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A Compact Design of Micro-ring Resonator Chains for Optical Phase Manipulation

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Micro-ring Resonators (MRRs) have been widely studied for their advantages of high quality factor and the convenience to be integrated. The optical phase manipulation based on MRR chains is usable for many important applications. In this paper, we investigate the phase response of lattice and cascaded MRR chains with different configurations. Based on the analysis results, a novel compact design of a MRR chain has been proposed.

I Introduction

The applications of the micro-ring resonators (MRRs) which have emerged a few years ago in the field of integrated photonics are gaining high interests in terms of integration, design flexibility and footprint [1-4]. MRRs require no facets or gratings to realize optical feedback and are therefore particularly suited for monolithic integration with other components. The devices based on loss-less MRRs can also be used to manipulate the phase response and its high-order derivatives (e.g., group delay, dispersion). These applications of MRRs are based on the concept of the optical all-pass filter (OAPF). The manipulation of group delay is of key importance for slow and fast light and optically-phased antenna array [3-5]. However, for MRR-based OAPF, the delay (peak value) is inversely proportional to the bandwidth (defined when the value is falling to 90% of its maximum, same as below). The main shortcoming of the cascaded MRR chain is its relatively large footprint. The lattice MRR chain can be used to reduce the footprint or, in other words, to provide higher phase manipulation capacity with the same footprint as of the cascaded case. To further reduce the footprint, the compact lattice MRR chain with a small ring placed inside a big ring is proposed.

II. Theoretical Model and Analysis

1. The modelling and analysis of single MRR
The structure of a single MRR OAPF is depicted in Fig.1. A straight waveguide is coupled with the micro-ring. The coupling ratio of the formed directional coupler can be controlled by adjusting the gap and the coupling length between the straight waveguide and the ring. The phase shift can be realized by tuning the refractive index of the ring waveguide with thermal-optical or electro-optical methods. If the loss in the straight waveguide and the ring can be neglected, all input optical power will eventually arrive at the output port and thus the amplitude of the transfer function will be constantly loss-less regardless of the wavelength. This structure is the basic OAPF based on a single MRR and its group velocity response can be expressed as below,

$$GroupDelay(f) = \frac{T_r * \sqrt{1-t}}{2 - \sqrt{1-t} - 2t\cos(2\pi T_r f + \Delta\varphi)} \quad (1)$$

where the through and cross transmissions of the directional coupler are expressed by $t = \sqrt{1-\kappa}$ and $r = j\sqrt{\kappa}$ respectively, and κ is the power coupling ratio. The T_r is the propagation time of photons for a round trip in the micro-ring. Using Eq. (1), the group delay response of lossless MRR with 1 mm circumference and 1.46 refractive index is shown in Fig.2 with different values of t. The $\Delta\varphi$ caused by refractive index change is set to zero for all cases. The data is modulated on the envelope of the light wave and thus the value of group delay determines the delay of modulated signal while the bandwidth also determines the pass-band. It is obvious that a trade-off must be made between the bandwidth and the group delay values. The following discussion of cascaded and lattice MRR chains is based on double rings with the same radius.
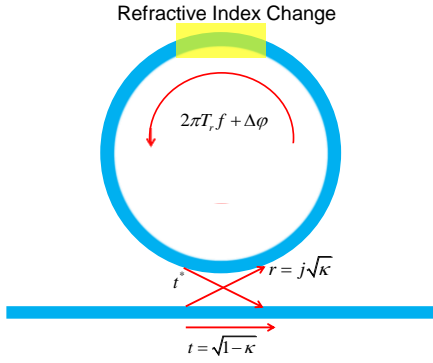

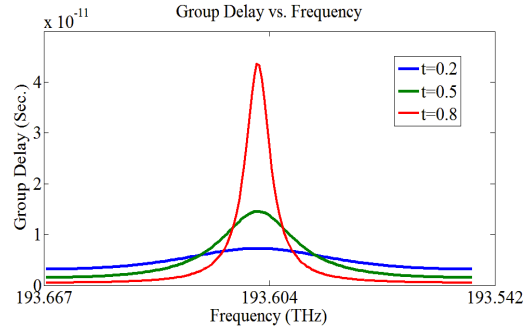Fig. 1. Principal scheme of the loss-less single MRRs

