Experimental observations of separation-changeable soliton pairs in a fiber laser mode-locked by nonlinear polarization rotation technique

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The soliton pairs with changeable temporal separation in a passively mode-locked fiber laser are investigated experimentally. Temporal separations of pulses are as large as tens of nanoseconds, which are almost four orders of magnitudes larger than the pulse duration. The mechanism of the changeable separation mainly attributes to the variation of the linear phase delay in the cavity. Soliton pairs with large temporal separations and their variable characteristics are different from the operation of typical harmonic or bound state of solitons. These novel states in this report can be considered as the quasi-bound states.

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1. Introduction

Passively mode-locked erbium-doped fiber ring laser based on nonlinear polarization rotation (NPR) technique has been intensively investigated in last decades [1-4]. It can generate one or more pulses per round trip. By choosing suitable pulse duration and wavelength, it has the potential application as sources in the time-division-multiplexing (TDM) system or wavelength-division-multiplexing (WDM) system or some other fields [5, 6]. Various soliton pulses have been investigated recently [7-11]. Multi-pulse operations have been reported by using Ti: sapphire laser [12-14]. They have also been observed in the passively mode-locked ring fiber lasers [15]. Experimental studies revealed that the dual-soliton has the exactly the same features as those reported for the single-pulse soliton. Generation of widely separated bound pulses with 1300 pulse widths in Yb-doped double clad fiber laser has been investigated [16]. Relative phase locking has been observed in bunches of N pulses separated by more than 20 pulse widths in a passively mode-locked fiber ring laser [17]. Besides, harmonic mode-locked fiber lasers have been reported [18-20]. When the pump power is lower, the mode-locked fiber laser can operate in the fundamental frequency. While by promoting the pump power to a little higher level and adjusting the polarization controllers (PCs), it is possible to form a state of multiple soliton pulses with equal separations in the cavity. The soliton pulse repetition rate is several times more than the cavity fundamental repetition rate. However, we give the experimental observation of the novel dual-soliton states whose temporal separation can be varied. The temporal separation is much larger than the soliton duration. This is the intrinsic character of the passively mode locked fiber lasers.

In this paper, NPR technique is employed to investigate the separation-changeable solitons pairs in the passively mode-locked fiber laser. We can obtain the state of two pulses with fixed temporal separation of 0.8 ns and 10 ns, which are almost four orders of magnitudes larger than the pulse duration. Soliton pairs with large temporal separations and their variable characteristics are different from the operation of typical harmonic or bound state of solitons. The interaction of the soliton is varied by changing the phase delay in the cavity. These novel states in this report can be considered as the quasi-bound states.

2. Experimental setup

The setup of the proposed fiber ring laser is shown in Fig. 1. A piece of 5.5 m Erbium-doped fiber (EDF) with group velocity dispersion (GVD) of -42 ps/nm/km is used as the gain medium. The other fibers in the cavity are single-mode fiber (SMF) with GVD of 17 ps/nm/km at 1550 nm. The total length of the cavity is 20.5 m with the net cavity dispersion of -0.0306 ps^2. A polarization dependent isolator (PD-ISO) is used to force the unidirectional operation of the ring and generate the linear polarization light in the cavity. A 70:30 fiber coupler is used to extract the output laser through its 30% port. The laser is pumped by a 980 nm laser diode with the maximum power of 300 mW. The fiber laser also consists of other passive components such as a 980/1550 nm wavelength-division multiplexer coupler (WDM) and two polarization controllers (PCs). An optical spectrum analyzer (Yokogawa AQ-6370) and an 11-GHz oscilloscope (LeCroy SDA) together with a 12-GHz photo-detector are used to monitor the spectral and the temporal evolution of the laser output, respectively. A RF spectrum analyzer (Agilent E4447A) is used to measure the RF spectrum. The pulse characteristic is monitored by an autocorrelator.

NPR technique is utilized to achieve mode-locking. Because of self- and cross-phase shifts imposed on the two orthogonal polarization components, the polarization state evolves nonlinearly as a pulse propagates along the fiber. The PCs together with the PS-ISO let the central intense part of the pulse pass but blocks the low-intensity pulse wings. As the pulses propagating in the cavity, stable mode locking is obtained [21].

