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Novel Optical Delay Line Overcomes Bandwidth-Delay Limit for Enhanced Beamforming Performance

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***Abstract*— We propose a novel, reconfigurable delay line architecture that achieves a (2N-1) times greater tunability range compared to previously reported architectures. This design overcomes the bandwidth-delay product constraint and surpasses the tunability range by 67% and offers a 1.5x reduction in controllers and power consumption.**

Keywords—delay line, optical phase array, filter, true time delay, microwave photonic, programmable photonic, quantum photonic

I. INTRODUCTION

Optical true-time delay lines (OTTDLs) are key components in many applications, such as quantum photonics, optical communications, computing, and sensing. OTTDLs can be used to delay photons for a variety of purposes, such as implementing quantum gates and circuits, synchronizing data, buffering data, and implementing microwave photonics systems and optical beam-forming architectures [1,3]. The two main approaches to designing OTTDLs are wavelength-dependent delay lines and length-dependent delay lines. Wavelength-dependent delay lines, offer a high tunability range and small footprint but are limited by delay reconfiguration flexibility and bandwidth. Length-dependent delay offer high bandwidth, simple tuning, and low dispersion (vs. resonant lines) [3-6]. However, their tunability is limited and varies with size. Common implementations include switchable lines with discrete delays and MZI-based lines with tunable couplers for continuous tuning [5]. Tunability refers to the ability to continuously adjust the time delay experienced by the light signal passing through the device. While increasing imbalance in MZIes can improve tunability, it reduces free spectral range and bandwidth [5]. To overcome the limitation of bandwidth-delay product in MZI-based delay lines, cascading multiple stages of MZIs can be used [4,6]. These architectures increase the overall group delay, but they either introduce group delay dispersion [6] or require a complex characterization strategy and more couplers hence high power for delay tuning [4]. In this work, we have proposed an easily controllable cascaded MZI-based delay line architecture with greater tunability range and bandwidth delay product compared to previously reported architectures [4-6]. The proposed architecture achieves a delay tunability of $\tau = T \times (2N-1)$, where T is the maximum single stage delay and N is the number of stages. In contrast, the delay tunability range of previously reported MZI-based cascaded architectures is $\tau = NT$. For example, for N = 2 (two-stage) and 3 (three-stage), the proposed architecture has 50% and 67% better tunability range, respectively. The proposed architecture requires fewer couplers, which reduces the power required for coupler tuning.

II. DEVICE DESIGN

This work proposes a novel delay line architecture with two cascaded Mach-Zehnder interferometer (MZI) stages connected via a switch (C) as shown in Fig. 1. Tunable couplers of each stage and switch are implemented using two balanced MZI-based to vary the coupling ratios continuously from 0 to 1. In each stage of the MZI, there is an imbalance (ΔL) between the two arms such that the length of the first arm (L_1) is half that of the second arm (L_2). To maintain the overall light path the same as the first stage, the lengths of L_1 and L_2 in the second stage should be adjusted by the length of the waveguide (L_f) connecting the output of the second stage to the input of the switch [see Fig. 01]. A thermo-optic phase shifter in one arm of an MZI is placed to tune the operating frequency of the circuit. The coupling coefficient of switch C is toggled between 0 and 1 to select the required MZI stage. Coupling coefficients of the first and second stage tunable coupler are set to K_1 and K_2, respectively. The maximum time delay given by each stage is $T = (n_g \Delta L)/c = FSR^{-1}$ where c is speed of light and ng is waveguide group index.

III. DEVICE OPERATION AND ANALYSIS

This section explores how the coupling coefficient (K) in our proposed architecture influences the group delay (τ) and light propagation within the device. Figure 2 shows the transmission (dB) and normalized group delay ($\tau'=(\tau-\tau_0)/T$) versus normalized frequency ($f'=(f-f_o)/FSR$) for different coupling coefficient combinations where τ_0 is minimum group delay, when light travel's shorter arm of MZI. At K = 0 and 1, light is confined to the shorter and longer arms, respectively, resulting in fixed minimum and maximum group delays. For K = 0.5 (τ = 0.5), the conventional transfer function of the Mach-Zehnder is formed and the minimum bandwidth is equal to FSR/2, where the group delay at operating frequency (f_o) is half. Interestingly, when K varies between 0 and 1, light travels through both arms, leading to a linear relationship between K and group delay ($\tau = \tau_0+KT$). This control scheme offers a spectrally flat intensity, meaning the light intensity remains constant around f_0 [see Fig. 1(a)]. This increased tunability of τ' is a key advantage. Figure 2(b) visually depicts this relationship. Each colored gradient represents a specific control setting: blue (C = K_2 = 0, varying K_1) for τ' variation from 0 to 1, red (C=K_1=0, varying K_2) for τ' from 1 to 2, and green (C=K_1=1, varying K2) for τ' from 2 to 3.

