Enhanced efficiency thermo-optic phase-shifter by using multi-mode-interference device

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Abstract. We demonstrate a method for power reduction in thermo-optic based Mach-Zehnder interferometer (MZI) by using the multimode region of a 2x2 Multi-Mode-Interferometer (MMI) as the modulation region. The light is circulated through the same multimode region twice and therefore utilizes the already present change in temperature leading to additional phase change, and an increase in efficiency. Power saving of 29.6% compared to a conventional thermo-optic phase shifter using single mode waveguides has been experimentally demonstrated. The reported devices show minimal insertion loss penalty compared to generic devices and do not add any additional fabrication complexity. Such an approach could also be applied to higher speed devices, for example those employing free carrier effects.

1 Introduction

Thermo-optic phase-shifters have found wide application such as in switching, advance communications [1], and neural networks [2]. More complex devices including Mach-Zehnder modulator arrays, MZI [3] and ring resonator modulators [4] are now being implemented on Silicon-on-Insulator (SOI) platform due to the compatibility and cost benefits [5,6]. Various thermo-optic phase-shifter based interferometric devices are summarized in [7,8] with different approaches to minimize $P_\pi * \tau$, where P_π is the power required to for temperature change and τ is the $1/e$ limiting time constant of heat diffusion.

Tuneability in silicon MMI have been recently demonstrated [9,10]. In [11], reduction in power consumption was demonstrated by utilizing dense packaging of waveguides, arranged in double spiral geometry to increase the overlap of induced temperature distribution. In this work we present an alternative technique for power reduction by passing light through the same modulation region twice thus making more efficient use of the modulation effect.

2 Device design

In our approach, we designed a 2x2 port MMI modulator device with heaters on top of the multi-mode region acting as the modulation region. Fig. 1 shows top view of the device where multimode region length is chosen as the first self-imaging length or commonly known as cross configuration. In the work of [9] the MMI structure itself performs the switching function where the mode interference is modified by the thermally induced refractive index change, causing the light to switch between output ports. In this work, the MMI length is short and the heating more uniformly distributed over the MMI region and therefore the power outputted from each port does not significantly change during modulation.

The light enters the MMI device from top left port and exits from the bottom right port, which is then reintroduced into the device via in-port 2 (top right) and using a 180-degree bend. The final output is available from bottom left port.

Since light passes through the same modulation region twice, power applied to cause the change in refractive index of the multi-mode waveguide can be utilized for phase change on second pass as well, effectively reduce the power to 50% of the power required compared to the single pass through a multimode case.

The MMI width was chosen as 6 µm, with the ports tapering from 0.45 µm to 1.5 µm and positioned at a gap of 0.53 µm symmetrically along the width. The MMI length was simulated to be 89.60 µm for cross configuration, and the heater length and width chosen to be 80 µm and 2 µm respectively. The MMI modulator was placed in both arms of an imbalanced MZI and one of the arms was actuated to observe the change in intensity from the imbalanced MZI output. Similar devices with multi-mode region length 179.20 µm, corresponding to bar configuration, and heater length and width of 160 µm and 2 µm were also fabricated. Normalization devices with exact heater dimensions (as used in both cross and bar MMI MZI configurations) were fabricated for comparison.

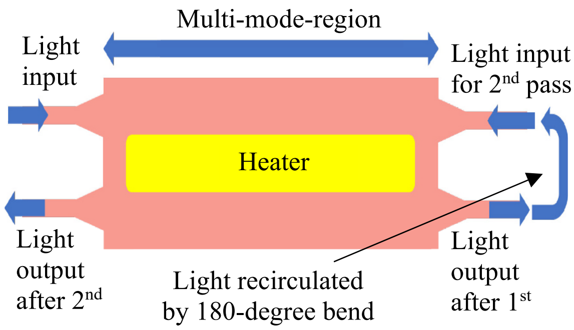

Fig. 1. Top view of the 2x2 MMI used as phase modulator.

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2.1. Fabrication

Fabrication of the devices was performed within a CORNERSTONE MPW run on 220 nm SOI, within the nanofabrication cleanroom facilities at the University of Southampton. The first two steps involved defining the grating couplers and RIB waveguides with 100 nm Silicon slab by DUV lithography and ICP etching. This is followed by depositing a 1µm thick PECVD SiO_2 cladding followed by two lift-off steps for the heater filament and contacts pads. The heater filament is made of TiN and has a thickness of 150 nm and the contact pads consist of a stack of Ti (30 nm) and Au (200 nm).

2.2 Device characterisation

Light from a tuneable laser source was coupled into and out of the devices by using fibres aligned with chip grating couplers. A Keithley power supply was used to power the heaters. The MMI MZ devices recorded an additional insertion loss lower than 0.5 dB compared to the normalization MZ device.

The phase shift was calculated using the formulae

$$\Delta\varphi = \frac{2\pi\,\Delta\lambda}{FSR} \qquad (1)$$

, where $\Delta\varphi$ is the change in phase compared to when no voltage is applied, $\Delta\lambda$ is the change in the spectral dip due to the applied voltage and FSR is the free spectral range of the imbalanced MZI.

Fig.2 shows the power vs phase shift comparison between normalization MZ devices and identical MMI based devices for both fabricated heater length. For devices with heater length 80 µm, normalization MZI show a value of 24.23 mW per π phase shift whereas the MMI MZI devices recorded 17.05 mW per π phase shift. This translates to a power saving of 7.18 mW or 29.6 % compared to the normalization MZI.

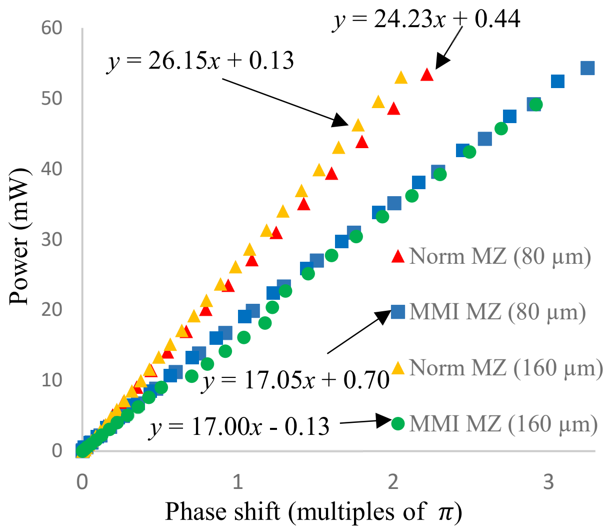

Fig. 2. Power vs phase shift for devices with heater lengths of 80 µm and 160 µm. Normalization MZI are represented by triangles, and MMI based MZI devices are represented as blue squares (80 µm) and green circles (160 µm).

Similarly, for devices with heater length of 160 µm, the normalization MZ device showed a value of 26.15 mW per π phase change and the MMI MZI devices recorded a value of 17 mW leading to and power saving of 9.15 mW or 35%.

3 Conclusion

A proof of concept for enhancing the efficiency of thermo-optic phase shifters has been demonstrated by utilizing the multimode region of a 2x2 MMI as the modulation region and traversing the light twice through it. The experimentally demonstrated devices show a power reduction of in excess of 29.6% compared to thermo-optic phase shifters using single mode waveguides.

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