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Designing Optical Switches Based on Silica Multimode Interference Devices

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Abstract

A novel approach to design N×N silica-on-silicon optical switches based on phase-compensated and cascaded multimode interference structures is presented. Taking into consideration of weakly guiding features of silica-on-silicon waveguides, instead of using self-imaging theory, we apply a two-step design approach: In the first step the multimode sections are optimized for minimum loss and best uniformity. In the second step the phase shifting compensations are obtained by accurate calculation of relative phases of MMI sections. Using this novel approach we designed a 4×4 optical switch and achieved better device performance from our numerical simulation results. Compared with the configuration from the self-imaging theory, the results from our designing approach can reduce the device loss and crosstalk by 1dB and 8dB, respectively.

I. Introduction

The cascaded N×N MMI couplers structures with generalized Mach-Zehnder configuration have proposed to realize the switch function [1-2]. Commonly the switches are made of high index contrast structures that strongly guiding approximation is well satisfied. Good device design could be obtained by directly using the self-imaging theory based on the strongly guiding approximation.

Recently MMI couplers based on silica-on-silicon waveguides [3] have attracted lots of research interests because of their advantages: low cost, low material loss and easy fiber coupling [4]. However silica-on-silicon waveguides are low index contrast structures and the strong guiding approximation is no longer well satisfied. Hence the appropriate design approaches are required for MMI devices based on silica-on-silicon waveguides.

Previously silica-on-silicon MMI switches have also been studied [5]. However, they had considered only 2×2 devices and the weakly-guiding modification of the self-imaging theory had not been discussed. In this paper we propose a novel design approach for N×N optical switches based on planar silica-on-silicon waveguide structure. Considering weakly guiding features of silica-on-silicon waveguides, instead of using self-imaging theory, we apply a novel 2-step designing approach to give good performance devices.

II. Device Modeling

The silica-on-silicon switch structures are showed as Fig.1. N (N = 4) phase shifting waveguide arms link two MMI couplers, each having a phase shifter. The structure is designed to be single-moded in the transverse direction. Thus a correspondent 2D representation can be found using the effective index method. In this paper we used the 2D model to discuss the problem.

The transfer matrix method can be used to do device modeling [2]. Different sections of the optical switches, MMI couplers and phase shifting waveguide arms, are described by special transfer matrixes. The products of these matrixes are the total transfer matrixes of the optical switches:

$$T^{NN}_{Switch} = T^{\cdot}_{coupler}\Lambda \cdot T_{coupler} \tag{1}$$

The $T_{coupler}$ is a transfer matrix of a N×N MMI coupler and it's elements $t_{coupler,ji}$ are field transfer coefficients from input i to output j. The value of $t_{coupler,ji}$ can be calculated using mode propagation method [3]:

$$t_{coupler,ji} = \sum_{0}^{m-1} \frac{\int \Psi_i^{in}(y)\Psi_v(y)dy}{\int [\Psi_v(y)]^2 dy} \exp[-\beta_v L_{mmi,coupler}] \frac{\int \Psi_v \Psi_j^{out}(y)dy}{\int [\Psi_j^{out}(y)]^2 dy} \tag{2}$$

In Eq.(2) $\Psi_i^{in}(y)$ is the power normalized eigenmode of the field at input guide i. $\Psi_v(y)$ are the power normalized eigenmodes in MMI section and $v = 0, 1, \cdots, m-1$. $\Psi_j^{out}(y)$ is the power normalized eigenmode of the field at output and it is same as $\Psi_i^{in}(y)$. β_v is the propagation constant for the v-th mode in the MMI section. $L_{mmi,coupler}$ is the length of the MMI section.

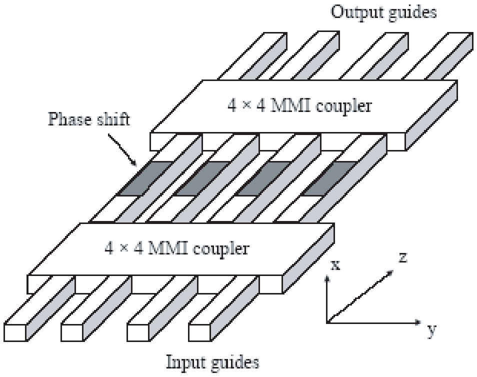

Figure 1: Schematic diagram showing a 4×4 optical switch

The phase shift is applied in a given arm j by an amount $\Delta\Phi_j$. The arms in the switch can be described by the diagonal N × N matrix:

$$\Lambda = \begin{bmatrix} e^{J\Delta\Phi_1} & & & & \\ & \ddots & & & \\ & & e^{J\Delta\Phi_j} & & \\ & & & \ddots & \\ & & & & e^{J\Delta\Phi_N} \end{bmatrix} \tag{3}$$

where $J = \sqrt{-1}$.

