Silicon Based Photonic Devices and Their Applications

QIANG LI

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Tryck: Kista Snabbtryck AB
Abstract

The integration of modern electronic devices for information processing is rapidly approaching an interconnect bottleneck. Silicon photonics can be a promising solution for circumventing this bottleneck, as already being anticipated by many electronics manufacturers including HP, IBM and Intel. In particular, optical interconnects can expedite data transfer both between and within microchips. This thesis aims at two basic building blocks of silicon photonics: waveguides and resonators and addresses their applications in optical signal processing and their potential integration with plasmonic devices.

Firstly, the basic theories of waveguide and resonator are introduced. For a single resonator which acts as a basic signal processing unit, the transmission, phase shift and group delay exhibit unique characteristics. Mode splitting is observed in both a single resonator and a coupled-resonator system. By tuning the configuration of the coupled-resonator system, one can obtain different transmission characteristics for more advanced signal processing.

Secondly, the fabrication and characterization of silicon waveguides and resonators used in the thesis are introduced. The fabrication is carried out with e-beam lithography followed by inductively coupled plasma etching. A vertical grating coupling method is adopted to characterize the transmission spectrum.

Thirdly, based on a single-ring resonator, three kinds of signal processing are experimentally demonstrated: (1) 10 Gb/s format conversion from non-return-to-zero to alternate-mark-inversion signal; (2) a microwave photonic phase shifter providing a tunable phase shift of 0–4.6 rad for a 20 GHz signal; (3) a delay line providing maximal delay times of 80 ps, 95 ps, 110 ps and 65 ps, respectively, for signals in return-to-zero, carrier-suppressed return-to-zero, return-to-zero duobinary, and return-to-zero alternate-mark-inversion formats.

Fourthly, based on a single-ring resonator with mode-splitting, two kinds of signal processing are experimentally demonstrated: (1) a dense wavelength conversion using the free carrier dispersion effect with a data rate ranging from 500 Mb/s to 5 Gb/s; (2) a maximum pulse advancement of 130 ps for a 1 ns signal pulse.

Since silicon photonic devices are limited by diffraction limit, we further look into their hybridization with the diffraction-limit-free plasmonic devices. Two directional couplers from a Si photonic waveguide to a hybrid Si-metal plasmonic waveguide and to a metal-insulator-metal plasmonic waveguide are investigated. The proposed hybrid couplers feature a short coupling length, a high coupling efficiency, a high extinction ratio and a low insertion loss.

Keywords: silicon photonics, waveguide, resonator, all-optical signal processing, plasmonics, directional coupler, coupled-mode theory
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<td>AMI</td>
<td>Alternate-mark-inversion</td>
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<tr>
<td>BPF</td>
<td>Bandpass Filter</td>
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<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
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<td>CMT</td>
<td>Coupled Mode Theory</td>
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<tr>
<td>CSRZ</td>
<td>Carrier-suppressed Return-to-zero</td>
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<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>EIT</td>
<td>Electromagnetically Induced Transparency</td>
</tr>
<tr>
<td>EIA</td>
<td>Electromagnetically Induced Absorption</td>
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<tr>
<td>ER</td>
<td>Extinction Ratio</td>
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<tr>
<td>FCD</td>
<td>Free Carrier Dispersion</td>
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<tr>
<td>FSR</td>
<td>Free Space Range</td>
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<td>FWHM</td>
<td>Full Width at Half Maximum</td>
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<td>GVD</td>
<td>Group Velocity Dispersion</td>
</tr>
<tr>
<td>IL</td>
<td>Insertion Loss</td>
</tr>
<tr>
<td>MIM</td>
<td>Metal-insulator-metal</td>
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<tr>
<td>MZM</td>
<td>Mach-zehnder Modulator</td>
</tr>
<tr>
<td>NRZ</td>
<td>Non-return-to-zero</td>
</tr>
<tr>
<td>OCS</td>
<td>Optical Carrier Suppressed</td>
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<tr>
<td>PC</td>
<td>Polarization Controller</td>
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<td>PIC</td>
<td>Photonic Integrated Circuits</td>
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<tr>
<td>PRBS</td>
<td>Pseudo-random Bit Sequence</td>
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<tr>
<td>RF</td>
<td>Radio-frequency</td>
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<td>RZ</td>
<td>Return-to-zero</td>
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<tr>
<td>RZ-DB</td>
<td>Return-to-zero Duobinary</td>
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<td>RZ-AMI</td>
<td>Return-to-zero Alternate-mark-inversion</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon-on-insulator</td>
</tr>
<tr>
<td>SPP</td>
<td>Surface Plasmon Polariton</td>
</tr>
<tr>
<td>SW</td>
<td>Standing-wave</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse-electric</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse-magnetic</td>
</tr>
<tr>
<td>TW</td>
<td>Traveling-wave</td>
</tr>
<tr>
<td>TOD</td>
<td>Third Order Dispersion</td>
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<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexed</td>
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</tbody>
</table>
List of Symbols

\( \omega_0 \) resonant frequency
\( \lambda_0 \) resonant wavelength
\( \beta \) propagation constant
\( \delta \) normalized frequency detuning
\( \theta \) effective phase shift
\( \tau \) group delay
\( \mu \) mutual-coupling coefficient
\( L_c \) coupling length
\( L_0 \) effective propagation length
\( Q_i \) intrinsic quality factor
\( Q_w \) waveguide-cavity coupling quality factor
\( Q_c \) cavity-cavity coupling quality factor
\( Q_t \) total quality factor
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Chapter 1

Introduction

1.1 Background

For the last 40 years, silicon has revolutionized the electronics industry. The number of transistors per chip doubles every two years on average during the last four decades, which is elegantly described by Moore’s law [1]. Today, nearly three billion transistors can be packed into an area with a size of only a fingernail [2]. As the Moore’s law continues, the integration of modern electronic devices for information processing is rapidly approaching an interconnect bottleneck due to increased signal delay and high electronic power dissipation, which is thus a substantial hindrance to further advances in the electronic industry. Photonic devices, on the other hand, possess a significantly high bandwidth and reduced power dissipation and thus may offer new solutions for circumventing these problems. However, any optical solution must be cost-efficient for mass production. Under such a circumstance, silicon photonics has been a hot research topic in both academy and industry. Silicon has become a material of choice for passive photonic integrated devices owning to the following several unique characteristics:

(1) silicon is transparent at infrared wavelengths used in optical transmission;

(2) silicon has an extraordinary high refractive index ($n=3.45$), which leads to a strong light confinement and thus enables dramatic downscaling of devices compared to other semiconductor materials;

(3) the mature industrial infrastructure of CMOS renders the manufacture of silicon photonic components in high volume considerably cost-effective;

(4) silicon has a fairly strong Kerr nonlinearity, which can be greatly enhanced in a silicon waveguide with a small cross-sectional area.

Silicon’s key drawback for photonics applications is its indirect bandgap, which
makes emission of laser light extraordinarily difficult. So the lasers that drive optical communications are unavoidably made of III-V materials. Silicon/III-V hybrid laser, which combines the light-emitting properties of III-V semiconductor materials with the process maturity of silicon, has been developed to address the lack of a silicon laser and enable fabrication of low-cost, mass-producible silicon optical devices [3].

The research into silicon photonics has been booming since 2004, both in the industry and academy. Specialized companies involved in silicon photonics include Intel, IBM, HP, Bell Labs, Luxtera, Kotura, Lightwire, NTT, etc. Several exciting developments in active and passive silicon photonic components in these companies are highlighted below:

1. Intel’s goal is to develop a silicon photonics technology platform that enables a new breed of monolithic opto-electronic devices manufactured in a low cost CMOS process [4]. Some recently developed key devices from Intel include the first GHz silicon modulator in 2004 [5], the first pulse and continuous-wave silicon Raman laser in 2005 [6, 7], the first electrically pumped hybrid silicon laser in collaboration with University of California, Santa Barbara in 2005 and silicon-based avalanche photodetector with 340 GHz gain-bandwidth product in 2008 [3, 8].

2. IBM is working on the development of on-chip optical interconnects for future multi-core processors based on silicon photonics to overcome severe constraints of today’s copper interconnects [9]. IBM has developed 10 GHz silicon modulator in 2007 [10], as well as an all-optical buffer capable of delaying 10 bits of 20 Gbps optical signals in 2007 [11] and an ultrafast optical switch for 40 Gbps optical signals in 2008 [12], both based on cascaded silicon optical resonators [13].

3. HP has entered into the silicon photonics using silicon photonics to connect blades, boards, chips and eventually cores on the same chip; this has become a strategic goal. HP has demonstrated one of the world’s smallest silicon ring resonators [14].

The universities involved in silicon photonics include Cornell University, University of California, Los Angeles (UCLA), University of California, Santa Barbara (UCSB), University of Texas, University of Surrey, Ghent University, Kyoto University, Yokohama National University, and many others. Several exciting developments concerning silicon photonics in these universities are highlighted below:

1. Cornell University has demonstrated an all-optical wavelength conversion, an optical storage, a 12.5 Gbps silicon modulator based on the silicon ring resonator [15–18].

2. Ghent University has demonstrated a vertical grating coupler, a flip-flop memory on a silicon chip, a 10 GHz gate based on a III-V/SOI microdisk [19–21]. High-speed signal processing based on silicon-organic hybrid slot waveguides has also been demonstrated [22].
1.2 Outline of this Thesis

Kyoto University has fabricated PhC resonators with quality factors up to 2.5 million [23–25].

There are still some issues concerning silicon photonics to be addressed, including the theory of resonators and their applications in optical communication. Especially, a single ring resonator with mode-splitting has not been addressed in the above research. Therefore, this thesis will focus on the theory and applications of silicon waveguide and resonator. In the theory aspect, the coupled mode theory is mainly adopted for analysis of resonators. In the application aspect, optical signal processings based on ring resonators are mainly addressed.

The silicon photonics technology outperform the microelectronics in terms of operating speed. However, a major problem with photonic devices is its comparatively large critical dimension available compared with their electronic counterparts. When the sizes of photonic devices shrink to the wavelength of light, the light propagation is obstructed by diffraction limit, thereby limiting the minimum size of optical structures in photonic integrated circuits (PICs). Surface plasmons polaritons (SPPs), which are optically induced oscillations of free electrons at the surface of a metal, harbor immense potential for the implementation of optical interconnections at nanoscale. However, plasmonic nanostructures usually suffer severe losses owing to the inherent absorption inside the metal, which make them impractical to transfer signals across the entire PIC chip solely by plasmonic waveguides. Therefore, it becomes increasingly important to be able to realize seamless integration of plasmonic and conventional photonic devices on the same chip to take advantage of the strengths of each technology.

Therefore, this thesis will also address the integration of silicon waveguides with plasmonic waveguides.

1.2 Outline of this Thesis

This thesis is organized as follows: in chapter 2, the coupled-mode theory is adopted to analyze the characteristics of a single resonator and a coupled-resonator system; in chapter 3, the fabrication and characterization of silicon waveguides and resonators are briefly introduced; in chapter 4, three signal processings based on a single silicon ring resonator are demonstrated, including all-optical NRZ-to-AMI format conversion, all-optical microwave photonic phase shifter and all-optical delay line; in chapter 5, two signal processings based on a single silicon ring resonator with mode-splitting are demonstrated, including all-optical dense wavelength conversion and all-optical fast-light; in chapter 6, the directional couplers from silicon waveguides to plasmonic waveguides, including a hybrid Si-metal plasmonic waveguide and a metal-dielectric-metal plasmonic waveguide, are proposed and their performances are analyzed; in chapter 7, conclusion and future work are given; the author’s contributions to the published papers are provided in Chapter 8.
Chapter 2

Basic Theory of Optical Waveguide and Resonator

Waveguides and resonators are two elemental building blocks for nanophotonics. In this chapter, we introduce the basis of waveguides and resonators. For waveguides, effective index method and rigorous vectorial method are introduced. For resonators, we use temporal coupled mode theory (CMT) to investigate the characteristics of a single resonator and a coupled-resonator system. The results are included in Paper I\(^1\) and Paper II\(^2\).

2.1 Optical Waveguide

Here, we consider a two-dimensional cross section of a strip waveguide, as is shown in Fig. 2.1. There are two families of modes (TE or TM) in this strip waveguide. For TE modes, the main electric components are polarized in the \(x\) direction. For TM modes, the main electric components are polarized in the \(y\) direction. The effective index method can be used to find approximate solutions for the propagation constants of this two-dimensional strip waveguide.

For the two-dimensional silicon strip waveguide shown in Fig. 2.1(a), it can be regarded as a combination of one horizontal waveguide (Fig. 2.1(b)) and one vertical waveguide (Fig. 2.1(c)). We consider the TE mode propagating in this two-dimensional strip waveguide. The cross section has a dimension of 450 nm \(\times\)


Chapter 2. Basic Theory of Optical Waveguide and Resonator

Figure 2.1: (a) Two-dimensional strip waveguide. (b) and (c) are the one-dimensional horizontal waveguide and vertical waveguide in the effective index method, respectively.

