

Multiwavelength erbium-doped fiber laser employing a nonlinear optical loop mirror

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Abstract

A stable and broad bandwidth multiwavelength erbium-doped fiber laser is proposed and demonstrated successfully. A nonlinear optical loop mirror which induces wavelength-dependent cavity loss and behaves as an amplitude equalizer is employed to ensure stable room-temperature multiwavelength operation. Up to 50 wavelengths lasing oscillations with wavelength spacing of 0.8 nm within a 3-dB spectral range of 1562–1605 nm has been achieved. The measured power fluctuation of each wavelength is about 0.1 dB within a 2-h period.

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1. Introduction

Multiwavelength erbium-doped fiber lasers (EDFLs) attract a lot of interest due to their potential applications in dense wavelength-division-multiplexed (DWDM) fiber communication systems. Important features of multiwavelength sources for DWDM applications include large channel-count, uniform output power, small power fluctuation, and precise and stable wavelength spacing that complies with the ITU-wavelength grid. Multiwavelength sources also find applications in fiber sensors and optical instrumentations. Since erbium-doped fiber (EDF) is a gain medium with homogeneous broadening, the existence of gain saturation causes mode competition between different wavelengths, and it is difficult to achieve stable multi-wavelength oscillations in EDFs at room temperature. In

order to reduce the cross-gain saturation and suppress the mode competition, different techniques have been proposed to realize multiwavelength oscillations at room temperature in EDFs. These include the introduction of polarization hole burning (PHB) effect [1–5], and various nonlinear effects such as four-wave mixing in photonic crystal fiber [6–9] and stimulated Brillouin scattering [10,11], in the laser cavity. Other methods by inserting frequency shifter in the laser cavity [12–15], incorporating a section of multimode fiber [16,17] or a multimode FBG [18] in a laser cavity, and employing specially designed erbium-doped fibers [19,20] or cavity structures [21,22] were also reported.

Nonlinear optical loop mirrors (NOLM) have been used as fast saturable absorbers to passively mode-lock laser oscillators and to reshape optical pulses [23,24]. In this letter, a NOLM is used as an amplitude equalizer to induce intensity-dependent loss (IDL) and alleviates the mode competition caused by homogeneous gain broadening in EDF. This technique is quite effectively and a multiwavelength laser source with stable and uniform output of up

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to 50 wavelengths with a spacing of 0.8 nm anchored on the ITU wavelength grid has been achieved.

2. Experimental setup and principle

The configuration of the proposed laser is shown in Fig. 1. It is composed of a NOLM and an amplifying unidirectional loop. The amplifying unidirectional loop consisted of a commercial high power erbium-doped fiber amplifier (EDFA), a Fabry–Pérot (F–P) thin-film filter, a polarization controller (PC) and an output coupler with a splitting ratio of 1:9. The EDFA (Amonics AEDFA-27-B) provides the optical gain and has a saturation output power of 500 mW. The F–P filter has a free spectral range of 0.8 nm, a finesse of better than six, and an insertion loss less than 2 dB. The NOLM is constructed by splicing together the outputs of a 7:3 splitting ratio fused fiber coupler. A PC and a 2.1-km long conventional single-mode fiber (SMF) were inserted inside the loop. PCs were used at the input of the NOLM as well as inside the NOLM for polarization biasing of the loop. The laser output was taken via the 10% output port of the fused fiber coupler and was measured using an optical spectrum analyzer with 0.05 nm resolution.

The mechanism of the laser under stable multiwavelength operation at room temperature can be easily understood from the transmission characteristic of the NOLM. The transmission of an NOLM is given in [24] as

$$T = 1 - 2\alpha(1 - \alpha)\{1 + \cos[\theta + (1 - 2\alpha)\phi]\} \quad (1)$$

where α is the splitting ratio of the NOLM, θ is the additional phase difference induced by the PCs, $\phi (=2\pi n_2 P_1 L / \lambda A_{\text{eff}})$ is the nonlinear phase shift, n_2 is the nonlinear refractive index coefficient, L is the loop length, λ is the operating wavelength, A_{eff} is the effective fiber core area, and P_1 is the input power.

