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A Wavelength Switchable Passively Harmonically Mode-locked Fiber Laser with Low Pumping Threshold Using Single-Walled Carbon Nanotubes

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Abstract— We propose and demonstrate a wavelength switchable passively harmonically mode-locked fiber laser with low pumping threshold using single-walled carbon nanotubes (SWCNT). When the pumping power of 980 nm laser diode is 60 mW, passive mode-locking (PML) of a soliton erbium doped fiber laser at the 23rd harmonic of fundamental cavity frequency is experimentally observed at the central wavelength of 1530 nm. By only adjusting the polarization of laser in the cavity, another PML at the 13th harmonic is successfully achieved at 1554 nm. The supermode suppression (SMS) of each wavelength is larger than 30 dB. The pulses at 1530 nm are characterized in details with a repetition rate of 328.44 MHz, a transform-limited pulse width of 1.3 ps, and a timing jitter of 142.6 fs.

Index Terms—Optical fiber laser, ultrafast optics,

I. INTRODUCTION

Generation of ultrashort optical pulses with high repetition rate is a rapidly evolving field including many scientific researches and various applications, such as optical frequency metrology, high-speed optical sampling, and laser ranging. The rare-earth-doped fiber lasers with passive mode-locking (PML) technique are promising systems for fulfilling the requirements due to the inherent properties of fibers including a large spectral gain bandwidth, compact size, and easy maintenance. Through harmonic PML techniques [1-5], the repetition rate of pulsed laser can be significantly increased with respect to its cavity fundamental repetition rate. Various PML techniques, such as nonlinear loop mirror (NOLM) [1], nonlinear polarization rotation (NPR) [5], and semiconductor saturable absorber mirrors (SESAM) [6], have been successfully demonstrated. However, fiber lasers mode-locked with NPR and NOLM will generally not be environmentally stable. Although SESAMs become a popular choice as a mode-locker, it tends to be damaged, perhaps due to the large modulation depth [7]. Recently, carbon nanotube based saturable absorber (CNT-SA) exhibits unique properties of fast saturable absorption and wideband wavelength range [7-9]. While SESAMs have to be fabricated using sophisticated epitaxial technology, CNT-SAs can be manufactured with relatively simple technology and at low cost. On the other hand, when a fiber laser operates in the

anomalous cavity dispersion regime, generally after mode-locking is achieved, soliton shaping of the mode-locked pulses automatically occurs as a result of natural balance between the anomalous cavity dispersion and the fiber nonlinear Kerr effect. Under such condition, it is possible to generate several pulses per cavity round trip with a watt-level pumping source. Recently, a soliton erbium-doped fiber laser (EDFL) operating at the 322nd harmonic of the fundamental cavity frequency has been demonstrated with a pumping power above 2 W using NPR techniques [5]. Besides the repetition rate, it is crucial to obtain high supermode suppression (SMS) together with a low timing jitter. The 31st harmonic PML in an Yb-doped soliton fiber laser has been reported with a SMS of 45 dB and a root-mean-square (RMS) timing jitter of 6 ps [10]. In this paper, we experimentally demonstrate a wavelength-switchable harmonic PML in a soliton EDFL with low pumping threshold using single-walled CNT (SWCNT). To the best of our knowledge, it is the first time that such a wavelength-switchable and stable fiber laser is passively harmonically mode-locked with a low pumping power.

II. EXPERIMENTAL SETUP AND OPERATIONAL PRINCIPLE

Fig.1 Experimental setup of SWCNT-based passively mode-locked fiber laser.

The wavelength switchable SWCNT-based passively mode-locked fiber laser is schematically shown in Fig. 1. It consists of a self-made fiber-connector-type SWCNT saturable absorber, a polarization controller (PC), an EDF, a 980/1550 nm wavelength-division-multiplexer (WDM), and a fused fiber coupler with a 10% output. The polarization-insensitive isolator provides unidirectional operation, while the polarization of laser cavity can be adjusted by the PC. A 980 nm laser diode (LD) is used to provide a pumping power up to 70 mW. An optical spectrum analyzer (OSA) with a resolution of 0.01 nm, a 50-GHz oscilloscope, and a 40 GHz electrical spectrum analyzer (ESA) together with a 40-GHz photodetector are used

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to monitor the laser output. The SWCNT-polyvinyl alcohol (PVA) is plated on the surface of a fiber-connector [11] and operated in transmission-mode to mode-lock a ring cavity laser, as shown in Fig. 1. The highly concentrated EDF (OFS-EDF150) has a length of 1.8 m with a dispersion of -50 ps/nm/km at 1550 nm. The other fibers in the cavity are 1 m dispersion shifted fiber (DSF) with a dispersion of 0.7 ps/nm/km and 11.2 m standard single-mode fiber (SMF) with a dispersion of 17 ps/nm/km at 1550 nm, respectively. The total length of the cavity is 14 m and the net cavity dispersion is anomalous. When the self-started mode-locking is obtained, the soliton operation always exhibits a common feature, namely under strong pumping strength multiple soliton pulses are always generated in the laser cavity, and in the steady state all the solitons have exactly the same pulse properties: the same pulse energy and pulse width. The phenomenon of multiple soliton generation is determined by the response speed of saturable absorber, the peak power clamping effect of the cavity, the birefringence of cavity and the gain competition between multiple solitons together [12]. Thus, harmonic PML can be achieved based on multiple soliton generation. The existence of an artificial comb filter from the birefringence of the cavity, together with the gain profile of EDF, results in a wavelength-switchable lasing [13]. The wideband saturable absorption of the SWCNT further facilitates the self-started mode-locking of the laser. As a result, the emission wavelength of harmonic PML can be switched by adjusting the polarization in the laser cavity.

