Wavelength-tunable Passively Mode-locked Erbium-doped Fiber Laser Based on Carbon Nanotube and a 45 °Tilted Fiber Grating

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ABSTACT: A wavelength-tunable all-fiber Erbium-doped mode-locked fiber laser based on carbon nanotubes and 45 °tilted fiber grating (TFG) is demonstrated. We investigated the effect of PDL of 45TFG in the tuning range of a mode locked laser. The central wavelength of the laser can be tuned continuously from 1559.85 nm to 1564.46 nm with a tuning range of 4.6 nm using a weak 45TFG and from 1553.37nm to 1568.63 nm with a tuning range of 15.26 nm using a strong 45TFG. The laser maintains high signal to noise ratio > 50 dB across all the wavelength tuning range.

Key words: Mode locked fiber laser; Erbium fiber laser; Carbon nanotube; Tilted fiber grating

1. Introduction

Nowadays, wavelength tunable mode-locked fiber lasers have attracted significant interests because of their widespread application in biomedical research, spectroscopy, fiber-optic sensors, optical instrumentation and telecommunications [1-5]. A number of methods can be employed to realize the mode locking operation of a wavelength tunable fiber laser. To achieve passive mode locking, two major approaches can be employed including artificial saturable absorber (SA) and physical SA. The clear advantages of using fiber nonlinearity based artificial SA is its low cost and ease of implementation. Typical artificial SA consists of nonlinear polarization rotation (NPR) [6,7], nonlinear amplifying loop mirror [8,9], nonlinear loop mirror [10]. However, even wide band tuning can be achieved [11], the inherent polarization sensitivity of the lasers claims that tunability would inevitably break the mode-locking operation during wavelength tuning. Hence, a physical SA in addition to an intracavity tunable filter manifests to be a better option.

Although semiconductor saturable absorber mirror serves to be a sophisticated SA, the limited bandwidth is an inherent drawback of wavelength tuning [12]. Recently, the development of nanomaterial as advanced nonlinear photonic devices has successfully demonstrate physical SA with wide band response including carbon nanotube [13,14], graphene [15,16], topological insulator [17,18], chalcogenide material [19]. Among these, although wavelength tuning have been demonstrated [20-23], the fabrication of 2D, topological insulator photonic device has not been shown to be highly mature. Carbon nanotubes, as a well-studied nonlinear photonic material, have exhibited excellent SA properties with comfortable performance in fiber laser applications. So far, various types of SA based on CNT have been demonstrated including filling in hollow core fiber [24], deposition on D-shaped fiber [25], deposition on tapered fiber [26], microfluidic injection [27] and sandwich structure [28]. Carbon nanotube polymer composite film offers special merits over the other methods such as well-developed fabrication procedures, ease of operation, robust, polarization insensitive thus rendering a better way of physical incorporation in the laser cavity.

The tunable filters incorporated in the mode-locked fiber laser cavity act as a key element for continuous wavelength tuning. By far, various types of tunable filters have been demonstrated for wavelength tuning in a mode-locked fiber laser including Fabry-Perot interferometer (FPI) [29], mechanical tunable filter [30], stretchable fiber Bragg grating (FBG) [31], and birefringence filter [32]. Both FPI and mechanical tunable filters are bulky therefore reduces the integrity of the fiber laser system. Although modified FBG could offer a wide tuning range, the circulator in the laser cavity would induce extra loss. Recently, a new type of W-shape long period grating (LPG) has been developed for wide range mode-locked laser wavelength tuning [33]. However, such LPGs are difficult to fabricate and temperature sensitive. Due to the inherent fiber birefringence, the utilization of birefringence filter in a mode-locked fiber laser offers good opportunity for efficient wavelength tuning. To obtain intracavity birefringence filtering effect, a piece of high-birefringence fiber and polarizing element have always been employed [34]. The incorporation of either device would inherently introduce extra loss, complexity and cost of the laser system. It is therefore desirable to have a low loss and standard fiber compatible birefringence filter. The 45 °tilted fiber grating (45TFG) inscribed in a standard single mode fiber (SMF) features huge *s*-light loss and negligible *p*-light loss is an ideal polarizing device to achieve intracavity birefringence filter. With the advantages of all-fiber structure, low fabrication cost, strong polarization dependent loss (PDL) and low insertion loss, 45TFG have been already applied in many fields such as spectrometer [35], in-fiber Lyot filter [36], single polarization fiber laser [37], mode locked fiber laser [38-40].

