Broad-Band Wavelength-Tunable, Single Frequency, and Single Polarization Bismuth Oxide-Based Erbium-Doped Fiber Laser

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***Abstract*—We demonstrate a broad-band wavelength-tunable Bismuth Oxide-based Erbium-doped fiber (Bi-EDF) laser covering both the conventional wavelength band and the long wavelength band. It features single frequency and single polarization oscillation; the former is obtained by making the cavity length short and incorporating an intracavity narrow-band fiber Fabry–Pérot filter, and the latter is achieved with a sigma laser configuration using nonpolarization maintaining fibers. Tuning over 90 nm (1520–1610 nm) is achieved by utilizing the broad gain bandwidth of Bi-EDF amplifier.**

***Index Terms*—Continuous-wave lasers, laser resonators, laser tuning, optical fiber lasers, rare-earth materials.**

I. INTRODUCTION

A BROAD-BAND wavelength-tunable single frequency light source is important for several applications in photonic networks and optical sensing systems. Due to their narrow linewidths and inherent compatibility with optical fiber communication systems, Erbium-doped fiber lasers have received considerable attention. However, the realization of stable single frequency oscillation in fiber lasers is difficult. The long length of the laser cavity easily induces multimode oscillation and mode hopping unless we stringently select a longitudinal mode by using a narrow bandwidth optical filter [1], [2]. Additionally, birefringence of the laser cavity can also cause mode hopping between the two eigenstates of polarization unless only one eigenstate of polarization is selected [3]. Another important issue for fiber lasers is the range of wavelength tunability. The wavelength tunability of a conventional silica-based Erbium-doped fiber laser is normally limited to the conventional wavelength band (C-band) by the gain bandwidth of the active fiber. By careful optimization of the active fiber length, pump powers, and the laser cavity loss, the wavelength tunability has been extended to the long wavelength band (L-band) [4].

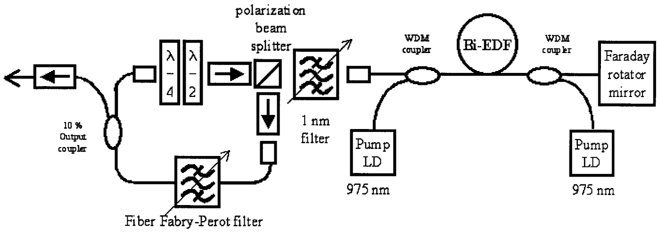

Fig. 1. Configuration of a broad-band wavelength-tunable, single frequency, and single polarization Bi-EDF laser.

In this letter, we report operation of a broad-band wavelength-tunable single frequency fiber laser covering both the C-band and the L-band using a 22.7-cm-long Bismuth Oxide-based Erbium-doped fiber (Bi-EDF) amplifier [5]–[7]. Because the Bi-EDF has a wide gain bandwidth that covers both the C-band and L-band, 90-nm continuous wavelength tunability is demonstrated. The short length of the Bi-EDF enables us to obtain single frequency oscillation. By combining these properties with a sigma configuration for single polarization oscillation, even with nonpolarization-maintaining fibers, we achieve stable single-frequency single-polarization operation with broad-band wavelength tunability.

II. LASER CAVITY DESIGN

Fig. 1 shows the experimental setup of the broad-band wavelength-tunable, single-frequency, and single-polarization fiber laser. To achieve wide wavelength tunability, a 22.7-cm-long Bi-EDF (type T2M) was used as the gain medium [5]–[7]. The Erbium concentration was 6470 wt. ppm. The refractive index of the core was 2.03, and that of the cladding, 2.02 at 1550 nm. The peak absorption at 975 nm was 127 dB/m. Both ends of the Bi-EDF were fusion spliced to SiO_2 fibers. The insertion of the Bi-EDF was 0.90 dB at 1560 nm, which includes the background passive loss of 0.16 dB and the splicing losses of 0.74 dB [5]. The Bi-EDF was bidirectionally pumped with two 975-nm diodes. The power of each pump laser was set to 250 mW, so that the total pump power was 500 mW. The typical power conversion efficiency of the Bi-EDF was around 19% [5].

