Improved Optical 1xN On-Chip-Switches Based on Generalized Mach-Zehnder Interferometers

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Abstract—We present a theoretical study of 1xN optical routing networks consisting of generalized Mach-Zehnder switches, that are based on multimode interferometers. This work gives a brief overview of the necessary phase conditions and resulting phase shifter requirements in the 1xN switches. Using the presented approach as 1x4 switch with parallel phase shifters, a 20% phase-shifter-loss reduction becomes possible.

I. INTRODUCTION

In the field of integrated silicon photonics the routing of optical signals is an important task, e.g. for applications in the domain of modern optical communication systems. Different architectures to build such suitable 1xN switches have been presented in the literature. A compact approach [1-5] is based on the integrated generalized Mach-Zehnder interferometer (GMZI) with additional phase shifters, which is called the generalized Mach-Zehnder switch (GMZS). For this case, two NxN multimode interferometers (MMIs) are connected by passive waveguides and active phase shifters (see Fig. 1(a)). MA- ch-Zehnder switching are shown. The phase-shifters are aligned in parallel in the general Mach-Zehnder switch (a), which includes NMMIs. The 1xN network in (b) is based on cascaded 2x2 MZI switches.

II. ANALYSIS OF THE 1X5 SWITCH

In order to get a general idea of how to determine the necessary phase shifts, the method is exemplary shown for the 1x5 GMZS in the following. Here, the 1x5 transfer matrix T from the first input to the N outputs can be expressed by

\[
T = ABA (1 0 0 0 0)^T
\]

where \( A \) is the transfer matrix for the MMI and \( B \) the transfer matrix for the phase shifter array. \( \phi_0 \) is an additional global phase shift occurring for all outputs and \( \Delta \phi_i \) is the phase shift introduced by the i-th phase shifter. Using the first input, the necessary phase shifter conditions for enabling the routing to all outputs, can be calculated. The conditions are listed in Table I. Here, for all \( N \) routing configurations a corresponding global phase shift is included (denoted by \( a, b, c, d, e \)).

TABLE I  

<table>
<thead>
<tr>
<th>Output</th>
<th>( \Delta \phi_1 )</th>
<th>( \Delta \phi_2 )</th>
<th>( \Delta \phi_3 )</th>
<th>( \Delta \phi_4 )</th>
<th>( \Delta \phi_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( a + \frac{\pi}{4} )</td>
<td>( a + \frac{\pi}{4} )</td>
<td>( a + \frac{\pi}{4} )</td>
<td>( a + \frac{\pi}{4} )</td>
<td>( a + 0\pi )</td>
</tr>
<tr>
<td>2</td>
<td>( b + 0\pi )</td>
<td>( b + \pi )</td>
<td>( b + \pi )</td>
<td>( b + \frac{\pi}{4} )</td>
<td>( b + 0\pi )</td>
</tr>
<tr>
<td>3</td>
<td>( c + 0\pi )</td>
<td>( c + \frac{\pi}{4} )</td>
<td>( c + \frac{\pi}{4} )</td>
<td>( c + 0\pi )</td>
<td>( c + \frac{\pi}{4} )</td>
</tr>
<tr>
<td>4</td>
<td>( d + \pi )</td>
<td>( d + \frac{\pi}{4} )</td>
<td>( d + \pi )</td>
<td>( d + \frac{\pi}{4} )</td>
<td>( d + 0\pi )</td>
</tr>
<tr>
<td>5</td>
<td>( e + \frac{\pi}{4} )</td>
<td>( e + 0\pi )</td>
<td>( e + \frac{\pi}{4} )</td>
<td>( e + 0\pi )</td>
<td>( e + \frac{\pi}{4} )</td>
</tr>
</tbody>
</table>
Then, the necessary active phase change in each of the five phase shifter arms is optimized and calculated by varying a, b, c, d and e with a step size of \( \pi/5 \) and with the help of a Matlab algorithm. Following this calculation, an active phase shift of \( 4\pi/5 \) for all phase shifters is sufficient and enables all \( N \) routing constellations. The corresponding variable values are depicted in Table II and can be applied to Table I to get the necessary phase shifter settings.

Note that in a 2x2 MZI switch the routing can be arranged by a minimal active phase shift of \( \pi/2 \) in both arms using two phase shifters or by \( \pi \) using a single phase shifter in only one arm for covering both switching states. The shown optimization to reduce the phase shift is analog to this circumstance. Please also note that the numbering of the inputs and outputs in this section is from top (1) to bottom (\( N \)), which is not consistent with [6-7] but with [1].

### III. RESULTS FOR 1xN SWITCHES

In this work, the principle operation described in section 2 is applied to 1xN switches based on the architecture of Fig. 1(a) for \( N \) up to 8. Here, the step-size for the phase variation and a,b,c,d,e,… is defined by \( \pi/N \). The resulting minimal calculated necessary phase shifts are depicted in Table III. Moreover, Table III sums up the corresponding, individual variable values. Note that the shown variable-settings are not necessarily exclusive. In Table III, the phase values are tending to rise with \( N \) but are not always rising. While for a 1x4 switch the necessary active phase shift is \( \pi \), this phase shift is \( 4\pi/5 \) for a 1x5 switch, which is 20% less.

This fact indicates that using only 4 outputs of a 1x5 GMZS is more advantageous than using a 1x4 GMZS because, as a direct consequence, the effective active phase shifter length can be reduced for a given voltage swing and a given phase shifter technology by 20%.

### IV. CONCLUSION

The presented 1xN switch architecture based on generalized Mach-Zehnder interferometers enables the parallel operation of active phase shifters. This work examines the necessary phase conditions for the routing of a specific input signal to one of the \( N \) outputs. It is shown, that a 1x5 switch requires less active phase shift than a 1x4 switch. As a consequence, the use of specific switch architectures is recommended for reducing the effective phase shifter length. Especially for the application of phase shifters at high switching frequencies with high optical losses such as plasma-dispersion-based phase modulators, the reduction of the effective phase shifter length using this approach can be a significant advantage. As a perspective, the experimental demonstration of the calculated phase shift reduction will be realized in further works and the implementation of the functional principle in arrayed waveguide gratings is intended.

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### REFERENCES


