On-Chip Silicon Based Photonic Structures:
  - Photonic Band Gap and Quasi-Photonic Band Gap Materials

By

Yasha Yi

Submitted to the Department of Physics on April 30\textsuperscript{th}, 2004 in partial fulfillment of the requirements for the degree of

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Abstract

This thesis focuses on integrated silicon based photonic structures, photonic band gap
(PBG) and quasi-photonic band gap (QPX) structures, which are based on high refractive
index contrast dielectric layers and CMOS compatibility. We developed a new type of
silicon waveguide – Photonic Crystal (PC) cladding waveguide is studied based on PBG
principle. The refractive index in the new PC cladding waveguide core therefore has a
large flexibility. Low index core (e.g. SiO₂) or hollow core waveguide can be realized
with our PC cladding waveguide structure. The fabrication of the waveguide is
compatible to CMOS process. To demonstrate the PBG guiding mechanism, we utilized
prism coupling to the Asymmetric PC cladding waveguide and the effective index of the
propagation mode is measured directly. The measured effective mode index is less than
both Si and Si₃N₄ cladding layers, which is clear demonstration of the photonic band gap
guiding principle. We also fabricated and measured the PC cladding channel waveguide.
Potential applications include high power transmission, low dispersion, thin cladding
thickness and nonlinear properties engineering. Secondly, we developed a Si-based
multi-channel optical filter with tunability, which is based on omnidirectional reflecting
photonic band gap structure with a relatively large air gap defect. Using only one device,
multi channel filter with tunability around two telecom wavelength 1.55µm and 1.3µm by
electrostatic force is realized. Four widely spaced resonant modes within the photonic
band gap are observed, which is in good agreement with numerical simulations. The
whole process is compatible with current microelectronics process technology. There are
several potential applications of this technology in wavelength division multiplexing
(WDM) devices. Thirdly, to further extend the photonic crystal idea, we studied the
quasi-photonic crystal structures and their properties, especially for the fractal photonic
band gap properties and the transparent resonant transmission states. A-periodic Si/SiO₂
Thue-Morse (T-M) multilayer structures have been fabricated, for the first time, to
investigate both the scaling properties and the omnidirectional reflectance at the
fundamental optical band-gap. Variable angle reflectance data have experimentally
demonstrated a large reflectance band-gap in the optical spectrum of a T-M quasicrystal,
in agreement with transfer matrix simulations. The physical origin of the T-M
omnidirectional band-gap has been explained as a result of periodic spatial correlations in the complex T-M structure. The unprecedented degree of structural flexibility of T-M systems can provide an attractive alternative to photonic crystals for the fabrication of photonic devices.

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am looking forward to more exciting results. To Jessica Sandland who helped me on the prism coupling measurement, which is the first important results for the project.

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Chapter 1

Introduction

This thesis discusses molding the flow of light on chip using silicon based photonic structures. Silicon is one of the most important materials for microelectronics. The natural abundance of Si element and the mature method to make large volume pure silicon wafers makes Si the most thoroughly studied material in the world. Because of the superior properties of SiO₂ and the interface between Si and SiO₂, the current microelectronic process mainly focuses on silicon and silicon-based materials. Moore’s law, which says the numbers of devices on chip will double every 18 month, has been followed for decades since the 1960’s. Current feature size of the chip for the state of the art processors has entered the 130nm node, which is rapidly going into the 65nm node region. Due to the fundamental physical limit and quantum tunneling effect, the gate oxide will not be an insulator any more when the thickness of the oxide layer is only tens of atoms, which makes it useless. RC delay for microelectronics is the limit that inhibits the chip speed going to the higher speed. The need to solve this bottleneck problem is very urgent.

Microphotonics comes to rescue. It relieves the basic constraint of above problem, at least in principle, there is no fundamental physical limit associated with photonics to make the speed to go to the THz range. However, molding the flow of light is more challenging than electrons. One is the large wavelength of the photons, which is almost as
same as the chip device feature size, while the wavelength of electrons is on the order of angstroms. The other is the vector property of the photons, which requires considering the polarization. Nevertheless, microphotonics has become the next promising technology and is studied widely all over the world.

When combining the silicon materials and microphotonics, Si microphotonics is superior to other III-V based materials [1-2], because we can utilize current CMOS facilities. Furthermore, Si microphotonics is not only important for information technology, but also is very promising for future applications in the biomaterials, biomedicine and bioMEMS fields [3-4].

Because of the invention of the optical fiber, most optical devices are using the total internal reflection principle to guide light. This method is practical for many applications we discussed above. However, the index guiding method requires the guiding materials to have a higher refractive index than the cladding layers, which imposes severe constraints on the design and some applications. The discovery of Photonic Band Gap (PBG) materials in 1987 opens a new way to guide the light, which is based on photonic band gap principle [5-9]. Similar to the electronic band gap in semiconductors, photonic crystals are like the photonic semiconductors for photons, which can be used to mold the flow of light in a new way. The uniqueness for this guiding mechanism is the flexibility to choose the materials to guide light, low index core materials or even air can be used to guide the light based on the photonic band gap principle [10-12]. This is very important for future applications like high power laser transmission, material dispersion reduction
and nonlinear optical properties engineering as well as biomaterials and biomedicine fields.

However, nothing is free, it also applies to the photonic crystals. Although photonic band gap materials provide a very promising method to guide the light, the complexity of the 3D photonic structures makes it very difficult to fabricate what have been proposed, which has a full photonic band gap. There is need to find a way to circumvent this problem. Fortunately, the discovery of the omnidirectional photonic band gap in 1D photonic crystal structures with high index contrast layers gives us opportunities to fulfill most of the functionalities of 3D photonic crystals, while keeping the fabrication process relatively easy and feasible [13-18].

In this thesis, we will focus on on-chip silicon based photonic structures, especially for the silicon based omnidirectional photonic band gap structures. The design, fabrication and their applications will be discussed in detail. The thesis is divided into the following chapters with an introduction on the photonic band gap structures in chapter 2, followed by the defect and localized states study in chapter 3, which is the foundation for the following chapters. Then we proceed with the applications to on-chip silicon-based PC cladding waveguide, multichannel optical filter with tunability, and the photonic quasicrystal structures:

In chapter 2, silicon based photonic band gap structures are introduced, one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) photonic band gap structures
and their optical properties are reviewed. Particularly, one dimensional photonic band gap structures with an omnidirectional band gap are discussed in detail, which requires high index contrast dielectric pairs and is equivalent to 3D photonic crystals in most cases. In order to be Si CMOS compatible, the material choices and deposition methods for the dielectric layers are also discussed. We use Si/SiO$_2$ and Si/Si$_3$N$_4$ as two examples, which satisfy all the requirements for realizing an omnidirectional reflector on a Si chip and the fabrication is CMOS compatible.

In chapter 3, the defect states within the photonic band gap structures are discussed in detail. Defect states are resonant states with light strongly localized around defect sites and have many applications on filtering, modulation and lasing. One of the most important challenges is how to engineer the defect states [19-21]. In this chapter, the localization properties of the defect states are studied, the exponential decay and strong EM field enhancement in the microcavity states are discussed. We first introduce the general properties of the microcavity states in a PBG structure, including 2D and 3D systems. Then, we focus on the 1D system with high index contrast dielectric layers. The fabrication process with CMOS compatibility is also addressed.

