Switchable Multiwavelength Erbium-Doped Fiber Laser With a Multimode Fiber Bragg Grating and Photonic Crystal Fiber

Xinhuan Feng, Hwa-Yaw Tam, *Senior Member, IEEE*, and P. K. A. Wai, *Senior Member, IEEE*

***Abstract*—In this letter, a simple switchable multiwavelength erbium-doped fiber laser is proposed and demonstrated. The wavelengths are determined by a multimode fiber Bragg grating which has a wavelength separation of 0.8 nm. Five-wavelength operation at room temperature can be achieved by employing a highly nonlinear photonic crystal fiber to induce four-wave mixing effect. The proposed laser can operate either in a stable five-wavelength mode or wavelength switching modes by varying the states of polarizations of the laser cavity.**

***Index Terms*—Erbium-doped fiber laser (EDFL), four-wave mixing (FWM), multimode fiber Bragg grating (MM-FBG), photonic crystal fiber (PCF).**

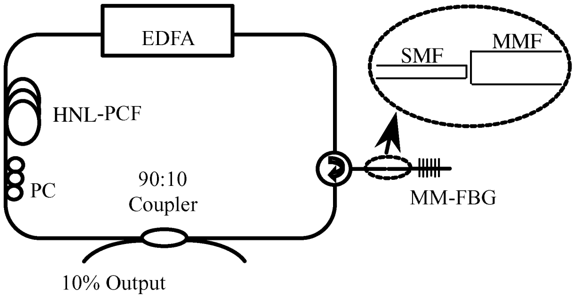

Fig. 1. Schematic diagram of the proposed laser.

I. INTRODUCTION

MULTIWAVELENGTH fiber lasers are useful light sources for wavelength-division-multiplexed fiber communication systems, fiber sensors, and optical instrumentations. Various techniques have been proposed to realize switchable multiwavelength oscillations in erbium-doped fiber lasers (EDFLs) by utilizing cascaded fiber Bragg grating (FBG) cavities [1], a tree, inline topology of FBGs [2], FBGs written in birefringent fibers [3], a long-period FBG written in a polarization-maintaining fiber [4], and a sampled FBG [5]. Recently, Liu *et al.* reported multiwavelength EDFLs using a length of highly nonlinear photonic crystal fiber (HNL-PCF) in the laser cavity. They employed two FBGs with one variable optical attenuator (VOA) [6], three FBGs with two VOAs [7], and four FBGs with four VOAs [8] for wavelength selections to achieve dual-wavelength, triple-wavelength, and four-wavelength oscillations, respectively. It is difficult for their configuration to achieve scalability, multiwavelength oscillation with equal wavelength spacing, and wavelength tunability.

A multimode FBG (MM-FBG) in the offset launch configuration has been used to tune the output wavelength for fiber lasers having a single output wavelength [9], [10]. In this letter, we report a stable multiwavelength EDFL by employing an MM-FBG for multiwavelength selections. Simultaneous lasing of five wavelengths with 0.8-nm spacing was achieved by inserting a length of HNL-PCF in the cavity to induce the four-wave mixing (FWM) effect. The laser can operate either in a five-wavelength lasing mode or wavelength switching modes by the adjustment of a polarization controller (PC). In the wavelength switching modes, single-wavelength, dual-wavelength, triple-wavelength, and four-wavelength operations have been obtained. The proposed switchable multiwavelength fiber laser has a simple configuration.

II. EXPERIMENTAL SETUP AND PRINCIPLE

The configuration of the proposed laser is shown schematically in Fig. 1. It consists of a commercial erbium-doped fiber amplifier (EDFA), 20 m of HNL-PCF, a PC, an output coupler, and an MM-FBG. The EDFA provide the gain, which can offer 500-mW output saturation powers. The HNL-PCF is used for the generation of FWM to obtain stable multiwavelength oscillations. It has a zero-dispersion wavelength around 1550 nm and the dispersion slope near the zero-dispersion wavelength is very small ($\sim$0.0004 ps/nm^2/km), so that the phase-matching condition for FWM is easily satisfied. The nonlinearity coefficient of the PCF is about 30.6/W/km and the total insertion loss of the PCF is less than 1 dB. The MM-FBG is introduced into the cavity via an optical circulator for multiwavelength selections. The PC is used to adjust the states of polarization (SOPs) of the lights incident to the HNL-PCF. All the fibers in the cavities are single-mode fibers (SMFs) except for the 0.3-m section of multimode fiber (MMF) which contain the MM-FBG. The laser output is taken via the 10% port of a 90 : 10 fused fiber coupler and is measured using an optical spectrum analyzer with 0.1-nm resolution.