In this letter, we proposed and demonstrated a wavelength-tunable all-fiber Erbium-doped mode-locked fiber laser based on CNTs and 45TFG. The fiber laser is mode-locked by single wall CNTs-Polyvinyl alcohol (PVA) composite film. The polarization controller combined with the SMF based 45TFG forms an intracavity birefringence filter. When adjusting the polarization controller, the central wavelength of the laser can be tuned continuously. Two distinct 45TFGs have been examined to investigate the PDL effect on the laser tuning performance. The central wavelength of the laser can be tuned continuously from 1559.85 nm to 1564.46 nm with a tuning range of 4.6 nm using a weak 45TFG. A maximum tuning range of 15.26nm from 1553.37 nm to 1568.63 nm was obtained using a strong 45TFG. The demonstrated laser system features low cost, robust, all-fiber structure and compact design.

2. Characteristics of CNT SA

CNTs are fabricated through high-pressure CO conversion, which is commercially available and purified. As for the preparation of CNT-PVA composite film, firstly, 2 mg of carbon nanotubes are put into 10 mg of deionized water which mixed with 10 mg of sodium dodecylbenzene sulfonate (Sigma-Aldrich) surfactant, then ultrasonic treatment of the mixed solution for one hour using the commercial ultrasonic processor (Nanoruptor, Diagenode) under the condition of 200W. Secondly, centrifugation was (Beckman Coulter) carried out with the resulting solution for an hour under the condition of 25000RPM. The solution was then mixed with PVA powder and placed in a Petri dish. Finally, the CNT-PVA film can be obtained by placing the Petri dish containing the latest mixed solution in the dryer for several days. Fig.1(a) shows the absorption spectrum of the CNT-PVA film with typical features of HiPCo CNTs between 1000 and 1600 nm. The absorption intensity at 1550 nm is close to 0.2. Measured Raman spectrum of the SWCNTs/PVA film under pump laser of 532 nm is shown in Fig.1(b). From Fig.1(b), we can see the frequency of the radial breathing mode (RBM) is 250 cm^{-1} so the average diameter of SWCNTs can be calculated as ~ 0.88nm [41]. The existence of RBM (250 cm^{-1}) and G mode (1588 cm^{-1}) proves that the carbon nanotubes are single walled. The CNT-PVA film does not show large amount of defects due to the weak D mode. We also measured the nonlinear transmission of the CNT-PVA film using the typical twin-power method as shown in Fig.1(c). From Fig.1(c), we can clearly see that the CNT-PVA film has 6.2% modulation depth which is ideal for laser mode locking.

