EUROPEAN CONFERENCE ON INTEGRATED OPTICS

Variable photonic integrated delay lines, a review

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We present a comparison between various continuously variable true-time optical delay lines integrated on chip. Ring resonators and Mach-Zehnder based architecture are reviewed showing the superior properties of MZI structures. A topology that breaks the delay-bandwidth product limit is proposed, achieving a continuously tuneable delay from 0 to 100 ps across a bandwidth of 21 GHz with no signal distortion.

Keywords: *Variable delay lines, Beam forming networks, silicon photonics*

INTRODUCTION

Continuously variable true-time delay lines allow to arbitrary control the propagation delay of an optical signal and can be exploited for a variety of applications. Typical examples include synchronization and buffering of optical signals, optical signal processing and microwave photonic systems, optical coherence tomography, optical beam forming networks for phased-array antennas and more [1-5]. The control of a variable delay with a compact and non-moving device is very difficult to achieve in every field, (analog) electronic, microwave, photonics, acoustic, etc, especially if a large variation of delay, good dynamic, large bandwidth, and operation over a broad wavelength range is required.

Whatever it is the architecture of the device, the delay T is given by

$$T = \frac{n_g\, L_{eff}}{c}$$

where n_g is the group index of the material or the structure used to induce the delay, L_{eff} is effective length of the optical path and c is the speed of light. The delay T must be no- or weakly frequency dependent to realize a real true-time delay. The approaches can be clustered into two categories, resonant and non-resonant structures. The first one includes photonic crystals, microring resonators (MRRs) and material resonances (especially in gases), whereas the non-resonant approach exploit arrangements of Mach-Zehnder Interferometers (MZI). In case of interferometric structures, the spectral response is periodic.

It is worth to mention that a longer delay is achieved always at the expense of narrower operating bandwidth, as a result of an intrinsic limitation of the bandwidth-delay product. Further, whatever it is the architecture, the insertion loss of a delay line is given by

$$IL = \alpha L_{eff} = \alpha \frac{c\,T}{n_g}$$

where α is the attenuation of the material or waveguide per unit length. In conclusion, the most important parameter for the realization of a variable delay line is the ratio α/n_g, the architecture must guarantee a small frequency dependence behaviour and the device must be reconfigured according to the desired delay.

This review focuses on delay lines implemented as photonic integrated circuits, basically with MRRs and MZI. The former has the advantage of a reduced footprint but has narrow bandwidth, large chromatic dispersion, is affected by nonlinear effects due to intra-cavity field enhancement and require a complex control strategy. The MZI based one has a larger operational bandwidth, a simpler and more accurate control strategy, more resiliency to nonlinearities and a lower group delay dispersion, yet with a larger footprint.

TUNABLE MACH-ZEHNDER AND RING RESONATOR AS BUILDING BLOCK OF DELAY LINES

The MZI and the MRR shown in Fig. 1(a,b) are the two classical building blocks to induce a controllable delay. The tunable directional coupler allows to control the spectral response and hence the group delay. The MRR is typically used around the resonance frequency where the group delay can be very large, being equal to the roundrip time multiplied by the finesse. Large delays can be obtained with small rings and weak coupling coefficients but with a very large spectral dependence inducing severe detrimental effects on the delayed signal. The MZI instead, in the configuration of fig. 1 a), provides a controllable delay with a much larger bandwidth-delay product.