In chapter 4, a new type of planar waveguide with Photonic Crystal (PC) cladding, which guides light according to the PBG principle, is developed. The refractive index of the new PC clad waveguide core has a large flexibility. Low index core (e.g. SiO$_2$) or hollow core waveguides can be realized with the PC clad waveguide structure. The fabrication of the waveguide is compatible with CMOS processing. To demonstrate the
PBG guiding mechanism, we utilize prism coupling to an asymmetric PC clad waveguide and the effective index of the propagation mode is measured directly. The measured effective mode index is less than either of the Si and Si\textsubscript{3}N\textsubscript{4} cladding layers, which is a clear demonstration of the photonic band gap guiding principle. We fabricate and measure a PC clad channel waveguide, where the light is guided in the low index core materials. The waveguide transmission loss and bending loss are measured and analyzed for the first time. Potential applications for these novel structures include high power transmission, dispersion engineering, reduced cladding thickness and nonlinear optical devices.

In chapter 5, a Si-based multichannel optical filter based on an omnidirectional reflecting photonic band gap structure with a relatively large air gap defect is fabricated and measured. Using only one device, a multichannel filter with MEMS tunability around two telecom wavelengths 1.55\textmu m and 1.3\textmu m by electrostatic force is realized. Four widely spaced resonant modes within the photonic band gap are observed in agreement with the design principles. The device fabrication process is low temperature and compatible with current microelectronics process technology. The device is capable of a continuous tuning in the 1200nm – 1700nm range for WDM application. Finally, an alternative approach to tuning through free carrier injection is designed and simulated [22-39].

In chapter 6, we study photonic quasicrystal structures and their properties. The fractal photonic band gap properties and the transparent resonant transmission states are
simulated and measured [40-63]. The Fibonacci structure and the Thue-Morse structures are presented in detail. Aperiodic Si/SiO₂ Thue-Morse (T-M) multilayer structures are fabricated, for the first time, to investigate both the scaling properties and the omnidirectional reflectance at the optical band gap. Variable angle reflectance measurements reveal a large photonic band gap, in agreement with our transfer matrix simulations. From the Fourier analysis, the physical origin of the T-M omnidirectional band-gap has been explained as a result of periodic spatial correlations.

In chapter 7, we conclude with a summary and discussion of future works.
Chapter 2

Silicon based photonic band gap structures

Silicon based PBG structures are introduced in this chapter, 1D, 2D and 3D photonic band gap structures, and their optical properties are reviewed. Particularly, 1D PBG structures with an omnidirectional band gap are discussed in detail. The high index contrast requirement to form an omnidirectional reflector for 1D alternating dielectric layers are studied. In order to be Si CMOS compatible, the material choices and deposition methods for the dielectric layers are also discussed. We use Si/SiO$_2$ and Si/Si$_3$N$_4$ as two examples, which satisfy all the requirements for realizing an omnidirectional reflector on a Si chip.
Introduction to 1D, 2D and 3D photonic band gap structures

Like the electronic band gap in the semiconductors, a periodic photonic lattice also induces a photonic band gap [5-9]. There is also a certain range of frequencies for which the propagation of photons is prohibited. For the photonic crystal system, the periodic modulation of the dielectric constant makes the photons feel a periodic optical potential, similar to the electronic band gap in semiconductors for which the band gap separates conducting bands and valence bands, the photonic band gap also separates photonic bands, which are Bloch-like wavefunctions. The main difference is the electromagnetic (EM) field is a vector, so that we need to take into account the polarization properties.

![Illustration of photonic crystals](image)

**Figure 2-1.** Illustration of photonic crystals for 1D, 2D and 3D. The different colors represent materials with different refractive index. The structures are composite materials consisting of periodic array of materials with differing refractive index.

Fig. 2-1 shows the periodic modulation of the dielectric constant by varying the materials. To have a complete (for all \( k \) vectors and polarizations) photonic band gap,
high index contrast ($\Delta n/n$) between the different materials and certain crystal symmetry need to be satisfied. Since the photonic band gap concept was proposed in 1987 [5,6], the diamond structure with Si/air was shown to have a complete photonic band computationally [64-66]. The dimension of the crystal lattice constants is in the order of $\lambda/n$ and typically is very small.

The first photonic crystal structure shown to have a fully 3D photonic band gap was created at microwave range, which typically has a cm or mm length scale. The structure was made to work by drilling air holes in a dielectric material, as shown in Fig. 2-2. The resulting structure has the symmetries of the diamond structure. The fabrication process for this structure is quite complicated. A mask consisting of a triangular array of holes covers a slab of material. Each hole is drilled through three times, at the angles shown. The resulting crisscross of holes below the surface of the slab, suggested by the cross hatching shown here, produces a fully three-dimensionally periodic fcc structure. Supplementing these operations with three additional drilling operations, all lying within the plane of the slab, can create the diamond symmetry.
Figure 2-2. The first 3D photonic crystal that has a full photonic band gap, and the method of constructing an fcc lattice is shown [5].

Because of the scalability of Maxwell equation, essentially all the structures can scale to the desired wavelength. The above structure can also be made at a 1.55\(\mu\)m wavelength range, which is the typical telecomm wavelength, or in the visible and infrared wavelength ranges, depending on applications.

For optical wavelengths at the micron scale, the fabrication is quite challenging, as the current microelectronics fabrication process typically has a dimension control at scale of tens of nanometers, which is a typical size for optical devices on a chip. The optical loss due to the fabrication-induced uncertainty is the main reason why photonic crystal-based devices still have very high losses and are not practically useful. As we know in the solids for electrons, in addition to defects, there are two types of disorder: compositional disorder and topological disorder. Similar to electrons, the disorder induced by
fabrication uncertainty also leads to same types of disorder for photons. According to Anderson localization model, if the periodic lattice is broken locally, the photons will be localized around these lattice sites, and the EM wave function has an exponential decay behaviors:

\[ \Psi(r) \sim \exp(-r/\zeta) \]

where \( \zeta \) is the localization length. These disorder induced photonic localized states will affect the Bloch states drastically and also lead to large optical loss in the photonic crystal based devices. The localized states induced by defects and disorder can be thought of many resonators with some quality factor \( Q \). The photonic crystal waveguide is a line defect with high \( Q \). If this waveguide can couple to many localized states discussed above, there will be a loss \( Q_l \) associated with the line defect waveguide, so the total \( Q_t \) will be:

\[ 1/Q_t = 1/Q_l + 1/Q_l \]

and the loss \( \alpha \) has the relation with \( Q_t \):

\[ v_g \alpha = \omega/Q_t \]

here \( v_g \) is the group velocity. We can obtain the waveguide loss and see the localized states induced by fabrication uncertainty has large effects on the photonic crystal waveguide loss, as loss \( Q_l \) is low.

Several methods and strategies have been proposed to circumvent this problem by designing simpler photonic crystal structures, while still having a complete photonic band gap. Recently two structures, MIT 3D and woodpile structure (Fig.2-3 and Fig.2-4) with omnidirectional band gaps were designed. For the MIT 3D structure, which is shown in
Fig. 2-3, it has the advantages that, although it is still a three-dimensional system, it is based on two-dimensional photonic structures. It can be fabricated using a layer-by-layer method, with each layer shifted by a small distance, and after three layers deposition, the same fabrication process is repeated again. It has a complete photonic band gap with a $\Delta \omega / \omega = 0.21$ for a refractive index 3.5, which is referred to a 21% mid gap range [67].

