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Low-voltage MEMS optical phase modulators and switches on a indium phosphide membrane on silicon

In this paper, an optical switch based on a microelectromechanical phase modulator is presented. Phase tuning is achieved by tuning the vertical gap between two vertically coupled waveguides through the application of a reverse bias on a p-i-n junction. An effective refractive index tuning $\Delta n_{eff}$ of 0.03 and a phase shift of more than $3\pi$ rad at telecom wavelengths are measured with an on-chip Mach–Zehnder interferometer (MZI), with a phase-tuning length of only 140 $\mu$m. With a bias voltage of 5.1 V, a half-wave-voltage-length product ($V_p L$) of $5.6 \times 10^{-3}$ V cm is achieved. Furthermore, optical crossbar switching in a MZI is demonstrated with a 15 dB extinction ratio using an actuation voltage of only 4.2 V. Our work provides a solution to on-chip, low-voltage phase modulation and optical switching. The switch is fabricated on an indium-phosphide membrane on a silicon substrate, which enables the integration with active components (e.g., amplifiers, lasers, and detectors) on a single chip.

Photonic integrated circuits (PICs) have found applications in optical communications, data processing and routing in data centers, and optical sensing. Optical phase modulation is a basic functionality for integrated interferometric switches and filters, as well as active arrayed-waveguide filters, for beam steering and for more complex programmable optical circuits. As reconfiguring the optical path is difficult on a chip, one needs to tune the refractive index of waveguides to modify the phase. There are many physical mechanisms being used for controlling the refractive index of waveguides, among which the most commonly used are the electro-optic (Pockels) effect, the thermo-optic effect, and carrier injection/depletion. While the electro-optic effect allows phase tuning with negligible power dissipation, most commonly used materials for PICs (e.g., silicon, silicon nitride, and indium phosphate) have very small electro-optic coefficients. Therefore, it takes a large interaction length (a few millimeters to centimeters) to get a sufficient phase shift, or additional electro-optic materials have to be applied onto the waveguides. Alternatively, one can integrate microheaters close to a waveguide and tune the refractive index by exploiting the thermo-optic effect or inject/deplete carriers in semiconductor layers to change the index through the plasma effect. However, both methods require continuous current driving and the corresponding power dissipation and heat load can be challenging to tackle when a large number of modulators is needed, e.g., for tunable laser arrays, optical cross connects, self-configuring networks, and beam steering.

Microelectromechanical systems (MEMS) provide a power-effective solution for reconfigurable optical devices and have been widely used for projection, free-space wavefront modulation, and switches. Most of the existing applications are based on moveable micromirrors, which are not compatible with photonic integrated circuits. By perturbing the evanescent field of light propagating in a waveguide, the effective refractive index of the waveguide mode can be tuned and therefore the phase changed. The speed of the MEMS-based phase modulation (millisecond to microsecond-range) is not adequate for data transmission; therefore, they are not meant to replace electro-optic or current-injection modulators. On the other hand, the unique advantages of low-power consumption and large tunability make them suitable for applications such as network switching, beam steering, optical sensing and other scenarios where speed is not crucial but high power efficiency is important. In the last decade, a number of MEMS-based on-chip phase modulators have been reported on different materials. In silicon photonics, phase shifting has
been achieved by moving a free-standing waveguide to reconfigure the optical path,\(^\text{11}\) tuning the width of a slot waveguide,\(^\text{14}\) and deforming a waveguide.\(^\text{15}\) However, either they have a very limited tuning range or their measured modulation depth is rather small (<3 d B). Recently, a silicon-on-insulator MEMS phase shifter was theoretically proposed,\(^\text{16}\) which has potentially a faster response and lower loss than the previous modulators on silicon. On the silicon nitride platform, modulators have been demonstrated with an in-plane moveable H-resonator,\(^\text{17}\) which has \(V_{\text{g}} L = 0.17\) V-cm. An out-of-plane moveable microbridge\(^\text{18}\) shows better modulation efficiency, at the cost of covering the microbridge with metal and therefore introducing additional losses. A plasmonic phase modulator was demonstrated by tuning the metal-insulator-metal gap\(^\text{19}\) at a wavelength of 780 nm; however, much higher plasmonic losses are expected at telecom wavelengths due to a higher imaginary part of the permittivity of metal. So far, making a nonmetallic phase modulator with a high modulation depth, large tuning range, and low actuation voltage is still a challenging task. The compact footprint and low power consumption also make MEMS a strong candidate for on-chip optical switching. The compact footprint and low power consumption also make MEMS a strong candidate for on-chip optical switching.

