

Multiwavelength erbium doped fiber laser based on microfiber Mach-Zehnder interferometer

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Last decade, the research on multiwavelength erbium-doped fiber lasers (MWEDFLs) was increased dramatically due to its very interesting advantages and a wide range of applications. Many comb filters were proposed to lase multiwavelength from fiber lasers such as Fabry-Perot filter (FPT), photonic crystal fiber (PCF), and Sagnac loop mirror. However, all those filters suffer the disadvantage of less compactness. On the other hand, microfiber Mach-Zehnder interferometer which is fabricated from conventional single mode fiber (SMF) is considered to be the most compact designed to generate multiwavelength fiber lasers. In this paper, we have successfully generated four wavelengths centered at 1549.52 nm, 1553.2 nm, 1556 nm, and 1558.8 nm from erbium doped fiber the laser. Very good stability was observed when the output of the demonstrated laser investigated over one and half an hour. The proposed multiwavelength laser can be seen as a promising multiwavelength light source for various applications including wavelength division multiplexing (WDM) transmission, modern optical communication system, and optical fiber sensor network.

(Received September 25, 2018; accepted April 8, 2019)

Keywords: Multiwavelength, EDFL, Microfiber, Comb filter

1. Introduction

Owing to their many valuable advantages such as very simple structure, highly resistance to electromagnetic interference, stable output and constant free spectral range (FSR) characteristic, multiwavelength erbium-doped fiber lasers (MWEDFLs) have been utilized as efficient light sources in a wide range of applications including wavelength division multiplexing (WDM) transmission, modern optical communication system, fiber spectroscopy, terahertz difference signal generation, frequency mixing, differential absorption lidars (DIALs), radio over fiber (RoF), and optical fiber sensor [1-7]. Moreover, multiwavelength fiber lasers based on erbium-doped fiber (EDF) as a gain medium have further advantages such as low-cost setup, low pump power threshold [8], high-power conversion efficiency [3], and operate in 1.5-micron wavelength regions which are under the conventional communication band [8-10]. In addition to the gain medium, another very important key component in a demonstration of MWFLs is the comb filter which is responsible for introducing the intermodal interference inside the cavity and specify the mode spacing [11]. Hence, researchers have directed huge efforts toward developing a comb filter with high performance.

Up to this date, many approaches have been proposed and used to construct MWFLs based on comb filtering effect. In 2005, a tow Tunable optical filters (TOF) are used to generate a dual-wavelength erbium-doped fiber laser. The generated wavelengths can be selected using the TOF [12]. A year later, a Fabry-Perot filter (FPF) in an erbium-doped fiber laser cavity was proposed as an interferometer for multiwavelength lasing [13]. While in

2012, J. M. Sierra-Hernandez et al. was fabricated an interferometer by splicing a piece of photonic crystal fiber (PCF) between two segments of a single-mode fiber. They achieved a single, double, triple or quadruple line by varying the polarization state of the cavity [3]. In 2016, another method using a 20-km-long single-mode fiber together with a Sagnac loop mirror as random distributed feedback to experimentally construct a multi-wavelength erbium-doped fiber laser [14]. Most recently, in 2018, the bitapered optical fiber with a Fabry-Perot (FP) was used to form up interference in the laser cavity to obtain until 5 stable laser lines by using curvature and strain [15]. The above-mentioned comb filters are all fabricated with conventional fibers, meaning that the comb filters are not so compact. However, in some applications of multiwavelength fiber laser, the intracavity comb filter with compact design is more favorable [16]. On the other hand, tapered fibers or optical microfibers which can be easily fabricated using a normal single-mode fiber (SMF) have the advantages of more compact, large evanescent fields, and nonlinearity [17-19]. Due to these very interesting optical properties of the microfibers, they were exploited in designing various devices such as selective excitation of the fundamental mode in multimode fibers, broadband single-mode filters and couplers, and comb-like filters for tunable lasers [20-22]. Recently, a stable dual-wavelength ytterbium-doped fiber laser with a narrowly spaced was successfully demonstrated using a tunable bandpass filter and a microfiber-based Mach-Zehnder interferometer [18]. Last year, a switchable ytterbium-doped fiber laser from dual to quad-wavelengths was also demonstrated using non-adiabatic microfiber interferometer (N-MI) inside the laser cavity [23].

In this work, A quad-wavelength EDFL is demonstrated using a tapered fiber as a comb filter. The tapered fiber is fabricated by heating and stretching a piece of the optical fiber after the polymer protective cladding has been removed. The comb filter with spacing around 3 nm was successfully achieved. The MWEDFL operates at central wavelengths of 1549.52 nm, 1553.2 nm, 1556 nm, and 1558.8 nm. The stability of the proposed laser system was also investigated over 90 minutes, it found that MWEDFL has very good stability with a wavelength fluctuation less than 0.01 nm and peak power fluctuation of 5 dBm only.

