Frequency division of optical pulse train based on an optoelectronic oscillator

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***Abstract*—An optoelectronic-oscillator based repetition rate divider for a mode-locked laser is proposed. A 101.8-MHz optical pulse train is divided to be a 50.9-MHz optical pulse train, i.e., a division factor of 2 is achieved.**

Keywords—frequency division, optoelectronic oscillator

I. INTRODUCTION

The advent of the mode locking technologies make it easy to generate an optical pulse train (OPT) with ultra-high peak power and ultra-narrow pulse width. Due to the outstanding coherence between each optical spectral component, the mode-locked laser (MLL) is employed in various scientific research fields, such as optical sampling [1], photonic radars [2], quantum optics [3]. Generally, MLLs can be classified into two types: passive MLL and active MLL. Compared with the active MLL, the passive MLL attracted more attentions thanks to its ultra-low timing jitters which is quite rigorous for specific applications such as microwave signal generation and processing [4] and high resolution spectroscopy [5]. However, its repetition rate is hardly to be tuned since it is inversely proportional to the cavity length of the MLL, seriously limiting their utility in many applications. In order to improve the repetition rate tunability of OPT, it is essential to adjust the repetition rate of the OPT outside the laser cavity. One approach to achieve frequency division is to use an acousto-optic modulator [6], where the modulation signal and the OPT are both synchronized to an Rb atomic clock, and the modulation signal is generated by a frequency synthesizer or a pulse generator, which has a complex structure and is difficult to synchronize at arbitrary frequencies.

In this paper, a frequency divider to realize repetition rate division of OPTs is proposed and demonstrated based on an optoelectronic oscillator (OEO). The key component in the proposed scheme is a Mach-Zehnder modulator (MZM), which serves as an optical switch and also an electrical to optical converter in the optoelectronic oscillation loop. When the bias voltage of the MZM is set appropriately, the repetition rate of the pulse train can be divided by the time the OEO reaches a steady state. The use of the OEO eliminates the need for external signal source and complicated synchronization setup.

II. PRINCIPLE

The schematic diagram of the proposed OEO-based frequency divider is shown in Fig. 1. An OPT with a repetition rate of f_{rep} is generated by an MLL and is straight forward to the MZM, which is then split into two ways by an optical coupler (OC). One way is connected to an oscilloscope (OSC) to monitor the repetition rate and the amplitude of the OPT, and the other way, which remains in the loop for optoelectronic oscillation, is injected into a photodetector (PD) that converts the optical signal into an RF signal. An bandpass filter (BPF1) with a narrow bandwidth and an appropriate central frequency is followed to eliminate the undesired harmonics of the MLL. An electrical amplifier (EA) is utilized to amplify the signal from BPF1, and BPF2 is used to remove the redundant noise introduced by the EA. As same as the traditional OEO, the BPFs determine the frequency of the oscillating signal. An electrical coupler (EC) located after the BPF2 is utilized to divide the oscillation signal into two paths. One is served as a monitoring signal linked to an electrical spectrum analyzer (ESA) to observe the output of the OEO, while the other path is transmitted to the MZM to construct the OEO after passing through a phase shifter (PS). When the central frequencies of the BPFs equal $1/2{\cdot}f_{\mathrm{rep}}$ or $1/3{\cdot}f_{\mathrm{rep}}$ or $2/3{\cdot}f_{\mathrm{rep}}$, one-second or one-third repetition rate division can be achieved, respectively.

The mathematical deduction is conducted below. Since the whole process of an OEO is relatively complicated, only the steady-state is considered here for simplicity. The OPT from the MLL can be written as

$$E_{\mathrm{pulse}}(t) = \sqrt{P}\sum_{n=0}^{\infty}\delta\Big(t - n\frac{1}{f_{\mathrm{rep}}}\Big), \tag{1}$$

