Multiwavelength Erbium-Doped Fiber Ring Laser Incorporating an SOA-Based Phase Modulator

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***Abstract*—A novel room-temperature multiwavelength erbium-doped fiber (EDF) laser is demonstrated. Stable multiwavelength lasing at room temperature is realized by incorporating a semiconductor optical amplifier (SOA)-based phase modulator in the laser cavity. The SOA is biased below the transparent point with a sinusoidal signal applied to achieve phase modulation, to suppress the homogenous line broadening of the EDF. Stable multiwavelength lasing with wavelengths up to 26 and wavelength spacing as small as 0.19 nm is demonstrated at room temperature.**

***Index Terms*—Erbium-doped fiber (EDF), multiwavelength fiber laser, phase modulation, semiconductor optical amplifiers (SOAs).**

I. Introduction

ONE OF the main challenges for erbium-doped fiber (EDF) lasers is to achieve stable multiwavelength lasing with small wavelength spacing at room temperature. The main obstacle preventing us from achieving this goal is the homogeneous line broadening of the EDF at room temperature, which leads to cross-gain saturation and wavelength competition. One direct solution to this problem is to cool the EDF in liquid nitrogen (77 K) to suppress the homogenous line broadening [1], [2], but the technique is not suitable for practical applications because of the complexity and bulkiness of the system. Another solution to this problem is to incorporate inhomogeneous gain medium in the laser cavity, such as semiconductor optical amplifier (SOA) [3], [4], but at the cost of higher noise figure. Recently, a multiwavelength fiber ring laser operating at room temperature was reported by Bellmare *et al.* [5], in which a stable multiwavelength operation was realized by incorporating an acoustooptic frequency shifter in the ring cavity. The effect corresponds to a reduction of homogeneous line broadening. However, the acoustooptic frequency shifter has a high insertion loss. Another approach was recently proposed by Zhou *et al.* [6]; instead of using an acoustooptic frequency shifter, an electrooptic $LiNbO_3$ phase modulator or an all-fiber phase modulator is employed. Multiwavelength lasing at room temperature was demonstrated when the phase modulator was driven by a sinusoidal signal. A major drawback of the technique using an electrooptic phase modulator is that the sinusoidal signal applied to the phase modulator should have a high drive voltage, which could be much smaller by using an all-fiber phase modulator. However, an all-fiber phase modulator based on a piezo-transducer not only has a large size, but also has a long laser cavity length. In addition, the extra tension applied to the fiber would also reduce its life time.

In this letter, we propose a novel multiwavelength EDF ring laser that allows stable multiwavelength lasing at room temperature by using an SOA-based phase modulator in the laser cavity. The SOA is biased below the transparent point with a low-voltage sinusoidal modulation signal applied to generate phase modulation. The homogenous line broadening of the EDF in the laser cavity is significantly suppressed. In the proposed configuration, multiwavelength selection is performed using a Lyot–Sagnac loop consisting of two sections of polarization-maintaining fiber. Stable multiwavelength lasing with multiwavelengths up to 26 and wavelength spacing as small as 0.19 nm is demonstrated at room temperature. The effects of various phase modulation parameters on the performance of the multiwavelength laser are also experimentally investigated.

II. Experimental Setup

It is known that any small perturbation in the laser cavity will result in the energy distribution change of the laser modes [7]. In an EDF-based ring laser, different wavelengths experience different net gain, depending on the polarization state and the wavelength. Because of homogeneous line broadening of EDF, the fiber laser using EDF as gain medium suffers from a strong competition among the wavelengths, which makes it impossible to generate stable multiwavelengths at room temperature.

By solving the rate equation, one nontrivial stable solution can be obtained [8]. However, due to the change of energy distribution over the lasing wavelengths which is resulted from homogeneous line broadening, the oscillation wavelengths are competing to be the dominant over others. An SOA-based phase modulator incorporated in the laser cavity acts as an optical cavity buffer, producing elastic compression and expansion of the cavity length. Assuming that the phase modulation provided by the SOA is $\phi_m(t)$ at a modulation frequency ω_m, the cavity length will be shifted by $\phi_m(t)/\beta$ at the frequency ω_m, where β is the propagation constant of light in the fiber. When the rate of the cavity length shift is comparable with the relaxation time of the laser, none of oscillation mode will be temporarily dominant over others; a stable simultaneous multiwavelength lasing at room temperature is possible.

