# Photonic generation of microwave frequency shift keying signal using a single-drive Mach–Zehnder modulator

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**Abstract:** We propose and experimentally demonstrate a new scheme for photonic generation of microwave frequency shift keying (FSK) signal by employing one single-drive Mach–Zehnder modulator (MZM). In the proposed method, an electrical signal with different radio frequency (RF) amplitudes and direct current (DC) components for bit '0' and bit '1' is generated. After amplification, the signal is fed into a single-drive MZM which is biased at the quadrature and null points of its transmission curve for bit '0' and bit '1', respectively. Due to the different RF amplitudes, a microwave FSK signal can be obtained after photodetection, where the space frequency is the same as the RF frequency and the mark frequency is twice as large as the RF frequency. The feasibility of the proposed scheme is verified by a proof-of-concept experiment. 5/10-GHz and 10/20-GHz microwave FSK signals with different bit rates are successfully demonstrated.

**OCIS codes:** (060.2330) Fiber optics communications; (060.5625) Radio frequency photonics.

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## 1. Introduction

Microwave photonics (MWP) utilizes photonic devices to generate and process microwave signals in optical field, which can overcome the bandwidth bottleneck of electrical components [1]. Thanks to the intrinsic advantages of optical devices, photonic generation of microwave signal can reduce the system complexity and cost compared with radio frequency (RF) domain methods [2, 3]. In recent years, the MWP has been proved to be a promising solution for many applications such as broadband wireless access networks, radio-over-fiber (ROF) systems, and satellite communications [4, 5].

Recently, photonic generations of microwave signals with different modulation formats, including amplitude shift keying (ASK), phase shift keying (PSK), and high-order modulation formats, have attracted increasing attentions [6–18]. In Ref [6, 7], optical carrier suppression (OCS)-ASK signal can be used to generate microwave ASK signal. Moreover, photonic generation of phase-coded microwave signal has been proposed in optical domain, which can reduce the system complexity and increase the RF frequency of the generated signal [8–13]. High-order modulation formats, such as microwave amplitude differential phase shift keying (ADPSK), quaternary phase shift keying (QPSK), and quadrature amplitude modulation (QAM) signals, have been demonstrated by using MWP [14–17]. However, microwave frequency shift keying (FSK) signal as a fundamental digital modulation format in wireless communication has rarely been realized through photonic technology. In Ref [18, 19], wavelength switched optical frequency comb can obtain different microwave FSK signals by utilizing spectral line-by-line shaping. P. Xiang et al. have reported a scheme for photonic generation of microwave FSK signal employing different delay interference in the two polarization states of polarization modulated optical short pulses [20]. Microwave signals with different modulation formats can also be obtained by using optical mixing [21,22]. However, the optical mixing scheme has complex structures, requiring a number of optical devices.

In this paper, we propose and experimentally demonstrate photonic generation of microwave FSK signal using only one single-drive Mach–Zehnder modulator (MZM). In electrical domain, a unipolar ASK signal mixes with an RF signal. The output signal from the mixer is combined with an on-off keying (OOK) signal which has the same bit information as the ASK signal. Therefore, bit '0' and bit '1' of the generated signal have different RF amplitudes and direct current (DC) components. Then the signal is amplified and fed to a single-drive MZM. Due to the different RF amplitudes and DC components for bit '0' and bit '1', a microwave FSK signal can be obtained after electrical-optical-electrical (EOE) conversion. Theoretical analysis and simulations verify the feasibility of the proposed scheme. Simulations are conducted for 10/20-GHz and 20/40-GHz microwave FSK signals with different bit rates. Furthermore, a proof-of-concept experiment demonstrates the generation of 5/10-GHz and 10/20-GHz microwave FSK signals at different bit rates.

