IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 1, February 2018

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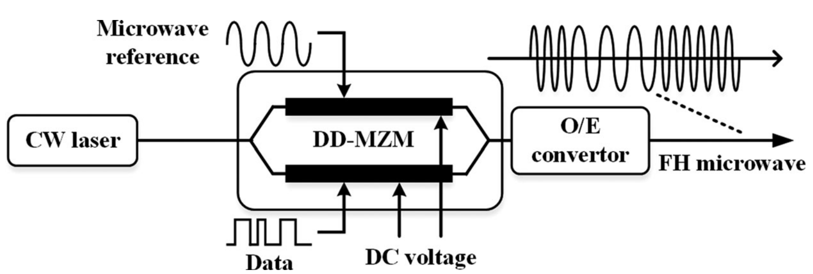

DOI: 10.1109/JPHOT.2018.2797273
1943-0655

High-Speed and Wideband Frequency-Hopping Microwave Signal Generation via Switching the Bias Point of an Optical Modulator

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DOI:10.1109/JPHOT.2018.2797273

Manuscript received December 19, 2017; revised January 16, 2018; accepted January 20, 2018. Date of publication January 24, 2018; date of current version February 21, 2018. This work was supported in part by the National Natural Science Foundation of China under Grant 61601297, in part by Open Fund of IPOC (BUPT) and in part by the Fundamental Research Funds for Central Universities. (e-mail: ychen@ce.ecnu.edu.cn).

Abstract: A novel photonic approach to generate high-speed and wideband frequency-hopping microwave signal via switching the bias point of a dual-drive Mach-Zehnder modulator (DD-MZM) is proposed and experimentally demonstrated. The core component of the system is a DD-MZM. By switching the bias point of the DD-MZM between the quadrature transmission point and the minimum transmission point, frequency hopping between two frequencies can be realized with an ultra-high frequency-hopping speed and a very wide bandwidth. The proposed approach has a compact structure and good tunability. A proof-of-concept experiment is performed to verify the principle of the proposed technique. Tunable frequency-hopping microwave signals between two frequencies of 4 and 8 GHz, 9 and 18 GHz, or 12 and 24 GHz are generated with a frequency-hopping speed up to 1 GHz.

Index Terms: Microwave photonics, frequency hopping, radar, modulators.

1. Introduction

Frequency-Hopping (FH) microwave signal is an important kind of signal widely used in wireless communication systems and radar systems [1], [2]. For the wireless communication system, the FH microwave signal can significantly increase the capacity of the system without introducing interferences. For the radar system, the FH microwave signal can greatly increase the time-bandwidth product (TBWP) to provide both high detection range and high range resolution [3], [4]. Conventionally, FH microwave signals are generated in the electrical domain using electronic devices, which is a very mature technique. However, the well-known electronic bottleneck limits the operating bandwidth and reachable frequency of the electronic devices, thus leading to a relatively small FH range (limited to GHz) of the electrical FH microwave signal generator. In addition, the FH speed of the electrical FH microwave signal generator is also limited to order of kHz [5]. As a result, the traditional electrical FH microwave signal generator cannot fulfill the new requirement raised by the latest applications, where large FH range and high FH speed are desired.

