Silicon-chip-based Frequency Quadrupling for Optical Millimeter-wave Signal Generation

Fangfei Liu[1], Tao Wang[1], Liang Zhang[1], Jing Wang[2], Min Qiu[2], Yikai Su[1]
1State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, 800 DongChuan Rd, Shanghai Jiao tong University, Shanghai 200240, China
Phone: +(21)34204425, Fax: +(21)34204370, Email: yikaisu@sjtu.edu.cn
2Department of Microelectronics and Applied Physics, Royal Institute of Technology (KTH)
Electrum 229, Kista 16440, Sweden

Abstract: We propose a prototype of a silicon-chip-based frequency quadrupling system integrating a single-drive silicon Mach-Zehnder modulator and a microring resonator. A proof-of-concept demonstration of 40-GHz millimeter-wave signal generation using 10-GHz driving signal is experimentally provided.

OCIS codes: (060.5625) Radio frequency photonics, (130.3120) Integrated optics devices

1. Introduction

Optical millimeter-wave (MMW) generation is a key technique in radio-over-fiber (RoF) systems, where efficient and cost-effective methods to generate microwave/MMW signals are of importance [1,2]. Various schemes for MMW signal generation using frequency multiplication have been reported, including using four-wave mixing [3], external modulator [1,2] and so on. However, these methods are limited by their sizes and difficult to integrate with other electronic/optical analog signal processing modules if to further reduce the cost of the RoF systems. Recently developed silicon photonics technology provides a promising platform for integration of photonics with standard electronics. Various building blocks such as silicon Mach-Zehnder modulator (MZM) and microring resonator have been demonstrated. Here we propose an integrated frequency quadrupling system consisting of a silicon MZM and a microring resonator, and concept-prove 40-GHz MMW signal generation using 10-GHz driving signal. This system has potential to be integrated with other photonic microwave signal processing systems. In addition, by designing the free spectral range (FSR) of the microring resonator, this system can be used for optical up-conversion in wavelength-division-multiplexer (WDM) RoF system.

2. Principles

The schematic diagram of the silicon-chip-based frequency quadrupling system is shown in Fig. 1(a). The single-drive silicon MZM is biased at the transmission maximum and driven by an electrical sinusoidal signal with a frequency of f_{RF} and an amplitude of V_π, the modulated optical signal is Gaussian-like pulse train with a repetition rate of $2f_{RF}$ [4]. The structure of the microring resonator is a ring evanescently coupled to two straight waveguides. The transfer function of the microring resonator at the through port can be expressed as $T(\omega)=[j(\omega-\omega_0)+(1/\tau i+1/1/\tau e')-1/\tau e]/[j(\omega-\omega_0)+(1/\tau i+1/1/\tau e')+1/\tau e]$ [5], where ω_0 is the resonance frequency, $1/\tau i$ is the power decay rate due to the intrinsic loss, $1/\tau e$ and $1/\tau e'$ are the power coupling to the waveguide connecting to the through port and drop port, respectively, which are related to the reciprocal of photon lifetime as $1/\tau =1/\tau i +1/\tau e'+1/\tau e$. Compared with the single waveguide coupled microring, it is easier to achieve critical coupling condition with the double waveguide structure. When the microring resonator operates in the critical coupling region ($1/\tau i +1/\tau e'=1/\tau e$), the transfer function can be approximated as $T(\omega)=j\tau(\omega-\omega_0)$, which is a typical function for a first-order differentiator. Therefore, the microring resonator can further differentiate the Gaussian-like pulse train into odd-symmetry Hermite-Gaussian pulses (OS-HG) [5] with a repetition rate of $4f_{RF}$. After square-law detection using a photodiode (PD), desired $4f_{RF}$ MMW signal can be generated. With the state-of-art technology, silicon MZM with footprint as small as $0.001mm^2$ has been reported [6]; thus the size of the whole system could be within $0.01mm^2$.

3. Proof-of-concept experiment

We fabricate a double-waveguide coupled silicon microring resonator with race track structure. The scanning electron microscope (SEM) photo of the device is shown in Fig. 1(b). The device is fabricated on an SOI wafer with a straight coupling region of ~3 μm and bending radius of ~20 μm. The air gap between the straight waveguide and the race track is ~100 nm. The widths of the straight waveguide and the ring are 450 nm and 550 nm, respectively. Fig. 1(c) provides the transmission spectrum at the through port of the microrong resonator. The notch depth for the resonance at ~1542.92 nm is ~22 dB with a 3-dB bandwidth of ~0.37 nm, which indicates that the microring resonator operates near the critical coupling condition. The spectrum is periodic with an FSR of 4.18 nm. The FSR can be designed to be consistent with the WDM channel space by increasing the radius so that this system can be used for up-conversion in WDM RoF systems.

