Accurate Design of Optical Microring Resonators

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***Abstract*— In this article we present and test a model for large microring resonators based on implementation of the bi-directional Eigenmode Expansion Method for rigorous modelling of vectorial field propagation in the coupling region and using accurate solutions for the bend mode propagating in the ring.**

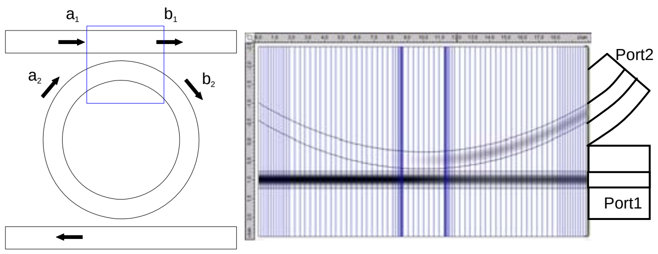
Keywords – microring resonator; Eigenmode Expansion Method; EME; bend modes;

INTRODUCTION

The Finite-Difference Time-Domain (FDTD) method is the most commonly used methodology for modelling of smaller MicroRing Resonators (MRR). It can account for many material properties, such as refractive index anisotropy, various types of dispersion characteristics and nonlinearity. Although FDTD is efficient in modelling MRRs of small dimensions, long computation times and large memory requirements arise when dealing with microring resonators of larger radii.

I. DESCRIPTION OF THE METHODOLOGY

The microring resonator is divided into two computational domains (see Fig. 1a): the coupling region, which is simulated using EigenMode Expansion (EME) [1,2], and the propagation in the ring, which is modelled by calculating the bend mode. Both calculations are performed with the software package FIMMWAVE/FIMMPROP [3].



(a) (b)

Figure 1. (a) Schematic view of the microring resonator (blue square limits the coupling region); a1, a2, b1 and b2 represent optical fields propagating in the corresponding microring resonator regions. (b) Intensity profile for the coupler; the vertical lines show the discretisation along the z-axis.

A. Modelling of Coupling Region a via EME method

The EME method is used to model the field propagation in the coupling region between the bus waveguide and the ring. EME provides a fully-vectorial and bi-directional modelling of the coupling region relying on rigorous resolution of Maxwell's Equations [1]. It can therefore model high refractive index contrasts and wide angles and can be applied to the simulation of Silicon-On-Insulator (SOI) devices. The EME technique discretises the coupler into z-direction invariant waveguide sections (see Fig. 1b). The optical field in each section is expressed in terms of a superposition of the forward- and backward-propagating guided modes and discretised radiation modes. The solutions are obtained in the form of scattering matrices, giving the transmission and reflection coefficients between the modes of the ring waveguide and the modes of the bus waveguide. Coupling to the bend modes of the ring waveguide is calculated via the construction of *port waveguides* with a new tilted and curved frame of reference (Fig. 1b – Port2) in which the bend modes are calculated with an advanced Finite-Difference bend mode (FDM) solver [3] (used also for the rest of the ring). Overlap integrals between fields in the domain of the coupler and the bend modes of the port waveguides are then computed, taking the rotation of the reference frames into account.

B. The Microring Resonator Model

For single mode waveguides, the relationship between the amplitudes (see Fig. 1a) in the coupling region can be written as a linear system:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} t & i\kappa \\ i\kappa^* & t^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \qquad (1)$$

where t and κ are the transmission and coupling coefficients. The feedback after one loop of the ring can be expressed as: $a_2 = b_2 e^{i\phi}\alpha$ with $\phi = 4\pi^2 R \cdot neff(\lambda_0)/\lambda_0$, where $neff$ and α are computed by the bend mode solver, R is the radius of the ring, and λ_0 the free-space wavelength. Solving the linear system allows us to calculate the transmission for the microring:

$$T = \frac{|t|^2 + |\alpha|^2 - 2\alpha t\cos\phi}{1 + |\alpha t|^2 - 2\alpha t\cos\phi}. \qquad (2)$$

II. NUMERICAL MODELLING RESULTS

C. Modelling of SOI Microring Resonators

The methodology was applied to simulate an SOI MRR based on the design presented in [4]. The ring waveguide has a radius of 40μm and is coupled to two diametrically opposed straight bus waveguides. The silicon waveguide has a cross-section width of 450nm and height 250nm and is placed on top of a thick silica layer. The width of the gap between the ring and the bus waveguides was varied between 30 and 140nm. The modes in the coupler and the bend modes in the port waveguide were calculated using the fully vectorial FDM mode solver [3].

Convergence of the results was observed for a mode solver grid size of 22nm. Mode calculations showed that the bus and bend waveguides were single mode. The bend modes were calculated with both PMLs and transparent boundary conditions and were found to be virtually lossless. The evolution of the transmission spectrum at resonance and the coupling coefficients for different gap widths are shown in Figure 2 below. The coupler was simulated in 3D in 25 minutes by FIMMPROP running on an Intel® Core™2 CPU at 2.4GHz.

