

Fast thermo-optical switch based on SOI waveguides

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ABSTRACT

Thermo-optical silicon-on-insulator (SOI) waveguide switch has been fabricated and characterized. The switch is based on a 2x2 Mach-Zehnder interferometer and 9 microns thick ridge waveguides. The extinction ratio of the switch is 17 dB with ultra-slow modulation and it is limited by the unoptimized directional coupler lengths. Thermo-optical switching with conventional on/off modulation was demonstrated up to 10 kHz. The average power consumption was 150 mW and the extinction ratio was 15 dB in 10 kHz square wave modulation. By using a novel modulation principle the maximum frequency was raised up to 167 kHz, while still maintaining the 15 dB extinction ratio in square wave modulation. With random binary modulation at 167 kHz frequency (3 μ s per bit) the extinction ratio remained above 13 dB and the average power consumption was 590 mW. The obtained frequency limits for square wave modulation correspond to a maximum of 1% deviation from the attainable extinction ratio limits. With less strict extinction ratio requirements the maximum frequencies can be much higher. The new modulation method can be used to radically speed up interferometric switches with a tolerable increase in the power consumption.

Keywords: Silicon-on-insulator, SOI, waveguide, thermo-optical switch, phase modulation, Mach-Zehnder interferometer

1. INTRODUCTION

Inexpensive and sufficiently fast optical switches are one of the key elements when the optical communication technology continues its expansion from the backbone networks to the access networks. Switches close to the end users must be inexpensively mass produced. Optical switches can be roughly divided into two categories based on their frequency range. Fast switches operate above 1 MHz and they are typically based on nonlinear effects, electro-optical modulation or current injection modulation. Slow switches operate below 1 MHz. Actually, they are typically based on thermo-optical (TO) modulation or micro-electro-mechanical systems (MEMS) that operate well below 10 kHz. The slow switches, and especially the thermo-optical switches, are typically much less expensive than the fast switches. There is clearly a lack of inexpensive switches that can operate in the 10-1000 kHz range. Currently available TO switches typically have a maximum frequency of 1 kHz or less.

In scientific papers there have been some examples^{1,2,3} of thermo-optical switches that operate above 10 kHz. Fischer et al, for example, have demonstrated a thermo-optical 1x1 Mach-Zehnder (MZI) switch with 5 μ s rise time and 150 mW power consumption by using silicon-on-insulator (SOI) technology². However, their small waveguide structure was not optimized for fiber coupling, the optical wavelength was 1300 nm and the continuously modulated operation was not reported.

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Silicon-on-insulator technology offers a relatively inexpensive method to fabricate thermo-optical switches. The high thermo-optical constant ($1.86 \cdot 10^{-4} \text{ K}^{-1}$) and good thermal conductivity of silicon can make SOI switches faster than most other TO switches. SOI technology can also be used to integrate different optical, electrical and micromechanical functions onto a common substrate. The advantages and disadvantages of SOI waveguides have been discussed in detail elsewhere^{4,5,6}.

In this work, TO switches have been realized based on SOI ridge waveguides with a large cross-section⁶. The waveguides have a modal fiber coupling loss clearly below 1 dB (<0.3 dB for optimized design), and a propagation loss below 0.5 dB/cm. Due to a thermal oxide cladding the waveguides are polarization dependent, but this property should be eliminated by choosing an appropriate cladding material, as the results from some polarization independent SOI waveguides indicate⁷. The switches are implemented by using a 2x2 MZI layout and the optical wavelength is 1550 nm. The devices have been operated by using both conventional modulation and a novel interferometric modulation technique. The continuously modulated 167 kHz operation of a TO switch with a large waveguide core and a 15 dB extinction ratio is the fastest result so far reported. The novel modulation principle is now proposed and demonstrated for the first time, and it can be applied to radically increase the operational frequency or the response time of other interferometric switches as well.

2. BACKGROUND ON THERMO-OPTICAL SWITCHING

Thermo-optical switches are often assumed to be limited clearly below the 10 kHz frequency due to the slow thermal conduction in optically transparent materials. In general, TO switches can be made faster by reducing the waveguide size. Unfortunately, this normally leads to higher optical losses, both due to the size mismatched fiber-waveguide interconnections and the increased scattering losses. Thermal conductivity between the heater and the waveguide should be maximized, but this is normally limited by the need for sufficient optical insulation. In low-index contrast (low Δn) waveguides the distance between the core and the heater element must be several micrometers. Increasing the thermal conductivity around the heated waveguide makes the switch faster, but it also increases the power consumption. This leads to a trade-off between the speed and the power consumption. In many waveguide structures the requirement for sufficient optical confinement also limits the possibility to increase thermal conductivity between the waveguide core and the underlying substrate.

