POLARIZATION CROSS COUPLING IN ASYMMETRIC PHOTONIC WAVEGUIDES

A Thesis Presented

by

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Abstract

Planar photonic microstructures in optically thin silicon membranes are becoming increasingly favored in emerging optical signal processing and sensing technologies. Two-dimensional photonic crystals slabs (2-D PC slabs) are especially interesting due to their ability to confine and manipulate light on small scales by a combination of photonic bandgap and index guiding. Line-defects defined in the otherwise periodic lattices are served as waveguides, and point-defects are used as miniaturized optical resonators.

The traditional photonic devices on a broad photonic bandgap which exists in dielectric membranes only for the transverse electric (TE) polarized light, restricting their operation to that particular polarization. Thus, the capabilities of photonic circuits can be significantly enhanced if both polarization modes are utilized. While independent manipulation of TE- and TM-polarized light in photonic crystal membrane has been demonstrated, polarization mixing between different polarization states has not been thoroughly investigated. This thesis explores polarization cross coupling between the quasi-orthogonal modes triggered by structural asymmetries in the guiding and localization regimes. The criteria for coupling are established by parity arguments applied to the field overlap integral. Two basic device geometries representing the fundamental building blocks of many existing photonic circuits, viz. (i) a photonic crystal line-defect waveguide and (ii) a photonic crystal mode-edge cavity, are studied computationally and experimentally. Polarization cross coupling between the TE- and TM-like modes in photonic crystal membranes is utilized in the development and demonstration of novel narrow-band grating filters and vertical add-drop cavity filter.

Critical Word: Photonic Crystals, PWE, FDTD, Asymmetric Waveguide, Vertical Asymmetry, Horizontal Asymmetry, Cavity, Guided Mode, Mode Coupling, Anti-crossing, Filter
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Chapter 1 Introduction to Photonic Crystals

1.1 Background of Silicon Photonics

Silicon is a semiconductor that can be used to manipulate both electrons and photons. Electronic devices based on silicon technologies are used extensively in the electronic communication systems today and will continue to advance the industry for the time to come. However, as the data rate exceeds 1Gb/s, the electronic transmission range is currently limited to a distance around 100m [1], which has to be reduced further as the data rate increases. To overcome this limitation, optics has been introduced to the long distance and high speed communication. By switching the carrier signal from electrical to optical, photonic components have to be implemented for signal generation, processing and transmission. Figure 1 shows the trend of transition from electrical communication to optical communication [1]. The uncertainty in the transition timing is indicated as the extending Moore’s law, which is because of the constant improvement of electrical communication systems.

![Figure 1: Timeline for the transition trend from electrical to optical communications [1].](image)

Also, on chip scale, the tremendous achievements in SoCs(System-on-a-chip) have been driven by Moore’s law for decades, and now silicon chip has already been taken for granted for many years. Its performance gets continuously improved as technology scales down [2, 3], high speed, low power and low cost chips are already available for most commercial electronic products. However, the scaling down
technology today does meet its bottleneck as the interconnect performance worsens the performance of the chips. That is, the ever increasing interconnect resistance and parasitic capacitance are no longer negligible in high-speed deep sub micrometer VLSI: the time delay due to interconnect becomes comparable with the delay due to logic gates, severely influencing the signal integrity [4, 5]; and half of the dissipated power comes from the interconnect, putting tight power constraint on high speed circuit design [6-8]. It is believed that silicon photonics can provide an alternative to address these problems by replacing the traditional electrical interconnects with optical interconnects. The advantages of silicon photonics for these on-chip networks including (1) the maximum compatibility with existing CMOS technology; (2) compact design with minimum chip area; (3) high speed photonic integrated circuits [9-11].

Hence, building optical components for communications and on-chip applications is required to advance the silicon industry. Understanding the functionality of the optical devices and systems studying the behavior of guided light flow in photonic waveguides with line defects, the coupling between different modes, and the implementation techniques of these optical devices become demanded research topics, which is also the focus of this thesis.

1.2 Photonic Crystals

Photonic crystals (PCs) are periodic high-index-contrast structures that inhibit light propagation in the stop bands of frequencies. After Yablonovitch’s initial theoretical proposal [12], the first PhC with the face centered-cubic lattice was fabricated four years later, opening the new research frontier in integrated optics [13]. In the view of the dimension of the lattice periodicity, ideally, there are three types of photonic crystals. A one-dimensional photonic crystal (1-D PC) consists of alternating layers of material with dielectric constants as reported first in [14]. A two-dimensional photonic crystal (2-D PC) consists of a periodic lattice along two of its axes with infinite homogeneous extension in the third dimension. The photonic band gap of this structure was first calculated by Joannopoulos et al. through the band structure
calculation with plane wave expansion (PWE) [15]; then the first demonstration of the 2-D photonic crystals showing band gap at near infrared radiation (IR) range was reported [16]. By introducing index periodicity in all 3 dimensions, photonic crystals exhibiting a complete photonic band gap can be realized. Even though the existence of the photonic band gap in three dimensional photonic crystals (3-D PCs) was demonstrated as early as 1990 [17], The study of these structures has proceeded more slowly than their two-dimensional counterparts due to the fabrication challenge; and many researches in 3-D PCs are still focusing on the fabrication techniques [18-20].

![Figure 2: (a) 1-D multilayer film. (b) 2-D PCs. (c) 3-D structure.](image)

1.3 Photonic Band Gaps

Like the periodicity of the atomic potential in silicon that causes forbidden energy bands for electrons, the periodic variations of the refractive indexes in photonic crystals results in forbidden band for photons—a photonic band gap is thus created.

The material dispersion of silicon can be expressed as

$$\omega = k \cdot \frac{c_0}{n_{si}}$$  \hspace{1cm} (1.1)
In which $\omega$ is the angular frequency of light, $c_0$ is the light velocity in vacuum, $k$ is the propagation constant and $n_{si}$ is the refractive index of silicon. This equation indicates that in homogeneous silicon materials, there is no photonic band gap.

However, with the periodic refractive index perturbation like a 1-D grating, the energy band would split at the boundary and the photonic bandgap between the first two energy bands is approximately by Bragg condition [21]

$$\Delta \omega \approx \frac{\Delta \varepsilon}{\varepsilon} \cdot \frac{\sin(\pi d / a)}{\pi} \cdot \omega_m$$  \hspace{1cm} (1.2)

In which $\Delta \varepsilon$ and $\varepsilon$ represent dielectric constant and dielectric perturbation respectively; $d$ is the length of the silicon slabs and $a$ is the lattice periodicity; $\omega_m$ is the mid-gap frequency [21].

![Normalized K Vector](image)

![Normalized Frequency](image)

Figure 3: The photonic TE band structure of silicon with 1-D grating ($d/a=0.5$).
The band structure varies as the ratio of $d/a$ changes. The band structure of 2-D PCs and 3-D PCs are much more complex, it also depends on the lattice type of the crystals, refractive indexes, periodic structures, defect types, polarization and frequency of the light [22-25]. However, the cause of the band gap is the same—the periodic perturbation of refractive index. Figure 3 shows the TE band structure of a 1-D photonic crystals with periodical grating calculated by plane wave expansion (PWE) [17, 26] with the shaded region representing the photonic band gaps. In all the band structures in this thesis, the K vector is normalized to $2\pi/a$. 
Chapter 2 Photonic Crystal Slabs

2.1 Introduction

Chapter 1 reviewed the concept of PCs with different dimensions. While 1-D PCs and 2-D PCs are only conceptual structures, 3-D PCs are very difficult to fabricate as stated before. Therefore, the concept of a planar photonic crystal slab (2-D PC slab) was proposed to overcome this problem [27-29]. A 2-D PC slab is essentially a 2-D PC with finite size in the 3rd dimension. It is an optically thin semiconductor membrane surrounded by a low-refractive index material (usually air), and perforated with a 2-D lattice of holes as shown in Figure 4. In such a structure, the localization of light in the vertical direction is caused by total internal reflection due to the high index contrast between the slab and the air; in the horizontal direction, the light is controlled by distributed Bragg reflection due to the periodicity of the lattice. In this chapter, we study the band structures of the 2-D PC slabs and the 2-D PC slab waveguide formed by removing one row of these air holes. Slab modes and guided modes with different polarizations are identified. The field distributions for different modes are also studied to establish coupling condition to be investigated in chapter 3.

