

Highly Stable and Switchable Dual-Wavelength Single Longitudinal Mode Thulium-Doped Fiber Laser Based on a Saturable Absorber

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Abstract— A highly stable, switchable dual-wavelength single-longitudinal-mode thulium-doped fiber laser is proposed and demonstrated. A uniform fiber Bragg grating is employed for wavelength selection, while a saturable absorber formed by thulium-doped fiber achieves single-longitudinal-mode operation. The experimental results show that the optical signal-to-noise ratios of the output lasers at the two wavelengths are 58.66 dB and 71.40 dB, respectively. During 60 min of continuous monitoring, the center wavelength drift remained below 0.03 nm, with peak power fluctuations under 0.602 dB. Across frequencies exceeding 2 MHz, the relative intensity noise of the laser consistently stayed below -123.84 dB/Hz. This wavelength-tunable, highly stable single longitudinal mode fiber laser is expected to be applied in fiber sensing and wavelength division multiplexing systems in the future.

Keywords—Thulium-doped fiber laser, wavelength-switchable, single longitudinal mode, saturable absorber, uniform fiber Bragg grating

I. INTRODUCTION

The 2 μm band lies in an important "eye-safe" window and encompasses strong absorption peaks of water molecules and various gases (such as CO_2 , NH_3 , and N_2O), making it an ideal light source for biological tissue ablation, medical surgeries, and gas sensing[1],[2]. Single longitudinal mode (SLM) fiber lasers in the 2 μm band feature high spectral purity and narrow linewidth, which can be widely applied in high-resolution spectroscopy, precision fiber sensing, and coherent optical communication, among other fields[3]–[6].

To achieve SLM operation, the core design principle of fiber lasers lies in effectively suppressing multi-longitudinal mode oscillation. Based on the physical length of the resonator cavity, cavity structures are primarily categorized into short-cavity and long-cavity types. While short-cavity structures offer compactness advantages, they are constrained by the length of the gain medium, typically resulting in lower output power and efficiency. Long-cavity structures can significantly enhance output power by utilizing longer gain fibers. However, their narrow longitudinal mode spacing complicates mode competition, necessitating effective mode-selective mechanisms to achieve stable SLM output. Currently, common mode-selective mechanisms primarily rely on two

principles. The first category employs narrowband filtering or nonlinear absorption effects to directly suppress all longitudinal modes except the target mode. Among these, saturated absorbers (SA) serve as passive components. Their intensity-dependent nonlinear transmission characteristics provide an adaptive, highly stable solution for mode selection. The second category utilizes the grating effect generated by compound ring cavity structures. Through the interference of multiple resonant cavities, the intracavity loss spectrum is periodically modulated, effectively increasing the longitudinal mode spacing and filtering out unwanted modes. While structurally mature, such approaches typically demand extremely stringent cavity length stability. Minor temperature or stress perturbations can easily cause spectral shifts, potentially triggering mode hopping. In contrast, the SA-based mode selection mechanism holds unique value due to its inherently simple principle and high system stability. For instance, Yan et al. [7] successfully achieved stable dual-wavelength SLM output at 1.94 μm in a long-cavity thulium-doped fiber laser (TDFL) by employing a polarization-maintaining chirped fiber grating as an ultra-narrowband filter combined with an unpumped thulium-doped fiber segment as a SA. Zhang et al. [8] achieved SLM lasing with a center wavelength of 1719.68 nm and a linewidth of 4.4 kHz in a TDFL by utilizing an unpumped section of thulium-doped fiber as a SA. Li et al. [9] achieved SLM laser output continuously tunable between 1950 nm and 2049 nm based on a tunable filter and a SA.

As the core light source in optical communication systems, multi-wavelength fiber lasers offer significant advantages such as compact structure, high pumping efficiency, high heat dissipation, and ease of integration into fiber systems. For instance, Ibarra-Escamilla et al. [10] achieved a dual-wavelength TDFL with tunable wavelength spacing using two independently tunable multimode interference filters, achieving a tuning range of up to 24 nm. In the same year, the team further extended the wavelength interval tuning range to 0.54 – 9 nm [11]. Han et al.[12] employed a sampling fiber Bragg grating to realize a single/dual-wavelength switchable SLM TDFL, achieving power fluctuations below 0.93 dB over 20 minutes during dual-wavelength operation. Li et al. [13]

proposed a dual-wavelength laser based on polarization-maintaining photonic crystal fiber. By adjusting the polarization state within the cavity, they achieved five distinct sets of dual-wavelength outputs.

