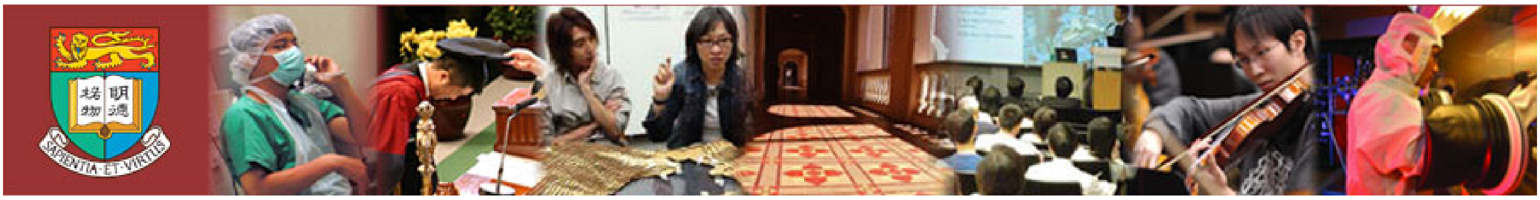

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Author(s)	**ZHOU, Y; Chui, PC; Wong, KKY**
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Multiwavelength Single-Longitudinal-Mode Ytterbium-Doped Fiber Laser

Yue Zhou, P. C. Chui, and Kenneth K. Y. Wong, *Senior Member, IEEE*

***Abstract*— We demonstrate a multiwavelength single-longitudinal-mode (SLM) ytterbium-doped fiber laser. Two Sagnac loop mirrors are inserted into the cavity to ensure multiwavelength and SLM operation, respectively. Three wavelengths with a wavelength spacing of 1.8 nm are generated under stable operation, and the linewidth of each wavelength is measured to be narrower than 100 kHz. A side-mode suppression ratio of greater than 56 dB is achieved for each wavelength. The maximum power fluctuation was less than 0.8 dB for each wavelength. This scheme has the potential to be employed as a useful source in optical communications, fiber optical sensing, and high resolution spectroscopy in the 1-μm wavelength band.**

***Index Terms*— Multiwavelength laser, optical fiber laser, single-longitudinal mode, ytterbium-doped fiber.**

I. Introduction

MULTIWAVELENGTH fiber lasers play important roles in wavelengthdivision multiplexing (WDM) fiber communications, fiber optical sensors and high-resolution spectroscopy [1]–[4]. Previous efforts on multiwavelength lasers have been demonstrated in erbium-doped fiber lasers, such as using sampled Bragg grating [1], incorporating a high birefringence loop mirror [2] and adopting a delayed interferometer in the cavity [3]. However, comparing with erbium-doped fiber lasers (EDFL) [1]–[4], ytterbium-doped fiber lasers (YDFL) under multiwavelength operation attracted relatively less attraction since YDF is not as commonly used as EDF in conventional communication band [5], [6]. Considering there is a growing demand for fiber lasers operating at wavelength band around 1 μm, it is highly desirable to further investigate the multiwavelength performance of ytterbium-doped fiber lasers. Furthermore, the YDFLs reported so far (cavity length typically $\sim$10 m) [5], [6] operated under multimode oscillation and mode hopping. Therefore, SLM operation is also highly desirable.

Several techniques have been demonstrated to achieve SLM operation for fiber lasers [7], [8]. For instance, an YDFL with 60-nm tuning range was achieved by using the passive multiple-ring cavity configuration [7] and a 40-nm tuning range semiconductor optical amplifier (SOA) based fiber laser using an unpumped YDF as a narrow-band auto tracking filter [8] have been demonstrated. On the other hand, SLM lasers with multiwavelength operation have been demonstrated in the C-band [9] and L-band [10], both in the telecommunication region around 1550 nm, but multiwavelength SLM sources has not been demonstrated in 1μm region so far. Compared with EDFLs operated in the C + L band (1550-1625 nm), YDFLs can have a broader lasing bandwidth in the spectral range of 970-1200 nm [11]. Furthermore, in applications such as space optical communication [12] and optical coherence tomography [13] 1-μm source is more favorable compared with 1.55-μm source.

