Design, Simulation and Characterization of Some Planar Lightwave Circuits

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Abstract

Optical devices based on planar lightwave circuit (PLC) technology have the advantages of small size, high reliability, possibility for large scale production, and potential integration with electronics. These devices are widely employed in optical telecommunications, sensing, data storage, imaging, and signal processing. This thesis focuses on some selected PLC based devices, such as power splitters, demultiplexers, triplexers and polarization beam splitters.

First, the basic principle of the waveguides and the simulation methods for PLC devices are discussed. A novel effective index method is introduced to reduce a two-dimensional structure to a one-dimensional one, and can be implemented for arbitrarily shaped waveguides. Numerical methods, such as finite-difference mode solver, beam propagation method, finite-difference time-domain method are introduced to analysis the mode profile of the waveguides, and the propagation properties of light in PLC devices.

Multimode interference (MMI) couplers are widely used in many PLCs, such as power splitters, ring lasers, optical switches, and wavelength division multiplexers/demultiplexers. In this work, concepts for improving the self-imaging quality of MMI couplers are analyzed and new designs are proposed. A significant improvement in performance together with compact sizes were obtained with taper sections at the input/output of MMI couplers based on SOI, and deeply etched ridges in MMI couplers based on SiO₂. A polarization insensitive dual wavelength demultiplexer based on sandwiched MMI waveguides was presented.

Novel devices including triplexers and polarization beam splitters were realized by using photonic crystal (PhC) structures. Two stages of directional couplers based on PhC waveguides are cascaded to form an ultracompact triplexer. The special decoupling property of the PhC waveguide based directional coupler was utilized in the design. A novel polarization beam splitter was realized by combining a MMI coupler and a PhC which works as a polarization sensitive reflector.

Finally, fabrication and optical characterization of an ultra-compact directional coupler and PhC structures in InP are presented. In a single etching step, by using the lag-effect in inductively coupled plasma reactive ion etching, a compact directional coupler (55 μm) is demonstrated. Carrier life times in PhC structures etched by chemically assisted ion beam etching were investigated, for emitter and switching applications.

**Key words:** planar lightwave circuit, waveguide, coupler, multimode interference, photonic crystal waveguide, (de)multiplexer, triplexer, polarization beam splitter, dry etching, carrier life time.
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Stockholm, April 2008
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<th>Description</th>
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<tr>
<td>1D</td>
<td>One Dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>ADI</td>
<td>Alternating Directional Implicit</td>
</tr>
<tr>
<td>AWG</td>
<td>Arrayed Waveguide Gratings</td>
</tr>
<tr>
<td>BPM</td>
<td>Beam Propagation Method</td>
</tr>
<tr>
<td>CAIBE</td>
<td>Chemically Assisted Ion Beam Etching</td>
</tr>
<tr>
<td>DUT</td>
<td>Devices under Test</td>
</tr>
<tr>
<td>EBL</td>
<td>Electron Beam Lithography</td>
</tr>
<tr>
<td>EIM</td>
<td>Effective Index Method</td>
</tr>
<tr>
<td>ICP-RIE</td>
<td>Inductively Coupled Plasma Reactive Ion Etching</td>
</tr>
<tr>
<td>MMI</td>
<td>Multimode Interference</td>
</tr>
<tr>
<td>MOVPE</td>
<td>Metal Organic Vapor Phase Epitaxy</td>
</tr>
<tr>
<td>MPA</td>
<td>Mode Propagation Analysis</td>
</tr>
<tr>
<td>FDM</td>
<td>Finite Difference Method</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite Difference Time Domain</td>
</tr>
<tr>
<td>FTTH</td>
<td>Fiber to the Home</td>
</tr>
<tr>
<td>PBS</td>
<td>Polarization Beam Splitter</td>
</tr>
<tr>
<td>PBG</td>
<td>Photonic Bandgap</td>
</tr>
<tr>
<td>PhC(s)</td>
<td>Photonic Crystal(s)</td>
</tr>
<tr>
<td>PLC(s)</td>
<td>Planar Lightwave Circuit(s)</td>
</tr>
<tr>
<td>PML</td>
<td>Perfectly Matched Layer</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon on Insulator</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
</tr>
<tr>
<td>TBC</td>
<td>Transparent Boundary Condition</td>
</tr>
<tr>
<td>TIR</td>
<td>Total Internal Reflection</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
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</table>
Chapter 1

Introduction

1.1 Background and Overview

Optical communication is one of the greatest successes people achieved in the last century. It provides an excellent solution for the flow of information. The explosive expansion of Internet services has led to a transformation from “telecommunication” to “data communication”. The digital data traffic has been doubling every half-year. To support this revolution, fiber-optic communication technologies have developed rapidly because it could offer much higher speed and larger capacity. The twisted-pair and coaxial-cable are being replaced by fibers gradually. After the long distance fibers have been settled, the choke point of the optical communication system is moving to functional photonic components which are used to connect the terminals and the customer. Different functional components including optical splitters, (de)multiplexers, and optical switches are required to add/drop signals.

The conventional way to build these functional components is to put each component into an individual temperature-controlled package and to connect these components in the functional unit. It is easy to replace a failing component by doing so. But it is difficult for assembly and packaging which account for more than 75% to the total component cost.

Planar lightwave circuits (PLCs) are vitally important in communication networks. Traditionally, PLCs were hampered by various problems such as polarization dependence and temperature sensitivity, and they were limited to only two dimensions and had also suffered from optical loss. Many of these problems have been solved, leaving PLCs with four major advantages: enhanced functionality, very low losses, compactness, and potential for mass production. Based on the well developed semiconductor fabrication technologies, PLCs can be built with complex functions and manufactured. These optical components might conform to the demands on high integration density and low cost. PLC has gradually become the leading technology, especially for the demultiplexer and splitter modules.

Compared to the discrete components such as the thin film based ones, the devices based on PLC technology are more promising due to their excellent performances such as compactness, mass-producibility, high reliability and high design flexibility. Just as the case for electronic integrated circuits, PLCs could bring down the cost of a circuit, as it provides the fabrication of a large number of components at the same time. The basic functions in PLCs are the generation, guiding, splitting, multiplexing, amplification, switching and detection of the light signal. Different devices such as arrayed waveguide gratings (AWG) [1, 2], matrix switches [3], star couplers [4], and multimode interference couplers [5, 6] have been developed based on PLC technology.
Chapter 1. Introduction

Figure 1.1. Some PLC technology based devices. (a) 32×32 Arrayed waveguide grating [2] ; (b) Optical switches [3] ; (c) Packaged coupler.

Figure 1.2. Schematic of optical waveguides with different geometrical structures. The high index layer is shown in dark grey and the low index layer in light grey. (a) Buried waveguide, (b) strip waveguide, (c) rib waveguide, (d) strip-loaded waveguide.

An optical waveguide is the basic unit for photonic components as is the electrical wire for electronics. In a certain sense, photonics could be viewed as the equivalent to electronics with the
electrical signal being replaced by an optical one. Whereas an electrical signal resides in the region of high electrical conductivity, an optical signal propagates along the region of high refractive index. There are several different geometrical structures that can be used to realize a waveguide (Fig. 1.2). Their basic working principle is the total internal reflection of light.

Optical waveguides and devices can be fabricated by using different materials including LiNbO$_3$ [7], SiO$_2$ [8, 9], Silicon on Insulator (SOI) [10, 11], Polymer [12], InP [13, 14], etc. Each material has advantages and disadvantages for a specific required function. Table 1.1 provides a summary of the material types available for waveguide manufacturing. For passive devices, SiO$_2$ is one of the most popular choices because of its outstanding advantages such as low cost, small propagation loss, and good matching to single mode fiber. SOI is a good candidate for high density integration due to its high index contrast but it is difficult to get light emission since silicon is indirect bandgap material. InP based materials are an ideal choice for monolithic integration because they can support both active and passive optical functions, including lasers, gain blocks, detectors and passive waveguides.

Table 1.1. Summary of the different materials used for PLC devices.

<table>
<thead>
<tr>
<th>Material</th>
<th>Waveguide Structure</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO$_3$</td>
<td>Ti$^++$ LiNbO$_3$</td>
<td>High Electro-Optic coefficient, non-linear effect, excellent high speed modulation</td>
<td>High loss</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>Ge:SiO$_2$</td>
<td>Very low loss</td>
<td>Suitable only for passive functions</td>
</tr>
<tr>
<td>Si</td>
<td>Si, SiO$_2$, Si Substrate</td>
<td>High refractive index contrast, high integration density, compatible with Si electronics</td>
<td>Indirect bandgap, unsuitable for lighting</td>
</tr>
<tr>
<td>InP</td>
<td>InGaAsP InP</td>
<td>Direct bandgap, good for light emitters, high speed modulation lighting</td>
<td>High cost, complex technology</td>
</tr>
<tr>
<td>Polymer</td>
<td>Polymer</td>
<td>Ease of fabrication, low cost, good Electro-Optic, Thermal-Optic performance</td>
<td>Stability, aging</td>
</tr>
</tbody>
</table>

Fiber-to-the-home (FTTH) networks have been considered to be the ultimate solution for future broadband access networks. It is envisaged that FTTH will achieve the dominant position in the near future. Power splitters (combiners) and demultiplexers are the basic building blocks for passive functions of FTTH networks. Power splitters are used to divide the optical power to different channels, while demultiplexers are for spatial combining or separation of different wavelengths. Different types of optical splitters such as 1×4, 1×8, and 1×32 have been made compact on a chip using Y-branches [15], Mach-Zehnder Interferometer [16] or multimode interference (MMI) couplers [17] which are typically based on PLC technology. The PLC based devices are superior to conventional fused-fiber type splitters in terms of low cost and mass
Chapter 1. Introduction

producibility. PLC type optical splitters have already been put into practical use in FTTH systems and their long term reliability for telecommunication has already been established.

One of the major barriers to the development of the passive optical network based FTTH systems is the cost. One of the key components for the triple-play multiplexing service is the optical network unit (ONU) whose cost can’t be shared by different users since it is located in each customer’s home. Thus, an ONU consists of a triple wavelength demultiplexer (triplexer) and opto-electronic devices such as laser diodes and photo detectors. Most of the triplexer transceivers used currently are bulky modules built on discrete optical components (e.g. thin film filters) which is difficult to integrate with other devices and difficult to package. This approach is expensive and has low manufacturing yield. PLC technology presents a possible solution for realizing triplexers with good performance, and lower layout complexity. Thus, for the optical access networks applications, low cost is required because the cost can’t be shared among many customers in the same way as the cost of the trunk line can be. Mass production will also decrease the cost of the devices.

One of the major issues in the development of PLC devices is to increase the integration density. A lot of effort has been put on discovering new structures, new principles to reduce the size of photonic devices. Different approaches including silicon nanowire waveguides [18-20], photonic crystal (PhC) waveguides [21-23], and surface plasmon waveguides [24, 25] have been implemented to reduce the size of the PLC devices. In PhC waveguides, unlike conventional waveguides that depend on total internal reflection (TIR) for the guidance of the optical field in a region of high refractive index surrounded by regions of lower refractive index, guided modes appear within the photonic band gap when the periodicity of PhC structure is broken or defects are introduced into it. By removing a single line of air holes, the simplest PhC waveguide is formed. In such a structure, light is confined to the waveguide by means of TIR in the vertical direction and by distributed Bragg reflection in the lateral direction. It is the confinement of the mode inside the line defect that can guide light around sharp corners with low bending loss. PhC waveguides based sharp bends, Y branches, power splitters, and cross junctions have been realized with both reasonable performance and compact size. By using this basic unit, complex functions such as wavelength demultiplexer, optical switches, wavelength filters, etc can be configured. However, optical loss is still a major concern.

As discussed above, improvement of the performance of PLCs and making them compact are important factors for PLCs to be successful. Besides improving state-of-the-art devices by new designs, novel solutions based on concepts such as PhCs are very attractive. The work done in this thesis is in this spirit. It proposes several new device designs to improve performance of PLCs at the same time making them compact. Furthermore, PhC-based devices are proposed that rely on their special properties. Apart from device design and simulations, some representative examples in InP based structures were also experimentally realized.

1.2 Thesis Outline

The scope of this thesis is the design and fabrication of some selected PLC devices, such as power splitters and demultiplexer based on multimode interference coupler; triplexers and polarization beam splitter (PBS) based on PhCs and directional couplers. This thesis is based on the published research papers (appended). The rest of the thesis is organized as follows:
Chapter 2 summarizes different numerical methods used in this thesis. The finite difference method is developed to solve the eigenmodes of the waveguide structure. The beam propagation method and the finite-difference time-domain method are used to investigate the light propagation in different PLC devices. An improved effective index method (EIM) which could be used for waveguides with arbitrary refractive index distribution was developed.

In Chapter 3, the multimode interference coupler and some related devices are presented. The degradation of self-imaging quality by multimode interference in the vertical direction of an SOI-based MMI device is analyzed. Taper structures are introduced at the junction between input/output waveguides and multimode region to suppress the excitation of the undesired vertical modes. The silica ridge waveguide is deeply etched and achieves a strong confinement in the lateral direction, which not only improves the quality of self-images in the MMI section but also reduces the device size dramatically.

Chapter 4 focuses on photonic crystals (PhC) and presents two PhC based PLC devices. First, two stages of directional couplers based on PhC waveguides are cascaded to form an ultra-compact triplexer. By combining a multimode interference coupler and some PhC structures, an ultra-compact polarization beam splitter is presented. The MMI coupler is designed to collect polarized light reflected by or transmitted through an internal photonic crystal structure.

Chapter 5 gives an overview of the fabrication technologies typically used in PLCs. This chapter presents the experimental work: fabrication and characterization of InP-based photonic crystal structures and presents a novel solution to realize ultra-compact directional couplers. Processing and material properties of InP-based PhCs are addressed. The fabrication is mainly based on clean room processing facilities including electron beam lithography and dry etching. Optical characterization techniques such as the setup with the end-fire coupling used to verify the performance of the fabricated devices and time resolved photoluminescence which was used to measure the carrier lifetimes in processed PhCs are presented. The feature size dependent effect for the Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) process has been investigated and by using this effect ultra-compact directional couplers are experimentally demonstrated.

Finally, Chapter 6 gives a summary of the publications together with the author’s contributions. In Chapter 7, a summary of the thesis together with future perspectives is given.

References


Chapter 1. Introduction


Chapter 2

Design and Simulation Methods

The design and simulation play a very important role in the development of the PLC devices. With suitable simulation tools, the design of PLC devices becomes much more efficient. By using efficient designs that provide good performance and compactness, the cost for product development could be reduced dramatically.

It is well known that lightwave is an electromagnetic field and most of the phenomena in photonic components can be described by the Maxwell’s equations which are used to analyze the behavior of the electromagnetic fields. One could obtain analytical solutions by solving the Maxwell’s equations only for simple structures (e.g. slab waveguide). But for most of the PLC devices, there are no such straightforward solutions. Numerical methods should be introduced to analyze the behavior of lightwave in these devices.

In this thesis, several different numerical methods have been developed for the design of PLC devices. The finite difference method (FDM) is used to analyze the mode characteristics of waveguides by solving the eigen equations of an optical waveguide. Beam propagation method (BPM) and finite-difference time-domain (FDTD) method are introduced to simulate the propagation of light in PLC devices. In the following sections, the basic working principles and procedures of these methods are summarized.

2.1 Wave Equations

Maxwell’s equations describe the fundamental theory behind most of the phenomenon in photonic components. We begin with the well-known Maxwell equations:

\[
\nabla \times \vec{E}(\vec{r},t) = -\frac{\partial \vec{B}(\vec{r},t)}{\partial t} - \vec{J}_m(\vec{r},t) \\
\nabla \times \vec{H}(\vec{r},t) = \frac{\partial \vec{D}(\vec{r},t)}{\partial t} + \vec{J}_e(\vec{r},t) \\
\n\nabla \cdot \vec{D}(\vec{r},t) = \rho_e(\vec{r},t) \\
\n\nabla \cdot \vec{B}(\vec{r},t) = \rho_m(\vec{r},t)
\]

(2.1)

where $\vec{E}(\vec{r},t)$ is the electric field, $\vec{H}(\vec{r},t)$ is the magnetic field, $\vec{D}(\vec{r},t)$ is the electric flux density, $\vec{B}(\vec{r},t)$ is the magnetic flux density, $\vec{J}_e(\vec{r},t)$ is the electric current density, $\vec{J}_m(\vec{r},t)$ is the magnetic current density, $\rho_e(\vec{r},t)$ is the electric charge density, and $\rho_m(\vec{r},t)$ is the magnetic charge density.

