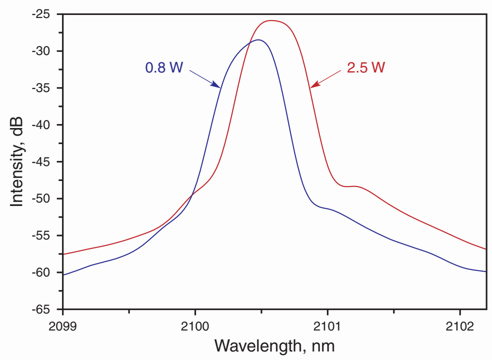
Abstract: We have made and studied a set of the fiber lasers based on Ho-doped fiber with high concentration of the active ions. For the first time the spectral efficiency in a range of 2.02 – 2.15 μm was determined. The highest output power of 4.2 W was detected at 2.1 μm with the efficiency slope of 34%. This value of the efficiency is highest for pure holmium-doped silica fibers.



Emission spectra of Ho-doped fiber laser for two values of the output power

Holmium fiber laser based on the heavily doped active fiber

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1. Introduction

Ho-doped fiber lasers exhibit oscillations at the longest wavelengths for lasers based on silica based fiber. Spectral range of lasing is centered near 2.1 μm [1,2], that determined by $^5I_7 \rightarrow {}^5I_8$ transition. It should be noted that in this spectral range there is a sharp growth of optical loss in silica glasses due to an influence of the molecular vibration. Thus, optical losses of the fiber SMF-28 are increased from approximately 0.2 dB/km at 1.600 μm up to 200 dB/km at 2.2 μm. Therefore to achieve the high lasing efficiency a length of the cavity should be not longer than several meters. It means that Ho-ions concentration should be high enough to provide an efficient oscillation using a short active fiber piece. On the other hand an increase of the active ions concentration can lead to the ions clustering and lost of efficiency through of the cooperative up-conversion. This phenomenon is well known for Er^{3+}-doped fibers [3].

Therefore there is a strong interest to study an efficiency of the Ho-laser based on heavily doped active fiber. Also it seems to be useful to measure the spectral efficiency of the laser oscillation since for Ho fiber lasers such data was not published. In this paper we have studied the lasing efficiency of six Ho fiber lasers with oscillation wavelengths from 2.02 to 2.15 μm. For every laser we optimized the cavity length to achieve the maximum output power.

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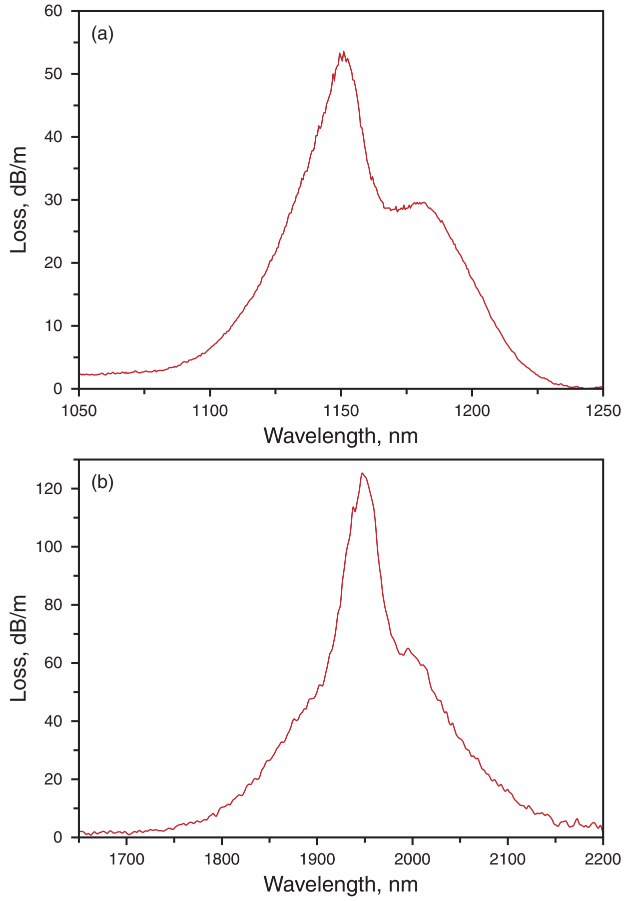

