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Stable and widely tunable single-/dual-wavelength erbium-doped fiber laser by cascading a twin-core photonic crystal fiber based filter with Mach-Zehnder interferometer

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ABSTRACT

A stable and widely tunable single-/dual-wavelength erbium-doped fiber laser (EDFL) is proposed by cascading a homemade twin-core photonic crystal fiber (TCPCF) based filter with Mach-Zehnder interferometer (MZI). By bending the TCPCF, single-wavelength lasing can be tuned from 1560.4 nm to 1583.44 nm with the tuning step of ~0.78 nm and the widely tunable wavelength range over 23.04 nm can be achieved. Furthermore, by adjusting polarization controller, the output lasing can be switched from single-wavelength to dual-wavelength; the dual-wavelength lasing with wavelength interval of 0.78 nm can be tuned over a range of 33.82 nm from 1559.72 nm/1560.48 nm to 1593.54 nm/1594.32 nm. The tuning step and the interval of dual-wavelength is determined by the MZI. The SMSR of single- and dual-wavelength are higher than 45 dB and 42 dB, respectively. In addition, the stability of output lasing is measured experimentally. Excremental results demonstrate that the wavelength drift is less than 0.02 nm and peak power fluctuations of single-/dual-wavelengths are less than 0.47 dB and 0.8 dB, respectively. Such wide tuning range, small wavelength drift and high power stability makes this tunable EDFL have a potential application in the fields of optical fiber communication and sensing.

1. Introduction

By taking advantages of widely tunable range, excellent stability and high side mode suppression ratio (SMSR), tunable erbium-doped fiber lasers (EDFLs) have attracted a great deal of attentions since they have wide applications in optical communication, optical fiber sensing, microwave generation [1–4]. One of the most widely used methods to realize a tunable EDFL is to introduce a filter into the laser as wavelength tuning components, for instances, fiber Bragg gratings (FBG) [5,6], interferometers including Fabry–Pérot interferometer and Mach-Zehnder interferometers [7–9], filters based on special fibers like few-mode fibers, hollow-core photonic bandgap fiber and twin-core fiber (TCF) [10–12], etc. Among them, TCF based filters have unique mode coupling characteristics and extremely compact in-fiber structure that they can be very helpful to implement a compact tunable EDFL [13,14]. Usually, the preform of conventional TCF is made by grooving or drilling technique. This makes the fabrication process complicated; furthermore, it is very difficult to fabricate conventional TCF with small core distance and thus the coupling length of conventional TCF is too long to make compact optical devices [15,16]. However, photonic crystal fibers (PCFs) have flexible structure design and stack and drawing method allows to construct fiber preform with more complicated structures, especially dual-core or multi-core PCFs [17,18]. By designing the hole pitch, the coupling length can be flexible controlled and thus the shorter coupling length can be achieved. Taking use of the advantage of stack and drawing method, an asymmetric twin core PCF (TCPCF) has been developed in our lab. With this homemade TCPCF, we construct a TCPCF based filter that is introduced into EDFL to obtain stable and widely tunable output lasing.

On the other hand, because of the homogeneous gain broadening of EDF at room temperature, tunable dual-wavelength lasing output is difficult to achieve. In order to attenuate mode competition caused by EDF and obtain tunable dual-wavelength lasing output simultaneously, it often needs a compound filter implanted in the laser cavity. For example, as early as 2004, a tunable dual-wavelength EDFL whose wavelength spacing can be tuned from 0.56 nm to 0.68 nm and the SMSR is 35.6 dB was realized by cascading a Hi-Bi FBG with a Sagnac fiber loop [19]. In 2007, a tunable dual-wavelength laser whose tuning range is over 20 nm and SMSR is ~30 dB was obtained by combing polarization-maintaining fiber based filter with a tunable bandpass filter [20]. The tuning range is obviously increased,

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but the SMSR is still relatively low. In recent years, with the commercialization of optical fiber devices and filter, the performance of tunable lasing output is significantly improved. In 2013, Yin et al. realized a tunable multi-wavelength EDFL by cascading TCF based filter with a nonlinear optical loop mirror and a standard MZI [21], which exhibit tuning range of 24 nm, SMSR of ~39 dB, and wavelength shift of 0.04 nm. In 2016, a tunable dual-wavelength EDFL was proposed by connecting a hollow core Bragg fiber based filter with a Sagnac fiber loop [22], which had the tuning range of 0.5 nm, SMSR of 50 dB and peck power fluctuation of 2 dB. In 2017, a quadruple-wavelength tunable laser was achieved by employing PM-FBG and MZI [23], which tunable range was ~2.6 nm and power fluctuation was ~0.9 dB while the SMSR was remained at 34.9 dB. Therefore, it remains a challenge for EDFL to own wide tunable range, high stability and high SMSR at the same time.

In this paper, a stable and tunable single-/dual-wavelength erbium-doped fiber laser (EDFL) with widely tuning range, high stability and high SMSR is constructed by introducing a cascading filter with TCPCF based filter and a standard Mach–Zehnder interferometer (MZI). Here the TCPCF-based filter simultaneously works as the wavelength selector and the polarization dependent element to induce PHB effect the same as our laboratory previous work[16]. In our experiment, the single-wavelength lasing of the tunable laser could be tuned within the wavelength range over 23.04 nm, and dual-wavelength lasing could be tuned in a much wider range of 33.82 nm. The mechanism of bending TCPCF for wavelength tunability is also illustrated. In addition, the wavelength and power stability of the output laser at room temperature were also investigated.