250 nm. The effective index for the TE mode in the one-dimensional waveguide shown in Fig. 2.1(b) is 2.92. Then by calculating the effective index of TM mode in the one-dimensional waveguide shown in Fig. 2.1(c), we can obtain an effective refractive index of 2.47 for the strip waveguide.

To precisely calculate the mode distribution and effective index of waveguides, other methods, such as beam propagation method, finite-different-time-domain (FDTD) method, finite-element method, can be used. These methods can precisely solve the Maxwell equations in the cross-section expressed as follows:

\[ \nabla \cdot \mathbf{D} = \rho_f, \]
\[ \nabla \cdot \mathbf{B} = 0, \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \]
\[ \nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t}, \]

with

\[ \mathbf{D} = \varepsilon \mathbf{E} \]
\[ \mathbf{B} = \mu \mathbf{H} \]

where \( \mathbf{E} \) and \( \mathbf{B} \) represent electric and magnetic fields, respectively; \( \rho_f \) and \( \mathbf{J}_f \) represent free charge density and current density, respectively; \( \varepsilon = \varepsilon_0 \varepsilon_r \) and \( \mu = \mu_0 \mu_r \);
2.2 Optical Resonator

\( \varepsilon_0 \) and \( \mu_0 \) represent permittivity and permeability of free space, respectively; \( \varepsilon_r \) and \( \mu_r \) represent relative permittivity and relative permeability of the medium, respectively. The full-vector wave equation can be written as

\[
\nabla \times \left( \frac{1}{\varepsilon_r \mu_r} \nabla \times H \right) - k_0^2 H = 0
\]

(2.7)

\[
\nabla \times \left( \frac{1}{\varepsilon_r \mu_r} \nabla \times E \right) - k_0^2 E = 0
\]

(2.8)

The field \( H \) and \( E \) can be expressed as \( H = H(x,y) \exp(-i\beta z) \) and \( E = E(x,y) \exp(-i\beta z) \), respectively. \( \beta \) is the propagation constant. Fig. 2.2 provides the mode distributions of the TE and TM modes in the silicon waveguide on top of a SiO\(_2\) substrate. The effective indice for the TE and TM modes are 2.36 and 1.78, respectively. More fields for the TE mode concentrate in the silicon waveguide compared with the TM mode; therefore, the TE mode has a higher effective index.

![Mode distributions of (a) TE and (b) TM modes in silicon strip waveguide with a dimension of 450 nm × 250 nm. The \( E_x \) component and \( E_y \) component are shown for the TE and TM mode, respectively.](image)

2.2 Optical Resonator

The optical resonator has been a subject of great interest as it is a vital functional building block for filtering, modulating, buffering, and switching for integrated optical processing in nanophotonics. Optical resonators can also be applied in the field of quantum information processing [26], optomechanics [27], sensing [28], etc.

The quality factor \( (Q_i) \) is usually used to describe how under-damped a resonator is. Higher \( Q_i \) indicates a lower rate of energy loss relative to the stored
energy of the resonator. The definition of the resonator $Q_i$ value is given by:

$$Q_i = \frac{\omega_0 U}{W_L}$$  \hspace{1cm} (2.9)

where $\omega_0$ is the resonator resonance frequency, $U$ is the energy stored in the mode, and $W_L$ is the energy loss rate.

There are two mechanisms of loss present in the resonator, namely, the material absorption loss and the radiation loss. The total loss rate is the sum of the material absorption rate and the radiation rate; therefore, $Q_i$ can be expressed as:

$$\frac{1}{Q_i} = \frac{W_L}{\omega_0 U} = \frac{W_{rad}}{\omega_0 U} + \frac{W_{abs}}{\omega_0 U} = \frac{1}{Q_{rad}} + \frac{1}{Q_{abs}}$$  \hspace{1cm} (2.10)

where $Q_{rad}$ and $Q_{abs}$ account for the radiation loss and absorption, respectively.

### 2.3 Waveguide Coupled Resonator

The resonator is usually coupled with a waveguide. The interaction between a single optical resonator and a waveguide has been theoretically studied based on the CMT [29, 30]. In CMT, an overall system is described in terms of a set of weakly coupled components, each of which can be analyzed using general principles [31]. A resonator is treated as an oscillator in time. The optical resonators can be generally categorized into two groups: standing-wave (SW) resonators and traveling-wave (TW) resonators. The photonic crystal resonator, distributed feed-back resonator are considered as SW resonators while the ring resonator is a typical example of a TW resonator. For a SW resonator coupled to a waveguide, its resonator mode decays equally into the forward and backward propagating waveguide mode; while for a TW resonator, the resonator mode decays in only one direction due to momentum matching. For characterizing a resonator, we define the following parameters: $\omega_0$ ($\lambda_0$) is the resonant frequency (wavelength); $a$ is the resonator mode amplitude; $s_i/s_t/s_r/s_d$ are the incident/transmitted/reflected/dropped waveguide mode amplitudes, which are normalized such that their squared values correspond to incident/transmitted/reflected/dropped power; $1/\tau_i$ and $1/\tau_w$ are decay rates due to intrinsic loss and waveguide coupling loss, respectively; $Q_i$ and $Q_w$ are resonator quality factors related to intrinsic loss and waveguide coupling loss, respectively; $Q_t$ is total quality factor ($1/Q_t = 1/Q_i + 1/Q_w$). $Q_w$ denotes the resonator-waveguide coupling and is referred to as ”waveguide coupling quality factor”, whereas $Q_c$ represents the resonator-resonator and is referred to as “resonator coupling quality factor”. The decay rates are related to the resonator quality factors by $Q_i = \omega_0 \tau_i/2$ and $Q_w = \omega_0 \tau_w/2$. We use $\delta$ to normalize the frequency $\omega$, which is defined by $\delta = (\omega - \omega_0)/\omega_0$, and $t(= s_t/s_i)$, $r(= s_r/s_i)$, $d(= s_d/s_i)$ to denote transfer functions for transmitted port, reflected port and dropped port, respectively.
2.3. Waveguide Coupled Resonator

Figure 2.3: Schematics of single resonators coupled to waveguides. (a) and (b) are SW resonators with side-coupling and shoulder-coupling configuration denoted as $S_1$ and $S_2$, respectively. (c) is a TW resonator denoted as $T_1$.

Figure 2.3 gives the schematics of single resonators coupled to waveguides. In this thesis, we use a disk and a ring to denote a SW and a TW resonator, respectively. For SW resonators, two different waveguide coupling configurations are considered, including the side-coupling configuration (Fig. 2.3(a)) and the shoulder-coupling configuration (Fig. 2.3(b)). Without loss of generality, we assume the resonator mode is symmetric about the vertical mirror plane perpendicular to the waveguide for $S_1$. For the other systems mentioned in this thesis, similar assumptions are made to ensure that all waveguide coupling coefficients are the same. For the $T_1$ system, the evolution of the electric field $a$ inside a resonator which is coupled to a single-mode waveguide can be described by the CMT:

$$\frac{d}{dt} a = \left(j - \frac{1}{2Q_w} - \frac{1}{2Q_i}\right) \omega_0 a - j \sqrt{\frac{\omega_0}{Q_w}} s_i$$  \hspace{1cm} (2.11)

The equation connecting the incident field $s_i$ and transmitted field $s_t$ can be expressed as follows:

$$s_t = s_i - j \sqrt{\frac{\omega_0}{Q_w}} a$$  \hspace{1cm} (2.12)

After combining Eq. 2.11 and Eq. 2.12, the transmission function of the TW resonator can be expressed as:

$$t = \frac{s_t}{s_i} = \frac{j \left(\frac{\omega - \omega_0}{\omega_0}\right) + \frac{1}{2Q_i} - \frac{1}{2Q_w}}{j \left(\frac{\omega - \omega_0}{\omega_0}\right) + \frac{1}{2Q_i} + \frac{1}{2Q_w}}$$  \hspace{1cm} (2.13)

The transfer functions at the transmitted ports of $S_1$, $S_2$ and $T_1$, denoted by $t_{S_1}$, $t_{S_2}$ and $t_{T_1}$, are given in Table 2.1. The transmission $T$, effective phase shift $\theta$ and group delay $\tau$ can be calculated as $T = \text{abs} (t)^2$, $\theta = \text{arg} (t)$ and $\tau = d\theta (\omega)/d\omega$, respectively and their values at resonance are also given in Table 2.1. Fig. 2.4 shows the transmission, phase shift and group delay of single SW and TW resonator coupled to a single-mode waveguide.
Table 2.1: Comparisons between single SW and TW resonators.

<table>
<thead>
<tr>
<th></th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>over-coupled ( T_1 )</th>
<th>under-coupled ( T_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t )</td>
<td>( \frac{j2\delta+1/Q_i}{j2\delta+1/Q_i+1/Q_w} )</td>
<td>( \frac{1}{1+Q_w/Q_i} )</td>
<td>( \frac{j2\delta+1/Q_i-1/Q_w}{j2\delta+1/Q_i+1/Q_w} )</td>
<td>( \frac{j2\delta+1/Q_i-1/Q_w}{j2\delta+1/Q_i+1/Q_w} )</td>
</tr>
<tr>
<td>( T(\omega_0) )</td>
<td>( \frac{1}{1+Q_i/Q_w} )</td>
<td>( \frac{1}{1+Q_w/Q_i} )</td>
<td>( \frac{Q_i^2}{1} )</td>
<td>( \frac{1}{1+Q_i/Q_w} )</td>
</tr>
<tr>
<td>( \theta )</td>
<td>(-\theta_1, \theta_1 \subset [-\pi/2, \pi/2] )</td>
<td>(-\pi/2, \pi/2 )</td>
<td>([0, 2\pi] )</td>
<td>(-\theta_2, \theta_2 \subset [-\pi/2, \pi/2] )</td>
</tr>
<tr>
<td>( \theta(\omega_0) )</td>
<td>0</td>
<td>0</td>
<td>( \pi )</td>
<td>0</td>
</tr>
<tr>
<td>( \tau(\omega_0) )</td>
<td>( -\frac{2Q_i}{Q_w} \frac{\omega_0}{\omega_0} )</td>
<td>( \frac{2Q_i}{\omega_0} )</td>
<td>( \frac{4/Q_w}{Q_i} \frac{\omega_0}{\omega_0} )</td>
<td>( \frac{4/Q_i}{1/Q_i-1/Q_w} \frac{\omega_0}{\omega_0} )</td>
</tr>
</tbody>
</table>

Figure 2.4: Transmission, phase shift and group delay of single SW and TW resonator. For \( S_1 \) and \( S_2 \), \( Q_i=16\times10^4 \), \( Q_w=2\times10^4 \). For over-coupled \( T_1 \), \( Q_i=4\times10^4 \), \( Q_w=3.2\times10^4 \). For under-coupled \( T_1 \), \( Q_w=4\times10^4 \), \( Q_i=3.2\times10^4 \). We assume \( \lambda_0=1550 \text{ nm} \) here and in the following figures.
2.4. Coupled-Resonator System with Mode-splitting

From the Table 2.1 and Fig. 2.4, we can draw the following conclusions:

1. When $Q_i - under - T_1 = 2Q_w - S_1$ and $1/Q_w - over - T_1 = 1/Q_i - under - T_2 = 1/Q_i - S_1 + 1/(2Q_w - S_1)$, the over-coupled $T_1$ (the TW resonator with $Q_i > Q_w$), under-coupled $T_1$ (the TW resonator with $Q_i < Q_w$) and $S_1$ have identical transmission spectra, as is shown in Fig. 2.4(a). Especially, the phase shift and group delay are completely the same for under-coupled $T_1$ and $S_1$. Therefore, we can treat the under-coupled TW resonator as a side-coupled SW resonator.

2. For the SW resonator, the transmission approaches zero for $S_1$ and unity for $S_2$ when $Q_i \gg Q_w$. For the TW resonator, the transmissivity is unity when $Q_i \gg Q_w$ and zero when $Q_i = Q_w$, i.e., the critical coupling condition is satisfied.

3. The over-coupled $T_1$ exhibits the largest phase shift range ($\sim 2\pi$). For $S_2$, the phase shift range is only $\pi$. For $S_1$ and under-coupled $T_1$, the phase shift ranges are $2\theta_1$ and $2\theta_2$, respectively, where $\theta_1 = \tan^{-1}\left[\sqrt{Q_i/Q_i(2Q_w)}\right]$ and $\theta_2 = \tan^{-1}\left(1/\sqrt{Q_i/Q_i^2 - 1}\right)$. The phase shift range can achieve $\pi$ only when $Q_i \gg Q_w$ for $S_1$ and $Q_w$ approaches $Q_i$ for under-coupled $T_1$.