Figure 4: 2-D PC slab with perforated air holes.
2.2 Two Dimensional Photonic Crystals and Photonic Crystal Slabs with Triangular Lattice

For 2-D PCs and 2-D PC slabs, different lattice types would exhibit very different band structures. These band structures are also polarization dependent, which means that they would vary for different polarization modes. This research focuses on the triangular lattice shown in Figure 5 because the well confined defect modes could be introduced in the wide photonic band gap caused by this lattice type. The triangle region with vertices of \( \Gamma \), X and M defines irreducible Brillouin zone.

\[ \text{Figure 5: Triangular lattice.} \]

2.2.1 TE(-like) Mode in 2-D PCs and 2-D PC Slabs

TE modes are the modes that have electric field perpendicular to the central axis of air holes in 2-D PCs [30]. To be exact, the electric field is strictly perpendicular to this axis wherever inside the 2-D PCs because the third dimension is infinite and homogeneous. However, inside the 2-D PC slabs, electric field is only strictly perpendicular to the central axis of air holes in the vertical symmetric plane of the slab. When deviated from the vertical symmetric plane, the field vector gets tilted and is no longer strictly TE due to the finite size of the third dimension. It is usually referred to as a TE-like mode in 2-D PC slabs.

Figure 6 shows the differences between the field distribution in 2-D PC and 2-D PC slabs. Despite the different vertical distributions, it is clear that both TE mode in 2-D PC and TE-like mode in 2-D PC slab are even in respect to the vertical symmetric plane.
Figure 6: Cross section view of electrical field distribution: (a) TE mode in 2-D PCs. (b) TE-like mode in 2-D PC slabs.

Figure 7: 2-D PCs TE band structure of triangular lattice slabs on Brillouin zone boundary.

As Figure 7 shows ($\Gamma$ to M is the Brillouin zone boundary as indicated in Figure 5), triangular lattice 2-D PCs exhibits a reliable photonic band gap for TE mode. The band structure of 2-D PC slabs is similar to that of the 2-D PCs except that the light line must be introduced. The modes above the light line are air modes that are not well confined by the slab because they couple into the air cladding and cause losses. In order to calculate all the modes (both the confined modes and leaky air modes) correctly, it is better to use finite difference time domain calculation (FDTD) [31, 32] instead of plane wave expansion (PWE),
because PWE always relies on periodic boundary condition which is not applicable to the modes above the light line. Figure 8 shows the band structure (from Brillouin boundary $\Gamma$ to $X$ for simplicity) of a PC-slab with triangular lattice calculated by FDTD. This band structure shows that 2-D PC slabs do not have a complete photonic band gap because the leaky modes above the light line always destroy the band gap. However, below the light line, we can still define an incomplete photonic band gap indicated as the yellow region in the plot. From now on, when talking about photonic band gap in 2-D PC slabs, we implicitly refer to the band gap below the light line. Thus, in the following parts of this thesis, we would not calculate these modes by FDTD, avoiding the innate problem of FDTD calculation such as mode-missing and fluctuations. Instead, PWE will be used to calculate the modes below the light line because these modes are the primary concerns of this research. In Figure 9, the band structure of the full 2-D Brillouin boundary from $\Gamma$ to $M$ is calculated with modes above the light line neglected by PWE simulation; the shaded region represents the photonic band gap below the light line.

![Figure 8: FDTD result of PC-Slab of TE-like band structure.](image)

Comparing the PWE result in Figure 9 with the FDTD result in Figure 8 within the Brillouin boundary from $\Gamma$ to $X$ below the light line, the calculated results of the band structure are similar and consistent, but
the corresponding value of each mode obtained by FDTD is slightly shifted, which is probably induced by
the innate difference of these two algorithms [33]. Besides, PWE simulation avoided mode missing and
fluctuations, producing smooth band structure below the light line.

![Band Structure](image)

Figure 9: TE-like band structure of triangular lattice slabs on 2-D Brillouin zone boundary.

### 2.2.2 TM (-like) Mode in 2-D PCs and 2-D PC Slabs

TM (-like) modes are orthogonal to TE (-like) modes in photonic crystals [30]. TM modes have electric
field parallel to the central axis of air holes in 2-D PCs. Because of translational symmetry in the third
dimension, the electric field is strictly parallel to this axis everywhere inside the 2-D PCs. However, in the
2-D PC slabs with finite third dimension, electric field is parallel to the central axis of air holes only in the
plane centered in the middle of the slabs as shown in Figure 10. Above and below this plane, the electric
field vectors are tilted and are no longer strictly TM modes. These modes are called TM-like modes. The
electric field of both TM mode in 2-D PCs and TM-like mode in 2-D PC slabs are odd with respect to the
central slab plane as shown in Figure 10.
Figure 11 shows the TM band structure of a 2-D PC with a triangular lattice, which exhibits no photonic band gaps. Similar to that of its 2-D counterpart, the calculated TM-like band structure of 2-D PC slabs in Figure 12 also shows no photonic band gap, which suggests that TM-like modes would always be transmitted through 2-D PC slabs within this frequency range.

Figure 10: Cross section view of electrical field distribution: (a) TM mode in 2-D PCs. (b) TM-like mode in 2-D PC slabs.

Figure 11: TM band structure of 2-D PCs with a triangular lattice on Brillouin zone boundary.
2.2.3 Summary

The simulation presented in section 2.2 shows that 2-D PC slabs have similar band structure to the 2-D PCs. Triangular lattice would support wide photonic band gap for TE polarization. TM-like modes exhibit no band gap in 2-D PC slabs with this triangular lattice and thus can always get transmitted through the structure within this frequency range. We also justified our choice of PWE over FDTD for band structure calculations. In the following sections, we focus on 2-D PC slabs with triangular lattice because one of the goals of our research is to investigate confinement of TE-polarized light and mode interactions between TE-like and TM-like in photonic crystal slab waveguides and cavities.
2.3 Light Propagation in Photonic Waveguide

Photonic crystal slab waveguide (W1 waveguide in this case) is formed by removing one row of air holes from the periodic lattice. This introduces a line defect inside the periodic lattice, adding guided modes inside the photonic stop band. The image of a free standing waveguide with missing-hole line defect is shown in Figure 13. Since our concern is the dispersion of the guided modes which are confined within the line defect, we take the original band structure and project the wave vectors onto the propagation direction. The projected band structure is shown in Figure 14.

![Image of photonic waveguides formed by missing-hole defect.](image)

Figure 13: Photonic waveguides formed by missing-hole defect.

All the leaky modes above the light line are neglected since PWE simulation generates useful results only below the light line and the leaky modes are not our concern. Below the light line, three guided modes are usually identified: (1) the fundamental TE-like guided mode; (2) and the second order TE-like guided mode; (3) the fundamental TM-like guided mode. In this simulation, the lattice constant of photonic crystals is 400nm, the filling factor is 0.3, the refractive index is 3.5, and the slab thickness is 220nm. This simulation used ideal photonic waveguide with perfect symmetry, and TE-like modes and TM-like modes are orthogonal as even modes and odd modes with respect to the central slab plane. However, in reality, due to the fabrication uncertainty, no waveguide is perfectly symmetric and thus TE-like modes and TM-like modes would no longer be orthogonal. Details about the parity and coupling will be discussed in Chapter 3.
2.3.1 Slab Modes

Slab modes are the continuous modes that are not confined horizontally in the line defect. In the case of 2-D PC slabs, these modes are only vertically confined by the index contrast between silicon materials and air, thus horizontally; they can propagate in any direction without be confined by the line defect. Depending on their polarization, the slab modes in 2-D PC slabs are classified as TE-like slab modes (orange region in Figure 14) and TM-like slab modes (blue region in Figure 14).

2.3.2 TE-like Guided Modes

Unlike the slab modes that propagate in any in-plane direction, the guided modes are confined to the line defect. In Figure 14, the fundamental TE-like guided mode and the second order TE-like guided mode are labeled as 1 and 2. The group velocities of these two guided modes are given by the slope $v_g = \frac{d\omega}{dk}$;
which approaches zero at the Brillouin zone boundary. This forms the mode edge of the TE-like guided mode, which is very important for creating hetero-junction cavities [34-36].

Although the electric field of these two TE-like guided modes is vertically even, their horizontal mode distributions are different. The RSOFT Full Wave FDTD simulation is used to calculate the electromagnetic field as a function of time and space. The calculated result in Figure 15(a) to Figure 15(c) shows the in-plane electric field distribution of the fundamental TE-like mode, and Figure 15(d) to Figure 15(f) shows the in-plane electric field distribution of the higher order TE-like mode. The parities of each electric component for TE-like guided modes are summarized in Table 1.

Figure 15: The field distribution of TE-like guided modes in 2-D PC slab waveguide: (a) $E_z$ of 1st mode. (b) $E_y$ of 1st mode. (c) $E_x$ of 1st mode. (d) $E_z$ of 2nd mode. (e) $E_y$ of 2nd mode. (f) $E_x$ of 2nd mode.

