Cascaded Tunable Optical Delay Line based on a Racetrack Resonator with Tunable Coupling and Stable Wavelength

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Abstract: We propose a novel integrated optical delay line based on a cascaded racetrack resonator with tunable coupler by push-pull operation of each stage to stabilize the resonant wavelength. The thermal tuning effect and the photonic characteristics of the whole integrated device is simulated to verify the characteristics of the tunable ODLs. The tuning of hundreds of ps is achievable with a very compact device and very small power consumption. The two-stage configuration can allow for reaching larger delay time or a wider bandwidth depending on the operation condition.

1 INTRODUCTION

Integrated optical delay lines (ODLs) are key components in photonic circuits for many applications. The optical delay line can be realized exploiting either a single stage or multiple cascaded stages. The use of two cascaded stages allow to increase either the delay tunability or the bandwidth of device compared to a single-stage ODL (Melati & Melloni, 2018). They can be found in numerous applications, such as optical signal processing and buffering in optical networks, beamforming and filtering in microwave photonic systems, bio-medical sensing, and 3D light scanning and ranging (Zhou, et al., 2018) (Melati, et al., 2018) (Han, et al., 2013) (Cardenas, et al., 2010).

Integrated on-chip ODLs exhibt multiple benefits correlated to bulk optics or fiber-based ODLs, such as the reduced cost, size, weight, and power consumption (Zhuang, et al., 2013) (Melati, & Melloni, 2018) (Melloni, et al., 2010) (Liu, et al., 2018) (Balbas, et al., 2007). The integrated optical delay lines have been illustrating for a variety of utilization (Pegios, et al., 2018) (Park, et al., 2008) (Capmany, & Novak, 2007) (Hyeon, et al., 2015).

Various integration platforms can be utilized to construct ODLs. There are several trade-offs in the delay line performances, like bandwidth and maximum delay, integration density and waveguide propagation loss needs to be acknowledging before picking the proper platforms. Silicon photonics platform based on the silicon-on-insulator (SOI) is regarded as one of the most promising technologies for large-scale high-density photonic integration because of its large index contrast, small bending radius and the use of compatible fabrication facilities in semiconductor foundries (Melloni, et al., 2010) (Xie, et al., 2007). There are several semiconductor foundries and research institutes providing the multi-project-wafer (MPW) process for SOI-based photonic integration, which can reduce the research and development cost for realizing tunable ODLs. Therefore, our design is based on the SOI platforms.

There are two common used approaches to tune the SOI-based ODLs: tuning with thermal heating or carrier-induced effects. Both tuning mechanisms change the refractive index of the waveguide and then change the phase. Thermal tuning is usually the choice for its simple device structure and low optical loss as long as the tuning speed is not the major concern. Tunable optical delay lines based on ring resonators have been demonstrated by several groups (Bogaerts, et al., 2012) (Poon, et al., 2004) (Katti, & Prince, 2018) (Xie, et al., 2014). Most of the designs are for optical signal processing or buffering. In these applications, the critical requirements include large enough true delay, wide bandwidth, and low higher-

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order phase variations that will lead to dispersion and signal distortion. Therefore, multiple stages of ring resonators are employed to achieve the desired delay with large bandwidth and low distortion (Cardenas, et al., 2010).

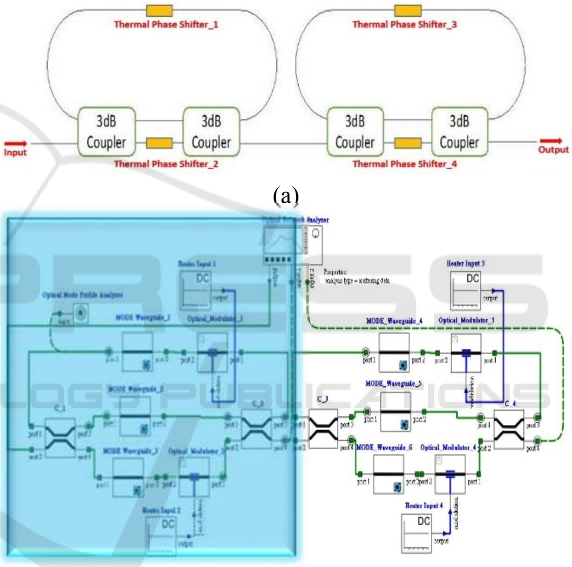
In this work, we design an optical delay line based on two-stage racetrack resonator equipped with tuning heaters. The design aims at the applications for optical and bio-medical sensing where the optical signal usually narrow linewidth.

