

# Photonic-Assisted Microwave Frequency Doubling based on Silicon Ring Modulator

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**Abstract**—We experimentally demonstrate an integrated optical millimeter-wave signal generator based on a silicon ring modulator. A 20 GHz microwave signal with 17 dB suppression ratio is obtained with a 10 GHz input signal.

**Keywords**—millimeter signal generator, silicon ring modulator

## I. INTRODUCTION

Millimeter (mm) wave signal generator is highly desirable in many applications such as radar, wireless communication radio-over-fiber (RoF) system, and so on. Since the generated mm-wave signal is usually distributed to a remote site through the fiber, mm-wave signal generation in the optical domain is able to simplify the RoF system and reduce its cost. The frequency multiplication technique, which uses a low-frequency RF oscillator and an electro-optical converter to generate a high-frequency RF signal, is undoubtedly a cost-effective solution. Most reported techniques to multiply the frequency of the RF signal are based on Mach-Zehnder modulators (MZMs) [1-3], or phase shifters [4]. Filters are required sometimes to suppress undesired optical harmonics. Although these MZMs offer satisfactory performances for the RF frequency multiplication, their sizes are normally on the scale of centimeter in order to produce enough phase shift and modulation depth, and therefore the power consumption is quite large. In this paper, we present, for the first time to our knowledge, a frequency doubling system based on an integrated silicon carrier-depletion ring modulator. A 20 GHz millimeter signal is successfully generated. Compared with MZMs, our scheme offers plenty of advantages such as compact footprint and ultra-low power consumption. Furthermore, the device is fabricated on silicon on insulator (SOI) platform which is CMOS compatible. Therefore, it has great potential for the low-cost, large-scale and high-density integration in the future.

## II. OPERATION PRINCIPLE

The carrier-depletion silicon ring modulator is widely used for on-off key modulation in optical interconnect systems. Here this device is used to double the frequency of the driving RF signal by tuning the operation wavelength. Its operation principle is shortly discussed in this section. According to the time rate equation [5], the static transmitted field in the bus waveguide of an all-pass ring modulator is expressed as

$$S_t = A \frac{j(\omega - \omega_0) + \frac{1}{\tau} - \frac{2}{\tau_e}}{j(\omega - \omega_0) + \frac{1}{\tau}} \exp(j\omega t) \quad (1)$$

where  $A$  and  $\omega$  are the amplitude and the angular frequency of the incident optical carrier, respectively,  $\omega_0$  is the angular resonance frequency of the ring. The optical field inside the ring decays as a result of the coupling with the bus waveguide and the propagation loss of the doped rib waveguide. The corresponding amplitude decay rates are denoted as  $1/\tau_e$  and  $1/\tau_i$ , respectively. Thus, the overall decay rate is  $1/\tau = 1/\tau_e + 1/\tau_i$ , which is twice the usually referred cavity photon lifetime. The parameter  $\mu$  denotes the mutual coupling between the ring and the bus waveguide. According to the power conservation law, the relationship between  $\mu$  and  $\tau_e$  is  $\mu^2 = 2/\tau_e$  [5].

The embedded PN junction allows the driving RF signal to change the density of free carriers inside silicon waveguide, and subsequently to shift the resonance frequency  $\omega_0$  and the amplitude decay rate  $1/\tau$  of the ring through the plasma dispersion effect. If a sinusoidal voltage signal in the small signal regime is applied on the device, the modulated optical field through the bus waveguide is deduced as [5]

$$S_t(t) = A \exp(j\omega t) \left\{ \frac{j(\omega - \omega_0) + \frac{1}{\tau} - \frac{2}{\tau_e} - jv_0\mu^2 \left[ \frac{\Delta\omega_0}{\Delta v_{pn}} + j \frac{\Delta(\frac{1}{\tau})}{\Delta v_{pn}} \right] f(\omega_1)}{j(\omega - \omega_0) + \frac{1}{\tau}} \cos \omega_1 t - \frac{jv_0\mu^2 \left[ \frac{\Delta\omega_0}{\Delta v_{pn}} + j \frac{\Delta(\frac{1}{\tau})}{\Delta v_{pn}} \right] f(\omega_1)}{[j(\omega - \omega_0) + \frac{1}{\tau}]^2 + \omega_1^2} \frac{\omega_1 \sin \omega_1 t}{[j(\omega - \omega_0) + \frac{1}{\tau}]} \right\} \quad (2)$$

where  $\Delta\omega_0/\Delta v_{pn}$  and  $\Delta(1/\tau)/\Delta v_{pn}$  denote the change rates of  $\omega_0$  and  $1/\tau$  with respect to the voltage dropping across the PN junction. If the ring modulator is critically coupled and works at the resonance wavelength, the static transmitted field in the bus waveguide (the first term inside the braces of Eq.2) is zero. Since the photocurrent at the receiver side is proportional to the power of the optical field, i.e., the square of the modulus of Eq. 2, we can get a microwave signal of doubled frequency after the photo-detection.

