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Yuanda Ling
Qianqian Huang
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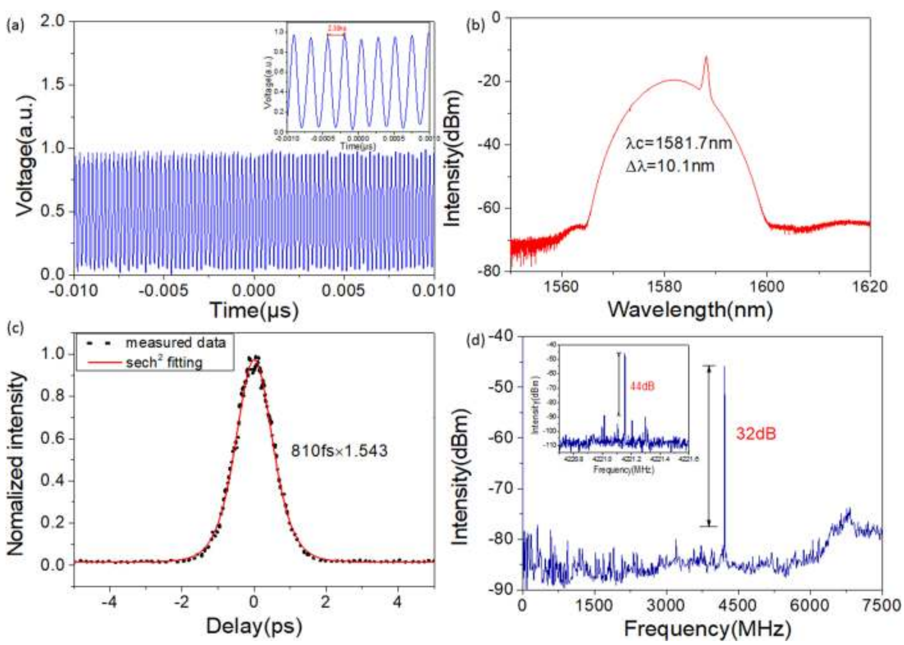
Chengbo Mou



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L-Band GHz Femtosecond Passively Harmonic Mode-Locked Er-Doped Fiber Laser Based on Nonlinear Polarization Rotation

Yuanda Ling, [1] **Qianqian Huang,** [1] **Chuanhang Zou,** [1] **Zhikun Xing,** [2] **Zhijun Yan**, [2] **Chang Zhao,** [1] **Kaiming Zhou,** [3] **Lin Zhang,** [3] **and Chengbo Mou** [1]

[1]Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai Institute for Advanced Communication and Data Science, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai University, Shanghai 200444, China
[2]School of Optical and Electronic Information, National Engineering Laboratory for Next Generation Internet Access System, Huazhong University of Science and Technologies, Wuhan 430074, China
[3]Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, U.K.

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Abstract: Via using an *L*-band optimized in-fiber polarizing grating device, a GHz *L*-band femtosecond passively harmonic mode-locked Er-doped fiber laser based on nonlinear polarization rotation is first demonstrated. In total, 4.22 GHz pulses with the duration of 810 fs and super-mode suppression ratio (SMSR) of 32 dB are obtained under the pump power of 712 mW corresponding to 215th harmonic order. The central wavelength of 4.22 GHz pulses is 1581.7 nm with 10.1 nm 3 dB bandwidth. Furthermore, under this fixed pump power, higher harmonic orders can also be attained by rotating the polarization controllers properly. The highest repetition rate we obtained is 7.41 GHz with the SMSR of 20.7 dB.

Index Terms: Fiber grating, harmonic mode-locking, Er-doped mode-locked fiber laser, nonlinear polarization rotation, L-band.