Regarding the properties of the optical components and the material we are dealing with, we make the following assumptions:
Chapter 2. Design and Simulation Methods

(1) There are no free charges nor current sources: \( \rho = 0, \rho_m = 0, J_v = 0, J_m = 0; \)

(2) The material is isotropic and dispersion is negligible: The relative permeability \( \varepsilon_r \) is a scalar and frequency independent;

(3) The material is non-magnetic: The relative permeability \( \mu_r = 1; \)

(4) The field intensity is low enough so that the relationship between \( \vec{D} \) and \( \vec{E} \) is linear.

Finally, the constitutive equations could be expressed as:

\[
\vec{D}(r,t) = \varepsilon_0 \varepsilon_r \vec{E}(r,t) \\
\vec{B}(r,t) = \mu_0 \vec{H}(r,t)
\]  

(2.2)

The free-space permittivity and magnetic permeability are \( \varepsilon_0 = 8.854187817 \times 10^{-12} \text{ F/m} \) and \( \mu_0 = 4 \times 10^7 \text{ H/m} \), respectively.

For harmonic waves with sinusoidal time dependence, we have:

\[
\vec{E}(r,t) = \vec{E}(r) e^{j\omega t} \\
\vec{H}(r,t) = \vec{H}(r) e^{j\omega t}
\]  

(2.3)

By substituting Eq. 2.2 and Eq. 2.3 into Eq. 2.1, the Maxwell equations could be rewritten as:

\[
\nabla \times \vec{E}(r) = -j \omega \mu_0 \vec{H}(r) \\
\nabla \times \vec{H}(r) = j \omega \varepsilon_0 \varepsilon_r \vec{E}(r) \\
\n\nabla \cdot \varepsilon_r \vec{E}(r) = 0 \\
\n\nabla \cdot \vec{H}(r) = 0
\]  

(2.4)

The wave equations for a homogenous waveguide are obtained from the Maxwell equations as:

\[
\nabla^2 \vec{E} + \nabla \left( \frac{\nabla \varepsilon_r \cdot \vec{E}}{\varepsilon_r} \right) + k^2 \vec{E} = 0 
\]  

(2.5-a)

\[
\nabla^2 \vec{H} + \nabla \left( \frac{\nabla \varepsilon_r \times \vec{H}}{\varepsilon_r} \right) + k^2 \vec{H} = 0
\]  

(2.5-b)

where \( k = \frac{2\pi}{\lambda_0} n = \omega \sqrt{\mu_0 \varepsilon_r} \) is the wave vector; \( \nabla^2 \) is the Laplacian operator:

\[
\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}
\]  

(2.6)
2.2 Finite-Difference Mode Solver

Eigenmode solvers play an important role in analysis and design of the waveguide structures. For most of the waveguide structures, there are no analytical solutions. Different numerical methods including, the Method of Lines (MoL) [1], the Method of Moments (MoM) [2], the Finite Difference Method (FDM) [3], the Boundary Element Method (BEM) [4], the Finite Element Method (FEM) [5] have been introduced to solve the eigenmodes. In this thesis, FDM is used since it provides good numerical efficiency and accuracy.

2.2.1 Basic Formulas

To demonstrate the basic principles, we just take into account the $E$ components. After some mathematical manipulations, we could obtain following equations from Eq. 2.5-a:

\[
\begin{pmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
= - \frac{\partial^2}{\partial z^2}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

\[P_{xx}E_x = \frac{\partial}{\partial x} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_x)}{\partial x} \right] + \frac{\partial^2 E_x}{\partial y^2} + n^2 k_0^2 E_x\]

\[P_{yy}E_y = \frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_y)}{\partial y} \right] - \frac{\partial^2 E_y}{\partial x \partial y}
\]

where

\[P_{yx}E_y = \frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_x)}{\partial x} \right] + \frac{\partial}{\partial x} \left[ \frac{\partial E_y}{\partial x} \right] + n^2 k_0^2 E_y\]

\[P_{xy}E_x = \frac{\partial}{\partial x} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_y)}{\partial y} \right] - \frac{\partial}{\partial y} \left[ \frac{\partial E_x}{\partial y} \right]
\]

Assuming that light is propagating along the $z$ axis, then the electromagnetic fields could be expressed as:

\[\vec{E} = \vec{E}(x,y) \exp(-j \beta z),\]

(2.9)

where $\beta$ is the propagation constant.

Noting that: $\frac{\partial}{\partial z} = -j \beta$, and $\frac{\partial^2}{\partial z^2} = -\beta^2$, the following equations are derived as:

\[
\begin{pmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
= (-\beta^2 + 2 j \beta \frac{\partial}{\partial z} + \frac{\partial^2}{\partial z^2})
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

(2.10)

For FDM, the eigenmode is considered for a $z$-invariant waveguide, so we have: $\frac{\partial}{\partial z} = 0$

and $\frac{\partial^2}{\partial z^2} = 0$, finally we can get a linear eigenvalue problem of the form:
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\[
\begin{pmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
= \beta^2
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

(2.11)

Eq. 2.11 is a full-vector eigenvalue equation describing the modes of an optical waveguide. The two coupled transverse field components \(E_x\) and \(E_y\) are the eigenfunctions while \(\beta\) is the corresponding eigenvalue. The terms \(P_{xy}\) and \(P_{yx}\) reveal that the two field components \(E_x\) and \(E_y\) are coupled. Taking the finite difference for the Eq. 2.8, one can obtain the corresponding eigen equations, from which both the eigen values (i.e., the propagation constants) and the eigen vectors (i.e., the eigen modal fields) can be obtained. After \(E_x\) and \(E_y\) are obtained, the other field components \((E_z, H_x, H_y, H_z)\) can be easily obtained from the Maxwell’s equations.

2.2.2 Perfectly Matched Layer Boundary Condition

For any numerical method, the computational domain can’t be infinite. Thus, the values of the fields on the boundaries must be defined so that the computational region appears to extend infinitely. With no truncation conditions, the scattered fields will be artificially reflected at the boundaries leading to inaccurate results. There are several types of boundary conditions commonly encountered such as Transparent Boundary Condition (TBC) [6], Complementary Operator Method (COM) [7], and Perfectly Match layer (PML) [8]. In the PML boundary condition, an artificial material region which has both electrical and magnetic conductivities is created to absorb the light wave which touches the boundary at any incident angle.

The idea of PML was first applied to the FDTD method [9]. Huang et al [7, 10] introduced PML to FDM and BPM to calculate the leakage loss of the waveguide. Mittra et al [11] found that PML is equivalent to adding a complex variable domain.

\[
x(\rho) = \int_{0}^{L} [1 - j\sigma(\rho)] d\rho
\]

(2.12)

where \(\sigma(\rho) = \sigma_{\text{max}} (\rho / L)^2\).

The amplitude of the incident planar wave will attenuate as \(\exp\left(-\alpha \int \sigma(\rho) d\rho\right)\) in the PML domain with a width of \(L\). There will be no reflection at the interfaces since there is on discontinuity of the materials between the different layers. The thickness of the PML layer \(L\) and \(\sigma_{\text{max}}\) should be optimized to obtain a suitable reflection ratio.
2.2.3 A Numerical Example

![Schematic configuration of the sandwiched Si/SiNx/Si waveguide.](image)

The mode profiles of the sandwiched waveguides are calculated by using FDM as a numerical example. We consider a Si/SiNx/Si waveguide [12] as shown in Fig. 2.1 with refractive indices $n=3.43$ (Si), $n_{co}=2$ (SiNx) and thickness of the layers $h_{cl}=250$ nm, $h_{co}=100$ nm, respectively. The computation window is 3 $\mu$m $\times$ 2 $\mu$m and the grid sizes are $dx=0.01$ $\mu$m, and $dy=0.01$ $\mu$m. Fig. 2.2 displays the field plot of the calculated fundamental modes. TE and TM denote the polarizations along the $x$ and $y$ axes, respectively. For such waveguide structure, electric fields of TM modes (dominant electric fields are polarized to $y$ direction) are strongly confined to the low-index SiNx region due to the electric field discontinuity between materials with different refractive index while the electric fields of TE modes distribute over the entire waveguide region.

![Mode profiles for the sandwiched waveguides shown in Fig. 2.1 (a) for TM and (b) for TE polarization.](image)

2.3 Beam Propagation Method

FDM presents an efficient way to solve the eigenmodes for a waveguide. However, FDM can’t be used to study the propagation characteristics of a z-variant optical waveguides, such as taper [13], Y-branch [14], or multimode interference (MMI) couplers [15]. For these devices, method such as BPM [16, 17] is mandatory. Different numerical methods including Fourier transform method [18],
the finite element method [19], and the finite difference method [20, 21] are employed in BPM. In this thesis, the finite difference method based BPM is used to investigate light propagation in the PLC devices.

### 2.3.1 Basic Formulas

By using slowly varying envelope approximation [22], the electrical field can be expressed as
\[ \vec{E} = E \exp(jk_0n_0z) \] (\(n_0\) is a reference refractive index). Eq. 2.7 can be rewritten as:
\[
\begin{pmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
= (n_yk_0^2 - 2jn_yk_0 \frac{\partial}{\partial z})
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]
\[ (2.13) \]

The above equation shows the full-vectorial form of the wave equation. For most of the applications, the semi-vectorial finite-difference beam propagation (SVFD-BPM) method which takes account of the discontinuities in the normal electric field components across the internal dielectric interface is proved to be efficiency and accuracy. For a SVFD-BPM, the coupling terms \(P_{xy}, P_{yx}\) between \(E_x\) and \(E_y\) are neglected, then the basic formulas are:

**Quasi-TE:**
\[
\frac{\partial}{\partial x} \left[ \frac{1}{n^2} \frac{\partial (n^2E_x)}{\partial x} \right] + \frac{\partial^2 E_x}{\partial y^2} + \left( n_y^2k_0^2 - n_x^2k_0^2 \right) E_x = -2jn_0k_0 \frac{\partial E_x}{\partial z}
\]
\[ (2.14-a) \]

**Quasi-TM:**
\[
\frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial (n^2E_y)}{\partial y} \right] + \frac{\partial^2 E_y}{\partial x^2} + \left( n_y^2k_0^2 - n_x^2k_0^2 \right) E_y = -2jn_0k_0 \frac{\partial E_y}{\partial z}
\]
\[ (2.14-b) \]

With an alternating directional implicit (ADI) method [23], each of the above two equation is split into two steps. By employing finite difference method, the equations are solved by first specifying a launch field at \(z=0\) and then integrating in \(z\) to obtain the field for the whole computational domain.

### 2.3.2 A Numerical Example

As we mentioned above, BPM is used to simulate the light propagation in the structures with varied refractive index in the propagation direction. Here we simulate a Mach-Zehnder interferometer with equal arms, the field distribution is shown in Fig. 2.3. The light is divided equally into the two arms and then interferes at the output junction. Since the two arms are equal (with 0 phase difference), the output light is just the same as the input light.
2.4 Finite-Difference Time-Domain method

The FDTD method [24-27] is a rigorous solution to Maxwell’s equations and does not have any approximations or theoretical restrictions. FDTD method could be used for complex structures which BPM can’t cope with or is not adequate enough. Since the first algorithm, written by Yee in 1966 [24], FDTD method has emerged as a primary means to computationally model many scientific and engineering problems dealing with electromagnetic wave interactions with material structures.

For a region of space where there is no flowing currents or isolated charges, we can rewrite Eq. 2.1 as:

\[
\nabla \times \bar{E} = -\mu \frac{\partial \bar{H}}{\partial t} - \sigma \bar{H} \\
\n\nabla \times \bar{H} = \varepsilon \frac{\partial \bar{E}}{\partial t} + \sigma \bar{E}
\]

(2.15)
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These two curl equations can be written in Cartesian coordinates as six simple scalar equations which could be solved with the FDTD method. Firstly, Eq. 2.15 is discretized according to Yee’s mesh [24]. Both E and H field components are put on a grid with grid points spaced $\Delta x$, $\Delta y$, and $\Delta z$ apart. As Fig. 2.4 shows, $E$ and $H$ fields are shifted to each other with a half of the step size. Furthermore, time is discretized in steps of $\Delta t$. The E field components are computed at times with a delay of $\Delta t/2$ compared to H field components. Finally, we could get the discretized forms of Eq. 2.15 as:

$$\tilde{H}_{n+\frac{1}{2}} = \left(1 - \frac{\sigma \Delta t}{2\mu_r}\right) \cdot \tilde{H}_{n+\frac{1}{2}} - \frac{\Delta t}{\mu_r} \cdot \nabla \times \tilde{E}^n \quad (2.16-a)$$

$$\tilde{E}^{n+1} = \left(1 - \frac{\sigma \Delta t}{2\varepsilon}\right) \cdot \tilde{E}^n + \left(\frac{\Delta t}{\varepsilon} + \frac{\sigma \Delta t}{2\varepsilon}\right) \cdot \nabla \times \tilde{H}_{n+\frac{1}{2}} \quad (2.16-b)$$

These equations can be iteratively solved by numerically with the central difference form.

In order to perform an accurate simulation, the spatial grid must be small enough to resolve the smallest feature of the field to be simulated. To obtain a stable simulation, the Courant condition should be fulfilled:

$$c\Delta t < \frac{1}{\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \quad (2.17)$$

where $c$ is the light speed in the material.

A time-dependent source is placed somewhere in the structure, and the E and H fields are calculated iteratively for each time step $\Delta t$. These fields are recorded for later analysis. The FDTD method can only simulate structures of a limited size since it requires huge amounts of physical memory to store the fields. PML boundary condition is added to absorb the light emitted by the simulated structure from the boundaries of the computational region.

**A Numerical Example**

For structures with complex refractive index distributions such as the photonic crystals, BPM cannot be used anymore since there are Bragg reflections in these structures. FDTD must be used while dealing with these structures. A simulation of light propagation in a sharp bend based on dielectric rod photonic crystal waveguide with 2D-FDTD is shown in Fig. 2.5. From the figure, one can find that almost 100% transmission can be achieved.
2.5 Effective Index Method

2.5.1 Conventional Effective Index Method

In this section, we discuss the effective index method, which allows us to analyze two-dimensional (2D) optical waveguide structures by simply repeating the slab optical waveguide analyses.

The scalar Helmholtz equation could be written as:

\[ \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + [n^2(x,y)k_0^2 - \beta^2]E = 0 \]  \hspace{1cm} (2.18)

We assume that the field \( E(x,y) \) could be written as the following form:

\[ E(x,y) = X(x)Y(y) \]  \hspace{1cm} (2.19)

Then we could rewrite Eq. 2.18 as:

\[ \frac{1}{X} \frac{\partial^2 X}{\partial x^2} + \frac{1}{Y} \frac{\partial^2 Y}{\partial y^2} + [n^2(x,y)k_0^2 - \beta^2]E = 0 \]  \hspace{1cm} (2.20)

We could solve the above function by separating it into two equations:

\[ \frac{1}{Y} \frac{\partial^2 Y}{\partial y^2} + [n^2(x,y)k_0^2 - n_{\text{eff}}(x)^2] = 0 \]  \hspace{1cm} (2.21)

\[ \frac{1}{X} \frac{\partial^2 X}{\partial x^2} + [n_{\text{eff}}^2(x)k_0^2 - \beta^2] = 0 \]  \hspace{1cm} (2.22)
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By solving Eq. 2.21, we could obtain \( n_{\text{eff}}(x) \) which is the effective index. Then we could obtain \( \beta \) by solving Eq. 2.22.

The effective index calculation procedure can be summarized as follows:
(a) Replace the 2D optical waveguide with a combination of 1D optical waveguides.
(b) For each 1D optical waveguide, calculate the effective index along the y axis.
(c) Model an optical slab waveguide by placing the effective indexes calculated in step (b) along the x axis.
(d) Obtain the effective index by solving the model obtained in step (c) along the x axis.

Fig. 2.6 schematically illustrates the above procedure.

