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Switchable dual-wavelength erbium-doped fiber ring laser with tunable wavelength spacing based on a compact fiber filter

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ABSTRACT

In this paper, using a compact fiber filter (CFF), we demonstrate a dual-wavelength erbium-doped fiber ring laser with tunable wavelength spacing. The two oscillation wavelengths are specified by a fiber modal interferometer (MI) and a fiber Bragg grating (FBG) embedded in the MI, which consists of the CFF. Due to the deeply saturated spectral hole-burning (SHB) effect in the erbium-doped fiber, stable dual-wavelength operation is achieved at room temperature and the wavelength spacing can be tuned from 9.29 nm to 11.11 nm continuously when the strain applied to the CFF is changed. By adjustment of the attenuator in the cavity, the laser can operate in dual-wavelength or in wavelength switching modes.

1. Introduction

Dual-wavelength erbium-doped fiber lasers (EDFL) have attracted much interest in recent years due to their applications in sensing [1], microwave photonic generation [2,3] and lidar-radar systems [4]. Because the effect of homogeneous gain broadening can lead to strong mode competition in the EDFL, it is difficult to obtain stable dual-wavelength operation at room temperature. Different methods have been proposed to solve this problem, such as cooling of the erbium-doped fiber (EDF) in liquid nitrogen [5], the use of four wave mixing effect in the high nonlinear fiber [6], enhancing the polarization hole burning (PHB) by utilizing a fiber Bragg grating (FBG) written in a high birefringence (Hi–Bi) fiber [7] and improving the spectral hole-burning (SHB) effect in the erbium-doped fiber [8]. Compared to the traditional dual-wavelength EDFLs, the laser which can realize the wavelength spacing tuning and switch will be more flexible and valuable [9–12]. Using two FBGs, Mable et al. propose a tunable dual-wavelength fiber laser, in which the spectral spacing can be tuned from 1.3 nm to 7.2 nm [11]. Guillermo et al. demonstrate a tunable dual-wavelength distributed-feed-back fiber laser, where the tunability is carried out by inducing two dynamic phase shifts superimposed locally in the FBG. The wavelength spacing is continuously tuned from 0.128 to 7 GHz [12]. Thus the research on the novel methods to realize the wavelength spacing tuning is very important.

In this paper, we propose a switchable dual-wavelength erbium-doped fiber ring laser with tunable wavelength spacing based on a compact fiber filter (CFF). The filter is composed of a FBG embedded in a fiber modal interferometer (MI). Stable dual-wavelength operation at room temperature can be achieved due to SHB effect in the erbium-doped fiber. Wavelength switching can be obtained by means of cavity loss control. Because of the different responses of the fiber MI and the FBG to strain [11], the wavelength spacing can be adjusted when we change the strain on the filter. The wavelength spacing can be tuned from 9.29 nm to 11.11 nm continuously, and it may be suitable for a tunable continuous-wave terahertz (THz) optical beat source.

2. Structure and theory of the compact fiber filter

Fig. 1 shows the configuration and fabrication of the compact fiber filter. The fiber MI consists of a segment of photosensitive fiber (PSF) which is spliced to two section of the single mode fiber (SMF). Point A is fused without core-offset and a core-offset is introduced at point B. Because the core diameter of the PSF is smaller than that of the SMF, considering the mismatch of the core, the cladding modes in the PSF will be excited and construct the modal interference with the core mode at the other end of the PSF. Using the phase mask technique, a fiber Bragg grating is also embedded in the PSF.

The operating principle of the MI can be explained by using the mode theory in the fiber. Assuming the light in the input SMF has a fundamental mode field distribution $E(r, 0)$ and the field profile

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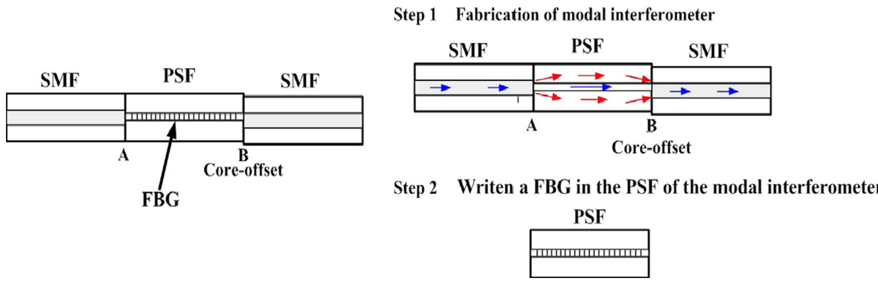

Fig. 1. Schematic configuration and fabrication of the compact fiber filter.

