A 100 W all-fiber linearly-polarized Yb-doped single-mode fiber laser at 1120 nm

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Abstract: A 100 W-class all-fiber linearly-polarized single-mode fiber laser at 1120 nm with an optical efficiency of 50% was demonstrated. The laser consists of a 4.2 m long Yb-doped polarization maintaining fiber with a core diameter of 10 μm and a pair of FBGs written in matched passive fiber. Linearly polarized output with a polarization extinction ratio of 15 dB is achieved by a cavity that selects both wavelength and polarization. Pulsed operations with square shaped pulses varying from 100 μs to 1 ms duration are achieved without relaxation oscillation.

OCIS codes: (140.3510) Lasers, fiber; (140.3615) Lasers, ytterbium; (140.3480) Lasers, diode-pumped.

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1. Introduction

Because of their high brightness and convenient thermal management, fiber lasers have drawn extensive attention in last decade. High output power lasers at many different wavelengths acrossing broad Yb-emission band have been reported. High power laser at 1120 nm has a variety of applications, such as pumping Raman fiber amplifier at 1178 nm [1] for laser guide star and Tm-doped fiber laser [2]. However, there are few high power 1120 nm fiber lasers

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reported. Codemard *et al.* reported a 100 W continuous wave (CW) Raman fiber laser operating at 1120 nm, cladding-pumped with a Yb-doped fiber laser [3]. Feng *et al*. reported a Raman fiber laser at 1120 nm of more than 150 W, core-pumped by a 1070 nm Yb-doped fiber laser [4]. A high power laser emitting directly from Yb-doped fiber would be preferred, since the laser configuration would be much simpler and overall efficient would be higher.

The conventional wavelength of high power Yb-doped fiber laser is between 1030 nm and 1090 nm. Single-mode fiber laser with output of 10 kW was reported at 1070 nm with a tandem pumping technology by IPG in 2009 [5]. Linearly polarized Yb-doped fiber lasers at longer wavelength beyond 1100 nm have indeed received much attention in recent years for generating yellow light via frequency doubling. However, amplified spontaneous emission (ASE) and parasitic lasing at shorter and higher-gain wavelengths are the key problems to overcome. With Yb-doped solid-core photonic bandgap fibers, the gain spectrum of Yb fiber can be engineered and a fiber amplifier of 167 W at 1178 nm with a slope efficiency of 61% was reported by Olausson *et al.* [6, 7]. Pumped by a 1090 nm laser, a laser with output power of up to 12 W at 1179 nm was achieved by Kalita *et al.* using a standard Yb-doped gain fiber [8].

In this paper, we report a 100 W-class linearly-polarized single-mode Yb-doped fiber laser at 1120 nm with an optical efficiency of 50%. Linearly polarized operation is achieved by cross-splicing a pair of wavelength matched fiber Bragg gratings (FBGs) written in polarization maintaining fiber. Macro pulse operation with square shaped pulses from 100 μs to 1 ms duration is demonstrated without relaxation oscillation at the beginning of pulses. Because of lower quantum efficiency, the 1120 nm Yb-doped fiber laser experiences higher thermal load than the lasers of conventional wavelengths and requires better thermal management.

2. Experiment configuration

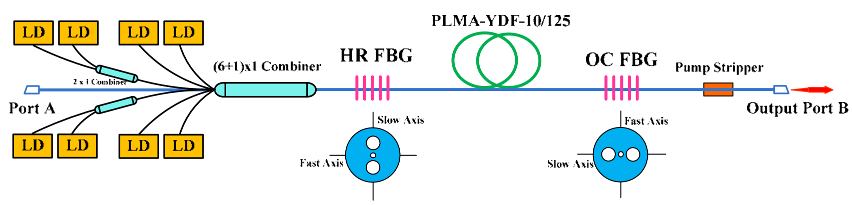

Fig. 1. Experimental configuration of the 1120 nm Yb-doped fiber laser

The 1120 nm fiber laser cavity consists of a pair of fiber FBGs and a Yb-doped gain fiber of 4.2 m in length as depicted in Fig. 1. The gain fiber (PLMA-YDF-10/125, Nufern Inc.), whose nominal cladding absorption is 4.8 dB/m at 975 nm, has a core and cladding diameter of 10 μm and 125 μm, respectively. The FBGs are written in matched passive fibers (PM085-LNA, Nufern Inc.). The FBG with a high reflectivity of 99% (HR-FBG) at 1120 nm is spliced to one end of the gain fiber. The other FBG with a reflectivity of 17% (OC-FBG) is spliced to the other end of the gain fiber as the output coupler after rotating 90 degree as shown in Fig. 1. The fast axis wavelength of the HR-FBG matches with the slow axis wavelength of the OC-FBG, and thus the cavity is constructed that only one polarization can oscillating in it [9]. The full width at half maximum (FWHM) bandwidth of the FBGs are 0.2 nm, which is necessary since the FBG wavelengths of two axes differ only by about 0.26 nm.

