# High-Power Fiber Laser

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## Abstract

**We discuss a theoretical feasibility of a development of effective fiber lasers with an average output power of tens of watts, and we demonstrate experimentally an average power of 3.9 W in the 1.54 um spectral range for the $Er^{3+}$-doped quartz fiber laser. For a single mode fiber laser an output power of about 1 W has achieved**

## Introduction

There was very high activity last years in the field of end-pumped rare-earth doped quartz and fluorozirconate glass fiber lasers. To date, all efforts were directed to the development of low-threshold single mode devices for applications in optical communications and optoelectronics. A number of single mode devices emitting at different wavelengths of about 650 nm, 820 nm, 930 nm, 980 nm, 1060...1100 nm, 1480 nm, 1530...1560 nm, 1880 nm, 2038 nm, 2350 nm, etc. with an average power of up to 50...200 mW have demonstrated [1-5].

## Background

The main goal of this work was to understand whether it is possible to increase an output power of such kind of lasers, and where are limitations in that way. It was very interesting also to compare advantages and disadvantages of fiber lasers with conventional flash lamp-pumped solid state lasers and with a quickly developing new line of crystal lasers based on LD pumping[6].

As our preliminary analysis showed, there are three essential advantages of fiber lasers in comparison with another's, which open perspectives of development of simple, compact, reliable and low cost devices with an average output power on the order of tens or hundreds of watts.

The first advantage is associated with the very high optical damage threshold of quartz fibers. There are given in Table 1 our experimental data on the maximal CW power density ( $P_d/S$ ) of 1.064 um CW YAG laser, that Nd-doped quartz fibers ( a core diameter of 50 um, a cladding of 125 um ), and 5 mm-diameter rods of YAG:Nd crystals and Nd-doped phosphate glasses are able to transmit without a breakdown. One can observe an optical damage threshold to fibers at fluences one to two orders of magnitude higher than to others, and it achieves enormous values mounting to 5...10 MW /cm$^2$ that even more then data given in [7] for inactivated quartz fibers. Such high damage threshold level is difficult to explain by a low optical losses in the fiber core and by a high temperature of quartz annealing. We believe that for a CW operation it is a thermal process in the main, and following local stresses are not so dramatic as in the case of a bulk active media due to a fast heat dissipation and to pulling transverse stresses from the cladding that are typical for quartz fibers [7].

The second advantage of fiber lasers is connected with a possibility to use highly opened cavities even for CW operation due to a very high single-pass gain which is possible to receive without problems. For instance, in our experiments [8] with optical amplifiers of Er-doped fibers, a gain of 30...40 dB per meter was have achieved easily ( see Fig.1 ). The Table 1 shows typical values of the output coupling ($1-R_1*R_2$) for the solid state CW lasers on a base of YAG:Nd crystals, Nd-doped phosphate

Tab.1

| | 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 |

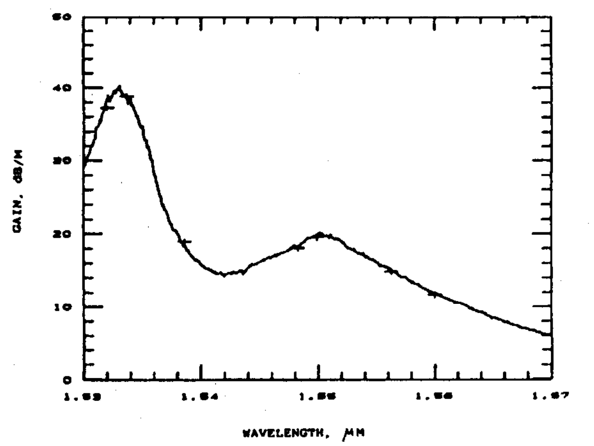

Fig.1 Spectral dependence of small-signal gain for SM erbium fiber amplifier.

