Silicon-Based Multimode Interference (MMI) Switch Utilizing Carrier Injection based Electro-Optic Effect

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I. Introduction

Silicon photonics is swiftly becoming a key technology with a wide range of applications in communication systems, LiDAR, sensing optical integrated circuits [1]–[5]. With ongoing advancement in the fabrication processes and techniques for semiconductor and photonic devices, the demand for silicon photonic chips is consistently on the rise. Silicon photonic devices offer inherent advantages such as low power consumption, low latency, high bandwidth and ease of integration with CMOS devices are therefore gaining prominence. A critical application within this field is optical switching []. In silicon photonic chips, switching functions are predominantly executed by micro-ring resonators or Mach-Zehnder interferometers (MZIs) [6], [7]. While ring resonators are compact and energy-efficient, their sensitivity to input wavelength and coupling gap poses significant challenges for realization. Conversely, MZIs exhibit greater tolerance to wavelength variations but suffer from larger cross-sections and associated insertion losses, making them less preferable. These limitations of ring resonators and MZIs have prompted researchers to explore alternative solutions. Multimode interference (MMI) splitter-based switches have emerged as ideal candidates for switching applications due to their compact size and reduced fabrication complexity [8], [9].

Most reported MMI switches are based on the thermo-optic (TO) effect [10]–[12], [14]. In these devices, indirect metal heaters generate Joule heating within the MMI splitter, thereby altering its refractive index to facilitate switching. While the majority of studies employ indirect metal heaters [12], [13], some research explores direct heating of the silicon substrate using n-i-n heaters [14]. Irrespective of the electrode type, the primary drawbacks of TO effect include high power consumption and slow operational speed, requiring tens of milliwatts of power to achieve the necessary refractive index change. An alternative method for achieving switching in silicon-based MMI switches is through the carrier injection-based electro-optic (EO) effect. In this approach, carriers are injected into the MMI using a p-i-n configuration. By carefully integrating two p-i-n structures within the MMI (as illustrated in Fig. 1), switching can be effectively enabled in the MMI splitter.

II. Device design & Principle of operation

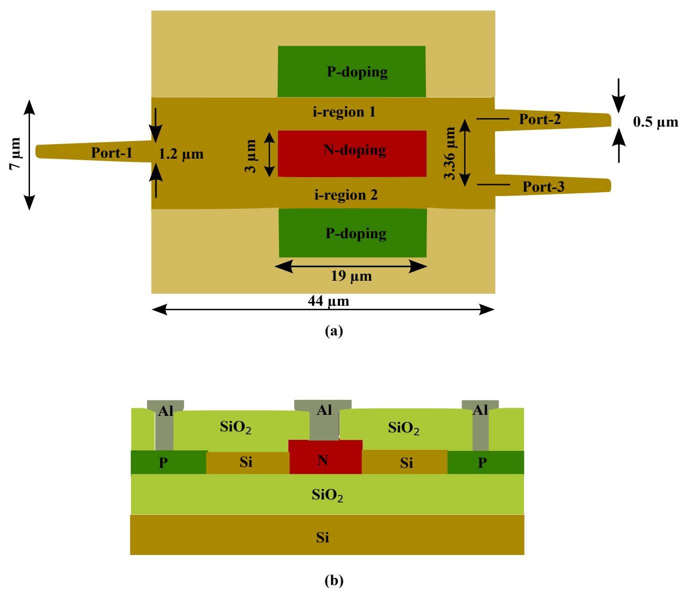

Fig. 1. Schematic of the proposed MMI switch (a) Top view (b) Cross-sectional view.

The schematic of the proposed MMI switch is shown in Fig.1. The device is designed as a 1×2 MMI splitter with dimensions of 7 μm in width and 44 μm in length. Both the input and output ports are tapered, with a tapered region width of 1.2 μm to minimize return loss. For carrier injection, two p-i-n junctions are incorporated, featuring an i-region width of 2 µm, a length of 19 μm, and P and N regions each with a width of 3 μm and a doping density of 4×10^{19} cm^{-3}. The doping density and i-region width are chosen to achieve an index change of -0.07 for an applied bias of 1.3 V. For choosing port-3, the upper p-i-n is biased and carriers are injected in to the i-region 1, which reduces the refractive index of the i-region 1 with respect to the surrounding by -0.07. This reduced refractive index obstructs the easy passage of light through i-region 1, which helps in obtaining light through port-3. Similarly, by changing the refractive index of i-region 2 we can obtain the signal from port-2. Fig.2, shows the electric field distribution in the MMI-switch with a p-i-n junction of length 19 μm and Table I shows the S-parameters for port-2 and port-3.

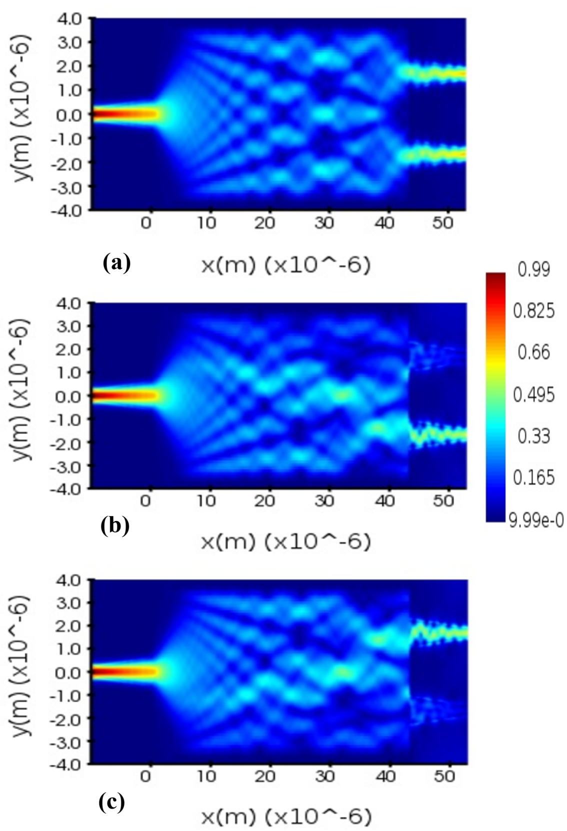

Fig. 2. Simulation result of electric field distribution in MMI switch (a) Without refractive index change in i-regions (b) Refractive index change in i-region 1 (c) Refractive index change in i-region 2.

TABLE I
S-PARAMETERS

Selected Ports	$\mathbf{S_{21}}$	$\mathbf{S_{31}}$
Both Ports	**0.44**	**0.44**
Port 1	**0.304**	**0.001**
Port 2	**0.001**	**0.304**

III. CONCLUSION

We have proposed and simulated a compact, low cross talk 1×2 MMI switch using carrier injection. The switching operation is carried out by changing the refractive index (Δn) of the i-regions using an applied voltage bias of 1.3 V. The device operates with a cross talk of -24.4 dB and has a small device foot-print of 7 μm × 44 μm.

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