In addition to the waveguide structure, also the switching structure, or the principal layout, effects the characteristics of a switch. Typical TO switches are based on a 1x1, 1x2 or a 2x2 MZI structure. Larger matrices are obtained by cascading these fundamental switching blocks⁸. The extinction ratio of a switch can be improved by directing the signal through more than one fundamental switching block in each switching node⁸. Two successive switches with 20 dB extinction ratios produce a total extinction ratio of 40 dB. The disadvantages of this principle are increased power consumption and larger device area. In general, the 2x2 switch is more difficult to realize than the 1x1 switch, or a modulator, while the 1x2 switch lies somewhere in between. This is due to the increased number of input and output ports and the requirement for even transmission between different ports. In a 1x1 switch, or in a modulator, the modulation can be based on absorption, while this is not possible in an interferometric 1x2 or 2x2 switch.

There are several tricks that can be used to increase the switching speed or to reduce the response time of the switch without modifying the actual switch structure. Firstly, the switching speed can be significantly increased if one satisfies with a lower output extinction ratio or, in another words, lower modulation depth. For example, a 3 dB extinction ratio can be achieved with a much higher frequency than a 20 dB extinction ratio. Secondly, single transitions between different switching states may be obtained with very short rise or fall times, but these do not automatically guarantee acceptable operation in continuously modulated operation. For example, an ultra-short rise time is not very useful if the fall time is much longer. In some cases the convergence of successive transitions may also cause e.g. heat build-up that

limits the maximum frequency. Finally, surprisingly fast operation may be obtained by using square wave modulation and so called overdriven switching (or overshooting)⁹. Unfortunately, this principle does not support any controlled switching operations.

Due to the multitude of parameters and switching principles one should be careful when comparing different switching solutions. In addition to the maximum switching speed itself, one should also pay attention to the type of the switch (1x1, 1x2, 2x2, ...), type of modulation (e.g. random or square wave), the insertion loss, the extinction ratio (or the modulation depth), the polarization characteristics, the power consumption and the price.

3. DEVICE DESIGN

A detailed description of the device design has already been published elsewhere¹⁰. Therefore, only a short summary and update of the design will be given here. It should be noted that the mask layout has not been optimized after the initial design, thus leaving plenty of room for future improvement with respect to e.g. extinction ratio and device size. The waveguide width in the old lithography mask is $W = 10 \mu\text{m}$. The SOI wafers used in this work had a slightly thinner SOI layer ($9 \mu\text{m}$) than the wafers used in the original design ($10 \mu\text{m}$)¹⁰. Therefore, the vertical dimensions of the waveguide were slightly modified to maintain single-moded operation. The silicon core is surrounded by $1 \mu\text{m}$ thick optically insulating oxide layers and the thin film heater is on top of the ridge. The SOI ridge waveguide structure is presented schematically in Fig. 1a.

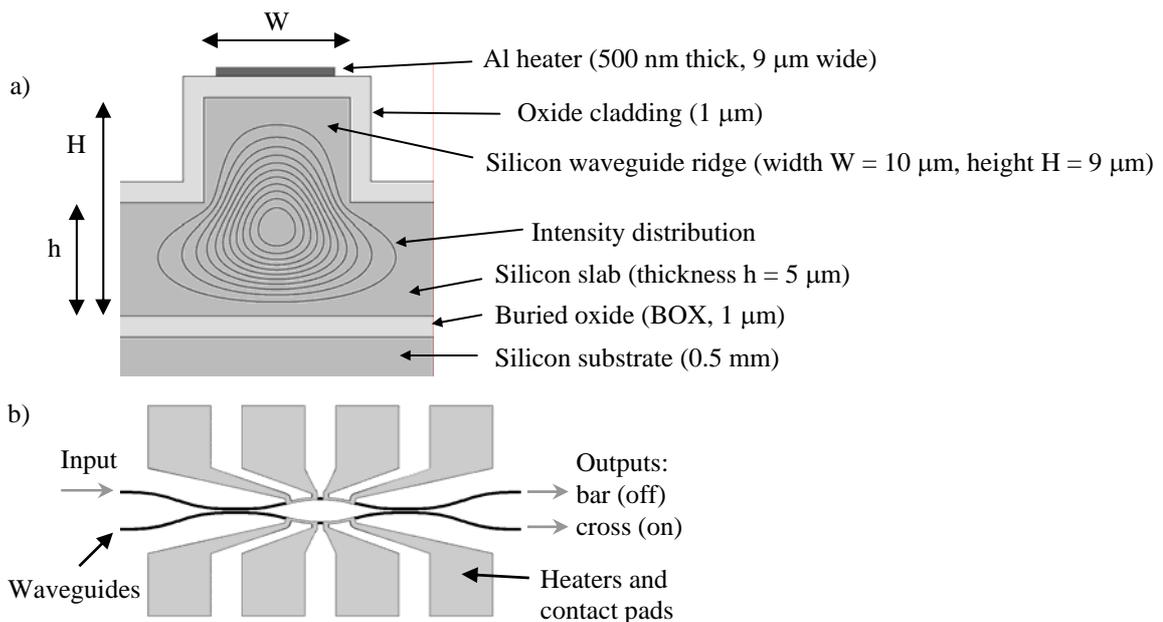


Figure 1: a) Cross-section of the SOI ridge waveguide with an aluminum heater on top of the ridge. The intensity distribution of the fundamental mode is shown with contour lines. b) A schematic layout (top-view) of the 2×2 MZI switch.

