JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 19, No. 3 - 4, March – April 2017, p. 127 - 131

Dual-wavelength fiber laser with a bent single-mode multimode single-mode fiber structure

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A stable dual-wavelength fiber ring laser operating at C-band region was successfully demonstrated based on a bent single-mode-multimode-single-mode fiber structure (SMS). A small load of 11.34 g is applied at the SMS package to provide bending at the multimode section in order to generate stable dual-wavelength lasing at room temperature. The proposed fiber laser operates at 1535.24 nm and 1540.00 nm with a wavelength spacing of 4.76 nm and a SNR of ~45 dB. At the pump power of 201 mW, the maximum power fluctuations of $\pm$1.34 dB and $\pm$1.26 dB were obtained at 1535.24 nm and 1540.00 nm respectively. The feasibility of application of SMS structure for dual-wavelength generation is verified.

(Received December 15, 2015; accepted April 6, 2017)

Keywords: Single-mode multimode single-mode fiber structure, Dual-wavelength laser, EDFL

1. Introduction

Dual-wavelength fiber lasers have been under intensive research in recent years due to its wide application potential in optical sensors [1-2], optical spectroscopy [3], the generation of soliton pulses [4], microwave signal generation [5], and microwave photonic filters [6]. In applications such as differential absorption measurements a dual-wavelength laser is ideal, where one wavelength is used as a reference and other as a probe [4]. Most recently, it was also found that dual-wavelength radiation can mitigate stimulated Brillouin scattering (SBS) effects in fiber amplifiers, which propose a new technique approach in scaling to high power lasers [7]. An erbium-doped fiber shows homogeneous gain broadening at room temperature. Due to severe gain competition between adjacent lasing wavelengths it is difficult to produce a multi-wavelength fiber laser using erbium-doped fiber [8-9]. Up to date, various techniques have been explored to achieve dual-wavelength lasing output with erbium doped fiber (EDF) as a gain medium, e.g. polarization hole burning [10], photonic crystal fiber [11] and fiber Bragg gratings (FBG) [12].

Recently, the multimode interference occurring in the single-mode–multimode–single-mode (SMS) fiber structure has been investigated and proposed as a basis for a number of novel fiber-optic devices [13-14]. Optical devices based on SMS fiber structures offer all-fiber solutions for optical communications and optical sensing with the advantages of ease of packaging and interconnection to other fiber optic components. For instance, Wang and Farrell [14] demonstrated a refractometric sensor using the SMS structure. More recently SMS structure along with fiber Bragg grating (FBG) [15] and multimode fiber (MMF) twined on a polarization controller (PC) [16] were used to generate dual-wavelength fiber laser. In this paper, a stable all-fiber dual-wavelength Erbium-doped fiber laser (EDFL) is demonstrated using a SMS structure. The structure is packaged with a Cr-39 plastic monomer plates which act as a cantilever to generate stable dual-wavelength lasing via bending of the MMF.

2. Experimental setup

The experimental setup of our dual-wavelength EDFL with a SMS structure is shown in Fig. 1. It includes a 70 cm long EDF as a gain medium, an optical isolator and 80/20 output coupler. The EDF has an absorption coefficient of 24.6 dB/m at 979 nm. A laser diode with wavelength of 980 nm is used to pump the gain medium via a wavelength division multiplexer (WDM). An isolator is used to ensure light oscillates in one direction with a SMS stage setup is connected after the isolator. The SMS setup was employed in this experiment as a wavelength selective filter. It consists of a 7.9 m long MMF with a step index profile and a core size of 105 μm which both ends are fusion spliced with a SMF-28 fiber. The MMF and some part of the SMF are sandwiched between two Cr-39 plastic monomer plates with epoxy is used to fix the whole structure. It is noted that, the center portion of the MMF sits at the center of the plates where the plate has a length of 17.5 cm, width of 4 cm and thickness of 0.05 cm. The package is clamped in 6 cm of length using a stage clamp to fix its position to produce a cantilever structure as shown in the diagram. A 80/20 coupler is used to tap the output of the laser while allowing 80% of the light to oscillate in the ring cavity. A 3 dB coupler was introduced to split the output light before it is probed by a power meter and an optical spectrum analyser (OSA) with the resolution of 0.02 nm for simultaneous measurement. The center location of applied load along the cantilever and the weight of load are adjusted accordingly until a stable dual-wavelength lasing is generated at a fixed room temperature. A load with a mass of 11.34 g and with distance of D_1 = 3 cm conditions were obtained to generate the dual-wavelength EDFL.

