Passively harmonic mode locked erbium doped fiber soliton laser with carbon nanotubes based saturable absorber

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Abstract: We have proposed and demonstrated passive harmonic mode locking of an erbium doped fiber laser with soliton pulse shaping using carbon nanotubes polyvinyl alcohol film. Two types of samples prepared by using filtration and centrifugation were studied. The demonstrated fiber laser can support 10th harmonic order corresponding to 245 MHz repetition rate with an output power of ~12 mW. More importantly, all stable harmonic orders show timing jitter below 10 ps. The output pulses energies are between 25 to 56 pJ. Both samples result in the same central wavelength of output optical spectrum with similar pulse duration of ~1 ps for all harmonic orders. By using the same laser configuration, centrifugated sample exhibits slightly lower pulse chirp.

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

References and links

1. M. E. Fermann and I. Hartl, "Ultrafast fiber laser technology," IEEE J. Sel. Top. Quantum Electron. **15**(1), 191–206 (2009).
2. D. J. Richardson, R. I. Laming, D. N. Payne, M. W. Phillips, and V. J. Matsas, "320 fs soliton generation with passively mode-locked erbium fiber laser," Electron. Lett. **27**(9), 730–732 (1991).
3. A. B. Grudinin, D. J. Richardson, and D. N. Payne, "Passive harmonic modelocking of a fiber soliton ring lasers," Electron. Lett. **29**(21), 1860–1861 (1993).
4. S. Gray, A. B. Grudinin, W. H. Loh, and D. N. Payne, "Femtosecond harmonically mode-locked fiber laser with time jitter below 1 ps," Opt. Lett. **20**(2), 189–191 (1995).
5. A. B. Grudinin and S. Gray, "Passive harmonic mode locking in soliton fiber lasers," J. Opt. Soc. Am. B **14**(1), 144–154 (1997).
6. B. C. Collings, K. Bergman, and W. H. Knox, "Stable multigigahertz pulse-train formation in a short-cavity passively harmonic mode-locked erbium/ytterbium fiber laser," Opt. Lett. **23**(2), 123–125 (1998).
7. F. Amrani, A. Haboucha, M. Salhi, H. Leblond, A. Komarov, P. Grelu, and F. Sanchez, "Passively mode-locked erbium-doped double-clad fiber laser operating at the 322nd harmonic," Opt. Lett. **34**(14), 2120–2122 (2009).
8. Y. C. Chen, N. R. Raravikar, L. S. Schadler, P. M. Ajayan, Y. P. Zhao, T. M. Lu, G. C. Wang, and X. C. Zhang, "Ultrafast optical switching properties of single-wall carbon nanotube polymer composites at 1.55 µm," Appl. Phys. Lett. **81**(6), 975–977 (2002).
9. S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, "Ultrafast fiber pulsed lasers incorporating carbon nanotubes," IEEE J. Sel. Top. Quantum Electron. **10**(1), 137–146 (2004).
10. S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, "Laser mode locking using a saturable absorber incorporating carbon nanotubes," J. Lightwave Technol. **22**(1), 51–56 (2004).
11. A. G. Rozhin, Y. Sakakibara, S. Namiki, M. Tokumoto, H. Kataura, and Y. Achiba, "Sub-200-fs pulsed erbium-doped fiber laser using a carbon nanotube-polyvinylalcohol mode locker," Appl. Phys. Lett. **88**(5), 051118 (2006).
12. F. Shohda, T. Shirato, M. Nakazawa, K. Komatsu, and T. Kaino, "A passively mode-locked femtosecond soliton fiber laser at 1.5 µm with a CNT-doped polycarbonate saturable absorber," Opt. Express **16**(26), 21191–21198 (2008).
13. A. V. Tausenev, E. D. Obraztsova, A. S. Lobach, A. I. Chernov, V. I. Konov, P. G. Kryukov, A. V. Konyashchenko, and E. M. Dianov, "177 fs erbium-doped fiber laser mode locked with a cellulose polymer film containing single-wall carbon nanotubes," Appl. Phys. Lett. **92**(17), 171113 (2008).
14. T. Hasan, Z. P. Sun, F. Q. Wang, F. Bonaccorso, P. H. Tan, A. G. Rozhin, and A. C. Ferrari, "Nanotube-polymer composites for ultrafast photonics," Adv. Mater. **21**(38-39), 3874–3899 (2009).