Using Eq. (1), we can obtain the transmission characteristics of NOLM as a function of input power for different θ , that is, for different setting of PCs. Typical values of $n_2 = 3.2 \times 10^{-20} \text{ m}^2/\text{W}$, $A_{\text{eff}} = 50 \text{ }\mu\text{m}^2$, and $\alpha = 0.3$, $L = 75 \text{ km}$, $\lambda = 1550 \text{ nm}$ were used in our calculation. Fig. 2 shows the transmission characteristic of the NOLM as a function of input power for $\theta = 0.5\pi, 0.667\pi, \pi, 1.333\pi, 1.5\pi$. As can be seen from the figure, the transmission can be increased or decreased with input power depending on the polarization setting of the PCs. When the PCs are set at a point

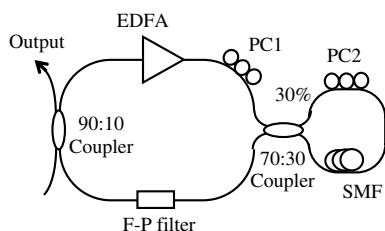


Fig. 1. Schematic diagram of the proposed laser.

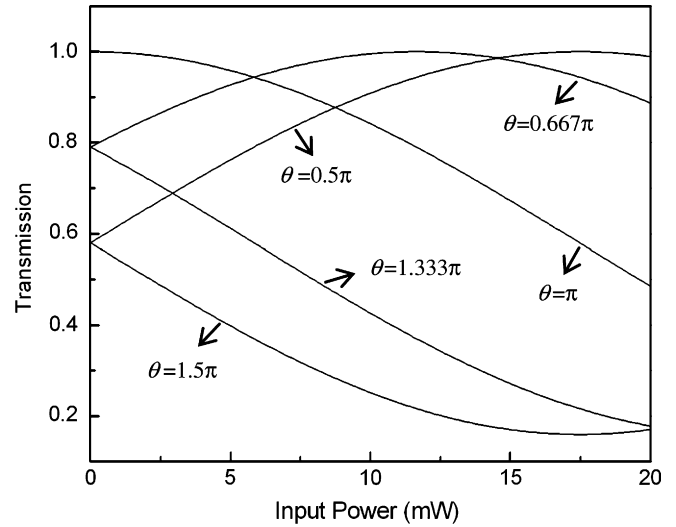


Fig. 2. Transmission characteristic of an NOLM as a function of input power for different θ .

where the transmittivity of the NOLM increases with the input signal power, the NOLM functions as a saturable absorber, which can lead to passive mode-locking and generates pulses [23]. The NOLM can also be biased to a point where it functions as an amplitude equalizer, whereby a high intensity beam would experience larger loss than that of a lower intensity one. The equalizing mechanism can effectively alleviate the mode competition in the EDF. As a result, the balance between the gain-clamping function of the NOLM and the mode competition effect of the EDF can lead to multiwavelength oscillations at room temperature, and also ensure uniform power distribution among wavelengths.

3. Experimental results

Using the mechanism described above and to confirm the existence of multiwavelength operation of the laser, we conducted experiments with the ring laser cavity configuration shown in Fig. 1. The laser system can be easily set to the proper biasing point by monitoring its output spectra as the PCs were adjusted. Fig. 3(a) shows the output spectrum of the laser emitting large number of laser lines spaced at 0.8 nm. Power distribution over wavelengths is very uniform and the amplitude difference among the 41 wavelengths is less than 1.6 dB. 50-wavelength operation was also obtained by adjusting the PCs, and the output spectrum is shown in Fig. 3(b). The amplitude difference among the 50 oscillation wavelengths is less than 3 dB within a spectral range of 1562–1605 nm. Both outputs have a wavelength spacing of 0.8 nm, which is determined by the F–P thin-film filter.

