Ultra-Broadband, Low-Power, 2x2 Electro-Optic Switch using Sub-Micron Silicon Waveguides

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Abstract: We present a broadband Mach-Zehnder electro-optic switch capable of simultaneously routing multiple channels within 110-nm optical bandwidth with only 3.1-mW power consumption and a 4-ns switching time. Switching bandwidth is maintained over 30°C temperature variation.

OCIS codes: (130.4815) Optical switching devices; (250.6715) Switching

1. Introduction

Short-range optical interconnects integrated in silicon have been proposed to solve the communication bottleneck of future electronic integrated circuits, both for chip-to-chip as well as for on-chip communication [1]. A broadband, low-power and temperature-insensitive silicon optical switch is a key device for enabling high-throughput, reconfigurable optical networks, capable of interconnecting the multiple processor cores and memory systems within a chip or a multi-chip module [2]. Here, we present an ultra-broadband, 2×2 Mach-Zehnder based electro-optic switch in silicon. The switch has an optical bandwidth of 110 nm, owing to broadband 50-% couplers, and it switches within 4 ns with a power consumption of only 3.1 mW.

2. Design and fabrication of a broadband switch in silicon

The optical bandwidth of a conventional, balanced 2×2 Mach-Zehnder (MZ) switch is determined by the wavelength sensitivity of its 50-% couplers. In order to obtain broadband MZ-based switches, wavelength-insensitive couplers can be built using two directional couplers with an intermediate phase delay [3]. When these broadband couplers are implemented in the MZ interferometer, following a point-symmetric configuration [4], a wavelength-insensitive MZ (WIMZ) switch is obtained, as shown in Fig. 1(a). Following this approach, we designed a wavelength-insensitive 50-% coupler using silicon-on-insulator (SOI) rib waveguides with 500×220-nm^2 cross sectional dimensions. It consists of two directional couplers with power-coupling coefficients $\kappa_1 = 0.4$ and $\kappa_2 = 0.8$, and a phase delay $\delta\phi = 0.54\pi$. This is equivalent with directional-coupler lengths of 15 μm and 24.5 μm, and a length imbalance of 160 nm in the phase-delay section of the coupler. The footprint of the switch with a 200-μm-long active p-i-n diode phase shifter is 50×400 μm^2.

The expected switching response of the silicon electro-optic WIMZ switch was calculated using the wavelength-dependent transfer matrix method, both for the ‘off’ and ‘on’ state of the switch. These calculations included the effect of the p-i-n diode injected free carriers on the real part as well as on the imaginary part of the refractive index of the silicon waveguide core [5], such that not only the phase shift but also the associated free-carrier absorption loss was taken into account. The resulting transmittance spectra T_{11} and T_{12} are shown in Fig. 1(b) ($T_{ij} = |b_j/a_i|^2$). In the ‘off’ state, the spectral range with -20-dB crosstalk is as large as 110 nm. In the ‘on’ state, which is obtained by injecting carriers in the p-i-n diode phase shifter to create a π phase shift, a crosstalk level of -19 dB or lower is obtained in the same 110-nm spectral window. As such, the bandwidth of the WIMZ switch is about a factor 3 larger than that of the conventional MZ switch with 50-% couplers consisting of a single directional coupler, which has a -20-dB bandwidth of 35 nm (not shown). The ‘on’-state carrier density is $N \sim 1.44\times10^{18}$ cm^{-3}, and the T_{11} and T_{22} ‘on’-state transmittance are calculated to be -0.8 dB, owing to the absorption loss caused by the injected carriers.

The proposed WIMZ switch was fabricated on 200-mm SOI wafers with a 2-μm-thick buried oxide layer and a 220-nm-thick top silicon layer, on a standard complementary metal-oxide-semiconductor (CMOS) fabrication line using 193-nm deep-UV lithography. The highly doped (10^{21} cm^{-3}) p-type and n-type regions of the lateral p-i-n diode were formed by ion implantation, approximately 500 nm away from the rib-waveguide core. NiSi ohmic contacts were formed over the implanted regions. Contact apertures overlaying the NiSi contacts were etched in a deposited dielectric stack and filled with W plugs. Subsequently, Cu metal contact pads were formed. Finally, SiO_xN_y-based optical couplers were formed overlaying the fully etched, inversely tapered access waveguides. These optical couplers provide efficient optical coupling from lensed and tapered fibers to the access wire waveguides.

