Spectral Tailoring of Random Fiber Laser Based on the Multimode Interference Filter

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ABSTRACT In this paper, we propose and experimentally demonstrate a novel scheme to tailor the spectrum of random fiber laser (RFL) based on the multimode interference effect. A fiber loop mirror (FLM) incorporating multimode interference filter (MMIF) with single mode fiber (SMF)-MMF-SMF structure acts as a wavelength-dependent point reflector in half-opened RFL. By varying the length of MMF, either single wavelength random lasing with specific wavelength or multiwavelength random lasing with selective wavelength spacing can be generated in MMIF-FLM-based RFL. Due to the wide wavelength range of the MMIF, cascaded multiwavelength random lasing can also be realized. The spectrum adjustable all fiberized RFL based on the MMIF shows distinct advantages, such as easy fabrication, wide operating wavelength range, and low-cost. Besides, the MMIF-FLM can has good power handling ability, by combining the MMIF-FLM and the short-length cavity, the proposed MMIF-based forward-pumping RFL also has a great potential to generate high power, high efficiency random lasing with the adjustable spectral property.

INDEX TERMS Random laser, fiber laser, multiwavelength laser, Raman gain, Rayleigh scattering.

I. INTRODUCTION

With the concept of random Rayleigh distributed feedback, a novel kind of 1D random fiber laser (RFL) was experimentally demonstrated in the long standard single mode fiber in 2010 [1]. RFLs have seized lots of attentions in recent years and their unique laser performances have been gradually explored in the aspects of high power, high efficiency [2]–[5], multiwavelength generation [6]–[15], narrow-linewidth [16]–[18] and polarized output [19]–[21]. With the good laser performance and relative simplicity of implementation, RFLs have also proved to be an important novel light source for applications in high power, high efficiency [2]–[5], multiwavelength generation [6]–[15], narrow-linewidth [16]–[18] and polarized output [19]–[21]. With the good laser performance and relative simplicity of implementation, RFLs have also proved to be an important novel light source for applications in high power, high efficiency [2]–[5], multiwavelength generation [6]–[15], narrow-linewidth [16]–[18] and polarized output [19]–[21].

With the incoherent feedback, random fiber laser can be generated with the lasing wavelength corresponding to the gain maxima. However, by inserting the wavelength-dependent elements in the cavity, the random lasing wavelength can be selected. A typical example is the FBG-based half-opened cavity RFL [3]. Multiwavelength generation with random Rayleigh distributed feedback can also be achieved with multiple FBGs [6], and it shows unique power-equalized uniform channels compared with conventional Raman fiber laser. However, the FBGs-based RFLs have the intrinsic drawbacks such as the lack of flexibility and high cost, especially for some special wavelength regimes. Several advanced schemes were proposed to realize multiwavelength RFLs, such as the all fiber Lyot filter incorporating tilted FBG and polarization maintaining fiber (PMF) [9], Hi-Bi photonic crystal fiber loop mirrors [13], polarization maintaining fiber loop mirror [15]. In these schemes, the use of PMF and photonic crystal fiber will increase the system’s cost and the fabrication difficulty (especially for splicing these fibers). Another way to realize multiwavelength RFL is utilizing the ‘active’ nonlinear processes such as stimulated Brillouin scattering (SBS) effect. The SBS based multiwavelength RFLs have been demonstrated in both the 1.5-μm band and 1-μm band [12], [14], and even more than 500 uniform Stokes lines can generated with hybrid Brillouin-Raman gain [10].
However, the wavelength spacing of SBS based multiwavelength RFLs is determined by the SBS frequency shift, which is a fixed value.

Here, we propose to use the multimode interference filter (MMIF) with SMF (single mode fiber)-MMF (multimode fiber)-SMF structure to tailor the spectrum of RFL. As a result, by changing the length of MMF, either single wavelength random lasing with specific wavelength or multiwavelength random lasing with selective wavelength spacing can be generated. Comparing with the previous schemes, the MMIF-based RFL is agile, easy to fabricate and cost-effective, which has the promising applications in optical communications, high power fiber laser, optical sensing and spectroscopy in various wavelength bands.