This paper presents a wavelength-switchable 2 μm SLM fiber laser based on an all-fiber structure. By integrating a uniform fiber Bragg grating (UFBG) with a SA, efficient SLM operation is achieved. Experimental results demonstrate that the laser exhibits a very high optical signal-to-noise ratio, long-term wavelength and power stability, and extremely low relative intensity noise (RIN) at both output wavelengths. The proposed approach holds promise for application in fiber lasers across other wavelength bands, further enhancing the performance of fiber lasers in practical applications.

II. EXPERIMENTAL SETUP AND THEORETICAL ANALYSIS

A. Experimental setup

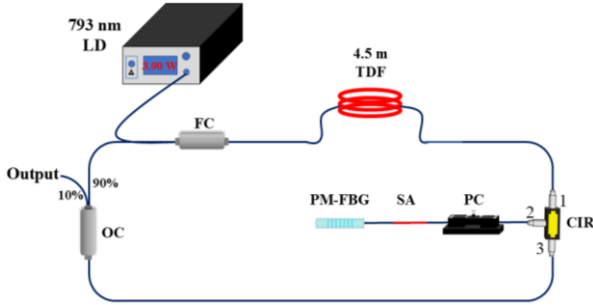


Figure 1. Configuration of the proposed SLM TDFL system.

Figure 1 shows the experimental setup of a switchable dual-wavelength SLM TDFL based on a SA and polarization-maintaining fiber Bragg grating (PM-FBG). The laser employs a 793 nm laser diode (LD) as the pump source. The pump light is injected into a 4.5 m-long thulium-doped fiber (TDF) through a 793/2000 nm fiber coupler (FC). The TDF is connected to port 1 of a fiber circulator (CIR), ensuring unidirectional laser propagation. A PM-FBG is inserted into the cavity as a wavelength-selective element, with its reflection peak located in the 2 μm band. A 1-meter-long unpumped section of thulium-doped fiber is employed as a SA, working in conjunction with a polarization controller (PC) to achieve SLM selection and stabilization. The laser is output through a 90:10 fiber coupler (OC), where the 10% port is used for spectral and power monitoring, while the 90% port laser is re-injected into the cavity. This structure enables stable switching between dual wavelengths by adjusting the polarization state within the cavity. The total length of the laser main ring cavity is 12.25 m.

The transmission and reflection spectra of the PM-FBG measured using a homemade ASE light source are shown in Figures 2(a) and (b). The full width at half maximum (FWHM) of the PM-FBG at λ_x and λ_y is 0.192 nm and 0.186 nm, respectively. The transmission depths are ~ 2.77 dB and ~ 2.81 dB, with corresponding reflectivities of 47.16% and 47.64%.

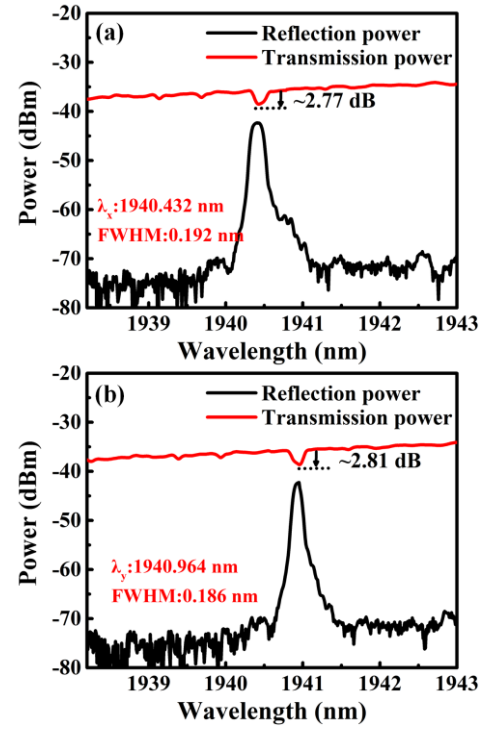


Figure 2. Transmission and reflection spectra of the PM-FBG under (a) polarization state x and (b) polarization state y.

B. Theoretical analysis

As a nonlinear optical element, the optical properties of a SA depend on the intensity of the incident light. As shown in Figure 1, when an SA is placed between the PM-FBG and a circulator, the intensity of the counter-propagating light within the cavity exhibits a periodic distribution, causing the absorption coefficient of the SA to modulate periodically. Since the refractive index is inversely proportional to the absorption coefficient, periodic variations in the refractive index result in periodic changes in the absorption coefficient, equivalent to embedding a narrow-band FBG [14]–[16]. Under this mechanism, longitudinal modes capable of forming stable standing waves experience lower absorption losses, while modes unable to create effective standing waves are suppressed due to higher absorption losses, effectively preventing mode hopping.