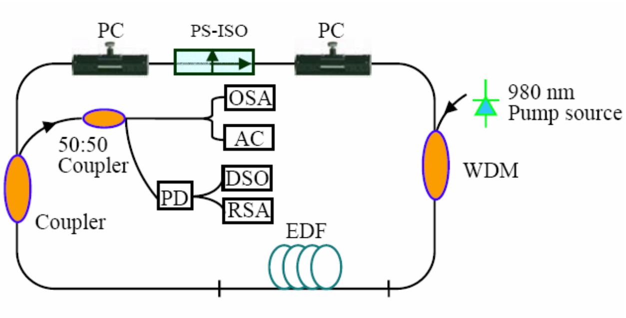

Fig. 1. Schematic diagram of the passively mode-locked ring fiber laser. PC: Polarization controller; WDM: Wavelength-division multiplexer; EDF: Erbium doped fiber; PS-ISO: Polarization sensitive isolator; PD: Photodetector; OSA: Optical spectrum analyzer; DSO: Digital storage oscilloscope; RSA: Radio frequency spectrum analyzer; AC: Autocorrelator.

3. Experimental results and discussion

When the pump power is about 8.35 mW, the proposed passively mode-locked fiber laser can operate in the fundamental cavity frequency state which is about 10 MHz corresponding to the cavity length of 20.5 m. The pulse can easily break when the pump power increases. Extra Pump strengths will lead to the pulse-break. Dual-pulse can be obtained when the pump power increase to about 10 mW. By promoting the pump power, three or more pulse will be got in our experiment. Because of the hysteresis effect [22, 23], the fiber laser can still maintain the mode-locking until the pump power is decreased less than 6.5 mW. The typical optical spectrum is shown in Fig. 2(a) when the pump power is about 8.35 mW. We can see that the 3-dB width of the optical spectrum is 7.5 nm. There are several pairs of spectral sidebands resulting from the interference between linear dispersive waves and the soliton waves. As the soliton circling in the cavity, a part of the energy leaves the cavity at the output coupler and constitutes a loss. The energy builds up to its original value after the pulse is amplified in the active fiber per round trip.

