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2016 Laser Phys. 26 025101
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Generation of an ultra-stable dual-wavelength ytterbium-doped fiber laser using a photonic crystal fiber

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Received 14 July 2015, revised 20 August 2015
Accepted for publication 19 October 2015
Published 17 December 2015

Abstract
This paper describes the demonstration of a simple ytterbium-doped fiber (YDF) laser that utilized a short length of photonic crystal fiber (PCF) in a ring cavity and adjustments to the polarization state of an incorporated polarization controller (PC) to achieve a stable dual-wavelength output. The dual-wavelength lasing operation exploited the Mach–Zehnder interferometer effect, and the laser output consistently achieved high power stability with a 0.8 dB fluctuation over a period of 30 min. This proposed setup has the capability for adjustable spacing of two lasing wavelengths from a minimum of 0.40 nm to a maximum of 3.40 nm, allowing for flexibility in dual-wavelength laser generation in addition to stable and reliable system features.

Keywords: dual wavelength, fiber laser, crystal fiber, ytterbium

(Some figures may appear in colour only in the online journal)

1. Introduction

Optical fibers have played a crucial role in the development of lasers, especially as an alternative to solid state and semiconductor designs, due to the resulting high beam quality, stability, reliability, superior thermal resistance and narrow bandwidth. In recent years, this attention has led to the development of multi-wavelength fiber laser sources to cater for increasing demands related to various optical applications such as photonic component characterization, optical sensing and optical instrumentation [1], and a particular focus on dual-wavelength fiber lasers (DWFL) operation due to special applications that can only be provided by DWFL. Examples of DWFL-specific applications include the photonic generation of microwave carriers [2], microwave photonic filters [3] and high-bit-rate soliton pulses [4]. Development and optimization of DWFL are becoming more important in optical fiber laser operations.

In the last decade, most of the research on DWFL has been undertaken with erbium-doped fibers (EDF) in the 1550 nm wavelength region. Various designs have been proposed for dual wavelength generation involving an EDF gain medium, with techniques such as polarization hole burning [5], the use of fiber Bragg gratings (FBG) [6], introducing a filter [7, 8] and many more being widely reported.

Despite a growing demand for 1 μm range fiber lasers that justifies further investigation of dual-wavelength lasers in a ytterbium-doped fiber (YDF) gain medium, there are very few reports such as [9] that relate to dual-wavelength laser generation in the 1 micron region using ytterbium as the gain medium. Most of the reports used a FBG as a wavelength selection filter to obtain a dual-wavelength output [10–12]. There is also a report describing the use of an array waveguide grating together with an optical channel selector to produce a stable dual-wavelength output [13]. In terms of spectral range, YDF can have a broader spectral range of 970–1200 nm...
In comparison to EDF which operates in the C + L band (1550–1625 nm). Furthermore, a 1 μm source is more desirable for applications such as space optical communication and optical coherence tomography [15] than a 1.55 μm source.

In this paper, we demonstrate a simple YDF laser with a short length photonic crystal fiber (PCF) incorporated in our ring cavity setup to obtain sets of stable DWFL output. To the best of our knowledge, this is the first time such an experiment has been proposed for a YDF-based gain medium. By using a PCF in our setup and carefully adjusting the light polarization state, we successfully achieved a dual-wavelength operation using a simple laser ring PCF based setup. This setup has a further advantage in that the dual-wavelength output was verified as stable and reliable.

2. Experimental setup

The experimental setup of the proposed DWFL using a PCF is shown in figure 1(a). The DWFL cavity consisted of a 974 nm laser diode with maximum output power of 600 mW and launch power of 75.1 mW (Oclaro Model LC96A74P-20R) connected to a 980/1060 nm wavelength division multiplexing (WDM) coupler. One port of the WDM was fusion spliced to a 70 cm YDF gain medium (DF1100 Fibercore) that has a peak absorption of 1300 dB m$^{-1}$ at 977 nm, and another port was coupled to the 90/10 optical coupler. The YDF output was subsequently connected to an isolator operating at a 1 μm range to ensure unidirectional laser ring operation. The isolator output was then connected to a PCF-based Mach–Zehnder interferometer (MZI). The constructed compact interferometer using a 10 cm length of few mode PCF with insertion loss of 7 dB was spliced into two segments of the single mode fiber (SMF). The PCF played the main function of stabilizing the DWFL output based on its birefringence coefficient and nonlinearity [8, 16]. The schematic depicted in figure 1(c) illustrates the MZI. The PCF has a solid core of 4.37 μm in diameter, and is surrounded by air holes with 5.06 μm diameter and separation of 5.52 μm between holes. Splicing of the PCF and single mode fiber (SMF) was done using Fujikura 45 PM splicer. These two spliced points were positioned in series and resulted in a simple MZI, whereby the length of the PCF was directly related to fringe spacing. The insertion loss of each splicing point was 3 dB. Details of the optical properties of this PCF-based MZI can be obtained in [8]. The PCF was attached to polarization controller (PC) that controlled the polarization state of the laser cavity. The PC output was connected to the 90/10 fused biconical optical coupler. The 10% end of this coupler was then connected to the input port of an optical spectrum analyzer (OSA) of type YOKOGAWA AQ6373 with a resolution of 0.02 nm.