Figure 1 (online color at www.lphys.org) Absorption bands around 1.15 μm and 1.95 μm of Ho-doped fiber

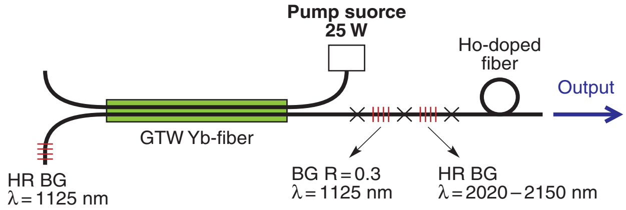

Figure 2 (online color at www.lphys.org) The laser scheme

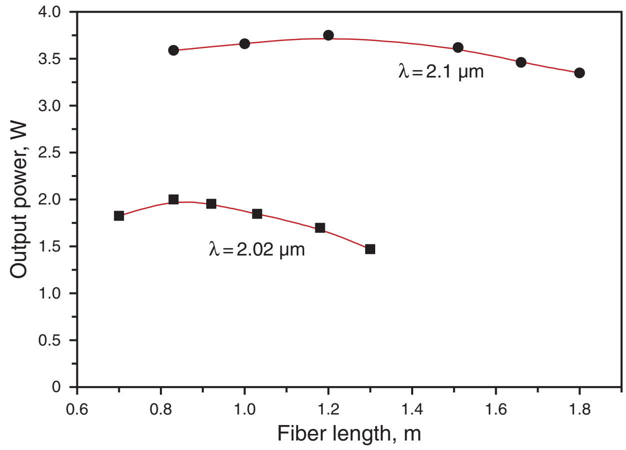

Figure 3 (online color at www.lphys.org) Output power vs. the active fiber length for two lasers

2. Experimental scheme

Active fiber was fabricated using MCVD-technology and solution doping technique. The fiber had a core diameter of 10 μm, a core-cladding index difference of 0.005. Fig. 1 illustrates absorption bands at 1.15 μm ($^5I_8 \rightarrow {^5I_6}$) and 1.95 μm ($^5I_8 \rightarrow {^5I_7}$). One can see that the absorption level determines an application of the short fiber pieces in the laser cavity since absorption peaks as high as 55 dB/m at 1.15 μm and 125 dB/m at 1.95 μm were measured. Based on the data about absorption cross-section from [4], Ho^{3+}-ions concentration can be estimated as 10^{19} cm^{-3}. However this data should be defined more accurately.

The laser scheme was extremely simple as it is shown in Fig. 2. To pump the Ho-fiber laser, we have used double-clad Yb^{3+}-fiber laser operating at 1.125 μm based on the GTWave active fiber consisting of an Yb-doped fiber and a passive multimode fiber in a common polymer coating with a refractive index lower than that of silica. Similar fiber was used in [5]. The application of Yb-doped fiber laser to pump Ho-fiber laser for the first time was suggested and realized in [6], and applied in [5] to get a power of 2 W at 2.1 μm and in [7] to build the broadband Ho-doped fiber radiation source. Also, an overlap between the oscillation band of Yb-fiber lasers and absorption band of Ho-doped fiber was used in [8] to get the pulse operation of Yb-doped laser. Pump wavelength was shifted from the absorption band center since the efficiency of the Yb^{3+}-fiber laser at 1.12 μm is essentially higher than at 1.15 μm [9, 10]. Yb-doped laser was pumped by semiconductor source fabricated by "Milon Laser" (Saint Petersburg) with an output power up to 25 W at 910 nm. The maximum power of Yb-doped laser was of 13 W.

