Thermally-controlled transparency in multi-ring cascaded filters

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Thermally-controlled transparency in multi-ring cascaded filters

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ABSTRACT

We propose a novel control scheme to induce transparency through thermal tuning in multi-stage cascaded ring structures. Higher-order MicroRing Resonator structures are fundamental blocks for high Q-factor filtering as well as wavelength-sensitive applications. Through the proposed thermal control scheme, which does not require additional heating elements with respect to the traditional calibration and uncertainty-compensation setup, we can manage both the central wavelength of the add-drop filter, as well as toggle the transparent state. Through this technique the add-drop filter can be switched off, allowing the signal to pass through without frequency-dependant effects and just introducing flat-band crosstalk.

Keywords: Microring Resonators. Photonic Integrated Circuits. Integrated Switching. Photonic Filters.

1. INTRODUCTION

MicroRing Resonators (MRRs) are fundamental building blocks of Photonic Integrated Circuits (PICs), with applications in almost all fields requiring wavelength filtering and switching. They represent a class of highly flexible components, allowing deployment in diverse fields such as optical switching and signal processing, photonic computing, and neuromorphic applications, as they have been extensively analyzed and characterized over the years.[1]

Single MRRs are typically not used except in simple filtering applications, with cascaded multi-ring devices being instead used for most applications requiring precise spectra tailoring or more complex functionalities. This is necessary to improve the pass-band transition, extinction ratio, crosstalk, and all other band properties, which cannot be directly designed or tuned in single-ring devices. By combining multiple rings together, we can increase the degree of freedom in the design, allowing the synthesis of custom filtering responses through the asymmetry in the rings resonances, couplings, and topological configuration.[2]

The added complexity of the circuit requires a tuning mechanism capable of aligning each ring in the system, compensating the manufacturing uncertainty, as well as allowing active tuning of the device during operation: this control scheme is typically used to align the resonance of the manufactured rings with the nominal design, or to shift the response of the system.[3] In this work, we showcase the effect of asymmetric tuning in a cascaded device, introducing switching capabilities on top of the traditional tuning and alignment: through control of the destructive interference and ring asymmetry, the overall device resonance can be turned off, leading to a frequency-independent transparent behaviour.

2. CASCADED RING STRUCTURES

The device under analysis consist of a four MRRs filter arranged in a two-stage ladder configuration. This filter, depicted in Fig. 1a, is made of two second-order elements coupled through two common waveguide rails, the upper bus designed to introduce a π phase shift between the two stages. This configuration can be scaled up to an arbitrary even number of rings, as odd-sized ladder configurations cannot be connected in cascade due to the contra-directional propagation of the field. Similarly additional stages can be added, although there is

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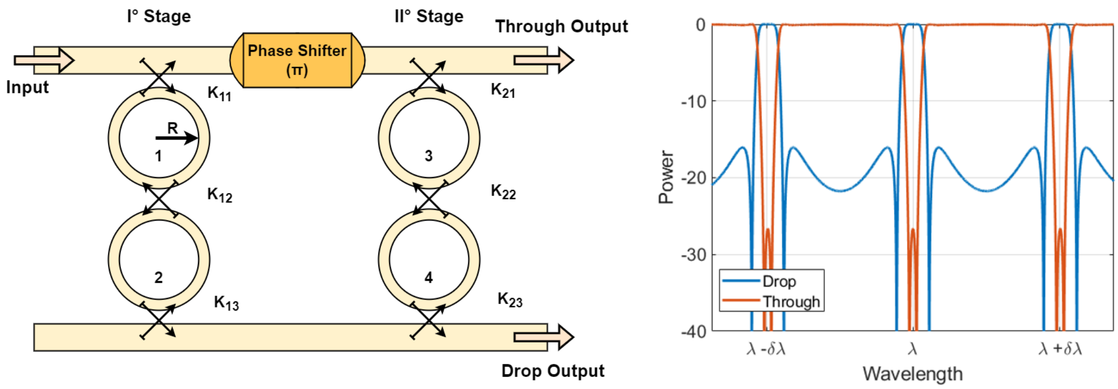
Silicon Photonics XIX, edited by Graham T. Reed, Andrew P. Knights,
Proc. of SPIE Vol. 12891, 128910N · © 2024 SPIE
0277-786X · doi: 10.1117/12.3002558



(a) (b)

Figure 1: (a) Two-stage Ladder MRR filter. (b) Output response of the Add-Drop element.

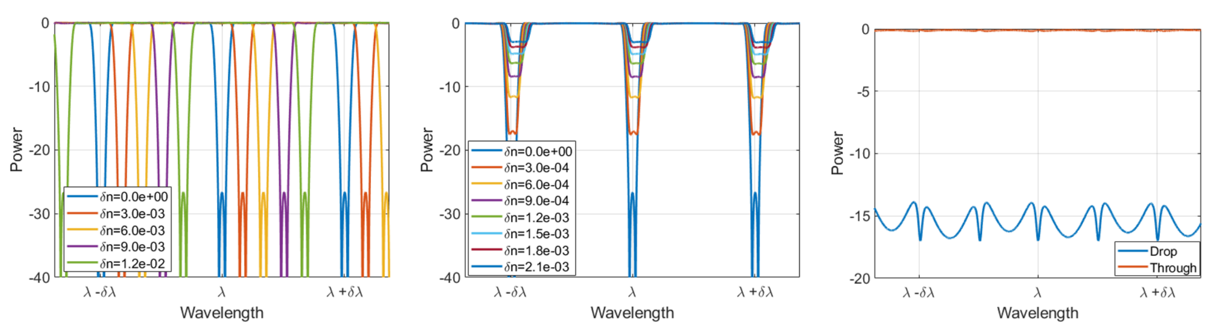
a diminishing advantage, as the footprint and calibration costs increase with respect to the added degree of freedom: the four-ring configuration represents a trade-off between the two and serves well as a test topology to highlight the asymmetric ring control.