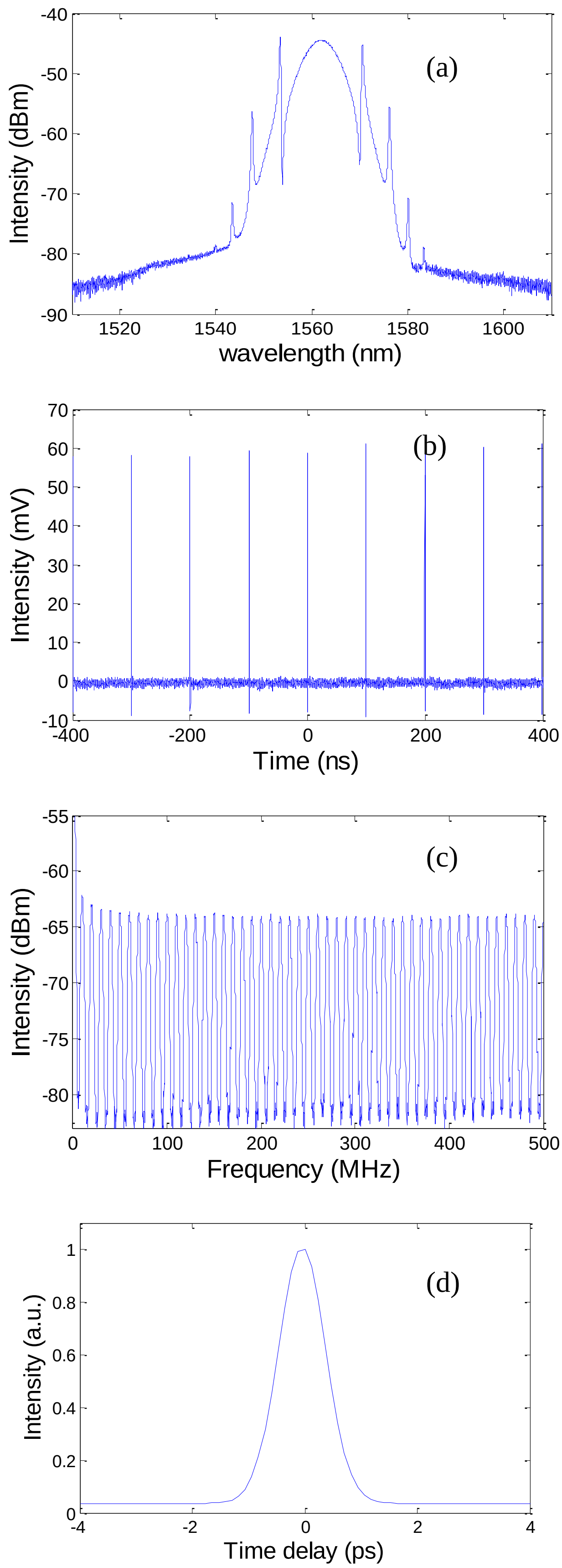

Fig. 2. (a) Optical spectrum, (b) Oscilloscope trace, (c) RF spectrum, and (d) Autocorrelation trace at the fundamental cavity frequency state.

The periodical vibration of soliton energy and the peak power amount to creating a nonlinear-index grating. The solitons adjust to perturbations by shading a part of their energy in the form of dispersive waves. Due to the periodic perturbations, dispersion wave of certain frequencies can be resonantly enhanced, leading to the spectral sidebands. The generation of the sidebands can be explained by the constructive interference condition. If the phase difference between the dispersion wave and the soliton satisfies the multiple of 2π per round trip, the intensity of dispersion wave grows on. As a result, the sidebands are observed form the spectrum [21].

The corresponding oscilloscope trace and the RF spectrum for pump power of 8.35 mW are shown in Figs. 2(b)-(c), respectively. The round-trip time of the cavity is about 100 ns corresponding to 10 MHz in the RF spectrum. Figure 2(d) shows the autocorrelation trace with the pulse duration of about 658 fs (A sech^2 pulse profile is assumed). The time-bandwidth-product (TBP) is about 0.633 which is a little larger than transform-limited. Because the errors always appear in the experimental, it is difficult to get pulses which are truly the transform-limited.

By carefully adjusting the PCs and promoting the pump power, the stable two pulses operation with separation of 0.8 ns is achieved. The pump power is about 10.52 mW. Figure 3(a) shows the typical optical spectrum with the center wavelength of about 1560 nm. The corresponding oscilloscope trace in multi-period and a pair of pulses state shows in Fig. 3(b). Fig. 3(c), (d) show the corresponding RF spectra in different spans of dual-pulse with the temporal separation of about 0.8 ns. The intensity of each pulse in the frequency domain is almost equal to each other, when the span is about 100 MHz. When the span of the RF spectrum analyzer is larger, the profile of the RF spectrum is not flat and becomes periodical variation as shown in Fig. 4(d). The minimum intensity can reach the lowest part. The period of envelope is 1.25 GHz corresponding to the temporal separation of about 0.8 ns in the temporal domain.

In the experiment, the temporal separation of the dual-pulse is not changed continuously by adjusting the PCs. The dual pulses in other temporal separation are not stable. And the generated pulse is moving far away from the first pulse, if we change the PC in certain polarization state. We can only get some discrete stable dual soliton pulses states such as the temporal separation of 0.8-ns, and 10-ns states. Through adjusting the PCs, the generate pulse is continuously move from 0.8 ns to 10 ns. The pulses states of 0.8-ns separations are more stable compared with the states of 10-ns separations. The temporal separation of the two pulses can be changed of about 10 ns which are much larger than the pulse duration. The corresponding optical spectra, oscilloscope trace, and the RF spectra are recorded, as shown in Figs 4(a)-(c), respectively.

