Ring-assisted modal conversion for on-chip mode-division multiplexing signal processing

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***Abstract*— We present a system composed of a two-mode waveguide coupled to a single-mode racetrack resonator. In this configuration, each resonance can be exploited to achieve a complete even-to-odd (odd-to-even) mode power conversion, thus allowing transparent channel switching in mode-multiplexed (MDM) networks. The spectral response of the system is evaluated by extending the single-mode scattering parameters formalism to the multi-mode propagation domain.**

Keywords*— *Optical networks on-chip; mode division multiplexing; microring resonators; photonic integrated circuits; silicon photonics; scattering parameters.

I. Introduction

As energy issues are increasingly affecting the scalability of high-performance multi-core microprocessor architectures, the implementation of optical links (Optical Network-on-Chip ONoC) between computational cores is foreseen as a possible way to increase data throughput while, at the same time, reduce the overall microprocessor power consumption [1].

The majority of the ONoCs solutions proposed so far in literature rely for their operation on wavelength-division multiplexing (WDM) techniques, hence exploiting the wavelength as a degree of freedom for channel allocation. Nevertheless, the effective use of WDM for on-chip signal networking is clearly subordinate to the availability of silicon-compatible laser sources, eventually multi-wavelength. Although some recent results confirmed the technological feasibility of silicon photonic transceivers including III-V bonded laser sources [2], the integration of active cavities on silicon remains a challenging task, with the existing technological solutions providing contrasting performance in terms of available optical power and electric-to-optical power conversion efficiency.

To reduce the number of laser sources required on the chip, or to optimize the use of the available ones, a possible solution relies on the exploitation of a further dimension inherent to optical communications, namely the modal order [3]. In mode-division multiplexing (MDM) systems, communication channels are allocated, on the same wavelength, to the various propagation modes of a multi-mode waveguide. Therefore, MDM techniques make available an additional degree of freedom (the transverse modal spatial distribution) for the design of on-chip integrated optical systems [4,5].

The deployment of a complete MDM-based on-chip interconnection network clearly requires the design of a full set of new functional building-blocks (routers, add-drops, mode converters) able to selectively process optical signals with respect to the modal order. In this work, we address in particular the issue of transparent mode-conversion, and we explore the operation of a configuration consisting of a two-mode waveguide laterally coupled to a single-mode resonator. The presence of the resonator breaks the translational invariance of the field propagation in the two-mode waveguide, thus enabling a cross-power exchange between the *even* and *odd* modes of the waveguide, which would be otherwise remain orthogonal.

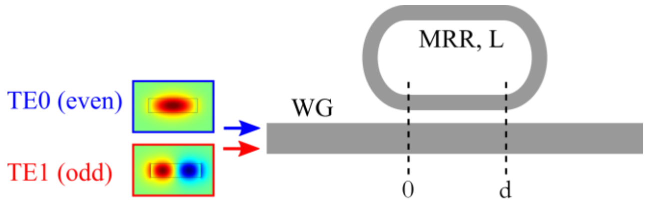

Figure 1: The system under investigation consists of a two-mode (TE_0,TE_1) waveguide (WG) coupled along a distance *d* to a single-mode racetrack resonator (MRR) of total perimeter *L*.

II. System Layout and Modal Transfer Function

The layout of the investigated configuration is presented in Fig. 1. A two-mode waveguide (WG) is coupled by means of directional coupler of length d to the single-mode racetrack resonator (MRR) of total perimeter L. The waveguide WG is designed to guide the fundamental *TE* mode with a transversal *even* symmetry (*TE0*) and a first order *TE* mode with a transversal *odd* symmetry (*TE1*), the two modes being characterized by their respective propagation constants β_{TE0} and β_{TE1} , with $\beta_{TE0} > \beta_{TE1}$. The (single) mode circulating in the microring MRR has propagation constant β and its losses are modeled by the parameter γ.

By taking advantage of a formal analogy holding between a two-mode waveguide and a system of two single-mode coupled waveguides [6], the coupling zone highlighted by the dashed rectangle in Fig 2(Top), is replaced by a ternary coupler between three single-mode waveguides, as sketched in Fig. 2(Bottom). This substitutions brings back the initial hybrid single/multi-mode propagation problem to an homogeneous single-mode one. Within this new layout, WG1 is the single-mode waveguide belonging to the microring, while WG2 and WG3 are the two single-mode waveguides

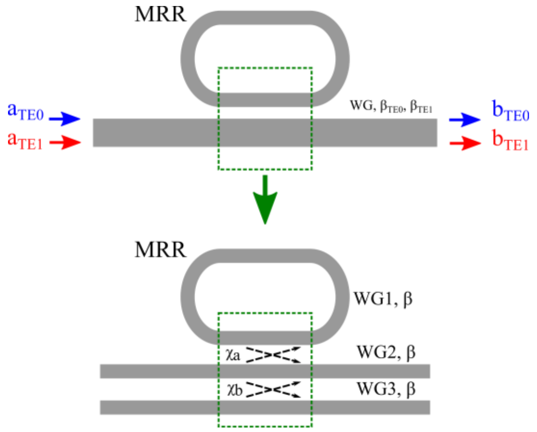

Figure 2: (Top) After substitution of the two-mode waveguide WG with an equivalent coupler between two single-mode ones (Bottom), the interaction zone highlighted by the green-dotted rectangle can be modeled as a ternary directional coupler between three single-mode waveguides (WG1,WG2 and WG3).

which result from the decomposition of the original two-mode section. The governing parameters of the transformed system are the propagation constant β, which is common to all the waveguides, and the two coupling constants (χ_a, χ_b) accounting for the power exchange between WG1 and WG2 and WG2 and WG3, respectively.