1. Introduction

High repetition rate ultrafast L-band fiber lasers have been widely concerned in recent years owing to the expansion requirement of the telecommunications window of the conventional C-band. Besides, fiber lasers emitting GHz repetition rate ultrashort pulses at L-band may be widely used in terahertz generation [1], spectroscopy [2], and biomedical diagnostics [3] and extend the applications in high-capacity telecommunication systems [4], optical frequency metrology [5] and high-speed optical sampling [6]. Therefore, GHz repetition rate ultrashort pulses L-band fiber lasers are highly desirable and technically interesting to both the scientific and industrial communities. To date, active mode locking and passive mode locking are two main methods to realize high repetition rate ultrashort pulses. Although active mode locking incorporating an external electro-optic modulator into a cavity is able to achieve GHz repetition rates easily, this method is bulky and the limited response of the external modulator would induce obstacles in attaining femtosecond pulses. Passive mode locking has been widely studied to generate ultrashort pulses with high repetition rates, which could be divided into two major ways including short cavity design and PHML. The reverse scaling of cavity length is an excellent approach to obtain GHz-level fundamental repetition rate pulses but it is highly dependent on the harsh requirement from which a short piece of active fiber should support enough optical gain. Furthermore, thermal control and all-fiber assembly could also induce technical difficulties with such short cavity. Nevertheless, resulting from the intrinsic energy quantization effect [7], [8], PHML with the all-fiber structure capability is able to achieve high repetition rate ultrashort pulse with reasonable signal-to-noise-ratio (SNR) and resolves the difficulty of the dependency on the specialty gain fiber. One key element to achieve effective PHML is the saturable absorber (SA). For example, physical SAs including graphene and carbon nanotubes (CNTs) have been utilized in the generation of L-band HML. In Ref. [9], utilizing few layers graphene as an effective SA, a passively HML fiber laser operating in L-band has been experimentally demonstrated. The harmonic order in this result can be changed from the second to the fourth with a very much limited repetition rate. Meng *et al.* also built up a passively HML Er/Yb co-doped double-clad fiber laser using a graphene SA. 5.88 GHz corresponding to 683rd harmonic order repetition rate was achieved. But the corresponding SMSR at 5.88 GHz is only 19 dB [10]. Recently, 550 MHz L-band HML pulses have been obtained by means of a carbon nanotubes film [11]. It is found that L band HML relies on physical SA could hardly reach GHz repetition rate with $>$30 dB SMSR. This may be partially because the physical SAs were not optimized for L band operation, although the fabrication of nanomaterial-based SA is less complicated than previously. On the other hand, nonlinear polarization rotation (NPR) have been long recognized as an effective SA with clear advantages including wavelength independency, high modulation depth, high thermal damage threshold, fast response time, low cost and compactness. Ultrashort pulse with high repetition rate generated through PHML based on NPR have been extensively examined. Grudinin *et al.* firstly reported the PHML with an Er/Yb co-doped mode locked fiber laser using NPR [12]. A 1.2 GHz PHML Er-doped fiber laser and two types of stabilization mechanisms for HML have been studied in 2007 [13]. Sobon *et al.* obtained 10 GHz HML pulses by utilizing double-clad fiber in an Er/Yb co-doped fiber laser based on NPR [14]. In 2016, Tao *et al.* systematically examined the influence of the dispersion and nonlinearity to HML based on NPR. By managing the dispersion and nonlinearity, 22 GHz repetition rate pulses with up to 40 dB SMSR have been obtained. The output pulse duration is 20.67 ps, and the TBP is 9.79 which indicating heavy chirp [15]. Very recently, a 14.5 GHz PHML in a dispersion compensated Tm-doped fiber laser has been demonstrated by Wang *et al.* [16]. However, an all-fiber L-band PHML laser based on NPR has never been demonstrated.