## 2. Principle and theoretical analysis

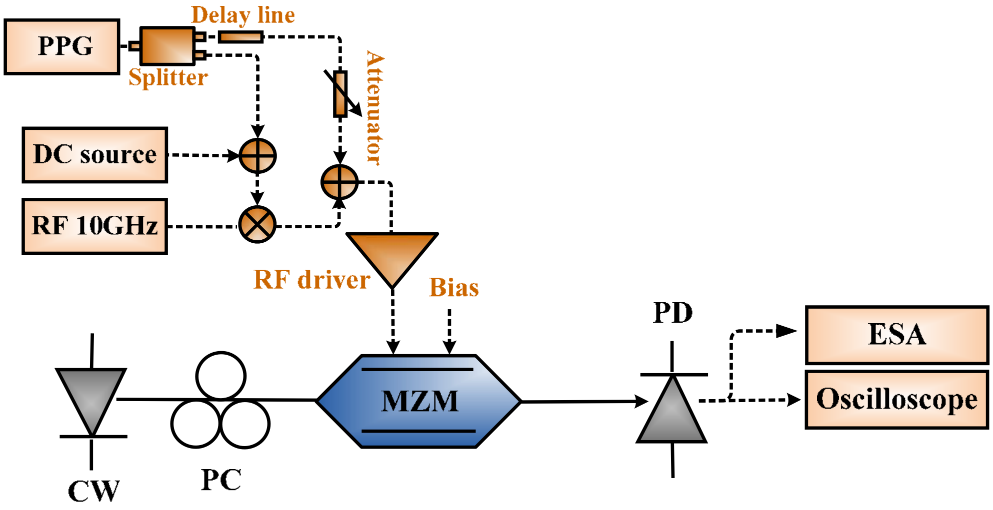

Fig. 1. Architecture of microwave FSK signal generation in optical domain.

Figure 1 depicts the proposed architecture of microwave FSK signal generation using a single-drive MZM. The principle of the electrical signal generation is illustrated in Fig. 2(a). A unipolar baseband ASK signal mixes with an RF clock (Fig. 2(a-i)). The output signal from the mixer is combined with an OOK signal which has the same bit information as the ASK signal (Fig. 2(a-ii)). When the angular frequency of the RF clock is $\omega_f = 2\pi f_{RF}$, the generated electrical signal can be expressed as

$$E_{in} = \overline{Data(t)} V_{RF0} \cos(\omega_f t) + Data(t) V_{RF1} \cos(\omega_f t), \qquad (1)$$

where $Data(t)$, $V_{RF0}$, and $V_{RF1}$ are the pseudo random bit sequence (PRBS) signal, the amplitudes of bit '0' and bit '1', respectively. Meanwhile, we define that $\alpha = \frac{\pi}{2}\frac{V_{RF0}}{V_\pi}$ and $\beta = \frac{\pi}{2}\frac{V_{RF1}}{V_\pi}$, where $V_\pi$ is the half-wave voltage of the MZM.

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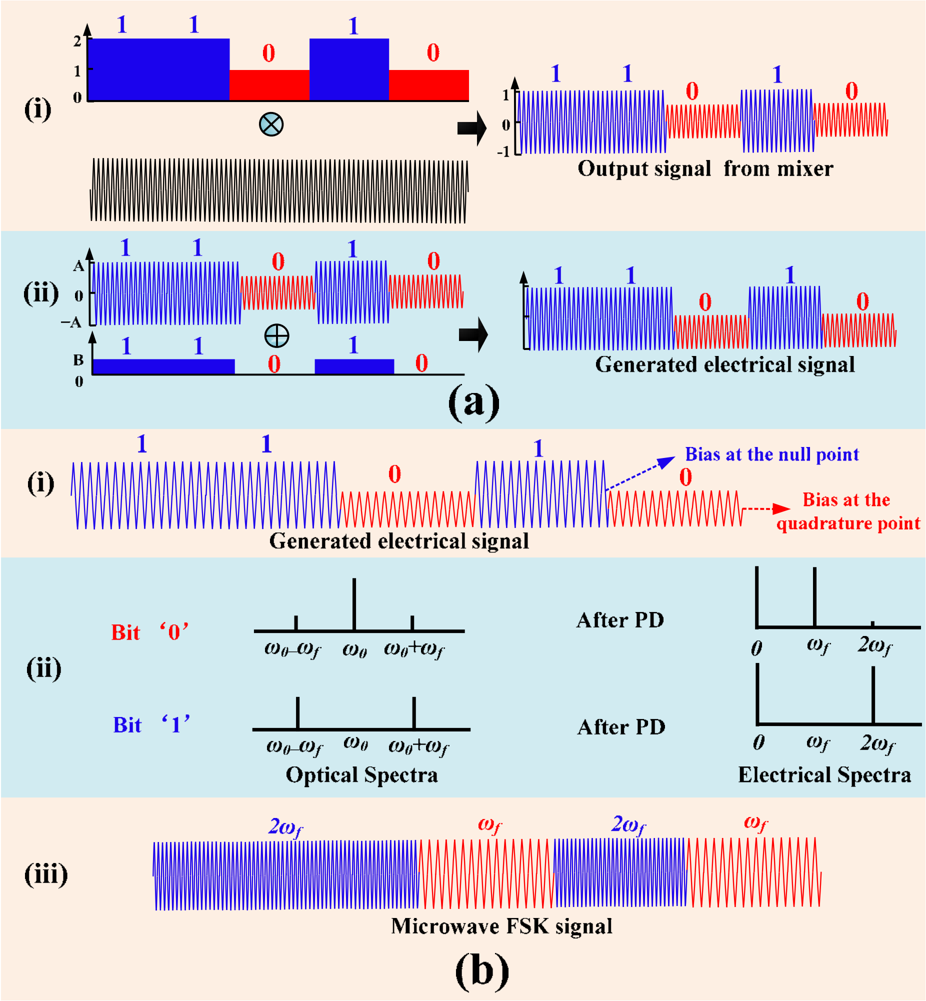

