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Tunable scalar solitons from a polarization-maintaining mode-locked fiber laser using carbon nanotube and chirped fiber Bragg grating

JIE WANG,[1,2] YAXI YAN,[1,2] A. PING ZHANG,[2] BO WU,[1] YONGHANG SHEN,[1,*] AND HWA-YAW TAM[2]

[1]*State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China*
[2]*Photonics Research Center, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China*
[*]*physyh@zju.edu.cn*

Abstract: Generation of tunable scalar solitons from a polarization-maintaining (PM) mode-locked fiber laser is presented. A single-walled carbon nanotube (SWCNT) absorber is used for self-started mode locking. A chirped fiber Bragg grating (CFBG) mounted on a cantilever is employed as a tunable all-fiber filter. Mode-locked solitons are obtained with typical pulse duration of ~6.94 ps and repetition rate of 28.94 MHz. Linearly polarized laser emission is characterized with degree of polarization (DOP) of ~99.5%. The wavelength of the emitted scalar soliton can be continuously tuned through adjusting the CFBG, while maintaining the polarization stability.

OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (060.2410) Fibers, erbium.

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1. Introduction

Tunable ultrafast fiber lasers have received tremendous attention because of their important applications in widespread fields, such as optical telecommunications, biomedical research, and spectroscopy [1–3]. Passive mode locking technique has been recognized as a routine approach to generate ultra-short pulses in fiber lasers, which includes nonlinear polarization rotation (NPR) [4], nonlinear optical loop mirrors (NOLM) [5], and semiconductor saturable absorber mirrors (SESAM) [6]. In the past decade, carbon nanotubes (CNT), graphene and other 2-D nano-materials (e.g. MoS_2 and WS_2) have attracted increased research interests owing to their inherent advantages such as ultrafast recovery time, suitable modulation depth and possibility of mass production [7–11]. Among these, single-walled carbon nanotube (SWCNT) dispersed in a polymer matrix has drawn much attention owing to its simple configuration and long-term stability [12]. Light and SWCNT interaction can be easily enabled by inserting the polymer film between two fiber connectors. In general, the saturable absorption of the SWCNT polymer film is polarization insensitive. As a consequence, vector solitons may be formed in the non-polarization-maintaining (PM) SWCNT mode-locked fiber lasers, which consist of two orthogonal polarization components [13, 14]. However, the polarization orientations of vector solitons could be unstable and might evolve from pulse to pulse [15, 16]. Additionally, they are vulnerable to external perturbations (e.g. vibrations, movements of fibers, and temperature variations). In contrast, scalar solitons from PM mode-locked fiber lasers consisting of PM optical fibers and components exhibit good polarization and environmental stabilities [17, 18]. However, the wavelengths of reported scalar solitons are not tunable to meet some practical applications.

To implement wavelength tuning in a mode-locked fiber laser, a tunable band-pass filter (TBF) is incorporated into its cavity. Wavelength-tunable mode-locked fiber lasers have been demonstrated by using free-space TBFs [19, 20]. However, large insertion loss would be introduced when the free-space coupled PM-TBF was used [21]. An all-fiber solution for in-cavity filtering is based on intra-cavity birefringence and polarization dependent loss of fiber components. For instance, artificial birefringence filters have been demonstrated in tunable mode-locked fiber lasers by adjusting polarization controllers [22, 23]. However, the birefringence filter cannot be constructed in a PM laser cavity. Another solution is to use fiber grating technique. A long-period grating filter has been demonstrated for a widely tunable mode-locked fiber laser [24]. Additionally, chirped fiber Bragg grating (CFBG) is of much interest because of its intrinsic advantages, including all-fiber structure, low insertion loss and potentially low cost. CFBGs have been demonstrated in wavelength-tunable and multi-wavelength non-PM mode-locked fiber lasers, respectively [25, 26]. A PM-CFBG has also been used as a non-tunable spectral reflector in a linear-cavity ytterbium fiber laser [27]. To the best of our knowledge, however, there are few reported works on exploiting CFBGs in all-fiber tunable PM mode-locked lasers, which are valuable for various polarization-sensitive applications.

