Chapter 1

Introduction

Dense-Wavelength-division multiplexing (DWDM) technology can increase transmission capacity and flexibility in future broadband optical fiber telecommunication networks [1-3]. The expansions in optical DWDM transmission are developed from point-to-point transmission to more complex multi-user network. The complete WDM system is composed of several optical devices such as Multiplexer/DeMultiplexer (Mux/DeMux), optical add/drop multiplexer (OADM), optical wavelength switch and optical filter, etc. Optical access networks are gaining increasingly interest. There are many ways to design and fabricate the optical communication devices. It is popular to integrate semiconductor technology into optical device. Some optical wavelength switch and optical filter have been presented [4-5]. Due to the conventional technology of waveguide fabrication, the size of the optical communication device is very large. Therefore, we implement the novel technology of microring resonator to reduce the size of the optical communication device, also integrate the nano-semiconductor technology. The final purpose of our design is achieving the photonic communication system on chip (PCSoC) [6].

Optical ring resonators are useful components for wavelength filtering, routing, switching, modulation, and multiplexing/demultiplexing applications. The ideal resonator for wavelength division multiplexing (WDM) systems has a wide free spectral range (FSR) and high finesse to accommodate many channels, high transmission at resonance to minimize insertion loss, and a large extinction ratio to minimize crosstalk. Ring resonators based on waveguide structures with weak lateral confinement have very low propagation loss; however, the small refractive index contrast of the weakly guiding structures leads to high radiative bending losses at ring/disk diameters below 1 mm. Therefore, the FSR, which is inversely proportional to the diameter, has been limited to 26 GHz (0.15 nm at 1.3 μm) for a single ring and 100 GHz (0.8 nm at 1.55 μm) for a double ring resonator. More recently, high-index-contrast semiconductor ring and disk resonators have attracted much attention. By etching down through the guiding layer, strong lateral confinement is achieved, thus allowing diameters below 1 mm with negligible bending losses. The advantages of these compact strongly guiding resonators include large longitudinal mode spacing and the potential for high-density integration with other semiconductor devices. For active devices, the wide FSR can yield single-mode operation above threshold. Several groups have demonstrated strongly guiding semiconductor ring lasers [7-8] with diameters in the range from 10μm to 500 μm and large waveguide widths from 4μm to 20 μm. To obtain light output, these ring resonators are coupled to output guides via junctions because directional couplers for strongly guiding waveguides require very small gaps; the low finesse that results from such strong output coupling is compensated by high gain in these active devices. Nanofabrication techniques now allow the realization of semiconductor microcavity ring and disk resonators with evanescent wave coupling to submicron-width waveguides across submicron-width air gaps, as proposed recently [9-10]. Microcavity resonators based on semiconductor waveguides with a very large lateral refractive index contrast (air-semiconductor-air) can have diameters as small as 1–2μm with negligible bending loss [11]. With diameters as small as 5 m, the FSR can be as wide as 6 THz (50 nm). For example, this FSR is wide enough to accommodate a set of WDM channels across the 30-nm erbium amplifier bandwidth. Thus, microcavity ring and disk resonators offer FSR's that are more than an order-of-magnitude wider than those previously achieved with larger weakly guiding ring resonators. With high-quality etching, the scattering losses can be kept low enough to achieve simultaneously a high finesse.

Integrated optic microring resonators are promising to implement the different filtering and switching functionalities [12-13]. Their small dimensions are advantageous for large-scale integration -VLSI photonics - and cost-limited applications. In this paper a wavelength selective ON/OFF switch is described, based on electro-optic tunable microring resonators. The switch allows for a broad Free Spectral Range (FSR) and the selection of a single wavelength band Optical ring and disk resonators are useful components for wavelength filtering, routing, switching, modulation, and multiplexing/demultiplexing applications [14]. The ideal resonator for wavelength division multiplexing (WDM) systems has a wide free spectral range (FSR) and high finesse to accommodate many channels, high transmission at resonance to minimize insertion loss, and a large extinction ratio to minimize crosstalk. Ring resonators based on waveguide structures with weak lateral confinement have very low propagation loss [15-16] An analytical description is also derived. Optical communications filters that are based on resonant wavelength selectivity may offer spectral responses that are superior to filters based on other wavelength sensitive mechanisms, including interference or feedback. For instance, the passband shape of a resonator filter can be custom designed by the use of multiply coupled resonators. Optical ring waveguide resonators are useful components for wavelength filtering, multiplexing, switching and modulation [17-18]. The major physical characteristics underlying these performance criteria are the size of the ring, the insertion loss, and the input and output coupling ratios. There are various components of losses, including sidewall scattering loss, bending radiation loss, and substrate leakage loss. Ring resonators based on (rib) waveguide structures with weak lateral confinement have very low sidewall scattering loss. The bending loss was estimated very small as the bending radius smaller then 5μm. Silicon-on-insulator (SOI) technology is a promising platform for the convergence of microelectronics and photonics. It has a large potential given the high photonic integration capabilities that are made possible by the high refractive-index contrast between silicon and typical cladding materials, the natural vertical confinement of optical waves given by the buried oxide layer, and the potential cost-efficient integration of photonic and electronic functions on the same substrate given by silicon technology.