![Figure 2.6. Schematic sketch illustrating the procedure of the effective index method.](image)

### 2.5.2 Modified Effective Index Method

By integration of Eq. 2.18 in a closed interval \([-Y/2, Y/2]\), one obtains:

\[
\int_{-Y/2}^{Y/2} \frac{\partial^2 E}{\partial x^2} \, dy + \int_{-Y/2}^{Y/2} \frac{\partial^2 E}{\partial y^2} \, dy + \int_{-Y/2}^{Y/2} \left[ k_0^2 n^2(x,y) - \beta^2 \right] E \, dy = 0
\]  

(2.23)

When \( Y \) is large enough, \( \int_{-Y/2}^{Y/2} \frac{\partial^2 E}{\partial y^2} \, dy = \frac{\partial E}{\partial y} \bigg|_{-Y/2}^{Y/2} \) is approximately 0 and can be neglected. By setting

\[
u(x) = \int_{-Y/2}^{Y/2} E(x,y) \, dy,
\]

(2.24)

and

\[
N(x) = \sqrt{\int_{-Y/2}^{Y/2} n^2(x,y) E(x,y) \, dy / \int_{-Y/2}^{Y/2} E(x,y) \, dy},
\]

(2.25)

then we have
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\[
\frac{\partial^2 u}{\partial x^2} + \left[k_0^2 N^2(x) - \beta^2\right] u = 0
\] (2.26)

Eq. 2.26 is the wave equation, where \(N(x)\) is the effective refractive index, \(u(x)\) is the equivalent 1D mode distribution. One should note that the propagation constant \(\beta\) keeps the same values as in the two dimensional one.

References


Chapter 2. Design and Simulation Methods


Chapter 3

Multimode Interference Coupler

3.1 Introduction

Multimode interference (MMI) couplers have developed rapidly in recent years since its first introduction by Ulrich and Ankele [1, 2]. MMI couplers are widely used in many PLCs, such as power splitters [3], ring lasers [4], optical switches [5], and wavelength division multiplexers/demultiplexers [6-8].

A multimode waveguide is a waveguide which supports several guided modes. When the input light enters the multimode interference section, high-order modes of the multimode waveguide section are excited. Through the interference between the excited modes, “images” of the input light can be formed. Theoretical work in Ref. 9 suggested means to improve image quality in terms of two physical sources, namely, larger mode counters and smaller phase errors. Higher-order guided waves offer a better image resolution due to their higher spatial frequency, while smaller phase error among different guided modes is paramount for large port counts. Based on self-imaging principle, MMI couplers offer the advantages of compact size, low cross-talk, and low power imbalance. Compared to directional couplers and Y splitters, MMI couplers show superiority in scalability, since they do not need to be cascaded in order to achieve large port counts.

3.2 Basic Principle: Mode Propagation Analysis

Different approaches such as ray optics [10], hybrid methods [11], and BPM [12] could be used to analyze multimode waveguides. However, a guided-mode propagation analysis (MPA) method [9] is preferred since it provides insight into the physical mechanism of multimode interference.

Figure 3.1. Schematic of a 1×4 MMI coupler.

A schematic of a 1×4 MMI coupler is shown in Fig. 3.1. It consists of single mode waveguides.
Chapter 3. Multimode Interference Coupler

input/output waveguides and a multimode region. For exact numerical modeling, a full 3D analysis is required. But the working principle can very well be explained by a 2D model without any loss of generality. We use a 2D model (using the effective index method) to show how MPA works. The effective refractive indices of the guiding and the cladding layers are \( n_{co} \) and \( n_{cl} \), respectively. The width and the length of the multimode region are \( W \) and \( L_{MMI} \), respectively. We suppose that the multimode region supports \( m \) modes with mode number \( \nu = 0, 1, \ldots, (m-1) \) at a free space wavelength \( \lambda_0 \).

The relation between the lateral wavenumber \( k_{x\nu} \) and the propagation constant \( \beta_\nu \) of the \( \nu \)th order mode can be described by the dispersion equation:

\[
k_{x\nu}^2 + \beta_\nu^2 = k_0^2 n_{co}^2.
\]  
(3.1)

For strong guiding waveguides, we have

\[
k_{x\nu} = (\nu - 1)\pi / W_e,
\]  
(3.2)

where \( W_e \) is the effective width of the multimode section.

By substituting Eq. 3.2 into Eq.3.1 and using the paraxial approximation, the propagation constant \( \beta_\nu \) can be expressed as:

\[
\beta_\nu \approx n_{co} k_0 - \frac{(\nu + 1)^2 \pi \lambda}{4 W_e^2 n_{co}}.
\]  
(3.3)

The beat length between the fundamental and the first mode can be defined as:

\[
L_\pi = \frac{\pi}{\beta_0 - \beta_1} = \frac{4 n_{co} W_e^2}{3 \lambda}
\]  
(3.4)

and Eq. 3.3 could be rewritten as:

\[
\beta_\nu \approx \beta_0 - \frac{\nu(\nu + 2)\pi}{3 L_\pi}
\]  
(3.5)

By assuming that the MMI has at least a few guided modes and that the radiative modes of the MMI section are not excited, the input field \( \psi(x,0) \) can be expanded in terms of all the guided modes in the multimode region:

\[
\psi(x,0) = \sum_\nu c_\nu \varphi_\nu(x),
\]  
(3.6)

where \( \varphi_\nu(x) \) is the \( \nu \)th order mode distribution and \( c_\nu \) is the \( \nu \)th order mode excitation coefficient, given by:

\[
c_\nu = \frac{\int \psi(x,0) \cdot \varphi_\nu(x) dx}{\sqrt{\int \varphi^2_\nu(x) dx}}.
\]  
(3.7)
The field $\psi(x, z)$ propagating along $z$ direction can be expressed as a superposition of all the guided modes, that is

$$\psi(x, z) = \sum_{\nu} c_{\nu} \varphi_{\nu}(x) \exp[j(\omega t - \beta_{\nu} z)]. \quad (3.8)$$

Finally we could obtain the following formula by substituting Eq. 3.5 to Eq. 3.8:

$$\psi(x, z) = \sum_{\nu} c_{\nu} \varphi_{\nu}(x) \exp[-j \frac{v(v+2)\pi}{3L_\pi} z] \quad (3.9)$$

From Eq. 3.9, one can easily find that the field at $z=L$ is determined by the mode excitation coefficient $c_{\nu}$ and the phase term: $\exp[-j \frac{v(v+2)\pi}{3L_\pi} L]$.

Under certain conditions, the field at $z = L$ will be a reproduction of the input field. By using the symmetry and anti-symmetry of the even and odd modes with respect to the plane at $x = W/2$, Eq. 3.9 shows that $\psi(x, z = L)$ will be a self-image of $\psi(x, z = 0)$ if the phase term satisfies the following condition,

$$\exp[-j \frac{v(v+2)\pi}{3L_\pi} L] = 1 \quad \text{or} \quad (-1)^v \quad (3.10)$$

At some special excitation position, some of the modes will not be excited. Thus, we could analyze the self-imaging properties by the following excitation types:

**A. General Interference**

“General interference” means that there is no specific restriction on the excitation position. It is found that there are $N$-folded images of the input field at a distance $L$ from $z=0$ [9]:

$$L = \frac{3pL_\pi}{N} \quad (3.11)$$

where $p$ indicates the imaging periodicity along $z$.

$N$-folded images are positioned at $x_i$ with phase $\phi_i$ given by the following:

$$x_i = p(2i - N) \frac{W_e}{N} \quad i = 1, 2, \ldots, N. \quad (3.12)$$

$$\phi_i = p(N-i) \frac{\pi}{N}$$

**B. Paired Interference**

The modes $\nu=2, 5, 8\ldots$, present a odd symmetry at $x = \pm W_e / 6$. By launching an even symmetric field at these positions, the excitation coefficients $c_{\nu}$ will be zero for $\nu=2, 5, 8\ldots$, since the overlap integrals of Eq. 3.7 between even symmetric input field and the odd symmetric modes
will vanish. For the other excited modes with \( c_v \neq 0 \), we have:

\[
\text{mod}_3 \left( v(v+2) \right) = 0 \quad \text{for} \quad v \neq 2, 5, 8, \ldots
\]  

(3.13)

Therefore, the length periodicity of the mode phase of Eq. 3.10 will be reduced three times. \( N \) folded self-images of the input field will be obtained at:

\[
L = \frac{pL_s}{N}.
\]  

(3.14)

The modes contributing to the imaging are mode pairs 0-1, 3-4, 6-7..., thus this mechanism is called paired interference. For this case, the number of the input waveguides is limited to two (at \( x = \pm W_y / 6 \)).

C. Symmetric Interference

If the excitation field is launched at the centre of the multimode region, only the even symmetric modes will be excited (\( c_v = 0 \) for \( v \) odd). For this case, we have:

\[
\text{mod}_4 \left( v(v+2) \right) = 0 \quad \text{for} \quad v \text{ even}
\]  

(3.15)

It is easy to find that the length periodicity of the mode phase of Eq. 3.10 will be reduced four times. \( N \) folded self-images of the input field will be obtained at:

\[
L = \frac{3pL_s}{4N}.
\]  

(3.16)

Since only the even modes are excited, the imaging is obtained by combinations of the even symmetric modes, and the mechanism is called symmetric interference. One should note that in this case the number of the input waveguides is limited to one (at \( x = 0 \)).

BPM simulated field distribution for MMI with different excitation types are shown in Fig. 3.2. The self-images are located at what we obtain from the MPA method.
Chapter 3. Multimode Interference Coupler

Figure 3.2. BPM simulated field distributions for an MMI with different excitation types: (a) General Interference; (b) Paired Interference; (c) Symmetric Interference.

For devices based on MMI, two important features are the insertion loss and non-uniformity which can be defined as:

\[ Loss = -10 \log_{10} \left( \frac{\sum_{i=1}^{N} I_i}{I_{in}} \right), \]

\[ NU = 10 \log_{10} \left[ \frac{\min(I_i)}{\max(I_i)} \right], \] (3.17)

where \( I_i \) is the output energy from the \( i \)-th output waveguide and \( I_{in} \) is the energy at the input waveguide.

In order to obtain low-loss 1-to-\( N \) splitters, the multimode waveguide is required to support at least \( N+1 \) modes.
3.3 Improved Performance for a SOI-based MMI Power Splitter

This section discussed and summarized the results obtained in Paper I.

3.3.1 High Order Modes in the Vertical Direction

Various materials such as silicon, InP, and SiO₂ have been used to implement MMI devices. Recently, silicon-on-insulator (SOI) has emerged as highly promising due to its excellent optical properties and the compatibility with the well developed CMOS integrated circuit technology. Besides, the size of the photonic components based on SOI could be reduced dramatically compared to the one based on SiO₂ due to the high refractive index contrast between silicon (n = 3.44) and SiO₂ (n = 1.46). For the SOI waveguide, a rib waveguide is preferred since it could give a high coupling efficiency to a standard single mode fiber. The height of the silicon core layer is usually chosen to be 3-11 μm [13]. However, for an SOI-based MMI device with such a large cross section, some vertical modes (with more than one peak in the vertical direction) can be excited and consequently there are multimode interferences in the vertical direction [14].

![Figure 3.3](image)

**Figure 3.3.** (a) Schematic of the cross-section of the SOI rib waveguide; (b) E12 mode and (c) E22 mode of the MMI section (\(W_{\text{MMI}}=60\ \mu\text{m}\)).

Fig. 3.3 (a) shows a schematic sketch of the cross-section of the SOI rib waveguide. The height of the silicon layer is chosen to be 5 μm to ensure a good coupling to the standard single mode fiber. The other parameters are chosen as follows: \(h = 2.0\ \mu\text{m}\), \(W = 4.0\ \mu\text{m}\), \(n_c = 1.0\), \(n_r = 3.44\), \(n_s = 1.46\) (these variables are indicated in Fig. 3.3 (a)) to ensure single mode propagation. The width of the MMI region is chosen to be \(W_{\text{MMI}}=60\ \mu\text{m}\). By using FDM, the guided modes of the MMI section are obtained. For the above MMI structure, it is found that there are two sets of modes: the lateral modes E1 and the vertical modes Ei2 (i = 1, 2, 3...) with 2 peaks in the vertical direction. The lowest two vertical modes are shown in Fig. 3.3 (b) and (c).

From the analysis presented in section 3.2, we know that self-images of the MMI device are formed by the superposition of the distribution of all the modes. In the vertical direction, there are
two sets of guided modes. From Eq. 3.4, the beat length $L_{\pi}$ is 11013 $\mu$m and 10843 $\mu$m long for $E_{i1}$ and $E_{i2}$, respectively. Therefore, the self-imaging positions for two sets of vertical modes are different. This indicates that the existence of the vertical modes $E_{i2}$ will reduce the quality of self-imaging. The beat lengths for the high order vertical modes are different from those for the lateral modes and consequently the self-images for different mode sets will be located at different positions. This results in the degradation of the imaging quality in an SOI-based MMI device.

### 3.3.2 Suppression of the High Order Modes in the Vertical Direction

From Eq. 3.9, we could find that the self-imaging quality is determined by both the propagation constants $\nu_{\beta}$ for all the guided modes and the field excitation coefficients $c_{\nu}$. The propagation constants $\nu_{\beta}$ for all the guided modes in the MMI section are obtained by FDM and the field excitation coefficient $c_{\nu}$ are calculated from the overlap of the input field with the $\nu$-th mode field of the multimode region. When the width $W_{\text{MMI}}$ is 60 $\mu$m, there are 26 $E_{i1}$ modes and 17 $E_{i2}$ modes in total (Only the guided modes are taken into account).

![Field Excitation Coefficients for two sets of guided modes for three different input waveguide widths](image)

Figure 3.4. The field excitation efficient for two sets of guided modes for three different values of input waveguide width $W_{T}$.

To increase the quality of the self-imaging, we must suppress the excitation of the high order vertical modes $E_{i2}$. Field excitation coefficients $c_{\nu}$ for two sets of guided modes for three different input waveguide widths are shown in Fig. 3.4. From the figure, we could find that when the input waveguide width increases, the excitation coefficients for low order modes increase.
while the coefficients for the high order modes decrease, \( c_n \) are almost zero for odd modes. This can be understood as follows, when the width of the input rib waveguide is small, the modal field distribution becomes asymmetric in the vertical direction. This will introduce a considerable excitation for the vertical modes with an odd symmetry in the vertical direction. When the width of input waveguide is large enough, the modal field distribution of the input rib waveguide becomes almost symmetric. This reduces the excitation of the vertical modes greatly.

![Figure 3.5. Schematic of the optimized MMI structure with tapers structures.](image)

To minimize the influence of the high order vertical modes, one must broaden the width of the input waveguide. At the same time, the input waveguide is required to be single mode. Therefore taper structures are introduced to connect the input/output waveguides and the multimode region.

The optimized MMI structure with tapers is shown on Fig. 3.5. By using Eq. 3.4, an estimate of the beating length of the multimode region can be obtained, i.e., \( L_{\text{MMI}} = 2065 \mu m \), which is not the optimal value due to the approximation in Eq. 3.3. Optimization is done by using a 3D-BPM. Finally, the optimized MMI structure could be obtained: the length of the multimode section is \( L_{\text{MMI}} = 2089 \mu m \) and the lateral positions of the output waveguides are at \( x = 7.9 \mu m, -7.9 \mu m, 23.3 \mu m, \) and \(-23.3 \mu m\).

![Figure 3.6. Insertion loss and non-uniformity of the designed MMI coupler with taper structures.](image)
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Insertion Loss and non-uniformity of the designed MMI coupler with different taper widths are shown in Fig. 3.6. From this figure, one sees that the insertion loss decreases as the width of the taper increases. For the case without tapers, the insertion loss is about 1.2127 dB. The minimal insertion loss is 0.076 dB when the width of the taper is 14 μm. Concerning the non-uniformity, it first decreases to a minimum value and then starts to increase. A minimum non-uniformity of 0.068 dB is obtained when the taper width is 9 μm. As a comparison, non-uniformity is 0.5509 dB without tapers. When the taper width becomes bigger than a certain value (~9 μm in our design), the non-uniformity degrades due to the coupling efficiency between the output waveguides. By considering both the insertion loss and the non-uniformity, the width of the taper structure is chosen to be 9.6 μm in our design. The corresponding insertion loss and non-uniformity are 0.101 dB, and 0.102 dB, respectively.

A 3D BPM is used to simulate the whole structure and the corresponding field distributions are shown in Fig. 3.7. From these figures, one sees that four folds are formed at the image plane (\(L_{\text{MMI}}\) is optimized with 3D BPM) as predicted. For the MMI coupler without tapered input/output waveguides, the imaging quality is poor (Paper I). In Fig. 3.7 (a) and (b), self-images with much higher quality are obtained for the optimized structure compared with the conventional design. It is obvious that the loss and uniformity performances have been improved greatly. The loss is reduced from 1.2127 dB to 0.101 dB (a reduction by 92%) and the non-uniformity from 0.5509 dB to 0.102 dB (a reduction by 81.5%).