Fabrication of the MM-FBG is performed by the phase mask method using 248-nm excimer laser. The grating period is about

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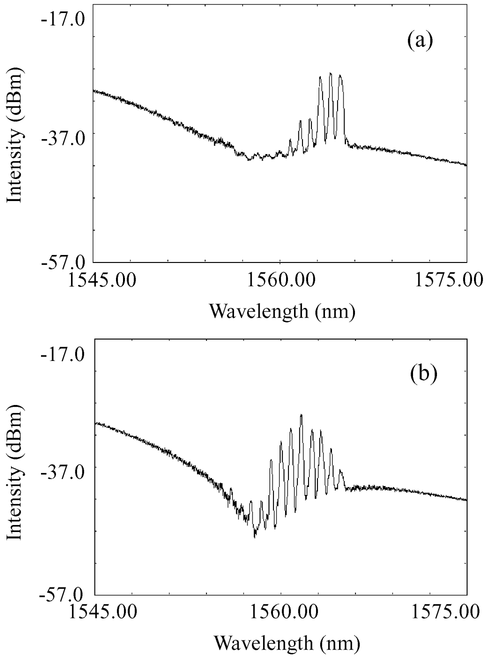

Fig. 2. Reflection spectra of the MM-FBG under (a) smaller offset; (b) larger offset between the SMF and the MMF.

1064.2 nm. The MMF used for fabrication of the MM-FBG is standard graded MMF with a numerical aperture of 0.275, a core diameter of 62.5 μm, and a refractive index of 1.47.

In the experiment, the lateral displacement between the SMF and the MMF was varied so that different spatial distributions of the MMF modes can be excited to obtain different reflection spectra. Fig. 2 shows the reflection spectra of the MM-FBG for two different lateral displacements. The three reflection wavelengths in Fig. 2(a) are about 1564.80, 1564.02, and 1563.21 nm. There are ten higher order modes reflected from the MM-FBG to the SMF, as shown in Fig. 2(b), and the reflection wavelengths in the middle of reflection spectra are 1563.21, 1562.42, 1561.61, 1560.80, and 1560.01 nm. The wavelength separation between adjacent reflection peaks is about 0.8 nm, which is determined by the properties of the MMF.

When several wavelengths reflected back from the MM-FBG have approximately equal reflectivities, and the total round-trip gain for each wavelength is equal to the round-trip loss, they will lase simultaneously. The same section of EDF in the cavity is shared by all lasing lines as intracavity gain medium. Thus, the lasing wavelengths may suppress each other through cross-gain saturations in the EDF because EDF behaves as a homogeneously broadened gain medium at room temperature. However, FWM effects lead to the energies transfers among the different wavelengths. The oscillation condition for each wavelength λ_i in our proposed multiwavelength fiber laser can be expressed as [1], [11]

$$R_i r_i \cdot V_i \cdot G_{i\mathrm{EDF}} G_{i\mathrm{FWM}} = 1 \tag{1}$$

where R_i and r_i are the output coupler reflectivity and the FBG reflectivity for λ_i, respectively, V_i is the round-trip losses in the fiber cavity for λ_i, $G_{i\mathrm{EDF}}$ is the gain obtained from the EDFA, and $G_{i\mathrm{FWM}}$ is the total gain obtained from all FWM processes.

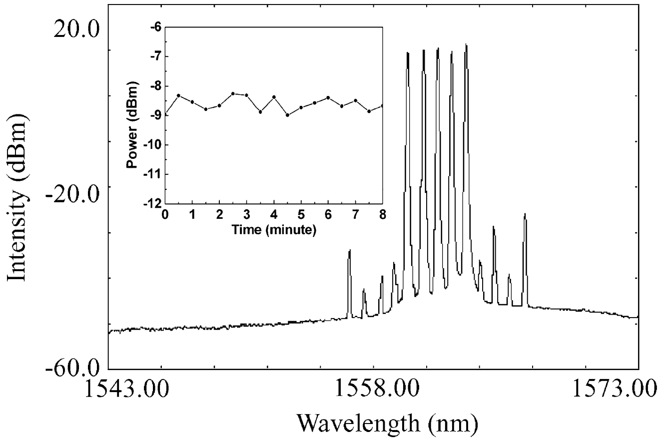

Fig. 3. Output of the laser under five-wavelength operation.

Therefore, if the gain in the FWM processes and the reflectivity of each wavelength are optimized, the oscillation conditions shown in (1) for multiple wavelengths can be satisfied, resulting in simultaneous multiwavelength oscillation [1]. If the oscillation condition for different λ_i is satisfied at different FWM efficiencies, wavelength switching operation can be achieved by varying the cavity's SOP.

