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Cost-effective method for generating >20 GHz pulse trains using actively mode locking fiber ring laser

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This study proposes a simple method to generate high-speed pulse of more than 20 GHz. Its cost performance ratio in an actively rational harmonic mode locking scheme is maximized when the multiplication factor $p = 4$ and 6. The operation is based on a relatively simple structure using the optical Mach–Zehnder modulator (MZM) biased at the minimum transmission peak and optical filtering via a Mach–Zehnder interferometer (MZI) comb filter. Stable and amplitude-equalized pulse trains with a repetition rate of ~20.345 GHz are successfully demonstrated.

Keywords: high-speed, millimeter wave, mode locking fiber laser, Mach–Zehnder interferometer, optical communications.

1. Introduction

A technique for generating pulse trains with high repetition rate is essential in high-speed optical communication systems [1], [2], millimeter wave and microwave photonic systems [3], and optical signal processing [4]. Obtaining ultra-high speed pulse trains at a few tens of GHz had proven to be difficult due to the limited operation bandwidth of the optical modulator and drive electronics. Several approaches have been attempted to overcome this problem and to increase the multiplication factor as high as possible given the low modulation frequency f_m [5]–[7]. Optimization of the biasing point of an optical Mach–Zehnder modulator (MZM) was utilized to double the fundamental driving RF frequency [5], [6]. In particular, high RF power (>25 dBm) has been incorporated to achieve quadruple frequency [7].

In another method, novel techniques called rational harmonic mode locking have been used to obtain the harmonic repetition rate of frequency f_m [8]–[10]. In this technique, when $f_m = (n + 1/p) f_c$ (where n and p are integers, and f_c is the fundamental cavity frequency), the pulse trains with a repetition rate of $f_{\text{out}} = p \times f_m = (np + 1) f_c$ are provided. Nonetheless, it suffers from amplitude fluctuations by randomly oscillating lower harmonics for $p > 2$. To suppress the lower harmonics, several methods have been proposed including additive pulse limiting [11], use of a Faraday rotator and a nonlinear loop mirror [12], use of a semiconductor optical amplifier loop mirror [13], and employment of an intra-cavity optical filtering via a Fabry–Perot etalon filter [14] and a composite ring cavity [15]. In spite of the good performance of these methods, their efficiency is still doubtful even in the cases of $p < 6$ when considering their cost performance ratio. To maximize the cost performance ratio, a study on simpler methods should be done. As such, a Mach–Zehnder interferometer (MZI) comb filter is proposed to suppress the unmatched lower modes. The MZI filter is encouraged by several outstanding terms (*i.e.*, low-cost, all-fiber device, *etc.*), however such method suffers from low finesse. In this study, a method capable of overcoming the low finesse of the MZI comb filter and maximizing the cost performance ratio when $p = 4$ and 6 was investigated.

2. Working principle

The main operation is done through the combination of frequency doubling in the optical MZM and optical filtering via MZI comb filter. It is assumed that the MZM is biased at the minimum transmission peak and is modulated at $f_m = (n + 1/4) f_c$. This corresponds to the 4-th rational harmonic mode locking. Since the MZM is biased at the minimum transmission peak, the fundamental modulation frequency in the ring cavity is doubled to $2f_m$. Hence, the odd multiple frequencies of f_m (*e.g.*, f_m, $3f_m$, $5f_m$, ...) would be appreciably suppressed (Fig. 1). The detailed operation will be experimentally described later.

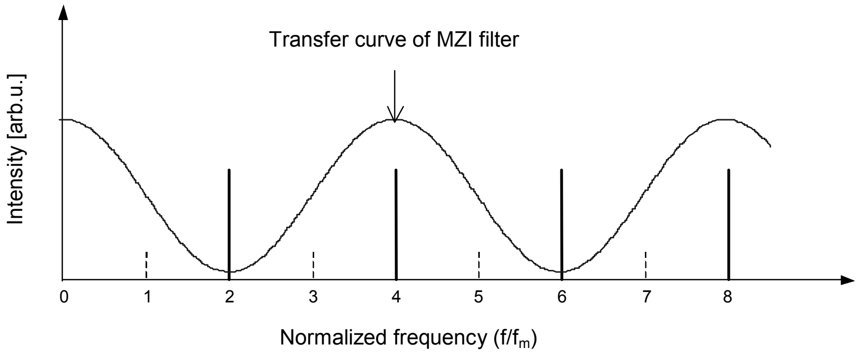

Fig. 1. Spectral view showing the working principle.