In this paper, we present a tunable PM mode-locked fiber laser using a fiber-optic tunable CFBG filter, generating linearly polarized scalar solitons. A CFBG with reflective bandwidth of ~4 nm is firmly mounted onto a plastic cantilever for wavelength tuning. Environmentally stable solitons are obtained around 1530 nm with pulse duration of 6.94 ps. By adjusting the CFBG, the emission wavelength can be tuned continuously while the polarization state is well maintained. The presented technique of tuning wavelength by a CFBG and using a broadband SWCNT absorber can be readily adopted for other fiber lasers ranging from 1 to 2 μm.

2. Experimental setup

Figure 1 illustrates the schematic diagram of the tunable PM mode-locked fiber laser. A 2.7 m long PM erbium-doped fiber (PM-EDF) (Coractive Er35-7-PM) is forward pumped with a 974 nm laser diode through a PM wavelength-division multiplexer (PM-WDM). Laser output is obtained from the 10% tap of a PM fiber coupler. A small piece of home-made SWCNT/PVA composite film is inserted between two PM fiber connectors (FC/APC) and acts as an in-fiber saturable absorber (SA). The used free-standing SWCNT/PVA film was prepared by using an efficient method similar to [28]. The nonlinear saturable absorption of the SWCNT absorber was characterized by use of an ultrafast pulsed laser, a variable attenuator and a power meter. The measured nonlinear absorption curve of the SA is plotted in Fig. 2. The experimental data is fitted based on a simplified two-level SA model [12]. The normalized non-saturable loss, modulation depth, and saturable optical intensity are 95%, 5% and 11MW/cm^2, respectively.

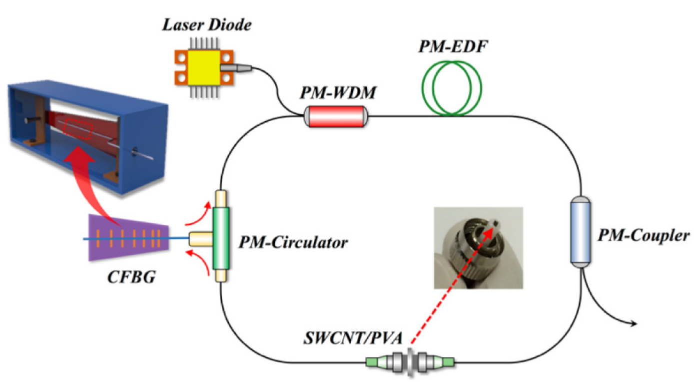

Fig. 1. Schematic diagram of the tunable PM mode-locked fiber laser incorporated with a CFBG. PM, polarization-maintaining; WDM, wavelength-division multiplexer; EDF, erbium-doped fiber; SWCNT/PVA, single-walled carbon nanotube/polyvinyl alcohol.

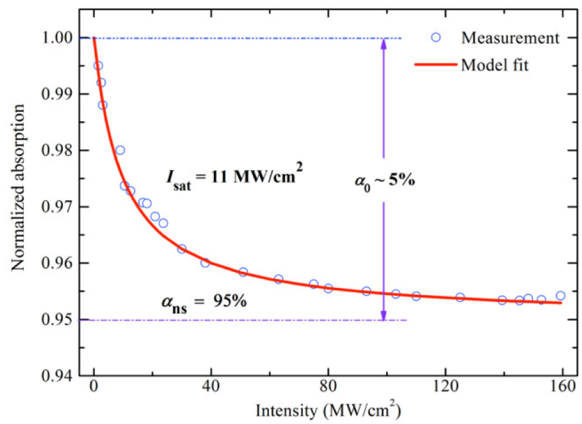

Fig. 2. Normalized nonlinear absorption of the SWCNT-based SA. The experimental data (circle symbols) is fitted with the solid curve.