![Image](image-url)

FIG. 1. (a) Scanning electron microscope (SEM) image of a Mach–Zehnder interferometer with a MEMS phase modulator in the lower branch. (b) SEM image of the MEMS-actuated phase modulator at an angled view. (c) Simulated \(n_{\text{eff}}\) of the guided mode in a double-membrane waveguide as a function of the gap dimension. Inset: simulated cross-sectional electric field magnitude distributions in the middle of the waveguides, with gaps of 100 nm (down) and 200 nm (up), respectively. (d) The schematic layer stack of the phase modulator. (e) Calculated phase difference (for a device length of 140 µm) as a function of the vertical gap displacement of the suspended waveguide. The displacement needed for a \(\pi\) phase shift (24 nm) is marked by a dashed line. In the insets, a sketch of the cross section of the modulator is shown.

Here, we demonstrate a MEMS phase modulator on the indium phosphide membrane on silicon (IMOS) platform.\(^\text{26}\) One of the advantages of this platform is that both passive and active components (e.g., lasers, detectors, and amplifiers) can be integrated monolithically on the same chip, which greatly reduces packaging complexity. On the other hand, lower waveguide bending radii and thus more compact device footprint than that of traditional indium phosphide (InP) devices can be achieved due to the high refractive contrast between InP and the underlying layer [SiO\(_2\)/Benzocyclobutene (BCB)]. A half-wave-length-product (\(V_{\text{g}} L\)) of 5.6 \(\times 10^{-3}\) V-cm is achieved. Using the proposed phase modulator, an optical crossbar switch with a low actuation voltage of 4.2 V and an extinction ratio of 15 dB is demonstrated.

The devices are fabricated in the NanoLabNL@TU/e facility at the Eindhoven University of Technology. Layers of InP and InGaAsP are grown lattice matched on an InP:Fe wafer by metal organic vapor-phase epitaxy (MOVPE) [see Fig. 1(d)]. The doping level of InP is \(1 \times 10^{18}\) cm\(^{-3}\) for both p and n layers. A 50 nm-thin p-InGaAs layer with a doping level of \(1 \times 10^{18}\) cm\(^{-3}\) is inserted for p-contact. The InP wafer is then flipped and bonded to a silicon wafer using BCB. After removing the InP substrate, a layer of silicon nitride is deposited by PECVD as a 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 by reactive ion etching (RIE) with CH\(_3\)F chemistry, followed by InP dry etching in inductively coupled plasma etching with CH\(_4\)/H\(_2\). Then, the same process is repeated to define the pattern on the second InP layer. An alloy of Ti-Pt-Au is used for Ohmic p- and n-contacts. Devices are released by a H\(_2\)SO\(_4\)/H\(_2\)O\(_2\)/H\(_2\)O (1:1:10) wet etch at 20 °C to remove the sacrificial GaInAsP layer selectively from InP. Drying is performed with a CO\(_2\) critical point dryer to prevent stiction. The cross section of the fabricated device is schematically shown in Fig. 1(d). Vertical actuation between two oppositely doped semiconductor membranes is used to obtain a relatively large electrostatic force, while keeping the guided mode far away from the metal layers.