Photonic generation of microwave signals has been a topic of interest during the past few years, by taking the advantages, such as low loss, large bandwidth, high operating frequency and immunity to electromagnetic interference, offered by modern photonics [6], [7]. Many research works have been done to generate different kinds of microwave signals, for instance, pure microwave signals [8], phase-coded microwave signals [9], [10], microwave square or triangular waveforms [11], [12], etc. Microwave photonics also provides a promising solution to generate FH microwave signals to overcome the disadvantages encountered in traditional electrical FH microwave signal generator and match the rapid development of FH technology in the latest applications. Different photonic-assisted FH microwave signal generation approaches have been proposed in recent years [5], [13]–[15]. In [13], frequency-sweep microwave signals are generated using a distributed Bragg reflector (DBR) laser cascaded with a Mach-Zehnder interferometer structure. The frequency sweeping is realized via tuning the wavelength of the laser by controlling the voltage of the phase section of the DBR laser. In [14], the interferometer structure is avoided by employing a fixed wavelength laser and a wavelength sweeping laser instead of the DBR laser. By sweeping the wavelength of the wavelength sweeping laser, a frequency-sweep microwave signal is generated. However, since two independent laser sources are used, an optical phase-locked loop (OPLL) with ultra-fast response time should be employed to dynamically lock the phase between the two lasers during fast wavelength sweeping. Furthermore, the tuning speed of the generated microwave signals in [13], [14] are limited to several MHz, which is associated with the modulation speed of the laser source. An optoelectronic oscillator (OEO) based FH microwave signal generation approach is proposed in [5]. By switching the polarization state of the continuous-wave (CW) laser using a polarization modulator (PolM), whose direct current (DC) bias port is driven by a control signal, the oscillation frequency is correspondingly shifted, resulting in the generation of a FH microwave signal. However, when the oscillation frequency is shifted, there should be a time for the establishment of a new stable oscillation, which will limit the FH speed. In addition, the control signal is applied to the DC port of the PolM, which has a relatively low response bandwidth, thus also leading to a limited FH speed. In the experiment, only 10-MHz FH speed is demonstrated. In [15], FH microwave signal generation based on an optically injected semiconductor laser is proposed, where the demonstrated FH speed is about 100 MHz.

In this paper, a novel photonic approach to generate high-speed and wideband FH microwave signal via switching the bias point of a dual-drive Mach-Zehnder modulator (DD-MZM) is proposed, which has a very simple system structure. By switching the bias point of the DD-MZM between the quadrature transmission point (QTP) and the minimum transmission point (MITP), frequency hopping between two frequencies can be realized with an ultra-high FH speed and a very wide bandwidth. A proof-of-concept experiment is performed. Tunable FH microwave signals bouncing between 4 and 8 GHz, 9 and 18 GHz, or 12 and 24 GHz are generated with a FH speed up to 1 GHz.

2. Principle of Operation

Fig. 1 shows the schematic diagram of the proposed high-speed and wideband FH microwave signal generator. A light wave generated from a CW laser is injected into a DD-MZM, which has two modulation arms with independent radiofrequency (RF) ports and DC ports. The RF ports of the two arms are driven by a microwave reference signal and a binary data signal, respectively, whereas the DC ports of the two arms are driven by a DC voltage to introduce a phase difference between the two arms. The optical signal generated from the DD-MZM is then sent to an optical-to-electrical (O/E) convertor to generate the desired FH microwave signal.

The optical signal from the CW laser is expressed as $E_{in}(t) = E_0 \exp(j\omega_c t)$, where E_0 and ω_c are the amplitude and angular frequency of the optical signal, respectively. A sinusoidal microwave reference signal $V(t) = V_0 \cos(\omega_s t)$, where V_0 and ω_s are the amplitude and angular frequency of the microwave reference signal, is applied to one modulation arm of the DD-MZM. A binary data signal with an amplitude of V_s is applied to the other arm of the DD-MZM, which is expressed as $V_s S(t)$. The DC bias voltage between the two modulation arms is V_{DC}. The optical signal from the

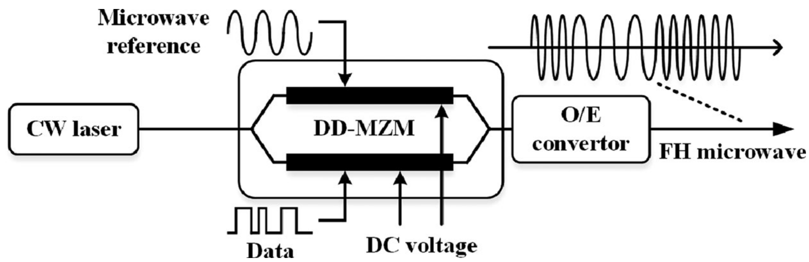

Fig. 1. Schematic diagram of the proposed high-speed and wideband frequency-hopping microwave signal generator. CW laser, continuous-wave laser; DD-MZM, dual-drive Mach-Zehnder modulator, O/E convertor, optical-to-electrical convertor.

