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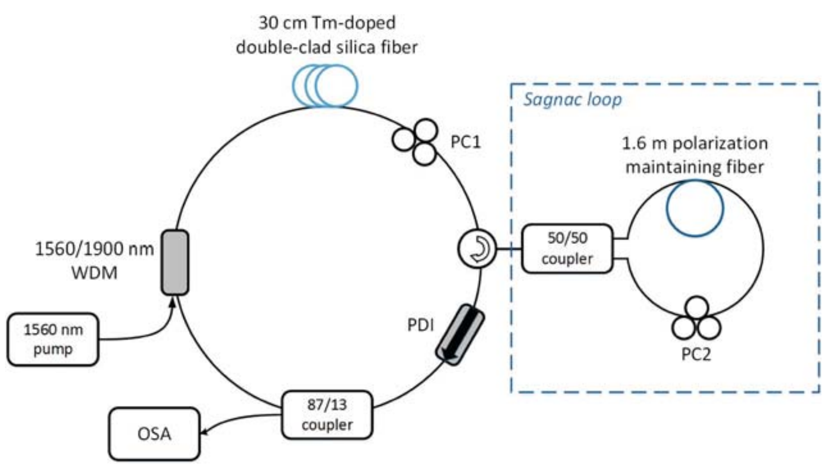

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Alternate Wavelength Switching in a Widely Tunable Dual-Wavelength Tm^{3+}-Doped Fiber Laser at 1900 nm

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Abstract: We demonstrate alternate wavelength switching in a widely tunable, dual-wavelength Tm^{3+}-doped fiber laser operating at 1900 nm. A comb filter based on a Sagnac loop incorporating a length of high-birefringence fiber is used to define the lasing wavelengths. By simple variation of a polarization controller within the laser cavity, alternate and sequential switching between single- and dual-wavelength output, as well as tunable operation over a range of 70 nm, is obtained.

Index Terms: Multi-wavelength fiber lasers, Thulium-doped fiber lasers.

1. Introduction

Mid-infrared laser emission at 1900 nm has potential applications in the fields of medical surgery, chemical sensing, and atmospheric light detection and ranging (LIDAR) measurement. Thulium ions (Tm^{3+}) provide an effective way to develop fiber lasers operating at 1900 nm via the $^3F_4 \rightarrow {}^3H_6$ transition and a number of Tm^{3+}-doped silica and fluoride fiber lasers (TDFLs) have been reported [1]–[3]. Features such as wavelength tunability, multi-wavelength operation, and reconfigurability (e.g., alternate switching between single and multi-wavelength output) offer increased flexibility and enhanced functionality in the various applications.

A number of tunable, single wavelength TDFLs have been demonstrated, including those based on grating filters [4], optofluidically tunable multimode interference fiber filters [5], and fiber Bragg gratings (FBGs) [6]; a continuous tuning range as large as 250 nm has been realized [7]. In terms of increased capabilities, dual-wavelength TDFLs based on volume Bragg gratings [8] and FBGs [9]–[11] as well as alternate switching between single and dual-wavelength operation, e.g., by adjusting a polarization controller (PC) in a linear cavity incorporating FBGs in high birefringence (Hi-Bi) fiber as wavelength selective elements [9], have been reported. Tunable spacing between the two lasing wavelengths was obtained using cascaded volume Bragg gratings [8] or cascaded FBGs in a nonlinear amplifier loop mirror [10]. Tunable dual-wavelength operation