Table 1: Horizontal parities of the individual field component of TE-like guided modes with respect to the propagation axis.

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<th>$E_x$</th>
<th>$E_y$</th>
<th>$E_z$</th>
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<tr>
<td>Fundamental TE-like mode</td>
<td>Odd</td>
<td>Odd</td>
<td>Even</td>
</tr>
<tr>
<td>Second-order TE-like mode</td>
<td>Even</td>
<td>Even</td>
<td>Odd</td>
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2.3.3 TM-like Guided Modes
Besides the TE-like guided modes, the fundamental TM-like guided mode is also below the light line (labeled as 3 in Figure 14). It is a guided mode that is well separated from the continuum of TM-like slab modes in the W1 waveguide. The electric field is vertically odd, and the in-plane distribution of each electric field component is shown in Figure 16.

![Figure 16: The field distribution of the 1st TM-like guided mode in 2-D PC slab waveguide: (a) E_z distribution. (b) E_y distribution. (c) E_x distribution.](image)

Table 2: Horizontal parities of the individual field component of TM-like guided mode with respect to the propagation axis.

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<th>E_x</th>
<th>E_y</th>
<th>E_z</th>
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<tr>
<td>Fundamental TM-like mode</td>
<td>Even</td>
<td>Even</td>
<td>Odd</td>
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### 2.3 Conclusion

This chapter reviewed the modes and band structures of the 2-D PC slabs. We chose the 2-D PC slabs with triangular lattice in this research because this lattice type provides a broad photonic band gap that can be used for efficient light confinement. We also discussed the simulation methods used to calculate the band structure and justified the reason for using PWE simulations to calculate the modes below the light line. We calculated the dispersion of the fundamental TE-like guided mode, the fundamental TM-
like guided mode, and the second order TM-like guided mode in 2-D PC slab waveguides through PWE simulation. The field distributions of the TE-like guided modes and TM-like guided mode in 2-D PC waveguide were also calculated by full wave simulation and the parities of these modes were analyzed. The importance of mode parities to polarization cross coupling will be discussed in chapter 3.
Chapter 3 Coupling Between TE-like and TM-like Guided Modes in Asymmetric 2-D PC Slab Waveguides

3.1 Introduction

Efficient mode coupling is important for various device applications such as wavelength-selective filters [37]. Polarization cross coupling between the fundamental TE- and TM-like guided modes in asymmetric photonic crystal waveguides is promising for innovative filters implementation. Previous research has established the concept of polarization cross coupling [38-40], but the interaction between guided modes was not systematically studied. Anti-crossing between the fundamental TE- and TM-like guided modes has not yet been reported, and no device applications have been investigated. In this chapter, we study the strength of coupling between the fundamental TE- and TM-like guided modes computationally, using PWE method. In section 3.2, the coupling criteria are established through parity arguments applied to the field overlap integrals; in section 3.3, the widths of mini-stop bands are extracted from the calculated dispersion diagrams, and the coupling coefficients are evaluated for asymmetric free standing waveguides. In section 3.4, the dispersions of SOI waveguides are discussed. Simulations show that modal anti-crossings are created by contra-directional coupling between guided modes in both free standing and SOI waveguides.

3.2 Mode Coupling Theory Applied to Coupling Between the TE-like Guided Mode and the TM-like Guided Mode in Asymmetric Waveguides

We model interactions between the TE-like guided mode and the TM-like guided modes as contra-directional coupling in which a forward propagating mode of one parity couples into the backward propagating mode of the other parity. In order for the two modes to couple, the frequency and phase
matching conditions need to be satisfied, and the modes must also overlap spatially. Modal overlap condition is difficult to analyze due to complicated field distributions of the guided modes. In the following analysis, we use the field overlap integral to specify the coupling condition. Using $\omega$ to represent the angular frequency; the coupling coefficient $\kappa$ is given by [38]

$$\kappa = \frac{\omega}{4a} \iiint \Delta \varepsilon(x, y, z) \overline{E_{TE}}(x, y, z) \overline{E_{TM}}(x, y, z) dV,$$  

(3.1)

where $\overline{E_{TE}}$ represents the electric field of the TE-like mode and $\overline{E_{TM}}$ represents the electric field of TM-like mode respectively, $a$ is the lattice constant, and the dielectric perturbation $\Delta \varepsilon$ is the dielectric variation imposed on top of periodic gratings and is defined as

$$\varepsilon'(x, y, z) = \varepsilon(x, y, z) + \Delta \varepsilon(x, y, z)$$  

(3.2)

Here, $\varepsilon(x, y, z)$ is the unperturbed dielectric variation, and the total dielectric variation $\varepsilon'(x, y, z)$ is a linear combination of $\Delta \varepsilon(x, y, z)$ and $\varepsilon(x, y, z)$.

Figure 17: 3-D domain of the overlap integral.

Using $V$ to represent the overlap integral domain with length of one lattice constant($a$) in the direction of the translational symmetry(x-direction); $V = V_z + V_z$, and $V_z = V_z$, then
We define the vertical symmetry and asymmetry in respect to $xz$ plane and horizontal symmetry or asymmetry in respect to $xy$ plane. The nature of the dielectric perturbation function $\Delta \varepsilon(x, y, z)$ determines whether the TE and TM-like modes couple or not.

Note that each electric field vector has three components $E_x$, $E_y$, and $E_z$. Using $\hat{x}$, $\hat{y}$, $\hat{z}$ to represent the unit vector in these directions, we can write the electric field amplitude of the TM-like mode and the TE-like mode as

\[
\begin{align*}
E_{TM}(x, y, z) &= E_{x, TM}(x, y, z)\hat{x} + E_{y, TM}(x, y, z)\hat{y} + E_{z, TM}(x, y, z)\hat{z} \\
E_{TE}(x, y, z) &= E_{x, TE}(x, y, z)\hat{x} + E_{y, TE}(x, y, z)\hat{y} + E_{z, TE}(x, y, z)\hat{z}
\end{align*}
\]  

Substituting equation 3.4 and 3.5 to equation 3.3, the coupling coefficient represented by field components along $x$, $y$, and $z$ direction can be written as

\[
K = \kappa_x + \kappa_y + \kappa_z
\]  

\[
\begin{align*}
\kappa_x &= \frac{\alpha}{4d} \iint_{V_z} \Delta \varepsilon(x, y, z) \left( E_{x, TE}(x, y, z) E_{x, TM}(x, y, z) \right) dV \\
&\quad + \frac{\alpha}{4d} \iint_{V_y} \Delta \varepsilon(x, y, z) \left( E_{y, TE}(x, y, z) E_{x, TM}(x, y, z) \right) dV
\end{align*}
\]  

\[
\begin{align*}
\kappa_y &= \frac{\alpha}{4d} \iint_{V_x} \Delta \varepsilon(x, y, z) \left( E_{y, TE}(x, y, z) E_{y, TM}(x, y, z) \right) dV \\
&\quad + \frac{\alpha}{4d} \iint_{V_y} \Delta \varepsilon(x, y, z) \left( E_{x, TE}(x, y, z) E_{y, TM}(x, y, z) \right) dV
\end{align*}
\]
\[
\kappa_z = \frac{\omega}{4a} \iiint \Delta \varepsilon(x, y, z) \left( E_{z, \text{TE}}(x, y, z) E_{z, \text{TM}}(x, y, z) \right) dV \\
+ \frac{\omega}{4a} \iiint \Delta \varepsilon(x, y, z) \left( E_{x, \text{TE}}(x, y, z) E_{x, \text{TM}}(x, y, z) \right) dV
\]  

(3.9)

In the following paragraphs, we discuss the evaluation of the coupling coefficient in 3 cases.

**Case 1: Vertically Symmetric Perturbation ( \( \Delta \varepsilon(x, y, z) = \Delta \varepsilon(x, -y, z) \) )**

Because TE-like modes are vertically even and TM-like modes are vertically odd by definition [30], then using equation (3.1), we could conclude that

\[
\iiint \Delta \varepsilon(x, y, z) \overline{E_{\text{TE}}}(x, y, z) \overline{E_{\text{TM}}}(x, y, z) dV = 0
\]  

(3.10)

Thus, the coupling coefficient \( \kappa \) is 0 in this case. This result indicates that, vertical asymmetry is necessary to cause coupling between TE-like and TM-like modes. As long as the dielectric perturbation is vertically symmetric, equation (3.10) is satisfied; this means that, without vertical asymmetry, horizontal asymmetry alone could not cause polarization cross coupling.