4. The dispersions at resonance for $S_2$ and over-coupled $T_1$ are normal and thus slow-light can be obtained. While for $S_1$ and under-coupled $T_1$, abnormal dispersion occurs at resonance and thus fast-light takes place.

2.4 Coupled-Resonator System with Mode-splitting

In this section, we analyze the mode-splitting characteristics of two identical resonators with direct coupling. Two situations are considered, where the coupling waveguide(s) is(are) placed either symmetrically or asymmetrically. The coupling coefficient between the two resonators is denoted by $\mu$ and is related to coupling quality factor by $Q_c = \omega_0/(2\mu)$.

2.4.1 Two Coupled Resonators with Symmetric Coupling Waveguides

Figure 2.5 shows two identical resonators with direct coupling. The coupling waveguides are in symmetric placement. In these cases, the degeneracy of the two resonator modes are lifted due to the coupling; hence a splitting in the resonant frequencies occurs. For two degenerate SW modes shown in Fig. 2.5(a) the transfer functions can be given as

$$t_{S3} = 1 - \frac{1}{2Q_w} \left(\frac{1}{j(2\delta + 1/Q_c) + 1/Q_i + 1/Q_w} + \frac{1}{j(2\delta - 1/Q_c) + 1/Q_i + 1/Q_w}\right) \tag{2.14}$$
Figure 2.5: Schematics of two identical coupled resonator modes with symmetric waveguide coupling. (a)-(c) consist of two SW resonators but with different waveguide coupling configurations ($S^3-S^5$). (d) consists of two TW resonators ($T^2$).

Following the same procedure, the transfer functions for the transmitted ports of $S^4$, $S^5$ and $T^2$ can also be obtained. From Eq. 2.14, we can see that the two degenerate modes with frequency $\omega_0$ are split into two resonant frequencies, namely $\omega_0 - \omega_0/(2Q_c)$ and $\omega_0 + \omega_0/(2Q_c)$. The waveguide coupling quality factor for the two split modes still keeps at $Q_w$. The separation of the two split resonances is solely determined by the coupling factor $Q_c$ for a fixed $\omega_0$. Figures 2.6, 2.7 and 2.8 illustrate the transmission, phase shift and group delay for the transmitted ports of $S^3$-$S^4$, $S^5$ and $T^2$, respectively. For the SW resonator system $S^3$, a decrease in $Q_c$ reduces the depth of resonance notch and further lifts the degeneracy of the two resonances, as shown in Fig. 2.6(a). The splitting in the transmission turns more and more obvious with increasing coupling. However, the dispersions at the two splittings in the transmission still keep anomalous and thus fast light always takes place, as shown in Fig. 2.6(b) and (c), respectively. We must point out that although the mode-splitting occurs as long as the coupling exists, it doesn’t necessarily mean that the splitting occurs in the transmission spectrum. This is because that the overall transmission is determined by the superposition of the two split modes with different amplitudes and phases. Here the two splittings can be seen in the transmission only when the coupling is large enough.

For the TW resonator system $T^2$, we consider two cases: (1) over-coupling case ($Q_i > Q_w$) shown in Fig. 2.8. As $Q_c$ decreases gradually, the coupling increases resonance notch depth. When $1/Q_c^2 = 1/Q_i^2 - 1/Q_w^2$, the transmission is zero at resonance and there is an abrupt $\pi$ jump in the phase shift. Once $Q_c$ decreases further, splitting takes place in the transmission and the dispersion at resonances shifts from normal to anomalous. For the dispersion response, slow-light occurs at the enhanced resonance and fast-light at the two splittings in the transmission. (2) under-coupling case ($Q_i < Q_w$). The under-coupled TW resonator can be regarded as a side-coupled SW resonator; therefore, the transmission, phase shift and group
Figure 2.6: The transmission, phase shift and group delay for different $Q_c$ for $S3$ (a-c) and $S4$ (d-f). $Q_t =10 \times 10^4$, $Q_w = 4 \times 10^4$. 
Figure 2.7: The transmission, phase shift and group delay for different $Q_c$ for $S5$. $Q_i=10 \times 10^4$, $Q_w=4 \times 10^4$.

delay characteristics for $T2$ in this case are completely the same as those for $S3$.

### 2.4.2 Two Coupled Resonators with Asymmetric Coupling Waveguide(s)

In this part, we analyze the cases that the waveguide-coupling for the two coupled resonators are asymmetric, which are shown in Fig. 2.9. The resonant frequencies for $a_1$ and $a_2$ are $\omega_0$ while the intrinsic quality factors are $Q_{i1}$ and $Q_{i2}$, respectively. The waveguide-coupling occurs only for mode $a_1$ in all three configurations. For the $S6$ configuration, the transfer function can be obtained as follows:

$$t_{S6} = 1 - \frac{1}{Q_w} \left( j2\delta + \frac{1}{2Q_{i2}} + \frac{1}{2Q_{i1}} + \frac{1}{2Q_w} \right)^2 + \left( \frac{1}{Q_c} \right)^2 - \left( \frac{1}{2Q_{i1}} - \frac{1}{2Q_{i2}} + \frac{1}{2Q_w} \right)^2$$

(2.15)

Following the same procedure, we can obtain the transfer functions for $S7$ and $T3$. Table 2.2 provides the mode-splitting characteristic for $S6$ for different coupling...
2.4. Coupled-Resonator System with Mode-splitting

Figure 2.8: The transmission, phase shift and group delay for different $Q_c$ for $T2$. $Q_i=10\times10^4$ and $Q_w=4\times10^4$.

Figure 2.9: Schematics of two identical coupled resonators with asymmetric waveguide coupling. (a) and (b) consist of two SW resonators with different waveguide-coupling configurations, denoted by $S6$ and $S7$, respectively. (c) consists of two TW resonators denoted by $T3$. 

- $S6$
- $S7$
- $T3$
Table 2.2: Mode-splitting characteristic for $S6$ for different coupling strengths.

<table>
<thead>
<tr>
<th>$\frac{2}{Q_c}$</th>
<th>$\omega_0$</th>
<th>$\frac{Q_i}{Q_{w}}$</th>
<th>$\frac{Q_w}{Q}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{Q_i} - \frac{1}{Q_{i2}} + \frac{1}{Q_w}$</td>
<td>$\omega_0$ - $\omega_0/(2Q_0)$</td>
<td>$\frac{2Q_iQ_{i2}}{Q_{i1} + Q_{i2}}$</td>
<td>$2Q_w$</td>
</tr>
<tr>
<td>$\frac{1}{Q_i} - \frac{1}{Q_{i2}} + \frac{1}{Q_w}$</td>
<td>$\omega_0 + \omega_0/(2Q_0)$</td>
<td>$\frac{2Q_iQ_{i2}}{Q_{i1} + Q_{i2}}$</td>
<td>$\frac{2Q_wQ_0}{(Q_0 + 2Q_w)}$</td>
</tr>
<tr>
<td>$\frac{1}{Q_i} - \frac{1}{Q_{i2}} + \frac{1}{Q_w}$</td>
<td>$\omega_0$</td>
<td>$\frac{2Q_iQ_{i2}}{Q_{i1} + Q_{i2}}$</td>
<td>$\frac{2Q_wQ_0}{(Q_0 - 2Q_w)}$</td>
</tr>
</tbody>
</table>

strengths. Here $(1/Q_0)^2 = \left[(1/Q_c)^2 - [1/(2Q_{i1}) - 1/(2Q_{i2}) + 1/(2Q_w)]\right]^2$. The mode-splitting depends greatly on the coupling strength: (1) when $2/Q_c > 1/Q_{i1} - 1/Q_{i2} + 1/Q_w$, the resonant frequency for the two split modes are $\omega_0 - \omega_0/(2Q_0)$ and $\omega_0 + \omega_0/(2Q_0)$, respectively, while the intrinsic quality factor and the waveguide coupling quality factor are the same; (2) when $2/Q_c < 1/Q_{i1} - 1/Q_{i2} + 1/Q_w$, the resonant frequencies for the two split modes are still $\omega_0$ but the waveguide coupling quality factors are different, which are $2Q_wQ_0/(Q_0 + 2Q_w)$ and $2Q_wQ_0/(Q_0 - 2Q_w)$, respectively; (3) when $2/Q_c = 1/Q_{i1} - 1/Q_{i2} + 1/Q_w$, the two split modes are degenerate, with the same resonant frequency and intrinsic quality factor and waveguide coupling quality factor. The transmission for $S6$ when $Q_{i2} \to \infty$ is given by:

$$T_{S6} = 1 - \frac{\delta^2 (2/(Q_{i1}Q_w) + 1/Q_w^2)}{\delta^2 (1/Q_{i1} + 1/Q_w)^2 + 4 (\delta^2 - 1/(4Q_c^2))^2} \tag{2.16}$$

We recall EIT equation from Ref. [32], $T_{ab} = \Omega_1^2 \Gamma \Delta^2 \left[\Delta^2 \Gamma^2 + 4(\Delta^2 - \Omega_2^2/4)^2\right]$ , where $\Omega_1$ and $\Omega_2$ are respective Rabi frequencies of probe field and pump field, $\Gamma$ is decay rate and $\Delta$ is detuning of probe field from atomic resonance. It can be seen that Eq. 2.16 is identical to the EIT equation [32]. Therefore, the EIT-like transmission is a special case of mode-splitting due to the coupling between resonator modes. From Eq. 2.16, two conclusions can be drawn: (1) $T(\omega_0) = 1$, meaning that complete transparency can be obtained in the transmission spectrum; (2) $T_{S6}$ achieves minimum at $\delta = 1/(2Q_c)$ and this minimum can be zero if $Q_{i1} \gg Q_w$.

Figure 2.10 plot the transmission, phase shift and group delay for $S6$ and $S7$. For $S6$, without direct coupling, the dispersion is abnormal and fast-light occurs at resonance. As the direct coupling increases, the EIT-resonance becomes obvious and the dispersion changes to normal in the EIT-like resonance. It can be seen that the delay is quite large at the EIT-like resonance, which is obviously demonstrated in Fig. 2.10(c) when $Q_c = 2 \times 10^5$. No complete transparency is achieved because we consider the loss of mode $a_2$ here.

For $S7$, the transmission at resonance forms a dip with increased direct coupling,
Figure 2.10: Illustration of the transmission, phase shift and group delay of resonators for S6 (a-c) and S7 (d-f). $Q_{i1}=10 \times 10^4$, $Q_w=4 \times 10^4$ and $Q_{i2}=10 \times 10^5$. 
which is called EIA. The EIA is an opposite effect of EIT and enhancement of absorption in EIA results from from atomic coherence induced by optical radiation [33]. Here, it originates from the direct coupling between two modes. The dispersion is abnormal and large fast-light occurs in this EIA-like resonance, as are shown in Fig. 2.10(e) and (f), respectively.

Figure 2.11: Illustration of the transmission, phase shift and group delay of resonators for \( T_3 \). \( Q_{i1}=10\times10^4 \), \( Q_w=4\times10^4 \) and \( Q_{i2}=10\times10^5 \).

Figure 2.11 provides the transmission, phase shift and group delay for \( T_3 \) when mode \( a_1 \) is in over-coupled case (\( Q_{i1} > Q_c \)). As direct coupling increases, a dip appears in the resonance notch first. When \( 1/Q_c^2 = (1/Q_w-1/Q_{i1})/Q_{i2} \), \( T(\omega_0) = 0 \), indicating that zero transmission is achieved with the aid of direct coupling. As the direct coupling increases further, the dip disappears and EIT-like resonance appears. Normal dispersion and large slow-light can be observed in the EIT-like resonance of \( T_3 \), which are the same as that of \( S6 \). The dispersions are normal in the two splittings, where slow-light occurs. This is different from \( S6 \), where abnormal dispersion and fast-light occur in the two splittings. For under-coupled case (\( Q_{i1} < Q_w \)), the transmission, phase shift and group delay are similar to those of \( S6 \) system.
2.5 Single Ring Resonator with Mode-splitting

It is meaningful to point out that mode splitting can also occur in a single TW-resonator system by introducing structural perturbations on the resonator [34, 35]. The incident wave $s_i$ only generates a counter-clockwise travelling mode $a$, which in turn induces $b$ due to the structural perturbation that is present along the ring sidewalls, as shown in Fig. 2.12. The mode $a$ and the mode $b$ are related by the mutual-coupling coefficient $\mu$. For the degenerate case, the mode $a$ and $b$ have the same resonance frequency $\omega_0$, the decay rate due to loss $1/\tau_i$ and the decay rate into the bus $1/\tau_w$. Near the resonant frequency, the evolutions of the electric field $a$ and $b$ inside the resonator can thus be described by:

\[
\frac{d}{dt}a = \left( j\omega_0 - \frac{1}{\tau_i} - \frac{1}{\tau_w} \right) a - j \sqrt{\frac{2}{\tau_w}} s_i - j \mu b \quad (2.17)
\]

\[
\frac{d}{dt}b = \left( j\omega_0 - \frac{1}{\tau_i} - \frac{1}{\tau_w} \right) b - j \mu a \quad (2.18)
\]

Given the equation connecting the incident field $s_i$ and transmitted field $s_t$, we obtain the transmission function of the ring resonator:

\[
t = \frac{s_t}{s_i} = 1 - \frac{1}{2Q_w} \left( \frac{1}{j \left( \delta + \frac{1}{2Q_c} \right)} + \frac{1}{2Q_i} \right) + \frac{1}{2Q_i} \quad (2.19)
\]

It can be seen that the mode $a$ is split into two resonance frequencies, namely $\omega_0 - \omega_0/(2Q_c)$ and $\omega_0 + \omega_0/(2Q_c)$. Therefore, the splitting separation is solely determined by the mutual coupling factor $Q_c$.

