Low-Voltage InP MEMS Optical Switch on Silicon

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ABSTRACT

In this paper, a novel MEMS Mach-Zehnder interferometer optical switch is presented. Switching is achieved by tuning the vertical gap between two coupled waveguides through the application of a reverse bias on a p-i-n junction. The switching requires a voltage as low as 4.4V and provides an extinction ratio above 15dB within a 34 nm bandwidth in the C-band. The device also serves as a very efficient optical phase modulator, being able to modify the optical phase by more than 4π with only 6.5V voltage in a 140μm-long waveguide. Our work provides a solution to on-chip optical switching for low-voltage applications. The switch is fabricated on an indium-phosphide membrane on a silicon substrate, which enables the integration with active components (e.g. amplifiers, lasers, detectors) on a single chip.

Keywords: Optical switch, MEMS, phase modulator, Mach-Zehnder interferometer, Indium-phosphide.

1. INTRODUCTION

Switching light efficiently is essential for the development of the next-generation optical networks. However, the currently available 3D MEMS (micro-electro-mechanical-system) optical circuit switches cannot be easily integrated on a chip and present switching times in the ms range. In the past decades several integrated MEMS optical switches on different platforms have been reported [1]-[4]. Most of these switches require tens of Volts to actuate, preventing their application in low-voltage applications. In this paper, we report a MEMS optical switch based on a Mach-Zehnder interferometer, which requires a switching voltage as low as 4.4V. Though the design can be implemented on various platforms, we fabricated it on an indium-phosphide membrane bonded on a silicon substrate [5], which provides the possibility to integrate our device with active optical components on a single chip.

2. APPROACH

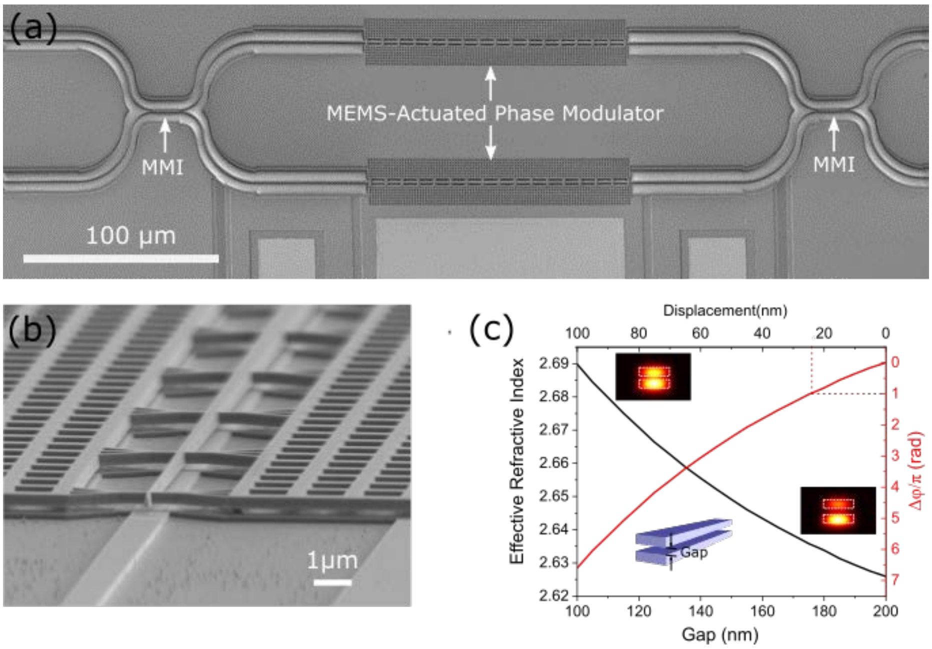

Figure 1. (a) Scanning electron microscope (SEM) image of a 2x2 switch. (b) Zoomed-in SEM image of the MEMS-actuated phase modulator. (c) Simulated ERI (effective refractive index) and phase difference (for a device length of 140 μm) as a function of vertical gap spacing and displacement of the suspended part. In the insets the sketch of the two waveguides and simulated cross-section electric field magnitude distributions in the middle of the waveguides, with gap of 100nm (left) and 200nm (right), respectively, are shown. The displacement needed for switching is marked by a dashed line.