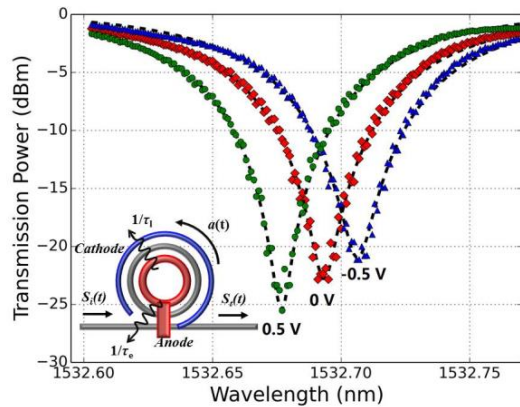
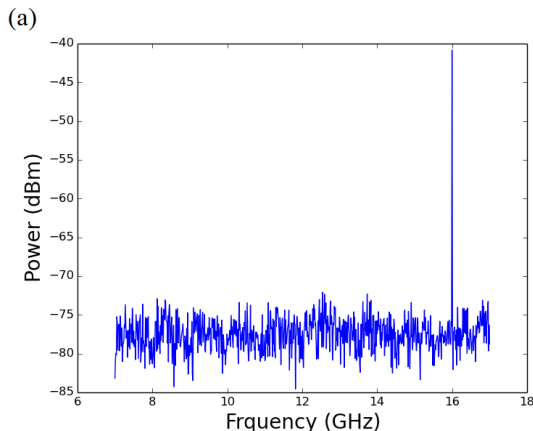


Fig. 1. Transmitted spectra of the ring modulator at different bias voltages. The inset is the schematic diagram of a typical ring modulator

### III. MEASUREMENT RESULTS

We test a typical carrier-depletion silicon ring modulator of 10  $\mu\text{m}$  radius. The doping concentration of the embedded PN junction is  $1 \times 18/\text{cm}^2$ . The etching depth and the dimension of the rib waveguide accommodating the PN junction are 150 nm and  $450 \text{ nm} \times 220 \text{ nm}$  respectively. Its transmission spectra at different bias voltages are illustrated in Fig. 1. The extinction of more than 20 dB at the resonance wavelength indicates that the ring is very close to the critical coupling. To demonstrate the frequency doubling, the input optical carrier of 1 mW is aligned to the resonance wavelength of the ring. The driving RF signal has amplitude of 900 mV. The modulated optical output from the ring modulator sequentially passes through an EDFA, a tunable filter and finally reaches an electrical spectrum analyzer with an optical head. The frequency conversions from 8 GHz to 16 GHz and from 10 GHz to 20 GHz are displayed in Figs. 2 (a) and 2 (b), respectively. The suppression ratios between the doubled frequency and the fundamental frequency are 35 dB for the 16 GHz signal, and 17 dB for the 20 GHz signal. We attribute the performance degradation as the input frequency rises to the limited modulation bandwidth of this device, which can be improved



by optimizing the design and the processing condition.

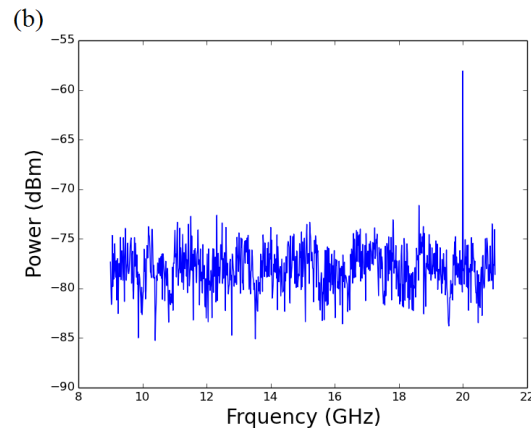


Fig. 2. Measured electrical spectra for (a) 8GHz to 16 GHz conversion and (b) 10 GHz to 20 GHz conversion.

### IV. CONCLUSION

We propose and experimentally demonstrate a microwave frequency doubling system based on an integrated silicon ring modulator. A 20 GHz signal is obtained from a 10 GHz input signal with 17 dBm suppression ratio. Compared with other techniques, we believe the silicon ring modulator provides a compact, and power/cost efficient candidate for the frequency multiplication in RoF systems.

### ACKNOWLEDGMENT

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