The pump diode lasers are injected to the laser cavity by a (6 + 1) × 1 combiner. The pump input fibers are multi-mode fiber with a core diameter of 105 μm and a NA of 0.22. The input and output signal fibers have the same parameters. Two additional 2 × 1 combiners are employed to combine the pump power, as shown in Fig. 1. The NA of input and output fibers of the 2x1 combiners are 0.15 and 0.22, respectively. Laser diodes (LDs), each with 25 W output, are used for pumping, whose output fiber is 105 μm with a NA of 0.15. The residual pump laser is removed from the output by a cladding mode stripper. All the fiber ends are cleaved with an angle of 8° to suppress parasitic oscillation around 1050 nm. As shown in Fig. 1, the entire laser is designed in an all-fiber configuration and can be packaged in small foot print.

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3. Experimental results and analysis

Parasitic oscillation at shorter wavelength around 1040~1060 nm, where gain is much higher, is indeed the major issue in developing high power 1120 nm Yb-doped fiber laser. We have increased the reflectivity of the output coupler to 17% in order to suppress it. In addition, one needs to carefully prepare the fiber end cleaves and fiber splices to minimize residual reflections, to prevent parasitic oscillation. The occurrence of parasitic oscillation may result in damage of fiber components, therefore, has to be avoided.

After careful preparation of the fiber ends and splices as well as controlling laser diode wavelength, lasing without parasitic-oscillation is achieved. The output spectra are measured with an optical spectrum analyzer (AQ 6370, Yakogawa Corp.) and shown in Fig. 2. A signal to ASE ratio of 50 dB is measured at full output. A zoom-in view of the laser emission at 1120 nm shows a FWHM linewidth of 0.21 nm measured with a 0.02 nm resolution. No evidence of lasing at the other polarization is observed in output spectrum.

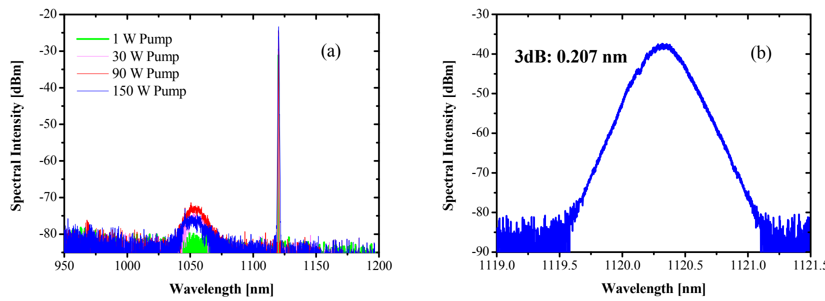

Fig. 2. (a) Laser output spectra at different pump power. (b) A zoom-in view of laser emission spectrum at maximum output.

The output power as a function of launched pump power is shown in Fig. 3. With a 202 W input pump, a maximum power of 101 W CW laser output at 1120 nm is obtained, corresponding to an optical efficiency of 50%. Higher slope efficiency is seen with pump power beyond 100 W, which can be attributed to the shift of laser diode wavelength toward the absorption peak of Yb ions. Due to the collectively broad spectrum of the eight laser diodes, the pump absorption is lower than expectation. A larger length of Yb doped gain fiber should improve the laser efficiency. The measured polarization extinction ratio (PER) is typically 15 dB with a Glan polarizer as shown in Fig. 4. The PER is less than what was achieved in an earlier work, in which, a 23 dB at 20 W fiber laser was obtained [9]. Since there is no evidence of lasing of the other polarization in laser output spectrum, we attribute the low PER to the depolarization effect, which may rise from slightly misaligned splices. However, 15 dB PER is within the requirement for pumping a polarization maintaining 1178 nm Raman fiber amplifier, which can be frequency doubled to 589 nm for laser guide star [1]. A lower power version of this laser has been used to produce up to 44 W 1178 nm single frequency laser in a Raman fiber amplifier [10].