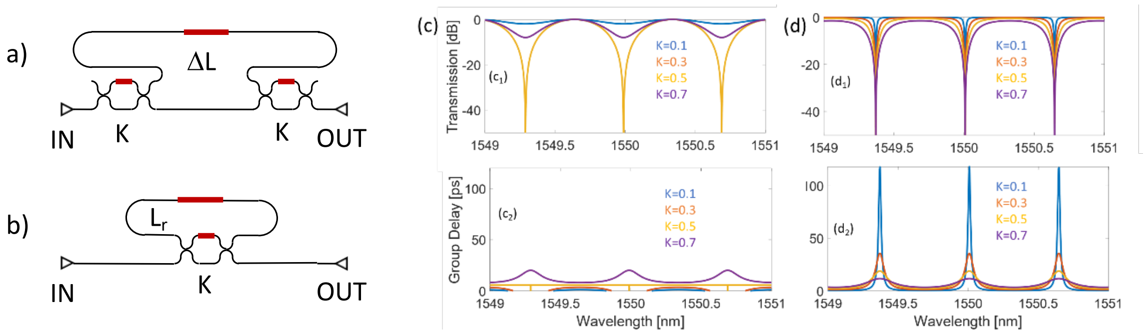

Fig. 1. Scheme of (a) MZI tunable delay line, (b) MRR delay line. (c, d) Spectral characteristics of the MZI and ring resonator.

The dependence of the normalized group delay on the coupling coefficient *K* at the operative frequency of the delay lines is shown in Fig. 2(a). For the ring, two different operative frequencies can be considered, in resonance and in antiresonance. Obviously, a resonating ring induces a delay much higher than off-resonance but the bandwidth-delay product is exactly the same, fig. 2b). The off resonance case has a much broader operating bandwidth, is more convenient but has never been considered a valid option to realize a delay line. For the Mach-Zehnder, the minimum normalized bandwidth (defined on the group delay) is about 0.31, reached for *K* equal to 0.25 and 0.75. For the ring resonator used off-resonance a minimum normalized bandwidth of 0.23 is reached at K ≃ 0.9. On resonance, the ring has an almost null normalized bandwidth with K ≃ 0.

The delay line based on a Mach-Zehnder interferometer has a bandwidth-delay product that is always larger than that of the ring and grows with *K*. The product goes to infinite for *K* = 0; 0.5 and 1 because for these values the bandwidth (defined on the group delay) is infinite. For a given value of the group delay, the bandwidth of the Mach-Zehnder delay line is hence always larger than the bandwidth of a ring-resonator-based delay line, even when used out of resonance.

Fig. 2(c) shows the value of the normalized group delay dispersion $\partial T/\partial\omega$. For the three cases, the dispersion is zero at the operative frequency of the delay lines. As expected, the ring resonator used on resonance exhibits a highly dispersive behaviour. On the contrary, the Mach-Zehnder and the off-resonance ring have a much smoother and similar dependence of the dispersion on frequency. The ring has a maximum dispersion that is almost twice that of the Mach-Zehnder at the same frequency. Lastly, the effect of propagation losses on the intensity transmission is strongly detrimental on the ring in resonance and almost negligible for the off-resonance ring and the MZI.

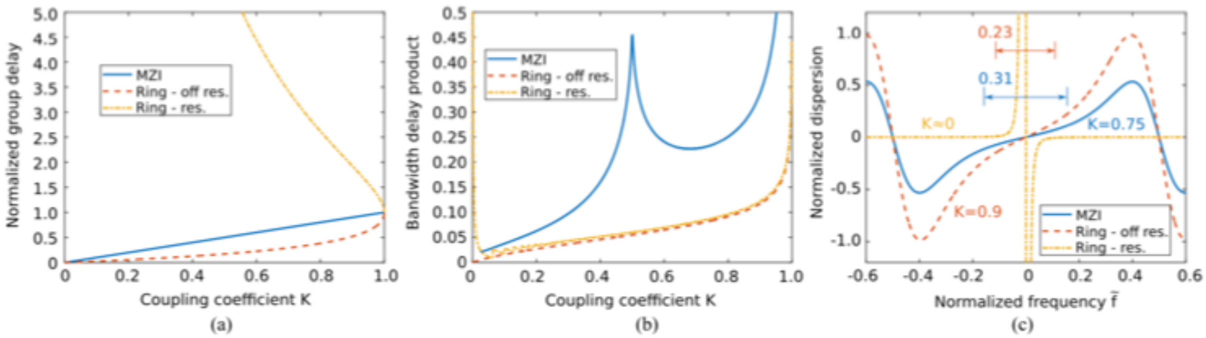

Fig. 2. (a) Normalized group delay and (b) bandwidth-delay product as function of the coupling coefficient K. (c) Group delay dispersion as function of the normalized frequency for the value of K that generates the minimum bandwidth. From [3].

