Long-term stabilization of a 10 GHz 0.8 ps asynchronously mode-locked Er-fiber soliton laser by deviation-frequency locking

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Abstract: Without using high speed RF feedback electronics, we successfully demonstrate a novel and economic long-term stabilization scheme for a 10 GHz 0.8 ps asynchronously mode-locked Er-fiber soliton laser by controlling the cavity length to lock the deviation frequency at 25 kHz. The required deviation frequency between the cavity harmonic frequency and the modulation frequency can be directly obtained from the low frequency electronic sideband of the laser output. The same feedback control unit is also useable for higher modulation frequencies, because the suitable deviation frequency always remains within the range of 15~40 kHz.

OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (060.5530) Pulse propagation and solitons; (320.7090) Ultrafast lasers

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1. Introduction

Over the past decades, a lot of research efforts have been devoted to develop mode-locked fiber laser sources that can meet the specific requirements for various applications. Among these works, one of the most challenging parts is to generate ultrashort pulses at high repetition rates directly from a mode-locked fiber laser [1-3]. This is because the two mode-locking techniques, i.e., passive mode-locking used for generating ultrashort pulses and active mode-locking used for obtaining high repetition rates, are typically not combined very well in a mode-locked fiber laser. Recently, a hybrid mode-locking technique based on asynchronous phase modulation has been demonstrated to be able to provide a good solution for this issue. 10 GHz 816 fs pulses with the supermode suppression ratio (SMSR) > 70 dB in the 1.55 μm wavelength can be directly obtained from the laser output, as long as the deviation frequency between the cavity harmonic frequency and the phase modulator's frequency is kept within a suitable range of 15~40 kHz [4-6]. Such sub-ps pulses with 10GHz or more repetition rates should be very useful for applications in high speed optical communication [7], ultrafast optical processing [8], and other scientific researches [3, 9]. However, in order to utilize these asynchronously mode-locked fiber soliton lasers in real applications, the long-term stabilization issues need to be considered first. Because of the long cavity length, mode-locked fiber lasers are unavoidably sensitive to environmental fluctuations due to temperature variation as well as vibration. These environmental changes will lead to a drift in the cavity harmonic frequency and thus destroy the stable operation of mode-locking in the long run. In the literature, several methods based on the techniques of RF phase locking have been successfully developed to long-term stabilize the typical mode-locked fiber lasers with synchronously active modulation [1, 10]. However, these schemes can not be directly applied to the asynchronously mode-locked lasers because in these cases, each harmonic frequency of the laser output will be accompanied with closely spaced frequency sidebands resulted form the slow modulation of the pulse timing position due to asynchronous phase modulation. This will cause some difficulty in the schemes of RF phase locking to cleanly obtain the cavity harmonic frequency. Therefore a new stabilization scheme is needed to be developed for asynchronously mode-locked fiber lasers.

In this paper, for the first time we propose and successfully demonstrate a new stabilization scheme for a 10 GHz 0.8 ps asynchronously mode-locked Er-fiber soliton laser. It is based on controlling the cavity length to lock the deviation frequency at a suitable value, i.e., 25 kHz. Rather than using high speed RF electronics to extract the 10 GHz cavity harmonic frequency, simple and low frequency feedback electronics is enough to directly measure the deviation frequency shift. This can be achieved because the frequency sidebands due to synchronous modulation will also appear in the output electronic frequency spectrum close to DC. The present method thus offers us an economic and simple approach with the same advantage as in Ref [11], in which the low speed electronics of several tens of kHz in the feedback control loop is enough to stabilize mode-locked fiber lasers with more than 10 GHz pulse repetition rates. Details of the experimental setups and the achieved results for the proposed stabilization scheme will be presented during the following sections.

2. 10GHz, 0.8ps asynchronously mode-locked Er-fiber soliton laser

Figure 1 shows the schematic of our experimental setup. Besides the mode-locked fiber laser, an additional feedback control loop is added to achieve long-term stabilization. One of the key components of this fiber laser is the $LiNbO_3$ phase modulator with enough polarization-dependence loss. The polarization-dependent loss combined with the effects of nonlinear polarization rotation (NPR) of the fiber can lead to the mechanisms of polarization additive pulse mode-locking (P-APM) and additive pulse limiting (APL) [3], which should have played the important roles of pulse formation, pulse shaping and pulse energy equalization in our laser. Depending on the polarization states of the two polarization controllers and the driving RF signals of the phase modulator, rich phenomena of various mode-locking regimes can be observed in this fiber laser system. They includes passive mode-locking,

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synchronously harmonic mode-locking, and asynchronously harmonic mode-locking. We have even observed 10 GHz bound two-soliton states when the laser is modelocked synchronously. Among these different operation regimes, asynchronous mode-locking has been demonstrated to be able to directly generate sub-ps soliton pulses with very high repetition rates [6].