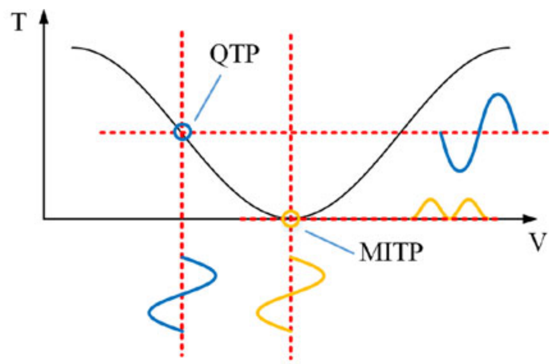

Fig. 2. Transmission characteristics of the DD-MZM in different transmission points. QTP, quadrature transmission point, MITP, minimum transmission point.

DD-MZM is expressed as

$$E(t) = E_{in}(t)\cos\left(\frac{\pi\left(V_0\cos\omega_s t - V_s S(t) - V_{DC}\right)}{2V_\pi}\right)\exp\left(j\frac{\pi\left(V_0\cos\omega_s t + V_s S(t) + V_{DC}\right)}{2V_\pi}\right), \quad (1)$$

where V_π is the switching voltage of the DD-MZM. By beating the optical signal in (1) in an O/E convertor, for example, a p-i-n photodetector (PD), the photocurrent from the O/E convertor is

$$\begin{aligned} i(t) &= RE(t)E^*(t) \\ &= \frac{1}{2}RE_0^2 + \frac{1}{2}RE_0^2\cos\left(\frac{\pi\left(V_0\cos\omega_s t - V_s S(t) - V_{DC}\right)}{V_\pi}\right), \end{aligned} \quad (2)$$

where R is responsivity of the PD. The normalized transmission function of the system can be expressed as

$$T = \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi\left(V_0\cos\omega_s t - V_s S(t) - V_{DC}\right)}{V_\pi}\right) \quad (3)$$

We can understand the transmission function in (3) in this way: the bias voltage V_{DC} introduces a static bias voltage, and the binary data signal $V_s S(t)$ introduces a dynamic bias voltage. The static bias voltage and the dynamic bias voltage jointly determine the bias point of the DD-MZM, so they determine the transmission characteristic of the input sinusoidal microwave reference signal in the system. Fig. 2 shows a diagram of the transmission characteristics of the DD-MZM in two specific bias points.

As can be seen from Fig. 2, when a sinusoidal microwave reference signal at the frequency of ω_s is applied to a DD-MZM, different bias points result in different transmission characteristics. For instance, if the DD-MZM is working at the QTP, the system has the best linearity, and an approximately sinusoidal microwave waveform at ω_s is correspondingly generated. In contrast, if the DD-MZM is working at the MITP, the system has large nonlinearity, and an approximately sinusoidal microwave signal at $2\omega_s$ is generated. Therefore, if the bias point of the DD-MZM switches between the QTP and the MITP, a FH microwave signal can be generated. To do so, we can use the static bias voltage V_{DC} to set the static bias point of the DD-MZM at the QTP, and use the dynamic bias voltage $V_s S(t)$ to switch the bias point between the QTP and the MITP. However, there is still an issue to be noticed: the transmission gains of the two bias points are not identical under small signal modulation condition. The gain of the microwave signal at ω_s at the QTP is larger than that of the microwave signal at $2\omega_s$ at the MITP, resulting in that the microwave signal at ω_s has higher power than the microwave signal at $2\omega_s$. If FH microwave signals with equal amplitude are desired, we can increase the power of the microwave reference signal.

Then, a theoretical analysis is investigated. As discussed above, we set $V_{DC} = V_s = V_\pi/2$, so (2) can be simplified as

$$i(t) = \frac{1}{2}RE_0^2 + \frac{1}{2}RE_0^2 \cos\left(m \cos \omega_s t - \frac{\pi}{2}S(t) - \frac{\pi}{2}\right), \tag{4}$$

where $m = \pi V_0 / V_\pi$ is the modulation index. Since $S(t)$ is a binary sequence, $i(t)$ is expressed as

$$i(t) = \begin{cases} \frac{1}{2}RE_0^2 - \frac{1}{2}RE_0^2 \cos(m \cos \omega_s t) & S(t) = 1 \\ \frac{1}{2}RE_0^2 + \frac{1}{2}RE_0^2 \sin(m \cos \omega_s t) & S(t) = 0 \end{cases}$$
$$\approx \begin{cases} \frac{1}{2}RE_0^2 - \frac{1}{2}RE_0^2 J_0(m) + RE_0^2 J_2(m)\ \cos\ (2\omega_s t) & S(t) = 1 \\ \frac{1}{2}RE_0^2 + RE_0^2 J_1(m)\ \cos\ (\omega_s t) & S(t) = 0. \end{cases} \tag{5}$$

