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SPECIAL TOPIC — Nanophotonics

Observation of 550 MHz passively harmonic mode-locked pulses at L-band in an Er-doped fiber laser using carbon nanotubes film*

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We demonstrate a passively harmonic mode-locked (PHML) fiber laser operating at the L-band using carbon nanotubes polyvinyl alcohol (CNTs-PVA) film. Under suitable pump power and an appropriate setting of the polarization controller (PC), the 54th harmonic pulses at the L-band are generated with the side mode suppression ratio (SMSR) better than 44 dB and a repetition frequency of 503.37 MHz. Further increasing the pump power leads to a higher frequency of 550 MHz with compromised stability of 38.5 dB SMSR. To the best of our knowledge, this is the first demonstration on the generation of L-band PHML pulses from an Er-doped fiber laser based on CNTs.

Keywords: passively harmonic mode locking, L-band, Er-doped fiber laser, carbon nanotubes film

PACS: 42.60.Fc, 42.65.Re, 42.70.–a **DOI:** 10.1088/1674-1056/27/9/094210

1. Introduction

With the widespread application of optical communication systems, the conventional C-band (1530–1565 nm) is unable to meet the ever-increasing requirements for transmission capacity. To alleviate this problem, the L-band (1565–1625 nm) as an extended wavelength range has been proven to be able to enlarge the optical communication capacity, where the silica fibers also feature low loss.[1] Moreover, it is worth noting that some potential applications such as high speed optical sampling, frequency comb generation, and optical communication have a high demand for repetition rate.[2–4] In consequence, exploring the mode locked fiber laser which combines two features of L-band operation and high repetition rate is of great importance.

In general, mode locked operation can be realized either actively or passively. Compared to active mode locking, passive mode locking is more desirable since it offers great merits of compactness, simplicity, stability, and better pulses quality.[5] Nowadays, various technologies have emerged to realize passive mode locking, for instance, the semiconductor saturable absorber mirror (SESAM),[6] nonlinear polarization rotation (NPR),[7] carbon nanotubes (CNTs),[8] and some other novel materials.[9,10] Especially, CNTs are identified as effective mode lockers since they exhibit distinct merits of ultra-short recovery time, easy fabrication, and wide operation wavelength range.[11] Previous studies have been successfully conducted at the L-band with fiber lasers based on CNTs. Sun *et al.* reported an L-band fiber laser firstly by using a carbon nanotubes-polyvinyl alcohol (CNTs-PVA) saturable absorber (SA) with a broad absorption at 1.6 μm.[12] In 2013, a passively mode-locked L-band fiber laser using a 180 cm highly bismuth–erbium-codoped fiber as the gain medium was presented, with a given pulse energy of 440 pJ and a pulse duration of 460 fs.[13] In order to achieve ultra-short pulses in this region, Kwon *et al.* designed a stretched-pulse L-band laser generating 110 fs pulse with a 70 dB signal-to-noise ratio (SNR).[14] However, all of the reports do not concentrate on the repetition rate of the lasers, where the frequency is limited at tens of MHz. Ordinarily, passively harmonic mode-locked (PHML) technology is deemed as one of the most efficient methods to achieve a high repetition rate, where the frequency of the laser can be multiplied when the pump power exceeds a certain value.[15] Nevertheless, there is no report on the generation of PHML pulses operating at L-band from an Er-doped fiber laser using CNTs.

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In general, there are two dominant types of CNTs SAs, namely, CNTs film and evanescent-field interaction CNTs. Compared to the evanescent-field interaction CNTs, the CNTs film possesses inherent advantages of easier fabrication procedure, higher flexibility, and compactness, which can be integrated to the cavity just by being inserted between two fiber connectors.[16] Recently, we have demonstrated that the CNTs film can serve as a practical SA to realize a high repetition rate in C band via HML.[17] In this paper, we demonstrate a PHML fiber laser performing in the L-band based on a CNTs-PVA film. Under advisable pump power and polarization state, 503.37 MHz pulses with a 44.7 dB side mode suppression ratio (SMSR) centered at 1595.54 nm are obtained, which corresponds to the 54th harmonic order. It should be emphasized that the level of SMSR reveals the excellent stability of our laser. When the pump power increases up to 212.8 mW, 550 MHz pulses with 38.5 dB SMSR are further achieved. To the best of our knowledge, such high repetition rate pulses centered at the L-band are first realized from a PHML Er-doped fiber laser using CNTs.