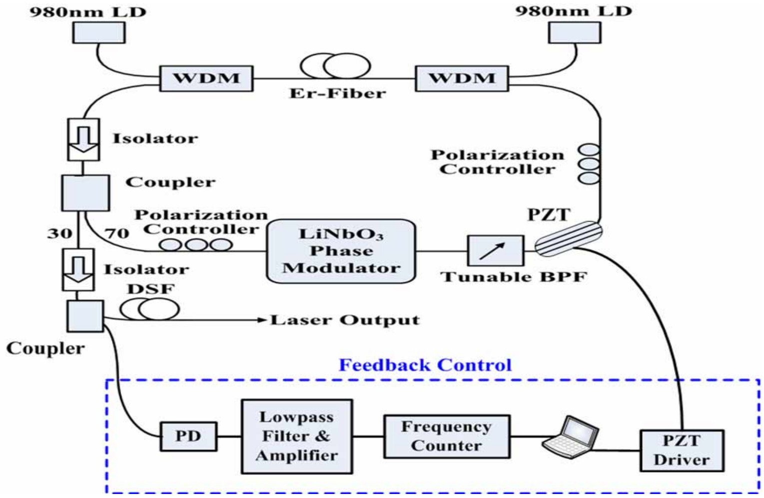
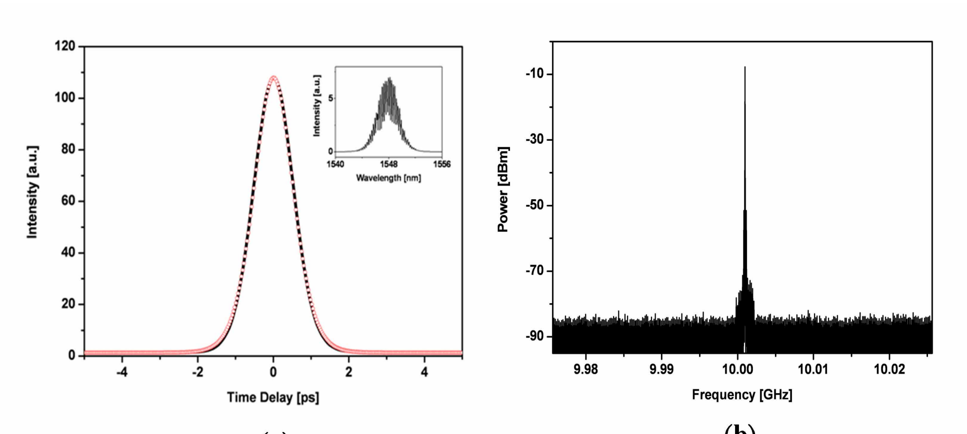


Fig. 1. Schematic of the mode-locked Er-fiber laser and the feedback control. BPF, band-pass filter; PD, photodiode; DSF, dispersion shift fiber.