Fig. 2. (a) Principle of the electrical signal generation. (a-i) Unipolar ASK signal mixing with an RF clock, (a-ii) combination of the output signal from the mixer and the OOK signal. (b) Generation of microwave FSK signal through EOE conversion. (b-i) RF amplitudes and bias points for bit '0' and bit '1', respectively, (b-ii) optical spectra and electrical spectra after photodetection for bit '0' and bit '1', respectively, (b-iii) waveform of the generated microwave FSK signal.

As shown in Fig. 2(b-i), the MZM is biased at the quadrature point of its transmission curve for bit '0'. Ignoring higher order sidebands with lower optical powers, as depicted in Fig. 2(b-ii), we only consider the first-order optical sidebands. The optical output signal is given by

$$\begin{aligned} E_{out0} &\approx E_0\left\{J_0(\alpha)\cos(\frac{\pi}{4})\cos(\omega_0 t)-J_1(\alpha)\sin(\frac{\pi}{4})[\cos(\omega_0+\omega_f)t+\cos(\omega_0-\omega_f)t]\right\} \\ &= E_0\frac{\sqrt{2}}{2}\{J_0(\alpha)\cos(\omega_0 t)-J_1(\alpha)[\cos(\omega_0+\omega_f)t+\cos(\omega_0-\omega_f)t]\}, \end{aligned} \tag{2}$$

where $E_0$ and $\omega_0$ are the amplitude and angular frequency of the optical carrier, respectively. $J_n$ is the $n$ order Bessel function of the first kind. The alternating current (AC) term of the signal after photodetection can be expressed as

$$i_{AC0} \propto \frac{|E_0|^2}{2}[-2J_0(\alpha)J_1(\alpha)\cos(\omega_f t) + J_1(\alpha)^2\cos(2\omega_f t)]. \tag{3}$$

In the meantime, the MZM is biased at the null point of its transmission curve for bit ‘1’, where the even-order optical sidebands are suppressed and optical carrier suppressed (OCS) modulation format is obtained. Therefore, the optical output signal and the AC term of the electrical signal after photodetection are written as

$$E_{out1} \approx E_0\left\{-J_1(\beta)[\cos(\omega_0+\omega_f)t + \cos(\omega_0-\omega_f)t]\right\}, \tag{4}$$

$$i_{AC1} \propto |E_0|^2[J_1(\beta)^2\cos(2\omega_f t)]. \tag{5}$$

By carefully adjusting the signal amplitudes and the bias voltage of the MZM, one can obtain

$$A = |J_0(\alpha)J_1(\alpha)| \approx J_1(\beta)^2 >> \frac{J_1(\alpha)^2}{2}. \tag{6}$$

To satisfy Eq. (6), the RF amplitudes of bit ‘1’ and bit ‘0’ are set to 1.3 $V_\pi$ and 0.8 $V_\pi$, respectively. Therefore, the generated electrical signal can be simplified as

$$i_{out} \propto \begin{cases} |E_0|^2 A\cos(\omega_f t) & \text{for bit ‘0'} \\ |E_0|^2 A\cos(2\omega_f t) & \text{for bit ‘1'} \end{cases}. \tag{7}$$

As observed in Eq. (7), the angular frequencies of the generated electrical signal for bit ‘0’ and bit ‘1’ are $\omega_f$ and $2\omega_f$, respectively. Meanwhile, bit ‘0’ and bit ‘1’ of the generated signal have the same amplitude. Therefore, a $f_{RF}/(2f_{RF})$ microwave FSK signal is successfully obtained.

