Integrated Photonic Generation of Microwave-Multiplicated Signal and Amplitude-Shift Keying Signal

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Abstract: We propose and experimentally demonstrate a simple and compact photonic scheme to obtain frequency-multiplicated microwave signal based on a single integrated silicon Mach–Zehnder modulator (MZM). Using the fabricated integrated MZM, we also demonstrate the feasibility of microwave amplitude-shift keying (ASK) modulation based on integrated photonic approach. In a proof-of-concept experiment, 2 GHz frequency-doubled microwave signal is generated using a 1 GHz driving signal. And 750 MHz/1 GHz frequency-tripled/quadrupled microwave signals are obtained with a driving signal of 250 MHz. In addition, a 50 Mb/s binary amplitude coded 1 GHz microwave signal is also successfully generated. Using the state-of-art MZM with pn-type diode structure, the frequency of the generated microwave signals is expected to be enhanced to one hundred GHz.

OCIS codes: (130.3120) Integrated optics devices; (062.5625) Radio frequency photonics.

1. Introduction

Photonicly generated microwave signals can find applications in many microwave photonic systems, such as broad-band wireless access networks, software-defined radio, antenna remoting, phased-array antenna, and radar systems [1]. Usually, optical microwave generation is based on heterodyne techniques. Two phase-correlated optical waves with a wavelength spacing corresponding to the desired frequency of the microwave signal are generated, and the microwave signal is generated by beating the two optical wavelengths at a square-law photo detector (PD). Several approaches to generate two phase-correlated optical waves have been proposed and demonstrated based on free space devices [2] and fiber devices [1, 3-5]. Among these approaches, microwave frequency multiplication based on external modulation using Mach–Zehnder modulators (MZMs) has been considered an effective solution for high frequency and tunable microwave signal generation. For example, in [3], using a single MZM, a frequency-doubled microwave signal is generated by adjusting the constant phase shift between two arms of the MZM to suppress all the even-order side bands. The beating of the ±1st-order side-bands at a PD would generate a frequency-doubled microwave signal. In addition, by introducing an optical notch filter to remove the optical carrier, a frequency-quadrupled microwave signal can also be generated [1].

Photonic generation of RF binary digital modulation signals is another key technology in microwave photonics. Amplitude-shift keying (ASK), phase-shift keying (PSK) and frequency-shift keying (FSK) are basic modulation formats in wireless communications, which convey information by modulating the amplitude, phase or frequency of a continuous carrier wave. Traditionally, these modulation microwave signals are generated in electrical domain using digital electronic circuits [6]. Due to the electronic bottleneck, the major difficulty of this traditional technique is that the frequency of the generated signals is limited to a few GHz. An effective method to generate high frequency RF signals is to generate RF signals in optical domain. These approaches are based on spatial light modulator (SLM) technologies or fiber devices. Similar to microwave frequency muiltiplication, the use of MZM is also considered to be a competitive approach to generate binary digital modulation signals. Microwave PSK and FSK has been proposed and realized based on commercial MZM [7, 8]. However, microwave ASK signal as a fundamental digital modulation format in wireless communication has rarely been realized using MZM.

Compared to using the fibered or free space devices to generate frequency-multiplicated microwave signals or binary digital modulation signals, silicon-on-insulator (SOI) based waveguides can offer distinct advantages of increased stability and reliability, low cost, small footprints, and compatibility with other integrated optoelectronic devices [9]. In the recent years, owing to the great success of silicon photonics, some passive microwave photonic devices (i.e. microwave photonic filters, microwave photonic phase shifters) based on SOI waveguides have been proposed and demonstrated showing excellent characteristics [10].

In this paper, we propose a simple yet effective approach to obtain frequency- multiplicated microwave signals or amplitude coded microwave signals based on a single integrated silicon MZM. In a proof-of-concept experiment, 2 GHz frequency-doubled microwave signal is generated using a 1 GHz driving signal. 750 MHz/1 GHz frequency-tripled/quadrupled microwave signals are obtained with a driving signal of 250 MHz. And a 50 Mb/s binary amplitude coded 1 GHz microwave signal is also successfully generated. The frequency of the generated microwave signals is limited by the operation bandwidth of the pin-type MZM. Using the state-of-art MZM with pn-type diode structure [11], the frequency of the generated microwave signals is expected to enhance to one hundred GHz.

2. Microwave signal multiplication

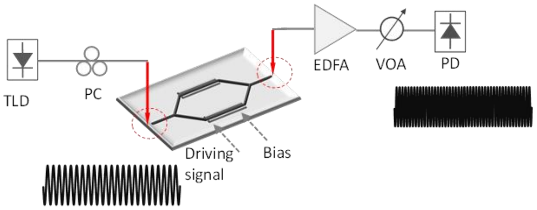

Fig. 1. Schematic illustration of the proposed photonic microwave signal multiplicator.

