



Tunable multiwavelength fiber laser based on a θ -shaped microfiber filter

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Abstract

We propose and experimentally demonstrate a flexibly tunable multiwavelength fiber ring laser based on a θ -shaped microfiber filter in conjunction with an erbium-doped fiber amplifier. The stable operation of the multiwavelength lasing is successfully achieved at room temperature, with the peak power fluctuation less than 0.519 dB. By micro-adjusting the cavity length of the filter, the channel spacing can be independently tuned within the gain range of the optical amplifier. We have achieved 0.084 nm-spacing 48 channel, 0.147 nm-spacing 25 channel, 0.190 nm-spacing 20 channel and 0.302 nm-spacing 15 channel lasing wavelengths at room temperature.

1 Introduction

Multiwavelength fiber lasers have attracted much attention due to their various advantages such as multiwavelength operation, simple structure, low cost and insertion loss, resulting in versatile applications to dense wavelength division multiplexed (DWDM) systems [1], optical fiber sensors [2], optical component testing [3], spectroscopy [4], etc. To obtain the multiwavelength lasing emission, it is vital to incorporate a multi-channel filter to generate multiwavelength output. A variety of all-fiber filters such as equivalent

Lyot birefringent fiber filters [5], fiber Sagnac loop mirrors [6], Mach–Zehnder interferometers [7], Fabry–Pérot filters [8], cascaded long-period fiber gratings [9] and chirped or sampled fiber gratings [10] have been proposed for wavelength selection. However, there are several disadvantages including high cost, complicated fabrication, difficulty of tuning and so on.

In recent years, optical microfiber, which refers to the fiber whose diameter is in microns level [11, 12], has advanced significantly owing to their tight confinement, high fractional evanescent field, robustness, configurability, flexibility and compactness. Particularly, since the refractive index contrast between the silica core and the air-clad is greatly higher than that of the conventional optical fiber, the nonlinear coefficient of the microfiber is higher, which can further conduce to oppress the mode competition in the laser cavity.

Meanwhile, with the increasing demand for the miniaturization of fiber-optic components or devices, a lot of microfiber-based filters with compact constructions, such as Microfiber loop resonators (MLRs) [13], Microfiber coil resonators (MCRs) [14], microfiber knot resonators (MKRs) [15], have been proposed and experimentally demonstrated. Nevertheless, these constructions lacking of stabilities, robustness or simplicity and their transmission spectra are always of uneven profile, or large linewidth, which limit their applications.

In addition, several investigations have been carried out on microfiber filter based lasers. For example, Liu et al. employed an MKR as a comb filter to obtain

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multiwavelength lasing oscillation [16]. In our previous work, Li et al. utilized cascaded MKRs with Vernier Effect in the fiber ring cavity to generate the SLM laser operation [17] and Jia et al. demonstrated a wideband multiwavelength fiber ring laser based on a microfiber Fabry–Pérot filter [18].

Tunability of the channel spacing is very useful for the above-mentioned applications of multiwavelength fiber lasers (particularly in some reconfigurable or upgradable optical communication systems). Previously, we have demonstrated a multifunctional, tunable and wideband θ -shaped microfiber filter [19, 20], which is more compact and tunable than traditional filters by utilizing the reflecting transmission.

In this paper, we further propose and experimentally demonstrate a tunable multiwavelength fiber laser by incorporating the θ -shaped filter in the ring cavity. This θ -shaped filter shows both superb comb filtering performance and ability of easy tuning. Channel spacing changing from 0.095 to 0.302 nm and channel number changing from 48 to 15 are experimentally demonstrated. The stability of the proposed multiwavelength fiber laser is also investigated at room temperature.

2 Working principle

Figure 1 shows the schematic configuration of the θ -shaped microfiber filter used in the proposed fiber ring laser [19]. A cavity divided by a bridge is fabricated using only one microfiber. There coexist clockwise (CW) mode, counter-clockwise (CCW) mode and their coupled mode in the particular structure, resulting in distinct reflective/transmitting filtering spectra. On the basis of the ultra-compactness, the reflected output of the proposed θ -shaped microfiber resonator is adopted in the optical fiber laser ring cavity to investigate the lasing output.