II. EXPERIMENTAL METHODS

Figure 1 shows a schematic representation of the multimode interference filter and its components. The multimode interference filter (MMIF) used in our work is formed by splicing a segment of step-index MMF (Si2014-E) between two standard SMFs (Corning SMF28). The MMF has $40 \ \mu m$ of core diameter and $125 \ \mu m$ of cladding diameter, the effective refractive index $n_c$ is equal to 1.45.

![FIGURE 1. Schematic diagram of a multimode interference filter.](image)

The signal light propagating along the SMF enters the MMF with an approximate Gaussian-shaped field distribution, and the guided modes of the MM fiber can express as the propagating field inside the SMF [33], [34], i.e.

$$E_{SM}(r, \theta, z = 0) = \sum_{N}^{1} \psi_{n} e_{n}(r, \theta, z = 0)$$

Where $E_{SM}(r, \theta, z = 0)$ is the fundamental mode of the SMF. $N$ and $e_{n}(r, \theta, z = 0)$ correspond to the number of excited modes and the n-th guided mode inside the MMF, respectively. $\psi_{n}$ is the field expansion coefficient and can be calculated from the following cross-correlation formula [34], [35].

In consideration of ignoring mode transitions, the input field of the MMF can be represented by a finite summation over the guided modes, so that the field $E_{MM}(r, \theta, z)$ can be written as

$$E_{MM}(r, \theta, z) = \sum_{N}^{1} \psi_{n} e_{n}(r, \theta, z = 0) e^{-i \beta_{n} z}$$

$$= e^{-i \beta_{1} z} \sum_{N}^{1} \psi_{n} e_{n}(r, \theta, z = 0) e^{-i(\beta_{n} - \beta_{1}) z}$$

Where $\beta_{1}$ and $\beta_{n}$ are the propagation constants of the fundamental mode and the n-th excited mode of the MMF, respectively.

According to equation (1) and equation (2), the reproduction of the input field occurs when the following condition is satisfied for all N modes.

$$(\beta_{n} - \beta_{1}) z = \Delta \beta_{n} z = m \pi \quad \text{with} \quad m = 0, 1, 2 \ldots ,$$

The propagation constants $\beta_{n}$ can be approximated as

$$\beta_{n} \simeq \frac{2 \pi}{\lambda_{0}} n_{c} - \frac{n_{c}^{2} \pi \lambda_{0}}{4 n_{c}^{2} D^{2}}$$

Where $n_{c}$ and $D$ correspond to the refractive index and diameter of the MMF core respectively, and $\lambda_{0}$ is the free-space wavelength.

We define $z_{m}$ as the beat length of the two lowest-order modes, which can be written as

$$z_{m} = \frac{\pi}{\beta_{1} - \beta_{2}} \simeq \frac{4 \pi n_{c} D^{2}}{3 \lambda_{0}}$$

Considering equation (4) and the restricted symmetric interference condition, the length at which single images are formed is given as [36]

$$z = m \left(\frac{3 \pi}{4}\right) \quad \text{with} \quad m = 0, 1, 2 \ldots ,$$

The wavelength spacing $\Delta \lambda$ can be calculated from equation (5) and equation (6), and be written as

$$\Delta \lambda = \frac{n_{c} D^{2}}{z}$$

Figure 2 shows the experimental setup for the MMIF based RFL. The 1365 nm pump is launched into a coil of 50 km SMF via the Port 1 of a wavelength division multiplexer (WDM). Port 2 of the WDM is the pass channel for 1455 nm light-wave, while Port 3 is the pass channel for 1555 nm light-wave. A segment of 40/125 μm step index MMF is spliced between two ports of a wide-band 3dB SMF coupler, forming the MMIF fiber loop mirror (MMIF-FLM). The MMIF-FLM can act as a wavelength-dependent point reflector. By combining the MMIF-FLM and random Rayleigh scattering in the 50 km SMF, a forward-pumping half-opened RFL is constructed. The far end of the 50 km fiber and 1550 nm port of the WDM are angle cleaved to avoid the Fresnel reflection. The spectral response of the MMIF can be tuned by the length of the MMF. Therefore, the spectral behavior can be tailored by...

