Optics Communications 366 (2016) 99–106

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Generic Wavelength-routed Optical Router (GWOR) based on grating-assisted vertical couplers for multilayer optical networks

Giovanna Calò*, Vincenzo Petruzzelli

Dipartimento di Ingegneria Elettrica e dell'Informazione-Politecnico di Bari, Via Re David n. 200, 70125 Bari, Italy

ARTICLE INFO

Article history:
Received 1 October 2015
Received in revised form
21 November 2015
Accepted 14 December 2015
Available online 28 December 2015

Keywords:
Integrated optics
Optical switches
Optical devices
Bragg gratings
Optical networks on chip

ABSTRACT

A Generic Wavelength-routed Optical Router (GWOR) based on grating-assisted vertical couplers is proposed to be used as 4×4 routing matrix in multilayer optical networks. The device exploits, as basic building blocks, four vertical grating-assisted couplers made of three vertically stacked waveguides. The central waveguide is patterned with a periodic Bragg grating that guarantees the wavelength routing of the signal at the Bragg wavelength. The design and the analysis of the grating-assisted vertical couplers, performed by two different numerical methods, the Bidirectional Beam Propagation Method based on the Method of Lines (MoL-BBPM) and the Finite Difference Time Domain (FDTD) method, are reported. Moreover, the GWOR matrix is analyzed, with a very limited computational effort, by suitably composing the numerically calculated transmittances of the 2×2 elementary building blocks. The proposed GWOR matrix achieves low values of the insertion loss (i.e. maximum insertion loss IL=0.2 dB) and crosstalk below −15 dB.

1. Introduction

The design of photonic interconnection networks relies on the composition and the connection of elementary components, i.e. basic building blocks, which are linked to build up the overall network. A promising application of photonic integrated networks is the on-chip optical communication among the different cores of a Chip Multiprocessor (CMP). These networks are able to improve the performances of the overall system in terms of communication bandwidth and power budget with respect to their electrical counterpart [1–3]. Among the components necessary for integrated photonic communication, such as multiplexers/demultiplexers [4], filters [5–6], modulators [7–10], and switches [11–15], the switches play a fundamental role for their capability of routing the signals along the network thus connecting the different transmitters and receivers.

Different design approaches, either exploiting active or passive components [16–21], can be chosen to build up a complex integrated communication network. In particular, active components, such as reconfigurable switches, can be used to implement reconfigurable networks, where the signal path is dynamically set by varying the switch states. This approach is advantageous in terms of reconfigurability of the network, but it has a counterpart in the increased power budget due to the switching mechanism (e.g. thermo- or plasma- optic effect [22–23]).

A power-efficient and performance-competitive alternative to actively routed networks is given by wavelength routed networks [24–26] in which the signal path is set, at the time of the network design, by the wavelength of the input optical signal. In this all-optical approach the routing mechanism does not affect the overall power budget and the delay of the signal is only due to the propagation time, since no path setup time is required. As a counterpart this approach gives less freedom in the reconfiguration of the network.

As the integrated network complexity increases, irrespective of the active or passive design approach, the topological constraints become more stringent. In this context, the scalability of the photonic network is limited by the increased number of necessary waveguide crossings. In fact, waveguide crossings introduce losses and scattering that become significant in large networks. To overcome these limitations, either in-plane solutions, such as optimized crossings [27–29], or multilayer photonic networks [30–32] have been proposed. Specifically, multilayer networks appear particularly promising since they can allow new design schemes and improve the performance of the overall network [30]. A multilayer photonic network comprises several photonic layers stacked above an electronic die by different fabrication steps of deposition and lithography. The electronic components, such as the different processors, communicate through the waveguides and devices composing the multilayer photonic network. In this context, the three-dimensional router becomes a key component to guarantee that the optical signal is suitably routed over the

* Corresponding author.
E-mail address: giovanna.calo@poliba.it (G. Calò).

http://dx.doi.org/10.1016/j.optcom.2015.12.027
0030-4018/

different layers of the photonic network thus assuring the communication between the different processors.

In this paper we conjugate the wavelength-routing with the multilayer design approach by proposing a Generic Wavelength-routed Optical Router (GWOR) based on grating-assisted vertical couplers, to be used as 4×4 routing matrix in multilayer optical networks. To the best of our knowledge this is the first time that grating-assisted vertical couplers are proposed to implement the wavelength routing in multilayer photonic networks. Conventional in-plane grating-assisted couplers have been successfully proposed in the literature to implement add-drop filters or multiplexers/demultiplexers, [4,33–35]. The proposed 4×4 wavelength routing matrix exploits four basic 2×2 building blocks, i.e. the grating-assisted vertical couplers, made of three vertically stacked waveguides. The central waveguide is patterned with a one-dimensional photonic band gap structure (1-D PBG, i.e. a periodic Bragg grating) that guarantees the wavelength routing of the signal at the Bragg wavelength.

The elementary 2×2 building blocks are designed and analyzed by two different numerical methods: the Bidirectional Beam Propagation Method based on the Method of Lines (MoL-BBPM) [36–38] and the Finite Difference Time Domain (FDTD) method [39]. Moreover, since the 3D simulation of the entire 4×4 matrix requires a huge amount of computational resources, a compositional approach is proposed to analyze the overall 4×4 GWOR, with a very limited computational effort, starting from the FDTD calculated spectra of the 2×2 elementary building blocks.