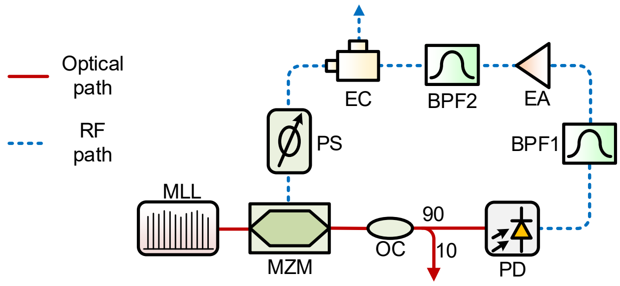

Fig. 1. Schematic diagram of the proposed frequency divider. MLL: mode locked laser; MZM: Mach-Zehnder modulator; OC: optical coupler; PD: photodetector; BPF: bandpass filter; EA: electrical amplifier; EC: electrical coupler; PS: phase shifter.

where P is the peak power of each pulse. The ideal central frequency of the BPF is $q \cdot f_{rep}$, and q equals 1/2, 1/3 and 2/3. Thus the microwave signal obtained from the OEO is written as

$$m(t) = A\sin\{2\pi[(N+q)f_{\mathrm{rep}}t]+\varphi\}, \tag{2}$$

where A and φ are the amplitude and phase of the microwave, respectively. N is an integer. The transfer function of the MZM can thus be expressed as

$$h(t)=\cos\{\frac{\pi a}{V_\pi}\cos[2\pi(N+q)f_{\mathrm{rep}}t]+\theta\}, \tag{3}$$

where a is the amplitude of the microwave, V_π and θ are the half-wave voltage and the bias phase of the MZM, respectively. In this way, the output of the MZM is generated, given by

$$\begin{aligned} E(t) &= E_{\mathrm{pulse}}(t)\cdot h(t) \\ &= \sqrt{P}\sum_{n=0}^{\infty}\cos[\frac{\pi a}{V_\pi}\cos(2\pi nq)+\theta]\delta(t-n\frac{1}{f_{\mathrm{rep}}}). \end{aligned} \tag{4}$$

By appropriately selecting values of a and θ, frequency division can be accomplished as shown in Eq. (4). For the case where q equals 1/2, the repetition rate of the OPT should be reduced by 2 times compared to its initial value. Accordingly, only n equals 0 and 1 are considered and a set of formulas can be obtained

$$\begin{cases} \cos(\frac{\pi a}{V_\pi}+\theta)=1 \\ \cos(-\frac{\pi a}{V_\pi}+\theta)=0 \end{cases}. \tag{5}$$

One of the solutions is

$$a=-\frac{V_\pi}{4},\quad \theta=\frac{\pi}{4}. \tag{6}$$

Thus Eq. (4) is turned to

$$E(t)=\sqrt{P}\sum_{k=0}^{\infty}\delta(t-2k\frac{1}{f_{\mathrm{rep}}}), \tag{7}$$

where k is an integer. It can be observed that the repetition rate is divided by 2 from the formula. For values of q equal 1/3 and 2/3, the derivation process is the same as when q equals 1/2, only the results of a and θ are different and displayed below,

$$a=-\frac{V_\pi}{3},\quad \theta=\frac{\pi}{3}. \tag{8}$$

In this way, repetition rate division factor of 3 can be realized.

Fig. 2 shows the simulation results for repetition rate division factors of 2 and 3, in which, the original pulses of the OPT (blue-solid), the transmission functions of the MZM (green-dotted) and the frequency divided pulses (orange-dashed) are displayed. The repetition rate of the original OPT is set to be 102 MHz, and the frequencies of the driving signal of the MZM are set to be 51 MHz, 34 MHz and 68 MHz, equivalent to 51 MHz + Nf_{rep}, 34 MHz + Nf_{rep} and 68 MHz + Nf_{rep}, respectively. Fig. 2(a) illustrates the case that the MZM is driven by the 51-MHz signal, causing a repetition rate division factor of 2. Fig. 2(b) and (c) show the results that the frequencies of the driving signal are 34 MHz and 68 MHz, respectively, leading to a repetition rate division factor of 3.

