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Dual wavelength single longitudinal mode Ytterbium-doped fiber laser using a dual-tapered Mach-Zehnder interferometer

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This paper describes a dual wavelength single longitudinal mode (SLM) demonstration for a proposed ytterbium-doped fiber laser. A dual-tapered Mach-Zehnder interferometer (MZI) was inserted into the laser ring cavity setup to ensure a stable dual wavelength and SLM operation. The consequent dual wavelength lasing operation had a wavelength spacing of 0.94 nm and a side mode suppression ratio (SMSR) of 50 dB, with the linewidth of this setup measured as 294.15 kHz. A stability test allowed for a measurement of max power fluctuation as less than 0.8 dB for each wavelength and which was indicative of a stable dual wavelength operation.
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Keywords: Dual wavelength, fiber laser, single longitudinal mode, mach-zehnder

1 INTRODUCTION

Development of dual wavelength fiber lasers (DWFLs) has gained much attention in recent years due to the needs of applications such as photonic generation of microwave carriers [1], microwave photonic filters [2] and high-bit-rate soliton pulses [3], that can only be satisfied by DWFLs. Most of the research in dual wavelength lasers within the last decade has utilized a gain medium of erbium-doped fiber (EDF), which results in emitted wavelengths of 1550 nm. Various proposals for dual wavelength laser generation exploiting EDF, including polarization hole burning [4], the use of fiber Bragg gratings (FBG) [5] and introduction of a filter [6, 7], are readily available in literature. However, there are far less reports on dual wavelength laser generation in the 1 μm region using ytterbium-doped fiber (YDF) as the gain medium [8]−[10], which is the interest of this paper.

Most of the proposed setups for DWFL with a YDF gain medium report the use of a FBG as a wavelength selection filter in order to obtain the dual wavelength output [11, 12]. There is also a report describing an arrayed waveguide grating used together with an optical channel selector to produce a stable dual wavelength output [13]. However, dual and multi-wavelength output for YDF reported so far has operated under multimode oscillation and mode hopping [9, 10] and as such has a severe disadvantage within applications such as optical coherence tomography (OCT) [14] that require a superior coherence and optical properties possessing extremely low noise. Such requirements are only achievable via single longitudinal mode (SLM) operation. SLM in YDF lasers may also be used for achieving second harmonic generation (SHG) [15] if lasing power is sufficiently large, and for optical wireless transmission with 830 nm laser sources [16]. Several methods have been reported so far to achieve SLM operation using YDF as a gain medium; one report [16] suggested the use of passive multiple-ring cavity configuration to obtain SLM operation in the 1 μm range, while another report demonstrated SLM operation using a semiconductor optical amplifier (SOA) and unpumped YDF that acted as a narrow-band filter. The only report [17] currently available addressing simultaneous multi-wavelength and SLM operation describes a demonstration of these simultaneous operations through the use of a Sagnac loop mirror. A high level of interest exists for dual wavelength SLM operation involving YDF due to potential applications in optical communication and optical sensing in the 1 μm region.

In this paper, a simple YDF laser with a dual-tapered Mach-Zehnder interferometer (MZI) fiber incorporated within a ring cavity setup to obtain simultaneous DWFL and SLM operation is proposed and demonstrated. Dual wavelength and SLM operation was achieved with utilization of the dual-tapered MZI fiber and careful adjustments to the light polarization state. The dual wavelength output possessed a 0.94 nm spacing and a side-mode suppression ratio (SMSR) of 50 dB, while the achieved SLM operation had a linewidth of each wavelength determined as 294.15 kHz via a self-heterodyne calculation method.