BREAKING THE BANDWIDTH-DELAY CONSTRAINTS

By combining elementary building blocks, a larger delay range or a larger bandwidth can be achieved. A pioneer study comparing photonic crystals and directly coupled ring resonators (CROW) is reported in ref. [2]. With CROW (or SCISSORS, with a more complex control) the delay can be arbitrary increased while keeping the bandwidth constant at the expenses of a higher *IL* and a larger dependence of the delay on the frequency. Excellent results were achieved in [1, 2] but sophisticated control and stabilization schemes must be adopted. MZIs can be combined and cascaded as in [6,7,8] achieving a larger bandwidth-delay product with a reasonably simple control scheme.

An advantageous architecture based on a set of parallel stacked MZI is shown in Fig. 3 [9]. This structure overcomes the typical limitations of the previous circuits, in particular breaking the bandwidth-delay product constraint. The

circuit is composed by four unbalanced MZIs (but the number can be arbitrary), configured in such a way that the (n+1)-th stage is the unbalance of the n-th stage. Each MZI is equipped with two tuneable couplers (TCs, labeled in the picture as K_{Ai} and K_{Bi}, where i=1,2,3,4), in order to continuously modify the group delay, and with a thermo-optic phase shifter (heater) in the upper arm, to adjust the operational central frequency. The tuneable couplers are implemented by means of balanced MZIs, with thermo-optic actuators placed in one of the arms.
When both TCs are in cross condition ($K_{Ai}=K_{Bi}=1$), each stage provides the maximum delay ΔT_{max} = 1/FSR= 25 ps, the FSR being 340 pm (40 GHz) for a MZI arm unbalance of 1.8 mm. Given a desired group delay ΔT_1, the first *M* (where $M = \Delta T_1/25$ ps) pairs of TCs need to be set in cross condition ($K_{Ai}=K_{Bi}=1$, i=1,.., M), and the (M+1)-th pair is tuned to get the residual delay, as described in [3]. The (M+2)-th pair (if present) has to be set in bar condition. This means that, for every chosen group delay, only the (M+1)-th MZI is effectively working as an interferometer, while all the other TCs are acting just as switches. Hence, the achieved delay-bandwidth product is 2 (while in a single-MZI is 0.5). The delay has been experimentally measured using a 10 Gb/s OOK NRZ modulated signal. The measurement has been performed for a delay of 0, 50 and 100 ps, fig. 3(c-e).
The bandwidth-delay product $B_{3dB}T_D$ of a delay line with M stages against the coupling coefficient $K=K_A=K_B$ is given in fig. 3(f). Defining the bandwidth as the wavelength interval where the group delay changes less than 5% with respect to the central wavelength value [11], the bandwidth-group delay product ($B_{5\%}T_D$) dependence against coupling ratio is reported in fig. 3(g). The benefit of MZI-based delay lines (with respect to all pass ring resonators, shown in red) is evident and becomes more and more evident as the number of stages increases.

