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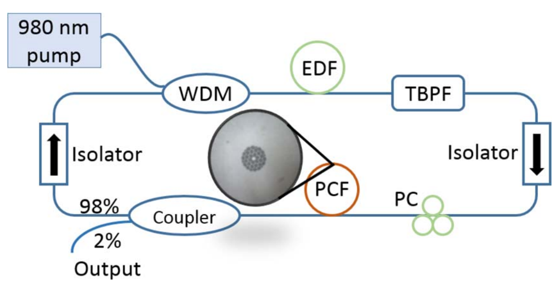

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Narrow Spacing Dual-Wavelength Fiber Laser Based on Polarization Dependent Loss Control

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Abstract: By controlling the polarization state of a simple ring erbium-doped fiber laser with photonics crystal fiber, polarization controller (PC) and tunable band-pass filter, this paper demonstrates stable operation of narrow spacing dual-wavelength fiber laser (DWFL). The flexibility of the tunable band-pass filter and PC allows the spacing tuning of the DWFL from 80 pm up to 600 pm. Such tuning ability offers flexibility in the application of DWFL, particularly in tunable microwave generation and radio over fiber. Throughout the experiment, the DWFL shows high power stability within 0.6 dB and wavelength shift of less than 10 pm. In addition to that, it also produces a narrow linewidth optical output of 3 pm with a high signal to noise ratio of more than 60 dB.

Index Terms: Dual-wavelength, erbium-doped fiber laser (EDFL), narrow spacing, polarization dependent loss (PDL).

1. Introduction

Optical technology development is growing dramatically in many applications such as optical communication systems, optical sensors, optical instrument testing, and fine spectroscopy due to its advantages over conventional electrical systems. Towards the popularization of optical applications, demands such as broader bandwidth, larger capacity, and multipurpose sensing have been on the rise. In this case, multi-wavelength fiber lasers have attracted a lot of interest in recent years to fulfil the great demand of various industrial applications. Within multi-wavelength applications, dual-wavelength fiber laser (DWFL) is an interesting field as it is important in special applications such as differential-absorption-LIDAR (DIAL) [1] measurement and generation of soliton pulse trains, beat signals at microwave frequencies [2], [3] and as terahertz sources [4]. Erbium-doped fibers (EDFs) are the most commonly used gain medium in fiber laser setup including multi-wavelength laser in both experimental and numerical simulation [5]. In addition to that, EDF lasers also offers flexibility such as wide tunability in laser operating wavelength for different applications [6], [7]. However, strong mode competition induced by the homogeneous broadening of EDF [8] has become the main challenge to achieve stable multi-wavelength oscillation in room temperature.

Various methods have been proposed to realize the multi-wavelength operation at room temperature by reducing cross-gain saturation and suppressing mode competition. These include polarization hole burning (PHB) effect [9], frequency-shifted feedback [10], cascaded stimulated Brillouin scattering [11] and four wave mixing [12]. In this paper, a simple EDF laser (EDFL) with a short length of highly nonlinear photonic crystal fiber (HN-PCF) incorporated in a ring cavity

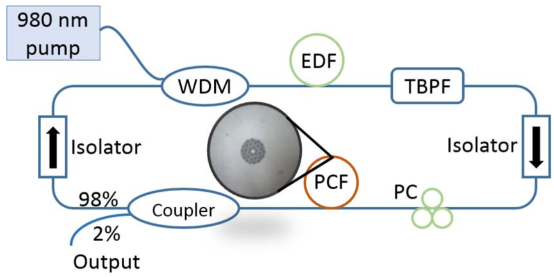


Fig. 1. Experimental setup of PDL based DWFL.

configuration is proposed to achieve stable and narrow spacing DWFL utilizing polarization dependent loss (PDL) effect. The setup is inexpensive and has the further advantage of a simple structure, adjustable narrow spacing of DWFL, and stable output.