**Case 2: Vertically Asymmetric and Horizontally Symmetric Perturbation ( \( \Delta \varepsilon(x, y, z) \neq \Delta \varepsilon(x, -y, z) \) and \( \Delta \varepsilon(x, y, z) = \Delta \varepsilon(x, y, -z) \) )**

Because of the vertical asymmetry, the integrals over \( V_z \) and \( V_{z+} \) are nonzero. The dielectric index perturbation is horizontally symmetric, that is \( \Delta \varepsilon(x, y, z) = \Delta \varepsilon(x, y, -z) \). If we reduce the symmetric domain from \( V \) to \( V_{z+} \), then equation (3.7) to (3.9) becomes

\[
\kappa_x = \frac{\omega}{4a} \iiint \Delta \varepsilon(x, y, z) \left( E_{x, \text{TE}}(x, y, z) E_{x, \text{TM}}(x, y, z) \right) dV \\
+ \frac{\omega}{4a} \iiint \Delta \varepsilon(x, y, z) \left( E_{x, \text{TE}}(x, y, -z) E_{x, \text{TM}}(x, y, -z) \right) dV
\]  

(3.11)
According to the above equations, if all the field components of the TE-like mode and the TM-like mode have opposite horizontal parities (one even and the other odd), then the coupling coefficient is zero because the integrands inside each integral term on the right side of equation (3.11), (3.12) and (3.13) vanishes. However, if the TE-like mode and TM-like mode have the same horizontal parity, the coupling coefficient between TE-like mode and TM-like mode in this situation is nonzero and the modes couple.

**Case 3: Vertically and Horizontally Asymmetric Perturbation (\(\Delta\epsilon(x,y,z) \neq \Delta\epsilon(x,-y,z)\) and \(\Delta\epsilon(x,y,z) \neq \Delta\epsilon(x,y,-z)\))**

In this case, because of the asymmetries, the first integral term and the second integral term in equation (3.2) are nonzero and they do not cancel each other whatever the parity of the two modes, resulting in non-zero coupling coefficient. Hence, this result suggests that TE-like mode and TM-like mode will always couple and cause mode splitting.

The parities of all the field components of the modes need to be identified to determine whether \(\kappa\) in equation (3.6) is zero. However, in reality, there is no need to check the parities of all the electric field components; the parities of any one field component is enough to determine whether the modes cross or anti-cross. Table 3 summarizes polarization cross coupling through asymmetries based on the parities of \(E_z\) component. In this table, TE-like H-Parity (\(E_z\)) stands for horizontal parity of \(E_z\) component of TE-like modes; TM-like H-Parity (\(E_z\)) stands for horizontal parity of \(E_z\) component of TM-like modes; VA stands for vertical asymmetry and HA stands for horizontal asymmetry of the perturbation \(\Delta\epsilon(x,y,z)\). The results ‘Yes’ and ‘No’ for ‘Coupling’ indicate whether the mode couple or not. For example, in row 1, when the
parities of the two modes are ‘Odd’, there is no coupling between these two modes in absence of vertical asymmetries. To sum up, this table shows the following: (i) Vertical asymmetry is essential for coupling; coupling is zero if vertical asymmetry is none-existent. (ii) When the two modes have the same horizontal parity, vertical asymmetry alone is enough for coupling. (iii) When the two modes have opposite horizontal parities, both vertical asymmetry and horizontal asymmetry are required for coupling.

Table 3: Polarization Cross Coupling through Different Parities and Asymmetries.

<table>
<thead>
<tr>
<th>TE-like H-Parity($E_x$)</th>
<th>TM-like H-Parity($E_z$)</th>
<th>VA</th>
<th>HA</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odd</td>
<td>Odd</td>
<td>None-existent</td>
<td>None-existent</td>
<td>No</td>
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<tr>
<td></td>
<td></td>
<td>None-existent</td>
<td>Existent</td>
<td>No</td>
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<td></td>
<td>Existent</td>
<td>None-existent</td>
<td>Yes</td>
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<tr>
<td></td>
<td></td>
<td>Existent</td>
<td>Existent</td>
<td>Yes</td>
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<tr>
<td>Odd</td>
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<td>None-existent</td>
<td>None-existent</td>
<td>No</td>
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<td></td>
<td></td>
<td>None-existent</td>
<td>Existent</td>
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<td></td>
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<td>Existent</td>
<td>Existent</td>
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<td></td>
<td></td>
<td>Existent</td>
<td>Existent</td>
<td>Yes</td>
</tr>
</tbody>
</table>

To be more specific, in photonic crystal waveguides, we consider the following two technologically important cases involving coupling between guided modes below the light line, and our focus is on the first one, which to our best knowledge, has not been reported before.

(1) The coupling between the fundamental TM-like guide mode and the fundamental TE-like guided mode requires both vertical asymmetry and horizontal asymmetry because in addition to the different parity of the vertical distribution, the horizontal parities of electric field distribution for
the fundamental TM-like guided mode are always opposite to those of the TE-like guide mode as shown in Table 1 and Table 2. In this situation, as Table 3 suggested, only when $\Delta \varepsilon(x,y,z) \neq \Delta \varepsilon(x,-y,z)$ and $\Delta \varepsilon(x,y,z) \neq \Delta \varepsilon(x,y,-z)$, could the integral in Equation (3.4) become none zero.

(2) The coupling between the fundamental TM-like guided mode and the second order TE-like guided mode only requires vertical asymmetry, because the horizontal electrical field distribution for both these two modes always have the same parity as shown in Table 1 and Table 2 in chapter 2.

The spectrally line width of the mini-stop band due to the contra-directional mode coupling is [41]

$$\Delta \omega_{pp} = \frac{4|\kappa|c}{n_{TE} + n_{TM}}$$

(3.9)

In which $c$ represent the light velocity in vacuum; $n_{TE}$ and $n_{TM}$ represent the effective refractive index of TE-like mode and TM-like mode respectively. In the following sections, we investigate how asymmetries influence propagation of the TE-like guided mode and TM-like guided mode in the photonic waveguide band structure with PWE simulations.

### 3.3 Band Structure of the Free Standing Asymmetric Waveguide

According to the coupled mode theory, coupling between two modes is manifested in the photonic band structure as an anti-crossing point [42]. PWE method gives a fast calculation of photonic band structure, which can be used to accurately predict the strength of coupling between TE-like mode and TM-like mode in asymmetric photonic waveguides by measuring the width of the anti-crossing [43]. In this section, we start with a one dimensional photonic slab waveguide with periodic gratings, then move to simulate the 2-D PC slab waveguides with different asymmetry. Optical properties of different photonic waveguides are compared, and the influence of asymmetries is evaluated.
3.3.1 1-D Photonic Slab Waveguide with Periodic Gratings

To validate the parity arguments introduced in the previous section, we start with the one dimensional photonic slab (1-D PC slab) waveguide with periodic gratings. Coupled mode theory predicts that all the modes in this structure are orthogonal, i.e. there are no anti-crossings between the two modes in the band structure. However, when proper asymmetries are introduced, different modes that satisfy frequency matching and phase matching condition can couple. In this simulation, the vertical asymmetry is caused by the 10 degrees tilt of the edge walls and the horizontal asymmetry is caused by displacement of \( d = d_2 - d_1 = 20 \text{nm} \) as shown in Figure 18 (b). The periodicity of the grating is 420nm, slab refractive index of 3.5, and length of each \( L = 0.4 \times \text{Period} \); the silicon slab is 200nm thick and 690nm \((W_2+W_2)\) wide. The calculated band structure is shown in Figure 19 (a).

Figure 18: 1-D PC slab waveguide: (a) Horizontally symmetric waveguide. (b) Horizontally asymmetric waveguide.
(a) Band structure of the 1-D PC slab waveguide in waveguide direction.

(b) The resolved rectangular section in (a) for the symmetric waveguide.
The band structures of the symmetric 1-D PC slab waveguide and asymmetric 1-D PC slab waveguide look the same at first sight because the perturbation is weak. As shown in Figure 19(b), with the vertical asymmetry only, the fundamental TM-like guided mode and TE-like guided mode intersect. High resolution band structure in Figure 19(c) indicates that there is no coupling in this case. However, when horizontal symmetry is broken, the modes anti-cross, forming a mini-stop band. It is worthwhile to point out that even though coupling between the two fundamental guided modes causes the mode splitting, there is no full mode gap for the TE-like guided modes, because a higher order TE-like mode exists at the anti-crossing frequency.

### 3.3.2 Asymmetric Photonic Crystal Waveguide Based on 2-D PC Slabs

The parity arguments presented in the previous section apply to photonic crystal waveguides [38], which is an example of a periodic gratings used extensively in various integrated photonic device applications.
[10, 44]. It was established that optical waves can be confined and guided in the waveguide formed by line defect [45]. Contra-directional coupling in two adjacent waveguides was demonstrated [42, 46-48], and narrow band filtering with a single asymmetric waveguide was also recently reported [49]. Evidence of weak interactions between TE-like and TM-like modes have been observed [39], but the polarization cross coupling between two fundamental guided mode has not been established. To the best of our knowledge, there are no reports of using polarization cross-coupling for device applications. Our work investigates polarization cross coupling between guided modes in line defect photonic crystal waveguides. A blend of coupled mode theory and band structure simulation is used to extract relevant design parameters for device application.