In this paper, by using NPR with an L-band optimized fiber polarizing component, we built up a GHz L-band femtosecond PHML Er-doped fiber laser. The harmonic orders from 1st to 215th can be obtained by simply increasing the input power from 47 mW to 712 mW corresponding to the mode-locking threshold and the maximum of available pump power, respectively. Under 712 mW pump power, the HML pulses of 215th order corresponding to 4.22 GHz repetition rate, 810 fs pulses centered at 1581.2 nm features a 32 dB SMSR. What's more, higher harmonic orders can be obtained by merely adjusting PCs with the input power fixed. The highest frequency we observed during the experiment is 7.41 GHz corresponding to 378th harmonic order. As far as we know, an L-band HML Er-doped fiber laser based on NPR is reported for the first time. We believe that the demonstrated fiber laser may find potential applications in optical communication systems, optical signal processing, imaging *etc.*

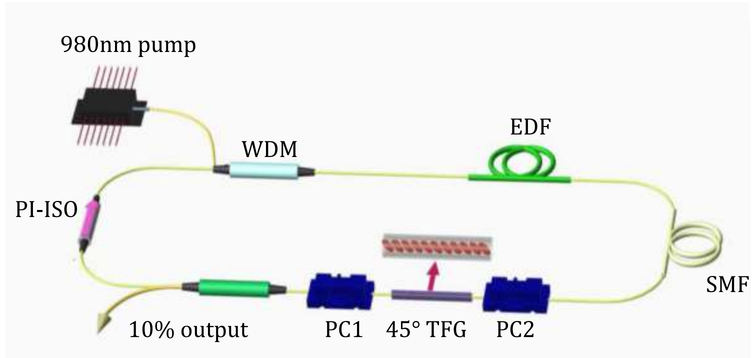

Fig. 1. Schematic configuration of the L-band mode locked Er-doped fiber laser. WDM – 980/1550 nm wavelength division multiplexer; EDF – Er-doped fiber; SMF – single mode fiber; PC – Polarization controller; PI-ISO – Polarization independent isolator; 45° TFG – 45° tilted fiber grating.

2. Experimental Setup

The experimental setup of the L-band HML Er-doped fiber laser is illustrated in Fig. 1. In this cavity, a strand of 178 cm highly-doped Erbium fiber (EDF OFS 80+) serves as the active medium, its peak absorption is about 80 dB/m at 1530 nm with a nominal dispersion of −48 ps/(nm·km) at 1550 nm. A polarization independent isolator (PI-ISO) is necessary for the unidirectionality of the optical path in the cavity. A 980 nm pump source is used to launch pump light into ring cavity via a 980/1550 nm wavelength division multiplexer (WDM). The single mode fiber (SMF) is 866 cm long with the group velocity dispersion (GVD) of −22.8 ps^2/km at 1550 nm. The overall cavity length is 10.52 m matching the fundamental frequency of 19.63 MHz. The net cavity dispersion is −0.08 ps^2 leading to the soliton operation. A SMF-based 45° tilted fiber grating (45° TFG) with $>$30 dB polarization dependent loss (PDL) at L-band region is sandwiched between two polarization controllers (PCs) to realize the NPR mode locking mechanism. It is worth mentioning that the 45° TFG is able to serve as an ideal in-fiber polarizer due to its larger PDL and low insertion loss at the designed band. Besides, the operating wavelength of the 45° TFG can be designed at a specific wavelength with broad bandwidth which is a unique advantage than other types of fiber polarizers. The detailed manufacturing process and the characteristics of 45° TFG can be found elsewhere [17]–[19]. 10% light beams are coupled out via a 90:10 fiber optical coupler (OC) for characteristics detection. The detecting instrument includes an oscilloscope (OSC, KEYSIGHT DSO90804A), an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with 0.05 nm resolution, a radio frequency (RF) spectrum analyzer with the frequency range up to 7500 MHz, a high-speed photodetector (PD, 12.5 GHz bandwidth, Newport 818-BB-51F) and an autocorrelator (FEMTOCHROME, FR-103WS).