2. Experimental Setup

The configuration of the DWFL system based on the PDL controlling is schematically shown in Fig. 1. The DWFL consists of a 980 nm pump laser diode, a 980/1550 nm wavelength division multiplexing (WDM), a 3 m EDF, a tunable band-pass filter (TBPF) with 1 nm bandwidth, isolators, a polarization controller (PC), a very short length of 10 cm HN-PCF, and a 2:98 fiber based coupler. The 980 nm pump laser is directed into the fiber laser ring cavity through a WDM to provide excitation to the gain medium. The TBPF is used to limit or confine the oscillation of dual-wavelength laser in a narrow spacing. Without the TBPF, the DWFL will tend to lase at wavelengths with a larger spacing. The isolators are used to assure unidirectional operation of the laser as to achieve a more stable lasing condition. The PC working at the C-band region is inevitably exploited to adjust the polarization of light propagating inside the ring cavity. By controlling the polarization state, the lasing wavelength is able to switch from one to the other and also creates multi-wavelength laser based on the polarization dependent spectral in the setup. The HN-PCF plays the main role in the setup to stabilize the DWFL based on its nonlinearity and birefringence coefficient. The micrograph of the HN-PCF cross-section structure is shown as the inset in Fig. 1. The HN-PCF is a solid core ($\sim$4.37 μm diameter) PCF surrounded by air holes with 5.06 μm diameter and separation of 5.52 μm between holes. The 2 : 98 fiber based coupler is used to direct part of the laser power out of the laser cavity for measurement, analysis, and application.

3. Experimental Results and Discussion

The 980 nm pump laser is set at 90.0 mW, with a launch power of about 71.5 mW after the WDM. The laser output is continuously monitored by an optical spectrum analyzer (OSA) from the 2% output of the fiber coupler. The PC is tuned to achieve single or DWFL from the setup. With similar setup, more lasing wavelengths are achievable by removing the TBPF from the ring laser. However, the current work focuses on narrow spacing DWFL for applications such as microwave generation and radio over fiber. Fig. 2 shows the experimental result of the DWFL with 81 pm spacing between two wavelengths lasing at 1553.726 nm and 1553.807 nm. Due to the dependence of the lasing wavelength on polarization states, lasing wavelength can be change by fine-tuning the PC. The adjustment of the PC will rotates the polarization states and allows continuous adjustment of the birefringence within the ring cavity to balance the gain and loss of the lasing wavelengths. By achieving dual-wavelength laser with similar peak powers, a stable DWFL can be obtained. During the experiment, the TBPF is first tuned to a center wavelength of 1553.726 nm to limit laser oscillation within 1553 nm to 1554 nm. The PC is then fine-tuned to obtained dual-wavelength laser with almost similar peak powers at -18.8 dBm and -19.0 dBm as taken from the 2% port at 1553.726 nm and 1553.807 nm, respectively, as shown in Fig. 2.

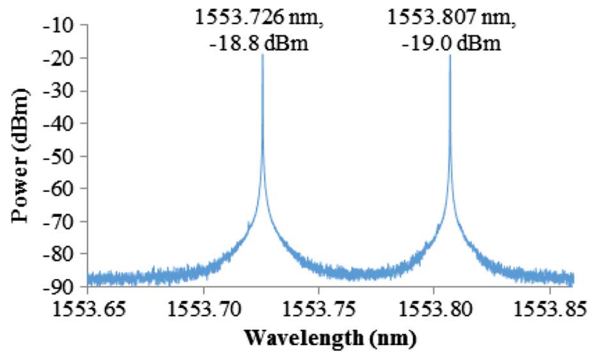


Fig. 2. Optical spectrum of DWFL lasing at wavelengths 1553.726 nm and 1553.807 nm with peak powers of −18.8 dBm and −19.0 dBm, respectively.

