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

Bharat Pant1, Weiwei Zhang1, Denh Tran1, Mehdi Banakar1, Han Du1, Xingzhao Yan1, Callum G. Littlejohns1, Graham T. Reed1 and David J. Thomson1
1Optoelectronic Research Centre, University of Southampton, Southampton, England
bharat.pant@soton.ac.uk

Abstract—We experimentally demonstrate 29.6% power reduction in thermo-optic based Mach-Zehnder interferometer (MZI) (compared to conventional devices) by using multi-mode region of 2x2 Multi-Mode-Interferometer (MMI) as the modulation region. The reported devices show minimal insertion loss penalty compared to generic devices and no additional fabrication complexity.

Keywords—thermo-optic-phase shifter, multi-mode-interference device, power efficiency

I. 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 interferometric devices based on thermo-optic phase-shifters have been studied [7,8], with approaches to minimize $P_\pi \times \tau$, where $P_\pi$ is the power required to achieve a $\pi$ phase shift and $\tau$ is the $1/e$ limiting time constant of heat diffusion. In this work we present a technique for power reduction by passing light through the same modulation region twice thus making more efficient use of the modulation effect.

II. DEVICE DETAILS

A. Device design

In our approach, we designed a 2x2 port MMI with heaters on top of the multi-mode region to enable it to act as the modulation region. Fig. 1 shows top view of the device where multimode region length is chosen as the first self-imaging length, 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. This should effectively reduce the power to 50% of the power required compared to a single pass through the multimode region.

The MMI width was chosen as 6 µm, with the ports tapering from 0.45 µm to 1.5 µm over a length of 20 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 multimode region length 179.20 µm, corresponding to the 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.

B. 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 (100 nm Silicon slab) by DUV lithography and ICP etching. This was followed by depositing a 1 µm thick PECVD SiO₂ 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).

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Fig 1. Top view of the 2x2 MMI used as phase modulator in the arms of imbalanced MZI (not shown here).

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).

C. Characterisation

Characterisation was performed as follows. 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

\[ \Delta \phi = \frac{2\pi \Delta \lambda}{FSR} \] (1)

where \( \Delta \phi \) 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 normalisation MZ devices and MMI based devices with heater lengths of 80 µm and 160 µm. For devices with heater lengths of 80 µm, normalization MZI devices display a value of 26.74 mW per π phase shift whereas the MMI MZI devices recorded 18.45 mW per π phase shift. This translates to a power saving of 8.29 mW or 31.00 % compared to the normalization MZI. Similarly, for devices with heater lengths of 160 µm, the normalisation MZ device showed a value of 27.00 mW per π phase change and the MMI MZI devices recorded a value of 18.45 mW leading to a power saving of 10.25 mW or 37.96 %.

III. 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% compared to thermo-optic phase shifters using single mode waveguides. Such an approach could also be applied to higher speed devices, for example those employing free carrier effects.

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