# Improvement of linearity in a silicon plasma dispersion phase modulator


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*Plasma dispersion modulators (PDMs), such as PIN based carrier injection modulators and PN based carrier depletion modulators, are widely used for high speed phase modulation in silicon photonic circuits, But their phase response is not linear, especially for injection modulator. This can be a problem in coherent communication systems that make use of complex multi-level quadrature modulation formats, as well as analog applications such as microwave photonics. In this article, a method to optimize the nonlinearity of the PDMs is proposed based on a configurable modulator circuit. The configurable modulator consists of a Mach-Zehnder interferometer (MZI) with a PDM and tunable couplers (TCs). The nonlinearity of the PDMs can be optimized by tuning the coupling ratios of the TCs and the phase delay between the two arms of the MZI, which is proved by simulation results.*


## Introduction

Electro-optic phase modulators are key components in silicon photonic circuits. Without the Pockels effect in common silicon waveguide, the preferred phase modulation mechanisms are based on the plasma dispersion effect [1]. A plasma dispersion modulator (PDM) is implemented by embedding a P(I)N junction into a silicon waveguide. By removing or injecting free carriers in the waveguide core, a PN or PIN based PDM can adjust the refractive index of the waveguide core and introduce a phase shift to the guided light. However, the free carriers also lead to optical absorption and the introduced phase shifts are not linear with the applied voltage. Fig. 1 show the directional current responses of depletion modulator and injection modulator. As can be seen, their phase response are not linear with the applied voltage, where the nonlinearity is defined by the maximum variance between the measurement results and the fitting line over the measurement range. Previously, several works were proposed to linearize silicon modulators[2-4]. In [2], a push-pull Mach-Zehnder (MZ) modulator with identical, nonlinear PN based silicon

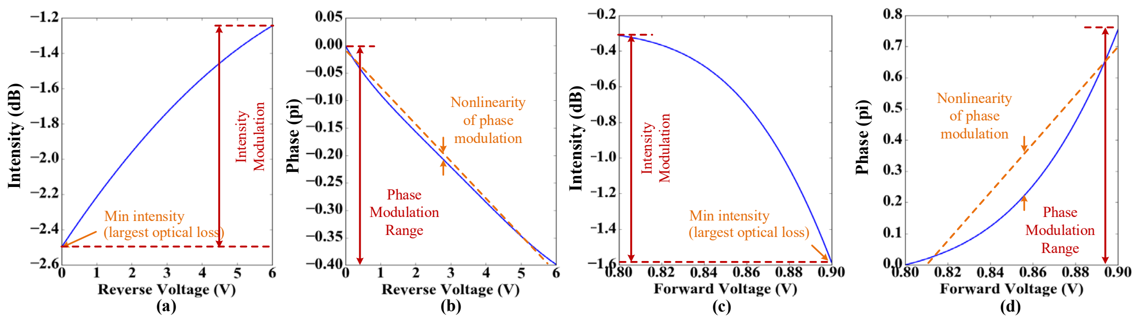



Fig. 1 (a) Measured intensity modulation and (b) phase modulation response of the used depletion modulator model (0 V to 6 V); (c) Measured intensity modulation and (d) phase modulation response of the used injection modulator model (0.8 V to 0.9 V).

phase modulators in two arms is proposed, and the nonlinearity of the sine-squared MZ transfer function is compensated by the nonlinearity of the embedded phase modulator, achieving a linearization. Later, differential driving is introduced to improve the linearity of the MZ modulator [3]. However, the proposed modulators only work on intensity modulation. In [4], a ring-assisted MZ modulator is demonstrated, in which two rings with super-linear phase response are coupled on the MZ arms. The results show high degree of linearization as well as a $LiNbO_3$ modulator, but it just works on a single wavelength.

Our previous work presents a configurable modulator to realize pure phase modulation with a PDM [5]. In this article, optimization of phase modulation linearity is implemented, which realized by tuning the splitting ratio of the couplers and the phase difference between the lights in two arms of the MZI. The nonlinearity of the PDM can be compensated by the nonlinearity of MZI. Simulation results show that the nonlinearity of depletion modulator can be optimized from 0.06 to 0.02, and the nonlinearity of injection modulator can be optimized from 0.198 to 0.1. Furthermore, other parameter metrices can also be optimized, for example the phase modulation range and overall insertion loss. In addition, compared to [2,3], the tunable coupling ratios brings a new freedom to the MZ modulator, thus a better performance is promising if the configurable modulator works as an intensity modulator.

