Behavior Model for Directional Coupler

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We present a parameterized model for the directional couplers that accurately incorporates its spectral dispersion. We have verified the model using the Finite Difference Time Domain (FDTD) simulations and the measurements from fabricated devices. We have demonstrated the extraction of the behavior model parameters from the fabricated directional couplers. Two different methods for the extraction of the parameters are implemented and discussed.

Introduction

An accurate design for compact integrated circuits requires computationally expensive, full-vectorial electromagnetic simulations (e.g. FDTD). To design complex circuits, efficient behavioral component models are needed, as FDTD simulations for complex circuits are impossible. The directional coupler is one of the fundamental building blocks in photonics circuits. It couples light from one port to another and is frequently used as a power splitting and combining component in devices like ring resonators, Mach-Zehnder interferometers and other filters.

We have built a behavioral model for the directional coupler (DC) that takes care of the coupling by accurately capturing its wavelength dependence and the contribution of its bend sections. The model incorporates dispersion to make it valid over a wider wavelength range, and at the same time uses a limited set of parameters to make parameter extraction possible.

Behavior model of a DC

According to the Coupled Mode Theory (CMT) [1], a DC with two identical parallel waveguides has an odd and an even supermode. The coupling between them brings power A in one waveguide to another as:

$$\mathrm{K}_{\mathrm{coupled}} = A\sin^2 k'L$$

where L is the length of the coupler, k' is the field coupling coefficient that determines the strength of the coupling in the straight coupling section. The field coupling coefficient depends on the difference between the effective indices of the odd (n_{odd}) and even (n_{even}) supermodes as:

$$k' = \frac{\pi}{\lambda}(n_{odd} - n_{even})$$

A real DC consists of not only a straight section but a couple of bend sections as well. So, the model should consider the power coupling in these bend sections too. Addition of the contributions from these bends k_0, result into the expression:

$$\mathrm{K}_{coupled} = A\,sin^2(k'L + k_0)$$

Since both k' and k_0 are dispersive, the model should also consider their dispersion, which is expanded into a polynomial series as:

$$k'(\lambda) = k'_0(\lambda_0) + (\lambda - \lambda_0)\frac{dk'}{d\lambda} + (\lambda - \lambda_0)^2\frac{d^2k'}{d\lambda^2}$$

$$k_0(\lambda) = k_0(\lambda_0) + (\lambda - \lambda_0)\frac{dk_0}{d\lambda} + (\lambda - \lambda_0)^2\frac{d^2k_0}{d\lambda^2}$$

For this work, we use second order polynomials and neglect higher orders because we found the higher-order terms to be very small both in simulation and experiment. But the model can easily be extended for more dispersive devices. Substituting it into the equation above, the power at the coupled port becomes:

$$\mathrm{K}_{coupled}(\lambda) = Asin^2(k'(\lambda)L + k_0(\lambda))$$

The power at the through port becomes:

$$\mathrm{K}_{through}(\lambda) = Bcos^2(k'(\lambda)L + k_0(\lambda))$$

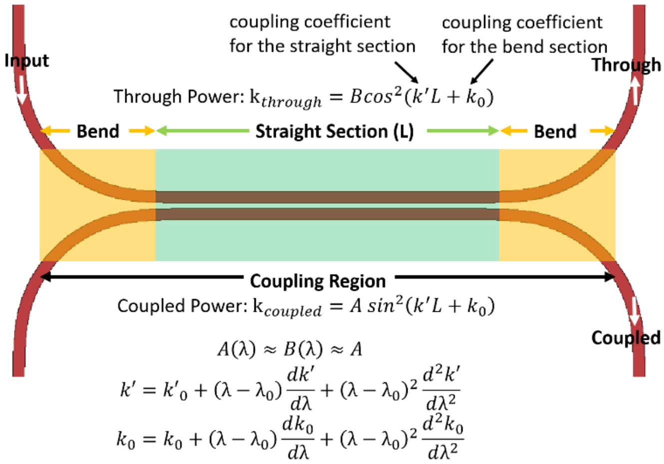

Figure 1 Behavior model for directional coupler

Verification from simulations

Before confirming the accuracy of our model from the measurements of fabricated devices, we have verified it by comparing it to the three dimensional (3D) FDTD simulations. It was found that spectral responses calculated by the Caphe circuit simulations [2] based on our model match pretty well to the responses calculated by the commercially available FDTD solver from Lumerical. A comparison between the calculated spectra based on our model and the 3D FDTD simulation is shown in Figure 2(a) below.

