Single-frequency phosphate glass fiber laser with 100-mW output power at 1535 nm and its polarization characteristics

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We demonstrate a high power single-frequency fiber laser. By using phosphate glass fiber as its gain media, the laser can achieve high output power of 100 mW in centimeter-long linear cavity. Single-frequency single-polarization operation with <5 kHz linewidth and 65-dB signal-to-noise ratio (SNR) is realized by using external cavity polarization feedback technology.

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Single-frequency fiber laser has become a hot research topic in the last decade for its widespread applications in lidar, coherent communication, remote sensing, atom frequency standard, etc.[1−4] Among the single-frequency technologies in fiber laser, the structure of short linear cavity is the simplest method. To increase the frequency spacing between longitudinal modes of the laser cavity, the length of the cavity should be shortened to several centimeters, which however limits the output power substantially[2]. In some applications, light sources with high output power are required. For instance, high output power is desired if a fiber laser is used as the seed light in a master oscillator power amplifier (MOPA) system. The introduction of phosphate glass fiber overcomes the problem of low power in short linear cavity laser because of much larger doping concentration than silicon fiber. The single-frequency Er^{3+}/Yb^{3+} co-doped phosphate fiber laser has gained great development in the last several years, achieving higher output power, narrower linewidth, and larger tuning range[3−5]. The single polarization operation is an important qualification for fiber laser in actual applications. However, the linear cavity fiber laser normally operates in two orthogonal polarizations because the cavity is polarization independent. The methods of writing fiber Bragg grating (FBG) on polarization maintaining (PM) fiber or pressing FBG with piezoelectric transducer (PZT) were successfully used to produce single polarization[6−8]. However, the mode matching loss between fibers of different types and the technique reliability are our consideration for finding an easier method.

In this letter, we report an all-fiber single-frequency linearly polarized Er^{3+}/Yb^{3+} laser. The single longitudinal mode operation is easily achieved because of short (2 cm) active fiber and narrow bandwidth filter. The dual-polarization operation in the same longitudinal mode is further eliminated by using a polarization selective feedback element. The element is based on a polarizing beam splitter (PBS) which is added to the output port of the laser and the feedback is provided by 4% Fresnel reflection at fiber facet. The experiment demonstrates good linear polarization characteristics of our fiber laser.

Single mode fiber made of Er^{3+}/Yb^{3+} co-doped phosphate glass exhibits extremely high optical gain per unit length with negligible ion clustering and is uniquely suited for short linear cavity single-frequency fiber lasers[9,10]. The phosphate fiber used here, made by Southern China University of Technology, has high erbium and ytterbium concentration of about 2.5×10^{20} and 5.3×10^{20} cm^{-3}, respectively[11]. The core and cladding outside diameters of the fiber are 5.4 and 125 μm, respectively, and the numerical aperture (NA) is 0.2, showing perfect mode matching with Corning HI 1060 fiber which is usually chosen as the pigtail of wavelength division multiplexer (WDM). Its small signal gain coefficient was measured on a 2.4-cm-long fiber pumped by a 976-nm laser diode (LD) with output power up to 500 mW through a WDM. The input signal of 1 μW is provided by a tunable external cavity laser (TECL). In order to overcome the influence of amplified spontaneous emission (ASE), the input signal is modulated in 1-kHz frequency and the gain is calculated by the amplification factor of the modulating amplitude. Figure 1 shows the measured gain versus pump power for different wavelengths. It is found that the fiber has the highest gain at 1535 nm and the peak gain tends to saturate at 10 dB with high pump power. Therefore, the gain coefficient is calculated to be 4.2 dB/cm, which is two orders larger than that of Er^{3+}/Yb^{3+} co-doped silica fiber.

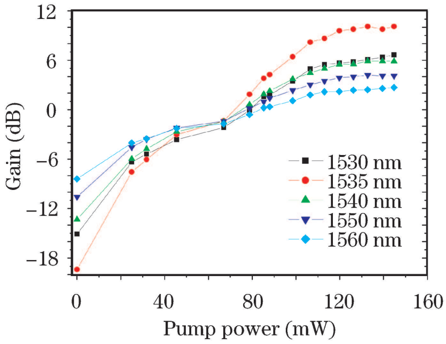

Fig. 1. Measured gain of 2.4-cm-long Er^{3+}/Yb^{3+} co-doped phosphate fiber.