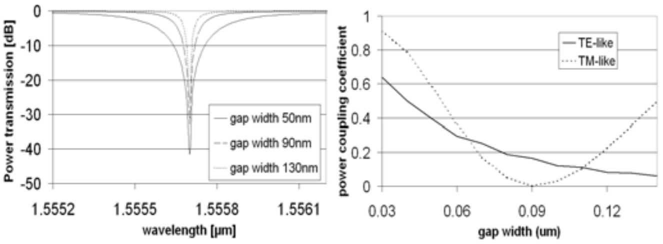


Figure 2. (left) Transmission spectrum around resonance for the TE-like polarisation, plotted in dB for a gap width of 50nm, 90nm and 130nm. (right) Evolution of the coupling coefficient between the bus and the ring plotted against gap width.

D. *Modelling of Fluorine-Implanted Lithium-Niobate MRR*

In this example we consider the microring resonator of 80 μm radius similar to that shown in Fig.1a. The MRR was fabricated from fluorine-implanted $LiNbO_3$ and presented in [5]. The bent and bus guides are slanted-wall rib waveguides, with refractive indices in the guiding region of 2.2 in horizontal and 2.14 in vertical direction, correspondingly (z-cut $LiNbO_3$ crystal). The refractive indices in the material on top of the rib is 1.5, and in the amorphised substrate 2.03, the width of the guiding region is 3.2 μm, and height 1.2 μm.

In the coupler and in the bent waveguide regions we solve anisotropic Maxwell Equation in order to take into account the crystal anisotropy. The bend mode effective indices and corresponding losses are calculated by fully-vectorial finite-difference method and shown at the Figure 3. For a wide range of bend mode curvature the effective index of the zero-order TE mode is significantly larger than that of the zero-order TM and first-order TE modes, resulting in the weaker confinement of the latter modes and, consequently, bigger bent losses.

Weaker confinement of the zero-order TM mode is caused by the crystal anisotropy ($n_{yy}<n_{xx}$). For the anisotropic bent waveguide of 80 μm radius the loss for the fundamental TE mode is 0.000228 1/cm, what is about 1000 times less than that for the zero-order TM mode, while for the isotropic case the modal loss for the zero-order TM mode is even smaller and of the same order as for the zero-order TE mode. mode.

Moreover, the anisotropy affects the polarisation mixing in the coupling region changing the coupling coefficient from TE bus mode to TM bend mode from 0.41% to a negligible 0.0149%, as the TM mode is further suppressed by 1000 times higher losses in the ring. The combination of these two effects explains the fact that TM mode is not observed in the experiment reported in [5].

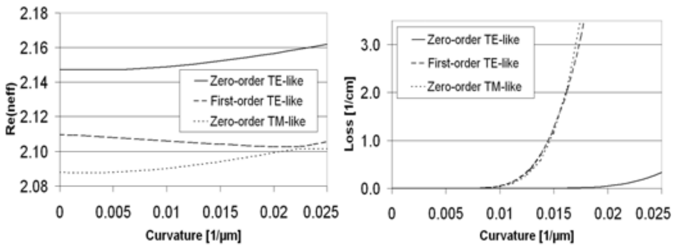


Figure 3. (left) The refractive indices and (right) the modal losses for zero-order TE (solid line), first-order TE mode (dashed line) and zero-order TM mode (dotted line) as a function of bend curvature (1/R).

The solid line at the Fig.4 presents the results for normalised transmission of the MRR reported in [5]. The gap between the bus and bend waveguides is equal to 0.2μm. The depth of the resonance matches that reported in the experiment.

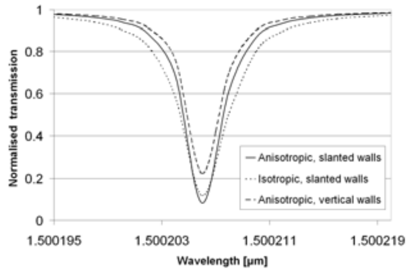


Figure 4. Numerical results for normalised transmission of the original fluorine-implanted LiNbO3 microring resonator (solid line), of the same resonator with vertical wall waveguides (dashed line) and of the same waveguide with isotropic refractive index (dotted line).

The dashed and dotted lines present the results of calculations for isotropic material approximation and for the case of vertical wall approximation. As one can see the depth and width of the calculated resonances are affected by the approximations.

III. MODEL POTENTIAL

The EME-based MRR model described in I.B can be readily improved to include bend mode phase deviation in the coupler, higher-order modes and to take account of reflections off waveguide wall fabrication imperfections. For multimode, eqn. (2) can be readily replaced with a matrix solution. In comparison, though FDTD can model reflections and phase effects it is limited in ring size, while use of BPM plus a matrix solution of the ring cannot deal with reflections or high index contrast accurately.

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