#165362 - $15.00 USD Received 23 Mar 2012; revised 10 May 2012; accepted 14 May 2012; published 31 May 2012

15. Y. Senoo, N. Nishizawa, Y. Sakakibara, K. Sumimura, E. Itoga, H. Kataura, and K. Itoh, "Polarization-maintaining, high-energy, wavelength-tunable, Er-doped ultrashort pulse fiber laser using carbon-nanotube polyimide film," Opt. Express **17**(22), 20233–20241 (2009).
16. C. Mou, S. Sergeyev, A. Rozhin, and S. Turistyn, "All-fiber polarization locked vector soliton laser using carbon nanotubes," Opt. Lett. **36**(19), 3831–3833 (2011).
17. A. Martinez, S. Uchida, Y. W. Song, T. Ishigure, and S. Yamashita, "Fabrication of Carbon nanotube poly-methyl-methacrylate composites for nonlinear photonic devices," Opt. Express **16**(15), 11337–11343 (2008).
18. F. Shohda, M. Nakazawa, J. Mata, and J. Tsukamoto, "A 113 fs fiber laser operating at 1.56 μm using a cascadable film-type saturable absorber with P3HT-incorporated single-wall carbon nanotubes coated on polyamide," Opt. Express **18**(9), 9712–9721 (2010).
19. Z. Sun, A. G. Rozhin, F. Wang, T. Hasan, D. Popa, W. O'Neill, and A. C. Ferrari, "A compact, high power, ultrafast laser mode-locked by carbon nanotubes," Appl. Phys. Lett. **95**(25), 253102 (2009).
20. F. Wang, A. G. Rozhin, V. Scardaci, Z. Sun, F. Hennrich, I. H. White, W. I. Milne, and A. C. Ferrari, "Wideband-tuneable, nanotube mode-locked, fibre laser," Nat. Nanotechnol. **3**(12), 738–742 (2008).
21. E. J. R. Kelleher, J. C. Travers, Z. Sun, A. G. Rozhin, A. C. Ferrari, S. V. Popov, and J. R. Taylor, "Nanosecond-pulse fiber lasers mode-locked with nanotubes," Appl. Phys. Lett. **95**(11), 111108 (2009).
22. Y. W. Song, S. Yamashita, E. Einarsson, and S. Maruyama, "All-fiber pulsed lasers passively mode locked by transferable vertically aligned carbon nanotube film," Opt. Lett. **32**(11), 1399–1401 (2007).
23. Y. W. Song, S. Yamashita, C. S. Goh, and S. Y. Set, "Carbon nanotube mode lockers with enhanced nonlinearity via evanescent field interaction in D-shaped fibers," Opt. Lett. **32**(2), 148–150 (2007).
24. K. Kieu and M. Mansuripur, "Femtosecond laser pulse generation with a fiber taper embedded in carbon nanotube/polymer composite," Opt. Lett. **32**(15), 2242–2244 (2007).
25. Y. W. Song, K. Morimune, S. Y. Set, and S. Yamashita, "Polarization insensitive all-fiber mode-lockers functioned by carbon nanotubes deposited onto tapered fibers," Appl. Phys. Lett. **90**(2), 021101 (2007).
26. S. Y. Choi, F. Rotermund, H. Jung, K. Oh, and D. I. Yeom, "Femtosecond mode-locked fiber laser employing a hollow optical fiber filled with carbon nanotube dispersion as saturable absorber," Opt. Express **17**(24), 21788–21793 (2009).
27. A. Martinez, K. M. Zhou, I. Bennion, and S. Yamashita, "In-fiber microchannel device filled with a carbon nanotube dispersion for passive mode-lock lasing," Opt. Express **16**(20), 15425–15430 (2008).
28. A. Martinez, K. M. Zhou, I. Bennion, and S. Yamashita, "Passive mode-locked lasing by injecting a carbon nanotube-solution in the core of an optical fiber," Opt. Express **18**(11), 11008–11014 (2010).
29. C. Mou, A. G. Rozhin, R. Arif, K. Zhou, and S. Turitsyn, "Polarization insensitive in-fiber mode-locker based on carbon nanotube with N-methyl-2-pryrrolidone solvent filled fiber microchamber," Appl. Phys. Lett. **100**(10), 101110 (2012).
30. J. W. Nicholson and D. J. DiGiovanni, "High-repetition-frequency low-noise fiber ring lasers mode-locked with carbon nanotubes," IEEE Photon. Technol. Lett. **20**(24), 2123–2125 (2008).
31. A. Martinez and S. Yamashita, "Multi-gigahertz repetition rate passively modelocked fiber lasers using carbon nanotubes," Opt. Express **19**(7), 6155–6163 (2011).
32. L. Yu-Chan, C. Kuang-Nan, and L. Gong-Ru, "Passively harmonic mode-locking of fiber ring laser using a carbon-nanotube embedded PVA saturable absorber," in *OptoeElectronics and Communications Conference (OECC), 2011 16th* (IEEE, 2011), pp. 788–789.
33. K. Jiang, S. N. Fu, P. Shum, and C. L. Lin, "A wavelength-switchable passively harmonically mode-locked fiber laser with low pumping threshold using single-walled carbon nanotubes," IEEE Photon. Technol. Lett. **22**(11), 754–756 (2010).
34. C. S. Jun, J. H. Im, S. H. Yoo, S. Y. Choi, F. Rotermund, D. I. Yeom, and B. Y. Kim, "Low noise GHz passive harmonic mode-locking of soliton fiber laser using evanescent wave interaction with carbon nanotubes," Opt. Express **19**(20), 19775–19780 (2011).
35. S. A. Zhou, D. G. Ouzounov, and F. W. Wise, "Passive harmonic mode-locking of a soliton Yb fiber laser at repetition rates to 1.5 GHz," Opt. Lett. **31**(8), 1041–1043 (2006).
36. A. Komarov, H. Leblond, and F. Sanchez, "Multistability and hysteresis phenomena in passively mode-locked fiber lasers," Phys. Rev. A **71**(5), 053809 (2005).
37. J. N. Kutz, B. C. Collings, K. Bergman, and W. H. Knox, "Stabilized pulse spacing in soliton lasers due to gain depletion and recovery," IEEE J. Quantum Electron. **34**(9), 1749–1757 (1998).

