Stable and uniform multiwavelength erbium-doped fiber laser using nonlinear polarization rotation

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Abstract: A novel and simple technique, based on nonlinear polarization rotation (NPR) effect, to generate stable multiwavelength oscillations in an erbium-doped fiber laser is proposed and successfully demonstrated. The NPR effect effectively induced intensity- and wavelength-dependent loss to alleviate mode competition caused by homogeneous gain broadening in erbium-doped fibers. Up to 28-wavelength lasing operation with wavelength spacing of 0.8 nm has been achieved. The outputs had uniform power distributions, and the power fluctuation in each wavelength is smaller than 0.2 dB within a period of an hour.

OCIS codes: (140.3500) Lasers, erbium; (140.3510) Lasers, fiber; (190.3270) Kerr effect

References and links

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1. Introduction

Multiwavelength erbium-doped fiber lasers (EDFLs) attract much 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.

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Multiwavelength sources also find applications in optical fiber sensors and optical instrumentations. Different techniques have been proposed to realize multiwavelength oscillations at room temperature in EDFLs. These include the introduction of polarization hole burning (PHB) effect [1], or nonlinear effects such as four-wave mixing [2] and stimulated Brillouin scattering [3] in the laser cavity. Other methods such as inserting frequency shifter in the laser cavity [4], and employing specially designed erbium-doped fibers [5] or cavity structures [6] were also reported.

Nonlinear polarization rotation (NPR) has been used as a fast saturable absorber in passively mode-locked fiber lasers to generate femtosecond pulses [7]. NPR had also been used for suppression of supermode noise and for amplitude-equalization of rational harmonic pulses in single-wavelength mode-locked fiber lasers [8-9]. Recently, Pan et al reported the use of NPR effect to suppress supermode noise in multiwavelength mode-locked fiber [10]. However,in our work to be reported in this paper, we apply the NPR effect to induce wavelength- and intensity-dependent loss (IDL) for the generatation of multiwavelength oscillations in EDFL. We demonstrated that IDL can effectively alleviate mode competition caused by homogeneous gain broadening in erbium-doped fibers (EDF). A stable and broad bandwidth multiwavelength laser source with a wavelength spacing of 0.8 nm anchored on the ITU-wavelength grid was constructed. Up to 28-wavelength lasing operation with uniform output power has been achieved.

2. Experimental setup

Figure 1 shows the schematic diagram of the proposed laser. The multiwavelength laser consists of a commercial erbium-doped fiber amplifier (EDFA), a length of single-mode fibers (SMFs), a Fabry-Pérot (F-P) thin-film filter, two polarization controllers (PCs), a polarizer, and an output coupler. The EDFA, which can deliver 500 mW output saturation powers, provides the required gain. The SMF is used to increase the Kerr nonlinearity. The F-P filter has a free spectral range of 0.8 nm and an extinction ratio larger than 10 dB. The PC-SMF-PC-polarizer structure is the key component of the proposed multiwavelength laser. The structure effectively induces intensity- and wavelength-dependent loss and acts as an intensity equalizer [8-9]. The laser output was taken via the 10% port of a 90:10 fused fiber coupler and was measured using an optical spectrum analyzer with 0.1 nm resolution.

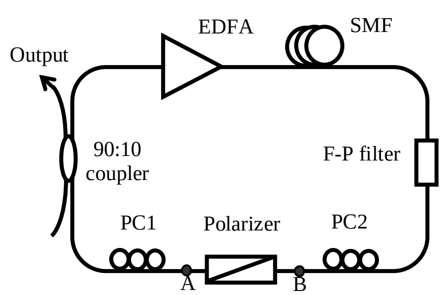

Fig. 1. Schematic diagram of the proposed multiwavelength laser.

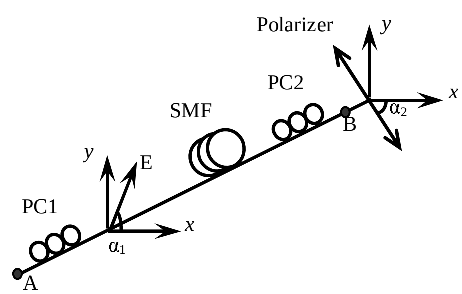

Fig. 2. Operation principle of the proposed laser. *E*: Electric vector of input signal; *x*: fast axis of SMF; *y*: slow axis of SMF.