![3D photonic crystals](image)

**Figure 2-3.** 3D photonic crystals that can be fabricated with a layer-by-layer process [67].

The woodpile structure, which is shown in Fig.2-4, can also be fabricated using a planar microelectronic process, up to 17% band gap range can be achieved for a refractive index 3.5 [65-66]. The two structures we mentioned are relatively easy to be fabricated compared to other 3D structures, but it is still a very complicated process and the fabrication is very time consuming.
Figure 2-4. The woodpile photonic crystal structure that has a 17% photonic band gap at the central frequency with a refractive index 3.5 in air.

Recently, a self-assembly method was also proposed as an alternative to realize the 3D photonic crystals [68, 69]. Fig. 2-5 shows the inverse-opal structure by self-assembly. It is composed of small 1μm silica spheres. Capillary forces during drying cause assembly in the meniscus. The advantages of self-assembly structures are that the structures are almost perfect without defects and smooth in the interfaces. It has extremely flat, large area opals of controllable thickness. The drawbacks are they have a relatively small complete band gap range, and they are very sensitive to defects, so that it is not easy to control the growth and engineering of this structure.
Figure 2-5. The inverse-opal structure of silica sphere fabricated by self-assembly [69].

IBM has reported fabrication and measurement; Fig. 2-6 shows the photonic band gap measurement by measuring the reflectivity. They claim good agreement between the theory and measurement for the self-assembly structure.

Although the 3D photonic structures and fabrication process as discussed above are already simpler than other 3D structures, it is still difficult to produce the above structures or to fabricate them directly. For planar light wave circuits, the control of the light in two dimensions is enough. It was recently proposed that a 2D photonic crystal plus index guiding in the third dimension can control the light in the plane even without a complete photonic band gap [70-77].
Figure 2-6. The reflectivity measurement (red) and theory (black) of the IBM 3D inverse opal photonic crystal structure fabricated by self-assembly.

Based on these ideas, the 2D photonic crystal slabs were designed to meet the requirements. Fig.2-7 shows two different structures, one is a 2D photonic crystal by making a periodic array of dielectric rods, and another is a 2D photonic crystal by making a periodic array of holes.
Figure 2-7. 2D photonic crystal structures. (a) is the square lattice of dielectric rods. (b) is the triangular lattice of air holes. [78].

Because we don’t have a complete band gap in the third dimension, the light has to propagate within some frequency range, which is defined by the light cone. The photonic band diagram is shown in Fig. 2-8 for the above two different 2D photonic crystal slabs. If a line defect is made to form a waveguide, the propagation range defined by the light cone basically requires the light within the plane. For the third dimension, we can think of it as an effective index slab waveguide, to meet the single mode condition; the thickness of the 2D plate should be on the order of wavelength. This makes it difficult to couple the light from the optical fiber to the thin plate. There are a lot of works to address this issue and many interesting methods have been suggested.
**Figure 2-8.** The projected band gap structures for the square, triangular 2D photonic crystals lattice [78].

**One-dimensional PBG with high index contrast dielectric layers**

The reason to pursue 2D and 3D photonic crystals is to have a complete photonic band gap for all angles. Recently, omnidirectional photonic band gap structures have been discovered for even one-dimensional photonic crystals, provided the index contrast of the alternative dielectric layers is high enough and meets certain conditions [13-15]. The high index contrast dielectric layers induce a large photonic band gap for wide angles, thus
pushing the light line inside the Brewster angle, which leads to the possible realization of an all-omnidirectional reflector for a 1D system.

**Figure 2-9.** The 1D photonic crystal with high index contrast structures on the left and the perfect metal on the right.

Fig. 2-9 shows the analogy between the dielectric omnidirectional reflector and the perfect metal. For the perfect metal, it is indeed an all-omnidirectional reflector in the microwave range and this property is widely used in coaxial cable transmission. Unfortunately, metal is very lossy in the telecom IR and visible wavelength ranges,
solution for optical carriers is dielectric film. Dielectric omnidirectional reflectors are unique in terms of their wavelength scalability.

Figure 2-10. The projected photonic band gap diagram for a 1D photonic crystal with a moderate index contrast between the pairs (A) and with a high index contrast between the pairs (B). From the diagram, the omnidirectional band gap for large index contrast is shown in black [14].
Fig. 2-10 shows the projected band gap diagram for one-dimensional photonic crystals with different index contrast in (A) and (B). (A) shows projected band structure of a multilayer film, the light line and Brewster line are also plot, we find a reflectivity range with only limited angular acceptance with $n_0 = 1$, $n_1 = 2.2$ and $n_2 = 1.7$ and a thickness ratio of $h_2/h_1 = 2.2/1.7$. (B) shows the projected band structure of a multilayer film with the light line and Brewster line, here we find an omnidirectional reflectance range at the first and second band. Propagating states are in light gray, evanescent states are in white; and the omnidirectional reflectance range is in black. The film parameters are $n_1 = 4.6$ and $n_2 = 1.6$ with a thickness ratio of $h_2/h_1 = 1.6/0.8$. From Fig.2-10, we see that the absence of a complete band gap in a one-dimensional system doesn’t preclude the omnidirectional band gap. The criterion is not that there be non-propagating states in the crystal, it is that there are no propagating states that can couple to the incident wave [14].
Figure 2-11. Range–midrange ratio for omnidirectional reflection, plotted as contours. For the solid contours the optimal value of $d_i/a$ was chosen. The dashed curve is the 0% contour for the case of a quarter-wave stack [13].

Material choices for the dielectric layers

From the criterion of the appearance of the omnidirectional band gap for one dimensional photonic crystal system, for silicon-based materials and CMOS compatibility consideration, we find two dielectric material systems meet the requirements. One is the Si/SiO$_2$ dielectric pair, with the refractive index $n_{Si} = 3.5$, $n_{SiO}_2 = 1.46$, which has an almost 30% omnidirectional band gap range. Another dielectric pair system for CMOS compatible materials is Si/Si$_3$N$_4$, which has $n_{Si} = 3.5$, $n_{Si3N4} = 2.0$, and this pair has more
than a 20% omnidirectional band gap range. We show the projected band gap diagram for the Si/SiO$_2$ system in Fig. 2-12.

**Figure 2-12.** The projected band gap diagram for a silicon based omnidirectional PBG structure.

The Si/SiO$_2$ is used as a dielectric pair.
Figure 2-13. The reflectivity spectrum for a Si/SiO₂ 1D photonic crystal, which shows an all angle photonic band gap for both TE and TM modes.

**Fabrication and measurement of silicon-based PBG**

We fabricated a 32 layer Si/SiO₂ one-dimensional photonic crystal through RF-magnetron sputtering in a Kurt J. Lesker CMS 18 UHV sputtering system. The Si and SiO₂ layers are deposited using Si and SiO₂ targets and have quarter wavelength thickness, respectively, at room temperature.
Figure 2-14. FTIR reflectivity measurements on a 32 layer Si/SiO₂ PBG structure for wide angles up to 70 degrees, which shows a wide-angle photonic band gap.

As we can see from Fig. 2-13, the omnidirectional band gap range is determined by the left band edge at normal incidence and by the right band edge of TM polarized light at 90-degree incidence. We measured the reflectance of a 32 layer PBG for wide-angle
incidence for TM polarized light up to 70 degrees, which is the limit of our angular measurements using FTIR. We can clearly see the wide-angle band gap range from our measurement in Fig. 2-14, which is in agreement with the simulation. The Si/Si$_3$N$_4$ system also exhibits a large omnidirectional range with more than 20% of the central frequency. In Fig. 2-15, we show the measurement for 5 pairs of Si/Si$_3$N$_4$ dielectric layers using a LPCVD deposition method and simulation.

