Rare-earth-doped high-power fiber lasers generating in near infrared range

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In this paper, high power double-clad fibre lasers are presented. We have built two experimental laser set-ups based on neo-dymium- and ytterbium-doped active media. A Yb^{3+}-silica fiber laser has been cladding pumped at 937 nm by a InGaAs semiconductor laser diode and generated 4 W cw output power with slope efficiency of 73 ±3%. However, Nd^{3+}-doped fiber laser generated over 10 W cw output power with a slope efficiency of 63%. As a result of the experiment, we have elaborated very efficient coherent sources of laser radiation that can be used in many industrial applications.

Keywords: fiber laser, double clad fiber, diode pumping laser.

1. Introduction

Fiber lasers have active media in the form of optical fibers whose cores are active ions doped. These devices were invented at the beginning of the 1960s [1]. They owe their existence to the rapid development of semiconductor lasers which ensure effective pumping. The dynamic development of new technologies in manufacturing optical fibers had also a great impact on the development of fiber lasers [2]. Thanks to the study of double-clad fiber laser elaborated by Po and Snitzer [3,4] and the possibility of obtaining diode pumps with a few dozens of watts, fiber lasers began to be considered as very attractive sources of coherent radiation in non-telecommunication applications.

A specific structure of active optical fibres and methods of its excitation is also a very important issue. Fibre amplifiers and the first lasers using this geometry of active medium were excited by introducing pump energy to the core from the front face or by means of directional couplers. This type of excitation meets some difficulties when single-mode fibres have to be excited with large powers (two dimensional diode array). These difficulties can be overcome using double cladding of active fibres [5–7].

An active double-clad optical fiber consists of a rare-earth doped core (small in diameter), which ensures propagation of waves (usually in basic mode TEM_{00}), an inner clad (directly sticking to the core) and a polymer outer layer (outer clad). The glass outer layer is used both as a layer limiting the laser radiaton inside single-mode core and multimode optical waive-guide (with high numerical aperture) to ensure propagation of the pump light. Every time the pump light crosses the core of the fiber it is ab-

sorbed and thereby the active dopant of the core is activated.

Such a system has two fundamental advantages: firstly, it does not require precise focusing radiation of pump sources and secondly, the active core is homogeneously pumped along the whole length of the fiber. Initially, this design had an axial symmetry. However, after some time scientists departed from the axial symmetry starting to use D-shaped or rectangle-shaped geometry. This change causes purposeful disturbance of the distribution of pump radiation inside the fiber. This leads up to more effective activation of the core [8]. Such a solution also has many advantages, among the most important ones are: the simplicity of the system and easy insertion of a pump beam into a fiber.

High-power fiber lasers based on double-clad rare-earth-doped silica-glasses have become of strong interest during the last few years. Fibre lasers have specific features in relation to conventional DPSSLs: high amplification, high efficiency and low threshold of generation due to very low resonator losses (~5 dB/km), diffraction limited beam (M^2 ~1), easy heat exchange with environment, high-power density in relation to pump power density.

2. Active dopants of high power fiber lasers

Fibre lasers belong to the family of wave-guide lasers and they can operate due to diode pump. The lately observed progress in the scope of fibre lasers technology has caused them to be treated as a separate group of high-power lasers [9–11]. The following ions are usually used as active dopants of these devices:

- neodymium   (Nd^{3+}) λ_g ~1060–1120 nm,
- ytterbium   (Yb^{3+}) λ_g ~1020–1180 nm,
- erbium   (Er^{3+}) λ_g ~1530–1565 nm.