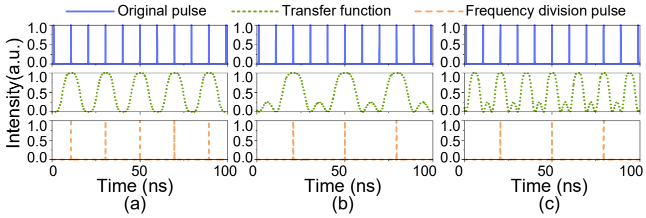

Fig. 2. The OPT before and after the MZM, and the transfer function of the MZM with (a) 51-MHz driven signal, (b) 34-MHz driven signal, and (c) 68-MHz driven signal.

III. Results

A proof-of-concept experiment is carried out based on the setup in Fig. 1. An OPT with a repetition rate of 101.8 MHz is emitted by an MLL (PriTel, FFL-FR-100MHz), which is transmitted to an MZM (iXblue, MXAN-LN-40). The output of the MZM is split into two paths using a 90:10 OC. The low power port is connected to an OSC (Tektronicx, DSA72004B) for monitoring, while the other port is injected into a PD (THORLABS, PDB450C). A BPF (BPF1) with a 3-dB bandwidth of 10 MHz and a central frequency of 50 MHz, corresponding to roughly half the repetition rate of the OPT, is followed to select the wanted frequency component. An EA and another BPF (BPF2) with the same central frequency as BPF1 are placed after BPF1. Subsequently, an EC divides the signal into two sections. One section feeds back to the MZM after passing through a PS to construct the OEO loop, and the other section, served as the RF output, is connected to an ESA (Rohde & Schwarz, FSV). By tuning the PS and the bias voltage of the MZM, a signal with a frequency of 50.9 MHz is stably generated as shown in Fig. 3, which means that the repetition rate of the OPT is divided by 2 successfully.

Fig. 4(a) shows the optical pulse envelope recorded by the OSC, where the blue-dotted and red-solid lines represent the original and the frequency-divided OPT, respectively. It can be seen from Fig. 4(a) that the repetition rate of the OPT is successfully divided by 2, and the time period becomes twice the original OPT. In Fig. 4(b), the frequency components of the OPT around 8 GHz are displayed, the blue-dotted and red-solid curves denoting the spectrum before and after the frequency division process, respectively. Fig. 4 clearly presents that the OPT repetition rate is successfully divided by 2.

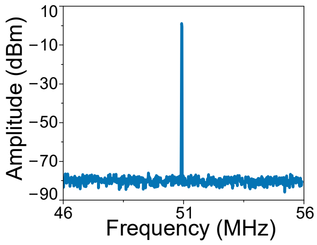

Fig. 3. Spectrum of the output microwave signal of the OEO.

Due to the limitations of the BPF we have, no experiments are carried out to demonstrate the repetition rate division factor of 3. However, the simulation results proves the feasibility of the scheme, and we believe that the one-third repetition rate division can be realized with suitable filters.

IV. Conclusion

In conclusion, an approach to performing repetition rate division for an MLL is proposed taking advantages of an OEO, which has been experimentally validated with promising results. Both simulation and experiment results

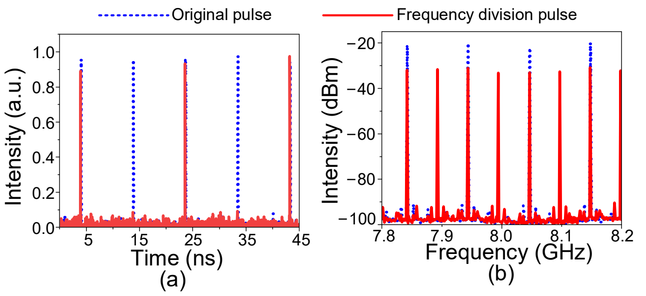

Fig. 4. (a) Waveform and (b) spectrum of the OPT when the repetition rate is divided by 2.

suggest that the repetition rate of the OPT can be frequency-divided successfully. A 101.8-MHz OPT is divided to be a 50.9-MHz OPT based on the proposed structure. And frequency division factor of 3 can also be realized if a suitable BPF is employed. The proposed system can significantly improve the frequency tunability of a passive MLL.

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