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Doubled Repetition Frequency in Regeneratively and Harmonically Mode-Locked Fiber Ring Laser

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Abstract: A regeneratively and harmonically mode-locked fiber ring laser that generated a pulse train with a doubled repetition frequency was experimentally demonstrated. We used a polarization-maintaining fiber laser and an electrical circuit that extracted a subharmonic clock to produce self-pulsing with a repetition frequency of 21.32 GHz while extracting the electrical clock at 10.66 GHz. The mode of operation depended on the bias point of the optical modulator. The doubled repetition frequency was observed when the modulator was biased in the vicinity of the voltage providing either the maximum or minimum transmission. Otherwise, the repetition frequency coincided with the modulation frequency. Detailed analyses of repetition frequencies suggested that the frequency-doubled pulse generation could be caused by rational harmonic mode-locking.

Keywords: Pulse lasers, Fiber lasers, Active mode-locking, Harmonic mode-locking, Rational harmonic mode-locking, Semiconductor optical amplifier, Clock extraction.

1. Introduction

Harmonic mode-locking is a technique for generating short pulses with a high repetition frequency [1]. In this class of active mode-locking, the modulation frequency is an integer multiple of the fundamental frequency of the laser cavity. The integer is called the harmonic order, and it can be set as large as several thousands. Using this technique, we can make long-cavity lasers, such as fiber ring lasers, configured as an optical pulse source for telecom applications that require a pulse repetition frequency of several tens of gigahertz.

Harmonically mode-locked fiber lasers are known to be vulnerable to temperature change. Because of the long fiber cavity, the fundamental frequency of the cavity becomes a function of temperature. To maintain pulsed oscillation in an environment with fluctuating temperature, we have to track the modulation frequency with an appropriate value based on the current temperature.

The stability of harmonically mode-locked lasers can be greatly improved by introducing a regeneration technique, in which the generated optical pulse train is detected to provide an electrical clock driving the mode locker [2-3]. This technique allows the laser to automatically adjust the pulse repetition frequency to an integer multiple of the cavity fundamental frequency, even as it fluctuates due to the temperature change.

In [4-5], we reported our experiments on pulse generation from a regeneratively mode-locked fiber

ring laser. In both experiments, we used the same experimental setup, in which a frequency divider was introduced into the clock extraction circuit. The results were, however, not similar. While ordinary harmonic mode-locking was reported in [4], a mode-locked pulse train with doubled repetition frequency was reported in [5].

The main difference between the two experiments was in the bias point of the Mach-Zehnder modulator used as the mode locker. A doubled repetition frequency was observed when biased in the vicinity of either the maximum transmission point or the minimum transmission point. To the authors' knowledge, [5] was the first report of repetition frequency-doubled operation of a harmonically mode-locked laser driven by a regenerated clock.

Multiplication of the pulse repetition frequency of harmonically mode-locked lasers has been reported in the context of rational harmonic mode-locking [6]. While harmonic mode-locking uses a driving clock with the same frequency as the pulse repetition frequency, rational harmonic mode-locking uses a subharmonic of the pulse repetition frequency. The repetition frequency of rational harmonic mode-locking then becomes an integer multiple of the clock frequency.

Our objective in this paper is to discuss the source of the doubled repetition frequency: is it rational harmonic mode-locking or ordinary harmonic mode-locking induced by the double-peaked profile of the optical transmittance? Here we report additional experiments exploring the origin of the frequency doubling.

The rest of this paper is organized as follows. A brief review of the principles and techniques for mode-locking of fiber lasers is found in Section 2. The experimental setup and results are discussed in Sections 3 and 4, respectively. Experiments to address the mechanism of mode-locking are described in Section 5, followed by brief conclusions in Section 6.

2. Harmonic and Rational Harmonic Mode-locking and Stabilization Using Regeneration Technique

In this section, we review harmonic mode-locking of a fiber ring laser and an associated clock regeneration technique. We also review rational harmonic mode-locking, a technique to multiply the repetition frequency, and the challenge of introducing the regeneration technique to this class of mode-locking.

