Wideband continuously tunable integrated delay line based on cascaded Mach-Zehnder

Abi Waqas
Politecnico di Milano
Milano, Italy
abi.waqas@polimi.it

Daniele Melati
National Research Council
Ottawa, Canada
daniele.Metati@polimi.it

Andrea Melloni
Politecnico di Milano
Milano, Italy
andrea.melloni@polimi.it

***Abstract*—A novel architecture based on cascaded Mach-Zehnder interferometer and equipped with tunable couplers is proposed for the realization of the tunable integrated optical delay line. We demonstrate that the delay line based on two cascaded Mach-Zehnder interferometer has the consistently larger bandwidth and bandwidth-delay product compared to a single stage. The presented device can be ideally operated with a single control signal and is experimentally demonstrated with true-time delay continuously tunable from zero to 124 ps.**

***Index Terms*—component, formatting, style, styling, insert**

I. INTRODUCTION

Optical delay lines provide a time delay for an optical signal and are emerging as a promising approach for applications where the dynamic control of the delay is required, such as synchronization, buffering, multiplexing and beamforming for phased array antennae [1], [2]. The realization of optical delay lines in integrated technologies allows miniaturization down to chip-scale and the integration with other optical functionalities such as filtering, modulation, and amplification. The ring resonator and photonic crystal based integrated circuits are very common devices to realize a delay line that exploits both the material and circuit resonances and tune the group delay up to several hundreds of picoseconds [3], [4]. Although these delay lines make possible to obtain large delays with very compact devices but generally at the expense of large losses and narrow bandwidth [5]. Coupled resonators can increase the operational bandwidth but generally require complex tuning strategies. Conversely, non-resonant delay lines achieve generally a smaller delay tunability compared to resonant devices but guarantee a much larger bandwidth and a finer control of the tuning. The most common non-resonant delay lines are based on switches in which paths with different physical lengths are selected by a series of switches thus changing the total propagation length and delay [6]. The drawback of this solution is the need for a large number of switches with a high on-off extinction ratio to guarantee the proper functionality. Further, the continuous tune of the delay is not possible since the control is necessarily done by discrete steps.

In this work, we propose a Mach-Zehnder based non-resonant integrated optical delay line equipped with tuneable couplers. The proposed structure can be realized using either a single stage or two cascaded identical stages. In both cases, the control scheme to tune the group delay in a continuous manner is simple, robust and hitless, since it can be performed without affecting power transmission at the operative wavelength (at least in the ideal lossless case) due to the reconfiguration of the circuit. We demonstrate that the exploiting the proposed control scheme, the use of two cascaded stages allows to increase bandwidth delay product (up to factor ~2) compared to a single-stage Mach-Zehnder delay line. In the end, the spectral characterization of a single-stage delay line, fabricated in indium phosphide (InP) technology, is reported, demonstrating a continuously tuneable delay from zero to 124 ps.

II. MACH-ZEHNDER BASED CASCADED DELAY LINE

The proposed device is schematically shown in Fig. 1 with two cascaded Mach-Zehnder interferometers and three tuneable couplers. All three tuneable couplers (K_1, K_2 and K_3) is realized using balanced Mach-Zehnder equipped with phase shifters on one arm that can be used to vary the coupling ratios in a continuous manner from 0 and 1. Both stages have an unbalance length ΔL between the two branches and phase shifters place on the shorter arm of each unbalance stage allows to tune the operative frequency of the device to match the incoming signal. The single stage circuit design is similar and includes first unbalancing stage only and two tuneable couplers K_1 and K_2 (box with dash lines in Fig. 1). The interferometric structures, in general, have two input and two output two ports but in this work, it is used as a single-input-single-output circuit in bar state [see Fig. 1].

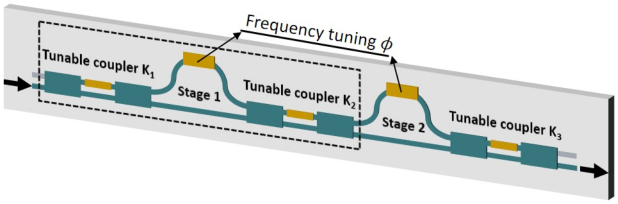

Fig. 1. Schematic of the proposed integrated optical delay line based on cascaded Mach-Zehnder interferometers with three tunable couplers. Box with dash lines shows the schematic of single stage delay line.

