L-band wavelength-tunable fiber laser mode-locked by all-polarization-maintaining nonlinear polarization rotation

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ABSTRACT

We achieved the first demonstration of a wavelength-tunable mode-locked fiber laser in the L-band using all-polarization-maintaining (all-PM) nonlinear polarization rotation (NPR). The all-PM configured laser features excellent repeatability and reliability. By increasing the pump power from 82.5 mW to 135 mW, a center wavelength-tuning from 1576.2 nm to 1592.2 nm is obtained. This non-mechanical tuning mechanism opens new possibilities for L-band wavelength-tunable lasers and their applications.

Keywords: Mode-locked, L-band, wavelength tunable, all-polarization-maintaining, nonlinear polarization rotation

1. INTRODUCTION

Wavelength-tunable mode-locked fiber lasers (MLFLs) have gained significant interest in the fields of optical spectroscopy, bio-imaging, and optical sensing [1-3]. Among them, L-band ultrafast lasers (1565 nm to 1625 nm) have shown great potential in applications such as optical sampling [4]. Various approaches to achieving wavelength-tunable mode-locking in the L-band have been investigated. A common method involves using a tunable bandpass filter for selecting the mode-locking wavelength. Devices like fiber Bragg Grating (FBG), long-period fiber grating (LPFG), and Sagnac loops have been extensively studied [5-7]. Moreover, research has focused on intracavity loss control using tunable-ratio optical couplers (TROC) or variable optical attenuators (VOA) [8,9]. Studies have also explored wavelength tuning through soliton self-frequency shift (SSFS) by launching L-band pulses through dispersion-shifted fiber (DSF). Since wavelength shift via SSFS depends on the injected pulse energy, tuning can be achieved by adjusting this energy [10]. Additionally, lasers using a polarization controller (PC) and a polarizer has been studied [11,12]. The fiber birefringence and the intracavity polarization state are altered by the PC, thus creating an invisible filter for wavelength tuning. However, the non-PM configuration in these research makes the lasers susceptible to environmental perturbations, while the inclusion of a polarization controller (PC) in the cavity compromises reliability and repeatability. Recent studies have investigated all-PM and all-fiber configuration, using thermal or strain controlled built-in fiber Lyot filters [13-15], though these tunable lasers mainly work in the C-band (1530 nm to 1565 nm) and slightly reach into the L-band near 1572nm. In those lasers, the wavelength tuning is achieved either mechanically or thermally. The spectrum filters, both external and built-in types, require strain or temperature changes to adjust filter transmission properties. The birefringence adjustment and intracavity loss control demand manual device manipulation. This mechanical or thermal tuning mechanism complicates the laser design and limits the tuning speed, posing challenges for real-world applications.

Modifying the pump power of the laser diode (LD) presents a promising tuning method that is neither mechanical nor thermal, and a figure-9 laser achieves this pump power tuning method in 2023 [16]. However, this laser achieves only a 5 nm tuning range and includes free-space components. Currently, no L-band tunable MLFLs have been reported that feature an all-fiber, all-PM design with a pump power controlled tuning approach. To address these issues, realizing tunable mode-locking in all PM fibers by nonlinear polarization rotation (all-PM NPR) offers an effective solution. In this work, we present the first experimental demonstration of an all-PM NPR MLFL that generates wavelength-tunable pulses in the L-band. By adjusting the pump power from 82.5 mW to 135 mW, the wavelength can be tuned from 1576.2 nm to 1592.2 nm.

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2. EXPERIMENT SETUP AND RESULTS

All-PM NPR lasers, achieved through angle splicing of several PMF segments, exhibit enhanced reliability and repeatability compared to the non-PM configured lasers [17-19].

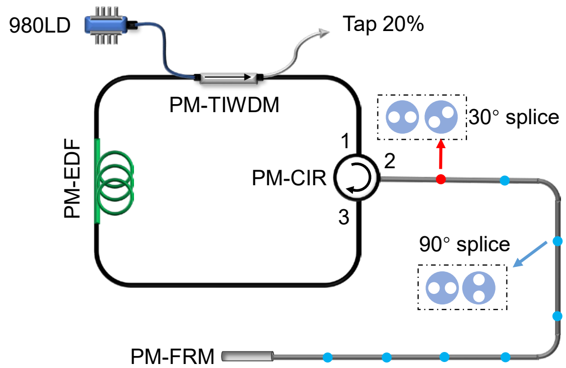

Fig. 1. Experiment setup of the tunable all-PM NPR laser. PM-TIWDM: PM tap isolating wavelength-division multiplexing; EDF: erbium-doped fiber (Nufern ESF-7/125); LD: laser diode; CIR: circulator; FRM: Faraday rotation mirror.