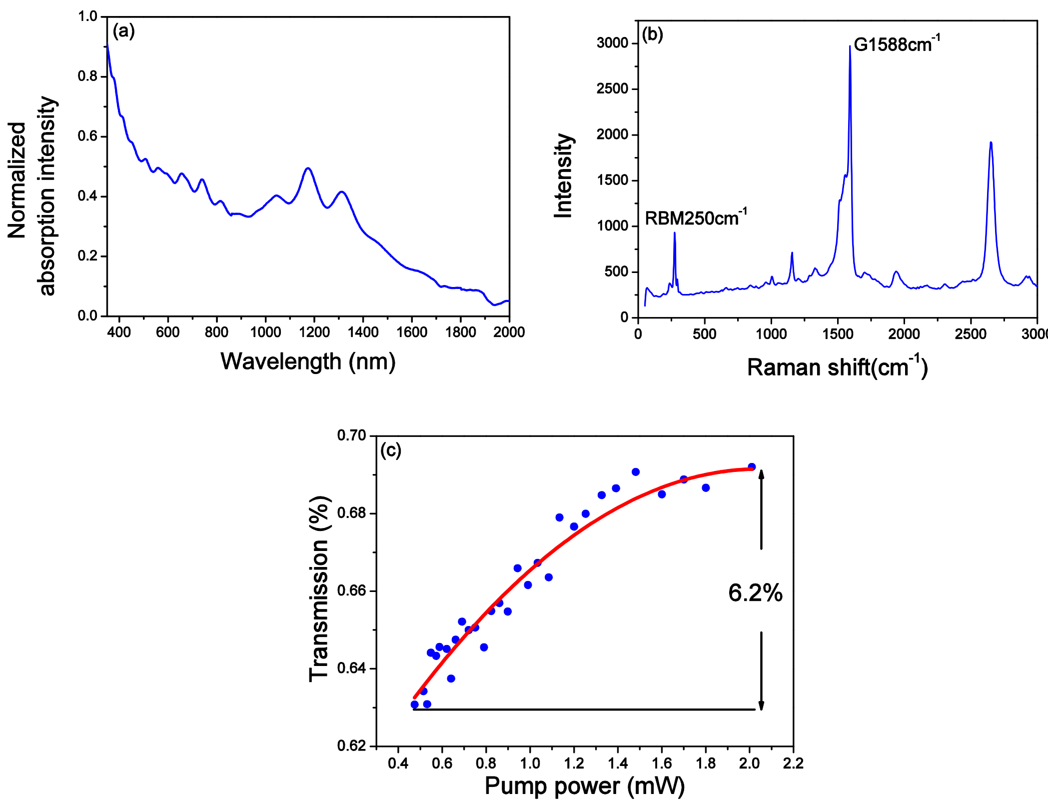

Fig.1. (a) Measured absorption spectrum of the CNT-PVA film. (b) Measured Raman spectrum of the CNT-PVA film. (c) Measured nonlinear transmission of the CNT-PVA film.

3. Characteristics of 45TFG

The 45TFG through UV inscription in a standard commercial single mode fiber (Corning SMF28e) is a new type of optical fiber device with internal tilted index fringes at 45° in the fiber core. Detailed description of the device fabrication procedure can be found in [42]. The PDL spectra of the 45TFGs were measured by a commercial optical component analyzer (Agilent N7788BD) integrating with a high precision tunable laser (Agilent 8164A). In the process of PDL measurement, resolution of high precision tunable laser (Agilent 8164A) is set to 0.001nm. In our experiment, we deliberately fabricate two 45TFGs with weak PDL of 8 dB (45TFG-a in Fig.2(a)) and strong PDL of 19 dB (45TFG-b in Fig.2(b)) respectively. The ripples from the PDL spectra is due to the radiation mode resonance between the fiber core and cladding/air boundary [37,38]. The ripples from the PDL spectra do not affect the laser performance.

Immersing the 45TFG in the refractive index gel or putting 45TFG in a thermal shrinking polymer tube can eliminate the ripples from PDL spectra. From Fig.2(c) and Fig.2(d), we can see the corresponding insertion loss of 8dB PDL 45TFG and 19dB PDL 45TFG are -4.14dB, -7.23dB respectively. This loss consists of a large number of loss caused by s-light coupled into cladding and extra loss caused by unsatisfactory connection and splicing . So in fact, insertion loss of 45TFG is low.