In this letter, we propose and demonstrate an YDFL which can generate multiwavelength lasing and SLM operation simultaneously. Two Sagnac loop mirrors are inserted into the cavity to ensure multiwavelength and SLM operation respectively. Three wavelengths lasing with a wavelength spacing of 1.8 nm around 1044 nm are demonstrated with stable operation. SLM operation is achieved with a side-mode suppression ratio (SMSR) of 56 dB and the linewidth of each wavelength is measured to be less than 100 kHz using a delayed self-homodyne method. This scheme could have important applications in optical communications, optical sensing and high resolution spectroscopy in the 1 μm wavelength band.

II. Experimental Setup

Fig. 1 shows the experimental setup of the multiwavelength laser. The cavity gain was provided by an YDFA with an output power of 10 dBm. An isolator was inserted inside the cavity to ensure the unidirectional oscillation of the laser. Two Sagnac loop mirrors were inserted inside the cavity to ensure multiwavelength and SLM operations respectively. The first Sagnac loop mirror was constructed using a 50/50 coupler, a polarization controller and a 1.5-m polarization-maintaining (PM) fiber. It was inserted into the cavity to perform as a comb filter to achieve multiwavelength oscillations. Another polarization controller (PC1) was used to control the state of polarization (SOP) of the PM-fiber based Sagnac loop filter input. The amplified spontaneous emission (ASE) from the YDFA output was split to two counter propagating waves by the 50/50 coupler, which recombined at the coupler after passing through the PM fiber. When light entered the YDFA, the SOP of each

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The authors are with the Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong (e-mail: yzhou@eee.hku.hk; pcchui@eee.hku.hk; kywong@eee.hku.hk).

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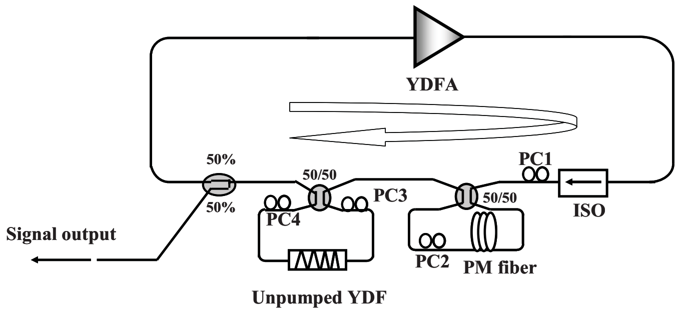

Fig. 1. Experimental setup of the multiwavelength laser. YDFA: ytterbium-doped fiber amplifier. ISO: isolator. YDF: ytterbium-doped fiber. PC: polarization controller.

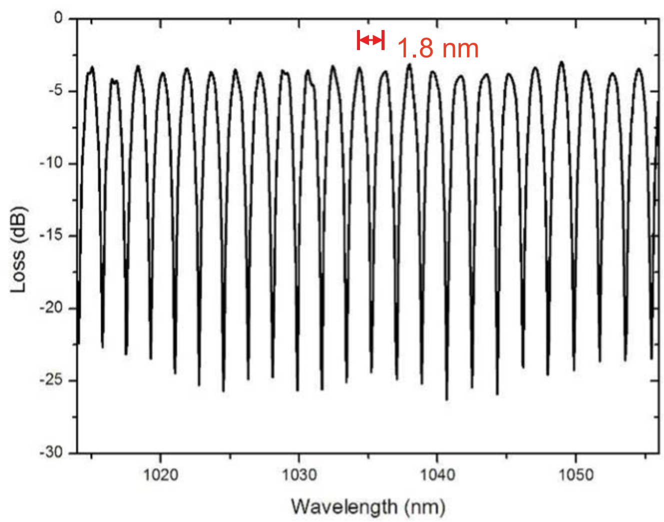

Fig. 2. Transmission spectrum of the PM-fiber-based Sagnac loop filter.