Ridge type silicon-on-insulator waveguides have a very large refractive index contrast (high Δn) between the silicon core ($n \approx 3.5$) and the surrounding oxide (or air) cladding ($n \approx 1.5$ or 1). Nevertheless, they can be single-moded (SM) even when the width and the height are both several micrometers. This is because the ridge (width W , total thickness H)

is surrounded by a slab waveguide (thickness h) that offers an "escape path" for the higher order modes. The SOI ridge waveguide is single-moded when both the conditions¹¹

$$\frac{W}{H} < 0.3 + \frac{h/H}{\sqrt{1-(h/H)^2}} \quad \text{and} \quad (1)$$

$$h/H \geq 0.5 \quad (2)$$

are satisfied. In the fabricated waveguide switch the width, the ridge height and the slab height were $W \approx 9 \mu\text{m}$, $H \approx 9 \mu\text{m}$, and $h \approx 5 \mu\text{m}$, respectively. Therefore, the device is operating at the boundary between single- and multi-moded operation. The validity of the above mentioned single-mode conditions can be, and has been, verified both by solving the propagating modes of different ridge waveguides numerically and by observing the output of realized ridge waveguides with an IR-camera. The modal fiber coupling loss between the waveguide and a standard single-mode fiber is clearly below 1 dB^{6,10}. This can be suppressed down to 0.3 dB by optimizing the waveguide cross-section¹⁰.

The waveguide switch consists of two cascaded waveguide couplers with thermo-optic heaters on both waveguide arms connecting the two couplers. A schematic layout of the 2x2 MZI switch is shown in Fig. 1b). The coupling coefficient for directional couplers is difficult to calculate accurately, because it is affected by the coupling between the bent waveguides, the etch depth, the linewidth changes (during the process), etc. Therefore, several directional couplers with different waveguide spacings and lengths were designed to determine their coupling behavior experimentally. Five different directional coupler lengths were used to define five different switch versions on the mask. These lengths determine the attainable extinction ratio of the switch.

The 2x2 MZI switch is in a cross state (off), when the heating elements are not operated. It turns into a bar state (on) when a temperature difference corresponding to a phase difference of $\Delta\phi = 180^\circ$ is applied between the two waveguide branches by operating one or more heaters. The optimum bar- and cross-states can be obtained only when the directional couplers are identical and their lengths correspond to perfect 50:50 (-3 dB) power division.

According to the thermal modelling¹⁰, a 3 K temperature change is enough to switch the output state of the device. The rise (0%→90%) and the fall (100%→10%) times were both estimated to be 200 μs and the electrical power consumption was estimated to be 120 mW. The response times correspond to a maximum frequency of approximately 2.5 kHz. Calculated cross-sections of two temperature change distributions during waveguide heating are plotted in Fig. 2. The cooling takes place with the same speed, but then the temperature change distributions are much more flat. Heat conducts very efficiently from the heater into the silicon ridge and then spreads horizontally along the silicon slab. Silicon has a relatively high TO constant ($1.86 \cdot 10^{-4} \text{ K}^{-1}$) and good thermal conductivity, while the oxide cladding is very thin. This results in a rapid optical phase change in the waveguide. Finally, heat diffuses through the thin buried oxide (BOX) layer into the silicon substrate that behaves as a small heat sink. The exact temperatures, diffusion times and heating powers are strongly dependent on the boundary conditions. These, on the other hand, depend on the actual environment around the chip. Modifications in the airflow and in the bonding of the chip to an underlying support plate may cause significant changes in the exact values.

In conclusion, according to the design and simulations, the SOI waveguide switch can be modulated much faster than most other TO switches. This is due to the good thermal conductivity between the heater, the core and the substrate, which is difficult to realize for low Δn waveguides. Only 1 μm thick oxide layers are sufficient to confine the waveguide optically, while the SOI layer acts as an efficient heat spreader¹⁰. The corresponding increase in the power consumption is unavoidable, but owing to the efficient heat confinement into the waveguide core, the power increase is very reasonable with respect to the increased frequency.

