European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Continuously Tuneable MZI-based Delay Line Overcoming Delay-Bandwidth Product

Matteo Petrini, Seyedmohammad Seyedinnavadeh, Francesco Morichetti and Andrea Melloni

Department of Electronics, Information and Bioengineering, Politecnico di Milano, 20133 Milano, Italy, *Corresponding Author:* matteo.petrini@polimi.it

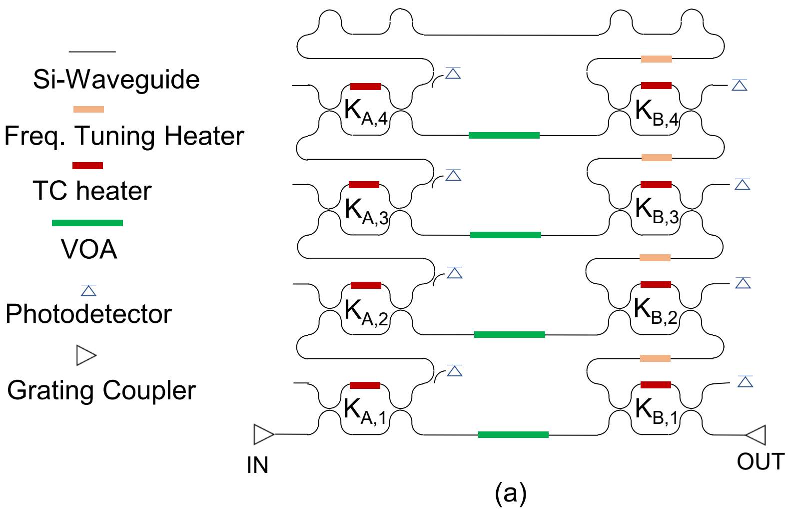
Abstract *A silicon photonic integrated circuit, implementing a novel delay-line architecture, is proposed. The device, based on a set of four nested Mach-Zehnder Interferometers, overcomes typical delay-bandwidth product. Showing a minimum bandwidth of 20 GHz, group delay can be continuously tuned between 0 and 100 ps.*

Introduction

Optical true-time delay lines are essential devices for synchronization and buffering of telecommunication signals [1], microwave photonics application [2] and optical beam-forming networks [3]. Silicon photonic integrated circuits (PICs) have been successfully exploited to implement this kind of functionalities on a chip, thanks to their appealing features, such as compact footprint, low-power consumption, inherent tuneability, CMOS-compatibly and easy integration with other optical or electronic devices, like filters, modulators or light-detectors.

In the past years, different topologies have been proposed to effectively realize optical delay lines, which are based on different filtering structures belonging to two main categories, resonant (IIR, infinite-impulse-response) and non-resonant structures (FIR, finite-impulse-response). Resonance-based devices, while providing quite long delays (more than hundreds of picoseconds) in a compact footprint [4], show a narrow bandwidth and a complex (and usually coarse) tuning strategy. On the contrary, FIR architectures present a shorter maximum achievable delay (which it is proportional to the geometrical size of the device itself), whereas their bandwidth is kept reasonably large and their control is, in general, finer and simpler, if compared with resonant delay lines. In literature, there are examples of FIR-delay lines, exploiting Mach-Zehnder Interferometers (MZIs), whose delay can be defined either continuously or by discrete steps. For instance, a continuously tuneable delay line can be implemented by using an unbalanced MZI with TCs [5]. However, regardless the time unbalance calibration, this kind of circuits is subjected to a strict bandwidth-delay constraint.

In this work we report on a novel circuit topology, based on four nested MZIs, to implement a non-resonant tuneable delay line, overcoming the band-delay limitation of conventional MZI architectures. The device, composed by four stages, can introduce a continuously tuneable delay between 0 ps and 100 ps. Its Free Spectral Range (FSR) results to be around 360 pm (or 40 GHz) and its minimum 3dB-bandwidth around 180 pm (or 20 GHz), for regardless the introduced delay.



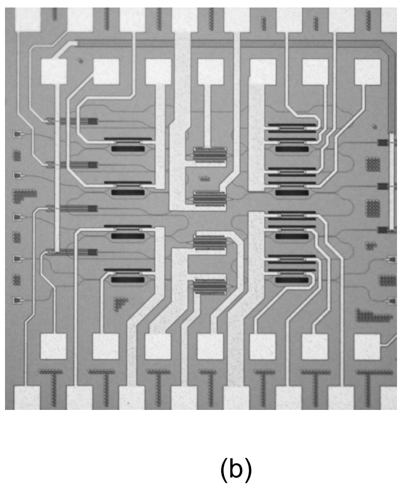


Fig. 1: (a) Schematics of the proposed topology based on four nested Mach-Zehnder Interferometers; (b) photograph of the fabricated device in Silicon-On-Insulator platform.