branch was not the same with each other. The polarization-hole buring (PHB) effect could be remarkably increased when the polarization controllers were finely adjusted [6]. Therefore, the mode competition caused by homogeneous gain broadening of the YDFA was much weakened and stable multiwavelength oscillation was established. Noted that an inline fiber Lyot filter could also be used here to construct the same optical filter, however, by using Sagnac loop the rotation of the principal axis of the PM fiber with a 45-degree angle is not required thus a simple fusion splicer without the fiber rotation could be used. The second Sagnac loop mirror was composed of a 50/50 optical coupler, two polarization controllers (PC3 and PC4) and a 2.5-m unpumped YDF. Due to the spatial-hole burning (SHB) effect, SLM operation could be well achieved. A 50/50 coupler in the cavity provided 50% feedback and 50% output. The output of the laser cavity was measured by an optical spectrum analyzer (OSA) with a 0.06 nm-resolution.

III. Results and Discussion

Fig. 2 shows the transmission spectrum of the PM-fiber-based Sagnac loop filter. As suggested in [6], the wavelength spacing of two adjacent transmission peaks of the Sagnac loop filter is given by the following equation:

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L} \tag{1}$$

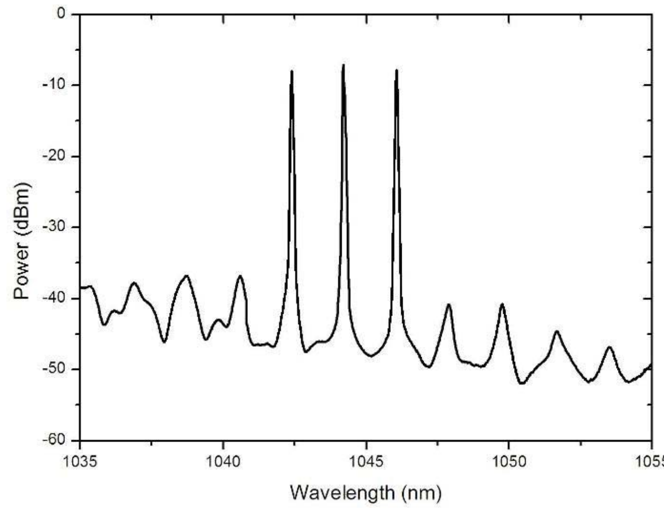

Fig. 3. Multiwavelength lasing spectrum.

where λ is the wavelength, Δn is the normalized birefringence ($\sim 4.0 \times 10^{-4}$), and L is the length of the PM fiber. In our experiment, we chose the PM fiber with a suitable length (1.5 m) to achieve a wavelength spacing of about 1.8 nm around 1040 nm. It is also shown that the Sagnac loop filter has an insertion loss of about 3.5 dB, a peak-to-notch contrast ratio of 21 dB and a peak fluctuation within 1 dB.

Fig. 3 shows the optical spectrum of the multiwavelength YDFL. When the polarization controllers were fine adjusted and the cavity loss were optimized, multiwavelength operation was achieved. The three lasing wavelengths were 1042.4 nm, 1044.2 nm and 1046 nm, with a wavelength spacing of 1.8 nm. The optical signaltonoise ratio (OSNR) of each oscillating signal was measured to be greater than 37 dB. A four or five-wavelength operation could also be achieved with a relatively low stability due to the gain competition. In order to achieve a four or five stable wavelength lasing, the SOP of each lasing wavelength needed to be adjusted to a correct value at the same time. However, in our experiment the PCs were simply made by winding a segment of the HI-1060 fiber in three paddles and thus the operation sensitivity was limited, which may also lead to the difficulty in adjusting the polarization state of the wavelengths greater than three simultaneously. Since the only wavelength-selective element inside the cavity is the PM-fiber-based Sagnac loop filter, our laser is not tunable and only the wavelengths at the gain peak of the YDFA could oscillate. However, potential wavelength tuning can be achieved by inserting a tunable filter with bandwidth around 10-nm inside the cavity. The wavelength spacing can also be tuned by adjusting the PM-fiber length of the Sagnac filter.