We explain that with the proper control design, the novel architecture doubles the group delay tunability range compared to a single-stage racetrack resonator ODL and achieves a limited delay-bandwidth product (DBP). The ODL design demonstrated in this paper can achieve a true delay ranging from tens of picoseconds to hundreds of picoseconds at a stable wavelength.

2 CASCADED INTEGRATED OPTICAL DELAY LINE

Figure 1 (a) shows the schematic of the 2-stage ODL where each stage is a tunable racetrack resonator with a tunable coupler. The tunable coupler is a symmetric Mach-Zehnder interferometer (MZI) with one of the two arms equipped with a thermal heater based phase shifter to tune the output ratio of the MZI. The peak delay occurs at the resonance condition of the racetrack resonator. The peak delay depends on the coupling ratio of the MZI output. In general, as the peak delay increases, the insertion loss of the ODL rises and the wavelength bandwidth decreases. On the same time, the peak wavelength where the peak delay occurs moves with the coupling ratio. In order to stabilize the peak wavelength in the application field of optical sensing, the two phase shifters of each stage is operated in push-pull mode. That is, as one phase shifter is heating up, the other one will be cooling down. The peak wavelength of the two stage can be aligned to double the peak group delay or shifted slightly to have a greater bandwidth.

To verify the operation characteristics of the proposed 2-stage ODL, the simulation using the Lumerical Solutions' Photonic Design Tools conducted here (Lumerical INTERCONNECT, 2019). The used to realize the two-stage integrated ODL, which details as shown in Figure 1. The block-diagrams component blocks used in the Lumerical Interconnect is depicted in Figure 1(b). The device architecture is constructed with six Lumerical MODE waveguides, four thermal modulators, four 3-dB couplers, four DC source components, and an optical network analyzer. In each component block, we import the exact file that comes from the MODE simulation. We import the saved data from MODE simulations into MODE waveguide and modulator components. The change of effective index as a function of input power of Heater 1, and Heater 3 can be deposited into the "Optical Modulator 1", and "Optical Modulator 3" respectively, and the change of effective index as a function of input power of Heater 2, and Heater 4 can be loaded into "Optical Modulator 2", and "Optical Modulator 4" respectively. In each component of MODE waveguide, we imported the proper file of TE mode thermal waveguide profiles. The response of the devices was measured through the Optical Network Analyzer that permits characterizing the power transmission spectrum and the group delay spectrum.



(a)

(b)

Figure 1: (a) Schematic of 2-stage tunable delay lines, (b) Lumerical INTERCONNECT blocks for the two cascaded identical stages ODL based on racetrack resonator and MZI. The box with blue shaded part includes the schematic of a single stage delay line.

3 TWO STAGE INTEGRATED OPTICAL DELAY LINE SIMULATION RESULTS

Figure 2 shows the group delay, power transmission, and wavelength at the resonant condition as a function of the input power of Heater 4 when the input power of Heater 1 and Heater 3 is fixed at 0 mW. It corresponds to the case that only the coupling coefficient of the ODL is tuned. By tuning the input power of Heater 4, from 0 to 7mW, the group delay, measured at the resonant peak varies from 35.62 ps to 201.43 ps, while the corresponding power transmission efficiency at the transmission dip in the spectrum, can be kept above 80% over the tuning range. However, the peak wavelength shifts from 1550.74 nm to 1550.85 nm during tuning. That is, the wavelength drifts at a rate of 0.0016 nm/mW regarding the input power of Heater 4. This wavelength drift will appear in a change in the group delay for a fixed wavelength. Also, Figure 3 shows the results for tuning the racetrack loop phase with Heater 3 by fixing the input power of Heater 2 and Heater 4 at 0 mW. During the tuning of Heater 3, the peak group delay and power transmission are almost constant, but the wavelength varies linearly with a slope of 0.031 nm/mW. Hence, Heater 3 can be used to correct the resonant wavelength without affecting the group delay and power transmission.