We define a critical coupling parameter $Q_{cri}$, $(1/Q_{cri}^2 = |1/Q_i^2 - 1/Q_c^2|)$, which indicates the magnitude of the mutual-coupling needed to achieve resonance-splitting.
Figure 2.13: Normalized transmission, effective phase shift and group delay for (a)(c)(e) $Q_w < Q_i$ and (b)(d)(f) $Q_w > Q_i$. 
2.5. Single Ring Resonator with Mode-splitting

Figure 2.13 depicts the normalized transmission, effective phase shift and group delay for $Q_w < Q_i$ and $Q_w > Q_i$, respectively. For the over-coupling ($Q_w < Q_i$) case, $Q_c \to \infty$ corresponds to the case of an over-coupled ring resonator without mutual-coupling. Normal dispersion and correspondingly slow light can be achieved without mutual-coupling. As the mutual-coupling increases ($Q_c$ decreases from $\infty$), the mutual-coupling enhances the resonance notch depth and has little impact on the effective phase shift and the delay if $Q_c > Q_{cri}$. At $Q_c = Q_{cri}$, the transmission is zero at resonance. However, once the mutual-coupling further increases ($Q_c < Q_{cri}$), resonance-splitting takes place. For the under-coupling ($Q_w > Q_i$) case, the mutual-coupling lowers the resonance notch depth in the transmission and leads to anomalous dispersion if $Q_c > Q_{cri}$. When $Q_c < Q_{cri}$, resonance-splitting also takes place. Anomalous dispersion and thus fast light can also be observed at the split resonances.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Resonance-splitting</th>
<th>Dispersion response</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_w &lt; Q_i$</td>
<td>$Q_c &lt; Q_{cri}$</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$Q_c &gt; Q_{cri}$</td>
<td>Yes</td>
</tr>
<tr>
<td>$Q_w &gt; Q_i$</td>
<td>$Q_c &lt; Q_{cri}$</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$Q_c &gt; Q_{cri}$</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2.3 summarizes the dispersive characteristics of coupled resonators with mutual-coupling, showing that resonance-splitting is always accompanied by fast light. For the over-coupled ring resonator, strong mutual-coupling can tune the effective phase shift from normal dispersion to anomalous dispersion; therefore fast light can be realized in the over-coupled ring resonator. For the under-coupled ring resonator, strong mutual-coupling can lead to resonance-splitting without reversing the dispersion characteristics at resonance.
Chapter 3

Fabrication and Characterization of Silicon Waveguide and Ring Resonator

3.1 Fabrication of Silicon Waveguide and Ring Resonator

Silicon has already been used as the substrate for most integrated circuits. Many fabrication processes in silicon photonics can be borrowed from existing CMOS techniques. Leading companies such as Intel and IBM are developing wafer-scale fabrication process using standard CMOS technology. However, many small companies and research institutes are still working on the sample scale.

In this thesis, SOI wafers from SOTEC are used. The top Si has a thickness of 250 nm and the SiO$_2$ layer below has a thickness of 3 $\mu$m, as is shown in Fig. 3.1. The ring/waveguide cross-section is $450 \times 250$ nm with an effective area of about 0.1 $\mu m^2$ for the TE mode. The whole process flow is given in Fig. 3.2.

![Figure 3.1: Schematic of the SOI wafer](image)
Chapter 3. Fabrication and Characterization of Silicon Waveguide and Ring Resonator

Figure 3.2: Process flow of the fabrication of waveguide and resonator

I. Start from the SOI. For the fabrication of waveguide and resonator, the negative resist MA-N-2403 is used as the protecting mask.

II. E-beam lithography is used to define the patterns including the waveguide and resonator.

III. After development in MAD 532, the patterns are formed in the resist layer.

IV. The inductively coupled plasma (ICP) etching is performed to transfer the pattern from the resist to the silicon. To achieve anisotropic etching of silicon and straight sidewalls, SF₆ and C₄F₈ are chosen as plasma source gases. SF₆ is the primary etchant and C₄F₈ provides sidewall passivation.

V. After etching, the remnant of resist is ashed away by high power O₂ plasma.
3.1. Fabrication of Silicon Waveguide and Ring Resonator

Figure 3.3: SEM photos of a single ring resonator. The radius is $5 \, \mu m$ and the air gap between the waveguide and resonator is $140 \, nm$.

Figure 3.3 shows the SEM photo of a ring resonator coupled to silicon wire waveguide. The waveguide is slowly tapered to a width of $10 \, \mu m$ at both ends, where gold gratings are added to couple light near-vertically from single mode fibers. For the fabrication of gold grating, the patterns are defined using the positive resist ZEP520A. Then electron beam evaporation is used to deposit the gold and a lift-off process is performed to form the gold grating.

Figure 3.4: SEM photos gold gratings added to the pre-fabricated waveguide. The period is $600 \, nm$ and gold stripe width is $200 \, nm$. 
3.2 Characterization of Silicon Waveguide and Ring Resonator

To couple light efficiently from single mode fiber (SMF) to silicon waveguide, gold gratings are added to both ends of waveguide, as is shown in Fig. 3.4. The vertical grating coupling method was first developed by Gent University [36]. The setup of this method is shown in Fig. 3.5. A SMF is stripped of its coating and cleaved to form a fiber probe. Then two probes are placed 10° off the sample normal plane to minimize interference between the fiber facet and the sample surface. Under a microscope, the two probes are moved to the center of the two grating areas. The gold gratings are highly polarization-sensitive and a polarization controller is usually inserted to select the TE-polarized light.

Figure 3.5: The setup for vertical fiber-grating coupling method

Figure 3.6 provides the transmission spectrum of the grating. The top silicon thickness is 250 nm and silica buffer thickness is 3 µm for the SOI sample. For this configuration, the peak transmission occurs around 1580 nm. The 3 dB bandwidth
of the grating coupler is around 30~40 nm. The grating couples only TE light with a minimal fiber-to-fiber loss of around 18 dB.

Compared with the inverted taper coupling approach, the vertical fiber-grating coupling approach has two merits: (1) No cleaving of the sample is needed; (2) High coupling efficiency can be obtained by optimizing the grating parameters. A experimental coupling efficiency of 69.5% has been reported [37]. One disadvantage of grating coupling is the bandwidth limit.
Chapter 4

Optical Signal Processing based on Single Ring Resonator without Mode-splitting

In this chapter, we experimentally demonstrate three kinds of signal processings based on a single ring resonator: (1) a 10 Gb/s format conversion from NRZ to AMI using the linear filtering effect of a silicon microring resonator; (2) a microwave-photonic phase shifter based on a 20-μm-radius silicon microring resonator, providing a tunable phase shift for a 20 GHz signal in a range of 0~4.6 rad; (3) a delay line based on a 20-μm-radius silicon microring resonator, which provides maximal delay times with error-free operations of 80 ps, 95 ps, 110 ps and 65 ps for RZ, CSRZ, RZ-DB and RZ-AMI signals, respectively. The results of these three signal processings are included in Paper III\textsuperscript{1}, Paper IV\textsuperscript{2} and Paper V\textsuperscript{3}, respectively.


4.1 All Optical NRZ-to-AMI Format Conversion

4.1.1 Background and Operational Principle

All-optical clock recovery is a key technique in future all-optical communication networks. Clock recovery based on non-return-to-zero (NRZ) format data, which has been widely used due to its simplicity and bandwidth efficiency, shows implementation difficulties due to the lack of discrete clock components. All-optical format conversion from NRZ to AMI, which can be exploited for clock recovery, has been demonstrated by various technologies including the use of the gain saturation effect of a semiconductor optical amplifier (SOA) [38], an asymmetric Mach-Zehnder interferometer [39], and self-phase modulation in a Fabry-Perot laser diode [40].

The operation principle of optical NRZ-to-AMI format conversion is based on the linear filtering effect provided by the silicon ring resonator. In the frequency domain, the carrier of the NRZ signal is suppressed and correspondingly the optical clock component is enhanced by the notch filter, as is shown in Fig. 4.1. Therefore, in the time domain, the signal after the silicon ring resonator exhibits discrete AMI pulses positioned in the transition edges of the NRZ signals.

![Figure 4.1: Schematics of an input NRZ signal, a microring notch filter transmission, and a converted AMI signal frequency spectra.](image)

4.1.2 Experimental Demonstration

The spectral response of the microring resonator is shown in Fig. 4.2. The black and red curves denote the measured and Lorentzian fitted resonance, respectively. The resonance at 1553.900 nm has a 20-dB notch and the 3-dB bandwidth is $\sim 0.234$ nm. Therefore, the $Q$ factor of this resonance is $\sim 6620$.

The experiment setup is depicted in Fig. 4.3. The tunable laser is tuned at the resonance wavelength of 1553.9 nm. The laser output is modulated by a MZM, which is biased at the quadrature point and driven by a 10-Gb/s electrical PRBS signal of $2^7 - 1$ pattern length. The generated NRZ signal is then coupled into the
4.1. All Optical NRZ-to-AMI Format Conversion

Figure 4.2: (a) SEM photos of the SOI 20-µm-radius micro-ring resonator, and (b) spectrum of the resonance at 1549.80 nm. Inset in (a): a zoom-in view of the coupling region.

Microring resonator by the vertical coupling system. As the gold grating coupler is polarization-dependent, a PC is inserted before the grating to make sure that the input signal is in TE mode. Two cascaded EDFAs after the resonator are used to compensate the coupling loss. The waveforms of the input NRZ signal and the converted AMI signal are recorded by the oscilloscope with an optical bandwidth of 20 G. The input power before the grating is around 0 dBm and the estimated power into the microring resonator is -10 dBm.

Figure 4.3: Experiment setup for the NRZ-to-AMI format conversion.

Fig. 4.4 (a) and (b) depict the waveforms of the input NRZ data and the converted AMI data, respectively. Sharp pulses of AMI data appear at both the rising and falling edges in "1" bits of NRZ data due to the effective suppression of the optical carrier and thus enhancement of the optical clock component in the notch filter transmission. The AMI data has a pulse width of 32 ps and provides well-defined 10-Gb/s clock information. However, it can be seen from Fig. 4.4(b) that the amplitude of the pulse train exhibits certain fluctuation.
Chapter 4. Optical Signal Processing based on Single Ring Resonator without Mode-splitting

4.2 All Optical Microwave Photonic Phase Shifter

4.2.1 Background and Operational Principle

Microwave-photonic phase shifter has been playing an increasingly important role in microwave signal processing such as phased-array beam-forming. Various techniques for realizing microwave-photonic phase shifters have been demonstrated, including distributed-feedback laser-wavelength converter [41], variable optical directional coupler [42], LiNbO$_3$ modulator [43], and using stimulated Brillouin scattering [44] or cross-phase modulation [45] in optical fibres. However, a practical implementation of arrays with thousands of elements is limited by the size and complexity of the above phase-shifting elements. The use of miniaturized and integrated devices to perform this function is thus of much interest due to advantages of low cost, compact size and on-chip integration. In this subsection we present and demonstrate a novel microwave-photonic phase shifter based on a 20-µm-radius silicon microring resonator. It features variable phase-shift tuning, reduced complexity, compact footprint, and easy integration.

