Low noise GHz passive harmonic mode-locking of soliton fiber laser using evanescent wave interaction with carbon nanotubes

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Abstract: Passive harmonic mode-locking in soliton fiber laser is presented with excellent noise characteristics by employing a single-walled carbon nanotubes saturable absorber designed to interact with evanescent wave of the laser field. The 34th harmonic mode-locking pulses at 943.16 MHz repetition rate were stably generated with 18 mW output power, >50 dB side-mode suppression and −140 dB/Hz relative intensity noise. Soliton energy control with polarization controller further increased the harmonic order to 61st, 1.692 GHz, but with compromised performance. Scaling to higher-order harmonic mode-locking is discussed for practical application in optical communication system.

OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (160.4330) Nonlinear optical materials.

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1. Introduction

After its introduction 6 decades ago [1], research activities on carbon nanotubes (CNTs) have increased significantly since early 90’s [2] to exploit their unique mechanical, chemical and electronic characteristics [3–5]. More recently, single-walled CNTs (SWCNTs) possessing semiconducting properties [6] have attracted great interests in nonlinear optics applications including optical limiting [7], ultrafast optical switching [8] and saturable absorber (SA) [9]. Particularly, there have been a number of reports on mode-locking in fiber lasers and solid-state lasers using SWCNTs as a SA [9–13] with the advantages of fast recovery time (around 1 ps), wide operation wavelengths (780 nm ~1.9 μm) and easy fabrication compared to the commonly used semiconductor saturable absorber mirror (SESAM). Moreover, evanescent wave interaction of laser light with CNT SA provides higher damage threshold and millimeter-length of nonlinear interaction, scaling up the output power in ultrafast fiber lasers [14–17]. For the evanescent wave interaction, CNT coated onto the half of a tunable directional coupler [18] is easy to fabricate with readily available conventional components and has a robust structure as a stand-alone device.

Passive mode-locking in anomalous dispersion regime of laser cavity has a sech^2 solitonic solution [19]. As the pump power increases, the soliton lasers are known to have a multi-pulsing instability due to the soliton energy quantization and saturable gain [20–25], producing multiple fundamental soliton pulses in one round-trip. The soliton pulses may be bunched, but can also be spaced evenly through the time-dependent gain relaxation process [24] resulting in passive harmonic mode-locking. While typical fiber lasers have tens of MHz repetition rate, its passive harmonic mode-locking can exhibit GHz repetition without extra active modulator. The harmonically mode-locked soliton source can be a potential light source for optical communication and frequency metrology provided that noise performance is satisfactory. Since the first demonstration of this kind of frequency multiplication [20], 1.1 W over 2 GHz from the 95.5 MHz fundamental repetition rate was reported through the nonlinear polarization evolution (NPE) method [22]. More recently, passive harmonic mode-locking of fiber laser using CNT SA was also reported for environmentally stable and self-starting operation compared to the NPE method [23]. However the limited nonlinear interaction of the ferrule-type CNT SA restricts its key performances such as repetition rate

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(328 MHz), output power (1.16 mW) and noise characteristics including super-mode suppression ratio (SMSR).

In this paper, we report GHz passive harmonic mode-locking of a fiber laser with low noise feature using the evanescent wave interaction with CNT SA. Our scheme enabled the fiber laser to deliver the pulses with 943.16 MHz repetition rate (34th harmonics of 27.74 MHz fundamental repetition rate) with the output power of 18 mW. In particular, it shows superior noise feature, for example, the relative intensity noise (RIN) in-between harmonics was the level of -140 dB/Hz with > 50 dB SMSR. When the 8.3 nm-wide (3dB) optical spectrum of the laser output is spectrum-sliced with an arrayed waveguide grating filter (AWG; 80 GHz 3-dB bandwidth for each channel), the output from single channel maintained a similar noise level with the original one due to the nature of phase locking between longitudinal modes in our laser. This opens up the possibility of using the laser for some wavelength division multiplexing (WDM) communication systems such as passive optical networks (PON). We also found the repetition rate could be increased up to 1.692 GHz by fine adjustment of the polarization state of the laser cavity for the same pump power of 195 mW although the stability, noise and spectral performance was compromised.