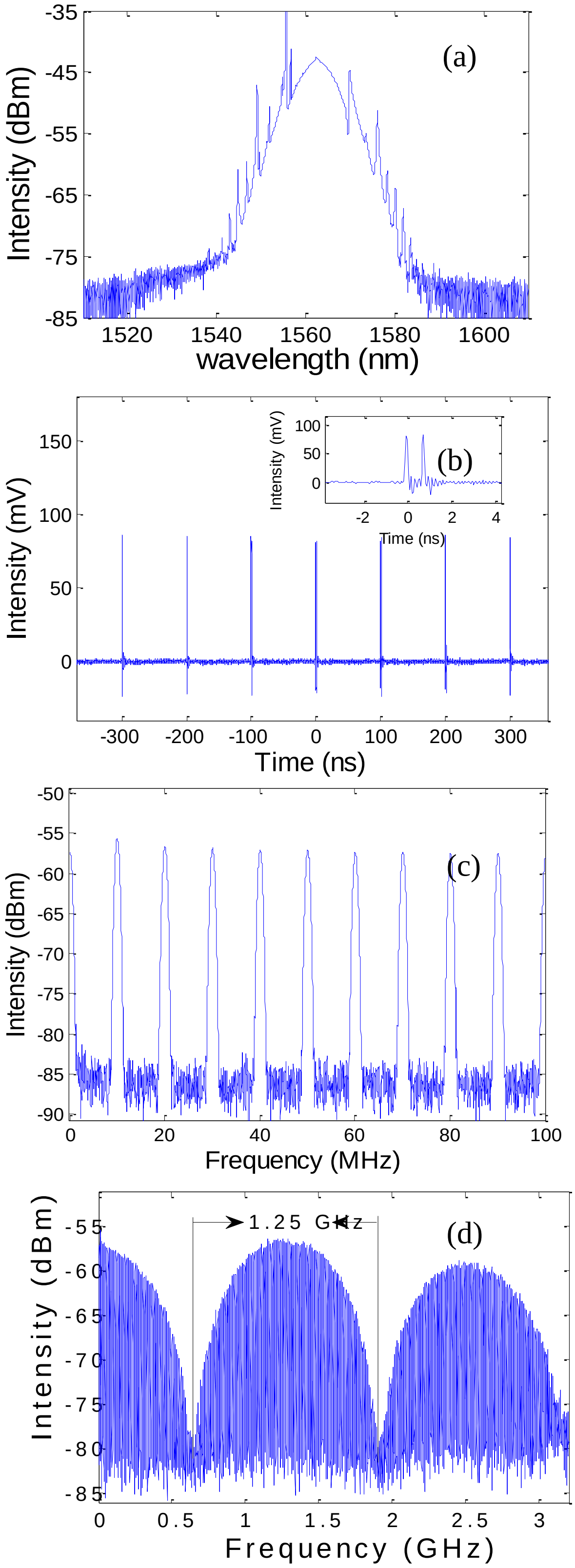

Fig. 3. (a) Optical spectrum for dual-soliton states with the temporal separation of 0.8 ns. (b) Oscilloscope traces. The upper right insert shows the pulses per round trip. RF spectra are in different spans. Span: (c) 100 MHz, (d) 2 GHz.

Fig. 4(a) depicts the spectrum when the temporal separation of the two pulses is 10 ns. And the resolution that can be required is beyond the one of our optical spectrum analyzer. The intensity of sidebands locate in the right sides becomes stronger and the sidebands in left side becomes lower than the one in Fig. 3(a) indicating the change of phase delay in the cavity. As a result, the spectrum in shorter wavelength region experiences higher intensity transmission. Both the spectra of different pulses separation are different form the spectrum that the fiber laser operates at the single pulse state. The dispersion wave becomes stronger at the dual pulse state than the one in single pulse states.