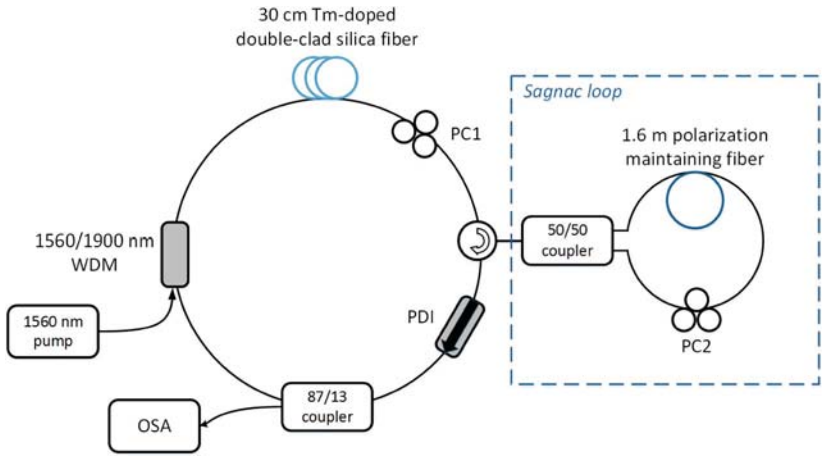

Fig. 1. Experimental setup of widely tunable and switchable TDFL. OSA: optical spectrum analyzer; PC: polarization controller; PDI: polarization dependent isolator.

(i.e., with a fixed wavelength spacing) was also shown, albeit over a relatively limited tuning range of only ~7 nm [11].

TDFLs using comb filters based on Sagnac loops incorporating a length of Hi-Bi fiber have also been investigated [12], [13]. In [12], a linear cavity was considered; by adjusting a PC within the Sagnac loop, tunable single wavelength lasing over a range of 10 nm was demonstrated. For certain settings of the PC, fixed dual-wavelength lasing with a wavelength spacing of 6.8 nm was also obtained. In [13], a ring cavity was implemented; again, by adjusting a PC within the Sagnac loop, the laser can generate a single tunable wavelength over a range of 20 nm. Moreover, by carefully controlling the PC, fixed multi-wavelength lasing (two, three, or four wavelengths) with a wavelength spacing of 2.5 nm was achieved. In both of these cases, the tuning range is limited and tunable multi-wavelength operation was not demonstrated.

In [14], a multi-wavelength laser based on polarization maintaining TDF, polarization rotation, and four wave mixing was reported. In particular, by adjusting PCs within the ring cavity, the number of output wavelengths can be set from one to five (with a wavelength spacing of 2.5 nm for multi-wavelength operation); further control of the PCs allowed for limited wavelength tuning ($<$ 3 nm). However, the ability to provide both alternate wavelength switching and tunable multi-wavelength operation over a broad wavelength range was not achieved.

In this paper, we report alternate wavelength switching in a widely tunable, dual-wavelength Tm^{3+}-doped fiber laser. We use a ring configuration with a comb filter based on a Sagnac loop incorporating a length of Hi-Bi fiber to define the lasing wavelengths. Moreover, we include a polarization dependent isolator (PDI) to suppress mode competition [15], [16], provide polarization selectivity, and allow for tunable and stable dual-wavelength operation. We realize tunable and alternate/sequential wavelength switching over an operating range of 70 nm from 1857 nm to 1927 nm by simple control of a PC in the laser cavity. This is the largest tuning range obtained from a dual-wavelength TDFL.

2. Experimental Setup

Fig. 1 shows the schematic of our widely tunable and switchable TDFL. We use 30 cm of a double-clad (DC) Tm^{3+} : silica fiber (TDF) manufactured by CorActive as the active medium. The gain fiber is doped with 40 000 ppm Tm^{3+}, has a core diameter $=$ 6 μm with a core numerical aperture (NA) of 0.23, a cladding diameter $=$ 125 μm with a cladding NA larger than 0.45, and is coated with 67.5 μm of acrylate. The gain fiber is spliced to SMF-28 fiber pigtails (splicing loss of ~0.9 dB) and is pumped at 1560 nm due to a higher photon conversion efficiency compared with 800 nm

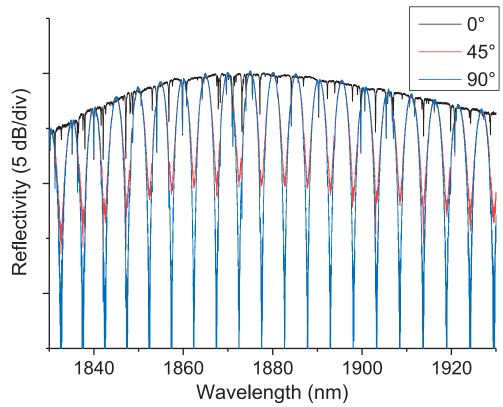

Fig. 2. Measured comb filter reflection response with PC2 set to provide a rotation of 0°, 45°, and 90°.

or 1060 nm pumping [17]. The pump consists of an external cavity laser and a high-power erbium-doped fiber amplifier (EDFA) with a maximum output power of 2 W. We adopt a forward pumping scheme since a separate characterization of the ASE output and gain characteristics of the DC-TDF show that it supports a broader wavelength range and higher output. The 1560 nm pump is launched into the gain fiber via a 1550/1900 nm wavelength division multiplexer (WDM) with an insertion loss of ∼2.2 dB; the maximum pump power that can be launched into the DC-TDF is ∼1.2 W. A first polarization controller (PC1) is used to adjust the polarization state of the lasing signals propagating in the ring cavity.