Figure 1(a) shows the scanning electron microscope (SEM) image of a MEMS phase modulator implemented within a Mach–Zehnder Interferometer (MZI). Two 50/50 Multimode Interferometers (MMIs) split/combine light into/from two branches. Figure 1(b) shows the details of MEMS part. A 140 µm tapered InP waveguide is suspended and connected with 15 µm-long cantilevers on both sides by nanotethers with a pitch of 8.5 µm. The length of the tapers is 60 µm on both ends of the coupler to ensure adiabatic coupling. Optical loss induced by the tapers is less than 0.3 dB for a TE input according to finite-difference time-domain (FDTD) simulations. The bottom InP ridge waveguide has a cross section of 1.1 µm \(\times 0.27\) µm. 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 since the mode is tightly confined in the waveguide. The layer of InGaAsP between the two InP membranes forms the intrinsic layer of the p-i-n junction and serves as a sacrificial layer.
to create the suspended part. At rest (no applied force), the vertical gap spacing between the suspended waveguide and ridge waveguide is 200 nm. The suspended stripe waveguide has a cross section of \( 1 \mu m \times 0.31 \mu m \). For the fundamental mode (TE polarized), most of the light is confined in the thicker suspended waveguide and air around it, as shown in the bottom inset in Fig. 1(c). In the actuated state, a reverse bias is applied to the junction. The electrostatic force brings the cantilever and the suspended waveguide down, resulting in less field in air and more in the ridge waveguide. This increases the effective refractive index (ERI) of the guided mode so that the phase difference between the two branches is increased.

To estimate the efficiency of the phase modulator, we simulated the ERI change of the waveguide using a finite-difference time-domain model. As shown in Fig. 1(c), the ERI modulation efficiency is about 6.4 \( \times 10^{-5} \) mm. The displacement of 1/3 of the original 200 nm gap, beyond which the electrostatic actuation would enter an unstable regime. For switching applications, a \( \pi \) phase shift is needed. Given the length of the coupler (140 \( \mu \)m including the tapers) in this work, the phase shift \( \Delta \phi \) as a function of the displacement is calculated [Fig. 1(e)]. A displacement of 24 nm is required for a \( \pi \) phase shift, well within the stable regime.

Considering a spring constant of \( k = 16 \) N/m and a junction capacitance \( C = 0.04 \) pF, as expected for the designed structure, a simple spring-charged-plate model predicts a switching voltage around 2 V. However, this value tends to be underestimated since in fabricated devices, the charge distribution is influenced by layer-stack, surface conditions, etc.

To characterize the transmission properties of the device, shallow-etched grating couplers are fabricated at both ends of the device to couple light from and to optical fibers. The gratings are designed for transverse-electric (TE) polarization and have a maximum coupling efficiency around 1550 nm. The transmittance is measured at different wavelengths from 1510 nm to 1600 nm with a tunable laser [Fig. 2(a)]. The observed spectral fringes with a free spectral range of 9 nm are due to the path difference between the two branches induced by the presence of the suspended waveguide in one arm and are modulated by the applied bias. The bandwidth of the device is limited here only by the bandwidth of the grating couplers. After subtracting the grating coupling loss, an insertion loss of 5 dB and a modulation depth of 13 dB are observed [Fig. 2(b)]. The phase shift and ERI variation as a function of voltage are extracted from Fig. 2(a) and plotted in Fig. 2(c). The first \( \pi \) phase shift is achieved at 4.15 V, which gives a \( V_{\pi}L \) of 0.058 V cm. Lithium niobate or polymer based modulators typically have a \( V_{\pi}L \) over 1 V cm, while modulators assisted by the BaTiO\(_3\) film\(^{28,29}\) and graphene\(^{1}\) can have \( V_{\pi}L \) close to 0.25 V cm. A recent paper reported indium tin oxide (ITO) based modulator giving a \( V_{\pi}L \) of 0.059 V cm, but with a loss over 33 dB.\(^{3}\)

The modulator presented here has therefore significant advantage compared to a non-MEMS based modulator in this metric. Due to an exponential decay of the optical field from the waveguide, the phase sensitivity improves with smaller gaps. With a prebias of 5.1 V, an ultralow voltage-length product \( V_{\pi}L \) of 5.6 \( \times 10^{-8} \) V cm is obtained, at the expense of operation close to the pull-in instability. The maximum phase shift is more than \( 3\pi \), which is among the highest measured MEMS-based phase shifts reported to date.\(^{20,31}\) By comparing with Fig. 1(c), a displacement of 60 nm is expected at 5.5 V, showing that our device can be tuned until close to the pull-in limit.