The SOA-based phase modulator offers the possibility of the optoelectronic integration on InP, requiring a much lower modulation power than that for $LiNbO_3$ phase modulator in order to obtain the same phase shift. Theoretical analysis of phase shift induced by a low-frequency signal applied to an SOA-based phase modulator and a conventional $LiNbO_3$ phase modulator reveals that the phase shift effect in the SOA is much stronger

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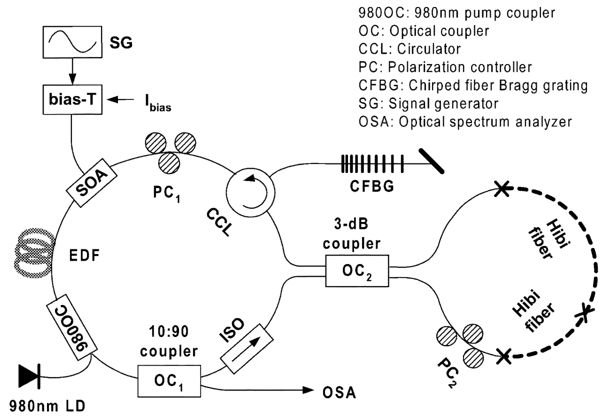

Fig. 1. Configuration of the multiwavelength EDF laser.

than that in the $LiNbO_3$ phase modulator [9]. Therefore, the performance of the fiber laser using an SOA-based phase modulator in terms of multiwavelength stability, wavelength spacing, and number of wavelengths is much better than using a $LiNbO_3$ phase modulator. A detailed theoretical analysis is beyond the scope of this letter and will be reported elsewhere [9].

The configuration of the proposed multiwavelength EDF laser is shown in Fig. 1. In the laser cavity, a length of 20-m EDF pumped by a 980-nm pump laser is used as the gain medium. An SOA-based phase modulator is incorporated in the laser cavity to suppress the homogeneous line broadening. The SOA is driven by a low-frequency sinusoidal signal with a bias just below the transparent point. The input light polarization state to the SOA is adjusted by a polarization controller (PC1).

The wavelength selection in the configuration is achieved by a Lyot-Sagnac loop serving as a multibandpass optical filter. The Lyot-Sagnac loop consists of two sections of high birefringence (HiBi) fibers, a 3-dB coupler, and a polarization controller. The polarization controller (PC2) is used to adjust the polarization state of the Lyot–Sagnac loop. The input light to the 3-dB coupler (OC_2) is split into two counterpropagating waves. Each wave is decomposed into 2^2 waves after traveling through the HiBi fibers. Depending on the phase difference, the birefringence, the length of fibers, and the polarization state of the polarization controller, different interference pattern could be obtained at the output port of the Lyot–Sagnac filter. The transmission function of the Lyot–Sagnac loop filter can be derived using Jones matrix [10]. In the experiment, the HiBi fibers are Corning HiBi fiber with $B = 4.0 \times 10^{-4}, L_1 = 8.75$ m and $L_2 = 22.25$ m. The overall cavity length of the fiber laser is about 64.5 m, with a round-trip frequency of 3.18 MHz.

A chirped fiber Bragg grating (CFBG) combined with a circulator is used as a bandpass filter to limit the wavelength range of the band-unlimited Lyot–Sagnac loop filter. The CFBG has a linearly increased period from 537.71 to 540.35 nm and a full-width at half-maximum of 7.8 nm at 1559.9 nm. The total loss of the CFBG and the circulator is 4 dB at 1560 nm.