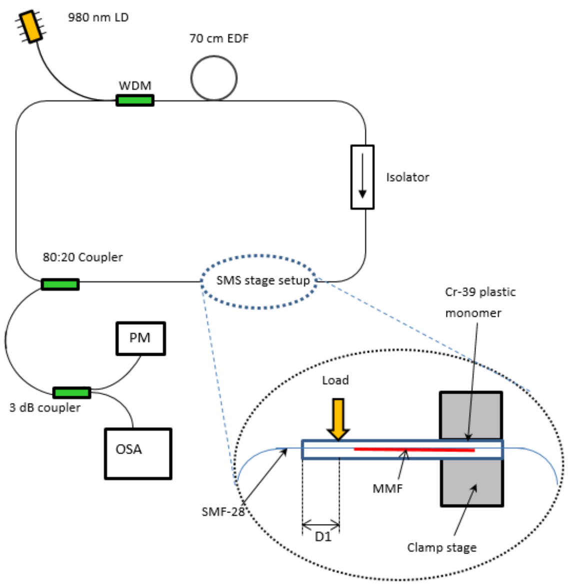


Fig. 1. Experimental setup of Dual-wavelength fiber laser generation based on bent SMS structure

3. Results and discussion

At first, the transmission spectrum of the SMS structure is investigated before incorporating the structure into the laser cavity. Fig. 2 shows the spectrum obtained at the pump power of 201 mW with zero loading as measured by using an OSA, at span of 100 nm and resolution of 0.05 nm. As shown in Fig. 2, the SMS structure has a bandpass spectral response, which is a result of multimode interference and recoupling within the fiber structure. The characteristic of the response is highly depends on the MMF characteristics such as length of fiber, core size and its bending condition [17]. The spectrum has broad spectral bandwidth with its peak power is located at about 1530 nm wavelength. Based on a power transmission measurement, the SMS device provides a high insertion loss of 14 dB. The back reflection which occurred at the splicing joint between the single-mode fiber (SMF) to MMF is the major culprit of such high losses of the SMS device.

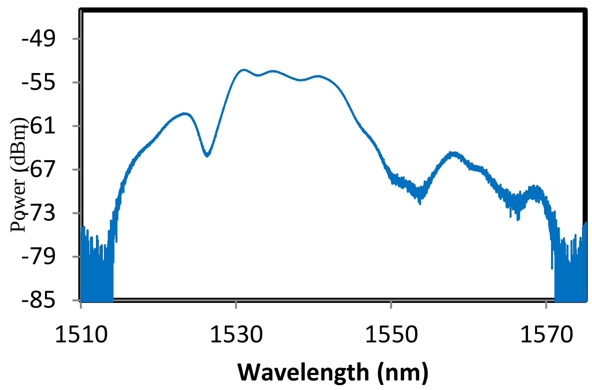


Fig. 2. Bandpass spectral response of the SMS with zero loading at pump power of 201 mW

