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Wavelength-switchable fiber laser based on few-mode fiber filter with core-offset structure

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ABSTRACT

We propose a wavelength-switchable erbium-doped fiber ring laser based on the few-mode fiber filter with core-offset structure. The filter is constructed by splicing a section of few-mode fiber with two segments of single mode fiber. Meanwhile, the excited modes are effectively selected by controlling the core-offset splicing carefully. The novel filter is based on the interference between fundamental mode and LP_{11} mode. The single-, dual-, triple- and quad-wavelength fiber laser is accomplished by adjusting the states of polarization controller at room temperature. The principle of operation is mainly based on the saturated spectral hole-burning effect and the balance between the gain and loss in the cavity.

1. Introduction

Fiber lasers are important light sources in wavelength-division-multiplexed (WDM) fiber communication systems, fiber sensing applications, optical detection, system diagnostics, and optical signal processing [1–5]. In many applications, the wavelength-switchable fiber laser is more flexible and effective than the fixed-wavelength fiber laser for wavelength protection, optical measurement and wavelength router. Importantly, in applications such as optical detection and optical signal processing, wavelength-switchable fiber laser is a useful light source with high precision [6].

Up to now, wavelength tunable fiber lasers have been attracted lots of attentions. Based on the Mach–Zehnder interferometers [7–9,18], fiber Bragg gratings (FBGs) [10,11], Sagnac loop mirrors [12,13], and in-line Fabry–Perot filters [14,15], various types of fiber filters [16,17] have been utilized to realize the wavelength-switchable fiber lasers. Wavelength-switchable fiber lasers based on Mach–Zehnder interferometers with different fiber structures have been widely applied. A stable C- and L-band tunable fiber ring laser was proposed and demonstrated experimentally using a two-taper Mach–Zehnder interferometer (MZI) as a filter [18]. The laser operated at a side-mode suppression ratio as high as 50 dB. The waist diameter should be controlled carefully with a uniform taper profile in the experiment. In additions, the laser was amplified by an L-band erbium-doped amplifier and an erbium-doped fiber, respectively. A temperature sensor based on a fiber laser with the core-offset fiber structure was demonstrated [2]. The operating wavelength of the laser is 1547.3 nm at room temperature, and the side-mode suppression ratio (SMSR) is greater than 47 dB. Fiber Bragg grating (FBG) is an ideal wavelength-selective intra-cavity component for fiber laser due to the advantage of fiber compatibility, ease of use. However, the typical FBG has low wavelength flexibility and usually is fabricated by UV laser writing technique on hydrogen-loaded fiber. The writing technique is complicated and the equipment is expensive in the applications. Based on a Sagnac loop mirror using elliptical core side-hole fiber, a tunable multi-wavelength SOA fiber laser with the SMSR over 30 dB was proposed and demonstrated in the experiment [19]. In-line Fabry–Perot (F–P) tunable filters are commercially available, but they are rather expensive and impractical in the all-fiber laser system with the piezoelectric stretching element [15]. In additions, multimode fiber (MMF) filters have a large tuning range of 32 nm with the SMSR about 40 dB [17]. It is a novel way to obtain a wavelength-selective advice based on the twin-core fiber (TCF). The effective refractive index difference between the two cores leads to the interference of the propagating lights when they meet at the second splicing point. The filter based on twin-core fiber has some advantages such as easy fabrication, small size, and good compatibility with the conventional fiber. The SMSR of the fiber laser reached 45 dB in the previous paper [20]. Meanwhile, the technology based on TCF was effective but some wasteful in the applications. On the other hand, another novel

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filter was proposed. It is based on two-mode fiber which supports only two modes (LP_{01} and LP_{11}) propagating in the core of the fiber. The filter based on TMF has some advantages such as high extinction ratio (ER), easy to splice with the single mode fiber (SMF). In the previous paper [21], high ER (> 20 dB) modal interference in a two-mode dispersion compensating fiber was utilized to build a compact, easy-to-fabricate tunable all-fiber optical comb filter. However, the strict rare earth doped technology and optical fiber drawing technology are needed in the manufacturing process of TMF. The parameters of the fiber should be carefully controlled for the purpose of two-mode propagating in the fiber. In contrast, the technical difficulty for the fabrication of few-mode fiber (FMF) is relatively reduced. The fiber is easy to be fabricated in technical difficulty in the experiment. Meanwhile, on the condition of controlling the splicing technology carefully, a comb filter based on FMF could be achieved in the experiment.

In this paper, a wavelength-switchable erbium-doped fiber (EDF) ring laser based on a novel filter is proposed. The novel filter is constructed by a section of FMF inserted into SMF with two core-offset fiber structures. By controlling the core-offset splicing carefully, two linear polarization modes (LP_{01} and LP_{11}) can be effectively excited at the first splicing point. When the light propagates along the fiber and reaches at the second splicing point, the power is re-coupled into the output SMF. The single-, dual- and triple-wavelength fiber laser is accomplished by appropriately adjusting the states of the polarization controller (PC) at room temperature. The switchable number is abundant comparing with the former experiment based on the wavelength-switchable fiber laser [22]. Meanwhile, the quad-wavelength fiber laser emission is achieved in the experiment except that the temporal stability should be enhanced by the methods of depressing the gain competition.