In the deduction of (5), small signal modulation condition ($m<<1$) is used. As shown in (5), FH microwave signals at two different frequencies are generate when $S(t)$ is 1 and 0, respectively. The FH speed equals to the data rate of the binary data signal, which can be higher than GHz because the binary data signal is directly applied to the RF port of the DD-MZM. Since the DC current is not equal when $S(t)$ is 1 and 0, there is a baseband modulation product. However, the baseband modulation product is far away from the frequencies of the FH microwave signal, and it is always outside the pass band of the radar transmit antenna, so its influence can be ignored. In addition, if FH microwave signals with equal amplitude are desired, we should set $J_1(m) = J_2(m)$, i.e., $m = 2.63$. In this case, higher-order harmonics are generated, which should be filter out to avoid the interference. In practical applications, such as in FH radar systems, radar antenna has a band-pass characteristic, which could avoid the interference from higher-order harmonics.

3. Experimental Results and Discussion

Fig. 3 shows the experimental setup of the proposed FH microwave signal generation system. A 16-dBm CW light wave generated from a laser diode (LD, Teraxion NLL) is injected into a DD-MZM (Fujitsu FTM 7937EZ) with about 35-GHz 3-dB modulation bandwidth through a polarization controller (PC). A microwave reference signal from a microwave signal generator (MSG, Agilent E8257D) is injected into one arm of the DD-MZM, whereas a binary data signal generated from a pulse pattern generator (PPG, Anritsu MP1763C) is amplified by an electrical amplifier (EA) and then applied to the other arm of the DD-MZM. The two DC ports of the DD-MZM are driven by a DC power supply. The optical signal at the output of the DD-MZM is sent to a PD (u2t) with a 3-dB bandwidth of 40 GHz, and the generated photocurrent from the PD is monitored by a digital sampling oscilloscope (DSO, Agilent DCA-J 86100C) after being filtered by an electrical band-pass filter (EBPF). The PPG and MSG are synchronized by a 10-MHz signal, whereas the DSO is triggered by a 1/64 clock from the PPG.

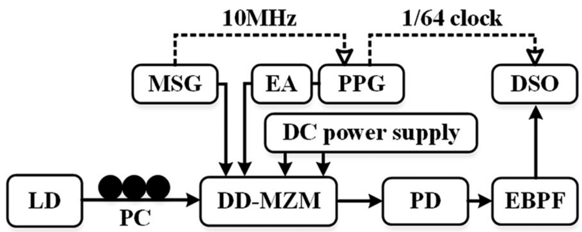

Fig. 3. Experimental setup of the proposed FH microwave signal generation system. LD, laser diode; PC, polarization controller; DD-MZM, dual-drive Mach-Zehnder modulator; MSG, microwave signal generator; PPG, pulse pattern generator; EA, electrical amplifier; PD, photodetector; EBPF, electrical band-pass filter; DSO, digital sampling oscilloscope.

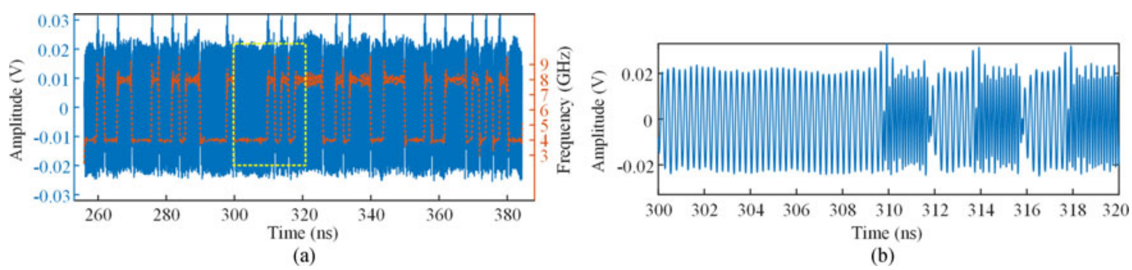

Fig. 4. (a) The measured FH microwave waveforms (blue full line), and the calculated instantaneous frequencies (red dotted line), when the frequency of the applied microwave reference signal is 4 GHz. (b) A zoom-in view of a section of the generated FH waveforms outlined in yellow dotted line in (a).