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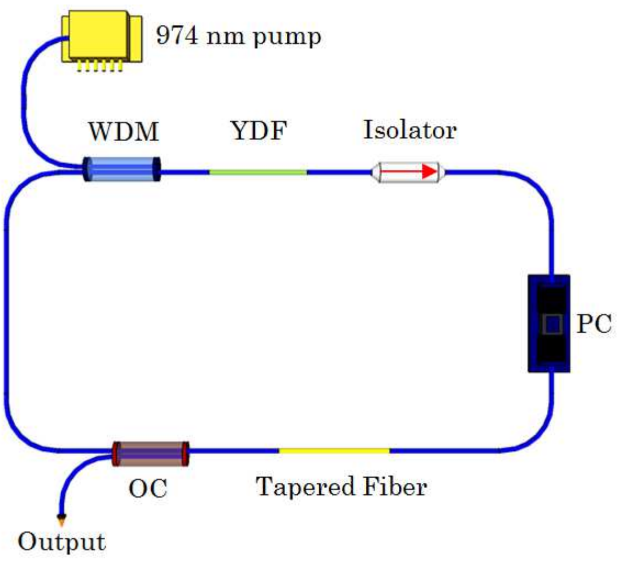

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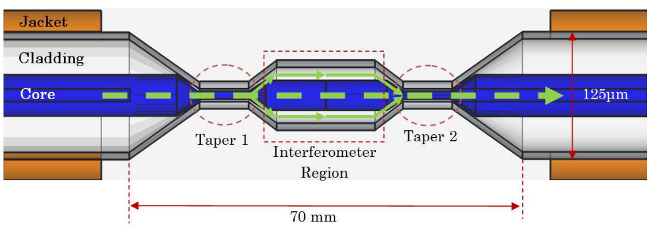

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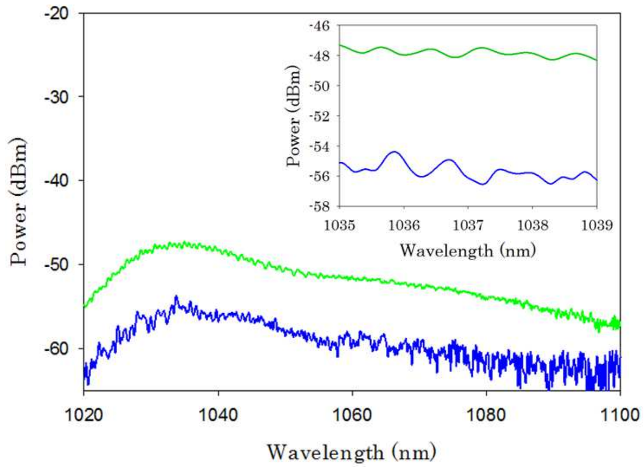
FIG. 1 (a) experimental setup of dual wavelength YDF laser, and (b) schematic diagram of non-adiabatic tapered fiber.



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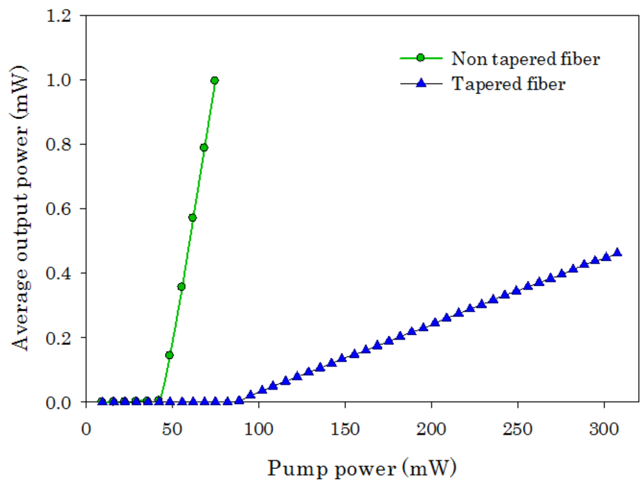