2. Characterization of CNTs-PVA film and experimental setup

Single wall carbon nanotube fabricated by the high-pressure CO (HiPCO) method is used in the experiment. The detailed fabrication procedure of CNTs-PVA film is summarized in Ref. [18]. The resultant CNTs-PVA film is characterized by the absorption spectrum as illustrated in Fig. 1(a). The broad absorption band ranges from 1000 nm to 1900 nm and the absorption strength is close to 0.16 at 1600 nm, which provides the possibility to achieve L-band operation. The measured Raman spectrum with an excitation wavelength of 532 nm is shown in Fig. 1(b), from which we can see that the CNTs-PVA film is single walled, evident by the presence of the radial breathing mode (RBM) and G mode (1588 cm^{-1}). Clearly, the weak D mode manifests few defects of the sample. Moreover, the RBM is equal to 250 cm^{-1} and the calculated mean tube diameter is ~ 0.88 nm. The measured nonlinear transmission is depicted in Fig. 1(c) giving a modulation depth of 6.2%, which provides solid evidence that the CNTs-PVA film can be considered as an effective SA to implement mode locking.

The experimental configuration of the proposed PHML fiber laser based on the CNTs-PVA film is illustrated schematically in Fig. 2. The pump light from a benchtop laser (OV LINK, Wuhan, China) at 980 nm is launched into the ring cavity through a wavelength-division multiplexer (WDM) made of OFS 980 fiber. A section of 8.18 m erbium-doped fiber (EDF Er30-4/125 from Liekki) with the peak absorption of 30 dB/m and a dispersion of $+14.45$ ps^2/km at 1590 nm is adopted as the gain medium to enable L-band lasing. The length of the EDF is much shorter than that used in Ref. [19] taking advantages of the high concentration of the EDF. Also, it is noteworthy that the mode field diameter at 1550 nm is 6.5 ± 0.5 μm, which is capable of introducing high nonlinearity into the cavity. A polarization-independent isolator (PI-ISO) is utilized to transmit the light in a clockwise direction. 10% beam is coupled out via an output coupler (OC) for detection. The optimization of polarization state in the cavity is realized by a polarization controller (PC). A piece of 2 mm×2 mm CNTs-PVA film embedded directly between two standard fiber ferrules is employed as a SA in conjunction with 90% port of the OC. The rest of the cavity is organized by 2.6 m OFS 980 fiber and 11.42 m single mode fiber (SMF). The group velocity dispersion (GVD) coefficients are $+4.5$ ps^2/km and -22.8 ps^2/km, respectively. The total length is 22.35 m and the overall dispersion is -0.13 ps^2, which results in a soliton operation.