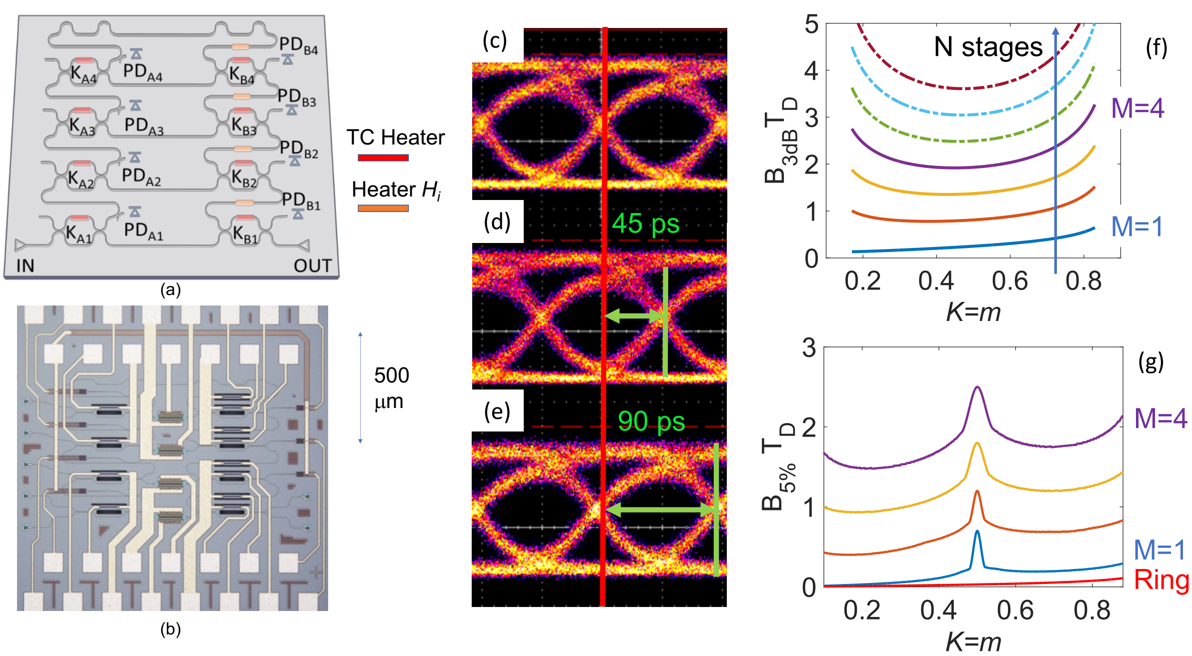

Fig. 3. (a) Schematic of parallel MZI delay line; (b) photograph of the device on a silicon photonics platform; (c-e) Eye diagrams of a 10Gbit/s signal propagating through the shortest path, when it is tuned for the condition M = 3 (45 ps delay) and when it propagates through the longest path. (f) Delay-bandwidth product as a function of K for different number of stages. (g) Same as (f), defining the bandwidth on the group delay flatness. The all-pass ring behavior is reported in red. From [9].

Acknowledgements: The research has been carried out in the framework of the EnTER project, Invitalia n. 0139934. Part of this work was carried out at Polifab, Politecnico di Milano, Milan, Italy.

References

[1] A. Melloni, et al., "Continuously tunable 1 byte delay in coupled-resonator optical waveguides," Optics Letters, 33, October 2008
[2] A. Melloni, A. Canciamilla, C. Ferrari, F. Morichetti, L. O'Faolain, T. F. Krauss, R. D. L. Rue, A. Samarelli and M. Sorel, "Tunable Delay Lines in Silicon Photonics: Coupled Resonators and Photonic Crystals, a Comparison," IEEE Photonics Journal, vol. 2, April 2010.
[3] D. Melati, A. Waqas, Z. Mushtaq and A. Melloni, "Wideband Integrated Optical Delay Line Based on a Continuously Tunable Mach–Zehnder Interferometer," IEEE Journal of Selected Topics in Quantum Electronics, vol. 24, p. 1–8, January 2018.
[4] J. F. Diehl, J. M. Singley, C. E. Sunderman and V. J. Urick, "Microwave photonic delay line signal processing," Applied Optics, July 2015
[5] C. Tsokos, et al., "True Time Delay Optical Beamforming Network Based on Hybrid Inp-Silicon Nitride Integration," JLT 39, 2021.
[6] A. Waqas, D. Melati and A. Melloni, "Cascaded Mach–Zehnder Architectures for Photonic Integrated Delay Lines," IEEE PTL 30, 2018
[7] Z. Mushtaq et al, "Multi-Stage Mach–Zehnder Based Continuously Tunable Photonic Delay Line," Wireless Personal Com. 121, 2021
[8] A. Melloni, D. Melati "Optical delay method and system", US Patent 10,890,717
[9] M. Petrini et al., Variable optical true-time delay line breaking bandwidth-delay constraints, Optics Letters, 48, 2, 2023