Considering a single-stage design, the operative frequency of the circuit f_0 can be defined as $2\pi f_0 \Delta L/c + \phi = (2N+1)\pi$, where ϕ is a constant phase shift applied through the phase shifter integrated in the interferometer [see Fig. 1] and N is an integer. If the two coupling ratios are chosen such that

$K_1 = K_2 = K$, the group delay τ at operative frequency f_0 in the bar, state can be written as $\tau(f_0) = \tau_0 + K(n_g \Delta L)/c = \tau_0 + TK$, where is T is the maximum achievable group delay depends on the unbalanced length ΔL, n_g is the group index of the waveguide, c is the speed of light and τ_0 is the minimum delay associated with the shortest branch of the interferometer. The simulation of the transmission and normalized group delay $[(\tau - \tau_0)/T]$ of the circuit is reported in Fig. 2 (a) and Fig. 2 (b), respectively, as a function of the normalized frequency [(f-f_0)/FSR where FSR the Free Spectral Range of the circuit] for different values of K from 0 to 1 and neglecting propagation losses. The minimum normalized group delay 0 corresponds to τ_0 whereas maximum normalized group delay 1 corresponds to τ_0 + T, the maximum group delay obtained travelling through the longest branch of the interferometer. As can be seen, at the frequency f_0 (marked with vertical dash lines in Fig. 2) the intensity transfer function of the circuit is constant and does not depend on K whereas the normalized group delay increases linearly with K. The normalized 3-dB bandwidth around f_0 can be calculated as $B = FSR/\pi \cdot \arccos\left[(K-0.5)^2/K(1-K)\right]$. The minimum bandwidth of B=FSR/2 is reached at K = 0.5.

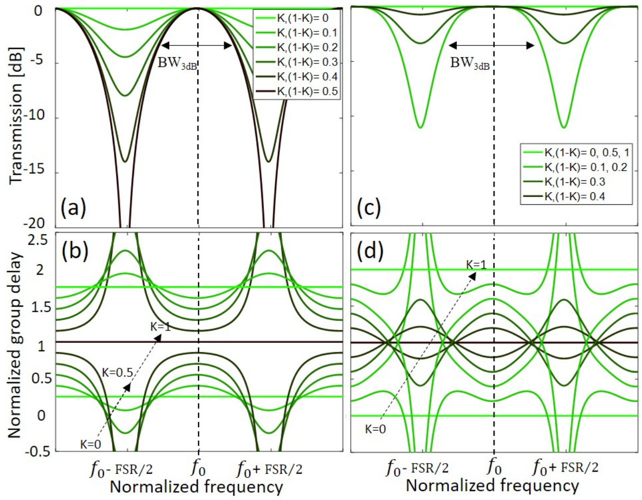

Fig. 2. Simulation of the transmission and the normalized group delay of a single stage delay line (a,b) and a two stage delay line (c,d) as a function of normalized frequency for different values of K. Vertical dash line shows the operative frequency.

The features of continuous delay tuning and constant output power at f_0 can be retained also with a delay line realized with two cascaded identical Mach-Zehnder interferometers. In this case, the three coupling ratios have to be chosen such that $K = K_1 = K_3 = (\sin^2\theta)$ and $K_2 = (\sin^2 2\theta)$, where θ is the phase delay induced by the phase shifter in the tunable couplers. This control strategy ensures the largest 3-dB bandwidth of the device and a linear dependence of the delay on K. Simulations of the power transmission and induced group delay of the cascaded delay line is shown in Fig. 2 (c) and (d), respectively, for different value of K (the choice of a value for K directly determines the coupling ratio of all the three couplers according to the relations reported above). As can be seen, the normalized group delay at the operative frequency now ranges from 0 to 2, according to the linear relation $\tau(f_0) = \tau + 2TK$. The actual group delay can hence be continuously changed from τ_0 to τ_0 + 2T, doubling the tuning range of the delay line compared to a single-stage circuit. Interestingly this increase does not come at the expense of a narrower operative bandwidth, as can be seen in Fig. 2 (c). The minimum 3-dB bandwidth is now obtained with K = 0.14 (K_2 = 0.5) and is about 27% larger than that of a single Mach-Zehnder, resulting also in a more flat-top passband.

