Fast Polarization-Insensitive Optical Switch Based on Hybrid Silicon and Lithium Niobate Platform

Shengqian Gao, Mengyue Xu, Mingbo He, Bin Chen, Xian Zhang, Zhaohui Li, Lifeng Chen, Yannong Luo, Liu Liu, Siyuan Yu, and Xinlun Cai

Abstract—We propose and demonstrate a polarization-insensitive and high-speed optical switch unit based on a silicon and lithium niobate hybrid integration platform. The presented device exhibits a sub-nano-second switching time, low drive voltages of less than 10 V, and low power dissipation due to electrostatic operation. The measured polarization dependence loss was lower than 0.8 dB. Moreover, the present devices could provide a building block for polarization-insensitive and high-speed optical matrix switches.

Index Terms—Silicon photonics, optical switch, power-efficient, electro-optics, lithium niobate, hybrid integration.

I. INTRODUCTION

HIGH-SPEED optical switch, with switching times in the micro- to nano-second region, is one of the key underpinning photonic devices for optical packet switching (OPS) [1] and optical burst switching [2], providing the advantages of bit rate and format transparency. Moreover, the recent advent of cloud and data-intensive computing has triggered a need for high speed and large-scale photonic switches, which could provide high bandwidth, low latency and energy-efficient optical interconnect among the servers and racks [3]–[5]. Leveraging an advanced complementary metal-oxide-semiconductor (CMOS) manufacturing process, silicon photonics has emerged as a powerful platform for high-density photonic integrated circuits to the possibility of low-cost and high-volume production of photonic integrated circuits (PICs) [6], [7]. To achieve nanosecond-scale switching times, free-carrier dispersion effect through carrier injection or depletion is widely exploited for high-speed electro-optic (EO) silicon switch fabrics. Unfortunately, free-carrier dispersion is intrinsically absorptive, degrading not only the insertion loss but also the extinction ratio of the switches.

Another well-known problem in silicon photonic switch is the large polarization-dependent loss (PDL) [8]. Efforts have been made to minimize PDL, either by polarization diversity approaches [9]–[11] or by making the components polarization-insensitive [12]–[15].

Recently, Lithium niobate hybrid integration platform has provoked great interests in the field of integrated photonics, and realized high performance field-induced electro-optical (EO) coefficient and second order nonlinearity [16]–[19]. The hybrid integrated platform keeps both advantages of silicon-based photonics and LN materials. In our previous work, we have demonstrated ultra-high speed and low loss Mach–Zehnder (MZ) modulators based on hybrid integration of lithium niobate (LN) phase shifter with passive silicon circuitry [20]. The devices exhibited low insertion loss of <2.5 dB, a modulation efficiency of 2.2 Vcm, and EO bandwidth of more than 70 GHz. In this paper, we demonstrate a polarization-insensitive MZ switch based on hybrid integration of LN phase shifter with silicon photonic circuits. The presented devices show sub-nanosecond switching speed, low drive voltages of around less than 10 V and low polarization dependence of <0.8 dB. Moreover, the present devices feature energy-efficient electrostatic operation with no power dissipation when holding the switch in the cross or bar state.

II. DESIGN AND FABRICATION

A schematic diagram of the polarization insensitive optical switch unit is shown in Fig. 1(a). The device consists of a bottom silicon waveguide layer, a top LN waveguide layer and vertical adiabatic couplers (VACs) which serve as low-loss interface between the two layers. Two dimensional grating couplers (2D-GC) are used as polarization splitters/combiners,
Fig. 1. (a) Schematic structure of the polarization insensitive FOS unit; (b) Cross section view of the X(Y)-polarization MZ switches.

which translate fiber polarizations into two orthogonal polarizations, normal to the grating periodicities, and couple with linear TE-modes in two different output arms [21].