To verify the side-mode suppression performance of the unpumped YDF Sagnac loops, the radio frequency (RF) spectrum was obtained by applying a filtered signal at 1042.4 nm to a 10-GHz photodetector (PD), which was measured by an electrical spectrum analyzer (ESA) from dc to 1-GHz span with a resolution bandwidth of 100 kHz. First, the YDF Sagnac loop mirror was disconnected. Fig. 4 (a) shows its measured spectra at the ESA. The mode spacing of the cavity was

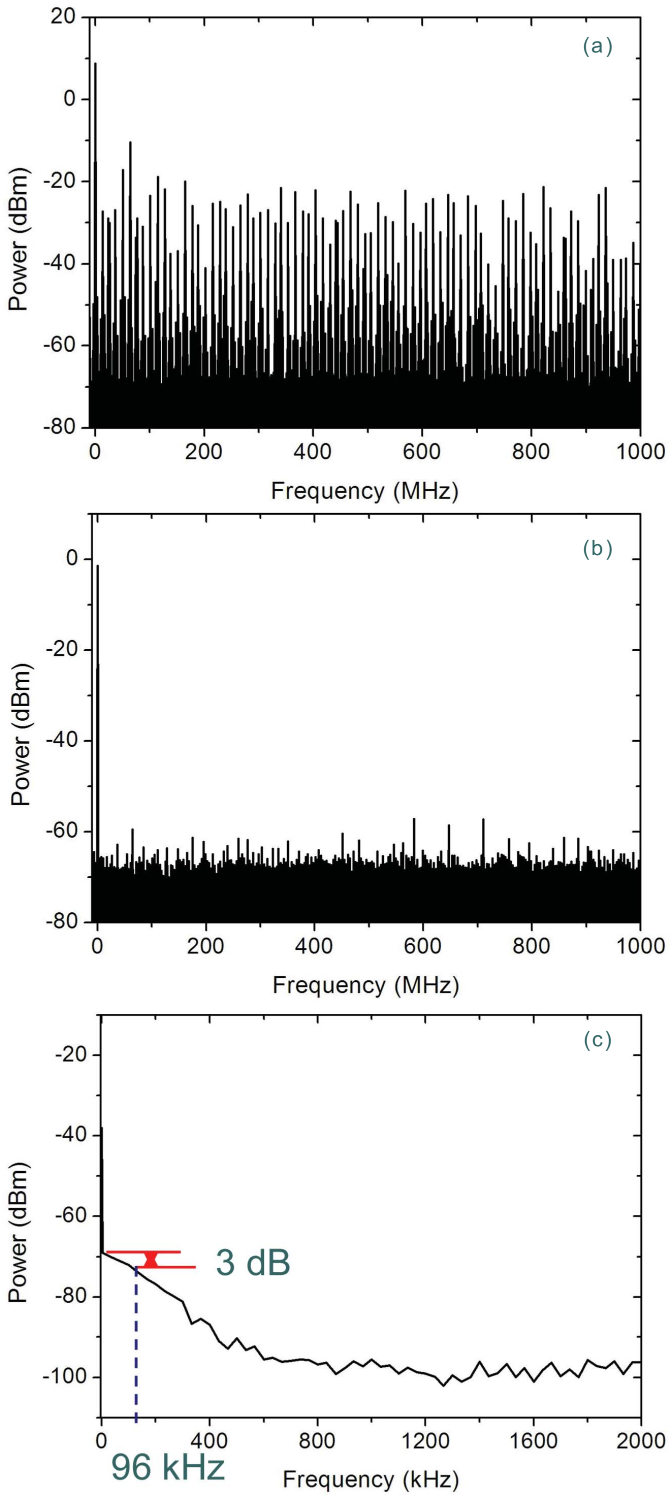

Fig. 4. Electrical spectra measured by applying the laser output to a photodetector for the signal wavelength at 1042.4 nm (a) with the YDF Sagnac loop disconnected, (b) with the YDF Sagnac loop connected, and (c) self-homodyne spectrum measured by using a 5-km SMF delay line.