III. COMPARISON OF DELAY LINES

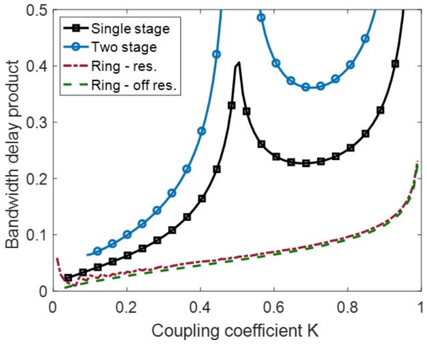

Fig. 3. Bandwidth-delay product calculated as function of the coupling coefficient K. Data are reported for the single stage delay line [black solid line with square marker], two stages delay line [blue solid line with circle markers] an all-pass ring resonator used out of resonance [green dashed line] and the same ring used at the resonance frequency [brown dot-dashed line].

Figure 4 reports the performance comparison of the proposed device (both single and two stages delay lines) in terms of bandwidth delay product with respect to delay line based on optical all-pass ring resonators. The ring delay line considered for the comparison has a single ring resonator equipped with a tunable coupler that allows controlling the amount of optical power coupled in and out of the resonant cavity. Also for this structure, the normalized group delay as a function of frequency and coupling coefficient K can be analytically calculated. For both cases, losses are neglected. Since the ideal case has taken into account here the 3-dB bandwidth cannot be defined for an all-pass filter, the bandwidth is measured directly on the spectrum of the group delay response for both the ring and the Mach-Zhender. In particular, the normalized bandwidth is defined as the difference between the two normalized frequencies around $f_0 = 0$ (the operative frequency) where the normalized group delay drops by 5%. As can be seen, a ring-resonator-based delay line has a product value that is almost identical when used in resonance or off resonance [green dashed and brown dot-dashed line, respectively]. The bandwidth-delay product slowly grows with K up to about 0.15 (excluding values of K either close to 0 or close to 1). The larger group delay of the ring when used at the resonance frequency is compensated by a narrow bandwidth whereas off resonance the opposite condition applies: a lower group delay is guaranteed on a much larger bandwidth. The Mach-Zehnder based delay line bandwidth-delay product that is always larger than that of the ring and grows with K. For both single stage and two stages delay line the product goes to infinite for K = 0, K = 0.5 and K = 1 because for these values the bandwidth (defined on the group delay) is infinite. For values of K greater than 0.4, the two-stage delay line has almost twice bandwidth-length product compared to a single stage.

IV. Experimental Results

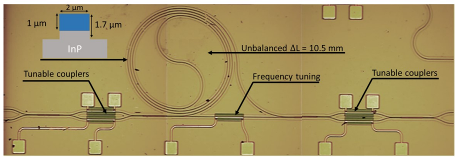

Fig. 4. Photograph of realized Mach-Zehnder based delay line with two tunable couplers.

In this section, we present the experimental results of a single stage delay line, the two-stage being not available. Figure 4 shows a top-view photograph of the single-stage optical delay line that was fabricated through a JePPIX Multi-Project Wafer Run on an InP-based technological platform. Balanced 2x2 Mach-Zehnder interferometers are exploited as tunable couplers and realized with 3-dB MMI couplers and 250-μm-long thermo-optic phase shifters. A phase shifter is integrated on the shorter arm of the unbalanced Mach-Zehnder to tune the operative frequency of delay line. The realized delay line has an unbalance length ΔL of 10.5 mm and expected maximum achievable group delay variation for the TE polarized mode of about 124 ps. The spectral characterization of fabricated device was performed in the optical domain using an Optical Vector Analyser that allows to characterize both power and group delay spectra.