We denote the fundamental frequency of the ring laser cavity as f_c. Harmonic mode-locking can be realized when the modulation frequency f_m is an integer multiple of f_c: $f_m = n \times f_c$, where the integer n is the harmonic order. If sufficient energy is provided in the cavity, n pulses will be generated in the ring cavity. Fig. 1(a) depicts a harmonically mode-locked ring laser with a harmonic order of eight. Thus, eight generated pulses circulate in the cavity.

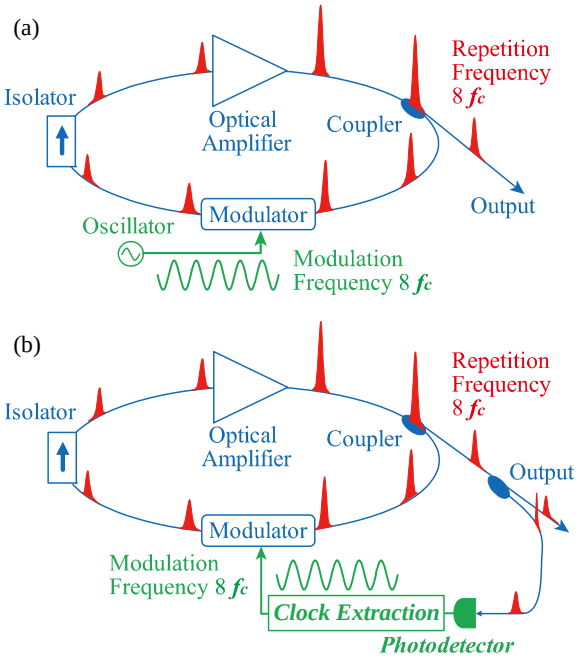


Fig. 1. (a) Harmonic mode-locking with harmonic order of eight and (b) its realization using regeneration.

The cavity length of fiber ring lasers often reaches several tens of meters, and the corresponding fundamental frequency becomes several megahertz. Considering application to telecommunications, where a bit rate of several tens of gigabits per second is expected, the repetition frequency should be on the order of tens of gigahertz, and a harmonic order of more than 1,000 is required.

Because the length of the fiber cavity is sensitive to temperature, the fundamental frequency of the fiber cavity changes according to the temperature drift in the environment; the corresponding modulation frequency for the harmonic mode-locking should be properly tuned to track the thermally induced change. To overcome this difficulty, a regeneration technique was developed [2-3].

Fig. 1(b) shows a regeneratively and harmonically mode-locked fiber laser with a harmonic order of eight. Part of the output pulse train is converted to an electrical pulse train, from which a sinusoidal clock of the pulse repetition frequency is extracted. This clock drives the modulator in the cavity. In this system, the modulation frequency is automatically adjusted to the pulse repetition frequency no matter as the cavity length changes under thermal drift.

When the regeneratively driven system is turned on, the modulating clock initiating the self-pulsing must be autonomously generated. This is realized by providing extremely high gain in the clock extraction circuit and by applying electrical phase shift to ensure positive feedback. This manipulation allows the laser

system to oscillate in the electrical domain and begin self-pulsing.

Our concern was whether we could apply the clock-regeneration technique to rational harmonic mode-locking. This class of mode-locking is realized when the modulation frequency is detuned from that of harmonic mode-locking by a fraction of the cavity fundamental frequency: $f_m = [n + (1/p)] \times f_c$, where the integer p is the rational harmonic order. Fig. 2 depicts the time relation between the modulation signal (indicated by the sinusoid) and pulses at the modulator when p is 2. One of the pulses labeled "A" returns to the modulator after circulating in the cavity with a delay of $1/f_c$, during which the modulation sinusoid goes through $n + (1/2)$ cycles. Hence, the pulse returns to the modulator at the timing of pulses labeled "B." After the next circulation, the pulse returns to the modulator with the timing of "A" pulses, so that the pulse becomes self-consistent after two circulations. The repetition frequency of the output pulses is then doubled. For the p^{th} rational harmonic order, the optical field becomes self-consistent after p circulations. In one cycle of sinusoidal modulation, p pulses will be generated, and thus the pulse repetition frequency will become $p\ f_m = (np + 1)\ f_c$.

