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Configurable Modulator based Optical Carrier Frequency Suppressed Intensity Modulation

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***Abstract*—A configurable silicon modulator is proposed, consisting of a phase modulator embedded in a tunable Mach-Zehnder interferometer. We present the analytical analysis and numerical simulations, as well as the experimental results for carrier suppressed intensity modulation.**

***Index Terms*—Optical modulator, programmable photonics, microwave photonics**

I. INTRODUCTION

Photonic integrated circuits are now widely used in data communication systems, optical quantum computing systems, LiDAR and microwave photonic systems [1]. In these applications, electro-optical modulators play an important role. Compatible with the CMOS processing, plasma dispersion modulators (PDM) have become the most popular modulator implementation in the process design kits of foundries. The plasma dispersion phase modulator is implemented by doping a P(I)N junction into a silicon waveguide. When the junction is reverse biased (depletion) or forward biased (injection), free carriers in the waveguide are removed or injected, resulting in a refractive index change of the doped waveguide and inducing a phase modulation in the guided light wave. This phase modulation can be converted into an intensity modulation by using interference in a Mach-Zehnder interferometer (MZI) and microring resonator. However, the changes in the density of free carriers in the waveguide also lead to changes in the optical loss, inducing a spurious intensity modulation of the light. This unwanted effect causes the response at the output of the ring or Mach-Zehnder modulator to be distorted.

At the same time, maturing foundry technology is driving research into larger and more complex photonic circuits, and in particular reconfigurable and programmable photonic integrated circuits [2], where light can be guided along different waveguide paths or formed into interferometers with electrically controlled tunable couplers (TCs) in the programmable optical circuit. In this way, programmable optical circuits can be a useful tool for a variety of applications, and with control algorithms they can be configured to different states to compensate for imperfections like manufacturing discrepancies.

We can apply this approach to the imperfections in the silicon photonic plasma dispersion modulators as well. Previously, we demonstrated a configurable modulator circuit which can be tuned to work as either an intensity modulator or a phase modulator [3]. In this paper, we elaborate the analytical model of this configurable modulator and show experimental results for intensity modulation with suppression of the carrier. Experimental results show that the optical carrier can be suppressed more than 40dBm. The technique does not change the modulator element itself and is also not limited to plasma dispersion modulators. Instead, an MZI structure is used to compensate the modulator imperfections. As such, it can be applied to existing platforms and standard building blocks from a process design kit (PDK), and the configurability makes it possible to adjust the circuit operating point based on measured modulation responses.

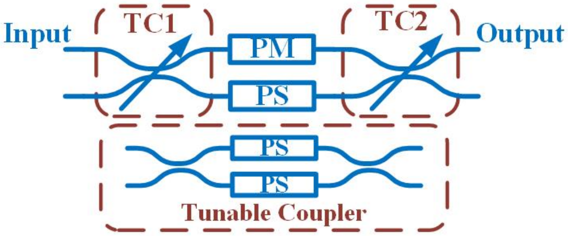

Fig. 1. Schematic of the proposed configurable modulator. PS: phase shifter; PM: phase modulator; TC: tunable coupler.

II. PRINCIPLE

The proposed configurable modulator circuit is an MZI structure consisting of two tunable couplers (TCs), a fast phase modulator and a (slow) static phase shifter, as shown in Fig. 1 [3]. The tunable coupler and phase shifter can be implemented by heaters, LCOS, MEMS or other tunable optical elements. Here we implement the tunable coupler as MZIs with heater-based phase shifters. By tuning the phase shifters in the TCs, the coupling ratio of the TCs κ_1 and κ_2 can be tuned from 0 to 1. The phase response of the TCs can be simplified because it can be fully compensated by the static phase shifter in the other arm of the MZI. Thus, the output field of the modulator circuit can be expressed as:

$$E_{out1} = [\sqrt{(1-\kappa_1)(1-\kappa_2)}\alpha \cdot e^{j\phi_s} - \sqrt{\kappa_1\kappa_2}e^{j\phi_{ps}}]e^{j(\omega_c t)} \tag{1}$$

where $e^{j(\omega_c t)}$ is the electrical field of the input light, κ_1 and κ_2 are the coupling coefficient of TC1 and TC2, α is the insertion

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loss of the modulator, ϕ_s is the fast phase shift introduced by the RF signal, and ϕ_{ps} is the static offset phase shifts generated by the phase shifter. Because of the symmetry of the circuit, we can assume that $\kappa_1 = \kappa_2$ can cover all use cases. And $\kappa = \kappa_1 = \kappa_2$ would be set within 0 to 0.5 because most light should be fed into the modulator to have a strongly modulated signal. Then, the modulated signal on the PM arm is:

$$\begin{aligned} e^{j(\omega_c t)} \cdot e^{j\phi_s} &= e^{j(\omega_c t + \pi \frac{V_{pp}}{V_\pi} \cos \omega_s t)} \\ &= e^{j(\omega_c t)} \sum_{n=-\infty}^{\infty} j^n J_n\left(\frac{V_{pp} \cdot \pi}{V_\pi}\right) e^{jn(\omega_s t)} \\ &\approx e^{j(\omega_c t)} \cdot [-J_2 e^{j-2(\omega_s t)} + jJ_1 e^{j-(\omega_s t)} + \\ &\quad J_0 + jJ_1 e^{j(\omega_s t)} + J_2 e^{j2(\omega_s t)}] \end{aligned} \tag{2}$$

where V_{pp} is the peak voltage of the modulated RF signal, V_π is the voltage for π phase shift and ω_s is the signal frequency. Here we used Bessel expansion of the first kind and J_n is the Bessel coefficients.