2. The Mach–Zehnder interference based on few-mode fiber

Few-mode fiber (FMF) is a special multi-mode fiber with several number of core modes [23,24]. In the experiment, the refractive index profile of the designed FMF is shown in Fig. 1(a). Meanwhile, the photomicrograph of the laboratory-made FMF facet is inserted in the figure. The fiber is fabricated by the modified chemical vapor deposition (MCVD) and the solution-doping technique. The fiber is doped with germanium in silica with a little subsidence in the core of fiber. The outer diameter of the FMF is about 140 μm. The maximal refractive index difference (MRID) of the fiber is about 1.44%. The linear polarization mode approximation is adopted in analysis. The effective refractive indices (ERIs) of the core modes with different wavelengths are shown in Fig. 1(b). In the remarkable wavelength ranges, several core modes could effectively propagate in the designed FMF.

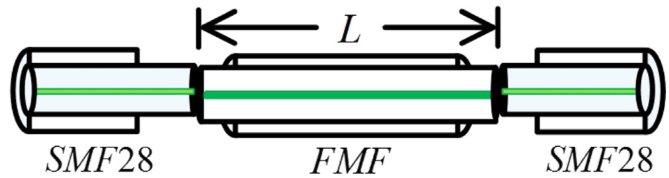

Fig. 2. Schematic diagram of the proposed fiber structure.

The proposed fiber filter with the core-offset structure is shown in Fig. 2. The standard SMF (Corning: SMF28-TM) is utilized to lead the power in/out of the fiber. The light from a broadband source (BBS) is injected into the FMF at the core-offset structure through the lead-in fiber. Only several core modes are effectively excited in the FMF. In the experiment, the excited core modes can be selected by adjusting the core-offset distance appropriately. The excited cladding modes are lost by absorption of the coating of FMF.

When the fundamental mode in the lead-in fiber is injected into the FMF at the first core-offset splicing region, the input power is coupled into two separate modes in the FMF. Due to different propagation constants, the relative phases of different modes change with the propagation in the fiber, leading to a grating-like intensity distribution with the period equal to the beating length. Therefore, interference occurs when optical beams from FMF meet at the second core-offset splicing region. The output power I can be expressed as [25]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\varphi) \quad (1)$$

where I_1 and I_2 are the power of the corresponding core modes propagating in the FMF, respectively. $\Delta\varphi$ is the phase difference between the modes which can be expressed as:

$$\Delta\varphi = 2\pi\Delta n_{eff}L/\lambda = 2\pi(n_{eff,1} - n_{eff,2})L/\lambda \quad (2)$$

where L is the length of the FMF, λ is the input wavelength in vacuum, Δn_{eff} is the effective refractive index difference (ERID) between the propagating modes, and $n_{eff,i}$ (i=1 or 2) is the effective refractive index of the core mode, respectively. When the phase difference satisfies the condition $\varphi=(2m+1)\pi$, $m=0,1,2,\ldots$, the attenuation maxima wavelength appears. The spacing between the adjacent attenuation peaks, namely: free spectral range (FSR), can be approximated by:

$$\Delta\lambda \approx \lambda^2/\Delta n_{eff}L \quad (3)$$

When the light from the source is injected into the MZI, the interference occurs at the lead-out fiber and is monitored by an optical spectrum analyzer (OSA) with the resolution of 0.02 nm. The transmission spectrum is shown in Fig. 3(a) with the 3 dB insertion loss. The length of the FMF is about 57 cm.

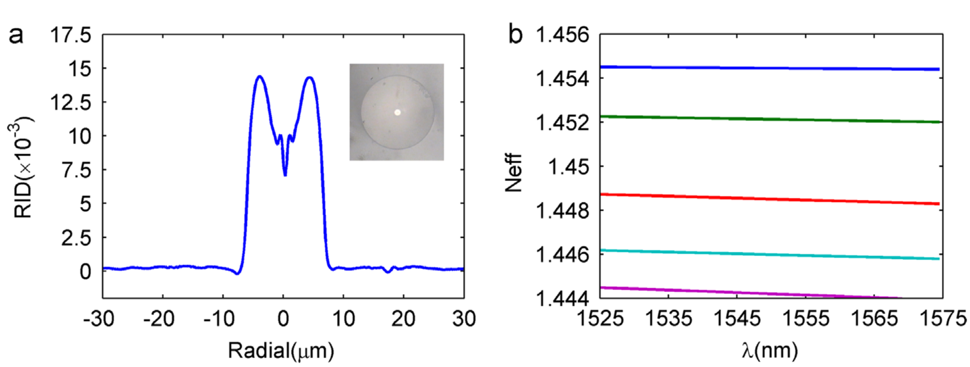

Fig. 1. (a) The refractive index profile of the designed FMF. (b) The ERI (Neff) changes with the different wavelengths.