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High repetition rate optical pulse generation from an actively mode-locked fiber ring laser

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Rational harmonic mode-locking of an Er-doped fiber ring laser has been successfully demonstrated up to the 16-th harmonic, of the RF frequency applied to the electro-optic modulator. This is the highest harmonic reported so far to our knowledge.

I. INTRODUCTION

High repetition rate mode-locked Er-doped fiber lasers have many applications for high-speed optical communication network systems. The various schemes to achieve a high repetition rate generation of optical short pulses have been reported by many research groups[1-5]. Among them, actively mode-locked fiber lasers are relatively easy because their pulse repetition rate is usually dependent on the frequency applied to the active mode-lockers. The pulse repetition rate of conventional active mode-locked lasers is the same as the modulation frequency $f_m(= m\Delta f_{cav})$, which corresponds to the m-th harmonic of the fundamental cavity frequency Δf_{cav}. However, when the driving frequency to the modulator is set to $f_m + \Delta f_{cav}/n$, harmonic mode locking takes place at $(mn + 1)\Delta f_{cav}$, where m and n are integral numbers. This technique has been referred to as rational harmonic mode-locking.

Recently, the technique of rational harmonic mode-locking has been demonstrated with actively mode-locked semiconductor lasers by Onodera et al.[6] The rational detuning of the modulation frequency can generate high repetition rate optical pulses. More recently, the rational harmonic mode-locked method has been expanded to fiber lasers [4,7,8], and a pulse repetition rate as high as 80 - 200 GHz has been obtained by Yoshida et al.[7]. The repetition rate was increased up to the second to fifth multiples of the externally applied modulation frequency.

In this letter, we report rational harmonic mode-locking up to 16-th multiple of the fundamental modulation frequency applied to an electo-optic modulator in an Er-doped fiber ring laser. A pulse repetition rate of 24 GHz, which was 16-th harmonic of the external RF modulation frequency of 1.5 GHz, was achieved by optimizing the modulation frequency.

II. EXPERIMENTS

The experimental set-up used for rational harmonic mode-locking in an erbium-doped fiber laser is shown in Fig. 1. The laser cavity comprises a 12.5-m long erbium doped fiber of erbium concentration of about 200 ppm, a polarization controller, a fiber pigtailed electro-optic modulator with a 3 GHz bandwidth, a polarization independent isolator, and a 10 % output coupler. The modulator was driven at 1.5 GHz by a RF-signal generator (HP8648C). The optical pumping is provided via a 1550/980 wavelength-division multiplexing coupler from a laser diode of central lasing wavelength of 980 nm. The output pulses are extracted from the 10 % output coupler, and are monitored with a background free autocorrelator, a sampling oscilloscope (Tektronics:CSA803, with a SD-32 sampling head), and an opti-

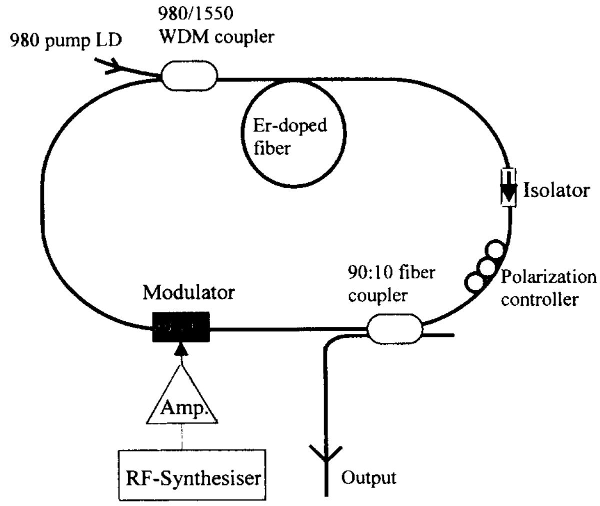
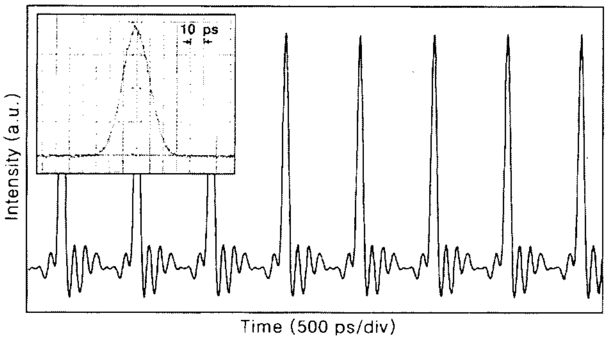
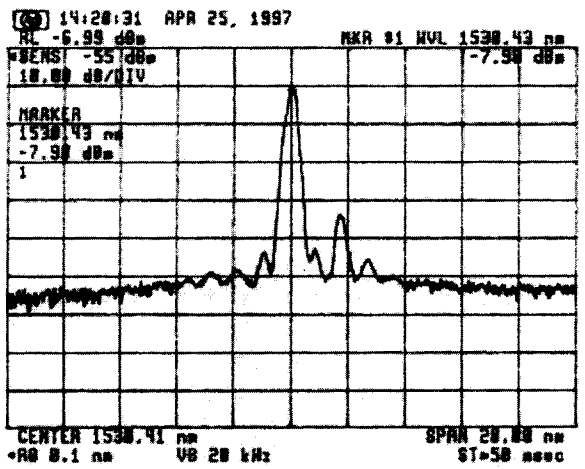


