Multiple pulses and harmonic mode locking from passive mode-locked Ytterbium doped fiber in anomalous dispersion region

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ABSTRACT

In this work, we investigate the passive mode-locked Ytterbium-doped fiber laser based on the nonlinear polarization rotation technique. With the grating pairs inside laser cavity for the GVD compensation, the total cavity dispersion is operated within anomalous dispersion region. As the laser operates at fundamental mode locking, it generates 35 MHz repetition rate mode-locked pulse with 3.3 ps pulsewidth and the optical spectrum reveals obvious Kelly side. After adjusting the waveplate or increase the pump power, the 2nd HML to 6th harmonic mode locking (HML) is demonstrated in this laser. Besides, we also generated the bound states of multiple solitons whose separation of each pulse is about several tens of picosecond. The number of solitons and the separation between sequential pulses could be controlled so that it could be used in optical communication.

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Keywords: Yb-doped fiber, nonlinear polarization evolution (NPE), harmonic mode locking, multiple pulse, bound pulse

1. INTRODUCTION

Passively mode-locked fiber lasers (PMFLs) with ultrashort pulses have attracted much attention because they are compact, robust, and low cost that have been widely used in scientific research and industrial application such as optical communication [1], ultra-fast probing technique [2] and industrial machining [3]. For the generation of robust ultrashort pulse from PMFLs, various saturable absorbers, such as the semiconductor saturable absorber mirror (SESAM) [4], carbon nanotube [5], graphene [6], graphene oxide [7] and various topological insulator like Bi_2Se_3 [8] and Sb_2Te_3 [9], are investigated. Besides, the artificial saturable absorbers like nonlinear amplifying loop mirror (NALM) [10], and nonlinear polarization rotation (NPR) mechanism [11-12] etc., are extensively adopted based on the optical kerr effect. Traditionally, PMFLs are operated at net anomalous dispersion region to create ultrashort pulse below one hundred fs by means of the pulse shaping effect. This technique relies on the positive kerr nonlinearity and negative dispersion compensation; however, the generated highest pulse energy from oscillator is limited. For the purpose of high energy pulse generation, dissipative soliton (DSs) [13] in operation at net normal dispersion [14, 15] and all normal dispersion (ANDi) [16] region provided the other choices. In addition, Lin et al have exhibited the several tens or one hundred nJ pulse from the ANDi PMFLs without additional use of amplifier by the elongation of cavity length [16, 17].

In comparing with the diode pump solid laser [18], relative long single mode fiber inside cavity of PMFL would accumulate serious nonlinearity. Thus, PMFLs have provided a platform for exploiting new kinds of phenomena, including the formation of soliton rain [19], harmonic soliton [2], dark soliton [20], multiple wavelength soliton [21], vector soliton [20], and bound-state soliton [22, 23], and so on. Due to their fundamental importance on the realization of the soliton interaction and fiber laser dynamics, the phenomenon of bound solitons operations and multiple solitons formation have been reported [24, 25]. According to the complex Ginzburg–Landau equation (CGLE), Malomed firstly pointed out that weakly stable two-pulse and multiple bound states of solitons could be formed in laser cavity [26]. Experimentally, the dynamics of bound state solitons has been widely reported in EDFLs based on the various mode-locked mechanisms such as the NPR mechanism around zero dispersion region [27, 28]. Through the NALM technique, the characteristics of bound state solitons in anomalous and normal dispersion regime have also been studied EDFL with a figure eight configuration [29]. In addition, the stable bound solitons operation with 10 GHz repetition rate have been studied by Hsiang et al. using the hybrid frequency modulation harmonic mode-locked technique [30]. In this work, we study the dynamics of pulses in PML YDFL based on the NPR mechanism by operation laser around net anomalous dispersion region. Through proper adjusting of the polarization state at certain pump power, the multiple soliton and harmonic mode locking can be generated.

