Behavioral Model of Silicon Photonics Microring with Unequal Ring and Bus Widths

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***Abstract*— Microring resonators (MRR) with non-identical ring and bus waveguide widths are easier to fabricate as they allow for larger gaps. For effective design exploration, we propose a new behavioral model for the directional coupler of an MRR with non-identical ring and bus widths, which can be used to calculate the MRR design performace. The analysis shows that the proposed modeling technique matches the corresponding 3D FDTD simulations well.**

I. INTRODUCTION

TO support the data traffic demands in the next generation high performance computing (HPC) systems, wavelength division multiplexing (WDM) links are expected to replace the electronic interconnects that suffer from high latency and losses. The emerging silicon photonics (SiP) platform appears to be a promising technology to achieve the bandwidth and power requirements of the next generation HPC systems. Due to small footprint and high wavelength selectivity, microring resonators (MRR) are widely used in WDM links as modulators at the transmitter-side, and as filters at the receiver-side. To optimize the link performance, a careful design of each of the components, and specifically the MRR devices, is required. Typically, MRR devices in a WDM link are designed for a specific wavelength band. Besides the ring resonance positions, the 'performance' of the MRRs is determined by its area, bandwidth, free-spectral range (FSR), Q-factor, extinction ratio and the insertion losses. Commonly, to find the best MRR design, a design exploration is performed by scanning a set of geometric parameters over a certain range of values. One can use 2D or 3D FDTD or FEM simulations to compute the relevant electromagnetic (EM) fields, and use these to calculate the MRR's performance. However, in this approach, it can take a relatively long time to find the appropriate MRR design that satisfies the link requirements. Alternatively, a compact model can speed up the design exploration significantly. For instance, the model proposed in Ref. [1] accurately describes the physical behavior of MRRs with equal bus and ring waveguide widths. However, in Ref. [2], it was shown that MRRs with a narrow bus width have better phase matching with the ring mode, weaker excitation of high-order modes, and slower mode decay in the cladding. This enables MRR devices with larger gap values that are less sensitive to fabrication tolerances. Yet, current compact

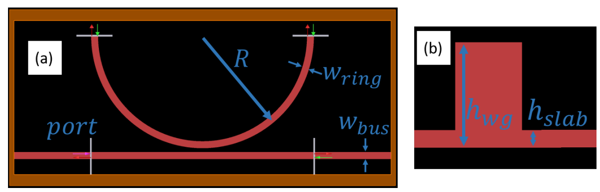

Fig. 1. (a) Schematic of the FDTD simulation setup for the bus-ring coupling section. (b) Cross-section of the slab waveguide.

models are limited to identical bus-ring waveguides widths. In this work, we propose a behavioral model for the coupling transfer function of the directional coupler (DC) of an MRR for unequal ring and bus widths. We show that the proposed modeling methodology nicely matches the corresponding 3D FDTD simulations.

II. MODELING METHODOLOGY AND ANALYSIS

The nominal performance of MRR devices, e.g., resonance, FSR, and bandwidth, can be determined from the coupling transfer function of a bus-ring pair. Fig. 1(a) shows a schematic of the bus-ring coupling section. A cross-section of the studied slab-waveguide is shown in Fig. 1(b). To find the coupling transfer function of the DC of the MRR, the following coupling differential equations are solved numerically [3]:

$$\frac{dA}{dz} = -j\kappa_a(z)B\exp(-j2\delta z) + j\alpha_a(z)A \tag{1}$$

and

$$\frac{dB}{dz} = -j\kappa_b(z)A\exp(j2\delta z) + j\alpha_b(z)B, \tag{2}$$

where A and B are the amplitudes of the propagated EM fields of the bus and ring waveguide, respectively, z is the direction of propagation, 2δ is the difference between the propagation constants, α_l and κ_l are the modified self- and cross-coupling coefficients, respectively, $A(z_{start}) = 1$, $B(z_{start}) = 0$ and $l = a, b$. The coefficients α_l and κ_l are a function of the self-, cross-, edge-coupling coefficients, κ_{ii}, κ_{ij} and c_{ij}, respectively, where $i, j \in \{1, 2\}$. The coefficients κ_{ii}, κ_{ij} and c_{ij}, and in-turn α_l and κ_l, are a function of the transverse EM fields and are gap dependent. Therefore, the transverse EM fields were calculated for various gaps using Lumerical's MODE solver tool. As can be seen from

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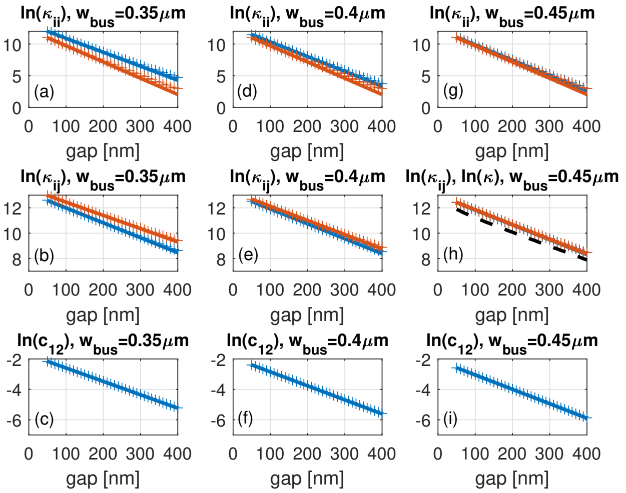

Fig. 2. The calculated coupling coefficients, κ_{ii}, κ_{ij}, and c_{12}, using Lumerical's MODE solver (cross bar) versus the fitted exponential curves (continuous curve) for $w_{bus} = 0.35, 0.4, 0.45\mu m$, $w_{ring} = 0.45\mu m$, $h_{wg} = 0.3\mu m$, and $h_{slab} = 0.05\mu m$ at $1310nm$.(h) The dashed black curve stands for $ln(\kappa)$.