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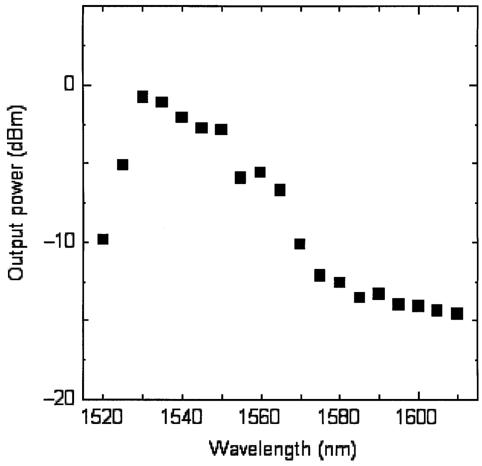

Fig. 2. Output power versus lasing wavelength.

In order to achieve single frequency oscillation along with the wide wavelength tunability, we used two optical filters inside the laser cavity. One was a fiber Fabry–Pérot (FFP) tunable filter (Micron Optics FFP-TF) which was used to select only one longitudinal mode [1], [2]. The FFP filter has a free spectral range of 10.75 GHz, a finesse of 114, and a bandwidth of 0.09 GHz. With the short length of the Bi-EDF, the total cavity length was about 1.8 m and the corresponding longitudinal-mode spacing was 106 MHz. The narrow FFP filter bandwidth limits oscillation to only one longitudinal mode. A second tunable bandpass filter with bandwidth of 1.0 nm was used for coarse tuning of the center wavelength. Although there were nominally 12 Fabry–Pérot modes of the FFP within this filter's bandwidth, the curvature of the filter and the multipass nature of the oscillation selected only one Fabry–Pérot mode. Thus, we achieved single frequency oscillation with broad-band wavelength tunability.

In order to obtain oscillation in a single polarization and suppress polarization mode competition, the laser cavity was a sigma configuration [8]. A Faraday rotator mirror at the end of the linear part of the sigma cavity ensures that the state of polarization of the reflected light is orthogonal to that of the incoming light. Orthogonality between the counter-propagating waves in the Bi-EDF is maintained independent of the birefringence of the active fiber. In the ring part of the sigma cavity, polarization-dependent isolators were used at both ends of the FFP filter. These prevented spurious modes induced by reflection from the FFP filter and ensured unidirectional propagation inside the ring part of the cavity. Thus, the single polarization oscillation was achieved even with nonpolarization maintaining fibers.

III. Experiments and Discussions

Fig. 2 shows the output power versus the center wavelength of the laser. A wavelength tuning of 90 nm from 1520 to 1610 nm was obtained because of the wide gain bandwidth of the Bi-EDF. The wavelength dependence of the output power was caused by the gain characteristics of the Bi-EDF [5]–[7]. Fig. 3(a)–(c) shows the optical spectra at 1520, 1550, and 1600 nm, respectively. They were measured using an optical spectrum analyzer with 0.01-nm resolution. These results show that the laser oscillated within only one Fabry–Pérot mode out of the 12 Fabry–Pérot modes in the optical bandpass filter bandwidth. However, the single frequency oscillation could not be confirmed by these results because of the measurement resolution.

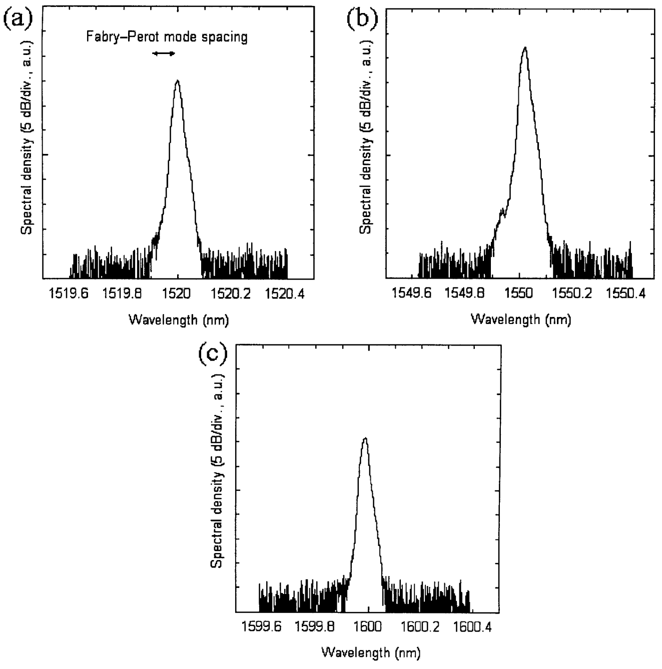

Fig. 3. Optical spectra measured by an optical spectrum analyzer when the center wavelengths were (a) 1520, (b) 1550, and (c) 1600 nm. Resolution bandwidth was 0.01 nm.

