Linearity Measurement of a Silicon Single-Drive Push-Pull Mach-Zehnder Modulator

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Abstract: We investigate the linearity of a silicon Mach-Zehnder modulator with single-drive push-pull configuration. The spurious free dynamic range for second harmonic distortion ($SFDR_{SHD}$) is 86 dB Hz$^{1/2}$ with 4 dB improvement over previous best result.

OCIS codes: (130.4110) Modulators; (230.2090) Electro-optical devices

1. Introduction

Optical modulators are widely used in microwave photonics such as subcarrier transmission, radio-over-fiber, and analog-to-digital conversion. The linearity of modulators is an important performance metric in microwave photonics. Recently, optical modulators made on the silicon platform have attracted considerable research interest because of their integration capability with CMOS microelectronic circuits and low manufacturing cost. Many methods to improve the linearity of silicon optical modulators have been proposed and demonstrated [1–3]. Microring modulators are not suitable for wideband microwave systems due to the poor spurious free dynamic range for the second-order harmonic distortion ($SFDR_{SHD}$) [4]. Ring-Assisted Mach-Zehnder (MZ) modulators have large spurious free dynamic range for the third-order intermodulation distortion ($SFDR_{IMD}$) of 106 dB Hz$^{2/3}$ [2]. The linearity of MZ modulator can be improved to 82 dB Hz$^{1/2}$ for $SFDR_{SHD}$ and 97 dB Hz$^{2/3}$ for $SFDR_{IMD}$ by using differential drive [3].

In this work, we present the linearity characterization of a silicon MZ modulator with a single-drive push-pull configuration. Compared with conventional differential drive, the single-drive scheme can effectively reduce the second harmonics distortion due to the two auto-aligned push-pull signals from one RF feed.

2. Modulator design

Figure 1(a) shows the schematic structure of our single-drive push-pull silicon MZ modulator. The single-drive configuration features low chirp, low capacitance (two junction capacitors are connected in series), and simplified RF connection interface [5]. The 3.3-mm-long traveling wave electrode uses co-planar metal strips in a ground-signal (GS) configuration. The arm length difference of the MZI is 90 μm. Figure 1(b) shows the cross-section of the MZ modulator. The silicon waveguides have a width of 500 nm and a slab thickness of 60 nm. The DC bias is applied to the middle n^+ doping region in the center of the MZI. The RF signal is applied to the outer p^+ doped regions. When the RF drive signal is V_{pp} (peak-to-peak), DC bias is V_d, the reverse voltage drop on the p-n junctions are (V_d-V_{pp}/4, V_d+V_{pp}/4) and (V_d+V_{pp}/4, V_d-V_{pp}/4), forming the push-pull configuration. Figure 1(c) shows the microscope image of our silicon MZ modulator.

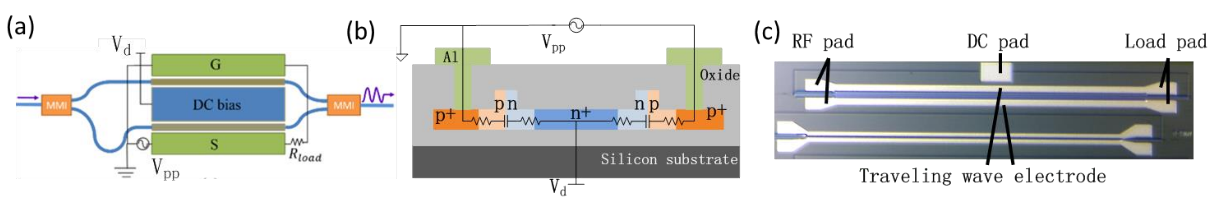

Fig.1. (a) Schematic structure of the MZ modulator. (b) Cross-section showing the single-drive push-pull configuration. (c) Microscope image of the fabricated device.

At the quadrature operation point, the transfer function of the MZ modulator is given by

$$P_{out} = P_{in}\left[\frac{1}{4}\left(e^{-2a_A}+e^{-2a_B}\right)-\frac{1}{2}e^{-(a_A+a_B)}\sin\left(\phi_A-\phi_B\right)\right] \tag{1}$$

where $\alpha_{A,\,B}$ is loss and $\phi_{A,\,B}$ is modulation phase shift of MZI active arms. α and ϕ can be expanded to the third order polynomial of drive voltage V as: $\alpha = \alpha_0 + \alpha_1 V + \alpha_2 V^2 + \alpha_3 V^3$ and $\phi = \varphi_1 V + \varphi_2 V^2 + \varphi_3 V^3$. For the push-pull drive,

