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A Wavelength Tunable All Polarization-Maintaining Fiber Mode-Locked Laser At Full C-Band With A High Repetition Rate Of 126 Mhz

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Abstract

We report a fully C-band wavelength-tunable mode-locked laser with an all-polarization-maintaining (PM) fiber architecture. A simple and compact laser design based on a fiber Fabry-Perot (FP) cavity enables the production of high-repetition-rate soliton pulses with a semiconductor saturable absorber mirror (SESAM) as a mode locker. Our fully C-band wavelength-tunable mode-locked laser has a repetition rate of 126.5 MHz, which is the highest repetition rate among C-band wavelength-tunable mode-locked lasers to the best of our knowledge. We observed a stable mode-locking state when the central wavelength was tuned from 1533.7 nm to 1565.6 nm. The broadband central wavelength tunability and high repetition rate of the all-PM mode-locked laser as demonstrated here will be compelling source for various applications, including optical communications, broadband spectroscopic LIDAR, and high-precision ranging.

Introduction

Compact, robust and high repetition rate fiber mode-locked lasers have played major roles in many applications [1, 2], including high-precision spectroscopy [3, 4], massive optical communications [5], biomedical research [6] and dimensional metrology [7–9], with their unique characteristics, such as an ultra-short pulse duration, high peak power, spectral purity and broad spectrum. Specifically, fiber-based mode-locked lasers have many advantages, including compactness, stable and robust operation, low power consumption, and cost-effectiveness. Such advantages have allowed fiber-based mode-locked lasers to enter the mainstream of the mode-locked lasers [10, 11]. Fiber mode-locked lasers have been demonstrated with various mode-locking techniques, including polarization-based methods such as nonlinear polarization rotation (NPR) [12] and a nonlinear optical loop mirror (NOLM) [13] as well as methods that rely on a saturable absorber, such as the semiconductor saturable absorber mirror (SESAM) [14], carbon nanotubes (CNT) [15], graphene [16, 17], and various 2D materials [18–20].

Saturable absorbers have been widely used to generate an ultrafast mode-locked laser, particularly due to their ease of use. Saturable-absorber-based mode-locked lasers are generally operated in the soliton pulse regime, where self-phase modulation and intracavity dispersion are balanced [21]. However, soliton mode-locking is associated with limited low output power levels and a relatively narrow spectral bandwidth. For example, soliton mode-locked lasers have output power of only a few milliwatts and a spectral bandwidth of a few nanometers at a central wavelength of 1550 nm [22]. To cover a wide spectral bandwidth, the power of soliton mode-locked lasers must be amplified, and they require nonlinear fiber for spectral broadening. Instead of power amplification and spectral broadening, wavelength-tunable mode-locked fiber lasers using a tunable bandpass filter inside the laser cavity have also been proposed to cover a broad spectral range.

Figure 1 shows an overview of current state-of-the-art C-band tunable mode-locked fiber lasers in terms of their wavelength range and pulse repetition rate [15, 23–36]. Wavelength-tunable mode-locked fiber lasers operating on the C-band are central-wavelength tuned with a thin-film filter [23, 26, 28], an intrinsic cavity birefringence filter effect [24, 36], a stretchable grating [25], a 45° tilted fiber grating [27, 33], a supermode interference filter [29], a birefringence Sagnac filter [30, 35], a cascaded dual-single-mode fiber-graded index multimode fiber-single mode fiber structure [31], and grating with aperture tuning [32, 34]. Many wavelength-tunable mode-locked fiber lasers have been reported with broad tunability of the wavelength; however, their repetition rates have remained below the range of tens of megahertz due to their long intracavity length. These mode-locked lasers with low repetition rates cannot easily realize high-performance frequency comb-based optical metrology due to their high timing jitter and poor laser noise. For such high-end frequency comb applications, high-repetition-rate mode-locked lasers are required for their high spectral purity and low timing jitter [37].