Fig. 4.5(b) shows the transmission and phase shift for a ring resonator with a 3-dB resonance bandwidth of 0.1 nm and a resonance notch depth of 6 dB. It shows that a phase shift of $\pi$ rad is achieved on resonance and the phase shift tuning range is 0-2$\pi$ rad. For an OCS microwave signal, a maximum phase shift of 2$\pi$ rad can be achieved if the two sidebands are located across the resonance. For the OCS signal, the output field can be expressed by:

$$E_{in}(t) = A_{-1} \exp(j2\pi(\nu_0 - f_{RF})t) + A_1 \exp(j2\pi(\nu_0 + f_{RF})t)$$

(4.1)

where $A_{-1}$ and $A_1$ are the amplitudes of the -1 order sideband and +1 order sideband, respectively. The spectrum of optical carrier suppressed (OCS) is plotted
4.2. All Optical Microwave Photonic Phase Shifter

Figure 4.5: (a) Scheme of a ring resonator and (b) its corresponding transmission and phase shift curve. (c) The spectrum of 20G OCS signal.

in Fig. 4.5 (c). If this signal is optically processed to change the two sidebands by a factor of $A \exp(j\theta)$ and $A' \exp(j\theta')$, respectively, the optical field then becomes:

$$E_{out}(t) = AA_{-1} \exp(j2\pi (\nu_0 - f_{RF}) t + j\theta) + A'A_1 \exp(j2\pi (\nu_0 + f_{RF}) t + j\theta')$$  \hspace{1cm} (4.2)

where $A(A')$ and $\theta(\theta')$ denote the amplitude loss and phase shift, respectively. The output signal is detected by a photo detector and the AC part of the output current from the photodetector (PD) is

$$i_{AC}(t) = 2RAA'A_{-1}A_1 \cos(2\pi \times 2f_{RF}t + \theta' - \theta)$$  \hspace{1cm} (4.3)

where $R$ is the responsivity of the photodetector. Thus the incurred phase shift from the resonance has completely transferred to the output signal.

The phase shift can be tuned by thermal nonlinear effect. As the thermo-optic coefficient is very large in silicon, this effect has a low power threshold and therefore the phase shift of the signal can be tuned by controlling the pump light power with a low value.
4.2.2 Experimental Demonstration

The 20-µm-radius silicon microring resonator is used in our experiment. The resonance at 1548.5 nm has a 6-dB notch and the 3-dB bandwidth is ∼0.1 nm, as is shown in Fig. 4.6. Fig. 4.7 depicts the experimental setup. The probe signal sits at the 1548.5-nm resonance. To facilitate the coupling of control light into the ring, we set the control light to a 1561.0-nm resonance, which has a 16-dB notch depth and a 3-dB bandwidth of ∼0.15 nm. A continuous wave (CW) signal from a tunable laser is fed into a single drive MZM, which is biased at the null and driven by a 10-GHz clock signal to produce a 20-GHz OCS signal. Both the pump light and the probe signals are coupled through a 3-dB coupler to the microring resonator by a vertical coupling system. An oscilloscope is used to record the waveforms and measure the phase shift.

![Figure 4.6: The spectral response around 1548.5 nm.](image)

![Figure 4.7: Experimental setup.](image)
We firstly measure the dependence of the phase shift and the output power on the signal wavelength, as shown in Fig. 4.8. The maximum phase shift is -4.6 rad and the output power variation is less than 2.2 dB, which mainly results from the loss of one sideband in the resonance region. We did not reach the desired maximum phase shift of $2\pi$ rad since the 20-GHz spaced sidebands do not completely cross the resonance and thus they did not experience the $2\pi$ relative phase shift. For the maximum phase shift of $\sim 4.6$ rad, the signal waveform still exhibits good quality, as evidenced in Fig. 4.9.

![Figure 4.8: The dependence of the phase shift and output power on signal wavelength.](image)

![Figure 4.9: The waveform of the 20G OCS signal when the maximum phase shift is 4.6 rad.](image)

Fig. 4.10 shows the dependence of the phase shift on the pump power, with the two sidebands of signals on the right side of the resonance or across the resonance, respectively. The maximum phase shift is the same as that shown in Fig. 4.8, demonstrating the feasibility of constructing a tuneable phase shifter by thermal nonlinear effect. The estimated required power in the ring resonator to obtain the maximum phase shift is only 20 mW.
4.3 All Optical Delay Line

4.3.1 Background and Operational Principle

On-chip optical delay line has attracted considerable interest due to its potential applications in future optical interconnections and packet-switching systems for data buffering and synchronization. Coupled resonator structure-based delay lines are attracting interests in terms of integration, design flexibility and footprint [46, 47]. Such a structure was implemented in polymer [48], silicon oxynitride [49] and silica [50]. The exploitation of resonances based on SOI structure is expected to outperform other slow-light media in terms of miniaturization and on-chip integration. In this subsection, we study the system performances of an on-chip delay line based on the silicon micro-ring resonator for different modulation formats, including return-to-zero (RZ), carrier-suppressed return-to-zero (CSRZ), return-to-zero duobinary (RZ-DB), and return-to-zero alternate-mark-inversion (RZ-AMI). The CSRZ format shows an optical π phase flip between adjacent pulses. In RZ-DB, a π-phase shift occurs whenever there are an odd number of 0-bits between two 1-bits; while for RZ-AMI the phase flips for each 1-bit, independent of the number of 0-bits in between. These four modulation formats show improved performances in high-speed optical systems relative to the conventional NRZ signal [51, 52]. The RZ and CSRZ signals have been widely used in long-haul high-capacity WDM networks. RZ-AMI enables reduced nonlinear impairments through transmission, while RZ-DB shows narrow spectral width and thus enhanced tolerance to dispersion.
4.3. All Optical Delay Line

The transmission function of a ring resonator can be expressed as:

\[ t = j \left( \frac{\omega - \omega_0}{\omega_0} \right) + \frac{1}{2Q_i} \frac{1}{2Q_w} - j \left( \frac{\omega - \omega_0}{\omega_0} \right) + \frac{1}{2Q_i} + \frac{1}{2Q_w} \]  \hspace{1cm} (4.4)

The transmission and phase shift characteristics for a ring resonator are related to the real part and imaginary part of Eq. 4.4, respectively, and the group delay can be obtained by differentiating the phase shift with respect to the frequency. Fig. 4.11 shows the transmission, phase shift and delay versus the normalized frequency detuning for a ring resonator. The parameters used in simulations are the same as those in the experiment for the comparisons between the simulation and experimental results. The maximum group delay is \( \sim 120 \) ps on resonance. Since the group delay is wavelength dependent, optically tuneable delay lines can in practice be implemented by detuning resonators through thermal effect, electro-optical effect by carrier injection, electro-absorption effect, or other methods.

![Figure 4.11: A plot of (a) transmission and phase shift, and (b) delay vs normalized frequency detuning for a ring resonator when \( Q_w \) and \( Q_i \) are \( 3.0 \times 10^4 \) and \( 7.0 \times 10^4 \), respectively.](image)

4.3.2 Delay Line for Different Modulation Formats

The micro-ring resonator used in the experiments is shown in Fig. 4.12(a). The spectral response of the micro-ring resonator is shown in Fig. 4.12(b). The resonance at 1548.875 nm has a \( \sim 10 \)-dB notch and the 3-dB bandwidth is \( \sim 0.1 \) nm. By fitting the measured spectral response with the transmission function given by Eq. 4.4, we obtain an intrinsic \( Q_i \) of \( 7.0 \times 10^4 \) and a waveguide coupling \( Q_w \) of \( 3.0 \times 10^4 \). Using the method presented in Ref. [53], we estimate that the coupling coefficient is \( \sim 0.27 \) and the loss is 10 dB/cm.
Chapter 4. Optical Signal Processing based on Single Ring Resonator without Mode-splitting

The experimental setup is depicted in Fig. 4.13. A single drive MZM is driven by a 5-Gb/s PRBS signal with a length of $2^{15} - 1$ to generate NRZ format. A second MZM, which acts as a pulse carver, is sinusoidally driven by a synchronized RF signal to produce CSRZ or RZ signals, respectively. The first single drive MZM is replaced by a dual-drive MZM when generating RZ-DB and RZ-AMI signals. The output signal is boosted by an EDFA and then filtered by a tunable BPF with a bandwidth of 1.6 nm. The signal power injected into the fiber is controlled below 0 dBm to avoid nonlinear effect. The output signal of the microring resonator is amplified using two cascaded EDFAs and the noise is suppressed using a band-pass filter. Before the receiver, a variable optical attenuator (VOA) is used in order to tune the received optical power for the bit error ratio (BER) measurements. In the following measurements, all the results in eye diagram have been defined at a BER of $10^{-9}$. The FWHM pulse width for the 5-Gb/s RZ signal is around 100 ps. For shorter pulse, signal distortion can be introduced due to the limit of the resonance bandwidth. By tuning the wavelength, signals operating on resonance and off resonance can be realized. The wavelength tuning can also be realized using pump heating [54] and the response time is around 1 $\mu$s [55].

A. RZ Data

Firstly, we demonstrate error-free operation of the 5-Gb/s RZ signal. Fig. 4.14 shows the eye diagrams when off-resonance and on-resonance, respectively. The maximum delay is $\sim$80 ps, corresponding to a fractional delay of $\sim$0.4. The signal eye diagram is widely open, revealing good signal fidelity for the RZ signal.

B. CSRZ Data

Fig. 4.15 provides the CSRZ eye diagrams and pulse pattern evolutions when
4.3. All Optical Delay Line

Figure 4.13: Experimental setup.

Figure 4.14: Eye diagrams for the 5-Gb/s RZ signal when off resonance and on resonance, respectively.
Chapter 4. Optical Signal Processing based on Single Ring Resonator without Mode-splitting

off-resonance and on-resonance, respectively. The induced maximum delay on resonance is \( \sim 95 \) ps and the corresponding fractional delay is \( \sim 0.5 \). Due to the pattern dependence, the ’1’-level fluctuations between two consecutive ’1’s with opposite phases appear in the eye diagram and the waveform, resulting in the signal degradation. The small ripples before each ’1’ bit are the consequence of the third order dispersion of the ring resonator when the signal is on resonance. Nevertheless, the eye diagram remains open.

\[\text{Figure 4.15: Eye diagrams for the 5-Gb/s CSRZ signal when off-resonance and on resonance, respectively.}\]

C. RZ-DB Data

Fig. 4.16 plots the eye diagrams and typical patterns for the 5-Gb/s RZ-DB signal when off-resonance and on-resonance, respectively. The obtained maximum delay is \( \sim 110 \) ps, which is longer than half a bit. Also small ripples appear before each ’1’ bit due to the third order dispersion. In the RZ-DB, there is no pattern of adjacent ’1’s having opposite phases, while consecutive ’1’s can still cause ’1’-level fluctuation, thus degrading the signal quality.

D. RZ-AMI data

For the 5-Gb/s RZ-AMI signal, the maximum delay is \( \sim 65 \) ps, corresponding to a fractional delay of \( \sim 0.35 \), as shown in Fig. 4.17.
4.3. All Optical Delay Line

Figure 4.16: Eye diagrams for the 5-Gb/s RZ-DB signal when off resonance and on resonance, respectively.

Figure 4.17: Eye diagrams for the 5-Gb/s RZ-AMI signal when off resonance and on resonance, respectively.
4.3.3 Delay and Distortion Analysis

(1) Delay analysis

From the above measurements, the maximum group delays for the 5-Gb/s RZ, CSRZ, RZ-DB and RZ-AMI signals are 80 ps, 95 ps, 110 ps and 65 ps, respectively. The 110-ps group delay obtained for the RZ-DB signal is very close to the predicted maximum value (~120 ps) according to the coupled mode theory analysis provided in Fig. 4.11(b). Following the RZ-DB are the CSRZ, RZ, and RZ-AMI in maximum delay values. This can be explained by their optical spectral features, as plotted in Fig. 4.18. For the RZ-DB signal, it exhibits a much narrower bandwidth compared with the other three modulation formats. The spectral compactness of RZ-DB signal enables that most of its components match the resonance and thus experience the maximum group delay. For the RZ-AMI signal, the carrier on the resonance frequency is completely suppressed while two sidebands carrying the signal experience less delay, thus leading to a decreased group delay. For the RZ and CSRZ signals, their spectral widths are between the RZ-DB and RZ-AMI formats, thus showing moderate group delays.

Figure 4.18: Optical spectra for the four modulation formats. The dashed curves representing the relative group delays are from Fig. 4.11(b).

(2) Distortion analysis

On the signal quality, the ring-resonator bandwidth is not a major limiting factor since it is larger than the signal bandwidth. The signal degradations mainly result from two factors: 1) dispersion and 2) data pattern dependence. While the waveguide itself is assumed to be dispersion-free, strong dispersive effects are induced by the resonant process. Fig. 4.19 depicts the group velocity dispersion
(GVD) and third order dispersion (TOD) curves for the ring resonator. While the GVD is zero on resonance, strong normal or anomalous dispersion can be obtained on the red or blue side of the resonance, respectively. The TOD achieves the maxima on resonance and is the main dispersion contribution to the signal distortion. The ripples appear before each ‘1’ bit, which were observed in the delayed CSRZ, RZ-DB and RZ-AMI signals, are related with the negative third-order dispersion on resonance [49].