2. 2x2 Grating-assisted wavelength router

The basic building block, to be assembled into higher order routing matrices, is a vertical grating-assisted coupler which can act as an add-drop filter for multilayer optical networks. The device is schematized in Fig. 1, which shows a three-dimensional scheme of the grating-coupler section. The device exploits three stacked waveguides, the central one of which is patterned to create a grating made of core layers alternated with substrate ones. The proposed device can be regarded as a 2×2 wavelength router (λ-router). In fact, according to the scheme reported in Fig. 1, the optical signal launched at port 1 is transmitted at port 2 (drop port) at the Bragg wavelength of the grating (e.g. $\lambda_1 = \lambda_B$), whereas all the other wavelengths (e.g. λ_2, λ_3, …) are transmitted at port 3 (through port), leaving port 4 (add port) isolated. The 2×2 router behavior is reciprocal in the sense that the signals launched at port 2 come out from port 1 (drop port) at the Bragg wavelength, otherwise they emerge from port 4 (through port).

The proposed device is made of silicon-nitride waveguides (Si_3N_4), it allowing the fabrication of multilayer circuits [30,40], embedded into silicon-dioxide (SiO_2). The refractive indices of the materials considered at the wavelength $\lambda = 1.55$ μm are $n_{Si3N4} = 1.980$ and $n_{SiO2} = 1.447$, respectively [41]. The different colors in Fig. 1 denote the three different layers of the multilayer optical network. Moreover, the relevant geometrical parameters of the structure are also evidenced in Fig. 1.

The device operation is based on the contra-directional coupling mechanism between the first two normal modes of the overall structure. The power is exchanged between these two modes thanks to the grating which assures the following synchronism condition, according to the coupled mode theory [42–44]:

$$\beta_1 + \beta_2 = \frac{2\pi}{\Lambda} \quad (1)$$

where Λ is the grating period and β_1 and β_2 are the propagation constants of the first two normal modes.

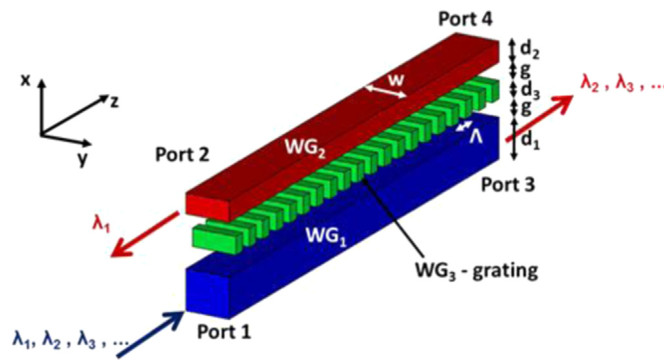

Fig. 1. Three-dimensional scheme of the grating-assisted vertical coupler.

3. Numerical models of the 2×2 wavelength router

The 2×2 wavelength router, i.e. the grating-assisted vertical coupler, has been analyzed with two different numerical models: the Bidirectional Beam Propagation Method based on the Method of Lines (MoL-BBPM) [36–38] and the Finite Difference Time Domain (FDTD) method [39]. Although based on different theoretical approaches, the two methods provide complementary results by assuring in the meantime reciprocal validation.

The MoL-BBPM is a semi-analytical method, implemented by a proprietary code, which calculates both the forward and the backward propagations along the longitudinal z direction of the waveguide structure. At the discontinuities between two alternating layers along the grating structure, it is possible to calculate the waves transmitted and reflected at each interface from the knowledge of the incident wave. The evaluation of the transmitted and the reflected waves is obtained, both in the backward and in the forward propagation directions, by imposing the continuity of the electromagnetic field components at the interfaces between the different dielectric layers. The overall electromagnetic field in the structure is given by the superposition of all the reflected and the transmitted waves calculated at each propagation step.

The MoL-BBPM is a frequency domain algorithm, whereas the FDTD is a time domain method which gives a fullwave analysis of electromagnetic propagation by discretizing the Maxwell equations both in time and space.

Both the numerical methods allow to take into account phenomena such as radiation losses, influence of the optical mode confinement, eventual presence of higher order modes or occurrence of strong coupling condition, which can influence the device performances.

Although equivalent transmittance spectra can be obtained, the two numerical methods can offer different advantages and information. In particular, being the FDTD a time-domain method, it can be more advantageous to simulate large bandwidths with a single simulation. Conversely, the MoL-BBPM is a frequency-domain method, therefore each frequency data set is calculated by a different simulation, but thanks to the used algorithm, it allows to separate the contribution of the forward and the backward electromagnetic waves, thus offering interesting insight for the device analysis.

The proposed device was optimized to achieve low values of crosstalk between the ports, low insertion loss, and to guarantee the signal routing around the wavelength $\lambda = 1.55$ μm. The geometrical sizes of the device, denoted as configuration A, are: waveguide width $w = 0.90$ μm, heights of the three waveguides $d_1 = 0.80$ μm, $d_2 = 0.40$ μm, $d_3 = 0.35$ μm, gap between the waveguides $g = 0.35$ μm, grating period $\Lambda = 0.454$ μm.

In order to simplify the complexity of the numerical models and to reduce the computational effort required, the three-