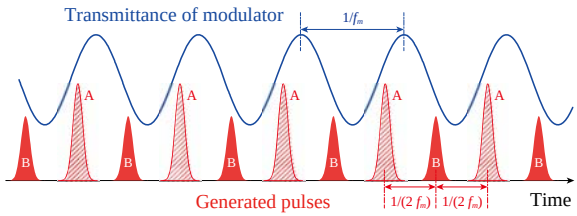


Fig. 2. Time relation between clock signal and generated pulses in rational harmonic mode-locking.

To introduce the regeneration technique to the rational harmonic mode-locking, we need to generate a modulating clock of a frequency f_m from the detected pulse train with a repetition frequency of $p\ f_m$. This function is realized by an electrical frequency divider, which is a digital circuit consisting of flip-flops and controlling logic gates.

The use of the frequency divider offers two advantages over frequency downconversion: the stability of the output amplitude and the high gain required at system start-up. These two merits originate from general features of digital electric devices, which are usually operated in saturated regions while providing extremely high gain in transient regions.

3. Experimental Setup

Fig. 3 shows the experimental setup. The ring laser resonator consisted of an LN intensity modulator (LNIM), an isolator, an erbium-doped fiber amplifier (EDFA), an optical bandpass filter (OBPF) with a bandwidth of 1 nm in full-width at half maximum, a 10 % output coupler, and a semiconductor optical amplifier (SOA). All fibers were polarization-maintaining.

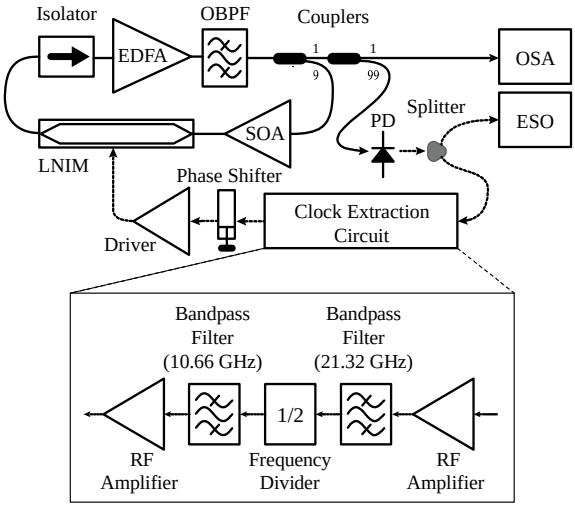


Fig. 3. Experimental setup. See text for abbreviations.

The optical gain in the cavity was mainly provided by the EDFA, while the SOA was operated in the vicinity of its transparency. The SOA was employed to suppress super-mode noise, which is the noise between competing sets of excited laser modes [4-6].

The laser output was split and fed to an optical spectrum analyzer (OSA) and to a high-speed photodetector (PD) with a bandwidth 60 GHz. The output of the PD was monitored by an electrical sampling oscilloscope (ESO), while it drove a clock extraction circuit. In the clock extraction circuit, the sinusoidal signal of 21.32 GHz synchronous with the output pulse train was extracted by an electrical bandpass filter and downconverted to its second subharmonic by the frequency divider. To eliminate distortion in the divider output, we used another bandpass filter that passed the frequency components around 10.66 GHz. An electrical phase shifter was employed to ensure positive feedback in the electrical domain. The driver of the modulator was an electrical amplifier with a limited bandwidth (8-12 GHz).

4. Results and Discussion

The operating mode greatly depends on the bias of the LNIM. For convenience, we define three bias points, the minimum transmission point H, the maximum transmission point Z, and the quadrature point Q. Fig. 4 depicts the relative intensity transmittance of the LNIM as a function of the applied voltage, where the minimum and maximum transmittances are scaled to zero and unity, respectively. The minimum and maximum transmittances were obtained when 6.448 V (H) and 1.230 V (Z), respectively, were applied to the modulator. The quadrature point was then estimated as 3.839 V (Q).

