Highly stable and tunable narrow-spacing dual-wavelength ytterbium-doped fiber using a microfiber Mach–Zehnder interferometer

Harith Ahmad
Muhammad A. M. Salim
Saaidal R. Azzuhri
Sulaiman W. Harun
Highly stable and tunable narrow-spacing dual-wavelength ytterbium-doped fiber using a microfiber Mach–Zehnder interferometer

Harith Ahmad,a,* Muhammad A. M. Salim,a,b Saaidal R. Azzuhri,a and Sulaiman W. Haruna

Abstract. We describe a successful demonstration of highly stable and narrowly spaced dual-wavelength output via an ytterbium-doped fiber laser. A microfiber-based Mach–Zehnder interferometer and a tunable bandpass filter were both placed into the laser ring cavity for the purpose of ensuring a stable and narrowly spaced dual-wavelength output. Experimental results comprised three sets of dual-wavelength lasing output with wavelength spacing of 0.06, 0.09, and 0.22 nm, respectively, and side-mode suppression ratio of ~50 dB. A subsequent stability test provided evidence that maximum power and wavelength fluctuation were less than 0.8 dB and 0.01 nm, respectively, and thus, the obtained output was considered to be highly stable in dual-wavelength operation. The proposed system offers advantages of flexibility in dual-wavelength laser generation in addition to excellent reliability. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.55.2.026114]

Keywords: ytterbium-doped fiber laser; narrow spacing; microfiber.

Paper 151246 received Sep. 10, 2015; accepted for publication Jan. 7, 2016; published online Feb. 16, 2016.

1 Introduction

Fiber lasers, in which the active gain medium is a doped optical fiber, have undergone tremendous optimization over the past couple of decades. Improvements to stability, reliability, thermal resistance, and beam quality have resulted in fiber lasers becoming suitable for various applications such as optical fiber sensing, communication, instrument testing, and high-resolution spectroscopy. Advancements in fiber laser in recent years have led to the development of dual-wavelength fiber laser (DWFL) operation, and consequent applications, such as microwave photonic filters, microwave carriers, and high bit-rate pulses, that can only be catered for by DWFL. Hence, operation of DWFL in optical fiber lasers is highly desirable and has gained wide attention within optical research communities.

In recent years, most of the research in DWFL has been undertaken using erbium-doped fiber (EDF), which emits in the 1550-nm wavelength region. Different techniques have been reported for obtaining DWFL, including polarization hole-burning, introducing a filter, the use of fiber Bragg grating (FBG), and many others. More recently, interest has been shown in the use of ytterbium-doped fiber (YDF) gain medium for optical fiber lasing in the 1060-nm region. The growing attentiveness shown in YDF, a situation that in itself encourages further study on the ytterbium gain medium in the context of fiber lasers, few reports exist with regard to DWFL generation using ytterbium as a gain medium, which is the research interest of this paper. Most of the research literature thus far has reported the usage of FBG as a wavelength-selection filter to generate dual-wavelength output in the 1-μm region. Another report has suggested the use of an array waveguide grating coupled with an optical channel selector to produce a stable dual-wavelength output in YDF gain medium. In terms of applicability, a 1-μm source is more suitable than a 1.55-μm source for applications such as space optical communications and optical coherence tomography. YDF also has broader spectral range (970 to 1200 nm) in comparison to EDF, which operates in the C and L bands, and as such, further investigation of DWFL for a 1-μm source is highly desirable.

Recent study in microfiber has found that the attractive features from simply tapering the single-mode fiber into a short length of microfiber can emulate complex devices such as Mach–Zehnder interferometer (MZI). Microfiber has several unique and interesting features such as high non-linearity, evanescent fields, and dispersion-tuning ability. A microfiber will nonadiabatically excite higher-order modes, with a consequent spatial-mode beating between core and cladding modes when connected to a single-mode medium. This beating creates a comb response equivalent to a wavelength-dependent loss. Some setups such as in Ref. 16 explored the multimodal interference in EDF lasers using multimode fiber (MMF) in a ring laser. However, the consequent lasing is below the gain curve and possesses a high noise threshold and low stability due to the MMF parameters. The introduction of taper fiber, with associated manipulation of diameter, length, and refractive index contrast, offers an ability to control the multimodal interference properties.