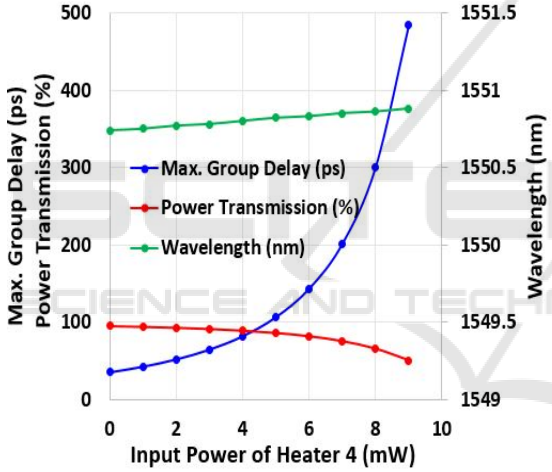


Figure 2: Simulation of the group delay, power transmission, and wavelength at the resonant peak versus the input power of Heater 4 when the other heater is at 0 mW.

Figure 4 shows the contour plot of the wavelength of the proposed ODL as a function of the input power of the two heaters. The contour plot will be used to illustrate how to tune the group delay and keep the peak wavelength intact. Figure 4 shows the tuning of the peak wavelength versus the power to heater 3 and 4, as indicated by the red arrows in Figure 4. The triangular background pattern shows in Figure 4 is the wavelength due to the push pull operation of the heaters tuning. This figure shows particularly one of the peaks between the several peaks caused by the ring resonance.

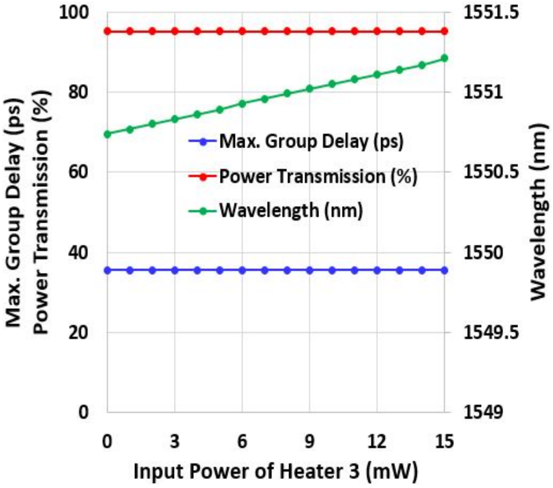


Figure 3: Simulation of the group delay, power transmission, and wavelength at the resonant peak versus the input power of Heater 3 when the other heater is at 0 mW.

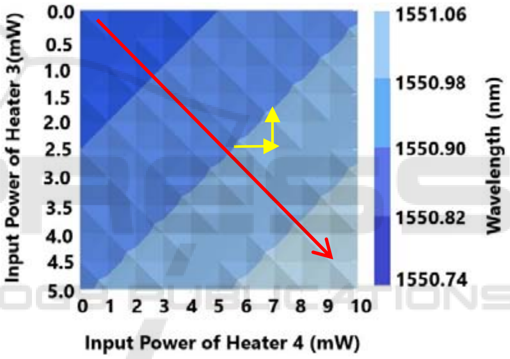


Figure 4: Contour plot of wavelength as a function of the input power of heaters.

Figure 5 shows that the peak group delay can be continuously tuned by simply changing the input power to Heater 4 while it remains fixed in the tuning of Heater 3. From Figures 2 & 3, the wavelength drift rate is different for tuning Heater 4 and Heater 3, respectively. Moreover, the tuning of Heater 3 and Heater 4, the shift of the wavelength is in the same direction (longer wavelength). To retain the wavelength in tuning the group delay, the two heaters require to be operated at the push-pull mode. That is, the heater input power to heater 3, must be decreasing as the input power to heater 4, increases.