Typically a microring resonator consists of two parallel dielectric waveguides which are evanescently coupled to a cylindrical/disc/ring shaped cavity. It excites the modes of the cylindrical cavity. Part of the input signal gets coupled to the cylindrical cavity and the remaining signal appears at the through port. In turn, part of it gets coupled to the Drop port waveguide. Depending upon given structural parameters, at resonance frequency all input power appears at the Drop port. But in practice, due to the radiation losses in cylindrical cavity, the transfer efficiency is not 100 %. We are interested in the design, simulation and analysis of 2D/3D active integrated optical microring resonator devices.

In this thesis, we also propose optical waveguide components for

DWDM device. The optical switch building on SOI wafers by microring in this chapter is planned. In the near future, large scale integrated optical systems with densely packed simple optical components will constitute the building blocks of optical communications networks and signal processing circuits. These optical circuits are faster, more scalable, and potentially less expensive than their hybrid optical analogs. Precise modeling and exacting fabrication of dielectric structures are necessary to build the next generation of integrated optical systems. Characteristics of our designed 32×32 microring routing are also presented. Based on our design parameters, we will use those parameters of this microring to simulate and analyze the expand structure such as 4×4、8×8、16×16 and 32×32 optical wavelength routing switch. The optical switch is one key component in WDM network and optical communication system. In the material of silicon-on-insulator (SOI), the active waveguide of voltage control[19] and ion spread[20] are the main streams of technology in now optical switch. Al, Ti, and Wu are the metals for electron switching on SOI optical device. The character of SOI has high transmission rate, low insertion loss, low power depletion, low polarization, and high data capacity transmission.

One promising technique is using the SOI [21-22] waveguide devices in the WDM optical communication systems [23-25]. CMOS (Complementary Metal-Oxide Semiconductor) electronics on SOI wafers have shown to be the future technology for low-power and high-speed applications. For this reason, some good SOI waveguide structures have been used for improving the optical insertion loss and the optical cross-talk phenomenon of 1.55μm and 1.3μm optical communication window [26-28]. The basic performance comparisons of several optical switches are shown in Table I.Currently, optical MEMS-based switches are distinguished based on mirror [29], membranes [30], and planar moving waveguides [31]. The former two are free-space switches and the latter are waveguide switches. Thermal optical switches are based on waveguide thermo-optic effect or thermal phenomena of the materials. Their main advantages are polarization-insensitive operation and switching speed on the order of a millisecond. Switches based on waveguide thermo-optic effect are called thermo-optic switches (TOSW), and we can fabricate them using planar lightwave circuit (PLC) technology [32]. The thermo-optic switches have two basic types: digital optical switches (DOSs) and interferometric switches. Another kind of thermo optic switches is based on thermal effects of the materials, such as thermo-capillarity optical switches [33], thermally generated bubble-type switches and thermo optic switches using coated microsphere resonators [34].