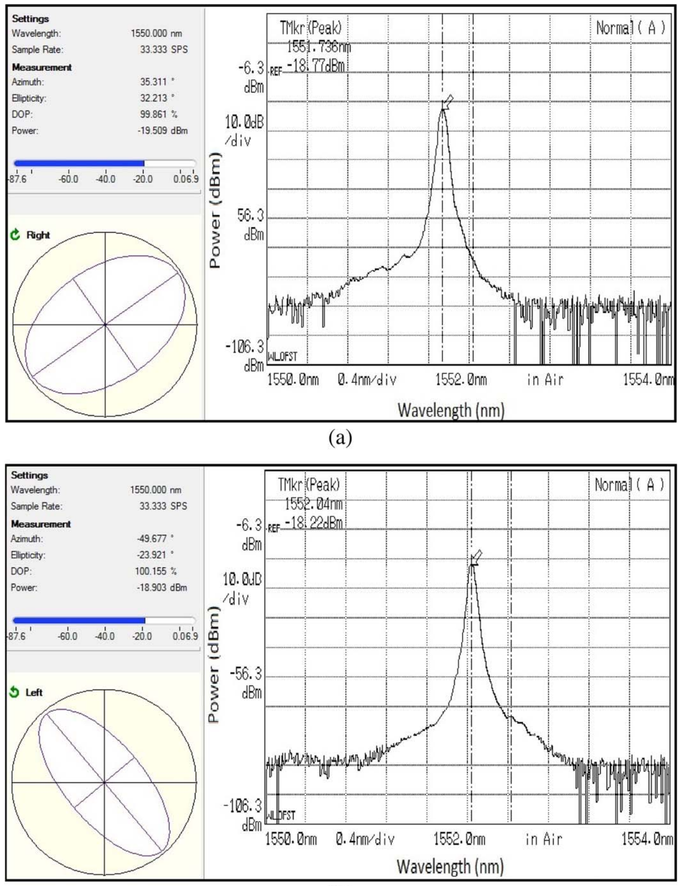
The simple design of the DWFL with a short ring cavity length of 6 m will achieve a narrow linewidth of only 3 pm as measured using OSA with spectral resolution of 0.17 pm. In addition to that, the short ring cavity also increases the stability of the setup, and in conjunction with the TBPF and PC enables high repeatability. Although there will be slight wavelength shifts for each experiments, achieving the lasing spacing of around 3 pm can be reproduced with certain effort. The DWFL also achieves a high signal to noise ratio (SNR) of more than 60 dB, similar to that as reported in [13]. The high SNR is basically contributed by two main factors; the first is the function of the TBPF in the ring cavity. The TBPF in the ring cavity allows only spectrum within the 1 nm range to pass through while filtering out other wavelengths, thus reducing the generation of amplified spontaneous emission (ASE) during the lasing period.

The second is the polarization state of both the lasers. Polarization state of the laser output is monitored using a polarization analyzer. When the laser operates under dual-wavelength condition, the polarization state of the laser output is a combination of both wavelengths polarization states. To obtain a single wavelength for analysis, the system is left untouched, with only the TBPF being adjusted such that the wavelength of interest falls just within the edge of the TBPF's band-pass region. As such, the longer of the two wavelengths is filtered out by shifting the TBPF's operating region towards the shorter wavelength, whereas the opposite is done for the longer wavelength region. The polarization state for each wavelengths for the DWFL at 1551.736 nm and 1552.040 nm are shown in Fig. 3(a) and (b), respectively.

The azimuth angle of the polarization state for 1551.736 nm and 1552.040 nm are at 35.311° and −49.677°, respectively. The azimuth angle between both wavelengths is 84.988°, which means that they are almost perpendicular to each other. Fig. 3 also shows that the polarization state is in ellipse polarize with ellipticity of 32.213° and −23.921°, which shows that both are in an opposite rotation angle.

It is known that PHB effect will reduce the SNR due to polarization dependent gain saturation by polarized signal at different wavelength. In the proposed DWFL, the two lasers are elliptically polarized with both polarization state perpendicular to each other. This condition will minimize the polarized saturated signal in the ring laser as the signals are not in the same polarization state. Hence, ASE emission due to the PHB effect will be reduced and leads to high SNR in the DWFL. In terms of stability of the DWFL, the peak power for both wavelengths is measured at 1 min interval for 15 min, as shown in Fig. 4. The peak power fluctuation for both wavelengths falls within 0.6 dB with a wavelength shift of less than 10 pm, which is considered very stable. Mode competition among wavelength due to the homogeneous broadening effect of the EDF has been suppressed to a very low level.

One of the advantages of the proposed setup is the capability of adjusting the spacing of the two lasing wavelengths. However, the spacing between any two wavelengths is limited to the setup and "pre-defined" by the survival modes in the ring cavity and polarization dependent spectral as polarization states for both wavelengths must be perpendicular. The flexibility of the TBPF in tuning



(a)

(b)

Fig. 3. Polarization state of each wavelength from dual-wavelength fiber laser at (a) 1551.74 nm and (b) 1552.04 nm.