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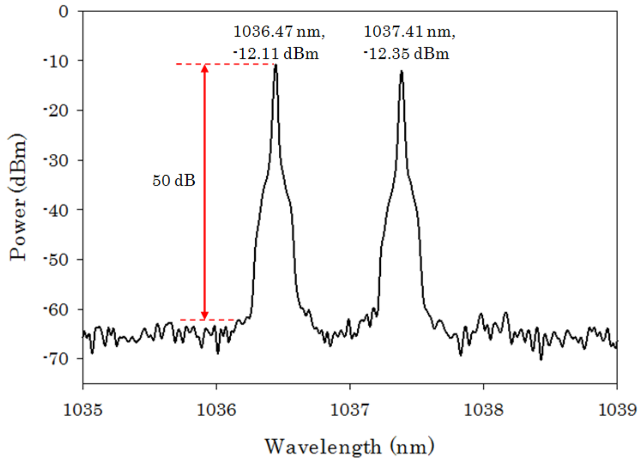
FIG. 2 (a) ASE spectrum, and (b) slope efficiency of lasing threshold, for tapered fiber (blue) and non tapered fiber (green).

2 EXPERIMENTAL SETUP

The experimental setup of the proposed dual wavelength generation using a dual-tapered MZI fiber is shown in Figure 1. The fiber ring consisted of a 974 nm central wavelength pump laser diode with 600 mW output power (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 gain medium comprising 70 cm YDF (DF1100 Fibercore) that had peak absorption of 1300 dB/m at 977 nm, and another port was connected to a 90/10 optical coupler. 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 was in the clockwise direction in the context of the Figure 1 layout. The output of the isolator was subsequently connected to a polarization controller (PC) that controlled the cavity state of polarization, and the PC output was attached to the dual-tapered MZI fiber, which was in turn connected to a 90/10 fused bi-conical optical coupler. This dual-tapered MZI fiber acted as a multi-modal interference medium in order to form a narrow band filter. The 10% end of the coupler was then connected to the input of an optical spectrum analyser (OSA) of type Yokogawa AQ6373 with a spectral resolution of 0.02 nm.

A cross-section overview of the dual-tapered MZI fiber is shown in Figure 1(b) in which the light is considered as propagating from left to right. The fiber jacket was removed from the region intended for tapering, and the heat and pull method [7] was applied in order to fabricate tapered fiber. Two areas, each being approximately 1 cm in length, were tapered to the core level and are depicted in Figure 1(b) as *taper* 1 and *taper* 2. These two sections acted as multimode fiber due to the large difference between the core and air refractive indices. Details regarding the optical properties of this dual-tapered MZI fiber can be obtained in [7], while transmission spectrum of the MZI filter with a non-polarized amplified spontaneous emission (ASE) source is depicted in Figure 2(a). The significant interference pattern, as observed clearly in the blue line of Figure 2, was responsible for the narrow lasing when the ring laser was closed. Lasing usually occurred at the interferences peaks, and simple adjustment of the polarization using a PC caused lasing to shift to another peak, or activated multi-peak lasing if supported by the cavity. The lasing threshold for this setup was 88.6 mW, as shown in Figure 2(b), with a total cavity length of 6 m.



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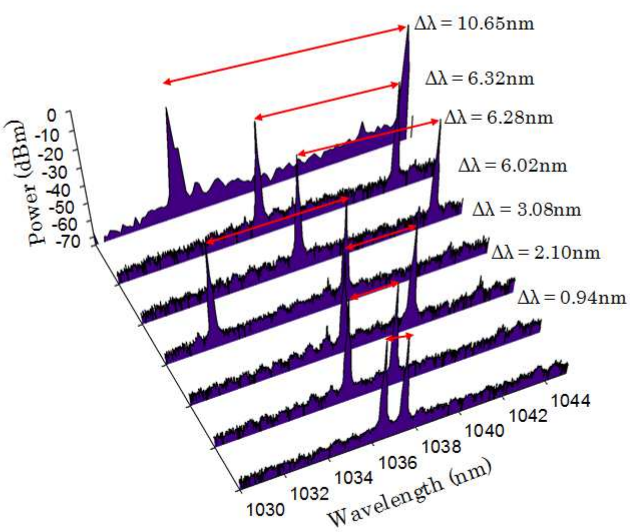