For the laser guide star application, pulsed laser emission with a kilohertz repetition rate at 589 nm is advantageous for gating out the Rayleigh scattering noise. Such a laser can be obtained by frequency doubling of a narrow band Raman fiber amplifier at 1178 nm, which is pumped by a pulsed 1120 nm fiber laser. Since Raman scattering is almost instantaneous, the amplified signal waveform will follow the pump waveform. Therefore, we investigated macro pulse operation of the 1120 nm Yb-doped fiber laser with pulse duration around several hundred micro-seconds. Square pulses without spikes are preferred for the application in laser guide star.

Such macro pulse operation can be achieved by pumping with a macro pulsed diode laser of an appropriate pulse width. But if a square-wave pump is applied, the laser output will have

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strong leading spikes due to the relaxation oscillation effect. Figure 5 shows an example of the optical pulse waveforms with leading spikes. Such pulses are not only undesirable for the laser guide star application, but also detrimental to the fiber laser system. We have solved the problem by adding the current waveform a small DC offset. Although the offset is only 0.5 A, it is sufficient for the Yb fiber laser to reach the threshold. At this condition, the laser is always operating above the threshold with no abrupt change of population inversion, and therefore, the relaxation oscillation is avoided. Figure 6 shows the resulting laser pulse waveforms with pulse duration of 1 ms, 500 μs, and 100 μs respectively, whose pulse shapes are square with no spikes.

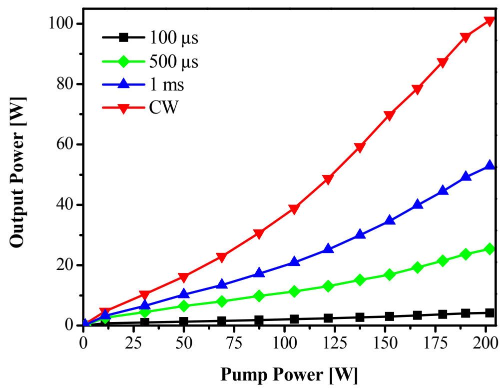

Fig. 3. Output power versus input pump power at CW and pulsed (500 Hz) operation conditions.

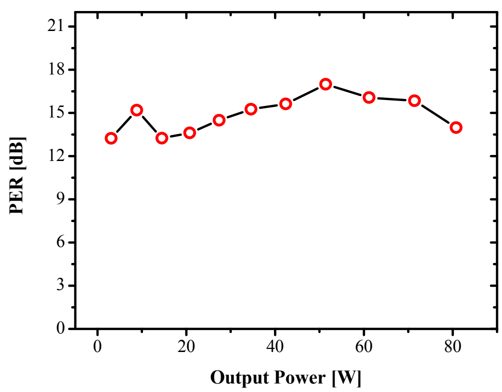

Fig. 4. Polarization extinction ratio as a function of output power

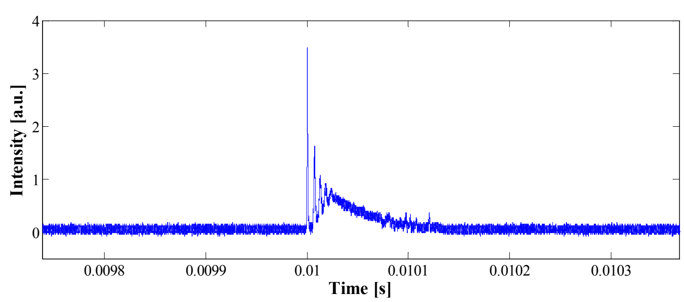

Fig. 5. An example of the laser pulses with leading sharp spikes due to relaxation oscillation if the laser is pumped with a square wave.

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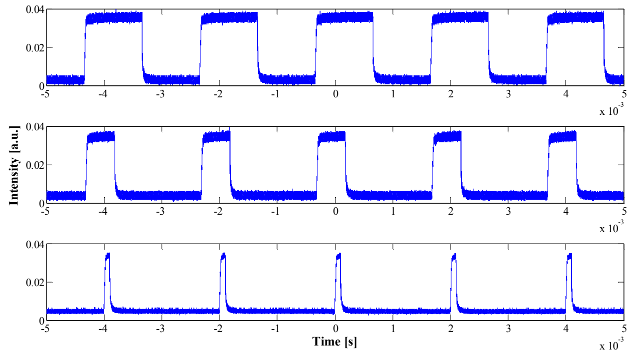

Fig. 6. Spikes-free macro pulse operation of the 1120 nm Yb fiber laser with different pulse durations.