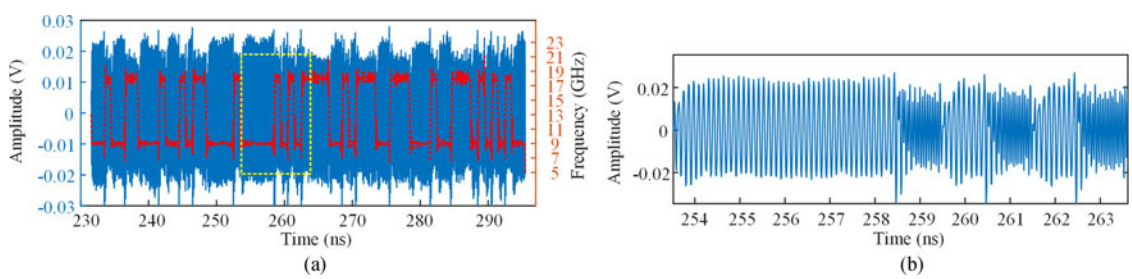

Fig. 5. (a) The measured FH microwave waveforms (blue full line), and the calculated instantaneous frequencies (red dotted line), when the frequency of the applied microwave reference signal is 9 GHz. (b) A zoom-in view of a section of the generated FH waveforms outlined in yellow dotted line in (a).

First, the frequency of the applied microwave reference signal is set to 4 GHz, and the data rate of the binary data signal, selected as a 64-bit pseudo-random bit sequence (PRBS) with the pattern of "1101100111011010011110111110101000011010001100011101100010101011," is set to 0.5 Gbps. Fig. 4(a) shows one period of the generated FH microwave waveform in blue full lines, and the calculated instantaneous frequencies of the waveform in red dotted lines using Hilbert transform. As can be seen from the calculated instantaneous frequencies, two frequencies around 4 and 8 GHz are obtained. It is also noticed that the curve of the instantaneous frequencies is consistent with the binary data applied to the DD-MZM. A zoom-in view of the generated FH microwave waveform outlined in yellow dotted lines in Fig. 4(a) is shown in Fig. 4(b). A microwave waveform with different carrier frequencies are observed, which is changed according to the 64-bit PRBS applied.

To study the frequency tunability of the proposed FH microwave signal generator, the frequency of the applied microwave reference signal is tuned from 4 to 9 GHz, and the data rate of the binary data signal is set to 1 Gbps, while keeping other parameters of the system unchanged. Fig. 5(a) shows one period of the generated FH microwave waveform in blue full lines, and the calculated

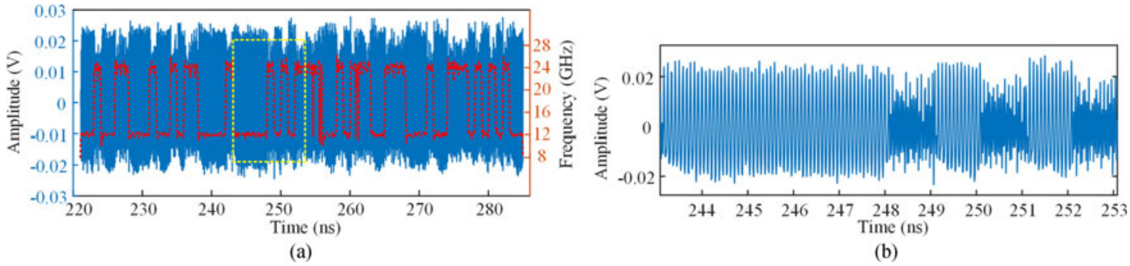

Fig. 6. (a) The measured FH microwave waveforms (blue full line), and the calculated instantaneous frequencies (red dotted line), when the frequency of the applied microwave reference signal is 12 GHz. (b) A zoom-in view of a section of the generated FH waveforms outlined in yellow dotted line in (a).