measured to be 12.37 MHz. The spectrum was very noisy and unstable owing to the mode hopping. When the YDF Sagnac loop mirror was connected, the beating signal disappeared and no mode-hopping was observed as shown in Fig. 4 (b). We can estimate the FWHM of the fiber loop mirror with a self-induced fiber Bragg grating (FBG) as $\Delta f < 11.2$ MHz by using the Eq. (5) from Ref. [14]. Therefore, the loop mirror allowed only SLM to oscillate and side-mode suppression ratio of greater than 56 dB was well achieved. Due to the bandwidth limitation of our ESA (26-GHz), the mode hopping between the three lasing wavelengths (> 500 GHz) could not be shown in Fig. 4(b). However, we continuously scanned our OSA for over 10 mins and the spectrum remained the same as shown in Fig. 3, which certifies that there is no obvious mode hopping between the three wavelengths. To measure the linewidth of the oscillating signal, a self-homodyne method was used, where a 5-km HI 1060 single-mode fiber (SMF) was used as the delay line. The measured self-homodyne spectrum is shown in Fig. 4 (c), where the linewidth was measured to be as narrow as 96 kHz. Similar RF spectrum and linewidth could be achieved when filtering out the other two oscillating wavelengths. Therefore, all the three wavelengths were SLMs.

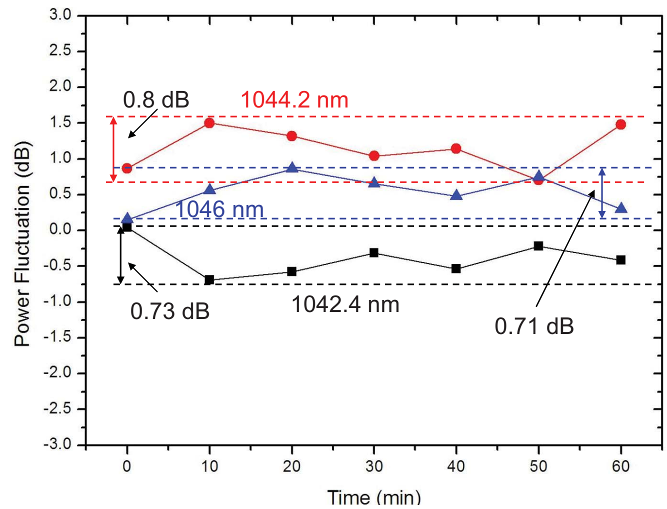

Fig. 5. Stability of the multiwavelength SLM YDFL.

In addition to the linewidth measurement, power stability was also one of the most important properties of YDFLs. To study the lasing wavelength stability, the power fluctuations of all three wavelengths were measured over 60 mins, which are shown in Fig. 5. The maximum power fluctuation was less than 0.8 dB for each wavelength, which shows the proposed multiwavelength laser was reasonably stable at the room temperature. Note that we performed the measurement of the three wavelengths separately by filtering out different wavelength one at a time. Thus, the power levels for the three wavelengths were not corresponding to the simultaneous measurement so the trend of the power fluctuation of each curve may simply due to the environmental fluctuations.

IV. Conclusion

In conclusion, we demonstrated a multiwavelength SLM YDFL. Three wavelengths with wavelength spacing of 1.8 nm could be generated under stable operation by fine adjustment of the polarization controllers and the linewidth of each wavelength was measured to be narrower than 100 kHz. The maximum power fluctuation was less than 0.8 dB for each wavelength. This scheme has the potential to be employed as a useful source in optical communications, fiber optical sensing and high resolution spectroscopy in the 1μm wavelength band.

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