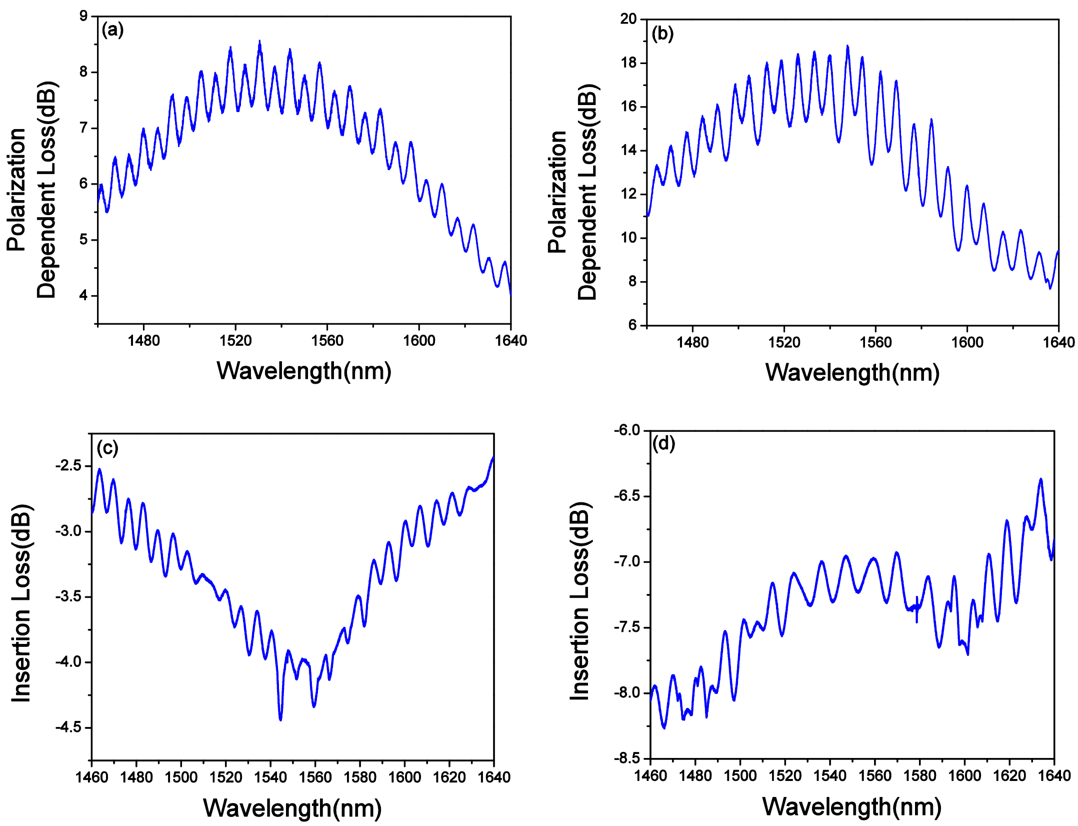

Fig.2. Measured (a) PDL response (c) insertion loss of the 45TFG-a; and (b) PDL response and (d) insertion loss of the 45TFG-b.

4. Experimental setup

The experimental setup of the wavelength tunable mode-locked fiber laser is shown in Fig.3. 112.5cm Erbium-doped fiber (EDF Er80-8/125 from Liekki) with group velocity dispersion (GVD) of −20 ps2/km is used as the gain medium of laser. The 45TFG is placed in between two polarization controllers (PC), and the cavity is changed by adjusting PCs to induce an intracavity birefringence filter. In the experiment, two 45TFG with PDL 8 dB and 19 dB at 1550 nm were used. During the process of replacing TFG, the physical length of the two 45° TFG was kept the same, so that the total cavity birefringence, nonlinearity and cavity length maintains unchanged. A 2×2 mm of SWCNTs-PVA composite film was sandwiched between two standard fiber connector ferrules as saturable absorber. A fiber pigtailed optical isolator is used to maintain unidirectional lasing operation. The fiber laser is pumped via the WDM by a 980 nm benchtop laser (OV LINK, Wuhan) with the maximum current of about 1100 mA which provide 686 mW optical power. The cavity consists of 247 cm OFS980 fiber with a normal dispersion β_2 = +4.5 ps^2/km. A 60:40 fiber couplers are employed to tap 40% of laser power out of the cavity. The rest of the cavity consists of SMF with length of 6.8 m and anomalous dispersion β_2 =-22.8 ps^2/km. The total length of the cavity is ~10.4 m and net dispersion is -0.369 ps^2 indicating soliton pulse formation. The output optical spectrum is monitored by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) and pulse trains are recorded by a 1 GHz oscilloscope (OSC, Tektronix MSO4104) with a 12.5 GHz photodetector (PD, Newport 818-BB-51F). The radio frequency (RF) spectrum of pulses is analyzed by a 22.5 GHz electronic spectrum analyzer (HP, E4407B). The pulse width is characterized by using a commercial autocorrelator (FEMTOCHROME, FR-103WS).

