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Generation of stable and narrow spacing dual-wavelength ytterbium-doped fiber laser using a photonic crystal fiber

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**ABSTRACT**

We demonstrate the design and operation of novel narrow spacing and stable dual-wavelength fiber laser (DWFL). A 70-cm ytterbium-doped fiber has been chosen as the gain medium in a ring cavity arrangement. Our design includes a short length photonic crystal fiber, acting as a dual-wavelength stabilizer based on its birefringence coefficient and nonlinear behavior and tunable band pass filter (TBPF) to achieve narrow spacing spectrum lasing. Our laser output is considered to be highly stable, with power fluctuation less than 0.8 dB over a period of 15 min. The flexibility and tunability of TBPF, together with polarization controller enable the spacing tuning of the DWFL from 0.03 nm up to 0.07 nm for 1040 nm region, and 0.10 nm up to 0.40 nm for 1060 nm region. The tunable wavelength spacing shows the flexibility of the DWFL in addition to stable and reliable properties of fiber laser in 1-μm region.

**KEYWORDS**

dual wavelength; fiber laser; ytterbium; narrow spacing

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1. Introduction

Optical fiber lasers are drawing significant attention as one of the key technologies in optical sensing, optical instrumentation, and photonic component characterization [1]. It has several distinct features when compared to solid-state semiconductor design such as high stability, better beam quality, and high thermal resistance. In recent years, one of the main current researches in optical fiber laser that has gain significant interest is generation of dual-wavelength fiber laser (DWFL). Due to the interest in applications such as microwave photonic filters [2], photonic generation of microwave carrier [3] and high bit rate soliton pulses [4], the focus on optimizing the DWFL has become more crucial and highly desirable.

In these past few years, a lot of DWFL researches have been reported with erbium-doped fiber (EDF) as the gain medium in the 1550-nm wavelength region. Various designs have been proposed to provide optimization for dual-wavelength lasing in the EDF. Techniques such as polarization hole burning (PHB) [5], the use of fiber Bragg gratings [6], introducing a filter [7,8], and many more are widely available in the literature. However, report on the dual-wavelength laser generation in the 1-μm region using ytterbium as the gain medium [9] is still limited and has become the interest of this paper.

Despite a growing demand of ytterbium-doped fiber (YDF) gain medium, there are very few reports on dual-wavelength laser generation in the 1-μm region laser sources. Most of the reports suggest the use of fiber Bragg grating as a wavelength selection filter to obtain a dual-wavelength output in the YDF [10–12]. Another report proposed the use of an array waveguide grating together with an optical channel selector to produce a stable dual-wavelength ytterbium-based output [13]. Recently, Harith et. al. [14] reported the use of microfiber Mach–Zehnder interferometer (MZI) to generate dual-wavelength YDF in the laser ring cavity. Ytterbium in particular has a several advantage when compared to the EDF. For example, in spectral range, the YDF has a broader spectral range of 970–1200 nm [15] in comparison to the EDF which operates in C + L band (1550–1625 nm). Applications such as space optical communication and optical coherence tomography [16] are more applicable to the 1-μm region and hence, justify the further investigation of the DWFL in the YDF gain medium.
In this paper, we demonstrated for the first time to the best of author’s knowledge, a simple YDF laser with a short-length photonic crystal fiber (PCF) and tunable band pass filter (TBPF) incorporated in our ring cavity setup to obtain sets of stable and narrow spacing DWFL output. By carefully adjusting the polarization state of the cavity and the TBPF, we successfully achieved a narrow spacing dual-wavelength operation using a simple laser ring PCF-based setup. Our proposed setup also shows a stable operation behavior, and has a potential to be further exploited for DWFL optimization in the 1-μm region source.

2. Experimental setup

The configuration of the DWFL system using a PCF-based MZI is illustrated in Figure 1(a). The DWFL consists of 974-nm laser diode, a 980/1060 nm wavelength division multiplexing (WDM), a 70-cm YDF gain medium, a TBPF with 1-nm bandwidth, a polarization controller (PC), an isolator, a short-length PCF of 10 cm, and a 90/10 optical coupler (OC). The laser is first pumped with 974-nm center wavelength laser diode with maximum output power of 600 mW and launch power of 182 mW (Oclaro Model LC96A74P-20R), connected to a 980/1060 nm WDM coupler. One port of the WDM was fusion spliced to a 70-cm YDF gain medium (DF1100 Fibercore) which has peak absorption of 1300 dB/m at 977 nm and another port was coupled to the 90/10 OC via its 90% port. The YDF output was then connected to an isolator to ensure unidirectional laser ring operation. The isolator output was then attached to the PCF-based MZI. A constructed compact interferometer using a few-mode PCF of $L = 10$ cm was spliced into two segment of SMF. The main function of the PCF is to stabilize the DWFL output based on its birefringence coefficient and nonlinearity [8,17]. Figure 1(b) illustrates the PCF-based MZI; these two spliced points were located in series and resulted in a simple MZI, whereby the length of the PCF was directly related to fringe spacing. The cross section of the PCF is shown in the inset of Figure 1(a), which has a solid core of 4.37 μm in diameter, and surrounded by air holes with 5.06 μm diameter and separation of 5.52 μm between holes. Splicing of the PCF and SMF fiber was done using Fujikura 45 PM splicer.