Electro-optical switches are based on electro-optic effects. The advantage of electro-optical switches is to offer relatively faster switching speed. There are many types of electro-optical switches such as $LiNbO_3$ switches [35], SOA-based switches [36], liquid crystal switches [37], electroholographic (EH) optical switches [38], and electronically switchable waveguide Bragg grating switches [39]. The first two are among the oldest optical switches, and the others are now types of electro-optic switches. The $LiNbO_3$ switch is based on the large electro-optic coefficient of $LiNbO_3$ [40]. One of its main applications is a 2×2 directional coupler based on interference, and the coupling ratio is regulated by changing the refractive index of the material in the coupling area. The major weak points of the switch are high insertion loss and high crosstalk [41]. Another application is a digital optical switch (DOS) based on mode evolution, and the DOS has a step-like switch response by applying voltage [42]. PLZT is a material with a higher electro-optic coefficient than $LiNbO_3$ [43]. Hence, PLZT electro-optic DOSs have better switch performance than other electro-optic switches. SOA-based switches are based on current-controlled optical switches. Some SOAs are used as a gate and turned OFF-ON by controlling the bias currents [44]. In this thesis, we present the novel design to the active microring resonator which applies to the optical routing network structure. We show our simulation results on the 2×2 microring cavity. We also utilize free carrier plasma effect (FCPE) to vary local refractive index so as we can change the signal light propagation direction. In chapter 2, we present our design idea and simulations results at section 2-3. We utilized the electro-optics characteristics to design an active control device. In chapter3, based on chapter 2`s parameters we designed the cross grid array microring resonator[45-46]. We present the simulations to 2×2、4×4、8×8、16×16 and 32×32 cross grid array microring resonator routing wavelength switch. We also analyze the SNR and path loss to each structure here. Based on every the simulated results, we conclude to the formula. In chapter4, we use the 2×2 optical microring resonator routing wavelength switch to apply in the application of optical cross connect

(OXC). With each of the network structure such as Crossbar、Double crossbar、 N-stage planer、Benes 、Dilated Benes and AS/AC, we analyzed the SNR and path loss of each of the network structure. Finally, I will give the conclusion at chapter 5. In this work, we report on a systematic study of compact SOI racetrack resonators. These resonators were realized using a waveguide structure with strong light confinement. A set of resonators with varying radii were designed, fabricated, and characterized for large FSR values. Resonators with radii as small as 2.678μm, with FSR as large as 37 nm have been simulated.

Table I. Continued next page

Switch type		Performance										
		Insertion loss	Switching speed	Crosstalk	Polarization dependent loss (PDL)	Transparency at 1550 nm optical window	Switch dimension	Non-blocking	Application	Actuation voltage/ power dissipation	Size	Ref.
Optical MEMS	Mirror/ gap-closing	< 1.7 dB (8×8) < 3.1 dB (16×16)	7 ms	≦ –50 dB	0.25 dB	Very good	8×8 16×16 32×32 up to 512 × 512	Yes	High capacity backbone network or OXC	(A few microwatts) ≦50 V	Hundred microns per unit/ footprint Module 10 cm	[29]
	Micro-optical fiber switch for a large number of interconnects using a deformable mirror (1×N)	2~3 dB	Sub millisecond	≦ –30 dB	Low	Very good 10μm around 1.55	1×N (N can be a very large number)	Yes	OXC	< 190 V	Multi mm×mm× mm	[30]
	1×2 MOEMS switch based on silicon-on-insulator and polymeric waveguides	~0.5 dB (theoretical)	32~200 ns	≦ –32 dB 35 dB (Isolation)	Low	Good 1250~1650 nm	1×2	Yes	Small scale switch or OADM	3~20 V	1600μm	[31]

Table I. Continued next page

	Silicon on silicon technology by LETI	1.5 dB (1×2) 2 dB (1×8)	< 1 ms (1×2) < 1 ms (1×8)	≦ –42 dB (1×2) ≦ –52 dB (1×8)	< 0.5 dB (1×2) < 0.3 dB (1×8)	Good 1250~1650 nm	1×2 1×8 2×2	Yes	Small scale switch or OADM	< 70V	2 mm	[32]
Thermal optical switch	Fully packaged polymeric four arrayed 2×2 DOS	3.5~4.0 dB (total)	< 5 ms	≦ –30 dB	0.2~0.7 dB	Good C band 1.3 and 1.5 wavelength window	2×2	Yes	Small scale switch or OADM	250 mW	45×12 mm^2 (4 arrayed 2×2)	
	Silica-based MZI interferometric switch	7.3 dB (16×16) 1 dB (2×2) 7.4 dB (8×8)	<4.1 ms 4.9 ms (< 200μs was reported)	60.7 dB (extinction ratio) > 30 dB > 50.4dB	0.11 dB Low	Good 1500-1610 nm (extinction ration> 40dB) covering C and L bands	2×2 8×8 16×16	Strictly	For practical large-scale switch	0.85 W (per unit)× 16=13.6 W	165×160×23 mm^3 (8×8) (the module size including cooling fin) 85×85 mm^2 (8×8) (on a 4-in silicon wafer)	[33]