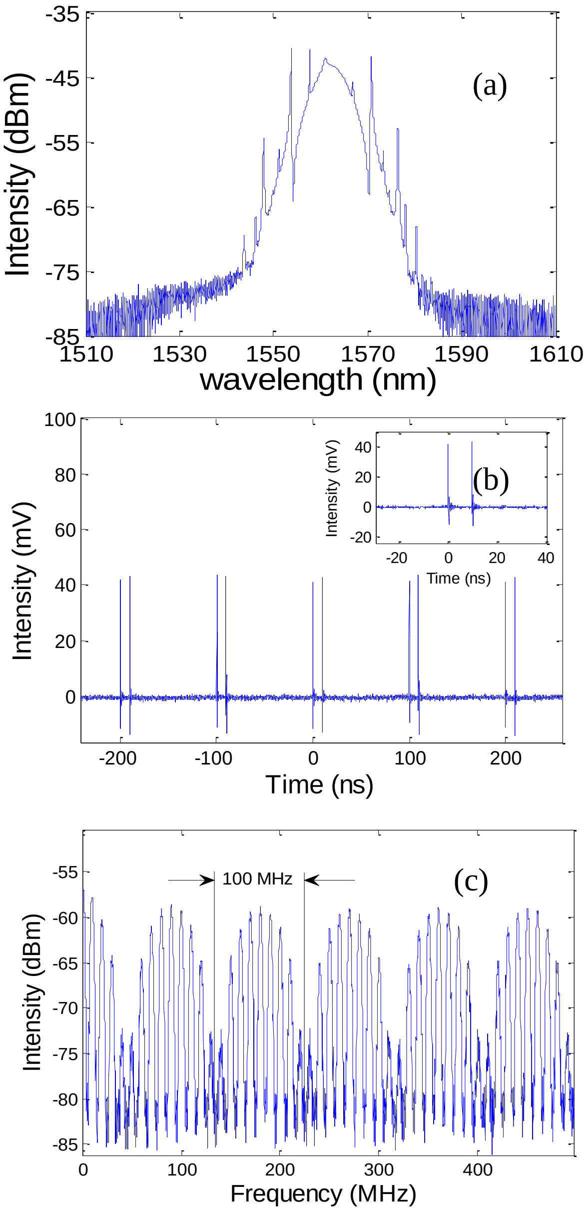

Fig. 4. (a) Optical spectrum for dual-soliton states with the temporal separation of 10 ns. (b) Oscilloscope traces. The upper right insert shows the pulses per round trip. (c) RF spectrum.

The temporal separation is equal to the reciprocal of the frequency period of the envelope. As shown in Figs. 4(b)-(c), the temporal separation of the two pulses is about 10 ns, while the period of the envelope is about 100 MHz in frequency domain.

The interaction between the solitons can be tuned by changing the birefringence of the cavity in our experiment. As a result, the temporal separation is changed. We believe that with proper cavity parameters, the proposed fiber laser can realize another tunable dual-soliton operation states.

More pulses operating in the cavity can be generated by increasing the pump power. We can get three or even more pulses per round trip by increasing the pump power. Fig. 5 gives the triple pulses operation states when the pump power is about 12.5 mW. For the four or more pulses per round trip, the time jitter plays more and more important role. So we didn't record the result of the more multi-pulses operation states.

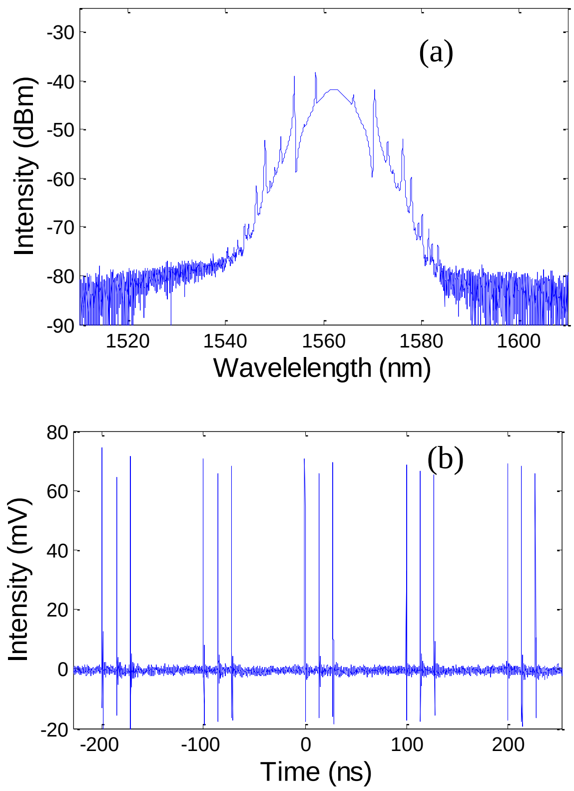

Fig. 5. The triple pulses operation state, (a) Optical spectrum for triple pulses states, (b) The corresponding oscilloscope traces.

