Characteristics of Overdriven Silica on Silicon Switching Devices

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Abstract
We have characterized the optical switching devices fabricated by the electron beam irradiation. The structure consists of silica on silicon layers where on top of it the MgF2 cladding layers have been deposited to engulfed the core layers. It shows that switching time of 2.0 μs has been achieved. To achieve faster switching speeds larger driving volateges should be used. In this case we have used bigger driving voltage that falls to zero exactly as the first extinction is reached, allowing an approximately three-fold increase in modulation speed.

Keywords: silica on silicon waveguides, switching devices, photonics devices, overdriven switching

1. Introduction
Optical switches are key components in advanced optical communications networks. Many different optical switching technologies are currently available or under development. Stable switching operation with low driving power is also necessary. Switches with these characteristics can be realized using the electro-optic effect [1] [2], the thermo-optic (TO) effect [3]-[5], or mechanical means [6]. Today, the leading technology for optical switching devices is Ti-diffusion in LiNbO3, where switching is achieved using the electro-optic effect. For example, switched directional couplers based on LiNbO3 devices are commercially available. These components can operate very fast, in the sub-nanosecond regime, but are generally polarization sensitive and expensive [2].

In some applications, polarisation insensitivity is more important than high switching speed (for example, by-pass switching in LAN’s with ring topologies and circuit switching for video distribution [9] [19]). In this case, optical waveguide switching using the polarisation independent TO effect, which gives switching times of the order of milliseconds, would be a good alternative.

The TO effect is the change in the optical index of refraction as a result of a temperature rise. Conventional TO phase shifters consist of a thin film heater deposited on the cladding of a buried channel guide. Since in a silica-on-silicon optical waveguide, the glass conductivity is larger than air, heat will be conducted to the silicon substrate, which acts as a heat sink. In the steady-state, the result is a linear temperature gradient between the heater and the substrate, which increases the average temperature of the core. However, relatively high power consumption is involved and lateral heat diffusion in the glass can cause a thermal crosstalk between two adjacent guides [9] [10]. These difficulties can be reduced by using a bridge-suspended waveguide structure, which lowers the required drive power and reduces the thermal crosstalk [7]. However, device switching times are lengthened proportionally.

The main purpose of this article is to explain on thermo-optic switching using Mach-Zehnder interferometer (MZI) structures. A thermo optic phase shifter consisting of thin film heater deposited on top of one Mach-Zehnderarms has shown to be very effective to change the effective refractive index of MZI so that the switching occurs.
2. Research Method

The Mach-Zehnder interferometer provides an elegant means of taking advantage of the thermo-optic effect. It consists of two back-to-back Y-junctions connected by two straight guide arms. The first Y-junction splits the input light into two components which travel along the straight guide and are recombined at the second Y-junction. Either or both the straight arms may have a heater to allow the relative phase of the recombining components to be altered. If the two are in phase, the guided output is high, and if they are out-of-phase, it is low.

When the heater is on, the average waveguide temperature beneath the heater increases. As a result the effective optical path length increases by \( \frac{dT}{dn} L \), where \( \frac{dT}{dn} \) is the thermo-optic constant of the silica waveguide, \( L \) is the heater length and \( \Delta T \) is the temperature rise [17]. The typical value of \( \frac{dT}{dn} \) for silica is \( 10^{-5} \text{C}^{-1} \). For example, heating a 10 mm long guide by 15.23°C will produce a \( \pi \) radians phase shift at 1.523 \( \mu \text{m} \) wavelength [5.18]. The driving power and the response time are dependent on the cladding layer thickness, the thermal conductivity of the waveguide and the substrate material. For silica on silicon, the heat supplied by the heater mainly diffuses into the Si substrate through the MgF\(_2\) layer just below the heater and then through SiO\(_2\) layer immediately beneath the MgF\(_2\). This is because the thermal conductivity of Si is much larger than that of SiO\(_2\), MgF\(_2\) and the surrounding air. Any lateral heat flow into the cladding glass is small, and all the glass reaches thermal equilibrium very quickly [17].

Transmission characteristics of Mach-Zehnder interferometers can easily be described by coupled mode theory. In the simplest case, assuming no loss and perfect \( Y \)-branches with a 3-dB splitting ratio, the output power is given by [17]:

\[
P_{out} = P_{in} \cos^2 \left( \frac{\phi}{2} \right)
\]

where \( P_{out} \) and \( P_{in} \) are the optical output and input powers respectively, and \( \phi \) is the phase difference between the two paths. A phase difference may be altered by changing the refractive index of one arm with respect to the other. If the change in refractive index is proportional to the temperature change, it must also be proportional to the power dissipated in the heater, so the output intensity is given by:

\[
P_{out} = P_{in} \cos^2 \left( \frac{\pi P}{2 P_\pi} \right)
\]

where \( P = \frac{V^2}{R} \) is the electric power dissipated in the heater, \( V \) is the applied voltage, \( R \) is the measured heater resistance, and \( P_\pi \) is the power which gives a \( \pi \) radians phase shift.