Several on-chip waveguide MEMS optical switches have been reported in the past on silicon\(^{20,22,24,25}\) and III-V semiconductors,\(^{21,23}\) typically requiring more than 10 V to actuate the device. Here, a low-voltage optical crossbar switch is demonstrated using the developed MEMS phase modulator [Fig. 3(a)]. The device is not as compact as another design we proposed in Ref. 33 but is less demanding and more tolerant for fabrication. To maximize the bandwidth, two identical modulators are inserted in both branches to make the optical path symmetric. In the default state, there is no phase difference between the two branches; therefore, light travels to the cross channel (channel2) after passing the two 50/50 MMIs. To switch light to the other output, one of the modulators is actuated to give a \( \pi \) phase shift, resulting in a change between constructive and destructive interference in the second MMI, and consequently, the light is switched from channel2 to channel1. The voltage for maximum switching is around 4.2 V, which agrees with the phase shift measured in Fig. 2(c). An extinction ratio above 15 dB is measured at the switching point. However, the optimal switching voltage slowly drifts toward larger values at longer wavelengths as more \( \Delta n_{\text{eff}} \) is needed to reach a \( \pi \) phase shift, as shown in Fig. 3(b). There is an extra 4 dB loss in the switch transmission compared to the device in Fig. 2. Calibration measurements show that the waveguide loss is 2.6 dB/mm, while the scattering loss induced by the supporting structure is 20 dB/mm in this work. They contribute 4.1 dB; insertion loss to the device. Other possible sources of loss include reflections from the MMI couplers. The loss in the bottom waveguide could be reduced by stripping the n-doped InP layer on top of it. The scattering loss from the supporting structures could be improved by employing a MMI structure and placing the supporting beams at the...
The energy consumed during a switching is approximately

\[ E_s = \varepsilon_0 AV_s^2/(d - z_s), \]

where \( V_s \) is the actuation voltage and \( z_s \) is the displacement needed for switching. \( A \) is the area of the cantilever, and \( \varepsilon_0 \) is the vacuum permittivity. This gives \( E_s = 1.5 \text{ pJ} \).

Assuming a worst-case situation of continuous switching at \( f = 1 \text{ MHz} \), the operating power is \( 1.5 \mu\text{W/π-phase shift} \). The power required for maintaining a static switching state is defined by the dark current of the tuning diode at the actuation voltage, which is \( 10 \mu\text{A} \) in our case. This relatively large dark current could potentially be improved by passivation of the diode. Even with the unoptimized performance, the total power < 42 \( \mu\text{W} \) is still much smaller compared to that of thermoptic modulators, which is in the milliwatt range.\(^7,8\)

Figure 4(a) shows the dynamic behavior of the modulator measured with an oscilloscope. While the fall time is dominated by the fundamental mechanical resonance, the rise time is longer (15 \( \mu\text{s} \)), likely related to a surface-state induced lag effect.\(^24\) A closer look at the transient response when the drive signal falls back to 0 V shows an oscillation with a period of 0.9 \( \mu\text{s} \) [Fig. 4(b)], which corresponds well to the mechanical resonance frequency at 1.1 MHz measured with an electrical signal analyser [Fig. 4(c)]. The mechanical quality factor is only 3.7 due to the air damping at atmospheric pressure. Figure 4(d) shows the displacement map of the fundamental mechanical mode calculated with a finite-element simulation software. While the entire suspended waveguide is moving in this mode, the middle part shows larger displacement than the rest. As the suspended waveguide is wider in the middle and tapered toward the two ends, this mode shape is very efficient for the tuning of ERI. The switching/modulating speed of the device is now limited by the lagged rise time of 15 \( \mu\text{s} \). It is possible to reduce the lag effect by a passivation and decreasing the exposed area between the metallic contact and cantilever,\(^25\) but this will need further investigation. The ultimate bandwidth limit of the modulator is given by the mechanical resonance frequency.

In summary, we have experimentally demonstrated an InP MEMS phase modulator with high efficiency and capability of tuning the phase by more than 3\( \pi \) rad within a 140 \( \mu\text{m} \) propagation length. By implementing the modulator in an MZI, we achieved an optical crossbar switch with a low actuation voltage of 4.2 V and an extinction ratio of 15 dB in a footprint of only 100 \( \times \) 400 \( \mu\text{m} \). The actuation time, which is currently limited to 15 \( \mu\text{s} \) by a lag effect, could potentially be reduced to below 1 \( \mu\text{s} \) by improved design or surface treatment. The device can be potentially integrated with lasers and detectors and find applications in the low-energy optical switch matrix and optical beamforming.

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