Optical generation of microwave frequency shift keying signals based on cascaded Mach-Zehnder modulators

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Based on cascaded Mach-Zehnder Modulators (MZM), a novel scheme for optical generating of microwave frequency shift keying (FSK) signal is designed and demonstrated. In the designed scheme, a microwave FSK signal with frequencies of two and four times the frequency of driving microwave signal for bit '0' and '1' is generated. The feasibility of the designed scheme is verified by a simulation experiment. With 5 GHz driving microwave signal, a 1 Gbit/s microwave FSK signal at 10/20 GHz is generated and transmitted over 30 Km single-mode fiber (SMF).

1. Introduction

Microwave frequency shift keying (FSK) signal has been used as a fundamental modulation format in wireless communication system, due to its strong abilities such as anti-jamming and anti-inter-symbol interference [1,2]. Traditional microwave FSK signals are generated by electronic devices in the electrical domain. However, it is well-known that the operating bandwidth and reachable frequencies of electronic devices are limited by electronic bottleneck, which resulting in a comparatively small frequency switching range (limited to GHz) and speed (limited to kHz) for electronic FSK signal generators. Therefore, the traditional microwave FSK hopping signal generator can not meet the requirements of new applications for large frequency switching range and high frequency switching speed.

In recent years, using the advantages of modern photonics, such as high operating frequency, anti-electromagnetic interference, large bandwidth and low loss, the photonic generation of microwave signals has become a research focus [3,4]. Microwave photonics also offers a meaningful solution for the generation of microwave FSK signals, overcomes the shortcomings of traditional electronic microwave frequency FSK signal generators. Up to now, several photonic microwave FSK signal generation schemes have been developed [5-9].

In [5] and [6], microwave FSK signals are generated by switching the bias point of single-drive Mach – Zehnder modulator (MZM) or dual-drive MZM, and the two frequencies of FSK signal are only one and two times the frequency of the microwave driving signal, respectively. In [7-9], high frequency FSK signals could be obtained by using a dual-polarization quadrature phase shift keying (DP-QPSK) modulator, in addition, a polarization modulator (PolM) or a tunable filtering switch (TFS) is employed. These mean complex structure and

high cost are required to achieve high frequency FSK signal.

In the manuscript, by switching the bias point of MZMs, a cascaded MZMs based photonic microwave FSK signal generation scheme is presented. The scheme is simple in structure and cost-effective, and the two frequencies of the generated microwave FSK signal are two and four times the frequency of the microwave driving signal.
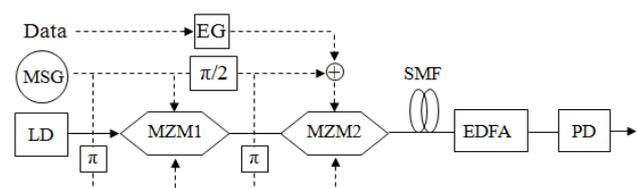
2. Principle

Fig. 1. Conceptual diagram of photonic Microwave FSK signal generation. LD: laser diode; MSG: microwave signal generator; EG: electrical gain; MZM: Mach-Zehnder modulator; SMF: single mode fiber; EDFA: Er doped fiber amplifier; PD: photo diode

Fig. 1 plots the conceptual diagram of cascaded MZM (MZM1 and MZM2) based optical generation approach for Microwave FSK signal. MZM1 is biased at the null point while MZM2 is biased at the full point. The lightwave $E_0 e^{j\omega_c t}$ output from laser diode (LD) is injected into the cascaded MZMs, ω_0 and E_0 are angular frequency and amplitude of the optical carrier, respectively. The cascaded MZMs are driven by microwave signal, and a π/2 phase shift is introduced between the driving microwave

signals of MZM1 and MZM2, and a π phase difference is applied between two arm driving signals of each MZM. In addition, MZM2 is also driven by electrical gained binary data signal $d(t)$. The input signal of MZM1 and MZM2 can be represented as $V_1(t) = V_m \sin \omega_m t$ and