3. Results and Discussion

In this experiment, when the pump power sets to 47 mW, stable single soliton operation can be obtained under suitable polarization state. The in-band absorption caused by excessive length of the gain fiber leads to operation of the L-band [20]. Fig. 2(a) shows the measured mode-locked pulse train. The pulse interval is 51 ns indicating a repetition rate of 19.6 MHz, which is consistent with the cavity length. The corresponding L band optical spectrum centered at 1603.31 nm with the 3-dB optical bandwidth of 15.33 nm is presented in Fig. 2(b). Besides, two small Kelly sidebands indicate conventional soliton state in our cavity which is attributed to the small net anomalous dispersion. Fig. 2(c) and 2(d) are measured RF spectra with different resolution bandwidth (RBW). The SNR of 52 dB demonstrates good stability of the pulses, as illustrated in Fig. 2(d). The output power of our laser is measured to be 0.29 mW. It is noted that the pulse duration could not be measured because of insufficient sensitivity of the autocorrelator. When we increase pump power beyond

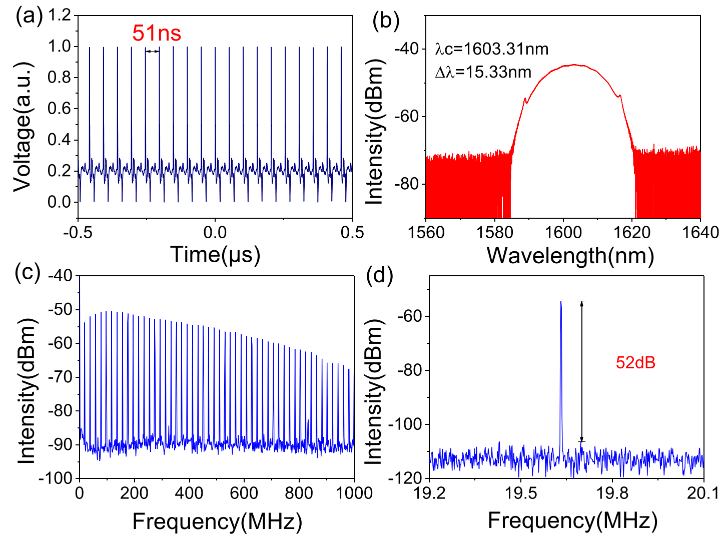

Fig. 2. Characteristics of fundamentally mode locked pulses (a) mode-locked pulse train; (b) Output optical spectrum; (c) wide span of 1000 MHz resolution bandwidth (RBW) and (d) narrow span of 1 MHz (RBW: 1 KHz).

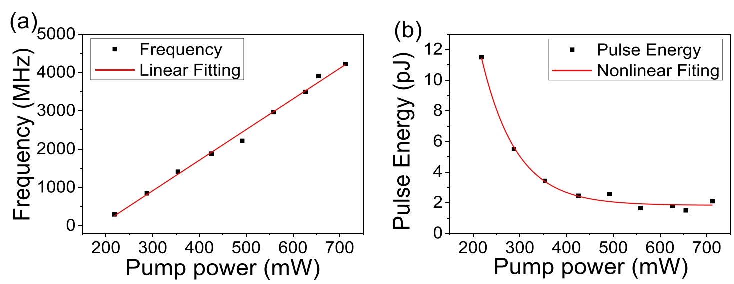

Fig. 3. Pulse trains evolution under different pump power: (a) HML frequency and (b) output pulse energy versus pump power.

218 mW, HML appears by adjusting PCs slightly, and the repetition rate of pulses is proportional to the pump power which is one of the typical behaviors of HML. However, if we set the pump power below 218 mW, no matter how we adjust PCs, HML will not occur which may be due to the lack of nonlinearity in the cavity. Fig. 3(a) shows HML frequency of the output pulses against the pump power from 218 mW to 712 mW. From the linear fitting we estimate the efficiency of repetition rate to pump power is about 7.95 MHz/mW. The measured output pulse energy versus pump power is illustrated in Fig. 3(b), the pulse energy gradually decreased from 11.5 pJ to 1.5 pJ with the pump power elevation. This is also partially in accordance to the soliton area theorem from which lower pulse energy would support higher harmonic order [21].