In this article, we report the highest repetition rate of a full C-band tunable mode-locked fiber laser. The Fabry-Perot type of laser cavity enables the repetition rate to exceed 100 MHz due to its simple structure. The all-polarization-maintaining fiber structure enables compact, robust and stable operation of the mode-locked laser [38–42]. The most widely used technique for a saturable absorber is the SESAM, which has been successfully commercialized while others are only demonstrated under laboratory conditions. The reliability and stability of the SESAM technique can sufficiently generate ultra-short pulses and mode-locking without any tight environmental control. In this study, the SESAM technique was used as a mode locker for turn-key operation. Our fully C-band wavelength-tunable mode-locked fiber laser maintains a mode-locking state as its central wavelength is tuned from 1533.7 nm to 1565.6 nm. The repetition rate of the fully C-band wavelength-tunable mode-locked fiber laser is 126.5 MHz, which is the highest repetition rate among all C-band wavelength-tunable mode-locked lasers reported thus far.

Design Of C-band Wavelength Tunable Mode-locked All-polarization Maintaining Fiber Laser

Figure 2 shows a schematic diagram of a C-band wavelength-tunable mode-locked erbium-doped fiber laser operating at a repetition rate of 126 MHz. It leverages certain advances in previous works focusing on high-repetition-rate Fabry-Perot type mode-locked lasers, specifically the all-polarization-maintaining (PM) fiber structure. The laser cavity is based on the Fabry-Perot type of fiber cavity, consisting fully of PM fiber and PM telecom-grade fiber components to maintain polarization of the optical pulses inside the cavity for environmental robustness.

The laser cavity consists of the SESAM structure, a tunable band-pass filter with a PM fiber pigtail of 520 mm, and 300 mm of PM erbium-doped fiber (PM-ESF-7/125, Nufern). Its key components are the SESAM for robust operation and self-start mode-locking and the tunable bandpass filter for central wavelength tuning. The SESAM (SAM-1550-23-2ps, BATOP) has a 14% modulation depth, 9% non-saturable loss and a 2 ps relaxation time constant. The SESAM is used to achieve self-mode-locking operation by absorbing low-intensity light and transmitting high-intensity light, such as pulsed light. The tunable bandpass filter (BTF-11-11-1525/1565, OZ optics) is based on a thin-film filter and can tune the transmitted central wavelength from 1525 to 1565 nm by tilting the angle of the incident light toward the tunable bandpass filter.

All of the fiber connections inside the laser cavity are butt-coupled using a FC ferrule connector without fiber splicing. This method induces additional optical loss about 1 dB, but it has advantages in that it offers control of the length of the laser cavity by cutting out the fiber and making the repetition rate of the mode-locked laser easy to adjust to the target position. This is also beneficial for assembly and maintenance. The net cavity dispersion was estimated to be -0.017 ps^2, making the laser cavity operable in the soliton mode-locking state. One of the end faces of PM erbium doped fiber dichroic was coated onto an FC/PC connector designed with 90% reflectance and 10% transmittance for 1550 nm and nearly 100% transmittance for 980 nm. A dichroic coating was applied to output coupler for a 1550 nm signal and enables a 980 nm pumping laser to be injected from the outside of the laser cavity. Emission wavelength tuning is provided by the tunable bandpass filter inside the laser cavity. The central wavelength of the tunable bandpass filter was tuned by tilting the angle of the bandpass filter. The other end face of the PM erbium-doped fiber was butt-coupled to one of the pigtails of the tunable bandpass filter through FC/APC connectors. The tunable band-pass filter was aligned to the slow axis of the PM fiber to define the polarization state of the mode-locked laser pulses. The other end face of the pigtail of the tunable bandpass filter with the FC/PC connector was butt-coupled to the SESAM.

Characteristics Of C-band Wavelength Tunable Mode-locked Fiber Laser

Mode-locking was typically self-starting at a pumping power of 200 mW at 980 nm, resulting in output power of 2 mW in the C-band spectrum. As shown in Fig. 3, the pulse train of the mode-locked fiber laser had temporal spacing of 7.9 ns, equivalent to a pulse repetition rate of 126.5 MHz as measured by a photo diode and high-speed oscilloscope. Figure 3(a) shows the pulse train of the stable and fundamental soliton pulse regime over 100 ns, indicating that there were no notable secondary pulses. Its RF spectrum shown in Fig. 3(b) had a signal-to-noise ratio of 80 dB for a fundamental repetition rate of 126.5 MHz at both a resolution bandwidth and a video bandwidth of 910 Hz. Its zoom-out view in inset of Fig. 3(b) shows the harmonics of the repetition rate up to 1.5 GHz with the resolution bandwidth and the video bandwidth of 240 kHz, which corresponds to a 3-dB bandwidth of the avalanche photodiode used in this study.

