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Stable and switchable single-longitudinal-mode dual-wavelength erbium-doped fiber laser based on a fiber ring filter

Wei He, Lianqing Zhu*

Beijing Engineering Research Center of Optoelectronic Information and Instruments, Beijing Information Science and Technology University, Beijing 100192, People's Republic of China

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ABSTRACT

A switchable dual-wavelength and single-longitudinal-mode (SLM) erbium-doped fiber laser (EDFL) based on a fiber ring filter (FRF) is proposed and demonstrated through a detailed experimental verification. In the design, the simple linear-cavity EDFL is composed of one 976-nm laser diode (LD), one fiber loop mirror (FLM), two cascaded fiber Bragg gratings (FBGs), and an EDF. To improve the laser stability, the FRF is spliced into a specially designed EDFL, which is fabricated from an EDF and two couplers with splitting ratios of 50:50 and 30:70, respectively. Both single- and dual-wavelength lasers can be realized by adjusting the variable attenuator (VA) between the two FBGs. In the proposed EDFL, the 1540-nm laser and the 1545-nm laser, respectively, incur laser-frequency shifts at room temperature of less than 3 pm and 2 pm over a period of 60 min. The single-wavelength 1540- and 1545-nm lasers show single-longitudinal-mode (SLM) operation within the frequency range of 0–500 MHz, as measured by the delayed self-heterodyne method using a 50-km single-mode fiber, and the 3-dB linewidths of the output of two lasers are about 2.8 kHz and 2.5 kHz, respectively.

1. Introduction

Switchable dual-wavelength single-longitudinal-mode (SLM) fiber lasers have attracted great attention for their extensive applications, in areas such as dense wavelength division multiplexing (DWDM) schemes [1], optical fiber sensors [2], microwave photonic generation systems [3], and spectroscopy analysis [4], because of their obvious advantages such as flexible laser output, narrow linewidth, high signal-to-noise ratio (SNR), system compactness, and long operating life [5].

In recent years, dual-wavelength operation has been realized by several different techniques. In 2014, a stable dual-wavelength EDFL based on a combination of FBGs and phase-shift FBGs was realized by Sergio Rota-Rodrigo; for that proposed EDFL, the wavelength shifts were, respectively, 2.56 pm and 7.61 pm, at room temperature, and the FWHM linewidth was smaller than 3.5 kHz [6]. In 2013, a single-mode switchable dual-wavelength EDFL with two cascaded FBGs was realized by Jianqun Cheng; in that EDFL design, the maximum peak power variations of the two lasers were 2.3 dB and 2 dB, respectively, when the EDFL was operated in the single-wavelength mode; when the EDFL was operated in the dual-wavelength lasing mode, peak power shifts of 1.4 dB and 0.7 dB were realized [7]. In 2013, a dual-wavelength ring EDFL with a photonic-crystal fiber and a tunable band-pass filter was demonstrated by Ahmad; for that EDFL, the wavelength fluctuations for both wavelengths were less than 10 pm [8]. In 2013, a switchable dual-wavelength polarization-maintaining ring EDFL using a novel filter was reported by Zou, and the wavelength shifts were less than 0.01 nm [9]; in the same year, Sierra-Hernandez achieved a multi-wavelength laser by using a photonic-crystal fiber as a Mach–Zehnder interferometer, and the laser emissions showed 0.02-nm wavelength shifts at room temperature [10]. In 2012, a dual-wavelength EDFL based on a PM-FBG and a F-P fiber ring filter was investigated by Wei; in that EDFL, the wavelength fluctuation was less than 0.05 nm [11]. In 2011, a 3-dB coupler was used by Jiang to generate a fiber feedback loop (FFL) to achieve a single-longitudinal-mode dual-wavelength EDFL, and both wavelength shifts were about 5 pm [12]. In 2010, Jae-Ho Han reported a switchable EDF ring laser using cascaded fiber Bragg gratings [13].

In the above methods, there are many schemes for realizing switchable dual-wavelength laser emission; in those proposed

* Corresponding author at: Beijing Information Science and Technology University, Beijing Engineering Research Center of Optoelectronic Information and Instruments, 12, East Qinghexiaoying RD, Beijing 100192, China. Tel.: +86 010 8242 6892.

E-mail address: zhulianqing@sina.com (L. Zhu).

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schemes, on the one hand, the EDFL usually has a long cavity, and it is easy to incur serious wavelength shifts and also difficult to obtain SLM operation at room temperature, however, in many applications such as DWDM and fiber sensors, the EDFL needs to have advantages such as tunability, narrow linewidth, and stability to increase the multiplexing number and constrain the crosstalk and the bit error rate; on the other hand, the additional components inserted into the EDFL in order to improve its performance increase the complexity and cost. Thus, it is valuable to study the methods for realizing an EDFL with stable laser output and narrow linewidth. In order to improve the laser stability and guarantee SLM operation, techniques such as using a saturable absorber (SA), comb filter [14], fiber feedback loop (FFL) [15], and self-feedback light injection [16] are most commonly employed. In this study, an EDFL based on a fiber ring filter (FRF) has been constructed and investigated, and the FRF was composed of simple and all-fiber component. Consequently, stable and switchable SLM dual-wavelength laser operation was realized at room temperature.