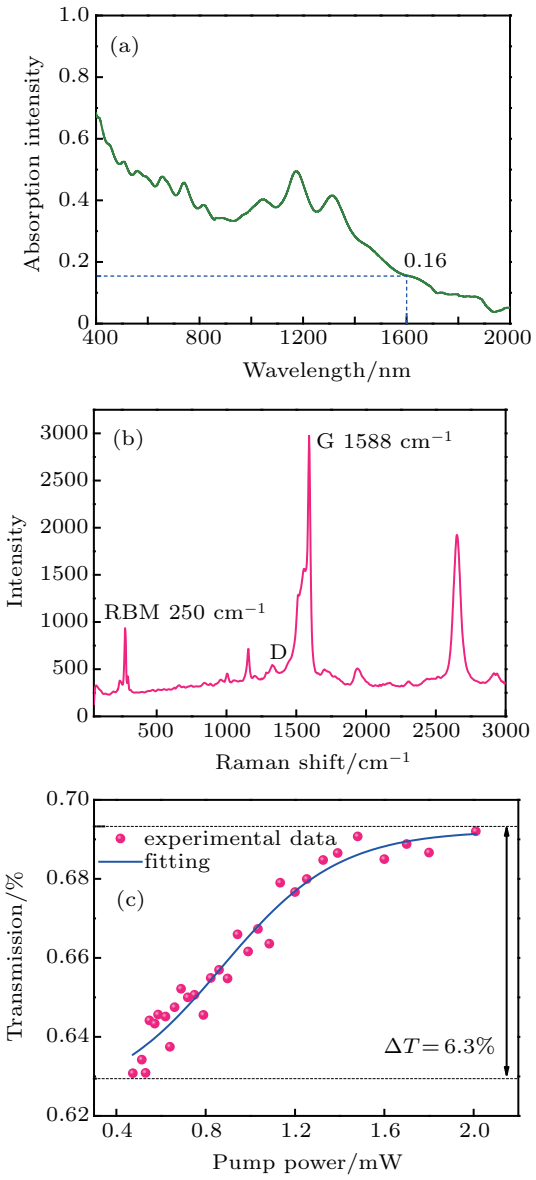


Fig. 1. (color online) The characteristics of CNTs-PVA film: (a) the linear absorption spectrum, (b) the measured Raman spectrum, and (c) the nonlinear transmission.

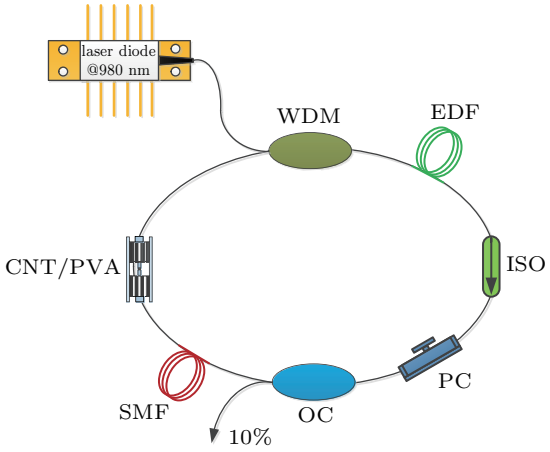


Fig. 2. (color online) Experimental scheme of the PHML fiber laser based on CNTs-PVA film.

The pulse signals can be visualized on an 8 GHz oscilloscope (OSC, KEYSIGHT DSO90804A) together with a 12.5 GHz photo-detector (PD, Newport 818-BB-51F). The radio frequency spectrum is recorded by a radio frequency (RF) spectrum analyzer (SIGLENT, SSA 3032X). The pulse spectrum is characterized by an optical spectrum analyzer (OSA, Yokogawa AQ6370C). Also, an autocorrelator (FEMTOCHROME, FR-103WS) is utilized to measure the pulse duration.

3. Experimental results and discussion

The mode-locked behavior occurs when the pump laser delivers up to 80 mW. However, the stable single pulse operation is hard to realize, no matter how to adjust the polarization state under the weak pump power. We conjecture that the phenomenon comes from the highly nonlinear effect introduced from the longer EDF, which features a high doping concentration and a relatively smaller mode field diameter as mentioned above. When the pump power reaches 92 mW, the 11st HML is implemented eventually with the proper setting of PC. Further increasing of the pump power will lead to a higher harmonic order. When the pump power is set to 202 mW, the laser operates at the harmonic of 54th with 5.35 mW output power, corresponding to a 503.37 MHz repetition rate, as shown in Fig 3. We can see from Fig. 3(a) that the pulses are spaced equally by a 1.99 ns interval with a similar amplitude. The optical spectrum centers at 1595.54 nm, with a 6.28 nm 3-dB bandwidth, as presented in Fig. 3(b). In general, the emitting wavelength of pulses is regulated by the length of the active fiber and the loss of the cavity.[20] Therefore, it is considered that the longer length of the highly doped EDF compared with some conventional C-band lasers[17,21,22] contributes to the in-band absorption which leads to L-band emission.[23] In addition, the existence of the Kelly band makes a clear indication of soliton generation.