In our simulation, we intentionally introduce vertical asymmetry and horizontal asymmetry to the 2-D PC slab waveguide by structural design. Mode coupling between TE-like and TM-like guided modes can be observed as an anti-crossing point in the calculated band structure. What is different here is that the asymmetry in 2-D PC waveguide allows us to study the coupling from the fast light regime of the TM-like guided mode into slow light regime of the TE-like guided mode. This structure also produces more design parameters to tune the coupling strength between the two guided modes by band structure engineering as discussed in section 3.3.3.2.

In this section, we investigate mode coupling between the fundamental TE-like and the fundamental TM-like guided modes, using PWE simulation. In section 3.3.2.1, we show the second order anti-crossing caused by coupling between the fundamental TM-like guided mode and the second order TE-like modes; in section 3.3.2.2, we show that horizontal asymmetry along is not enough for TE-TM coupling; in section 3.3.2.3, we demonstrate that the anti-crossing caused by coupling between the fundamental TE-like guided mode and the fundamental TM-like guided mode are related to both the vertical asymmetry and the horizontal in-plane asymmetry of the waveguide, and the mode splitting due to different degree of asymmetries are evaluated and analyzed.
3.3.2.1 2-D PC Slab Waveguide with Vertical Asymmetry Caused by Sidewall Tilt

In the free standing 2-D PC slab waveguides, a sidewall tilt of the etched holes is often the cause of vertical asymmetry. This asymmetry is expected to be essential to cause coupling between TE-like and TM-like modes. To study the role of the sidewall tilt, we calculated the dispersion diagram of a 2-D PC slab waveguide with lattice constant of 420nm, slab refractive index $n = 3.5$ to represent the silicon, and filling factor of 30%, sidewall tilt of 15 degrees. The calculated band structure is shown in Figure 20, and it exhibits coupling between the fundamental TM-like guided mode and the second order TE-like guided mode which is horizontally odd. The line width of the mini-stop band for the TE-like and TM-like guided mode is about 18nm in wavelength. It is the same anti-crossing as reported in [50]. The simulation result shows no anti-crossing between the fundamental TE-like guided mode and the fundamental TM-like guided mode, which is consistent with our earlier claims that the existence of the vertical asymmetry is not enough to cause the coupling between the two fundamental modes.
3.3.2.2 2-D PC Slab Waveguide with Horizontal Asymmetry

To study the influence of horizontal asymmetry, we define the horizontal asymmetry parameter as

\[
HA = \frac{R_2 - R_1}{R_1}
\]  

(3.5)

In which \( R_1 \) is the radius of the air holes in the bulk photonic crystals and \( R_2 \) is the radius of holes in two lines adjacent to the line defect as shown in Figure 21 (a). We use the waveguide structure with the same lattice constant and filling factor as before, but this time, the sidewall tilt is removed and the horizontal asymmetry is set to 10%, which means \( R_2 = 1.1R_1 \) as shown in Figure 21(a). In this case, there should be no coupling between TE-like and TM-like modes, and no anti-crossing should be observed in the band structure. This is because TE-like mode is vertically even and TM-like mode is vertically odd; according to Equation (3.2), the 3-D integration will go to zero.

In the simulation, the calculated band structure shown in Figure 21 (b) confirms this prediction that there is no polarization cross coupling for any guided mode if the structure is vertically symmetric.

![Figure 21: Schematic of the 2-D PC slab waveguide and band structure: (a) 2-D PC slab waveguide with horizontal asymmetry. (b) Projected band structure of this waveguide.](image)

30
3.3.2.3 2-D PC Slab Waveguide with Horizontal and Vertical Asymmetry

Our simulations have confirmed that vertical asymmetry is necessary to cause the coupling between TE-like mode and TM-like mode, which is consistent with the previous report [38]. As mentioned earlier, to cause coupling between the fundamental TE-like guided mode and the fundamental TM-like guided mode, both the horizontal and the vertical asymmetry are required. This section focuses on the polarization cross coupling between these fundamental modes. The influence of the horizontal and vertical asymmetry is studied through PWE simulation. Important applications of coupling between these two modes will be discussed in chapter 4.

![Graph](image)

(a) Anti-crossing between two fundamental modes with sidewall tilt 15 deg. (b) The relation between the sidewall tilt angle and the mode splitting in wavelength.

The horizontal asymmetry is set to 10%, which means by increasing the diameters of the two rows of the air-holes along one side of the line defect while keeping the diameters of all other holes unchanged. In Figure 22(a), the calculated anti-crossing between TE-fundamental mode and TM-fundamental mode is shown, and the splitting in wavelength is 1.492nm when the sidewall tilt is 15 degrees. Also, it can be
shown that keeping the in-plane asymmetry unchanged, the mode splitting decreases as the sidewall tilt angle decreases from 15 degrees to 0 degree as shown in Figure 22(b).

Our simulation also shows that, with a fixed vertical asymmetry (sidewall tilt = 10 deg) for the 2-D PC slab waveguide with the same lattice constant, slab thickness and filling factor, the width of the anti-crossing mini-stop band decreases as the horizontal asymmetry decreases. Thus, considering the simulation results in Figure 22(b) and Figure 23, it is safe to conclude that the width of the mini-stop band could be changed by modifying the degree of asymmetries—both vertical asymmetry and horizontal asymmetry.

![Graph showing mode splitting vs. horizontal asymmetry](image)

**Figure 23:** Relation between horizontal asymmetry and mode splitting in wavelength (tilt = 10 deg).

### 3.3.3 Evaluating the Coupling Coefficient and Penetration Length

The coupling coefficient can be related to the splitting of the anti-crossing modes, which also determines the penetration length of the guiding waves within the frequency range of the stop band. In section 3.3.3.1, we define the coupling coefficient and penetration length mathematically; in section 3.3.3.2, we explore different waveguide structures, and estimate the coupling coefficient as well as the penetration length inside the anti-crossing in these waveguide structures. The results show that the width of the anti-crossing can be controlled by design.
3.3.3.1 Definition of the Coupling Coefficient and Penetration Length

According to the mode coupling theory based on small perturbation, the maximum damping rate in the center of the stop band corresponds to the maximum imaginary part of the $K$ vector, which is the coupling coefficient by definition [41]. Thus, we can estimate the coupling coefficient and the penetration length inside the stop band through the following steps.

By definition

$$|\kappa| = \text{Im}(K)_{\text{max}}$$  \hspace{1cm} (3.6)

Using $a$ as lattice constant, $\omega$ as the arbitrary frequency and $c$ as the group velocity and define normalized frequency as

$$u = \frac{\omega a}{2\pi c}$$  \hspace{1cm} (3.7)

according to [51], for the coupling between two guided mode in photonic waveguide, the relation between coupling coefficient and mini-stop band can be modified to

$$\Delta u_{\text{anti}} = \frac{a}{2\pi c} \frac{4\kappa}{(1/v_{g1} + 1/v_{g2})}$$  \hspace{1cm} (3.8)

In our case, $\kappa$ represent the coupling coefficient of TE-like mode and TM-like mode; $v_{g1}$ and $v_{g2}$ represent the group velocity of unperturbed TE-like mode and TM-like mode; and $\Delta u_{\text{anti}}$ is the bandwidth of the anti-crossing mini-stop band.

$$\text{Im}(K)_{\text{max}} = \kappa = \frac{\pi c}{2} \left( \frac{1}{v_{g1}} + \frac{1}{v_{g2}} \right) \Delta u_{\text{anti}}$$  \hspace{1cm} (3.9)

We calculate the dispersion relations of the guide of interest using the plane wave expansion method in a super cell and extract the numerical value of the mini-gap spectral width from the band structure diagram.
The group velocity $v_{g1}$ and $v_{g2}$ of both modes are extracted from the slope of their dispersion relation, taken far from the coupling region. The value of the coupling constant $\kappa$ can then be derived from the knowledge of these three parameters, using equation (3.9). Hence, the penetration length can be calculated as $L = \frac{1}{2\kappa}$ [52].