In the next step, we have extracted the behavioral model parameters $k'(\lambda)$ and $k_0(\lambda)$ using the spectra generated by FDTD simulations of different directional couplers. We simulated a series of DCs having the same cross section (450 nm × 220 nm oxide-clad silicon waveguides with 250 nm gap) and the bend radii using the Lumerical FDTD solver. The cross section and the bend radii were same so all the devices had the same field coupling $k'(\lambda)$ and bend coupling $k_0(\lambda)$ coefficients. The only things varied for these FDTD simulations was the coupling length (L) of the directional couplers. DCs of different lengths were simulated to derive a relation between the power coupling $\mathrm{K}_{coupled}(\lambda)$ and the length of DCs (L). Since they follow a sinusoidal relation for the given wavelength so fitting to $\mathrm{K}_{coupled}(\lambda) = Asin^2(k'(\lambda)L + k_0(\lambda))$ will result into values of $k'(\lambda)$ and $k_0(\lambda)$ for that particular wavelength value. It should be mentioned here that the fitting will be more accurate if we choose the lengths in a way that at least one length value resides on the right side of the maximum power coupling to cover more than half a cycle of the sinusoidal curve. As shown in Fig. 2(b), $k'(\lambda)$ and $k_0(\lambda)$ are derived by fitting the $\mathrm{K}_{coupled}(\lambda)$ vs L graph for each simulated wavelength value.

To confirm the extracted values of $k'(\lambda)$ and $k_0(\lambda)$, the cross section was simulated using the Fimmwave Film Mode Matching solver, and a difference between the even and the mode effective indices was calculated to find out the value of $k' = 0.0427$ at 1550 nm using $k'(\lambda = 1550\text{ nm}) = \frac{\pi}{1550\text{ nm}}(n_{odd} - n_{even})$. This value is pretty close to the extracted value of 0.042 extracted from the FDTD.

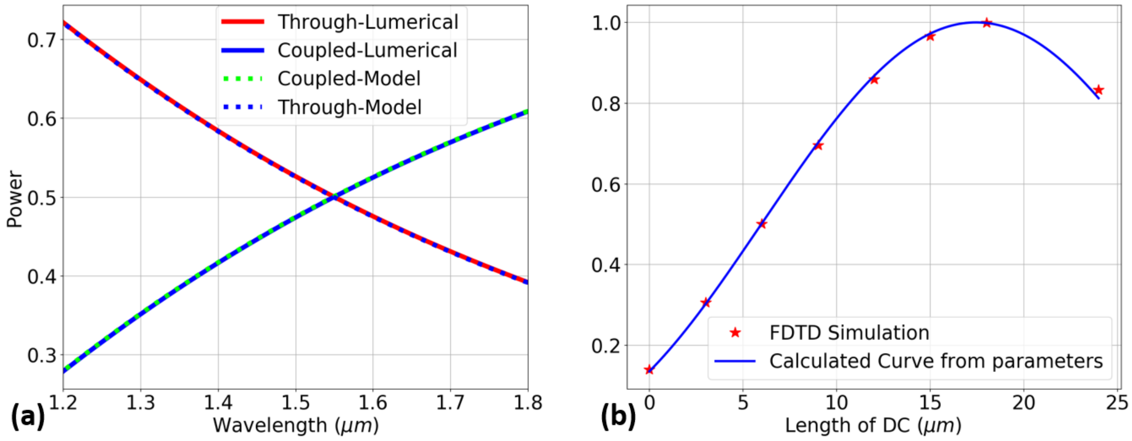

Figure 2. (a) A comparison showing a really good match between the directional coupler spectra generated using the commercially available FDTD solver from Lumerical and our dispersive behavioral model. (b) The red stars in the graph show the power couplings calculated using the FDTD simulations. The blue plot shows the fitted power couplings using our behavioral model. It should be mentioned here that such graphs are generated for each wavelength point and fitted to extract the values of field coupling $k'(\lambda)$ and bend coupling $k_0(\lambda)$ for the wavelength of interest. This particular plot was calculated for a wavelength of 1640 nm.

Extraction of coupling coefficients from fabricated DCs

For the highest accuracy, the model should be checked with reality, and its parameters should be extracted from measurements [3]. In order to validate the model from fabricated devices, 8 DCs of lengths 0.15µm, 10µm, 20µm, 30µm, 40µm, 60µm, 70µm and 80µm were fabricated using e-beam lithography through the Australian Silicon Photonics prototyping service at RMIT Melbourne. All DCs had the same designed cross-section (450 nm × 220 nm) and the same bend sections. It should be mentioned here that fabricated devices were air clad from the top. We have extracted the behavioral model parameters using two different techniques explained below.

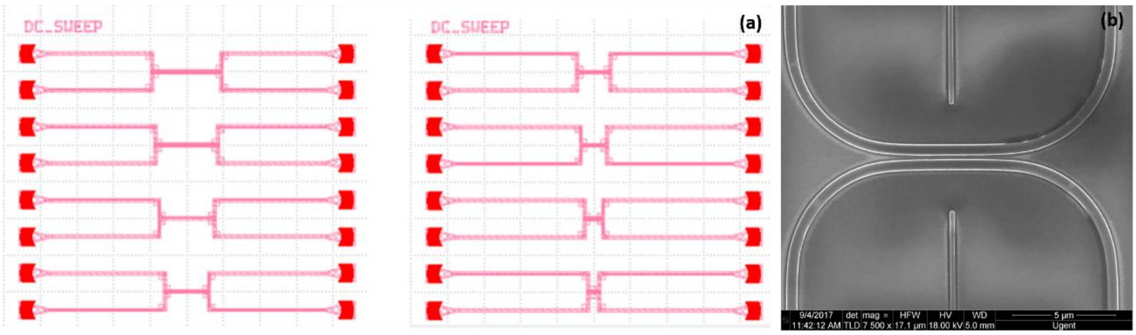

Figure 3. (a) The snapshot of the GDS file showing directional couplers of different lengths. (b) The plot showing the measured transmission response from the coupled port of the directional coupler having a coupling length of 20µm.