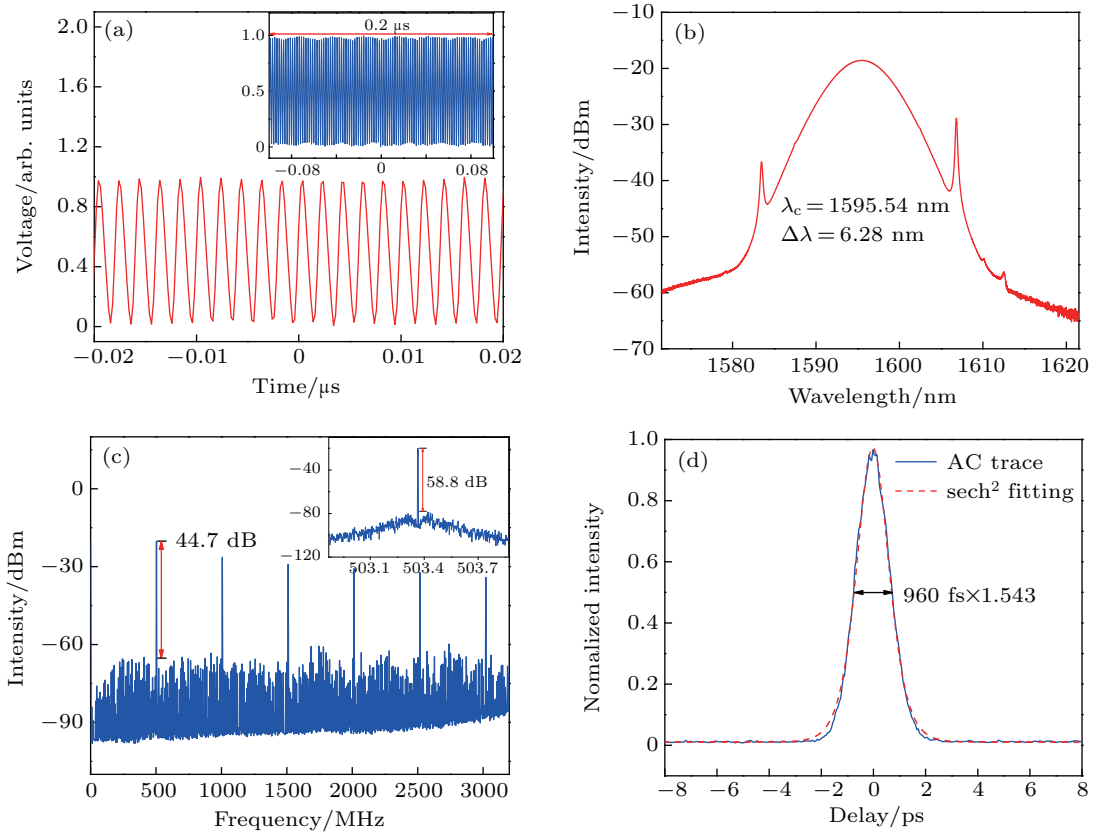


Fig. 3. (color online) The performances of the pulses under 202 mW: (a) pulse train at the 54th harmonic (inset: pulse train with the span of 0.2 μs), (b) optical spectrum centered at 1595.54 nm, (c) RF spectra with 3.2 GHz span and 10 kHz resolution bandwidth (RBW) (inset: RF spectrum within the range of 1 MHz), and (d) the measured autocorrelation trace.

The recorded RF spectra are depicted in Fig. 3(c) with the span of 3.2 GHz and RBW of 1 kHz. It is apparent that the frequency of the first pronounced peak is 503.37 MHz, which can be taken as further evidence of the 503.37 MHz repetition rate. Remarkably, the SMSR is 44.7 dB while the SNR is 58.8 dB shown in the inset of Fig. 3(c), which exhibits improvement over previous PHML operation at the C-band,[21,22] manifesting stable operation. The corresponding pulse duration is 960 fs since the pulses possess a secant hyperbolic profile illustrated in Fig. 3(d). Therefore, the time bandwidth product (TBP) is 0.71, which is higher than 0.315 due to the presence of slight pulse chirp.

