Advanced Control for Crosstalk Minimization in MZI-based Silicon Photonic Switches

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***Abstract*—Key drivers of crosstalk in MZI switch elements are identified in terms of phase error, electro-absorption loss, and coupler variations. An advanced control method is introduced that coordinates thermo-optic and electro-optic phase shifters to simultaneously mitigate these factors and improve crosstalk limit beyond equalized push-pull.**

Keywords—optical switching devices, silicon photonics

I. INTRODUCTION

Optical switching has shown promising potentials to revolutionize optical interconnect designs for data centers. Because of their benefits in small footprint, high energy efficiency, and CMOS affinity, integrated photonic switches on the silicon platform possess unique advantages to realize high capacity switch fabrics [1]. Photonic switch networks constructed with Mach-Zehnder interferometers (MZI) as switching elements (SE) can achieve nanosecond switching speed and has been demonstrated to scale up to 32x32 fabric port count [2]. Nevertheless, further scalability of the silicon integrated switch fabrics is limited by insertion loss and switching crosstalk. Since each routed lightpath may traverse a cascade of SEs, their loss and crosstalk accumulate and contribute detrimentally to a lightpath's power penalties. While insertion loss can be effectively compensated by integrating gain blocks [3], crosstalk contributes to the signal noise and is therefore challenging to eliminate. To alleviate the crosstalk levels of the switch, recent approaches have focused on novel element designs – in [4], Dupuis et al. demonstrated a nested MZI design with a measured crosstalk less than -34 dB at its operating wavelength; in [5], Lu et al., introduced a balanced nested MZI design that numerically shows less than -50dB crosstalk across an 8x8 fabric. While these new designs show meaningful reduction in SE crosstalk levels, they would significantly increase the device complexity and footprint. In this work, we introduce an optimal control strategy that minimizes the worst-case crosstalk level of an MZI SE. We present numerical analysis on the working principles of our technique, and experimentally validate its effectiveness to minimize crosstalk levels for every SE and optimize end-to-end performance of the fabric.

II. ANALYSIS

Specifically, we examine the design and operation of MZI SEs utilizing push-pull driving schemes with carrier injection phase shifters to achieve fast switching. Precise switching voltages of the electro-optical (EO) phase shifters can be determined accurately using techniques introduced in [6]. By designing a static $\pi/2$ path difference between MZI arms [2] or tuning to a $\pi/2$ phase bias using a thermo-optic (TO) phase shifter [7], equalized push-pull can reduce the required swing on each MZI arm and lower the crosstalk levels due to imbalanced loss. However, equalized push-pull drive cannot correct for stochastic variations in the fabrication process. In particular, non-uniform and non-ideal coupling coefficients of in- and out-couplers on each MZI SE introduce an additional source of crosstalk. Fig. 1A shows the crosstalk distributions of a Monte Carlo simulation of the MZI SE given couplers with a mean coupling coefficient of 0.5 and a standard deviation of 0.022 as reported in [8]. The coupler variations alone yield a median power crosstalk level of -33.6 dB in both Bar and Cross states.

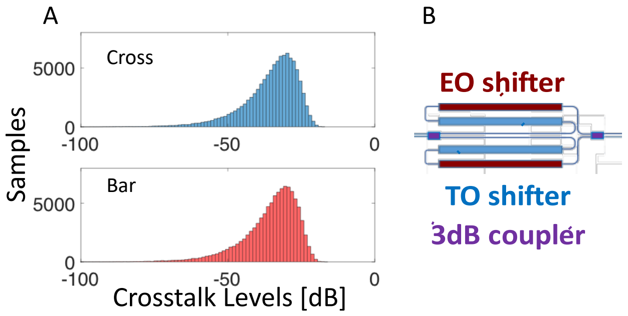

Fig. 1. (A) distribution of MZI crosstalk levels for Cross and Bar in 100000 trials given normally distributed coupling coefficients in the 3dB couplers; (B) schematic design of an MZI SE with both EO and TO phase shifters.

