Activated fiber lasers and prospects of their applications in medicine

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ABSTRACT

Perspectives to develop a new line of compact, simple-to-use, reliable and low-cost high-power laser devices on the base of activated glass fibers will discuss. They may find wide applications in multipurpose diagnostic, therapeutic, and surgical complexes, also as in a lot of special medical devices.

1. INTRODUCTION

Wide spreading into everyday clinical practice of laser diagnostic, therapy and surgery methods, that obtained excellent experimental approbation, is strongly restricted by big sizes, complexity of exploitation, low reliability and high cost of conventional gas and lamp-pumped solid-state lasers commonly used for these purposes. Compact and reliable semiconductor lasers can't improve the situation in the whole since, on the one hand, they cover relatively narrow spectral regions, namely 700 to 870, 1300 and 1500 to 1600 nm, and, on the other, their average and peak power usually does not exceed 10 to 100 mW which in many cases is insufficient. An exception may be laser diode bars developed recently [1] whose average output power already reaches several tens of watts and the mass production cost is expected to not exceed 10-100 $ per watt. However such diodes are still possible for the range of 790 to 830 nm only, and the huge divergence and astigmatism of the output emission make it difficult to use the most convenient means of the light delivery to the point of final use, i.e. fiber lightguides. It is difficult to obtain from the laser diodes high peak powers of several hundred watts to kilowatts which is necessary for many clinical methods.

The line of crystal lasers pumped by arrays or bars of laser diodes is one of promising ways of solving this problem [2]. Their spectral range covers many wavelengths from 470 nm up to 2700 nm, and the average and peak powers reach tens to hundreds of watts, respectively, at an efficiency of up to 8 to 10 %. In the nearest future substantial improvements in these characteristics is expected. However the cost of such devices remains insufficiently high due to expensive laser crystals and wavelength-selected high-power LDs, the necessity of LD's temperature stabilization, and known problems of heat sink of active elements.

In the present paper we will discuss other direction that promises to develop a new line of compact, simple-to-use, reliable and low-cost high-power laser devices characterized in that as the active medium they use quartz or fluorozirconate glass fibers with a core activated by with rare-earth ions. There was very high activity last years in the field. But to date, all efforts were directed to the development of low-threshold single mode devices for applications in optical communications and optoelectronics. A number experiments with single mode fibers emitting at different wavelengths with an average power of up to 10...100 mW have demonstrated. Some of them are given in Table 1. The main goal of our investigations was to increase an output power of such sort of lasers and to define where are limitations in that way.

2.BACKGROUND

As preliminary analysis showed, there are three essential advantages of fiber lasers in comparison with another's which promise to create the perspective devices with an average power of tens to hundreds watts. The first is associated with the high optical damage threshold of quartz fibers. As it is seen in Table 2, the optical damage threshold to fibers is one to two orders of magnitude higher than to others, and it achieves enormous values mounting to 5...10 MW /cm^2. The second advantage allows to use highly opened laser cavities even for CW operation due to a very high single-pass gain which is possible to receive in fibers at miliwatt level of excitation only. For instance, in our experiments [13] with optical amplifiers of Er-doped fibers, a gain of 30...40 dB per meter have achieved easily. The Table 2 shows also typical values of the output coupling $(1-R_1*R_2)$ for different CW lasers. In fiber lasers we may use an output coupling up to 0.9...0.95, which allows 20 to 50 times raise, up to 0.85...0.95, of the ratio Pout/Pin of output power density to the density inside laser cavity. As a result, in high power fiber lasers the output power density of 2...5 MW/cm^2 may be achieved which is hundreds times above than the potential of other lasers.

Table 1. Some experimental results for different types of fiber lasers to date

Activator	$\lambda_{em.}$ nm	P_{out} mW	Ref.
Nd	900–945	4	3
	900	60	*
	1050–1075	20	4
	1050–1113	100	*
	1340	10	5
Sm	651	30	6
Pr	1070	3	7
Yb	980	10	8
	1015–1140	5	9
Tm	2038	51	10
Ho	2080	5	11
Er	1550	8	12
	1536	2000	*

* - results obtained in present work.