![Graph showing % Reflectance vs Wavelength for 5 pairs Si$_3$N$_4$/Si](image)

**Figure 2-15.** Absolute reflectivity measurements and simulation for the 5 pair Si/Si$_3$N$_4$ PBG structure.
In this thesis, we will use the two material systems to demonstrate the application of CMOS compatible and silicon based PC clad waveguide, multichannel optical filters with tunability, and photonic quasicrystal structures in the following chapters, which forms the foundation of this thesis on silicon based photonic structures.
Chapter 3

Microcavity states and localization in silicon based photonic band gap structures

The microcavity states within the photonic band gap structures are discussed in this chapter. One of the most important challenge for the PBG structures is how to engineer the defect states, in this chapter, the localization properties of the defect states are studied in detail, strong EM field confinement in the microcavity states are discussed. We will first introduce the general properties of the microcavity states in a PBG structure, including 2D and 3D systems. Then we focus on the one-dimensional system with high index contrast dielectric layers. The fabrication process with CMOS compatibility is also addressed.
Microcavity states in photonic band gap structures

When there is an impurity in a perfect periodic semiconductor structure, it introduces localized states for electrons. Depending on the doping level of the impurity states, shallow localized states or deep-trapped localized states can be made, which form the foundation for modern microelectronics [79]. Similarly, as discussed in the previous photonic periodic structures, when there is a defect in a periodic system, photonic localized states will be introduced within the photonic band gap. Whereas a difference in local lattice potential introduced by defects leads to the microcavity states.

![Diagram of electric field distribution in a defect layer](image)

**Figure 3-1.** Illustration of the electric field distribution inside a defect layer in a 1D photonic crystal.
Fig. 3-1 shows a one-dimensional PBG structure with one layer thickness increased, so that it breaks the symmetry of the periodic system. Normally there is a photonic band gap within certain wavelength range, when there is defect in the original periodic lattice, a localized state within the photonic band gap will appear.
Figure 3-2. The appearance of a localized state within the photonic band gap when there is a defect layer. (a) is the perfect periodic crystal, and (b) is the same structure except that a defect layer is inserted into the photonic crystal.

Fig. 3-2 shows the formation of the localized state within the band gap. We here use the Si/SiO₂ system as an example. The structure is based on the high index contrast Si/SiO₂ dielectric pairs on a silicon substrate, with a quarter wavelength, and a central wavelength at 1.55μm. When the structure is perfectly periodic:
We can see from the reflectivity spectrum in Fig. 3-2 (a) that there is a large photonic stop band from 1.2 μm to 2.2 μm, with a 1000 nm band gap range. If the thickness of one layer is increased to half an optical wavelength and inserted into the original periodic structure:

\[ \text{SiO}_2/\text{Si} / \text{SiO}_2/\text{Si} / \text{SiO}_2/\text{Si} / \text{SiO}_2/\text{Si} / \text{SiO}_2/\text{Si} / \text{SiO}_2/\text{Si} / \text{SiO}_2/\text{Si} \]

There will then be a localized state within the band gap, as shown in Fig. 3-2 (b). In Fig. 3-1, we also show the electric field distribution at the localized state. The half wavelength cavity layer forms a symmetric resonance state. It is strongly localized in the defect layer and decays rapidly with distance becoming farther from the defect layer.

**Localization properties in 2D and 3D photonic band gap structures**

For 2-dimensional and 3-dimensional photonic band gap structures, not only can point defects be formed inside the periodic structures, but a line defect can also be formed, and this line defect can be a waveguide and make a sharp bend [19-21]. The basic principle is the same as we have discussed above with a one-dimensional system. For the last decade, much effort has been devoted to 2D and 3D systems, as richer defect engineering is promising to realize the integrated optical circuits at the micro scale on a chip. Due to fabrication complexity and scattering loss, the waveguide loss based on a 2D or 3D system is still too high. Fortunately, an all angle reflector based on high index contrast
dielectric pairs [14-15], which uses one dimensional structure, make it promising to realize the 2D and 3D functionality, while make the fabrication process much simpler. This forms the foundation for the next two chapters in this thesis and we will discuss them in detail [80-83]. In the following, we will give a brief introduction to recent work on the 2D and 3D systems.

Figure 3-3. Point defect states within the photonic band gap when the size of one rod is reduced (left) or increased (right) [7].
In Fig. 3-3, a point defect is formed inside the 2-dimensional photonic crystal, the left figure shows an air defect formation. By reducing the rod size, we can see the localized state start from the lower photonic band edge and finish at a state close to a midgap state. The right figure shows dielectric defect formation caused by increasing the rod size. The localized state in this case starts from the upper photonic band edge and finishes at a state close to the lower band edge. Similar to the acceptor and donor states for electrons, the air defect is like an acceptor photonic state and the dielectric defect is like a donor photonic state.

**Strong field confinement at the localized state**

\[ E_z \]

**Figure 3-4.** The electric field distribution when a point defect is created inside a 2D photonic crystal lattice [7].

We also illustrate the electric field distribution in Fig. 3-4, all the electric fields are strongly localized around the defect site. Depending on the geometry of the defects,
monopole defect states and dipole defects can be made. The rapid decay of the electric field due to the exponential behavior is clear, and only one or two lattices are enough for the electric field to decay completely. The engineering of the point defects have many important applications. For example, an antenna for microwave applications can be designed to have different polarization properties based on requirements. Defect engineering based on photonic crystals gives more design alternatives. When optically active materials are embedded into the defect sites, the strong light-matter interaction will enhance the light emission and make it promising to realize low threshold laser. Nonlinear materials can also be embedded into the defect sites and many nonlinear optical properties can be enhanced due to the strong interaction between the light and materials in the defect, such as second harmonic generations (SHG), optical bistability, multistability, and optical switching [84-98].

We have discussed some interesting properties about the point defects in a 2D photonic crystal system. Not only can point defects be made, but also line defects can be made to form a waveguide, and in this way, light can be strongly localized within the line defect.
Figure 3-5. A line defect is formed to make a waveguide by removing the rods along the line inside the 2D photonic crystal [19].

Fig. 3-5 shows a line defect in a 2D photonic crystal with one line of rods removed. The electric field localization in the line defect is illustrated, which forms a waveguide. Like the air defect and dielectric defect discussed above, increasing the rod size or changing the dielectric constants along the line can also form the dielectric line defect. The most important property of line defects in a 2D photonic crystal system is the possibility to create a sharp bend, which is the most important motivation to inspire many groups to pursue the waveguide in a 2D photonic crystal system.
Figure 3-6. The 100% transmission through the 90-degree sharp bend that is calculated for a 2D photonic crystal [19].

Illustrated in Fig. 3-6, theoretically 100% transmission bending using the line defects in 2D photonic crystal can be realized. For a 3D system, similar point defects and line defects in three-dimensional space can also be designed and engineered.
Figure 3-7. The point defect and line defect inside the 3D photonic crystals.

In the following, we will mainly focus on our work on defects in the silicon-based one-dimensional photonic crystals with high index contrast dielectric layers. The omnidirectional reflectivity due to high index contrast and the defect engineering will be discussed. We use different material systems as a defect layer, which will be also addressed in detail in the following sections.