To build Ho-doped lasers as the input coupler we used Bragg gratings with a reflection close to 100% and different resonance wavelength in a range of 2.02 – 2.15 μm. The grating was photoinscripted at an H_2-loaded SMF-28 fiber by means of the holographic technique [11]. The transmission spectrum of the grating was controlled by measuring the grating properties in the second order diffraction. The free fiber end was used as the output coupler.

To measure the output power of Ho-fiber laser, we cut unabsorbed pump power by a filter with a suppression of 30 dB at a wavelength of 1.125 μm. A spectrometer and a PbS-photodetector were used to measure the output spectrum of the fabricated lasers.

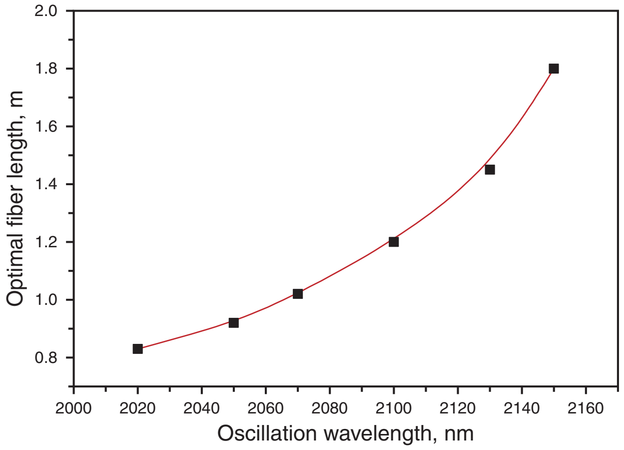

Figure 4 (online color at www.lphys.org) Dependence of the optimal fiber length on the laser oscillation wavelength

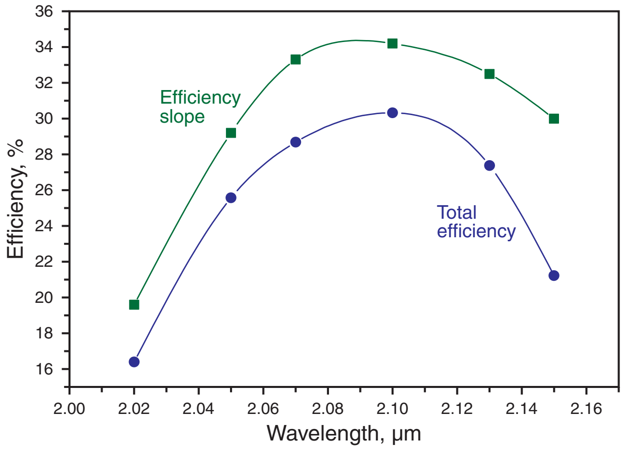

Figure 6 (online color at www.lphys.org) Spectra of the lasing efficiency

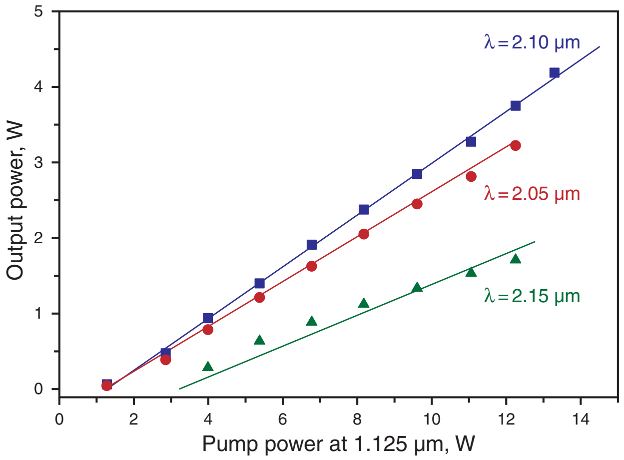

Figure 5 (online color at www.lphys.org) Dependence of the output power on the pump power of Yb-doped fiber laser for 3 Ho-doped lasers