The SOA-based phase modulator is a GaInAs buried heterostructure commercial amplifier with a cavity length of 500–600 μm. A dc bias and a sinusoidal signal from a function generator are applied to the SOA modulator via a bias tee. The SOA exhibits a transparent current of $\sim$110 mA and a 3-dB bandwidth of 75 nm around 1550 nm. When the bias current is 86 mA, which is below the transparent current, the SOA has

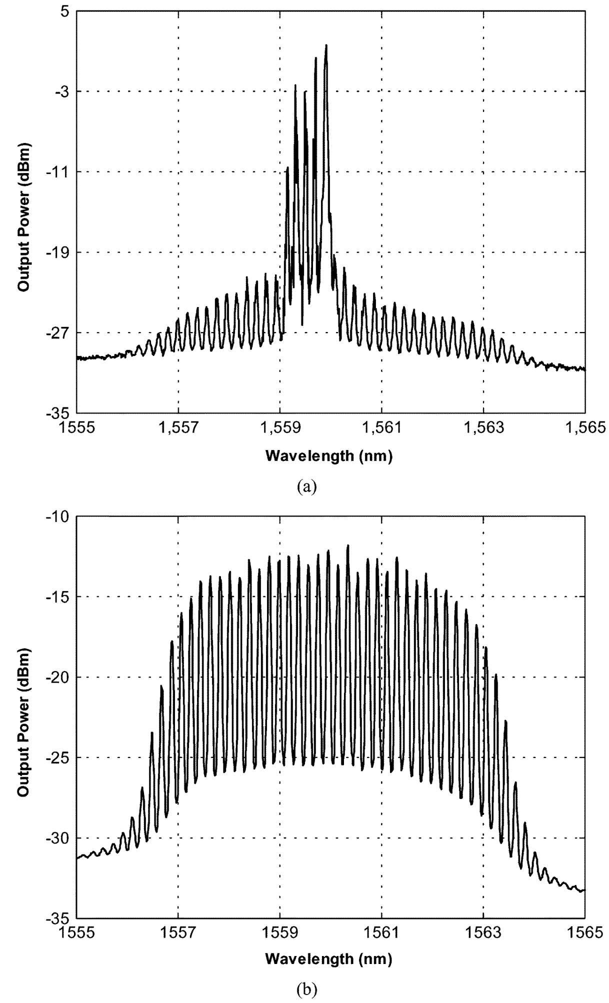

Fig. 2. Output spectrum of the fiber laser. (a) SOA biased at 86 mA without a sinusoidal modulation signal applied. (b) SOA biased at 86 mA with a 25-mV 30-kHz sinusoidal modulation signal applied.

an absorption loss of about 2 dB. As shown in Fig. 2(a), very few wavelengths can be generated if no sinusoidal modulation signal is applied to the SOA, because of the strong competition among the wavelengths caused by the EDF homogenous line broadening. In this situation, the SOA simply acts as a linear passive component.

III. Results and Discussions

By applying a 25-mV 30-kHz sinusoidal signal to the SOA while keeping the same bias current at 86 mA, the SOA acts as a phase modulator and the homogenous line broadening of the EDF is effectively suppressed. As can be seen from Fig. 2(b), multiwavelength lasing with up to 26 wavelengths at room temperature is achieved. The total output power is 6.3 dBm, which can be further increased if an additional EDF amplifier is incorporated in the laser cavity to compensate for the insertion loss caused by the passive component [3]. The 3-dB linewidth is measured to be 0.05 nm with an identical wavelength spacing of 0.19 nm. The wavelength spacing can be changed by adjusting the polarization controller PC2 in the laser cavity. The stability of the multiwavelength operation is also investigated. As can be seen from Fig. 3, no significant variations in the amplitudes

