Discretization Effects of Digital Control of Thermally Tunable 2×2 MZI Couplers

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***Abstract*—We describe how digital voltage driving of tunable 2×2 Mach-Zehnder couplers with thermo-optic phase shifters introduces discretization errors which significantly affect programmable photonic circuits. Performing quantitative analysis, we show that proper biasing of couplers and simultaneous driving of arms can improve discretization errors.**

***Index Terms*—Programmable Photonics, Tunable Couplers, Discretization Errors**

I. INTRODUCTION

State of the art technology in silicon photonics fabrication has enabled large-scale integration of Photonic Integrated Circuits (PICs) with thousands of optical components. This has paved the way for realization of programmable and generic photonic circuits that are the optical equivalent of field programmable gate arrays (FPGA) in electronics [1].

The key elements in programmable PICs are tunable 2×2 power couplers, which can be arranged in a mesh of waveguides to create reconfigurable paths for the optical signals [1]. These tunable unit cells operate either as an optical crossbar switch (in cross or bar) or as a tunable power divider. The common implementation consists of a *Mach-Zehnder interferometer* (MZI) with phase shifters in one or both arms [1]–[3]. By applying electrical signals the coupling between the input and output ports can be adjusted. The performance of a programmable circuit depends entirely on how accurate these coupling ratios can be controlled. Coupling errors can accumulate and propagate through the circuit, and result in optical losses and crosstalk.

In realistic integrated optical devices, various sources of error such as propagation losses, phase errors, and unbalanced beam splitters can severely impact performance of the tunable 2×2 couplers and consequently deteriorate behavior of the circuit. Even though the tunability of the 2×2 couplers can compensate some fabrication errors, imperfect control of the phase shifters in the MZI may actually induce additional errors. As in any realistic system the phase shifters are controlled by some form of digital circuit such as a digital-to-analog converter (DAC), the digital discretization can be a source of errors. As the cost of DACs increases with increased resolution, it is important to understand how the resolution of digital drivers affects the coupling control so we can design and control the 2×2 couplers in a way that is tolerant to digital driving.

Here, we compare three different implementations of thermally tunable 2×2 MZI couplers, and analyze their coupling errors caused by digital voltage drivers with different resolutions (4-8 bits).

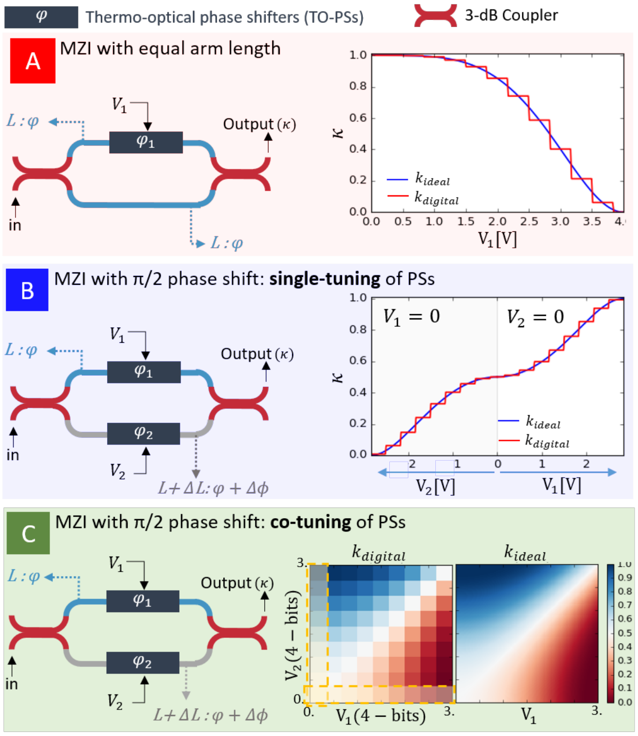

Fig. 1. Tunable 2×2 MZI couplers using thermo-optic phase shifters. Type A: MZI with equal arm lengths loaded with a heater on one arm. Type B,C: MZI with a $\pi/2$ phase delay (quadrature) loaded with heaters on both arms. In type B, the coupler is operated in push-pull, where only one of the phase shifters operating at any given time. In type C, the phase shifters are used together creating discrete 2D-space for the coupling. Yellow rectangles in the 2D-plot of type C corresponds to the discrete response of type B

II. DIGITAL MZI-BASED TUNABLE BASIC UNITS

Fig. 1 shows three possible types (A, B, C) of implementing MZI-based 2×2 couplers using thermo-optic phase shifters. These tunable couplers can be reconfigured by digital voltage drivers to tune between bar state and cross state.

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As seen in the Fig. 1, the MZI consists of two 3-dB couplers, and one or two thermo-optic phase shifters, which induce the desired phase shift by heating the waveguide with an electric current (Joule effect), making the phase shift proportional to the burnt electrical power in the heater [1]–[3]. For these simulations, we assume the heaters are voltage-controlled, so the phase shift can be written as $\phi_{PS} = \phi_{full}.V^2/V_{full}^2$. V_{full} is the voltage needed to induce the required full phase shift ϕ_{full} in the corresponding waveguide arm. We assume that we operate with a driving voltage of 5V, and we designed the heater resistance to have a $V_{full} = 4$V.