This paper represents a demonstration of a simple YDF laser (YDFL) with a microfiber MZI and tunable bandpass filter (TBPF) that together allowed for generation of tunable and narrowly spaced dual-wavelength lasing. The laser exploited a ring cavity that contained a 70-mm nonadiabatic microfiber with 2-μm diameter, wherein this microfiber excited higher-order modes in the single-mode cavity leading
to spatial-mode beating and an interference with an equivalence to wavelength-dependent loss. Closing the cavity and creating a ring laser cavity caused suppression of the amplified spontaneous emission (ASE) of the YDF and mode competition. The interference response of the nonadiabatic microfiber was polarization sensitive, and thus changes to the state of polarization (SOP) of the cavity via a polarization controller (PC) allowed for stabilization and tuning of dual wavelength with different spacing by means of nonlinear polarization rotation. The TBPF used in this experiment is to confine the oscillation of DWFL in a narrow spacing. Without the TBPF, the DWFL will tend to lase at wavelength with wider spacing. Three sets of stable dual-wavelength outputs, with wavelength spacing of 0.06, 0.08, and 0.20 nm, were demonstrated in the proposed setup, and these achieved dual-wavelength outputs had a side-mode suppression ratio (SMSR) of approximately 52 dB. The dual-wavelength output has been verified as stable and reliable, which signifies an additional attractive feature of this setup.

2 Experimental Setup

The experimental setup of the proposed dual-wavelength generation using microfiber MZI fiber is shown in Fig. 1. The fiber ring consisted of a 974-nm central wavelength pump laser diode with 600-mW output power (Oclaro Model LC96A74P-20R), which was connected to 980-/1060-nm wavelength division multiplexing (WDM) coupler. One port of the WDM was fusion-spliced to a gain medium comprising 70-cm YDF (DF1100 Fibercore), which had peak absorption of 1300 dB/m at 977 nm, and another port was connected to a 90/10 optical coupler (OC). Output of the YDF amplifier was then fusion-spliced to a polarization-insensitive isolator operating at the 1-μm range. This isolator was incorporated into the laser cavity to ensure unidirectional laser-ring operation, which in this case was in the clockwise direction. The isolator output port was then connected to a PC that controlled the cavity SOP. The PC output was attached to the MZI microfiber, which was in turn connected to a TBPF (Agiltron Inc., Product No. FOTF-023120323) for confining the oscillation of dual-wavelength laser to get narrowly spaced wavelength output, and the TBPF was then linked to the 90/10 fused biconical OC to complete the optical circuit. The 10% end of coupler was connected to the input of an optical spectrum analyzer (OSA) of type YOKOGAWA AQ6373 with a spectral resolution of 0.02 nm.

The cross-sectional overview of the microfiber MZI fiber is shown in Fig. 2, for which light is considered to propagate from left to right. The heat and pull method was used for tapered fiber fabrication, wherein the fiber jacket was removed from the tapered region prior to heating. Two areas, each with a length of approximately 1 cm, were tapered to the core level, and hence will be referred to as Taper 1 and Taper 2. Each of these two sections acted as a MMF due to the large difference between the core and air refractive indices.

A crucial characteristic of a microfiber MZI is the average peak-to-peak beating distance or wavelength spacing \( \Delta \lambda \), and dissimilar tapering structures, in term of length and diameter, will result in different beating effects. The wavelength spacing, \( \Delta \lambda \), is determined by

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

where \( \Delta n_{\text{eff}} \) is the effective refractive index difference between core and cladding, and \( L \) is the interferometer length.

Beating length, \( L_\beta \), is determined by

\[
L_\beta = \frac{2\pi}{\Delta \beta},
\]

where \( \Delta \beta \) is the propagation constant difference between core and cladding modes. A smaller microfiber MZI diameter or a longer tapered length will result in narrower and shaper peaks. These microfiber parameters determine the ability of the system to obtain stability, narrow lasing, and mode competition suppression in the cavity due to wavelength-dependent loss of the interference. Figure 3 shows the ASE spectrum directly from the YDFL output as a blue line, whereas the red line represents the ASE spectrum output after traversing the nonadiabatic microfiber. The aggressive interference pattern, seen clearly in the red line of Fig. 3, was responsible for the narrow lasing when the ring laser was closed. Lasing within the proposed setup usually occurred at the interferences peaks, and simple adjustments to the polarization using a PC and TBPF caused lasing to shift to another peak, or triggered multipeak lasing if supported by the cavity.