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2.1. Neodymium

Neodymium ions are a classical active dopant for solid-state lasers. Neodymium was used for the first glass laser demonstrated by Snitzer in 1961 [1]. Although Nd^{3+} ions were not the first ions lased in a solid, they have become the most important activator for crystalline and bulk glass lasers because of the power and efficiency available from the transition at approximately 1060 nm. Neodymium-doped fiber lasers also have good energy parameters. Figure 1 shows the relevant energy levels of the Nd^{3+} ions in silica.
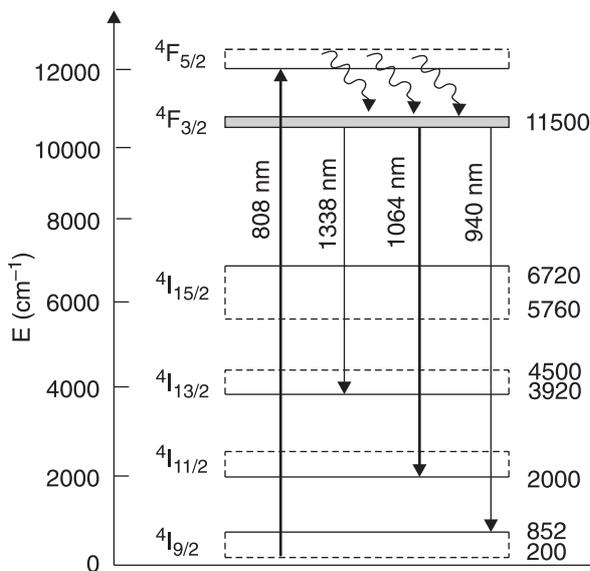
Fig. 1. Energy levels and transitions involved in laser oscillations of Nd^{3+} ions in glass matrix.

The strong $^4I_{9/2} \rightarrow {}^4F_{5/2}$ absorption transition at about 800 nm is extremely effective for exciting the $^4F_{3/2}$ metastable state, leading to very efficient Nd^{3+}-doped crystalline and fiber lasers pumped by AlGaAs laser diodes. However, a narrow absorption band of pump radiation, a disadvantage of this dopant requires temperature stabilization of pump diodes.

Neodymium ions have three main laser transitions, around: 1300 nm, 1060 nm and 940 nm. The $^4F_{3/2} \rightarrow {}^4I_{9/2}$ (940 nm) is a three-level system. The first fiber laser for this transition used silica optical fiber and operated in the cw regime at room temperature with a tuning range of 900–945 nm [12]. However, this transition is not of great technological interest for fiber or bulk glass devices, and it has not been extensively investigated.

Transition $^4F_{3/2} \rightarrow {}^4I_{11/2}$ corresponds to 1060 nm wavelength. This band provides four-level operation at room temperature. The thermal state lies roughly 10 kT above the ground state, leading to a thermal population of the $^4I_{11/2}$ of only 1 ion in 10^4. In addition, this 2000 cm^{-1} gap is small enough to provide a high nonradiative relaxation rate and prevent a buildup of population in the terminal level.

There is no ground state absorption (GSA) at the laser wavelength. As a result, the internal gain is positive even for a vanishingly small pump power, and the threshold power can be very small. Nonlinear losses amplified spontaneous emission (ASE) and large quantum defect ($\lambda_p/\lambda_g = 0.76$), both observed at high pumping power densities, are other disadvantages of neodymium ions used as an active dopant.

Transition $^4F_{3/2} \rightarrow {}^4I_{13/2}$ corresponds to 1300 nm wavelength. This transition provides true four-level operation because the terminal level is located ca. 20 kT above the ground state, sufficiently far to have negligible thermal population at room temperature. Moreover, the gap between the terminal state and the next lower one is small enough (2000 cm^{-1}) to provide a fast nonradiative relaxation rate and no population buildup in the $^4I_{13/2}$ is expected. The 1300 nm transition suffers from excited state absorption (ESA), reducing considerably the gain.

2.2. Ytterbium

Ytterbium is one of the most versatile laser ions in silica-based hosts. It offers very attractive features, in particular an unusually broad absorption band that stretches from below 850 nm to ca. 980 nm and from ca. 1010 nm to above 1070 nm, Fig. 2(a). Yb^{3+} ions in silica have just one broadband laser transition, between 0.97 and 1.2 µm. Therefore they can generate many wavelengths of general interest, e.g. for spectroscopy or for pumping other fiber lasers. The main transition of Yb^{3+} in silica is 1083 nm. It is a very useful wavelength because it can be used for optical pumping of He [13] and as a pump source for optical parametric oscillators to generate wavelengths in the 3.8–4.3 µm range for applications in gas detection [14]. Ytterbium-doped fiber lasers can be pumped by AlGaAs (~800–850 nm) or InGaAs (~980 nm) semiconductor laser diodes, by Nd:YLF (1047 nm) and Nd:YAG (1064 nm) lasers, which are generally available on the industrial market. Ytterbium ions are characterized by simplicity of its energy level diagram, Fig. 2(b).