FIG. 1. Experimental set-up for rational harmonic mode-locking.



(a)



(b)

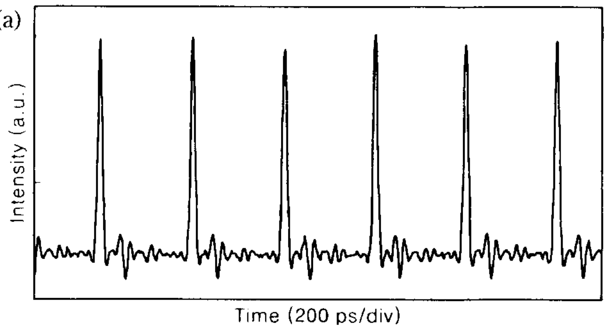
FIG. 2. Conventional mode-locked pulses at 1507.337 MHz. (a)Sampling oscilloscope trace (b) Optical spectrum output. Inset: Autocorrelation trace.

cal spectrum analyzer(Hewlett Packard: HP70004A).

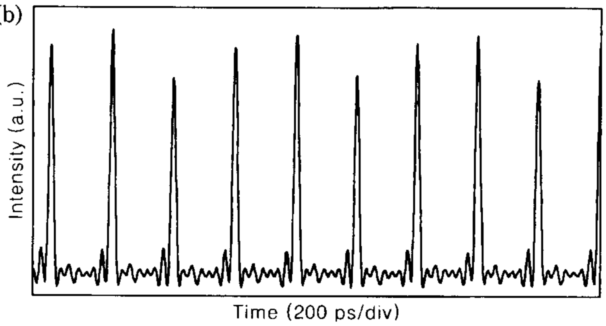
The fundamental cavity frequency was measured to be 9.36 MHz, and the total laser cavity length corresponding to the fundamental cavity frequency was about 22 m. Conventional active mode locking was obtained at the modulation frequency 1507.337 MHz, which was approximately the 161-st harmonic of the fundamental laser cavity frequency. The stable optical pulses were obtained by fine adjustment of the polarization controller and the RF driving frequency of the signal generator.

Fig. 2 shows the pulse traces measured with the sampling oscilloscope and an optical spectrum output of the conventional mode locked pulses at 1507.337 MHz. This repetition rate was exactly an integral multiple of the fundamental cavity frequency 9.36 MHz. The inset shows the autocorrelation trace of the single pulse shown in Fig. 2(a). The measured pulse width was ~ 15 ps when no chirp compensation was applied and the spectral line width was about 0.32 nm. The time-bandwidth product of the actively mode-locked pulses was about 0.6, which indicates that the output pulses are chirped. The average output power was measured to be 1.8 mW for the pump power of 60 mW.