The last factor is associated with the sink of a heat, which is dissipated in the active media at excitation. The temperature field calculations for different active elements showed that the lasers using rod-type active elements require as a forced water flow cooling, and the erbium fiber laser (emission at 1535 nm) having a output power level of 10 W don't need any cooling at all. Under the conditions the temperature grading over the core relative to the surface is negligibly small. Even under the pumping at 532 nm when the heat emission is 5 to 7 times higher than using 980 nm LD arrays as a pump source this difference does not surpass 0.01C. Under pumping from laser diodes the air cooling is possible even at output power of 100W.

At last we have to note that it's sufficiently easy to obtain the theoretical limit of lasing efficiency in the case of fiber lasers defined only by the energy difference between the pumping quantum and the emitted quantum. This is due to an extremely low level of the losses in the quartz fibers, by the possibility of using open cavities, and by the practically complete overlap of the pumping and emission channels under longitudinal excitation. For example, the predicted efficiency for Nd^{3+} lasers excited by laser diodes operating in the 800 nm spectral band is of about 70...75 %. Under this conditions the wavelength of laser pumping is not required to be strictly adjusted to the center of Nd^{3+} absorption band as it is typical for crystal lasers. In the Nd-doped quartz fibers the wavelength of a laser diode emission can be variable in the wide range between 790 nm and 820 nm. Consequently, there is no necessity in thermal stabilization of the laser diodes.

Table 2. Experimental data on the maximum CW power density (P_d/S), the optimal output coupling ($1-R_1R_2$), and an achieved output power density (P_{max}/S) of 1.064 um CW YAG laser, that Nd-doped quartz fibers (a core diameter of 50 um, a cladding of 125 um), 5 mm-diameter rods of YAG:Nd crystals, and Nd-doped phosphate glasses are able to transmit without a breakdown.

	Pd /S MW*cm-2	1-R1R2	Pout/Pin	Pmax/S kW*cm-2
YAG	0.3-0.5	0.9-0.95	0.05	15-25
PG	0.05-0.06	0.98-0.99	0.01-0.02	0.5-1
QF	5-10	0.04-0.1	0.85-0.95	4000-8000

3. EXPERIMENTAL

An experimental verification of above made estimations was carried out using different home-made quartz fibers with germano-silicate core activated by Nd or Er. Two pumping sources, both emitting at 532 nm, were involved in investigations. One of them was mode-locking COHERENT ANTARES YAG:Nd laser with 3...4 W average output power at a repetition rate of about 80 MHz. Other was a home-made AO-switched YAG:Nd laser with the average output power up to 20W in the form of 400 to 700 ns pulses with a repetition rate up to 30 kHz.

Results of our experiments are given in Table 1. For single-mode fiber with 6.5 um core doped by with Nd^{3+} of about 100 ppm, it was fixed sufficiently high output power of up to 100 mW at the spectral range of 1085-1112 nm. In other experiment we have used special 7 um core Nd-doped fiber characterized in that relative intensities of luminescence bands emitting at 900 nm and 1080 nm were reversed in such unusual way that the intensity of $^4S_{3/2}$ to $^4I_{9/2}$ transition (900 nm) occurs to be triple higher. The laser testing of such fiber allowed us to obtain in first an intensive emission in the spectral range of 890-900 nm with the output power of 60 mW. We have to note especially that we did not use in this experiment any selective mirrors. Unfortunately, in both our experiments the optical conversion efficiency was limited by an excited-state absorption process to the relatively low level of about 10-12 %. We believe the use of high-power laser diodes emitting at 800 nm as a pump source will allow to rise this efficiency to 50-70 % level.

In the next experiment we tested the 15 m single mode fiber with a core of 8.2 um doped by Er^{3+} in a concentration of 100 ppm. The output power of up to 1 W was obtained at 1535 nm at pumping power of 3.6 W which corresponds to a power density within the fiber around 3 MW/cm^2. The output coupling was of about 0.9. The achieved conversion efficiency of about 28 % is close to the limiting value of the given pumping method. There were no essential variations of lasing efficiency when the output coupling changed from 0.9 to 0.4.