2. Fabrication and characterization of the microfiber interferometer

A flame-brushing technique is employed to fabricate the microfiber Mach-Zehnder interferometer (MMZI) using a standard single mode fiber (SMF) as shown in Fig. 1. At first, we took off the coating from the area that needs to be tapered using a specific tool. Then, the fiber loaded into the machine using two fiber holders. After loading the fiber, A butane-oxygen mixture was used to produce a flame which is required to heat up and soften the fiber before and during the pulling process. After the fiber is heated up, it was pulled in a systematic way until it reached the expected diameter and length. A microscope is used to measure the actual length and diameter of the fabricated microfiber which was around 30 mm and 9 μm , respectively. The microscopy image and the schematic diagram of the MMZI are shown in Fig. 2 (a) and (b), respectively. This structure helps in exiting other modes besides the fundamental mode which is the only propagating mode in normal SMF. Consequently, in the MMZI, the fundamental mode HE₁₁ that propagate in its core will interfere with the closest higher order mode HE₁₂ propagating in cladding-air. The interfering power can be calculated using the following equation:

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

Here, I_1 and I_2 present the intensities of modes propagating in the core and cladding-air, respectively, while ϕ is the phase difference between them. Simply, ϕ can be calculated by the following formula:

$$\phi = \frac{2\pi(\Delta n_{eff})L_{eff}}{\lambda} \quad (2)$$

where Δn_{eff} is the difference of the effective refractive indices of the core and cladding-air modes, L_{eff} effective length of MMZI, and λ is the optical wavelength.

The spectral response of the fabricated MMZI was characterized using an amplified spontaneous emission (ASE) source as drawn in Fig. 3. The ASE source consists of a laser diode (LD) with 980 nm operation wavelength, wavelength division multiplexer (WDM), erbium doped fiber (EDF) as the gain medium, and finally optical isolator to prevent the light reflections. The ASE source was directly connected to the MMZI and to an optical spectrum analyzer (OSA) to observe its intermodal interference and insertion loss. Fig. 4 illustrates the output optical spectrum of the ASE source with and without the MMZI. The mode spacing ($\Delta\lambda$) of 3 nm can be clearly seen in the comb-like spectrum generated by the MMZI. This wavelength spacing mainly depends on the tapering structure of the microfiber, where a smaller diameter or a longer length will result in smaller spacing between the beating modes as indicated in the following equation:

$$\Delta\lambda = \frac{\lambda^2}{\Delta n_{eff} L_{eff}} \quad (3)$$

As known that the attenuation or intersection loss depends on the diameter of the tapered fiber. Where the attenuation increases as the diameter are decreased. In this experiment, the insertion loss measured was less than 5 dB due to the tapering process. However, this loss can be easily compensated by the amplification power of the EDF.