![Figure 3.7. 3D BPM simulated field distributions along an x-z cross-section and on the output plane of the MMI coupler with taper structures.](image)

3.4 MMI Power Splitter Based on Deep Etched SiO\(_2\) Waveguides

3.4.1 Deeply Etched SiO\(_2\) Waveguides

For passive PLCs, the silicon oxide (SiO\(_2\)) buried waveguide (shown in Fig. 3.8 (a)) is the most popular one due to low cost, small propagation loss and good matching to a single mode fiber (SMF) [15,16]. However, the bending radius has to be at least several millimeters for an
acceptable bending loss for a SiO\textsubscript{2} buried waveguide even with a super-high refractive index contrast $\Delta$ (e.g., $R = 1.5$ mm for $\Delta = 2.5\%$). Furthermore, the separation between two parallel SiO\textsubscript{2} buried waveguides should be larger than 25 $\mu$m to avoid the coupling between them. The size of devices based on SiO\textsubscript{2} buried waveguides are usually several millimeters, which limits the application of SiO\textsubscript{2} buried waveguides for achieving a higher integration density.

![Figure 3.8. Schematic of the cross section for (a) the conventional buried SiO\textsubscript{2} waveguide; (b) the deeply-etched ridge SiO\textsubscript{2} waveguide.](image)

In Paper II, we presented a deeply-etched SiO\textsubscript{2}-based ridge waveguide as a solution to the above mentioned limitations. The cross section of the deeply-etched SiO\textsubscript{2}-based ridge waveguide is shown in Fig. 3.8 (b). Due to the deep etching, the modal field is confined well by the air at the lateral direction and thus a very small (~200 $\mu$m) bending radius can be obtained for an allowable bending loss. This is very beneficial to improve the integration density of PLCs. In order to improve the coupling efficiency between the present waveguide and a SMF, taper structures are introduced at the end of input/output waveguides. The fabrication process of the waveguide is similar to the conventional SiO\textsubscript{2} waveguide. Furthermore, the three layers of thin film for the buffer, core and cladding can be deposited by using the PECVD (plasma enhanced chemical vapor deposition) technique in sequence, which is not interrupted by any other process.

We choose the refractive index of the buffer/cladding $n_s = 1.46$ and the refractive index contrast $\Delta = 0.75\%$, which is used in the conventional buried SiO\textsubscript{2} waveguides. The genetic optimization [17] is used to design the taper structure for a high coupling efficiency. Considering the difficulty of a deep etching process, the total etching depth is set to be smaller than 12 $\mu$m, i.e., $H<12$ $\mu$m. In order to achieve an allowable bending loss for a very small bending radius (about 200 $\mu$m), we choose the etching depth $h_{et}= 3$ $\mu$m. The core height $h_{co}$ is chosen under the single mode condition. The other parameters are set as follows: $h_{cl} = H - h_{co} - h_{et}$, $n_{bf}$= 1.46. We obtain the optimal results (with the genetic algorithm) as follows: $h_{co} = 5.984$ $\mu$m, $h_{cl} = 2.995$ $\mu$m, and $w_{tp}$ = 11.2 $\mu$m. The corresponding coupling loss is only 0.095 dB per facet.

The waveguide with this design is multimode and the width should be reduced by using a taper (Fig. 3.9-(a)) until the waveguide becomes single-mode. When the width is smaller than a critical width $w_0$, the effective refractive index of the fundamental mode is smaller than the refractive index ($n_{bf}$ = 1.46) of the buffer layer, which indicates that only leaky modes are supported. In this case $w_0 = 4.4$ $\mu$m. Therefore, one should have $w > w_0$ for the single-mode straight waveguide. For a single-mode deeply ridge waveguide, higher order leaky modes usually exist and thus the width should be small to increase the leakage loss of the higher-order modes [18]. Thus, we choose the width $w_S = w_0$ for a straight single-mode waveguide. On the other hand, we
found that the width $w_B$ of the bending section should be reduced to achieve an allowable transition loss for a desirable small bending radius (several hundreds of microns). Therefore, we introduce a taper to connect the straight waveguide (with a width $w > w_B$) and the bending section (as shown in Fig. 3.9. (b)) [19]. An offset can also be introduced to match the peaks of the straight and bending section so that the transition loss is reduced further [20]. With such a design, the width $w_B$ can be chosen optimally to reduce the transition loss of bending section. One should note that only leaky mode is supported in the bending section for the case of $w_B < w_0$ and the leakage loss (per centimeter) increases as the width decreases. On the other hand, the small bending radius $R$ makes a short bending section ($R \pi /2$) and thus the total leakage loss in the bending section is still very low.

![Figure 3.9.](image)

Figure 3.9. (a) Schematic sketch showing a taper at the end of input/output waveguide coupled to the SMF; (b) A 90° bent section showing the different geometrical parameters.

### 3.4.2 Compact MMI Power Splitter Based on Deeply Etched SiO$_2$ Waveguides

In this sub-section, we discussed and summarize the results obtained in Paper III. From the analysis in Section 3.2, we find that the quality of the self-imaging is depended on how the quadratic relation in Eq. 3.5 is fulfilled in the lateral direction [9]. The propagation constants of a strongly confined waveguide can fulfill this quadratic relation very well. The modes are so weakly confined that the eigen-mode spectrum deviates greatly from the ideally required mode spectrum for a typical weakly guiding optical channel waveguides. Thus the imaging quality is significantly degraded for the conventional SiO$_2$ buried waveguides. The multimode region should support a sufficient number of guided modes to ensure an excellent image of the input field. A strong lateral confinement can support the required number of guided modes with small width compared to the conventional weak guiding waveguide. Furthermore, the relative large separation between output waveguides results in a rather large device size for the conventional waveguides. Therefore, a deeply etched waveguide can not only help improve the image quality [21, 22] but also decrease the device size dramatically.

Kaalund introduced deeply-etched air trenches [23], which gives a strongly-confined multimode region and improved performances for MMI coupler (such as low excess loss and small non-uniformity). However, the device size is still large and a complicated fabrication
process (including multi-step etchings) is needed.

We design MMI power splitters based on the waveguide structures obtained in section 3.4.1: \( h_{co} = 5.984 \, \mu\text{m}, h_{cl} = 2.995 \, \mu\text{m}, w = 6.0 \, \mu\text{m} \). The width of the multimode region \( W_{\text{MMI}} \) depends on the minimal separation between the output waveguides and the number of the output waveguides. In this case, the separation \( d_o = 8 \, \mu\text{m} \) between output waveguides is small enough to achieve a large enough isolation between different output waveguides. Thus for a \( 1 \times 4 \) MMI coupler, the MMI width \( W_{\text{MMI}} \) is \( 32 \, \mu\text{m} \). For the MMI coupler based on conventional SiO\(_2\) buried waveguides, the MMI width is chosen to be \( W_{\text{MMI}} = 80 \, \mu\text{m} \) (the corresponding separation \( d_o = 20 \, \mu\text{m} \)).

\[ \text{Figure 3.10. The deviation of the FDM-obtained propagation constants from the quadratic relation given by Eq. 3.5.} \]

Firstly, we investigate how the quadratic relation in Eq. 3.5 is fulfilled. By using FDM, we can obtain the propagation constants for all guided modes supported in the multimode region. Fig. 3.10 shows the deviation of the FDM-obtained propagation constants from the quadratic relation given by Eq. 3.5. One could easily find that MMI based on deeply etched SiO\(_2\) waveguide has much smaller deviation in comparison with conventional SiO\(_2\) buried multimode waveguides because of the stronger confinement. The deviation in propagation constants results in phase errors for the guiding modes and thus degrades the self-imaging quality of the MMI devices.

A first estimate of the length of the \( 1 \times 4 \) power splitter could be obtained by using Eq. 3.4, and then optimized by using a 3D-BPM simulation. The optimized MMI lengths for the present and conventional MMI splitters are \( 245.5 \, \mu\text{m} \) and \( 1627.5 \, \mu\text{m} \), respectively. The 3D-BPM simulation results show that the MMI splitter based on deeply etched SiO\(_2\) waveguide has much smaller size and better imaging quality in comparison with the one based on conventional SiO\(_2\) buried waveguide.

Fig. 3.11 shows the field distribution \( E(x, y = 0, z = L_{\text{MMI}}) \) on the output plane of the MMI coupler. From this figure, one sees that the self-imaging and the uniformity are improved when deeply-etched multimode waveguide is used. The loss and the non-uniformity are reduced from 0.253 dB to 0.0275 dB and 0.423 dB to 0.0507 dB, respectively. Furthermore, the total device size
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is also reduced to only about 1/16 of conventional MMI coupler.

![Field distributions at the output plane (along a line) of MMI couplers. Solid line: deeply-etched SiO₂ waveguides; Dashed line: conventional buried SiO₂ waveguides.](image)

Figure 3.11. Field distributions at the output plane (along a line) of MMI couplers. Solid line: deeply-etched SiO₂ waveguides; Dashed line: conventional buried SiO₂ waveguides.

3.5 Polarization Insensitive Demultiplexer Based on MMI Coupler

3.5.1 Wavelength Division Multiplexer

In the last decade, the high-speed and broad-band optical networks have developed rapidly due to the demand for internet services. Wavelength division multiplexing (WDM) technology provides an efficient way to increase the number of the channels and achieve the demanded bandwidth. 1310/1550 nm WDM systems are frequently used in the fiber-to-the-home applications and asynchronous transfer mode passive optical networks (ATM-PON). There have been several approaches proposed to realize 1310/1550nm WDMs. Different PLCs including Mach-Zehnder interferometers [24], directional couplers [25], MMI coupler [26, 27], and arrayed waveguide gratings [28] were used to separate 1310/1550 nm signals. Among them, MMI based demultiplexers are attractive because of their larger fabrication tolerance and the broad bandwidth properties of MMI couplers. Recently, Grating-assisted MMI waveguides [29] and MMI waveguides with photonic crystal section [30] have been proposed to reduce the device size. However, most of the proposed MMI based demultiplexers could be used only for one polarization. Polarization dependence is a serious problem in actual systems.

In Paper IV, we demonstrate the design of a polarization-insensitive MMI 1310/1550 nm
demultiplexer based on sandwiched waveguides with a rather small device size due to the high
refractive index contrast of the waveguide structure. A summary of Paper IV is given below.

3.5.2 Design and Simulation Results

![Schematic configuration of the demultiplexer based on a MMI coupler.](image)

The basic working principle of a MMI coupler based 1310/1550 nm demultiplexer is shown in Fig.
3.12. It consists of one input waveguide, a multimode waveguide region, and two output
waveguides. From the analysis in section 3.2, we know that mirror images and self images will be
formed while \( z \) is odd and even multiples of the beat length \( L_\pi \) respectively. Besides, the
propagation constants \( \beta_0 \) and \( \beta_1 \) are wavelength dependent, thus the self-images will be produced
at different planes for different working wavelengths. When the overall length of the multimode
region \( L_{\text{MMI}} \) satisfies

\[
L_{\text{MMI}} = n \cdot L_\pi (1310) = (n + 1) \cdot L_\pi (1550), \quad (n \text{ is an integer})
\] (3.19)

the 1310/1550 nm wavelengths will be output at the two ports of the MMI coupler. When the
length of MMI region \( L_{\text{MMI}} \) satisfies Eq. 3.19, there will be a single image and a mirror image for
the two different wavelengths, e.g., the 1310 and 1550nm bands, respectively. The two wavelength
bands can be separated successfully. MMI demultiplexer can perform the separation of two
wavelengths using the difference between the beat lengths at these wavelengths.

To realize a compact device design, sandwiched waveguides [31-33] are used for MMI
demultiplexer. The guided light is strongly confined in the narrow low index layer between two
high index layers for a sandwiched waveguide. Schematic of the waveguide cross section and the
according mode profiles for such waveguides are shown in Fig. 2.1. One of the benefits for such
waveguide structures is that the refractive index of the SiN_\text{x} middle region can be adjusted
between \( n_{co} = 1.72\text{--}3.43 \) by ion-assisted deposition [34]. The width of the input/output waveguide
is set to be 1\( \mu \)m to ensure single mode propagation. The multimode region has the same vertical
geometry as the input/output sandwiched waveguides except that the waveguide width \( W_{\text{MMI}} \) is
varied. Restricted Interference is utilized to reduce the device size by placing the input and output
waveguides at a lateral offset of \( \pm W_{\text{MMI}}/6 \) with respect to the center of the MMI region.
The propagation constants $\beta_0$ and $\beta_1$ for the two lowest mode of the multimode region are obtained with a FDM. By using Eq. 3.4, we get the beat lengths for the MMI waveguides.

Firstly, we try to design polarization insensitive MMI couplers by choosing the refractive index of the SiNx middle region properly. We find that the points at which the beat length for the two polarizations are nearly identical and almost wavelength insensitive (as the MMI width $W_{MMI}$ increases $n_{co}$ values at the two crossing points increase, however, always to similar values). With this special property, we can realize polarization insensitive MMI waveguides at almost the same $n_{co}$ at both wavelengths 1310 nm and 1550 nm. Fig. 3.13 shows the difference in $L_{\pi}$ between two polarizations at optimized $n_{co}$ values (at these values, the difference in $L_{\pi}$ between two polarizations are smallest). From the figure, we could find the designed MMI waveguides are almost polarization independent for both wavelengths by properly choosing the refractive index of the SiNx middle region.

To realize demultiplexing function, we should find a suitable integer $n$ satisfying Eq. 3.19. We search for such a $n$ by changing the width of the MMI region. Finally, we find that when $W_{MMI} = 4.74$ µm (optimized $n_{co} = 2.56$), $R = 1.2 = 6/5$, Eq. 3.19 is satisfied by setting $n = 5$. The beat lengths for different wavelengths and different polarizations are: $L_{\pi}^{TE} (1310) = 73.09$ µm, $L_{\pi}^{TM} (1310) = 73.21$ µm, $L_{\pi}^{TE} (1550) = 60.9$ µm, and $L_{\pi}^{TM} (1550) = 60.8$ µm. Using Eq.3.19, the average length of the MMI region $L_{MMI}$ could be chosen as 365.46 µm to realize demultiplexing for both polarizations simultaneously. One should note that this value is an estimate due to the approximations in Eq. 3.4. By using a three-dimensional finite-difference beam-propagation-method (BPM), an optimized $L_{MMI} = 363.5$ µm is obtained.

By simulating the whole structure with 3D-BPM, we obtain the following insertion losses (IL) and extinction ratios (ER): at 1310 nm wavelength, $IL = 0.3$ dB and $ER = 21.7$ dB for quasi-TE

![Figure 3.13. Beat length ratio between quasi-TE and quasi-TM modes and the corresponding optimized $n_{co}$ value as a function of the MMI width $W_{MMI}$.](image-url)
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polarization, $IL = 0.67$ dB and $ER = 22.4$ dB for quasi-TM polarization; at 1550 nm wavelength, $IL = 0.41$ dB and $ER = 24.9$ dB for quasi-TE polarization, and $IL = 0.26$ dB and $ER = 23$ dB for quasi-TM polarization.

![Figure 3.14](image-url)  
Figure 3.14. Output powers (normalized to the input power) from Ports 2 and 3 as the wavelength varies (a) 1310 nm band; (b) 1550 nm band.

Bandwidth is an important parameter for a demultiplexer. From the wavelength response given in Fig. 3.14, bandwidths of 40 nm and 50 nm can be achieved for the 1310 nm and the 1550 nm bands, respectively. From this figure, we can also find that the present demultiplexer has similar performances for both polarizations.

References


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Chapter 4

PLC Devices based on Photonic Crystals

4.1 Introduction

4.1.1 Photonic Band Structures

Research on photonic crystals (PhCs) has been developing rapidly over the past few years because they enable the realization of photonic devices with high integration density through a strong optical confinement by photonic bandgap effects and due to the unique dispersion properties.

PhCs are periodic dielectric structures that have a band gap which forbids propagation of light with a certain range of frequencies. For a three-dimensional periodic structure with a sufficiently high refractive index contrast, the electromagnetic radiation in certain wavelength ranges can’t propagate through the structure in any direction. This wavelength range is called a photonic bandgap (PBG). Certain analogies can be drawn between PhCs for photons and semiconductors for electrons. A semiconductor material exhibits an electronic band gap in which there are no allowed electronic energy levels; similarly, a PhC has a PBG for which photons of specific frequencies are forbidden to propagate.