The first collapsed region diffracts the fundamental mode that passes through, and therefore the core and cladding modes are excited in the few mode PCF section. Some portion 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, $L$, is a product of the different effective refractive index of the core and cladding modes. As the effective refractive index of the cladding is smaller than that of the core, different optical paths that correspond to 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. When the modes reach the second collapsed area of the PCF, the cladding modes 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

$$\Delta \lambda = \frac{\lambda^2}{L \Delta n_e}$$  (1)

where $\Delta n_e$ is the effective refractive indices difference between the core and cladding modes and $L$ is the length of the fiber between the two splices area. The core and the cladding of the PCF play the role of arms of an MZI, while the collapsed points act as couplers splitting or combining light powers in the arms of the interferometer.

The transmission spectrum of the MZI filter with an unpolarized amplified spontaneous emission (ASE) source
is depicted in figure 2 with a free spectral range (FSR) of 0.20 nm. The reason for non-uniformity in the spectrum response is due to the different modes of MZI having dissimilar intensity. The laser output was extracted from the ring cavity by a 90:10 special wavelength fiber coupler. The 90% port was used to feedback into the laser cavity while the 10% port was laser output. An OSA (YOKOGAWA AQ6373) with a resolution of 0.02 nm is used for all the measurements and analysis.

Figure 2. Transmission spectrum of the MZI filter.

Figure 3. (a) Slope efficiency for laser threshold with PCF, and (b) dual wavelength lasing spectrum with centered wavelengths at 1036.13 nm and 1036.53 nm respectively.

3. Results and discussions

In the experiment, the pumping power for our YDF from the laser diode is set to 88.0 mW, as shown in figure 3(a), with a total cavity length of 5 m and slope efficiency of 0.3%. 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 incorporated in the laser setup. The adjustment of the PC will rotate the polarization states and allow for continuous adjustment of the birefringence within the ring cavity to balance the gain and loss of the lasing wavelengths. In order to obtain a dual wavelength laser it is necessary to change the polarization state. Figure 3(b) shows the optical spectrum of the dual wavelength output obtained from the PCF-MZI-YDF laser ring cavity setup. Spectral shifting of light was accomplished by adjusting the PC so as to change polarization states when light entered the ring cavity. The dual wavelength output obtained from the experiment was measured as 1036.13 nm and 1036.53 nm with a wavelength spacing of 0.40 nm, while the observed side mode suppression ratio (SMSR) was approximately ~50 dB. The polarization states of the dual-wavelength laser were different and perpendicular to each other [8].

Moreover, the spectral separation between these two lines can be varied by finely adjusting the polarization controller. As shown in figure 4, three sets of stable dual-wavelength were obtained as a result of adjusting the PC. The three acquired sets of the dual-wavelength lasing spectrum have wavelength spacing of 0.40 nm, 1.80 nm and 3.40 nm. The observed SMSR for all sets of dual-wavelength output is ~50 dBm.

The stability of all the dual-wavelength sets was tested over time. Figure 5 shows the dual-wavelength stability scan for each set in a period of 30 min with 3 min interval for each scan (10 iterations). These results showed a maximum
fluctuation of ~0.8 dB, which is displayed on the left-hand side of figure 5. The dual-wavelength demonstrated in this paper is evidently highly stable when this experiment is performed at room temperature. Furthermore, the results provide evidence that the homogeneous broadening effect of the YDF has been suppressed to a very low level. The setup proposed in this paper also has the advantage of having the ability to adjust the spacing of the two lasing wavelengths.

Figure 5. Dual wavelength and peak power stability test with tunable spacing of (a) 0.40 nm with \( \lambda_1 = 1036.13 \text{ nm} \) and \( \lambda_2 = 1036.53 \text{ nm} \), (b) 1.80 nm with \( \lambda_1 = 1035.60 \text{ nm} \) and \( \lambda_2 = 1037.40 \text{ nm} \), and (c) 3.40 nm with \( \lambda_1 = 1036.10 \text{ nm} \) and \( \lambda_2 = 1039.50 \text{ nm} \).
4. Conclusion

In conclusion, we demonstrated dual-wavelength fiber lasing with an ytterbium-doped fiber via a photonic crystal fiber. The observed SMSR of this proposed experiment was 50 dB, and a highly stable set of dual-wavelength output with power fluctuation of ~0.8 dB over a period of 30 min has been achieved. Fine-tuning the PC provides the setup with the capability to adjust the spacing between the dual-wavelength outputs. The dual-wavelength spacing tunings for our proposed setup are 0.4 nm, 1.80 nm and 3.40 nm with a wavelength range between 1035.60 nm and 1039.50 nm. Moreover, this proposed setup is simple, inexpensive, and offers flexibility in dual-wavelength laser applications.

Acknowledgment

We would like to thank the Ministry of Education (MOHE) and University of Malaya for the research funding, under grant number UM.C/625/1/HIR/MOHE/SC/29/01, RU002/2013, RP008A-13AET and RG143-12 AET.

References