3. Operation principle

Figure 2 illustrates the operation principle of the proposed laser. α_1 is the angle between the polarization direction of the input signal and the fast axis of the SMF, and α_2 is the angle between the fast axis of the SMF and the polarization direction of the polarizer. Both α_1 and α_2 can be altered by adjusting the polarization controllers PC1 and PC2, respectively. Linearly polarized light leaving the polarizer at point A of Fig. 1 is made elliptical by the polarization controller PC1. The state-of-polarization of the light rotates as it propagates in the SMFs due to the Kerr effect. The angle of rotation is proportional to the light intensity. The signal passes

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through PC2 before arriving at the polarizer which allows only a certain polarization to pass through. The combination of PC-SMF-PC-polarizer acts as an intensity-dependent loss. The transmittivity, T, of this structure can be expressed as [8]

$$T = \cos^2 \alpha_1 \cos^2 \alpha_2 + \sin^2 \alpha_1 \sin^2 \alpha_2 + \frac{1}{2} \sin 2\alpha_1 \sin 2\alpha_2 \cos(\Delta\phi_L + \Delta\phi_{NL}) \tag{1}$$

where

$$\Delta\phi_L = 2\pi(n_y - n_x)L/\lambda, \tag{2}$$

$$\Delta\phi_{NL} = -2\pi n_2 PL \cos 2\alpha_1 / \lambda A_{eff}, \tag{3}$$

n_x and n_y are the refractive indices of the respective fast and slow axes of the SMF. L is the length of the SMF between PC1 and PC2, λ is the operating wavelength, n_2 is the nonlinear (Kerr) coefficient, P is the instantaneous power of input signal, and A_{eff} is the effective fiber core area.

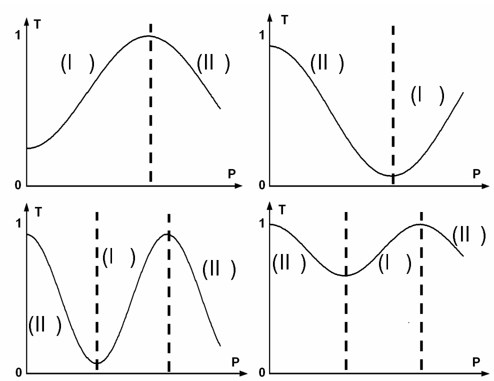

Fig. 3. Transmission effects due to NPR as a function of input power under different settings of the PCs. (I): regions for saturable absorber action; (II): regions for saturable transmitter action.

Figure 3 shows the transmittivity of the fiber loop as a function of the instantaneous input signal power for different values of angles α_1 and α_2. It can be observed that the transmittivity oscillates with input power. The values of α_1 and α_2 affect the phase, the amplitude, and the period of the transmittivity. In Region I, the transmittivity increases with the input signal power, the PC-SMF-PC-polarizer combination functions as a saturable absorber. In Region II, however, the transmittivity decreases with input signal power. That is, higher intensity input light experiences higher losses and the combination functions as an intensity equalizer. The intensity-dependent loss induced by NPR is different for different wavelengths. This inhomogeneous loss can be used to alleviate the mode competition induced by the homogeneous gain broadening of EDF. As a result, the balance between the inhomogeneous loss induced by NPR and the mode competition effect of the EDF can lead to stable multiwavelength oscillations at room temperature with uniform power distribution among wavelengths.

4. Experimental results

When the length of the SMF is ~400 m, we obtained 10-wavelength output by adjusting the PCs . As shown in Fig. 4, the power distribution over wavelengths is fairly uniform and the output power difference of the 10 oscillation wavelengths is less than 2 dB.

Figures 5(a) and 5(b) show two typical output spectra of the laser when the length of SMF is increased to ~2.09 km. Figure 5(a) shows the output spectrum of the laser under 18-wavelength operation. The output power difference among the 18 oscillation wavelengths is less than 1.2 dB. Figure 5(b) shows 23-wavelength operation by proper adjustment of the PCs. The difference in output power among the 23 oscillation wavelengths is slightly larger.

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In general, the output power difference can be decreased by reducing the number of output wavelengths.

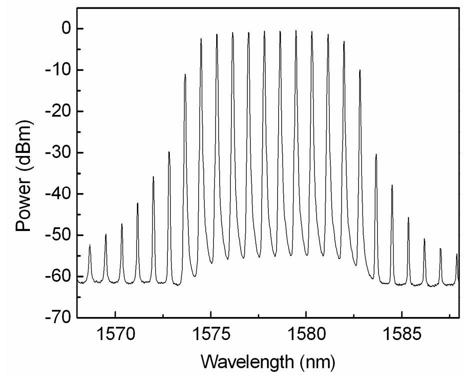

Fig. 4. Output spectra of the laser under 10-wavelength operation within 3-dB bandwidth when the length of SMF is about 400 m.