Hence, it is beneficial to establish an optimal control point for each individual MZI SE in a fabric, at which a calibrated push-pull drive achieves the minimal worst-case crosstalk between the SE's Bar state and Cross state. EO elements under forward bias induce both phase shift and loss due to free carriers; by balancing the EO-induced loss with coupler-induced intensity imbalance, the worst-case crosstalk of an MZI SE can be reduced in situ. The EO operating voltages are tunable via a TO bias, and thus giving control to correlated changes in index and absorption for silicon's plasma dispersion effects. Based on the models studied in [9], the free carrier induced loss at an arbitrary EO phase shift in silicon can be determined for the shifter structure, which offers an agile mechanism for tuning TO bias to adjust the EO loss in both MZI arms during push-pull drive. Experimentally, the minimal worst-case crosstalk can be achieved at a specific TO bias when the Bar state crosstalk and Cross state crosstalk coincide. Utilizing an SE design shown in Fig. 1B, the additional TO phase bias would modify the EO operating points and the corresponding EO-induced loss. Figs. 2A-2C illustrate the numerical comparison between equalized push-pull and TO-coordinated optimal push-pull, over a ±1 sigma variation range on the in- and out-couplers of a MZI.

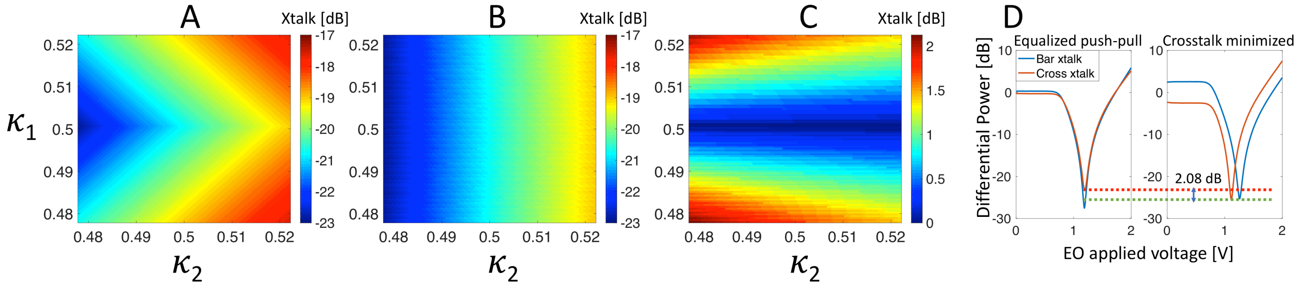

Fig. 2. (A) Simulated worst-case crosstalk power levels of an SE operated at equalized push-pull under coupler variations. (B) Simulated worst-case crosstalk power levels under optimized control with TO coordination under coupler variations. (C) Improvements in worst-case crosstalk by comparing results in (A) and (B). (D) Power difference between signal output and crosstalk output as the EO voltages are varied for an MZI SE under test. TO-coordinated operation (right) reduces the worst-case crosstalk by 2.08 dB. Simulations and experiments are performed at 1.55 µm with 150 µm phase shifters; κ_1 and κ_2 are the power coupling coefficients of the in- and out-couplers of the MZI respectively.

Note that the optimized control with TO-coordinated push-pull shown in Fig. 2B not only improves the crosstalk levels over the entire range of coupler variations, but also significantly reduces the crosstalk's susceptibility to the in-coupler, and thus increasing the robustness of the MZI to design and fabrication variations.

