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LOW-LOSS MEMS PHASE SHIFTER FOR LARGE SCALE RECONFIGURABLE SILICON PHOTONICS

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ABSTRACT

We experimentally demonstrate a silicon MEMS phase shifter achieving more than π phase shift with sub-dB insertion loss (IL). The phase is tuned by reducing the gap between a static suspended waveguide and a free silicon beam, via comb-drive actuation. Our device reaches 1.2π phase shift at only 20 V, with only 0.3 dB insertion loss – an order of magnitude improvement over previously reported MEMS devices. The device has a small footprint of $50 \times 70 \mu\text{m}^2$ and its power consumption is 5 orders of magnitude lower than that of traditional thermal phase shifters. Our new phase shifter is a fundamental building block of the next-generation large scale reconfigurable photonic circuits which will find applications in datacenter interconnects, artificial intelligence (AI), and quantum computing.

INTRODUCTION

Photonic integrated circuits have shown the potential to become the next-generation multipurpose computing platform [1]. To keep up with the increasing demand for raw computational power and functions, large reconfigurable circuits are required. Currently proposed reconfigurable optical networks rely heavily on phase shifters as the active tuning elements (*Fig. 1*), and the thermal actuation traditionally employed for this cannot satisfy the need for ultra-low power consumption when scaling up to larger circuits [2].

Photonic MEMS devices offer the ultra-low-power actuation required for further upscaling, but previously reported phase shifters either show significant optical losses, or insufficient actuation range. Propagation

length tuning instead of effective index tuning has enabled large phase shifts for small displacements, but the full power transfer condition for the couplers depends heavily on fabrication, due to the gap change upon release [3]. Effective index tuning was achieved by out-of-plane motion of a SiN_x bimorph with mechanical stoppers, but relies on a lossy Au-Cr layer at $1.55 \mu\text{m}$ [4]. Direct electrostatic gap tuning of slot waveguides has demonstrated phase shifts with very low footprint, but such slot waveguides are expected to be lossy [5].

Reconfigurable photonic circuits can employ different architectures, such as hexagonal meshes (as illustrated in *Fig. 1*), rectangular meshes, or even non-uniform meshes [6]. Depending on the chosen architecture, different figures of merit can be defined for the phase shifters in the unit cells. Nevertheless, four figures of merit stand out as the most relevant for upscaling of reconfigurable circuits: the device's insertion loss, the phase shift actuation range, the footprint, and the power consumption. The IL is defined as the total optical losses from input to output of the device: for MEMS devices it is dominated by oxide/air transition losses, and propagation losses in the suspended waveguide segments. The actuation range limits the maximal phase shift that can be attained in a single device. Depending on the mesh architecture, π - or 2π - phase shift is needed. While cascading devices with lower phase shifts could be an option, it limits the upscalability. The footprint of the device must be considered in the trade-off too, as chip size, and thus propagation losses in long routing waveguides, can become the performance limiting factor in larger circuits. Finally, the power consumption per device must be optimized. However, for MEMS devices it is very low and therefore not as critical as IL and footprint.

Here, we report on a silicon photonic MEMS phase shifter exhibiting a sub-dB IL and more than π phase shift over a 50 nm bandwidth in a footprint of only $50 \times 70 \mu\text{m}^2$.

DESIGN

The device presented here uses in-plane electrostatic actuators (comb-drives) to achieve effective index tuning over a propagation distance of $50 \mu\text{m}$, resulting in a phase shift of 1.2π . The effective index is tuned by changing the gap between the waveguide and a suspended movable Si beam (*Fig. 2*).

Our actuator was designed to operate at low voltages and the maximum phase shift was attained with only 20 V. Out-of-plane buckling due to post-release strain relaxation was avoided by using folded springs.

Figure 1. Large-scale photonic circuits rely on phase shifters for reconfiguration and to compensate for fabrication variations. The growing applications of reconfigurable photonics in interconnects, AI, and quantum computing require an upscaling only possible with low-loss, low-power phase shifters.