(b)

FIG. 3 (a) dual-wavelength lasing spectrum, and (b) dual-wavelength spectrums with tunable spacing of

(i) 0.94 nm at λ_1=1036.47 nm and λ_2=1037.41 nm

(ii) 2.10 nm at λ_1=1036.03 nm and λ_2=1038.13 nm

(iii) 2.10 nm at λ_1=1036.03 nm and λ_2=1038.13 nm

(iv) 3.08 nm at λ_1=1037.05 nm and λ_2=1040.13 nm

(v) 6.02 nm at λ_1=1032.27 nm and λ_2=1038.29 nm

(vi) 6.28 nm at λ_1=1037.31 nm and λ_2=1043.59 nm

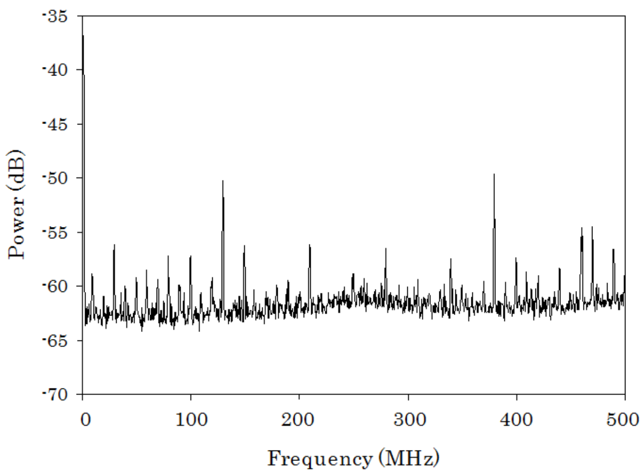
(vii) 6.32 nm at λ_1=1036.65 nm and λ_2=1042.97 nm

(vii) 10.65 nm at λ_1=1033.9 nm and λ_2=1044.55 nm

3 RESULTS AND DISCUSSION

Figure 3(a) shows the optical spectrum of the dual wavelength output obtained from the dual-tapered 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. Tuning of the PC caused a rotation of the polarization states and allowed for continuous adjustment of the birefringence within the ring cavity that acted to balance the gain and loss of the lasing wavelengths. The dual wavelength output obtained from the experiment was measured as 1036.47 nm and 1037.41 nm with a wavelength spacing of 0.94 nm, while observed SMSR was approximately 50 dB.

Additionally, the dependence of the interference peaks on the cavity state of polarization (SOP) meant a slight adjustment to the PC caused the wavelength of lasing to switch over to another wavelength as shown in Figure 3(b). The seven acquired sets of dual-wavelength lasing spectrum have a spacing tuning range between 0.94 nm and 10.65 nm.



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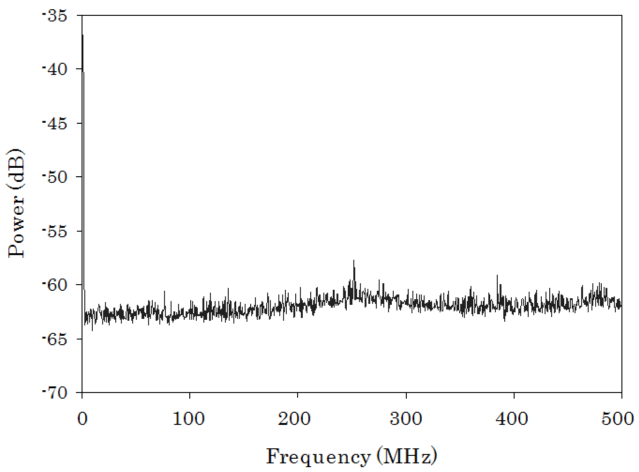

(b)

FIG. 4 RF spectrum of the cavity with (a) dual-tapered fiber disconnected, and (b) dual-tapered fiber connected.

