Narrow-linewidth single-polarization frequency-modulated Er-doped fiber ring laser

Pan Ou (欧　攀), Yudong Jia (贾豫东), Bin Cao (曹　彬),
Chunxi Zhang (张春熹), Shuling Hu (胡姝玲), and Di Feng (冯　迪)

School of Instrument Science and Opto-Electronics Engineering, Beihang University, Beijing 100083

Received January 4, 2008

We demonstrate a 1550-nm narrow-linewidth fiber ring laser with stable single polarization by using single-mode Er-doped fiber as active fiber and saturable absorber. A polarization-maintaining circulator is used to acquire single-polarization laser light with the degree of polarization of 99.8%—99.9%. The linewidth measured using a delayed self-heterodyne method is less than 0.5 kHz. Frequency of the fiber laser can be modulated by driving the waveguide phase modulator with proper voltage. A Mach-Zehnder interferometer with the optical path difference between two arms of about 36 km is used to study the long-distance coherent detection of the fiber laser for frequency-modulated continuous-wave application.

OCIS codes: 140.3510, 140.3500, 140.3560.
doi: 10.3788/COL20080611.0845.

Narrow-linewidth single-frequency laser, with its ultra-long coherent length or exceptional low phase noise, is of great importance in many applications. Optical sensing systems can take the advantage of the long coherent length to realize long-distance coherent detection. One example of coherent detection in optical sensing systems is the frequency-modulated continuous-wave (FMCW) technique[1,2]. It offers the possibilities of higher resolution, much higher sensitivity, and larger dynamic range, and is a powerful remote sensing technique for a variety of applications in both military and civilian markets[3].

A fiber laser using a trivalent rare-earth material as the active element has the potential for very narrow linewidth operation compared with other sources oscillating in the same spectral regions (e.g., semiconductor lasers). There are several efficient methods to generate single-frequency fiber laser with narrow linewidth[4−7]. Fiber ring laser using an un-pumped Er-doped fiber as the saturable absorber to form a narrow self-written filter is able to achieve high output power and maintain stable single-frequency operation with conventional concentrated Er-doped fiber[8−10].

The application of narrow-linewidth fiber lasers in coherent FMCW measurement is very attractive, because these lasers not only provide alternative highly coherent light sources, but also offer multiple wavelength regions at 1, 1.5, and 2 μm and many unique advantages over other solid-state lasers in terms of reliability, ruggedness, and compactness[11].

In this letter, we demonstrate a 1550-nm narrow-linewidth fiber ring laser which can stabilize both the polarization and longitudinal mode by using single-mode Er-doped fiber as active fiber and saturable absorber. We also study the frequency modulation of this fiber laser by using waveguide phase modulator and find its potential for long-distance coherent detection FMCW application.

A schematic diagram of the fiber laser is shown in Fig. 1. It is a traveling-wave fiber ring laser with a section of un-pumped Er-doped fiber acting as the saturable absorber to obtain single-frequency operation. The pump source is a 980-nm laser diode (LD) with the peak wavelength at 974.2 nm, which utilizes a double fiber Bragg grating (FBG) design for enhanced wavelength and power stability performance of the LD. The gain medium is a section of 4.8-m-long single-mode Er-doped fiber, whose peak absorption coefficient at 1530 nm is about 17.1 dB/m. The pump light is injected into one end of the gain fiber through a 980/1550 nm wavelength division multiplexer (WDM). An optical isolator, whose isolation ratio is 55 dB, is associated at the other end of the gain fiber to ensure traveling-wave operation of this section and filter out the residual pump light. A 50/50 single-mode coupler is used for the output of the fiber ring laser.

A polarization-maintaining (PM) circulator as a key component is applied to acquire stable and single polarization mode for the fiber laser. As we know that, if a PM active fiber is available, the polarization mode can easily be stabilized by the combination of all PM fiber components and a polarizer. This method may give an ideal solution, but there have been few experimental reports because PM active fibers are still special and very expensive[12]. Here the PM circulator has high isolation ratios as well as high extinction ratios at the corresponding ports. For example, the isolation ratios are 45 dB from port 2 to port 1 and 48 dB from port 3 to port 2;

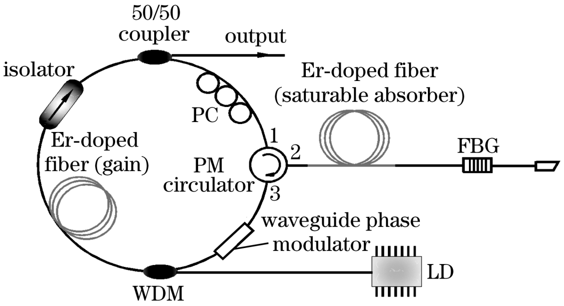

Fig. 1. Schematic diagram of the fiber ring laser.

the extinction ratios are 38 dB from port 1 to port 2 and 32 dB from port 2 to port3, respectively. As Zhou described, the introduction of a polarizer dramatically suppressed mode hopping and produced a linearly polarized output from the fiber ring laser[9], thus the fiber ring laser with the PM circulator should be more stable than that using a single-mode circulator and a polarizer. Firstly, the laser from port 2 of the PM circulator is highly polarized, which is beneficial to the stability of the un-pumped Er-doped fiber as saturable absorber to form a narrow self-written filter. Secondly, the laser from port 3 of the PM circulator is also highly polarized, which confirms the high polarization of the laser output at the 50/50 single-mode coupler. Finally, the special and very expensive PM Er-doped fiber is not needed.