For the resultant $p = 4$ pulse trains to be stable, their RF spectrum should contain only multiple frequencies of $4f_m$ (*e.g.*, $4f_m$, $8f_m$, $12f_m$, ...), removing all other frequencies (*e.g.*, $2f_m$, $6f_m$, $10f_m$, ...). This is achieved through intra-cavity optical filtering via the MZI comb filter with the free spectral range (FSR) of $4f_m$. The MZI comb filter consists of two 3-dB optical couplers interconnected through two paths of varying lengths. Assuming that the difference between these two paths is ΔL and that only one input, *e.g.*, input 1, is active, then two output power transfer functions of the MZI filter are given by:

$$\begin{bmatrix} T_{11}(f) \\ T_{12}(f) \end{bmatrix} = \begin{bmatrix} \sin^2(\beta\Delta L/2) \\ \cos^2(\beta\Delta L/2) \end{bmatrix}$$

where β is the propagation constant. The power transfer curve is shown in Fig. 1. It shows a periodically sinusoidal frequency. Note that all frequency components at $2f_m$, $6f_m$, $10f_m$, ..., are exactly positioned at minimal points of the MZI transfer curve and their powers must be suppressed at the output of the MZI filter. Hence, the effect of low finesse of the MZI comb filter can be reduced, especially when $p = 4$. Without complicated set-ups used in papers [11]–[13], then, $p = 4$ amplitude-equalized pulse trains can be obtained.

3. Experimental setup

The experimental setup is shown in Fig. 2. A 12 m erbium-doped fiber amplifier was pumped with a 980 nm pump laser diode through a 980/1550 WDM, and an isolator was inserted at the output port. The optical power injected into the laser cavity was 9 mW, driven by a pumping current of 250 mA. A $LiNbO_3$ MZM with 4 V switching voltage was used for the intensity modulation in the laser cavity. It was driven by the RF power of +18 dBm using a 10 GHz RF amplifier. The resultant pulse trains were extracted through a 90:10 optical coupler. They were measured using a sampling oscilloscope with 17.6 rise time and an RF spectrum analyzer with 3 MHz resolution bandwidth. The MZI was composed of two 3 dB optical couplers. An optical delay

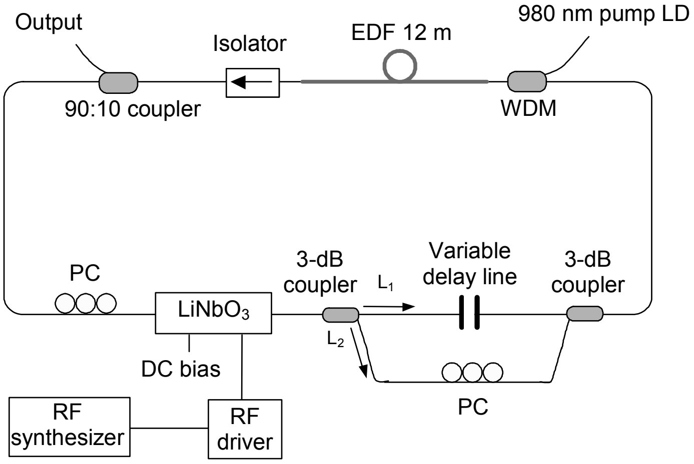

Fig. 2. Experimental setup (EDF – erbium-doped fiber, WDM – wavelength-division multiplexer, PC – polarization controller, $LiNbO_3$ – optical Mach–Zehnder modulator).

line was incorporated in the upper arm so as to offer the time delay between two paths to control the FSR of the MZI.

4. Results and discussion

For the $p = 4$ pulse multiplication, the RF signal of 5.08497 GHz, denoted by f_m, was applied to the MZM. For the cavity including the lower arm L_2, the fundamental cavity frequency f_c was measured as 5.0849 MHz (*i.e.*, cavity length of ~40.45 m). The 5.08497 GHz was approximately equivalent to the 1000-th harmonics for the fundamental cavity frequency.