Fabrication and measurements on high index contrast one-dimensional PBG structures with defects

Here, we will focus on two examples for microcavity states in a one dimensional Si/SiO$_2$ photonic band gap system. One is the molecular beam epitaxy (MBE) GaN layer as a defect layer. GaN is a wide band gap material for efficient doped light emission; another example is a SiO$_2$ layer as a defect layer by changing the layer thickness.

The GaN micro cavity structure is fabricated as follows:
The thickness of the Si and SiO₂ layers are at quarter wavelength, with the center wavelength at 1550nm. This sample is deposited by sputtering at room temperature. The GaN layer is deposited by MBE, with a thickness at 380nm. GaN layer’s refractive index is calibrated as 2.11 at 1550nm. The reflectivity spectrum is measured by Fourier Transformed Infrared Spectroscopy (FTIR), using CaF₂ as a beam splitter and MCTA as a photo detector. The responsivity of MCTA covers the infrared to far infrared wavelength range.
Figure 3-8. The micro cavity state within a photonic band gap when a GaN layer is inserted into periodic Si/SiO₂ dielectric stacks. (a) is the reflectivity measurement, (b) is the simulation.

The reflectivity spectrum is shown in Fig. 3-8, where (a) is the measurement result by FTIR. Here the defect state within the band gap is at 1560nm, and a small dip appears in the band gap range from 1200nm to 2200nm, which is the original stop band without the GaN layer. When the GaN layer is inserted into the periodic structure, a defect is formed.
(b) is the simulation result based on the fabricated structure, and a defect state at 1550nm appears in the stop band, which is in agreement with measurement, which confirms that the refractive index of GaN layer is 2.11 at 1550nm. From the measurement result, the full width of half maximum (FWHM) is 40nm, which means that the quality factor is 40. The simulation in Fig. 3-8 (b) shows that the FWHM at 1550nm is 26nm, which means the quality factor is 59. The application of the high quality GaN defect layer grown on the Si/SiO₂ based system is very promising to realize a silicon based light emitter, as Er can be doped into the GaN layer and the light emission from Er is in resonance with the defect state [153-154].

(a)

![SiO₂ layer as microcavity layer](image)
Figure 3-9. The micro cavity state within the photonic band gap when a SiO$_2$ layer is inserted into periodic Si/SiO$_2$ dielectric stacks. (a) shows the FTIR reflectivity measurement, (b) shows the simulation.

We also fabricated a structure with SiO$_2$ as the defect layer by changing the thickness of the previous quarter wavelength, the structure is as follows:
The structure with SiO₂ as a micro cavity layer was deposited at MIT’s Microsystems Technology Laboratory (MTL). The SiO₂ layer was deposited using a Plasma Enhanced Chemical Vapor Deposition (PECVD) method at low temperature 80°C; the Si layer was deposited by e-beam evaporation at room temperature. The refractive index of SiO₂ by PECVD is measured as 1.45 and the refractive index of Si by e-beam is 3.45. The periodic layers are designed as a quarter wavelength with the center wavelength at 1550nm. The micro cavity SiO₂ layer is deposited by PECVD by increasing the deposition time, so that the thickness is increased from 260nm to 400nm, which breaks the original lattice symmetry and a defect layer is formed.

We also measured the reflectivity using FTIR for this system. Fig. 3-9 (a) shows the reflectivity measurement for this structure. Here the stop band is from 1200nm to 2200nm, and the defect state, which appears inside the band gap, is at 1400nm, which is consistent with the simulation shown in Fig. 3-9 (b). The difference between measurement and simulation is the quality factor, which is 30 by measurement, while the simulation shows the quality factor should be 200. The almost seven times difference tells us the film quality using the present method is not very good. Actually, the SiO₂ film and the Si film are both amorphous layers, which means we can develop the deposition method to obtain high quality micro cavity layer. Nevertheless, the appearance of the defect states and of the photonic band gap in the structure is qualitatively in agreement with the design. We summarized our results in the following table:
Table 3-1 Summary of quality factor (Q) for GaN and SiO$_2$ as cavity layer

<table>
<thead>
<tr>
<th>Cavity layer</th>
<th>Q (Simulation)</th>
<th>Q (Experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN (380nm)</td>
<td>59</td>
<td>40</td>
</tr>
<tr>
<td>SiO$_2$ (400nm)</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>

(a)

Multichannel Microcavity

![Graph showing reflectivity (% vs. wavelength (nm))](image-url)
Figure 3-10. The multichannel cavity states inside the photonic band gap by engineering the cavity size and refractive index. (a) is the measurement and (b) is the simulation. From (a), the cavity layer thickness variation is about 7%.

For the microcavity states in photonic band gap structures, not only can one localized state be created, but also multiple localized states can be created for future applications to
multichannel filters in WDM system. In Fig. 3-10, a large cavity layer is inserted into the periodic Si/SiO\(_2\) stacks, multiple localized states appear in the original photonic band gap, the free spectral range between the localized states is very large, which is important for the multichannel application, so that the different channel will not mix each other. From the measurement result, as we used polymer as large cavity layer, the low Q and uneven resonance behaviors are due to the surface roughness of the thick cavity film. It is therefore critical to control the cavity layer thickness, surface uniformity and surface roughness and correlation to achieve high Q at the resonance wavelength.

As a design rule for the multichannel cavity states, the resonance states in the PBG are:

\[ v_m = \frac{c}{(2nL)} m, \quad m = \text{integer} \]

where \( v_m \) is the optical carrier frequency and falls within the photonic band gap, \( L \) is the cavity length and \( n \) is the cavity index. In this way, we can design the appropriate photonic band gap and cavity size for multichannel optical filters. For the quarter wavelength stacks, the band gap is proportional to the index contrast of the high and low refractive index layers:

\[ \Delta \omega/\omega = 2/\pi \times \Delta n/n \]

where \( n \) is the average index of the high and low dielectric layers.

In summary, in this chapter we have studied the localized states in the photonic band gap by creating defects in a periodic structure. Specifically, we concentrate on 1D photonic band gap structures with high index contrast dielectric layers, like Si/SiO\(_2\), Si/Si\(_3\)N\(_4\), and Si\(_3\)N\(_4\)/SiO\(_2\) pairs. All of them are silicon based and CMOS compatible materials, which is promising to realize the integrated circuits in the future.
Chapter 4

On-chip Silicon based Photonic Crystal Cladding Waveguide

A Photonic Crystal (PC) cladding waveguide is developed based on the Photonic Band Gap (PBG) principle. A low index core (e.g. SiO₂) or a hollow core waveguide can be realized with our PC cladding waveguide structure. The waveguide is compatible with the CMOS process. We used prism coupling to the asymmetric PC waveguide, and the measured effective mode index is less than that for both Si and Si₃N₄ cladding layers, which is a clear demonstration of the photonic band gap guiding principle. We also fabricated and measured the PC cladding channel waveguide. Potential applications include high power transmission, low dispersion, a thin cladding thickness and nonlinear properties engineering.
Introduction

Many future technologically important devices depend on guiding light on chip. Microphotonics, which is based on the current microelectronics process technology, is becoming one of the most promising methods to solve the bandwidth bottleneck due to RC delay of electronic signals. Photons, instead of electrons, will become the next information carriers, not only for telecommunications, but also for various other technologies, like bioMEMS, bioMedical applications, and sensors.