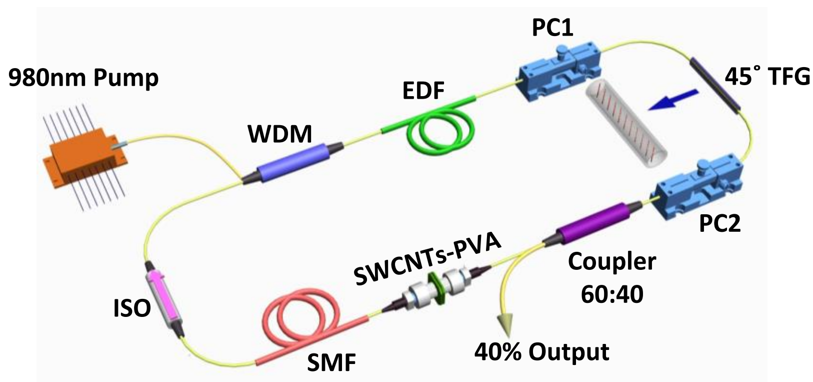

Fig. 3. Schematic diagram of the wavelength tunable mode-locked fiber laser. WDM, wavelength-division multiplexer; EDF, Erbium-doped fiber; PC(PC1,PC2), polarization controller; 45 ° TFG, 45 ° tiled fiber grating; OC, output coupler; SA, saturable absorber; SMF, single-mode fiber; OSI, Optical isolator.

5. Experimental results and discussion

5.1 Tunable mode locked fiber laser incorporating 45TFG with 8dB PDL

When the pump current is 70mA, continuous wave occurs. The laser began to generate mode-locked pulses at pump current of 250 mA. Through adjusting the PCs, the mode-locked pulse still exists, which indicates that 45TFG has little effect on the pulse initiation of the laser. Fig.4(a) shows the pulse train of the laser at 1561.75 nm under pump current of 270 mA with pulse interval 49.7 ns corresponding to the fundamental repetition rate of 20.12 MHz, indicating that the laser operates in a single pulse state. The measured RF spectrum of this fiber laser is depicted in Fig.4(b). The output pulses with SNR of 50dB indicating stable operation of the laser. By properly adjusting the two PCs, we find that the central wavelength can be tuned continuously. As shown in Fig.5(a), the central wavelength can be tuned from 1559.85 nm to 1564.46 nm with a tuning range of 4.6 nm. Pulse width at various wavelengths are shown in Fig.5 (b), which range from 1.2 ps to 2.9 ps. The minimum pulse width of 1.2 ps is obtained at 1562.64 nm. Fig.5(c) shows the 3 dB bandwidth and the average output power against central wavelengths, we can see that the bandwidth ranges from 1.6 nm to 4.1 nm and the corresponding average output power range from 0.9 mW to 1.51 mW individually. Under all cases, the time bandwidth product (TBP) is about 0.6, which is larger than the transform limit of 0.315, so the pulses can be dechirped to femtosecond outside the cavity. Also, the SNR maintains over 50 dB during wavelength tuning. When the pump current is further increased to 280 mA, the laser became unstable. Adjusting the polarization controller, the laser will alternate to multiple pulsing. Continue to increase pump power will result in damage of CNT SA film.

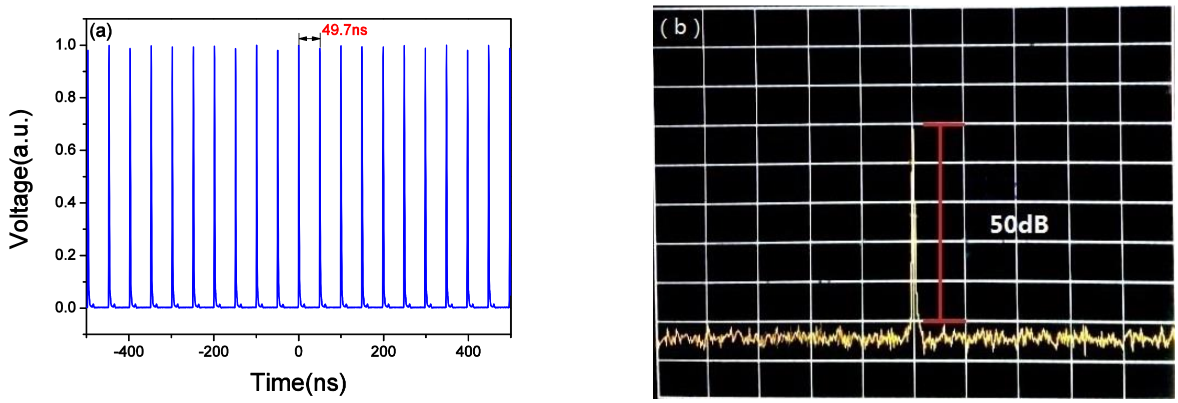

Fig.4. Measured characteristics of laser using 45TFG with 8 dB PDL under the pump current of 240mA, (a) A typical pulse train from the fiber laser; (b) The RF spectrum of the mode locked fiber laser.