The filtering response is largely dependent on the coupling coefficients between the rings and the waveguide, whereas the radii represent relative parameters, especially considering the ideal design and synthesis of the target spectrum response: the radius and effective index of the rings affect the resonance frequencies of the device and are typically designed to be equal. In our analysis and simulation, we consider all rings identical, while the coupling coefficients are chosen to produce a flat-top response with sharp roll-off.[4] The response shown in Fig. 1b is obtained for values of the coupling $\kappa_{11} = \kappa_{13} = 0.8$, $\kappa_{12} = 0.1$, $\kappa_{21} = \kappa_{23} = 0.3$, $\kappa_{22} = 0.2$, while it is assumed C-band range operation, with ring of radius $R = 15\,\mu m$ on the Si/SiO_2 standard integrated platform.

3. CONTROL SCHEME

As previously stated MRR-based device require calibration and tuning setups to compensate for their intrinsic fabrication uncertainty sensitivity. Although uncertainty-aware design techniques can be considered to minimise this effect,[5] as well as advanced models can be trained to predict the individual ring shift based on their output,[6] the most basic tuning setup still requires an independent control mechanism for each MRR. We assume thermal control based on micro-heaters, as it represents one of the most common and available solutions, although the result can be replicated with any tuning method that introduces a modulation of the effective index.

Simulations have been carried out in the Synopsys OptSim Suite, considering standard SOI waveguide characteristics and properties, and introducing index modulation under reasonable temperature shifts assumptions



(a) (b) (c)

Figure 2: Frequency response shift for (a) uniform index modulation (b) asymmetric index modulation (even-odd rings). (c) Output spectrum for the transparent toggled state.

($\Delta T_{max} = 100\,°C$, $\delta n/\delta T \approx 1.3 \times 10^{-4}\,K^{-1}$). As with traditional tuning, applying a constant and uniform thermal bias produces a uniform red shift of the device response, as depicted in Fig. 2a for shifts up to T_{max}: this assumes ideal calibration or uniformity between each of the rings. If we assume the same calibration conditions, but introduce an asymmetric index shift, the resonance and channel formation start to disappear, as depicted in Fig. 2b. These results have been obtained by applying the thermal shift to the odd-even MRR couple (Ring 1 and Ring 4), although the symmetrical even-odd case (Ring 2 and Ring 3) produces the same effects. This phenomenon can therefore be exploited to produce a transparent state in the device, turning off the add-drop channel formation and allowing switching of the whole cascade to a transparent lossy element. The condition for the formation of such a state is straightforward, as the biased MRR couple must be shifted by exactly half of the response period, aligning the pass-band of the nominal rings with the stop-band of the toggled ones. As depicted in Fig. 2c, the device experiences the toggled state for $T = 54\,°C$, with a flat frequency-independent response at the through port and average $-15\,dB$ crosstalk at the drop port. As expected, the drop response periodicity is double the original filtering response, showing the destructive interference between the response of the nominal rings and the shifted couple: the phenomenon can be leveraged in different devices due to the relative nature of the required index shift. Moreover, the spectrum and crosstalk level depend only on the original filter response, and the resulting loss in the transparent state is equal to two times the original off-band crosstalk.

4. CONCLUSIONS

We have showcased an application of asymmetric index control in a two-stage ladder MRR structure, which is capable of taking advantage of the destructive interference between the rings doublet to turn off the device resonance and allow a transparent state. The phenomenon can be extended to larger ladders and cascade devices, although topological adjustment is required in odd-sized chains. The transparent state can be triggered with index shifts compatible with standard tuning and calibration ranges, and does not require any additional heating pad or component with respect to the default control scheme needed for MRR-based devices.

REFERENCES

[1] Van, V., [*Optical microring resonators: theory, techniques, and applications*], CRC Press (2016).

[2] Peng, Z., Komatsubara, T., Yamauchi, M., and Arakawa, T., "Design of a series-coupled microring resonator wavelength filter using the digital filter design method," *J. Opt. Soc. Am. B* **38**, 2837–2846 (Oct 2021).

[3] Jayatilleka, H., Murray, K., Ángel Guillén-Torres, M., Caverley, M., Hu, R., Jaeger, N. A. F., Chrostowski, L., and Shekhar, S., "Wavelength tuning and stabilization of microring-based filters using silicon in-resonator photoconductive heaters," *Opt. Express* **23**, 25084–25097 (Sep 2015).

[4] Masilamani, A. P. and Van, V., "Design and realization of a two-stage microring ladder filter in silicon-on-insulator," *Opt. Express* **20**, 24708–24713 (Oct 2012).

[5] Shafiee, A., Mirza, A., Sunny, F., Banerjee, S., Chakrabarty, K., Pasricha, S., and Nikdast, M., "Inexact silicon photonics," in [*Photonics in Switching and Computing*], (2021).

[6] Tunesi, L., Khan, I., Masood, M. U., Marchisio, A., Ghillino, E., Curri, V., Carena, A., and Bardella, P., "Machine learning aided prediction of fabrication uncertainties in integrated multi-ring filters," in [*CLEO 2023*], *CLEO 2023* , STh4H.2, Optica Publishing Group (2023).