For simplification, we assume that the two coupling areas (I, II) possess the identical coupling efficiency k and loss coefficient γ . Besides, l_0 , l_1 , and l_2 represent the distances from port 3 to port 6, from port 2 to port 5 and from port 7 to port 4, separately. The effective cavity length of the filter, L , is given by Eq. (1). According to the transmission matrix

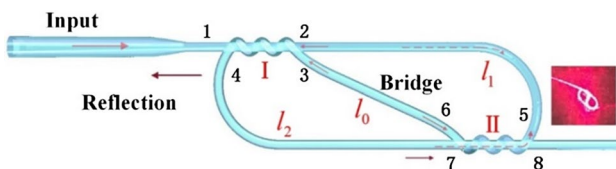


Fig. 1 Schematic configuration of the θ -shaped microfiber filter. Inset: picture of the filter

theory, the transmissivity can be calculated and then the reflected transfer function can be obtained by Eq. (2).

$$L = l_1 + l_2 \tag{1}$$

$$r = j \times \exp [j\beta(l_1 + l_0)] \times (1 - \gamma)(1 - k)^{1/2}k^{1/2} \times \left\{ \frac{2 \times (1 - \gamma)^{1/2}(1 - k)^{1/2} \frac{(1 - \gamma)(1 - k) \exp(j\beta L)}{[1 + (1 - \gamma)k \exp(j\beta L)]^2 +}}{2(1 - \gamma)^{1/2}(1 - k)^{1/2}} \frac{1}{1 + (1 - \gamma)k \exp(j\beta L)} \right\} \tag{2}$$

When satisfying the condition:

$$\beta L = \left(m + \frac{1}{2}\right)\pi. \tag{3}$$

The transmission output reaches maximum, while the reflection output achieves the minimum, corresponding to the resonance dips. Hence, the free spectral range (FSR) can be obtained as:

$$\text{FSR} = \frac{\lambda^2}{n_{\text{eff}}L}, \tag{4}$$

where n_{eff} is the effective refractive index of the microfiber. As depicted in Fig. 2b, a simulation of the θ -shaped filter is carried out with l_0 , l_1 , l_2 , k and γ of 2, 4, 4 mm, 0.1, and 0.3, respectively. It can be seen that the spectrum has an even profile and a wide bandwidth with the FSR of 0.226 nm, the 3 dB linewidth of 0.137 nm, which proves that the construction is a dense narrow-linewidth comb filter.

According to Eq. (4), the FSR can be altered continuously by only changing the effective refractive index or cavity length. It is worth noting that both the effective refractive index and cavity length will be influenced by surrounding temperature of the filter. Therefore, the proposed filter has the potential for temperature tuning and mechanical tuning fiber lasers [21]. In this paper, the cavity length is altered using microprobes to tune the lasing output. As shown in Fig. 2, when we change the value of L from 4, 6–8 mm, the FSR varies from 0.453, 0.302–0.226 nm, correspondingly. This simulation indicates that the filter has sufficient accuracy and range for the proposed fiber ring laser. The θ -shaped microfiber filter offers a large filtering range and great flexibility to control the FSR of the filtering spectra, which plays an essential role in generating tunable multiwavelength lasing.

Another vital item for the θ -shaped microfiber filter is the extinction ratio (ER) of spectrum, which is defined as the difference between the intensities of the highest fringe and the lowest fringe. On the basis of Eq. (2), ER depends on coupling efficiencies and coupling loss coefficients, which can be tuned by micro-adjusting the coupling areas. Moreover,

Fig. 2 **a** Enlarged spectra of the section within the dotted rectangle in **b** at different values of l_1 and l_2 . **b** Typical simulated spectrum of a θ -shaped microfiber filter