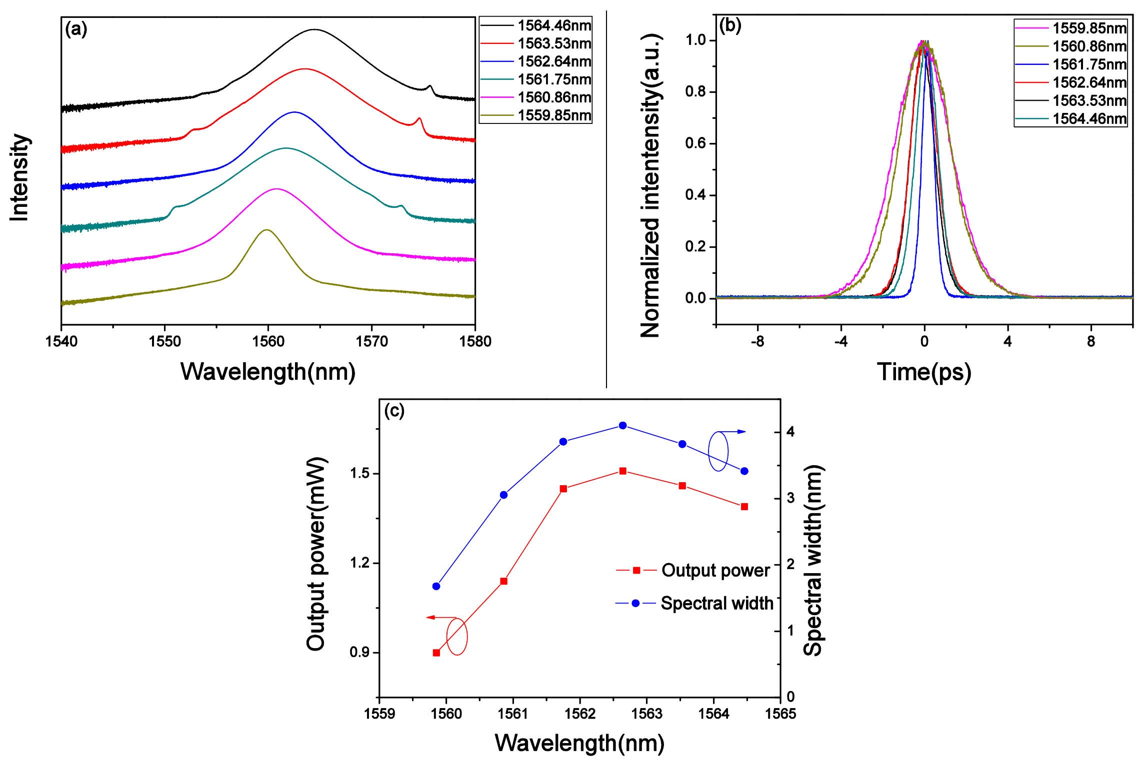

Fig.5. Measured performance of laser tunability using 45TFG with 8 dB PDL, (a)spectral evolution; (b)Autocorrelation traces of laser output at different central wavelengths; c)spectral width and average output power at different central wavelength.

5.2 Tunable mode locked fiber laser using 45TFG with 19dB PDL

At this point, the mode-locked threshold of the laser is 230 mA. Fig.6(a) shows the pulse train of the laser at 1561.69 nm under pump current of 240 mA with pulse interval 50 ns corresponding to the repetition rate of 19.99 MHz which indicating a minimum change of the cavity length. SNR is 54 dB as shown in Fig.6(b), indicating that the fiber laser is stable. Similarly, by properly adjusting the two PCs, the central wavelength can be continuously tuned from 1553.37 nm to 1568.63 nm with a tuning range of 15.26 nm as presented in Fig.7(a). Fig.7(b) shows the intensity autocorrelation among different wavelength. Maximum pulse width is 3.0 ps at the wavelength of 1553.37 nm, and minimum pulse width is 1.1 ps at wavelength of