![Figure 4.1. PhCs fabricated by different methods: (a) Micromanipulation [3]; (b) Holographic lithography [4]; (c) rods based 2D-PhC by PLC technology; (d) air hole based 2D-PhC by PLC technology.](image-url)
Chapter 4. PLC Devices based on Photonic Crystals

The possibility of two- and three-dimensional PhCs with corresponding two- and three-dimensional band gaps was first proposed by Eli Yablonovitch and Sajeev John in 1987 [1, 2]. The fabrication of 3D PhCs working at optical wavelengths is a challenging work since the periodicity of the structures must be in the same order of magnitude as wavelength. Different manufacturing solutions such as micromanipulation [3], glancing angle deposition [4], inverse opals [5], two photon lithography [6], holographic lithography [7], and auto-cloning [8] have been proposed and reported. Compared to 3D-PhCs, 2D-PhCs are easier to fabricate, and hence 2D-PhCs have received considerable attention.

There are a variety of applications for PhCs for manipulating light propagation and improving the efficiency of opto-electronic devices. By introducing defects in the periodic lattice, it is possible to control the propagation of light at desired wavelengths. Different applications such as photonic crystal fibers [9] waveguides [10], sharp bends [11], wavelength filters [12], demultiplexing [13, 14], and optical switching [15] have been investigated using PhCs.

PBG structures could be used to improve the efficiency of light-emitting diodes and lasers [16-18]. By introducing PhCs in LEDs, the light that does not radiate into the emission cone is suppressed by the PhCs, thus the external quantum efficiencies are enhanced greatly. Gain media can be incorporated into the PhCs to improve the output of light emission. A one dimensional periodic dielectric gain media structure will have a higher power output with the frequency at the band gap edge because of the reflection of the radiation back and forth between each gain layer which increases the simulated emission four fold. A two dimensional PhC is used to improve the

Figure 4.2. Representative application examples of PhCs. (a) Photonic Crystal Fiber [9]; (b) Demultiplexing [14]; (c) LED [17]; (d) Laser [18].
Chapter 4. PLC Devices based on Photonic Crystals

Lasing efficiency by inhibiting spontaneous emission out of the lasing plane and confining the light to be emitted along the defect path. Since dry etching is a common step in PhC fabrication, it can affect the performance of active devices due to etch-induced damage. On the other hand, it can reduce carrier lifetimes to be relevant for switching applications. These material issues are addressed in Chapter 5 and in Paper IX and X.

The confinement of light by the PBG provides an efficient way to obtain resonant modes with high quality factor (Q) with small mode volume (V). The strong optical confinement in PhC nanocavities can enhance the spontaneous emission rate which is a key phenomenon for reducing the threshold of nanolasers. Besides the large Q/V, PhC cavities are suitable for integration. It is flexible to integrate many cavities in a single chip, and they can be coupled with each other or via PhC waveguides.

Besides the above applications by using the bandgap property, PhCs has been used to control the propagation of light by their special dispersion property. Super prism [19, 20] and negative refraction [21, 22] are two well known phenomena which result from the special dispersion property of PhCs.

4.1.2 Two Dimensional Photonic Crystals

There are 1D, 2D, and 3D PhCs according to the periodicity of the dielectric constant in one, two, or three dimensions, respectively. 1D PhCs are periodic in only one axial direction, such as a stack of planar dielectric layers with alternating refractive index, whereas 2D PhCs are periodic in two directions and 3D PhCs are periodic in all three axial directions. 1D PhCs are the simplest ones which have been used as Bragg mirrors for a long time. The range of PBG of 1D PhCs depends on the angle of the incident light which limits the applications. Although having an omni-directional bandgap, 3D PhCs are difficult to fabricate. An alternative to 3D PhCs is the combination of a conventional waveguide structure and a photonic crystal- 2D PhCs. Most of the attention has been paid to 2D PhCs since the fabrication procedure is similar to that used for PLCs. Furthermore, 2D PhCs could also provide most of the functionality of 3D counterparts to modify the flow of light.

The PhC structures we are interested in are the two dimensional ones as they could be fabricated by using the PLC technology. 2D PhCs are created by etching holes or rods in a semiconductor layer structure. Two representative 2D PhC slabs and their band diagram are shown in Fig. 4.3. The band diagram is a relation between the wave vectors and the frequencies. By assuming that the 2D structure is invariant in the third direction y, we can split up the full vectorial problem into two uncoupled polarizations: The transverse electric (TE) mode with the electric field perpendicular to the rod (air hole) and the transverse magnetic (TM) mode with the electric field parallel to the rod (air hole). From the band diagram, we can see that a square lattice PhC composed of dielectric rods has a PBG for TM mode while a triangular lattice of air holes based PhCs has a PBG for TE mode. The magnitude of the band gap depends on the refractive index contrast between the dielectric and the background material, the radius of the rods (air holes). For a air hole structure, a gap for both TE and TM can be obtained by a suitable choice of the lattice parameters.
4.1.3 Photonic Crystal Waveguides

Conventional optical waveguides operate on the principle of the total internal reflection (TIR), which occurs when there is a refractive index difference between different layers. Light will be completely reflected by the interface of different materials for the photons that are incident at an angle less than a critical angle. Incident light greater than the critical angle can’t propagate in the waveguide and will be lost. There will be inevitable losses when the light propagates through a bend. Thus, the bending radius should be designed to be large enough to ensure a small loss and this will result in a large device size.

One of the exciting applications of PhCs is the manipulation of light with PhC waveguides which are formed by introducing line defects in PhCs. Unlike conventional waveguides that depend on TIR for the guidance of the optical field, guided modes appear within the PBG when the periodicity of PhC structure is broken or defects are introduced into it. By removing a single line of air holes, the simplest PhC waveguide is formed. In such a structure, light is confined to the waveguide by means of TIR in the vertical direction and by distributed Bragg reflection in lateral direction. It is the localization of a mode inside the line defect that can guide light around sharp corners with low bending loss. For a PhC waveguide, sharp bends with any bending angle that can be designed that is lossless theoretically.

Most of the basic functions which could be realized by the conventional waveguides have been developed by using PhC waveguides. PhC waveguide based sharp bends, Y branches, power splitters, and cross junctions have been realized with both reasonable performance and compact size. By using this basic unit, complex functions such as wavelength demultiplexer, optical switches, wavelength filters, etc can be configured.
Chapter 4. PLC Devices based on Photonic Crystals

4.2 Compact Triplexer Design

PhC is a good candidate for compact device design. In this section, an ultracompact triplexer (Paper V) is presented by cascading two stages of PhC waveguide-based directional couplers. The special decoupling property of the PhC waveguide-based directional coupler is utilized for the design. A taper coupling region and an additional directional coupler are introduced to achieve high extinction ratios and reduce the crosstalk, respectively.

4.2.1 What Is A Triplexer?

“Last mile” delivery for the fiber-optic communication has become very important in recent years. The traditional methods such as copper wires or coaxial cable can not provide the increasing requirement for the bandwidths. Fiber to the home (FTTH) provides an efficient way to deliver signals over the fiber directly to a home or business. More robust video, internet and voice services are enabled since FTTH gives much higher bandwidth to consumers compared to traditional methods. Cost is an obstacle for the further development of the FTTH technology. Triplexer transceivers are key components in FTTH networks and these components continue to be the most expensive part. Mass production of low cost triplexer transceivers is the most challenging part for the deployment of the FTTH in the access networks.

According to the ITU G.983 standard, the three commonly used wavelengths in passive
optical networks (PONs) are 1310, 1490, and 1550 nm. A triplexer is used to demultiplex two downstream signals (1490/1500 nm) from a single fiber to a receiver and at the same time to couple the upstream signal (1310 nm) from a transmitter to the same fiber. Fig. 4.5 shows how triplexers work in a bi-direction communication system.

Most of the existing triplexers used today are constructed by cascading bulk thin film filters to perform triplexing functions. The performance for this type of triplexers is quite high, however it is difficult to integrate with other devices and difficult to package which make it unsuitable for mass production and cost reduction. PLC is more promising due to its properties such as the small size, high reliability, and possibility for large scale production. PLC optical bench has been introduced by J. H. Song [23] to replace bulk chassis, but TIFs are still needed to be manually assembled into the trenches. PLC based WDM filters such as arrayed-waveguide gratings [24], planar lens [25], cascaded directional coupler [26], and Y-branches with reflectors [27] have also been utilized to realize triplexing function, but the typical size of the reported triplexers is several millimeters.

### 4.2.2 Triplexers based on Photonic Crystal Waveguide Directional Couplers

![Figure 4.6. Schematic configuration for the triplexer based on PhCW directional coupler.](image)

The basic principle of a triplexer utilizing two cascaded photonic crystal waveguide (PhCW) directional coupler is shown on Fig. 4.6. There are two stages of PhCW-based directional couplers. It is difficult to find a coupling length which is a common multiple for the three wavelengths simultaneously. A special property called decoupling is utilized for this design. The directional couplers are designed to be decoupled at wavelength 1310 nm (upstream signal channel). Thus, wavelength $\lambda_1$ (1310 nm) will propagate through the PCW #1 without any coupling to the other output port. The other two wavelengths (i.e., 1490 nm and 1550 nm) are separated by properly choosing the length ($L$) for the coupling region of the first directional coupler (coupler #1). $L$ should satisfy $L = mL_c(1550)$ and $L = nL_c(1490)$, where $m$ is an odd integer, $n$ is an even integer, $L_c(1550)$ and $L_c(1490)$ are the coupling lengths at 1550 nm and 1490 nm, respectively. Finally, the second...
directional coupler (coupler #2) separates the wavelengths of 1310 nm and 1490 nm to Ports #1 and #2, respectively.

Unlike the directional coupler based on conventional waveguide, here the length of the coupling region must be a multiple of the period of the lattice. Thus, relations $L=mlc(1550)$ and $L=nlc(1490)$ can’t be satisfied exactly. The performance of the device will be degraded. To improve the extinction ratios, we taper the coupling region for Coupler #1 symmetrically. The radii of the rods in the coupling region decrease linearly from $r=0.2a$ (at the left edge) to $R_c$ at the centre of the coupling region and then increase back to $r=0.2a$ (at the right edge), i.e., $r(z)=R_c+(r-R_c)|z-L/2|/(L/2)$ ($z=0$ at the centre). For this optimal design, the extinction ratios for the wavelengths of 1490 nm and 1550 nm are increased from 8 dB and 10 dB to 18.34 dB and 16.36 dB, respectively. On the other hand, the decoupling property is no longer satisfied at 1310 nm in the tapered coupling region and some power is coupled from PCW #1 to PCW #3, and this introduces an inevitable reduction of the extinction ratio (from 26.27 dB to 12.32 dB) for $\lambda_1=1310$ nm. In order to improve the extinction ratio for 1310 nm, an additional directional coupler is introduced to filter out the power at wavelength 1310 nm from Port #3 (which is for the channel of 1550 nm). Coupler #3 also has a decoupling point at wavelength $\lambda_3=1310$ nm and the wavelength of 1550 nm is almost coupled to PCW #4. With such a design, the residual power of 1310 nm is taken out from an auxiliary port.

![Figure 4.7. FDTD simulated field distributions for the PCW directional coupler based triplexer at (a) $\lambda=1310$ nm; (b) $\lambda=1490$ nm; (c) $\lambda=1550$ nm.](image)

We use a 2D-FDTD method to simulate light propagation in the whole triplexer and the results are shown on Fig. 4.7 and on Table 4.1. The extinction ratios for the wavelengths of 1490 nm and 1550 nm are more than 18.0 dB and 16.0 dB, respectively (better than the results for a dual-wavelength demultiplexer [28]). The 1dB bandwidths of the spectral responses for the three channels (at ports #1, #2, #3) are about 48 nm, 20 nm, 15 nm, respectively. Here we note that the bandwidth will be very narrow if one uses photonic crystal cavities [29] to drop/separate wavelengths. The total size of the present triplexer is about 50 $\mu$m×20 $\mu$m, which is only 1/100 of the conventional PLC-based triplexer [24].
### Table 4.1. Output powers of 3 wavelengths at 3 ports of the triplexer shown in Fig. 4.7.

<table>
<thead>
<tr>
<th>Input Wavelength (nm)</th>
<th>Port #1 (dBm)</th>
<th>Port #2 (dBm)</th>
<th>Port #3 (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1310</td>
<td>-0.0264</td>
<td>-23.2224</td>
<td>-28.8723</td>
</tr>
<tr>
<td>1490</td>
<td>-15.6043</td>
<td>-0.1634</td>
<td>-20.2642</td>
</tr>
<tr>
<td>1550</td>
<td>-17.2252</td>
<td>-20.2340</td>
<td>-0.1252</td>
</tr>
</tbody>
</table>

#### 4.2.3 Polarization Insensitive Triplexer based on Sub-micron Silicon Waveguides

PhC based devices usually work for only one polarization. To realize a device with a compact design, silicon sub-micron waveguides are also good candidates. The high refractive index contrast in these waveguides allows for a strong confinement of light, therefore highly integrated optical systems are possible with ultra-sharp bends. Various devices such as arrayed waveguide gratings, ring resonators, and polarization splitters have been demonstrated by using sub-micron silicon waveguides. Although this type of waveguides is very polarization sensitive, devices which could work for both polarizations have been proposed by carefully adjusting the geometry of the waveguides. In Paper VI, we proposed a polarization insensitive triplexer by using directional couplers based on sub-micron silicon rib waveguides, and is discussed below.

![Figure 4.8](image)

*Figure 4.8. The schematic configuration of the present triplexer (a) top view; (b) cross section of the basic structure of the directional coupler.*

Fig. 4.8 (a) and (b) show the configuration of the present triplexer and the cross section of the directional coupler based on submicron silicon waveguide, respectively. The whole triplexer consists of three directional couplers. To realize a triplexer which could work for both polarizations, we must find directional couplers which are polarization insensitive. We choose a waveguide width $w=500\text{nm}$, and then we calculate the coupling length for both polarizations for directional couplers with different gaps $d$. Fig. 4.9 shows the variation of the coupling length with the gap width $d$ for all the three wavelengths. One could find that the polarization insensitive points ($L_c(\text{TE})=L_c(\text{TM})$) are all located around $d=120\text{ nm}$ (nearly wavelength insensitive). This special property makes this polarization insensitive design feasible.
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Figure 4.9. Coupling length for different wavelengths as a function of the gap width $d$.

The basic configuration of a triplexer utilizing directional couplers is shown in Fig. 4.8 (a). There are two stages of directional couplers (which are all designed to be polarization insensitive). The length ($L$) for the coupling region of the first directional coupler (DC1) is chosen to separate the three wavelengths into two groups (1490 nm in one waveguide; 1310 nm and 1550 nm in another). Thus, $L$ should satisfy $L = m_1 L_{c(1310)}$, $L = m_2 L_{c(1550)}$, and $L = n L_{c(1490)}$, where $m_1$ and $m_2$ are odd integers, $n$ is an even integer, $L_{c(1310)}$, $L_{c(1550)}$ and $L_{c(1490)}$ are the coupling lengths for 1310 nm, 1550 nm and 1490 nm, respectively. Then the second directional coupler (DC2) separates the wavelengths of 1310 nm and 1550 nm. For the output channel of 1490 nm, an additional directional coupler (DC3) is also used to reduce the crosstalk from the 1550 nm and 1310 nm channels.

By using 3D BPM, we simulate the field propagation in the whole triplexer. The output powers at different output ports (normalized to the input power) are shown on Table 4.2. The proposed triplexer works properly for both polarizations with high performances.

Table 4.2. Output powers (normalized to the input power) of three wavelengths at the three output ports of the present triplexer.

<table>
<thead>
<tr>
<th>Input Wavelength (nm)</th>
<th>Port #1 (dB)</th>
<th>Port #2 (dB)</th>
<th>Port #3 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TE</td>
<td>TM</td>
<td>TE</td>
</tr>
<tr>
<td>1310</td>
<td>-26.02</td>
<td>-21.53</td>
<td>-0.35</td>
</tr>
<tr>
<td>1490</td>
<td>-15.18</td>
<td>-27.08</td>
<td>-21.2</td>
</tr>
<tr>
<td>1550</td>
<td>-0.29</td>
<td>-0.16</td>
<td>-15.18</td>
</tr>
</tbody>
</table>
4.3 Polarization Beam Splitter Based on PhC Assisted MMI Coupler

4.3.1 Polarization Beam Splitter

A polarization beam splitter (PBS) is used to split the incident beam into two beams of different polarizations. Unlike absorptive polarizers, PBSs do not absorb or dissipate the energy of the rejected polarization state and the two polarization states should be separated into different ports without attenuation for further processing. A PBS is an important functional device in photonic integrated circuits when the two polarization components are needed to be analyzed or used simultaneously.