Figure 4 shows the optical characteristics during the process of central wavelength tuning. By adjusting the tunable bandpass filter, the central wavelengths of the mode-locked fiber laser were tuned over the full C-band spectrum. Figure 4(a) shows typical optical spectrums of C-band wavelength-tunable mode-locked lasers within a tuning range. We observed a single soliton mode-locking state while the central wavelength was tuned from 1533.7 nm to 1565.6 nm. The observed optical spectrums showed a signal-to-noise ratio exceeding 50 dB. The 3 dB bandwidth (or full width at half maximum, FWHM) of the optical spectrums were typically less than 1 nm. It should be noted that the typical 3 dB bandwidth of the optical spectrum without a tunable bandpass filter inside the laser cavity is approximately 8 nm, as shown by the cyan-colored line in Fig. 4(a). Such a reduction of the 3 dB bandwidth appears to originate from the tunable bandpass filter. Note that, asymmetrical spectrums during spectral tuning was seemed to be caused by net gain of the erbium doped fiber and tunable bandpass filter. As a result of narrowing the 3 dB bandwidth in the optical spectrum, the pulse durations within the tuning range were a few picoseconds while the pulse duration without the tunable bandwidth was 437 fs, in the range of $sech^2$-shaped pulses.

Figure 5 shows in more detail the pulse duration and the 3 dB bandwidth of the optical spectrums. As shown in Fig. 4, the pulse durations and the 3 dB bandwidth within the tuning range were a few picoseconds and less than 1 nm, respectively. The time bandwidth product (TBP), defined as the product of the temporal and spectral widths of the optical pulse and used to characterize the optical pulse in both the time and frequency domain, were calculated within the tuning range. The TBPs within the tuning range were close to 0.4. The TBP of the transform-limited sech2 pulses is 0.315, indicating chirp-free pulses. The TBPs indicated that the measured pulses had small chirps, which may have been generated from the delivery fiber to the optical autocorrelator.

Conclusion

Here, we demonstrated an all-polarization-maintaining fiber-based C-band wavelength-tunable mode-locked laser with a repetition rate of 126.5 MHz. Our laser has highest repetition rate among C-band tunable mode-locked lasers thus far. Our simple and all-PM structure of a FP laser cavity enables our laser to operate robustly and stably with a high repetition rate, which is necessary for high-precision frequency comb applications [43–49]. We also examined the performance the proposed laser in both the optical and microwave domain and confirmed that it maintained a soliton mode-locking state with central wavelength tuning from 1533.7 nm to 1565.6 nm, a range covering the full C-band. The tuning range of the central wavelength was limited by the tunable bandpass filter inside the laser cavity. Because erbium-doped fiber used as a gain medium can emit the L-band, the tuning range can be extended to the L-band region if using a tunable bandpass filter with a wider tuning range. This mode-locked laser enables high-capacity optical communications, high-precision dimensional metrology and broadband spectroscopic LiDAR.

Declarations

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Data availability. All data generated or analysed during this study are included in this published article and its supplementary information files.