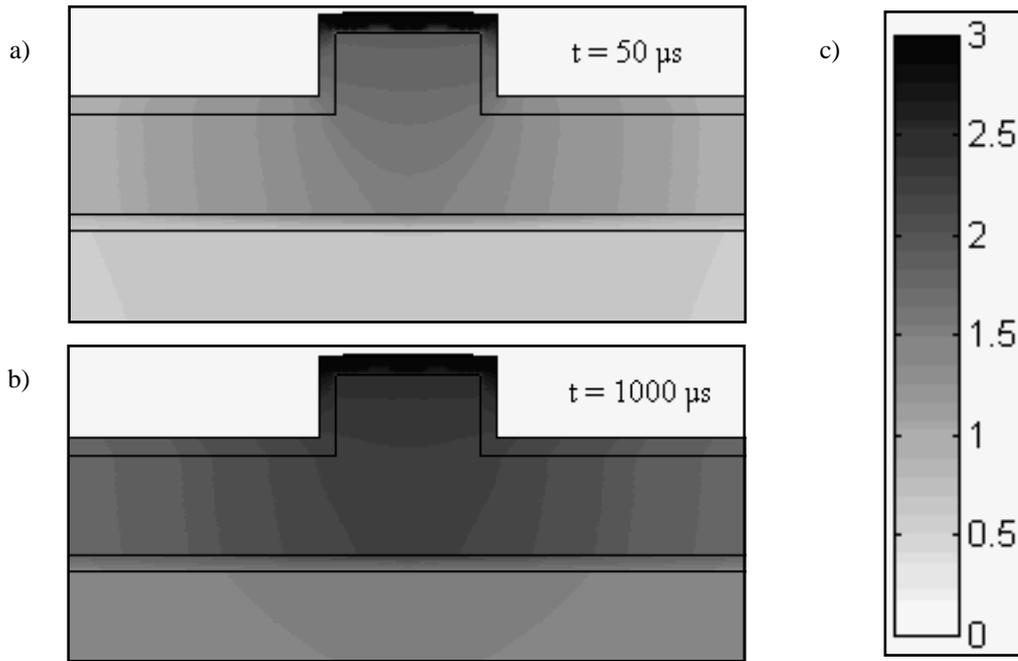


Figure 2: Calculated cross-sections of two temperature change distributions. The heat is generated in the thin film heater lying on top of the waveguide ridge and the total heating power is 10 mW. a) Situation $50 \mu\text{s}$ after the heating has started. b) Situation 1 ms after the heating has started (stabilized situation). c) Temperature change scale.

4. FABRICATION

Bond-and-etchback SOI (BESOI) wafers were used for fabricating the SOI waveguide switches. The active silicon layer thickness was $9.3 \mu\text{m}$ and the buried oxide layer thickness was $1 \mu\text{m}$. This BOX thickness was enough to prevent any leakage of optical power into the underlying silicon substrate.

The switch fabrication was done in two phases. First, passive SOI waveguide structures were defined and second, thermal control was introduced by fabricating heating structures on top of the waveguides.

Waveguide fabrication was started with growing a 500 nm thick oxide layer using plasma-enhanced chemical vapor deposition (PECVD). This oxide layer was used as a hard mask in silicon etching. The waveguide structure was patterned using standard photolithography and the pattern was dry etched into the hard mask. Then the structure was etched into SOI using inductively coupled plasma (ICP). The ICP etching process was started with a long etch step with continuous passivation. Then the etching continued with alternating passivation and etching steps (etching gas SF_6 , passivation gas C_4F_8). This was done to ensure side-wall verticality. The durations of the etching and passivation cycles were both 5 s . After removal of the resist and the passivation polymers in oxygen plasma, the oxide mask was removed by wet etching in buffered hydrofluoric acid. A scanning electron microscope (SEM) image of a cleaved test waveguide endface after ICP etching and mask removal is shown in Fig. 3. It clearly shows the high verticality and smoothness of the etched side-walls.

After the ridge waveguide fabrication an approximately $1 \mu\text{m}$ thick thermal oxide (TOX) was grown on top of the waveguide. This oxide served as an upper cladding for the waveguide, insulating the waveguide optically from the

heating elements. Thermal oxidation also reduced any surface roughness that might be present on the waveguide surface after ICP etching, and thinned the SOI layer down to 9 μm . A 500 nm thick Al layer was sputter deposited. It was patterned using standard photolithography and dry etching to form the heaters and their contact pads. After the dicing and the polishing the optical chips were glued on top of supporting plates with thermally conducting glue. Then the contact pads were wire bonded to provide the necessary electrical contacts and the chips were ready for the measurements.

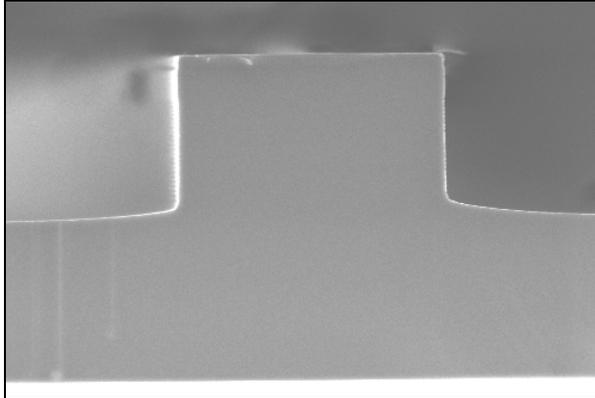


Figure 3: SEM image of an SOI waveguide cross-section after the ICP etching. The total height H , etch step $H-h$ and width W of the waveguide are approximately 9 μm , 4.3 μm and 8 μm , respectively. These are similar, but not exactly the same dimensions as in the switch.