instantaneous frequencies of the waveform in red dotted lines using Hilbert transform. It is observed that the instantaneous frequencies of the waveform are bouncing between 9 and 18 GHz. A zoom-in view of a section of the waveform outlined in yellow dotted lines is shown in Fig. 5(b). A microwave waveform with different carrier frequencies are observed, which is also changed according to the 64-bit PRBS applied. The frequency of the applied microwave reference signal is further increased to 12 GHz. One period of the generated FH microwave waveform and the calculated instantaneous frequencies are shown in Fig. 6(a). The instantaneous frequencies are bouncing between 12 and 24 GHz. A zoom-in view of a section of the waveform outlined in yellow dotted lines is also shown in Fig. 6(b), where microwave carrier frequency changing according to the 64-bit PRBS is observed.

Since the sampling rate of the DSO used in this measurement is about 80 Gs/s, the fidelity of the waveforms in Fig. 5(b) and Fig. 6(b) are relatively low. However, the 80 Gs/s sampling rate is already much higher than twice the highest frequency of the waveforms requested by Nyquist's sampling theorem, so the low fidelity of the waveform does not influence the correctness of the results. Although high-speed FH microwave signals can be generated using the simple structure proposed in this paper, there is still a limitation that the two hopping frequencies have to be related by a factor of two. The fixed relationship between the two frequencies may limit its applications in some scenarios, where more flexible FH is highly desired. The advantage of this approach is that the operating bandwidth is very large and the FH speed is very high. In the experiment, the 3-dB bandwidth of the DD-MZM is about 35 GHz, and the modulation speed of the DD-MZM can be up to 40 Gbps, which means the frequency of the applied microwave reference signal can be up to 35 GHz, and the data rate of the applied binary data signal can be as fast as 40 Gbps. Based on the parameters of the DD-MZM, FH microwave signals can be generated with its frequency bouncing between 35 and 70 GHz with a much fast FH speed than 1 GHz.

It is also noticed from the experimental results in Figs. 4–6 that small amplitude fluctuations appear in the temporal waveforms of the two hopping frequencies when the frequency of the applied microwave signal increases from 4 to 9 and 12 GHz, which may be caused by several reasons, including DC bias drift, amplitude fluctuation of the binary data signal and the applied microwave signal. In our experiment, the DC bias voltage is provided by a DC power supply with no feed-back control, so the transmission characteristic of the DD-MZM may drift from the initial state in long-term operation, which results in the deviation from the ideal working condition, and leads to an amplitude fluctuation. The binary data signal is generated from a PPG and then amplified by an EA. The data rate of the binary data signal from the PPG is 0.5 Gbps in Fig. 4, and is tuned to 1 Gbps in Figs. 5 and 6. The change of the data rate may lead to small amplitude variation of the binary data signal due to the amplification characteristic of the EA, so that an amplitude fluctuation is introduced in the generated FH microwave signal. The microwave signal applied to the DD-MZM is generated from a MSG. When the frequency of the microwave reference signal is tuned in the experiment, the power of the signal applied to the modulator may have small changes due to the different attenuations of the cable at different frequencies, which will also lead to amplitude fluctuation of the generated FH microwave signal.

4. Conclusion

In conclusion, a novel FH microwave signal generation approach is proposed based on a DD-MZM. By switching the bias point of the DD-MZM between the QTP and the MITP, a FH microwave signal is generated with large frequency tunability and high FH speed. The proposed technique is investigated experimentally. The generation of FH microwave signals with frequencies bouncing between 4 and 8 GHz, 9 and 18 GHz, or 12 and 24 GHz is demonstrated with a FH speed up to 1 GHz. The proposed FH microwave signal generator provides a new method for the generation of high FH speed and high-frequency FH microwave signal, which may find applications in FH communication and radar systems.

Acknowledgment

The author gratefully acknowledges Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University of Aeronautics and Astronautics, for providing some devices and equipment in the experiment.

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