Front. Optoelectron. China 2009, 2(1): 81–85
DOI 10.1007/s12200-009-0003-2

RESEARCH ARTICLE

Short cavity single-frequency all-fiber Er/Yb co-doped laser

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Abstract A 5-cm-long Er/Yb co-doped all-fiber laser is studied. Two fiber Bragg gratings (FBGs) are written in the Er/Yb co-doped sensitive fiber using UV beams. A 980 nm pumping laser diode (LD) is used, and output wavelength is selected by two FBGs. The single-frequency laser is achieved at 1544.68 nm. The 3 dB spectrum width is 0.08 nm, while the side mode suppression ratio is 55 dB. The maximum output power exceeds 4 mW for pump power of 140 mW and the stability is less than ± 0.01 dB. Single-frequency operation is verified using a scanning Fabry-Perot (F-P) interferometer. Relative intensity noise is less than – 100 dB. A 10 Gbit/s code rate is used in the fiber laser transmission experiment. A good optical eye diagram is received after 21 km single-mode fiber transmission. A simple distributed Bragg reflection (DBR) fiber laser array is designed. The wavelength difference of output laser array is 0.8 nm, conforming to the ITU–T channel spacing standard of wavelength-division multiplexing systems.

Keywords optoelectronics and laser, Er/Yb co-doped fiber (EYDF), fiber laser, single-frequency, relative intensity noise

1 Introduction

Fiber lasers have been developed intensively over the last ten years. There is a high number of applications in optical communications systems, remote optical sensors, and spectroscopy [1–5]. Our main concern is their possible use as optical sources for wavelength-division multiplexing systems. The short resonant-cavity can produce narrow linewidth single-frequency lasers, which is an ideal source for wavelength-division multiplexing systems. In an Er/Yb-doped fiber, the pump energy is efficiently absorbed by the strong Yb^{3+} absorption over just a few centimeters. The Yb^{3+} ions can be pumped over a wavelength range extending from 800–1100 nm, whereupon energy transfer occurs to excite the erbium ions [6–10]. The incorporation of Yb^{3+} significantly increases laser stability against cluster-driven self-pulsation [11,12]. The distributed Bragg reflection (DBR) Er/Yb co-doped single-frequency fiber laser based on fiber Bragg gratings (FBGs) is simple and inexpensive, and the configuration of laser is conveniently integrated into a wavelength-division multiplexing all-optical network [13,14].

A single-frequency Er/Yb co-doped short cavity fiber laser is reported in this paper. The single-frequency operation is realized by using a 5 cm section of the Er/Yb co-doped fiber (EYDF) as a short cavity, and two FBGs are written in the Er/Yb co-doped fiber as the reflectors for depressing the cavity loss [2]. The laser output power exceeds 4 mW when pump power is 140 mW. The bandwidth of output laser was measured as 0.08 nm by 3 dB at 1544.68 nm, and the side mode suppression ratio is 55 dB. The single-frequency laser is verified by an interferometer. Relative intensity noise is less than – 100 dB. A 10-Gbit/s code rate is used in the fiber laser transmission experiment. The signal is transmitted in 21 km without regeneration. The eye diagrams of optical transmission are measured, showing perfect long-haul transmission with high-speed modulation.

2 Short cavity Er/Yb fiber laser set-up

The experimental configuration of the short cavity Er/Yb fiber laser array is shown in Fig. 1. For a narrow linewidth operation and single-mode laser, resonant-cavity is a section of 5 cm Er/Yb co-doped fiber. Two FBGs are written in the Er/Yb co-doped sensitive fiber by using a UV-excimer laser. The Er/Yb co-doped fiber is pumped by a 980 nm LD through a 980/1550 nm wavelength division multiplexer (WDM). The fiber laser is protected from

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Received November 21, 2007; accepted March 13, 2008

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reflections by optical isolators, and the isolation and return loss are more than 50 and 60 dB respectively. The reverse output can insure that no residual pump power contributed to the measurement. The other fiber end is terminated by small diameter turns and angle polishing. The WDM adopted aims to lessen the back reflection of 1550 nm light and enhance the stability of the fiber laser. All connections are either fusion spliced or use FC/APC connectors. An isolator is spliced into the 1550 nm arm of the WDM and used as the output port. All unconnected fiber end faces are immersed in index-matching gel to prevent the back reflection.