High-Power, High-Energy, and High-Intensity Laser Technology II, edited by
Joachim Hein, Proc. of SPIE Vol. 9513, 951314 · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2178624

2. EXPERIMENTAL SETUP AND RESULTS

The schematic setup of ring configuration of PML YDFL is shown in Fig. 1 (a). The gain medium is a 40-cm-long ytterbium-doped fiber with the absorption of 280 dB/m at 920 nm and the core diameter of 4 μm that was pumped by a pigtail laser diode with central wavelength around 976 nm through a 980/1060 nm wavelength division multiplexer (WDM). The mode-locked mechanism was based on the nonlinear polarization evolution (NPE) comprising of two quarter wave-plates, one half-waveplate and polarization beam splitter (PBS) cube. Thus, we coupled the light into free space by the one collimator and recollimated back to the fiber using the other collimator. In addition, the dispersion delay line by the two grating pairs with 600 lines/mm groove density was used to induce anomalous dispersion inside laser cavity. With proper set the diffraction distance between two gratings, the total intra-cavity dispersion of laser was set at net-normal dispersion regime. In considering the GVD parameter of HI1060 (approximately 230 fs^2/cm at 1036 nm wavelength) and the dispersion from grating pair, the net dispersion of laser cavity was estimated to be about -0.019 ps^2. An optical isolator was used to ensure uni-directional propagation inside laser cavity and the laser output was taken from the NPE rejection port. Outside laser cavity, we used an 80/20 beam splitter (BS) to separate the laser into two beams. The transmitted light through the BS (20%) was used to measure the autocorrelation trace of the mode-locked pulse by the autocorrelator ((FR-103XL, Femtochrome Research inc.), Fig. 1(b)) and monitored the laser dynamics of the PML YDFL. The time trace of mode-locked pulses was measured by a high-speed photodetector (EOT inc) and visualized through a 2GHz high-speed oscilloscope (200 GHz sampling scope, WaveRunner 620Zi, LeCroy inc. Fig. 1(c)). Besides, we used the optical spectrum analyzer (OSA, AQ-6315E, Ando inc.) to obtain the optical spectrum and pulse repetition rate of mode-locked pulse.