The output intensity can be calculated by the elements of the total transfer matrix. If a single input beam of optical intensity I_i^{in} is fed into input guide i and at output port k

$$I_{Switch,k}^{NN,out} = \left|t_{Switch,ki}^{NN}\right|^2 I_i^{in} \tag{4}$$

III. Device Designing

The purpose of the device designing is to achieve low loss and small crosstalk devices. The design of MMI couplers and phase compensation for a desired switch state can be found using the self-imaging theory [6]. However for silica-on-silicon waveguides are weakly guiding structures, the configurations from self-imaging theory can only be regarded as first-approximate design. For finding better design with lower loss and smaller crosstalk we introduce a novel 2-step approach: 1) Optimal MMI coupler configurations are found; 2) Accurate phase compensations are calculated.

Optimal Design of MMI Couplers

Using the self-imaging theory, if the width of the MMI coupler is fixed the length of the MMI coupler can be found by

$$L_{mmi,coupler} = \frac{3L_\pi}{N} \tag{5}$$

where L_π is the beat length of the two lowest order modes in MMI section. The $L_{mmi,coupler}$ here can be used as first-approximation design and put in Eq.(2) to calculate device performance.

The optimal designing of MMI couplers based on weakly guiding structure has been discussed recently. In [3] we gave detail discussions of optimal design of N×N MMI couplers based on silica-on-silicon structures. It was show that the length of the MMI section can be varied in a well-defined range to find optimal device performance. The range linked to the propagation constant spacing of fundamental and higher order modes of the MMI section. In that range we can find the optimal length $L_{mmi,coupler}^{optimal}$ as the MMI coupler design to replace the self-imaging result Eq.(5).

Accurate Phase Compensation

The reciprocal characteristics of the MMI couplers can be used to find the phase compensation for a desired switch state. For an N×N switch, the compensating phases $\Delta\Phi_j|_{output=k,input=i}$ can be determined by

$$\Delta\Phi_j|_{output=k,input=i} = \Phi^{in}_{coupler,kj} - \Phi^{out}_{coupler,ji} \tag{6}$$

where the relative phases $\Phi^{out}_{coupler,ji}$ is the output from the first N×N coupler and $\Phi^{in}_{coupler,kj}$ is the required relative phases of all inputs for the second N×N coupler with light out only at output k. According to reciprocal characteristics, the required input relative phases, $\Phi^{in}_{coupler,kj}$ is negative of $\Phi^{out}_{coupler,jk}$, which is the relative phases of the output from the N×N coupler with input k is fed. Thus we have

$$\Delta\Phi^{NN}_j|_{output=k,input=i} = -\Phi^{out}_{coupler,jk} - \Phi^{out}_{coupler,ji} \tag{7}$$

Same as the length of MMI coupler, the relative phases from MMI couplers can be found by the self-imaging theory [2,6] as the first approximation:

$$\Phi^{Out}_{Coupler,ji} = -\frac{\pi}{2}(-1)^{i+j+N} + \frac{\pi}{4}[i + j - i^2 - j^2 + (-1)^{i+j+N} \cdot (2ij - i - j + 0.5)] \tag{8}$$

For silica-on-silicon waveguides a novel approach to find the accurate values is need. Remember that the element of a transfer matrix of a MMI is the field transfer coefficient from one input to one output. Each element is a complex. Thus the argument of the complex, or $\arg(t_{coupler,ji})$ is the accurate phase relation between the output field and the input field. So we can use $\arg(t_{coupler,ji})$ to calculate relative phases $\Phi^{in}_{coupler,kj}$ instead of using the self-imaging theory Eq.(8). Then the accurate phase compensation $\Delta\Phi_j|_{output=k,input=i}$ can be found using Eq.(7).