1. Introduction

Short pulse mode locked fiber lasers are useful light sources with advantages including good beam quality, alignment free, efficient heat dissipation and simple configuration [1]. This type of laser with comparable performance to the conventional bulky counterparts has many applications such as material processing, telecommunication, nonlinear science and biomedical research. Typically, fiber lasers operate at repetition rate of the order of tens of megahertz due to the relatively long laser cavity (normally in meters scale). For some applications it is desirable to have high repletion rate fiber lasers for instance, in the fields of telecommunication, spectroscopy and metrology. Passive mode locking has been extensively used and studied to generate ultrashort pulses in fiber lasers. To generate high repetition rate

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pulses in mode locked fiber lasers, one could employ either a short cavity (could be centimeter scale) or harmonic mode locking (HML). Although short cavity fiber laser would provide robust design and compact configuration, they do rely on short piece of high gain fiber which inherently limits the output power of the laser and makes them cumbersome to manipulate. HML, however, removes the difficulty in dealing with centimeter scale fiber devices while maintaining high repetition rate performance. A 10 GHz repetition rate soliton fiber laser was demonstrated based on HML through nonlinear amplifying loop mirror [2]. Nonlinear polarization rotation (NPR) based HML soliton fiber lasers were presented showing subpicosecond timing jitter around 500 MHz repetition rate [3,4]. A hybrid saturable absorber based HML fiber laser was also been studied indicating the possibility of hundreds HML orders at gigahertz rate [5]. Stable 2.6 GHz HML fiber laser using a short piece of high gain fiber with a semiconductor saturable Bragg reflector was reported [6]. A 3 GHz HML double-cladding fiber laser with 54 mW output power has been demonstrated recently using NPR [7].