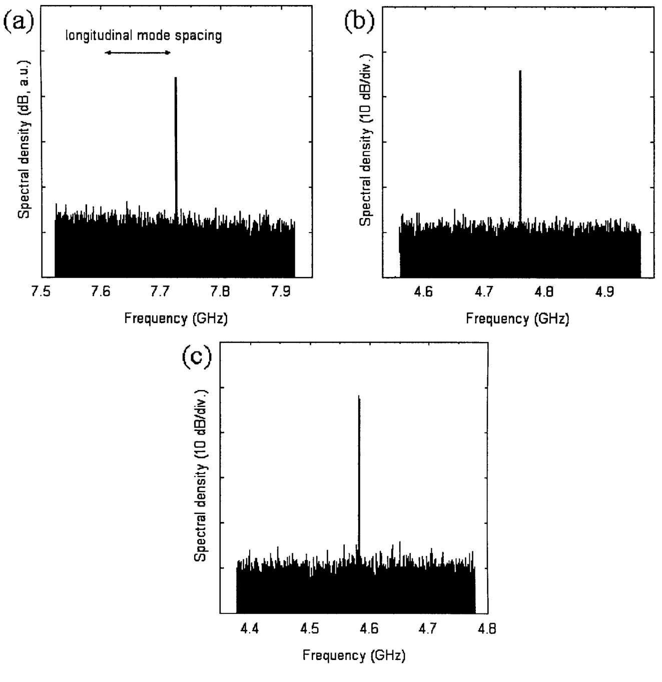

Fig. 4. Optical spectra measured by heterodyne detection when the center wavelengths were (a) 1520, (b) 1550, and (c) 1600 nm. The linewidth of the local oscillator was 290 kHz.

In order to confirm the single frequency operation, we also measured the laser spectrum measurement with much higher resolution using an optical heterodyne receiver. The laser output

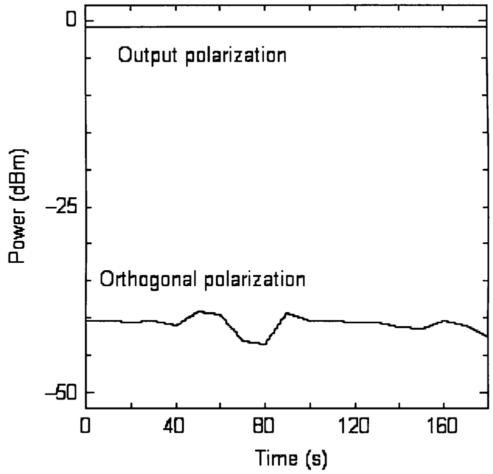

Fig. 5. Measured power variations of the laser output after the polarizer.

was combined with a wavelength-tunable local oscillator and the beat spectrum was observed with a photodetector and a spectrum analyzer. The linewidth of the local oscillator was 290 kHz. Therefore, the resolution of the measurements was much less than the longitudinal mode spacing. Fig. 4(a)–(c) shows the beat spectra for the center wavelengths of 1520, 1550, and 1600 nm, respectively. Because there were no other longitudinal modes observed, these results show that the laser was in single longitudinal-mode oscillation. Considering the linewidth of the local oscillator, the inherent linewidth of the laser was less than 290 kHz. For long term stability against mode hopping it is possible to use active mode stabilization to compensate for temperature drifts and/or vibrations [9].

Single polarization operation was confirmed by monitoring the output with a polarizer over a period of time. There was only one polarizer angle that maximized the power. Fig. 5 shows the measured output powers versus time after the polarizer, oriented first for maximum transmission and then for the orthogonal polarization state. This figure shows that the laser operated in a single polarization and was polarization stable.

IV. CONCLUSION

We have demonstrated a broad-band wavelength-tunable, single frequency, and single polarization Bi-EDF laser. The recently developed Bi-EDF makes possible broad-band wavelength tunability. A 90-nm wavelength tuning from 1520 nm to 1610 nm covering both the C-band and the L-band was obtained by utilizing the large gain bandwidth of the Bi-EDF. The short length of the Bi-EDF made it easier to obtain single frequency oscillation. By combining these attributes with the polarization stabilization provided by a sigma configuration, even with nonpolarization-maintaining fibers, we realized single frequency and single polarization operation of the laser along with broad-band wavelength tunability.

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