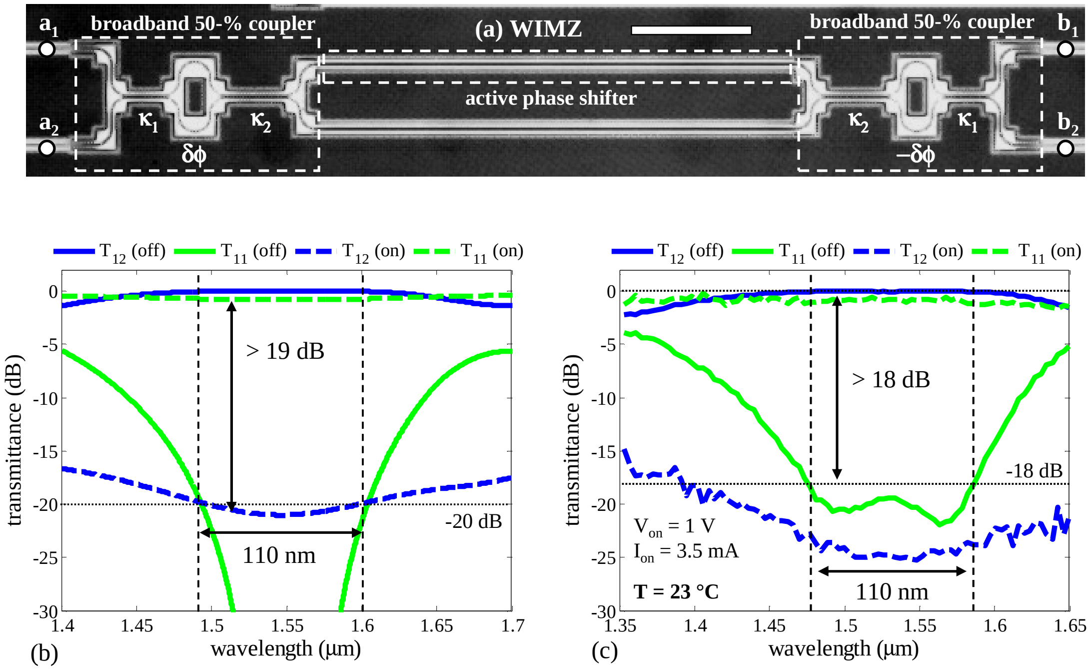

Fig. 1. (a) Microscope image of the WIMZ switch. The scale bar is 50-μm long. (b) Calculated and (c) measured WIMZ steady-state switching response as a function of wavelength.

3. Measurement results

The bandwidth of the fabricated WIMZ devices was characterized by coupling TE-polarized light from a broadband LED source to one of the input ports of the switch and analyzing the intensity spectrum of the transmitted light signal at both output ports. First, this analysis was performed at 23°C for all four transmission paths in the switch 'off' state, yielding the transmittance spectra T_{12} and T_{11} for the 'off' state. The obtained intensity spectra measured at the respective output ports were normalized against the sum of the intensity spectra of both output ports, with the input signal at the same input port, and are shown in Fig. 1(c). It can be seen that the 'off'-state crosstalk levels are lower than -18 dB over the designed spectral range of 110 nm, centered around a wavelength of 1530 nm. Similar crosstalk levels were measured for the T_{21} and T_{22} 'off'-state transmittance.

Subsequently, a steady-state forward-bias voltage V_D was applied to the p-i-n diode in the phase-tuning section, and this voltage was fine-tuned to obtain maximum extinction of both the T_{12} and T_{11} transmittance within the optical bandwidth of the WIMZ switch, which we refer to as the 'on' state of the WIMZ switch. Again, the reported transmittance spectra were normalized against the sum of the intensity spectra of both output ports, recorded in the switch 'off' state. Maximum extinction was found to occur at the 'on'-state voltage $V_{on} = 1\pm0.01$V, and an 'on'-state current $I_{on} = 3.5\pm0.1$mA. The resulting T_{12} and T_{11} spectra for the 'on' state are also shown in Fig. 1(c). It can be seen that the 'on'-state crosstalk levels between T_{12} and T_{11} are lower than -23 dB over the wavelength window of interest. The 'on'-state crosstalk levels between T_{21} and T_{22} were measured to be lower than -17 dB over the 110-nm bandwidth. The difference in obtained crosstalk when using different input ports is most likely caused by a slight deviation from 50-% coupling in the broadband coupling section. The T_{11} and T_{22} 'on'-state transmittance were measured to be -0.9±0.4 dB. These values agree well with the simulated value of -0.8 dB. The 'off'-state insertion loss arising from bending, scattering and absorption in the device was estimated to vary from 1.1±0.2 dB at 1480 nm to 2.0±0.2 dB at 1590 nm. The total 'on'-state insertion loss was then estimated to vary from 2.0±0.2 dB at 1480 nm to 2.9±0.2 dB at 1590 nm.