The digital-to-analog converter will discretize the 0-5V voltage with n bits, resulting in 2^n voltage levels. This implies that we will get a corresponding discrete set of coupling κ values.

In Fig. 1a, we show a MZI with equal arm lengths (Type A), and one of the arms is loaded with a heater. This MZI requires a $\phi_{full} = \pi$ phase shift to couple from cross to bar state. The coupling response of the MZI shows that the discretization errors (indicated for 4-bit discretization for visual clarity) increase dramatically for larger voltages. This is because of the phase shifter quadratic response, but also because of the sinusoidal response of the MZI.

In contrast, Fig. 1b-c show an MZI with a $\pi/2$ phase delay between the arms, and a thermo-optic phase shifter in each arm. This biases the MZI at quadrature point: when both phase shifters are off, the MZI acts as a 50/50 beam splitter. Tuning one arm will decrease the coupling, while tuning the other will increase the coupling. In this configuration the full tuning range can be achieved with a $\phi_{full} = \pi/2$ in either one or the other phase shifter. Also, the quadrature bias shifts the nonlinear heater response with respect to the sinusoidal MZI response, spreading the discretization error more uniformly across the coupling range.

Type C differs from Type B in that we operate both phase shifters together. This co-tuning of the phase shifters, together with the nonlinear response of the heaters, creates a discrete 2D-space to control the coupling κ using the digital voltages V_1 and V_2. This 2D discretization increases the resolution of the tuning, with a voltage pair that brings the resulting $\kappa_{digital}$ closer to the desired value κ_{ideal}. The yellow boxes in Fig. 1 indicate the coupling levels of Type B as a small subset of the levels available in Type C.

III. ERROR SCALING OF THE DIGITAL DRIVING

For further analysis, Fig. 2 plots the $\kappa_{digital}$ response of the three discussed couplers versus the ideal (desired) couplings for a 4-bits voltage driver. Comparing the curves clearly show that the MZI in quadrature increases the accuracy of the coupling selection for Type B. And co-tuning of the phase shifters considerably improves the performance of Type C. We quantified the maximum step size (σ_{max}) illustrated by the black arrow in Fig. 2 for each curve, and this for different resolutions of the DAC. The inset of Fig. 2 shows the variation of σ_{max} versus different voltage resolutions (4-8 bits) for the three types. As expected, by increasing number of bits, the maximum step size of the coupling for all 2×2 coupelrs decreases. And, interestingly, using the co-tuning scheme results in a noticeable reduction of σ_{max} in Type C, without needing to resort to more expensive electronics; for instance, even with a very low resolution control (4-bits), σ_{max} is decreased from 19% (type A) to 2.5% (Type C).

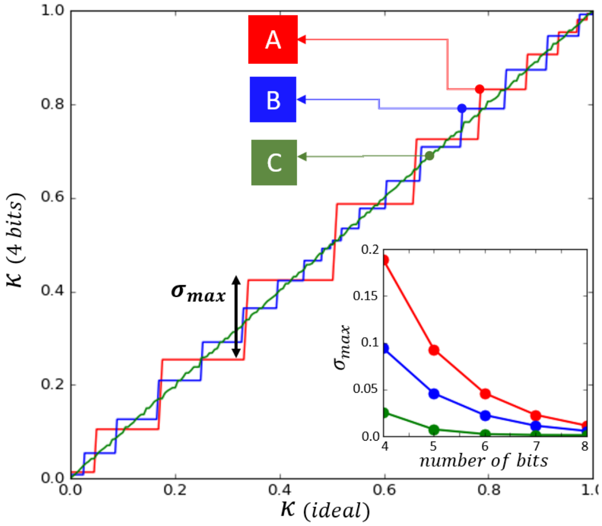

Fig. 2. Digital couplings κ of three different types of tunable couplers, demonstrated in the Fig. 1, versus desired ideal couplings for a 4-bits digital voltage driver. Inset: comparison of maximum step size (σ_{max}) of the digital couplers for different resolution of 4-8 bits. Black arrow indicates σ_{max} of the type A.

Although co-tuning of two phase shifters significantly improves performance of a tunable coupler, it may have some downsides. For example, it increases the energy consumption or may complicate driving due to thermal cross-talk in the heaters, requiring larger separation and therefore larger footprints. On the other hand, coupling errors adds up and adversely grow in large-scale circuits.

IV. CONCLUSION

We discussed the effect of discretized voltage driving in three different implementations of tunable 2×2 MZI couplers with thermo-optic phase shifters. The discrete voltage response of the digital drivers causes an staircase error, resulting in a nonuniform discrete coupling response of the MZIs. Simulation results reveal that using an MZI in quadrature with two phase shifters, and co-tuning of both phase shifters, can significantly reduce the discretization error.

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