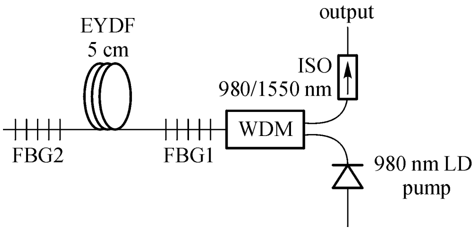


Fig. 1 Configuration of short cavity Er/Yb co-doped fiber laser

A significant improvement is the newly developed photosensitive Er/Yb co-doped fiber, which has a highly photosensitive B/Ge/Si annulus around the Er/Yb core. This eliminates the large splicing joint loss between the Er/Yb co-doped phosphosilicate fiber and the FBGs written in telecommunication fibers. It also reduces the cavity loss and makes the DBR fiber laser more efficient.

The 5-cm-long Er/Yb co-doped fiber used as gain medium has 1.200×10^{-3} of erbium ion concentration, with a numerical aperture of 0.14 and a cutoff wavelength of 1162 nm. It has a peak absorption coefficient of 29 dB/m at 1535 nm and 227 dB/m at 974 nm respectively. The background loss is 125 dB/km at 1550 nm.

A pair of FBGs are fabricated directly in the Er/Yb co-doped fiber. The jacket of the fiber is stripped off before UV exposure. The two gratings, one 10 mm long and the other 8 mm long, are both written with a 248 nm KrF excimer laser operating at 600 mJ/pulse and a repetition rate of 10 Hz for about 12 minutes. The separation distance between the two gratings is about 3 cm and the splice is connected to a Corning SMF-28 fiber.

The reflectivity of the FBGs is more than 90%, which reduces the laser cavity parasitic loss. The Bragg reflection wavelength and bandwidth are 1544.68 and 0.24 nm respectively. One of the FBGs produced a slightly lower reflectivity than that for the high output power of the fiber laser, which has a narrow bandwidth to provide sufficient lasing mode selection. The two FBGs have the same central reflected wavelength measured by an optical spectrum analyzer (Anritsu MS9710B), shown in Fig. 2. The Bragg wavelength is 1544.6 nm and the bandwidth is 0.32 nm.

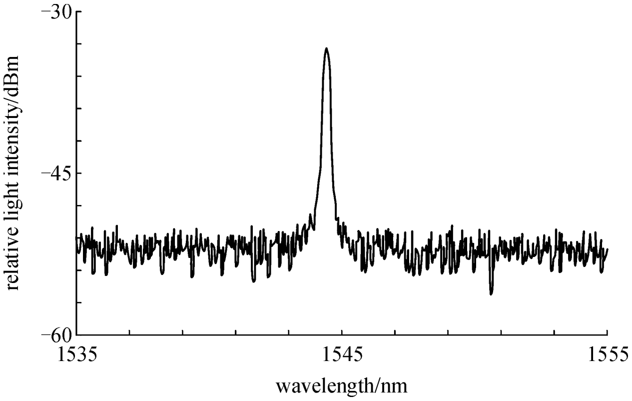


Fig. 2 Reflection spectra of FBGs

3 Experiment and analysis

From the laser spectrum shown in Fig. 3, the optical bandwidth of output laser is measured as 0.08 nm by 3 dB at 1544.68 nm (resolution adopted is 0.07 nm), and the side mode suppression ratio is more than 55 dB. The characteristics of output power of the fiber laser are measured with an optical power meter (NOYES OPM4) shown in Fig. 4. The output power exceeds 4 mW for pump power of 140 mW.

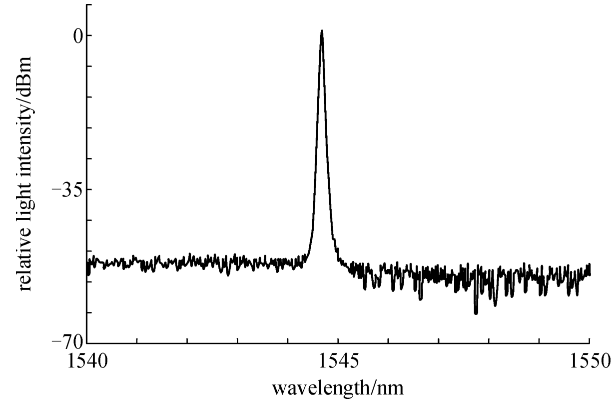


Fig. 3 Output spectrum of fiber laser

The length of the cavity is 5 cm, giving a longitudinal-mode spacing as narrow as 2 GHz. We verified a single-frequency operation by using the scanning Fabry-Perot interferometer with a 7.5 GHz free spectral range (FSR) and a finesse of 300. Figure 5 shows oscilloscope traces corresponding to one FSR and a single lasing longitudinal-mode (frequency) observed by a 200 MHz digital oscilloscope (Rigol DS5202CA, sampling 1 GSa/s). Only one frequency can be found each scanning period. The modes adjacent to the lasing mode are completely suppressed, but not robust.