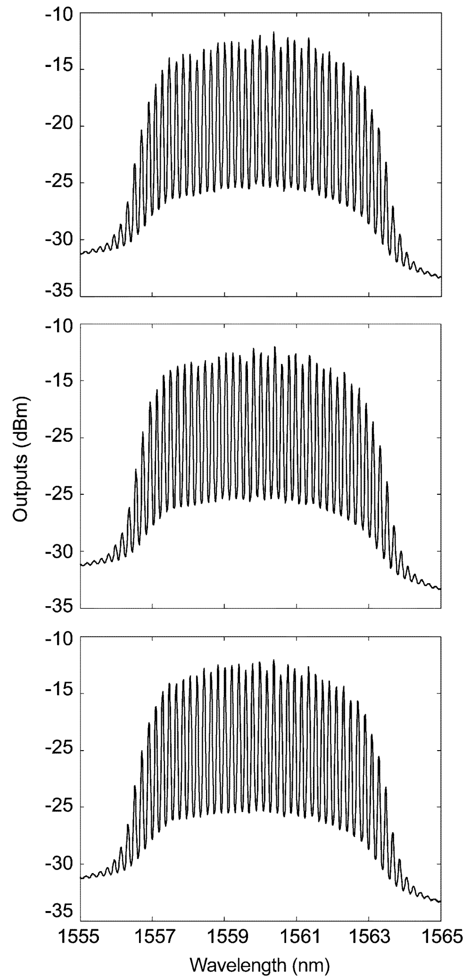

Fig. 3. Output spectra of the fiber laser taken at 10-min interval.

of the multiwavelengths are observed when three measurements are taken at a 10-min interval.

The effects of the SOA bias current, modulation frequency, modulation voltage, and modulation wave type on the performance of the multiwavelength laser are also investigated. During the experiment, when the SOA is driven by a constant current below the transparent point ($\sim$110 mA), the SOA acts as a passive component with certain absorption determined by the bias current. When a bias current is lower than 40 mA, the lasing cannot be started because the high absorption of the SOA leads to a net gain below the threshold in the laser cavity. When the dc bias current is from 40 to 100 mA, multiwavelength lasing can be achieved by applying a low-frequency sinusoidal modulation signal, ranging from 20 to 300 kHz, which also verifies that the modulation applied to the SOA is not performing a mode-locking operation, since the modulation frequency is not the multiples of the round-trip frequency of the laser cavity. Moreover, it is found that to maintain the same optical signal-to-noise ratio (OSNR), for a higher modulation frequency, a higher modulation voltage is required. For instance, with an identical OSNR of 20 dB, the modulation voltage for a modulation frequency of 20 kHz is 10 mV, while it is 622 mV for a modulation frequency of 200 kHz.

In terms of the types of modulation signal used, it is found that the multiwavelength lasing can be achieved by applying not only a sinusoidal or a sawtooth signal, but also a square-wave signal, which is impossible in the fiber laser using an optoelectronic phase modulator [4]. This also proves that the use of an SOA is more effective in the suppression of the homogenous line broadening than a $LiNbO_3$ phase modulator. To further confirm the above conclusion, the SOA in the laser cavity is replaced by a JDS Uniphase 10-GHz $LiNbO_3$ phase modulator. It is found that only a few wavelengths (3–4) can be generated. In the experiment, the $LiNbO_3$ phase modulator is driven by a 12-V sinusoidal signal with a modulation frequency 25–30 kHz. Note that the modulation voltage is much higher than that for the SOA-based phase modulator (only several tens of mV), and the modulation frequency range is also much narrower than that for the SOA (20–300 kHz). Moreover, it is found that the peak power at all lasing wavelengths fluctuates, which indicates that the stability of the multiwavelength operation with the $LiNbO_3$ phase modulator is worse than that with the SOA. The results conclude that the frequency shift introduced by the SOA modulator is more effective than that by the $LiNbO_3$ phase modulator.

IV. Conclusion

We have proposed and demonstrated a stable room-temperature multiwavelength fiber ring laser using an SOA-base phase modulator to suppress the homogeneous line broadening. Stable multiwavelength lasing with multiple wavelengths up to 26 and wavelength spacing as small as 0.19 nm at room temperature was demonstrated. The effects of the modulation voltage, frequency, and modulation signal type on the performance of the multiwavelength laser were also investigated. The experiments showed that the SOA-based phase modulator was more effective than the $LiNbO_3$ phase modulator in suppressing the homogeneous line broadening.

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