$V_2(t) = V_m \sin(\omega_m t + \pi/2) + V_\pi d(t)$, respectively. Where ω_m and V_m are angular frequency and amplitude of microwave signal, respectively. V_π is the half-wave voltage of each MZM. Thus, the output optical field from the cascaded MZMs (MZM1 and MZM2) can be expressed as

$$E_o(t) = \frac{E_i}{4} e^{j\omega_c t} [e^{j\frac{\pi(V_m \sin \omega_m t + V_\pi)}{V_\pi}} + e^{j\frac{\pi[V_m \sin(\omega_m t + \pi)]}{V_\pi}}]$$

$$\bullet [e^{j\frac{\pi[V_m \sin(\omega_m t + \pi/2) + V_\pi d(t)]}{V_\pi}} + e^{j\frac{\pi[V_m \sin(\omega_m t + 3\pi/2)]}{V_\pi}}]$$

$$= \frac{E_i}{4} e^{j\omega_c t} [-e^{jm \sin \omega_m t} + e^{-jm \sin \omega_m t}][e^{j\pi d(t)} e^{jm \sin(\omega_m t + \pi/2)} + e^{-jm \sin(\omega_m t + \pi/2)}]$$

$$= \frac{E_i}{4} e^{j\omega_c t} [-e^{j\pi d(t)} e^{jm[\sin \omega_m t + \sin(\omega_m t + \frac{\pi}{2})]} - e^{jm[\sin \omega_m t - \sin(\omega_m t + \frac{\pi}{2})]}$$

$$+ e^{j\pi d(t)} e^{jm[\sin(\omega_m t + \frac{\pi}{2}) - \sin \omega_m t]} + e^{-jm[\sin \omega_m t + \sin(\omega_m t + \frac{\pi}{2})]}]$$

$$= \frac{E_i}{4} e^{j\omega_c t} [-e^{j\pi d(t)} e^{j\sqrt{2}m \sin(\omega_m t + \frac{\pi}{4})} - e^{-j\sqrt{2}m \cos(\omega_m t + \frac{\pi}{4})}$$

$$+ e^{j\pi d(t)} e^{j\sqrt{2}m \cos(\omega_m t + \frac{\pi}{4})} + e^{-j\sqrt{2}m \sin(\omega_m t + \frac{\pi}{4})}]$$

$$= \frac{E_i}{4} e^{j\omega_c t} [\sum_{n=-\infty}^{\infty} J_n(\sqrt{2}m) e^{jn(\omega_m t + \frac{\pi}{4})} (e^{jn\pi} - e^{j\pi d(t)})$$

$$+ \sum_{n=-\infty}^{\infty} j^n J_n(\sqrt{2}m) e^{jn(\omega_m t + \frac{\pi}{4})} (e^{j\pi d(t)} - e^{jn\pi})] \tag{1}$$

where $m = \pi V_m / V_\pi$ is modulation index of each MZM, and $J_n(x)$ is the n order Bessel function of the first kind.

As data bit is "0" or "1", the generated photonic microwave could be written as

$$E_o(t) \propto \begin{cases} 2\sum_{k=-\infty}^{\infty} (j^{2k+1} - 1) J_{2k+1}(\sqrt{2}m) e^{j(2k+1)(\omega_m t + \pi/4)}, & d(t) = 0 \\ 4\sum_{k=-\infty}^{\infty} J_{4k+2}(\sqrt{2}m) e^{j(4k+2)(\omega_m t + \pi/4)}, & d(t) = 1 \end{cases} \tag{2}$$

Ignoring the higher-order harmonics, the above equation can be simplified to

$$E_o(t) \propto \begin{cases} 2[(-j-1) J_{-1}(\sqrt{2}m) e^{j(-\omega_m t - \pi/4)} + (j-1) J_1(\sqrt{2}m) e^{j(\omega_m t + \pi/4)}], & d(t) = 0 \\ 4[J_{-2}(\sqrt{2}m) e^{j(-2\omega_m t - \pi/2)} + J_2(\sqrt{2}m) e^{j(2\omega_m t + \pi/2)}], & d(t) = 1 \end{cases} \tag{3}$$

It can be deduced from eq. (3) that $\pm$1st-order sidebands with frequency of $\pm f_m$ are generated at the output of cascaded MZMs for bit '0'. While for bit '1', $\pm$2nd-order sidebands with frequency of $\pm 2f_m$ are generated.