The comb filter is based on a Sagnac loop incorporating a length of polarization maintaining fiber (PMF) as the Hi-Bi fiber. A second polarization controller (PC2) is used to adjust the reflectivity of the Sagnac loop (operating as a mirror) [18]. In our experiments, we use 1.6 m of PMF in the Sagnac loop; this results in a comb filter with a wavelength spacing or free spectral range (FSR) of ∼5.4 nm at 1900 nm. Fig. 2 shows the measured reflection response of the Sagnac loop for different settings of PC2. When PC2 is set to produce no rotation to the input beam, the Sagnac loop has no comb filter response; on the other hand, when PC2 is set to produce a pure rotation of 90° as a half-wave-plate, the Sagnac loop produces a comb filter response with the greatest peak-to-notch contrast (more than 20 dB).

A polarization independent circulator, connecting the gain fiber, comb filter, and a PDI, ensures unidirectional propagation in the laser cavity. In conjunction with the comb filter, the PDI provides a wavelength dependent loss induced by a wavelength dependent polarization rotation mechanism to suppress mode competition and hence increase stability [15], [16]; it also provides polarization selectivity. Note that we can replace the combination of the polarization independent circulator and PDI using a single polarization dependent circulator.

An 87/13 fiber coupler is used to extract the output from the ring cavity (13%); the laser output is measured using an optical spectrum analyzer with 50 pm resolution. The estimated cavity loss of the laser is ∼18 dB which is mainly from losses in the Sagnac loop and the 1550/1900 WDM.

3. Results

First, we optimize PC2 to provide the largest peak-to-notch contrast (> 20 dB) and then increase the pump power. Single wavelength lasing occurs at a threshold of 560 mW. When the pump power is increased further to 580 mW, dual-wavelength operation becomes possible. For a pump power larger than 700 mW, we can obtain alternate wavelength switching over a 70 nm range from 1857.95 nm to 1927.25 nm by simply adjusting PC1 (PC2 is unchanged from its initial setting). In particular, we can realize the following three operations: 1) single wavelength tuning in discrete steps of 5.4 nm, 2) tunable dual-wavelength operation with tuning in discrete