In the Yb structure of energy level only a ground state ($^2F_{7/2}$) and a metastable state ($^2F_{5/2}$) spaced by approximately 10000 cm^{-1} exhibit. All other levels lie in the ultraviolet region. The absence of higher energy levels reduces the incidence of multi-photon relaxation and excited state absorption phenomenon (ESA). A Yb-doped fiber laser is typically pumped into the higher sublevels of the $^2F_{5/2}$ manifold. At wavelengths below about 990 nm, it behaves as a true three-level system [transition A in Fig. 2(a)], whereas at the longer wavelengths, from ~1000 to ~1200 nm [transition B in Fig. 2(a)], it behaves as a quasi-four-level system.

Because of absence of higher energy levels, high concentration of Yb^{3+} is possible in silica-based hosts, often up to several thousand ppm. Nowadays, Yb^{3+} dopant is regarded as the main dopant of high-power fiber lasers.
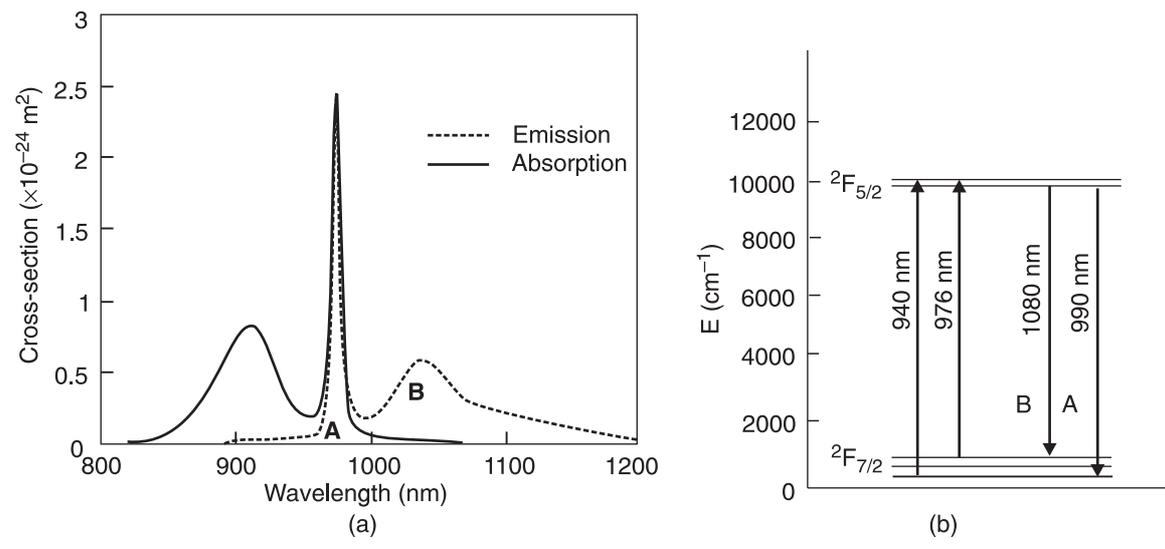
Fig. 2. The absorption and emission cross section of Yb^{3+} in silica (a) and energy level diagram of Yb^{3+} in silica (b).

3. Measurement set-up

The aim of the experimental research was to measure output power versus absorbed pump power and to estimate the level of slope efficiency of the examined fiber lasers. To reach this goal we built a measurement set-up that is presented in Fig. 3.

As pump sources for the fibers, high-power laser diode modules (with additional transmitting optical fibers) generating at a wavelength of 937 nm for Yb dopant and 808 nm for Nd dopant were used. The special cylindrical optics transformed the beam to a spot size of less than 400 μm to couple the pump light into the transmitting fiber. The transmitting fiber (1.5 m length) was characterized by the numerical aperture NA = 0.22. The laser diode modules (HLU25F400-940P and HLU30FAC400-808) were produced by LIMO Micro-Optics & Laser Systems (Jena, Germany) and delivered 25 W and 30 W continuous output power, respectively. The spectral width of the pump beams (FWHM) was smaller than 3 nm and a temperature drift (0.3 nm/K) made the pump match the maximum of absorption band of the active dopant.