The received signal is detected by photo diode (PD) according to square law. Therefore, the generated microwave signal after PD can be written as

$$I(t) = RE_o(t)E_o^*(t) \propto \begin{cases} J_1^2(\sqrt{2}m)(1 - \cos 2\omega_m t), & d(t) = 0 \\ 2J_2^2(\sqrt{2}m)(1 - \cos 4\omega_m t), & d(t) = 1 \end{cases} \tag{4}$$

where R is the responsibility of PD. As observed in eq. (4), the frequencies of the generated microwave signal for bit '0' and bit '1' are $2f_m$ and $4f_m$, respectively. As a consequence, a $2f_m$ and 4fm microwave FSK signal is achieved.

3. Results and discussion

To test the effectiveness of the designed photonic microwave FSK generation scheme shown in Fig. 1, simulation was carried out based on OptiSystem software, and the parameters were set to follow the theoretical values. The wavelength of the optical wave output from LD is 1553.6 nm and the frequency of driving microwave signal of the cascaded MZMs is 5 GHz. The insert loss and half-wave voltage of each sub-MZM is 5 dB and 4 V, respectively. The resulting photonic microwave FSK transmitted over single mode fiber (SMF) at a data rate of 1 Gbit/s, the attenuation coefficient and dispersion of the SMF is 0.2 dB/km and 16.75 ps/nm/km, respectively. An optical amplifier (OA) is used to remain the received optical power of RoF link. The noise figure and gain of the OA is 4 dB and 20 dB, respectively. Under square law detection, a PD with responsivity of 0.8 A/W, thermal power density of 1e-22 W/ Hz and dark current of 10 nA is used to detect received signal. Radio frequency (RF) spectrum analyzer and Oscilloscope visualizer are employed to observe electrical spectrum and the waveform of microwave FSK signal.
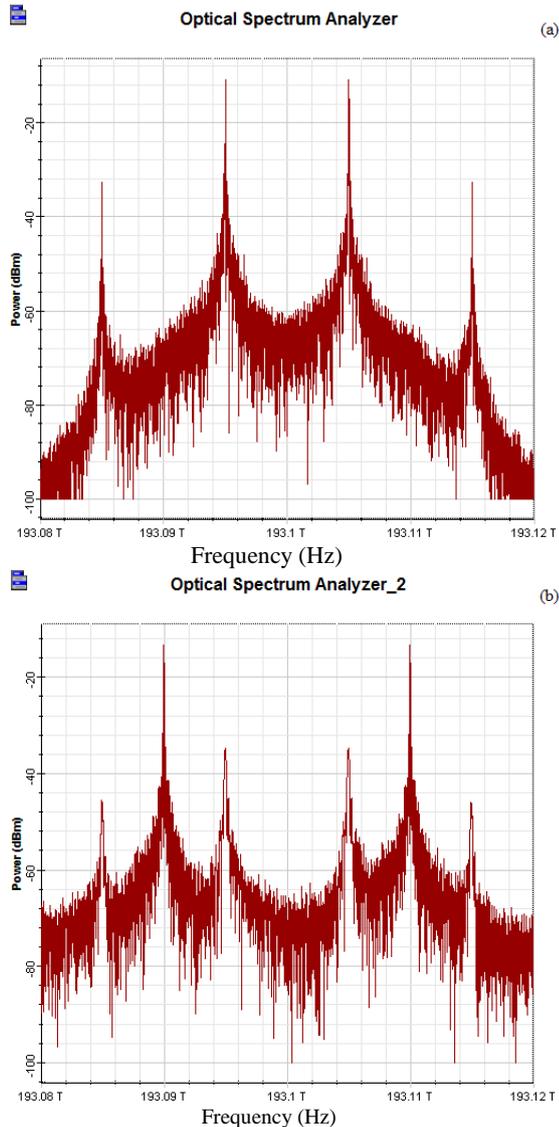
Fig. 2(a) and Fig. 2(b) depict optical spectrum of the generated photonic microwave FSK signal at the output of cascaded MZMs in the cases that the data bits are all '0' or all '1', respectively. The optical sideband suppression ratio (OSSR)s of the generated photonic microwave signal are 21 and 22 dB for bit '0' and '1', respectively. Here we set modulation index (MI) of MZM to 1.8 to make generated FSK signal with equal amplitude for bit '0'and '1'. We can see that the designed approach produces photonic microwave consisting of two tones spaced at 10 GHz for bit '0', which is two times the frequency of the driving signal, while produces photonic microwave consisting of two tones spaced at 20 GHz for bit '1', which is four times the frequency of the driving signal.