Fig. 3 shows the dual-wavelength and single-wavelength lasers, which were obtained by the fiber laser cavity at the pump power of 201 mW measured at a span of 60 nm and resolution of 0.1 nm. The single wavelength laser operating at 1540.38 nm was obtained when zero load is applied. As small load with a mass of 11.34 g is applied on the Cr-39 plate of the SMS structure to bend the MMF to generate the dual-wavelength laser. The appropriate bending of MMF causes non-symmetrical refractive index distribution along the MMF and cavity loss is created at particular wavelengths due to the change of phase constants between propagation modes [18]. Together with the gain provided by the EDF, a stable dual-wavelength laser can be generated where the spatial mode beating helps to minimize the mode competition effect [16]. This suggests that the MMF required a small amount of bending to significantly change the laser spectrum from single to dual-wavelength laser. This shows that the mode interference behaviour in the MMF is highly influenced by the MMF bending. When, insufficient weight is applied, only a single wavelength laser is observed that has been shifted to shorter wavelength from wavelength of 1540.38 nm.

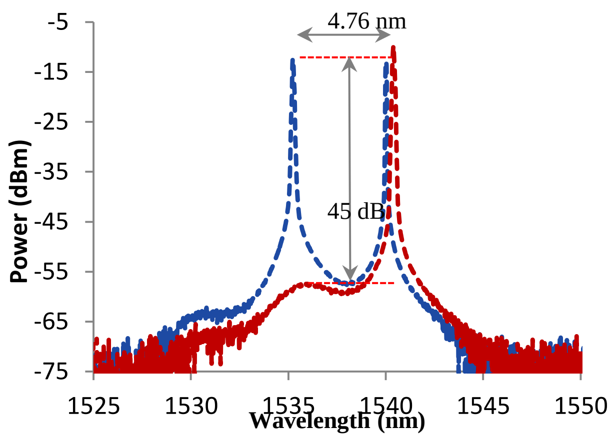


Fig. 3. Dual-wavelength and single wavelength fiber laser spectra at pump power of 201 mW

Noted that, the dual-wavelength laser is insensitive to polarisation states as inserted a PC into the cavity does not change the laser behaviour. In contrast as reported by Zhao et. al. [16] the number of laser wavelengths tend to change by adjusting the PC. However, the setup utilized a long MMF fiber (2.5 m) that was twined on a PC to obtain such effect. In our setup, via bending of the MMF, a maximum of three laser wavelengths is achievable when larger weight than 11.34 g is applied. Fig. 3 also shows that the dual-wavelength laser produces two peaks at wavelengths of 1535.24 nm and 1540 nm with a wavelength spacing of 4.76 nm and a SNR of ~45 dB at the pump power of 201 mW. The difference between the two peak powers is 0.46 dB. Fig. 4 shows the dual-wavelength laser output measured at a fix pump power of 201 mW at a time interval of 5 minutes for duration of 30 minutes at the same OSA setting. Its corresponding wavelengths and peak powers over time are illustrated in Fig. 5 (a) and (b).

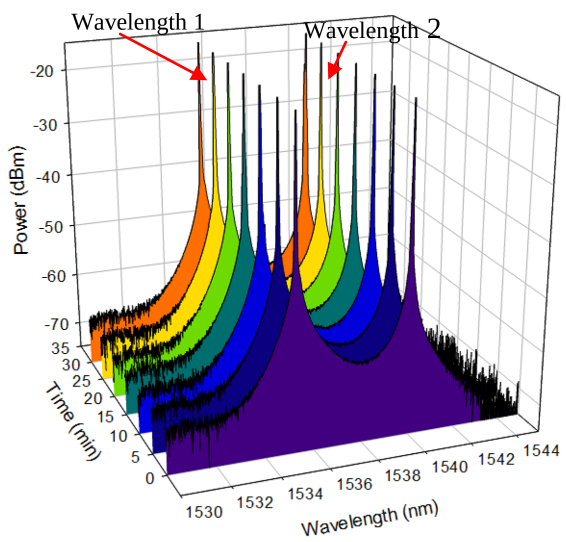
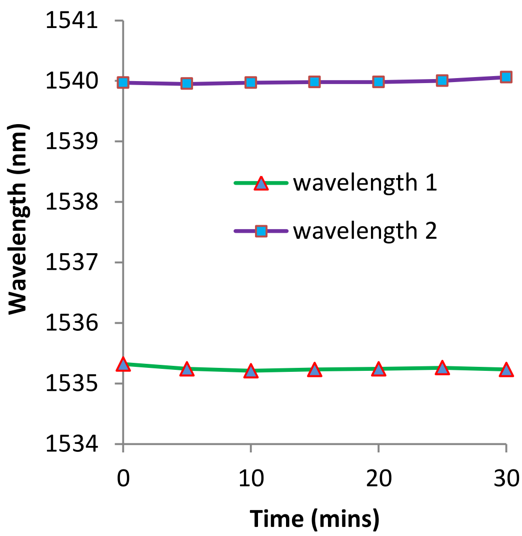