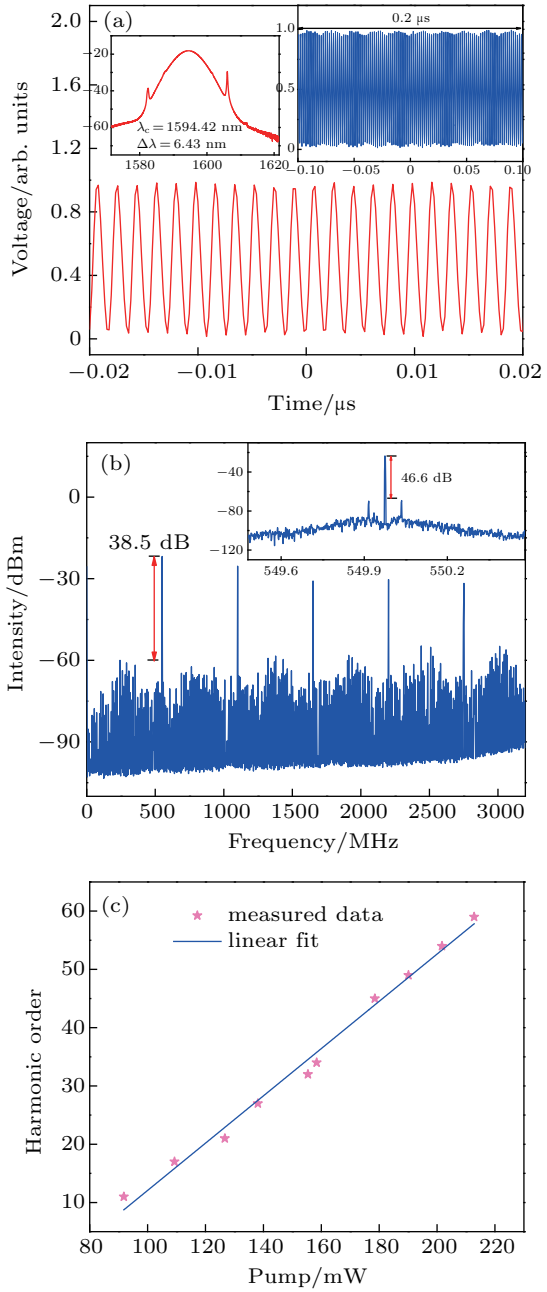


Fig. 4. (color online) (a) The observed pulse train of 550 MHz pulses (insert: the left one is optical spectrum, the right one is the pulse train spanning 0.2 μs), (b) measured RF spectra at 550 MHz (inset: RF spectrum centered in 550 MHz), and (c) harmonic order versus the given pump power.

Additionally, the repetition rate can scale up to 550 MHz at 59th harmonic under 213 mW pump power. From Fig. 4(a), we can see that the pulse train is still orderly aligned and exhibits equal spacing while the spectrum is almost the same as that in Fig. 3(b). Nevertheless, the pulse train shows a relatively small SMSR of 38.5 dB, which still manifests good stability. As described so far, 11st to 59th harmonic orders are found with pump power increasing. The relationship between the two factors is plotted in Fig. 4(c), showing an almost linear slope. Furthermore, it is noted that the value of SMSR stays higher than 44 dB when the harmonic order ranges from 11 to 54, which is much higher than that in Ref. [17], showing superb stability. The pulses are capable of stable operation for several hours once HML occurs. It is worth emphasizing that our laser always works in the L-band region regardless of the harmonic order. Nevertheless, the Q-switched operation appears as the pump power further increases. As a consequence, the pulse energy becomes high enough immediately to damage the CNTs-PVA film-based SA. Enlightened by the experimental results reported in Refs. [24] and [25], we expect to further expand the frequency by optimizing the cavity dispersion and nonlinearity.

4. Conclusion

A PHML fiber laser operating at the L-band based on CNTs-PVA film is experimentally demonstrated. The 54th harmonic pulses at a repetition rate of 503.74 MHz centered at 1595.54 nm with 44.7 dB SMSR are obtained under appropriate polarization status and suitable pump power. The highest recorded repetition rate in our laser is 550 MHz with compromised stability when the pump power increases to 213 mW. To the best of our knowledge, this is the first report about the achievement of HML operation at the L-band in an Er-doped fiber laser using CNTs. The noteworthy stability of the laser is demonstrated by the high level of SMSR. The laser we proposed here features favorable performances for some applications such as L-band optical communication systems, spectroscopy, etc.

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