Fig. 2. Optical spectrum of the generated microwave FSK signal. Data bits are (a) all '0' and (b) all '1'
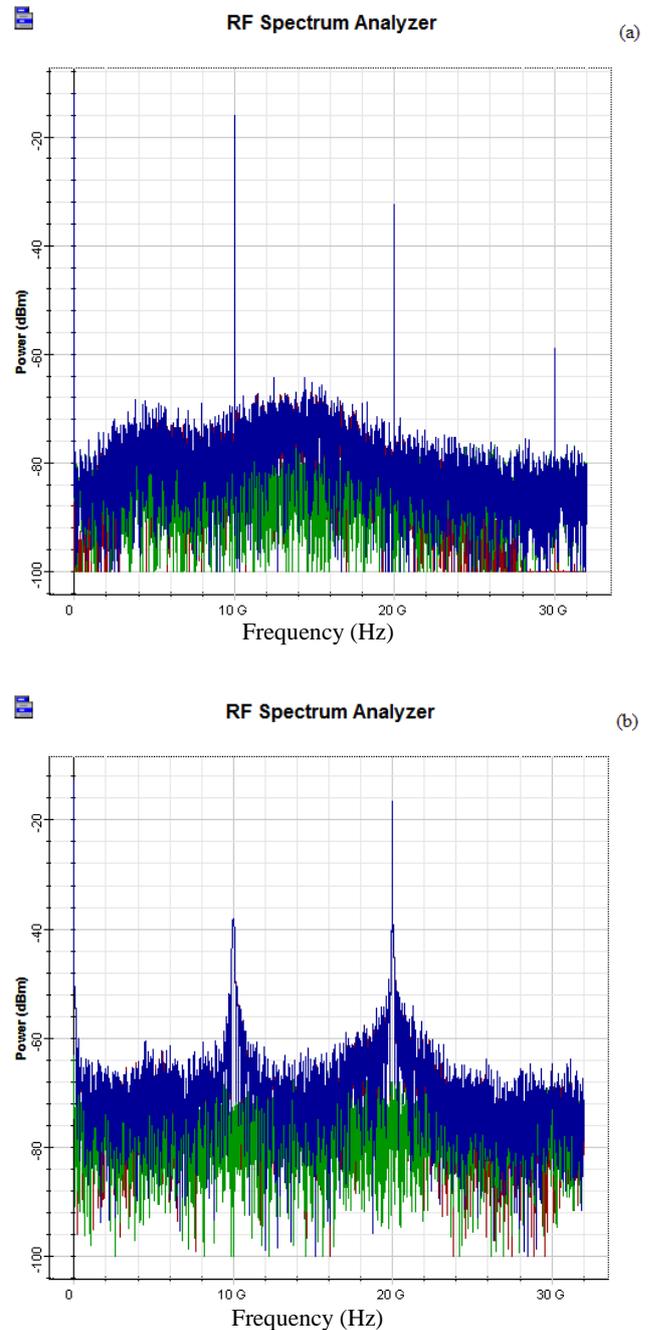

Fig. 3. RF spectrum of the generated microwave FSK signal. Data bits are (a) all '0' and (b) all '1' (color online)

Fig. 3(a) and Fig. 3(b) plot radio frequency (RF) spectrum of the generated microwave FSK signal at the output of PD in the cases that the data bits are all '0' or all '1', respectively. The RF sideband suppression ratio (RFSSR)s of the generated microwave FSK signal are 16 and 17 dB for bit '0' and '1', respectively. As can be seen from Fig. 3 that FSK signal with frequencies of 10 GHz and 20 GHz is obtained, note that the frequency of the driving microwave signal at the transmitter is 5 GHz. This means that a $2f_m$ and $4f_m$ microwave FSK signal is generated.