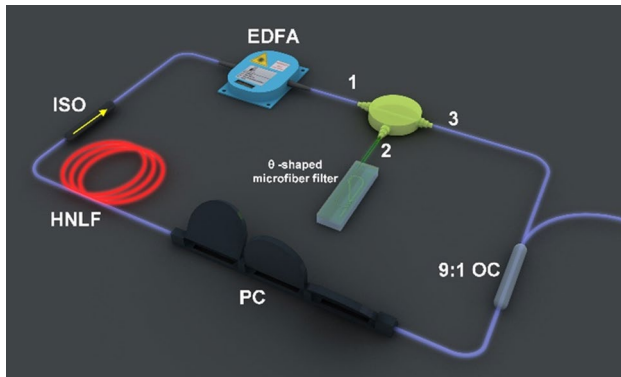
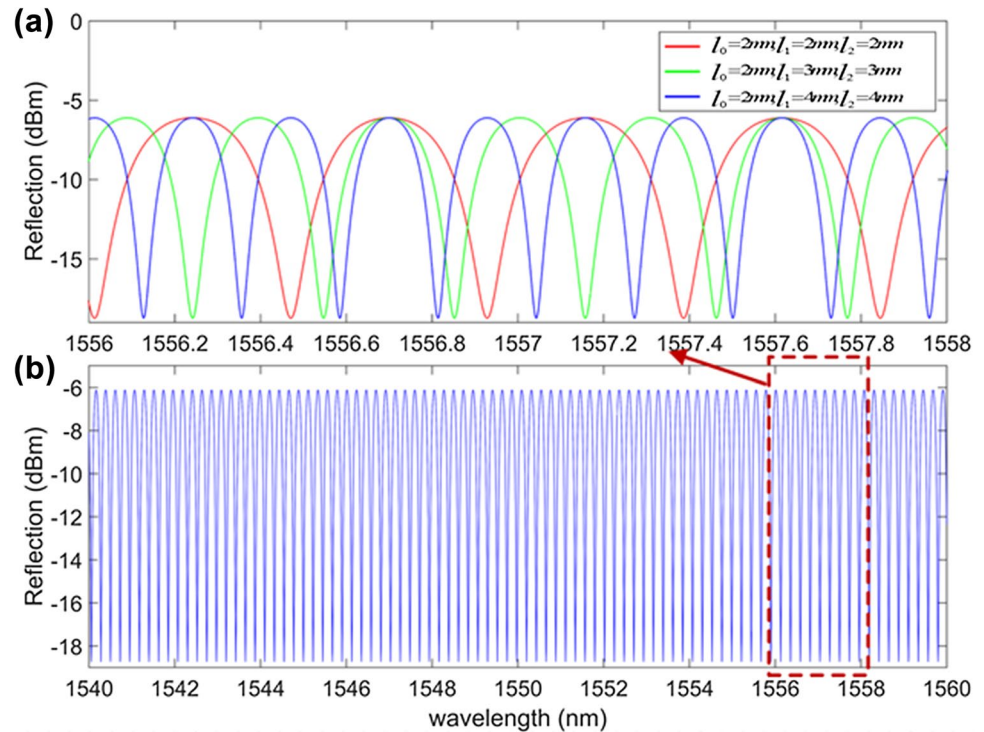


Fig. 3 Experimental setup of the proposed laser

according to the simulation result, ER will increase when the coupling efficiencies or loss coefficients decrease. Obviously, higher ER can lead to higher side-mode suppression ratios (SMSR) of the laser.

3 Experimental setup and results

The experimental setup of the proposed laser is illustrated in Fig. 3. In the ring cavity, an erbium-doped fiber amplifier (EDFA) acts as the gain medium. An isolator is implemented to sustain the unidirectional oscillation. A polarization controller (PC) is used to manipulate the polarization state. A 1-km spool of highly nonlinear fiber (HNLF, dispersion of

-0.396 ps/nm/km at 1545 nm and nonlinear coefficient of 11/W/km) is employed to suppress the mode competition and broaden the output spectrum. The laser output is extracted from the 10% port of a 90:10 optical coupler (OC) and 90% power remains inside the cavity for feedback. The θ -shaped microfiber filter and circulator form the part to provide filter property to obtain the multiwavelength lasing oscillation. The mechanism of multiwavelength lasing generation can be attributed to the inhomogeneous loss.