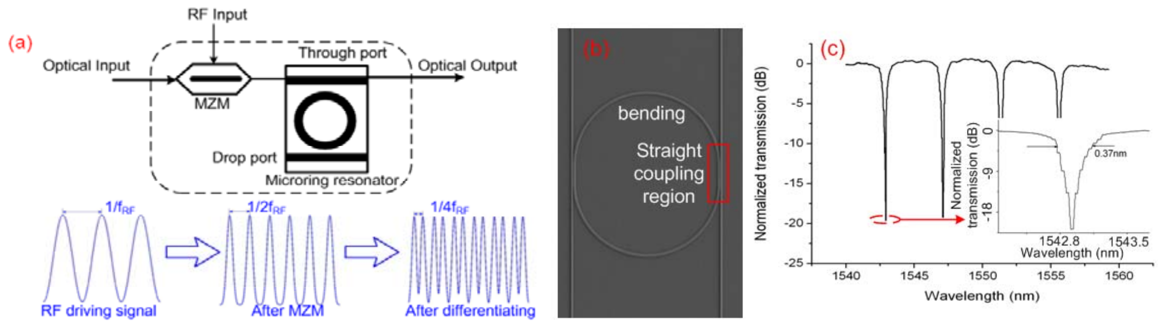

Fig. 1. (a) Schematic diagram and illustration of the silicon-chip-based frequency quadrupling system; (b) SEM photo and (c) transmission spectrum of the microring resonator.

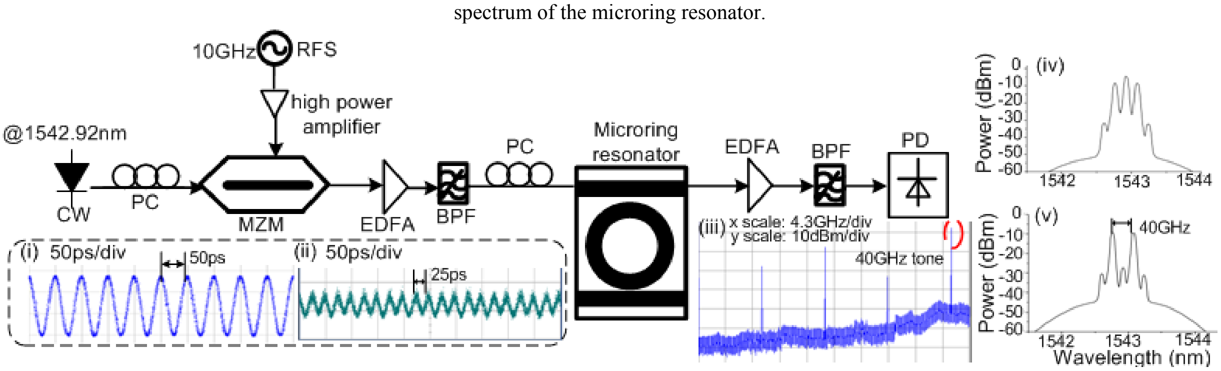

Fig. 2. Experimental setup of the frequency quadrupling system. Waveform after (i) MZM, (ii) detection using 40-GHz PD; (iii) RF spectrum; Optical spectrum after (iv) MZM, (v) microring resonator.

Fig. 2 depicts the experimental setup to realise frequency quadrupling based on the proposed scheme. Due to the unavailability of the silicon MZM, we use a single drive $LiNO_3$ MZM instead in the experiment. The MZM is biased at the transmission maximum and the 10-GHz signal generated from the RF synthesizer (RFS) is amplified using a high power amplifier to achieve a peak-to-peak driving voltage of ~12 V. A polarization controller (PC) is inserted before the microring resonator to guarantee that the input light is TE mode. Two Erbium doped fiber amplifiers (EDFAs) are used to compensate the ~20 dB fiber-to-fiber coupling loss. The optical spectrum after the MZM and the microring resonator are shown in Fig. 2(iv)(v). The two main lobes of the optical spectrum are separated by 40 GHz, which also can be verified by the waveforms in Fig. 2(i)(ii). After square-law detection using a 40-GHz PD, the 40-GHz MMW signal is successfully generated with a period of 25 ps, which is half of the period of the signal at the output of the MZM; the 40-GHz tone is ~10 dB higher than other tones in the RF spectrum as shown in Fig. 2(iii). The side tones will be removed in a practical RoF system.

4. Conclusion

We have proposed a compact integrated frequency quadrupling system based on silicon chip. 40-GHz MMW is successfully generated using 10-GHz signal. This work was supported by the NSFC (60777040), Shanghai Rising Star Program Phase II (07QH14008), the Swedish Foundation for Strategic Research (SSF) through the future research leader program, and the Swedish Research Council (VR)

References:

[1] J. Yu, Z. Jia, L. Yi, Y. Su, G. Chang, and T. Wang, "Optical millimeter-wave generation or up-conversion using external modulators," Photon. Technol. Lett. **18**, 265-267 (2006).
[2] C. Lin, P. Shih, J. Chen, W. Xue, P. Peng, and S. Chi, "Optical millimeter-wave signal generation using frequency quadrupling technique and no optical filtering," Photon. Technol. Lett. **20**, 1027-1029 (2008).
[3] Q. Wang, H. Rideout, F. Zeng, and J. Yao, "Millimeter-wave frequency tripling based on four-wave mixing in a semiconductor optical amplifier," Photon. Technol. Lett.**18**, 2460-2462 (2006).
[4] P. Winzer and R. Essiambre, "Advanced optical modulation formats," In Proc. IEEE **94**, 952-985 (2006).
[5] F. Liu, T. Wang, L. Qiang, T. Ye, Z. Zhang, M. Qiu, and Y. Su, "Compact optical temporal differentiator based on silicon microring resonator," Opt. Express **16**, 15880-15886 (2008).
[6] W. Green, M. Rooks, L. Sekaric, and Y. Vlasov, "Ultra-compact, low RF power, 10 Gb/s silicon Mach-Zehnder modulator," Opt. Express **15**, 17106-17113 (2007)