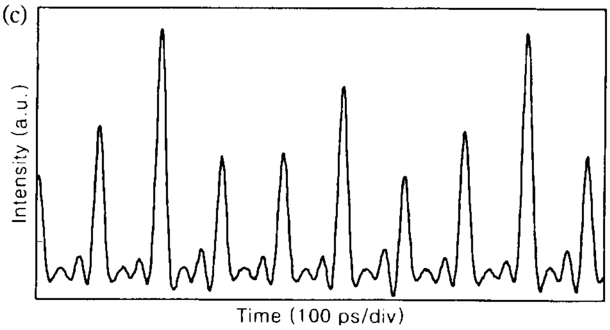
(a)



(b)



(c)



(d)

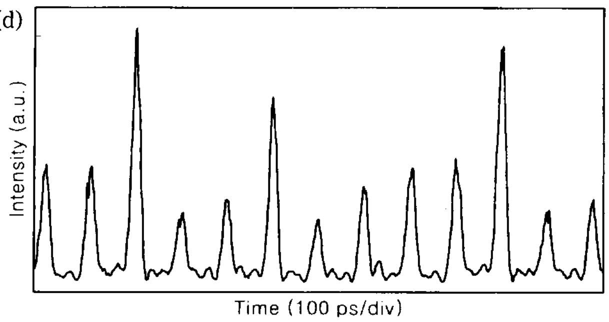


FIG. 3. Sampling oscilloscope trace of rational harmonic mode-locking pulses. (a)n = 2, f = 3.0146 GHz (b) n = 3, f = 4.521 GHz (c) n= 6, f = 9.042 GHz (d)n = 8, f = 12.056 GHz.

Fig. 3 shows the average sampling oscilloscope traces of the mode-locked laser pulses when the rational harmonic number n are 2, 3, 6 and 8, respectively. Fig. 3(a) shows the result of the 2-nd rational harmonic mode-locking by detuning the modulation frequency from 1507.337 MHz by $\Delta f_{cav}/2 (= 4.68 \text{ MHz})$. The amplitude of each output pulse was almost the same, which agreed with the observation of Yoshida in Ref.[7]. However, in the case of higher harmon-

