
A REVIEW OF DEVICES FOR INTEGRATED SILICON PHOTONIC SWITCHES

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ABSTRACT

In this paper, we review devices used in silicon photonic switches. Devices in switches are divided into active and passive devices. Active devices consist of microring resonator, contra directional couplers, mach zhender switches. Passive devices consist of waveguide crossings and arrayed waveguide gratings. We also list the state of the art in devices in a comparison table.

Keywords Switching · Photonic Integrated Circuits · Optical Switching Devices

1 Introduction

Optical switching in datacenters enable reconfigurable datacenter networks [1]. Space switches are reported in [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Some notable demonstrations of wavelength selective switches (WSS) are reported in [18, 19, 20, 21, 22, 23, 24]. We proposed a WSS in [25] and later demonstrate in [26, 27, 18, 28, 29]. WSS with half the number of devices and with multicasting is also reported in [30, 31]. For details on WSS, refer to the review in [32]. In this paper, we give a short overview of different optical devices used in integrated photonic switches.

The major contributions of this paper are as follows:

1. If one were to use the devices mentioned in this paper in the switches, the optical loss is lower than one achieved with typical devices found in literature.
2. This review will help researchers to focus on system level design than starting from deigning devices while building bigger systems.
3. The device designs reported in this paper are freely available and can be easily reproduced as compared with black box foundry process design kit (PDK).

A silicon photonics PDK is reported in [33]. A CMOS compatible PDK is reported in [34]. Devices from both these efforts and other papers are combined in this review. In Section 2, we give an overview of tuning mechanism used in devices. In Section 3, we review state of the art in Active devices. In Section 4, we review state of the art in Passive devices. In Section 5 Discussions, we summarize the findings in a table.

2 Tuning Mechanism

In this section, we consider tuning mechanism used in integrated optical filters and switches. We consider three types of tuning mechanisms. Thermal tuning, electro-optic tuning and tuning based on kerr effect. Thermal tuning tunes on the order of 10s of nm and is useful for filters when tuning across multiple channels is required [35, 36, 37]. In thermal tuning, current is injected into a resistor near which can be a doped silicon waveguide, Tungsten wiring or Ni-silicide.

Tuning time is on the order of μs . Thermal undercut of the ring resonator is reported in [38]. This arrangement has a lower power consumption than other MRRs. A comparison of silicon photonic heaters is provided in [39]. Adiabatic designs reduce overlap between optical mode and the heater and reduce optical loss [40].

The heater vias are the bottleneck in these designs and burnout when we pass a lot of current. We show that tuning times for MRR are on the order of 10s of μs as compared to 1 μs as tuning across many wavelengths is required [18]. This tuning time is much smaller as compared with time required for arbitration in a software defined network (SDN) (1s).

Optical loss is much higher for electro-optic tuning. There are multiple ways to tune MRR with electro optic tuning. We consider only carrier-injection tuning [41] as it is relevant for switches. In carrier-injection tuning we pass current which changes the refractive index of the waveguide. This leads to a change in resonant wavelength of the MRR.

We review active and passive devices used in switches in the next two sections.

3 Active Devices

We review active devices used in switches in this section. Active devices have thermal heaters or carrier injection phase shifters.

3.1 MRR

Microring resonator (MRR) is a device with a circular waveguide coupled to a straight waveguide or waveguides used for switching or filtering a particular wavelength from a WDM channel. MRRs can be either first order, higher order coupled ring resonators [42, 43] or series coupled [44]. A flat top filter shape with high out of band rejection is required for lower crosstalk in a switch. Higher order rings have these features and are sensitive to fabrication variation: optical waveguide shape, coupling gap and thickness uniformity of the wafer. A review of MRRs is reported in [45]. Theoretical approach for coupled resonator optical waveguides (CROW) is reported in [42].

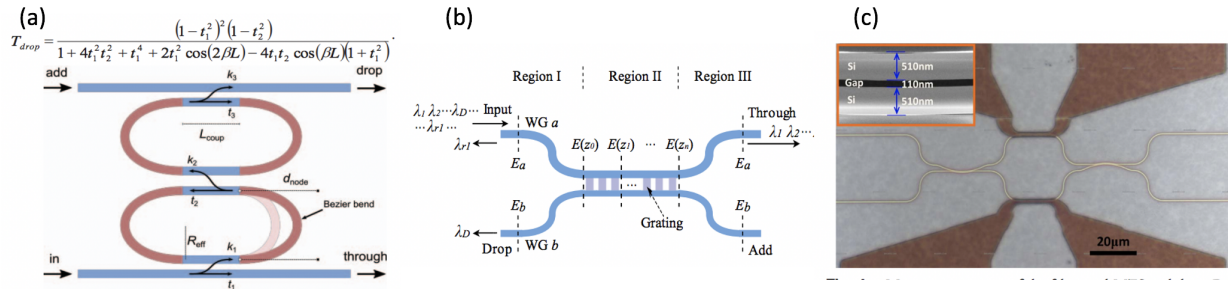


Figure 1: (a) second order MRR with thermal tuning and low insertion loss [46], (b) contra directional coupler [47], (c) MZI [48]

Ring resonators in silicon photonics process have a footprint of $10\mu m \times 10\mu m$ for FSR greater than $20nm$. Switching speed of $1\mu s$ are reported by thermal tuning [40] and $1ns$ by electro optic tuning [49]. Thermal tuning tunes farther than electro-optic tuning with minimal optical loss. We reported a $15\mu s$ rise time to tune across the multiple WDM channels of the MRR in [18]. In most papers, $1/e$ switching time is reported but for wavelength selective switching, tuning across whole FSR is required which can be more than $30nm$ for 8 channel at 400 GHz spacing. MRRs in InP and SiN platform have higher footprint and power consumption due to their size and lower index contrast.