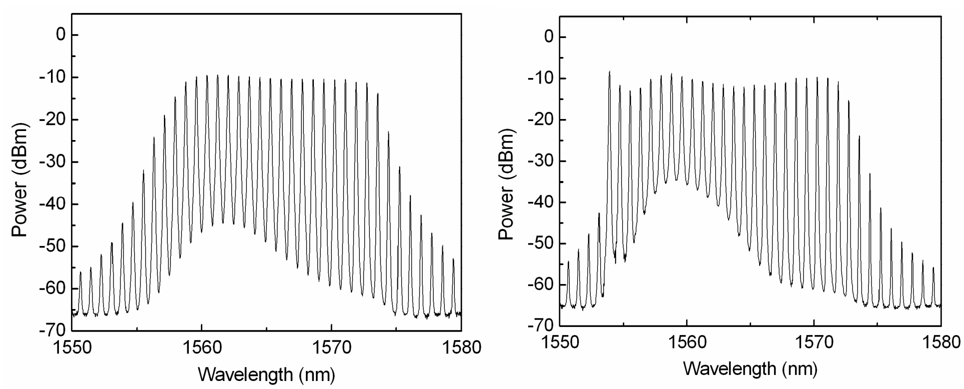

Fig. 5. Output spectra of the laser under (a) 18-wavelength operation, and (b) 23-wavelength operation within 3-dB bandwidth when the length of the SMF is about 2.09 km.

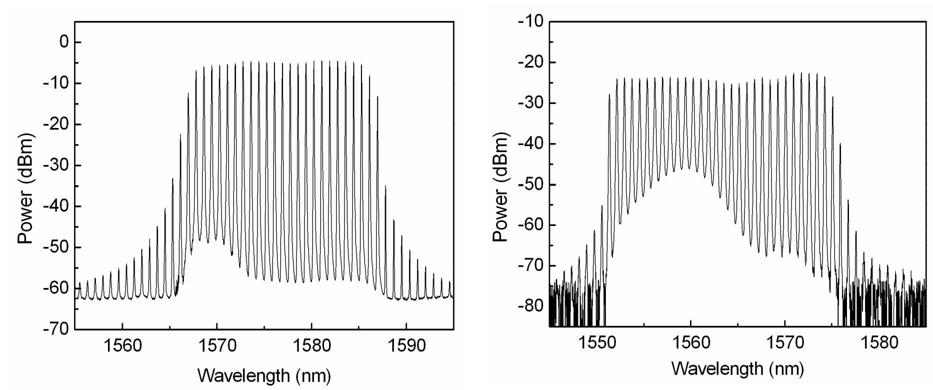

Fig. 6. Output spectra of the laser under (a) 22-wavelength operation with a 10% output coupler, and (b) 28-wavelength operation with a 1% output coupler when the length of the SMF is about 1.2 km.

When the length of the SMF was ~1.2 km, the maximum number of lasing wavelengths is 30. The output power difference however increased to ~5 dB. Figure 6(a) shows the output spectrum of the laser under 22-wavelength operation. The output power difference among the 22 oscillation wavelengths is less than 1.5 dB. We then replaced the 90:10 coupler in the cavity by a 99:1 coupler in order to increase the optical power in the cavity. Figure 6(b) shows the spectrum of the laser under 28-wavelength operation. The output power difference is less than 2 dB.

The wavelength spacing for all output wavelengths is 0.8 nm anchored on the ITU-wavelength grid as determined by the F-P thin-film filter. The measured 3-dB bandwidth of each channel is ~0.04 nm when the resolution of the optical spectrum analyzer was set to 0.01 nm. For WDM sources, it is desirable to have a stable output power in addition to uniform power distribution over a wide spectral range. The output power fluctuations of the laser were studied by filtering out one channel with a bandpass filter. The measured power variation as a function of time is shown in Fig. 7. The fluctuation of the signal power is less than 0.2 dB in a period of one hour. The power stability could be further improved by using a short length of high nonlinear fiber.