Based on simulation analysis of the SA at a center wavelength of 1940 nm, the calculated FWHM results for the dynamic narrowband filter are as follows [17], [18]:

$$FWHM = \frac{\Delta n c}{n^2 \lambda^2} \sqrt{(\Delta n)^2 + \left(\frac{\lambda}{L}\right)^2} \quad (1)$$

Where c is the speed of light, n is the effective refractive index of the TDF, Δn is the refractive index variation, and λ is the central wavelength.

As shown in Figure 3, the FWHM decreases with increasing length of the saturated SA. When the SA length is 1 m, the calculated FWHM is 22.6 MHz.

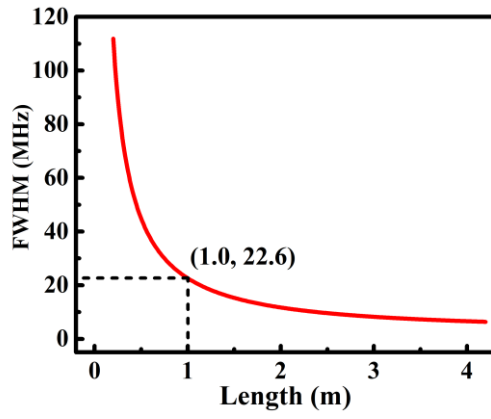


Figure 3. Transmission and reflection spectra of the PM-FBG under (a) polarization state x and (b) polarization state y.

The longitudinal mode spacing $\Delta\nu$ of the main cavity can be expressed as:

$$\Delta\nu = c / nL_m \quad (2)$$

Where L_m is the total length of the laser main cavity.

The total cavity length of this laser is 12.25 m, corresponding to a main cavity longitudinal mode spacing of approximately 17 MHz. The FWHM of the SA filter is 22.6 MHz, approximately 1.33 times the main cavity longitudinal mode spacing. This falls within the 1–2 times range required for SLM selection, enabling effective suppression of adjacent longitudinal modes and achieving stable single longitudinal mode oscillation.

III. RESULTS AND DISCUSSIONS

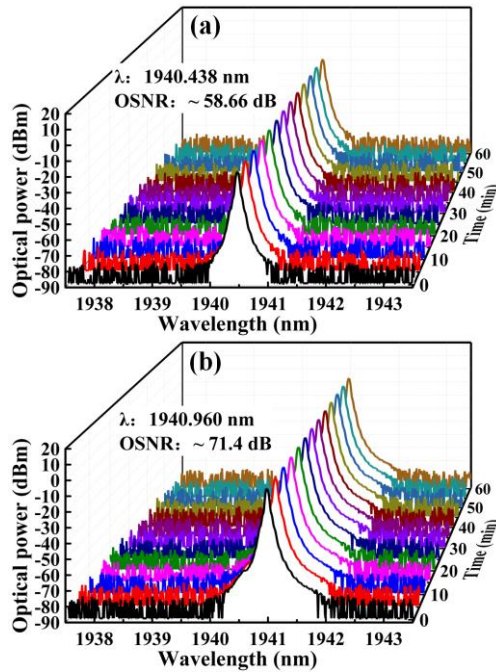


Figure 4. Spectral monitoring of (a) 1940.438 nm and (b) 1940.960 nm lasers over 60 minutes

All spectral data were acquired at room temperature. During experiments, the laser was mounted on an aluminum

platform to suppress mechanical vibrations. Stable continuous-wave laser output was achieved when the pump power exceeded the threshold of 2.5 W. At a pump power of 3 W, the output spectra corresponding to different polarization states were obtained by adjusting the PC, as shown in Figure 4. Specifically, the spectrum in Figure 4 (a) exhibits a central wavelength of 1940.438 nm with an OSNR of approximately 58.66 dB. The spectrum in Figure 4(b) features a central wavelength of 1940.960 nm and an OSNR of approximately 71.4 dB.