Traditionally, silica optical fiber is the de-facto standard for the transportation of light. Such a fiber has higher refractive index core than the cladding layers and the guiding principle is based on total internal reflection (TIR). However, many future important devices require light guiding in low index materials or even in a hollow core, so that the flexibility to choose suitable materials is becoming more important. In this chapter, we will discuss a new way to guide light on chip, which uses a photonic band gap guiding principle instead of TIR.
Figure 4-1. Comparison of the guiding principle between PBG guiding and index guiding

In Fig. 4-1, the comparison between the index guiding waveguide and photonic band gap guiding is illustrated. The propagation constant $\beta$ determines whether light propagates or is evanescent. If $kn_1 < \beta < kn$, where $k$ is the vacuum wave constant and $n_1$ is the refractive index of the cladding material, $n$ is the refractive index of core material, then conventional TIR occurs. But when $\beta$ is even smaller than $n_1$, only photonic band gap principle can be used to guide the light. In this way, light can be guided in low index core materials or even in air, and it basically relieves the constraints on the traditional TIR method. As shown in Fig.4-1, if the stacks have a PBG for a range of $\beta$ at a given optical wavelength, two regimes of PBG guidance can be identified. In the first, light propagates
in the layers of a high index material but is evanescent in the low index material. The high index layers support guided modes. Resonant tunneling between adjacent high index layers permits leakage of light through them, provided $\beta$ lies within the pass bands. The width of the pass bands depends on the strength of the coupling between the layers. Between the pass bands lie band gaps. If a high index core layers with different widths support a mode inside a band gap, it is not resonant with the other layers and light leakage by tunneling is frustrated. The frustrated tunneling form of PBG thus strictly guides the mode. In the second regime of PBG guidance, light can propagate in a low index core material and photonic band gap guidance is satisfied when $\beta < n_1$ and $\beta < n_2$, where $n_1$ and $n_2$ are the dielectric cladding pairs.

There are a lot of works focusing on guiding light in hollow core fibers for long haul communications [10-16, 99-129]. These structures are expected to show wide wavelength flexibility, because for hollow core, the waveguide loss is no longer limited by materials properties. Following the fiber drawing process, many attempts are being tried in different groups all over the world; Fig.4-2 and Fig.4-3 show different types of photonic crystal fibers.
Figure 4-2. Design of different types of photonic crystal fibers

Figure 4-3. SEM pictures of different types of photonic crystal fibers.
In Fig.4-2, a) shows a fiber with a pure silica core surrounded by a reduced index photonic crystal cladding material. The guidance is by modified total internal reflection. b) is an air-guiding fiber in which light is confined in a hollow core by the band gap of the 2D air-glass photonic crystal cladding. In c), the light is confined to a low index region by a photonic band gap, but the core is made of pure silica, while the holes in the cladding are filled with a high index liquid. d) shows a hollow cylindrical multi-layer fiber with an all-solid cladding. In these pictures, white represents air, blue represents a low index solid such as silica, and red represents a high-index material. Fig. 4-3 shows the cross section SEM pictures of fabricated photonic crystal cladding fibers. a) is a band gap guiding fiber in which light is trapped in a ring of glass around a central hole. b) is a strongly TIR guiding photonic crystal fiber. c) is a photonic crystal fiber formed from commercial SF₆ glass. d) is a hollow core photonic band gap fiber. All these fibers are fabricated by a similar drawing process to that for traditional optical fibers, which is shown in Fig. 4-4.
Figure 4-4. A stack of glass tubes and rods (a) is constructed as a macroscopic “preform” with the required photonic crystal structure. It is then fused together and drawn down to fiber (c) in two stages using a standard fiber-drawing tower. To soften the silica glass, the furnace (b) runs at 1800° to 2000°C.

In this chapter, we will discuss the photonic crystal cladding waveguide on chip. The fabrication process is quite different from the fiber drawing process, and CMOS
compatibility is emphasized, as it is promising to integrate these new PC cladding waveguide on chip with other components.

**Silicon-based photonic crystal cladding waveguide with high index contrast dielectric layers**

In this work, we developed a new silicon-based waveguide with low refractive index materials (SiO$_2$ or air) as a core, with stratified high index contrast dielectric layers as cladding, and the guiding mechanism is based on Photonic Band Gap (PBG) principle. We use Si/SiO$_2$ or Si/Si$_3$N$_4$ dielectric pairs as the cladding layers. Since they have high index contrast, the photonic band gap range is very large. Also, they have the omnidirectional band gap range, which means they are comprised of a perfect reflector around the designed wavelength range (e.g. 1550nm) for both TE and TM modes from any incident angle. The omnidirectional bandgap is not strictly necessary for guiding the light in a low index core, but its presence strongly enhances the confinement of the light in the low index core and correlated with the polarization-independent and large bandgap range around the designed wavelength. Because of the high index contrast between Si/SiO$_2$ (2.0) and Si/Si$_3$N$_4$ (1.5), the cladding thickness is less than 2μm, which is much thinner than the conventional silica bench waveguide.
Design of different types of PC cladding waveguide

The silicon based PC cladding waveguide can be designed as a slab waveguide, ridge waveguide and channel waveguide, which are in parallel to the index guiding waveguide design. The different types of PC cladding waveguides are shown in Fig. 4-5.

![Asymmetric waveguide](image)

![Symmetric waveguide](image)

![PBG Rib](image)

![PBG Channel](image)

**Figure 4-5** The four categories of PC cladded waveguides with high index contrast layers and low index core materials.

Fig. 4-5 (a) is the Asymmetric PC cladding waveguide, where the waveguide core is a low index material, with one side clad by high index contrast dielectric layers. Fig. 4-5
(b) is the Symmetric PC cladding waveguide, with both sides clad by high index contrast dielectric layers, Fig. 4-5 (c) is the PC cladding Rib waveguide, with the shallow etched core, and Fig. 4-5 (d) is the PC cladding channel waveguide with the fully deep etching core.

For the PC cladding channel waveguide, depending on the structure, there are several designs, which are illustrated in Fig. 4-6.

Figure 4-6. Different types of PC cladded channel waveguides.
For all the above different types of PC cladding waveguide, form the practical realization and fabrication perspective, the Asymmetric PC cladding waveguide, Symmetric PC cladding waveguide, PC channel waveguide B and PC channel waveguide C are the most promising to be fabricated by current microelectronics process technology and can be CMOS compatible.

In the following, we will use the PC cladding channel waveguide as an example to study the mode structure and dispersion relationship. We will see that they are very similar to the metallic waveguide.

**Mode structure and dispersion for the PC channel waveguide**

Maxwell's equations in a waveguide that has a core of linear material with index $n$ are:

$$-\nabla_\perp^2 \mathbf{E} = \left[ \left( \frac{n \omega}{c} \right)^2 - k_x^2 \right] \mathbf{E},$$

Where $z$ is the direction of uniform translational symmetry.

If the core of the waveguide is surrounded by perfectly conducting material – metallic waveguide, we can divide our problem into TE ($E_z = 0$) and TM ($H_z = 0$) polarizations. For a rectangular cavity of dimensions $l_x$ by $l_y$ and index $n$, solutions will be of the form:

$$\omega = \frac{1}{n} \sqrt{k_x^2 + \omega_{pq}^2},$$

where,
\[ \omega_{pq}^2 = \left( \frac{p}{2l_x/a} \right)^2 + \left( \frac{q}{2l_y/a} \right)^2. \]

TEM modes \((p = q = 0)\) are not allowed due to the fact that the metal cavity has an equipotential surface unable to support a non-trivial TEM mode. TE modes will have at least one non-zero quantum number, whereas TM modes are required to have both be non-zero. These findings are summarized in Fig. 4-7.