In order to achieve asynchronous mode-locking, the modulation frequency is detuned from the cavity harmonic frequency by 15~40 kHz [4-6]. With fine adjustments of the polarization controllers, sub-ps soliton pulses at 10 GHz with a high supermode suppression ratio can be obtained. Important parameters that determine the optical characteristics of this fiber laser include the average cavity dispersion and the total 980 nm pump power, since the soliton pulses in the cavity should follow the area theorem. When the fiber laser is pumped by 980 nm laser diodes with the total power of 750 mW and the average cavity dispersion parameter β_2 is estimated to be -5.3 ps^2/km, 22.5 mW of the 10 GHz 0.8 ps soliton pulse train is directly obtained from the laser output. Figure 2(a) shows the auto-correlation trace of the laser output. The pulse-width obtained from the fitting curve is 0.8 ps, with the assumption of sech^2 pulse shape. The inset in Fig. 2(a) shows the optical spectrum of the pulse. The center wavelength is at 1548 nm and the FWHM bandwidth is 3.3 nm. The time-bandwidth product of the pulse is 0.33, indicating that the pulses are nearly transform-limited and have little chirp. Figure 2(b) shows the RF spectrum near 10 GHz with the span of 50 MHz (almost 6 times of the cavity frequency) from the photodiode which detects the laser output. The supermode suppression ratio (SMSR) is greater than 70 dB, indicating that asynchronous mode-locking can provide an effective method to solve the typical noise issues in the mode-locked lasers with slow gain relaxation. The shorter pulse-width and the higher supermode suppression ratio are the two main advantages that can be obtained in asynchronous mode-locking when compared to synchronous mode-locking. The reasons may be explained as follows. Asynchronous mode-locking periodically induces the timing position difference between the center of the modulation signal and the soliton pulse. When the soliton pulse arrives at the phase modulator, it will experience the corresponding carrier frequency shift according to this timing position difference. The induced carrier frequency shift will further cause the soliton pulse to have a different group velocity and introduce another timing position shift through the cavity dispersion. Therefore the soliton pulses in asynchronous mode-locking have the slow periodic modulation both in the timing position and in the optical carrier frequency. Such periodic modulation can lead to shorter pulse-width and higher SMSR in the following way. On one hand, the wider effective optical filter bandwidth due to the sweep of the optical carrier frequency can be helpful for obtaining the shorter pulse width. On the other hand, the high SMSR can result from the noise suppression effects similar to those in the sliding filter scheme of soliton transmission control. The nonlinear soliton pulses with the slow periodic modulation of the carrier frequency can still survive in the laser cavity, while the linear noises with the periodic modulation will be filtered out due to the continuing frequency shifts by the phase modulator. Besides asynchronous mod-locking, the effects of APM, APL and self-phase modulation with filtering may also have helped to achieve the above two advantages [3, 6, 12].



(a) **(b)**

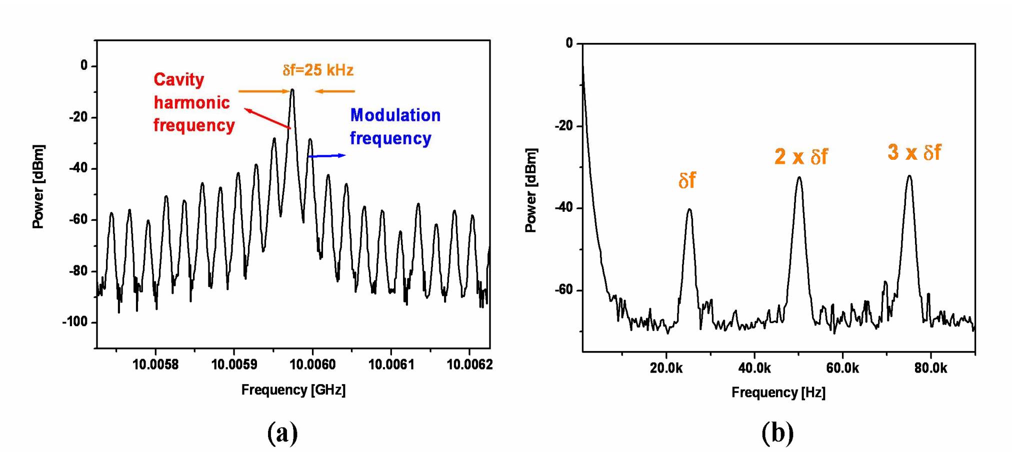
Fig. 2. Characteristics of the pulses from asynchronously mode-locked fiber laser. (a) Autocorrelation trace (black solid curve) and the fitting curve (red open circles), assuming a sech^2 pulse shape. (inset , optical spectrum on a linear scale). (b) RF spectrum near 10 GHz with a span of 50 MHz; SMSR > 70 dB.

3. Long-term stabilization scheme of the asynchronously mode-locked fiber laser

In this section we first report the observation of the frequency sidebands in the electronic frequency spectrum from the photodiode that detects the laser output. Then we show how to utilize these special characteristics due to asynchronous mode-locking to get the deviation frequency shift from the frequency sidebands near DC. Finally, the stabilization scheme based on locking the deviation frequency at 25 kHz is described, and the long-term stabilization of a 10 GHz 0.8 ps asynchronously mode-locked Er-fiber soliton laser is demonstrated.