The MZM was biased at $V_\pi/2$, where V_π was the switching voltage. Since the applied RF signal had the on-off swing in the linear gain curve of the MZM, the signal

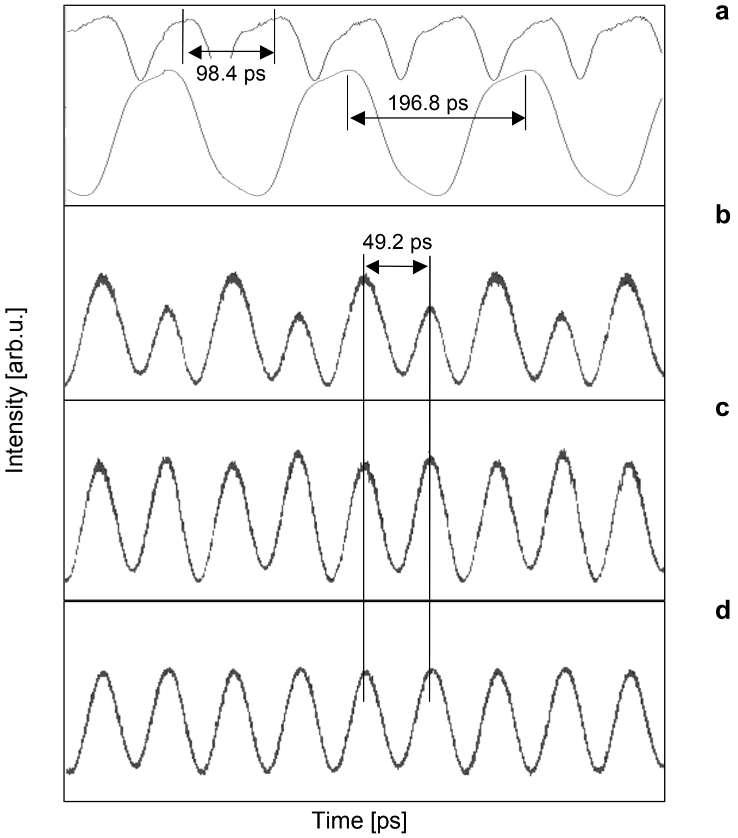

Fig. 3. Oscilloscope traces when $p = 4$; **a** – lower line: input electrical driving signal, upper line: output trace of the MZM; **b** – harmonic mode locking without the MZI filter (f_{m1} = 5.08497 GHz ≈ $1000 f_c$); **c** – rational harmonic mode locking without the MZI filter (f_{m1} = 5.08625 GHz ≈ $(1000 + 1/4) f_c$); **d** – rational harmonic mode locking with the MZI filter (f_{m1} = 5.08625 GHz).

with the same frequency as that of the input RF signal was observed at the output of the MZM. This is shown in the lower trace in Fig. 3**a**.

While the bias of the MZM was moved to 0 V, the minimum transmission peak of the MZM, the input RF signal was put in the nonlinear gain curve; hence the output signal of the MZM was doubled in frequency. Examining the upper trace in Fig. 3**a**, it was shown that the resulting signal frequency was approximately $2f_m$: ~10.169 GHz with a repetition period of ~98.4 ps, where the modulation depth decreased by 1/2. Figures 3**b** and 5**a** show the temporal and RF spectral shapes at the output of the ring laser. Although the doubled frequency $2f_m$ corresponded to 2000-th harmonic frequency, the temporal pulse trains were inconsistent with typical harmonic mode locking pulse trains, due to the decreased modulation depth. Also, the dominant frequency components at $2f_m$ and $4f_m$ were observed, as expected.

Modulation frequency was slightly increased by $f_c/4$ (~1.272 MHz) to 5.08625 GHz, denoted by f_{m1}. This was the case of 4-th rational harmonic mode locking with the frequency doubling in the MZM. The resulting pulse trains are shown in Fig. 3**c**. Compared to those in Fig. 3**b**, the pulse amplitudes were remarkably equalized due to the rational harmonic mode locking effect. Nonetheless, further studies should be done to improve the pulse quality.