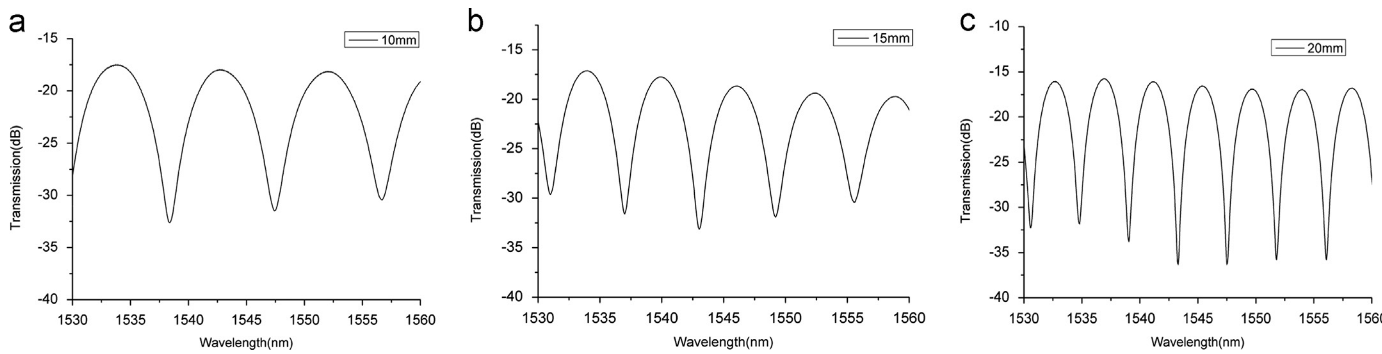

Fig. 2. Transmission spectra of the MI with different lengths of the PSF.

within PSF is $\psi(r)$, the excited field in the PSF can be written as

$$\psi(r) = \sum_{m=1}^{M} \psi_m(r) \tag{1}$$

$$E(r,0) = \sum_{m=1}^{M} \eta_m \psi_m(r) \tag{2}$$

$\psi_m(r)$ represents the mth eigenmode in the PSF. M is the total number of the mode in the PSF and η_m is the excitation coefficient for each mode. According to the mode orthogonal relationship, η_m can be expressed as

$$\eta_m = \frac{\int_0^\infty E(r,0)\psi_m(r)rdr}{\int_0^\infty E(r,0)E(r,0)rdr} \tag{3}$$

Since the modes in the PSF own different propagation constants β_m, at a certain propagation distance z, the field can be calculated by

$$E(r,z) = \sum_{m=1}^{M} \eta_m \psi_m(r) e^{j\beta_m z} \tag{4}$$

Finally, at the output cross section of $z=L$, due to the longitudinal coupling between the modes $E(r, L)$ in the PSF and the guide mode $E_0(r)$ in the output SMF, the overlap integral of their modal fields determines the normalized output intensity as

$$T = 10\log_{10} \frac{\left| \int_0^\infty E(r,L)E_0(r)rdr \right|^2}{\int_0^\infty |E(r,L)|^2 rdr \int_0^\infty |E_0(r)|^2 rdr} \tag{5}$$

Considering the transmission loss, using Eq. (5), the light propagation in the whole structure can be analyzed. The core diameter of the PSF and SMF is 4 μm and 9.9 μm, respectively. The cladding diameter of the two kinds of fiber is both 125 μm. In the SMF, the refractive indices of the core and cladding are 1.450 and 1.445. In the PSF, the refractive indices of the core and cladding are 1.470 and 1.442. According to the theoretical and experimental analysis in Ref. [13], to obtain the maximum extinction ratio(ER) in the transmission spectra of the MI, the core-offset at the point B should be 8 μm.

When the length of the PSF is changed, the wavelength spacing $\Delta\lambda$ between the two adjacent transmission maximums of the MI can be expressed as

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L} \tag{6}$$

where Δn is the difference of the effective refractive index in the core and cladding, λ the free-space wavelength in the vacuum, L is the length of the PSF, respectively. We can find that $\Delta\lambda$ is inversely proportional to the length of the PSF. Using the tunable laser and power meter in the lightwave measurement system (Agilent 8164), the transmission spectra of the MI are recorded. Fig. 2 (a–c) shows the transmission spectra of the MI when the length of the PSF is 10 mm, 15 mm and 20 mm, respectively. The experiment results are well consistent with the theoretical predictions.

When a FBG is written in the PSF, due to the reflection of the FBG, there will be a dip in the transmission spectrum of the CFF, which is corresponding to the center wavelength of the FBG.

3. Experiment setup and results

Fig. 3 shows the configuration of the fiber laser. It is mainly composed of erbium-doped ring cavity and the CFF. The core-offset in the CFF is set as 8 μm. Because the reflectivity of the FBG is proportional to the length of the FBG when the index perturbation is constant [14], to increase the wavelength spacing $\Delta\lambda$ between the two adjacent transmission maximums of the MI and obtain higher reflectivity of the FBG, the length of the PSF is optimized and chosen as 10 mm. The ultraviolet laser we used is Innova 90 °C Fred, and the output power is 35 mW when the FBG is written in the PSF. The transmission spectrum of the CFF is shown in the Fig. 4. It can be found that there is a dip in the spectrum, which is caused by the reflection of the FBG. According to the operation principle of the filter, the fiber laser can be considered as the dual-cavity oscillator. Cavity 1 operates in the direction (A–B–C–D–G–A), while cavity 2 operates in the direction (A–B–C–E–F–D–G–A) due to the reflection of the FBG. The two