The microfiber used for constructing the filter was obtained by flame-heated taper drawing with the drawing speed of 0.15 mm/s and distance of 70 mm and its diameter was about 2.37 μm . The θ -shaped microfiber filter sample is shown in the inset of Fig. 1. Furthermore, a glass slide with a low refractive index Teflon film is employed to reduce the energy leakage as well as support the θ -shaped microfiber filter. And then, they are protected by a glass cover to isolate ambient disturbances such as contamination and air flow. A broadband light source is injected into the filter to observe the filtering effects. Figure 4 exhibits a stable comb reflection filtering spectrum of the filter monitored in the interrogator within the wide range from 1510 to 1590 nm. A zoom-in spectrum of Fig. 4 can be seen in Fig. 5e with FSR of 0.19 nm and ER more than 10 dB, which just fits the simulation results in Fig. 2.

Through carefully adjusting and fixing the θ -shaped microfiber filter inserted in the laser ring cavity, stable lasing with a pump power of 40 mW is achieved. The FSR of the θ -shaped microfiber filter is altered by manually

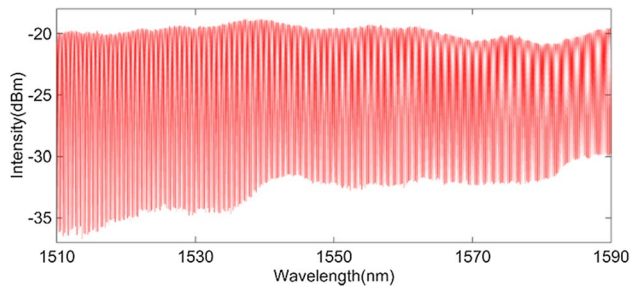


Fig. 4 Reflection filtering spectrum of the filter

changing the cavity length. Two fiber microprobes are used to micro-adjust the cavity length with the precision of less than 1 mm. Figure 5 presents the comb reflection filtering spectrum and the corresponding output spectrum of the multiwavelength fiber ring laser when the channel spacing is tuned to 0.084 nm [(a) and (b)], 0.147 nm [(c) and (d)], 0.190 nm [(e) and (f)], and 0.302 nm [(g) and (h)]. The wavelength span of the optical spectrum analyzers (OSA) is set to 12 nm for Fig. 5a, c, e and g as well as 4 nm (different value) for Fig. 5b, d, f, h. The resolution and sensitivity of

the OSA used in the measurement are 0.016 nm and -65 dBm, respectively. One can see from Fig. 5a, c, e and g that dynamic decreasing of the channel numbers within 3 dB bandwidth as 48, 25, 20, and 15, respectively, and the SMSR of each lasing channel are all higher than 18 dB.

For practical applications, the stability of the proposed laser is validated at room temperature. The optical spectrum is monitored to verify the stability of the proposed multiwavelength fiber laser during 1 h. Figure 6 provides the repeated scanning spectrum per 10 min for the 20 lasing channels with the channel spacing of 0.190 nm, which indicates the stability of the laser.

Figure 7 shows the wavelength shifts of 7 channels during 1 h, with no obvious shifts observed within the OSA resolution. The power fluctuations of output lasing wavelengths are also tracked. Figure 8 exhibits the power fluctuations of the 7 lasing wavelengths. Among all these lasing wavelengths, the peak locating at 1564.34 nm has the smallest power fluctuation of only 0.136 dB, varying from -20.461 to -20.325 dBm, while the peak locating at 1560.93 nm has the largest power fluctuation of 0.519 dB, varying from -20.345 to -19.826 dBm. It can be seen that the output spectrum