In order to minimize the insertion loss of the fiber ring cavity, a polarization controller (PC) is directly located at one arm of the single-mode coupler, and the insertion loss between the PC and port 1 of the PM circulator is 0.1 dB. The optimal polarization coupling for a round-trip in the fiber ring laser can be obtained by adjusting the PC.

A section of 3.6-m-long un-pumped Er-doped fiber, which is the same type as the gain fiber, is placed between port 2 of the PM circulator and a 1550-nm FBG as a saturable absorber. The FBG has 99.7% reflectivity at 1550 nm and 3-dB bandwidth of 0.1 nm. It is used as a coarse wavelength-selective element to establish a standing wave in the un-pumped Er-doped fiber and thus form the narrow-band tracking filter at 1550 nm. The insertion loss between the FBG and the un-pumped Er-doped fiber is 0.02 dB.

A lithium niobate waveguide phase modulator is inserted between port 3 of the PM circulator and the WDM. This modulator comprises electro-optic material, so that the refractive index is varied according to the change of the voltage on the material inside modulator. The uniform and simultaneous change in refractive index modulates the frequency of the laser light produced within the laser cavity. In the experiment, when a modulation signal is introduced, the frequency of the output laser is modulated.

The total cavity length is approximately 29 m, corresponding to a longitudinal mode spacing of 7.1 MHz. The fiber laser cavity is placed in a styrofoam case, which is in a chamber with controlled temperature, to make the system less sensitive to environmental perturbation such as temperature, vibration, and noise.

In experiments, the pump LD is driven by ILX Lightwave LD controllers LDC-3744B, the light power is measured by ILX Lightwave fiber optic power meter FPM-8210H, and the degree of polarization (DOP) is measured by General Photonics DOP meter DOP-101. These instruments are controlled by a computer with LabVIEW program through general purpose interface board (GPIB) or serial interface.

We have written a LabVIEW controlling program. Under its control, LDC-3744B drives the pump LD to sweep with current increasing or decreasing at a step of 1 mA (corresponding to 0.55-mW pump power), and the data of output power measured by FPM-8210H are recorded by the program at the same time. Figure 2 shows the 1550-nm output power versus the pump power, in which the data recorded when the pump power is increasing or decreasing are given separately. We can find that when the pump power is increasing, the lasing threshold is 105 mW, and when the pump power is decreasing, the threshold is 47 mW. The critical output power at both thresholds is about 5.5 mW. This optical bistability between both threshouds is due to the saturable absorber effect of the un-pumped Er-doped fiber.

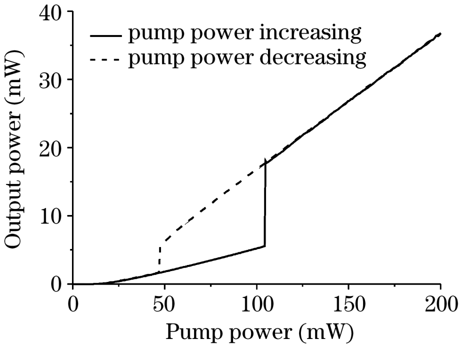

Fig. 2. Output power at 1550 nm versus pump power.

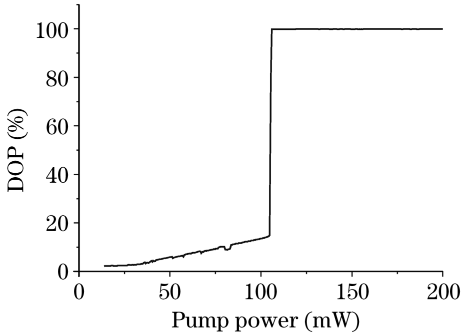

Fig. 3. DOP versus pump power.

Figure 3 shows the DOP of the fiber laser output versus the pump power when it is increasing. It is found that when the pump power is above the threshold, the DOP only varies in the range of 99.8%—99.9%. That means the fiber laser operates in single-polarization state and its DOP is very stable.

The emission spectrum of the fiber laser measured by the optical spectrum analyzer (OSA) is shown in Fig. 4. The signal-to-noise ratio (SNR) is determined by the amplified spontaneous emission (ASE) and is larger than 50 dB. The resolution of the OSA is limited to 0.01 nm, which is not enough to describe the performance of such

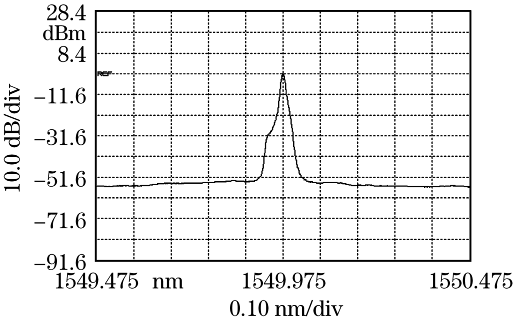

Fig. 4. Emission spectrum of the fiber ring laser.

