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Grating-assisted vertical couplers for signal routing in multilayer integrated optical networks

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ABSTRACT

Grating-assisted vertical couplers, which behave as add-drop filters, are proposed for wavelength routing of the signal among the different layers of on-chip multilayer optical networks. The device implements a 2×2 wavelength router which can be assembled into higher-order three-dimensional matrices. In particular, simple design criteria are found through a rapid and efficient optimization approach based on the mode analysis and demonstrated by the Finite Difference Time Domain (FDTD) simulations. The proposed numerical method is valid either for in-plane or for vertical grating-assisted couplers and it requires negligible computational effort. Different configurations of grating-assisted vertical couplers are designed and their spectral behavior is analyzed by the FDTD. The proposed devices achieve low values of the crosstalk between the different ports (below −20 dB) and of the input reflection (below −15 dB).

1. Introduction

Photonic interconnection networks can provide a huge communication bandwidth and a favorable power budget with respect to their electrical counterpart [1,2]. A promising application of photonic integrated networks is the data communication among the different cores in Chip Multiprocessor (CMP) architectures [3]. As the integrated network complexity increases, the topological constraints become more stringent, since the increased number of necessary waveguide crossings limits the scalability of the photonic network. Different approaches have been proposed in the literature to improve the scalability of photonic networks either using optimized in-plane components, such as optimized crossings [4–6], or exploiting multilayer photonic networks [7–9]. Although more technologically challenging than in-plane ones, multilayer networks can open up new possibilities for the exploration of new network design solutions and new design paradigms. Vertically stacked layers can allow new and efficient placing and routing schemes for the different optical devices, increasing the integration density of the functional elements with an overall improvement of the performances of the optical network [7].

In an integrated photonic communication network different components, such as multiplexers/demultiplexers [10], filters [11], modulators [12–15], and switches [16–18], must be assembled. Most research has been devoted to in-plane components, whereas new design solutions for multilayer networks are still to be widely investigated. In particular, three-dimensional structures, such as waveguide crossings [8], ring resonators [19,20], three-dimensional vertical links based on waveguide couplers and multi-mode interference (MMI) transitions [9] have been designed and/or fabricated.

In the context of multilayer integrated networks, this paper proposes grating-assisted vertical couplers to implement add-drop filters capable of routing the signal, according to its wavelength, within the different layers of the network. The proposed device exploits three vertically stacked waveguides. In order to guarantee the add-drop filter behavior, the central waveguide is patterned with a one-dimensional photonic band gap structure (1-D PBG, i.e. a periodic Bragg grating). In-plane grating-assisted couplers have been successfully designed and fabricated to implement add-drop filters, multiplexers/demultiplexers, [10,21–25]. Grating-assisted vertical couplers assembled into 4×4 matrices have been proposed, for the first time, by the authors to implement the wavelength routing in multilayer on-chip photonic networks [26]. The analyzed device can be used in multilayer networks to implement add-drop filters or multiplexers/demultiplexers. Moreover, it can be regarded as a 2×2 wavelength router which can be assembled in higher-order three-dimensional matrices (e.g. as proposed in [26] and in [27–29] exploiting other routing technologies such as in-plane Mach-Zehnder switches, ring resonators, and photonic crystals). In photonic networks on chip, all the devices necessary for the signal generation, modulation, routing, detection, and thermal tuning contribute to the overall power budget. Thanks to the all-optical routing mechanism, the proposed device does not affect the overall power budget since it does not require additional power consumption

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thus allowing the realization of efficient multilayer networks. Moreover, since the scalability of the photonic network is limited by the number of necessary waveguide crossings, that introduce significant losses and scattering in large networks, the use of the proposed multilayer design approach is an interesting solution to improve the scalability of the network.

This paper, an extension of the previously published paper [26], focuses on the design methodology, proposing a very simple and low-time consuming approach for the design of grating-assisted couplers, based on both the mode analysis and the Finite Difference Time Domain (FDTD) techniques. The proposed design approach, valid either for in-plane or for vertical grating-assisted couplers, accounts for the effect of the electromagnetic field distribution which is responsible of undesirable crosstalk and input reflection. Input reflection is undesirable especially when connecting the basic device into higher order matrices to build up an on-chip network. The relevant figures of merit can be optimized by using suitable design maps obtained by applying the proposed simplified design procedure, thus avoiding intensive and time consuming FDTD simulations. By accounting the mode profile, the discrepancy between the results obtained by the FDTD and by the Coupled Mode Theory (CMT) [30] can be overcome.

2. Grating-assisted vertical coupler

The structure proposed is a grating-assisted vertical coupler which acts as an add-drop filter for multilayer optical networks. Fig. 1(a) shows a three-dimensional scheme of the grating-coupler section which is made of three stacked waveguides. The central waveguide is patterned to create a grating, made of core layers alternated with substrate ones.

According to the scheme reported in Fig. 1(a), the optical signal launched at port 1 is transmitted at the drop port (port 2) if its wavelength is coincident with the Bragg wavelength (e.g. $\lambda_B=\lambda_1$). Conversely, all the other wavelengths (e.g. λ_2, λ_3, ...) are transmitted at the through port (port 3) and the add port (port 4) remains isolated. Similarly, if the input signal is launched at port 2 it is transmitted at port 1 (drop) at the Bragg wavelength, otherwise it is transmitted at port 4 (through).