After a straightforward application of the (single-mode) scattering parameter approach, the transfer matrix relating the mode amplitudes on the input ($a_{TE0,}a_{TE1}$) and output ($b_{TE0,}b_{TE1}$) ports of the system finally reads as:

$$\begin{pmatrix} b_{TE0} \\ b_{TE1} \end{pmatrix} = [\,J\,] \cdot \begin{pmatrix} a_{TE0} \\ a_{TE1} \end{pmatrix} = \quad (1)$$

$$= \begin{bmatrix} J_{11}(\beta,\chi_a,\chi_b,\gamma) & J_{12}(\beta,\chi_a,\chi_b,\gamma) \\ J_{21}(\beta,\chi_a,\chi_b,\gamma) & J_{22}(\beta,\chi_a,\chi_b,\gamma) \end{bmatrix} \cdot \begin{pmatrix} a_{TE0} \\ a_{TE1} \end{pmatrix}.$$

For the explicit form of the elements of $[J]$ we refer the reader to Ref. [7].

All the elements of the matrix $[J]$ present an explicit dependence on the spectral parameter β, hence the degree of mode mixing introduced by the system heavily depends on the working wavelength. In the case of a transparent medium ($\gamma = 0$), and for an operating wavelength corresponding to one of the microring resonances ($\beta L = m\pi$ with m integer), the diagonal terms of $[J]$ vanish. The matrix assumes an anti-diagonal symmetry which enables a complete TE0 to TE1 (respectively, TE1 to TE0) mode switching. More explicitly, a TE0 mode on the input port is converted to a TE1 one as it transit through the system and vice versa. On the anti-resonance wavelengths ($\beta L = (2m+1)\pi$) the vanishing terms in $[J]$ are the diagonal ones and any incident modal state is transferred to the output port unaffected.

In Fig. 3 we report the evolutions of the b_{TE0} and b_{TE1} output mode amplitudes for the case of a purely TE0 excitation on the input port ($a_{TE0} = 1; a_{TE1} = 0$), calculated via the Eq. (1) as a function of the (normalized) spectral parameter βL. As expected, on the microring resonance the TE0 mode power on the input port is completely transferred to

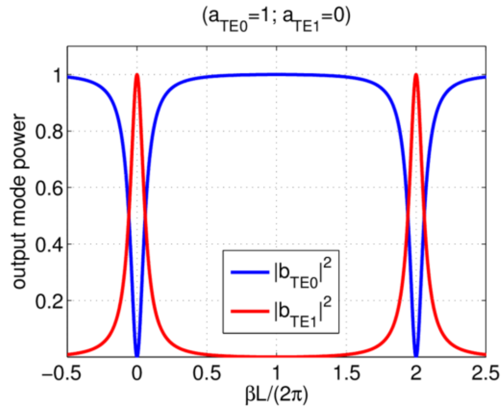

Figure 3: Evolution against the spectral parameter β of the TE0 (b_{TE0} - blue solid line) and TE1 (b_{TE1} red solid line) mode amplitudes on the output port of the system when on the input port is injected a purely TE0 mode (a_{TE0}=1, a_{TE1}=0). On each microring resonance the TE0 mode is completely converted to the TE1 one.

the TE1 mode on the output port ($b_{TE1} = 1$), while on the anti-resonances no conversion takes place. Moreover, between the resonance peaks anti-resonance conditions, an intermediate degree of mode mixing is achievable.

III. Conclusions

We presented a configuration consisting of a two-mode waveguide coupled to a single-mode microring resonator. The presence of the microring breaks the symmetry of the system thus enabling cross-mode conversion when operating on one of the resonances. Thanks to its mode-processing capabilities, this configuration is suitable to find application as a functional building-block in MDM photonic integrated circuits.

Acknowledgment

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http://www.3d-opt-many-cores.cominlabs.ueb.eu/

References

[1] Bergman, K., Carloni, L.P., Biberman, A., Chan, J., Hendry, G.: Photonic Network-on-Chip Design. Springer-Verlag New York (2014).

[2] Zhang, C., Zhang, S., Peters, J.D., Bowers, J.E.: 8x8x40 gbps fully integrated silicon photonic network on chip. Optica 3 (7), 785–786 (2016).

[3] Y. Ding, J. Xu, F. Da Ros, B. Huang, H. Ou, and C. Peucheret, "On-chip two-mode division multiplexing using tapered directional coupler based mode multiplexer and demultiplexer," Opt. Express vol. 21, no. 8, pp. 10376-10382, (2013).

[4] L.-W. Luo, N. Ophir, C. P. Chen, L. H. Gabrielli, C. B. Poitras, K. Bergman, and M. Lipson, "WDM-compatible mode-division multiplexing on a silicon chip," Nature Commun., vol. 5, 3069, (2014).

[5] J. Wang, Sailing He, and Daoxin Dai, "On-chip silicon 8-channel hybrid (de)multiplexer enabling simultaneous mode- and polarization-division-multiplexing," Laser & Photonics Reviews. 8(2): L18–L22 (2014).

[6] Boucher, Y.G.: Analytical model for the coupling constant of a directional coupler in terms of slab waveguides. Optical Engineering 53(7), 071,810 (2014).

[7] Boucher Y.G., Parini A., and Féron, P., "Resonant modal conversion in a two-mode waveguide", Opt. Quant. Electron. (2017) 49: 42.