![FIGURE 2. Experimental setup for the MMIF based RFL.](image)
using different length of MMF in MMIF-FLM. For cascaded operation, another MMIF-FLM attaches to the 1550 nm port of the WDM to form the half-opened cavity for the 1550 nm random lasing. The output of the laser is at the far end of the fiber, an optical spectrum analyzer (OSA) with 0.02 nm resolution and an optical power meter (PM) are used to monitor the spectrum and power of the random lasing, respectively.

### III. RESULTS AND DISCUSSIONS

First, we investigate the spectral tailoring of 1.45 \( \mu \text{m} \) random lasing only, and in this case the Port 2 (1550 nm port) of the WDM is angle cleaved. With the increase of 1365 nm pump power launched into the fiber spool, the 1.45 \( \mu \text{m} \) Stokes light can generate in both forward and backward direction. The backward Stokes light will experience the spectral reshaping in the MMIF-FLM1 and then be reflected by MMIF-FLM1. In this way, the distributed Rayleigh backscattering and MMIF-FLM1 form the half-open cavity. The 1.45 \( \mu \text{m} \) random lasing with specific spectrum determined by the MMIF can generate once the pump power exceeds the threshold, which is \( \sim 0.75 \text{W} \) in our case.

#### A. SINGLE WAVELENGTH SELECTION

According to equation (7), we can deduce that the wavelength spacing increases with the decrease of MMF’s length. When the wavelength spacing of MMIF exceeds the Raman gain bandwidth, single wavelength random lasing with determined wavelength can generate in the proposed MMIF-based RFL. Therefore, in this case, the MMIF-FLM acts as a function of output wavelength selection, which is similar as the FBG. Comparing with FBG, the flexibility improves significantly by using MMIF-FLM, one can change the laser wavelength by simply tuning the length of MMF. Figure 3 shows the laser spectra of two cases with 5 cm and 7 cm of MMF, respectively. The pump power is 1.33 W. Single wavelength generation with OSNR > 35 dB can be realized in both cases.

![Figure 3. Spectrum of single wavelength random lasing with different MMF length.](image)

It can be seen that the central wavelength changes from 1452 nm to 1462 nm when the length of MMF changes from 5 cm to 7 cm. The 3 dB bandwidths are 1.3 nm and 1 nm for 5 cm case and 7 cm case, respectively. It should be noted that the continuous tuning of output wavelength could be further achieved by applying strain on the MMF [35].

#### B. MULTIWAVELENGTH GENERATION

With the relatively long (meter level) MMF, the MMIF can serve as the comb filter for the RFL, and multiwavelength random lasing with adjustable wavelength spacing and wavelength number can generate. Figure 4 shows the spectra evolution of 1.45 \( \mu \text{m} \) multiwavelength random lasing with 2 m long MMF in the MMIF-FLM. When the pump power exceeds the threshold, the random lasing is first stimulated around the left peak of Raman gain curve. Three peaks with the wavelength spacing about 1.214 nm dominate at 0.94 W of pump power. The peaks around the right peak of Raman gain curve can also generate with the increase of pump power. Further increasing the pump power to 1.72 W, more lasing lines can generate and the multiwavelength lasing lines become flatter. Therefore, it can be seen the spectrum shape and the number of generated lasing lines depend on the pump power.