Figure 4.19: Functional dependence of the GVD and TOD on the normalized frequency detuning for a ring resonator when \(Q_w \) and \(Q_i \) are \( 3.0 \times 10^4 \) and \( 7.0 \times 10^4 \), respectively. The GVD and TOD are normalized to the maxima.

The phase-modulation scheme associated with certain data patterns plays a key role in signal quality. Two major degrading factors are: (1) interaction between two consecutive ‘1’s with opposite phase, namely the ‘1 -1’ pattern; (2) level fluctuation for consecutive ‘1’s with the same phase, i.e., the ‘1 1’ pattern. For the CSRZ and RZ-AMI signals, the ‘1 -1’ is a typical pattern and there is no ‘1 1’ pattern, two consecutive ‘1’s with opposite phases destructively interact with each other and thus lead to the ‘1’-level fluctuation and degrade the signal quality. For the RZ-DB signal where no ‘1 -1’ pattern exists, the ‘1 1’ is a typical pattern that contributes to the ‘1’-level fluctuation.

(3) Delay-bandwidth product analysis

For a signal ring resonator, the maximum delay on resonance is given by:

\[
T_D = \frac{(1 - r^2) a}{(a - r)(1 - ra)\tau_d}
\]

where \(a\) represents the single-pass amplitude transmission related to \(Q_i\), \(r\) is the reflective coefficient related to \(Q_w\), and \(\tau_d\) is the single-pass delay.
We use the 3-dB spectral width to characterize the bandwidth of this delay line. It requires that the main lobe of the power spectrum of the modulated signal should be smaller than the 3-dB spectral width $\Delta f_{FWHM}$, which is given by:

$$\Delta f_{FWHM} = \frac{(1 - ar) \frac{1}{\tau_d}}{\pi \sqrt{ar}}$$  \hspace{1cm} (4.6)

Therefore, the delay bandwidth product can be denoted in the approximation of $a = 1$ as:

$$\Delta f_{FWHM} T_D = \frac{(1 + r)}{\pi \sqrt{r}} \simeq \frac{2}{\pi}$$  \hspace{1cm} (4.7)

In our case, the resonance of the microring has a 3-dB bandwidth of $\sim 0.06$ nm ($\sim 7.5$ GHz). The RZ-DB signal achieves the maximum delay-bandwidth product ($\sim 0.55$).
Chapter 5

Optical Signal Processing based on Single Ring Resonator with Mode-splitting

In this chapter, we experimentally demonstrate two kinds of signal processings based on a single-ring resonator with mode-splitting: (1) a dense wavelength conversion using the free carrier dispersion effect in the ring resonator; (2) fast-light using the anomalous dispersion at the two split resonances in the ring resonator. The results of these two signal processings are included in Paper VI\(^\text{1}\) and Paper II\(^\text{2}\), respectively.

5.1 All Optical Dense Wavelength Conversion

5.1.1 Background and Operational Principle

Wavelength conversion is an important function for all-optical networks to alleviate the data blocking due to wavelength contention in the dynamic, high-capacity WDM networks. All-optical wavelength converter is regarded as a promising alternative to optical-electronic-optical wavelength conversion. It has been demonstrated in a variety of media, such as highly nonlinear fibers [56], semiconductor optical amplifiers [57], periodically poled lithium niobate crystal [58], and GaAs


Chapter 5. Optical Signal Processing based on Single Ring Resonator with Mode-splitting

microring resonator [59]. The wavelength conversions have been demonstrated in silicon straight waveguides by exploiting four-wave mixing [60, 61], and in silicon ring resonators based on the FCD effect and resonance shift [62]. The use of microring resonator with a high quality factor can compensate the weak nonlinearity of the miniaturized silicon devices and thus relax the power requirement.

For the wavelength conversion based on the FCD effect in a silicon ring resonator, a pump light and a signal light are required, and they work at different resonances. The signal light is usually a continuous wave (CW). When the pump power is high (logic 1), free carriers are generated inside the ring resonator from two-photon absorption. The free carriers give rise to a refractive index change through FCD effect and cause the blue-shift of the resonances. The transmission of the signal is therefore changed. When the pump power is low (logic 0), these carriers will recombine mainly due to surface recombination in the case of submicron structures. Therefore, the resonant wavelength and the transmission of the signal relax back. The information carried by the pump light is thus transferred to the signal light and wavelength conversion is implemented. In the previous reports, however, the pump and signal resonances are separated by at least one FSR [62]. For the small-radius ring resonator in SOI, the FSR is usually large, thus limiting the choices of wavelengths/channels that can be adopted for the conversion. A conventional microring with a FSR below 1 nm requires a diameter of a few 100 microns [63]. For a ring resonator side coupled to a waveguide, if periodic roughness (grating) on the sidewall of the ring is introduced, both propagating and counter-propagating modes can be excited. The induced resonance-splitting eliminates the need of separating the pump and signal by at least a FSR and enables more channels for conversions, thus significantly increasing the system capacity.

As shown in Section 2, the resonance splitting is caused by the mutual coupling between the modes inside the ring resonator. The incident wave only generates the counter-clockwise travelling mode, which in turn induces the counter-propagating mode due to the grating that is present along the ring sidewalls. The two modes are related by the mutual coupling factor $Q_c$. It can be seen that the cavity mode is split into two resonance frequencies, namely $\omega_0 - \omega_0/(2Q_c)$ and $\omega_0 + \omega_0/(2Q_c)$. Therefore, the splitting separation is solely determined by the mutual coupling factor $Q_c$.

5.1.2 Experimental Demonstration

The micro-ring resonator used in the experiments has a radius of 10 µm. The SEM photo of the silicon microring resonator is provided in Fig. 5.1(a). Fig. 5.1(b) shows the grating on the ring sidewall. The width of the grating ridge is $\sim 20$ nm and the period ranges from $\sim 50$ nm to $\sim 100$ nm. They are determined by a variety of parameters during the E-beam process, mainly the scan step size, line-scan intervals, exposure dose, and developing time, which has been detailed in Ref. [34]. Since the
5.1. All Optical Dense Wavelength Conversion

Figure 5.1: The SEM photos of (a) the silicon microring resonator with a radius of 10 µm and (b) the grating on the side-wall of the ring resonator. Inset in (a) is a zoom-in view of the coupling region.

period and amplitude of the grating can be tuned by changing these parameters, the mutual coupling factor $Q_c$ and accordingly the splitting separation can be controlled during the fabrication.

Figure 5.2 shows the spectral response of the ring resonator. The notches around 1550 nm are fitted using Eq. (2.19). The distance between the two split resonance is only 0.413 nm. The obtained intrinsic $Q_i$, waveguide-cavity coupling $Q_w$, and mutual coupling $Q_c$ are $6.5 \times 10^4$, $2 \times 10^4$ and $3.7 \times 10^3$, respectively, indicating a strong mutual coupling and thus resonance-splitting.

Figure 5.2: The transmission spectrum demonstrating the resonance-splitting effect.

The experimental setup is depicted in Fig. 5.3. The pump wavelength $\lambda_{p1}$ is chosen to offset the thermal nonlinear effect. The signal wavelength $\lambda_1$ is fixed at the left resonance for the non-inverted case and $\lambda_2$ at the shorter-wavelength edge of the left resonance for the inverted case. A MZM, driven by an electrical PRBS
signal of $2^7 - 1$ pattern length, is used to generate NRZ signal. The pump light is boosted by a high power EDFA followed by an attenuator to adjust the pump power. The pump light and the signal light are combined through a 90:10 coupler and launched into the microring resonator by the vertical coupling system. The output signal of the microring resonator is amplified using two cascaded EDFAs, each followed by a $\sim 0.3$ nm BPF to separate the signal from the pump, and then sent to an oscilloscope to record the waveforms. As the gold grating coupler is polarization-dependent, two PCs are inserted before the coupler to make sure that the input pump and signal lights are in TE mode. The pump power into the input of the waveguide is $\sim 7.7$ dBm and the signal power is $\sim 4$ dBm at the input of the fiber.

![Experimental setup for dense wavelength conversion.](image)

Fig. 5.4 shows the dense wavelength conversion results for data rates of 500 Mb/s, 1 Gb/s, 2 Gb/s and 5 Gb/s, respectively. Both non-inverted and inverted waveforms are provided. With signal wavelength at $\lambda_1$, the transmission of the signal light increases when the carriers are generated and resonances are blue-shifted, resulting in a non-inverted conversion, as shown on the left of Fig. 5.4. With signal wavelength at $\lambda_2$, the transmission of the signal light decreases when the resonances are blue-shifted, resulting in an inverted conversion, shown on the right of Fig. 5.4. As the bit rate increases, the extinction ratio for the converted signal is reduced, mainly resulting from the long carrier lifetime. The carrier lifetime induces a lower extinction ratio for the single '1's, since they have much shorter rise time and falling time compared with the consecutive '1's and thus can not respond to the pump signal rapidly. According to the equation in Ref [62], the resonance
5.1. All Optical Dense Wavelength Conversion

shift of a 3-dB bandwidth of the ring resonator corresponds to an effective index change of $\sim 1.5 \times 10^4$. The calculated required pump power is $\sim 8 \text{ dBm}$.

Figure 5.4: Dense wavelength conversions at 500 Mb/s, 1 Gb/s, 2 Gb/s and 5 Gb/s. The horizontal axes represent the time (unit: ns) and the vertical axes represent the normalized intensity.

For intrinsic silicon, the carrier lifetime limits the available operation speed. The carrier lifetime can be greatly reduced by using a reverse-biased p-i-n junction [64],
or by ion implantation [65]. The pump power needed for wavelength conversion can be further reduced by fabricating ring-resonators with much higher $Q$ factors, by employing smaller radius and by improving the efficiency of the fiber-to-waveguide coupling.

5.2 All Optical Fast-light

5.2.1 Background and Operational Principle

Fast light is challenging and interesting for the scientific community specifically in the context of information velocity [66–68], since superluminal signal velocities can be achieved without violating Einstein causality [69]. Fast-light can be used to accelerate rather than buffer signals to avoid traffic congestion. The fast light is typically achieved in a medium with a very large anomalous dispersion at the signal frequency. Experimental demonstrations of fast light have been realized based on stimulated Brillouin scattering (SBS) in optical fibers [70], coherent population oscillation in erbium-doped fiber amplifiers [71], alexandrite crystal [72] and quantum-dot semiconductor optical amplifiers (SOA) [73], electromagnetically induced absorption in atomic vapors [68], and structural dispersion in coupled resonator structures [74].

For the ring resonator, it has been commonly regarded that fast light can be only realized in the under-coupled region while over-coupling leads to slow light. Here, we report experimental demonstration of fast light in over-coupled ultra-compact silicon ring resonator with resonance-splitting, relying on the large anomalous dispersion in the split resonances.

5.2.2 Experimental Demonstration

Figure 5.5 shows the spectral response of the ring resonator. The notches around 1550 nm are fitted using Eq. 2.19. For the 10-µm-radius ring resonator, the coupling $Q_w$, intrinsic $Q_i$, and mutual-coupling $Q_c$ are $1 \times 10^4$, $1 \times 10^5$ and $1.5 \times 10^5$, respectively.

The schematic diagram of the experimental setup is depicted in Fig. 5.6. The signal source is a 500-Mb/s RZ pulse train with a duty cycle of 50% produced by two cascaded MZMs. The FWHM of the signal pulse is 1 ns. The 3dB bandwidth (calculated from the resonance dip) is below 0.02 nm. Therefore, we use the 500-Mb/s signal to avoid distortion. For shorter pulse, signal distortion can be introduced due to the limit of the resonance bandwidth. The generated signal is boosted by an EDFA and then filtered by a tunable BPF with a bandwidth of 1.6 nm. The power sent into the input fiber is controlled below 0 dBm to avoid
5.2. All Optical Fast-light

Figure 5.5: The transmission spectrums with resonance-splitting for the 10-µm-radius ring resonator.

nonlinear effects. The output signal of the microring resonator is amplified by an EDFA and the noise is suppressed using another band-pass filter. An oscilloscope is used to record the temporal traces of the pulses after propagating through the ring resonator with resonance-splitting.

Figure 5.6: Experimental setup.

Figure 5.7 shows the normalized temporal signal waveforms after experiencing the fast light propagation through the ring resonator when the signal wavelength is on resonance. It is clearly observed that signal advancement is achieved with minor signal distortion. The achieved signal advancement is about 130 ps on resonance. Figure 5.8 shows the signal advancement as a function of signal wavelength, demonstrating that the advancement can be continuously tuned if the resonance of the microring can be varied. The measured delays agree well with the theoretical
calculation based on the coupled mode theory.