The X-cut LN thin film is used in the top waveguide layer, which serve as high-speed EO phase modulator where ultrafast Pockels effect occurs. The bottom silicon circuit supports all of the passive functions of routing the lightwave across the chip, and it consists of two 3 dB multimode interference (MMI) couplers that split and combine the optical power, and two-dimensional grating couplers (2D-GC) for polarization-insensitive off-chip coupling. The VACs are formed by silicon inverse tapers and superimposed LN waveguides. A mode calculation (using finite difference eigenmode solver, Lumerical Mode Solution [22]) indicates that for TE mode nearly 100% optical power can be transferred from silicon waveguide to the LN waveguide, and vice versa [20].

The input signal, coupled through the 2D-GC, is decomposed into two orthogonal polarization components, X-polarization (X-pol) and Y-polarization (Y-pol), and are coupled into a pair of orthogonal waveguides, both in the TE mode (see in Fig. 1(a)). Sharing the same polarization and dispersion, they are switched by the corresponding X- and Y-polarization MZ switches designed for only TE mode, and then sent to the two output 2D-GC (Output-1 and Output-2). The Cross section of the device is shown in Fig. 1(b). The LN waveguides have a top width of $w = 1 \, \mu m$, a slab thickness of $s = 420 \, nm$, a rib height of $h = 180 \, nm$. The thickness/width of electrodes were set to $t/m = 600 \, nm/19.5 \, \mu m$, and the gap between the waveguides and electrodes was set to $2.75 \, \mu m$. The electrodes are designed in a capacitive drive push–pull configuration, so that applied voltage induces a positive phase shift in one arm and a negative phase shift in the other. The length of the arms of the MZ switches are designed to be 4 mm.

The device fabrication process is shown in Fig. 2. The device was fabricated in a silicon-on-insulator (SOI) wafer, with 3-μm thickness buried oxide (BOX) and 220-nm thickness silicon waveguide. Firstly, a shallow etched 70 nm 2D-GCs and a 220nm Si waveguide were defined by e-beam lithography (EBL) and inductively coupled plasma (ICP) using hydrogen bromide (HBr), successively. Then a X-cut LN on insulator (LNOI) wafer with silicon substrate, commercially available from NANOLN, was cleaned up (by DI water: NH$_4$OH: H$_2$O$_2$ = 3:1:1), then baked and flip-bonded to the patterned SOI wafer through an adhesive bonding process using benzocyclobutene (BCB) at a certain temperature and pressure. The thickness of BCB could be controlled by the rotation speed and time. After that, the substrate of the LNOI was removed by mechanical grinding and ICP (isotropic dry etching, sulfur hexafluoride). Then, the BOX layer was removed by a dry etching process (RIE, Trifluoromethane:Argon = 1:3). Hydrogen silsesquioxane (HSQ, FOX-16 by Dow Chemical) was then spin-coated on the 600-nm thick LN membrane followed by EBL patterning. Through plasma etching in an inductively coupled (ICP) etching system, the waveguide patterns are transferred into LN. Finally, a liftoff process was performed to produce the Au electrodes. The scanning electron microscope (SEM) image of the fabricated electrode and LN waveguide are shown in Fig. 3(a). Fig. 3(b) shows the cross-section of the fabricated LN waveguides with a sidewall angle of 60°. The total footprint of the device is about 6.0 mm×1 mm.

III. EXPERIMENTAL RESULTS

The 2D-GCs are the key components for realizing the polarization insensitive operation [23], [24]. The optical micrograph of the 2D-GCs used in the present device is shown in Fig. 4 (a). To measure the PDL, one of the most important performance metrics, two identical 2D-GCs were connected in a back-to-back configuration as shown in Fig. 4 (b). Here we...
have defined two orthogonal polarized input light, horizontal polarization (H-pol) and vertical polarization (V-pol) that both rotated 45° to X-Pol or Y-Pol. The H- or V-polarized input light is defined by using a TE grating coupler, highest transmission for V-pol and lowest for H-pol, which was co-fabricated with the present device. The measured coupling spectra for H- and V-polarization, illustrated in Fig. 4 (c), indicate that the PDL is less than 0.8 dB for C-band. The H- or V-polarized input light was calibrated by measuring the transmission of a TE grating coupler for V-polarization, which was co-fabricated with the present device. As shown in Fig. 4(c), the measured coupling efficiencies is −6.9 dB at the central wavelength of 1547 nm and the 1-dB and 3-dB bandwidth are measured to be 27 nm and 43 nm, respectively. The coupling efficiency of the present 2D-GCs is relatively low due to the unoptimized thickness of the BOX layer in the current SOI wafer (3 μm). The coupling efficiency can be significantly improved by using a substrate transfer technique as demonstrated in ref. [24].