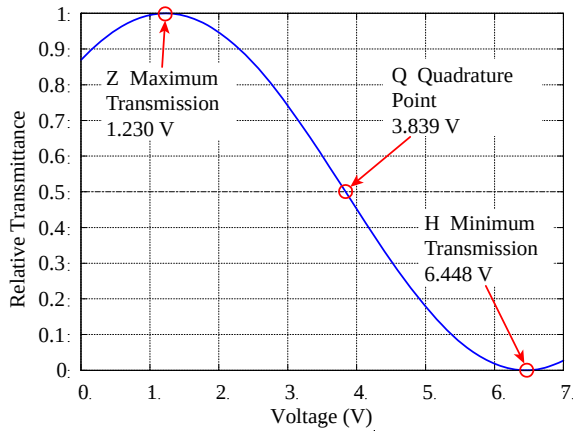
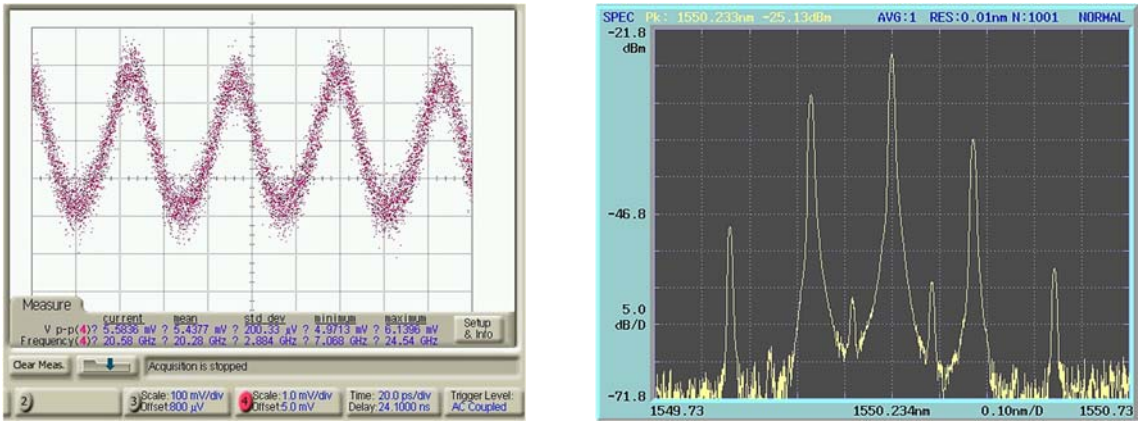


Fig. 4. Relative transmission of LNIM as a function of applied voltage.

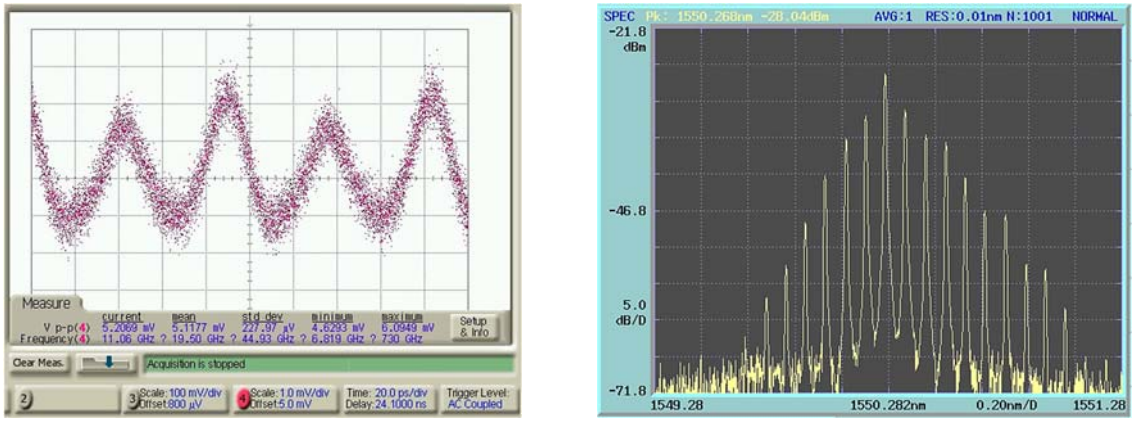
Fig. 5 (a) and Fig. 5 (b) show the oscilloscope traces of the detected pulse train and the corresponding optical spectrum, respectively, when the modulator was biased in the vicinity of the minimum transmission point H. A pulse train with a repetition frequency of 21.32 GHz was successfully obtained; the spectrum shows clear separation of 0.17 between adjacent longitudinal modes, which corresponds to the repetition frequency. We confirmed that the electrical signal driving the optical modulator was almost sinusoidal with a frequency of 10.66 GHz, the second subharmonic of the repetition frequency.