3.2 Contra directional couplers

Contra directional couplers (CDC) are grating filters that can be designed for a very wide filter shape. The filtered wavelengths propagate in opposite direction to the input direction and rest of the wavelengths pass to the through port. These filters can be used as a broadband filter to drop multiple WDM channel and have infinite free spectral range. Switches with very high port counts can be designed with these devices. Apodized contra directional couplers with thermal tuning are reported in [47, 50]. In apodization, the strength of the grating follows a gaussian curve. Apodization can produce flat top filter shapes with higher out of band rejection. A tunable MRR-contra directional switch is reported in [51]. Contra directional couplers with heaters are also reported in [52].

3.3 MZI

Mach zehnder interferometer (MZI) is a device with two directional couplers and a waveguide section between them. These switches have a higher footprint than (MRR) and can be tuned with carrier -injection phase shifters or thermal tuning. A low power MZI with thermal tuning is reported in [48]. A fast nanosecond MZ switch is reported in [53]. Low power thermal tuning with adiabatic bends and integrated thermal tuners is reported in [54]. Many switching networks on chip use broadband directional couplers or multi mode interferometers (MMI). These switches are used to build bigger integrated fiber switches that switch all wavelength division multiplexing (WDM) channels from a fiber.

4 Passive elements

In this section, we provide an overview of passive elements.

4.1 AWGR

Arrayed waveguide grating router (AWGR) consists of input and output waveguides, two free-propagation slab regions, and arrayed waveguides where each neighboring waveguide has a constant path length difference. Each input port of the AWGR can communicate with different output port with specific WDM wavelengths based on the wavelength routing function. Since AWGR is an interferometric device, the phase errors cause a degraded crosstalk. Silicon nitride (SiN) AWGR is superior to silicon AWGR in mitigating the degraded crosstalk since the variation of the average effective index of the arrayed waveguides is lower. The state-of-the-art SiN AWGR can have the adjacent and non-adjacent channel crosstalk as low as -39 dB and -33.5 dB, respectively [55].

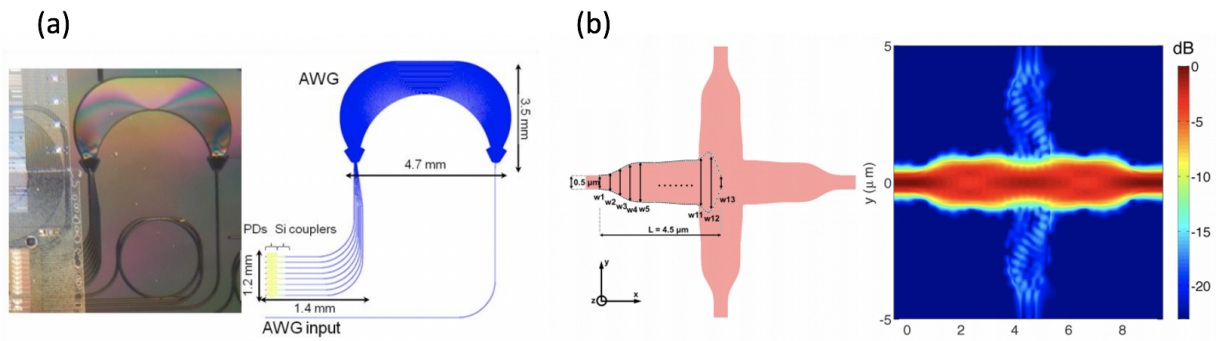


Figure 2: (a) ultralow crosstalk AWG [55], (b) Waveguide Crossing [56]

4.2 Waveguide crossing

Waveguide crossing is a device used for crossing optical waveguides [57]. Optical waveguide width is higher at the junction to focus the mode at the intersection of the two waveguides to minimize optical scattering. Waveguide crossings with loss of less than 0.02 dB and crosstalk less than -37 dB are reported for SOI platform in [56]. This device is $9\mu\text{m} \times 9\mu\text{m}$. These waveguide crossings use optimization algorithms to change the layout of the crossing. Straight waveguide crossing incur a larger optical loss. Other notable crossings are reported in [58]. Silicon and silicon nitride trilayer waveguide crossings are reported in [59]. These gratings have greater size as compared with SOI waveguide crossings but enable more complex photonic integrated circuits.

5 Discussion

The following table summarizes the best devices and we bold their best metrics.

Device	Size	Power Consumption	Switching Speed	Tuning Mechanism	Comments
MRR [36]	$8\mu m \times 10\mu m$	2.4 mW	$170\mu s$	Thermal	-
MRR [40]	-	20 mW	$1\mu s$	Thermal	-
Single λ MZI [54]	200 μm length	$12.7mW\pi phase$	$2.4\mu s$	Thermal	-
Broadband MZI [48]	100 μm length	-	-	Thermal	1dB IL 140 nm
CDC [52]	312 μm	-	-	Thermal	55 dB contrast < 0.5 dB loss
AWGR [55]	-	-	-	-	-33.5 dB Crosstalk
Waveguide Crossing [56]	$9\mu m \times 9\mu m$	-	-	-	0.02 dB

6 Conclusion

We report state of the art devices in integrated silicon photonic switches. The devices from the table can be easily reproduced and fabricated in a silicon photonic foundry.

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