Figure 5.7: The normalized traces of the pulsed signal showing a clear advancement and a minor signal distortion.

Figure 5.8: Temporal advancements for 1-ns pulse signal with respect to the signal wavelength for the 10-\(\mu\)m-radius ring resonator.

Compared with the 4.9 ns advancement for a 65 ns signal that has been demonstrated in a fiber-based 56.5-\(\mu\)m-radius ring resonator [74], our demonstration for the 10-\(\mu\)m-radius ring resonator has the advantages of a larger relative advancement and a more compact footprint.
Chapter 6

Directional Coupling between Silicon Waveguide and Plasmonic Waveguide

As has been mentioned in preceding chapters, the silicon photonics technology may offer new solutions for circumventing the interconnect bottleneck in the microelectronic technology. However, a major problem with photonic devices is the far lower density of integration available compared with their electronic counterparts. This problem may be alleviated to some extent by using the plasmonic technology.

In this chapter, we focus on the hybrid Si-metal plasmonic waveguide and the MIM slot waveguide. For the MIM slot waveguide, the modal size is mainly decided by slot size and can thus be squeezed significantly smaller than the diffraction limit [75, 76]. For the hybrid Si-metal plasmonic waveguide, it is capable of maintaining subwavelength field confinement and simultaneously a relatively long propagation length. The butt-coupling between these two plasmonic waveguides and dielectric waveguides has been investigated theoretically and experimentally [77–81]. Here, we focus on the directional coupling between these plasmonic waveguides and dielectric waveguides. The hybrid directional couplers are fundamental building blocks for splitting or redirecting signals in PICs and have a wide range of applications in optical communication systems including spatial switches, power splitters, modulators, etc. The results of these directional couplers are included in Paper VII\(^1\) and Paper VIII\(^2\), respectively.


6.1 Directional Coupling between Silicon Waveguide and Hybrid Si-metal Plasmonic Waveguide

6.1.1 Eigenmode of Hybrid Coupler

Figure 6.1 shows the schematic of the proposed asymmetric directional coupler. The left arm is a hybrid Si-metal plasmonic waveguide, which consists of a bottom Si waveguide with a dimension of $W_1 \times H$ and a top Ag slab with a dimension of $W_1 \times T$. The Ag slab is aligned vertically with respect to the bottom Si waveguide but separated from it with a SiO$_2$ gap of the thickness $g$. The right dielectric Si arm has the same height as the Si waveguide forming the plasmonic arm. Both arms are embedded in SiO$_2$. The width of the right Si arm is $W_2$ and the distance between the two arms is $d$.

Using the commercial finite-element package FEMLab from COMSOL, the field profiles of the bound eigenmodes supported by the hybrid coupler can be accurately calculated. The permittivity used in simulations are $-129+3.3i$ [82], 11.9 and 2.1 for Ag, Si and SiO$_2$ at $\lambda=1550$ nm, respectively. The following structure parameters are chosen in simulation: $H=340$ nm, $W_1=200$ nm, $W_2=297$ nm, $g=40$ nm, $T=100$ nm. The obtained effective indice ($n$) for both plasmonic mode and Si dielectric mode are 2.21. For the plasmonic mode, the propagation loss is 0.052 dB/µm and the corresponding propagation length ($L_0$) is 83 µm, which is relatively high compared with other types of plasmonic waveguides with subwavelength field confinement. Figure 6.2 provides the electric field profiles of the five bound eigenmodes at $d=250$ nm. There are two quasi-TM modes: even mode (termed as $e$-mode) and odd mode (termed as $o$-mode) originating from the coupling between the decoupled TM plasmonic mode and the decoupled TM dielectric mode. There are also two quasi-TE modes: the quasi-TE mode 1 (termed as $t1$-mode) originating from the decoupled TE dielectric mode and the quasi-TE mode 2 (termed as $t2$-mode) originating from the coupling between the two decoupled TE modes in the plas-
6.1. Directional Coupling between Silicon Waveguide and Hybrid Si-metal Plasmonic Waveguide

Figure 6.2: Five bound modes supported by the hybrid coupler at $d=250$ nm. (a) quasi-TM-even mode ($n=2.26$). (b) quasi-TM-odd mode ($n=2.16$). (c) quasi-TE mode 1 ($n=2.09$). (d) quasi-TE mode 2 ($n=1.53$). (e) TEM mode ($n=1.47$). For the quasi-TM modes, quasi-TE modes and the TEM mode, the $E_y$ components, the $E_x$ components and the $|\vec{E}|$ are depicted, respectively.

The directional coupling characteristics of the hybrid coupler are determined by the whole set of eigenmodes, including all the bound modes and radiation modes (termed as $r$-modes). In the following analysis, the subscripts $d$, $p$, $j$, $r$ represent the decoupled dielectric mode, decoupled plasmonic mode, bound modes and radiation modes, respectively. The components for each mode are assumed normalized.

Consider the case that at $z=0$, the field is launched into the dielectric waveguide only, the field $\vec{E}$ inside the coupler can be expressed as a summation over all bound modes, together with a term representing the radiation field as [83]:

$$\vec{E}(x, y, z) = \sum_j C_{dj} \vec{E}_j(x, y)e^{i\beta_j z} + \vec{E}_r(x, y, z)$$ (6.1)

where $\vec{E}_j$ and $\vec{E}_r$ are the electric field distributions of the $j$th bound eigenmode and the radiation modes, respectively. $\beta$ is the complex propagation constant (\(\beta = \ldots\).

\[\text{monic waveguide and dielectric waveguide. The coupler also supports a TEM mode (termed as t3-mode) with most of the field focused around the four corners of the metal.}\]
Chapter 6. Directional Coupling between Silicon Waveguide and Plasmonic Waveguide

\( \beta_r + i\beta_i \). The coupling coefficient \( C_{mn} \), which characterizes the coupling from \( m \)-mode to \( n \)-mode, can be expressed as

\[
C_{mn} = \int \int \vec{E}_m \times \vec{H}_n \cdot \hat{z} dS/2
\]

where \( S \) is the infinite cross-section and \( \hat{z} \) is the unit vector in the propagation direction \([83]\). The output electric fields for both arms can be expressed as follows:

\[
\vec{E}_d(x, y, z) = \sum_j C_{dj} C_{jd} e^{i\beta_j z} \vec{E}_j(x, y) + \vec{E}_{rd}(x, y, z)
\] (6.2)

\[
\vec{E}_p(x, y, z) = \sum_j C_{dj} C_{jp} e^{i\beta_j z} \vec{E}_j(x, y) + \vec{E}_{rp}(x, y, z)
\] (6.3)

where \( \vec{E}_{rd} \) and \( \vec{E}_{rp} \) represent the radiation fields coupled to the dielectric mode and the plasmonic mode, respectively.

For the hybrid coupler, the \( e \)-mode and the \( o \)-mode account for at least 95% of the coupled power in the whole range of \( d \) investigated here; therefore the characteristics of the coupler are mainly determined by these two eigenmodes. The portion of power coupled to \( t1 \)-mode is below 5%. The portions of power coupled to \( t2 \)-mode and \( t3 \)-mode are both below 0.001% due to their huge refractive index differences compared with the input dielectric mode. The total power coupled to all the \( r \)-modes is below 0.2%. Therefore, the \( r \)-modes are not considered in the simulation.

![Figure 6.3](image)

Figure 6.3: (a) Magnetic field and (b) electric field intensities in the coupler as functions of the position \( z \) when the fields are excited by the dielectric modes at \( z=0 \) (\( d=250 \) nm), respectively. The magnetic field is taken at plane \( y=170 \) nm (in the silicon waveguide) while the electric field at plane \( y=360 \) nm (in the SiO\(_2\) gap). The arrows indicate where the fields in the coupler are excited.

Figure 6.3 shows magnetic field and electric field intensities in the coupler as functions of the position \( z \) when the fields are excited by the dielectric modes. It can be seen that the electric field gradually transfers to the plasmonic waveguide.
and the electric field intensity in the plasmonic waveguide is far higher than that in the silicon waveguide.

Figure 6.4 provides the power from the two output arms versus the interaction length $z$ ($z$ is normalized to the coupling length $L_c$, $L_c = \pi/(\beta_{er} - \beta_{or})$), which exhibits damped sinusoidal behavior along the propagation. As $z$ increases, the field transfers from the dielectric arm to the plasmonic arm gradually due to the interference of the $e$-mode and the $o$-mode. By controlling the interaction length, the power ratio between the two output arms can be changed and thus a power splitter between the plasmonic waveguide and the dielectric waveguide can be realized. At $z = L_C/2$ (Point A), the asymmetric directional coupler works as a 50:50 power splitter. At $z = L_C$ (Point B), the coupling efficiency $\eta$ (the output power from the plasmonic waveguide divided by the input power into the dielectric waveguide) can be as high as 94% even if the propagation loss is taken into consideration and the field distributions in two uncoupled arms are different. The propagation loss in this case is 0.026 dB/µm. The extinction ratio (ER), which is defined as the ratio of output power on the plasmonic arm to output power on the dielectric arm at $z = L_C$, is 18 dB.

![Figure 6.4](image-url)

Figure 6.4: Output power from the two output arms versus the interaction length $z$ at $d=250$ nm when the field is fed from the dielectric arm. The output power is normalized to the input power.

Figure 6.5 provides effective indice and losses of the $e$-mode and the $o$-mode versus $d$. Both eigenmodes have lower loss than the plasmonic waveguide because almost half of the fields concentrate in the dielectric waveguide. As $d$ increases, the effective refractive indice of both modes converge to 2.21, which is the index for the decoupled plasmonic mode or the dielectric mode. The losses for both modes converge to 0.026 dB/µm, which is half of that of the decoupled plasmonic waveguide.
Chapter 6. Directional Coupling between Silicon Waveguide and Plasmonic Waveguide

2.1 Directional Coupling

2.2 Analysis

2.3 Comparison

6.1.2 Performance Analysis

(1) Coupling length and coupling efficiency

The coupling length $L_c$ versus the arm separation $d$ is given in Fig. 6.6, where $L_c$ is normalized with respect to the propagation length $L_0$. At $d=150$ nm, $L_c$ is 3.3 $\mu$m, which is only 4% of $L_0$. As $d$ increases, the coupling between the two arms becomes weak and $L_c$ increases exponentially. At $d=550$ nm, $L_c$ is close to $L_0$. Figure 6.6 also provides the coupling efficiency $\eta$ versus $d$ at $z = L_c$. The coupling efficiencies are above 90% at $d \leq 350$ nm. Therefore, this directional coupling can be implemented to efficiently excite the hybrid plasmonic mode with the conventional dielectric mode. $\eta$ decreases sharply with an increasing $d$, which is caused by the increase in the coupling length and the propagation loss. At $d=550$ nm, $\eta$ is still above 60%. The coupling efficiency of the hybrid coupler degrades as the operating wavelength derivates from 1550 nm. However, the 3-dB bandwidth of the coupling efficiency can be as wide as 180 nm at $d=250$ nm and $L=7.63$ $\mu$m.
6.2. Directional Coupling between Silicon Waveguide and Metal-dielectric-metal Plasmonic Waveguide

Figure 6.7: ER and IL at $z = L_c$ versus $d$.

(2) Extinction ratio and insertion loss

Figure 6.7(c) provides the ER and the insertion loss (IL) of the hybrid coupler as functions of $d$ at $z = L_c$. The ERs are above 13 dB when $d$ varies from 150 nm to 550 nm. For a conventional symmetric dielectric directional coupler, the ER improves with increasing $d$ [84]. However, in our proposed asymmetric directional coupler, the ER improves with increasing $d$ at $d<400$ nm and degrades at $d>400$ nm. The maximum ER is as high as 23 dB at $d=400$ nm. As $d$ decreases, the difference between the amplitudes of the excited $e$-mode and the $o$-mode at the input end increases and this unequal excitation of the $e$-mode and the $o$-mode thus leads to the degradation of ER at $d<400$ nm. At $d>400$ nm, the coupling length and the induced propagation loss increase approximately exponentially with $d$, thereby degrading the ER greatly. The ILs are below 0.5 dB at $d\leq350$ nm. As $d$ increases, the propagation loss increases and thus the IL increases correspondingly.

6.2 Directional Coupling between Silicon Waveguide and Metal-dielectric-metal Plasmonic Waveguide

6.2.1 Eigenmode of Hybrid coupler

The proposed vertical hybrid coupler is shown in Fig. 6.8. It consists of two arms: the lower arm is the silicon dielectric waveguide with a dimension of $W1 \times H1$; the upper arm is the MIM plasmonic waveguide with a dimension of $W2 \times H2$ for the slot. The plasmonic slot and the dielectric arm are vertically aligned with an edge-to-edge separation of $s$. The two arms are embedded in SiO$_2$. To guarantee a strong coupling between the two arms, the effective refractive indices of the guided modes in the two arms should be close. The TE mode ($E_x$ is the main electric field component) supported by the MIM plasmonic waveguide couples with the TE mode
Chapter 6. Directional Coupling between Silicon Waveguide and Plasmonic Waveguide

Figure 6.8: Schematic diagram of the hybrid directional coupler. The up region denotes Au and the down region denotes Si. $z$ is the light propagation direction.

guided by the silicon waveguide and two eigenmodes (quasi-even and quasi-odd) are consequently formed in the hybrid coupler.