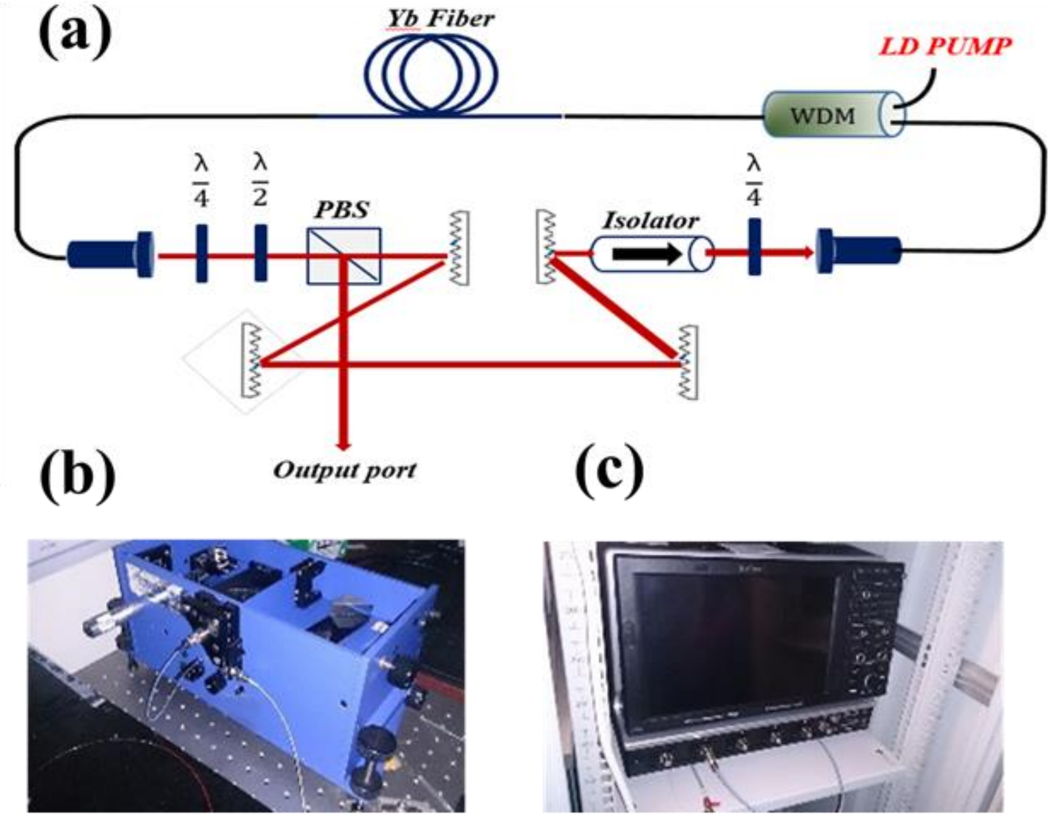

Fig. 1. (a) Schematic setup of PML YDFL (Yb Fiber, ytterbium-doped fiber, $\lambda/4$, quarter-wave plate; $\lambda/2$, half-wave plate; Isolator, ensures uni-direction propagating in the cavity; WDM, wavelength-division multiplexer); (b) the autocorrelator used to measured pulsewidth, and (c) high speed real time oscilloscope.

With appropriate pump power, a robust and stable continuous-wave mode-locked (CW-ML) pulses without pulse splitting or multiple pulses could be generated as shown in Fig. 2. The time trace of single-pulse operation in Fig. 2(a) indicates that the interval of sequential pulse is about 28 ns which correspond to 35 MHz repetition rate. The long-term stability of the PML pulse train without amplitude modulation or fluctuation is shown in the inset of Fig. 2(d). The optical spectrum in Fig. 2(b) illustrates the central wavelength at 1036 nm and obvious Kelly sideband that illustrates the operation of laser is around net anomalous dispersion region. This Kelly sideband is first reported by the Kelly [31] that was attributed to the phase match of the CW with the soliton. Through the autocorrelator, the pulsewidth of the pulse can be measured whose autocorrelation (AC) trace (blue curve) is shown in Fig. 2(d). After fitting by the Gaussian pulse (red curve), the FWHM of pulse is about 4.7 ps that corresponds to the pulsewidth τ_0 about 3.3 ps.