Pump sources were cooled by water-cooling system. To control the working temperature we used a Peltier cell. Pump radiation coming out of transmitting fiber, thanks to shaping system (two aspheric lenses, AR-coated) was launched into the active optical fiber. To protect laser diode module from destruction by laser light we used a dichroic mirror, which was highly transmissive for pump wavelength (808 nm in case of Nd optical fiber and 940 nm in case of Yb optical fiber) and highly reflective for laser generation wavelengths (for Nd optical fiber – 1064 nm, for Yb optical fiber – 1080 nm).

The research was carried out for two active fibers: the Yb-doped fiber and the Nd-doped fiber, both produced in IPHT Jena (Germany). The fibers examined were characterised by the parameters which have been specified in Table 1.

All ends of the active fibers were cut at a right angle and then precisely polished. Both optical fibers were characterized by different than circular (D-letter, square) shape of the inner clad. In case of double-clad fibers with axial symmetry pumping efficiency is relatively low (ca. 30%). The weak absorption of helical modes of pump light
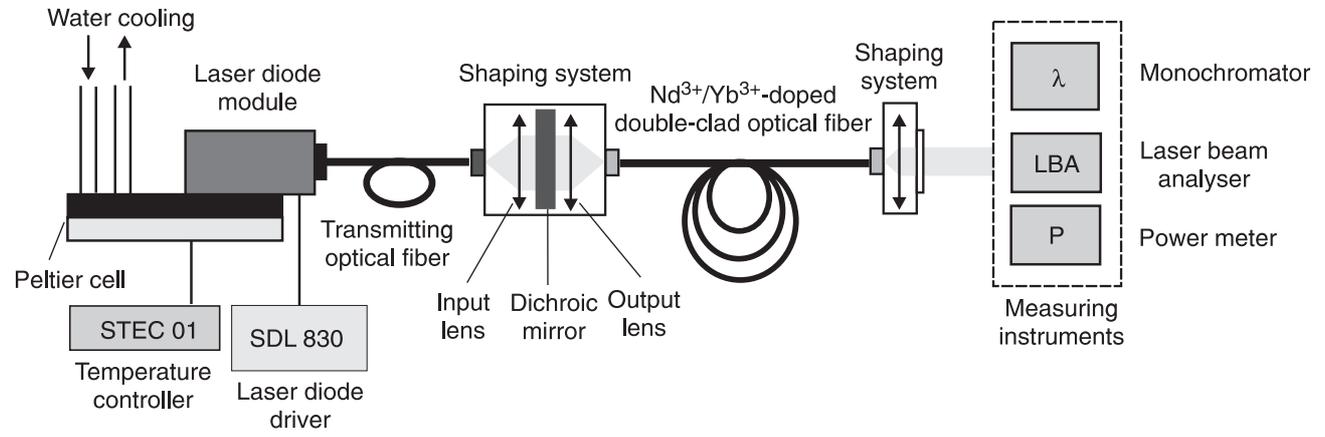
Fig. 3. Experimental set-up of Yb-doped fiber laser.

(which does not cross an active fiber core) is responsible for that. Therefore, breaking an inner clad symmetry is applied.

4. Results of experimental research

The fiber laser output power as a function of the absorbed pump power is shown in Fig. 4. As a result of our experiment we obtained 10.4 W cw output power from the Nd-doped fiber laser with slope efficiency at the level of 63±2%. In the same system configuration we obtained 4 W cw output power for 20 m ytterbium-doped fiber laser with a slope efficiency of 72 ±3%.

The transmission of input shaping system (in case of Nd fiber) equalled 89 %. However, the shaping system used for Yb fiber guaranteed only ca. 30% launching of pump light into the active fiber. This fitting element was not optimal, mainly due to financial constrains. We calculated that for this system configuration it is possible to launch more than 70% of pump light. In the near future, using the suitably designed shaping system we will be able to obtain more than 10 W output laser power at 1084 nm.