5. NEW MODULATION PRINCIPLE

Traditional modulation is based on turning the heating power simply on and off. In some cases bias voltages are used to stabilize the power consumption or to optimize the off-state of a nonideal switching structure. However, there are only two different heating states in traditional modulation. The advantage of this method is simple control electronics, but the exponential stabilization ($\Delta T = \Delta T_{\infty} (1 - e^{-t/\tau})$) of the temperature difference seriously limits the attainable frequency. The purpose of the new modulation principle is to remove this limit by optimizing the time-dependent heating powers in both waveguide branches. The principle is mainly focused on binary switching operation, but it may also be applicable for analog switch control.

In the new modulation principle the switching operation is divided into four different spans (time intervals) that each correspond to a single transition between two successive control bits. The spans are the on-span (binary 1 \rightarrow 1), the fall-span (1 \rightarrow 0), the off-span (0 \rightarrow 0), and the rise-span (0 \rightarrow 1). The heating power patterns in both waveguide branches (P_1 , P_2) are optimized separately within each span, as illustrated schematically in Fig. 4. The duration of each span is the same as the duration of one control bit, but the selection of the span is based on two bits, instead of one.

The control powers are optimized according to the following logic. The static on-span remains unchanged compared to the traditional modulation ($P_1 = P_{\text{on}}$, $P_2 = 0$, $\Delta\phi = 180^\circ$). The static off-span, on the other hand, is biased so that both waveguide branches are heated with approximately equal power ($P_2 \approx P_1 = P_{\text{bias}}$, $\Delta\phi = 0^\circ$). This increases the average power consumption, but it also radically increases the switching speed, as will be shown below. Both the off- and the on-spans are static with respect to time, so that the switching state may remain stable for long periods of time (e.g. for binary ...1111111111...). During the rise-span, P_1 forms a high power peak, while P_2 drops from P_{bias} to zero. The

resulting temperature difference is a sum of the heating of the first waveguide and the cooling of the second waveguide. This generates a very fast rise time for the phase difference ($\Delta\phi = 0^\circ \rightarrow 180^\circ$) between the waveguides. The fine structure of P_1 is optimized so that the phase difference reaches and maintains the allowed phase range as soon as possible. Similarly, during the fall-span P_1 drops from P_{on} to zero, while P_2 forms a high power peak. Therefore, while the first branch cools down, the second branch heats up, until the temperatures meet ($\Delta\phi = 180^\circ \rightarrow 0^\circ$). Then both branches cool down, while maintaining the phase difference ($\Delta\phi \approx 0^\circ$) within an allowed range. If the switching is optimized for a given frequency f , then the operational frequency can be easily reduced by inserting additional on- and off-type delays between all the spans. It should also be noted that the modulation frequency corresponds to two spans, not one.

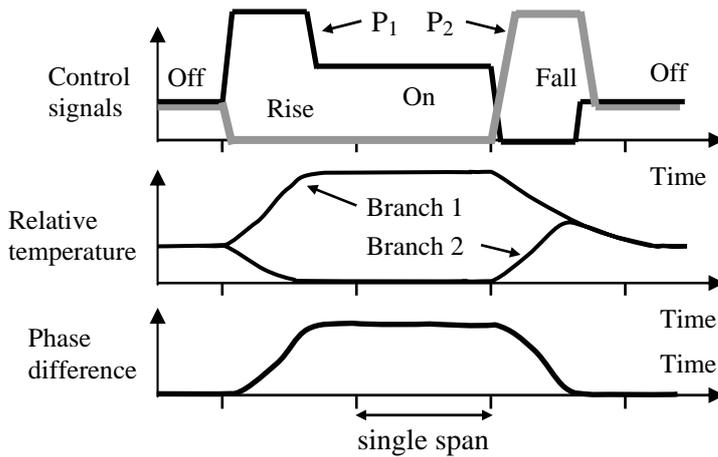


Figure 4: Schematic of the novel modulation principle.

The main advantage of the proposed principle is that the exponential temperature stabilization does not limit the operation and the maximum frequency can be radically increased. The increased complexity in the control electronics is not a serious problem if some kind of simple control electronics is anyway used to control the switch. With suitable software the optimization is not very difficult and fine tuning between similar devices can be carried out very fast.

6 RESULTS

The fabricated waveguides and waveguide switches were characterized optically by directly butt-coupling a polarization maintaining fiber (PMF) to the input end and a multi-moded fiber (MMF) to the output end of each waveguide. The MMF was connected to a fast photodetector. One axis of the PMF was carefully aligned parallel to the chip surface, i.e. horizontally. This ensures that the polarization states of the input fiber are coupled directly to the polarization states of the waveguide with minimum cross-talk (below -25 dB). Input power from a 1550 nm laser was then coupled very accurately to either polarization axis of the PMF and a transmission maximum from the PMF to the MMF was located by iteratively aligning both the input and the output fiber with respect to the waveguide.

