Generation of the numerator = 2 rational harmonic mode-locked pulses in fiber ring lasers

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In conventional rational harmonic mode-locking, optical pulse trains with the repetition rate of $(pn+1)f_c$ are generated when the modulation frequency of the in-cavity modulator is set at $f_m = (n+1/p)f_c$, where n and p are both integers, f_c is the fundamental cavity frequency. In this paper, we report that rational harmonic mode locking phenomenon takes place in the fiber lasers when the modulation frequency is set at $f_m = (n+2/p)f_c$. The pulse generations are experimentally demonstrated when the numerator of the rational corresponds to 2 in 5th and 7th order rational harmonic mode-locking.

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Rational harmonically mode-locked fiber lasers have attracted much attention because of their ability to generate the high repetition frequency optical pulse trains by applying driving radio frequency (RF) slightly deviated from the multiple of the fundamental cavity frequency. Recently, the rational harmonic mode-locking fiber lasers have been made great progress on many schemes[1,2]. Froursa *et al.*[3] reported the rational harmonic mode-locking in a σ-cavity fiber laser. Li *et al.*[4] reported the rational harmonic mode-locking in a figure-of-eight fiber laser. Tang *et al.*[5] reported the all optical rational harmonic mode-locking in a fiber laser using a nonlinear optical loop modulator. Wu *et al.*[6] obtained the 22nd rational harmonic mode-locking. Yoshida *et al.*[7] obtained rational harmonic mode-locking pulses up to 80−200 GHz.

In rational harmonic mode-locking, the pulse amplitude becomes severely uneven, except when the repetition rate is twice that of the RF frequency. Uneven amplitudes will create difficulties in the application of these pulses. To solve this problem, some methods have been suggested, such as the utility of intensity- dependent loss[8], the additive-pulse limiting technique[9], the injection-locked fiber laser with nonlinear optical loop mirror[10], the technique of nonlinear polarization rotation[11], the configuration using semiconductor laser amplifier in a loop mirror[12], and the way of using modulator as both mode locker and equalizer[13].

In conventional rational harmonic mode-locking, an optical pulse train with a repetition rate of $(pn+1)f_c$ is generated when the modulation frequency of the in-cavity modulator is set at $f_m = (n+1/p)f_c$, where n and p are integers, f_c is the fundamental cavity frequency[6]. In this paper, we report that rational harmonic mode-locking takes place in an actively mode-locked fiber laser when the modulation frequency of the modulator is set at $f_m = (n+2/p)f_c$, where p equals to 5 and 7.

The experimental configuration is illustrated in Fig. 1. A 1550/980 nm wavelength division multiplexer (WDM) coupled 120-mW, 980-nm laser as co-propagating pump was coupled into the 20-m erbium-doped fiber (EDF). Two isolators (ISO1 and ISO2) were used to propagate the lasing power along a single direction with the co-propagating pump. A laboratory manufactured lithium niobate intensity modulator with an insertion loss of 7dB and a modulator bandwidth of 2.5 GHz was used as the mode locker, which was driven by a frequency-tunable RF signal synthesizer. Finally, a 10:90 coupler was used to output the lasing power. Here, the fundamental cavity frequency f_c was about 6.5 MHz. In the experiment, we concentrated on the observation of the rational harmonic mode-locking generation when the modulation frequency f_m was in the range of 130.0−140.0 MHz. The value of the driving frequency could be read from the RF synthesizer with the reading precision of 1 MHz. The shortest and most stable optical pulses were obtained by carefully tuning the driving frequency. The repetition rate of the mode-locked pulse trains was measured using an oscilloscope (HP 54610B) after a photo detector (model 1623, New Focus Inc.). As the bandwidth of the detector was 1 GHz, here, the measured pulse width was about 1 ns.

Figure 2 shows the averaged oscilloscope traces of the detected pulse trains recorded at different values of RF driving frequency of 130.0, 131.4, 131.7, 131.9, 132.2, 132.5, and 133.3 MHz. To confirm the generation mechanism of the pulses in Fig. 2, we analyzed the relation of the repetition frequencies of the pulse trains with the RF driving frequency. In Fig. 2(a), it is such a conventional mode-locked pulse whose repletion frequency is equal to the RF driving frequency of 130.0 MHz, and is 20 times

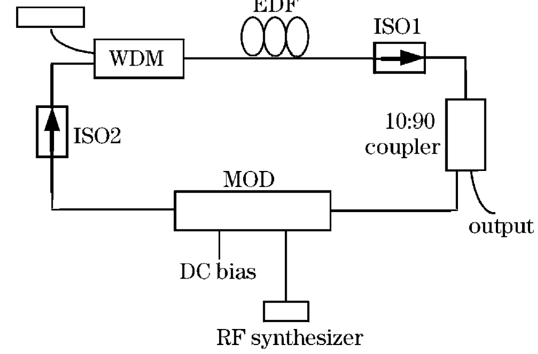

Fig. 1. Experimental configuration. ISO: isolator; MOD: intensity modulator.

