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)). MMIs are well known as reliable, fabrication-tolerant and low-loss on-chip elements [6]. Previous studies have shown the switching capability of such systems. An optical signal can be routed from one of any input waveguides to any of the N output waveguides by the help of the N phase shifters. This principle can be expanded to NxN networks with the design presented in [2], to enable a full routing-redistribution of N input signals at the outputs. To examine the necessary phase conditions for the phase shifter array in a 1xN GMZS, suitable phase conditions can be derived from the matrix formalism, which is presented e.g. in [1], using the transfer matrices of the included MMIs [6-7] and of the phase-shifter array. This work investigates the minimal necessary active phase shifts, which enable the full 1xN switching capability, and examines the advantages of using 5x5-MMIs compared to the counterpart with two cascaded 2x2 switches (see Fig. 1(b)). With the help of a parallel arrangement of the phase shifters, instead of the tree arrangement in Fig. 1(b), the effective phase shifter length can be reduced by implementing the GMZS architecture. E.g., for large N the necessary active phase shifts in the N parallel phase shifters of a GMZS are limited to 2π, but in the design of Fig. 1(b) the light has to pass through $\log_2(N)$ phase shifters, each enabling an active phase shift of π/2. Nevertheless, this work shows that specific configurations of the GMZS with a small number of outputs (N), especially N = 5, are very attractive for integrated on-chip-switches.

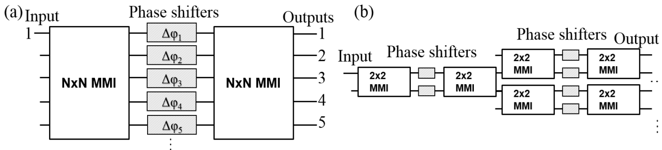

Fig. 1. Different schematic MMI-based architectures for optical on-chip-switching are shown. The phase-shifters are aligned in parallel in the general Mach-Zehnder switch (a), which includes NxN MMIs. The 1xN network in (b) is based on cascaded 2x2 MZI switches.

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 1xN transfer matrix ***T*** from the first input to the N outputs can be expressed by

$$\boldsymbol{T} = \boldsymbol{ABA}\,(1\;0\;0\;0\;0)^{\mathrm{T}}$$
$$= \frac{e^{\mathrm{i}\varphi_0}}{5}\begin{pmatrix} e^{\mathrm{i}\left(\Delta\varphi_1-\frac{18\pi}{5}\right)}+e^{\mathrm{i}\left(\Delta\varphi_2+\frac{12\pi}{5}\right)}+e^{\mathrm{i}\left(\Delta\varphi_3-\frac{2\pi}{5}\right)}+e^{\mathrm{i}\left(\Delta\varphi_4+\frac{8\pi}{5}\right)}+e^{\mathrm{i}(\Delta\varphi_5+2\pi)} \\ e^{\mathrm{i}\left(\Delta\varphi_1-\frac{3\pi}{5}\right)}+e^{\mathrm{i}(\Delta\varphi_2+\pi)}+e^{\mathrm{i}(\Delta\varphi_3+\pi)}+e^{\mathrm{i}\left(\Delta\varphi_4+\frac{9\pi}{5}\right)}+e^{\mathrm{i}\left(\Delta\varphi_5+\frac{9\pi}{5}\right)} \\ e^{\mathrm{i}(\Delta\varphi_1-2\pi)}+e^{\mathrm{i}\left(\Delta\varphi_2+\frac{12\pi}{5}\right)}+e^{\mathrm{i}\left(\Delta\varphi_3+\frac{4\pi}{5}\right)}+e^{\mathrm{i}(\Delta\varphi_4+2\pi)}+e^{\mathrm{i}\left(\Delta\varphi_5+\frac{14\pi}{5}\right)} \\ e^{\mathrm{i}(\Delta\varphi_1-\pi)}+e^{\mathrm{i}\left(\Delta\varphi_2+\frac{11\pi}{5}\right)}+e^{\mathrm{i}(\Delta\varphi_3+\pi)}+e^{\mathrm{i}\left(\Delta\varphi_4+\frac{13\pi}{5}\right)}+e^{\mathrm{i}\left(\Delta\varphi_5+\frac{11\pi}{5}\right)} \\ e^{\mathrm{i}\left(\Delta\varphi_1-\frac{4\pi}{5}\right)}+e^{\mathrm{i}(\Delta\varphi_2+2\pi)}+e^{\mathrm{i}\left(\Delta\varphi_3+\frac{8\pi}{5}\right)}+e^{\mathrm{i}(\Delta\varphi_4+2\pi)}+e^{\mathrm{i}\left(\Delta\varphi_5+\frac{16\pi}{5}\right)} \end{pmatrix} \quad (1)$$