During multiwavelength oscillations, various FWM processes affect one wavelength. The FWM power in each wavelength results from multiple mixing products of these channel signals, in which complex relations are involved. Consequently, the power transfers to one wavelength can be from these many FWM processes, which can be expressed as $G_{i\mathrm{FWM}}$. On the other hand, the FWM efficiency depends on the relationship of the SOPs of the input lights and is proportional to the intensity beating between them. It becomes zero when the SOPs of the input lights are orthogonal to each other and reaches maximum when their SOPs are identical [12]. By adjusting the PC within the ring cavity, we can introduce different FWM efficiencies for different FWM processes. Thus, each laser line has a $G_{i\mathrm{FWM}}$ different from that of the other wavelengths, and the intensity of this gain depends on the FWM efficiencies, which can be varied by adjusting the SOPs of the input lights. The value of $G_{i\mathrm{FWM}}$ involving different wavelengths can be adjusted to satisfy the oscillation condition for different λ_i shown in (1).

Therefore, the balance between the gain obtained from the FWM processes and the mode competition effect of the EDFA can lead to multiwavelength oscillations at room temperature. By adjusting the polarization states of the waves, the FWM efficiencies for different wavelengths can be controlled to some extent and consequently, wavelength switching can also be obtained.

III. RESULTS AND DISCUSSION

In the experiment, by adjusting the offset between the SMF and the MMF, and the state of the PC, simultaneous five-wavelength oscillation was obtained. Fig. 3 shows the output spectrum. The five wavelengths are at 1563.21, 1562.42, 1561.61, 1560.80, and 1560.01 nm. The wavelength spacing is 0.8 nm. The inset in Fig. 3 shows the power fluctuation of the filtered

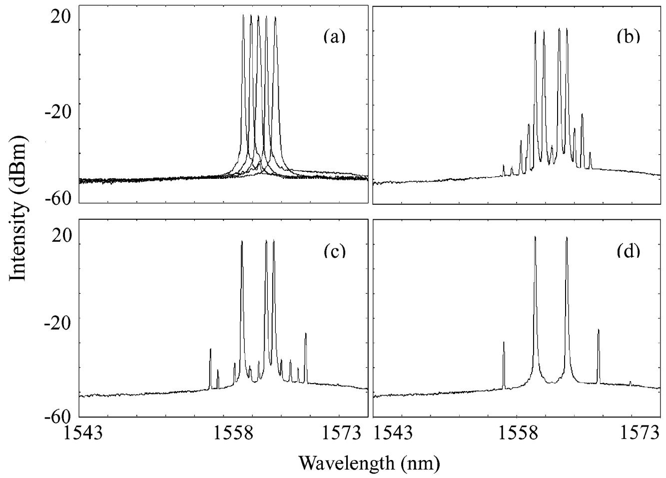

Fig. 4. Typical output spectra of the laser under (a) five single-wavelength; (b) four-wavelength; (c) triple-wavelength; (d) dual-wavelength operations through adjustment of the PC.

output at 1560.80 nm versus time. The maximum power fluctuation is 0.75 dB.

At the same fiber offset, through carefully adjusting the state of the PC, five single-wavelength, four-wavelength, triple-wavelength, and dual-wavelength operations have been obtained, as respectively shown in Fig. 4(a)–(d). The laser outputs exhibit good performances with over 55 dB of optical signal-to-noise ratio. The output power under each operation is greater than 60 mW.

It can be seen from (1) that the reflectivity of the MM-FBG for different wavelengths could also be used as a parameter to realize the multiwavelength oscillation and wavelength switching conditions. Thus, minor adjustment of the offset between the SMF and the MMF can also lead to wavelength switching. But this switching method is not as easy and convenient as by simply adjusting the PC.

As would be expected, bending and twisting the fiber led to the change in the output characteristic. This is because of the perturbation-induced birefringence, which would change the polarization states of the light to the HN-PCF.

It should be noted that a wavelength switching range of about 10 nm has been achieved through adjustment of the offset of the SMF and the MMF when the laser was under triple-wavelength operation. Tunable multiwavelength output can be easily obtained by tuning the MM-FBG because all wavelengths will be shifted equally. While for the setup in [6]–[8], it is more complicated to tune all the FBGs to achieve multiwavelength tuning with the wavelength spacing remain unchanged.

IV. CONCLUSION

A simple switchable multiwavelength EDFL is proposed and demonstrated. The wavelengths are determined by an MM-FBG and the wavelength separation is 0.8 nm. Multiwavelength operation at room temperature can be achieved due to the FWM induced by an HNL-PCF. The proposed laser can operate either in a five-wavelength oscillation mode or wavelength switching modes by adjusting a PC. For wavelength switching, single-wavelength, dual-wavelength, triple-wavelength, and four-wavelength operations have been obtained. The MM-FBG was used as an equally spaced multiwavelength selection element, offering the advantages of easy wavelength tuning and a simple configuration.

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