PBSs have been implemented on crystals with birefringent properties such as quartz and calcite. An unpolarized light incident on their surface is split by refraction into two rays. However, these type of PBSs are not suitable for integration. PLCs provide an efficient way to develop PBSs. Various PBSs based on PLCs have been reported. PBSs have been designed by using metal clad directional couplers [30]. However, the metal cladding introduces large loss in the devices. An asymmetrical Y-junction structure [31] or a Mach-Zehnder interferometer [32] based PBSs have been reported. The fabrication for these PBSs requires complex processes such as photo bleaching and poling. Directional couplers [33, 34] and MMI couplers [35] have also been used for the realization of polarization-splitting. However, these kinds of PBS usually have a large size since the total length should be integral multiples of the coupling lengths for both polarizations.

In Paper VII, a novel PBS was realized by combining a MMI coupler and a PhC structure and is discussed in the following. The PhC structure is placed in the multimode section of the MMI coupler working as a polarization sensitive reflector. One polarization is reflected and the other one transmits through the PhC structure. The size of the proposed PBS is rather small since the length of the MMI region is no longer needed to be integral multiples of the coupling lengths for both polarizations.

4.3.2 Design and Analysis

The schematic configuration of the PBS based on a PhC-assisted MMI coupler is shown in Fig. 4.10. It consists of one input port (Port1), two output ports (Port2 and Port3), a multimode region with length $L_t$, and a PhC structure located in the middle of the multimode region with a distance of $L_r$ to the input port.
The MMI coupler works like a regular MMI splitter while the internal PhC structure works as a polarization sensitive reflector. Therefore, the forward propagating field $\psi_f(x,L_t)$ and the backward propagating field $\psi_r(x,0)$ could be expressed as [36]

$$
\psi_f(x,L_t) = t \cdot \sum_v c_v \varphi_v(x) \exp\left[j \frac{\nu (\nu + 2) \pi}{3L_g} L_t\right],
$$

$$
\psi_r(x,0) = r \cdot \sum_v c_v \varphi_v(x) \exp\left[j \frac{\nu (\nu + 2) \pi}{3L_g} \cdot 2 \cdot L_r\right].
$$

(4.1)

In Eq. 4.1, one should note that transmission and reflection coefficients for all the guided-modes are assumed to be same.

By setting $L_t = L_{g}^{TM}$ and $L_r = L_{g}^{TE} / 2$, we obtain

$$
\psi_f(x,L_t) = t \cdot \psi(-x,0)
$$

$$
\psi_r(x,0) = r \cdot \psi(-x,0).
$$

(4.2)

From Eq. 4.2, one sees that single-fold self-images are formed at the forward and backward directions if we choose appropriate lengths $L_t$ and $L_r$. The self-image quality also depends on the transmission and reflection coefficients $t$ and $r$. Thus, the PhC structure should be designed to make the TE and TM polarizations highly reflected and highly transmitted, respectively.

In this work, we consider a PhC structure with a triangular lattice of air holes (with a period of $a$) in an InP/GaInAsP/InP sandwich structure (with refractive indices $n=3.17$, $3.35$, $3.17$) structure with a GaInAsP layer of 420 nm, the effective index of the slab is $n_{eff}=3.24$ [37]. Fig. 4.11 shows the photonic bandgap depending on the radius (normalized to the period) of the air holes. From the figure, one notices that the overlap of bandgaps (indicated by arrows) for TE and TM polarizations is only for $r/a > 0.43$. For $0.2 < r/a < 0.43$, there is only bandgap for TE polarization and there is no bandgap for TM polarization. Such PhC structures could be used to separate the two polarizations.
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Figure 4.11 Gap map for PhC structures with a triangular lattice of air holes etched in InP/InGaAsP/InP.

One should notice that small $r/a$ is preferred since the optical losses in the PhC increases with $r/a$. But at the same time the bandgap should be large enough to ensure a large bandwidth. Finally, the radius of the air hole is chosen to be $r=0.26 \ a$. For TE polarization there is a bandgap ranging from 0.215 to 0.256 ($a/\lambda$), however, no bandgap is observed for the TM polarization. In this case, the transmission and reflection coefficients of such a PhC structure for TE and TM polarizations should be $t_{TE} \approx 0$, $r_{TE} \approx 1$ and $t_{TM} \approx 1$, $r_{TM} \approx 0$. The length of the PhC is chosen to be seven periods to ensure large enough reflection for TE polarization.

By using two-dimensional BPM, we obtain the beat lengths for TE and TM polarizations $L_{TE} = 44.85 \ \mu m$ and $L_{TM} = 48.25 \ \mu m$, respectively. Thus we obtain the lengths $L_{TE} = 48.25 \ \mu m$, $L_{TM} = 22.4 \ \mu m$ from formulas $L_{TE} = L_{TM}^{TM}$ and $L_{TM} = L_{TE}^{TE}/2$.

From FDTD simulation, we find that there is inevitable reflected power for TM polarization beam and consequently the extinction ratio for the TM polarization is degraded. We introduce a PhC structure consisting of hexagonal lattice of rods (with radius $r=0.375 \ a/\lambda$) at Port2 to prevent the undesirable power of the TM polarization (note that the internal PhC structure of the air hole type is for reflecting the TE polarization).

Finally, we use a FDTD method to simulate the whole structure. The field distributions at the wavelength of 1.55 $\mu m$ are shown in Fig. 4.12 (a) and (b). From this figure one sees that the two polarizations are separated successfully. The insertion loss and the extinction ratio are: $IL=0.74$ dB and $ER=22$ dB for TM polarization, $IL=0.54$ dB and $ER=27$ dB for TE polarization.
Figure 4.12. FDTD simulated field distributions at $\lambda = 1.55 \ \mu m$ in the present PBS. (a) TE polarization; (b) TM polarization.

Figure 4.13. Normalized output powers from two output ports (Port2 and Port3) of the present PBS.

The wavelength response of the present PBS is shown in Fig. 4.13. Due to the anomalous dispersion of the PhC and the wavelength insensitive performance of the MMI coupler, our PBS can have a low insertion loss (<2 dB) and a low crosstalk extinction ratio (<-20 dB) over a large wavelength range of 1500-1600 nm for both polarizations.

References


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Chapter 5

Fabrication and Optical Characterization

This chapter deals with the experimental work done in the thesis and primarily focuses on fabrication of some InP-based photonic components/structures including photonic crystals.

5.1 Introduction

The fabrication technologies for PLCs are similar to those used in the manufacturing of micro-electronic circuits, particular for PLCs based on Si. This is one of the advantages which makes mass production of PLCs possible. Compared to conventional bulk optical components such as lenses, mirrors, and thin film filters, PLCs have the advantages of easy alignment, high stability, and low cost.

![Diagram of PLC fabrication processes](image)

Figure 5.1. The typical fabrication processes used in the manufacturing of PLCs.

Fig. 5.1 shows typical process steps in PLC fabrication. Below a brief description of these steps is given.

1. Film deposition: Growth or deposition thin films of desired materials is the first step in device fabrication. Different technologies are employed to get uniform, smooth, and defect-free films. For example, Plasma Enhanced Chemical Vapor Deposition (PECVD), Metal Organic Vapor Phase Epitaxy (MOVPE), and sol-gel are used for SiO_2 film, III-V materials, and polymers, respectively. In this thesis work, InP/InGaAsP/InP hetero-structure was grown by MOVPE.

2. Hard mask deposition: Different materials such as metals, SiN_x, SiO_2 are usually deposited as hard masks. Such hard masks are necessary when the selectivity between the resist and the etched material is low. However, the choice of the mask material depends on the process and the specification of the end application. In this thesis work, SiO_2 is chosen to be the hard mask since it has a good selectivity over InP for most of the dry etching processes.

3. Pattern generation: Optical lithography is carried out to transfer the designed structures of PLCs into a photo-resist. For the structures with lateral dimension below half a micron, the resolution of the conventional I-Line (365nm) steppers is not sufficient. New lithography technologies including deep ultra-violet (DUV) lithography, nano-imprint lithography (NIL),
electron beam lithography (EBL) are utilized to define the high resolution patterns for PLC devices. EBL was mainly used in this work, owing to its flexibility.

(4) Pattern transfer: By using resist as the mask, the pattern defined by lithography can be transferred to the hard mask through a dry etching step appropriate to the mask material. For example, in this work, the SiO$_2$ mask was etched using fluorine reactive ion etching (RIE).

(5) Etching: A highly anisotropic etch process is needed for etching of the pattern into the target films. Plasma based dry etching is commonly used for this step. Several different techniques are available and a variety of chemistries have been developed for etching different materials. Inductively coupled plasma reactive ion etching (ICP-RIE), and chemically assisted ion beam etching (CAIBE) were used in this work to etch InP-based materials.

(6) Mask removal: The hard mask is usually removed after etching process by an appropriate wet chemistry.

After the above steps, the fabricated samples still need to be cleaved and mounted before optical characterization. For more complex devices, it is common to have multiple pattern generation and transfer. In such a case, the flow shown in Fig. 5.1 has to be repeated and alignment of patterns is often an important aspect. Additional steps such as deposition of metal contacts, annealing etc are also required for electrically driven devices.

Fig. 5.2 schematically illustrates basic procedures used in this thesis for fabricating photonic crystals in InP based materials and involves the different steps discussed above.

![Figure 5.2. The basic procedures for fabricating two dimensional photonic crystals in InP-based slab waveguide structures.](image)

### 5.2 Electron Beam Lithography

The process of defining PLC patterns on the substrate of interest is known as lithography. The requirement for the resolution of the lithography process increases dramatically for densely integrated PLCs and for components having nano-scale features. The latter could be nano-components or those which are composed of nano-structures/nano structured materials.
Single mode waveguides exhibit lateral dimensions of a few to several hundred nm and the diameter for photonic crystal holes (rods) are even smaller, approximately 100-300 nm, depending on the wavelength etc. The conventional optical lithography can’t be used due to the limitation on the resolution. Innovative techniques such as deep ultraviolet lithography [1], nano imprint lithography (NIL) [2], and focused ion beam (FIB) patterning [3] are under development. However, for lateral structuring below the resolution limit of photolithography (< 200 nm), electron beam lithography (EBL) [4-6] is by far the most widely spread lithography tool. Compared to other nano structuring methods, it combines high resolution with excellent flexibility and reasonable patterning speed. Besides, there is no strict restriction on the substrate size. A major drawback of EBL is the low throughput due to the serial exposure; however, its other advantages make it an excellent research tool.

Fig. 5.3 shows a schematic diagram of a typical EBL system. The EBL system usually consists of the following parts: (1) an electron gun that supplies the electrons; (2) an electron column that focuses the electron beam; (3) a mechanical stage that positions the wafer; and (4) control unit.

The electrons are generated by the electron gun and accelerated to the desired energy typically ranging from 1keV to 100 keV. A beam blanker is located below the gun to blank the beam. The electrons then pass through a series of condenser lens combined with an objective lens and finally are focused on the sample. There exist a large amount of aberrations due to the imperfection of these condenser lenses. Circular apertures with different sizes are used to enhance the convergence of the electrons. The diameter of the focused beam decreases with the aperture size, however, the current in the e-beam also decreases which results in a longer exposure time. The writing progresses in a serial mode which is controlled by the pattern generator. The pattern generator controls the beam blanker and the deflection unit to generate the desired patterns.
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![Figure 5.4. The typical flow of process steps in EBL.](image)

The EBL generally consists of the following process steps (Fig. 5.4):
1. A layer of resist can be formed by spin-coating. The thickness of the resist is controlled by the speed of spin-coating and the viscosity of the resist;
2. Soft-bake is processed to drive out the solvent and consolidate the resist film;
3. The resist film is exposed in the desired regions by electron beam scanning;
4. The wafer is then treated in a developer and unwanted areas of the resist layer are removed;
5. Hard baking of the resist and O$_2$ plasma ashing just before etching.

The EBL system used in this work is a Raith Turnkey 150 system (Nanofabrication laboratory, KTH). The main process parameters are listed in Table 5.1.

Table 5.1 EBL process parameters/materials used in this thesis.

<table>
<thead>
<tr>
<th>Resist</th>
<th>ZEP520A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Coating</td>
<td>4000 rpm (thickness ~370 nm)</td>
</tr>
<tr>
<td>Soft bake</td>
<td>180°C 10 min on hotplate</td>
</tr>
<tr>
<td>Gun Voltage</td>
<td>25kV (Maximum for our system)</td>
</tr>
<tr>
<td>Dose</td>
<td>47 μC/cm$^2$ (waveguide), 52 μC/cm$^2$ (PC)</td>
</tr>
<tr>
<td>Development</td>
<td>4 min Pxylol, 2 min Isopropanol</td>
</tr>
</tbody>
</table>

The resolution of EBL is often constrained by the resist. The Ebeam resist can be categorized into two types, positive resists and negative resists. For positive resists, the exposed areas are removed by development while the un-exposed areas are removed for negative resists (Fig. 5.5). ZEP520A, a high resolution positive resist, is used in this thesis work.
Different apertures (ranging from 7.5 μm to 120 μm) are available in this system. As we know, the smaller the aperture size the higher is the resolution. But the beam current is also reduced when reducing the aperture size resulting in long exposure times. For our device structures, there are usually long input/output waveguides which do not require high resolution and also PhCs where high resolution is necessary. Thus, we divide the whole device structures into two parts. PhCs are first exposed with a small aperture (7.5 μm) and width of the step size 6 nm. The second step is the exposure of the access waveguides with a larger aperture (30 μm) at a larger step size (about 20 nm). Fig. 5.6 shows the PhC devices fabricated by EBL. It is found experimentally that higher exposure efficiency is achieved with an acceptable resolution.

5.3 Dry etching

In order to transfer the pattern into the desired film/substrate, it is necessary to etch the films or the substrate. There are two classes of etching processes: (1) wet etching where the material is dissolved in a chemical solution. Even through simple, wet etching is isotropic and is not desirable
for PLC fabrication; (2) Dry etching which can provide anisotropic etching. It is an enabling technology that could not only provide vertical sidewalls in the etched substrates but also different profiles can be generated. Dry etching may be accomplished through physical removal of the material by ion sputtering or through chemical reactions using chemically reactive gases. Most often a combination of both physical sputtering and chemical reactions are used.

The dry etching techniques involved in this thesis include reactive ion etching (RIE) [7], inductively coupled plasma RIE (ICP-RIE) [8], and chemically assisted ion beam etching (CAIBE) [9]. Fluorine based RIE was used for the etching of the SiO₂ hard mask; ICP-RIE processes were investigated and developed for ridge waveguides and directional couplers; Ar/Cl₂ CAIBE process with sample heating particularly suitable for deep etching was used for photonic crystal. In this case, we use an already established process. Here the emphasis was on the development of damage and its implications on PhC material properties.

5.3.1 Reactive Ion Etching

RIE is a widely used dry etching technique which is a process that involves both physical sputtering and chemical reaction. A typical RIE system consists of a vacuum chamber with a wafer platter (Fig. 5.7). A strong RF (radio frequency) power source is applied to the wafer platter which is isolated from the rest of the chamber. The RF source is usually at 13.56 MHz and the power is typically a hundred to a few hundreds watts. Several gases enter into the chamber through the inlets at the top of the chamber. Plasma is generated in the gas mixture by applying the RF power source. A negative voltage will develop on the wafer platter which is charged by some of the electrons reaching the platter. On the other hand, the plasma ions themselves develop a positive potential due to the higher concentration of positive ions compared to free electrons. The positive plasma ions will be accelerated toward the wafer platter due to the large voltage difference. The energetic ions bombard the surface of the sample, and at the same time the reactive species react with the material, forming compounds which can be desorbed.

Figure 5.7. Schematic of a reactive ion etching system.
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In general, the chemical part is usually isotropic and will result in undesired over-etching, sometimes in non-vertical sidewalls. In such cases, most commonly fabrication of a chemically passivating layer during etching is employed. This is also applicable in other etching methods. This technology is the so-called “Bosch process”. A passivation gas is added in the etching chemistry to create a protective coating on the surface of the sidewall. Deep etching with vertical sidewalls could be achieved by using such processes.

