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# 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

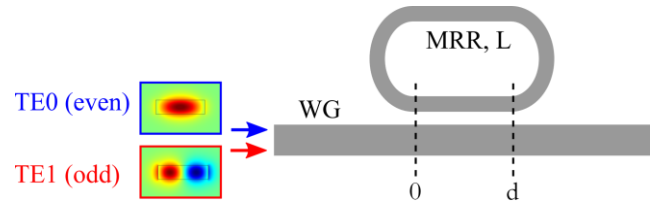


Figure 1: The system under investigation consists of a two-mode ( $TE_0, TE_1$ ) waveguide (WG) coupled along a distance  $d$  to a single-mode racetrack resonator (MRR) of total perimeter  $L$ .

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.

## 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 ( $TE_0$ ) and a first order  $TE$  mode with a transversal *odd* symmetry ( $TE_1$ ), the two modes being characterized by their respective propagation constants  $\beta_{TE_0}$  and  $\beta_{TE_1}$ , with  $\beta_{TE_0} > \beta_{TE_1}$ . The (single) mode circulating in the microring MRR has propagation constant  $\beta$  and its losses are modeled by the parameter  $\gamma$ .

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

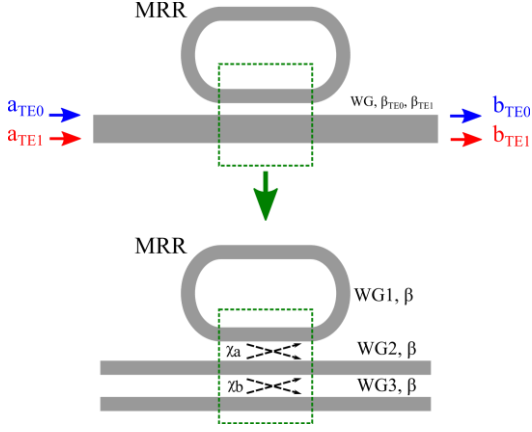


Figure 2: (Top) After substitution of the two-mode waveguide WG with an equivalent coupler between two single-mode ones (Bottom), the interaction zone highlighted by the green-dotted rectangle can be modeled as a ternary directional coupler between three single-mode waveguides (WG1, WG2 and WG3).

which result from the decomposition of the original two-mode section. The governing parameters of the transformed system are the propagation constant  $\beta$ , which is common to all the waveguides, and the two coupling constants ( $\chi_a$ ,  $\chi_b$ ) 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:

$$\begin{pmatrix} b_{TE0} \\ b_{TE1} \end{pmatrix} = [J] \cdot \begin{pmatrix} a_{TE0} \\ a_{TE1} \end{pmatrix} = \begin{bmatrix} J_{11}(\beta, \chi_a, \chi_b, \gamma) & J_{12}(\beta, \chi_a, \chi_b, \gamma) \\ J_{21}(\beta, \chi_a, \chi_b, \gamma) & J_{22}(\beta, \chi_a, \chi_b, \gamma) \end{bmatrix} \cdot \begin{pmatrix} a_{TE0} \\ a_{TE1} \end{pmatrix}. \quad (1)$$

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  $\beta$ , 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  $\beta L$ . As expected, on the microring resonance the TE0 mode power on the input port is completely transferred to

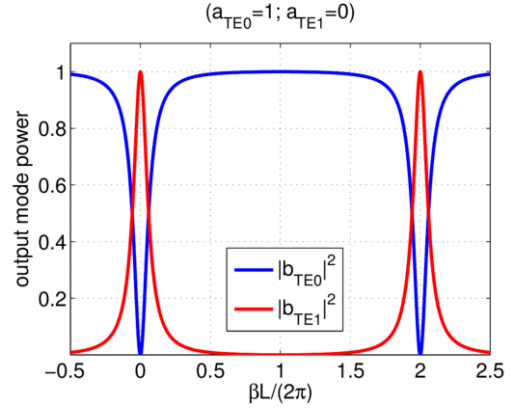


Figure 3: Evolution against the spectral parameter  $\beta$  of the TE0 ( $b_{TE0}$  - blue solid line) and TE1 ( $b_{TE1}$  - red solid line) mode amplitudes on the output port of the system when on the input port is injected a purely TE0 mode ( $a_{TE0}=1, a_{TE1}=0$ ). On each microring resonance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

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