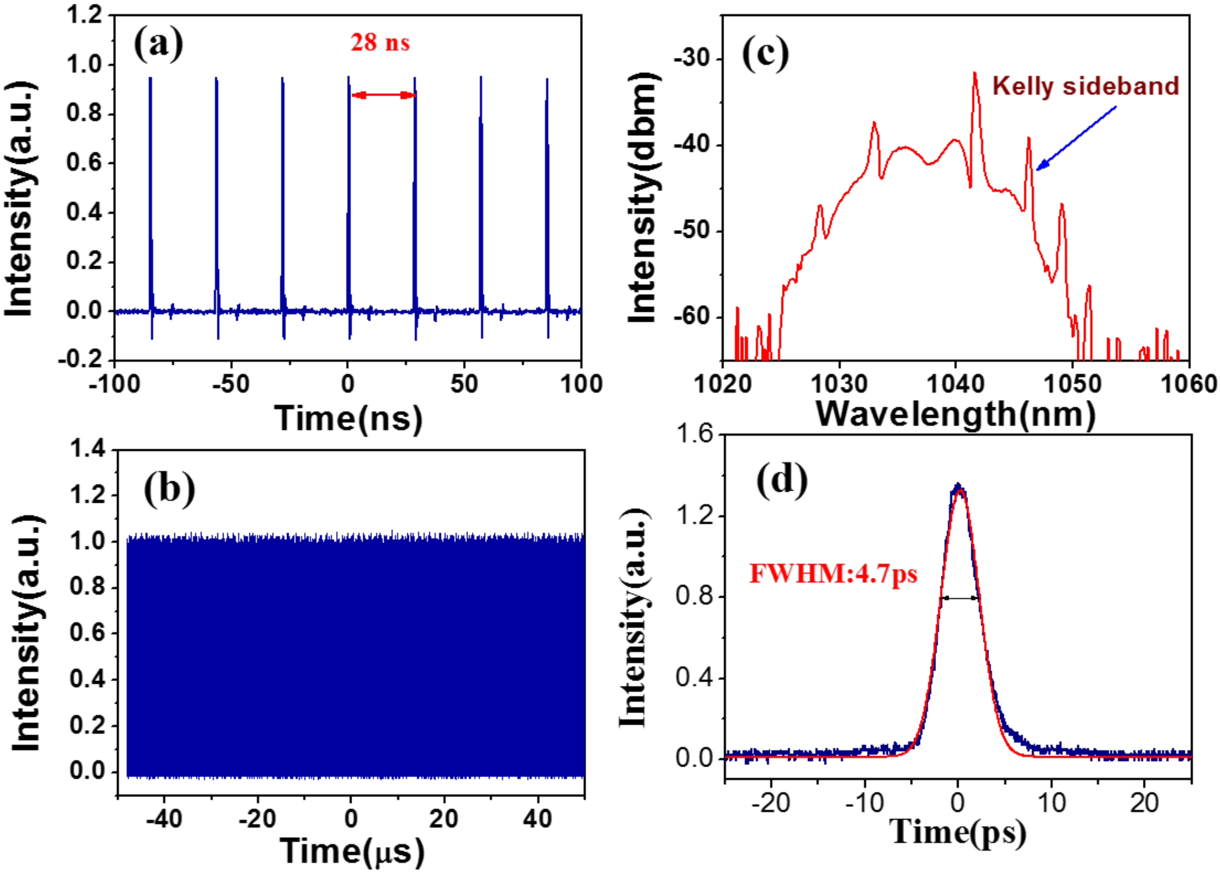

Fig.2 Fundamental mode-locking of the YDFL with (a) time trace measured from oscilloscope, (b) long time operation of mode-locked pulse, (c) optical spectrum and (d) measured AC trace (blue solid curve) and theoretical fitting curve (red solid curve).

In this laser, the harmonic mode-locking (HML) can be experimentally observed when the splitting pulse reveals equal time spacing. The phenomenon of HML has been previously reported in the solid state laser like Cr:YAG [32] and Ti:sapphire laser [33]. An analytic model based on the interaction between the pulses through the transient gain depletion and recovery dynamics in the gain medium [34] was proposed to explain these phenomena. In considering the loss difference into the gain dynamics, we recognize that gain depletion and recovery mechanisms are responsible for the underlying physics of multiple pulses with unequally time spacing around nanosecond [33]. Figures 3(a), 3(c) and 3(e) reveal the time trace of the 2nd, 3rd, and 6th order harmonic mode locking in which the time interval between adjacent pulses become one-half (14 ns), one third (9.4 ns) and one sixth (4.7 ns) of the fundamental mode-locked pulse. In addition, the corresponding AC trace are shown in Figs. 3(b), 3(d) and 3(f) that indicate the FWHM of the pulsewidth are 5.7 ps, 4.7 ps and 8.9 ps, respectively.