3.1 Frequency sidebands due to slow periodic modulation of pulse timing position

The slow periodic modulation in the pulse timing position is one of the main characteristics of asynchronous mode-locking and can be observed experimentally from the RF spectrum of the laser output. Figure 3(a) shows the same RF spectrum as in Fig. 2(b), except with a smaller span of 500 kHz. The main cavity harmonic frequency is 10.005974 GHz, and the modulation frequency is 10.005999 GHz. The frequency difference δf between the main cavity harmonic frequency and the modulation frequency is 25 kHz. The slow 25 kHz modulation of the pulse timing position is the reason that causes the appearance of the frequency sidebands in the RF spectrum. As show in Fig. 3(a), the frequency components around 10 GHz compose a series of frequency sidebands with the spacing equal to the deviation frequency of 25 kHz. These frequency sidebands around 10 GHz should cause some difficulty in the long-term stabilization schemes based on the technique of RF phase-locking, since it may be unfeasible to extract the 10 GHz main cavity harmonic frequency from these closely spaced frequency components in the feedback control loop [1, 10]. Such frequency sidebands will also exist at other multiples of the pulse harmonic frequency. Most importantly, similar frequency sidebands can also be observed near DC. As shown in Fig. 3(b), three sideband peaks at multiple deviation frequencies (δf , 2×δf , and 3×δf) can be clearly observed. The frequency sidebands near DC provide us a simple approach to obtain the deviation frequency shift by using only low frequency electronics. It can be used as a good error signal required in the feedback control loop for stabilizing the fiber laser, since the shift of the cavity harmonic frequency due to environmental fluctuations will also directly cause the shift of the deviation frequency.



(a) (b)

Fig. 3. Frequency sidebands observed in the electronic frequency spectra. (a) 500 kHz span, near 10 GHz. (b) 90 kHz span, near DC. *δf* : deviation frequency.

3.2 Long-term stabilization based on deviation-frequency extraction and locking

In order to achieve long-term stabilization of the asynchronous mode-locked Er-fiber soliton laser successfully, both the asynchronous mode-locking and the hybrid mode-locking mechanisms should be maintained during the stabilization operation [6]. The former mechanism relies on maintaining a suitable deviation frequency of 15-40 kHz between the modulation frequency and the cavity harmonic frequency. For the latter mechanism, the optical polarization evolution along the laser cavity should not be perturbed by the cavity length control unit. In this way, the polarization additive mode locking (P-APM) and additive pulse limiting (APL) can continue to maintain the same effects of pulse formation and pulse energy equalization. To meet the first requirement of keeping a suitable deviation frequency, we feedback-control the cavity length by a PZT to lock the deviation frequency at a suitable frequency, i.e., 25 kHz. As to the second requirement, since we do not observe obvious polarization changes when the cavity length is detuned by the PZT, it is automatically satisfied. The shift of the deviation frequency can be obtained by using a low-pass filter to extract the first peak closest to DC from the frequency sidebands near DC.

Our actual experiment to demonstrate long-term stabilization is described as follows. The asynchronously hybrid mode-locked fiber laser is fixed on the aluminum plate with a temperature controller to reduce the environmental temperature change. A PZT wound with the single-mode fiber is put in the laser cavity to adjust the cavity length. As shown in Fig. 1, the feedback control loop composes a sharp cutoff (135dB/Octave) low-pass filter, an amplifier, a frequency counter, a computer, and a high voltage amplifier to drive the PZT. A small fraction of the laser output is detected by the photodiode. The low-pass filter can remove all the sideband peaks except for the first frequency peak closest to DC. The measured electronic spectrum after the low-pass filter and the amplifier is shown in Fig. 4, in which the deviation frequency peak around 25 kHz can be clearly seen. The frequency counter can measure the deviation frequency and sends its digital output to the computer. The computer will then process the signal with suitable signal processing methods and then send the

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frequency error signal to the PZT driver to lock the deviation frequency at 25 kHz. The maximum amount of the frequency shift that can be produced by our PZT unit is about ± 25 kHz, which seems to be enough for long-term stabilization as long as the environmental temperature fluctuations are reduced to be small enough by the temperature controller. When the fiber laser is operating without the stabilization scheme, the typical deviation frequency is about ± 4 kHz in 7 minutes as shown in Fig. 5(a). Experimentally, a deviation frequency shift larger than 10 kHz will severely affect the stability of asynchronous mode-locking. Long-term stable operation is achieved when the stabilization scheme is turned on, as is shown in Fig. 5(a). The deviation frequency shift can be controlled to be within ± 300 Hz, limited by our frequency counter unit. Figure 5(b) shows the stabilized 10 GHz pulse train measured from a fast sampling oscilloscope.