The relative intensity noise of the short cavity fiber laser

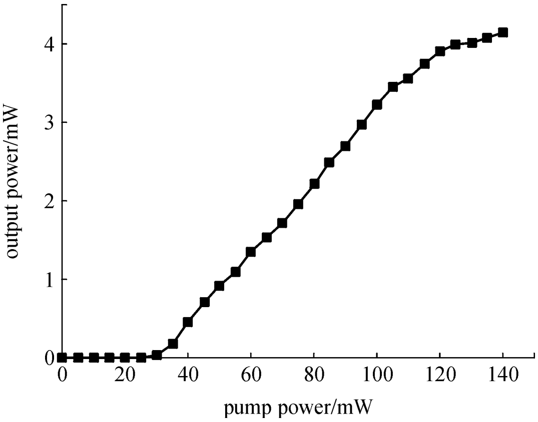


Fig. 4 Output power of fiber laser as a function of pump power

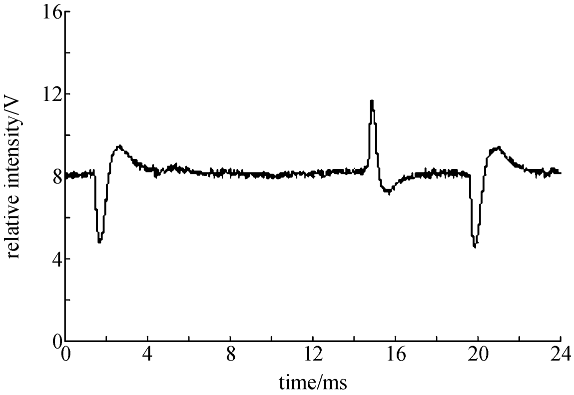


Fig. 5 Fabry-Perot interferometer scan of fiber laser output free spectral ranges of 7.5 GHz

is less than −100 dB, as shown in Fig. 6. The lower intensity noise can insure carrier frequency quality in communication.

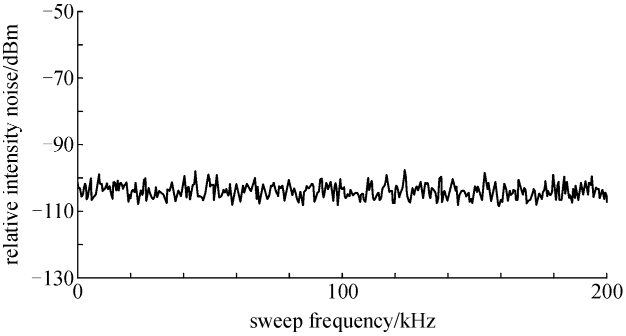
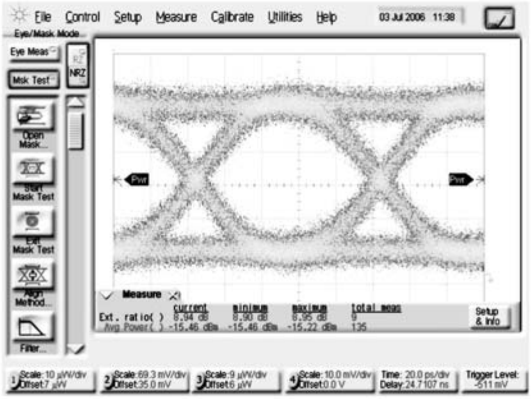


Fig. 6 Relative intensity noise of fiber laser

Eye diagram plot is a type of bit error ratio (BER) measurement, which shows points taken from a sampled version of the data. This plot graphically displays the 0s and 1s from the data and shows how efficiently the system can convert between them. Figure 7 shows the sending optical eye diagram of the fiber laser, while Fig. 8 shows the receiving optical eye diagram after a 21 km transmission. Sufficient and wide open 'eye' where no dots appear in the eye opening show good signal recovery.



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              current     minimum     maximum     total meas
Ext. ratio( )  8.94 dB     8.90 dB     8.95 dB     9
Avg Power( )  -15.46 dBm  -15.46 dBm  -15.22 dBm   135
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1 Scale: 10 µW/div   2 Scale: 69.3 mV/div  3 Scale: 9 µW/div   4 Scale: 10.0 mV/div  Time: 20.0 ps/div     Trigger Level:
  Offset: 7 µW         Offset: 35.0 mV       Offset: 6 µW        Offset: 0.0 V         Delay: 24.7107 ns     -511 mV
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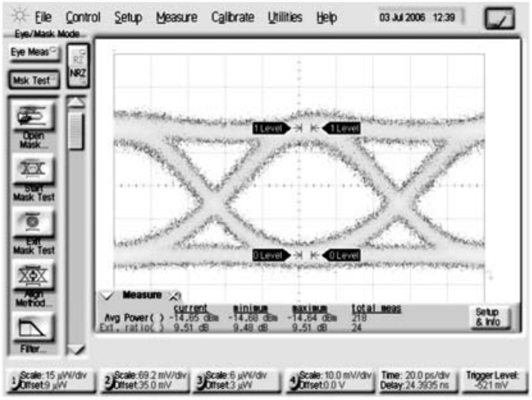
Fig. 7 Optical eye diagram of 10 Gbit/s signal