3.3.3.2 Coupling Coefficient and Penetration Length in 2-D PC Slab Waveguides with Different Asymmetries

In this part, the coupling coefficients and penetration lengths in 2-D PC slab waveguides with different asymmetries is determined using procedures outlined in section 3.3.3.1. According to the simulation result in section 3.3.2, it is obvious that the width of the mini-stop band in 2-D PC slab waveguides can be controlled by proper design of the asymmetry. Two effective ways to control the coupling coefficient between the two modes are studied. In both cases, the weakly perturbed structures still maintain their guiding capabilities while producing sufficiently strong polarization cross coupling for practical applications.

Case 1: Controlling the Coupling Coefficient by Adjusting the Size of the Air Holes

In this case, we study the asymmetric photonic waveguide with 10 deg sidewall tilt and 10% horizontal asymmetry. From the PWE simulation result, we extract the group velocity of $v_{TE} = 0.095c$, and $v_{TM} = 0.219c$, and $\Delta u_{anti} = 1.2e^{-4}[a/\lambda]$. According to Equation (3.9), the coupling coefficient $\kappa$ is then $0.0028/a$, and the penetration length $L = \frac{1}{2\kappa} = 178a$. This says that a waveguide with length of $178a$ is required to cause $e^{-1}$ reduction in optical intensity [52]. Then, we enhanced the horizontal asymmetry by increasing the size of the air-holes on one side of the 2-D PC slab waveguide by 20% relative to the bulk and obtained the resolved splitting of $\Delta u_{anti} = 2.6e^{-4}[a/\lambda]$. Following the procedure described above, we obtained coupling coefficient $0.0048/a$, and the penetration length $L = 104a$. Comparing this to the previous simulation, the coupling coefficient is nearly doubled and the size of the 2-D PC slab waveguide is reduced nearly by half.
Case 2: Changing the Coupling Coefficient by Changing the Sidewall Tilt of the Air Holes

In case 1, we already obtained the penetration length of 178$a$ for the asymmetric waveguide with horizontal asymmetry of 10% and the sidewall tilt of 10 degrees. In case 2, we keep the horizontal asymmetry at 10% and increase the sidewall tilt to 15 degrees. Following the same procedure as in case 1, we extract the group velocity $v_{TE} = 0.1201c$, and $v_{TM} = 0.2760c$ for TE-like mode and TM-like mode respectively. The resolved splitting in normalized frequency $\Delta u_{anti} = 1.8e-4[a/\lambda]$, and the calculated coupling coefficient is $0.0034/a$. Thus, the penetration length is 147$a$. The reduction of the penetration length is an evidence of stronger polarization cross coupling caused by increased sidewall tilt of the air holes.

The two case studies provide the following insight for device applications:

1) Both vertical and horizontal asymmetries can be modified to tune the strength of coupling in waveguides.

2) Stronger asymmetries reduce the penetration length, which is desired in compact filter designs. On the other hand, stronger coupling increases the band width of the anti-crossing. There is a tradeoff between the device size and the filtering line width.

3.4 Band Structure of the Asymmetric Waveguide on SOI

In the previous sections, the free standing 1-D PC slab waveguides and 2-D PC slab waveguides with different asymmetries were studied and the polarization cross coupling in these structures were established. However, these free standing waveguides are not quite practical for large scale implementation because they are fragile [53]. In real application, SOI is often used as a platform for implementing asymmetric waveguide, which is also very attractive for its compatibility to standard CMOS [54-56]. Waveguide on SOI is intrinsically asymmetric in the vertical direction due to the silica substrate claddings. The losses of the propagation modes [57] in SOI photonics was studied, and the
transmission characteristics were measured [40]. Besides the propagating losses, transmission measurement revealed narrow dips that were presumably caused by mini-stop bands, resulting from polarization cross coupling. Other papers have related these small dips to the crossings in band structure [40, 58]. However, if these modes really cross, they are orthogonal mode that should not couple into each other. Hence, we believe that the intersections of these modes are very narrow anti-crossings. The cause of mode coupling could be explained in the following way: first of all, the silica substrate causes vertical asymmetry; then, the fabrication uncertainties like size, shape and position variations are probably the cause of horizontal asymmetry; the effect of fabrication induced asymmetries will be presented in the discussion section. In this chapter, our simulations still focus on designed asymmetries to establish the anti-crossings in the SOI waveguides where vertical asymmetry is created by silica substrate. We start with the 1-D PC slab waveguide on SOI platform, and extend our results to 2-D PC waveguide slabs on SOI. We focus on coupling between the fundamental TE-like and the fundamental TM-like modes.

3.4.1 1-D PC Slab Waveguide with Periodic Gratings on SOI Platform

One dimensional photonic slab waveguides with the same gratings as the one in Figure 17 is simulated on silicon dioxide substrate. The sidewall tilt is removed because we only study the vertical asymmetry caused by the silica substrate. The simulation clearly shows the intersection of the fundamental TE-like guided mode and the fundamental TM-like guided mode below the light line in band structure. In Figure 25(b), no mode splitting is observed as expected because the SOI waveguide is designed with intrinsic vertical asymmetry only. This confirms that the two guided modes would not couple because they are orthogonal as the parity arguments predicted. In Figure 24(c), the waveguide is designed to have both the vertical asymmetry caused by the silica substrate and the horizontal asymmetry caused by the same displacement as the one in section 3.3.1, thus the coupling between these two guided modes causes a 10nm-wide anti-crossing. Different from situation in the free standing structure, there is no higher order mode going across the mini-stop band, which means that, below the silica light line, the mini-stop band
for both TM-like guided mode and TE-like guided mode actually exists. We expected that the same type of anti-crossing could be observed in 2-D PC slab waveguide.

(a)

(b)

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3.4.2 SOI Photonic Waveguides Based on 2-D PC Slabs

A 2-D PC slab waveguide on SOI platform is simulated. The lattice constant of this waveguide is kept at 420nm; the filling factor is 30%; the slab thickness is 220nm; and horizontal asymmetry is 10%. The sidewall tilt is removed because our concern in this simulation is the vertical asymmetry caused by the silica substrate. The projected band structure of the SOI 2-D PC slab waveguide calculated by PWE is shown in Figure 25(a), which is similar to that of the free standing counterpart except for the following differences:

1) The lossless mode is pushed down due to the dielectric light line. It means that the modes above the dielectric light line would couple with the silica substrate and become lossy; in Figure 25(a), these modes are marked as substrate modes.
2) The fundamental TE-like mode couples into the TM-like mode with anti-crossing very close to the mode edge. This means that the anti-crossing mini-stop band would not be greatly widened due to the increased coupling caused by the silicon dioxide substrate. Thus, narrow stop-band filtering behavior would still be expected in SOI photonic waveguide.

3) The second order anti-crossing between the fundamental TM-like guided mode and the second order TE-like guided mode no longer exists.

4) The slope of the fundamental TE-like guided mode becomes obviously flatter than that the counterpart in the free standing waveguide, which means that TE-like guided mode in SOI is a slow mode and its guided pass-band is narrow.

Through PWE simulation, the anti-crossing of 300pm wide is observed, and the mode splitting is shown in Figure 25(b). Also, the slopes of the two guided modes clearly show that the TM-like guided mode effectively coupled into the slow TE-like guided mode. Repeating the procedure used to calculate the coupling coefficient and penetration length for the free standing waveguide and extract data from the PWE simulation for this SOI waveguide; the calculated coupling coefficient is about 0.0055/\(a\), and the penetration length is about 90\(a\). This result suggests that, in presence of horizontal asymmetry, silica substrate causes the vertical asymmetry that contributes to the anti-crossing. Thus, the filtering behavior caused by the anti-crossing is also expected in SOI waveguides with enhanced asymmetries.
Figure 25: (a) Projected band structure of the 2-D PC slab waveguide on silica. (b) Resolved anti-crossing in the rectangular region.
When compared to the free standing photonic waveguide, SOI photonic waveguides have similar optical properties with the following two added benefits:

1) SOI photonic waveguides have more reliable performance than their free standing counterparts. Due to the release of the substrate, the free standing photonic waveguides are prone to collapse when exposed to the outside pressure or environment changes. On the other hand, SOI photonic waveguides are supported by silicon dioxide substrate that increases the reliability of the devices.

2) The vertical asymmetry of SOI waveguide is well defined by the index contrast between the silicon dioxide substrate and the air ‘superstrate’. The presence of silica substrate causes strong vertical asymmetry for the waveguide system.

One drawback of the SOI photonic devices is that the substrate causes additional losses, which reduces the mode confinement for guiding.

### 3.5 Conclusion

Even though the mode coupling theory is well established and the coupling between waveguides were observed before, we believe the splitting caused by coupling between the fundamental TE-like guided mode and the fundamental TM-like guided mode is first clearly observed in the band structure of the asymmetric 2-D PC slab waveguides.