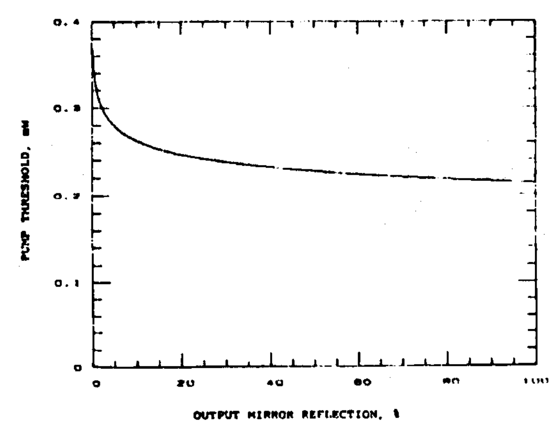

Fig.2 Threshold pump power of CW erbium fiber versus output mirror reflection. Power is normalized to crossection of 1 $um^2$. Pumping wavelength is 532 nm

glasses, and Er-doped quartz fibers. In fiber lasers, in difference from other variants, we may use an output coupling up to 0.9...0.95 (see Fig.2 also), which allows 20 to 50 times raise, up to 0.85...0.95, of the ratio $P_{out}/P_{in}$ of output power density to the density inside laser cavity. As a result, in high power fiber lasers the output power density of 4... 8 MW/$cm^2$ may be achieved which is hundreds times above than the potential of other lasers. We want to note also that this magnitude by tens of times higher than typical output power densities of laser diodes.

Next factor which essentially effects the cost, dimensions, reliability, and other parameters of high-power solid-state lasers is associated with the sink of a heat, which is dissipated in the active media at excitation. In this connection, we undertook an attempt to compare requirements to heat- removing systems for CW lasers on quartz fibers and other active media with similar output power ( 10 W ).

The temperature field calculation for the case of a long cylindrical rod is sufficiently simple. It is defined by solution of the stationary equation for the heat conductivity

$$\frac{1}{R}\cdot\frac{d}{dR}\cdot\left[R\cdot\frac{dT}{dR}\right]+\frac{W(R)}{\lambda}=0$$

with the boundary conditions:

$$\lambda\cdot\left[\frac{dT}{dR}\right]_{R=R0}+\alpha\cdot(T(R0)-T)=0$$

This solution has the form

$$T(R)=\frac{1}{\lambda}\cdot\int_{R}^{R0}\frac{dR}{R}dR\cdot\int_{0}^{R0}W(R)\,R\,dR+\frac{1}{R\alpha}\cdot\int_{0}^{R0}W(R)\cdot R\,dR \qquad (1)$$

where:

T - is the medium temperature
R0 - is the cylinder radius
$\lambda$ - is the heat-conductivity coefficient
$\alpha$ - is the heat-exchenge coefficient
W(R) - is the power of the volume-heat evolution

Under the condition of uniform distribution of heat sources in the volume, the Eq.1 takes the form

whence the surface temperature will be

$$T(R)=T+W\cdot\frac{R^2}{4\lambda}\cdot\left[\frac{2\lambda}{R0\alpha}+1-\left[\frac{R}{R0}\right]^2\right].$$

$$Ts = W \cdot \frac{R0}{2\alpha} + T \quad ,$$

and the temperature difference from the center to the surface

$$Tc - Ts = W \cdot \frac{R0^2}{4\lambda} \quad ,$$

Similar expressions for the doped fiber will have the form of

$$Ts = W \cdot \frac{R1^2}{2R0\alpha} + T \quad , \quad Tc - Ts = W \cdot \frac{R1^2}{4\lambda} \, ,$$

where R1 is the fiber core radius.

The calculation results are given in Table 2 where D and L are the diameter and the length of an active medium respectively. The estimations are taken for the case of krypton lamp pumping (YAG: $Nd^{3+}$ crystal), laser diode pumping (YAG: $Nd^{3+}$, phosphate glass, quartz fibers with a core diameter of 100 or 300 um), and also for the pumping by the second harmonic of an YAG: $Nd^{3+}$ laser (the quartz fiber having 100 um diameter core).

The Table 2 also shows that the lasers using active elements in the form of a rod require as a minimum forced water cooling, with the fiber laser having a output power level of 10W air cooling being adequate. Under the conditions, average fiber temperature raising does not exceed 4 C, and 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, this difference does not surpass 0.01 C. Under pumping from laser diodes, the air cooling is possible even at output power of 100W. The conditions of a heat-sink in the present case may be easily improved by making the waveguide longer since the length variation in a sufficiently wide limits does not lead to degeneration of laser efficiency.

Also we should like to note that in solid-state lasers with the rod-type active elements the problem of intrinsic stresses due to a large gradient of the temperature between the center of a rod and the surface arises. These stresses pose still stricter restrictions on the maximum levels of the output power of solid-state lasers. In the case of high-power laser realization on the base of multimode fibers this factor becomes negligent.