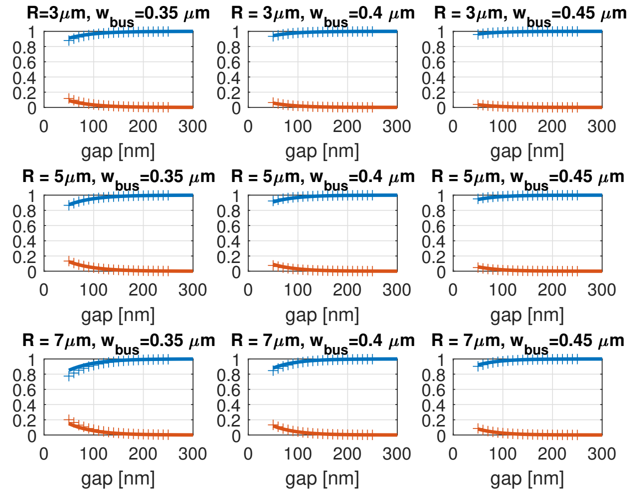

Fig. 3. Comparison between the predicted bus-ring coupling coefficients (solid lines) and the 3D FDTD simulation results (crossbar markers) for $w_{ring} = 0.45\mu m$, $w_{bus} = 0.35, 0.40, 0.45\mu m$, $h_{wg} = 0.3\mu m$, $h_{slab} = 0.05\mu m$, and radii $R = 3, 5, 7\mu m$ at $\lambda = 1310nm$. The blue and the red colors stand for $|t|^2$ and $|k|^2$, respectively

Fig. 2(a)-(i), the coefficients κ_{ii}, κ_{ij} and c_{ij} can be fitted to exponential curves as a function of the gap.

To validate the proposed modeling methodology of the DCs with non-identical widths, a Lumerical 3D FDTD simulation of the coupling section of the MRR structure with a slab waveguide was set up. A schematic of the FDTD simulation layout and the waveguide cross-section are shown in Fig. 1(a)-(b). The wavelength is $1310nm$ and the slab waveguide consists of silicon (Si, $n_1 = 3.507$) with a silicon dioxide (SiO_2, $n_2 = 1.447$). The waveguide height is $h_{wg} = 0.3\mu m$, where the slab thickness is $h_{slab} = 0.05\mu m$, and the ring waveguide width is $w_{ring} = 0.45\mu m$. Following the methodology in the previous paragraph, the through and the coupling transfer functions, $t = A(z_{end})$ and $k = B(z_{end})$, respectively, were calculated and compared to the FDTD simulation results. Yet, to improve the fitting between the model and the FDTD, we found that two modifications are needed. First, we noticed that the cross-coupling coefficient κ_{ij} of coupling sections with identical waveguide widths differ from the coupling coefficient $\kappa = 0.5\frac{2\pi}{\lambda}(n_{even} - n_{odd})$, which is the coupling coefficient obtained by using the procedure proposed in Ref. [1]. Whereas the latter expression can be derived from spatial coupled mode theory, in our geometry, due to the high index contrast between the core and the cladding this equality breaks down [4]. Therefore, we used an ad hoc rescaling of the coupling coefficients κ_{ii}, κ_{ij} and c_{ij}, by a factor $F = \frac{\hat{\kappa}_{ij}}{\kappa}$, where $\hat{\kappa}_{ij}$ is the cross-coupling coefficient for the case of $w_{ring} = w_{bus}$. We noticed we can reuse the same F value for similar geometries with $w_{ring} \neq w_{bus}$. Second, in MMRs with $w_{ring} \neq w_{bus}$ and small gaps, non-orthogonality of the unperturbed waveguide modes result in $|t|^2 + |k|^2 \neq 1$ [3]. Therefore, in our behavioral model, we normalize $|t|^2$ and $|k|^2$ by $|t|^2 + |k|^2$. Both ad hoc adjustments significantly improve the fitting between the model and the FDTD results over a broad range of MRR geometries. Figure 3 shows a good agreement between the proposed behavioral model and the FDTD results for $w_{ring} = 0.45\mu m$, $w_{bus} = 0.35, 0.4, 0.45\mu m$, $h_{wg} = 0.3\mu m$, $h_{slab} = 0.05\mu m$, and radii of $R = 3, 5, 7\mu m$ at $1310nm$. This new behavioral model is a crucial first step in the extension of the design exploration methodology proposed in Ref. [1] towards MRR designs with non-identical widths, which are often used in practice.

III. Conclusions

Current compact models are limited to identical bus and ring widths. In this work, we present a behavioral model for MRRs with unequal ring and bus widths. Our model contains two ad-hoc modifications that allow the use of coupled mode theory, despite the high refractive index contrast in c-Si MRRs around $1310\,\mathrm{nm}$. The behavioral model matches the 3D FDTD simulations well and will be a key component in the design exploration of MRRs with non-identical waveguide widths.

Acknowledgements

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