where ***A*** is the transfer matrix for the MMI and ***B*** the transfer matrix for the phase shifter array. φ_0 is an additional global phase shift occurring for all outputs and $\Delta\varphi_i$ 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
Phase-Conditions For Routing To Specific Outputs

Output	$\Delta\varphi_1$	$\Delta\varphi_2$	$\Delta\varphi_3$	$\Delta\varphi_4$	$\Delta\varphi_5$
1	$a+\frac{8\pi}{5}$	$a+\frac{8\pi}{5}$	$a+\frac{2\pi}{5}$	$a+\frac{2\pi}{5}$	$a+0\pi$
2	$b+\frac{3\pi}{5}$	$b+\pi$	$b+\pi$	$b+\frac{1\pi}{5}$	$b+\frac{1\pi}{5}$
3	$c+0\pi$	$c+\frac{8\pi}{5}$	$c+\frac{6\pi}{5}$	$c+0\pi$	$c+\frac{6\pi}{5}$
4	$d+\pi$	$d+\frac{9\pi}{5}$	$d+\pi$	$d+\frac{7\pi}{5}$	$d+\frac{9\pi}{5}$
5	$e+\frac{4\pi}{5}$	$e+0\pi$	$e+\frac{2\pi}{5}$	$e+0\pi$	$e+\frac{4\pi}{5}$

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TABLE II
CALCULATED PHASE SHIFT AND CORRESPONDING VARIABLE-VALUES

Necessary active phase shift	a	b	c	d	e
$\frac{4\pi}{5}$	$\frac{2\pi}{5}$	$\frac{9\pi}{5}$	$\frac{4\pi}{5}$	1π	0π

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 π 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 π/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 π, 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%.

TABLE III
CALCULATED PHASE SHIFTS AND CORRESPONDING VARIABLE-VALUES FOR VARIOUS 1xN-SWITCHES

N	Necessary active phase shift	a	b	c	d	e	f	g	e
2	$\frac{\pi}{2}$	0π	0π						
3	$\frac{2\pi}{3}$	0π	$\frac{1\pi}{3}$	$\frac{2\pi}{3}$					
4	π	0π	$\frac{3\pi}{4}$	$\frac{3\pi}{4}$	$\frac{1\pi}{2}$				
5	$\frac{4\pi}{5}$	$\frac{2\pi}{5}$	$\frac{9\pi}{5}$	$\frac{4\pi}{5}$	1π	0π			
6	$\frac{4\pi}{3}$	0π	0π	$\frac{1\pi}{6}$	$\frac{2\pi}{3}$	$\frac{2\pi}{3}$	$\frac{1\pi}{2}$		
7	$\frac{9\pi}{7}$	0π	$\frac{3\pi}{7}$	$\frac{10\pi}{7}$	$\frac{5\pi}{7}$	$\frac{12\pi}{7}$	0π	$\frac{6\pi}{7}$	
8	$\frac{5\pi}{4}$	0π	$\frac{7\pi}{8}$	$\frac{15\pi}{8}$	1π	0π	$\frac{7\pi}{8}$	$\frac{15\pi}{8}$	$\frac{1\pi}{4}$

Using e.g. the plasma-dispersion-based phase-shifters in [8], the total active phase-shifter loss is 9 dB for a 1x4 network with the design in Fig. 1(b), which can be reduced by at least 20% or 1.8 dB using the switch architecture in Fig. 1(a) with 5x5 MMIs. The reduction in total active phase-shifter loss is even higher if tapering losses at the phase-shifter-waveguide junctions are included. Whereby this study is limited to N < 8, this study should be expanded to higher N.

IV. CONCLUSION

The presented 1xN switch architecture based on generalized Mach-Zehnder interferometers enables the parallel operation of active phase shifters. This works 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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