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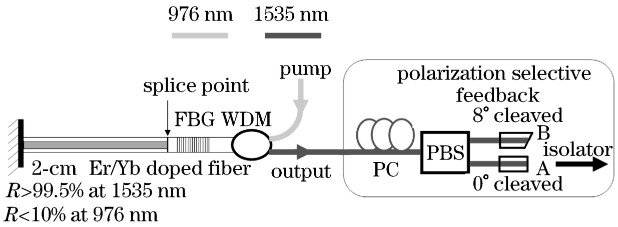

Fig. 2. Experimental setup of phosphate glass fiber laser.

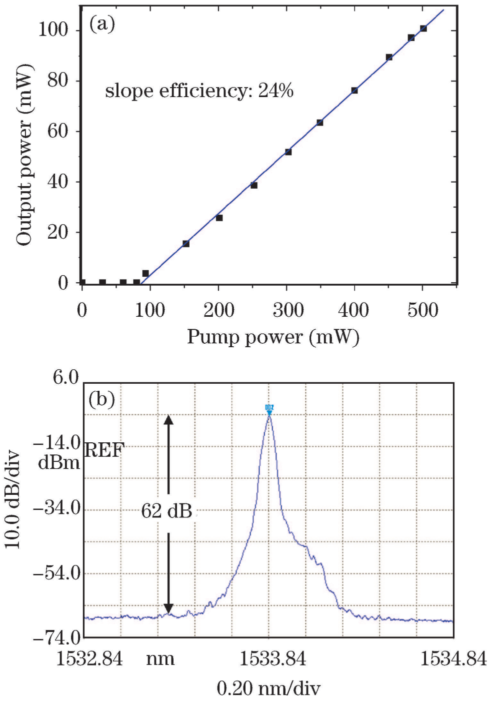

Fig. 3. (a) Output power as a function of pump power; (b) laser spectrum.

The experimental setup is shown in Fig. 2. The active fiber is a 2-cm-long phosphate fiber. The laser cavity is composed of a FBG with reflectivity of 60% at 1533.84 nm and bandwidth of 0.1 nm butt-spliced to the phosphate fiber and a mirror with reflectivity of >99.5% at 1535 nm. Taking the effective length of FBG into account, the whole cavity length is estimated to be about 2.8 cm. The measured output power versus pump power is given in Fig. 3(a). The lasing threshold is about 90 mW, and the maximum power reaches 100 mW for 500-mW pump power. As the curve in Fig. 3(a) shows no trend to saturate with the highest pump power, the fiber laser can achieve higher output power if higher pump power is available. The slope efficiency is 24%. Figure 3(b) shows the optical spectrum of the laser with resolution of 0.01 nm, showing a signal-to-noise ratio (SNR) of 62 dB.

The single longitudinal mode operation was verified by measuring beat signal between the fiber laser and TECL, as shown in Fig. 4, where the sinusoidal wave corresponds to the frequency modulating of the TECL with a ratio of 300 MHz/V. Two peaks can be observed in one modulating period at slightly different positions for downward and upward scanning due to the hysteresis of PZT used for frequency scanning in TECL. The TECL has the function of scanning frequency in a limited range of about 3.6 GHz and regulating the central wavelength with a resolution of 100 MHz. As the scanning range is less than the estimated mode spacing, the central wavelength is tuned during the scanning to demonstrate longitudinal mode characteristics. It is found that only one beat signal appears when tuning the central wavelength of TECL around the bandwidth of FBG, indicating the single longitudinal mode operation of our laser.

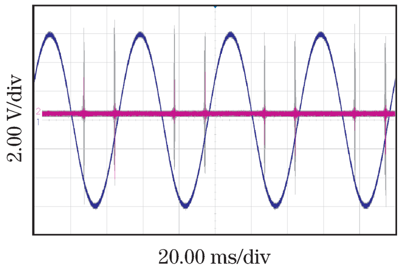

Fig. 4. Beat signal waveform between frequency modulated TECL and fiber laser.

The homodyne spectrum of the laser was measured using Mach-Zehnder interferometer with 30-km delay line. We get the homodyne full width of 90 kHz at 20 dB below the peak, as shown in Fig. 5(a), corresponding to full-width at half-maximum (FWHM) of 9 kHz. The laser linewidth is 4.5 kHz according to the homodyne theory that the actual laser linewidth is half of the FWHM in homodyne spectrum. However, we also observe the signal at 145 MHz, as shown in Fig. 5(b). It is considered as a beat signal of two light with 145-MHz deviation in frequency. As the frequency difference is much smaller than the mode spacing, it is feasible to consider that the laser is dual-polarization operation. The polarization extinction ratio (PER) is measured to be only 6 dB, implying that it is not a single linearly polarized operation. The nondegenerate operation of two polarizations may be considered as the result of small birefringence in the laser. The very small PER may be due to the FBG as it is very difficult to fabricate absolutely polarization-dependent-loss-free FBG.