III. IMPLEMENTATION

Since the temperature dependence of silicon's refractive index has an opposite sign as the free carrier induced index change, increasing the TO phase bias on one MZI arm would induce an increase in the EO operating voltage on the same arm and a decrease in the EO operating voltage on the other arm. If the EO voltages between the two arms have a large discrepancy, the TO bias can be applied to the arm with the lower EO voltage to equalize the EO operating points. Once the starting push-pull operating points are determined without TO bias, the Bar and Cross crosstalk levels can be estimated by differential power levels at the switch output [10]. Monitoring the change in crosstalk levels, a linear voltage ramp is applied to the TO element on the arm with the lower EO bias. This is done under the heuristic that minimized crosstalk can be achieved in the vicinity of equalized EO voltages. As the TO bias changes in fine steps, the EO Bar and Cross voltage are rapidly re-determined because they vary slowly under small increments in TO bias [10]. The appropriate TO bias is determined when both the Bar crosstalk and Cross crosstalk levels coincide. Note that if the desired TO bias is not determined on one arm, the same procedure can be applied to the TO element on the other arm using the same feedback process. The crosstalk reduction achieved by this technique in a single MZI SE is experimentally demonstrated and shown in Fig. 2D. Note crosstalk-minimized operation has slightly unequalized push-pull EO voltages. We further apply the optimal control technique to all 6 SEs of a 4x4 Beneš switch fabric and achieve an average reduction of 1.72 dB per SE over equalized push-pull. The fabric, optimized at the SE level, would further enable intelligent routing to improve lightpath power penalties and performance [11].

IV. CONCLUSION

Crosstalk reduction of individual SEs in a switch fabric can drastically reduce path power penalties and enable continuing scaling of the fabric dimensions. We examine crosstalk originated from MZI coupler variations in addition to phase error and EO loss, which cannot be corrected under equalized push-pull. A TO-assisted crosstalk reduction technique is introduced to determine the optimal push-pull operating points by balancing the EO loss with coupler imbalance and further lower the crosstalk limit. The efficacy of the technique is examined via numerical analysis and validated experimentally.

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REFERENCES

[1] Q. Cheng, M. Bahadori, S. Rumley, and K. Bergman, "Highly-scalable, low-crosstalk architecture for ring-based optical space switch fabrics," Proc. IEEE Optical Interconnects Conference (OI), pp 41-42, 2017.

[2] L. Qiao, W. Tang, and T. Chu, "32 × 32 silicon electro-optic switch with built-in monitors and balanced-status units," Scientific Reports, Vol. 7, 2017.

[3] Q. Cheng, A. Wonfor, J. L. Wei, R. V. Penty, and I. H. White, "Low-energy, high-performance lossless 8×8 SOA switch," proc. OFC, 2015.

[4] N. Dupuis et al., "Ultralow crosstalk nanosecond-scale nested 2 × 2 Mach–Zehnder silicon photonic switch," Opt. Lett., Vol. 41, pp 3002-3005, 2016.

[5] Z. Lu, D. Celo, H. Mehrvar, E. Bernier, and L. Chrostowski, "High-performance silicon photonic tri-state switch based on balanced nested Mach-Zehnder interferometer," Scientific Reports, Vol. 7, 2017.

[6] Y. Huang, et al., "Automated calibration and characterization for scalable integrated optical switch fabrics without built-in power monitors," Proc. ECOC, paper M1A3, 2017.

[7] B.G. Lee et al., "Four- and eight-port photonic switches monolithically integrated with digital CMOS logic and driver circuits," Proc. OFC, 2013.

[8] J. C. Mikkelsen, W. D. Sacher, and J. K. S. Poon, "Dimensional variation tolerant silicon-on-insulator directional couplers," Opt. Express, Vol. 3, pp 1171-1180, 2011.

[9] M. Nedeljkovic, R. Soref, and G. Z. Mashanovich, "Free-carrier electrorefraction and electroabsorption modulation predictions for silicon over the 1–14 µm infrared wavelength range," IEEE Photon. J., Vol. QE-23, pp 123-129, 1987.

[10] Y. Huang, Q. Cheng, and K. Bergman, "Automated calibration of balanced control to optimize performance of silicon photonic switch fabrics," Proc. OFC, paper Th1G2, 2018, in press.

[11] Q. Cheng, M. Bahadori, Y. Huang, S. Rumley, and K. Bergman, "Smart routing tables for integrated photonic switch fabrics," Proc. ECOC, paper M1A2, 2017.