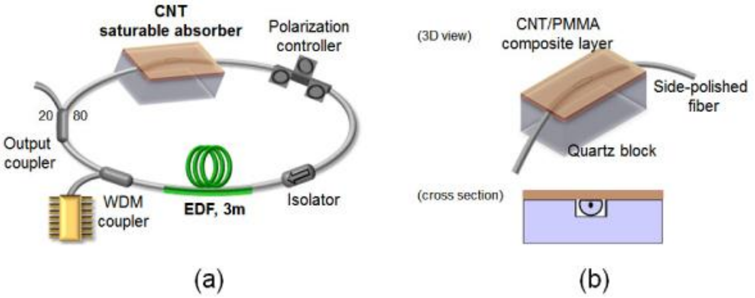

Fig. 1. Schematic of (a) mode-locked fiber laser with CNT SA and (b) CNT SA coated onto the half of a tunable directional coupler for evanescent wave interaction.

2. Experimental setup

Fiber ring laser for passive harmonic mode-locking was built as schematically shown in Fig. 1(a). A 977-nm laser diode pumped 3-m erbium-doped fiber (EDF) having normal dispersion ($D = -20$ ps/nm/km) through a WDM coupler. The EDF had a mode field diameter of 6.1 μm and absorption of 11.9 dB/m at around 980 nm. Polarization-insensitive isolator ensured unidirectional operation of the laser. A fused fiber coupler with a 20% output was positioned after the gain medium section and a polarization controller (PC) was inserted for the adjustment of the cavity birefringence. The CNT SA mode-locker shown in Fig. 1(b) was fabricated by spin-coating the SWCNT/PMMA (Poly-methyl methacrylate) mixture on side-polished fiber as described in Ref. [17]. The side-polished fiber having insertion loss less than 0.1 dB had an index matching oil drop test loss of about 20 dB. The fabricated CNT SA had loss ranging from 4.9 dB to 17 dB depending on polarizations at low intensity [17]. The evanescent wave interaction with the CNT over few-mm-long length makes the SA endure high power laser operation, which enables higher-order harmonic mode-locking for applied higher pump power. The total length of the cavity was about 7.2 m and the net dispersion was estimated to be - 0.0145 ps^2. In the main experiment, the pulse train at low repetition rate was monitored with a photo-detector (1 GHz bandwidth) and an oscilloscope (500 MHz bandwidth). A radio frequency (RF) spectrum analyzer with 1.8 GHz bandwidth was used for the measurement of laser pulse train at the frequency range up to 1.6 GHz. An optical spectrum analyzer (OSA) measured laser output spectrum with 0.05nm resolution.

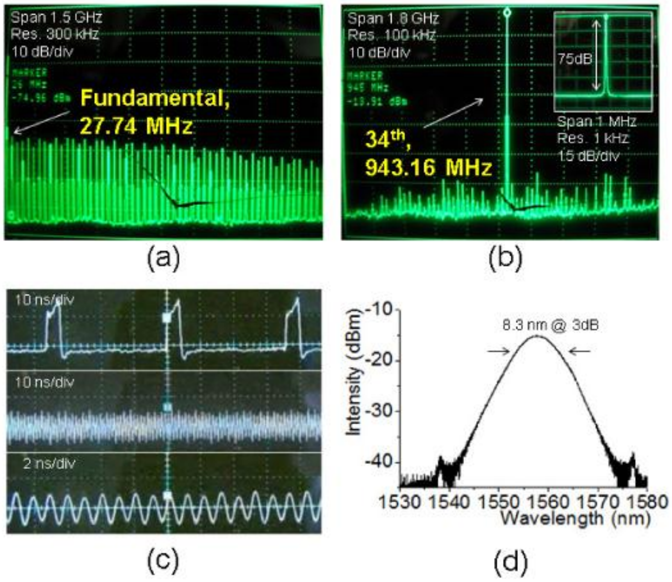

Fig. 2. Output characteristics of the mode-locked pulses. (a) RF spectrum of fundamental mode-locking pulse of 27.74 MHz (b) RF spectrum of 34^{th} harmonic mode-locking of 943.16 MHz and its extended view with 1 MHz span (inset) (c) Oscilloscope (500 MHz bandwidth) signal of two kinds of pulse states at 34^{th} harmonic mode-locking. Bunched pulse state (top), equi-distant state (middle) and its extended view in time scale (bottom). (d) Optical spectrum of the 34^{th}, 943 MHz mode-locked pulse.