Fig. 2. The group delay response for single MRRs

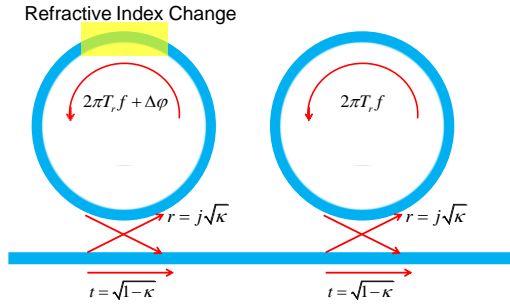## 2. The modelling and analysis of cascaded MRR chain

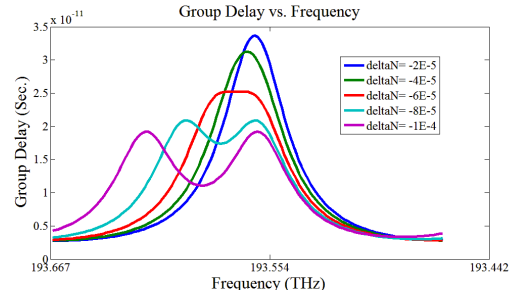Fig. 3. The principal scheme of cascaded double chain

Fig. 4. The group delay response of cascaded double chain

The cascaded double chain is depicted in Fig.3. Two MRRs are serially coupling with the same straight waveguide. According to Eq.1, the coupling ratio and the refractive index can be adjusted to allow different combinations. The coupling ratio will impact the bell shape and the delay while the refractive index change will allow the shift of response curve along the frequency axis. Thus it is obvious that the combination will get the maximum bandwidth with the same power coupling ratio. The group delay response of cascaded double MRR chain with the same value of t can be expressed as below.

$$GroupDelay(f) = \frac{T_r * \sqrt{1-t}}{2 - \sqrt{1-t} - 2t\cos(2\pi T_r f)} + \frac{T_r * \sqrt{1-t}}{2 - \sqrt{1-t} - 2t\cos(2\pi T_r f + \Delta\varphi)} \quad (2)$$

Using Eq. (2), the group delay response of cascaded double chain with 1mm circumference and 1.46 refractive index is shown in Fig.4 with different values of refractive index changes. $t = 0.555$ is chosen to allow the maximum 37.5GHz bandwidth with 20ps group delay which will be later compared with the lattice one.

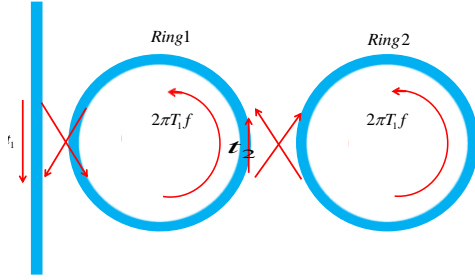3. The modelling and analysis of compact lattice MRR chain

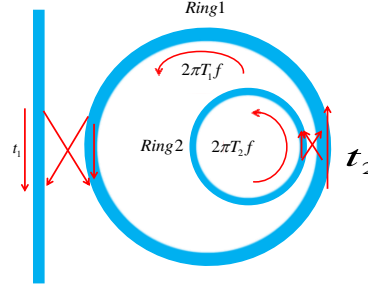Fig. 5. The principal scheme of lattice double chain   Fig. 6. The principal scheme of compact lattice double chain

The lattice double chain is illustrated in Fig.5. The two rings have the same radius. Here the transfer function for lattice double chain with arbitrary radius is given. Then we will employ it to analyze the (compact) lattice chains. The transfer function and group delay function can be presented as below

$$H(f) = \frac{t_1(1 - t_2 e^{j2\pi fT_2}) - e^{j\omega T_1}(t_2 - e^{j2\pi fT_2})}{1 - t_2 e^{j2\pi fT_2} - t_1 e^{j\omega T_1}(t_2 - e^{j2\pi fT_2})}, \quad GroupDelay(f) = -\frac{d}{df}\tan^{-1}\left(\frac{\text{Im}(H(f))}{\text{Re}(H(f))}\right) \quad (3)$$