In addition to uniform power distribution over wavelengths within a wide spectral range, power stability is also an important parameter. The output power fluctuation of a single laser line was measured by filtering out one channel

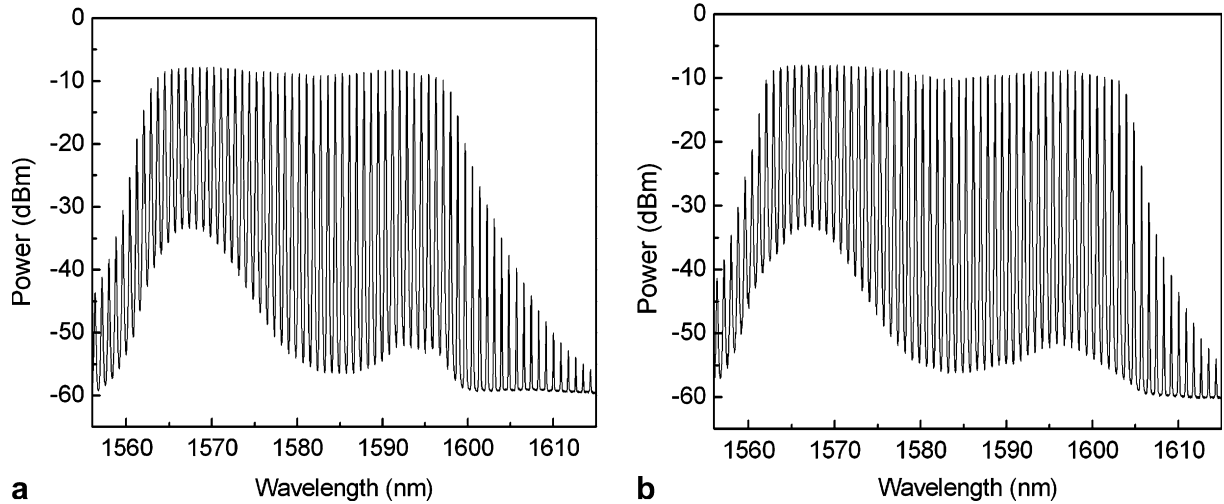


Fig. 3. Output spectra of the laser at two different adjustments of the PCs: (a) 41 wavelengths with amplitude variation of 1.6 dB and (b) 50 wavelengths with amplitude variation of less than 3 dB.

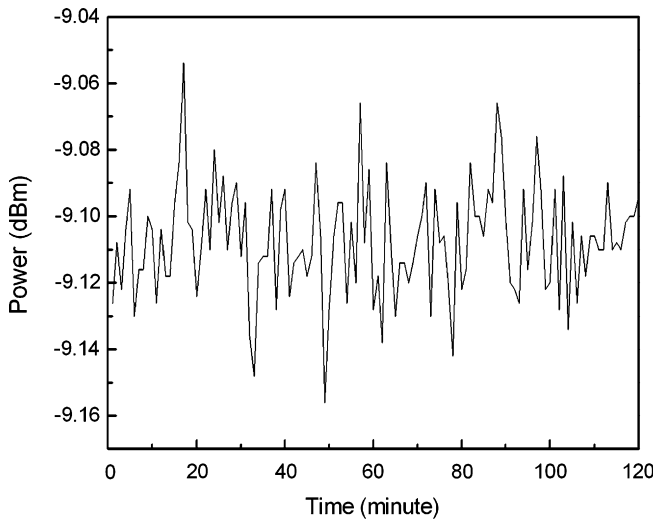


Fig. 4. Output power fluctuation versus time.

with a bandpass filter. The measured power variation over a 2 h period is shown in Fig. 4. The signal power fluctuation was measured to be about 0.1 dB over a 2 h period using an optical power meter without averaging.

It can be observed from Fig. 2 that the change in transmission with input power depends on the polarization settings. When the transmission rate is low (the loss is high), fewer wavelengths will have sufficient gain to compensate the cavity loss at the corresponding wavelengths. Thus, smaller number of wavelength will oscillate in the cavity. In our experiments, output spectra of the laser with number of wavelengths varying from 3 to 50 were obtained by adjusting the PCs. Fig. 5(a) and (b) give two examples, respectively showing 8-wavelength and 25-wavelength within the 3 dB spectral range. Notes that in the 8-wavelength oscillation case, the peak powers are with values of about -2 dBm and the extinction ratios are greater than 55 dB.