When the modulator was biased in the vicinity of the maximum transmission point Z, two pulses were observed within one cycle of the driving sinusoidal wave, as shown in Fig. 6(a), whereas Fig. 6(b) is the corresponding optical spectrum. In this case, however, the adjacent pulses had different shapes. Because the basic pattern of the pulse train is a pair of adjacent pulses, the repetition frequency of the basic pattern is 10.66 GHz, corresponding to a mode separation wavelength of 0.085 nm.



(a) (b)

Fig. 5. (a) Oscilloscope trace of pulse train when the modulator was biased in the vicinity of the minimum transmission. Horizontal scale is 20 ps/div, and vertical scale is linear arbitrary units. (b) Corresponding optical spectrum. Horizontal scale is 0.1 nm/div, and vertical scale is 5 dB/div.

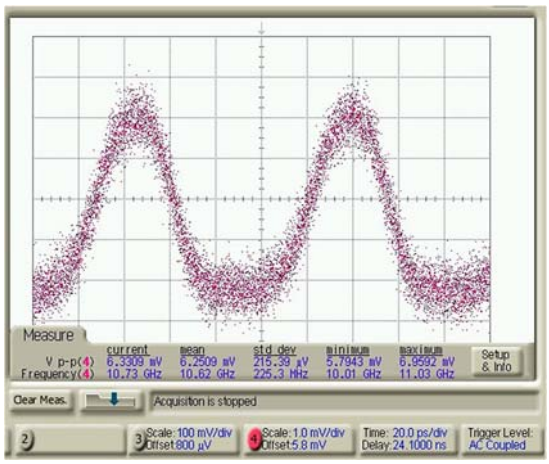


(a) (b)

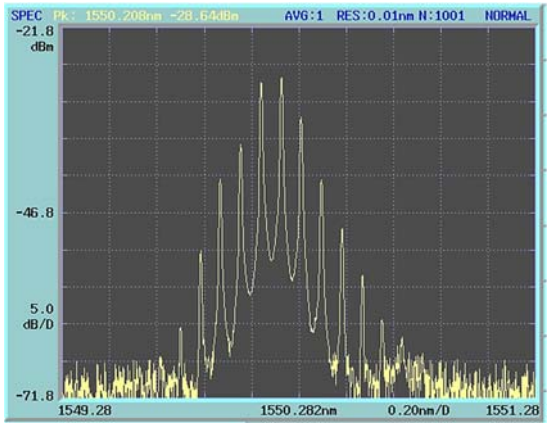
Fig. 6. (a) Oscilloscope trace of pulse train when the modulator was biased in the vicinity of the maximum transmission. (b) Corresponding optical spectrum. The scales are the same as those in Fig. 5.

Fig. 7(a) and Fig. 7(b) show the observed oscilloscope trace and the optical spectrum, respectively, when the modulator was biased in the vicinity of the quadrature point Q. The pulse repetition frequency was 10.66 GHz, the same frequency as that of the extracted clock. This mode of operation is the same as what was reported in [5].

Now, we discuss the relation between the bias points and the operation modes in relation to the temporal transmission of the modulator. When the modulator is biased at the minimum transmission point H and driven by a sinusoid with frequency f_m, the temporal transmission of the modulator shows a cyclic change with a frequency of $2f_m$, as depicted in Fig. 8(a). Since mode-locked pulses are developed in time with the maximum transmissions, a repetition frequency of $2f_m$ can be obtained.



(a)



(b)

Fig. 7. (a) Oscilloscope trace of pulse train when the modulator biased in the vicinity of the quadrature point. (b) Corresponding optical spectrum. The scales are the same as those in Fig. 5.