At high pump power of over 200 W and high power confinement in the core diameter of 10 μm, proper heat management is essential in the laser design. In addition, due to the high absorption of the gain fiber and low quantum efficiency for 1120 nm emission in comparison with that of 1070 nm emission (87% versus 91%), heat deposition per unit length of this laser is high. The temperature rise can be large and result in fiber damage if the heat is not dissipated properly. An analysis of temperature distribution is conducted according to the theoretical model reported in [11],

$$T_0 = T_c + \frac{qa^2}{2hc} + \frac{qa^2}{4k_1} + \frac{qa^2}{2k_2}\ln(\frac{b}{a}) + \frac{qa^2}{2k_3}\ln(\frac{c}{b}) \tag{1}$$

where T_0 is the temperature at the center of the fiber core, T_c is the ambient temperature which is 290 K in our experiment, q is the dissipated heat per unit volume, and h is the convective heat transfer coefficient. The core radius a, inner cladding radius b and outer cladding radius c are 5 μm, 62.5 μm and 125 μm, respectively. k_1, k_2 and k_3 are thermal conductivities of core, inner cladding and outer cladding, which take values of $k_1 = k_2 = 1.38$ W/(m·K), $k_3 = 0.2$ W/(m·K). A rate equation model is developed to calculate the pump and laser power distribution along the fiber length. Assuming the quantum defect is the only source of thermal load, the heat distribution can be calculated directly. The center of the core and surface temperature distributions along the gain fiber are calculated for the 1120 nm laser and a corresponding 1070 nm laser at a pump power of 200 W, and the results are shown in Fig. 7(a). The temperature is highest at the beginning of the gain fiber and drops steeply. Under strong convection air cooling condition (h = 100 W/(m^2·K)), the maximum temperature of the 1120 nm fiber laser can be calculated to be about 50 K higher than that of a 1070 nm fiber laser. Figure 7(b) shows the maximum surface temperature as a function of convective heat transfer coefficient for the 1120 nm and 1070nm laser, respectively. The temperature of 350 K, which is a safe point for fiber polymer, requires a convective heat transfer coefficient of 450 W/(m^2·K) for the 1120 nm laser as compared to 350 W/(m^2·K) for the 1070 nm laser. Therefore, efficient heat dissipation is necessary for high power 1120 nm fiber lasers. The requirement in thermal management is more stringent than that in the 1070 nm Yb fiber laser. In the experiment, the gain fiber was spooled on the surface of a water-cooled metal cylinder and fitted in round grooves precisely machined according to the diameter of gain fiber.

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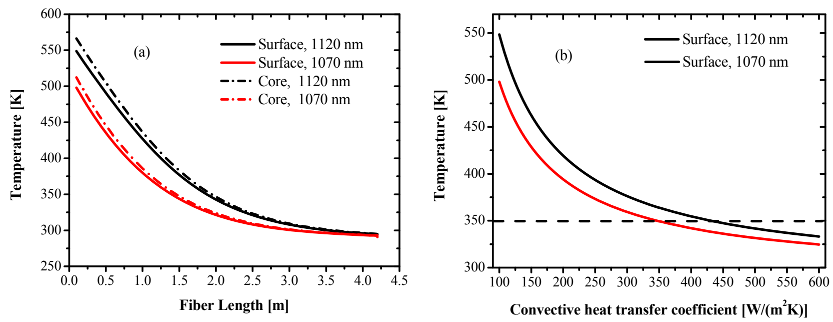

Fig. 7. (a) Core and surface temperature distributions along the gain fiber at a pump power of 200 W with h = 100 W/(m^2·K) for the 1120 nm and 1070 nm laser, respectively. (b) Surface temperature at pump injection point versus convective heat transfer coefficient h.

4. Conclusion

In summary, we have successfully demonstrated a 100 W class all-fiber linearly-polarized single-mode Yb-doped laser at 1120 nm with an optical efficiency of 50%. The laser cavity consists of a 4.2 m long Yb-doped polarization maintaining fiber with a core diameter of 10 µm and a pair of FBGs written in the matched passive fiber. Linearly polarized operation is achieved by cross-splicing the two FBGs that are wavelength matched so that only one polarization oscillates in the cavity. Macro pulse operation with square shapes from 100 µs to 1 ms duration is demonstrated without relaxation oscillation spikes at the beginning of pulses. The maximum output power of this laser is limited by the available pump diodes and can be scaled up further. An earlier version of the laser has been used as the pump laser for a single frequency polarization maintaining Raman fiber amplifier at 1178 nm, which is frequency doubled to 589 nm for laser guide star.

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