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Figures

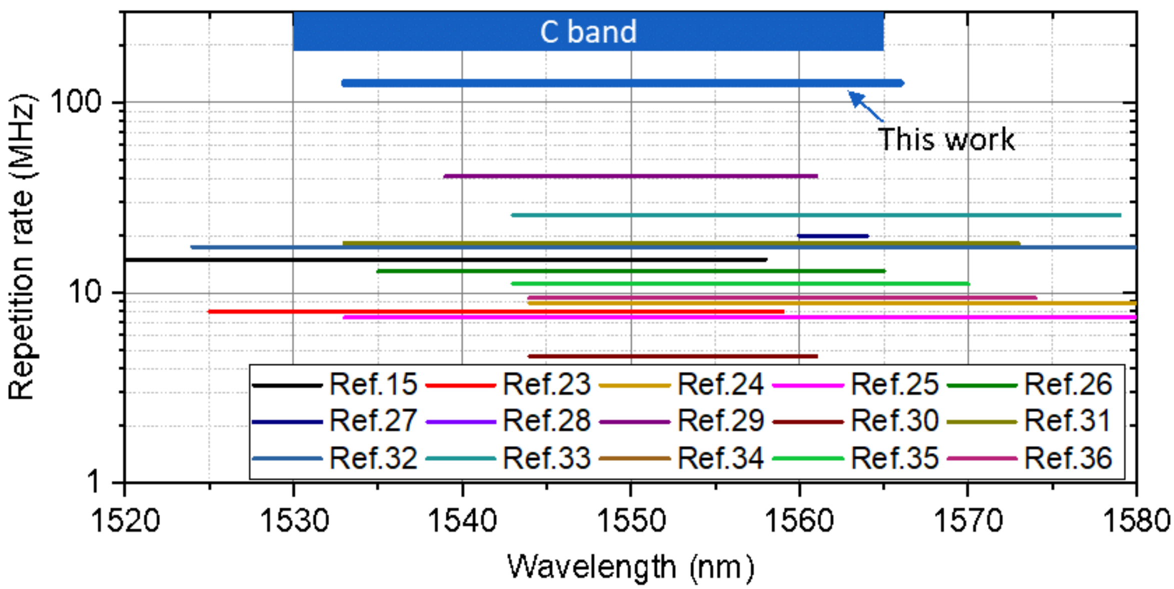

Figure 1

Current state-of-the-art C and L band tunable mode-locked laser in terms of repetition rate and central wavelength range.

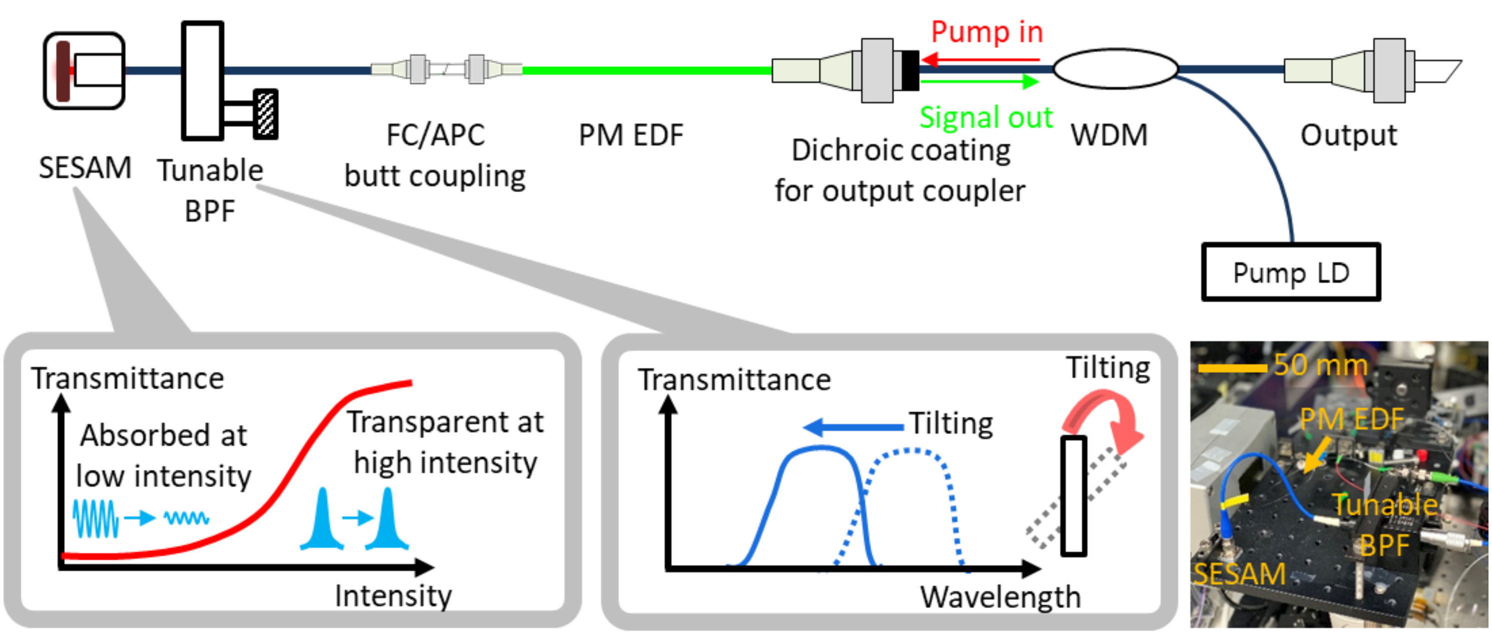

Figure 2

Configuration of C-band wavelength-tunable mode-locked all PM fiber laser. Left bottom inset shows working principle of the semiconductor saturable absorber mirror. Center bottom inset shows working principle of the tunable bandpass filter. Right bottom inset shows photography of proposed laser. SESAM: semiconductor saturable absorber, BPF: bandpass filter, PM EDF: polarization maintaining Erbium-doped fiber, WDM: wavelength division multiplexer, Pump LD: pump laser diode.