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              current     minimum     maximum     total meas
Avg Power( )  -14.65 dBm  -14.68 dBm  -14.64 dBm   218
Ext. ratio( )  9.51 dB     9.48 dB     9.51 dB     24
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1 Scale: 15 µW/div   2 Scale: 69.2 mV/div  3 Scale: 6 µW/div   4 Scale: 10.0 mV/div  Time: 20.0 ps/div     Trigger Level:
  Offset: 9 µW         Offset: 35.0 mV       Offset: 3 µW        Offset: 0.0 V         Delay: 24.3935 ns     -521 mV
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Fig. 8 Optical eye diagram of 10 Gbit/s signal transmitted by 21 km

4 DBR fiber laser array

On the basis of the previous short cavity fiber, a simple DBR fiber laser array has been designed, and the configuration is shown in Fig. 9. It used a wavelength-division multiplexing coupler at 1550 nm to connect the output port of two DBR fiber lasers, and an isolator is spliced to the common arm of the WDM and used as the output port.

Figure 10 shows the output spectrum of the fiber laser array measured by optical spectrum analysis (OSA). The wavelength difference of output laser array is 0.8 nm, conforming to the ITU–T channel spacing standard of wavelength-division multiplexing systems.

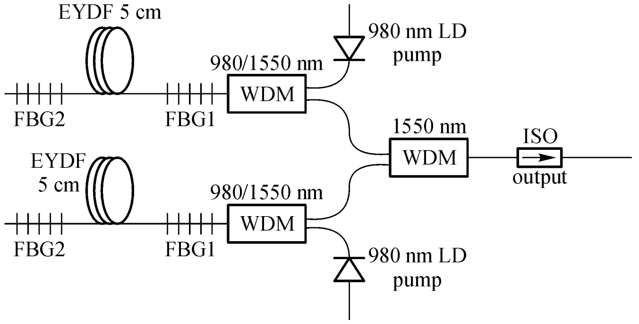

Fig. 9 Configuration of DBR fiber laser array

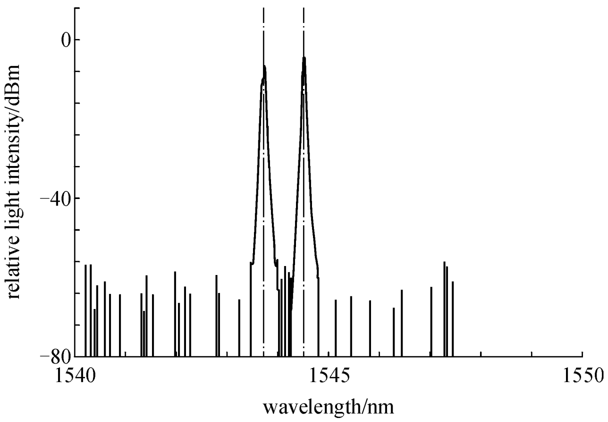

Fig. 10 Output spectrum of fiber laser array

5 Conclusion

A short cavity single-frequency Er/Yb co-doped all-fiber laser and a fiber laser array have been demonstrated. The single-frequency operation is realized by using a 5 cm section of Er/Yb co-doped as a short cavity. Two FBGs are written in the Er/Yb co-doped fiber. The output power exceeds 4 mW for pump power of 140 mW. The single-frequency is observed by an interferometer with FSR of 7.5 GHz. This laser has stable single-frequency operation at 1544.68 nm and side mode suppression ratio of 55 dB. Compared with similar studies at home and abroad [15–17], the performance of 10 Gbit/s fiber laser transmission experiment is perfect. The wavelength difference of laser array is 0.8 nm, conforming to the ITU–T channel spacing standard of wavelength-division multiplexing systems. Short cavity single-mode fiber lasers and laser arrays operating in 1.55 μm will be widely applied in future dense wavelength-division multiplexing (DWDM), coherent optical communications systems and distributed optical sensing systems [18–20].

Acknowledgements This work was supported by the Jilin Province Science and Technology Development Scheme (No. 20050525).

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