In order to comparison, we give the bound state of two pulses and second harmonic mode-locking in this paper. The bound states of the dual-pulses operation states can be observed by adjusting the PCs to certain polarization states as shown in Fig. 6. In this case the temporal separation of the pulses is about 110 ps as seen from the autocorrelation trace. So it is hard to distinguish from the oscilloscope trace. And the spectrum is modulated due to the stronger interaction of the dual-pulses. But the main profile of the spectrum is similar like the ones mode locking in the fundamental cavity state. Because we use EDFA to amplify the output pulses, the experimental autocorrelation trace has a small peak locating beside each main peak. The autocorrelation trace indicates that dual pulses with separation of 110 ps generate in the cavity per round trip. We can only get the large temporal separation bound state in this fiber cavity. In this case the pulses characteristics are similar with the bound states with several picoseconds [24]. So we still call this operation states bound states.

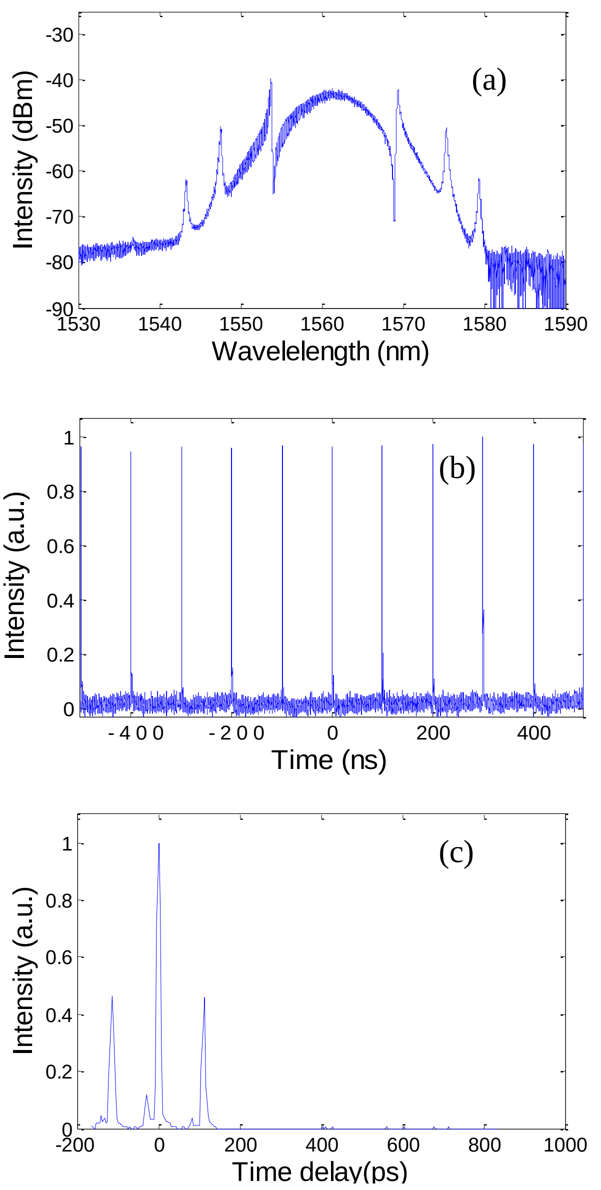

Fig. 6. The bound state of dual pulses operation states. (a) Optical spectrum, (b) Oscilloscope trace, and (c) Autocorrelation trace at the bound state of dual pulses operation states.

The second harmonic mode locked mode of the proposed fiber laser can also be observed from the experiment as shown in Fig. 7. The spectrum is similar like the fundamental mode states. The oscilloscope trace and the RF spectrum indicate that the proposed fiber laser operates at the repetition rate of 20 MHz which is two times of the fundamental cavity frequency rate.

