# $2 \times 2$ Thermooptic Silicon Oxynitride Optical Switch Incorporating the Cascaded Multimode Interference Waveguides 

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## INTRODUCTION

Various waveguide devices being reported recently based on the multimode interference (MMI) effect include $N_{\mathrm{x}} N$ power splitters/combiners [1-3], switches based on Mach-Zehnder interferometers (MZIs) [4], optical multiplexers/demultiplexers [5], and ring lasers [6]. For the conventional $2 \times 2$ MZI- and MZI-MMI-based optical switches, their overall lengths are usually longer than what are desired in order to ensure their output waveguides are being placed sufficiently far apart from each other in order to minimize the optical and electrical parasitical couplings. Therefore, reducing the length of a switching device while not adding unnecessary burden to its fabrication process become a top priority for realizing an optimal optical switch with much reduced footprint and low propagation and scattering losses.

In order to reduce the beat length, what Mašanović et al. have done [7] is to cascading $1 \times 2$ symmetric MMI splitter (to evenly split the power into two) with $1 \times 1$ general MMI stage (to produce mirrored image). Their goal is to realizing $1 \times 2$ power splitter with wider spacing between two output waveguides while keeping the overall length of the device shorter compared to a conventional $1 \times 2$ MMI splitter. The other benefits also include a significant reduction in the waveguide scattering and radiation losses by avoiding the use of the S -bends and Y-branches in the design of MZIs. Therefore, with somewhat drastically different from Mašanović et al.'s approach, what we propose to do, as depicted in Fig. 1, is to cascading four $1 \times 1$ general MMI waveguides (or MMIs in short, placing two at each input and output terminal of MZI switch) with one $2 \times 2$ paired MMI; our goal is to produce a multistage MMI-based MZI switching device with high extinction coefficient and low propagation and scattering losses.

## EXPERIMENTS

The schematic drawings showing the device structure and the cross-sectional profile of the multimode waveguide with SiON core buried in $\mathrm{SiO}_{2}$ layers taken along the AA' line (not drawn to scale) are depicted in Fig. 1. The entire $2 \times 2$ MZI optical switch consists of multiple stages of MMI waveguides cascaded together, that is, with two general MMIs ( $W_{\text {Gen }}=51 \mu \mathrm{~m}$ and $L_{\text {Gen }}=11030 \mu \mathrm{~m}$ ) at each input and output terminal of a $2 \times 2$ paired MMI ( $W_{\text {Paired }}=102 \mu \mathrm{~m}$ and $L_{\text {Paired }}=6960 \mu \mathrm{~m}$ ) located at the middle section of the device. The widths of input/output waveguides and the connecting waveguides between the general and paired MMIs are set at 10 and $12 \mu \mathrm{~m}$, respectively, in order to compensate in advance the
possible width losses due to photolithography and inductively-coupled plasma (ICP) dry etching. The dimensions of these MMI waveguides are chosen in order to reflect a fact that the sum of $\left(L_{\text {Gen }}+L_{\text {Paired }}\right)$ is still comparably shorter than the length of $2 \times 2$ general MMI waveguide if the spacing $(T)$ between the two input or two output waveguides is to be maintained at $116 \mu \mathrm{~m}$. Notice that the waveguide spacing $T$ is purposely set to be a rather large value in order to minimize the possible crosstalk between the output waveguides while refraining from the use of S-bends because of their associated propagation and scattering losses.

Before we proceeded on fabricating and characterizing the foregoing device, the functionality of the entire $2 \times 2$ MMI switch must be simulated beforehand using the finite-difference beam propagation method (FD-BPM). Note that the SiON thermo-optic coefficient ( $d n / d t$ ) of $2.35 \times 10^{-5} /{ }^{\circ} \mathrm{C}$ was used in the FD-BPM simulation. The simulated result depicted terms of bar and cross output powers versus the applied heater temperature is presented in Fig. 2. Accordingly, the first cross-over point corresponding to the initiation of light switch from bar to cross port occurs at $12^{\circ} \mathrm{C}$, while the second cross-over point for light output going from cross to bar port begins to take place at around $33^{\circ} \mathrm{C}$. It would be evidenced later through experimentation that its result agreed rather well with the simulation.


FIG. 1. Schematic drawings of cascaded $2 \times 2$ MMI optical switch and the cross-sectional profile of the multimode waveguide with SiON core buried in $\mathrm{SiO}_{2}$ layers taken along the AA' line (not drawn to scale).

## RESULTS AND DISCUSSION

The switching characteristics of these devices were obtained by applying a voltage to the heating electrode. The result showed that the light initially switching from the bar to cross port at heating power of $\sim 0.82 \mathrm{~W}$ and with the extinction coefficient of higher than 13 dB was clearly detected. By further increasing the heating power, the light can be switched in an alternate fashion between the two output ports, where their power splitting ratios at different heater temperatures are measured and shown in Fig. 3. The Al heater temperature corresponding to each bias applied to the Al electrode could be measured by using the temperature coefficient $\left(a_{\mathrm{Al}}\right)$ of the Al electrical resistivity; here, $a_{\mathrm{Al}}=0.0043 /{ }^{\circ} \mathrm{C}$.


FIG. 2. The switching characteristic of a $2 \times 2$ MMI waveguide switch as simulated using the finite-difference beam propagation method (FD-BPM).


FIG. 3. The normalized power splitting ratio between bar and cross output channel of $2 \times 2$ MMI optical switch measured at different aluminum heater temperatures.


FIG. 4. Optical response (upper trace, $10 \mathrm{mV} /$ div) of 2 x 2 MMI optical switch under an electrical bias switching (lower trace, $5 \mathrm{~V} /$ div) with a heating power of 0.82 W is applied. The horizontal time scale is set at $500 \mu \mathrm{~s} / \mathrm{div}$.

Finally, as shown in Fig. 4, with the heating power of $\sim 0.82 \mathrm{~W}$ applied, the rise and fall times of this device were obtained as 360 and $395 \mu$ s, respectively. The microsecond response time of thermooptic switch is considered adequate for most types of polarization independent optical switching. An improvement in switching response is certainly possible through the optimization of the overall device geometry and electrode layout.

## CONCLUSIONS

In summary, the multistage MMI-based 2 x 2 $\mathrm{SiO}_{2} / \mathrm{SiON} / \mathrm{SiO}_{2}$ optical switches utilizing the thermooptic effect were successfully designed and fabricated. Both the simulation and experimental results agreed rather well with each other, except with a minor discrepancy due to a rather imprecise SiON thermo-optic coefficient used during the simulation. Our experimental results have demonstrated that a minimal heating power of $\sim 0.82 \mathrm{~W}$ is required to initiate the optical switching while the highest extinction coefficient of higher than 13 dB could be achieved. Finally, the rise and fall times of these devices obtained are in a neighborhood of 360 and $395 \mu \mathrm{~s}$, respectively. Details with regard to the devices simulation, fabrication process, and their characterizations will be reported during the upcoming SSDM 2009 conference.

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