Verification of the SLM operation in the proposed setup was undertaken by connecting the 10% output from the coupler to a RF analyzer (Anritsu MS2683A with a detection range from 9 KHz to 7.8 GHz) via a Thorlabs D400FC fiber optic photodetector in order to analyse the beating signal of the spectrum. An initial observation of the beating mode, wherein the dual-tapered fiber was disconnected from the cavity setup, across a scan range from 0 to 500 MHz is depicted in Figure 4(a). It can be seen that the spectrum is very noisy and unstable due to mode-hopping within the cavity. Connecting the dual-tapered fiber to the cavity setup caused the beating noise to disappear, with no mode-hopping observed in the resulting spectrum shown in Figure 4(b).

Measurement of the SLM full width at half maximum (FWHM) linewidth involved application of the heterodyne

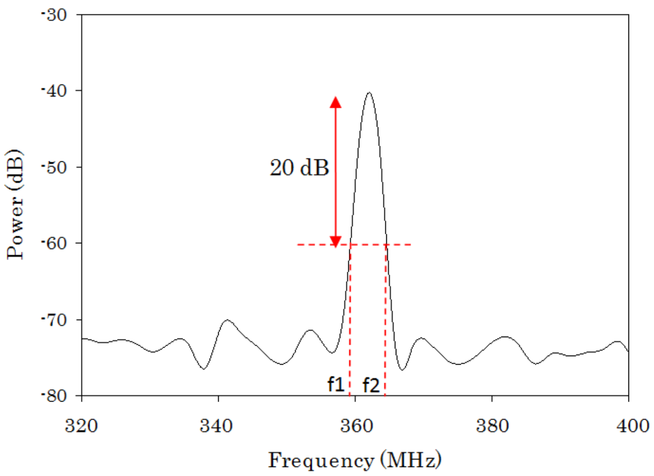

FIG. 5 measured FWHM linewidth spectrum using a heterodyne linewidth method.

technique linewidth relations method described in [18] and given by the following equation:

$$\sqrt{99}\Delta\nu = \Delta f_{20\mathrm{dB}} \qquad (1)$$

where $\Delta\nu$ is the FWHM linewidth and $\Delta f_{20\mathrm{dB}}$ is the frequency difference for a measured full-width point at 20 dB. The measured FWHM linewidth resulting from the heterodyne method is shown in Figure 5. Applying the equation in 1 $f_2 = 3.63 \times 10^8$ Hz and $f_1 = 3.59 \times 10^8$ Hz resulted in a $\Delta\nu$ linewidth value of 294.15 kHz, thus providing a verification of SLM operation in the experiment.

All the obtained dual wavelength sets were stability tested over time due to power stability being one of the most important characteristics of DWFL. Figure 6 shows a dual wavelength stability scan for a period of 30 minutes incorporating intervals of 3 minutes for each scan over a total of 10 iterations. Figure 6(a) displays a very stable lasing wavelength over the test period and Figure 6(b) illustrates power fluctuation during the scan, in which the maximum fluctuation is observed as less than 0.8 dBm. Such results proved that the wavelength and average power were stable over time and experienced only a very small power fluctuation at room temperature. It should be noted that a test measurement of the dual wavelength was performed simultaneously with these stability tests, and as such these results confirmed the stability and reliability of the proposed setup.