As designated by the yellow arrows in Figure 4 and 5 as an example, the input power of Heater 4 is increased to increase the group delay, then the input power to Heater 3 needs to be decreased to keep the same peak wavelength.

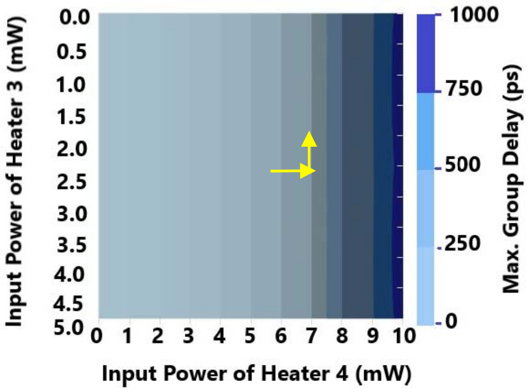


Figure 5: Contour plot of peak group delay as a function of the input power of heaters.

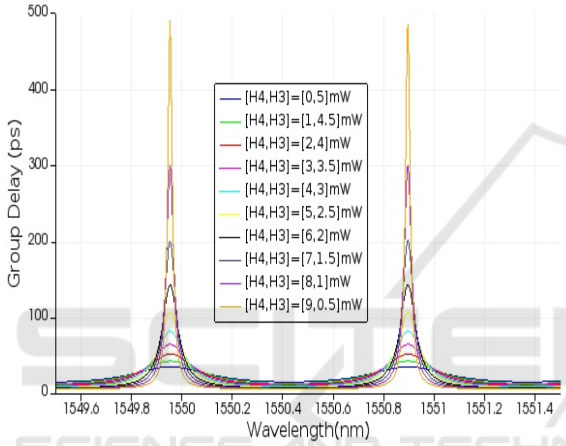


Figure 6: Group delay as a function of the wavelength for [(H4, H3) = (0,5), (1,4.5), (2,4), (3,3.5), (4,3), (5,2.5), (6,2), (7,1.5), (8,1), (9,0.5)] mW, where H3 and H4 indicate the power to Heater 3 and 4, respectively.

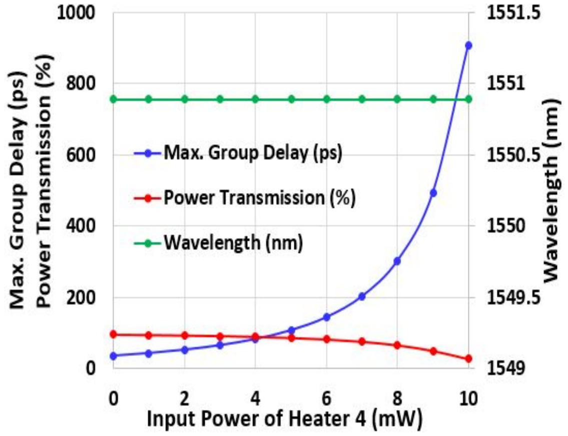


Figure 7: Peak group delay, power transmission, and wavelength as function of the input power of heater 4.

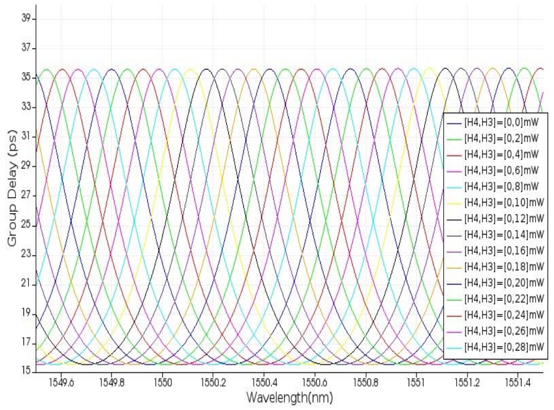


Figure 8: Group delay as a function of the wavelength for [(H4, H3) = (0, 0-28)] mW.