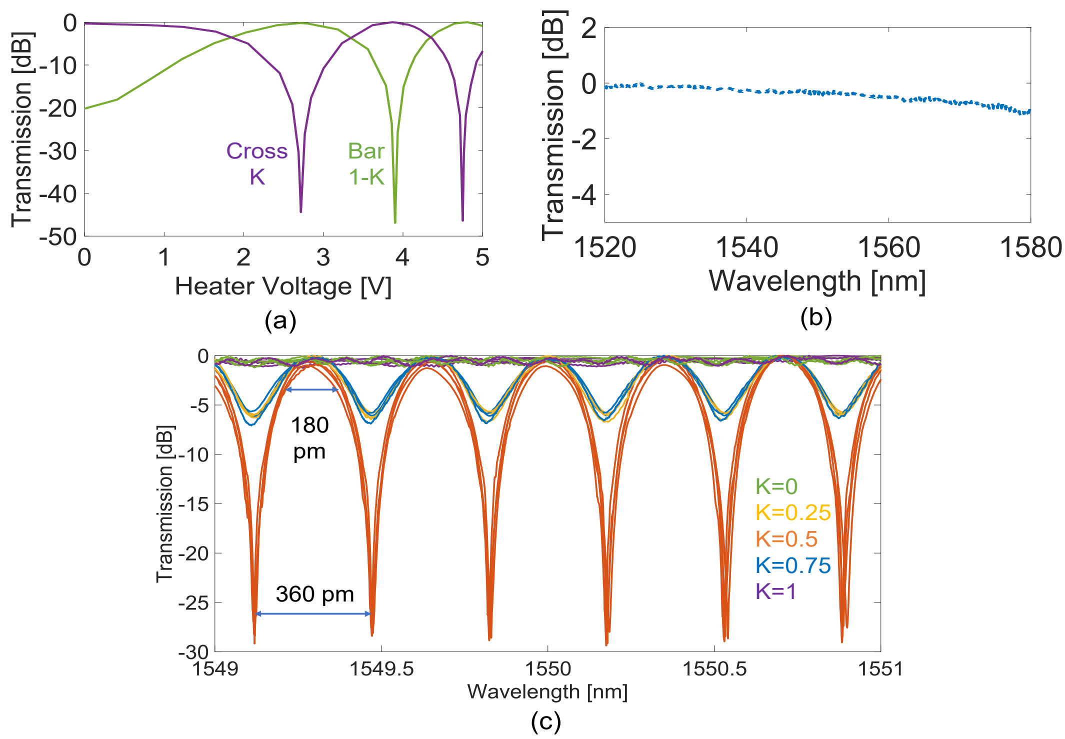


Fig. 2: (a) Electrical power-Transmission characteristic for the two ports (K and 1-K) of a TC and (b) its spectrum for K=1 (cross port). (c) Power spectral response of the proposed circuit, for different values of K (0, 0.25, 0.5, 0.75, 1), and for different values of M (1,2,3,4).

Design and Calibration

The proposed device is sketched in fig. 1(a), while a microphotograph of the realized device [fabricated on a commercial 220-nm silicon photonic platform, by Advanced Micro Foundry (AMF)] is shown in fig. 1(b). The circuit topology is based on a set of four unbalanced MZIs, organized in such a way that the N-th interferometer is the unbalance of the (N-1)-th stage. MZIs are equipped with Tuneable Couplers (TCs), labelled as $K_{X,i}$, where x = {A, B} indicate the first or the second TC of each MZI and i= {1,2,3,4} indicate the MZI stage. TCs are implemented by means of balanced MZIs, with 50:50 directional couplers (around a wavelength of 1550 nm). One of the arms is equipped with a thermo-optic actuator (85 μm long), to set the desired K. Tap photodetectors (PDs) are integrated at one output of each TC in order to effectively monitor the coupling ratio. Every stage presents an unbalance ΔL (of 1.85 mm) between the two arms. Thermal tuners (orange strips in Fig. 1) are placed in one of the two arms, allowing a precise frequency tuning. The other arm equipped with an integrated variable optical attenuator (VOA, green strips), to introduce a controllable loss and kill spurious paths. Optical I/Os are accessed by using grating couplers.

The time unbalance (ΔT) introduced by each MZI of the circuit (with respect to its own shortest path) linearly increases with K. The maximum achievable ΔT is

$$\Delta T = \frac{c\, n_g}{\Delta L} = FSR^{-1} \quad (1)$$

where n_g is the waveguide group index, c is the vacuum speed of light. Thus, each stage of the proposed architecture allows the introduction of a true delay of around 24 ps (considering n_g = 3.89, for the silicon waveguide around 1550 nm). When, for example, a delay ΔT longer than 24 ps (but lower than 48 ps) is requested, the TC pair of the first MZI stage is set completely to cross condition (i.e., $K_{A,1}$=$K_{B,1}$=1), while those of the third MZI stage are set to completely to bar condition (i.e., $K_{A,3}$=$K_{B,3}$=0), thus decoupling the fourth MZI stage from the rest of the circuit. and those of the second stage set the residual delay. In this way, for each requested delay, only one interferometer is actually activated, while the previous stages just accumulate delay. Notably, even though ΔT increases, there is no bandwidth (or FSR) narrowing.