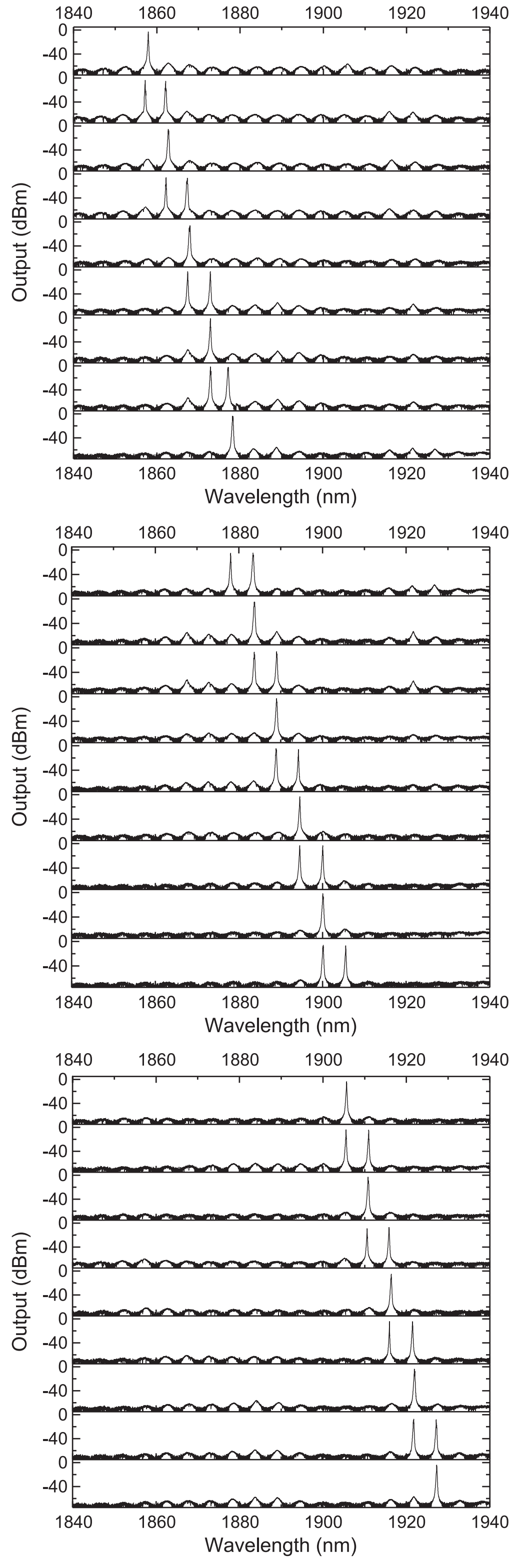

Fig. 3. TDFL output. Tuning and alternate wavelength switching from 1857.95 nm to 1927.25 nm.

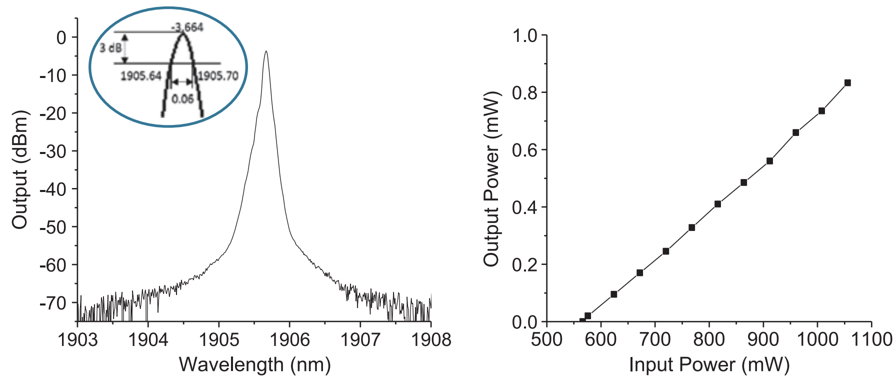

Fig. 4. (a) Full width at half maximum for the proposed single-wavelength laser at 1905.6 nm. (b) Measured output laser power at 1905.06 nm as a function of the input launched power.

steps of 5.4 nm, and 3) *sequential* switching between single and dual-wavelength output in discrete steps of 5.4 nm over the 70 nm tuning range. The results are summarized in Fig. 3. Throughout the tuning range, the signal-to-noise ratio (SNR) of each output wavelength exceeds 50 dB. By adjusting both PC1 and PC2, it is possible to shift the fringes of the comb filter and hence obtain tunable single and dual-wavelength operation in a continuous manner as in [12] or [13] albeit over a more limited tuning range. When the PDI is removed, stable single or dual-wavelength operation during tuning cannot be obtained.

Fig. 4(a) shows the output spectrum for single wavelength operation at 1905.6 nm. The measured full width at half maximum (FWHM) is $<$ 0.06 nm and is limited by the resolution bandwidth of the OSA. The laser is not expected to exhibit single longitudinal mode (SLM) operation due to the relatively long cavity length. To achieve SLM operation, approaches such as using a length of unpumped active fiber as a saturable absorber [19] or incorporating a compound ring resonator into the main cavity [20] are required. The output power as a function of pump power is shown in Fig. 4(b). The threshold pump power is 560 mW and the slope efficiency is $\sim$0.2%. The laser exhibits similar characteristics at other output wavelengths. The low slope efficiency of this laser is attributed in part to the high cavity loss; reducing component insertion loss and splicing losses should improve the efficiency.

Fig. 5(a) shows repeated scans of the laser output spectra for single-wavelength operation at 1905.6 nm (recorded every 180 seconds). The center wavelength variations are less than 0.02 nm, while output power fluctuations are less than 0.7 dB, as shown in Fig. 5(b). Repeated scans of the laser output spectra for dual-wavelength lasing at 1905.6 nm and 1911 nm are shown in Fig. 5(c). While such measurements do not show fast variations, they provide a reasonable indication of longer term laser stability.