The effective transfer of very small features into semiconductor films is very important for device fabrication. The EBL resist ZEP520A which we used in this work has poor selectivity while etching the semiconductor and limits the achievable etch depths. Thus, a two-step etching process with an intermediate hard-mask is employed in this work. A CHF$_3$ based RIE etching process was chosen for etching the SiO$_2$ hard mask. The machine used to perform the RIE is an Oxford Plasmalab80 system. The operation parameters are: the flow of CHF$_3$ = 25 sccm, plasma power = 100 W, and chamber pressure = 15 mT. A 260 nm thick SiO$_2$ hard-mask is patterned successfully almost without any undercut and erosion.

5.3.2 Inductively Coupled Plasma-Reactive Ion Etching

For the RIE system, there is a drawback that the density and energy of the ions are provided by the same power source, and can not be controlled independently. Further, the ion densities are also low and the process pressures high. The more sophisticated inductively coupled plasma reactive ion etching system (ICP-RIE) (Fig. 5.8) is employed to overcome these drawbacks. Two independent RF power sources are introduced to independently control the plasma density and the ion energy. Energy is coupled inductively into the plasma by a coil around the chamber. The ICP source produces a high density of ions/reactive species at relatively low pressures.

The different masses of the charge carriers (electrons and positive ions) cause a depletion of electrons close to the sidewalls of the plasma chamber, resulting in an electric field (DC-bias) between the plasma and the chamber wall. Through this field, electrically charged positive ions are accelerated. Vertical etching can be achieved since the ions hit the sample at almost normal incidence. The energetic ions can etch the underlying material chemically by forming volatile etch products and physically remove the atoms by sputtering. The latter part is also contributed by chemically inert ions, if present in the chemistry.
Different chlorine based chemistries have been used for InP etching. For the etching of InP with pure Cl\(_2\), the surface tends to be very rough due to the formation of InCl\(_x\) clusters which is non-volatile at temperatures below 150°C. High energy sputtering has been used to enhance the desorption rate of InCl\(_x\). Another effect of this is heating of the sample which also helps in desorption of InCl\(_x\). The sample is usually mounted on a Si carrier which provides some thermal isolation and it is also thought that Si from the carrier gets re-deposited on the sidewalls, providing a passivation effect [10]. However, high energy ion bombardment will cause damage and surface roughness. For better performance, it is thus better to provide separate sample heating thereby the ion energy can be reduced. Inert gases are used to dilute Cl\(_2\) and reduce the neutral radical density of Cl\(_2\). This also helps in reducing roughness. Different gas mixtures such as Cl\(_2\)/N\(_2\) [11], Cl\(_2\)/H\(_2\) [12], Cl\(_2\)/Ar [13], Cl\(_2\)/CH\(_4\)/H\(_2\) [14], and Cl\(_2\)/O\(_2\) [15] have been demonstrated for InP etching. Among them, Cl\(_2\)/CH\(_4\)/H\(_2\) is preferred since it provides smooth surfaces and vertical sidewalls.

In this work, the ICP-RIE experiments were performed in an Oxford Plasmalab System 100 module with RF generators operating at 13.56MHz. This process module has been designed for high gas flows at low pressure, producing high density plasmas for etching and delivers ions/reactive species to the substrate efficiently with a uniform high conductance path from the gas injection point at the top of the source. In ICP process, the etching and passivation occurs simultaneously. The etching and passivating gases are Cl\(_2\) and CH\(_4\), respectively. During the etch cycle, Cl\(_2\) gas supplies chlorine radicals, which etch InP isotropically. Passivation effect helps to reduce the sidewall surface roughness and lateral etching. The verticality is ensured by the thin polymer film deposited on the etched sidewalls to prevent the lateral etching. The sidewall roughness, etching depth, and the shape of the sidewall are dependent on the process parameters such as ICP power, RF power, pressure, and chemical composition of the gases. InP etching was performed with different process parameters in this work to find an optimized process condition which provides a reasonably smooth surface and vertical sidewalls. A comparison of recipes is shown in Table 5.2 and on Fig. 5.9. The purpose of this study was not to make a detailed...
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investigation of the etch processes, and quantify the roughness, profiles etc; but rather to find a process with reasonable properties suitable to fabricate some devices demonstrators. (Paper VIII)

We find that Recipe I gives the best results (smooth surfaces and vertical sidewalls). If we decrease the ICP power (Recipe II), the surface roughness increases and the etch rate reduces. This due to reduced density of reactive species and also due to reduced heating. For Recipe III, the physical sputtering decreases with the lower RF power. Here also the bottom roughness is present. However, the sidewall roughness could be comparable with Recipe I, but due to the lower RF power the etch rate is lower.

Table 5.2. ICP process parameters for InP etching. For all the processes, chamber pressure=4mT and etching time=2 min.

<table>
<thead>
<tr>
<th>Recipe</th>
<th>Etching Rate</th>
<th>Selectivity</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Cl₂/CH₄/H₂ (sccm) 9/7.5/5.5 ICP/RF power: 2000W /175W</td>
<td>900 nm/min</td>
<td>10:1</td>
<td>low</td>
</tr>
<tr>
<td>II. Cl₂/CH₄/H₂ (sccm) 9/7.5/5.5 ICP/RF power: 1000W /175W</td>
<td>300 nm/min</td>
<td>12:1</td>
<td>high</td>
</tr>
<tr>
<td>III. Cl₂/CH₄/H₂ (sccm) 9/7.5/5.5 ICP/RF power: 2000W /100W</td>
<td>750 nm/min</td>
<td>10:1</td>
<td>Moderate</td>
</tr>
<tr>
<td>IV. Cl₂/CH₄/H₂ (sccm) 7/15/15 ICP/RF power: 2000W /175W</td>
<td>500 nm/min</td>
<td>7.5:1</td>
<td>very high</td>
</tr>
</tbody>
</table>

Figure 5.9. SEM pictures of the mesas etched with different recipes. Results obtained from Recipe I, II, III, IV, are shown in (a), (b), (c), (d), respectively.
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Figure 5.10. SEM pictures for the etched waveguide and PhC with the optimized recipe: (a) 1.5 μm wide waveguide (b) PhC with hole radius 200 nm.

With the optimized recipes (Recipe I), both waveguide and PhC structures are etched. SEM pictures of the cross-sections are shown in Fig. 5.10. The waveguide is etched with highly vertical sidewall and smooth surface. For the PhC structure, the hole shape is somewhat conical and the holes are not deep enough (~1 μm). The hole profile, at least in the top 500 nm requires further optimization. Concerning this as well as the hole depth, the sample can be separately heated and deep etching can be achieved. The deeply etched PhCs etched by using Ar/Cl₂ CAIBE is discussed in the next section. However, the PhC etched by ICP is still valid for etching PhCs membrane type structures.

Lag effect describes the common phenomenon in dry etching process that the etching rate for the smaller trenches (or smaller holes) is slower than that for the larger trenches (or larger holes). The lag effect will cause etching non-uniformity and make the end point control difficult. For most of the applications, the etching conditions should be optimized to minimize the lag effect. In our ICP etching experiments, we also observe a strong lag effect when the gap is very small (~100 nm). We utilize the lag effect positively to reduce the number of process steps in the fabrication of certain type of devices.

A SEM picture of the etched trenches with different widths is shown on Fig. 5.11. The measured etch profile of the trenches as a function of width is shown in Fig. 5.12. The depth is normalized to the etch depth of a 5 μm wide trench. The results show that the ICP etching is a strongly feature size dependent process.

Figure 5.11. A SEM picture of etched trenches with different width by using ICP.
5.3.3 Chemically Assisted Ion Beam Etching

Ion beam etching provides additional control of the etching process by decoupling the ion current from the plasma bias and pressure. Thus ion energy and density can be varied independently together with a possibility to change the angle of incidence and the operating pressures are also low. In Chemically Assisted Ion Beam Etching (CAIBE), the kinetic and chemical etching are separated which enables a stronger degree of control of the sidewall profile.

Fig. 5.13 depicts the basic working principle of the CAIBE system. Ar plasma is generated by coupling RF power via a dielectric window through a coil. The ion flux is determined by the ion density within the plasma established by the RF power. The ion beam energies used in CAIBE process are usually below 1keV with 200 to 600 eV used most often to achieve high quality etching profiles, small etching induced damage, and an acceptable etching rate. The beam energy and current can be controlled independently over a wide range of operating conditions. The collimation of the beam is achieved by a diaphragm together with an electron gun placed in the chamber. The electrons neutralize the positively charged beam, reducing the divergence. The energetic ions bombard the sample surface; at the same time a reactive gas injected over the sample provides the chemical etching.
Thus physically assisted chemical etching is the operational principle of CAIBE. In the absence of the reactive gas, CAIBE reverts to the familiar ion-sputtering or milling process.

The CAIBE system used in the thesis work is a Nordiko 3000 ion beam etching system consisting of a high vacuum chamber and a two-grid ion gun. Chlorine based chemistry was used in this work. Cl\(_2\) was introduced into the chamber via a perforated ring surrounding the sample and Ar is in the plasma. Cl\(_2\) will react with indium on the surface of the sample and form InCl\(_x\) compounds. As we mentioned before, InCl\(_x\) is non-violate at room temperature. Thus, a halogen lamp was introduced into the chamber to radiatively heat the sample. A process temperature above 225°C results in good desorption of the InCl\(_x\) compounds. At the same time, phosphorous is preferentially removed by argon sputtering. Thus, both the process temperature, the gas composition, and the Ar\(^+\) ion density should be optimized to obtain a high quality etching. Process parameters are shown in Table 5.3. In this work, we used the already established process for etching InP-based PhCs [9].

Table 5.3. Typical process parameters for Ar/Cl\(_2\) CAIBE system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl(_2) gas flow</td>
<td>&lt;1.5 sccm</td>
</tr>
<tr>
<td>Ar gas flow</td>
<td>1-5 sccm</td>
</tr>
<tr>
<td>Positive grid voltage V(_+)</td>
<td>400 V</td>
</tr>
<tr>
<td>Negative grid voltage V(_-)</td>
<td>-100 V</td>
</tr>
<tr>
<td>Process Pressure</td>
<td>1-3×10(^{-4}) Torr</td>
</tr>
<tr>
<td>Temperature</td>
<td>250-280 °C</td>
</tr>
<tr>
<td>RF power</td>
<td>25-80 W</td>
</tr>
<tr>
<td>RF frequency</td>
<td>13.56GHz</td>
</tr>
</tbody>
</table>
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Figure 5.14. Photonic crystal etched in InP/InGaAsP/InP using Ar/Cl\textsubscript{2} CAIBE. (a) Top view; (b) Cut view.

Fig. 5.14 shows the PhC structure etched by Ar/Cl\textsubscript{2} CAIBE. From the cross section, we could find the achievable etching depth is as deep as 5 μm. The top section of the hole is nearly cylindrical, while the bottom part is conical.

5.4 Optical Characterization Methods

5.4.1 End-Fire Method

To characterize PLC devices, the end-fire method is commonly used. The main idea behind this characterization method is to couple externally-generated light into one facet of the device under test (DUT) and to measure the transmitted power at the output of the DUT. No active material for on-chip light generation is required but the interpretation of the spectra is complicated by the multiple reflections at the cleaved facets giving rise to Fabry-Perot patterns.

The sketch of the end-fire measurement setup used in this work is shown in Fig. 5.15(a). External light is provided by an amplified spontaneous emission (ASE) source covering a broadband wavelength range from 1530 nm to 1610 nm. This unpolarized light is coupled into the cleaved facet of the input waveguide through a focusing gradient index (GRIN) lens. After propagation through the DUT, the PLC device, light is collected by a microscope objective and split into two beams, one to an infrared (IR) camera and the other to an optical spectrum analyzer (OSA) through a multimode or a single mode fiber. Polarizers are inserted after the beam splitter to collect the desired polarized light. The transmission spectrum is measured by OSA. The DUT is mounted on a motorized stage for optical alignment and to improve reproducibility in the measurement. With the IR camera, the alignment is made easier. Fig. 5.16 shows the IR camera captured images from the straight ridge waveguide and the W3 PhC waveguide (i.e., a three row missing line defect waveguide), respectively.
A single ridge waveguide with the same length as the DUT is usually fabricated on the same sample. It can be taken as a reference to deduce the absolute transmission of the DUT. By subtracting the transmission through the reference waveguide from the measured spectrum through the DUT, we can simultaneously obtain the losses and the spectral properties while excluding the coupling losses at the facets.

Figure 5.16. Images captured by the IR camera from the output of (a) a straight waveguide; (b) a W3 PhC waveguide.
5.4.2 Time-resolved Photoluminescence Measurement Setup

Photoluminescence and time-resolved photoluminescence are some of the established methods employed to analyze the surface recombination velocity of optoelectronic materials. A photoluminescence measurement setup is used to get the photoluminescence spectrum of the PhCs. The excitation laser for PL is CW, so the rate of excitation equals the rate of recombination, and the photo-generated carrier density is constant in time. To investigate the pico-second dynamics of the generated carriers within PhCs, a laser pulse much shorter than the average recombination time is needed. In this thesis, picosecond response time-resolved photoluminescence setup is used to investigate the carrier lifetimes of dry-etched InP-based photonic crystals (Papers IX and X). For this study, we used a InGaAsP quantum well (QW) emitting at 1120 nm in the slab structure into which the PhC was patterned. Thus PL of the QW and its decay can be used as a sensitive monitor for the process induced modification of the material. Time-resolved PL measurement setup shown in Fig. 5.17 can be used to determine carrier lifetimes, and to identify and characterize various recombination mechanisms in the material. A tunable mode-locked Ti:sapphire laser (pulse length 100 fs, repetition rate 76 MHz, wavelength 790 nm) was used for excitation. Carrier lifetime measurements were performed by detecting the photoluminescence signal with a synchroscan streak camera combined with a 0.25 m spectrometer, providing a temporal resolution of 5 ps.

![Diagram of time-resolved PL measurement setup](image)

Figure 5.17. Schematic of the time-resolved PL measurement setup.

Fig. 5.18 shows a representative PL decay curve obtained from an etched PhC field. By using a mono-exponential decay: 
$$y(t) = A_0 \cdot \exp(-t / \tau)$$, we find that the measured data is well fitted which suggests that either a single dominating defect level or a distribution of defect states behaving like a single level. From this fitting, we could extract the decay time $\tau$. 

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Figure 5.18. A representative PL decay curve (gray) obtained from an etched PhC field. The solid smooth line shows the exponential fit to the measured data.

5.5 Ultra-compact Directional Couplers Realized in InP

We observed strong lag effect when we etched the InP structures with ICP-RIE system. From the analysis in section 5.3.2, we found that the etching depth for the 5 μm-wide trench is almost twice that for the 100 nm-wide trench. This phenomenon is incompatible with most of the device design requirements. But for a directional coupler, the wide trenches could be utilized for the waveguide bending part which requires deep etching while the 100 nm-wide trench groove is good for the coupling region which benefits from shallow etching (Paper VIII). The coupling lengths $L_c$ for directional couplers with different etching depths of the grooves are obtained by

$$L_c = \frac{\pi}{(\beta_e - \beta_o)}$$

where $\beta_e$ and $\beta_o$ are propagation constant of even and odd mode, respectively.

Here, $\beta_e$ and $\beta_o$ are calculated by using finite difference (FD) method. In all the simulations, the groove width is 120 nm wide. Fig. 5.19 (a) and (b) show the calculated mode profiles for the fully etched and shallowly etched grooves in directional coupler, respectively. The power is much easily transferred from one waveguide to the other for the shallowly etched directional coupler. $L_c$ is only 64 μm when the etching depth for the groove is 1 μm (which corresponding to the case when lag effect exists) while $L_c$ is 1620 μm for the fully etched one (the depth of the groove is equal to the mesa height or the outer trench depth).
We fabricated directional couplers with different coupling region lengths (10 μm – 70 μm). Fig. 5.20 (a) shows the SEM picture for one of the fabricated directional couplers with a length of 50 μm. S-bend waveguides were connected to both the input and output ports in order to increase the distances between the input/output waveguides. From the cross section (Fig. 5.20 (c)), we find that the waveguides are etched to 2.2 μm to ensure that the bending loss could be neglected. Due to the ICP lag, the etching depth for the 120 nm wide groove is only 1.05 μm.
Finally, the end-fire method was used to characterize the fabricated directional couplers. The output powers from both bar-port and cross-port for DCs with different coupling region length $L$ were measured. The measured transmission power was normalized for each measurement to $P_{\text{bar/cross,norm}} = P_{\text{bar/cross}} / (P_{\text{bar}} + P_{\text{cross}})$. With such normalization, the measurement results are independent of the incoupling efficiency and the waveguide loss. Fig. 5.21 shows the measured normalized transmitted power for both bar-port (square) and cross-port (circle).