To achieve wavelength tuning, a home-made CFBG centered at ~1530 nm is incorporated into the laser cavity via a PM fiber circulator. As shown in Fig. 3(a), the CFBG is glued onto one surface of a left-angled triangle cantilever beam with length L = 20 cm, width w = 3 cm, and thickness of 0.5 cm. When the screw is translated along the direction of x-axis, the central wavelength of the CFBG is shifted due to the elongation and photoelastic effects. However, the spectral profile of the CFBG remains unchanged and no ripples have been observed on the top of the reflection spectrum. As the lateral stress on the CFBG is so weak, the induced birefringence is relatively low and does not significantly affect the laser polarization. The used CFBG was fabricated by means of a Talbot interferometer and a 213-nm pulsed laser [29]. To obtain high reflectivity, non-PM photosensitive fibers (Corning OTI) were loaded in hydrogen at ~15 bar for two weeks. Gaussian apodisation was applied to avoid spectral interference ripples. To suppress polarization cross-coupling in the non-PM fibers, the CFBG is closely spliced to the PM fiber (PMF) as shown in Fig. 3(a). The estimated splice loss is ~0.05 dB. Measured optical spectra of the CFBG are shown in Fig. 3(b), where it can be seen that the reflection top is flat and smooth without apparent interference ripples. The central wavelength and 3-dB spectral width are ~1530 nm and ~4.33 nm, respectively. Additionally, the reflectivity is estimated as high as ~97%. Based on the transfer matrix method (TMM), the time delay curve of the CFBG is also numerically simulated as shown in the inset of Fig. 3(b). It can be observed that the ripples of the delay curve are efficiently suppressed with the Gaussian apodisation. The group velocity dispersion (GVD) of the CFBG is calculated to be ~5 ps/nm.

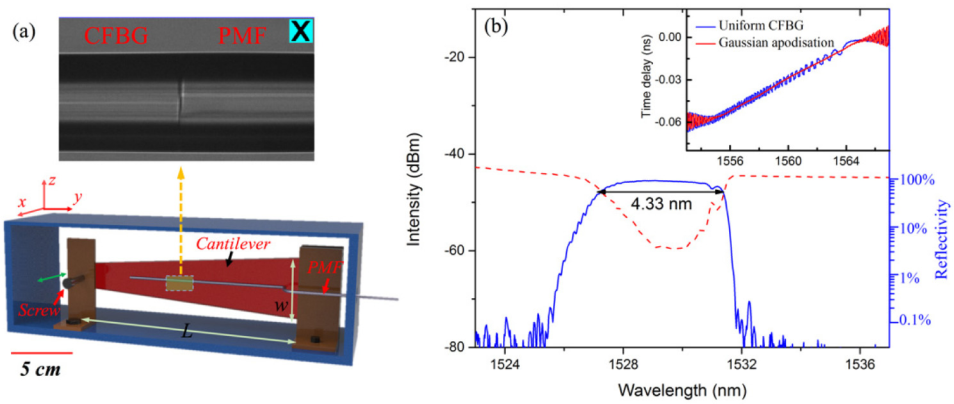

Fig. 3. (a) Microscope image of fusion splicing between CFBG and PMF (top) and setup of the cantilever beam (bottom), and (b) measured reflection (blue curve) and transmission (red dash curve) spectrum of the CFBG.

3. Experimental results and discussions

In the experiment, the laser transited from continuous wave state to mode locking state after the pump power was increased to higher than 46 mW. Different from the non-PM laser cavities, no polarization controllers were incorporated here. Under pump power of 88 mW, typical optical spectrum of the PM mode-locked laser is shown in Fig. 4. The central wavelength is ~1530 nm as determined by the CFBG. Distinct Kelly sidebands of the spectrum indicate that the mode locking operates in the net anomalous dispersion regime. The 3-dB spectral width is measured to be ~0.48 nm. In order to investigate the dispersion effect of the used filter, the CFBG together with the PM circulator were removed and replaced by a PM isolator. Stable mode locking was observed again but at the wavelength of ~1555 nm as shown in the inset of Fig. 4. The 3-dB spectral width changes to be ~8.76 nm. Successful mode locking at the two wavelengths verifies a broadband operation range of the SWCNT-based SA.

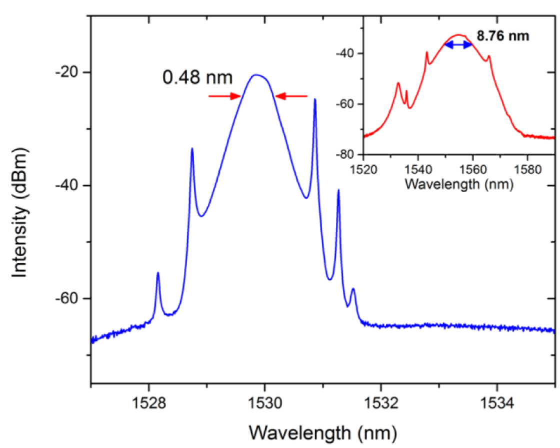

Fig. 4. Typical optical spectrum of the PM mode-locked laser with and without (inset) the CFBG.