Finally we have to note that it's rather 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 emited 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

Table 2.

| | D mm | L cm | S/V cm−1 | PUMP nm | λ Wcm−1 xC−1 | T C | Ts C | Tc−Ts C | α Wcm−2 xC−1 | Pdis W | Pout W |
|---|---|---|---|---|---|---|---|---|---|---|---|
| YAG | 4 | 5 | 5 | lamp | 0.1 | 20 | 40 | +8 | 0.4 w flow | 50−100 | 10 |
| YAG | 4 | 5 | 5 | LD,810 | 0.1 | 20 | 40 | +0.8 | 0.04 a,w flow | 5−10 | 10 |
| PG | 3 | 5 | 3 | LD,810 | 0.005 | 20 | 40 | +10 | 0.04 a,w flow | 5−10 | 10 |
| QF1 | 0.1 | 2000 | 180 | LD,810 | 0.01 | 20 | 24 | +0.001 | 0.0001 air | 2−3 | 10 |
| QF2 | 0.1 | 2000 | 180 | 532 | 0.01 | 20 | 40 | +0.01 | 0.001 air | 10−20 | 10 |
| QF3 | 0.3 | 2000 | 60 | LD,810 | 0.01 | 20 | 40 | +0.5 | 0.002 air | 20−30 | 100 |

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.

## Experimental

An experimental verification of above made estimations was carried out using the erbium doped quartz fiber laser as example. Two pumping sources, both emitting at 532 nm, were involved in the investigation. 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 homemade 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.

In the experiment with a 15 m single mode fiber with a core of 8.2 um doped by $Er^{3+}$ in a concentration of 100 ppm, we obtained an output power of up to 1 W 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.

The second experiment involved a multimode 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.3. 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 1535 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. Details of this experiment will discuss elsewhere. .

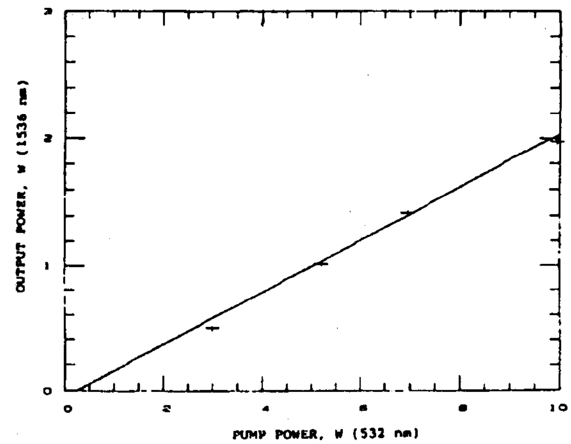


Fig.3 Output power of 28 um Er-doped fiber laser versus launched pump power at 532 nm.

At last, we have obtained preliminary results of testing of the new erbium fiber with 32 um activated core and additional 50 um inactivated waveguide cladding at the outer fiber diameter of 125 um. When pumped by 14 W average power into the intermediate core, the fiber was emitted of about 3.9 W with the conversion efficiency of 28 %.

## Comments

The preliminary experimental data allow to speak 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. These fiber lasers 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

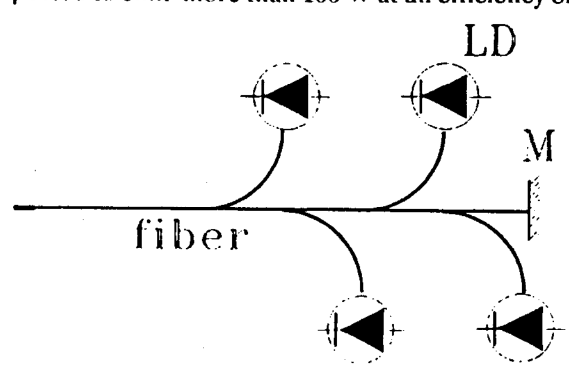


Fig.4 One of the possible configuration of high-power LD-pumped fiber lasers

to 50% [9]. Fig.4 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%.

## Acknowledgments

The authors gratefully acknowledge Drs. A.I.Zayatz, R.R.Loryan, and P.I.Baskov of Institute of Electrovacuum Glass, Dr. L.M.Blinov of IRE AS USSR, Moscow for manufacturing of the special fibers, Prof. Yuri V.Gulyaev, and Dr. Vitaly M.Firsov for support of the work.

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