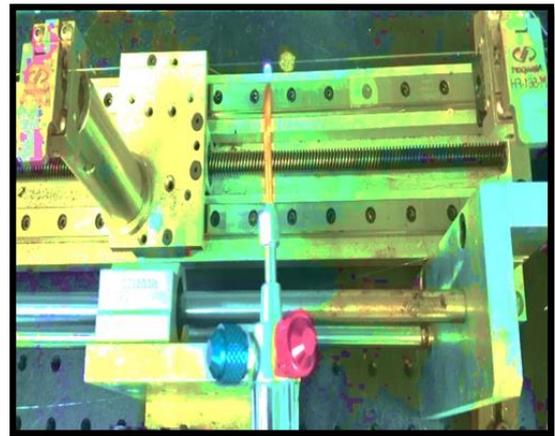


Fig. 1. A flame-brushing technique

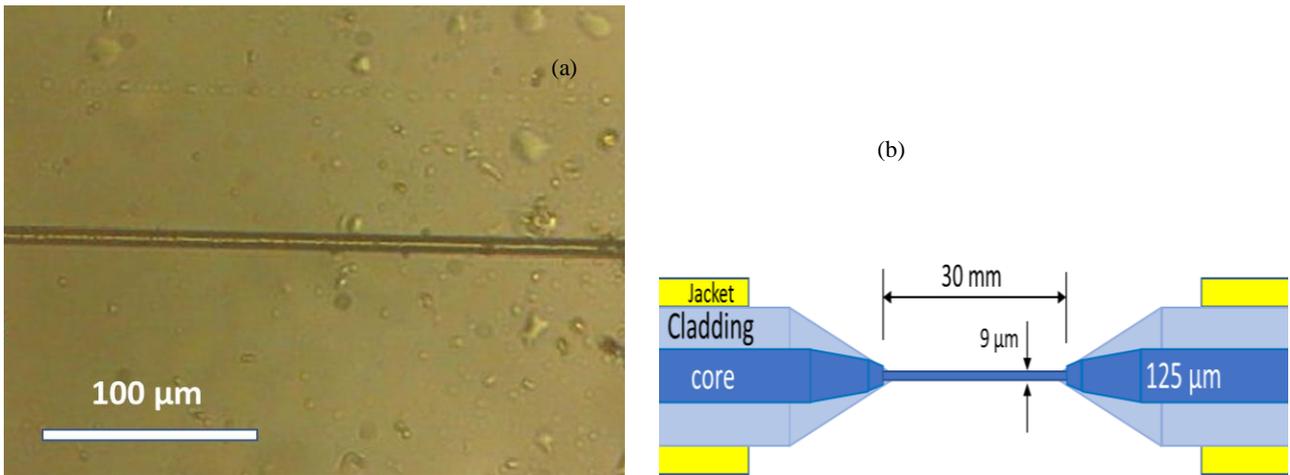


Fig. 2. (a) Microscopy image of the MMZI, (b) The schematic diagram of the MMZI

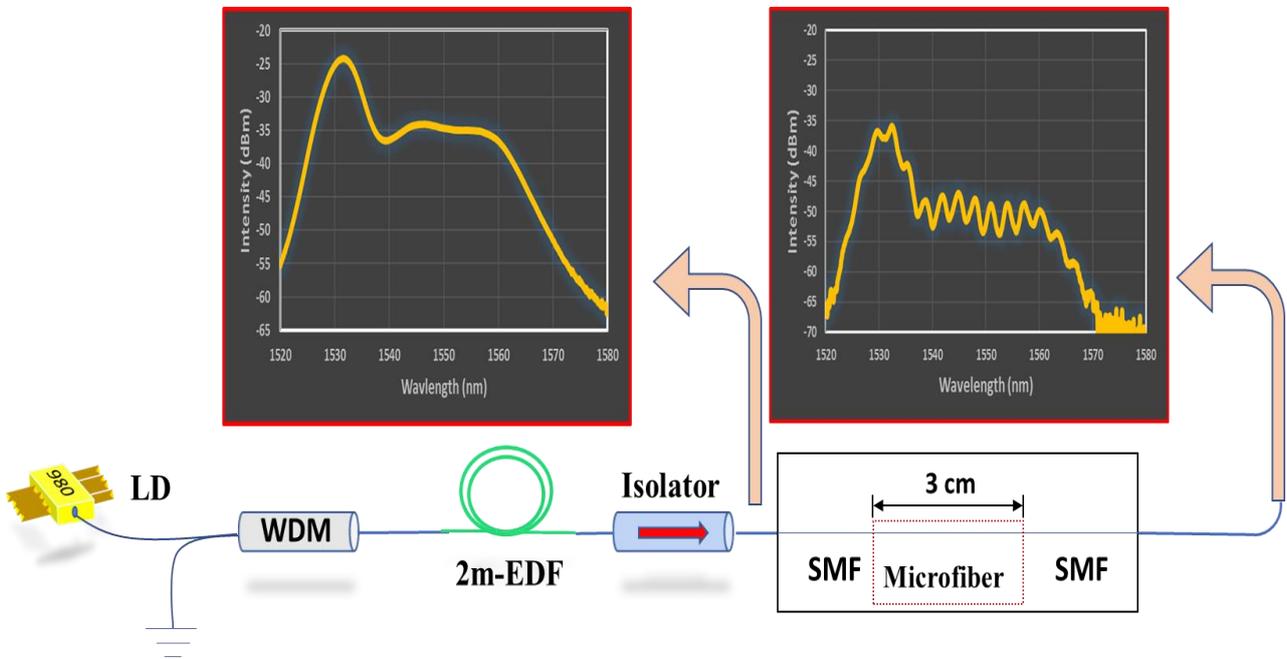


Fig. 3. ASE source

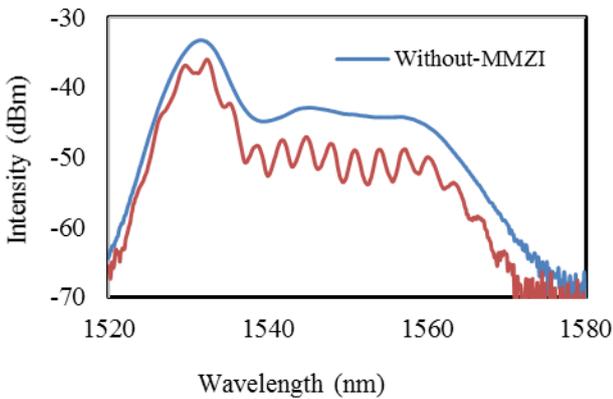


Fig. 4. Output optical spectrum of the ASE source with and without the MMZI

3. Experimental setup of MWFL

The experimental setup of the proposed quad-wavelength laser is drawn in Fig. 5. At first, an LD with 980 nm is used as a pump power to pump the gain medium through a WDM. 2 m EDF is used to serve as a gain medium and provide an operating wavelength in the C-band. Then, a polarization insensitive optical isolator was connected directly after the gain medium to ensure the unidirectionality in the laser cavity, in addition, to prevent the light from reflecting back and consequently protect the LD and WDM from damage. Next, an optical coupler is inserted to provide a feedback of 90% back to the cavity and extract the rest to the output. The 30 mm MMZI with a 9 μm diameter is incorporated in the feedback as the main component responsible to generate the multiwavelength. Finally, the output of the laser was

connected to an optical spectrum analyzer (OSA) in order to investigate the spectrum in term of operation wavelength, power, and mode spacing of the proposed laser.

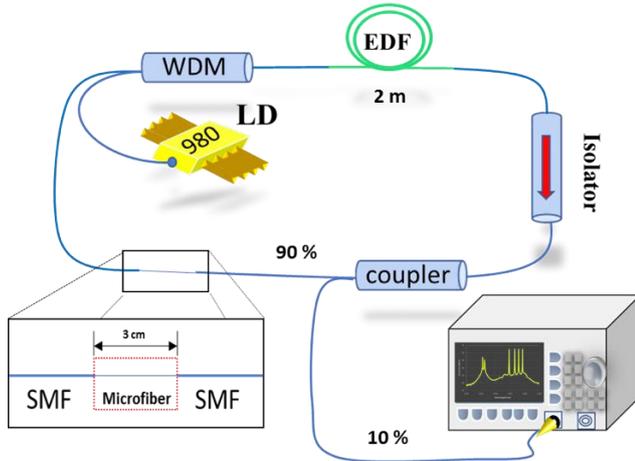


Fig. 5. Experimental setup of the proposed quad-wavelength laser

4. Results and discussion