Figure 1 (a) shows the SEM image of our optical switch. It is 2x2 switch based on Mach-Zehnder Interferometer (MZI). Two 50/50 Multi-Mode Interferometers (MMIs) split/combine light into/from two branches. MEMS-actuated modulators are implemented in both branches to ensure a symmetric optical path. Figure 1 (b) shows the details of MEMS part. A 140µm tapered InP waveguide is suspended and connected with 15µm cantilevers on both sides. The length of tapers is 60µm on both ends of the coupler to ensure adiabatic coupling. The bottom InP ridge waveguide is 1µm wide. Below the ridge waveguide the bonding layer is composed of silicon nitride, BCB and silica. The low refractive index of the bonding layer ensures a small mode volume confined in the waveguide. A layer of InGaAsP between the two InP membranes forms the intrinsic layer of the p-i-n junction, and serves as sacrificial layer to create the suspended part. At zero bias the vertical gap spacing between the suspended waveguide and ridge waveguide is 200nm, and light exits through the cross port after interference due to the symmetry of the optical path. In the actuated state, a reverse bias is applied to the junction. The electro-static force brings the coupler down and increases the ERI of the waveguide by evanescent coupling, so that the phase difference between the two branches changes. The light is switched to the through port when the phase difference reaches π.

To estimate the displacement of coupler needed for a π phase shift, we simulated the ERI change of the waveguide using a FDTD model (commercial software Lumerical FDTD Solutions). As showed in Fig. 1 (c), the ERI modulation rate is about 6.4×10^{-4}/nm. Given the length of coupler (140µm including the tapers) in this work, a displacement of 24nm is needed for a π phase shift.

3. FABRICATION

The switches are fabricated in the NanoLabNL@TU/e facility at the Eindhoven University of Technology. An InP wafer with two doped InP layers and an InGaAsP intermediate layer is grown by MOCVD. The doping level of InP is 1×10^{18} cm^{-3} for both p and n layer. The InP wafer is then flipped and bonded to a silicon wafer using benzocyclobutene (BCB). After removing the substrate of the InP wafer, a layer of silicon nitride is deposited by PECVD as hard mask. The waveguides and MEMS are defined by electron beam lithography using ZEP520 as resist. The mask is then transferred to the silicon nitride layer in RIE by CHF_3, followed by InP dry etching in ICP by CH_4/H_2. Then the same process above is repeated to define the pattern on the second InP layer. Metal contact pads (Ti 25nm/Pt 75nm/Au 200 nm) are formed by evaporation and lift-off process. Finally, the device is released by etching with $H_2O/H_2O_2/H_2SO_4$ solution and dried in a super-critical dryer.

4. EXPERIMENTAL RESULTS

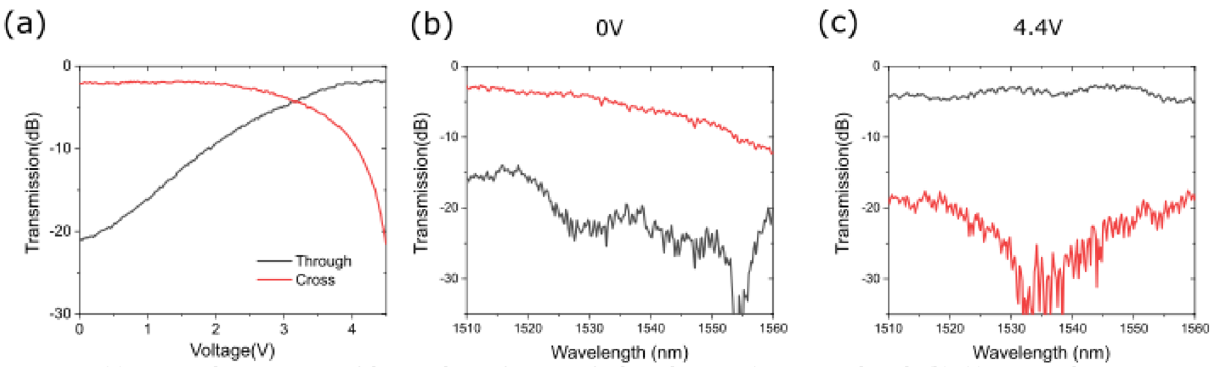

Figure 2. (a) Measured transmission of the switch as a function of voltage bias at 1530nm wavelength. (b), (c) Measured transmission spectra of the switch at 0V (b) and 4.4V (c).