## 3. Simulation and experiment results

The proposed photonic generation of microwave FSK signal is simulated by using Virtual Photonic Incorporation (VPI, 8.7) Transmission maker. A bipolar non-return-to-zero (NRZ) signal is respectively combined with two DC sources to generate a unipolar ASK signal and an OOK signal. Then the ASK signal mixes with an RF clock, and the output signal is combined with the OOK signal through an electrical combiner. By setting the parameters of each device, an electrical signal can be successfully obtained as depicted in Fig. 2(b-i). A continuous-wave (CW) light at 1550 nm with 5-dBm optical power is sent to a single-drive MZM, where another DC source is used to control the bias voltage of the MZM. A high-speed photo detector (PD) converts the optical signal to electrical domain. Meanwhile, signal analyzers are employed to observe the waveforms of the generated electrical signals, microwave FSK signals, and the electrical spectra of the microwave FSK signals.

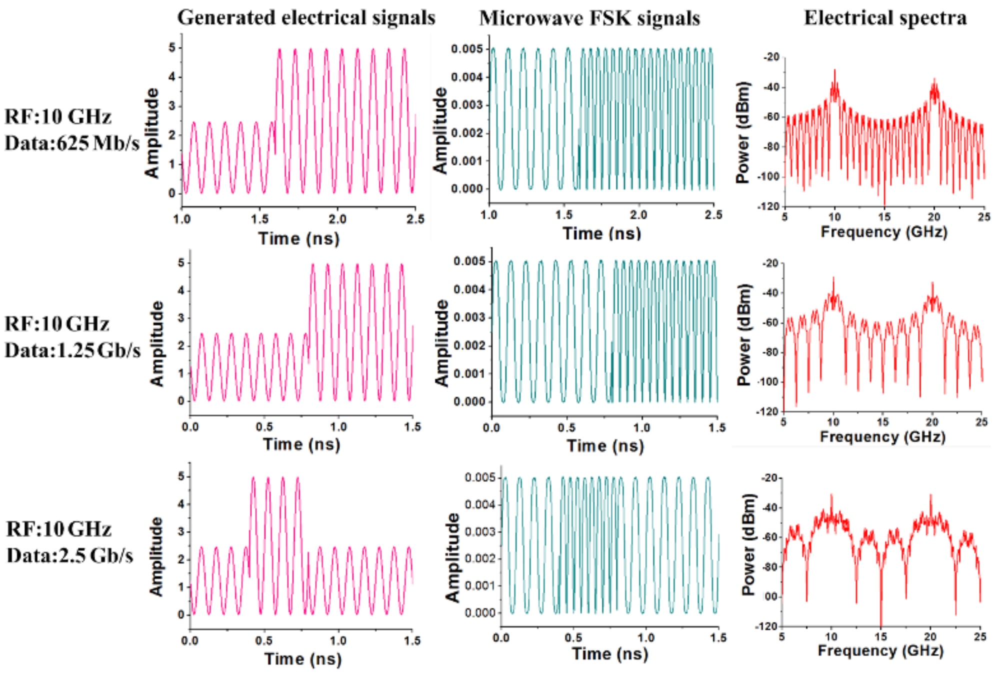

Fig. 3. Simulation results with 10-GHz RF clock at bit rates of 625 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, respectively.