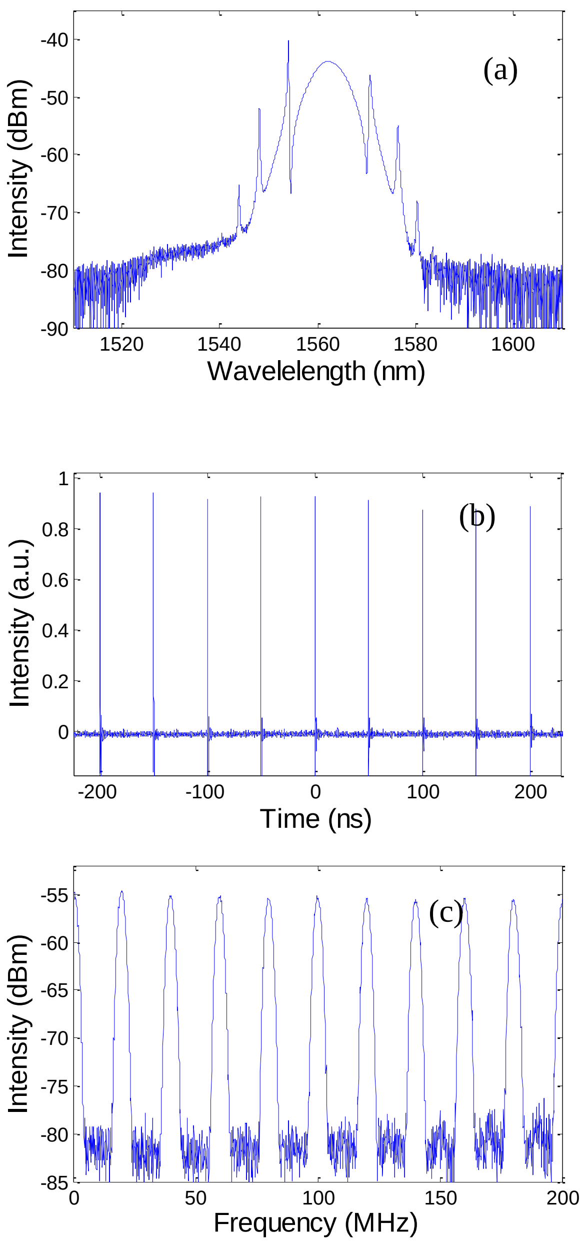

Fig. 7. The second harmonic mode locked mode of the proposed fiber laser, (a) Optical spectrum, (b) Oscilloscope trace, (c) RF spectrum.

However, the mentioned tunable dual pulse operation modes are neither the same with harmonic mode-locking where the pulses hold the same temporal separation and distribute uniformly in the cavity, nor bound states where the pulses locate very closely (about picoseconds level) [25-27]. These observed tunable dual-pulse states in this report can be mentioned as the quasi-bound states.

The bound states are quite different from the other multiple pulse states. The pulses are bounded together as one pulse in the cavity. While the repetition rate of harmonic mode locking states are several times more than the fundamental mode locking states, which the pulses has the equal separation in the cavity. The mentioned quasi-bound states are different states, the strength of the pulses in the cavity per round trip are less than the bound state. And the separation of the pulses is much larger than the bound states in the cavity. In our experiments, the observed bound states have the separation of about 110 ps which is quite smaller than the quasi-bound states.

4. Conclusions

Dual-pulse generation in a passively mode-locked soliton fiber ring laser is experimentally studied based on NPR techniques. In the two pulses generation regime, the temporal separation of the two pulses per round trip can be changed by adjusting the PCs. Two different dual pulses states with fixed temporal separation of 0.8 ns and 10 ns can be obtained, which are almost four orders of magnitudes larger than the pulse duration. These dual-soliton states with large temporal separations and their variable characteristics are different from the operation of typical harmonic or bound state of solitons. The novel dual pulses states can be named as the quasi-bound states. The tunable pulses have the potential application in the optical communication systems.

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