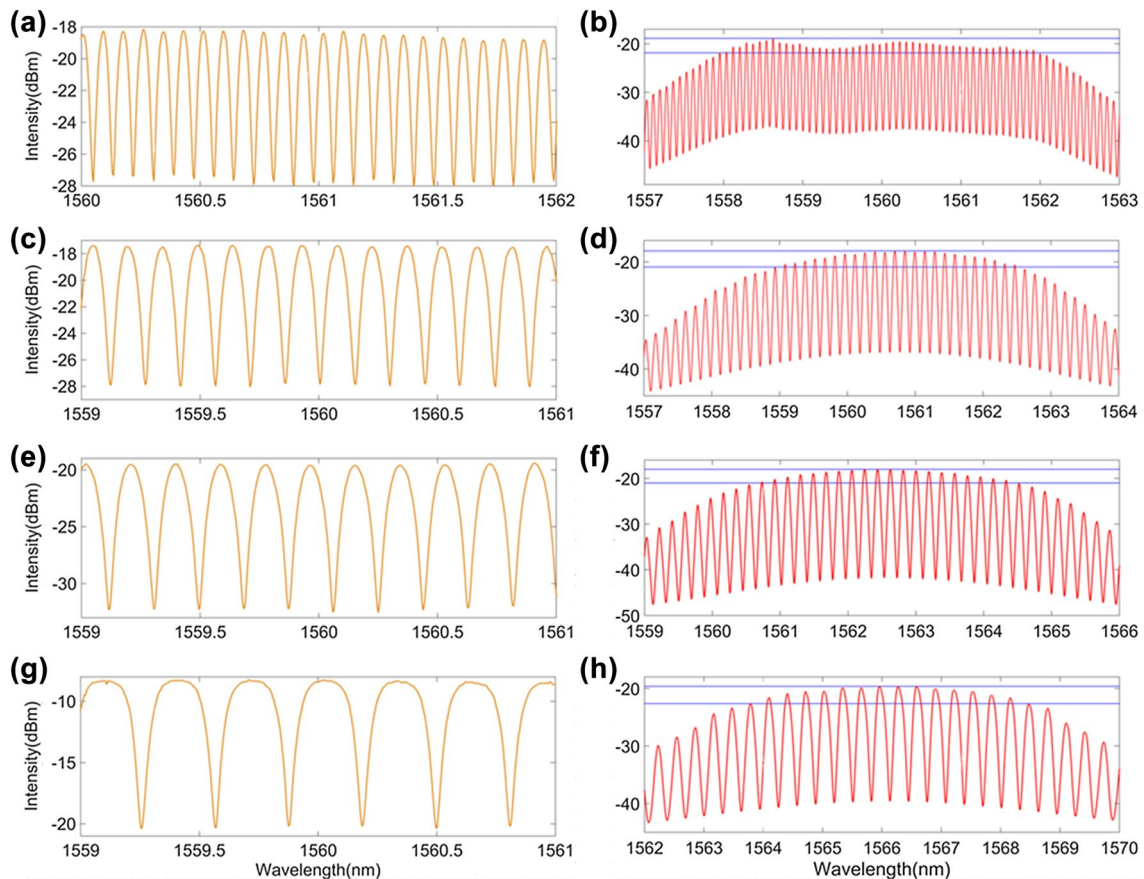


Fig. 5 Comb reflection filtering spectrum and the output spectrum of the proposed multiwavelength fiber ring laser when the channel spacing is tuned to 0.084 nm (a, b), 0.147 nm (c, d), 0.190 nm (e, f) and 0.302 nm (g, h)