The experiment setup of our tunable all-PM NPR laser is shown in Fig. 1, and all the components and fibers are the PM type. A slow-axis working PM tap isolating wavelength-division multiplexing (PM-TIWDM) serves as a polarizer, WDM, isolator and 20% output coupler. A 1.5 m PM-EDF (Nufern ESF-7/125) works as the gain medium. The artificial saturable absorber (NPR section) consists of 21 m PMF (Fujikura SM15-PS-U25A), a PM circulator (PM-CIR), and a slow-axis working PM Faraday rotation mirror (PM-FRM). The 21 m PMF is segmented into several sections by 90° angle splicing (blue dots) between the 30° angle splicing (red dot) and the FRM. The slow-axis working PM circulator (PM-CIR) functions as a polarizer. The total cavity length is about 50 m, with a net group velocity dispersion (GVD) of -1.03ps^2 at 1550 nm, indicating the laser operates in the soliton regime.

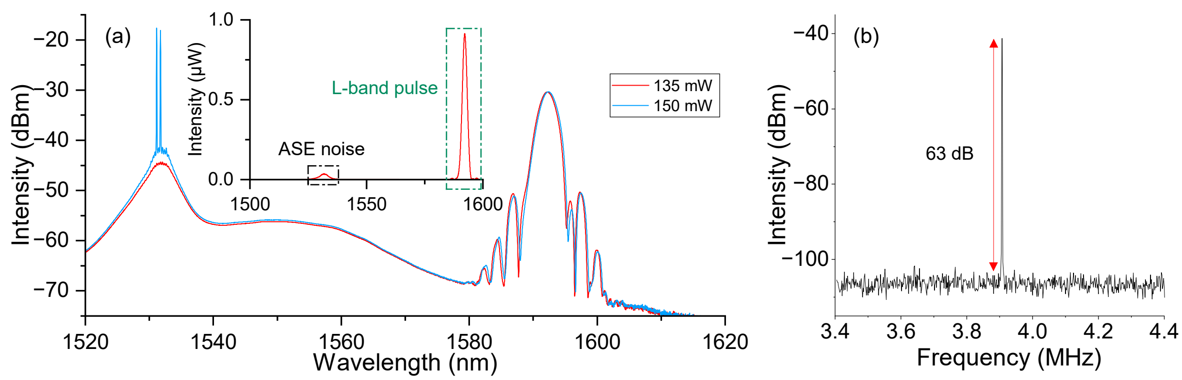

Fig. 2. Laser performance. (a) optical spectrum in logarithmic at pump power of 150 mW and 135 mW; inset: optical spectrum in linear scale at pump power of 135 mW; (b). RF spectrum (span, 1 MHz; RBW, 100Hz).

The laser self-starts at a pump power of 260 mW and exhibits in a multi-pulsing mode. Stable single soliton pulsing is achieved by gradually reducing the pump power to 135 mW. The center wavelength of the laser is 1592.2 nm with an average output power of 120 µW. The optical spectrum is presented in Fig. 2(a), with the inset showing the spectrum in linear scale. From the optical spectrum, the estimated output power of the L-band soliton pulse component at 1592.2 nm is ~108 µW, and the ASE component (1525-1565 nm) contributes to approximately 10 % (~12 µW) of the total measure output average power. Further increasing the pump power to 150 mW results in continuous wave (CW) lasing at 1530 nm, while the L-band soliton pulse remains almost unchanged. The radio frequency (RF) spectrum of the laser output at single-soliton pulsing mode is shown Fig. 2(b), with a resolution bandwidth (RBW) of 100 Hz and a span of 1MHz. The signal-to-noise ratio (SNR) is measured to be ~ 63 dB. center frequency of 3.9 MHz corresponds well with the approximate 50 m laser cavity length. Further reduction in the pump power causes the pulse's center wavelength to blue shift, reaching 1576.2 nm at 82.5 mW pump. Lowering the pump power below 82 mW, however, results in a transition from mode-locking to CW lasing.