Figures 6.9(a) and (c) depict the electric field ($E_x$) amplitude of the two eigenmodes supported by the coupler at $s=250$ nm, which is obtained from the finite-element-method based commercial software Comsol Multiphysics. The relative permittivities used in simulations are $-132+12.65i$ [85], 11.9 and 2.1 for Au, Si and SiO$_2$ at 1.55 $\mu$m wavelength, respectively. To ensure a good coupling between the two waveguides, the following structural parameters are used in simulation: $W_1=260$ nm, $H_1=220$ nm, $W_2=150$ nm and $H_2=200$ nm. The obtained effective indices for both the decoupled MIM plasmonic mode and the silicon dielectric mode are around 1.6 at 1.55 $\mu$m wavelength. The propagation loss is 0.36 dB/$\mu$m and the corresponding propagation length ($L_0$) is 12 $\mu$m for the decoupled MIM plasmonic mode. When the two waveguides are placed close to each other, they will couple with each other, thus resulting in energy exchanges in between. Figures 6.9(b) and (d) provide the corresponding electric field ($E_x$) profiles along $x=0$. It can be seen that the electric fields in the plasmonic arm are much stronger than those in the dielectric arm. For the quasi-even eigenmode, the electric field oscillation orientations in the two arms are the same while they become opposite in the quasi-odd eigenmode. The quasi-odd eigenmode exhibits a dip in the coupled region.

The coupling strength between the plasmonic waveguide and the dielectric waveguide is separation-dependent. Figures 6.10(a) and (b) provide effective indices and propagation losses of the two eigenmodes versus the arm separation ($s$). The quasi-odd mode, which is cut-off at $s<150$ nm, has a lower refractive index than the quasi-even mode. As $s$ increases, the effective refractive indices for both modes approach 1.63, which is the refractive index of the decoupled plasmonic mode or
6.2. Directional Coupling between Silicon Waveguide and Metal-dielectric-metal Plasmonic Waveguide

Figure 6.9: Electric field amplitudes ($|E_x|$) of (a) the quasi-even and (c) the quasi-odd modes supported by the hybrid coupler. The arrows indicate electric field oscillation orientations in $x$-$y$ plane. (b) and (d) are corresponding electric field ($E_x$) profiles along $x=0$. The dashed lines in (b) and (d) indicate the boundaries of both arms.

The dielectric mode. The quasi-even mode locates more in the MIM slot compared with the quasi-odd mode. Consequently, it has a larger loss than the quasi-odd mode. The losses of both modes approach 0.18 dB/µm as $s$ increases, which is half of that of the decoupled MIM plasmonic mode. This is reasonable since half of fields locate in the silicon dielectric waveguide for both quasi-even and quasi-odd modes.

We have obtained the two eigenmodes supported by the hybrid coupler based on the finite-element-method. Considering the case that the fields in the coupler are excited by the dielectric mode ($\vec{E}_d$) at $z=0$, the electric field $\vec{E}$ in the hybrid coupler can be expressed as a linear combination of the two eigenmodes ($\vec{E}_e$ and $\vec{E}_o$) and all the radiation modes. The radiation modes, which occupy a negligible portion in the hybrid coupler, are not considered in the simulation. Figures 6.11(a) and (b) show the electric field and magnetic field distributions along $x=0$ in the
directional coupling between silicon waveguide and plasmonic waveguide

Figure 6.10: Effective refractive indices ($n_{eff}$) and losses of the two eigenmodes versus the arm separation ($s$).

coupler as functions of the position $z$ when the field is excited by the dielectric mode at $z=0$, respectively. As $z$ increases, the field transfers from the dielectric arm to the plasmonic arm gradually due to the interference of quasi-even and quasi-odd eigenmodes. At coupling length $L_c$, almost all the fields transfer to the plasmonic arm even if the two arms are completely different. The coupling length is a measure of the beating length of the two eigenmodes inside the coupler and can be related to propagation constants of the two eigenmodes and phases of coupling coefficients.

Figure 6.11: (a) Electric field and (b) magnetic field intensities along $x=0$ in the coupler as functions of the position $z$ when the fields are excited by the dielectric modes at $z=0$ ($s=250$ nm), respectively. The arrows indicate where the fields in the coupler are excited.

The output power from the two arms versus the interaction length $z$ is provided in Fig. 6.12. The power exchange between the two arms takes place every coupling length $L_c$ and thus the output power shows attenuated oscillations with an increasing interaction length. The power splitting ratio between the plasmonic arm and
the dielectric arm can be controlled by tuning the interaction length. At \( z = L_c \), 73\% of the input power is converted from the dielectric mode to the plasmonic mode when the propagation loss is taken into consideration. Hence, this directional coupling provides a different approach for efficiently exciting the MIM plasmonic mode.

![Figure 6.12: Output power from the two output arms versus the interaction length \( z \) at \( s=250 \text{ nm} \).](image)

### 6.2.2 Performance Analysis

1. Coupling length and coupling efficiency

   Figure 6.13(a) shows the coupling length of the hybrid coupler versus the arm separation \( s \). It can be seen that \( L_c \) increases exponentially with \( s \). At \( s=150 \text{ nm} \), the coupling length is 2.5 \( \mu \text{m} \), which is only 1/5 of the propagation length of the decoupled MIM plasmonic waveguide. At \( s=250 \text{ nm} \), the coupling length is 4.5 \( \mu \text{m} \). The coupling length is almost the same as \( L_0 \) at \( s=450 \text{ nm} \).

   Figure 6.13(b) shows the coupling efficiency of the hybrid coupler versus the arm separation. The obtained maximum coupling efficiency is 73\% at \( s=250 \text{ nm} \). The coupling efficiencies are above 60\% in the range of interest. At \( s<250 \text{ nm} \), the coupling efficiency degrades due to the increase in the in-coupling and out-coupling losses. At \( s>250 \text{ nm} \), the increase in the propagation loss lowers the coupling efficiency.

2. Extinction ratio and insertion loss

   The extinction ratio of the hybrid coupler versus the arm separation is shown in Fig. 6.14(a). The extinction ratio exceeds 10 dB in the whole range of interest. At
Chapter 6. Directional Coupling between Silicon Waveguide and Plasmonic Waveguide

Figure 6.13: Coupling length ($L_c$) and coupling efficiency ($\eta$) versus the arm separation ($s$) when the fields are excited by the dielectric mode. $L_c$ is normalized to the propagation length of the decoupled plasmonic waveguide $L_0$.

$s=250$ nm, the extinction ratio is around 16 dB. The maximum extinction ratio is 17 dB, which occurs at $s=300$ nm. The extinction ratio degrades with a decreasing $s$ at $s<300$ nm. This is mainly caused by the unequal excitation of the quasi-even and quasi-odd eigenmodes at $z=0$. When $s>350$ nm, the extinction ratio degrades with an increasing $s$, which is mainly caused by the increase in the coupling length. The coupling length increases exponentially with $s$ and thus the propagation loss increases correspondingly, thereby degrading the extinction ratio at large $s$. The total insertion loss of the coupler is shown in Fig. 6.14(b). The propagation loss in the coupler increases exponentially with $s$, which is mainly caused by the increase in the coupling length. The minimum insertion loss is -1.4 dB, which occurs at $s=250$ nm.

Figure 6.14: (a) Extinction ratio (ER) and (b) insertion loss (IL) versus the arm separation ($s$) when the field is excited by the dielectric mode.
Chapter 7

Conclusion and Future Work

In this thesis, we focus on silicon based photonic devices (waveguide and resonator) and their applications.

In chapter 2, the basic theories of waveguide and resonator are introduced. For the two-dimensional single-mode strip waveguide, both TE and TM modes can be obtained approximately by the effective index method or accurately by solving the full-vectorial Maxwell equations. For a single resonator, the transmission, phase shift and group delay exhibit unique characteristics. Mode splitting is observed for both a single resonator and a coupled-resonator system. By tuning the configuration of the coupled-resonator system, one can obtain different characteristics in transmission spectra.

In chapter 3, we demonstrate three kinds of signal processing using a single ring resonator. By using the linear filtering effect, we experimentally demonstrates a 10 Gb/s format conversion from NRZ to AMI. A microwave-photonic phase shifter, which provides a tunable phase shift of $0\sim -4.6$ rad for a 20 GHz signal, is demonstrated based on a 20-$\mu$m-radius silicon microring resonator. A tunable delay line based on the delay characteristic of a single resonator is demonstrated. The maximal delay times are 80 ps, 95 ps, 110 ps and 65 ps, for the RZ, CSRZ, RZ-DB, and RZ-AMI formats, respectively.

In chapter 4, we demonstrate two kinds of signal processing using a single ring resonator with mode-splitting. All-optical dense wavelength conversions in a 10-$\mu$m-radius resonance-split silicon microring resonator, based on free carrier dispersion effect, are demonstrated. The dense wavelength conversions are performed at data rates from 500 Mb/s to 5 Gb/s. We also demonstrate a maximum pulse advancement of 130 ps with a low distortion for a 1-ns signal pulse in a 10-$\mu$m-radius silicon ring resonator.

In chapter 5, we theoretically demonstrate two efficient asymmetric directional
Chapter 7. Conclusion and Future Work

couplers between plasmonic waveguides with subwavelength field sizes and Si waveguides. The proposed hybrid couplers feature a short coupling length, a high coupling efficiency, a high extinction ratio, a low insertion loss and is capable of being integrated into the silicon platform. These two directional couplers can also be used to efficiently excite the hybrid Si-metal plasmonic mode and metal-dielectric-metal plasmonic mode with conventional dielectric mode. We expect these asymmetric directional couplers can be used for signal routing, power splitting/combining, etc, between plasmonic waveguides and dielectric waveguides in future PICs.

There are some issues that are worthy of further addressing.

(1) Chapter 3 predicts a series of new phenomena in a coupled resonator system. It would be interesting to fabricate these resonator systems based on Si ring resonators or PhC cavities and confirm their transmission, phase shift and group delay characteristics.

(2) The mode splitting in a single-ring resonator can be introduced by other structural disturbances. The grating used to excite the counter-propagating mode can be controlled so that the mutual coupling strength between the two modes can be better controlled. More research work on precisely controlling the mutual coupling is highly demanded.

(3) Optical signal processing based on two or more coupled (or uncoupled) resonators has not been demonstrated in this thesis. Systems composed of two or more coupled resonators will provide more degrees of freedom for optical signal processing.

(4) Due to limited amount of time, the two proposed directional couplers are left without being experimentally demonstrated. They can be fabricated in experiment. They can be used for power splitting, combining, coupling and polarization control, etc.
Chapter 8

Summary of Contributions

**Paper I:** Coupled mode theory analysis of mode-splitting in coupled cavity system. 

*Author’s Contributions:* I performed the coupled mode theory analysis and finished the first draft of the manuscript.

**Paper II:** Fast light in silicon ring resonator with resonance-splitting. 

*Author’s Contributions:* I performed the theoretical analysis and the experiment of fast-light measurement. I finished the first draft of the manuscript.

**Paper III:** All optical NRZ-to-AMI conversion using linear filtering effect of silicon microring resonator. 

*Author’s Contributions:* I performed the experiment of NRZ-to-AMI conversion and finished the first draft of the manuscript.

**Paper IV:** Optically tuneable microwave photonic phase shifter based on silicon microring resonator. 
Chapter 8. Summary of Contributions

Author’s Contributions: I performed the theoretical analysis and the experiment of tunable phase shift measurement. I finished the first draft of the manuscript.

Paper V: System performances of on-chip silicon microring delay line for RZ, CSRZ, RZ-DB and RZ-AMI signals.

Author’s Contributions: I performed the theoretical analysis and the experiment of delay measurement. I finished the first draft of the manuscript.

Paper VI: Dense wavelength conversion and multicasting in a resonance-split silicon microring.

Author’s Contributions: I performed the theoretical analysis and the experiment of dense wavelength conversion. I finished the first draft of the manuscript.

Paper VII: Asymmetric plasmonic-dielectric coupler with short coupling length, high extinction ratio, and low insertion loss.

Author’s Contributions: I designed the hybrid coupler and analyzed its performance. I finished the first draft of the manuscript.


Author’s Contributions: I designed the hybrid coupler and analyzed its performance. I finished the first draft of the manuscript.
Bibliography