## Principle

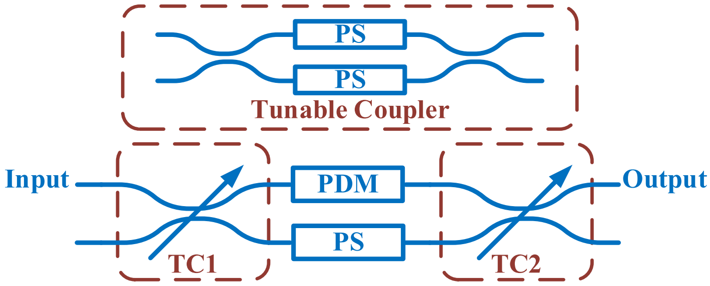



Fig. 2 Structure of the configurable modulator. PDM: plasma dispersion modulator; PS: phase shifter; TC: tunable coupler.

The proposed configurable modulator is a tunable MZI where a PDM, a phase shifter and two tunable couplers are embedded , as shown in Fig. 2. The used phase shifter can be implemented by low speed effects such as heat and liquid crystal infiltration. And the used tunable coupler is implemented by MZI structure, whose splitting ratio can be tuned from 0 to 1 by tuning the phase shifters on both arms [6].

The output signal of the reconfigurable modulator can be expressed as [5]:

$$E_{out} = \left[\sqrt{(1-\kappa_1)(1-\kappa_2)}\alpha(V)e^{-j\phi_m(V)} + \sqrt{\kappa_1\kappa_2}e^{-j(\phi_s-\pi)}\right]E_{in} \tag{1}$$

in which $\kappa_1$ and $\kappa_2$ are coupling ratios of tunable couplers, $\alpha(V)e^{-j\phi_m(V)}$ is the modulation response of the PDM and $e^{-j\phi_s}$ is the phase response of phase shifter.

Using Tylor expansion, we can get that

$$E_{out} = \left[ \sqrt{(1-\kappa_1)(1-\kappa_2)}\alpha(V)\left(\cos(\phi_m(V)) - j\sin(\phi_m(V))\right) + \sqrt{\kappa_1\kappa_2}\left(\cos(\phi_s - \pi) - j\sin(\phi_s - \pi)\right) \right] E_{in} \tag{2}$$

Regarding to the phase response of the configurable modulator, we can get that:

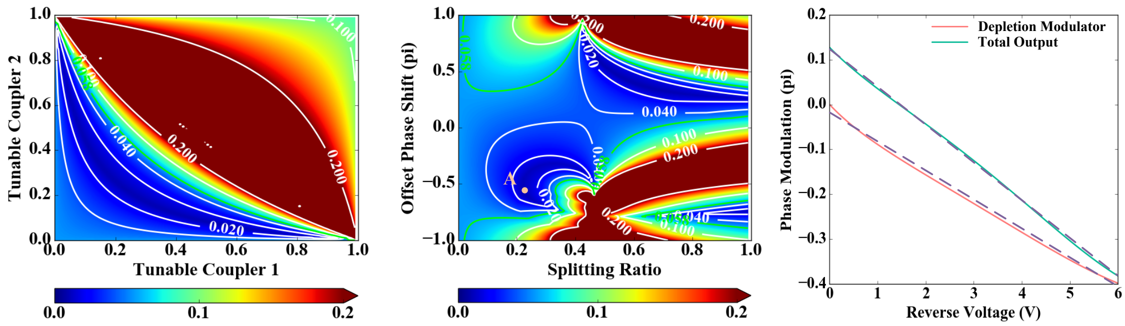
$$\angle T(V) = \angle \frac{E_{out}}{E_{in}} = \arctan\left[ -\frac{\sqrt{(1-\kappa_1)(1-\kappa_2)}\alpha(V)\left(\sin(\phi_m(V))\right) + \sqrt{\kappa_1\kappa_2}\sin(\phi_s - \pi)}{\sqrt{(1-\kappa_1)(1-\kappa_2)}\alpha(V)\left(\cos(\phi_m(V))\right) + \sqrt{\kappa_1\kappa_2}\cos(\phi_s - \pi)} \right] \tag{3}$$

To linearize the phase modulation, we need to zeroize the second and higher order derivatives of *T(V)*. Because *T(V)* is related to $\kappa_1$, $\kappa_2$ and $\phi_s$, we do parameter sweeps to optimize the final results to avoid solving complicated equations.