The output of the PCF was connected to the PC that controlled the polarization state of the laser cavity and the PC output was attached to the TBPF. The TBPF output was then connected to the input of 90/10 fused biconical OC. The 10% end of coupler was then connected to the input port of an optical spectrum analyzer of type YOKOGAWA AQ6373 with a resolution of 0.02 nm. Figure 2 shows the transmission spectrum of the PCF-based MZI filter with unpolarized amplified spontaneous emission (ASE) source. The aggressive interference pattern, seen clearly in the red line of Figure 2, was responsible for the narrow lasing when the ring laser was closed. Lasing usually occurred at the interference peaks, and by finely controlling the system polarization state, the lasing wavelength is able to switch from one to the other and creates single- or multi-wavelength laser output.

The first collapse region diffracts the fundamental mode which is passed by and therefore, the core and cladding modes are excited in the few modes PCF section. Some part of the fundamental core mode of the PCF can be coupled to a single or several cladding modes of the PCF. Phase shifting in the same physical length of $L$ is a product of different effective refractive index of core and
cladding modes. As the effective refractive index of the cladding is smaller than core, the different optical paths corresponding arms of the MZI can be achieved. The fundamental and cladding modes accumulate a phase difference along the PCF due to different phase velocities. This phase difference depends on the length of the PCF and the wavelength of the guided light. By reaching the modes to the other collapsed area of the PCF, the cladding modes are going to recouple to the core mode. Since the phase difference and the phase velocities are wavelength dependent, the optical power transmitted by the interferometer will be minimum at certain wavelengths and maximum at the others. The separation between consecutive peaks of a two-mode interferometer is given by:

\[
\Delta \lambda = \frac{\lambda^2}{\Delta n_{\text{eff}} L}
\]

(1)

where \(\Delta n_{\text{eff}}\) is the effective refractive indices difference between the core and cladding modes and \(L\) is the interferometer length. The core and the cladding of the PCF play the role of arms of a MZI, while the collapsed points act as couplers splitting or combining light powers in the arms of the interferometer.

3. Results and discussion

In the experiment, the pumping power for our YDF from the laser diode is set to 202.0 mW. As the emission laser lines directly depend on the spectral transmission peaks produced by the PCF, it is necessary to shift this spectral pattern in order to change the laser characteristics. In our case, we performed the spectral shifting by adjusting the PC and TBPF incorporated in the laser setup. The adjustment of the PC will rotate the polarization states and allows continuous adjustment of the birefringence within the ring cavity to balance the gain and loss of the lasing wavelengths. In order to obtain a narrow spacing dual-wavelength laser, it is necessary to adjust the TBPF and then followed by tuning the PC. The TBPF has a wide range of tuning wavelength starting from 1018 to 1070 nm. In this experiment, the TBPF is adjusted until the single wavelength is set to 1040 nm. The PC is tuned to achieve dual wavelength at the same power, sometime we also need to fine tune the TBPF to obtain dual-wavelength laser. We obtained two sets of stable narrow spacing dual-wavelength that are 0.03 and 0.07 nm using a simple design of the DWFL with a short cavity length of 6 m as shown in Figure 3(a). The observed side mode suppression ratio (SMSR) for both sets of dual wavelength is 50 dB. The high SMSR contributed by the TBPF in the ring cavity allows spectrum within 1 nm wavelength range to pass through thus reducing the generation of the ASE.