IV. Numerical Calculations and Results

We analyze the particular case of 4×4 switches based on silica-on-silicon MMI couplers to test our theoretical approach. The operation wavelength is 1.55 um, and the core index is chosen to be 1.461 and the cladding index 1.453. The thickness of the core is 5 um. The access waveguides have width of 5 um and are single mode. The width of the MMI section is set to 85um, based on the need to minimize coupling between the 4 output waveguides. Because the system is little polarization only TE modes are discussed.

The optimization is done first to find the optimal design of the 4×4 couplers. Using the method discussed in [3] when the width is fixed as 85 um the length can be varied from 7.456 mm to 7.716 mm. Fig.2 shows the optimal calculation.

We defined the loss as the difference between the input power and the sum of the powers from all 4 output guides and the uniformity as the difference between the maximum and minimum output powers. The optimal length for the MMI couplers is $L^{Optimal}_{mmi,coupler} = 7.55mm$, for both low loss and good uniformity, instead of the self-imaging result $7.456mm$.

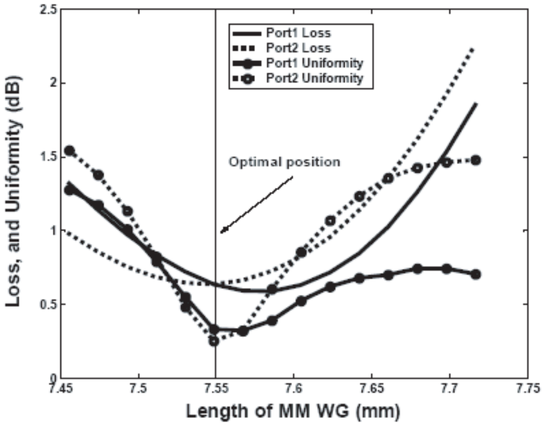

Figure 2: The optimal calculation of the 4×4 coupler with the variation of the length in the well-defined range

Table 1: The performance for the designed 4×4 switch is calculated for different switching status when port 1 is fed. The relative phase is set in the range from 0 to 2 π. And Arm1 (Port 1) is the reference for the relative phases.

Switched output port k	Accurate phase compensation $\Delta\Phi\ _j\|_{input=1}$ (π)				Loss(dB)	Crosstalk(dB)			
	Arm1	Arm2	Arm3	Arm4		Output port1	Output port2	Output port3	Output port4
1	0	0.48	0.45	1.95	1.27	N/A	-31.80	-30.43	-46.25
2	0	1.99	0.94	0.96	1.27	-31.57	N/A	-47.08	-26.22
3	0	0.96	1.99	0.99	1.27	-31.45	-48.16	N/A	-32.35
4	0	1.49	1.49	0.00	1.27	-45.57	-25.63	-28.56	N/A

Table 2: The performance for the designed 4×4 switch is calculated for different switching status when port 2 is fed. The relative phase is set in the range from 0 to 2 π. And Arm1 (Port 1) is the reference for the relative phases.

Switched output port k	Accurate phase compensation $\Delta\Phi\ _j\|_{input=2}$ (π)				Loss(dB)	Crosstalk(dB)			
	Arm1	Arm2	Arm3	Arm4		Output port1	Output port2	Output port3	Output port4
1	0	1.99	0.94	0.96	1.27	N/A	-28.68	-26.22	-55.26
2	0	1.51	1.43	1.98	1.28	-31.78	N/A	-55.34	-30.42
3	0	0.48	0.48	0.00	1.28	-26.79	-54.07	N/A	-33.02
4	0	1.01	1.98	1.01	1.27	-62.12	-29.45	-32.30	N/A

Tabs. 1 and 2 give the configuration and performance of the designed optical switches. The calculation shows that the optimal length and accurate compensating phase result good performance devices. The loss is about 1.27 dB and the crosstalk is less than -25dB. We also calculated the device performance with configurations from the self-imaging theory, or Eqs. (5) and (8), for comparison. We find that for the first-approximation design, device losses are about 2.3 dB and the crosstalks are less than -17dB. Our novel approach reduces loss and crosstalk by about 1 dB and 8dB, respectively.

V. Conclusion

Designing N×N optical switches based on planar silica-on-silicon waveguide has been discussed in this paper. Instead of using self-imaging theory, we apply a novel designing approach to get good performance optical switches. In numerical simulations, using the novel approach a 4×4 optical switch is designed and turns out good device performance. Compared with the configuration from the self-imaging theory, the design from our approach can reduce the device loss and crosstalk by 1dB and 8dB, respectively.

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