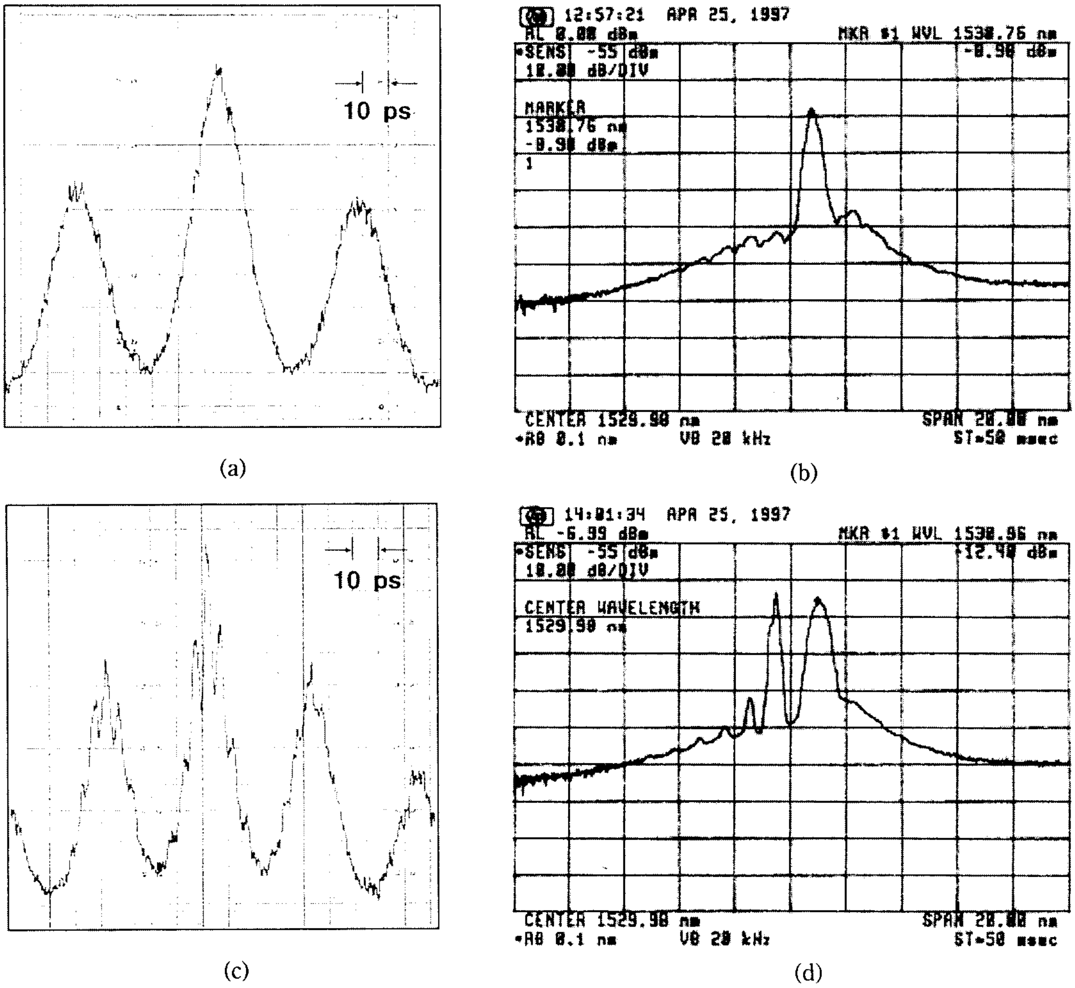


FIG. 4. Rational harmonic mode-locking pulses. (a)Autocorrelation trace (n=12, f=18.084 GHz) (b)Optical spectrum of (a) (c) Autocorrelation trace (n=16, f=24.112GHz) (d) Optical spectrum of (c).

ics than n=2 as shown in Figs. 3(b), 3(c) and 3(d), the output pulses have unequal amplitude because unmatched lower order harmonics distort the pulse amplitude. The detuning of the modulation frequency by $\Delta f_{cav}/3$ (3.12 MHz), $\Delta f_{cav}/6$ (1.56 MHz) and $\Delta f_{cav}/8$ (1.17 MHz) from 1507.337 MHz provided pulse repetition rates of 4.521, 9.042 and 12.056 GHz, respectively. The pulse widths of the 3-rd, 6-th and 8-th harmonic mode-locking were measured to be approximately 13 ps when no chirp compensation was used. The pulse widths are almost the same in all cases. Fig. 4 shows the result of the rational harmonic mode locking at n=12 and n=16. Figs. 4(a) and 4(c) show the autocorrelation traces generated at the detuned the modulation frequencies from 1507.337 MHz by $\Delta f_{cav}/12$ (= 0.78 MHz) and $\Delta f_{cav}/16$ (= 0.585 MHz), respectively. The pulse repetition rates correspond to 18.084 and 24.112 GHz, respectively. The intervals between the adjacent pulses were approximately 56 ps and 40 ps, respectively. In the case of n=12 and n=16, the frequencies of the rational mode locking correspond to the 1932-nd and the 2576-th harmonic of the fundamental cavity frequency, respectively. In the 16-th rational harmonic state, the amplitudes of the pulse traces were largely distorted, and were not uniform because of the existence of the lower order harmonics. Figs. 4(b) and 4(d) show the optical spectra of the mode-locked pulses corresponding to the oscilloscope trace shown in Figs. 4(a) and 4(c), respectively. For both spectra the center wavelength was 1531 nm, and the full width at half maximum was 0.34 nm. The small modulation peak around the central peak in Fig. 4(c) may be attributed to a beat signal between the left side peak wavelength and the main oscillation wavelength as shown in Fig. 4(d). The wavelength interval between the two peaks was about 1.8 nm, which corresponds to 3 ps separation in the time domain. The time-bandwidth products of the mode-locked pulses for both rational harmonics were measured to be about 0.6. The output pulses seem to be slightly chirped.

We obtained the rational harmonic mode-locking for another modulation frequency of 2.5 GHz. Rational harmonics up to n=2 - 11 of the fundamental modulation frequency of 2.5 GHz were also observed. As the modulation frequency is increased, the maximum rational order is decreased because the total lasing power is limited. Further work is needed to equalize the distorted pulse amplitudes in the high order rational harmonic pulses.

III. CONCLUSION

We have successfully demonstrated to the 16-th rational harmonic mode-locking of an Er-doped fiber ring laser by controlling the RF drive frequency applied to the electro-optic modulator. The pulse repetition rate of 24 GHz, which was the 16-th harmonic of the external modulation frequency of 1.5 GHz, was achieved by optimizing the modulation frequency.

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