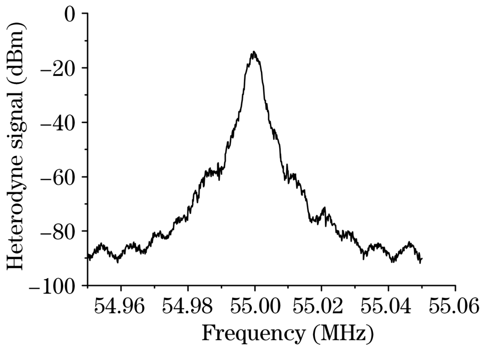

Fig. 5. Line shape of the self-heterodyne signal.

a narrow linewidth of the single-frequency fiber laser. We study the linewidth of the fiber laser using a delayed self-heterodyne method. Figure 5 shows the resulting line shape of the self-heterodyne signal when a delay of 25 km is used, which presents the interference fringes (beat notes) because the delay length is much shorter than coherence length of the fiber laser. In order to deduce an accurate measure for the linewidth of the laser from the experiment, we determine the full-width at half-maximum (FWHM) of the signal, which lies 20 dB below the signal maximum. A full width of 8 kHz in the heterodyne signal is observed, corresponding to a Lorentzian FWHM of the laser linewidth of only 400 Hz. These data suggest a linewidth of less than 0.5 kHz.

For the sake of long-distance coherent detection of the fiber laser for FMCW applications, a Mach-Zehnder interferometer whose optical path difference between two arms is about 36 km has been used. Three types of waveforms, sawtooth-wave, triangular-wave, and sinusoidal-wave, with a frequency of 1 kHz are applied to the waveguide phase modulator. Figure 6 shows the beat signals produced by the FMCW interferometer with sawtooth-wave frequency modulation signals. These beat signals agree with the theoretical analysis of Zheng[1]. As the waveguide phase modulator has a wider bandwidth than piezoelectric transducer (PZT) actuator, the narrow-linewidth single-polarization Er-doped fiber ring laser using waveguide phase modulator has a number of FMCW applications for long-distance coherent detection.

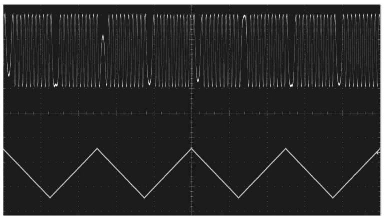

Fig. 6. Waveform of the beat signals (upper) from the FMCW Mach-Zehnder interferometer with sawtooth-wave frequency modulation signals (lower).

In summary, we have proposed and demonstrated a 1550-nm frequency-modulated narrow-linewidth fiber ring laser which can stabilize both the polarization and longitudinal modes by using single-mode Er-doped fiber. The fiber laser contains a PM circulator and a waveguide phase modulator that are used to acquire single-polarization light and modulate frequency of the fiber laser respectively. When the frequency-modulated fiber laser is applied to a Mach-Zehnder interferometer, we observe the beat signals. This frequency-modulated narrow-linewidth single-polarization Er-doped fiber ring laser enables a number of FMCW applications for long distance coherent detection.

P. Ou's e-mail address is oupan23@gmail.com.

References

1. J. Zheng, Appl. Opt. **43**, 4189 (2004).
2. J. Zheng, Appl. Opt. **45,** 2723 (2006).
3. C. J. Karlsson, F. Å. A. Olsson, D. Letalick, and M. Harris, Appl. Opt. **39,** 3716 (2000).
4. G. A. Ball, W. W. Morey, and W. H. Glenn, IEEE Photon. Technol. Lett. **3,** 613 (1991).
5. J. L. Zyskind, V. Mizrahi, D. J. DiGiovanni, and J. W. Sulhoff, Electron. Lett. **28,** 1385 (1992).
6. C. Spiegelberg, J. Geng, Y. Hu, Y. Kaneda, S. Jiang, and N. Peyghambarian, J. Lightwave Technol. **22,** 57 (2004).
7. C. Lü, Z. Wang, B. Yun, and Y. Cui, Chin. Opt. Lett. **3,** 212 (2005).
8. Y. Cheng, J. T. Kringlebotn, W. H. Loh, R. I. Laming, and D. N. Payne, Opt. Lett. **20,** 875 (1995).
9. Z. Meng, G. Stewart, and G. Whitenett, J. Lightwave Technol. **24,** 2179 (2006).
10. J. Yang, R. Qu, G. Sun, J. Geng, H. Cai, and Z. Fang, Chin. Opt. Lett. **4,** 410 (2006).
11. J. Geng, C. Spiegelberg, and S. Jiang, in *Proceedings of 2005 Quantum Electronics and Laser Science Conference* 1983 (2005).
12. R. Zhang, B. Yu, Z. Cao, S. Zhen, J. Zhu, and R. Liu, Opt. Commun. **274,** 392 (2007).