The layout of the Mach-Zehnder 1x1 single mode optical switches used to investigate thermo-optic switching in irradiated waveguides is shown in Figure 1. The device has two straight arms of 10 mm length and an additional thin film of Ti metal, to act as a heater electrode.
The waveguides were formed in PECVD silica-on-silicon. Irradiation parameters of 1.06 C/cm² charge dose at 30 keV energy were chosen to obtain essentially polarization independent insertion losses of ≈ 1 dB at $\lambda = 1.523 \, \mu m$ for 3.4 cm lengths of straight guide with an oil cladding. The guide width was 7 $\mu m$, and the index difference between the core and buffer layer was $\Delta n = 6 \times 10^{-3}$. Insertion losses for an electrodeless interferometer measured using an oil cladding were 2.0 dB (TE) and 2.5 dB (TM), with the difference being ascribed to slight birefringence. The heater was deposited above one arm of each interferometer by patterning a 0.1 $\mu m$ thick layer of sputtered Ti metal into 50 $\mu m$ wide strips fed by 4 mm wide bus bars, and a dummy electrode was placed above the unheated arm to avoid any phase or amplitude imbalance [14].

The current for the heater was supplied by a signal generator. However, due to the very low maximum voltage (10 V) provided by the source, a high power driving circuit was needed. Figure 2 shows the driver used in the experiments. It consists of two transistors (TR1 and TR2), which are used as a power switches. A minimum driving voltage of 0.7 V turns on the transistor TR1 which in turn switches transistor TR2 on and off allowing the supply voltage of $+V$ to be
dropped across the heater. With a suitable DC supply, this circuit provides a maximum output of up to 65 V [22].

![Driver circuit used to control the Ti heater](image1)

**Figure 2.** Driver circuit used to control the Ti heater

### 3. Results and Analysis

The measurement of switching characteristics was performed using a laser at a wavelength of 1.523 μm. The incident light was butt-coupled into the input end facet of the device using a single mode fibre. The circuit of Figure 2 was used to supply current to the heater and hence obtain a phase shift. The output light was detected using a photodetector, and the time variation of the detected signal was displayed on an oscilloscope.

Three types of experiment were carried out. In the first experiment, the variation of transmission with heater power was measured by applying a low frequency square-wave voltage of varying amplitude to the heater. In the second, faster-varying signals were used and the frequency response of the switch was measured. In the third, overdriven switching characteristics were measured. Figure 3 shows the variation of normalised transmission with heater power, which follows the conventional sinusoidal form. Points are experimental data; the solid line represents the calculated transmission as given by a best fit to Equation (2). Switching performance was essentially similar to devices demonstrated by other technologies [3] [15]. The lack of phase bias in the curve suggests that there is no phase shift between the two-interferometer arms, although the relatively poor extinction ratio (10 dB) suggests unequal splitting in the Y-junctions. The first extinction was obtained at a power of ≈ 0.5 W while the second was obtained at a power of ≈ 1.6 W.

![Variation of normalized transmission with heater power for a thermo-optic Mach-Zehnder interferometer modulator formed by irradiation](image2)

**Figure 3.** Variation of normalized transmission with heater power for a thermo-optic Mach-Zehnder interferometer modulator formed by irradiation.
Figures 4 (a), (b), (c) show switch characteristics obtained using a square wave heater drive at frequencies of 125 Hz, 500 Hz and 1 kHz, respectively. Complete switching is clearly achieved at the lowest frequency. However, as the drive frequency is raised, the relatively slow response of the switch quickly limit its ability to reach the ON and OFF states fully. Minimum switching times of \( \approx 0.5 \) ms are slightly shorter than results obtained with topographic guides with a much thicker silica cladding, formed by flame hydrolysis deposition [17].

In the previous set of experiments, the switch was driven using a voltage exactly sufficient to reach the first extinction. Faster switching speeds can in fact be achieved by using larger driving voltages. For example, Figure 4 (a) shows the switch characteristic obtained using a square wave of voltage 64 V at a frequency of 125 Hz. Here, the heater power is sufficient to
drive the switch past the first extinction, through the following maximum, and then to the second extinction. Due to the increased drive power, the first extinction is reached extremely rapidly. Figure 4 (b) shows the corresponding trace obtained at 3 kHz.

![Graph showing the overdriven switch characteristic](image)

Figure 4. Overdriven switch characteristic obtained using a square wave heater drive with a voltage of 64 V and a frequency of (a) 125 Hz, (b) 3 kHz.

In this case, the drive signal falls to zero exactly as the first extinction is reached, allowing an approximately three-fold increase in modulation speed over the corresponding result shown in Figure 3 (c). A periodic switching at similar speed may be obtained using shaped drive pulse, where an initially large switching voltage is followed by a smaller holding voltage.

4. Conclusions

We have characterized the switching devices based on Mach Zehnder interferometer where thin layers of evaporated MgF$_2$ can be used as a cladding for waveguides formed by electron beam irradiation of PECVD silica-on-silicon. Switching can be realized by using a thin film heater to induce refractive index changes in waveguide structures. An unequal splitting in the Y-junctions results in poor extinction, however, a major disadvantage. Switches based on directional couplers would be a good alternative, but heating one waveguide without affecting the other in such a closely-spaced geometry is extremely difficult.

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