Due to the very small diameter of 2 μm for the microfiber, it can easily be damaged from external noises and contamination material such as dust, with potential power loss, instability, and induced mode-hopping. Therefore, the fiber was carefully packaged, similar to the technique described in Ref. 19, so as to provide isolation and protection from the external environment while preserving the properties of the fiber.
3 Results and Discussions

In this experiment, the pumping power from the laser diode for the YDF was fixed at 275.0 mW, which corresponds to a 0.4-mW laser output. As the emission laser lines were directly dependent on the spectral transmission peaks produced by the microfiber MZI, alterations to the lasing characteristics required a shift in this spectral pattern. Spectral shifting in the laser experimental configuration was achieved via adjusting the incorporated PC and TBPF. Variation to the PC caused a rotation to occur in the polarization states and a change of the birefringence within the ring cavity, which could be suited to balance the gain and loss of the lasing wavelengths. Suitable adjustments to the TBPF followed by a tuning of the PC allowed for operation of a narrow-spacing dual-wavelength laser. The TBPF had a wide range of tuning wavelength that spanned 1015 to 1079 nm. Initially, the TBPF was tuned to achieve a single-peak lasing at a center wavelength of 1039 nm, and then the PC was finely adjusted so as to obtain dual-wavelength lasing that had nearly the same peak power level. Moreover, the spectral separation between these two lines could be varied by finely readjusting the PC as shown in Fig. 4. Without the TBPF, more lasing wavelength can be achieved from the setup. However, we only focused on the narrow-spacing DWFL that is very useful for applications such as microwave generation and radio over fiber. In this manner, three sets of stable narrow-spacing dual wavelength, at 0.06, 0.08, and 0.20 nm, were obtained by using a simple design of DWFL with a short cavity length of 6 m. The observed SMSR for all sets of dual wavelength was in excess of 50 dBm, and this high SMSR was in part due to the TBPF in the ring cavity allowing spectra within 1-nm wavelength range to pass through and thus reduce the generation of ASE.

Particular advantages of this proposed setup were the flexibility of the TBPF with a wide tuning range that allowed for tuning the laser wavelength to various regions, and the capability via PC adjustments to modify the narrow spacing of dual-wavelength output.

Each dual-wavelength set was stability tested over a period of 15 min at room temperature, and Figs. 5–7 show the dual-wavelength stability scan for these sets. The maximum power fluctuation was less than 0.8 dBm, and wavelength fluctuation was below 0.01 nm. As such, the...
dual-wavelength operation demonstrated in this paper can be considered as highly stable at room temperature. Furthermore, the results provide evidence that the homogeneous broadening effect of YDF has been suppressed to a very low level, and this aspect contributes to the highly stable and narrowly spaced dual-wavelength lasing output.

4 Conclusion
This paper gives a detailed description of a successful demonstration of dual-wavelength fiber lasing via YDF in association with a microfiber MZI and TBPF. A highly stable set of dual-wavelength output was achieved, for which power fluctuation of approximately 0.8 dBm and wavelength fluctuation of less than 0.01 nm were observed over a period of 15 min, and the observed SMSR of the proposed experiment was more than 50 dB. The proposed configuration allowed for modification of the narrow spacing between dual-wavelength outputs via the TBPF, with the dual-wavelength narrow-spacing tuning range encompassing 0.06 to 0.22 nm. This setup represents a simple, inexpensive, and flexible means for dual-wavelength laser application, and the authors anticipate that the results will spur consideration of further refinements and research in this area.

Acknowledgments
This work was supported by University of Malaya (RU 002/2013, RP008A-13AET, and RG143-12AET).

References


Harith Ahmad received his undergraduate education at University of Malaya where he obtained a first class degree in physics and went on to do his master’s degree in High Voltage Technology and a doctorate in Laser Technology from the University of Wales in the United Kingdom. His areas of expertise are fibre optics and waveguides (plannar lightwave circuit), quantum electronics and lasers (laser technology) and fibre optics & waveguides (fibre optic technology).

Muhammad A. M. Salim graduated from Universiti Teknologi Malaysia (UTM) with Honours Degree (material physics) in 2003 and subsequently received his MSC in laser and optical technology from UTM, in 2007. Currently he is doing his PhD in Fiber Laser at Photonics Research Centre, University of Malaya (UM) since 2013. He has been promoted as senior science officer in Advanced Photonic Science Institute (APSI) and has serving for Faculty of Science, UTM since August 2008. His current research focusing in ytterbium doped fiber laser, microfiber, nonlinear optics, pulse laser, and new material of saturable absorber.

Saaidal R. Azzuhri received his BEng (telecommunication) from University of Malaya in 2004. After completing his study, he worked as a Network Engineer in Telecom Network (TMNet), the biggest ISP provider in Malaysia before deciding to further his study and received his MSc in IT from Malaysia University of Science and Technology (MUST) in 2008. He obtained his PhD in University of Queensland, Australia in Wireless Networks System. His current research focusing in 1-micron fiber laser, microfiber, planar optical waveguide, and wireless network.

Sulaiman W. Harun received his BEng (electrical) from The Technological University of Nagaoka in 1996. He received his MSc (2001) and PhD (2004) in physics from University of Malaya. After completing his study, he joins the Department of Electrical Engineering, University of Malaya, focusing in pulsed laser, microfiber and optical waveguide research.