Recently, single wall carbon nanotubes (CNT) has attracted a lot of attention due to their high optical nonlinearity and fast recovery time as a saturable absorber in a mode locked erbium doped fiber laser (EDFL) [8–10]. Since then, various techniques and configuration have been investigated for CNT mode locker in EDFL. CNT embedded in various kinds of polymer matrix as a mode locker have been extensively studied [11–18] including high power [19], wavelength tunable [20] and pulse duration tunable [21] lasers. Evanescent field interaction with CNT for enhanced nonlinearity in fiber laser mode locking has been reported using either a D-shaped fiber [22,23] or a tapered fiber [24,25]. Furthermore, liquid CNT solvent have been studied as a fiber laser mode locker by employing either a hollow fiber [26] or a optical fiber based microchannel [27–29]. However, all of these CNT mode locked fiber lasers operates at fundamental repetition rate of tens of megahertz. By shortening the cavity length, a 447 MHz repetition rate EDFL was demonstrated [30]. Up to 19 GHz repetition rate was recently achieved by using an extremely short cavity [31]. Moreover, HML of CNT based mode locked fiber laser is less studied. Very recently, CNT embedded polymer film was reported for HML of erbium doped fiber laser [32,33] for hundreds of megahertz repetition rate while evanescent field interaction based CNT mode locker can support 1.69 GHz in an EDFL [34].

In this paper, we report investigation on CNT polyvinyl alcohol (PVA) film based HML of an EDFL using the direct contact method. Based on the different preparation procedure of the CNT PVA samples, we have evaluated the performance of filtrated and centrifugated CNT PVA film in an EDFL for passively HML. The demonstrated laser is able to show stable operation at its 10th harmonic of 245 MHz repetition rate with the output power of ~12 mW. In particular, the filtrated CNT sampled mode locked EDFL shows relatively low timing jitter of below 10 ps at almost all harmonic orders. We have also characterized the time bandwidth products (TBP) of the laser with both samples at all harmonic orders showing pulse chirp properties.

2. CNT sample preparation and characterization

Efficient absorption of CNTs at specific wavelength is determined by the band gap of the specific chiralities of semiconducting single wall CNT_S. We use 0.4 mg of commercial grade CoMoCAT CNTs from SWeNT Inc (SWeNT CG200 Lot#000-0012) with carefully selecting CNTs which exhibit absorption at 1.5 µm region. The CNTs were then dissolved in 10 ml distilled water containing 8 mg of sodium dodecylbenzene sulfonate (from Sigma-Alrich) as surfactant. The solution was then dispersed by ultrasonication using a commercial kit (NanoRuptor, Diagenode) for one hour at 21 kHz and 250 W. 50% of the dispersed solution was then filtrated through a 1 µm glass microfiber filter and the remaining 50% was then subjected to ultracentifugation with Optima Max-XP ultracentifugation (Beckman Coulter) for one hour at 25000 rpm at 17 °C. Both resulting solutions were then mixed with polyvinyl alcohol (PVA) distilled water solution afterwards in the Petri dish separately. CNT PVA film saturable absorbers were then obtained after drying at room temperature in the desiccator chamber for a few days namely F-CNT PVA and C-CNT PVA for the filtration and

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centrifugation processed CNTs respectively. The resultant film thickness is 85 µm and 75 µm for C-CNT PVA and F-CNT PVA individually. The performance of the saturable absorbers is characterized by the absorption spectrum as shown in Fig. 1 through a commercial wide band spectrometer (UV-NIR Perkin Elmer). It can be seen from Fig. 1 that the F-CNT PVA has higher absorption than C-CNT PVA sample. This means that concentration of CNTs is much higher in F-CNT/PVA sample than in C-CNT/PVA sample. As both CNT PVA samples are prepared with random orientation of CNTs, they are expected to have very low polarization dependency. Pronounced absorption peaks at 1.5 µm can be seen in the absorption spectrum for both samples.

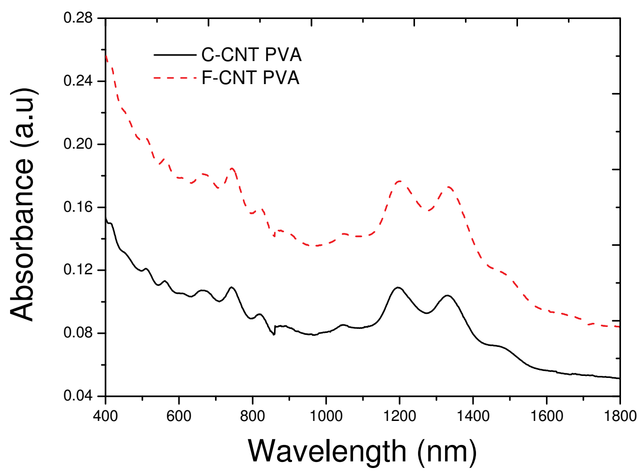

Fig. 1. Absorption spectrum of the CNT PVA sample.