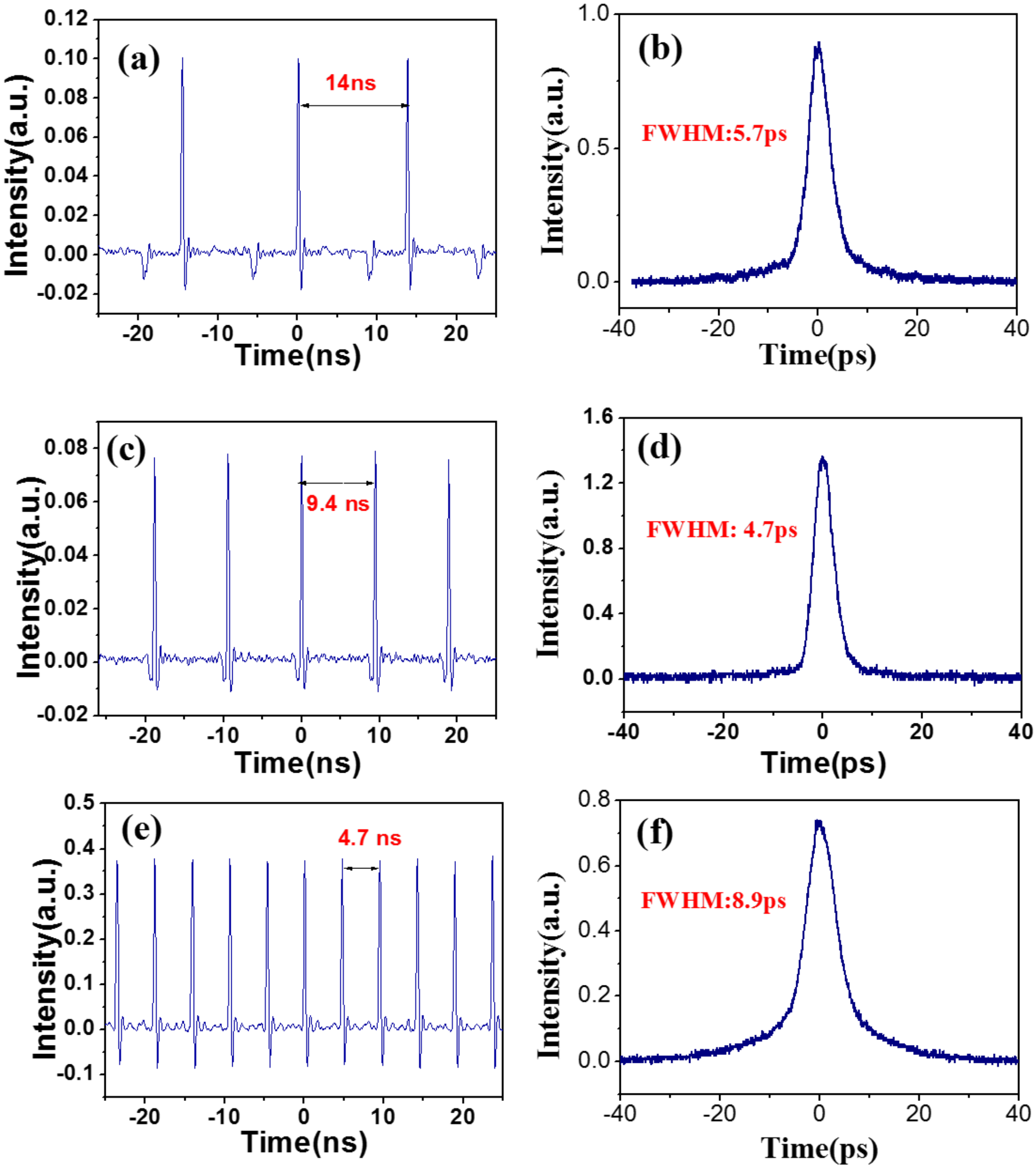

Fig.3 Time trace of the YDFL at (a) 2nd, (c) 3rd, and (e) 6th HML state, and the corresponding AC trace at (b) 2nd, (d) 3rd, and (f) 6th HML state.

At certain polarization state, bound state of multiple soliton is generated from YDDL within anomalous dispersion region. At this state, multiple pulses are generated with relative short splitting time that can only be measured from the autocorrelator. Figures 4 (a), 4(c), and 4(e) reveal the AC trace for the bound state of the double, triple and quadruple soliton where the splitting pulses are around several tens of picosecond. Owing to the resolution of the equipment, the measured time trace from the oscilloscope is similar to that from the fundamental mode-locking state as shown in Fig. 2(a). The time spacing between bound soliton are around 65 ps, 50 ps and 25 ps, respectively, as shown in Figs. 4(a), 4(c) and 4(e). We can also observe the occurrence of the Kelly sideband on the corresponding spectrum as shown in Figs. 4(b), 4(d) and 4(f), respectively, that demonstrates the net GVD of the laser is around anomalous dispersion region.