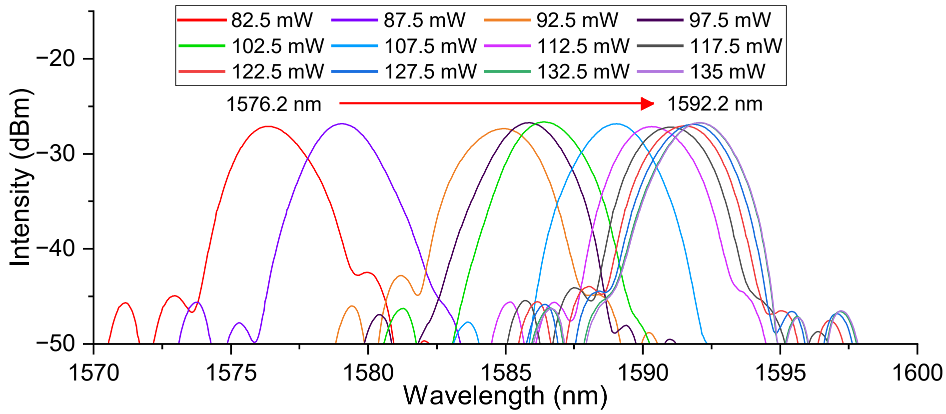

Fig. 3. Wavelength-tuning spectra (1576.2nm to 1592.2 nm) at varying pump powers from 82.5 mW to 135 mW.

Fig. 3 illustrates the wavelength-tuning spectra at various pump powers, showing a tuning range of 16 nm (1576.2 nm to 1592.2 nm) achieved by altering the pump power from 82.5 mW to 135 mW. This 16 nm range has been consistently repeatable, both by increasing or decreasing the pump power, as confirmed through multiple tests. Additionally, a fast wavelength tuning speed is achieved owing to the non-mechanical nature of the tuning mechanism, with immediate wavelength changes observed on the OSA following pump power adjustments.

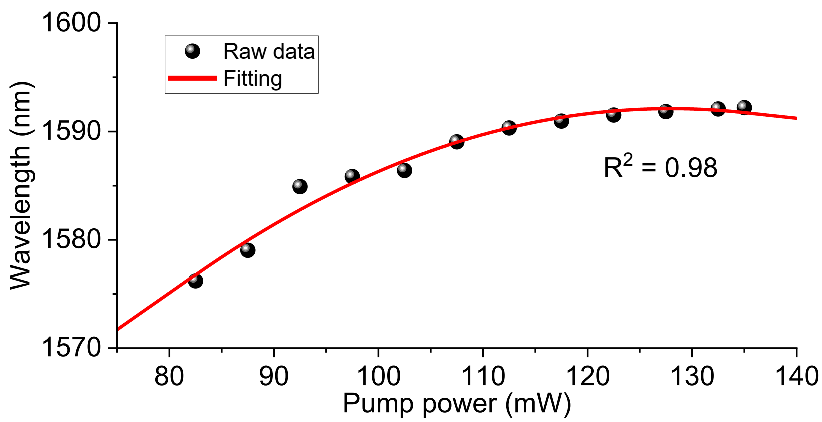

Fig. 4. Center wavelength versus pump and the quadratic polynomial fitting result.

The laser output center wavelength shift versus pump power is shown in Fig. 4. A quadratic polynomial fit of the wavelength to pump power results in an R-square (R^2) value of 0.98, suggesting a nonlinear relationship between pump power and pulse center wavelength. This nonlinear correlation of the pump power tuning mechanism is likely attributed to the gain saturation nature and shifts in the gain profile of the erbium-doped fiber at different pump power levels. Typically, the gain peak undergoes a blue-shift towards shorter wavelengths as the pump power increases [20], a trend that is in contrary to what we have observed in our laser, where the center wavelength red shifts to longer values with increasing pump power. The pump-power dependent wavelength tuning mechanism is therefore not originated from the pump-power dependent gain-peak shift of the erbium-doped fiber and is a topic for further investigations.

3. CONCLUSION

In summary, we have successfully reported the first all-PM NPR fiber laser capable of generating wavelength-tunable soliton pulses in the L-band. The laser features all-PM and all-fiber configurations and a non-mechanical tuning method by controlling the pump power. A 16 nm (1576.2 nm to 1592.2 nm) tuning range is achieved by changing the pump power from 82.5 to 135 mW. Our laser demonstrates improved repeatability and reliability, paving the way for new opportunities in L-band wavelength-tunable lasers and their diverse applications.

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