3. Experimental setup

Figure 2 illustrates the schematic configuration of the CNT mode locked EDFL. The EDFL constitutes ~80 cm of highly doped erbium fiber (EDF Er80-8/125 from Liekki) as the active medium, it has a nominal absorption coefficient of 80 dB/m at 1530nm. One fiber pigtailed isolator (OIS) is employed to ensure single direction oscillation of the laser, the laser is forwarded pumped through a grating stabilized 980 nm laser diode (LD) using a 980 nm/1550 nm wavelength division multiplexing (WDM) with a maximum output power of 500 mW. One set of commercial diode laser driver and controller (from Thorlabs) is employed to stabilize the performance of the pump. 50% light is coupled out the laser cavity via a standard fused fiber coupler. An in-line polarization controller (PC) is employed to optimize the intracavity birefringence of the laser cavity. The CNT mode locker was incorporated into the laser cavity via the popular sandwiched structure using two standard fiber connector ferrules, index matching gel (n = 1.452) has been applied between the ferrules to minimize the transmission loss. This pre-packaged saturable absorber is then connected into the laser cavity via fusion splicing to maintain the all fiber configuration. The total length of the laser cavity is ~8.4 m. This corresponds to a fundamental repetition rate of ~24.66 MHz and roundtrip time of ~40.55 ns. The overall cavity dispersion is estimated to be ~ + 16.8 ps/nm/km indicating anomalous dispersion regime and respective soliton pulse formation. The output beam is characterized via a low noise photodetector (Newfocus 1GHz), a high speed sampling oscilloscope (LeCroy Wavepro7Zi, 40Gb/s sampling rate) and an electrical spectrum analyzer (HP8652). The pulse duration is measured by a commercial optical autocorrelator (APE PulseCheck) without any amplification and an optical spectrum analyzer (ANDO AQ6317B) is used to record the optical spectra with 0.05 nm resolution.

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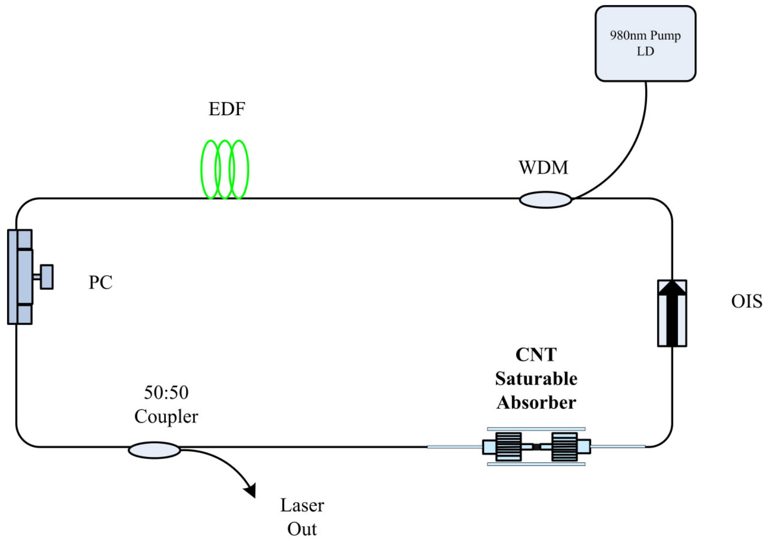

Fig. 2. Schematic configuration of the CNT PVA based HML EDFL.