To suppress such undesirable frequency components at $2f_{m1}$, the MZI comb filter was used. This could be made by connecting the path including the upper arm. The FSR of the filter was adjusted into $4f_{m1}$ (~20.345 GHz), the frequency components at $2f_{m1}$, $6f_{m1}$, $10f_{m1}$, ..., were exactly matched to the minimal transmission points of the MZI filter and appreciably removed. As a consequence, perfectly amplitude-equalized pulse trains were obtained (Fig. 3**d**). The corresponding optical and RF spectra are shown in Figs. 4 and 5**b**. In the optical spectrum, the lasing wavelength was 1564 nm when the polarization state in the ring cavity was well tuned for overall pulse

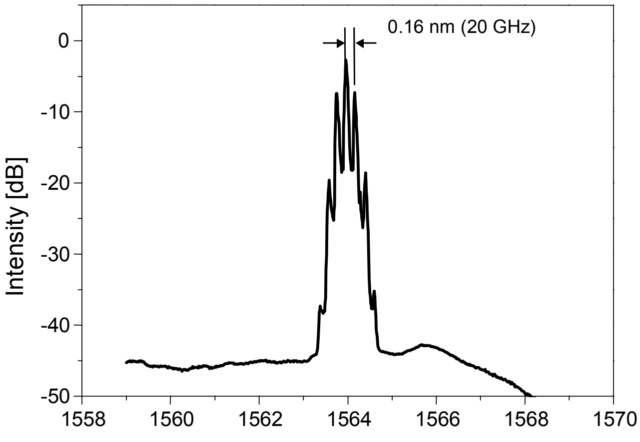

Fig. 4. Optical spectrum when $p = 4$ rational harmonic mode locking with the MZI filter ($f_{m1} = 5.08625$ GHz).

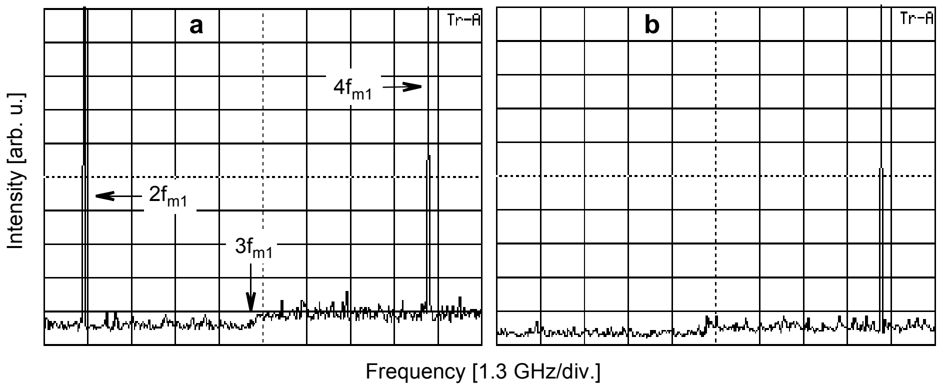

Fig. 5. RF spectra when $p = 4$; **a** – harmonic mode locking without the MZI filter ($f_{m1} = 5.08497$ GHz); **b** – rational harmonic mode locking with the MZI filter ($f_{m1} = 5.08625$ GHz).

amplitudes to be equalized. The spectral linewidth at 3 dB was 0.089 nm, showing the optical signal-to-noise ratio of >45 dB. From the figure, the free spectral range of ~0.16 nm (20 GHz) can be evidence confirming the pulse repetition rate of ~20 GHz.

In the RF spectrum, the unmatched lower harmonics (*i.e.*, $2f_{m1}$, $3f_{m1}$) observed in Fig. 5**a** were suppressed (Fig. 5**b**).

In addition, to demonstrate the case of $p = 6$, the modulation frequency was changed to 3.39082 GHz (f_{m2}); this in turn was detuned by 1/6 at the 667-th harmonics of f_c. Before connecting the MZI filter, the pulse trains of Fig. 6**a** were obtained by biasing the MZM at the minimum transmission peak. Great amplitude fluctuations were observed. As seen in Fig. 7**a**, the frequency component at $3f_{m2}$ (~10.172 GHz) was a dominant noise source. This term was removed by the MZI filter. Figure 6**b**

