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Combining FDTD with coupled mode theories for bistability in micro-ring resonators

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Abstract

An association of the finite-difference time domain (FDTD) method together with coupled mode theories (CMTs) has been applied to the study of the bistable properties of whispering gallery mode (WGM) micro-ring resonators. The semi-analytical results obtained are compared with numerical nonlinear full calculations (nonlinear FDTD). It is shown that CMTs allow a good quantitative description of the stationary and dynamical behaviors of the bistability in such micro-resonators. As an example, we treat the case of a polymer micro-ring in a symmetrical dual coupling configuration.

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1. Introduction

Micro-cavities (spheres, disks and rings) have been well studied in the past few years and are attractive elements for integrated optics. In these structures, light can be guided and confined efficiently in high quality factors Q whispering gallery modes (WGMs). Using the filtering properties of such cavities, integrated ring and disk micro-resonators coupled to waveguides have been demonstrated for semi-conductors [1], Si–SiO_2 [2] or polymers [3,4]. The high Q of these resonators allows one to obtain very low threshold dispersive nonlinear effects [5–7]. Ibrahim et al. [8] have demonstrated that all optical switching in micro-ring resonator using the third-order nonlinearity associated with two photons absorption of III–V semiconductors compounds. This experimental realization shows that micro-ring resonators are good candidates for integration of all-optical

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signal processing. In this purpose, it is crucial to model precisely the non-linear behavior of micro-ring resonator with low time consumption. The modelling of this kind of micro-resonator needs to know the values of the coupling coefficients between straight and highly curved waveguides. Unfortunately, no exact analytical expression of these coefficients are available and numerical methods like wave expansion or finite difference time domain (FDTD) method are commonly used to solve this problem. For an extensive review of these methods, see [9,10]. The objective of this paper is to show how linear FDTD and coupled mode theories (CMTs) (i.e., A. Yariv's matrix approach [11] and H. Haus's mode amplitude method [12]) can be combined to describe the bistable behavior of micro-ring resonator. In our approach, coupling coefficients [11] are calculated by linear FDTD during one round trip of light in the ring resonator which limit the duration of the numerical simulations. By comparing the semi-analytical results obtained by CMTs with numerical nonlinear full calculations (nonlinear FDTD) we show that CMTs give good quantitative informations in the stationary and transient regimes as it has already been made in photonic crystal point defect microcavities [13]. We start by a structural description of the micro-resonators studied. Then, we introduce the nonlinear FDTD which will be used to test the results of CMTs. In Section 4, we will present the analytical model used for determining the expression of bistability threshold intensity in a micro-ring with asymmetric coupling and propagation losses. This formalism will be applied to the case of polymer micro-ring with high nonlinear index in Section 5. The last paragraph will be devoted to the study of the transient regime.

2. Structural configuration

The generic structure we study in this paper, depicted in Fig. 1, is a polymer micro-ring coupled to two straight waveguides in a symmetrical dual coupling add-drop configuration [8]. The width of the waveguides and the ring is $e = 1$ μm. The light confinement is obtained both in the ring and the waveguides by etching the polymer material. Consequently, the index contrast between the core ($N = 1.6$) and the air is approximatively $\Delta n = 0.6$. The effective index n_{eff} of the mode propagating in the structure is calculated assuming only a two-dimensional confinement. The radius of the ring is $R = 15.5$ μm, which leads to a value of the free spectral range compatible with 10 Gbit/s WDM optical network [14]. The gap between the waveguides and the ring is noted h and will be

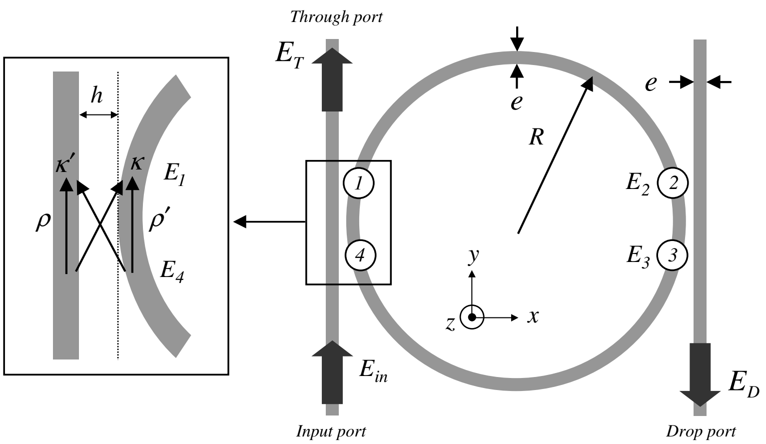

Fig. 1. Description of the structure. E_{in} is the input field, E_T the transmitted field and E_D the extracted field. E_m is the field in the ring at the point m, with $m \in \{1, 2, 3, 4\}$. κ, κ', ρ and ρ' are the field coupling coefficients. R is the mean radius of the micro-ring, e is the common width of waveguides and micro-ring and h is the width of the air-gap between the straight waveguides and the ring.