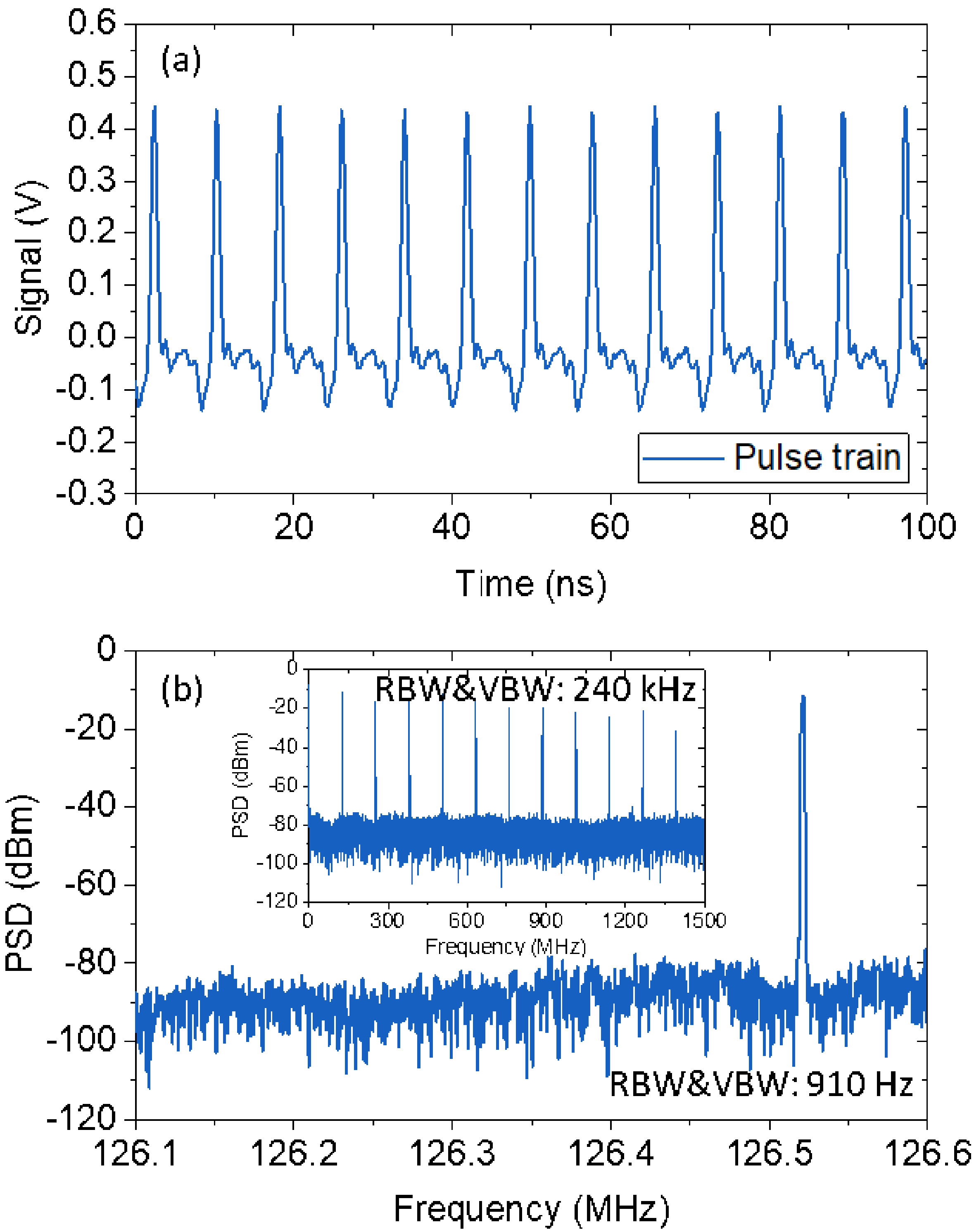

Figure 3

RF characteristics of C-band wavelength-tunable mode-locked all PM fiber laser. (a) Output pulse trains over 100 ns. (b) RF spectrum of fundamental repetition rate with 910 Hz of RBW and VBW. Inset shows its zoom-out view.