To ensure the laser working in a single linearly polarized mode, a fiber PBS (New Focus) with an

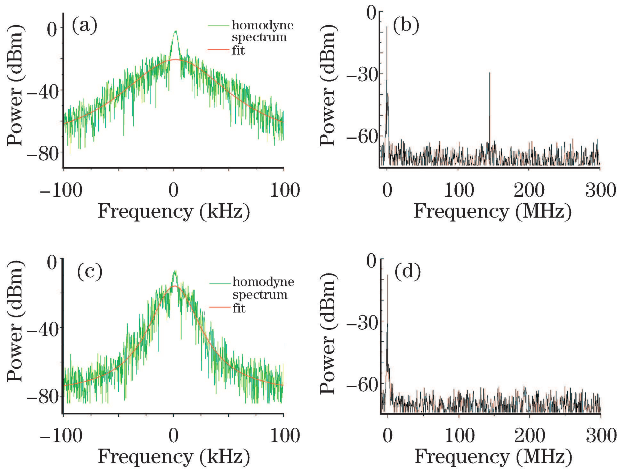

Fig. 5. Homodyne spectra of laser (a), (b) without and (c), (d) with polarization selective element at different scales.

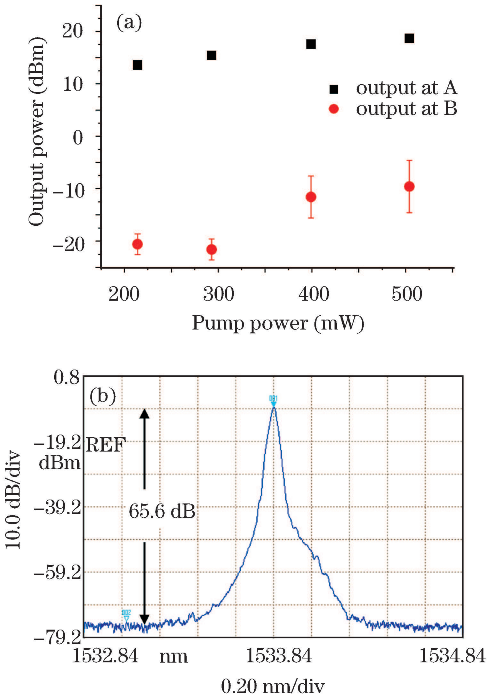

Fig. 6. (a) Output power from ports A and B of PBS when the highest contrast is obtained; (b) optical spectrum from port A.

extinction ratio of 20 dB was spliced to the output fiber port. The two output ports of PBS, A and B, were cleaved perpendicularly and angulately, respectively, to provide feedbacks with difference of ~4%, which is enough to ensure one polarization state lasing and suppress the other. The polarization controller (PC) was used to cancel the residual birefringence of the fiber between the FBG and PBS.

The designing idea is verified in our experiment. The measured output powers at ports A and B were found to be quite different. Since the slight feedback from A helps the corresponding polarization mode predominate in the gain competition, the output from A is much larger than that from B at any position of PC. The highest contrast was obtained after carefully adjusting the PC, as shown in Fig. 6(a). The contrast is larger than 23 dB for 500-mW pump power, showing single-polarization operation in the fiber laser. Owing to the mode matching loss in connection of the external feedback element, the slope efficiency declines to 18%. The homodyne −20-dB linewidth is improved to 40 kHz, corresponding to Lorentzian FWHM of 4 kHz and laser linewidth of 2 kHz, as shown in Fig. 5(c). Even though the 30-km delay line may be not long enough to avoid coherent effect in homodyne measurement, the laser linewidth is no more than 5 kHz. It is noticed by comparing Figs. 5(b) with (d) that the beat signal at 145 MHz disappears when the PBS is used. It is confirmed that the signal at 145 MHz is attributed to the beating of two polarization modes. The measured optical spectrum also shows improved SNR of 65 dB, as shown in Fig. 6(b). The experimental results indicate that the PBS not only plays a role of polarizer, but also provides a polarized feedback to enhance the oscillation of one polarization mode and weaken the other mode greatly.

In conclusion, we have demonstrated a compact phosphate fiber laser with 100-mW output power and investigated its polarization characteristics. By utilizing a polarization selective feedback element, single-polarization single-frequency operation is achieved with <5 kHz linewidth and 65-dB SNR. The experimental results indicate that the short cavity phosphate glass fiber laser is promising as a high power single-frequency, single-polarization laser, and has good foreground in variety of applications.

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