## Simulation and discussion

First, a simulation based on a PN based depletion modulator is implemented. The direct current of the used modulator model is shown in Fig. 1 (a) and 1(b) [7]. As can be seen, for reverse biased voltage from 0 to 6V, the depletion modulator provides a 0.4$\pi$ phase modulation (from 0° to -71.7°) and its nonlinearity can be calculated as 0.058.

From the discussion above, we can use $\kappa_1$, $\kappa_2$ and $\phi_s$ to linearize the phase modulation of the reconfigurable modulator. Firstly we sweep the $\kappa_1$ and $\kappa_2$, and the results are shown in Fig. 3(a). It can be found that the figure is symmetric across the diagnose, which means $\kappa_1$ and $\kappa_2$ are exchangeable, matching the Eq. (3). Thus, we can assume $\kappa_1 = \kappa_2 = \kappa$. Then we sweep $\phi_s$ and $\kappa$ to get the lowest phase modulation nonlinearity and results are shown in Fig. 3(b). Choosing the lowest point A in Fig. 3(b), we can get the optimized linearized phase modulation, which is shown in Fig. 3(c). For PN junction based depletion modulator, the nonreality of 0.058 can be reduced to 0.0085.




(a) (b) (c)

Fig 3. PN based depletion modulator simulation. (a) Simulation results for sweeping coupling ratio of both tunable couplers from 0 to 1 with a fixed phase shift $\phi_s = 0$; (b) Simulation results for sweeping coupling ratio and phase shifts; (c) Phase response of the configurable modulator at $\kappa = 0.24$ and $\phi_s = -0.57\pi$.

For the modelling of a PIN based injection modulator, we measured a device with a length of 500μm, and the intensity and phase response are shown in Fig. 1(c) and 1(d) [5]. Because the PIN junction varies the refractive index dramatically with the forward biased voltage, we limited the voltage range from 0.8 V to 0.9 V, with a phase modulation of 0.75 $\pi$, and a modulation nonlinearity of 0.198. Again, a sweep for $\phi_s$ and $\kappa$ is implemented and the results are shown in Fig.4 (a). At the optimized operation point B. the modulation nonlinearity can be suppressed to 0.011, and the phase response is shown in Fig. 4(b).

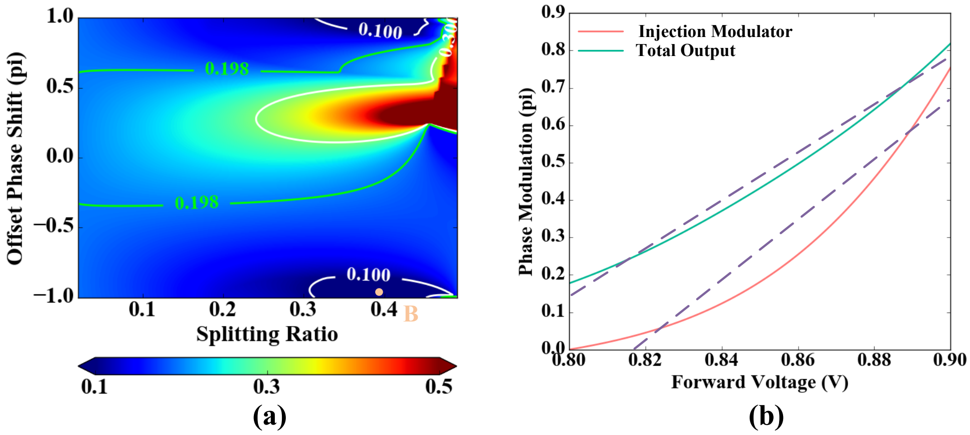



Fig. 4. PIN based injection modulator simulation. (a) Simulation results for sweeping coupling ratio and phase shifts; (c) Phase response of the configurable modulator at $\kappa = 0.4$ and $\phi_s = -0.9\pi$ .

If the configurable modulator is set as an intensity modulator, it can also be linearized by tuning the coupling ratios and the offset phase shifts. Compared to previous works [2,3], a new degree of freedom, tunable coupling ratio, is introduced and a better performance is promising.

## Conclusion

In this paper, we proposed a configurable modulator, and used it to linearize the phase modulation of plasma dispersion modulators.

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