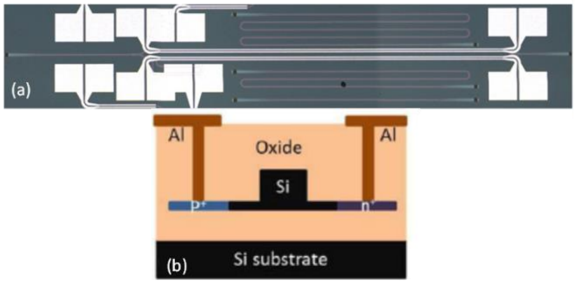

Fig. 2. (a) Microscope image of the fabricated integrated MZM. (b) Cross-sectional view schematics.

Figure 1 illustrates the schematic illustration of the proposed photonic frequency-multiplicated microwave signal generation system using an integrated silicon MZM. Continuous-wave (CW) light from a tunable laser diode (TLD) is sent to the MZM. The driving signal and the dc-bias is combined by a bias-tee and applied to the MZM. The output light intensity of the MZM can be written as

$$I=\frac{1}{2}I_0[1+J_0(m)\cos\phi_0]+I_0\cos\phi_0\sum_{n=1}^{\infty}(-1)^n J_{2n}(m)\cos(2n\omega_{RF}t)+I_0\sin\phi_0\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(m)\cos[(2n-1)\omega_{RF}t] \qquad (1)$$

where I_0 is the intensity of the input optical carrier. $\varphi_0=\pi V_b/V_\pi$ is the constant phase difference between the two arms determined by the constant dc-bias V_b. constant dc-bias voltage. V_π is the half-wave voltage of the MZM. And V_{RF} and ω_{RF}, respectively, are the amplitude and angular frequency of the applied electrical drive voltage. $m=\pi V_{RF}/V_\pi$ is the modulation indice of the MZM. J_n is the nth order Bessel function of the first kind.

It follows from Eq.(1) that if the modulator is biased at V_π, the odd components will be suppressed. Ignoring the high order harmonic wave, a frequency-doubled microwave signal is obtained. In addition, by adjusting the driving microwave signal amplitude to let $J_2(m)=0$, the quadruple response will dominant the output, and a frequency-quadrupled signal can be obtained. Similarly, a frequency-tripled signal is generated by suppressing the even components and $J_1(m)$ term of the signal. Figure 2(a) shows the optical microscope image of the fabricated device. The waveguides are 220 nm high with a 60 nm slab. The width of the waveguide is 500 nm. The active arm length is 1.8 mm while the arm length difference between two arms are 494 µm. Figure 2(b) shows the cross-sectional view schematics of the doped waveguide.The n and p doping regions are 4 µm wide, and each has a separation of 0.6 µm from the waveguide sidewall. The doping concentration is about 10^{20} cm^{-3}.

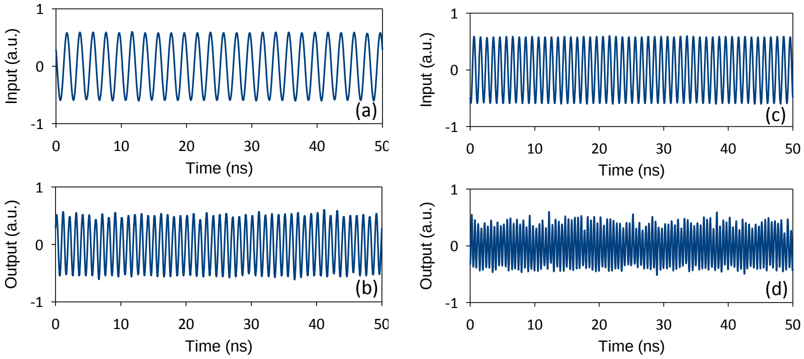

Fig. 3. Waveforms of (a) the input 500 MHz driving signal, and (b) the generated 1 GHz frequency-doubled signal, (c) the input 1 GHz driving signal, and (d) the generated 2 GHz frequency-doubled signal.

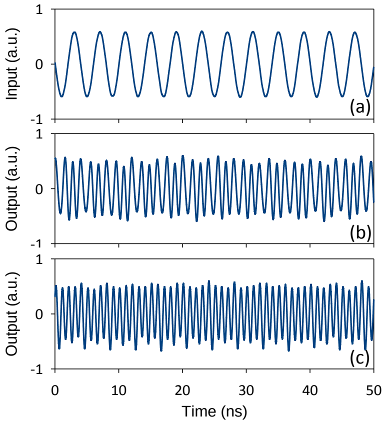

Fig. 4. Waveforms of (a) the input 250 MHz driving signal, (b) the generated 750 MHz frequency-tripled signal, and (c) the 1 GHz frequency- quadrupled signal.