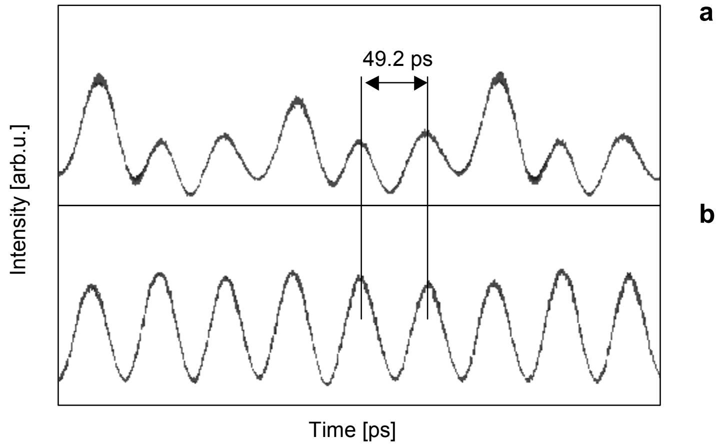

Fig. 6. Oscilloscope traces when $p = 6$; **a** – rational harmonic mode locking without the MZI filter ($f_{m2} = 3.39082\ \text{GHz} \approx (667 - 1/6) f_c$); **b** – rational harmonic mode locking with the MZI filter ($f_{m2} = 3.39082$ GHz).

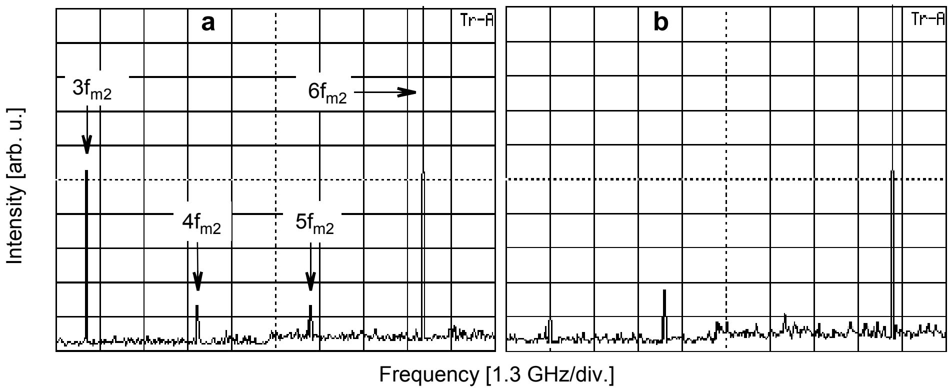

Fig. 7. RF spectra when $p = 6$; **a** – rational harmonic mode locking without the MZI filter (f_{m2} = 3.39082 GHz); **b** – rational harmonic mode locking with the MZI filter (f_{m2} = 3.39082 GHz).

gives the resulting pulse trains whose amplitudes were remarkably equalized. In the RF spectrum of Fig. 7**b**, it was shown that the frequency component at $3f_{m2}$ disappeared. Nonetheless, low frequency peaks were observed at $2f_{m2}$ and $4f_{m2}$ because the transfer curve of the MZM was not minimal on those positions.

In summary, it is impossible to remove all undesirable frequency components simultaneously through optical filtering using the MZI filter due to its very low frequency selectivity (*i.e.*, low finesse). Nonetheless, this study demonstrated that highly stable pulse trains could be generated especially for $p = 4$ rational harmonic mode locking. The modulation frequency was doubled by biasing the MZM to the minimum transmission peak. The doubled frequency $2f_m$ was removed through the MZI filter with the FSR of $4f_m$. This scheme can also be useful in providing 8-th pulse trains by quadrupling frequency $4f_m$, which could be achieved by driving the modulator with high RF power (>25 dBm) [7] and adjusting the FSR of the MZI filter into $8f_m$.

The method proposed has a very simple structure composed of the MZI for optical filtering. It was also proven that its ultimate performance is good enough to be applicable in generating high-speed optical pulses at sub-millimeter wave band. More compact and stable implementation may be possible with the help of current state-of-the art planar lightwave circuits (PLC) technology.

5. Conclusions

A simple method of maximizing the cost performance ratio in generating > 20 GHz pulse trains for $p = 4$ rational harmonic mode locking fiber laser was employed. The applied RF frequencies were 5.08625 GHz ($p = 4$) and 3.39082 GHz ($p = 6$), which were doubled at the output of the MZM. The 4-th and 6-th harmonics of the modulation frequency were selected using the MZI comb filter with the FSR of ~20.345 GHz. Other lower harmonics were suppressed.

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