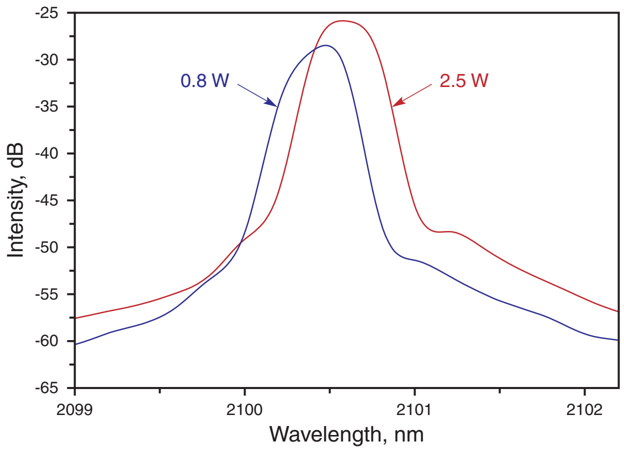

Figure 7 (online color at www.lphys.org) Emission spectra of Ho-doped fiber laser for two values of the output power

3. Results and discussion

We have made and tested six laser schemes with resonance wavelength at 2.02, 2.05, 2.07, 2.10, 2.13, and 2.15 μm. For every laser length of the active fiber was optimized to get the maximum output power by the pump level at 1.125 μm of 12.2 W. Fig. 3 illustrates the output power vs. fiber length for 2 lasers operating at 2.02 and 2.10 μm. One can see that an optimal fiber length strongly depends on the oscillation wavelength. Also, for short operation wavelength the optimal choice of the length is more critical for the maximum power achievement. Fig. 4 shows a dependence of the optimal fiber length on the oscillation wavelength where there is a sharp growth of the optimal fiber length with the increase of the operation wavelength.

For every laser with optimized fiber length we have measured a dependence of the output power on the pump power of Yb-doped fiber laser at 1.125 μm. Fig. 5 shows the corresponding dependencies for 3 lasers emitting at 2.05, 2.10, and 2.15 μm. The highest output power of 4.2 W was obtained at the wavelength of 2.10 μm. Efficiency slope was of 34% that corresponds to the quantum efficiency slope of 64%. As far as we know, these values are highest for pure holmium-doped silica fibers. Laser emitting at 2.15 μm exhibited the growth of the output power in time. Thus, the output power was increased from starting value of 1 W to steady-state power of 1.7 W during approximately 6 min. We believe that this effect is connected with a self-heating of the fiber that leads to the ASE suppressing due to a broadening of the absorption band [12].

The measurement dependencies of the output power on the pump power for all lasers allowed us to determine spectra of the efficiency slope and total efficiency for the pump power of 12.2 W. The corresponding dependencies are shown in Fig. 6. One can see that the efficiency slope higher than 30% is observed in the band of 0.1 μm.

Oscillation spectra were measured for a laser emitted at 2.10 μm for two values of the output power, namely 0.8 and 2.5 W. Correspondent spectra are shown in Fig. 7 in logarithmic scale. A width of the emission band for both cases can be estimated as 0.35 nm that is practically coincides with the spectral resolution of the spectrometer. Nevertheless one can see some long wavelength shift of the peak under power growth. Also we observed a spectrum broadening of the band pedestal with the output power increase.

4. Conclusion

We have made and studied a set of the fiber lasers based on Ho-doped fiber with high concentration of the active ions. For the first time the spectral efficiency in a range of 2.02 – 2.15 μm was determined. The highest output power of 4.2 W was detected at 2.10 μm with the efficiency slope of 34%. This value of the efficiency is highest for pure holmium-doped silica fibers. The achieved power is sufficient for the set of applications. Taking into account that realized laser has advantages of all-fiber design based on the commercially available components; we can believe that fiber Ho-lasers can compete with solid-state lasers operating in this spectral range [13–15].

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