Figure 2. In-plane comb-drive actuators reduce the gap between a free silicon beam and a static suspended waveguide. As a result, the effective index of the guided mode is increased, which leads to a phase shift as light propagates through the interaction region.

FABRICATION

The device was implemented using standard suspended silicon photonics fabrication techniques, starting with an SOI wafer (device layer 220 nm, BOX layer 2 μm). As illustrated in Fig. 3, two e-beam lithography exposures were done: The first one defines grating couplers, waveguides, and actuators (110 nm

Figure 3. Fabrication of our silicon photonic MEMS: a) Starting SOI substrate. b) Waveguide and actuator definition by a first e-beam lithography of HSQ and etching (110 nm step). c) Second e-beam lithography and etching down to the oxide, for suspending waveguides and actuators. d) Final suspended structures, after resists stripping, timed liquid HF SiO_2 etching, and critical point drying.

etched), while the second one was used for the suspended parts, relying on an additional 110 nm etch down to the SiO_2 BOX surface. The release was performed using liquid hydrofluoric acid (HF) and critical point drying (CPD) [7].

Although the device was patterned using e-beam lithography, the smallest feature size is 200 nm. Therefore, both lithography steps are compatible with wafer level silicon photonics foundry platforms, such as the IMEC iSiPP50G [8]. Finally, wafer level MEMS release has been shown before, both with vapor and liquid HF [9].

Figure 4. Top view optical microscope image of a phase shifter. Light travels from a ridge waveguide into the suspended waveguide. For characterization of the phase-shift, the device is included in one arm of a Mach Zehnder interferometer.

RESULTS

Fig. 4 shows the fabricated phase shifter with in-plane comb-drive actuators. For characterization, the device was included in one arm of an integrated

Figure 5. Measured transmission spectra for different actuation voltages. The spectra of the interferometer shift, as the phase is changed in the active arm. A maximum phase shift of 1.2π was obtained at wavelength of 1550 nm.

unbalanced Mach-Zehnder interferometer, to directly read the phase shift from the interferometer spectrum shift upon actuation (Fig. 5).

The drive voltage was increased from 0 V up to 20 V, obtaining phase shifts of up to 1.2π over an optical bandwidth of 50 nm. The measured actuation curve was fitted to an exponential, corresponding to the exponential mode effective index change with gap reduction (Fig. 6). However, the change in gap is quadratic and not linear with respect to the drive voltage, due to the comb-drive actuator. Therefore, the chosen fitting is not completely accurate, but since the comb-drive was designed to be stable at voltages up to 35V, it can be considered linear for our voltage range.

Figure 6. Measured data at 1550 nm with exponential fit. Inset: phase shift obtained with respect to wavelength. The device achieved a π -phase shift over a 50 nm bandwidth.

The transmission spectra of the MZI was also used to calculate the IL of 0.3 dB. While the total phase difference between both arms determines the free spectral range (FSR), the power imbalance affects the curvature of the peaks and drops. The spectra were therefore fitted to extract the power offset parameter, from which the relative loss between both arms was calculated. The additional propagation losses in the passive MZI arm were simulated, in order to estimate the absolute losses in the active arm, corresponding to the IL of our device.

The device did not display any hysteresis for the voltage range 0-20V, i.e. no phase shift drift was measured when setting the voltage back to 0V. Higher phase shifts were obtained at 21 and 22 V, but the 0V-state changed, suggesting a new mechanical stable state.

CONCLUSIONS

We have fabricated and tested a silicon photonic MEMS phase shifter with sub-dB IL and more than π phase shift over a 50 nm optical bandwidth at 1550 nm.

The low loss, combined with low-power electrostatic actuation and a small $50 \times 70 \mu\text{m}^2$ footprint, shows great potential of MEMS phase shifters as key components in large-scale reconfigurable networks for multi-purpose

computing platforms, with emerging applications such as datacenter optical interconnects, artificial intelligence, and quantum computing.

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