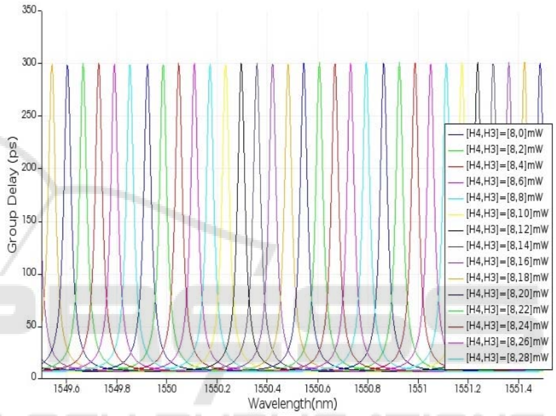


Figure 9: Group delay as a function of the wavelength for [(H4, H3) = (8, 0-28)] mW.

Figure 6 depicts the tuning spectrum for the push-pull operation. Since the wavelength drift rate for tuning Heater 3 is about double of that for tuning Heater 4, the input power for Heater 4 and Heater 3 is of a step of 1 mW and 0.5 mW, respectively, for the spectra shown in Figure 7. During group delay tuning, the resonant wavelength is almost fixed. The summary of the group delay, power transmission, and wavelength by tuning the two heaters together at the push-pull mode is as shown in Figure 7. The wavelength keeps constant while the group delay is tuned by more than one order of magnitude.

Figures 8 and 9 show that the peak group delay can be tuned over one free spectral range (FSR) by using less than 30 mW of the Heater 3 power when the input power of Heater 4 is 0 and 8 mW for different delay time. Due to the periodic delay-time characteristics, Figures 8 and 9 indicates that the proposed two-stage tunable delay lines can be tuned to track the wavelength of the input light sources over a wide wavelength range and provide the needed group delay.

4 CONCLUSIONS

We present here a novel way of tuning the group delay of a two-stage optical delay line by operating the thermal heater at push-pull mode. The peak group delay and resonant peak wavelength can be tuned almost independently. The group delay is tuned by the heater in one arm of the balanced MZI coupler to vary the effective coupling coefficient to the resonator. On the other hand, the thermal tuning on the racetrack loop can correct the wavelength drift without affecting the group delay. The simulation using the practical device structure of a semiconductor foundry is pursued to demonstrate the group-delay tuning characteristics of such a racetrack-resonator.

The targeted applications for such tunable optical delay lines are for optical sensing and/or bio-medical sensing, where the light source usually has very narrow linewidth. We demonstrate the tuning of group delay to nearly 40 ps while fixing the resonant wavelength by adjusting the heating power of Heater 3. The maximum group delay can be achieved by tuning the coupling coefficient to have an even sharper resonant peak with a tradeoff on the transmission power. The tuning of hundreds of picosecond is achievable with a very compact device and very small power consumption. The use of two cascaded identical stages with the described control scheme allows to double both the tunability range of the group delay compared to a single-stage ODL.

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REFERENCES

Melati, D., & Melloni, A. (2018). On-chip continuously tunable optical delay line based on cascaded Mach-Zehnder interferometer. In proceedings of the Optical Fiber Communication Conference, OSA, San Diego, California, USA.

Zhou, L., Wang, X., Lu, L., Chen, J., (2018). Integrated optical delay lines. COL. Rev. 16, pp. 101301:1-101301:16.

Melati, D., Waqas, A., Mushtaq, Z., & Melloni, A., (2018). Wideband integrated optical delay line based on a continuously tunable Mach-Zehnder interferometer. IEEE J. Sel. Topics Quantum Electron. 24, pp.1-8.

Han, X., Wang, L., Zou, P., Wang, Y., Zhang, S., Gu, Y., Wang, J., Jian, X., & Zhao, M., (2013). A Tunable Optical Waveguide Ring Resonator for Microwave Photonic Filtering. In Proceedings of the IEEE International Topical Meeting on MWP, Alexandria, VA, USA, 28-31.

Cardenas, J., Foster, M. A., Sherwood-Droz, N., Poitras, C.B., Lira, H L., Zhang, B., Gaeta, A. L., Khurgin, J.B., Morton, P., & Lipson, M., (2010). Wide-bandwidth continuously tunable optical delay line using silicon microring resonators. Opt. Express. 18, pp. 26525–26534.