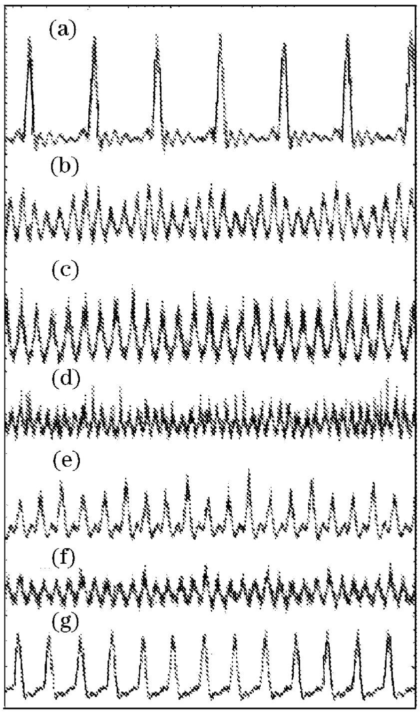

Fig. 2. Output pulse trains of actively mode-locked fiber laser. (a) f_m=130.0 MHz; (b) f_m=131.4 MHz; (c) f_m=131.7 MHz; (d) f_m=131.9 MHz; (e)f_m=132.2 MHz; (f) f_m=132.5 MHz; (g) f_m=133.3 MHz. The time coordinate is 5 ns/div.

of the fundamental cavity frequency. However, the repetition frequencies in the following pulse trains are quite different to the driving frequencies.

As it is known, if the driving frequency is with a slight detuning of f_c/p from the multiple of the fundamental cavity frequency, the pulse train with a repetition frequency of $(pn+1)f_c$ will be generated. Figure 2(b) is such a 5th order rational harmonic mode-locked pulse train, as the driving frequency f_m = 131.4 MHz =(20+1/5) f_c and then the detuning to the multiple of the fundamental cavity frequency is $f_c/5$. Similarly, the pulse train in Fig. 2(c) was generated by the 4th order rational harmonic mode-locking, as the detuning of the driving frequency to the multiple of the cavity frequency is $f_c/4$. Figure 2(d) shows the 7th order rational harmonic mode-locked pulse, the detuning is $2f_c/7$. Figure 2(e) shows the 3rd order rational harmonic mode-locked pulse, the detuning is $f_c/3$. Figure 2(f) shows the 5th order rational harmonic mode-locked pulse, the detuning is $2f_c/5$. Figure 2(g) shows the 2nd order rational harmonic mode-locked pulse, the detuning is $f_c/2$.

We can find that the pulses in Figs. 2(b), (c), (e), and (g) are the conventional rational harmonic mode-locked pulses, in which the numerator of the ration for the detuning is 1. However, the pulse distributions in Figs. 2(d) and (f) are very similar to the conventional 7th and 5th rational harmonic mode-locked ones, as the repetition rates of the pulses are the same as conventional 7th and 5th rational harmonic mode-locked ones. But their detuning are twice of those in the conventional rational harmonic mode-locked pulse. In other words, the numerator of the ration is 2. The result is important as it demonstrates that the numerator = 2 rational harmonic mode-locked pulse is generated when the modulation frequency of the modulator is set at $f_m = (n+2/p)f_c$. In conventional rational harmonic mode-locking, if the pulses are generated at the pth order harmonic wave of the RF modulation frequency, the phase-shifted pulses are positioned relatively every $2\pi/p$ before the pulses are back to the same phase as their starting period, and that means p round trips are necessary to obtain the same gain[1]. Here, the phase-shifted pulses are positioned relatively every $4\pi/p$ before the pulses are back to the same phase as their starting period.

During the experiment, the rational harmonic mode-locking did not take place when the detuning of the RF driving frequency was $f_c/7$. When the numerator of the detuning of the RF driving frequency was 1, the highest repetition rate pulse train was the 5th order harmonic wave of the RF driving frequency. But the 7th order harmonic wave appeared when the detuning was $2f_c/7$. The result shows that it is helpful to make easier to obtain higher repetition rate pulse train if using the numerator = 2 rational harmonic mode-locking.

We reported the rational harmonic mode locking took place in an actively mode locked fiber ring laser when the detuning of the RF driving frequency to the multiple of the cavity frequency was $2f_c/p$. The experiment demonstrated that the pulses were generated when the numerator = 2 in 5th and 7th order rational harmonic mode-locking. This technique is useful for generating high repetition rate pulse trains.

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