We can obtain similar behavior when the modulator is biased at the maximum transmission point Z. As shown in Fig. 8 (b), the frequency of the modulator transmission is $2f_m$, so that two pulses can be developed within one cycle of the sinusoidal driving voltage. In this case, however, the extinction ratio of the modulator transmission is smaller than what is expected at the minimum transmission point H. The smaller extinction ratio leads to weaker pulse shaping, resulting in adjacent pulses having different shapes.

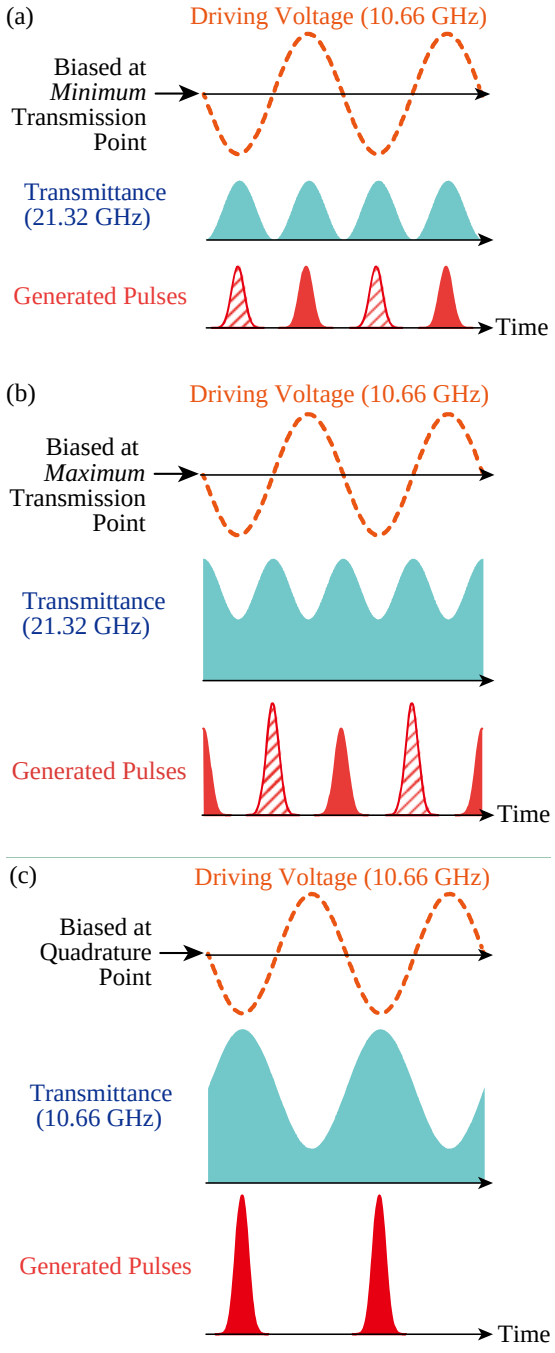


Fig. 8. Relation between driving voltage, transmission intensity of modulator, and generated pulses for (a) minimum, (b) maximum and (c) quadrature bias points.

When the modulator is biased at the quadrature point Q, the frequencies of the driving voltage and modulator transmission coincide, as shown in

Fig. 8(c). Therefore, the frequency multiplication observed in the first two cases cannot occur.

5. Rational or Ordinary Harmonic Mode-locking?

We observed in Section 4 that doubled repetition frequency was associated with a pair of transmission peaks occurring within one cycle of the regenerated 10.66 GHz clock. However, experimental results showed that the number of pulses was identical to the number of transmission peaks. Therefore, the pulsed operation could be caused by ordinary harmonic mode-locking at 21.32 GHz because there was no evidence to support rational harmonic mode-locking.

To identify the mode-locking mechanism, we conducted additional experiments using the setup in Fig. 9, which was similar to that shown in Fig. 3 except that a sinusoidal signal from a frequency synthesizer was applied to the LNIM. By changing the modulation frequency, we searched for the frequency ranges that realize harmonic or rational harmonic mode-locking. We measured the clock frequency using an electrical spectrum analyzer (ESA).