6.1 Results without modulation

Before carrying out the switching measurements, the waveguides, switches and some separate directional couplers were characterized without heating them. This showed that the waveguides were single-moded and that the couplers were strongly polarization dependent. The latter is due to the thermal oxide cladding that induces a stress distribution into the

silicon core. The waveguides and couplers maintain the polarization state with an extinction ratio better than 15 dB, so they could be used to realize polarization maintaining or polarizing devices. However, for the majority of applications, the devices should be polarization independent. Such SOI ridge waveguides have indeed been realized⁷, so the switches reported here could be made polarization independent by optimizing the fabrication process. All the following results are obtained with TE polarized input light (electric field along the substrate plane).

Preliminary characterization also revealed that even the best switch had slightly non-ideal DC lengths. This is not surprising, since the coupler length was varied only coarsely, as already discussed in Chapter 3. The best switch was chosen for the switching experiments and it had a maximum extinction ratio (ER) of 17 dB (98:2). During the phase modulation (switching), this is an optimum value that represents 100% phase modulation ($\Delta\phi = N \times 180^\circ$).

6.2 Results with traditional modulation

The switch was first tested by using traditional modulation with a square wave signal generator. The heating power P in the active (heated) waveguide branch was adjusted so that the on-state was optimized for very slow modulation ($f \ll 1$ kHz, $P = P_{on}$, $\Delta\phi = 180^\circ$). The power consumption in the on-state was $P_{on} \approx 300$ mW. The transmission and the extinction ratio were found to be the same for both the bar and the cross-state of the switch with slow modulation. Therefore, the following measurements were carried out by measuring only the cross-path transmission through the switch. Optimized heating with very slow modulation determined the limits for the attainable transmission variation. The maximum frequencies for square wave modulation were determined by requiring a maximum of 1% deviation from the target transmission in both switching states. This is a very strict requirement and in an ideal switch structure it would correspond to an output extinction ratio of 20 dB. Due to the nonideal directional couplers, it only corresponds to 15 dB (97:3) extinction ratio in these measurements.

The maximum frequency for square wave modulation was found to be approximately 10 kHz. The measured result is shown in Fig. 5. Much faster modulation was obtained with extinction ratios smaller than 15 dB (e.g. 100 kHz for 3dB modulation). Both the maximum frequency and the power consumption were somewhat higher than the simulated values. This is probably due to the differences in boundary conditions.

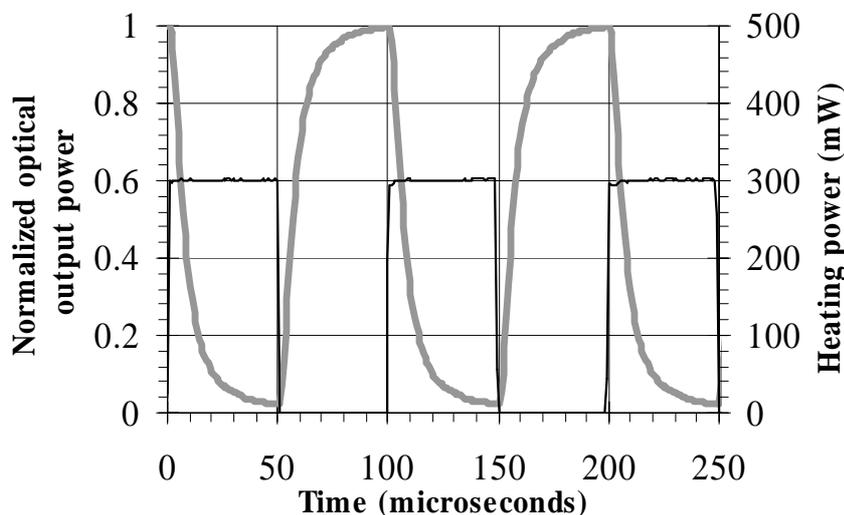


Figure 5: Normalized optical output power (thick gray line) for the cross-path through the thermo-optical switch and a control signal for the heating (black line) as a function of time at 10 kHz modulation. Deviation from the optimum (static) transmission minimum and maximum is below 1%.

6.3 Results with the new modulation principle

The proposed modulation principle was tested by applying it to the thermo-optical SOI waveguide switch described above. The control electronics was built from basic electronic components, and software was developed to control the system. The control circuit for one heating resistor consisted of one 16F84 microprocessor connected to an 8-bit digital to analog converter (DAC) made from an operation amplifier and a resistor network. The DAC's output was connected to the heating resistor via a power transistor to provide sufficient output current. For operating both branches of the switch, two of these circuits were built. The total cost of electronics was less than \$25, the two microprocessors being the most expensive parts. The desired voltage patterns were generated by the software and sent via the computer's parallel port to the microprocessors' input ports. After receiving the complete patterns the processors started to repeat them until new patterns were transmitted.