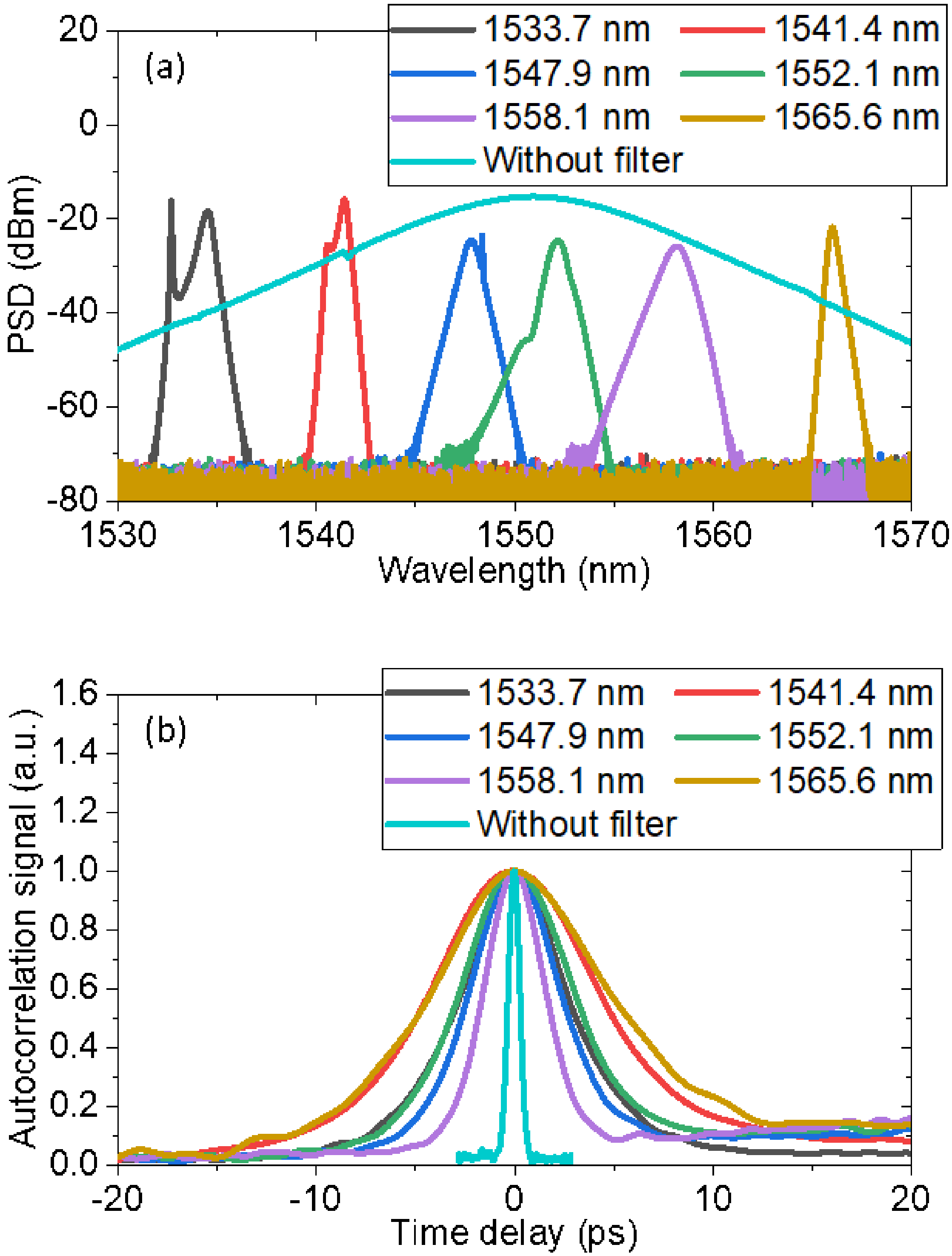

Figure 4

Optical characteristics of C-band wavelength-tunable mode-locked all PM fiber laser. (a) Spectral characteristics measured by optical spectrum analyzer. Central wavelength was tuned from 1533.7 nm to 1565.6 nm, while mode-locking was maintained. Lower part shows some important absorption lines at C-band wavelength. (b) Temporal characteristics measured by optical autocorrelator, while central wavelength was tuned from 1533.7 nm to 1565.6 nm.