The bandwidth-delay product (BDP) is a key performance metric [3, 6] for OTTDLs. Figure 3 shows the proposed architecture's BDP normalized with FSR for various coupling coefficients. Unlike conventional designs [5,6], our architecture maintains constant bandwidth and flat group delay spectra even with more stages, overcoming the BDP constraint. The minimum 3dB bandwidth (B3dB) is consistently half the FSR when τ' is tuned from 0 to 3 , and BDP is infinite for K near 0 and 1. For other K values, BDP reaches a minimum at K=0.5. As stages increase, BDP increases. The key innovation is the unique two-stage MZI configuration with specific coupling coefficients. This achieves 0-3 τ' tunability, matching a

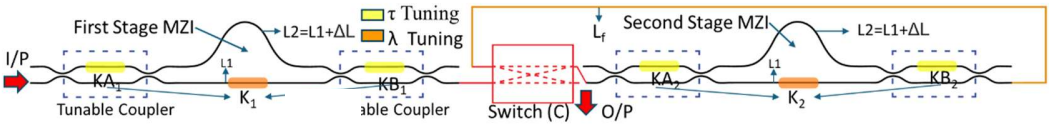


Figure 1: Schematic of proposed delay line. The device is used as one input and one output port

three-stage design, but with fewer stages and reduced complexity.

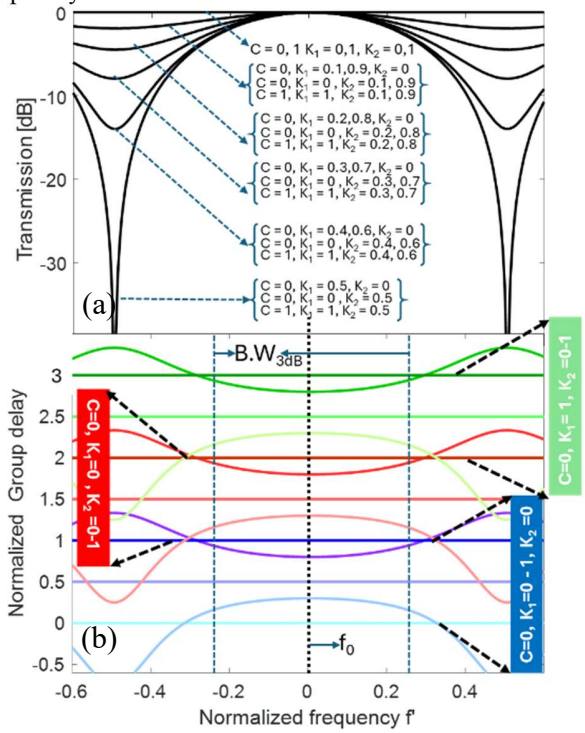


Figure 2: (a) Transmission spectra and (b) normalized group delay spectra for different combinations of coupling coefficient K.

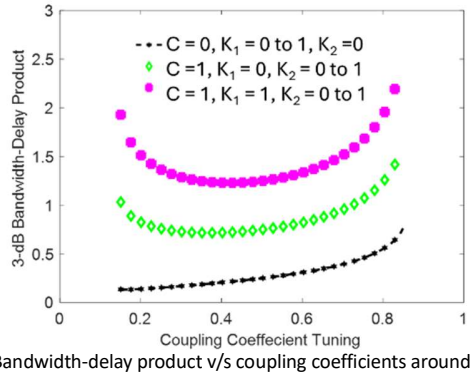


Figure 3: Bandwidth-delay product v/s coupling coefficients around f_0.

IV. Beamforming Application

Beamforming circuits rely on delay lines, but existing options face limitations. Resonant lines offer long delays with a small footprint but limited bandwidth, while non-resonant lines provide wider bandwidth but lack continuous tunability and have a bandwidth-delay product trade-off [2]. Our proposed architecture addresses these limitations. It overcomes the bandwidth-delay product constraint and surpasses the tunability range of existing cascaded MZI-based architectures by 67% (offering ~1.5x less power consumption) with fewer controllers. For example, consider a 1x4 beamforming circuit aiming for 90-degree beam steering. Here, the input light is divided into four outputs, each routed through a dedicated delay line (array element). By adjusting the delay in each line, the beam direction is controlled. With a signal bandwidth of 30 GHz and half-wavelength spacing between elements, the required total delay per element is approximately 50 ps. While a single delay line can achieve 16.7 ps (inverse of twice of signal bandwidth), a three-stage delay line would be needed to reach 50 ps. Existing non-resonant delay lines suitable for this application might require 36 controllers (9 per channel) [4-6]. Our design achieves the same results with only 28 controllers (7 per channel), reducing power consumption. Further optimization is possible by using variable-length delay lines. Unlike other designs, each delay line in our architecture is accessible separately. This allows customizing the delay range for each channel based on its specific needs. In a 1x4 configuration, the middle channels require a smaller delay range compared to the outer channels. Employing delay lines with a reduced tuning range (using only the first stage with three controllers instead of all seven) for the middle channels can significantly reduce the total number of controllers and their associated power consumption. This optimization strategy offers significant advantages for beamforming circuits. It streamlines the beam steering process while reducing the number of controllers and overall circuit complexity. In our specific example, the optimized arrangement reduces the controller requirement from 36 to just 20 (a 1.5x reduction), leading to lower power consumption. We have previously demonstrated the functionality of a single-stage delay line through experiments [5]. Fabrication of cascaded delay lines and the associated beamforming circuit is currently underway, and results will be presented in future work.

V. Conclusion

We propose a continuously reconfigurable tunable true-time optical delay line breaking the bandwidth-delay product constraint. By overcoming limitations in existing delay lines and offering variable-length customization, our design paves the way for optimized beamforming circuits with improved performance, a 67% better tunability range, and a 1.5x reduction in controllers and their associated power consumption.

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