With the pump power increased to 712 mW, we can obtain stable 4.22 GHz 810 fs pulses with output power of 8.95 mW, corresponding to 215th harmonic order. The characteristics of output pulses are illustrated in Fig. 4. We can identify that the interval of pulses is 0.238 ns from Fig. 4(a). Note that the inset in Fig. 4(a) shows the amplitudes of the stable pulse train on the oscilloscope. From Fig. 4(b), we know that the central wavelength is 1581.7 nm with 10.1 nm 3-dB bandwidth. Besides, the CW component locates apart the top of spectrum which has been proved to be an important cause of stable HML [13], [22], [23]. From Fig. 4(c), it can be seen that the measured pulse duration is 810 fs assuming a secant hyperbolic pulse shape. The corresponding time bandwidth product (TBP) is 0.981 indicating chirp. Here, we should emphasize that at other frequencies below 4.22 GHz, we can also obtain femtoseconds-level output. Fig. 4(d) and the inset are RF spectra

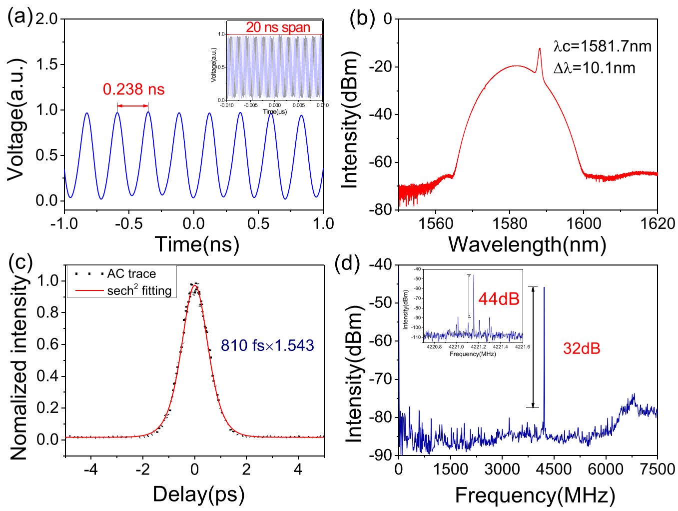

Fig. 4. Measured characteristics of the 4.22 GHz HML pulses (a) oscilloscope trace; (b) corresponding optical spectrum; (c) autocorrelation trace and (d) RF spectrum in 7500 MHz span and inset: RF spectrum in 1 MHz span.

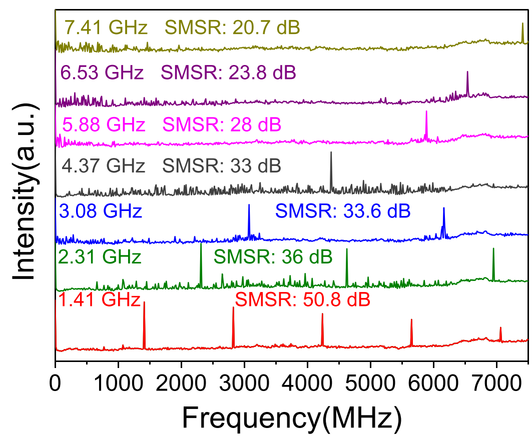

Fig. 5. Different harmonic orders under 712 mW represented by radio frequency spectra.

in 7500 MHz span with 100 kHz resolution and in 1 MHz span with 1 kHz resolution respectively. From Fig. 4(d), we can see that the SMSR is 32 dB and the SNR is 44 dB. Both of these parameters indicate the good stability of the laser. We have to take a note that such stable HML could maintain at least several hours once it occurs.