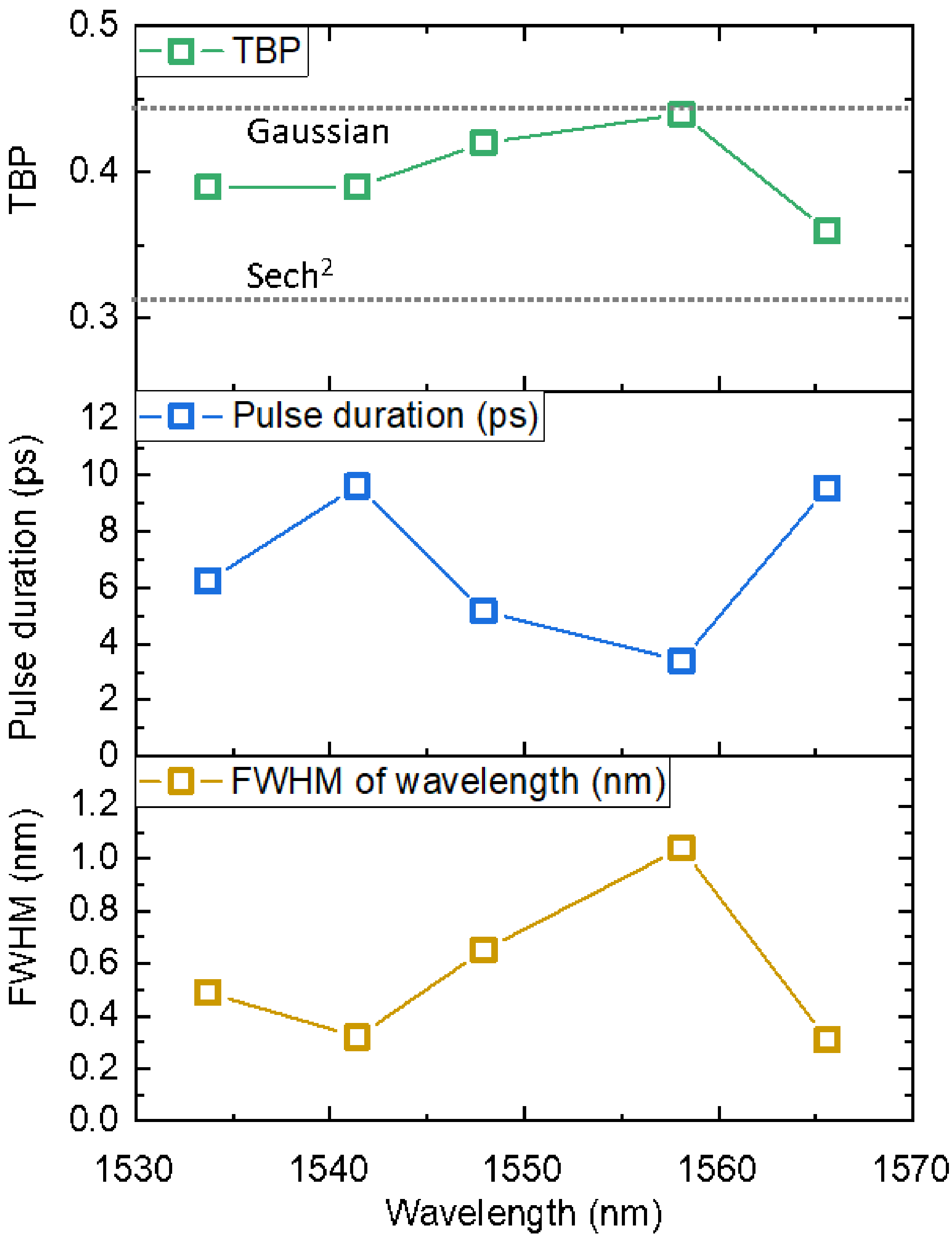

Figure 5

Quantitative optical characteristics of C-band wavelength-tunable mode-locked all PM fiber laser for each central wavelength. Upper section shows time bandwidth product (TBP). Middle section shows pulse duration. Lower section is optical 3-dB bandwidth.