Ultra-broadband low-loss 2×2 MZI (Mach-Zehnder interferometer)-based thermo-optic switch with bent directional couplers on silicon

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Abstract: A low-loss and broadband silicon-based thermo-optic Mach-Zehnder switch (MZS) is proposed and demonstrated with 2×2 3dB bent directional-couplers. The demonstrated MZS has a ~140nm bandwidth for excess loss of <1dB and extinction ratio of >20dB.

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1. Introduction

An optical switch is a key building block to enable the all-optical signal routing and switching in reconfigurable photonic network systems. Among various optical switches developed previously, on-chip Mach-Zehnder switches have been attractive because of the footprint compactness [1] and large-scaled optical switch matrix have also been demonstrated [2]. Particularly, in the past decade, silicon photonics has attracted intensive attention as an excellent platform for ultra-compact photonic integrated circuits (PICs). In addition, silicon has very large thermo-optic coefficient (~1.8×10⁻⁴/K at the wavelength of 1.55μm) as well as high heat conductivity (~149W/m·K), which helps realize compact and efficient thermal-tunable/switchable optical devices [3-8]. One should note that it is also important to achieve a broad band response for high extinction ratio (ER) as well as low excess loss regarding the application for reconfigurable wavelength-division-multiplexed (WDM) photonic networks [9-13]. For a 2×2 MZI optical switch, one of the key to achieve broad band is to introduce an 2×2 optical coupler with a coupling ratio of ~50%; 50% over a broad band.

There are some popular structures for 2×2 optical couplers, e.g., multimode interferometers (MMIs), directional couplers (DCs), etc. However, their bandwidth is limited [10]-[11]. As an alternative, a MZI-based 2×2 coupler consisting of two DCs and asymmetrical phase arms is available to be low-loss and broadband [14] and has been used to realize an optical switch with a bandwidth of ~110nm recently [10]. The challenge is that the coupling ratios of the two DCs and the phase difference of the MZIs’ arms need to be controlled very carefully. Furthermore, the device becomes quite long and complex. Another potential option for realizing 2×2 3dB couplers is utilizing asymmetrical straight directional coupler (ADC) which has two waveguides with phase control sections whose widths are modified slightly [15-16]. Recently bent DCs were proposed to obtain a broadband operation for power splitting [18-19]. For this type of coupler, the two waveguides have uniform core widths and their widths can be chosen to be the same, and there is no experimental demonstration yet for broadband 2×2 3dB-couplers based on bent DCs on the silicon-on-insulator (SOI) platform. In this paper, we propose and demonstrate a broadband and low-loss SOI-based MZI optical switch with 2×2 bent DCs. For our fabricated optical switch demonstrated here, the bandwidth for an excess loss of <1dB and an ER of >20dB is as large as ~140nm, which is the best one reported until now to the best of our knowledge.

2. Structure, fabrication and characterization

As shown in Fig. 1(a), the present 2×2 silicon thermo-optic switch consists of two bent DCs and two symmetrical MZI arms. In particular, the two bent DCs are arranged point-symmetrically so that the two MZI arms are balanced (i.e., the interference order m=0). Fig. 1(b) shows the schematic configuration of the bent DC, where R₁ and R₂ are respectively the radii of the inner and outer bent waveguides in the coupling region, θ is the angle-length of the coupling region, W₁ and W₂ are respectively the widths of the inner and outer bent waveguides, and G is the width of the gap between these two bent waveguides. In the present design, we choose W₁=W₂=W and one has R₂=R₁+G+W. In this case, there is phase mismatch between the fundamental modes guided in these two bent waveguides because their radii are different [20]. As a consequence, it prevents to achieve complete power exchange between these two bent waveguides. Fortunately, for the 2×2 optical couplers used for the present MZI optical switch, there is no need to obtain complete coupling and the desired coupling ratio is ~50%; 50%, which can be achieved by choosing the angle-length θ appropriately.

As an example, we choose the following parameters for the bent DC: θ=22°, R₁=35μm, W=510nm, and G=110nm. The three-dimensional finite-difference time-domain (3D-FDTD) simulation shows that the designed bent DC enables a broadband operation and the coupling ratio varies from 45%: 55% to 50%: 50% in the
wavelength band from 1518nm to 1666nm. With this coupler, the MZI shows very low excess loss (almost 0dB) and an high ER (>20dB) over a broad band of ~148nm, which is four fold enhancement compared with an MZI optical switch with the conventional DC (whose bandwidth is ~35nm for achieving an ER of >20dB [10]).

The designed MZI optical switch is then fabricated with the regular steps including the E-beam lithography process, an inductively coupled plasma (ICP) etching process, the PECVD (Plasma Enhanced Chemical Vapor Deposition) process, and the metal deposition. Fig. 1(c) shows fabricated MZI optical switch with bent DCs. The parameters are W=510nm, G=110nm, R 1=35μm and θ=22º. The fabricated devices were characterized by using the setup with a ultra-broadband light source and an optical spectrum analyzer (OSA). Regarding that the grating coupler has a limited 3dB-bandwidth, we use a measurement with two steps by tuning the tilted-angle of the fibers so that it is able to measure the transmissions in a ultra-broad band.

Fig. 2. Normalized measurement results for the fabricated optical switch based on bent DCs with G=120nm, W 1=510nm, W 2=510nm, R 1=35μm and θ=22º. (a) the off-state; (b) the on-state.

Fig. 2(a)-2(b) shows the measured spectral transmissions of the MZI optical switch when the operation wavelength ranges from 1510nm to 1700nm. These results have been normalized by using the corresponding transmissions of a straight waveguide with grating couplers on the same chip. From this figure, it can be seen that the excess loss is less than 1dB in a wide band (~140nm) for both the on-state as well as the off-state. Such large bandwidth is expected according to the theoretical investigation. Fig. 2 also shows that the ER at the cross port for the on-state (see the dark-blue solid line) is wavelength-insensitive and the ER is higher than 20dB over a broad band, which is guaranteed in principle because the two beams for the interference at the cross port are balanced.
perfectly in theory. In practice, the measured ER is 20–25dB in the broad band, which is mainly caused by the slight difference between the two bent couplers with identical design due to the fabrication error. The off-state also has very low excess loss (~1dB) at the through port and high extinction ratio (>20dB) at the bar-port over the wavelength band from 1518nm to 1658nm. From Fig. 6, it can be seen that there are two specific wavelengths (e.g., ~1540nm and ~1636nm) where the ER is very high, which agrees well with the simulation result (also shown in this figure). For the present optical switch, the bandwidth for an excess loss of <1dB as well as an ER of >20dB is about ~140nm, and the bandwidth for an ER of >17dB is even as large as ~150nm, which is the best one reported until now to the best of our knowledge.

3. Conclusion

In summary, we have proposed and demonstrated a broadband and low-loss silicon-based MZI switch by using bent DCs as the 2×2 3dB power splitters. The bent DC enables low loss as well as the desired coupling ratio of ~50%:50% over a broad band of wavelength. The fabricated MZI optical switch has a ~140nm bandwidth for an excess loss of <1dB and an ER of >20dB, which is the best one reported until now to the best of our knowledge. The present MZI optical switch also has excellent reproducibility and consequently it become very promising to develop large-scale N×N optical switches in the future.

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