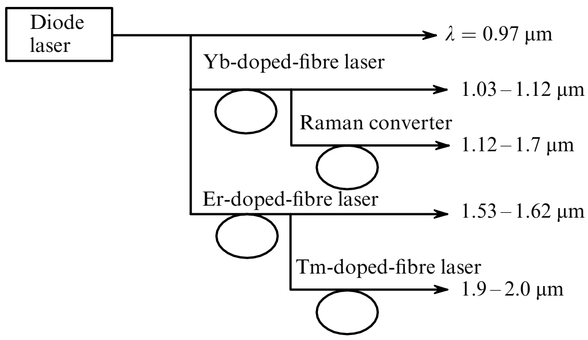

Figure 2. Family of IRE-Polus laser modules.

The fibre lasers described above are based on standardised diode-laser pumping modules (they can also be used in medical apparatuses as sources of the working radiation) and control electronic modules and, thus, are easily combined as components of medical apparatuses. This standardisation simplifies the maintenance of such devices.

Note that the list of the employed wavelengths can be extended by using diode lasers emitting at other wave-

Table 1. Parameters of fibre lasers produced by IRE-Polus Co.

Laser	Output power/W	Wavelength/μm	Pulse duration/ns	Pulse repetition rate/MHz	Power instability in 6 h (%)	Efficiency (%)	Consumed power/W	Temperature/°C
cw, Yb-doped fibre	100*	1.075 – 1.095	–	–	< 5	⩽ 30	< 700	0... + 40
cw, Er-doped fibre	15	1.545 – 1.565	–	–	< 1	> 8	180	−20... + 60
Modulated, Yb- or Er-doped fibre	20	1.03 – 1.12 1.53 – 1.62	1 – 1000	0 – 100	< 3	⩽ 30	–	−20... + 60
cw Raman	10	1.12 – 1.7	–	–	< 2	⩽ 10	–	−20... + 60
cw, Tm-doped fibre	15	1.9 – 2.0	–	–	< 5	> 5	180	−20... + 60

*The maximum output power (100 W) for one single-mode Yb-doped-fibre laser is specified. Using the summation of the powers of several such lasers in a common integral fibre device, lasers with a power of up to 2 kW in the output fibre are designed and used for industrial purposes. In the nearest future, the output power is planned to be raised up to 6 and 10 kW.
Note: at a supply voltage modulation, the pulse and pause durations are longer than 10 ms.

Table 2. Parameters of laser scalpels developed by IRE-Polyus Co.

Laser scalpel	Wavelength/μm	Maximum output power/W	Operating mode	Mass/kg	Mastering stage
Lason-10P*	0.97	10	Continuous	7	Production
LS-0.97	0.97	30	Continuous, pulsed, and repetitively pulsed	⩽ 9	Production
LS-1.56	1.56	10		⩽ 9	Production
LS-1.06	1.06	10		9	Tests
LS-1.9	1.9	3		9	Tests
LS-0.97/1.56	0.97	10		9	Tests
LS-0.97/1.56	1.56	2.5		9	Tests

*Jointly with the 'Pribor' Federal Scientific Production Centre.
Note: the pulse and pause durations are 10 – 2000 ms, the wavelength of the pointer is 0.53 or 0.67 μm, the fibre diameter is 400 – 600 μm, the size of the apparatus is 120 × 260 × 330 mm, the power supply parameters are 220 V, 50 Hz, and < 150 W, and the service life of laser diodes is > 20 000 h.

lengths, for example, in the red spectral range used in the photodynamic therapy of tumours [10].

4. Additional opportunities appear due to the fact that high power levels in the IRE-Polus fibre lasers are reached in the single-mode regime. This allows the coupling of the working radiation to a very thin working fibre, at whose exit the radiation has ideal spatial characteristics. Using the focusing optics at the fibre exit, one can obtain a waist with a minimum possible ratio of the spot diameter to the caustic length in the working zone. The focusing optics can be placed in a manual holder or combined with the operating microscope (a slit lamp). Consequently, it becomes possible to design a laser instrument ensuring a high power density for operations on microscopic areas.

5. It is important that the effect of laser radiation depends not only on its wavelength but also on its time parameters. The time characteristic of fibre-laser radiation can be controlled in a wide range (see Table 1). A significant limitation in this case is the impossibility of obtaining high peak powers because of a destruction of the optical fibre.

The practical implementation of these potentialities was started by the Lason-10P apparatus designed jointly with the 'Pribor' Federal Scientific Production Centre and was continued by the development of LS medical laser apparatuses at the IRE-Polus. Their characteristics are listed in Table 2.

Some of these devices have been certified and have a permission of the RF Ministry of Public Health for their application in medical practice. Some devices exist as prototypes that undergo tests necessary for obtaining this permission.

During clinical tests and the subsequent practical use of Lason-10P and LS apparatuses, it has been shown that these devices are reliable, convenient, and easy to operate. It is very important that many medical technologies that were implemented (in some cases, also developed) using these apparatuses made it possible to replace laborious and painful operations, which require a subsequent long-term hospitalisation, by a least-invasive, organ-saving, and almost painless treatment suitable for a doctor and patient under polyclinic conditions or at a one-day hospital.

The thermoplastics of cartilages mentioned above [4] and operations for treating various disorders of the ear, nose, and throat [11 – 13], gynecological [14], urological, and oncological diseases are among these applications. Due to the radiation coupling through a fibre, the apparatuses have shown good results in least-invasive endoscopic and laparoscopic operations [15]. Many applications have been realised in medical practice, but the results are not published.

Currently, the ischemic heart disease is efficiently treated using the method of laser revascularisation of the myocardium, which restores the blood circulation by perforating several tens of holes in the myocardium by a laser beam. Note that this technique was used for treating more than 12000 patients in the USA [16]. In this case, bulky and rather expensive facilities based on CO_2 lasers were used. Even a Russian system Perfokor [17] costs about $250 000. However, such operations can be performed with diode-laser-based apparatuses. For example, the results of a treatment with a 30-W laser at a wavelength of 0.81 μm are presented in [18]. The investigations at the Research Institute of Cardiology (Tomsk Scientific Center, Siberian Division, Russian Academy of Medical Sciences) have shown that the use of radiation at a wavelength of 0.97 μm allows one to reduce the required power to 10 W. Several operations of laser revascularisation of the myocardium were carried out with a Lason-10P apparatus at the Sergeev Khabarovsk regional hospital No 1. This device costs less than $10000. The high reliability of diode lasers is an important factor determining their application in medicine.

Therefore, it can be asserted that we have a developing family of low-cost, reliable, and easy-to-operate laser instruments for surgery and power therapy. They operate in various regions of the near-IR range and require no special operating conditions. Putting into medical practice the techniques based on the use of these apparatuses makes it possible to perform many operations in polyclinics, while their execution using conventional methods requires a hospitalisation.

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