As it will be better detailed in the following, the operating principle of the device is based on the contra-directional coupling between the first two normal modes (supermodes) of the three-waveguide structure. The power exchange between these two modes is promoted by the presence of the grating which can be seen as a periodic perturbation of the original structure, i.e. the three stacked waveguides [30–32]. The

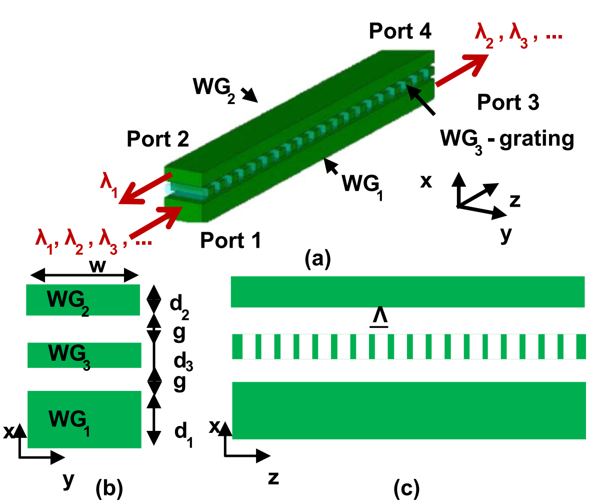

Fig. 1. Grating-assisted vertical coupler: (a) Three-dimensional scheme, (b) cross section, and (c) longitudinal section.

contra-directional coupling occurs at the wavelength which satisfies the synchronism condition (i.e. the Bragg wavelength):

$$\lambda = \Lambda(n_1 + n_2) \tag{1}$$

where Λ is the grating period, with 50% duty cycle, and n_1 and n_2 are the effective refractive indices of the first two normal modes.

Similar coupling mechanism is allowed between the forward and the backward propagating waves pertaining to each normal mode. This coupling, which does not actually contribute to the device operation, occurs when:

$$\lambda = 2\Lambda n_i \tag{2}$$

where the subscript i=1, 2 denotes the effective refractive index of the first or the second supermode.

The significant geometrical parameters of the structure are schematized in Fig. 1(b) and (c), where the cross and the longitudinal sections of the device are reported, respectively.

The waveguides are made of silicon-nitride (Si_3N_4), which allows the fabrication of multilayer circuits [7,20], and they are embedded into silicon-dioxide (SiO_2). Nonetheless, the design criteria that will be proposed in the following can be extended to other materials as well as to coplanar grating-assisted couplers. The refractive indices of the materials considered at the wavelength λ=1.55 µm are n_{Si3N4}=1.980 and n_{SiO2}=1.447, respectively [33].

3. Device performance

To better underline the design criteria, we consider a first example of grating-assisted coupler with the following geometrical sizes: w=0.90 µm, d_1=0.50 µm, d_2=0.3 µm, d_3=0.2 µm, and g=0.3 µm. The width value w=0.90 µm was designed to assure a good field confinement in the y direction, whereas the other geometrical values were, in this case, arbitrarily chosen. The effective refractive indices of the first two normal modes for the quasi-TE polarization are n_1=1.6847 and n_2=1.5984 and they were calculated by the Refractive Effective Index Method (REIM) [34,35]. The effective refractive index values calculated by the REIM were verified to agree very well with the ones calculated by the 3-D Finite Element Method (FEM). From Eq. (1) the grating period Λ=0.472 µm was chosen, with 50% duty cycle, to allow the contra-directional coupling at the wavelength λ=1.55 µm.

Fig. 2 shows the profiles of the y-component of the electric field E_y as a function of the spatial coordinate x, calculated by the REIM method at λ=1.55 µm. The scheme of the three-waveguide structure is also reported. Moreover, Fig. 3 shows the transmittances at the drop 2 (black curve), through 3 (red curve), and add 4 (green curve) ports, together with the transmittance at the input port 1 (blue curve), due to the back reflection. The results in Fig. 3(a) and (b) were calculated,

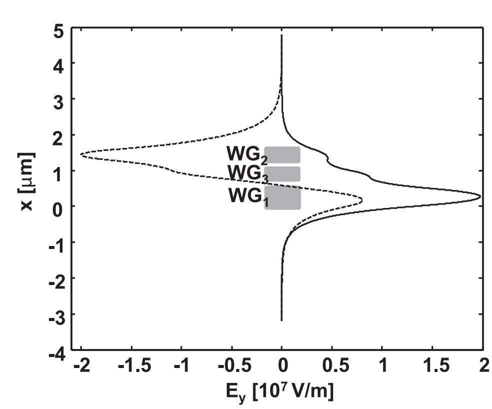

Fig. 2. Profiles of the y-component of the electric field E_y as a function of the only spatial coordinate x, calculated by the REIM method at λ=1.55 µm, with w=0.90 µm, d_1=0.50 µm, d_2=0.3 µm, d_3=0.2 µm, and g=0.3 µm. The cross section of the three-waveguide 3-D structure is also sketched.