![Figure 4. Spectra evolution of 1.45 \( \mu \text{m} \) multiwavelength random lasing with 2 m MMF.](image)

Figure 5 shows the spectra of RFL with different MMF length in MMIF-FLM. The pump power is 1.80 W in all cases. By increasing the MMF length from 20 cm to 4 m, the number of generated lasing lines increases from 2 to 20. Besides, relatively good spectrum flatness is achieved in all cases, showing the MMIF-based RFL can generate high performance multiwavelength random lasing with controllable spacing and number. The measured wavelength spacing versus MMF length is plotted in Fig. 6. The spacing decreases gradually from 4.708 nm to 0.56 nm when MMF length increases from 20 cm to 4 m. The theoretical values calculated by equation (7) are also plotted in Fig. 6. The experimental results coincide with the theoretical ones well.
Figure 7 shows the output lasing power as a function of 1365 nm pump power with different MMF length in the MMIF-FLM. All the cases exhibit similar output curves with about 0.85 W of the 1st-order random lasing and about 2 W of 2nd-order Raman random lasing. More than 150 mW of output power can be achieved for 1.45 μm random lasing at last. The result verifies that the length of MMF in the MMFI-FLM will not affect the power performance of RFL significantly.

Fig. 8 shows the generated spectra with different placement of MMIF. The length of MMF is 5 m and the pump power is 1.88 W. When the MMIF is placed at the far end of the SMF, it acts as the passive spectral filter. The envelope of generated spectrum repeats in general the generation spectrum of the RFL with broadband FLM [37]. However, when the MMIF is inserted in the FLM, the combination of MMIF and FLM acts as wavelength-dependent point reflector, with the function of intra-cavity filtering. Therefore, in this case, the shape of the spectrum changes and more lasing combs with significant improvement of flatness can be realized. The result validates the importance of MMIF-FLM in spectral reshaping of RFL.

C. CASCADED OPERATION
Due to the wide operation wavelength range of the MMIF, we can also demonstrate the cascaded multiwavelength RFL based on the MMIF-FLM. In this case, another MMIF-FLM2 is attached to the 1550 nm port of the WDM. The length of MMF is 4 m for both the MMIF-FLM1 and MMIF-FLM2. It should be noted that, by using a WDM with the pass channel for both 1.45 μm and 1.55 μm light, only one MMIF-FLM is need and the configuration for cascaded RFL can be further simplified. Fig. 9 depicts the spectral evolution of both 1st-order and 2nd-order random lasing.
FIGURE 9. Spectra evolution of cascaded random lasing at different pump power: (a) 1st-order; (b) 2nd-order.

The spectral evolution of 1st-order random lasing is similar with the case in Fig.4. However, due to the lower 2nd-order lasing threshold, the spectrum of 1.45 µm multiwavelength lasing cannot be as flat as the case without MMIF-FLM2. As for the spectral evolution of 2nd-order random lasing, the spectrum is unstable with many random spikes when the pump power is just above the threshold. Further increasing the pump power, the spectrum can gradually become stable and flattened. Finally, at 2.79 W of 1365 nm pump power, 19 stable lasing lines in the 1.56 µm regime can be realized.

Figure 10 shows the output power as a function of 1365nm pump power for both the 1st-order and 2nd-order random lasing. The measured threshold for the 1st and the 2nd-order random lasing is about 0.85W and 1.66W, respectively. As the 1st-order random lasing start to appear, the output power of the pump lasing decreases rapidly and a nearly full depletion of the transmitted pump power is observed with 1.54W. The maximum output power for the 1.45 µm multiwavelength random lasing is 120 mW and 260 mW of 1.56 µm multiwavelength random lasing can output at 2.8 W of pump power.

FIGURE 10. Output power versus pump power for cascaded RFL.

IV. CONCLUSION

In this paper, a MMIF-FLM based RFL is proposed and experimentally demonstrated with adjustable lasing spectrum. By varying the length of MMF, either single wavelength random lasing with specific wavelength or multiwavelength random lasing with selective wavelength spacing can be generated. We also demonstrate the cascaded multiwavelength random lasing in both the 1.45 and 1.56 µm. The spectrum adjustable RFL based on the MMIF shows distinct advantages such as all fiber structure, low-cost, easy fabrication and wide operating wavelength range. Further work can be done to tailor the spectrum of short cavity based high power RFL [2]–[4] with the MMIF. With the good power handling ability of MMIF-FLM, the MMIF-FLM based forward-pumping RFL has a great potential to generate high power, high efficiency random lasing with the selective wavelength or multiwavelength behavior without using FBG.

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REFERENCES


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