1561.69 nm. Variation of average output power against 3 dB spectral bandwidth within the wavelength tuning range are also depicted in Fig.7(c). It can be see clearly that average output power range from 0.958 mW to 1.74 mW and 3 dB bandwidth of spectrum range from 1.6 nm to 4.7 nm. As in the case of 45 °TFG with 8dB PDL, the wavelength can not be tuned when the pump current is increased to more than 280 mA. At the same time, when adjusting the polarization controller, single pulse will be split into multiple pulses.

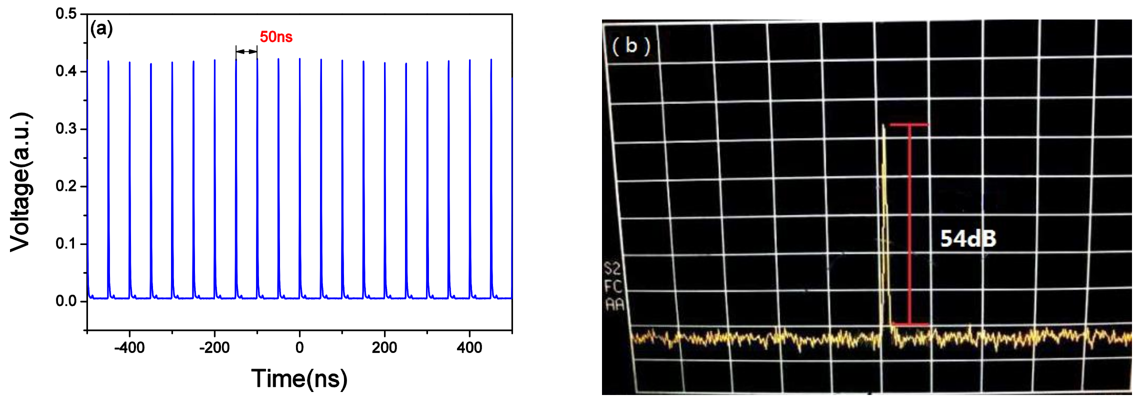

Fig.6. Measured characteristics of laser using 45TFG with 22 dB PDL under the pump current of 240 mA (a) A typical pulse train from the fiber laser; (b)RF spectrum of the mode locked fiber laser.