We can easily find that it is not possible to reach repetition rate beyond 4.22 GHz by simply elevate the pump power because of the available maximum pump power. Meanwhile, when the pump power fixed at the maximum 712 mW, an interesting phenomenon was found that by adjusting PCs carefully, we can obtain a wide range of harmonic mode locking frequencies from 1.4 GHz to 7.41 GHz, as shown in Fig. 5. It can be seen from Fig. 5 that, at 1.41 GHz repetition rate, the SMSR is over 50 dB which can be comparable to some fundamentally mode locked fiber laser. From 2.31 GHz to 4.37 GHz, the SMSR are over 30 dB manifesting a stable status within the PHML fiber laser systems. Above 5 GHz, the SMSRs are observed to be still over 20 dB. The highest achievable repetition rate in this scenario is 7.41 GHz, which corresponding to 378th harmonic order. The SMSR of 7.41 GHz pulses is 20.7 dB which is higher than the previous report of L-band PHML [9]–[11]. From the results, we know this maybe an alternative approach to obtain higher repetition rate when the process of increasing pump power is unavailable. We speculate the observation of different harmonic orders under the fixed pump power is attributed to the NPR defined gain spectral distribution. It is well known that the typical transmission function of NPR induced intracavity comb filter can be described as follows [24], [25]:

$$T = \cos^2\theta_1 \cos^2\theta_2 + \sin^2\theta_1 \sin^2\theta_2 + \frac{1}{2}\sin(2\theta_1)\sin(2\theta_2)\cos(\Delta\varphi_L + \Delta\varphi_{NL}) \quad (1)$$

In this equation, θ_1 and θ_2 are the angles between the polarization direction of the polarizer and the fast axis of the fiber. $\Delta\varphi_L = 2\pi L\,\Delta n/\lambda$ is the linear phase shift, where Δn is fiber birefringence, L is the cavity length and λ is the operating wavelength. $\Delta\varphi_{NL} = 2\pi n_2 PL\,\cos(2\theta_1/\lambda A_{eff})$ is nonlinear phase shift. Here, n_2 is the nonlinear coefficient, P is the input power and A_{eff} is the effective fiber core area. The channel spacing and the amplitude of the comb filter are strongly dependent on the intracavity birefringence. From equation (1) we could deduce that the transmission characteristics are periodically changing with the oscillating wavelength. By rotating PCs in the cavity, the intracavity birefringence can be varied. Consequently, the channel spacing and the amplitude of the filter can be tuned which will have an impact on the gain spectrum. Hence, the circulating intracavity power can be tuned by adjusting the orientation of the PCs appropriately. With respect to the energy quantization effect and the peak power-limiting effect in the cavity, different harmonic orders within an exact range may be obtained according to the birefringence variation. This has also been confirmed experimentally by observing the wavelength shift at each available harmonic order. Besides, we did not observe the condensed soliton phase with large background as described in [26] which may be due to the length of our cavity is not long enough. It is noticed that CW components have been constantly found in HML spectrum, however, the actual relationship between CW and harmonic mode locking performance is still unexplored. Additional characterization of relative intensity noise and timing jitter is under investigation.

4. Conclusions

We have experimentally demonstrated L-band GHz femtosecond passively HML pulses generated from the NPR-based Er-doped fiber laser. The harmonic order from 1st to 215th could be attained linearly as the pump power increases. The maximum stable HML frequency is 4.22 GHz with the SMSR of 32 dB, the corresponding pulse width is 810 fs. In addition, as the pump power fixed at 712 mW, stable HML pulses at other repetition rates are also obtained under different state of polarization by adjusting PCs carefully. The highest repetition rate we obtained is 7.41 GHz with the SMSR of 20.7 dB. Note that the spectra of output pulse trains are in L-band regime once the mode-locked state occurred. As far as we know, this is the first realization of the NPR-based L-band HML Er-doped fiber laser. We show the possibility of L band ultrafast fiber laser with 10 GHz under watts level pump in standard single cladding fiber geometry. Such demonstrated fiber laser has potential applications in many areas, such as L-band optical communication system, terahertz generation and laser ranging *etc*.

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