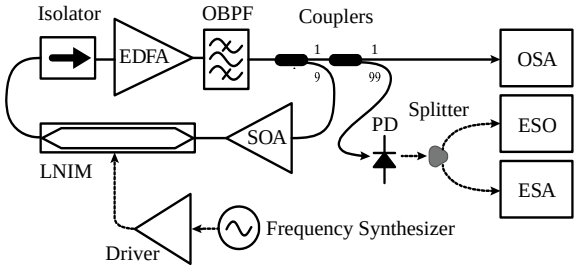


Fig. 9. Experimental setup to identify mode-locking frequencies. See text for abbreviations.

Fig. 10 shows the frequency ranges realized by pulsed oscillation, where the ranges are shown by thick vertical bars (red) with two thin horizontal lines indicating the upper and lower limits. The horizontal axis is the rational harmonic order *p*, whereas a rational harmonic order of 1 implies ordinary harmonic mode-locking.

Ordinary harmonic mode-locking was realized every 10.0 MHz over a frequency range that varied from 210 kHz to 250 kHz. From this result, we estimated the fundamental frequency of the laser cavity as 10.0 MHz.

Ranges of rational harmonic mode-locking showed a similar cyclic behavior, though the frequency was offset by about 5.0 MHz (exactly half of the fundamental frequency) and the range varied from 450 kHz to 530 kHz.

It is interesting to compare the frequencies of the regenerated clock observed in Figs. 5 and 6. The blue dots in Fig. 10 are the results, where H and Z correspond to the LNIM bias at the minimum transmission point (Fig. 5) and the maximum transmission point (Fig. 6), respectively. In both cases, the frequency of the regenerated clock fell within the range of rational harmonic mode-locking. All the trials we conducted produced the same results.

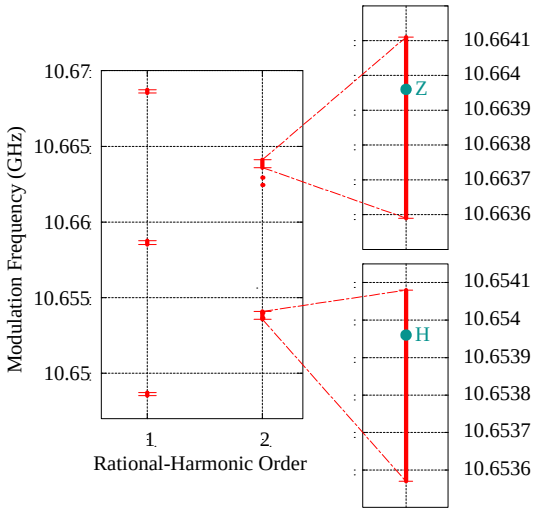


Fig. 10. Modulation frequencies achieving harmonic or rational harmonic mode-locking. Rational harmonic of the first order implies harmonic mode-locking. Filled circles are frequencies of the regenerated clock when repetition frequency doubling was observed. Bias of LNIM: Z is the maximum transmission point and H is the minimum transmission point.

If ordinary harmonic mode-locking at 21.32 GHz occurred, the regenerated clock frequency could be caused by the other mechanism by chance. However, this was not observed. Thus we conclude that the rational harmonic mode-locking is the origin of repetition frequency doubling.

6. Conclusions

In this paper, we reported our experiments with a regeneratively and harmonically mode-locked fiber ring laser in which a clock extraction circuit with frequency divider was introduced.

The operating mode changed according to the bias of the optical modulator. When the modulator was biased in the vicinity of the minimum or maximum transmission point, the pulse repetition frequency was doubled. Otherwise, the repetition frequency was identical to the modulation frequency. Good uniformity in the pulse shape was obtained in the vicinity of the minimum transmission point. Experiments using an external modulation signal showed that doubling of the repetition frequency was caused by rational harmonic mode-locking.

It is still an open question whether higher-order multiplication of the repetition frequency is possible. The present results suggest that it would be necessary to introduce several transmission peaks within one

cycle of the regenerated clock. To realize such a modulation profile, we must employ a modulator with an extremely low half-wave voltage and apply a large voltage swing spanning several transmission peaks. Since the operating frequency is fixed, resonant-type optical modulators [7] could be used for this application.

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