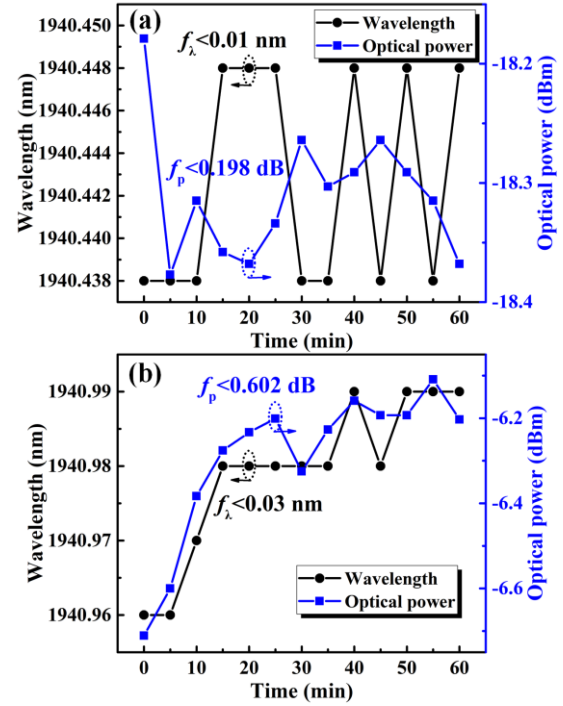


Figure 5. Output spectral variation at (a) 1940.438 nm and (b) 1940.960 nm over 60 minutes

Figure 5 shows the stability monitoring results over one hour. The center wavelength fluctuations for both wavelengths were less than 0.03 nm, and the peak power fluctuations were below 0.602 dB. This indicates that the laser exhibits excellent output stability when operating at both wavelengths.

To verify the SLM characteristics of the laser at different wavelengths, RF spectrum measurements of the output light were performed using a 12.5 GHz photodetector (PD, ET-5000F) and a 26.5 GHz signal analyzer (Keysight N9020A). The results are shown in Figure 6. The frequency range scanned was 0–1000 MHz, with a resolution bandwidth (RBW) set to 100 kHz. During 60 minutes of continuous monitoring, the spectrum within the 0–1000 MHz range was recorded every 10 minutes. The experimental results showed no non-zero beat frequency signals across the entire observed band, indicating that the laser maintains stable SLM operation at both wavelengths.

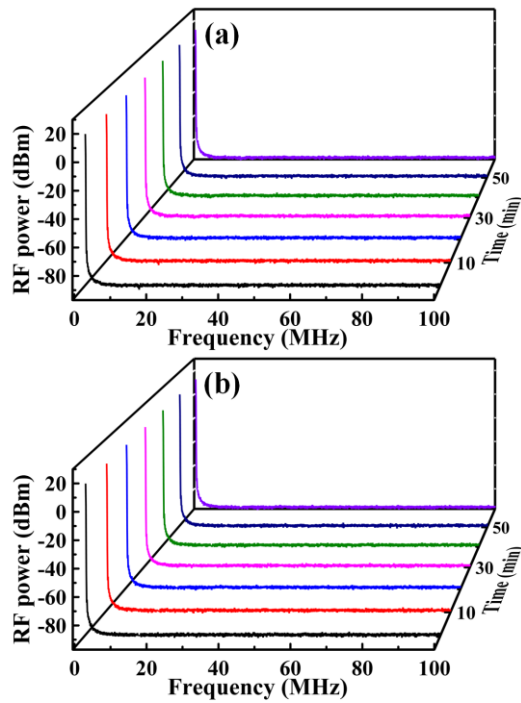


Figure 6. RF spectra at laser central wavelengths of (a) 1940.438 nm and (b) 1940.960 nm from 0 to 100 MHz over 60 minutes.

The RF spectrum within the 0–1000 MHz range was measured as shown in Figure 7. No non-zero beat frequency peaks were observed in the spectrum, further confirming that the laser operates in a stable single longitudinal mode.

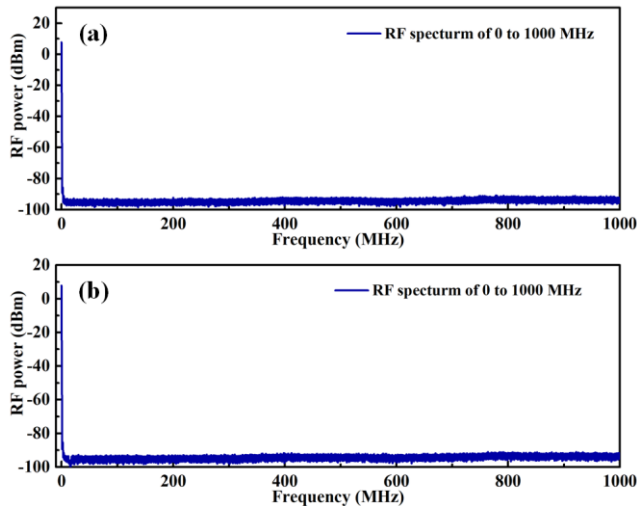


Figure 7. RF spectra at laser central wavelengths of (a) 1940.438 nm and (b) 1940.960 nm from 0 to 1000 MHz

To verify the mode selection function of the SA, it was replaced with an equal-length single-mode fiber for comparison. As shown in Figure 8, distinct longitudinal mode signals with a spacing of 17.0 MHz were observed in the 0–100 MHz RF spectrum. This measured value aligns with the theoretical spacing calculated from Equation (2), indicating that removing the SA restored the laser to multi-longitudinal-

mode oscillation. This confirms that the SA enables single-longitudinal-mode output.