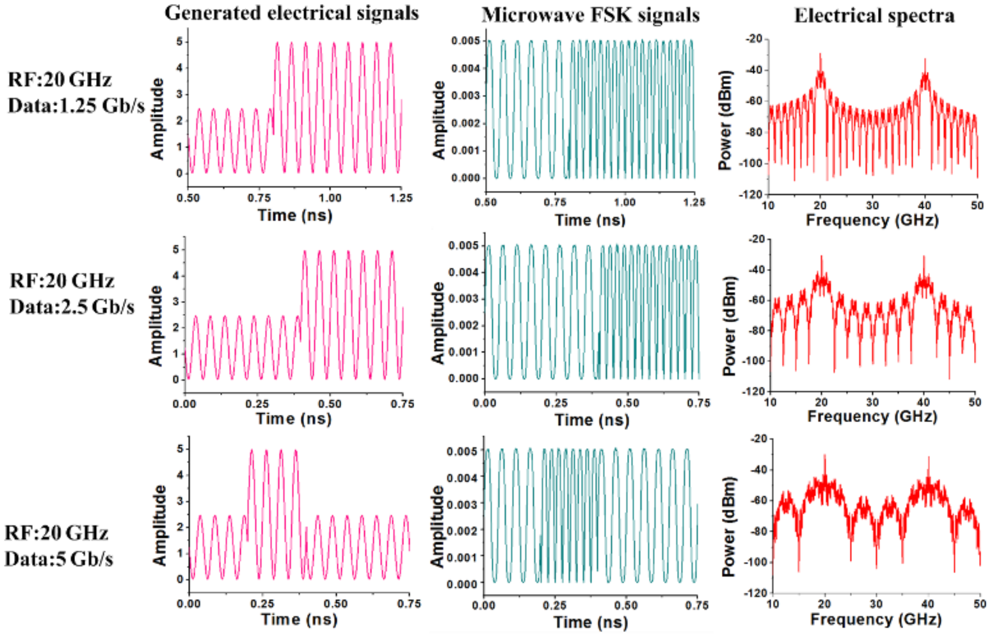

Fig. 4. Simulation results with 20-GHz RF clock at bit rates of 1.25 Gb/s, 2.5 Gb/s, and 5 Gb/s, respectively.

To verify the tunability of the bit rates, 625-Mb/s, 1.25-Gb/s, and 2.5-Gb/s microwave FSK signals are demonstrated, where the RF frequency is set to 10 GHz. The waveforms of the generated electrical signals, microwave FSK signals, and the electrical spectra of the microwave FSK signals with different bit rates are respectively shown in Fig. 3. Moreover, as depicted in Fig. 4, the microwave frequency is tuned to 20 GHz to show the frequency tunability of the propose method, where the bit rates of the generated microwave FSK signals are 1.25 Gb/s, 2.5 Gb/s, and 5 Gb/s, respectively.

A proof-of-concept experiment is proposed to verify the feasibility of the microwave FSK signal generation by using a single-drive MZM. As shown in Fig. 1, a pulse pattern generator (PPG, Anritsu MP1763c) is used to generate OOK signals with different bit rates, where the PRBS word length is set to $2^{31}-1$. The OOK signal is divided into two parts by an electrical splitter. One part is combined with a DC source to obtain an ASK signal, and then mixed with an RF clock from Agilent E8257D, as described in Fig. 2(a-i). The other part is attenuated and combined with the output signal from the mixer, as illustrated in Fig. 2(a-ii). Here, synchronization between the ASK signal and the OOK signal is realized by using an electrical delay line. A CW light with 5-dBm optical power at 1550 nm is fed into a single-drive MZM which is driven by the amplified electrical signal. By properly setting the amplitude of each signal and the bias voltage of the MZM, microwave FSK signals with different bit rates can be obtained by utilizing the aforementioned method.

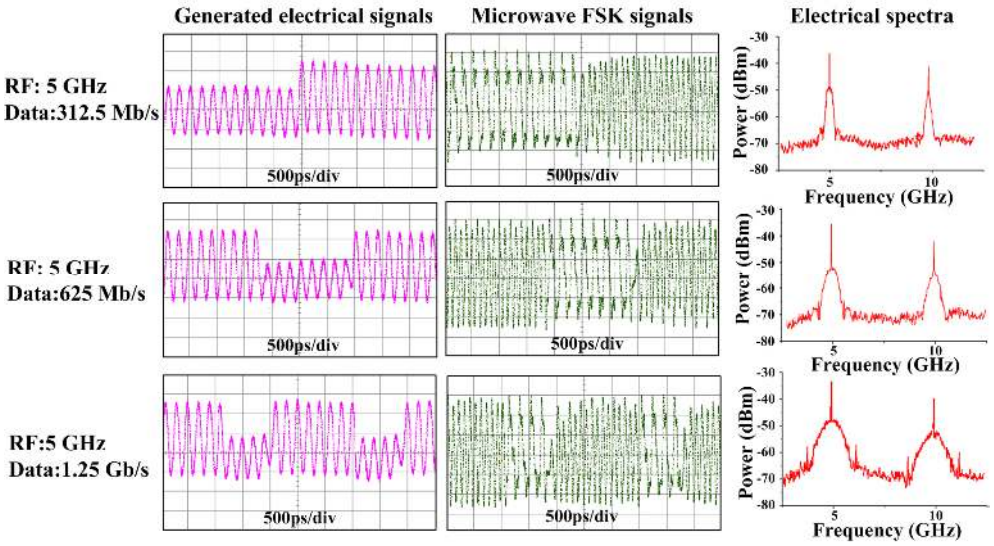

Fig. 5. Waveforms of the generated electrical signals, microwave FSK signals, and the electrical spectra of the microwave FSK signals with 5-GHz RF clock at bit rates of 312.5 Mb/s, 625 Mb/s, and 1.25 Gb/s, respectively.