where t_1 and t_2 denote the through amplitude transmission for waveguide-ring1 coupling and ring1-ring2 coupling, respectively. The T_1 and T_2 denote the round-trip time for ring1 and ring2. Using Eq.3, the group delay response of lattice double chains with 1 mm circumference and 1.46 refractive index are depicted in Fig.7 with different values of t_1 and t_2. We can clearly see that the group delay increases when the t_2 increases while the bandwidth decreases at the same time. The bandwidth is 86.5GHz for a 20 ps delay 37.5GHz band for a 85 ps delay. It is obvious that the lattice structure is better than cascaded one in terms of bandwidth or delay.
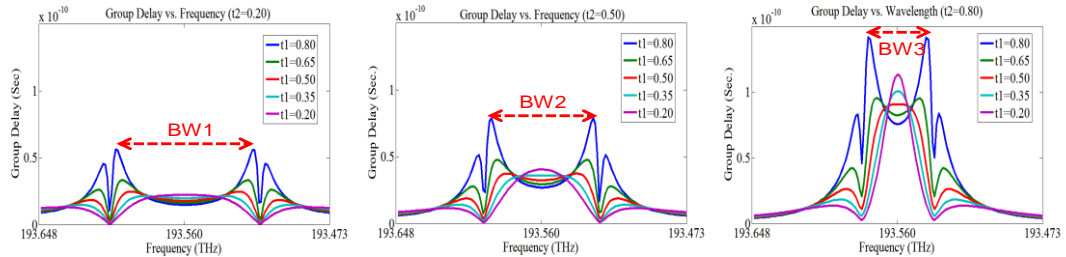

Fig. 7. The group delay response of lattice double chain

The structure of the compact lattice double chain including a small ring with 0.5 mm circumference and a big ring with 1mm circumference is shown in Fig.6. Its group delay response is (shown in Fig.8) compared with the response of lattice chain with two big rings with 1mm circumference. t_1 and t_2 are 0.6 and 0.8 respectively for both chains.

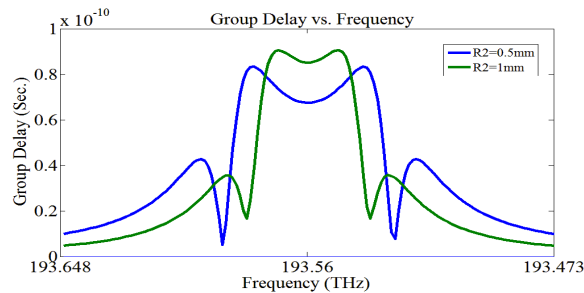The comparison indicates that the small ring broadens the bandwidth while reasonably reduces the group delay.

Fig. 8. The principal scheme of lattice double chain

IV. Conclusion

In this paper, the single MRR, cascaded MRR chains and lattice MRR chains have been studied for group delay manipulation. The results have shown that the lattice MRR chains could provide higher phase manipulation capacity than other types of schemes. Moreover a novel compact lattice MRR chain was proposed for further reduction of the footprint. The result suggested that such compact lattice MRR can be successfully applied for group delay manipulation.

Acknowledge

References

[1]   Chamorro-Posada P., Fraile-Pelaez F. J., and Diaz-Otero F. J., "Micro-Ring Chains With High-Order Resonances," *Lightwave Technology, Journal of,* vol. 29, pp. 1514-1521, 2011.

[2]   Baoqing Su, Chunxia Wang, Qiang Kan, and Hongda Chen, "Compact Silicon-on-Insulator Dual-Microring Resonator Optimized for Sensing," *Lightwave Technology, Journal of,* vol. 29, pp. 1535-1541, 2011.

[3]   Leimeng Zhuang, Roeloffzen C. G. H., Meijerink A., Burla M., Marpaung D., Leinse A., Hoekman M., Heideman R. G., and van Etten W., "Novel Ring Resonator-Based Integrated Photonic Beamformer for Broadband Phased Array Receive Antennas—Part II: Experimental Prototype," *Lightwave Technology, Journal of,* vol. 28, pp. 19-31, 2010.

[4]   Meijerink A., Roeloffzen C. G. H., Meijerink R., Leimeng Zhuang, Marpaung D. A. I., Bentum M. J., Burla M., Verpoorte J., Jorna P., Hulzinga A., and van Etten W., "Novel Ring Resonator-Based Integrated Photonic Beamformer for Broadband Phased Array Receive Antennas—Part I: Design and Performance Analysis," *Lightwave Technology, Journal of,* vol. 28, pp. 3-18, 2010.

[5]   Boyd Robert W., Gauthier Daniel J., and Gaeta Alexander L., "Applications of Slow Light in Telecommunications," *Opt. Photon. News,* vol. 17, pp. 18-23, 2006.