The advantage of this proposed setup is the flexibility of the TBPF in tuning the laser wavelength in different wavelength regions within the tuning range of the TBPF and hence the capability to adjust the narrow spacing DWFL by adjusting the PC. Therefore, in order to obtain dual wavelength in other wavelength region, the TBPF is tuned to achieve single-peak laser at center wavelength of 1064 nm, then the PC is fine adjusted until dual-wavelength laser achieved with almost same peak power level. Moreover, the spectral separation between these two lines can be varied by finely readjusting the PC. Figure 3(b) shows three sets of stable narrow spacing dual-wavelength that are 0.1, 0.2, and 0.40 nm at other wavelength region. The observed SMSR for all sets of dual wavelength is increasing from 37 to 49 dB with the decreasing spacing wavelength from 0.40 to 0.1 nm.

\[\text{Figure 3. Spectral separation of tunable dual wavelength in (a) 1040 nm region, (b) 1060 nm region. (The color version of this figure is included in the online version of the journal.)}\]
The PHB effect is the products from an anisotropic saturation produced by a polarized saturating signal launched into the gain medium fiber. The difference in polarization will produce different gains from the active medium, and will affect lasers with birefringence components. The PHB effect will be at its maximum when the linearly polarized saturating signal is aligned with the major axis of the dipole. The polarization state is reduced when the saturating signal is circular or elliptical. The total effect is contributed by both signal and pump laser. Whenever the relative polarization states of the signal change (polarization mode dispersion effect), the differential gain magnitude of the signal will also be changed. The emission of two wavelengths with orthogonal polarization states can be simultaneously generated by fiber lasers [19]. Effects of DWFL generation with orthogonal polarization states are widely available in the literature and have been reported in [20–23]. It will minimize the

It is worth mentioning that all the dual-wavelength sets were stability tested over time. Figures 4 and 5 show the dual-wavelength stability scan for each set in the period of 15 min at 1040 nm and 1064 nm wavelength region respectively. They showed a maximum fluctuation of ~0.8 dB, which is shown on the right side of Figure 4 and wavelength fluctuation of less than 0.01 nm. We can say that the dual wavelength demonstrated in this paper is stable in the experiment done at room temperature. We proved that the homogeneous broadening effect of the YDF has been suppressed to a very low level. Incorporating a PC into the ring cavity prompted a wavelength-dependent polarization rotation that caused a variation of polarization states emerging through the multiple wavelengths in the YDFA. If the polarization states remain unchanged, all wavelengths would have closely identical polarization states in the YDF. Increasing the number of peaks oscillating in the cavity requires the exploitation of PHB effect [18]. The PHB effect is the products from an anisotropic saturation produced by a polarized saturating signal launched into the gain medium fiber. The difference in polarization will produce different gains from the active medium, and will affect lasers with birefringence components. The PHB effect will be at its maximum when the linearly polarized saturating signal is aligned with the major axis of the dipole. The polarization state is reduced when the saturating signal is circular or elliptical. The total effect is contributed by both signal and pump laser. Whenever the relative polarization states of the signal change (polarization mode dispersion effect), the differential gain magnitude of the signal will also be changed. The emission of two wavelengths with orthogonal polarization states can be simultaneously generated by fiber lasers [19]. Effects of DWFL generation with orthogonal polarization states are widely available in the literature and have been reported in [20–23]. It will minimize the
Figure 5. Dual wavelength and peak power stability test with tunable spacing of (a) 0.10 nm with $\lambda_1 = 1064.529$ nm and $\lambda_2 = 1064.631$ nm (b) 0.20 nm with $\lambda_1 = 1064.152$ nm and $\lambda_2 = 1064.392$ nm, and (c) 0.40 nm with $\lambda_1 = 1064.148$ nm and $\lambda_2 = 1064.556$ nm.
polarized saturated signals in the laser cavity as the signals are in the different polarization state, resulting in enhanced PHB effect. The only two modes that can exist in the cavity are those in which the polarization states are perpendicular to each other. By fine-tuning the PCs, we could achieve two orthogonally polarized lasers. In fact, PCF–MZI together with the PC acts not only as a filter in order to filter out the two wavelengths of orthogonal polarization states, but will also enhance the PHB effect in the cavity. Therefore, both the homogeneous gain broadening of the YDF and the wavelength competition will be reduced. In such circumstances, fine-tuning the PC will result in stable dual-wavelength lasing states.

4. Conclusion

In this paper, we demonstrated the narrow spacing DWFL on the ytterbium-doped fiber using a PCF-based MZI fiber. The dual-wavelength narrow spacing tuning range for our proposed setup is between 0.03, 0.07, 0.1, 0.2, and 0.40 nm. The observed SMSR of our proposed experiment is 50 dB for spacing wavelength below 0.1 nm and decreasing from 49 to 37 dB with wavelength spacing above 0.1 nm. We achieved stable dual-sets of dual-wavelength output with power fluctuation of ~0.8 dB over a period of 15 min and wavelength fluctuation less than 0.01 nm. Using the TBPF, our setup has the capability of adjusting the narrow spacing between dual-wavelength outputs. Moreover, our proposed setup is simple and inexpensive, and offers flexibility in dual-wavelength laser application.

Disclosure statement

No potential conflict of interest was reported by the authors.

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