Generalizing the approach, when an arbitrary input signal is coupled to the PIC and a generic group delay τ_{g0} is requested, the following quantities are calculated

$$M = \left\lfloor \frac{\tau_{g0}}{\Delta T} \right\rfloor, \quad (2)$$

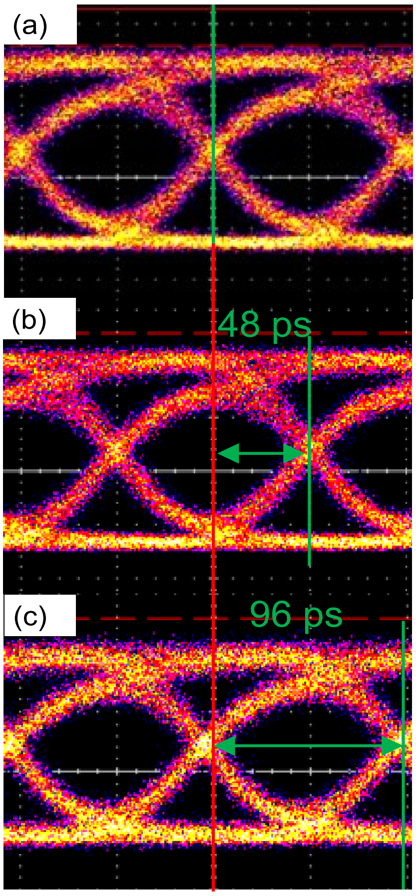


Fig. 3: (a) Eye diagram of the 10Gbit/s probe signal, when it travels through the shortest path of the delay line, (b) when it is tuned for the condition M=3, k=0 (a delay of 48 ps, equal to half of the maximum, is accumulated) and (c) when it propagates through the longest path and a delay of 96 ps is accumulated.

that is the number of MZI stages providing the maximum delay ΔT, and

$$k = (\tau_{g0} - M\,\Delta T)/\Delta T \,, \qquad (3)$$

that is the additional fractional delay ($0 < k < 1$) provided by of the last connected MZI stage and the coupling ratio of its own TCs (recalling linearity between the status of tuneable couplers of a MZI based delay line and introduced group delay [5]).

To achieve such overall delay τ_{g0}, the coupling coefficient $K_{A,i}$ and $K_{B,i}$ (with i=1,.., M-1) are put in cross condition by maximizing or minimizing (respectively) the optical power sensed by their output PDs. $K_{A,M+1}$ and $K_{B,M+1}$ (if present) are consecutively set to bar condition by minimizing the optical power measured by their PDs. Then, $K_{A,M}$ is intentionally put in bar condition, in order to finely tune $K_{B,M}$ in such a way that its coupling ratio results equal to *k.* When the setpoint is achieved, $K_{A,M}$ is finely tuned, too. Following this tuning approach calibration convergence of the entire PIC is reached in few tens of milliseconds (limited by the minimum number of iterations to reach the set-point). The algorithm is thermal-cross talk free, exploiting Thermal Eigenmode Decomposition (TED) technique [6].

Experimental Results

The functionality of the presented multi-stage delay line has been validated through spectral and time domain measurements. Fig. 2(a) shows the evolution of the coupling ratio of a TC with respect to the voltage applied to the heater (for both ports, Cross and Bar). When no driving current is applied to the actuator, the TC is in cross condition. Figure 2(b) shows the wavelength domain transmission in complete cross condition, demonstrating that the coupling ratio is almost constant (within ±1dB) along a range of more than 60 nm. A custom electronic board, executing the algorithm presented in the previous paragraph, was developed to control the entire delay line. In order to obtain different time unbalances, the device was calibrated to different working points. In particular conditions $K_{A,i}$ = $K_{B,I}$ = 0, 0.25, 0.5, 0.75, 1 for i=1,2,3,4 have been considered. Measured In-Out spectral responses for the mentioned conditions are reported in fig. 2(c). For a given value of *k*, regardless the order of the stage to be tuned (and hence the introduced time delay), the FSR and the 3dB-bandwidth remain constant. This means that the proposed architecture enables to provide additional delay without any bandwidth narrowing, or in other words it breaks the bandwidth-delay constraint that MZI based delay lines are generally subjected to.

This result was assessed by performing time domain measurements on a 10 Gbit/s OOK NRZ modulated signal. An optical oscilloscope, placed at the output of the device, was employed to quantify the delay introduced by the device. The transmission experiment was carried out for all the cases mentioned before. For example, Fig. 3(a) shows the signal which propagates through the shortest path of the device (i.e., M=1, *k*=0), while fig. 3(c) through the longest (M=4, k=1). Fig. 3(b), instead, refers to the condition M=3, *k*=0, according to which half of the maximum delay is introduced.

Acknowledgements

The Authors acknowledge the staff of Polifab (www.polifab.polimi.it), the microelectronic facility of Politecnico di Milano, for the support in the assembly of photonic chips.

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