By feeding the modulated signal to a high speed photo diode (PD), we can get the recovered signal as:

$$I_{pd} \propto E_{out1} \times E^*_{out1} \tag{3}$$

Combining Eq. (1,2,3), if the modulator is a pure phase modulator, α is irrelevant to the RF signal. Then we can get the optical carrier power and the PD outputs at different harmonics:

$$I_{\omega_c} \propto [(1-k)\alpha J_o - \kappa]^2 + 2\kappa(1-\kappa)\alpha J_0(1 - \cos \phi_{ps}) \tag{4}$$

$$I_{\omega_s} \propto 4J_1\kappa(1-\kappa)\alpha \sin \phi_{ps} \cdot \cos \omega_s \tag{5}$$

$$I_{2\omega_s} \propto 2(-2J_0J_2(1-\kappa)^2\alpha^2 + 2\kappa \cos \phi_{ps}) \cos 2\omega_s \tag{6}$$

Because the RF signal is relatively small, $J_0 \approx 1$, then if a carrier suppressed modulation is needed, the modulator circuit can be set as $\kappa = \alpha(1-\kappa)$ and $\phi_{ps} = pi$, which corresponds to a balanced MZM operating at the null point. In the meantime, I_{ω_s} is at its minimum state and $I_{2\omega_s}$ is maximized.

However, normal plasma dispersion modulators are not pure phase modulators, which means:

$$\alpha(V) = \alpha_1 + \alpha_2(V_{pp} \cos \omega_s t) \tag{7}$$

where α_1 is the insertion loss of the embedded modulator at 0V and α_1 is the loss factor coefficient with the applied voltage. For a carrier depletion modulator, α_2 is negative with reversed biased voltage. And for most phase modulators, α_2 is very small.

Combining Eq. (1,2,3,7), a generic linear model of the configurable modulator circuit response is revealed, which can be used to configure the modulator circuit for different functions with optimized performance. Here we show the numerical simulation and experimental results for pure phase modulation and intensity modulation use cases with a configurable modulator circuit [3].

Another point can be found from Eq. (5) is that the recovered RF signal at the original frequency depends on the offset phase shifts ϕ_{ps} when the κ is set, while the upper and lower sidebands in the optical domain have an equal amplitude and opposite phase, which can be found from Eq. (2). Thus, for the RF signals the full circuit (configurable modulator + PD) is comparable to a balanced MZI - PD system for the optical signal, where the recovered optical power is also just related to the offset phase shifts. With this understanding, we can design configurable multi zero-pole pair microwave photonic filters with a much simpler specification.

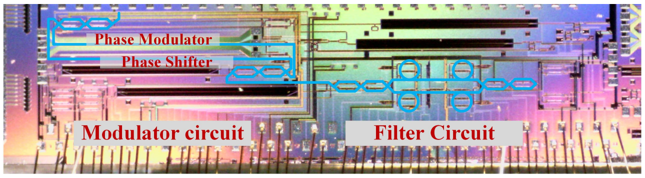

Fig. 2. A fabricated sample of the proposed configurable modulator circuit together with an optical configurable filter.

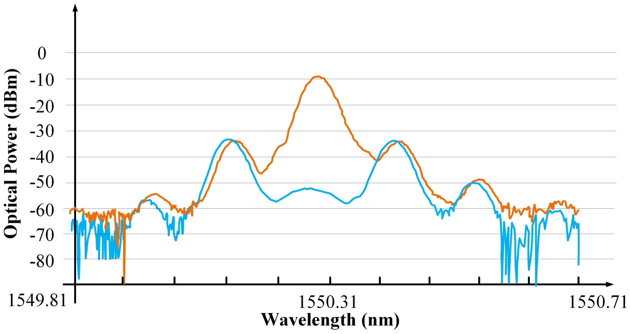

Fig. 3. Optical spectrum of an intensity modulation at linear point (yellow) and an optical carrier suppressed modulation at null point.

III. Experiments and Conclusion

Fig.2 shows a fabricated sample of the proposed configurable modulator circuit together with an optical configurable filter in IMEC's iSiPP50G platform. We configured it to demonstrate intensity modulation with a suppressed optical carrier. The laser light coming from a grating coupler is modulated by a 20GHz RF signal at 7dBm power. Fig. 3 shows the resulting optical spectrum which measured by an Anritsu MS9740A spectrum analyzer. The yellow curve shows an intensity modulation at the linear operating point while the blue curve shows the carrier suppressed modulation at the null point. In the plot we can see the carrier is suppressed for 45dB, indicating that this configurable modulator can be used for RF frequency doubling.

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