In comparison to the similar approach for SLM operation with YDF reported in [17], the proposal demonstrated in this paper achieved a comparable SMSR and a higher linewidth in the kHz range while utilizing a simpler setup and less equipment for SLM output. In regards to dual wavelength laser operations, the approach discussed in this paper has a similar SMSR and power stability to the work presented in [11, 12] that used FBG as a wavelength selective filter. Fabrication of FBG requires expensive equipment such as UV laser and phase mask [19] when compared to the low cost and reliable dual-tapered MZI component fabricated in-house. Therefore, the proposed dual-tapered MZI fiber is shown to be an ex-

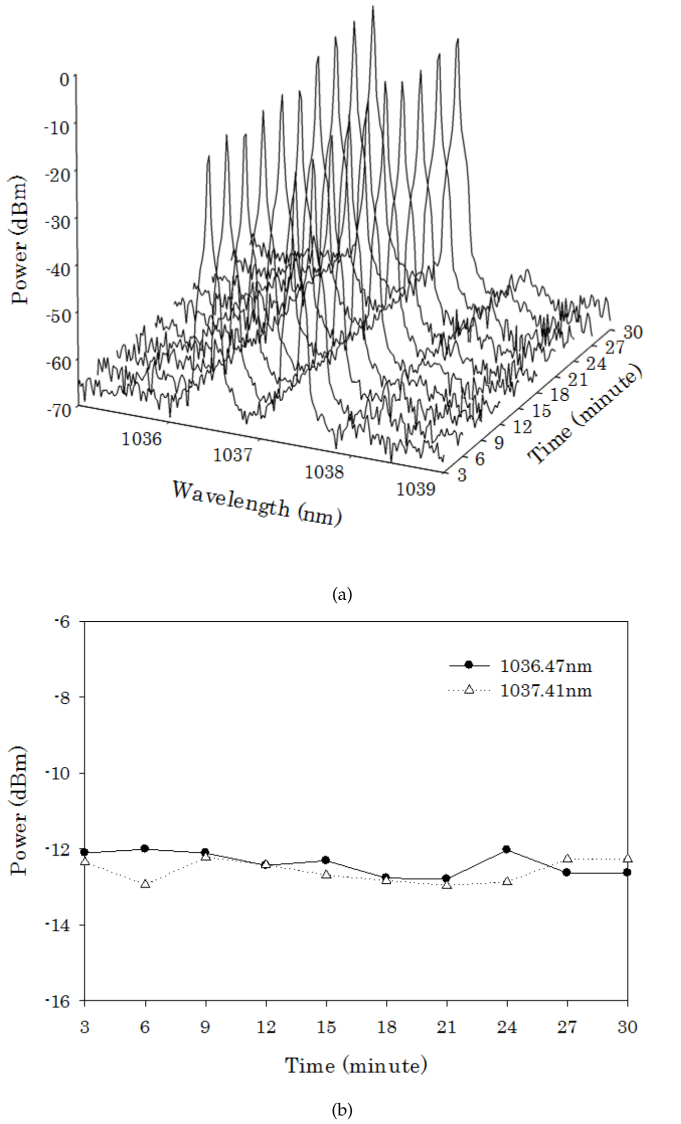

FIG. 6 (a) dual wavelength output scan, and (b) peak power stability test for spectral spacing of 0.94 nm with λ_1=1036.47 nm and λ_2=1037.41 nm.

cellent choice as a wavelength filter, and has suitability for applications such as OCT, micromachining and optical wireless [20].

4 CONCLUSIONS

This paper describes in detail a successful demonstration of a dual wavelength generation and SLM operation utilizing YDF and a dual-tapered fiber MZI filter. Fine-tuning the PC in the proposed setup resulted in generation of dual wavelength lasing with measured wavelength spacing of 0.94 nm and a SMSR of approximately 50dB. The SLM linewidth resulting from the experiment was calculated via the heterodyne technique as being 294.15 kHz, while a stable dual wavelength output with maximum power fluctuation of 0.8 dBm over a period of 30 minutes was achieved. These results mean that the proposed setup relative to similar reported approaches has key advantages of simpler setup, lower cost deployment, and highly stable operation under room temperature for the 1 μm wavelength region. The authors of this paper anticipate such findings presented here will spur further developments and applications in this area.

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