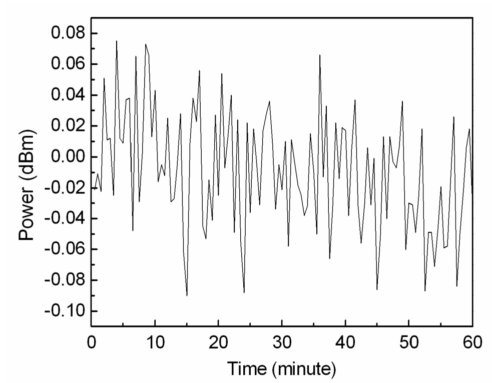

Fig. 7. Output power fluctuation versus time.

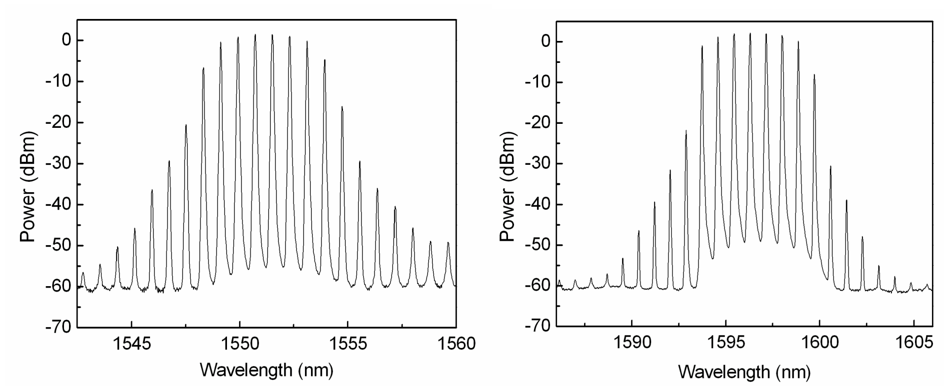

Fig. 8. Output spectra when the output wavelengths are near (a) 1550 nm, and (b) 1600 nm.

As observed from Eq. (2) and Eq. (3), both the linear and nonlinear phase shifts are wavelength dependent, therefore the PC-SMF-PC-polarizer combination can also induce wavelength-dependent loss. It is thus possible to tune the output wavelength through adjustment of the PCs. We observed that when the laser operates with fewer numbers of wavelengths, the output wavelengths can be tuned over a wide wavelength range by adjusting the PCs. Figures 8(a) and 8(b) show two typical output spectra when the laser operated around 1550 nm and 1600 nm, respectively.

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5. Discussions

Applying NPR technique, we obtained multiwavelength operation with the number of wavelegnths varying from 2 to 28 by simply adjusting the PCs. The output spectra are very flat. The adjustment of the PCs affects the offset and the amplitude of the transmission curve as well as the period of the curve. When the transmission is low (i.e., the loss is high), fewer number of wavelengths will have sufficient gain to compensate for the cavity loss for lasing action to occur.

We also observed that an optimum length of SMFs exists for maximum number of multiwavelength oscillations. In the experiment, the maximum number of wavelength for L = 0, 0.4 km, 1.2 km, and 2.09 km are 4, 10, 30, and 23, respectively. From Eq. (1) to Eq. (3), the period of the transmission curve is related to the length of the SMF between the two PCs. When the length of fiber is short, the transmission term changes slowly as the power increases. The NPR-induced inhomogeneous loss 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 structure functions as intensity equalizer will be small, and consequently, few wavelengths can oscillate. Note that for a given L, increasing the power in the cavity can broaden the power range for intensity equalizer action. This explains the increase to 28-wavelength operation when the output coupler was changed from 90:10 to 99:1.

If the polarizer is removed from the laser cavity, broadband multiwavelength operation cannot be obtained. Without any additional SMFs in the cavity, only single wavelength output is possible. If the 2.09-km long SMF was inserted, five-wavelength operation can be achieved because of the nonlinearity of the long SMF. However, the output wavelength cannot be tuned and the number of oscillating wavelengths cannot be varied by adjusting the PCs.

6. Conclusion

In conclusion, we have proposed and successfully demonstrated a novel and simple technique, based on nonlinear polarization rotation effect, to generate stable multiwavelength oscillations in an erbium-doped fiber ring laser. NPR effect is used to induce wavelength- and intensity-dependent loss and acts as an intensity equalizer. Up to 28-wavelength lasing operation with a wavelength spacing of 0.8 nm anchored on the ITU frequency grid has been obtained. The outputs had uniform power distributions. The measured power fluctuation in each wavelength is less than 0.2 dB when monitored over a period of an hour.

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