We first investigate the generation of frequency-doubled microwave signal. Figure 3 (a) (b) show the waveforms of the original 500 MHz driving signal and the generated 1 GHz signal. Figure 3 (c) (d) show the obtained 2 GHz signal when the driving signal frequency is 1 GHz. Figure 4 illustrates the results of the generation of frequency-tripled and frequency- quadrupled signal with a driving signal of 250 MHz. The imperfections of the waveforms come from the influence of incompletely suppressed high-order components. The frequency of the generated microwave signals is limited by the operation bandwidth of the pin-type MZM. The frequency can be further increased by adopting pn-type diode structure [11].

3. Microwave ASK modulation

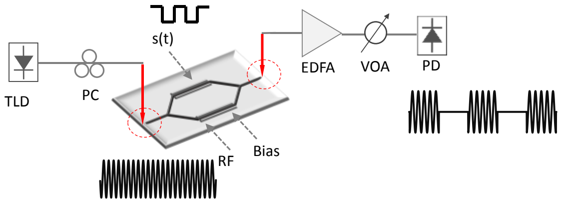

Fig. 5. Schematic illustration of the proposed photonic microwave ASK signal generator.

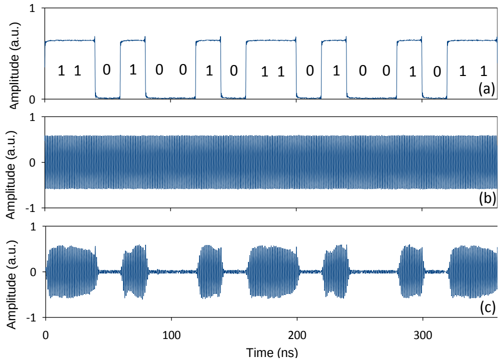

Fig. 6. Waveforms of (a) the original 50 Mb/s baseband signal with a pattern of “110100101101001011”. (b) original 1 GHz microwave carrier signal, and (c) the output ASK signal.

Using the fabricated integrated MZM, we also demonstrate the feasibility of microwave ASK modulation using integrated photonic approach. Figure 5 illustrates the schematic illustration of the proposed photonic microwave ASK signal modulation system using an integrated silicon MZM. The microwave carrier signal and the binary coding signal *s* (*t*) are applied to the two RF ports of the MZM, respectively. The AC term of the detected signal at the output of the PD can be written as

$$i_{AC} \propto 2J_1(m)\cos(\omega_{RF}t)\sin(\gamma s(t)-\phi_0)+J_0(m)\cos(\gamma s(t)-\phi_0) \qquad (2)$$

where ω_{RF}, m, V_{RF}, V_π and φ_0 are defined as previously mentioned. $\gamma=\pi V_s/V_\pi$ are the modulation indice in the arm which the binary coding signal is applied. The second term in Eq. (2) is located in baseband. Assuming φ_0=0, it can be easily eliminated by an electric filter. Assuming $\gamma=\pi/2$, the amplitude of the obtained signal is

$$i=\begin{cases}2J_1(m)\cos(\omega_{RF}t) & s(t)=1\\ 0 & s(t)=0\end{cases} \qquad (3)$$

As can be seen, the amplitude of the carrier is “1” with bit “1”, and “0” with bit “0”. Therefore, two-level ASK signal can be generated. Figure 6(a) shows the waveforms of the original 50 Mb/s baseband signal with a pattern of “110100101101001011”. The original 1 GHz microwave carrier is shown in Fig. 6(b). Figure 6(c) shows the modulated ASK signal.

In summary, a simple and compact photonic scheme to obtain frequency-multiplicated microwave signal has been proposed and experimentally demonstrated based on a single integrated silicon MZM. In a proof-of-concept experiment, 2 GHz frequency-doubled microwave signal is generated using a 1 GHz driving signal. And 750 MHz/1 GHz frequency-tripled/quadrupled microwave signals are obtained with a driving signal of 250 MHz. Using the fabricated integrated MZM, the feasibility of microwave ASK modulation has also been demonstrated. A 50 Mb/s binary amplitude coded 1 GHz microwave signal is successfully generated. The frequency of the generated microwave signals is limited by the operation bandwidth of the pin-type MZM. Using the state-of-art MZM with pn-type diode structure, the frequency of the generated microwave signals can be further increased. With future improvement, one would expect to see a compact high frequency microwave signal generator or modulator based on silicon MZM structure benefiting from integrated microwave photonics device .

4. Acknowledgements

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