The fall- and the rise-spans were optimized by adjusting P_1 and P_2 in 1 μs time steps. Shorter time steps would ease the optimization at high frequencies, but the used control electronics could not handle any shorter steps. Already at 1 μs steps the DAC strongly distorts fast voltage transients and generates sharp voltage peaks. Each span should include at least three time steps for any meaningful optimization, so the maximum frequency with 1 μs time steps is $f_{\text{max}} = (2 \cdot 3 \mu\text{s})^{-1} = 167 \text{ kHz}$. Due to the simple and inexpensive electronics, the voltage patterns had very non-ideal shapes, but the feasibility of the new modulation principle could still be demonstrated, as will be shown below.

After appropriate optimization, $\Delta\phi$ could be changed between 0° and 180° in less than 3 μs , as can be seen from the optical response shown in Fig. 6. With square wave modulation the 15 dB extinction ratio was still achieved at the 167 kHz frequency that corresponds to 3 μs long spans and, thus, the limits of the control electronics. If a much lower extinction ratio would be accepted, such as 3 dB, then the maximum frequency could probably be raised close to the MHz regime. Unfortunately, the available control electronics was not sufficiently fast for such tests. The modulation at 167 kHz was tested with various different bit sequences, including back and forth transitions, as well as long chains of successive ones or zeros. The internal structure of each span remained constant in these experiments. For all bit sequences the extinction ratio remained above 13 dB (95:5). An example of the optical response with respect to a bit sequence at 167 kHz is shown in Fig. 6.

At 167 kHz operation the average total heating powers (including both branches) during the off-, on-, fall-, and rise-spans were 120 mW, 350 mW, 760 mW, and 1130 mW, respectively. With respect to square wave modulation, the power consumption is increased due to the high power peaks that correspond to changes in the switching state (rise- and fall-spans). In random modulation all spans are equally popular and the average heating power becomes 590 mW and in ultra-slow (...000001111111...) modulation the average heating power drops to 230 mW. Square-wave (...01010101...) modulation produces a worst-case average power of 950 mW. Relatively high peak powers are necessary for high frequency modulation, but because of the unoptimized electronics they became unnecessarily high in these measurements.

Any frequency between 10 kHz and 167 kHz can be obtained by optimizing the fall- and rise-spans with respect to the power consumption and the required minimum extinction ratio. When certain basic frequencies have been optimized, one can obtain the intermediate frequencies simply by inserting additional delays between the spans. This allows for rapid frequency fine tuning. Some sample frequencies were optimized to estimate the dependence of average heating power on the frequency. In this experiment, square wave modulation was used and a 15 dB extinction ratio was required for both switching states. The on- and off-spans again corresponded to static operation and single rise- and fall-spans were required to produce a stable output state (no overdriving). Table 1 summarizes the results at various frequencies between 10 kHz at 167 MHz. The average power consumption with random modulation was found to vary approximately linearly with respect to the frequency f , and an estimation for the power can be obtained from the formula $P_{\text{ave}} \approx 116 \text{ mW} + f \cdot 2.8 \text{ mW/kHz}$.

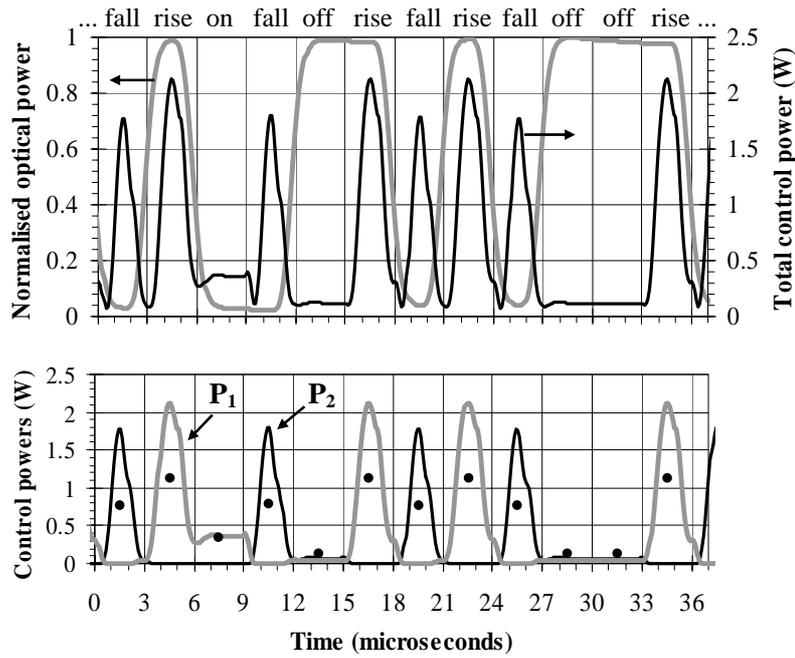


Figure 6: Measured switching at 167 kHz (3 μ s/bit). Upper plot: Optical response (cross-path output) and total heating power. Lower plot: heating powers P_1 , P_2 , and the average heating power for each span (black dots). Optical signal has a 2 μ s delay with respect to the heating power (span labels on top refer to the heating pulses).