$\phi_A - \phi_B = 2\varphi_1 V + 2\varphi_3 V^3$ and $a_A + a_B = 2\alpha_0 + 2\alpha_2 V^2$. Assuming the RF drive voltage has two frequency tones, it can be written as $V = V_0\cos(w_1 t) + V_0\cos(w_2 t)$. With Taylor expansion and Jacobi-Anger expansion, the term $e^{-(a_A+a_B)}\sin(\phi_A - \phi_B)$ in Eq. (1) is expressed as:

$$\begin{aligned}&\left[\left(2-9\alpha_2V_0^2\right)J_0(z)J_1(z)+6\alpha_2V_0^2J_1(z)J_2(z)+\alpha_2V_0^2J_0(z)J_3(z)\right]\left(\cos(w_1t)+\cos(w_2t)\right)+\\&\left[\left(7\alpha_2V_0^2-2\right)J_1(z)J_2(z)-3\alpha_2V_0^2J_0(z)J_1(z)+2\alpha_2V_0^2J_0(z)J_3(z)-3\alpha_2V_0^2J_2(z)J_3(z)\right]\left(\cos(2w_1-w_2)t+\cos(2w_2-w_1)t\right)\end{aligned} \quad (2)$$

where $J_n(z)$ (n = 1, 2, 3) is Bessel function, $z = 2\varphi_1 V_0 + 3\varphi_3 V_0^3/2$. According to Eq. (2), SHD due to phase modulation is completely cancelled.

In order to enable push-pull operation, the differential drive modulator needs two input RF signals with exactly reversed phase. However, slight length mismatch between the two input cables can cause the two signals desynchronized, increasing SHD. In comparison, the single-drive configuration can generate the push-pull signals using one RF signal without the troublesome of synchronization, which can guarantee low SHD.

3. Experimental results

In order to find the wavelength for best SFDR, we measured the output power ratio between fundamental tones and distortions (F/SHD and F/IMD) versus wavelength at V_d = 0V. The input signal consists of two tones at frequencies 1005 MHz and 1015 MHz. The fundamental output power (F) at each frequency is set to -50 dBm. Both traces of F/SHD and F/IMD have two peaks at the positive and negative slopes of the transmission spectrum. The peak wavelength is located close to the quadrature operation points. The wavelength for best SFDR is 1551.5 nm. The F/SHD and F/IMD are 74.4 dB and 58.9 dB, respectively. The output signals including F, SHD, and IMD were measured while the power of the two input tones was varied. The reconstructed RF spectra for SHD at 2030 MHz and IMD at 1025 MHz are shown in Fig. 2(b) with 10 Hz resolution bandwidth. The noise floor is observed to be -146 dB. Figure 2(c) shows the output power as a function of input power for F, SHD, and IMD. The noise floor is -156 dB at 1 Hz resolution bandwidth. Spurious free dynamic range of 86 dB $Hz^{1/2}$ and 96.3dB $Hz^{2/3}$ are obtained for $SFDR_{SHD}$ and $SFDR_{IMD}$, respectively. Compared to the previous result [3], The $SFDR_{SHD}$ is improved 4 dB as the SHD is greatly suppressed by the exact π phase shift between the drive voltages on MZI arms.

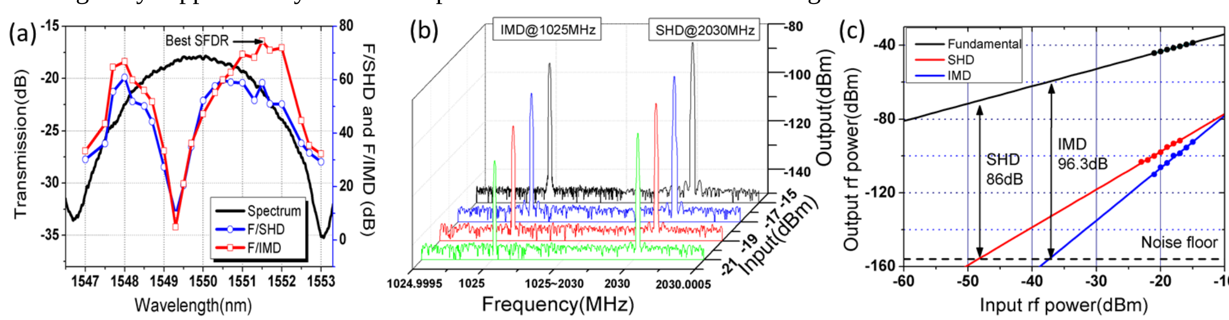

Fig. 2. (a) Measured transmission spectrum and F/SHD and F/IMD at various wavelengths. (b) Reconstructed RF spectrum of IMD and SHD at four input power levels. (c) SFDR of the MZ modulator due to SHD and IMD. Dots represent measured values.

4. Conclusion

We characterized the linearity of a silicon Mach-Zehnder modulator with single-drive push-pull traveling wave electrode. The $SFDR_{SHD}$ is measured to be 86 dB $Hz^{1/2}$ with 4 dB improvement over previous best result. The $SFDR_{IMD}$ is 96.3 dB $Hz^{2/3}$.

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