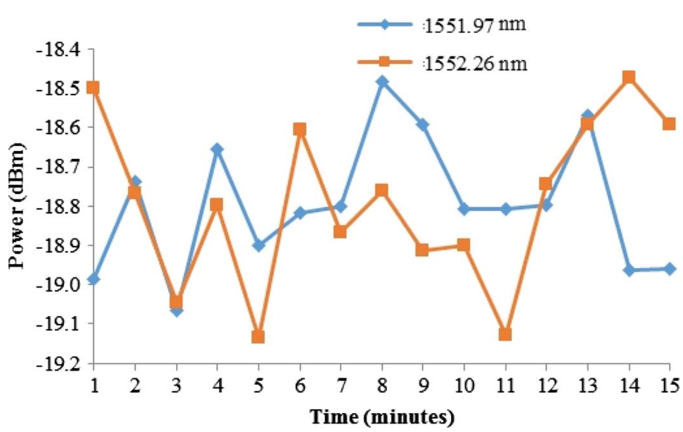


Fig. 4. Optical power fluctuation of both lasing wavelengths at 1551.97 nm and 1552.26 nm for 15 min.

the laser wavelength will allow the DWFL to operate in different wavelength regions and hence achieving different wavelength spacing by further tuning the PC. Fig. 5 shows the DWFL operating at different wavelength regions with different wavelength spacing and stability throughout a 15 min with 1 min internal for each scan. To perform an accurate multiple scan of the power fluctuation for

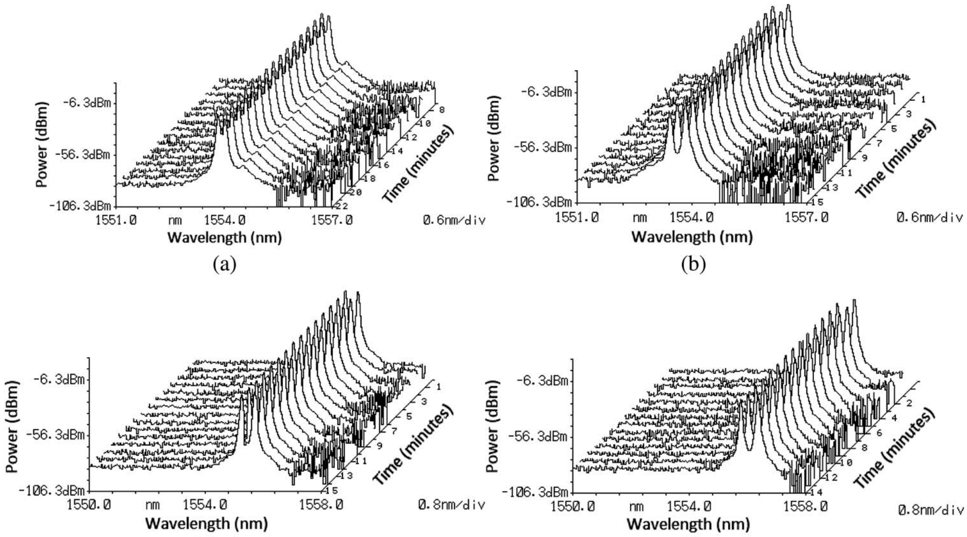


Fig. 5. Stability of DWFL with narrow spacing of (a) 170 pm at 1553.85 nm and 1554.02 nm, (b) 410 pm at 1553.42 nm and 1553.83 nm, (c) 440 pm at 1555.27 nm and 1555.71 nm, and (d) 590 pm at 1555.78 nm and 1556.37 nm over 15 min with interval scanning of every 1 min.

15 min period, OSA that comes with the time interval multiple scan function is used. The fluctuation of the laser peak power is observed to be stable within the fluctuation of 0.6 dB. In addition to the 80 pm spacing shown in Fig. 2, Fig. 5 shows different wavelength spacing at 170 pm, 410 pm, 440 pm, and up to 590 pm at different wavelength regions. It is possible to achieve a larger wavelength spacing by fine adjustment on the TBPF and PC.

4. Conclusion

The dual-wavelength fiber laser based on erbium-doped fiber and photonic crystal fiber in a ring cavity utilizing the PDL was demonstrated. The short ring cavity setup generated DWFL with 3 pm narrow linewidth at full width half maximum. Utilizing the birefringence of the photonic crystal fiber and PC, high SNR of more than 60 dB is achieved with the proposed setup. The polarization of each laser in the DWFL is studied and analyzed. The flexibility of the proposed setup in selecting different spacing between the two lasing wavelengths with proper adjustment of the tunable band-pass filter and PC as to achieve a stable DWFL output with peak power fluctuations of less than 0.6 dB and wavelength fluctuation of less than 10 pm is demonstrated. The wavelength spacing tuning range of the DWFL is between 80 pm and 600 pm.

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