3. Experimental results and discussion

Mode-locking of the laser starts from the pump power around 6 mW. Figure 2(a) is the RF spectrum of the mode-locked pulse at the pump power of 7 mW where stable and self-starting laser operation was observed at the fundamental repetition rate of 27.74 MHz corresponding to the cavity length of about 7.2 m. As we increase the pump power, the repetition rate corresponding to the multiple integers of 27.74 MHz was observed in consecutive order. Figure 2(b) shows the RF spectrum of the 34^{th}, 943 MHz harmonically mode-locked pulse when the maximum pump power of 195 mW was applied. The average output power was 18 mW for the given pump power. In the RF spectrum, the background noise was suppressed to about -75 dBc from the RF peak as shown in the inset of Fig. 2(b) where the resolution bandwidth was set to be 1 kHz with 1 MHz span range. The SMSR was larger than 50 dB over 1.8 GHz span as seen in the figure, which is enhanced by 20 dB compared to the previous research [23]. We also observed multi-pulsing instability at 34^{th} harmonic pulse generation. Figure 2(c) shows the signal measured from the oscilloscope with 500 MHz bandwidth. The multiple pulses within a period stably exist as a bunched pulsing state (upper trace in Fig. 2(c)) or equi-distant pulsing state (middle trace in Fig. 2(c)) depending on the settings of the polarization controller in the cavity. The bunched pulse had broadened pulse duration with irregular shape in the oscilloscope measurement and its RF spectrum showed the harmonics of fundamental repetition rate with a periodical envelope. The physical origin of bunched pulse is not clearly understood at present and under investigation. The period of equi-distant pulsing state was about 1 GHz from the extended time scale of the oscilloscope (bottom trace in Fig. 2(c)) though we could not exactly measure the pulse shape due to the limited bandwidth of the oscilloscope. The optical spectrum of the laser output at 34^{th} harmonic mode-locking is shown in Fig. 2(d). The 3-dB spectral bandwidth was 8.3 nm. We measured pulse duration in another experimental set of passively harmonic mode-locked laser, which resulted in a nearly transform-limited time-bandwidth product value of 0.321. The Kelly side-band appeared in the spectrum of Fig. 2(d) also supports solitonic behavior of the laser output. Based on this, the pulse duration of about 320 fs was estimated for our laser. Under the condition of stable harmonic mode-locking, laser operation was maintained for several hours of our experimental measurement without any degradation of laser performance including noise characteristics.

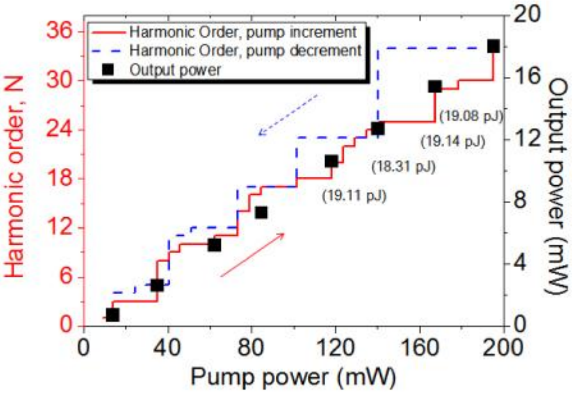

Fig. 3. Hysteresis of the harmonic orders (red line: pump increment, blue dash: pump decrement) and output power (black square dot) as a function of applied pump power.

Figure 3 summarizes the harmonic order and the output power of our laser for a given pump power. As we increase the pump power from 7 mW to 195 mW, the number of fundamental soliton pulses in a period was increased stepwise as shown in the red line of Fig. 3. Output power increment is denoted by the black square dot in Fig. 3 for comparison, which exhibits also nearly linear slope indicating uniform soliton energy generation per pulse for each harmonic mode-locking order. We estimated the energy in each soliton pulse for several cases of 20th, 25th, 29th and 34th harmonic mode-locking, and they came out to be uniform between 18.31 ~19.14 pJ with similar optical spectral characteristics. At a low pump power up to about 50 mW, a few different harmonic orders were distinctively observed, and the data in Fig. 3 are the case of most commonly generated one repeatedly observed. Once a stable multi-pulsing is established, its order is maintained to some extent as we decrease the pump power (blue dash in Fig. 3), resulting in hysteresis phenomena due to the soliton stability [21, 25]. As described so far, the order of harmonic mode-locking is proportional to the pump power, and at present the harmonic order and corresponding repetition rate is limited by the pump power. The pulse rate can continue to increase until the gain material is bleached by the pump power as long as the performance of the CNT SA is guaranteed. Since our CNT SA was previously used for the laser mode-locking with more than 50 mW output [17], we expect several GHz repetition rate can be achieved with a highly doped fiber accompanied by sufficient pump power when cavity dispersion is properly managed.