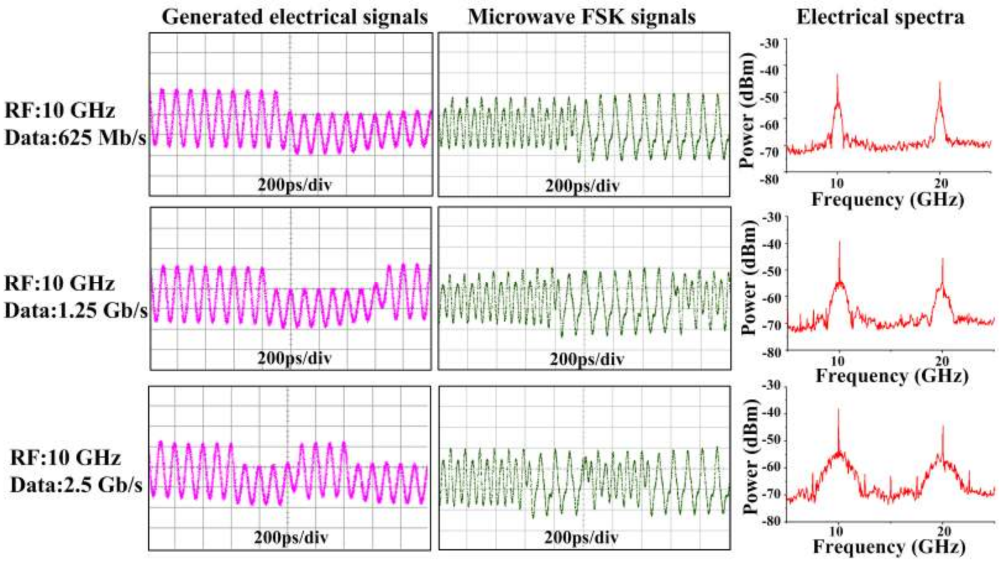

Fig. 6. Waveforms of the generated electrical signals, microwave FSK signals, and the electrical spectra of the microwave FSK signals with 10-GHz RF clock at bit rates of 625 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, respectively.

Signals with different bit rates are experimentally demonstrated with RF clocks of 5 GHz and 10 GHz, respectively. Higher frequency signals are not tested due to the lack of the high-speed mixer. In the experiment, the half-wave voltage of the MZM is about 5 V. The amplitudes of bit ‘1’ and bit ‘0’ of the generated electrical signal after amplification are about 6.5 V and 4 V, respectively. Then the MZM is driven by the generated electrical signals, and the microwave FSK signals can be obtained by adjusting the bias voltage of the MZM. The waveforms of the generated electrical signals, microwave FSK signals, and the electrical spectra of the microwave FSK signals are shown in Figs. 5 and 6, where the waveform transition times of the generated FSK signals are about 200 ps and 100 ps, respectively. In our experiment, the generated FSK signals can remain stable for more than 10 minutes. For practical applications, feedback control can be used to overcome the bias drifting problem [23]. Due to imperfect responses of electrical splitter, mixer, delay line, combiner, and amplifier, the experimental results show some differences from our predictions, which can be improved by using electrical devices with better performances.

## 4. Conclusion

We have proposed and demonstrated a new method for photonic generation of a microwave FSK signal using only one single-drive MZM. In our scheme, an electrical signal is obtained, where bit ‘0’ and bit ‘1’ of the generated signal have different RF amplitudes and DC components. After EOE conversion, a microwave FSK signal can be obtained, where the space frequency is equal to the RF frequency and the mark frequency is twice as large as the RF frequency. 5/10-GHz and 10/20-GHz microwave FSK signals with different bit rates have been experimentally demonstrated to verify our proposal. Experimental results show that the proposed scheme has a simple structure and high tunability for generation of microwave FSK signal in optical domain.

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