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Authors	Waqas, Abi;Kaim Khani, Talha;Corbett, Brian
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Reconfigurable optical delay line breaking the bandwidth-delay limit

Abi Waqas[1,2], Talha Kaim Khani[2], Brian Corbett[1]
[1]*Tyndall National Institute, Lee Maltings, University College Cork, T12 R5CP, Cork, Ireland*
[2]*Department of Telecommunication, Mehran University of Engineering and Technology, Jamshoro, Pakistan*
Email: abi.waqas@tyndall.ie

***Abstract*— We propose a continuously tunable true-time delay line with easy coupler control. It is based on multiple Mach-Zehnder interferometers with two couplers setting. One setting achieves a flat-top group delay spectra, breaking the bandwidth-delay limit, while the other offers a large transmission bandwidth.**

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. OTTDLs can be classified into resonant and non-resonant types. Resonator-based OTTDLs have longer group delays and a smaller footprint, but non-resonant OTTDLs have a wider bandwidth and are simpler to control. However, both resonant and non-resonant delay lines have limitations in the bandwidth-delay product [1-3]. In previously published work [4], Mach-Zehnder based delay line (1MZDL) exhibits an inverse relationship with the Free Spectral Range (FSR). In this configuration, the FSR is precisely twice of the system's bandwidth (BW = FSR/2). When the goal is to extend the delay, this means we need to reduce the FSR, which, in turn, leads to a decrease in the available bandwidth. To overcome this limitation we extended our work [5], and proposed an architecture implementing a two-stage Mach-Zehnder-based delay line (2MZDL) that doubles the group delay tunability range. However, 2MZDL compared to 1MZDL induces a larger dispersion. In this work, we propose a novel reconfigurable multistage Mach-Zehnder based integrated optical delay line arranged in series, with two different coupler operation states. The device can introduce a continuously variable true-time delay, breaking the bandwidth-delay product limit. With two different coupler operating states, the device can achieve either larger transmission bandwidth or a flat group delay spectrum.

II. PROPOSED DELAY LINE ARCHITECTURE

The proposed device is schematically shown in Fig. 1. The topology implements two cascaded Mach-Zehnder interferometers with four tunable couplers whose coupling ratios can be varied from 0 to 1. All tunable couplers are realized with two balanced Mach-Zehnder couplers equipped with phase shifters on one arm to vary the coupling ratios continuously from 0 to 1. The two cascaded stages are simply two single-stage delay lines connected in series, with the output of the second coupler of the first stage connected to the input of the first coupler of the second stage. Both stages have the same unbalance length, ΔL, and a phase shifter on one arm to tune the operating frequency of the device to match that of the incoming signal. The maximum time delay given by each stage is $T = (n_g \Delta L)/c = FSR^{-1}$ where c is speed of light and n_g is waveguide group index. For ease of readability, we will refer to the first stage as A and the second stage as B. K_{A1} and K_{A2} are the first and second tunable couplers of the first stage (A). K_{B1} and K_{B2} are the first and second couplers of the second stage (B) of the proposed delay line.

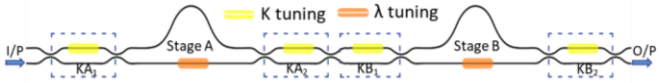


Figure 1: Schematic of proposed delay line. The device is used as one input and one output port.

III. ANALYSIS OF PROPOSED DELAY LINE

The proposed delay line has two states of operation. In the first operation state, the delay line is used as a single-stage delay line, requiring only two couplers to tune, either in stage A or B. In this example, stage B is tuned while stage A toggles between the shorter and longer arms. Figure 2 shows the normalize transmission and group delay (τ) spectra of the proposed delay line for different values of coupling coefficient K and different modes of coupler operation, which are discussed below. The coupling ratios K_{B1} and K_{B2} of stage B are chosen to be the same, $K_{B1} = K_{B2} = K_B$. For $K_B = 0$ and 1, all the input light is coupled to the shortest ($\tau = 0$) and longest arms ($\tau = 1$) of the Mach-Zehnder, respectively, and then directed to the output. In these cases, both the transmission and the group delay are frequency independent. For $K_B = 0.5$ ($\tau = 0.5$), the conventional transfer function of the Mach-Zehnder is formed. Interestingly, the group delay characteristic is once again frequency independent (except for ± FSR/2, where the delay is undefined). For all other values of K_B, both the intensity and the group delay are frequency dependent. However, at the operating frequency marked with a vertical dashed line in Fig. 2, the transmission does not depend on K_B, whereas the normalized group delay (τ) increases linearly with K_B. The minimum bandwidth is equal to FSR/2 and is obtained for K = 0.5, where the group delay at operating frequency is half. To tune the delay from 0 to 1, the coupling ratio of stage A ($K_{A1} = K_{A2} = K_A$) is set to 0, and the normalized group delay (τ) of stage B is tuned from 0 to 1, as shown in Fig. 2(b). To tune the normalized group delay (τ) from 1 to 2, K_A is set to 1, and τ of stage B is tuned from 0 to 1. This enables normalized group delay tuning of the delay line from 0 to 2 while maintaining the same spectral characteristics as a single-stage delay line. The group delay spectrum around the operating frequency is flatter for a two-stage delay line, compared to the group delay spectrum reported in [4].