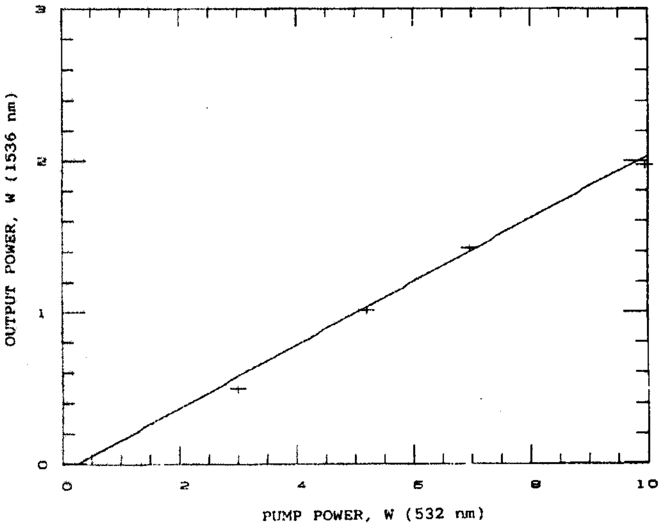

Fig.1 Output power of 28 um Er-doped fibre laser versus launched pump power at 532 nm.

The last experiment involved a multimode erbium fiber with a core of 28 um diameter having Er^{3+} concentration of 40 ppm and NA = 0.2. The obtained oscillation power versus the pumping power is shown in Fig.1. At an optimum fiber length of 20 m, output coupling of 0.96, and an input power of 10 W, the output laser emission at 1536 nm reached 2 W. The threshold pumping power did not exceed 200 mW. In accordance with our predictions there was no need for a fiber cooling. A fiber temperature did not rise more then by 1 C when several rings of the fiber were posed free-hanging into quiet air . Also there were no fiber degradation in spite of rather heavy pumping conditions.

At definite parameters of the cavity and the pumping, the oscillations were pulsed at 30 kHz with the pulse width close to that of the pumping. The peak power of this pulses reached 50 W.

4. CONCLUSION

The received experimental data allow to conclude about adequacy of the evaluations concerning the possibility of creating of efficient high-power fiber lasers. Transition to pumping sources of a higher power having a larger diameter of activated core permits to expect an average lasing power of tens and hundreds of watts. Lasers of this type are capable of operation in CW and pulse modes as well as in the Q-switch mode in the spectral ranges of 0.65, 0.9 to 0.94, 0.98, 1.02 to 1,14, 1,53 to 1.60, 1.9 to 2.1, 2.3, 2.7 um, and in the ranges of their harmonics. They will compete successfully in future with high-power crystal lasers for many applications. The most promising pumping sources of such lasers are seen in arrays of laser diodes which in the nearest future are expected to emit more than 100 W at an efficiency of 30 to 50%. Fig.2 shows one of a possible version of the high-power fiber laser pumped by LD arrays. The total efficiency of such systems is expected to reach 20 to 30%. They may find wide application in medicine in multipurpose diagnostic, therapeutic, and surgical complexes, also as in a lot of special medical devices.

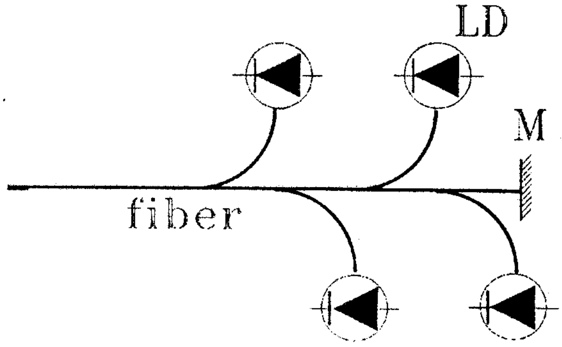

Fig.2 One of possible configuration of high-power LD-pumped fibre lasers.

5. ACKNOWLEDGMENTS

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