4. Results and discussion

We first examine the laser behavior with the F-CNT PVA saturable absorber. The laser mode locking self started at the pump power of ~42.5 mW with its fundamental repetition rate of ~24.66 MHz regardless its initial polarization status. The higher threshold compared to some previous results may due to the high gain fiber and higher output coupling ratio [33,34]. As we increase the pump power, the laser repetition rate continues to increase with multiple integers of the fundamental frequency indicating HML. At lower harmonic orders (i.e. 2nd & 3rd), stable pulsing can be found with simply increasing the pump power. For harmonic orders over 3, stable pulsing may be achieved by tuning the PC. Figure 3(a) shows the evolution of the optical spectrum of the laser output from fundamental frequency to the 9th order HML with a bandwidth around ~4 nm and central wavelength of ~1563 nm. The characteristic Kelly side bands can be observed throughout the increase of pump power indicating soliton pulse shaping for all orders of HML. Timing jitter is a critical parameter for HML fiber lasers. In order to characterize the timing jitter, we use the method similar to [35] to perform the measurement. A 3 dB coupler was used to feed 50% of the laser output to another identical photodetector that connected into the second channel of the oscilloscope as data clock. The timing jitter is then calculated by the build-in program of the oscilloscope. The measured timing jitter at 221 MHz, 9th harmonic order is ~4.8 ps. The 9th HML laser is stable at this pump power without any noticeable degradation of performance at the laboratory conditions for several minutes. Figure 3(b) plots the timing jitter and output energy against the harmonic order. In Fig. 3(b), one can see that the timing jitter is below 10 ps for all harmonic orders while the output pulse energies are from 35 to 56 pJ which is higher than the work reported in [33,34]. Figure 3(c) shows the pulse duration and time bandwidth product (TBP) as a function of the harmonic order. It is shown in Fig. 3(c) that at all harmonic orders, the pulses are slightly chirped with the pulse duration of ~1 ps. Figure 3(d) shows the radio frequency (RF) spectrum of the 9th order HML laser pulses with 221 MHz repetition rate at 141 mW pump power. In the RF spectrum, the background noise (SNR) was suppressed by 68 dB while the supermode suppression (SMSR) ratio is ~40 dB. The measured pulse duration is ~0.877 ps with an average output power of ~12.38 mW. This output power is an order of magnitude higher than the previous result [33]. The 3 dB bandwidth of the output optical spectrum is ~3.89 nm indicating a TBP of ~0.41 of the output pulses. This value is slightly higher than the theoretical transform-limited value of 0.32 for soliton pulses showing that the pulse is chirped. For all orders of HML, the measured SMSR from RF spectra are all between

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30 dB and 40 dB. At 156 mW pump power, the laser can operate at its 11th HML but with a higher timing jitter ~27 ps. We have observed multiple pulsing instability when the pump power is further increased. The F-CNT PVA sample also suffers potential thermal damage at pump power level beyond this point due to its polymer nature. Once the stable HML condition is found, we have observed the hysteresis phenomena due to the soliton stability while decreasing the pump power which means the harmonic order is maintained to certain level during the pump power alleviation process [36].

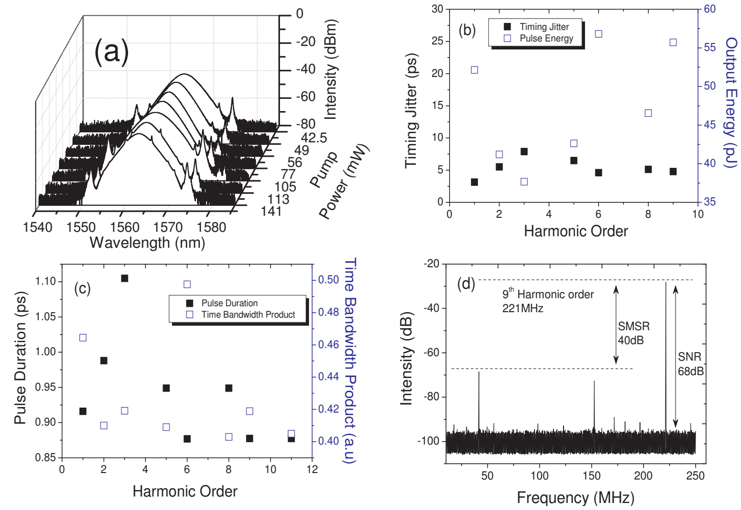

Fig. 3. F-CNT PVA mode locked EDFL (a) Evolution of optical spectrum under different pump power; (b) Measured timing jitter (black solid square) and output energy (blue empty square) against the harmonic order; (c) Measured pulse duration (black solid square) and time bandwidth product (blue empty square) over the harmonic order; (d) Measured RF spectrum of the 9th HML at 221 MHz.