In the first method, we used the power coupling at a fixed wavelength for multiple DC lengths and extracted the parameters by fitting of the $K_{coupled}(\lambda)$ vs L graph, Figure 3(a), for each measured wavelength value as mentioned in the previous section. The process is repeated for all wavelength points to get the dispersive coupling coefficients as shown in Figure 4(b and c). It can be noticed that the extracted values of field coupling $k'(\lambda)$ and bend coupling $k_0(\lambda)$ are not varying smoothly with the wavelength because fitting is performed independently for each wavelength point. In this case, no effort was made to remove the oscillations in the transmission spectrum from imperfect grating couplers and backreflections.

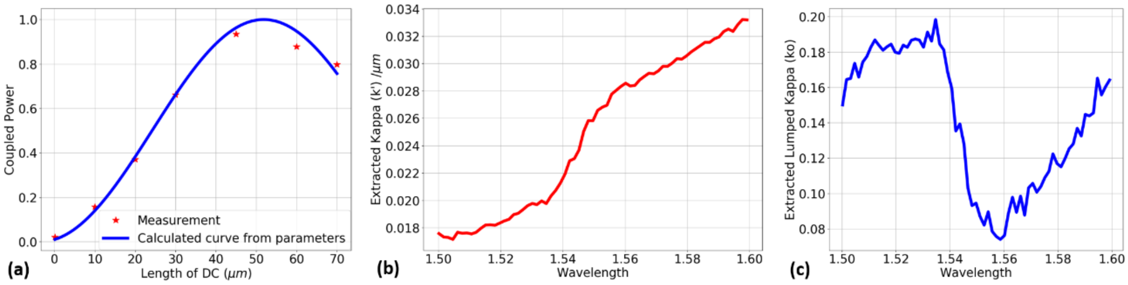

Figure 4. (a) The plot shows the measured and the fitted power coupling for different lengths of directional couplers. (b) The plot showing the extracted field coupling coefficient. (c) The plot shows the extracted bend coupling coefficient.

In the second method, we fitted the complete transmission spectrum of four DCs simultaneously. DCs of lengths 10µm, 20µm, 30µm and 45µm were used for the fitting. As, $k'(\lambda)$ and $k_0(\lambda)$ are the same for these four lengths (not taking into account device-to-device variability) the only varying parameter for these fittings is length of the directional couplers (L). Since we fit the entire spectrum with the model, the noise plays less of a role in the parameter extraction. It is a much simpler procedure since we can extract all 6 parameters in a single operation. In principle, it only requires two DCs to extract all the parameters (the additional devices make the method more robust) while the first method required at least 8 devices to get a decent fit. So, it is more practical and cost-saving. It can be noticed that the extracted $k'(\lambda)$ and $k_0(\lambda)$ using both methods are comparable with an exception that extracted parameters vary much more smoothly over the wavelengths using the second approach.

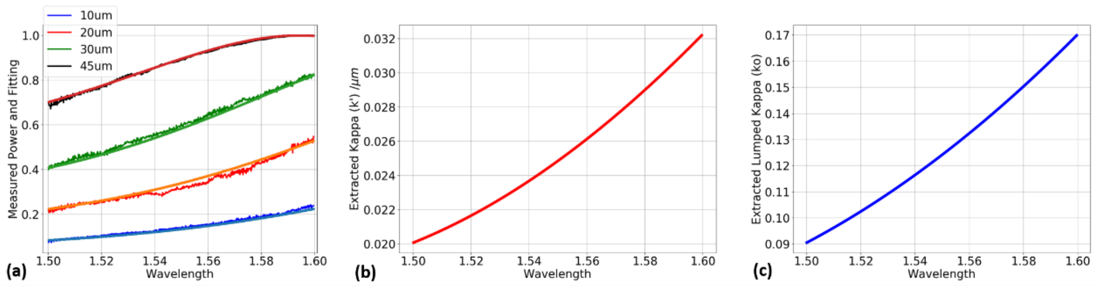

Figure 5. (a) The plot shows the measured and the fitted spectra from the coupled spectra of the directional couplers. The used lengths for these fitting were 10µm, 20µm, 30µm and 45µm. (b) The plot showing the extracted field coupling coefficient. (c) The plot shows the extracted bend coupling coefficient.

Conclusions

To conclude, a parameterized behavior model for directional couplers is presented and validated using FDTD simulations and the measurements from fabricated devices. The presented model was used to extract parameters and evaluate performance of the fabricated DCs. Two extraction methods were applied and compared. Extracting parameters by fitting the complete transmission spectrum of DC offers robust and accurate results. Also, it is a simpler method requiring fewer devices and is suggested for DC parameter extraction.

References

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