Table 1: Summary of square wave switching characteristics at various frequencies by using the traditional modulation (10 kHz) and the novel modulation. A maximum of 1% deviation was required with respect to the attainable response range that was limited by the physical switch structure (nonideal coupler lengths). A fixed off-state (bias) is assumed, except for the 10 kHz modulation (no bias).

Case	Span length (μ s)	Frequency (kHz)	Average power 1 ^[1] (<i>random</i>) (mW)	Average power 2 ^[2] (<i>worst-case</i>) (mW)	Average power 3 ^[3] (<i>slow</i>) (mW)	Average power 4 ^[4] (<i>lin. fit</i>) (mW)	Peak power (mW)
1 ^[5]	50.0	10.0	150	150	150	144	300
2	6.3	79.4	331	427	235	338	608
3	5.3	94.4	371	506	235	380	787
4	4.3	116.0	436	638	235	441	1352
5	3.3	151.6	528	822	235	540	1848
6	3.0	167.0	590	945	235	584	2180

^[1] With random modulation.

^[4] Estimation based on the linear fit of random modulation.

^[2] With back and forth modulation (...101010101...).

^[5] With traditional square wave modulation (...101010101...).

^[3] With ultra-slow modulation (...0000011111...).

7. CONCLUSIONS

By using a simple and inexpensive 2x2 MZI switch based on SOI technology, traditional TO modulation at 10 kHz frequency was obtained with 150 mW average power consumption. With a novel modulation principle the modulation

frequency was then pushed up to 167 kHz. The extinction ratio still remained at 15 dB for square wave modulation and it was 13 dB for random binary modulation. The extinction ratio is limited below 17 dB due to the nonideal coupler lengths, so the measured extinction ratios deviate only 1-3% from the attainable limits. The average power consumption with random modulation was 590 mW at 167 kHz. We expect that a reduction of the core size, optimization of the thermal insulation, improved electronics and less strict extinction ratio requirements can improve the frequency to power ratio and increase the frequency to the MHz range. The results indicate potential in realizing inexpensive thermo-optical switches in the 1-1000 kHz frequency range by using SOI technology. The very successful first testing of the proposed new modulation principle also encourages further testing with other interferometric switch structures. The basic principle could be used to speed up many existing switches in many different frequency ranges.

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REFERENCES

1. G. Cocorullo, M. Iodice, I. Rendina, and M. Sarro, "Silicon thermo-optical micromodulator with 700-kHz, -3-dB bandwidth", *IEEE Photon. Technol. Lett.* **7**, pp. 363-365, 1995.
2. U. Fischer, T. Zinke, B. Schüppert, and K. Petermann, "Singlemode optical switches based on SOI with large cross-section" *Electron. Lett.*, **30** (1994), 406-408.
3. S. A. Clark, B. Culshaw, E. J. C. Dawnay, and I. E. Day, "Thermo-optic phase modulators in SIMOX material", *Proc. SPIE* **3936**, pp. 16-24, 2000.
4. B. Jalali, "Silicon-on-insulator photonic integrated circuit (SOI-PIC) technology", *SPIE Proc.* **2997**, pp. 60-71, 1997.
5. T. Zinke, U. Fischer, B. Schüppert, K. Peterman, "Theoretical and experimental investigation of optical couplers in SOI", *Proc. SPIE* **3007**, pp. 30-39, 1997.
6. T. Aalto, S. Yliniemi, P. Heimala, P. Pekko, J. Simonen, M. Kuittinen, "Integrated Bragg gratings in silicon-on-insulator waveguides", *Proc. SPIE* **4640**, pp. 117-124, 2002.
7. P. D. Trinh, S. Yegnanarayanan, F. Coppinger, B. Jalali, "Silicon-on-insulator (SOI) phased-array wavelength multi/demultiplexer with extremely low-polarization sensitivity", *IEEE Photon. Technol. Lett.* **9**, pp. 940-942, 1997.
8. A. Himeno, K. Kato, and T. Miya, "Silica-based planar lightwave circuits", *IEEE J. Sel. Topics in Quantum Electron.* **4**, pp. 913-924, 1998.
9. H. Nishihara, M. Haruna, and T. Suhara, *Optical Integrated Circuits*, McGraw-Hill, New York, 1989.
10. T. Aalto, P. Heimala, P. Katila, "Integrated optical switch based on SOI-technology", *Physica Scripta* **T79**, p. 123-126, 1999.
11. R. A. Soref, J. Schmidtchen, K. Petermann, "Large single-mode rib waveguides in GeSi-Si and Si-on-SiO₂", *IEEE J. Quantum Electron.* **27**, pp. 1971-1974, 1991.