A compact design of micro-ring resonator chains for optical phase manipulation

Citation for published version (APA):

Document status and date:
Published: 01/01/2011

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
A Compact Design of Micro-ring Resonator Chains for Optical Phase Manipulation

Z. Cao, Y. Jiao, E. Tangdiongga, H.P.A. van den Boom and A.M.J. Koonen
COBRA Institute, Eindhoven University of Technology, NL 5600 MB Eindhoven, The Netherlands
z.cao@tue.nl

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,
where the through and cross transmissions of the directional coupler are expressed by \( t = \sqrt{1 - \kappa} \) and \( r = j \sqrt{\kappa} \) respectively, and \( \kappa \) 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.

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.
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

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

\[
H(f) = t_1(1 - t_2 e^{j2\pi f T_1}) - e^{j2\pi f T_1} (t_2 - e^{j2\pi f T_2}) , \quad \text{GroupDelay}(f) = -\frac{d}{df} \tan^{-1}\left(\frac{\text{Im}(H(f))}{\text{Re}(H(f))}\right)
\]  

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.

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.

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.

Acknowledgements

The authors would like to thank Dr. Raz from COBRA Research Institute of TU/e for his useful information about phase manipulation and Dr. Leijtens from COBRA Research Institute of TU/e for his assistance applying simulation tools. This work is partly supported by The Netherlands Organization for Scientific Research NWO under the project grant Smart Optical-Wireless In-Home Communication Infrastructure (SOWICI).

References