4. Summary

We have demonstrated a widely-tunable and switchable dual-wavelength TDFL using a comb filter based on a Sagnac loop incorporating a length of Hi-Bi fiber. A tuning range of over 70 nm from 1857 nm to 1927 nm has been achieved, which is the largest tuning range for a dual-wavelength TDFL. By simply controlling a PC in the cavity, tuning and alternate/sequential switching between single- and dual-wavelength operations is possible. The output of each lasing wavelength has an SNR larger than 50 dB, while the FWHM is $<$ 0.06 nm. We believe that this laser offers capabilities that may be useful for fiber optic sensing applications in the 1900 nm wavelength range, for example LIDAR [21], or where the availability of multiple and tunable wavelengths can enhance or provide additional information, such as multi-wavelength absorption spectroscopy [22] or fiber cavity ring-down spectroscopy [23].

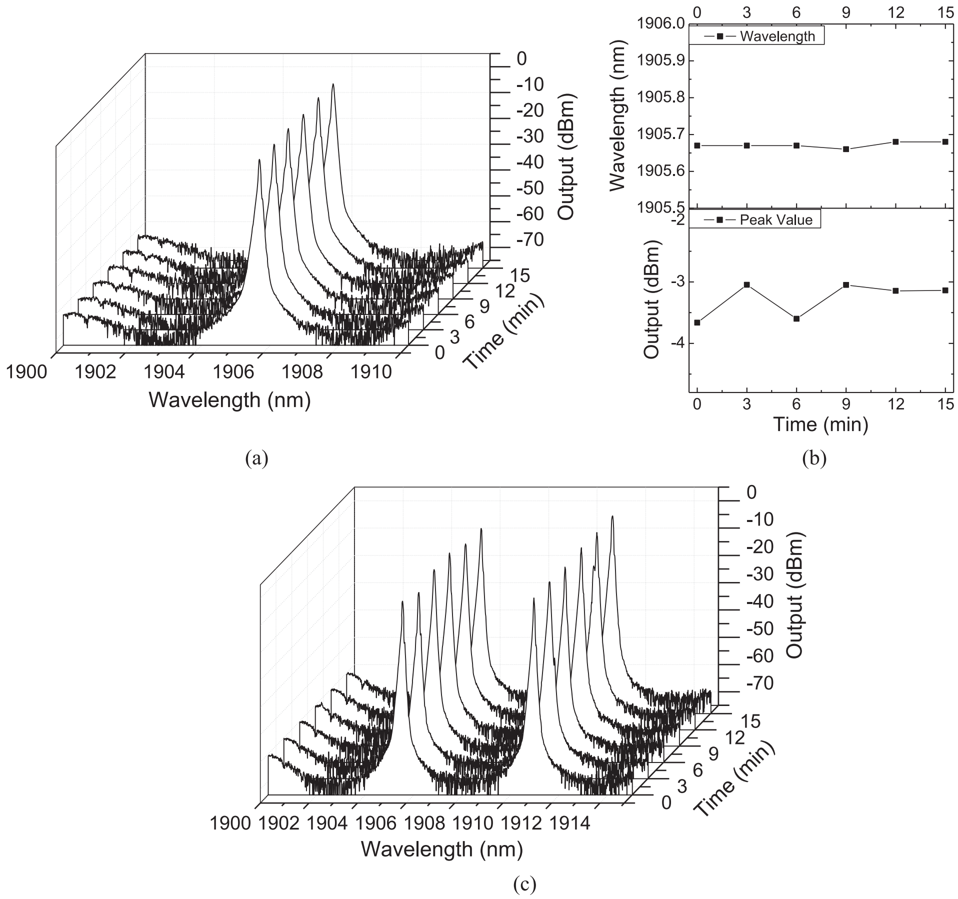

Fig. 5. (a) Six repeated scans of single-wavelength output spectra with span of 10 nm over 15 min. (b) Measured center wavelength shift and output power variation of single-wavelength lasing at 1905.6 nm. (c) Six repeated scans of dual-wavelength output spectra with span of 15 nm over 15 min.

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