Next we have examined the C-CNT PVA sample for HML in the same EDFL by replacing the F-CNT PVA sample with C-CNT PVA at the end of the fiber ferrule. The laser has shown the same threshold level and fundamental repetition rate. The laser with C-CNT PVA could support a maximum of 10 harmonic orders at the pump power of 141 mW showing a repetition rate of 245 MHz. Figure 4(a) shows the evolution of the optical spectrum of the laser from fundamental frequency to its 10th harmonic order. It describes a similar central wavelength of 1563 nm compared to the laser with F-CNT PVA sample. The SMSR for all harmonic orders with C-CNT PVA is between 39 dB and 49 dB. The timing jitter and output pulse energy against the harmonic order is depicted in Fig. 4(b). Figure 4(b) indicates that with C-CNT PVA sample, the EDFL shows similar timing jitter performance and slightly lower output pulse energy compared to F-CNT PVA sample based laser. One may notice that for the 7th order HML, the timing jitter is ~16 ps, which is much higher than the other harmonic orders. The reason for this is still unknown. In Fig. 4(c), it illustrates the pulse duration and TBP against the harmonic order which shows C-CNT PVA sample based EDFL outputs similar pulse duration with slightly lower chirp. Figure 4(d) shows the RF spectrum of the EDFL at its 9th harmonic order with 221 MHz repetition rate. At 221 MHz repetition rate, the EDFL presents a SMSR of 40 dB with a SNR of 48 dB. Multiple pulsing was also observed when the pump power is over 141 mW for C-CNT PVA sample. Further driving the pump power may induce thermal damage to the CNT sample.

As we described so far, the harmonic order is defined by the pump power and is limited around 10. Following the discussion in [34], the evanescent field based CNT saturable absorber is able to support much higher harmonic orders. However, the CNT polymer films have the advantage of ease of manipulation and low cost. We expect higher repetition rate mode locked by the CNT polymer films could be achieved when the cavity dispersion is properly managed. Moreover, the concentration of CNT may also affect the HML. For both samples, at its maximum harmonic order, the laser is stable for a few mins, this could be because the high pump power damaged the PVA film which cause degradation of the CNT sample. For lower harmonic orders, with both samples, the laser gives stable performance over hours at the laboratory condition.

The principle of harmonic mode locking is still in debate. Grudinin *et al* [5] proposed that acoustic effect plays an effective role in laser harmonic mode locking. Kutz *et al* [37] justified that the gain recovery could dominate the behavior of harmonic mode locking. The exact role of CNT in HML is still under investigation. Future work will address more on the mechanism of HML using CNT. We expect the demonstrated fiber laser can offer an effective platform for studying HML.

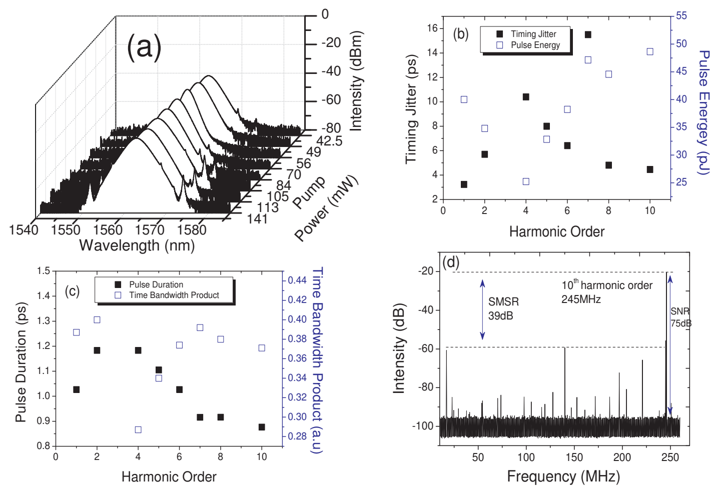

Fig. 4. C-CNT PVA mode locked EDFL (a) Evolution of optical spectrum under different pump power; (b) Measured timing jitter (black solid square) and output energy (blue empty square) against the harmonic order; (c) Measured pulse duration (black solid square) and time bandwidth product (blue empty square) over the harmonic order; (d) Measured RF spectrum of the 9th HML at 245 MHz.

5. Conclusion

In conclusion, we have experimental investigated the centrifugated and filtrated CoMoCAT CNT PVA thin film saturable absorber for HML in an EDFL. The demonstrated EDFL outputs chirped soliton pulses with ~1 ps pulse duration for both types of CNT PVA films. The EDFL shows a maximum of 10th harmonic order operation at 245 MHz with the output power of ~12 mW with the C-CNT PVA saturable absorber which is higher than the previous results using a CNT polymer film mode locker. The timing jitter of the EDFL with both CNT PVA saturable absorbers is measured to be lower than 10 ps. The EDFL also shows higher SMSR ratio then some previous results. Although the absorption for both CNT PVA samples is different, it does not make a huge difference on their performance in HML of EDFL.

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