The mode-locked pulses were then analyzed by using an optical autocorrelator (FR-103XL, Femtochrome Inc.), a photodetector and an oscilloscope. Figure 5 shows the autocorrelation (AC) traces of the emitted pulses. With the assumption of a $sech^2$ profile, the pulse duration of the CFBG-incorporated laser is evaluated to be 6.94 ps. The time-bandwidth

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product (TBP) is calculated as ~0.43, indicating that the mode-locked pulses are somewhat chirped. In comparison, the CFBG-omitted laser produces much narrower pulses with duration of ~370 fs as shown in the inset of Fig. 5. As a result, it can be inferred that the large anomalous dispersion of the CFBG broadens the mode-locked pulses. As shown in Fig. 6(a), the pulse-to-pulse separation of the tunable PM laser is 34.55 ns, corresponding to a repetition rate of 28.94 MHz. The radio frequency (RF) spectrum peak owns a moderate signal-to-noise ratio (SNR) of ~60 dB, which could be attributed to the small modulation depth of the SWCNT SA. Average output power increases proportionally to the pump power as shown in Fig. 6(b). The maximum average output power is 2.17 mW, and the corresponding pulse energy is ~63 pJ. Under higher pump powers, the mode locking state was observed to be unstable owing to over heat accumulation on the SA.

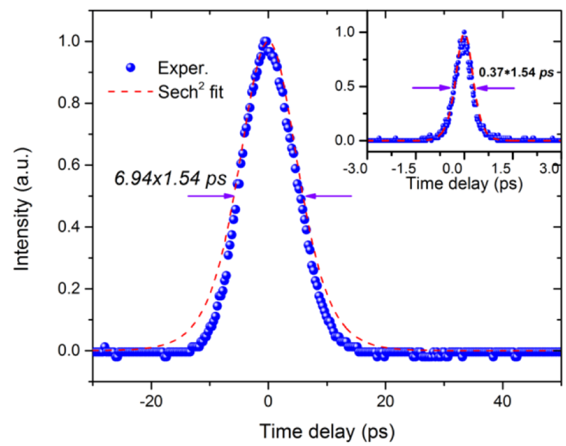

Fig. 5. Autocorrelation trace (AC) of the PM mode-locked fiber laser with and without (inset) the CFBG.

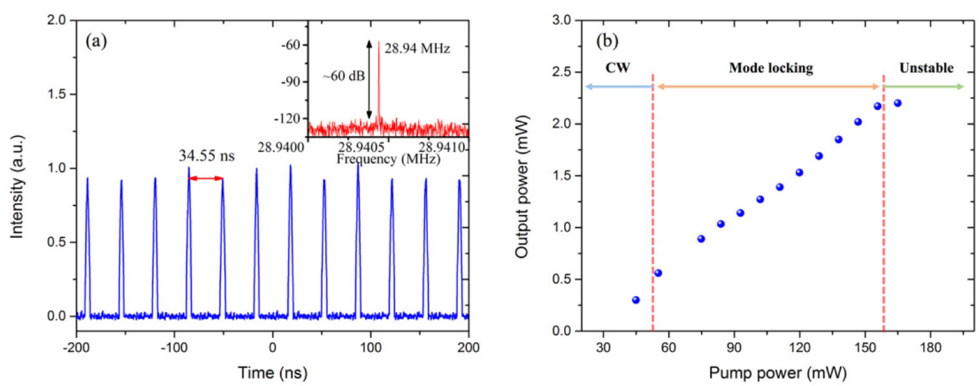

Fig. 6. (a) Pulse train and RF spectrum, and (b) average output power as a function of pump power of the tunable PM mode-locked fiber laser with the CFBG.

Moreover, the polarization property of the PM laser emission was characterized by using a polarimeter (Profile PAT9000). As shown in Fig. 7, the degree of polarization (DOP) is measured to be ~99.5% and well maintained over a long period of time with relatively little variation, confirming the generation of scalar solitons. The corresponding polarization ellipticity varies between −1.5 and −1° over a measurement period of 100 seconds.