The simulation results suggest that the orthogonality of TE-like modes and TM-like modes is broken in asymmetric waveguides. We systematically investigated the mode coupling in the free standing waveguide in which vertical asymmetry is caused by the sidewall tilt and the SOI waveguide in which the vertical asymmetry is caused by the silica substrate. In both cases, as long as both the vertical asymmetry and horizontal asymmetry exist, the coupling between the fundamental TM-like guided mode and the fundamental TE-like guided mode would cause an anti-crossing mini-stop band. Our simulations also demonstrate that the splitting of these two modes is spectrally narrow because coupling is usually weak.
We studied different waveguides with different asymmetries, and evaluated the coupling coefficients in different cases.
4.1 Introduction

Narrow band optical filters are important signal processing components with several inherent advantages over the traditional electronic radio frequency (RF) filters. The advantages include higher operation speeds, low losses and immunity to electromagnetic interference. Traditionally, high spectral selectivity is achieved with low refractive index contrast structures utilizing Bragg gratings [59-61]. By properly designing the strength of Bragg gratings, the narrow band filtering behavior can also be realized with high refractive index contrast structures [62-64]. However, these gratings filters are strongly polarization dependent, which means that the filtering behavior changes with the polarization state of the input light. In reality, polarization state changes randomly in optical fibers, and it is usually required to adjust the input light to obtain the desired polarization state. To eliminate the polarization dependent behavior, we explore polarization cross coupling to achieve narrow band filters for both polarizations in asymmetric photonic crystal waveguides.

4.2 The Narrow Band Filter with a Polarization Independent Mini-stop

In the previous chapter, we have established that the anti-crossing between the fundamental TE-like guided mode and the fundamental TM-like guided mode achieves a stop band for both polarizations. Based on this, we use the asymmetric free standing 2-D PC slab waveguide to implement a wavelength selective narrow band filter for optical systems. The advantage of this method is that the filtering behavior becomes independent of the polarization state of the input light. In this section, we will demonstrate the functionality of the polarization independent filter experimentally.
An asymmetric 2-D PC slab waveguide can be used as a narrow-band optical filter. Within the frequency range of the anti-crossing mini-stop band, the input light with both TE and TM polarizations would not be guided. In our structure, the horizontal asymmetry is created by increasing the radius of two rows of holes on one side of the line defect by 10%. The vertical asymmetry, on the other hand, is caused by the sidewall tilt of 10 deg. The SEM image of the fabricated structure is shown in Figure 26. The total length of the waveguide is 1mm, which is long enough to sufficiently damp the intensity of the modes within the range of mini-stop band.

Optical transmission spectra of the fabricated structure were obtained with a tunable laser (AD4321) coupled into the guiding layer using a tapered single-mode optical fiber [65]. The spectra of the 1mm-long asymmetric PhC waveguide are shown in Figure 27. Transmission for both polarizations contains a ~2 nm-broad dip in the transmitted intensity, confirming the polarization-insensitive narrow band filtering capability of the asymmetric periodic waveguides. The measured spectral width of the mini-stop band is nearly twice as broad as the width of the anti-crossing obtained by the PWE simulations (~1 nm). This is caused by random variations of the sizes, shapes and positions of photonic lattice elements created during the fabrication process [66, 67]. As seen in Figure 27(b), TE transmission is affected by disorder more significantly because the TE-like mode propagates with a slow group velocity and is therefore susceptible to disorder-induced scattering [68]. Also, due to the introduced horizontal asymmetry, the observed transmission dip is about -17dB, which is much more pronounced than the transmission dips observed in symmetric structures in [40].
Figure 26: SEM image of the asymmetric photonic waveguide.

Figure 27: Transmission characteristics of the asymmetric 2-D PC slab waveguide: (a) Mini stop band in the TM Transmission. (b) Mini stop band in the TE transmission.
4.3 TM Light Filter with Multiple Mini-stop Bands on SOI Platform

As argued before, SOI photonic devices are attractive for their CMOS compatibility and reliability. Since the SOI platform is asymmetric in the vertical direction due to the presence of the silica substrate. The polarization independent filter in a free standing slab can also be easily implemented on the SOI platform. However, a careful analysis of the band structure reveals that W1 waveguide on SOI are not suitable for polarization insensitive filtering. The PWE simulation result in Figure 25(a) shows that the wavelength range of the fundamental TE-like mode is less than 7nm in total. Its upper bound is set by the frequency of the slab mode, and lower bound is set by the photonic band gap. Also, the anti-crossing between the fundamental TE-like guided mode and TM-like guided mode is very close to the TE-like mode edge. Considering the silica cladding and slow light effect, the TE-like mode is extremely lossy. However, even though it is difficult to implement a polarization independent filter with this present design, it is still possible to implement a TM band-stop filter on the SOI platform because the fundamental TM-like guided mode does not have this problem and the filtering behavior can be identified in transmission measurement.

To get a filter with multiple narrow stop bands, we introduced several asymmetric waveguide sections as shown in Figure 28. In our experiment, we measured a filter with the serial connections of 4 asymmetric waveguides, and each section has 150 periods, which is much longer than the theoretic penetration length in chapter 3, and is thus sufficient for damping of the mode in the mini-stop band. The measured transmission is shown in Figure 29. The 4 sharp dips correspond to the 4 mini-stop bands at different wavelength ranges within the IR range. This filter’s compact design on SOI platform makes it potentially useful for wavelength division multiplexing. Optimized SOI filter structure needs to be studied to make the filtering behavior polarization insensitive.
4.4 Conclusion

In conclusion, we applied the coupling-induced anti-crossing to the narrow band filter design. The filter implemented in a free standing asymmetric 2-D PC slab waveguides exhibits a polarization independent filtering behavior. A filter with multiple narrow stop bands in TM-like transmission is also built on an SOI platform. Through these filter designs, we confirmed that stronger dips in transmission could be observed when horizontal asymmetry is enhanced. These structures are promising for various applications such as wavelength-division-multiplexing (WDM).
Chapter 5 Cavity Excitation and Vertical Add-Drop Cavity Filter

5.1 Introduction

High quality (Q) factor optical cavities capable of confining photons are desired for many optical applications, such as sensing [69, 70] and optical signal manipulations [71, 72]. Two-dimensional photonic crystal nanocavities are currently the focus of research interests because they are able to strongly confine photons within an ultra-small volume [73, 74]. For varieties of device applications, it is necessary to employ an effective way to excite resonant modes inside the cavity. This chapter focuses on an innovative cavity excitation method based on polarization cross coupling. Our simulations suggest that the parity arguments developed to describe coupling between guided modes still hold for coupling from a guided mode into a cavity mode. With asymmetries present, TE-like cavity modes can thus be excited with TM-polarized input light, suggesting applications as a vertical add-drop cavity filter.

5.2 Mode Edge Cavities and Excitation Method

The mode edge cavities, similar to those studied by Asano et al [34]. and Kuramochi et al. [75] have the following advantages: they are compact in size, compatible with standard CMOS processing technologies and usually exhibited high quality factors [34, 36, 76]. These cavities are formed by shifting several circular air-holes laterally and along the waveguide. This creates a discontinuity of TE-like pass band edge as Figure 31 shows, forming a heterojunction photonic cavity in which TE-like photons with a specific energy could be confined by the so called mode gap effect [77]. The TE-like localized mode has modal profile matching with the TE-like guided mode and the cavity mode can be excited by coupling from the waveguide mode. In integrated optics, where all the photonic devices are integrated on a silicon chip, evanescent side coupling from an adjacent waveguide is the most straightforward way to excite high
Q cavities in a 2-D plane [34, 36, 38, 78]; however, for this evanescent side coupling to work, the following issues need to be considered:

1) The feeding waveguide needs to be properly designed so that it supports a guided mode at the cavity resonance.

2) The distance between the cavity and the feeding waveguide needs to be properly selected. If the cavity is too close to the waveguide, the resonant mode is likely to out couple into the waveguide, reducing the quality factor. If the cavity is too far away from the waveguide, the resonant mode is unlikely to be excited due to poor evanescent coupling.

Figure 30: Heterojunction mode edge cavity: (a) Cavity excitation based on polarization cross coupling. (b) Traditional excitation mechanism based on evanescent coupling from an adjacent feeding waveguide.

Figure 31: Discontinuity of the TE-like pass band and photon confinement.
Figure 32: Coupling between the cavity mode and guided mode of the feeding waveguide in K space.

There is an alternative way of coupling light into the waveguide-based mode edge cavities and the feeding waveguide could be avoided with this method. It is based on polarization cross coupling between the TE-like guided mode and the TM-like guided mode presented in chapter 3. As mentioned before, the mode edge cavity is formed by a short section of a waveguide, and the coupling considerations discussed in chapter 3 applies to coupling between waveguide mode and cavity mode. Thus, following the parity considerations from chapter 3, the cavity excitation by polarization cross coupling is possible if vertical and horizontal asymmetries are introduced. In the following section, we will establish the cavity excitation through polarization cross coupling, validating coupling between the TM-like guided mode and the TE-like localized mode in cavity-waveguide systems.