The main advantage of this stabilization scheme is that it provides a simple and economic approach to stabilize asynchronously mode-locked fiber lasers. The high speed electronics are not required in the feedback control loop and it is much easier to deal with the electronics in the kHz range. Furthermore, the same feedback control unit is suitable for even higher modulation frequencies. This is because the suitable deviation frequency always remains within the range of 15~40 kHz, despite the change of the pulse repetition rate.

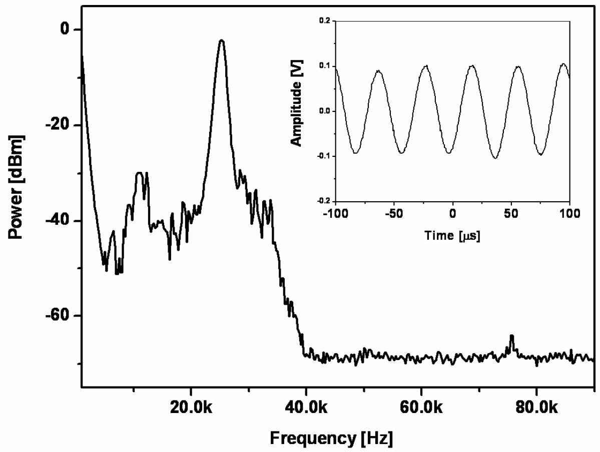
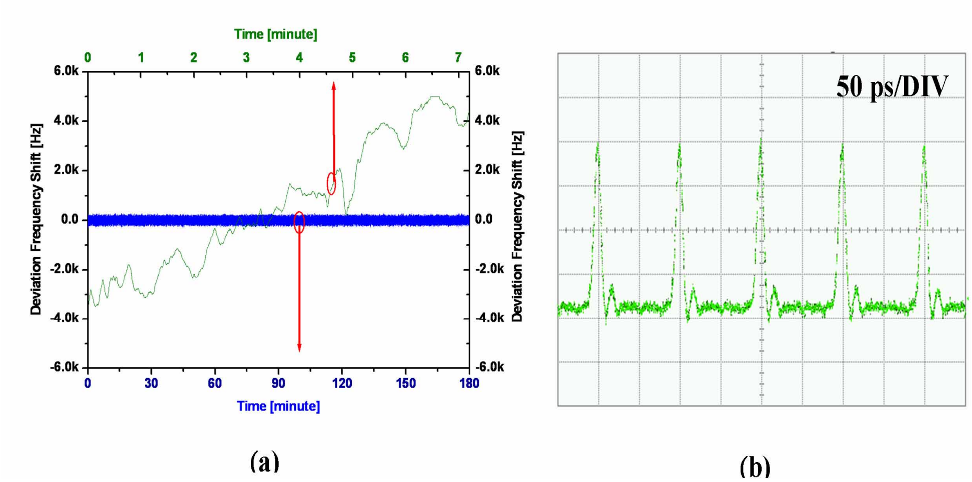


Fig. 4. Deviation frequency in the electronic frequency spectrum near DC after the low-pass filter and the amplifier in the feedback loop (inset, signal in the time domain).



(a)

(b)

Fig. 5. Stabilization of the asynchronously mode-locked fiber laser. (a) Deviation frequency shift: without the stabilization scheme, green curve with the upper axis; with the stabilization scheme, blue curve with the lower axis. (b) 10 GHz pulse train from a fast sampling oscilloscope.

4. Conclusion

To conclude, without using high speed RF feedback electronics, the long–term stabilization of a 10 GHz 0.8 ps asynchronously mode-locked Er-fiber soliton laser has been proposed and demonstrated for the first time by controlling the cavity length to lock the deviation frequency at 25 kHz. The stabilization scheme is simple and economic, since only electronics in the kHz range are required for long-term stabilizing the mode-locked fiber laser with a 10 GHz repetition rate. Moreover, the same low frequency feedback control unit is suitable for other modulation frequencies, even when the pulse repetition rate is raised up to 40 GHz or more. Based on this stabilization scheme, stable sub-ps pulses with high repetition rates can be stably obtained from asynchronously mode-locked Er-fiber soliton lasers for real applications.

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