Optics Communications 339 (2015) 123–128

Contents lists available at ScienceDirect

Optics Communications

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

Efficient design of polymer micro-ring resonator filters based on coupled mode theory and finite difference mode solver

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ARTICLE INFO

Article history:
Received 3 July 2014
Received in revised form
3 November 2014
Accepted 6 November 2014
Available online 13 November 2014

Keywords:
Microring resonators
Polymer photonics
Optical losses
Finite differences
Mode solvers
Coupled mode theory

ABSTRACT

Polymer photonics have been identified as a strong candidate technology for producing low-cost optical devices. In this paper, we provide a time efficient framework for designing polymer micro-ring devices based on Coupled Mode Theory (CMT) and a Finite Difference Mode Solver. We benchmark two alternative methods for modeling the coupling regions of the micro-ring filter in 3D. We deduce that compared to full blown finite difference time domain simulations, CMT can provide accurate results in just a small fraction of time. The proposed model allows the study of bending losses on the spectral properties of the device, that can be otherwise modelled using time demanding FDTD or less accurate simplified analytical expressions.

1. Introduction

Ring resonators [1] are receiving increased attention because of the multitude of potential applications including the realization of add-drop filters, optical modulation and switching, optical signal processing, dispersion compensation, single mode lasers and biosensors. In wavelength division multiplexed (WDM) applications, they can be utilized as compact wavelength filters or constitute the building blocks of more elaborate box-like response filter designs [2]. Integrated micro-ring resonators have been demonstrated in a variety of platforms, including silicon, III–V and polymer materials [3]. Polymer technology has been identified as a strong candidate technology for producing low-cost devices. Indeed the available synthesis and flexible processing together with the ease in tailoring the optical properties of photonic polymers make them ideal for application in personal, local area and medium-haul optical networks [4]. In order to fully evaluate the potential of polymer micro-ring resonators in photonic applications it is important to develop the appropriate theoretical tools. The most common route found in the literature is the use of FDTD algorithms [5,6]. FDTD being a first principles method can model accurately nearly all aspects of polymer micro-rings at the expense though of computational time and resources. This deterrent characteristic of FDTD has motivated alternative approaches that include Beam Propagation Method (BPM) [7], CMT [8] and simple phenomenological analytical expressions [8]. BPM can only model relatively large curvatures hence its use is restrictive and thus is not very popular in the micro-ring resonators community. Analytical expressions are strongly dependent upon experimental results while their applicability is not universal. CMT on the other hand is a fast method that yields good accuracy results. CMT is usually applied assuming closed form solutions for the ring and the straight waveguide modes in a two dimensional formulation [9]. In the present contribution we elaborate CMT method to model 3-D micro-ring thus improving accuracy and flexibility. Unlike previous works, our approach also involves the use of a FDMS for the calculation of the effective refractive to be subsequently used in the CMT formalism, while the CMT/FDMS model is compared against 3D-FDTD calculations.

In particular we discuss how the FDMS for bent waveguides can be applied to rigorously incorporate the effect of radiation losses of the polymer ring waveguide. We pay particular attention to curvature-induced losses because of the relatively small index contrast of polymer waveguides. As a consequence, bending losses pose important limitations in the performance of the device specifically in the minimum allowable ring radius and thus at the achieved free spectral range (FSR). This is in contrast to other material systems like e.g. III–V semiconductors where the waveguide index contrast is relatively high and also it is possible to fabricate active micro-rings that compensate for losses. While other sources of loss such as scattering loss due to fabrication

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http://dx.doi.org/10.1016/j.optcom.2014.11.033
0030-4018/

imperfections can be reduced by perfecting the fabrication techniques, bending losses are an inherent feature of polymer micro-ring structures and therefore set the ultimate limits in terms of device performance. In other words, in polymer ring devices, bending losses are one of the most important design parameters.

The theoretical model can be used to estimate performance related "macroscopic" parameters such as the free spectral range (FSR) and the 3 dB bandwidth Δf_{3dB} and translate these into a set of "microscopic" features related to the structural parameters of the device, such as the ring radius R or the minimum gap g between the straight waveguide and the ring and coupling coefficient. The rest of the paper is organized as follows: in Section 2 we present the FDMS algorithm and use this to calculate the bending losses. In Section 3 we develop the 3D CMT model and benchmark it against 3D-FDTD simulations. We then use the findings of Sections 2 and 3 to produce in Section 4 design curves of various performance parameters of polymer micro-rings and discuss the influence of structural characteristics.

2. Estimation of the bending losses

Fig. 1(a) shows a micro-ring add/drop filter consisting of the ring resonator side-coupled to two straight waveguides. The part of the spectrum of the input signal near the resonant frequencies of the ring is coupled through the resonator to the drop port. The field exchange occurs in the coupling regions highlighted in the figure. The coupling strength depends on the proximity of the ring and the straight waveguide and determines the bandwidth of the power transfer function of the device. Fig. 1(b) shows an example cross-section for both the ring and the straight waveguides. In the subsequent discussion, we will demonstrate the pivotal role of the real and imaginary parts of the effective refractive index of the mode of the ring waveguide $n_e = n_r + jn_i$. The imaginary part n_i incorporates the effect of optical losses due to curvature-induced radiation losses or scattering loss due to fabrication imperfections. To estimate n_e we can use an FDMS [10] to estimate the dependence of n_r and n_i on the radius R of the ring. FDMS is based on the discretization of the structure according to Yee's cell [11] and the use of finite differences in order to transform Maxwell's equations in cylindrical coordinates to an algebraic eigenproblem of the form:

$$\begin{bmatrix} \mathbf{Q}_{\rho\rho} & \mathbf{Q}_{\rho y} \\ \mathbf{Q}_{y\rho} & \mathbf{Q}_{yy} \end{bmatrix} \begin{bmatrix} \mathbf{h}_\rho \\ \mathbf{h}_y \end{bmatrix} = \beta^2 R^2 \begin{bmatrix} \mathbf{h}_\rho \\ \mathbf{h}_y \end{bmatrix} \tag{1}$$

where $\beta = (2\pi n_e/c)f$ is the propagation constant, the vectors $\mathbf{h}_\rho$ and $\mathbf{h}_y$ contain the values of the tangential magnetic field components estimated on the Yee cell and $\mathbf{Q}_{\rho\rho}$, $\mathbf{Q}_{\rho y}$, $\mathbf{Q}_{y\rho}$ and $\mathbf{Q}_{yy}$ are square matrices, the elements of which depend on the value of the dielectric constant on the various points of the cell and the boundary conditions. In our calculations we have used a uniaxial perfectly matched layer (UPML) formulation [12] to eliminate artificial reflections from the edge of the computational cell. It consists on applying the dielectric tensor $\varepsilon_0 \varepsilon \bar{\bar{s}}$ in Maxwell's equations where ε is the relative permittivity of the structure.

$$\bar{\bar{s}} = \begin{bmatrix} s_y s_\rho^{-1} \tilde{\rho} & 0 & 0 \\ 0 & s_\rho s_y^{-1} \tilde{\rho} & 0 \\ 0 & 0 & s_y s_\rho \tilde{\rho}^{-1} \end{bmatrix} \tag{2}$$

The corresponding magnetic tensor is also applied in Maxwell's equations. The PML parameters s_ρ and s_y are related to the absorption coefficients σ_ρ and σ_y in the usual manner [12], while $\tilde{\rho}$ is obtained via the transformation:

$$\tilde{\rho} = \int_0^\rho s_\rho(\rho') d\rho' \tag{3}$$

We have implemented the UPML-FDMS in GNU-OCTAVE and benchmarked it against the results of [9] obtaining excellent agreement. Fig. 2 shows the values of the real and imaginary part of n_e for the ρ-polarization for the waveguide shown in Fig. 1 (b) assuming a square waveguide core with $w = h = 2$ μm while the cladding height $h_c = 5$ μm. For simulation purposes we also assume that the cladding width is finite and equal to $w_c = 14$ μm. The refractive index is $n_1 = 1.565$ for the core (corresponding to SU8 at $\lambda = 1.55$ μm [13]), while the cladding index is $n_2 = 1.44$ and the surrounding material is air ($n_0 = 1$). The grid size used in the FDMS calculation is $\Delta = 0.05$ μm and dielectric averaging as described in Ref. [14] is used in order to enhance the convergence of the method.

3. Model of the polymer microring resonator

The next step is to model the coupling regions of the micro-ring structure shown in Fig. 3(a) and estimate the coupling coefficient κ which determines the spectral properties of the micro-ring filter and can be calculated using a variety of methods, including coupled mode theory (CMT) and finite difference time domain (FDTD) methods. In CMT framework, the field can be written as a superposition $\boldsymbol{E} = a_s(z)\mathbf{E}_s + a_b(z)\mathbf{E}_b$ and $\boldsymbol{H} = a_s(z)\mathbf{H}_s + a_b(z)\mathbf{H}_b$ of the isolated guided modes of the straight and the bend waveguide denoted by ($\mathbf{E}_s$,$\mathbf{H}_s$) and ($\mathbf{E}_b$,$\mathbf{H}_b$), respectively. Using reciprocity relations one can determine the coupling coefficients and derive the

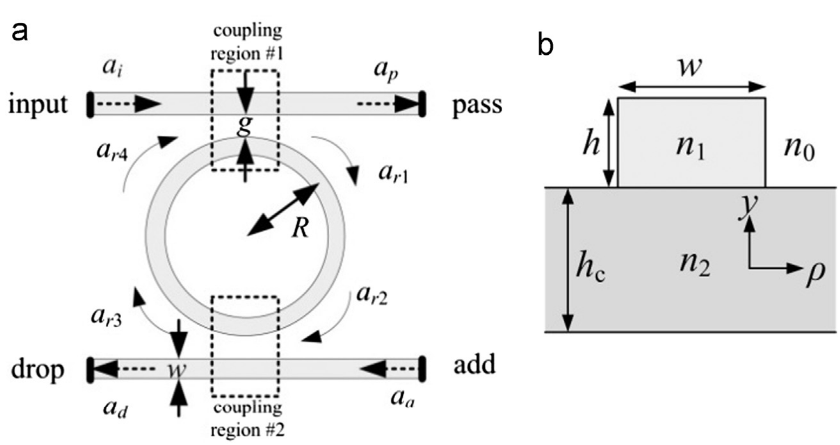

Fig. 1. (a) A micro-ring resonator add/drop filter and (b) an example waveguide cross-section.