As it is shown in Fig. 4, along with the increase in absorbed pump power the output laser power increases proportionally linear for Nd-doped fiber. In case of Yb-doped fiber after crossing 4.5 W of absorbed pomp power we can observe the decrease in increment of laser power. This phenomenon was caused by limited ability of the cooling system.

We also estimated a parameter of the beam quality M^2. It is one of the most important parameters of lasers. The quality of beam is measured as the departure from basic mode TEM_{00} and we can numerically express it by M^2. In an ideal case, (mode TEM_{00}) M^2 equals one. This parameter decides about many other parameters of a laser, first of all possibility of focusing a laser beam. The literature reports on special research projects whose aim is to carry out a method of improvement in beam quality of various types of lasers [15]. In this respect, fiber lasers are unique. Beam generated by a single-mode fiber, by the force of event, without using additional procedures ensuring single-mode
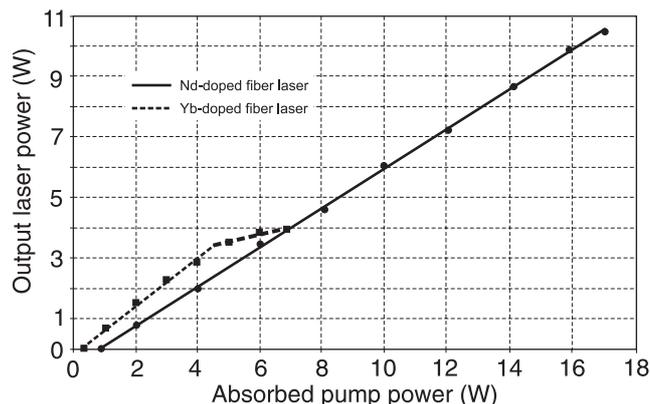
Fig. 4. Output laser power vs. absorbed pump power of investigated fiber laser.

generation has a distribution which is very similar to Gaussian's distribution. Such procedures are essential when we work with other diode pumped solid-state lasers.

Our measurements pointed that M^2 was close to one. For Nd-doped fiber laser M^2 was 1.43 while for Yb-doped fiber laser M^2 equalled 1.28. It shows that we have obtained coherent sources of radiation with a very good spatial parameter of the optical beam. Nd-doped fiber laser generated at 1064 nm wavelength, while Yb-doped fiber laser delivered radiation at wavelength of 1084 nm.

In the near future we intend to increase the level of output power as well as slope efficiency of examined systems mainly by means of improving excitation efficiency and by increasing the number of pumping LEDs.

5. Conclusions

Fiber lasers are often called the lasers of the 21st century. By their nature they have a lot of advantages over conventional laser systems due to their ability to incorporate a laser medium and a laser power delivery system into a single element. It is commonly believed that they will help to solve a number of difficult technical problems occurring in the most modern technological and medical processes. It is

Table 1. Comparison of parameters of active fibers.

	Nd-doped optical fiber	Yb-doped optical fiber
Fiber core diameter	12 µm	6.5–7.5 µm
Numerical aperture (core)	0.12	0.06
Fiber inner clad dimensions	φ 400 µm	120×120 µm
Numerical aperture (inner clad)	0.38	0.6
Shape of inner clad	"D" letter	square
Attenuation in an active core	4.7 dB/km	8–12 dB/km
Dopant concentration	1300 ppm	$3–10×10^{19}$ cm^{-3}
Length	20 m	20 m

expected that in the near future new structures of fiber lasers systems (particularly structures characterized by high pump efficiency) will make it possible to obtain power exceeding 1 kW or more cw power.

The experimental research concerning high-power fiber lasers that has been conducted at the Institute of Optoelectronics MUT let work out the first such laser systems in Poland.

Acknowledgements

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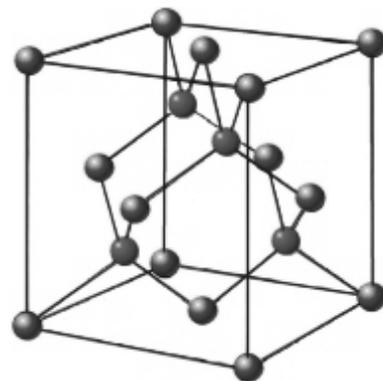
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