The measured transmission power varies with the length of the coupling region and by fitting the curve with the function $\cos^2(\pi / 2 \cdot L / L_c)$ and $\sin^2(\pi / 2 \cdot L / L_c)$, the coupling length $L_c$ can be obtained. Here the cosine and sine functions represent the power intensity in the bar-port and cross-port as a function of the coupling region length $L$, respectively. A coupling length of about 55 µm was extracted from the fitting from Fig. 5.21. The value is a little bit smaller than what we obtained from the simulation (64 µm). This is reasonable since the conical shape of the coupling region (see Fig. 5.20 (c)) makes the power transfer much easier.
5.6 Carrier Lifetime in CAIBE Etched Photonic Crystals

5.6.1 Carrier Lifetime in Photonic Crystals

InP-based materials are potential candidates for active components at the operating wavelengths from 1.2 to 1.7 μm. Various active functionality such as lasing [16], switching [17], and tuning [18] are investigated by using InP-based PhCs. Carrier lifetime is one of the most important parameters which will influence the performances of these active functionalities. This is the object of Papers IX and X and the obtained results are briefly discussed below. The requirements on the carrier lifetime are very different depending on applications. For ultra-fast switching applications, carrier lifetimes should be in the ps range which is much faster than the ns range typical in bulk InP layers. For lasing applications, carriers lifetimes should be very long (~ ns) since the PhC laser performance is limited by the nonradiative surface recombination in the quantum well regions.

The carrier lifetime can be affected by the fabrication processes. It is therefore crucial to investigate the impact of the PhC fabrication on the carrier lifetime in InP-based materials. Dry etching is a widely used tool in PhC fabrication due to its high anisotropy, the availability of selective etches, and precise control. Many works have been done to investigate the defects and damages introduced by dry etching [19-21]. Previous works indicate that defects that reduce carrier lifetimes mainly come from the dry etching process [21]. However, very few works address this issue in PhC fabrication.

5.6.2 Pattern Design and Fabrication

The sample used in this work was grown by MOVPE on an InP substrate. The vertical structure is shown in Fig. 5.22 (b) where a 10nm InGaAsP quantum well is embedded in a 500nm thick
undoped InP layer. The PhC fields are triangular lattices of air holes with period $a$ varying from 290 nm to 520 nm and the radius $r$ from 80 nm to 130 nm (air filling factor from 15% to 40%). The PhC fields are fabricated with a size of $30 \times 30$ $\mu$m$^2$ to ensure an easy focusing on the PhC fields. The PhCs were etched by using Ar/Cl$_2$-based CAIBE. The gas flow for Ar and Cl$_2$ are 6 sccm and 1 sccm, respectively. The chamber pressure during etching was $2.5 \times 10^{-4}$ Torr. The sample was heated to temperature 250 °C using a halogen lamp. The etch rate under the present condition is around 100 nm/min. The InP layer above the 10nm thick InGaAsP quantum well is about 250 nm so three minutes etching is needed to etch through the quantum well. To investigate the influence of the dry etching process on the carrier lifetimes, the PhCs are etched with different etching times, ranging from 3 min to 50 min.

![Etched Trench](image)

Figure 5.22. Schematic of the designed PhC structure. (a) Top view; (b) Cross Section; (c) Variation of etch depth with etch time for the PhC with $a=520$ nm and $d=210$ nm.
5.6.3 Results and Discussion

![Diagram](image)

Figure 5.23. (a) The definition of the sidewall area density; (b) Inverse carrier lifetime varies with the sidewall area density.

To quantify the relationship between the overall PhC fields and the carrier lifetime, we use a parameter called side wall area density $S/A$ which is defined as the ratio of the etched sidewall area to the total sampling volume:

$$\frac{S}{A} = \frac{\pi d}{\frac{\sqrt{3}}{2} a^2 - \frac{\pi}{4} d^2} \quad (5-1)$$

We measured the carrier lifetime for all the fabricated PhC fields with different periods and radius and the decay time was extracted from the measurement curve for each of them. Inverse carrier lifetime is shown in Fig. 5.23(b) as a function of the side wall area density. The evolution of the reverse carrier lifetime with side wall area density is well fitted with a linear relation:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + v_s \cdot \frac{S}{A} \quad (5-2)$$

where $\tau_0$ is the carrier lifetime of the un-etched area and $v_s$ is the surface recombination velocity.

From the slope of the measured data sets, we could extract the surface recombination velocity for the PhC fields with different etch time. Fig. 5.24 shows the evolution of $v_s$ as function of etch time. From the shape of the curve, we find that the accumulation of the dry-etching induced damage is not linear. From Fig. 5.25, we find that the exposed sidewall of the QW can be subjected to bombardment of both the incoming ions and the scattered energetic ions or ejected species from the lower portions of the etched holes. Since the increase of the surface recombination velocity is not linear, the bombardment on the sidewalls due to the divergent ions from the incident beam is not the main contribution. Thus, the scattered energetic ions contribute to most of the damage. It is known that the sputtered species are ejected from the surface following a cosine distribution with the maximum probability along the direction of specular reflection. Therefore, the probability that the ejected species reach the QW region will also reduce.
for sufficient etch-depths, in particular if one considers the conical shape of the bottom positions of the holes. A more detailed discussion is given in Paper X.

![Figure 5.24. Evolution of the surface recombination velocity as a function of etch time.](image)

Figure 5.24. Evolution of the surface recombination velocity as a function of etch time.

![Figure 5.25. Schematic sketch of an etched hole with conical bottom shape, showing the incident ion and some possible directions of the scattered ion and ejected species.](image)

Figure 5.25. Schematic sketch of an etched hole with conical bottom shape, showing the incident ion and some possible directions of the scattered ion and ejected species.

References


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Chapter 6

Guide to the Papers

Paper I. Improved performance of a silicon-on-insulator-based multimode interference coupler by using taper structures
In this work, high order modes in the vertical direction of a MMI coupler are analyzed. The vertical high order modes of an SOI-based MMI device degrade the self-imaging quality dramatically. Taper structures are introduced at the junction between the input/output waveguides and the multimode region to suppress the excitation of the undesired vertical modes. Low insertion loss and small non-uniformity are achieved for a 1×4 MMI coupler with taper structures. For the optimal design, the loss and the non-uniformity are 0.101 and 0.102 dB, respectively, which are only 8% and 18.5% of those for the conventional design without tapers.

Contribution of the author: Device design, numerical simulations, and major part of writing.

Paper II. Deeply-etched SiO$_2$ ridge waveguide for sharp bends
In this paper, we investigate the deeply-etched SiO$_2$ ridge waveguides and discuss the advantages over conventional SiO$_2$ buried waveguides. It is shown that, on one hand, deeply etched SiO$_2$ ridge waveguides allow a much smaller bending radius due to the strong confinement by the air-SiO$_2$ interface in the lateral direction. On the other hand, the refractive index contrast is small (<1.5%), resulting in a weak confinement of the optical mode in the vertical direction which introduces a large modal field and thus the coupling loss to a singlemode fiber can be small.

Contribution of the author: Participation in the device design, simulation and analysis.

Paper III. Design of a compact multimode interference coupler based on deeply-etched SiO$_2$ ridge waveguides
In this paper, a compact multimode interference (MMI) coupler is proposed which uses deeply-etched SiO$_2$ ridge waveguides. The strong confinement in the lateral direction of the deeply-etched SiO$_2$ ridge waveguides substantially improves the quality of the self-images in the MMI section. By using the three dimensional beam propagation method, a 1×4 MMI power splitter is designed as a numerical example. Good performances such as a low insertion loss, small non-uniformity are achieved for the 1×4 MMI power splitter and the total device size of the present MMI power splitter is reduced to about 1/16 of that based on SiO$_2$ buried waveguides.

Contribution of the author: Participation in formulating the concept, design and numerical simulations.
Paper VI. A polarization insensitive 1310/1550nm demultiplexer based on sandwiched multimode interference waveguides

In this paper, we demonstrate the design of a polarization insensitive 1310/1550 nm demultiplexer based on sandwiched multimode interference waveguides. Firstly, polarization insensitive multimode waveguides are achieved by choosing a suitable refractive index of the SiN middle region. By adjusting the width and length of the multimode region, the wavelengths of 1310 nm and 1550 nm are separated successfully. Three-dimensional beam propagation method is used to simulate the whole structure. A low insertion loss and a broad bandwidth can be achieved at 1310 and 1550nm bands for both polarizations simultaneously. The total size of the device is about 360 μm × 10 μm, which is much smaller than some conventional demultiplexers such as arrayed waveguide gratings.

Contribution of the author: Device design, numerical simulations, and major part of writing.

Paper V. Novel ultracompact triplexer based on photonic crystal waveguides

In this paper, an ultracompact triplexer is presented by cascading two stages of photonic crystal waveguide (PCW) based directional couplers. The device was designed to function as a triplexer for 1310, 1490, and 1550 nm wavelengths, relevant for fiber-to-the-home applications. The special decoupling property of the PCW based directional coupler is utilized for the design. A taper coupling region and an additional directional coupler are introduced to achieve high extinction ratios and reduce the crosstalk, respectively. The total size of the present triplexer is only 50μm×20μm, and the good performance is verified with FDTD simulations.

Contribution of the author: Device design, numerical simulations, and major part of writing.

Paper VI. Design of a polarization insensitive triplexer using directional couplers based on sub-micron silicon rib waveguides

In this paper, we proposed a polarization insensitive triplexer by using directional couplers (DCs) based on sub-micron silicon rib waveguides. The DCs are designed to be polarization insensitive by carefully choosing the geometrical parameters. Three wavelengths are separated to different output ports by cascading DCs. Two cascaded DCs separate the three wavelengths 1310, 1490, and 1550 nm and an additional DC is added to reduce the crosstalk. The total length of the present triplexer is only 400 μm, and simulation with three-dimensional beam propagation method shows good performances for both polarizations.

Contribution of the author: Device design, numerical simulations, and major part of writing.

Paper VII. Proposal for an ultra-compact polarization beam splitter based on a photonic crystal-assisted multimode interference coupler

In this work, a novel polarization beam splitter (PBS) is realized by combining a MMI coupler and a photonic crystal (PhC). The PhC structure is introduced in the multimode section of the MMI coupler working as a polarization sensitive reflector. The PhC was designed to have a bandgap
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only for the TE polarization. Thus, TE polarization is reflected and TM polarization transmits through the PhC structure. The size of the proposed PBS is rather small since the length of the MMI region is no longer necessary to be integral multiples of the coupling lengths for both polarizations. The designed PBS have a low insertion loss (<2 dB) and a high extinction ratio (<-20dB) over a large wavelength range of 1500-1600 nm for both polarizations. 

Contribution of the author: Device design, numerical simulations, and major part of writing.

Paper VIII. Ultracompact directional couplers realized in InP by utilizing feature size dependent etching

In this work, we investigate the lag effect in a ICP dry etching process and demonstrate how this effect can be positively used to realize ultracompact directional couplers. The lag effect is appreciable when the trench width is smaller than 300 nm. Ultracompact directional couplers were implemented experimentally by utilizing lag effect. Directional couplers with the coupling length as short as 50 μm were realized in a single etching step and a 1×2 power splitter is demonstrated. Importantly, the proposed method also reduces the number of processing steps typically necessary for such designs.

Contribution of the author: Fabrication, characterization, data analysis and writing.

Paper IX. Evidence for accumulated sidewall damage in dry etched photonic crystals

In this paper, we investigate the effect of etch duration on the carrier lifetime in PhC structures etched by Ar/Cl₂ chemically assisted ion beam etching on InP based material with an InGaAsP quantum well. The carriers in the quantum well are optically excited and we measure the photoluminescence decay time using a time resolved photodetection with streak camera. The results show an evidence of accumulated side-wall damage during the etching process. The carrier lifetimes could be tailored from several hundred to a few tens of ps depending on the device requirements.

Contribution of the author: Optical measurements, part of data analysis and writing.

Paper X. Development of damage and its impact on surface recombination velocities in dry-etched InP-based photonic crystals

In this paper, we investigate the material damage introduced by dry etching of InP-based photonic crystals. The carrier lifetime of the PhC structures with InGaAsP quantum well inside was measured by time resolved photoluminescence. A geometrical model based on sputtering theory and the modification of the hole shape was used to explain the accumulation of sidewall damage. The results show quite good agreement with the experimental data.

Contribution of the author: Optical measurements, part of data analysis and writing.
Chapter 7

Conclusion and Future Work

In summary, this thesis work focuses on investigations of new designs of and uses novel working principles in some selected photonic devices for optical communication applications based on PLC technology. The main objective has been to provide better performance and compactness compared to existing/conventional device designs. In particular, power splitters and demultiplexers based on multimode interference coupler; triplexers and polarization beam splitter (PBS) based on PhCs and directional couplers are investigated in this thesis.

Some numerical methods, including the FD, BPM and FDTD methods have been developed and utilized in the design and optimization of the PLC devices.

The basic principle and the analysis method for MMI couplers were discussed. By introducing taper structures at input/output waveguides to suppress the excitation of the high order modes, the performances of MMI couplers are improved dramatically. A deeply-etched SiO$_2$ waveguide structure was proposed which has a very small (~200$\mu$m) bending radius with an allowable bending loss. By using the deeply-etched SiO$_2$ waveguides, MMI couplers are realized with compact size and good performance compared to the one based on conventional SiO$_2$ waveguides.

Two dimensional photonic crystals which could be realized by using the PLC technology are good candidates for decreasing the size of integrated photonic components. In this work, an ultra-compact triplexer is demonstrated by cascading two photonic crystal directional couplers. The special property called decoupling is utilized in our design instead of finding a common multiple for coupling lengths. By tapering the coupling region, we could adjust coupling length continuously (instead of multiples of lattice period). By combining a multimode interference coupler and PhC structures, an ultra-compact PBS is presented. The MMI coupler is designed to collect polarized light reflected by and transmitted through an internal photonic crystal structure.

Finally, fabrication technology for PLCs was reviewed. In particular, techniques such as ebeam lithography, RIE, ICP-RIE and CAIBE are discussed and used to fabricate InP-based photonic devices, including photonic crystal structures. An important contribution was the demonstration of a InP-based compact directional coupler using the lag effect in ICP-RIE. This work shows that the lag effect can be used positively and dramatically reduces the number of process steps. The accumulated sidewall damage induced by dry etching and its influence on carrier lifetime in InP-based photonic crystals were investigated. The work provides evidence for accumulated sidewall damage and stresses the importance of process induced modification of the PhC material properties. An interesting finding was that the carrier lifetime can be modified from appreciably long lifetimes for emitter applications and down to a few tens of ps, relevant for switching applications.

As a general conclusion, PLCs are one of the most promising technologies for realizing optical components in communication systems, due to compactness, mass-producibility, high reliability and high design flexibility.
The future work includes:
1. Fabrication and demonstration of some of the designs proposed in this thesis, in particular the PhC based PBS, and polarization insensitive compact directional couplers. To this end, one must reduce the sidewall roughness and improve the fabrication accuracy.
2. Development of PLC devices by combining the conventional waveguides and photonic crystal waveguides. Conventional waveguide and PC waveguide have their own advantages, how to utilize their advantages maximally is clearly an important aspect that will be relevant for PLCs.
3. Hybrid integration: Different materials have their own properties and applications. By using bonding, we could integrate functional devices in one platform, e.g., InP based transceivers and Si based passive components. On the other hand, monolithic integration is also attractive if all the devices can be realized in the InP technology. This is challenging since it involves many different material combinations (InGaAsP etc), complex regrowth steps, etc, but it could be made simpler for specific applications using intelligent designs. For example, FTTH components have efficient designs it can bring the costs down.
4. Expansion of the application area of PLC based devices. Most of the works in this thesis focus on optical communication. PLC technology could also be implemented in other applications such as bio-sensing, imaging, illumination, etc. This is a major step since one has to investigate how the existing devices can be used for such applications and new devices/materials will have to be developed to address these areas.