![Dispersion relations of metallic channel waveguide (lines) and PC cladding channel waveguide (dots). They have very similar dispersion relations.](image)

**Figure 4-7.** Dispersion relations of metallic channel waveguide (lines) and PC cladding channel waveguide (dots). They have very similar dispersion relations.

For a PC cladding waveguide structure, the two key modifications from the theory pertaining to a perfect conductor are the losses associated with a finite number of layers, and a phase-shift that changes with frequency within the gap. The first factor can be made arbitrarily small with a sufficient number of cladding layers. The second factor, on the
other hand, cannot be eliminated. The phase shift will be less than \( \pi \) for the lower half of the gap, and above \( \pi \) in the upper half of the gap. Qualitatively, that leads us to predict that modes predicted by the theory for the metallic waveguide will be "pushed" toward the center of the gap. The results obtained numerically (Fig. 4-7) show modes that look quite similar to those predicted for the metallic waveguide, as well as dispersion relations, which are close to the metallic predictions but still differ from them in the qualitative way mentioned above. The mode structure and electric field confinement are illustrated in Fig. 4-8, which shows the most of the electric field are confined in the low index core materials.

**Figure 4-8.** The mode structures for PC cladding channel waveguide for some higher order modes. We can see the strong confinement of the field in the low index core.
Asymmetric PC cladding waveguide

In this section, we fabricated an asymmetric PC cladding waveguide with SiO\textsubscript{2} as the low index core layer and Si/Si\textsubscript{3}N\textsubscript{4} as the high index contrast cladding pairs with quarter wavelength thickness. To demonstrate the photonic band gap guiding principle, we utilized the prism coupling method to couple the light to the asymmetric PC waveguide. In this way, the effective refractive index of the propagation mode can be measured, which demonstrates that the PBG guiding of light in the low index core is realized.
Figure 4-9. Illustration of the Asymmetric PC cladding waveguide, which was fabricated at the Microsystems Technology Laboratory at MIT.

An asymmetric PC waveguide configuration is illustrated in Fig.4-9. The SiO₂ guiding layer (with refractive index $n_g$) is between the air ($n_a=1$) and the high index contrast Si₃N₄ ($n_1$) and Si ($n_2$) cladding pairs, which are deposited on the silicon substrate. For a conventional dielectric optical waveguide, it is not possible to guide light in low index SiO₂ core materials. In the following, we will show that, utilizing the photonic band gap principle, guided modes do indeed exist, provided the wavelength is within the photonic band gap range of the one dimensional Si/Si₃N₄ photonic crystal. Due to the large index
contrast of the Si and Si$_3$N$_4$ pairs, the simulation shows that the guided modes are very robust, as there is a large photonic stop band for both TE and TM modes at wide incident angles.

In the case TE modes, the only field components are $E_y$, $H_x$, and $H_z$. Assume the light is propagating along the z direction, we can take $E_y(x, z) = E_y(x) e^{i \beta z}$. The solution is as following:

$$E(x) = \begin{cases} \exp(q_a(x+t)), & x < -t \\ c_1 \cos(k_g x) + c_2 \sin(k_g x), & -t \leq x \leq 0 \\ E_K(x) \exp(i K x), & x \geq 0 \end{cases}$$

Where,

$$E_K(x) = [(a_0 e^{ik_1 x(\text{N} \cdot \Lambda)} + b_0 e^{-ik_1 x(\text{N} \cdot \Lambda)}) e^{-ik(x - n A)}] e^{i K x},$$

and $q_a = \sqrt{\beta^2 - (\omega n_d / c)^2} \cdot \Lambda / 2$, $k_g = \sqrt{((\omega n_d / c)^2 - \beta^2) / 2}$, $t$ is the thickness of waveguide core, $\Lambda$ is the period of the cladding layers.

From the above wave equations, the guided modes and their dispersion relations can be calculated. In Fig.4-10 (a), the electrical field intensity distribution is shown for the fundamental TE mode. It is clearly seen that the electric field is strongly confined in the low index SiO$_2$ core, and decays rapidly in the cladding pairs. In previous works, small index contrast dielectric pair structures have been studied in terms of Bragg reflection. Here, we emphasize that, due to the large index contrast between the Si and Si$_3$N$_4$ pairs, a large photonic bandgap with a wide incident angle can be realized and are crucial for the following important characteristics, which will be discussed in the following sections.

We also simulated the light propagation in the PC waveguide using FDTD method. Fig.4-10 (b) is a snapshot of the guided mode propagation. It is in consistent with the electric
field intensity calculation, which shows that the light is strongly guided in the low index SiO$_2$ core layer.

Figure 4-10. (a) The propagation mode profile for the asymmetric PC cladding waveguide for the fundamental TE mode. It is clearly seen that the electrical field is strongly confined in the SiO$_2$ core. (b) The FDTD simulation of the asymmetric PC waveguide, which shows the light guiding in the low index SiO$_2$ core.
Fabrication of the Asymmetric PC cladding waveguide

The PC cladding waveguide is fabricated using CMOS compatible process. Starting from 6-inch Si wafers, the 194nm Si₃N₄ layer is deposited at 775C by a Low Pressure Chemical Vapor Deposition (LPCVD) method, with a deposition rate at 23A/min. The 110nm Poly-Si layer is deposited at 625C by the LPCVD method, with a deposition rate at 100A/min. The oxide core is deposited by LTO (Low temperature oxide), followed by 850C thermal annealing to form a stoimetric and solidified oxide. Different oxide thickness at 4μm, 5μm and 6μm are deposited by LTO followed by a thermal anneal. Chemical Mechanical Polishing is used to make the oxide core smooth to reduce the scattering loss by surface roughness. Fig. 4-11 (a) is a TEM picture of the Asymmetric PC cladding waveguide; Fig. 4-11(b) is a magnification of the PC cladding layers. It is clearly seen that by using LPCVD deposition method, accurate thickness control of the Si and Si₃N₄ layers can be achieved. The interface between the two dielectric layers is very smooth, which is important for good waveguide performance.
Figure 4-11. (a) The TEM image of the asymmetric PC cladding waveguide, including the bottom cladding PBG layers (Si/Si₃N₄) and the SiO₂ core. (b) a magnification of the image of PBG layers, which shows good thickness control and a smooth interface between the Si and Si₃N₄ layers.

Figure 4-12. The TEM image of the asymmetric PC cladding waveguide
We use Si/Si$_3$N$_4$ layers as PBG cladding pairs, hence the refractive index contrast between the Si (3.5) and Si$_3$N$_4$ (2.0) pairs is high ($\Delta n=1.5$), a large photonic band gap and an omnidirectional band gap are expected for this system. Only a few layers are enough to achieve more than 99% absolute reflectivity. This is crucial for the performance of this kind of waveguide based on the PBG guiding mechanism, as in principle, only infinite layers can reach 100% absolute reflectivity and truly guided modes exist. In practice, all the modes are leaky modes with a complex propagation constant. This is why a high index contrast system is superior, few layers means that more practical devices can be achieved within fabrication process tolerances.