2. Tunable cascading filter based on TCPCF

2.1. Structure and principle

The TCPCF-based filter shown in Fig. 1 (a) is formed by splicing a segment of homemade TCPCF between two segments of SMF. The cross section of TCPCF is shown in Fig. 1 (b). One core is arranged at the center of TCPCF to easily align with the core of the SMF and another core is designed to place off the axis of the TCPCF to enhance a bending response. The outer diameter of the homemade TCPCF is 125 μm, the air hole pitch is 7.5 μm and the diameter of air holes is 5.25 μm. The diameter of two germanium-doped cores is 3 μm and the refractive index difference between the germanium-doped core and the pure silica is 0.003. Since the two cores of TCPCF can be considered as two parallel waveguides, the coupling of energy occurs when light propagates through the two cores.

In our experiment, by using core-to-core mode to splice the TCPCF and SMF, the input optical power is all injected into the central core and the power will transfer between the twin cores. Here, we assume that the parameters of twin cores are consistent and the normalized input light amplitude matrix can be expressed as $\mathbf{A}(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$. According to coupled-mode theory [24,25], the normalized output amplitude may be expressed in terms of the transfer matrix as

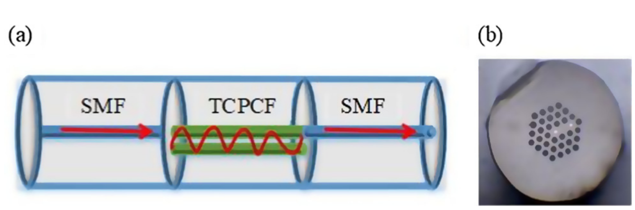

Fig. 1. Schematic diagram of the proposed TCPCF based filter (a) and the cross section of homemade TCPCF (b).

$$\mathbf{A}(z) = \mathbf{T}(z)\mathbf{A}(0), \quad (1)$$

where **T** is the transfer matrix of the TCF-based filter, which can be expressed as

$$\mathbf{T}(z) = \begin{bmatrix} \cos(Sz) - j\cos(\frac{K}{S})\sin(Sz) & -j\sin(\frac{K}{S})\sin(Sz) \\ -j\sin(\frac{K}{S})\sin(Sz) & \cos(Sz) + j\cos(\frac{K}{S})\sin(Sz) \end{bmatrix} \quad (2)$$

Here,$S = \sqrt{K^2 + \delta^2}$, $\delta = (\beta_2 - \beta_1)/2$where β_1 and β_2 are the propagation constant of twin cores and the coupling coefficient K is a function of wavelength. According to Eqs. (1) and (2), the output amplitude of central core after transmitting a length z is given by Eq. (3)

$$A(z) = \left[\cos(Sz) + j\frac{\delta}{S}\sin(S)\right]\exp(-j\delta z) \quad (3)$$

Assuming that the parameters of the two cores are the same, the value $\delta = (\beta_2 - \beta_1)/2 = 0$. Thus the output power of central core after transmitting a length z is

$$P(z) = A(z)A^*(z) = \cos^2(Kz) \quad (4)$$

According to equation (4), when the condition

$$K(\lambda_n) = (n + 1/2)\pi/z, (n \in N^*) \quad (5)$$

is satisfied, the transmission power $P(z)$ reaches the peak. Fig. 2 shows experimentally measured transmission spectrum of TCPCF based filter. The free spectral range refers to wavelength space between two adjacent dips (or peaks).

Making λ_n and λ_{n+1} be the wavelengths corresponding to two adjacent peaks, the FSR of TCPCF can be calculated as

$$\Delta\lambda_{TCF} = \frac{\pi}{z\frac{K(\lambda_n) - K(\lambda_{n+1})}{\lambda_n - \lambda_{n+1}}} \approx \frac{\pi}{z\frac{\partial K(\lambda)}{\partial\lambda}} \quad (6)$$

Eq. (6) indicates the FSR is inversely proportional to the length of the TCPCF and the derivative of the coupling coefficient to the wavelength. It can be seen from Fig. 2 that FSR is ~25 nm when the length of TCPCF is 11.2 cm. By changing the length of TCPCF, the transmission spectrum of TCPCF based filters is depicted in Fig. 3. It can be observed that the FSR decreases as the length of TCPCF increases, which are consistent with the theoretical expectation.

In order to achieve a constant tuning step during tuning process, we cascade a MZI with the TCPCF-based filter to construct a compound filter, as shown in Fig. 4. Here, the path difference ΔL of two arms of MZI is fixed at ~2.1 mm. According to the equation $\Delta\lambda_{MZI} = \lambda^2/(n \cdot \Delta L)$, the calculated FSR $\Delta\lambda_{MZI}$ is ~0.78 nm when the wavelength λ is 1550 nm and refractive index n of the

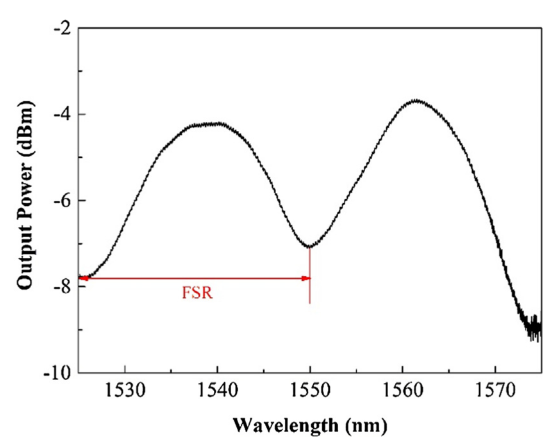

Fig. 2. Transmission spectrum of TCPCF based filter.