Figure 2 (a) - (c) shows the transmission of the switch described above (the fiber coupling loss has been subtracted). At zero bias most of the transmission is in the cross port due to the zero phase difference between the two branches. The transmission gradually shifts to the through port with the increase of the reverse bias, until -4.4V where the extinction ratio reaches a maximum. In the actuated state the spectra of the through port is almost flat from 1510nm to 1560nm, while that for cross port at default state experiences a decline at longer wavelength side, due to the suboptimal design of MMIs. Overall, the extinction ratio remains above 15dB from 1523nm to 1557nm, which gives a bandwidth of 34nm.

To characterize the performance of our device as a phase modulator we also fabricated and measured devices with the modulator only in one of the branches. The ridge waveguide of the other branch is of the same length but a smaller width of 500nm. This causes a default path difference and therefore a small free spectral range, as showed in Fig. 3(a). However we found that the extinction ratio is similar to the devices with two modulators, indicating the insertion loss of the phase modulator is negligible. It is showed in Fig. 3(b) that the MEMS phase modulator is able to tune the phase by 4.8π rad before reaching pull-in, among the highest in literature [6]-[8] for this low actuation voltage. The corresponding ERI tuning range is as high as 0.047. Comparing with simulation it can be estimated that the maximum displacement of the coupler is about 80 nm, i.e. 40% of the initial gap. This large travel range is presumably due to the leveraged bending of the doubly clamped actuator [9]. The simulated mechanical frequency is 550 kHz, which indicates a potential switching time around 1 μs.

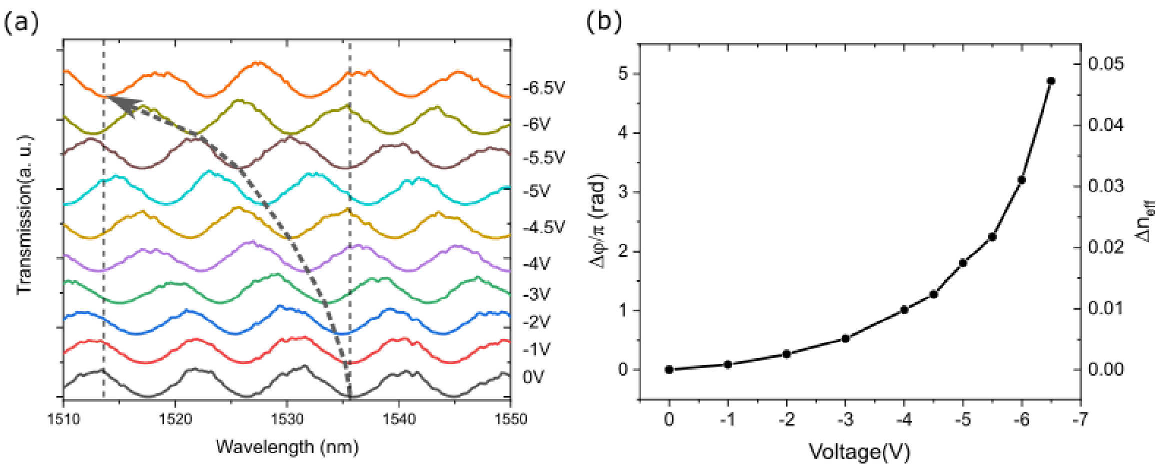

Figure 3. (a) Transmission spectra of a Mach-Zehnder interferometer with MEMS modulator in only one branch at reverse bias from 0V to -6.5V. Curves have been offset for clarity. Dashed line with an arrow tracks the wavelength shift of dip. (b) The optical phase shift and ERI change a function of voltage, extracted from (a).

5. CONCLUSIONS

We have demonstrated experimentally a 2x2 InP MEMS optical switch on silicon substrate. The footprint of the device is about 100x400 μm^2, with a small actuation voltage of 4.4V. The extinction ratio is above 15dB within a bandwidth of 34nm around C-band. The proposed device also serves as an efficient optical phase modulator, capable of tuning the phase by 4.8π rad within a coupling length of 140 μm. The device can be potentially integrated with lasers and detectors to find applications in optical communication and sensing.

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