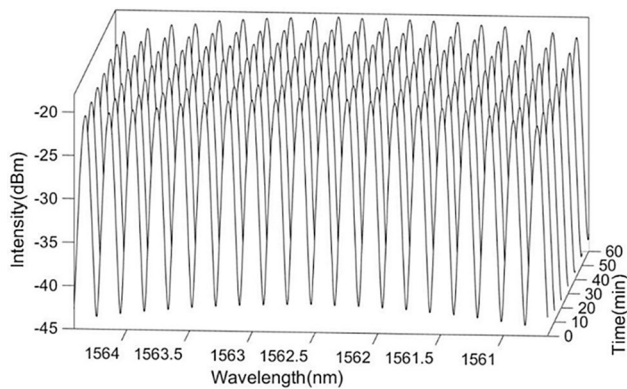


Fig. 6 Scans of wavelength stability and intensity fluctuation

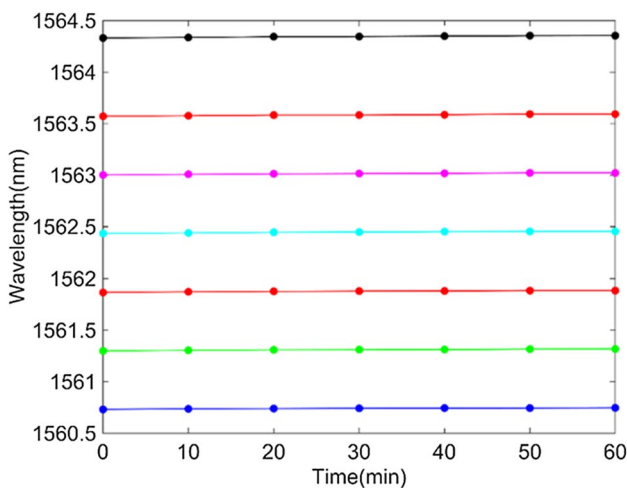


Fig. 7 Wavelength shifts of 7 channels between 1560 and 1565 nm within 1 h

is very stable in both wavelength and power at room temperature. Besides, the stability results of the proposed laser are qualified comparing with the reported microfiber-based lasers and tunable multiwavelength lasers [18, 22–24].

4 Conclusion

A stable multiwavelength fiber ring laser of tunable channel spacing based on a compact θ -shaped microfiber filter has been demonstrated in this paper. The combination of the microfiber and a section of HNLF is employed to induce the inhomogeneous loss mechanism into the laser cavity. Moreover, the channel spacing of the present multiwavelength fiber ring laser can be tuned by adjusting the microfiber cavity length. Multiwavelength lasing with channel spacing of 0.084, 0.148, 0.190 and 0.302 nm has been experimentally demonstrated. 20-wavelength lasing with a

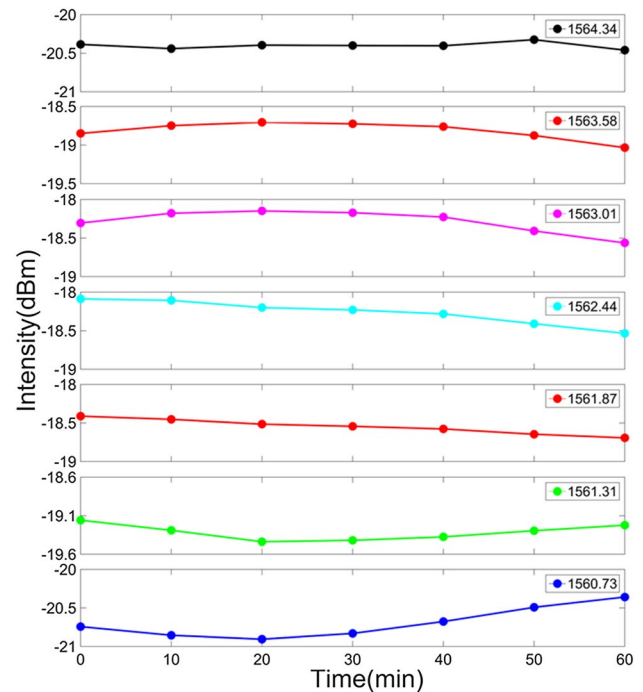


Fig. 8 Power fluctuation tracking of 7 lasing lines between 1560 and 1565 nm within 1 h

wavelength spacing of 0.190 nm has been achieved and the maximal fluctuation of each peak power for ten main lasing channels is less than 0.519 dB within 1 h, which indicates the multiwavelength fiber ring laser is quite stable at room temperature. The fiber laser offers a compact, simple, and low-cost design for a multiple wavelength outputs that can be adopted in future applications.

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