5.3 Simulation of the Cavity Excitation Based on TM-TE Mode Coupling
5.3.1 Simulation of the Free Standing Cavity-Waveguide Systems

In the following simulation, we used the free standing asymmetric photonic cavity-waveguide system shown in Figure 30 (a). The lattice constants of the individual cavities are: \( a_3=410 \text{ nm} \), \( a_2=405 \text{ nm} \), \( a_1=400 \text{ nm} \). The filling factor is 0.3, the thickness of silicon slab is 220nm and sidewall tilt is 4 degree. We placed the TM polarized light source at the input of the waveguide and calculate the cavity mode with RSOFT Full Wave FDTD simulation. The resonant mode at 1.5545 \( \mu \text{m} \) with quality factor of \( \sim 3 \times 10^5 \) was calculated and the simulated mode profile is shown in Figure 33.

![Figure 33: Cavity mode in free standing device.](image)

In order to study the cavity excitation quantitatively, we define the excitation efficiency from the TM-like mode to TE-like mode as

\[
\eta = \frac{I_{\text{TM-excitation}}}{I_{\text{TE-excitation}}} \tag{4.1}
\]

In which, \( I_{\text{TM-excitation}} \) represents the optical intensity of the cavity mode excited with a TM-polarized source inside the cavity; similarly, \( I_{\text{TE-excitation}} \) represents the optical intensity of the cavity mode with TE excitation source inside the cavity. Since the horizontal asymmetry (defined in chapter 2) is controllable as a design parameter, in this simulation, we keep the sidewall tilt at 4 degrees, and gradually increase the
horizontal asymmetry from 0 to 0.1. The result shown in Figure 34 indicates that the excitation efficiency \(\eta\) increases with the horizontal asymmetry.

![Figure 34: Excitation efficiency VS horizontal asymmetry.](image)

While asymmetry enhances the coupling strength between the TE-like and the TM-like modes, it also reduces the quality factor of the cavity because of the increased coupling-induced leakage. Significant asymmetry not only reduces the quality factor, it could also destroy the guiding property of the waveguide. Thus, we study only structures with weak asymmetries in these simulations.

To further test the validity of the coupling criteria developed in chapter 3, we simulated the cavity-waveguide system with vertical sidewall tilt only and horizontal asymmetry only separately; in both cases, no cavity mode excitation was observed. Thus, it is safe to say that both horizontal asymmetry and vertical asymmetry are required to cause the coupling between the fundamental TM-like guided mode and the TE-like localized mode.

### 5.3.2 Simulation of the Cavity-Waveguide System Based on SOI Platform

As discussed before, SOI photonics has innate vertical asymmetry due to the presence of silica substrate. Thus, the mode edge cavity excitation method used in the free standing photonic cavities also applies to
photonic cavities on SOI. In our simulation, we study a line defect photonic crystal waveguide with vertical sidewalls on SOI. We excited the mode edge cavity by sending TM polarized light into the structure and obtained the resonant wavelength of 1.5604 μm with quality factor of 4036. The low quality factor in the SOI device is expected because the mode coupling into silica substrate causes additional losses, which also suggests that SOI photonic crystals are not as good a candidate for the implementation of ultra-high Q cavities as their free standing counterparts. The improved structural stability of the SOI cavity devices is traded for the reduction of the quality factor.

As for the influence of the horizontal asymmetry, we also carried out the same procedure as we did for the free standing structure. Figure 35 shows the relation between the horizontal asymmetry and the excitation efficiency for the mode edge cavity on SOI.

![Figure 35: Excitation efficiency VS horizontal asymmetry on SOI.](image_url)
5.3.3 Significance of the Cavity Excitation with the TM-TE Coupling

1) Advantages

Compared to the traditional side coupling excitation method, the cavity excitation based on polarization cross coupling has one obvious advantage. No feeding waveguide is used in this excitation method, which reduces the size of the cavity waveguide system. By using the TM-like light as a source to excite the cavity inside the waveguide, we can have reliable coupling since the band structure of the 2-D PC slab waveguide always shows the anti-crossing between the TE-like and TM-like guided modes when asymmetry is present.

2) Device Applications

By delivering TM polarized light into the mode-edge cavity through polarization cross coupling, the cavity-waveguide system effectively serves as a vertical add-drop cavity filter with polarization conversion. This cavity filter takes the input as TM-polarized light, filters out the TE-like mode at the resonant frequency and delivers it in the vertical direction.
5.4 Conclusion

In conclusion, we applied the results of coupled mode theory and PWE simulations to study the mode edge cavity excitation. Our simulations suggest that the mode edge cavities can be excited by sending TM-polarized light, and excitation efficiency can be adjusted by modifying the asymmetries of the structure. With the same method, we also confirmed that the mode edge cavity on SOI platform can be excited. The advantage of the cavity excitation by coupling from the TM-like guided mode is justified through comparing it to the traditional side coupling method, and its potential application as a vertical add-drop cavity filter is suggested.
Discussion: Cavity Excitation in Fabricated Structure

Our simulations in chapters 3 and 4 have established that asymmetries are needed to cause polarization cross coupling, which can be utilized in narrow-band filtering and photonic crystal cavity excitation. While intentional asymmetries are needed to implement a filter, they are not necessary to couple TM-like light into mode edge cavities, because weak asymmetries introduced at fabrication are usually sufficient for cavity excitation.

No fabricated photonic crystal structure is perfectly symmetric. For example, the etched sidewalls are usually slightly tilted, breaking the vertical mirror symmetry; and the unavoidable nano-scale fluctuations of the sizes, positions and shapes of photonic crystals break the horizontal symmetry. This makes polarization cross coupling between TE and TM-like mode inevitable.

In [40], polarization cross coupling on SOI was studied, and the authors focused on investigating the vertical asymmetry caused by silica substrate. However, to have coupling between the fundamental modes whose anti-crossing is mapped to the transmission dip, horizontal asymmetry must play a role. It is probably the in-plane disorder that breaks the horizontal symmetry, and caused polarization mode coupling. The evidences of weak coupling in form of small dips in transmission reported by [40] could have been more significant, and the waveguides would have shown the filtering behavior if intentional horizontal asymmetry was introduced into the waveguides.

Our present simulations do not consider random fabrication disorder. However, we have observed the effect of random disorder experimentally. In particular, our cavity excitation experiment demonstrates that the fabrication disorder does cause asymmetries that allow the TM-like mode and the TE-like mode to couple.
In the experiment, a double heterojunction mode edge cavity was fabricated on SOI wafer and released in HF. The silicon structure was designed with lattice constant of $a_0=416\text{nm}$, $a_1=408\text{nm}$, and $a_2=400\text{nm}$ with 30% air filling factor on a 220nm thick wafer. No intentionally designed asymmetry is present and all the asymmetries in this structure are due to the fabrication imperfections.

![SEM image of the measured mode edge cavity.](image)

Figure 37: SEM image of the measured mode edge cavity.

By adjusting the polarization controller, we can filter out the TM polarized light from the laser source(AD4321) and send it to the input port of the cavity-waveguide system. The measured resonance of the mode edge cavity was observed as an isolated mode. Thus it demonstrates that TM polarization light excites the TE resonant mode by coupling via the innate asymmetry created at fabrication. In Figure 38, we could clearly see that the ultra-high Q cavity mode was excited, which is consistent with the result in previous paper [65]. On the other hand, the TE polarized light cannot excite the cavity because the stop band prevents its propagation and does not allow it to reach the cavity inside the waveguide.

From the measured result, we can estimate the line width of this resonant mode at 1576nm, and calculate the quality factor of this cavity from $\frac{\lambda}{\delta\lambda}$, where $\delta\lambda$ is the -3dB bandwidth, leading to measured quality factor $\approx 30,000$. The success of this cavity excitation indicates that the TM-like guided mode is coupled
into the TE-like localized mode through the vertical asymmetry caused by sidewall tilt and horizontal asymmetry caused by in-plane disorder.

![Figure 38: Measured cavity mode.](image)

To sum up, the question of how the fabrication induced asymmetries compare to the designed asymmetry is still a very challenging problem. Qualitatively, we expect that any kind of the asymmetry, intentionally or unintentionally introduced, would cause the polarization cross coupling [65]. Quantitatively, finding a mathematical model to describe these fabrication induced asymmetries, calculate the band structure, and estimate the coupling coefficient would probably be the only way to accurately predict the cavity excitation in the real structure.
References


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