Zhuang, L., Hoekman, M., Beeker, W., Leinse, A., Heideman, R., van Dijk, P., & Roeloffzen, C., (2013). Novel low-loss waveguide delay lines using Vernier ring resonators for on-chip multi-λ microwave photonic signal processors. Laser Photon. Rev. 7, pp. 994–1002.

Melloni, A., Canciamilla, A., Ferrari, C., Morichetti, F., O’Faolain, L., Krauss, T.F., de La Rue, R., Samarelli, A., & Sorel, M., (2010) Tunable delay lines in silicon photonics: Coupled resonators and photonic crystals, a comparison. IEEE Photonics J. 2, pp. 181–194.

Liu, Y., Whichman, A. R., Isaac, B., Kalkavage, J., Adles, E.J., Clark, T.R., & Klamkin, J., (2018). Ultra-low-loss silicon nitride optical beamforming network for wideband wireless applications. IEEE J. Sel. Topics Quantum Electron. 24, pp. 1-10.

Balbas, E. M., Pandraud, G., & French, P. J., (2007) Thermo-Optical Delay Line for Optical Coherence Tomography. Proc. of SPIE 6717, pp. 671704:1-671704:9

Pegios, M. M., Alexzndris, G. M.., Terzenidis, N., Cherchi, M., Harjanne, M., Aalto, T., Miliou, A., Pleros, N., & Vyrsokinos, K., (2018). On-Chip SOI Delay Line Bank for Optical Buffers and Time Slot Interchangers. IEEE Photonics Technology Letters. 30, pp. 31-34.

Park, H., Mack, J. P., Blumenthal, D. J., & Bowers, J. E., (2008). An integrated recirculating optical buffer. Opt. Express. 16, pp. 11124-11131.

Capmany, J., & Novak, D., (2007). Microwave photonics combines two worlds. Nature Photonics. 1, pp. 319–330.

Xia, F., Sekaric, L., & Vlasov, Y., (2007). Ultra compact optical buffers on a silicon chip. Nature Photonics. 1, pp. 65–71.

Hyeon, M. G., Kim, H. J., Kim, B. M., & Eom, T. J., (2015). Spectral Domain Optical Coherence Tomography with Balanced Detection Using Single Line-Scan Camera and Optical Delay Line. Optics Express. 23, pp. 23079-23091.

Bogaerts, W., De, H. P., van Vaerenbergh, T., De, V. K., Kumar, S. S., Claes, T., Dumon, P., Bienstman, P., van Thourhout, D., & Baets, R., (2012). Silicon microring resonators. Laser & amp Photonics Rev. 6, pp. 47–73.

Takahashi, H., Carlsson. P., Nishimura, K., & Usami, M., (2004). Analysis of Negative Group Delay Response of All-Pass Ring Resonator with Mach-Zehnder Interferometer IEEE Photonics Technology Letters. 16, pp. 2063-2065.

Green, W. M., Lee, R. K., deRose, G. A., Scherer, A., Yariv, A., (2005). Hybrid InGaAsP-InP Mach-Zehnder Racetrack Resonator for Thermo-Optic Switching and Coupling Control. Optic Express. 13, pp. 1651-1659.

Poon, J. K., Scheuer, J., Mookherjea, S., Paloczi, G. T., Huang, Y., & Yariv, A., (2004). Matrix analysis of microring coupled-resonator optical waveguides. Optics Express. 12, pp. 90-103.

Katti, R., & Prince, S., (2018). Photonic Delay Lines Based on Silicon coupled Resonator Optical Waveguide Structures. Silicon. 10, pp. 2793-2800.

Xie, J., Zhou, L., Zou, Z., Wang, J., Li, X., & Chen, J., (2014). Continuously tunable reflective-type optical delay lines using microring resonators. Optics Express. 22, pp.817-823.

Lumerical Solutions' Inc.Innovative Photonic Design Tools, URL:http://www.lumerical.com (accessed on 14 March 2019).