We also measured the noise characteristics of the laser. Using a 3.5 GHz avalanche photodiode (APD) and a 20 GHz RF spectrum analyzer, the RIN values were measured as shown in Fig. 4. As a reference, the noise property of a separate amplified spontaneous emission (ASE) source was also measured for comparison. In the measurement, the input power to the APD was set to be same in all measured sources. In case of harmonic mode-locking of 943.16 MHz repetition rate, the RIN value was close to the photodiode noise level at around −140 dB/Hz except at the harmonics of the mode-locked frequency while the ASE source filtered by an AWG with wavelength channel width of 80 GHz (3dB) and Gaussian shape exhibited around −110 dB/Hz in the range from 10 MHz to 1.5 GHz. The RIN level of filtered ASE source is degraded compared to that of original ASE spectrum due to the spontaneous-spontaneous beat noise [26]. In order to examine the performance of the harmonically mode locked laser as a spectrum sliced source for WDM applications, we sent the laser signal through the same AWG filter. RIN measurement for the single channel output from the AWG yielded similar results as that of the original laser source shown in Fig. 4(a) because of the phase-locked relationship between longitudinal modes of the mode-locked laser. The noise characteristics in low frequency range are displayed in the inset of Fig. 4(a). The noise level measured within 10 MHz span was less than −120 dB/Hz both for the laser and its filtered light source. This laser source can be suitable for WDM-PON communication system [27]. Finally we found that harmonic order could be further increased by a fine tuning of the PC for a given pump power. Figure 4(b) shows the result of 61st, 1.692 GHz harmonically mode-locked pulse at the pump power of 195 mW. In this case, however, the spectral bandwidth of the laser was reduced to 5.4 nm and the estimated pulse energy was 9.26 pJ. The laser operation is also too sensitive for the polarization state variation to retain long-term stability. There is also some deterioration of RIN level around −120 dB/Hz. We suspect that this behavior originates from polarization-dependent properties of our SA, which might modify fundamental soliton condition of the laser cavity. At present, it is difficult to exactly measure the SA performance that exhibits polarization dependence in our experimental condition. We currently investigate the characterization method of our SA and its optimization condition to achieve higher repetition rate with better noise feature.

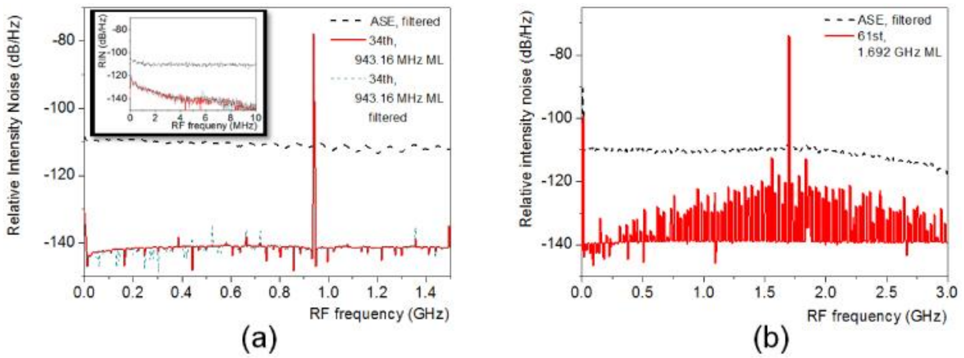

Fig. 4. Relative intensity noise of (a) 34th, 943.16 MHz mode-locked pulse (compared with ASE source) in 1.5 GHz span and 10 MHz span (inset) (b) 61st, 1.692 MHz one in 3 GHz span after the change of PC condition.

4. Conclusion

In summary, we demonstrate passive harmonic mode-locking of soliton fiber laser based on CNT SA interacting with evanescent wave of a laser. With the advantages of high damage threshold and long length of nonlinear interaction in our SA, stable 34th, 943.16 MHz repetition rate and high output power of 18 mW was achieved from the 27.74 MHz fundamental frequency. Side-mode suppression was higher than 50 dB and RIN value was around −140 dB/Hz. Lowered soliton energy through PC adjustment further increased the repetition rate to 61st, 1.692 GHz. The harmonic order can be possibly increased to several GHz with highly doped fiber and sufficient pump power. The outstanding noise performance makes this laser a potential light source for WDM communication systems and frequency metrology.

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