Oscilloscope Visualizer
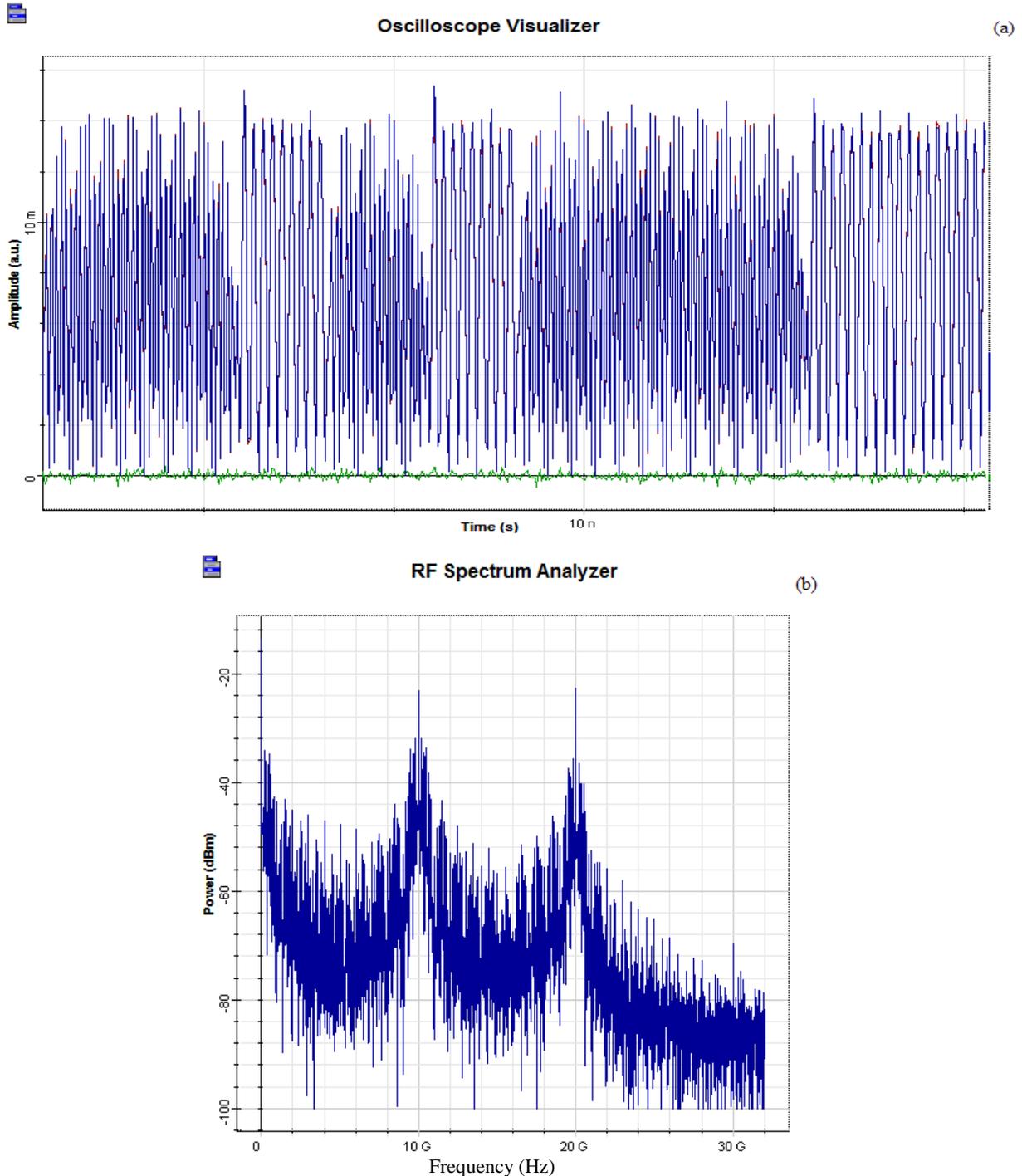
(a)

RF Spectrum Analyzer

(b)

Fig. 4. The waveform (a) and electrical spectrum (b) of the generated microwave FSK signal (color online)

The data rate of the binary data signal, selected as a 10-bit sequence with the mode of '1101011100', is set to be 1 Gbit/s. The waveform of generated microwave FSK signal and electrical spectrum are shown in Fig. 4 (a) and Fig. 4 (b), respectively. As also can be found from Fig. 4 that FSK signal with frequencies of two times and four times of driving microwave frequency is achieved. In addition, the two frequency components of the generated microwave FSK signal have roughly equivalent amplitudes.

4. Conclusion

A novel photonic scheme based on cascaded MZMs is proposed and demonstrated to generate high frequency microwave FSK signal. The feasibility of our scheme is verified by theoretical analysis and simulation experiment. When the frequency of driving microwave signal is fm, the microwave FSK signal with frequencies of $2f_m$ and $4f_m$ is generated. The OSSR of the generated photonic microwave FSK signal is higher than 20 dB. Simulation results show that the designed photonic scheme has a simple structure and strong stability for generating microwave FSK signal.

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