Fig. 4. Dual-wavelength fiber laser at the pump power of 201 mW at different time interval

From Fig. 5 (a), it is observed that the first 1535.24 nm wavelength and the second 1540.00 nm wavelength show the maximum wavelength variation of ±0.07 nm with a mean wavelength spacing of 4.76 nm. Figure 5 (b) indicates that the maximum power fluctuations of ±1.34 dB and ±1.26 dB were obtained for the first and second wavelengths, respectively. Moreover, a maximum peak power difference of ±2.01 dB is obtained between the two wavelengths mentioned. Fig. 6 shows the performance of the dual-wavelength laser as the pump power is varied from 113 mW to 245 mW. Fig. 7 (a) and (b) show the relation between the corresponding peak wavelength and power, respectively against the pump power.

It is shown in Fig. 7 (a) that both wavelengths are unchanged as the pump power is varied with the wavelength spacing is maintained at 4.76 nm. On the other hand, the peak powers of both wavelengths increase gradually as the pump power is increased, where the increase rate of the peak power is reduced as the pump power is increased up to a maximum of -10.94 dBm and -11.32 dBm at the first and second wavelength respectively. It can also be seen, that as the pump power is increased, the difference between the peak powers is reduced down to a small value of 0.38 dB at the pump power of 245 mW. Fig. 8 shows the average output power of the dual-wavelength laser against the pump power when the pump power is increased from 113 mW to 245 mW. The curve exhibit linear curve having a slope efficiency of 0.0017 mW/mW. The small slope efficiency of the laser is contributed by the high insertion loss of the SMS device and also due to the 3 dB coupler is used before measuring the laser power.



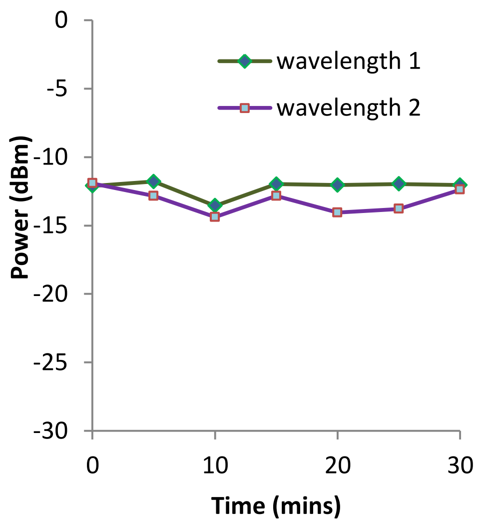


Fig. 5. (a) Wavelengths and (b) power stability performance of the dual-wavelength fiber laser at the pump power of 201 mW