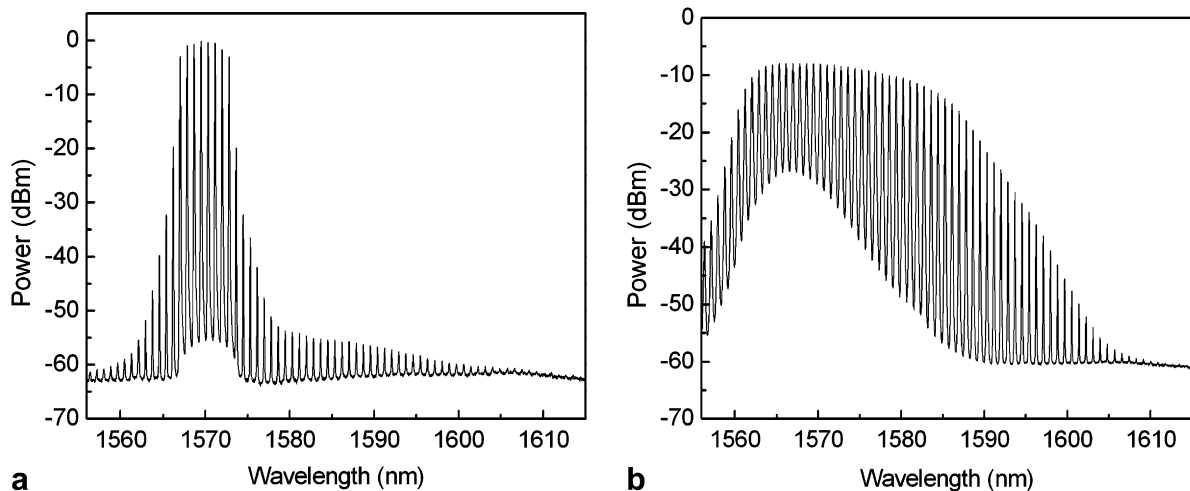


Fig. 5. Output spectra of the laser at two different adjustments of the PCs: (a) 8-wavelengths and (b) 25-wavelengths within amplitude variation of 3 dB.

The EDFA was operated at the same pump conditions for all experimental results. The total output power of the laser is about 60 mW at different polarization settings. All the spectra in Figs. 3 and 5 were measured using 0.1 nm resolution. When the resolution of the OSA was set to 0.05 nm, the measured 3 dB bandwidth of one channel is 0.05 nm, which is the highest resolution of the optical spectrum analyzer. The polarization states of the output wavelengths are random, because there are no elements to induce polarization hole burning effect.

From Eq. (1) and the expression of ϕ , the period of the transmission curve is related to the length of the SMF. We observe that there exists an optimum length of SMFs to achieve the maximum number of multiwavelength oscillations. If L is too short, the transmission term changes slowly as the power increases. The NOLM-induced IDL effect is therefore not strong enough to compensate for the mode competition among many wavelengths. On the other hand, if L is too long, the transmission term varies too fast when the power increases. The range of power in which the NOLM functions as an amplitude equalizer will be small, and consequently, fewer numbers of wavelengths can oscillate. We have used different length of SMF in the NOLM varying from 0.2 km to 5.4 km, and the best results were obtained with a 2.1 km SMF.

4. Conclusion

In conclusion, we have proposed and successfully demonstrated a stable and broad bandwidth multiwavelength EDFL with potential applications in DWDM systems. A NOLM which induces intensity-dependent loss in a laser cavity and functions as an amplitude equalizer was employed to obtain stable multiwavelength oscillations in EDFL at room temperature. Up to 50 wavelengths lasing operation with uniform power distribution has been achieved. The spacing of the lasing wavelengths is 0.8 nm, located at the ITU-wavelength grid by using an F-P thin-film filter. The power fluctuation of the laser output wavelength was measured to be about 0.1 dB within a 2 h period.

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