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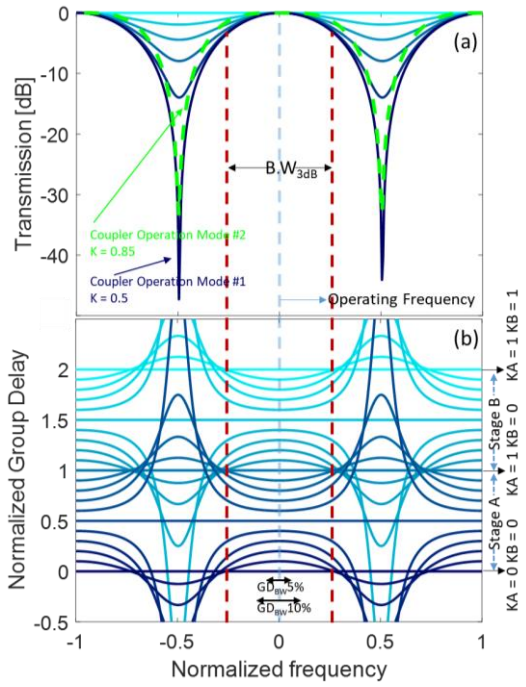


Figure 2: (a) Normalized transmission and (b) group delay spectrum for different values of coupling coefficient. Color gradient from dark blue to light blue represent the tuning of coupling coefficient from 0 to 2.

Figure 3 (right axis) shows the normalized linear group delay tuning from 0 to 2 around the operating frequency with the discussed operating condition. Regardless of the total delay, only one Mach-Zehnder interferometer (MZI) operates as an interferometer at a time, enabling the bandwidth-delay limit to be broken. Therefore, the 3 dB bandwidth of the delay line is equal to FSR/2, as for a single-stage MZI-based delay line [3]. Figure 3 (left axis) report the bandwidth delay product for 3 dB transmission bandwidth (black solid line) and 5% group delay bandwidth (blue solid line). Group-delay bandwidth is defined where the delay is changed by 5% around the operative frequency. The transmission and group delay bandwidth goes to infinite where undefine. Figure 3 shows that the bandwidth-delay product increases linearly with the increase in stages. Compared to the two-stage delay line reported in [5], the delay line in this work has 80% and 70% higher group delay bandwidth where the delay is changed by 5% and 10%, respectively, while maintaining the same tunability range. This result proves that the proposed delay line allows us to overcome the bandwidth-delay limit. Based on the reported results, the delay can be increased linearly with the number of stages without narrowing the bandwidth. This means that the number of stages can be increased to achieve a longer delay without sacrificing bandwidth. These results are in line with those of multiple Mach-Zehnder interferometers (MZIs) arranged in parallel [3]. However, the control operation proposed in this work requires only two fully tunable couplers, regardless of the number of stages. The other couplers can be simple on/off switches, simplifying characterization and operation. This approach could also be used to simplify the operation and characterization of the architecture proposed in [3], which requires all coupling pairs need to be continuously tuned and characterized using a complex algorithm.

In the second mode of operation, the phases of all four couplers are changed simultaneously by setting $K_{A1} = K_{A2} = K_{B1} = K_{B2} = K = \sin^2(\theta)$, where θ is the phase shift induced by the coupler controller. This control scheme ideally enables operation of the delay line using a single controller. This mode of operation provides a 27% higher transmission bandwidth (see Fig. 2a green dash line) than a single-stage delay line but at the cost of higher group delay dispersion [4]. The spectral characteristics of the delay line in this mode are the same as those reported in our previous work [4], but with four couplers instead of three. For a detailed discussion of the spectral characteristics in this mode of operation, refer to [5]. The proposed architecture overcomes all the shortcomings of the work published in [4, 5] and combines the advantages of both structures.

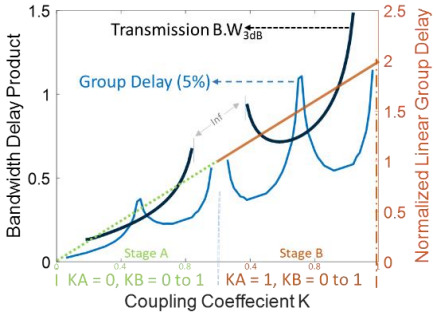


Figure 3: Right axis: Normalized group delay when stages A and B are tuned. Left axis: Bandwidth-delay product for different coupling coefficients, black line: transmission bandwidth, blue line: group delay bandwidth.

IV. Conclusion

We propose a continuously reconfigurable tunable true-time optical delay line based on Mach-Zehnder interferometers connected in series. The proposed topology breaks the bandwidth-delay product, allowing higher delays without narrowing the bandwidth. The proposed device has two operation states: one for high transmission bandwidth and the other for high group delay bandwidth with a flat group delay spectrum. This makes it ideal for wideband application e.g., microwave photonics beam steering, where multiple delay lines can be connected to form a beamforming circuit that electronically controls the radio beam direction.

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