The operation of a multiwavelength laser can be simply explained by using the Mach-Zehnder (MZ) interference mechanism. It is created by the laser system, where the comb response generates a wavelength dependent loss that restrains the mode hopping and mode competition [10]. By proposing a single mode cavity from a multimode medium, the MZ effects can be emulated whereby the core and the cladding play the MZ arms role [11]. In normal single mode fiber, there is only one longitudinal mode propagating which is the fundamental mode or the core mode. While in the microfiber, when the refractive index of the core mode reaches to its continuously. Due to the presence of the core and cladding modes in the tapered fiber, an intermodal beating will occur between them and will then result in generating a comb-like spectrum which is very important for the demonstration of the MWFL. In this work, the fabricated microfiber was used as an MMZI and incorporated inside an optical ring resonator for the multiwavelength generation. The comb-like intermodal interference pattern generated by the MMZI was utilized to construct a stable quad-wavelength EDFL. The optical spectrum of the proposed quad-wavelength EDFL is shown in Fig. 6. The four wavelengths are centered at 1549.52 nm, 1553.2 nm, 1556 nm, and 1558.8 nm with a mode spacing around 3 nm. While, the signal to noise ratio (SNR) of each peak was approximately 35, 34.4, 32.6, and 31.8 dB, respectively. There were two other wavelengths presented at a center wavelength of 1530 nm, and 1531 nm. However, those wavelengths were unstable and rapidly fluctuated. Therefore, they were eliminated.