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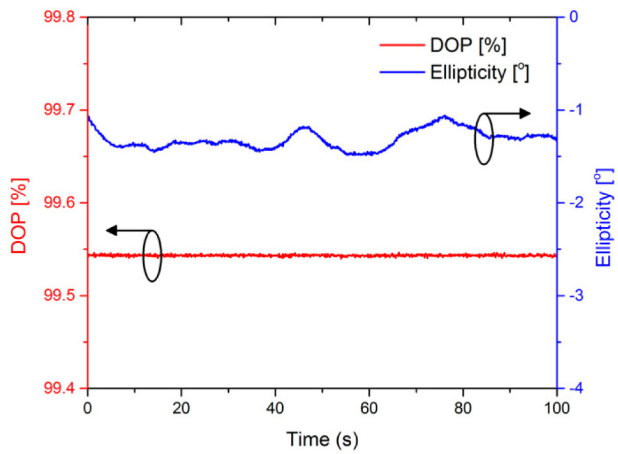

Fig. 7. Measured DOP and polarization ellipticity of the tunable PM mode-locked laser over 100 seconds period.

With pump power of 93 mW, the wavelength of the mode-locked laser was continuously shifted from 1530 to 1537.7 nm by adjusting the cantilever. The limited tuning range of laser wavelength is correlated with the insufficient laser gain at wavelengths shorter than 1530 nm. As shown in Fig. 8(a), the always-on Kelly sidebands mean that the mode locking stability is maintained during the wavelength tuning procedure. The spectrum peak fluctuates a little along with wavelength tuning because of the inhomogeneous gain profile around 1530 nm. The pulse duration and spectral width of the mode-locked pulse as a function of wavelength are plot in Fig. 8(b). The pulse duration varies between 6.5 and 8.8 ps and does not show clear dependence on the lasing wavelength. The corresponding spectral width changes from 0.34 to 0.63 nm, indicating that the pulses are close to the transform limit. Typical AC traces of the mode-locked laser are shown in the inset of Fig. 8(b). In principle, a potential of broader tuning range could be obtained by cascading multiple different CFBGs based on the proposed technique.

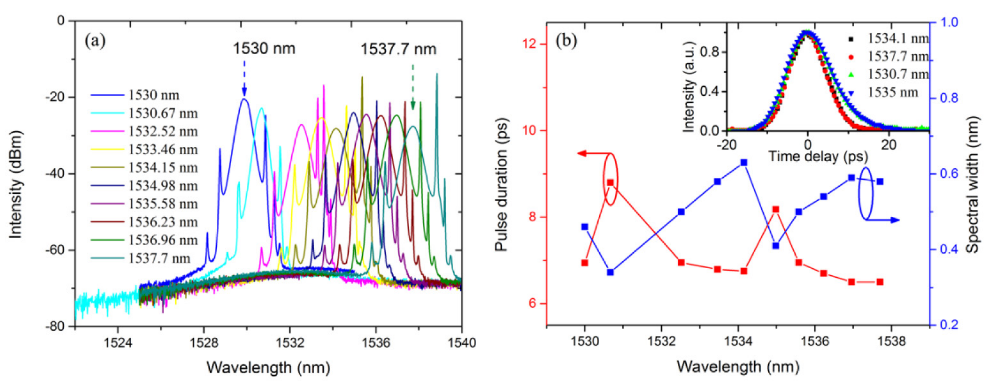

Fig. 8. (a) Continuous spectral evolution and (b) corresponding pulse duration and spectral width as a function of wavelength of the tunable PM mode-locked laser with the CFBG.

4. Conclusions

In conclusion, we have demonstrated a tunable scalar soliton generation in a PM mode-locked fiber laser based on SWCNT and a CFBG. Typical pulse duration is measured to be 6.94 ps with a repetition rate of 28.95 MHz. Linear polarization of laser output is maintained for a long period of time with ~99.5% DOP. The emission wavelength is tuned continuously from

1530 to 1537.7 nm. Such a tunable scalar soliton fiber laser provides an environmentally stable and linearly polarized ultra-short pulsed source for various applications including but not limited to nonlinear frequency conversion.

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