The measured transmission of the X- and Y-polarization MZ switches at different driving voltages was shown in Fig. 5. Light wave from a wavelength tunable laser was coupled to the waveguides of the device via a polarization controller (PC) and a single mode fiber. A back-to-back configuration of one 2D-GC and two TE grating couplers is co-fabricated on the chip to calibrate the input X-, or Y-polarization. To test the switch extinction level, we measured transmittances at the output-1 and output-2 ports for Bar/Cross states, results plotted in Fig. 5 as a function of the voltages applied to the electrode. The transmittances at the Output-1 and Output-2 ports, when the X- or Y-polarization was introduced to Input-1 port, are plotted in Fig. 5 as a function of the voltages applied to the electrode. The X-polarization switch takes the cross/bar state at a voltage of 8.59 V/3.62 V, while Y-polarization switch takes the cross/bar state at a voltage of 9.52 V/4.55 V. Thus, the circuit would give a polarization insensitive cross or bar state when both of the X- and Y-polarization switches take their cross or bar state at the same time. Both of the extinction ratio of the switches for X- and Y-polarization was measured to be >40 dB, as shown in Fig. 5. The on-chip insertion loss of the polarization diversity switch was estimated to be around 2 dB by subtracting the coupling loss of 2D-GCs. It should be noted that the circuit is very energy efficient because it consumes power only when the state changes, and no power is consumed when holding the switch in the cross/bar state. The measured Dc Vπ is 4.97 V. The simulated capacitance of two electrostatic electrodes between one LN waveguide is 0.36 pF (using Finite Element Method, COMSOL Multiphysics [25]). Considering that, the energy consumption of this device is estimated as per bit of 8.8 pJ/bit.

To examine the spectral response of the circuit, the transmittance spectra of the cross and bar ports in the cross and bar states for X-, Y-, and a mixed polarization are shown in Fig. 6. Extinction ratios of 26 dB and 28 dB have been achieved in the C-band at both cross and bar output ports for X- and Y-polarizations, respectively. In addition, Fig. 6(c) shows the transmission spectra for the V-polarization, which forms an angle of approximately 45 degrees to the X- or Y-polarization directions. An extinction ratio of at least 28 dB was obtained for V-polarization, which further confirms the broadband polarization insensitive operation of the circuit.

Finally, we characterized the dynamic switching properties of the EO switches. A square-wave electrical signal with...
a repetition rate of 500 MHz and a duty cycle of 50%, generated from an arbitrary waveform generator (AWG, MICRAM), was applied to the electrode of the phase shifter through a RF probe. A 50 GHz broadband amplifier (SHF 807) was used to amplify the driving signal to the switch together with a DC bias. The optical output intensity is recorded using an oscilloscope (Tektronix DSA8300). As shown in Fig. 7, the rising and falling times were measured to be 100 ps and 312 ps, respectively, indicating an ultra-fast switching speed.

IV. CONCLUSION

In conclusion, we have designed and demonstrated a polarization-insensitive and high-speed optical switch circuit based on the hybrid silicon and LN platform. The polarization-insensitive operation was achieved with a polarization-diversity technique by using 2D-GC with low PDL of less than 0.8 dB in C-band. The demonstrated device exhibits switching speed of less than 1 ns, an insertion loss of 2 dB and a low drive voltage of around 9.52 V. The switch demonstrated here could provide a building block for polarization-insensitive, high-speed and large-scale silicon photonic matrix switches.

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