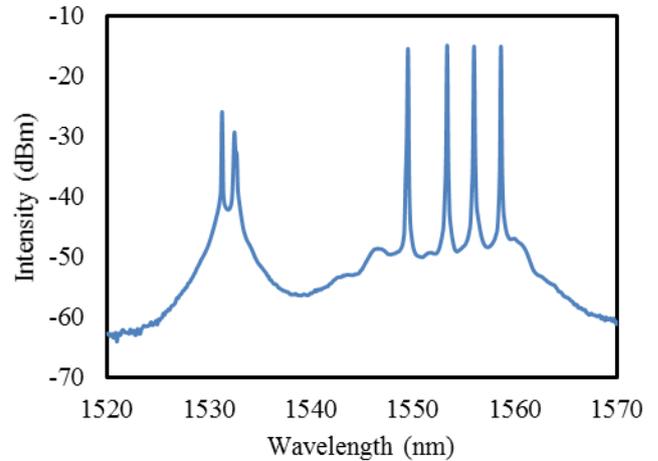


Fig. 6. The optical spectrum of the proposed MWFL

Very good stability was observed by scanning the spectra of the quad-wavelength lasing oscillations repeated for nine times with a time interval of 10 minutes as shown in Fig. 7. The peak wavelength shifts were also investigated over time for the four produced wavelengths as shown in Fig. 8. It can be seen that the fluctuation of the central wavelengths with time is almost unnotable, less than 0.1 nm measured by the OSA. The intensity of the four wavelengths is also observed to be quite stable where the peak fluctuations are less than 2 dB. Fig. 9 shows the output powers of the four generated wavelengths with time. The power fluctuations mainly come from the fluctuating of the 980 nm pump power as well as the cavity loss due to temperature variant.

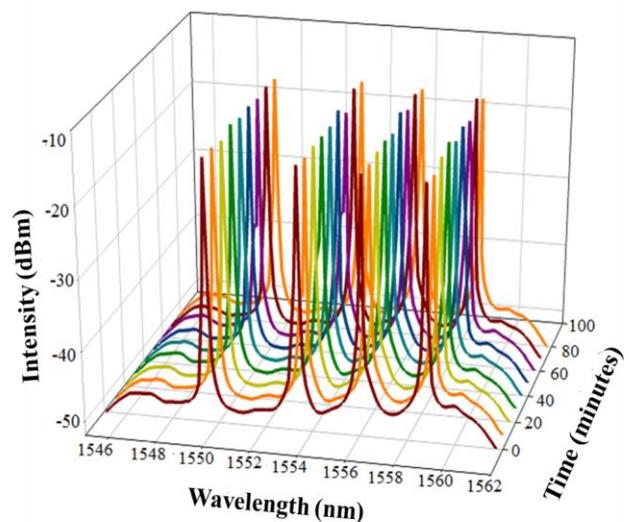


Fig. 7. The optical spectrum over 90 minutes

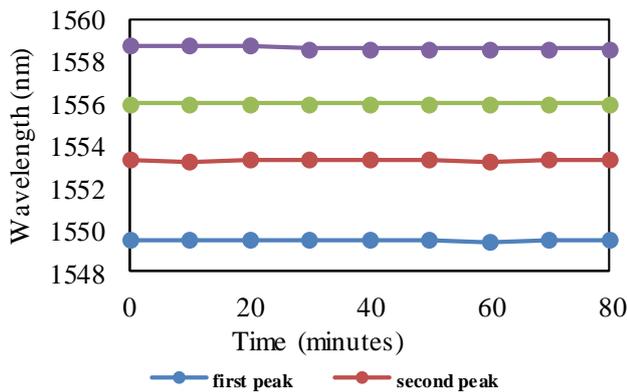


Fig. 8. The wavelength variation over 90 minutes

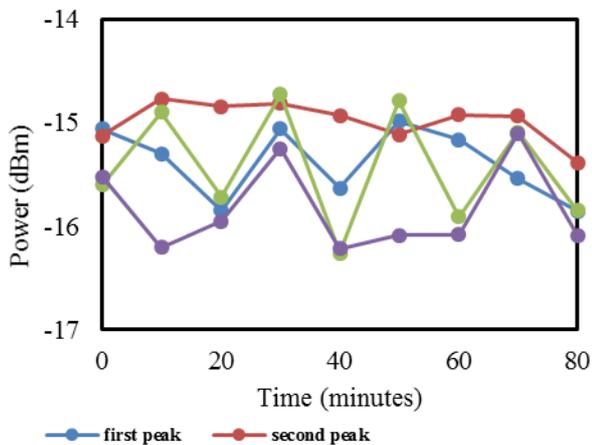


Fig. 9. The output power fluctuation over 90 minutes

5. Conclusion

Microfiber Mach-Zehnder interferometer was fabricated using a flame-brushing technique and used to construct a multiwavelength erbium-doped fiber laser very stable four peak wavelengths at 1549.52 nm, 1553.2 nm, 1556 nm, and 1558.8 nm were obtained. During nineteen minutes of monitoring of the laser output, the fluctuation of the central wavelengths was almost unnoticeable, less than 0.1 nm. While the intensities of the four wavelengths also observed to be quite stable, within 2 dB.

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