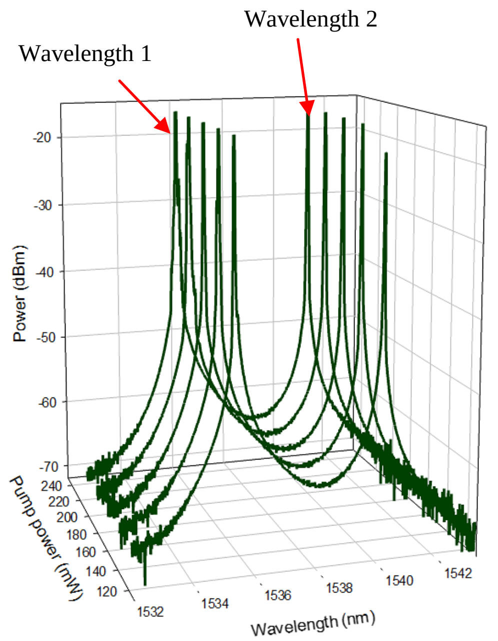
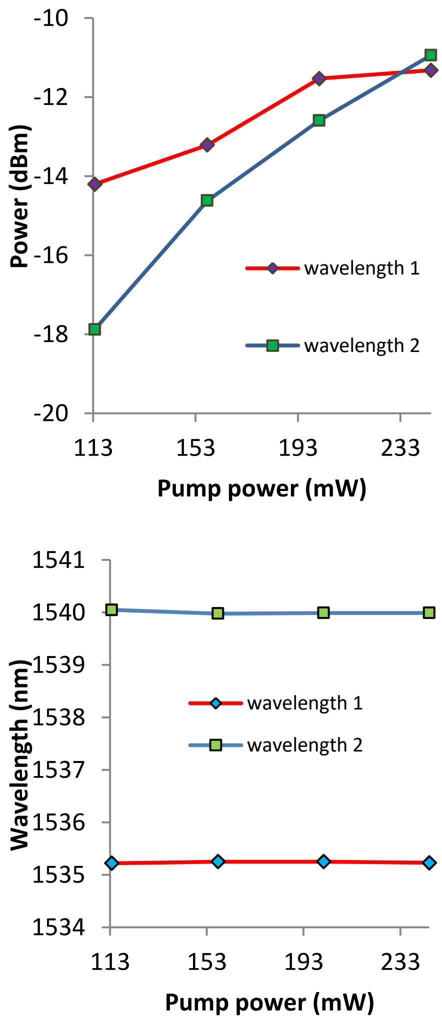


Fig. 6. Output spectra of the dual-wavelength fiber laser at different pump power



a

b

Fig. 7. a) Power and b) wavelength performance of the dual-wavelength fiber laser at different pump power

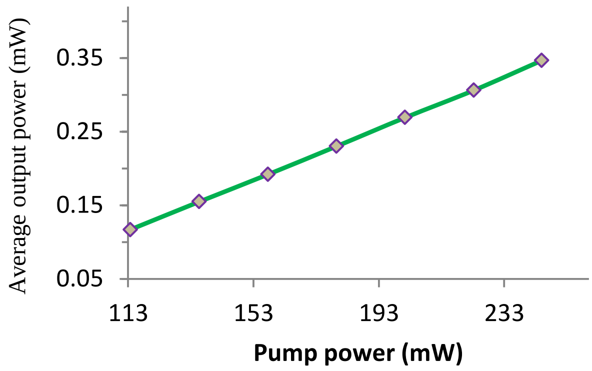


Fig. 8. Average output power against pump power for the dual-wavelength laser

4. Conclusion

The generation of stable dual-wavelength fiber ring laser at C-band was demonstrated via bending of single-mode-multimode-single-mode fiber structure. At the pump power of 201 mW, the DWFL can provide a wavelength spacing of 4.76 nm, SNR of ~45 dB and with peak wavelengths at 1535.24 nm and 1540.00 nm. The stability test on the dual-wavelength laser at a fixed pump power, shows a maximum wavelength variation of ±0.07 nm at both wavelengths. On the other hand, maximum power fluctuations of ±1.34 dB and ±1.26 dB were obtained at the shorter and longer wavelengths of the laser respectively with a maximum peak power difference of ±2.01 dB. The peak power difference however, can be further reduced if the setup is pumped at higher pump power.

Acknowledgment

This work is financially supported by Ministry of Higher Education Grant Scheme (FRGS/1/2015/SG02/UITM/03/3) and PPP University of Malaya Grant Scheme (PG098-2014B).

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