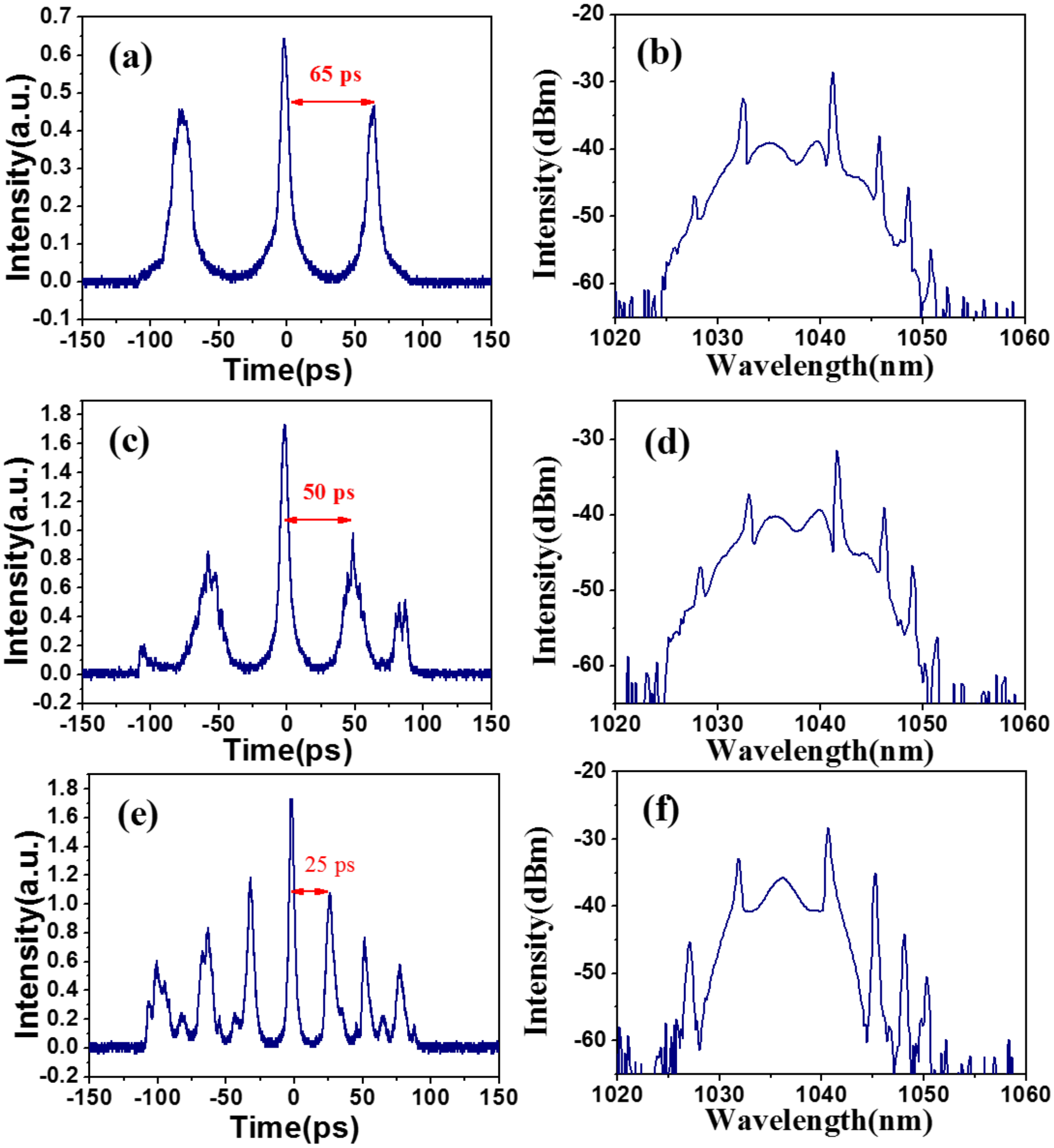

Fig.4 The measured AC trace for the bound state of (a) double soliton, (c) triple soliton, and (e) quadruple soliton and corresponding spectrum for the bound state of (b) double soliton, (d) triple soliton, and (f) quadruple soliton.

3. CONCLUSION

In this work, harmonic mode-locking and bound states of multiple solitons were investigated in ring cavity configuration Ytterbium-doped fiber laser based on the nonlinear polarization evolution (NPE) using half-waveplate and quarter-waveplate in free space. By adding the two grating pairs with 600 lines/mm groove density inside laser cavity for the group velocity dispersion, the total cavity dispersion of laser was operated within anomalous dispersion region. With proper cavity optimization, the fundamental ML with the 35 MHz repetition rate and 3.3 ps pulsewidth was produced whose optical spectrum reveals the Kelly sideband. After adjusting of the waveplate or increase the pump power, the harmonic mode locking was generated that revealed the multiple pulses with equal time interval between sequential pulses. In our laser, the 6th HML with the 210 MHz pulse repletion rate can be measured whose time interval between pulses about 4.7 ns. Besides, we also demonstrated the bound state of multiple solitons whose pulse separation between two pulses about several tens of picosecond. At certain pump power and polarization adjustment, the number of solitons and the pulse separation could be controlled and can be used in optical communication.

ACKNOWLEDGMENT

This work is financially sponsored by National Science Council in Taiwan, R.O.C., under the grand no. NSC 102-2112-M-027-001-MY3 and 102-2112-M-009 -016 -MY3

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