2. Experimental methods

The experimental schematic diagram of the proposed SLM dual-wavelength EDFL is shown in Fig. 1. One laser diode with a center wavelength of 976 nm was used as the pump laser, a segment of the EDF was chosen to be the gain medium, and the cavity was composed of two FBGs with different reflection wavelengths and a fiber loop mirror (FLM). The pump laser was coupled into the EDF (labeled EDF1 in the figure) by a 976/1550-nm wavelength division multiplexer (WDM); the FLM, which served as one end of the cavity, was fabricated by splicing together two ports of a coupler with a 50:50 splitting ratio; and the laser at point A in the figure was injected into the FRF through Coupler1. Moreover, two isolators (ISOs) were employed to enforce the direction of propagation, and the polarization state of the EDFL was modulated by a polarization controller (PC).

In our EDFL design, the FRF was constructed from a second EDF (labeled EDF2 in the figure) and two couplers with splitting ratios of 50:50 and 30:70, respectively. The laser output from the FRF was injected into the cavity through the 30% port of Coupler3 (which had a 30:70 splitting ratio) to form a self-feedback light injection structure in order to improve the stability of the laser. Ultimately, switching of the single-longitudinal-mode (SLM) laser between single- and dual-wavelength operation can be achieved by adjusting the variable attenuator (VA) between the two FBGs.

The key component of the EDFL was the FRF, the schematic of which is presented in Fig. 2. The optical fields incident on the 2 × 2 Coupler1 through the input ports are represented as E_1 and E_2, and the coupler's output optical fields are represented as E_3 and E_4.

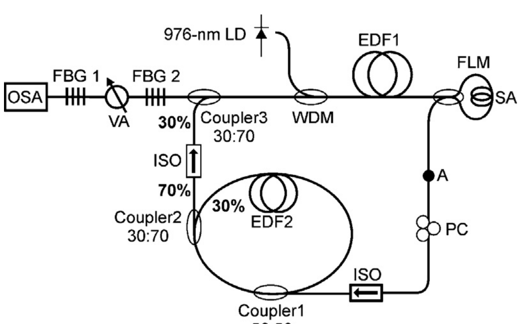

Fig. 1. Schematic diagram of the switchable dual-wavelength EDFL based on a FRF.

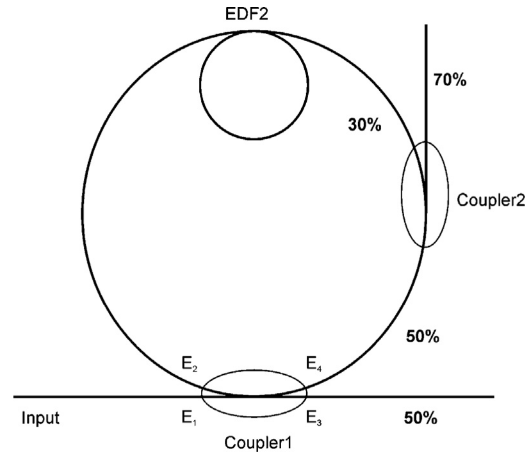

Fig. 2. Schematic diagram of the FRF.

When an optical wave is injected into the FRF by Coupler1, the output optical fields can be expressed as shown in Eq. (1),

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{1-r} & i\sqrt{r} \\ i\sqrt{r} & \sqrt{1-r} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} \tag{1}$$

where r is the splitting ratio of Coupler1.

In our FRF design, Coupler1 has a 50:50 splitting ratio at a wavelength of 1.5 μm, so r is 0.5. For $r = 0.5$, E_4 can be deduced from the above equation to be

$$E_4 = i\sqrt{r}E_1 + \sqrt{1-r}E_2 \tag{2}$$

After the E_1 optical field is coupled into the FRF, half of the light was transmitted through Coupler2, and then was divided into two paths. The optical output from the 30% port of Coupler2 was injected into EDF2, which imparted a time delay τ and a weak gain g, while the light exiting through the 70% port was injected into the cavity to form a self-feedback light injection structure. By accounting for the propagation of the field through EDF2 and Coupler2, E_2 can be written as shown in Eq. (3),

$$E_2 = ge^{j\tau\omega} \tag{3}$$

where ω is the angular frequency of the optical fields. So a mathematical expression for the optical field E_4 can be obtained by substituting Eq. (3) into Eq. (1) and Eq. (2), respectively, and the transmission of the FRF, T, can be written as

$$T = \frac{|E_4|^2}{|E_1|^2} = \frac{r}{1 + g^2(1-r) - 2g\sqrt{1-r}\cos\tau\omega} \tag{4}$$

The time delay τ is written as $\tau = 2\pi/\text{FSR}$. Here, FSR is the free spectral range of the FRF, and FSR can be written as FSR = c/nl, where n is the effective index ($n = 1.446$ in our system) and l is the length of the FRF.

When $r = 0.5$, EDF2 is 2-m long; the total length of the FRF, l, is 2.6 m; $g = 1.2$; and the FSR of the FRF is 79.7957 MHz. As shown in Fig. 3, the transmission spectrum of the FRF, T, can be numerically simulated, and the FRF shows a high-finesse comb filter effect, and the 3-dB bandwidth $\Delta\omega$ can be calculated to be 4.3156 MHz. Therefore, when $\Delta\omega$ is smaller than the FSR of the EDFL, the FRF can inhibit the generation of unnecessary longitudinal modes to improve the laser stability and guarantee SLM operation. For the proposed EDFL, the length of the gain medium EDF1 is 8 m, and the total length of the EDFL is 9.5 m, so the FSR of the EDFL, $\Delta\Phi$, is 21.8388 MHz, and $\Delta\omega$ is less than $\Delta\Phi$.

In the experiment, the reflection wavelengths of FBG1 and FBG2 are 1540 and 1545 nm, respectively. The pump LD, which produces