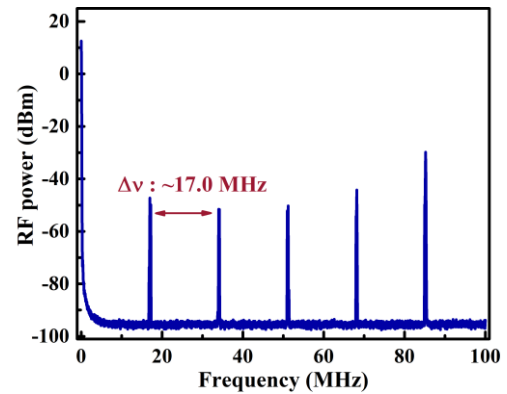


Figure 8. RF spectrum from 0 to 100 MHz for the main cavity without SA.

Figure 9 shows the RIN spectrum of the output laser in the 0–5 MHz frequency band, with an inset of the local details in the 0–200 kHz range. As shown in the figure, above the 2 MHz frequency band, the RIN of this TDFL is lower than -123.84 dB/Hz and -124.05 dB/Hz, respectively, meeting the noise requirements of the light source for interferometric fiber sensing systems [19]. The relaxation oscillation peaks are located at approximately 137.6 kHz and 133.2 kHz, respectively, mainly caused by thermal disturbances and fluctuations in cavity losses [20].

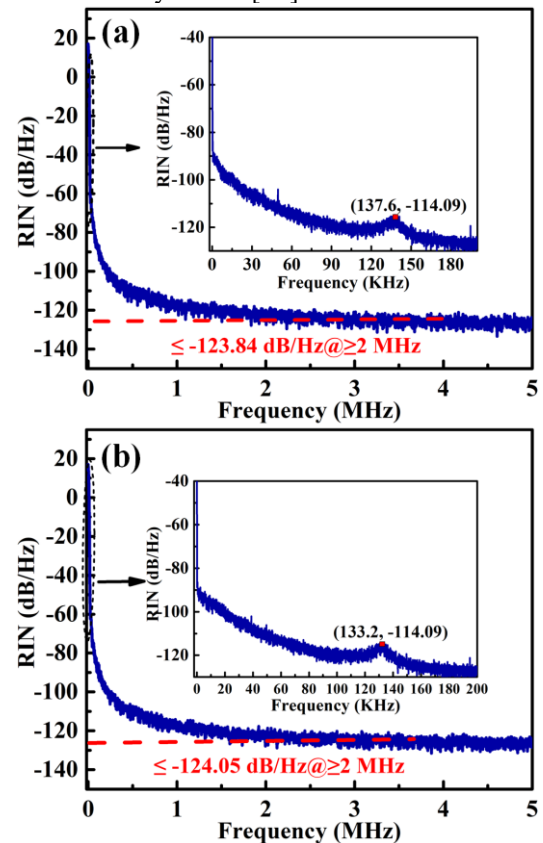


Figure 9. RIN spectra at the output laser of (a) 1940.438 nm and (b) 1940.960 nm

IV. DISCUSSION

This study proposes and validates a highly stable, dual-wavelength switchable SLM thulium-doped fiber laser based on a UFBG and a SA. The laser employs a UFBG for wavelength selection and utilizes a segment of TDF as a SA. Its stable SLM operation is achieved through the dynamic self-tracking narrowband filtering characteristics of the SA. The synergistic operation of these components enables the laser to maintain high wavelength purity and mode stability while offering flexible dual-wavelength switching capability. Experimental results demonstrate that this laser exhibits outstanding performance in long-term stability, noise suppression, and wavelength controllability, making it suitable for applications demanding stringent light source stability.

The simple, all-fiber structure offers good environmental adaptability and system compatibility, providing a reliable, high-performance light source solution for high-precision fiber sensing, dense wavelength division multiplexing systems, and coherent detection. This study further validates the feasibility of achieving stable, switchable single-longitudinal-mode output in the 2- μm band using a SA-based mode-selection mechanism, offering valuable insights for the practical development of such lasers.

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