The temperature dependence of the WIMZ switch was tested by repeating the same transmission measurements at 30°C and at 50°C. Very similar switching characteristics were obtained, confirming the temperature insensitivity of the optical switch response. It should be noted though that the 'on'-state electrical bias level at these temperatures was slightly different as compared to the measurements at 23°C: $V_{on} = 0.99\pm0.01$V and $I_{on} = 3.3\pm0.1$mA at 30°C, and $V_{on} = 0.97\pm0.01$V and $I_{on} = 3.0\pm0.1$mA at 50°C. This bias offset originates from the temperature dependence of the electrical properties of the p-i-n diode itself.

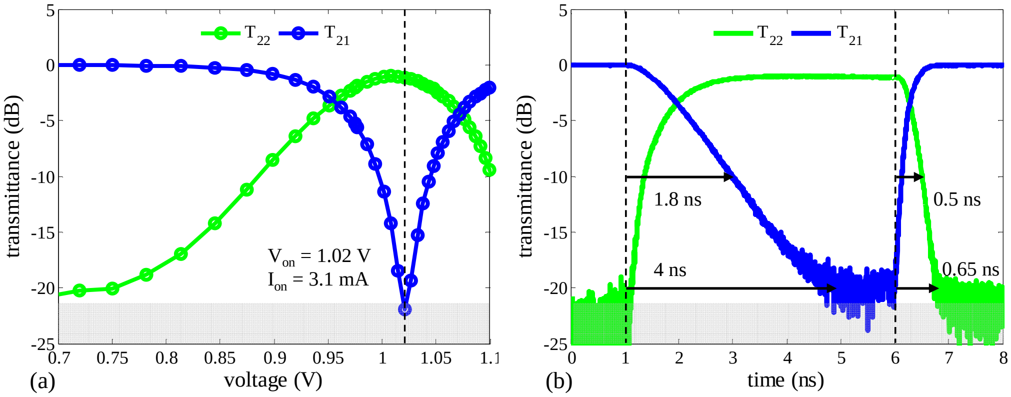

Fig. 2. (a) Switching response at 1518 nm, for 100-ns-long pulses. (b) Time-resolved switching response for a 5-ns-long pulse. The grey area indicates the noise floor of the measurement.

In order to study the intrinsic, free-carrier induced switching response of the device, fully decoupled from possible self-heating of the p-i-n diode, we performed a series of time-resolved transmittance measurements using a TE-polarized, coherent light source at a fixed wavelength of 1518 nm and at 23°C. A drive signal consisting of 100-ns long pulses with variable peak-to-peak voltage, zero bias voltage, and a 10-% duty cycle was applied to the switch, and the switch transmittance was evaluated 60 ns after arrival of each pulse. The resulting T_{21} and T_{22} transmittance values are shown as a function of applied peak voltage of the pulses in Fig. 2(a). The 'on' state is reached at a peak voltage V_{on} = 1.02±0.02V, with an 'on'-state crosstalk of less than -20 dB. The 'on'-state drive current I_{on} = 3.1±0.1mA obtained under pulsed drive conditions is (slightly) lower as compared to the one obtained under steady-state drive conditions at the same temperature. This can be explained by self heating of the p-i-n diode under the steady-state drive condition, which results in a counteracting thermo-optic phase shift. As such, the intrinsic power consumption of the WIMZ switch in the 'on'-state is estimated to be 3.1 mW. The series resistance of the device was measured to be 8±2 Ω.

The 'off'-'on' switching time for obtaining 20-dB crosstalk was measured to be 4 ns, while 'on'-'off' switching time was 0.65 ns, as illustrated by the time-resolved transmittance curves in Fig. 2(b). Switching times for obtaining 10-dB crosstalk were measured to be 1.8 ns and 0.5 ns respectively.

4. Conclusion

In conclusion, we have demonstrated an ultra-broadband Mach-Zehnder based optical switch in silicon, operated through carrier injection in a p-i-n diode. The optical bandwidth of the switch is 110 nm, which is three times larger than that of a conventional MZ switch. Crosstalk levels of 17 dB and lower were demonstrated in fabricated devices over the designed optical bandwidth for both switching states and with full 2×2 switching functionality. The power consumption was shown to be very low (3.1 mW) and switching times were in the nanosecond range. The optical response of the switch was shown to be largely temperature insensitive. These switching characteristics are essential for realizing high-throughput, low-power, reconfigurable, short-range optical interconnects.

Acknowledgement

This work was supported in part by the DARPA APS Program, under contract HR0011-08-C-0102. The authors gratefully acknowledge the efforts of the staff of the Microelectronics Research Laboratory (MRL) at the IBM T. J. Watson Research Center, where the devices were fabricated.

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