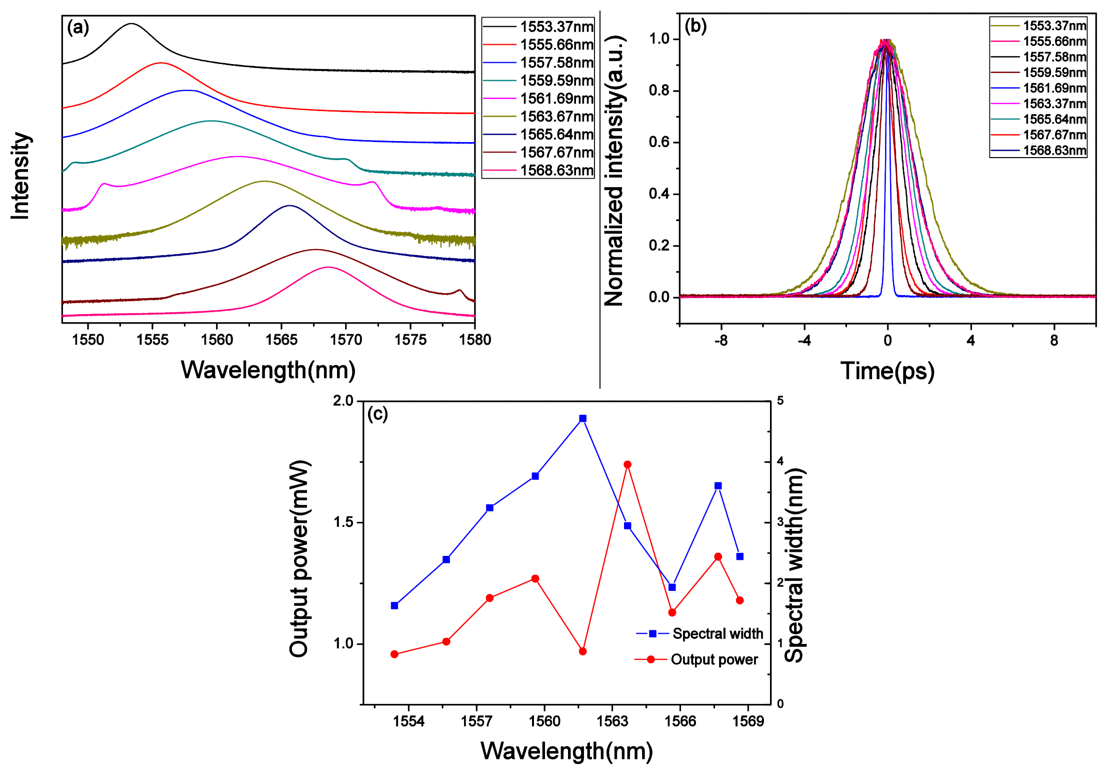

Fig.7. Measured characteristics of tunable mode-locked laser using 45 °TFG with 19 dB PDL (a) spectral evolution; (b)autocorrelation traces of laser output at different central wavelengths; (c)spectral width and average output power at different wavelength.

From the experimental results above, we can see that wavelength tuning range using 45TFG with 19 dB PDL is about 3 times as much as 45TFG with 8 dB PDL. The laser with a 19 dB PDL 45TFG also shows slightly higher SNR 54 dB. The reason for this difference may be resulted from the polarization dependent gain of Erbium fiber. With low PDL 45TFG, *s*-light would still occupy certain amount of gain so that the *p*-light induced gain may not be high enough to generate enough nonlinear refractive index change through the cavity. The resulting intracavity birefringence filter will exhibit a low visibility. Therefore, at the low gain region of Erbium fiber, this will degrade mode locking operation even with a physical SA. Hence, a larger PDL 45TFG may be ideal to form a wider range of wavelength tuning mode locked laser. In addition, one may notice that we did not mention NPR as a hybrid SA in our laser system. The reason is that typical NPR requires a high mode locking threshold than physical SA in a fiber laser system. In our lasers, we tried 45TFG mode locking with the absence of CNT demonstrating a threshold of more than 540 mA. We can conclude that there is no hybrid NPR effect in our lasers, the mode locking is initiated by CNT SA and the wavelength tuning is a result of birefringence filter.

6. Conclusion

We have proposed and demonstrated a wavelength-tunable all-fiber Erbium-doped mode-locked fiber laser based on CNTs and 45TFG. By simply adjusting the PCs, the central wavelength of the laser can be tuned continuously from 1559.85 nm to 1564.46 nm with a tuning range of 4.6 nm using 45TFG with 8 dB PDL, and the laser can generate 1.2 ps minimum pulse width, maximum average output power 1.51 mW and maximum 3 dB bandwidth 4.1 nm pulses at 1562.64 nm with SNR of 50 dB. Comparatively, the central wavelength of the laser can be tuned continuously from 1553.37 nm to 1568.63 nm with a tuning range of 15.26 nm using 45TFG with 19 dB PDL and maximum average output power is 1.74 mW with SNR of 54 dB. The laser features an all-fiber structure with compact design and robust control. Our wavelength-tunable fiber laser have potential applications in biomedical research, spectroscopy, fiber-optic sensors, optical instrumentation and optical telecommunications. Our further work is to obtain a 45TFG with much larger PDL (> 40 dB) and to further improve the wavelength tuning performance.

Funding

The authors would like to acknowledge support from National Natural Science Foundation of China (NSFC) (61605107,61505244); Young Eastern Scholar Program at Shanghai Institutions of Higher Learning (QD2015027); Young 1000 Talent Plan Program of China; support from the Ministry of Higher Education, Sultanate of Oman; Marie Sklodowask-Curie IEF project(H2020-MSCA-IF-2014_ST, Proposal#:656984); Marie-Curie Inter-national Research Staff Exchange Scheme “TelaSens” project, Research Executive Agency Grant No. 269271, Programme: FP7-PEOPLE-2010-IRSES.

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