The normalized power transmission and group delay spectra measured for the device between λ = 1534.9 nm and λ = 1535.02 nm are shown in Fig. 4(a) and 4(b) for different K values from 0 to 1 (TE mode). The coupling coefficients of two tunable couplers are tuned by feeding the current to phase shifter. The vertical dashed lines mark the operative wavelength λ_0 = 1534.96 nm. The measured spectral behaviour is in agreement with the simulations shown in Fig. 2(a) and 2(b). For K $\simeq$ 0 power transmission and group delay are almost wavelength independent and the latter is at minimum causing the light to travel in the shortest branch of the delay line. Increasing current and hence the coupling coefficient K, a strong frequency dependence appears in the spectra but at the operative wavelength normalized power transmission is almost constant while group delay steadily increases. As expected the deepest notches are obtained with K $\simeq$ 0.44 (close to 0.5) whereas for K $\simeq$ 1 power transmission and group delay is again wavelength independent and later reaches at a maximum of 124 ps. The measured FSR of about 8 GHz is consistent with the maximum measured group delay variation of 124 ps. At K $\simeq$ 0.44, the 3-dB bandwidth is about 4.47 GHz.

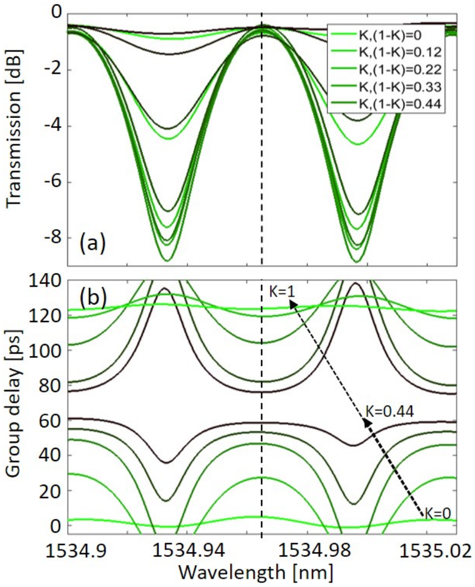

Fig. 5. Measurements of (a) transmission and (b) group delay spectra of single stage delay line for different values of K. Unbalance length of realized device is ΔL = 10.5 mm.

V. CONCLUSION

To conclude, we have presented an integrated device based on two cascaded Mach-Zehnder interferometer implementing a non-resonant optical delay line with the very simple control scheme. Using two cascaded stages and controlling the tunable couplers according to the proposed scheme allows increasing the bandwidth-delay product with a factor of 2 and the bandwidth of the device of about 27 % compared to a single-stage delay line. The group delay of the device is continuously tuned by varying the coupling ratios of the couplers without affecting power transmission at the operative frequency, preventing modulation of the amplitude of the optical signal due to the reconfiguration of the circuit. The spectral characterization of the fabricated device demonstrated group delay tunability from zero to 124 ps

References

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nature photonics*, vol. 1, no. 6, pp. 319–330, 2007.

[2] A. Melloni, F. Morichetti, C. Ferrari, and M. Martinelli, "Continuously tunable 1 byte delay in coupled-resonator optical waveguides," *Optics letters*, vol. 33, no. 20, pp. 2389–2391, 2008.

[3] J. Cardenas, M. A. Foster, N. Sherwood-Droz, C. B. Poitras, H. L. Lira, B. Zhang, A. L. Gaeta, J. B. Khurgin, P. Morton, and M. Lipson, "Wide-bandwidth continuously tunable optical delay line using silicon microring resonators," *Optics express*, vol. 18, no. 25, pp. 26 525–26 534, 2010.

[4] R. L. Moreira, J. Garcia, W. Li, J. Bauters, J. S. Barton, M. J. Heck, J. E. Bowers, and D. J. Blumenthal, "Integrated ultra-low-loss 4-bit tunable delay for broadband phased array antenna applications," *IEEE Photon. Technol. Lett*, vol. 25, no. 12, pp. 1165–1168, 2013.

[5] G. Lenz, B. Eggleton, C. K. Madsen, and R. Slusher, "Optical delay lines based on optical filters," *IEEE Journal of Quantum Electronics*, vol. 37, no. 4, pp. 525–532, 2001.

[6] M. S. Rasras, C. K. Madsen, M. A. Cappuzzo, E. Chen, L. T. Gomez, E. J. Laskowski, A. Griffin, A. Wong-Foy, A. Gasparyan, A. Kasper *et al.*, "Integrated resonance-enhanced variable optical delay lines," *IEEE photonics technology letters*, vol. 17, no. 4, pp. 834–836, 2005.