Table I. Continued next page

	PLC thermooptical switch (DC-SW) (based on 1×2 MZI)	12.8 dB (8×16) (average)	13.8 ms	≦ –25 dB on/off 57.8 dB (average)	Low	Good 1500-1610 nm	8×16 8×8 256×256	Strictly	Medium scale matrix, promising for large-scale matrix	0.55 W	330×300 mm^2 (8×16)	
	Thermocapillarity optical switch	0.11 dB (transmission loss) < 1.3 dB (reflection loss) 4 dB (for shortest path) 10 dB (for the longest path)	6 ms (room temperature)	≦ –60 dB (15~25℃)	Low	Good 1500-1610 nm or whole window	2×2 8×8 16×16 N×N (N can be a large number)	Strictly	Large scale	0.15 W (2×2) self latching	16×16 mm^2 (2×2) 23×23 mm^2 (16×16)	[34]
	Thermooptical switch using coated microsphere resonators	Exceptionally low	The order of 100 ms	Very high Q> 10^8	Low	Good 1550 nm window	1×2	Unknown	Unknown	405 nm laser 10^4 mW/cm^2	250μm (diameter)	[35]

Table I. Continued next page

	Bubble actuated switch	0.07 dB (transmission loss per crosspoint) 2.9 dB (fiber to fiber reflection losses) 4.5 dB per 32 ×32 unit	1 ms (switch off time reduced to 100μs)	≦ –70 dB (per cross-point)	< 0.1 dB	Very good	32×32	Good	Strictly	25 W switch		[41]
Electro-optical switch	Ti: LiNbO$_3$ DOS 1 ×2	4 dB (1×2) (Fiber to fiber losses)	On-off 5 ns frequency: several hundred megahertz	Crosstalk suppression > 45 dB	Independent	Good 1520-170 nm	1×2	Potentially	Moderate sized switch matrices switch	18 V	3-in	[36]
	PLZT DOS 1×2 8×8	5 dB mainly fiber coupling loss 1 dB/cm propagation loss	20ns frequency: 10 MHz	≦ –22 dB ≦ –40 dB	Independent	Good	1×2 8×8	Yes	Small scale switch or OADM	10 V	About 12 mm 36mm	[37]

Table I. Continued next page

	SOA-based switch	0 dB	200 ps (10 ps was forecast)	≦ –12 dB	Dependent but (<1 dB) can be realized		1×4 1×8	Yes	Small scale switch or OADM	200 mA	25×5×3 mm^3	[44]
	Semiconductor space switch based on MMI couplers	< 1.5 dB	< 120 ps	≦ –20 dB	Dependent but low value can be realized	So so	2×2	Yes	Small sale switch or OADM	About 10 V	490×11 μm^2	[39]
	Electro-Holographic (EH) optical switch (1×2)	0.5 dB (per switching operation)	< 10 ns	Crosstalk is avoided by management and monitor-ing	Very low	Good 1.3 μm and 1.5 μm work windows	1×2 2×2 240×240	Strictly	OXC competes with 3D MEMS on scalability but is better suited for switching individual wavelengths rather than groups of wave-length	So so. Trellis's 240×240 port switch consumes less than 300 W. High voltages are required, placing demands on the electronic supply equipment.	1.5×1.5 mm^2 (per KLTN switch unit)	[40]

	Liquid crystal optical switch (2×2) NLC (nematic liquid crystal) FLC (ferroelectric liquid crystal)	<1 dB <2 dB	ms (NLC) 35.3 μs (FLC)	≦ –35 dB (NLC)	0.2 dB	Very good C band	2×2 64×64 Benes OXC at most 80 input ports	Yes/ strictly	OADM	Very low (lower than MEMS)	mm^3	[44]
	Liquid crystal holographic switch 1×8 3×3	<10 dB 19.5 dB	ms	–30 dB (typical) > –40 dB (typical)	Low	Very good	1×8 3×3	Strictly	OADM protection and restor-ation	Multi-volt	< 1mm×1 mm	[42]
	Electronically switchable waveguide Bragg gratings switch (2×2)	< 1 dB	10~50 ns	Unknown	Very low	Good 100 nm around 1.55 μm	2×2 cascading small scale switch	Strictly	OADM	Typically 50 mW	Unknown	[36]
Acousto optical switch	Acousto-optical switch	< 4 dB (1×2) overall	300 ns	32 dB (extinction ratio)	Very low	Good 1.55 μm	1×2 small scale	Strictly	Wave-length selective switch	200 mW	2.5 cm long	[43]

Table I. Summary of the general performance of the optical switch technology including optical MEMS-based switching, thermal optical switching, electro-optical switch, and acousto-optic switching