III. EXPERIMENTAL RESULTS AND DISCUSSION

With appropriate setting of the PC, self-started fundamental mode-locking at 1554 nm is easily achieved when the pumping power is only 12 mW. As shown in Fig.2 (a), there exists a continuous wave (CW) component at 1530nm due to the insufficient pumping power and imperfect state of polarization. After increasing pumping power to 60 mW, the PML operating at the 13th harmonic is observed by monitoring the temporal waveforms. However the CW component, which is experimentally verified with a measured 3 dB spectral width $\Delta \lambda$ less than 0.04 nm, still occurs, as shown in Fig. 2 (a). Then we achieve the fundamental mode-locking at 1554 nm again with the same pumping power. After adjusting the PC, it is experimentally observed that the wavelength of PML is successfully shifted to 1530nm and less residual component appears at 1554 nm. With the pumping power of 12 mW, the average output power of fundamental mode-locking at 1530 nm is 35 μ W, corresponding to 2.45 pJ pulse energy. By increasing the pumping power to 60 mW, PML operation at the 23rd harmonic is observed at 1530 nm, as shown in Fig. 2(b). The average output power of the 23rd harmonic mode-locking is 1.16 mW, corresponding to 3.53 pJ pulse energy. The achieved order of harmonic mode-locking is different under the same pumping power, due to the different soliton energy at each wavelength. The self-started mode-locking is always achieved at the same pumping power level, and immediately after the fundamental mode-locking multiple solitons are formed in the cavity. Fig. 3 (a) shows the temporal waveform of fundamental PML at 1554

nm. The repetition rate of pulses is the fundamental cavity repetition rate, 14.28 MHz, corresponding to the pulse separation of about 70 ns. When the pumping power is increased to 60 mW, the repetition rate of pulses becomes 185.64 MHz, which is 13 times of fundamental cavity

Fig. 2 Optical spectral. (a) 1554 nm, (b) 1530 nm.

Fig. 3 Temporal waveforms of fiber laser. (a) Fundamental PML at 1554nm, (b) Harmonic PML at 1554nm, (c) Fundamental PML at 1530nm, (d) Harmonic PML at 1530nm.

Fig.4 RF spectrum of the output pulse. (a) Fundamental PML at 1554 nm, (b) Harmonic PML at 1554 nm, (c) Fundamental PML at 1530 nm, (d) Harmonic PML at 1530nm.

Fig. 5 Autocorrelation trace and a sech² fitting.

Fig. 6 Phase noise measurement at 328.44 MHz harmonic.

repetition rate, as shown in Fig. 3 (b). At this state, decreasing the pumping power to 12 mW and adjusting the PC, we observe that the fundamental PML shifts to 1530 nm and generates pulse trains with a repetition rate of 14.28 MHz. Further increasing the pumping power to 60 mW and adjusting the PC, 23 solitons with uniform separations are observed, as shown in Fig. 3(d). Thus, the laser is passively mode-locked at the 23rd harmonic with a repetition rate of 328.44 MHz. The passively harmonic mode-locking is self-started with turn-key operation. Usually, the SMS is used to evaluate the passively harmonic mode-locking by analysis of the RF spectrum of the output pulse. The RF spectra of the fundamental mode-locking and the HML at each wavelength are measured, as shown in Fig. 4 (a) and (c) clearly show that the laser emitted at either 1554 nm or 1530 nm is mode-locked at the fundamental repetition rate of 14.28 MHz with a resolution bandwidth of 100 Hz. Meanwhile, the peak at 185.64 MHz of Fig. 4 (b) and 328.44 MHz of Fig. 4 (d), with a resolution bandwidth of 30 kHz clearly demonstrated that the harmonic PML with SMS is larger than 30 dB at each wavelength. Fig. 5 shows the autocorrelation trace of the pulses mode-locked at the 23rd harmonic. A good fit is obtained by using a sech²-pulse profile, yielding a full width at half-maximum (FWHM) of 1.3 ps. Since $\Delta\lambda$ is 3 nm, the time-bandwidth product is 0.316, indicating that the pulses are almost transform-limited. Following the same procedures, the pulse mode-locked at the 13th harmonic at 1554 nm is also transform-limited with a FWHM of 1.0 ps. Using the method given in [9], the average dispersion value of laser cavity at 1530 nm is $-2.65 \text{ ps}^2 / \text{km}$, while the average dispersion value of laser cavity at 1554 nm is $-3.53 \text{ ps}^2 / \text{km}$. Fig. 6 shows the

phase noise of pulses with a repetition rate of 328.44 MHz, measured with signal source analyzer (R&S FSUP26). The timing jitter integrated from 100 Hz to 10 MHz is 142.6 fs.

IV. CONCLUSIONS

We have demonstrated a wavelength-switchable passively harmonically mode-locked fiber laser with low pumping threshold using SWCNT. When the pumping power of 980 nm LD is 60 mW, the fiber laser is passively mode-locked at either the 23rd harmonic at 1530 nm or the 13th harmonic at 1554 nm. The measured SMS of each wavelength is more than 30 dB. The pulses at 1530 nm are characterized with a repetition rate of 328.44 MHz, a transform-limited pulsewidth of 1.3 ps, and a timing jitter of 142.6 fs.

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