**Properties of high index contrast dielectric layers and perfect absolute reflectivity**

In Fig.4-13, the measured absolute reflectivity of 5 pairs of Si/Si$_3$N$_4$ layers is shown in dashed line. The transfer matrix method is used to simulate the reflectivity for 5 Si/Si$_3$N$_4$ pairs, which is shown in solid line. The measurement and simulation are in very good agreement with each other for wavelengths larger than 1000nm, particularly, for the stop band from 1200nm to 2000nm. For our fabricated PC cladding waveguide, 6 pairs are deposited. We also compared the measurements for 6 and 5 pairs of Si/Si$_3$N$_4$ layers, and it is clear that the absolute reflectivity within the stop band for 6 pairs are higher than for 5 pairs, the band edge is also sharper, which is shown Fig.4-14.
Figure 4-13. The measurement and simulation of the absolute reflectivity of 5 pairs of Si/Si$_3$N$_4$ layers.
Figure 4-14. Measurement of the absolutely reflectivity of 5 pairs and 6 pairs of Si/Si$_3$N$_4$ layers.
**Prism coupling to the Asymmetric PC cladding waveguide**

To demonstrate the photonic band gap guiding mechanism, it is important to directly measure the effective index of the guiding mode. For the asymmetric PC waveguide, the prism-coupling method is utilized to couple the PBG propagation mode. In this way; the effective index of the propagation mode can be measured, which will give direct proof of the PBG guiding mechanism. The prism coupling to the PBG waveguide set up is illustrated in Fig.4-15. The prism is mounted on the asymmetric PC waveguide, and the air gap between the prism and the PC waveguide is about 100nm. Laser light with our interesting wavelengths (1300nm and 1550nm in our case) is coupled into the prism; the laser light will be reflected and collected by a detector if there is no mode coupling.

![Diagram](image)

**Figure 4-15.** The illustration of the set up for the prism coupling to the asymmetric waveguide.
The prism and the PC waveguide are mounted on a rotation stage, when the rotation stage is rotated to a certain angle, there is mode coupling between the prism and the PBG waveguide due to phase matching. A very sharp dip is observed at this angle, which is shown in Fig.4-16. In this way, the mode index is obtained. Fig. 4-16 shows the prism coupling to the Asymmetric PC cladding waveguide for 4μm oxide core materials. Five dips in the light intensity are observed, which represents the five propagation modes, the measurement results of the effective mode index are 1.4383, 1.4173, 1.3812, 1.3287 and 1.2577. We also calculated the multimode effective index for the 4μm Asymmetric PC cladding waveguide. Five propagation modes are found and the simulation results are 1.443, 1.422, 1.386, 1.335 and 1.266, which are in very good agreement with the experiment. In Fig. 4-17, the prism coupling to the Asymmetric PC cladding waveguide for a 5μm oxide core are also illustrated. Six propagation modes within the band gap are observed. The effective propagation mode indexes are measured as 1.4435, 1.4258, 1.4009, 1.3647, 1.3167 and 1.2556.
Figure 4-16. The measurement of the mode coupling between the prism and the PC cladding waveguide for 4um oxide core. Five dips represent the five propagation modes; the effective mode index is measured as 1.4383, 1.4173, 1.3812, 1.3287 and 1.2577.
Figure 4-17. The measurement of the mode coupling between the prism and the PC cladding waveguide for 5um oxide core. Six dips represent the six propagation modes; the effective mode index is measured as 1.4435, 1.4258, 1.4009, 1.3647, 1.3167 and 1.2556.

Demonstration of the photonic band gap guiding principle

The effective index of the fundamental propagation TE mode at $\lambda=1550\text{nm}$ for a 5\textmu m core oxide asymmetric PBG waveguide is measured as $\beta_{TE1550\text{nm}}=1.4435$. This is less than those of cladding layers, i.e.,

$$\beta_{TE1550\text{nm}} < n_{\text{Si$_3$N$_4$}}, \quad (n_{\text{Si$_3$N$_4$}} = 2.0).$$

$$\beta_{TE1550\text{nm}} < n_{\text{Si}}, \quad (n_{\text{Si}}=3.5).$$
This is clear demonstration of the PBG guiding principle, since for a conventional index guiding waveguide, the effective mode index must be larger than the refractive index of the cladding layers. From this method, we also find a way to couple the light to the PBG guiding mode. The measured effective mode index is also in good agreement with the calculation, which is 1.431 at 1550nm for the TE mode. The waveguide loss is also measured, which is 0.42dB/cm loss at $\lambda=1550$nm.

**Figure 4-18.** The waveguide loss measurement for a PC cladding waveguide with a 5µm oxide core for the fundamental TE mode at 1550nm. The loss is measured as 0.42dB/cm.
Figure 4-19. The waveguide loss measurement for a PC cladding waveguide with a 5µm oxide core for the fundamental TM mode at 1550nm. The loss is measured as 0.47dB/cm.

For the TM mode, the effective mode index is measured as $\beta_{\text{TM1550nm}} = 1.4408$ at 1550nm, the waveguide loss for TM mode is 0.47dB/cm. We also measured the effective mode index and propagation loss at 1307nm for both fundamental TE and TM modes, for
our 5\textmu m oxide core asymmetric PBG waveguide, which has $\beta_{TE_{1307}\text{nm}}=1.4325$ with a propagation loss of 0.24dB/cm and $\beta_{TM_{1307}\text{nm}}=1.4425$ with a propagation loss 0.69dB/cm.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4-20.png}
\caption{The waveguide loss measurement for a PC cladding waveguide with a 5\textmu m oxide core for the fundamental TE mode at 1307nm, the loss is measured as 0.24dB/cm.}
\end{figure}
**Figure 4-21.** The waveguide loss measurement for a PC cladding waveguide with a 5μm oxide core for the fundamental TM mode at 1307nm, the loss is measured as 0.69dB/cm.

From above results, an operation wavelength range for both the TE and TM modes is demonstrated, which is due to the large photonic band gap for both TE and TM modes induced by the high index contrast between the Si and Si$_3$N$_4$ layers. Furthermore, the omnidirectional band gap in the Si and Si$_3$N$_4$ system is very helpful to confine the light in the low index core for both the TE and TM modes within a large wavelength range, as demonstrated above. Compared with an ARROW waveguide and a low index contrast Bragg waveguide, the superior advantage of the large photonic band gap and omnidirectional band gap are clearly demonstrated.
In summary, a photonic crystal cladding waveguide with large index contrast dielectric layers is developed. Prism coupling to the asymmetric PC cladding waveguide is achieved and the effective index of the propagation mode is measured, which demonstrated the photonic band gap guiding principle. Light guiding in the low index core is achieved with low loss for both TE and TM modes, with a large operation wavelength range. Thin PC cladding layers due to the large index contrast between the Si and Si$_3$N$_4$ layers indicates an advantage over the traditional silica bench waveguide.

**PC cladding channel waveguide**

As discussed in the previous section, the PC cladding channel waveguide can be designed as different structures. Of all these channel waveguides, PC cladding channel waveguide B and PC cladding channel waveguide C are possible to be realized by a CMOS compatible process, as the fabrication process is basically planar. In the following, we will concentrate on the PC cladding channel waveguide C. Depending on the low index core materials, it can be hollow or oxide. For the hollow core waveguide, a more complicated fabrication process needs to be developed, like wafer bonding. So here we will focus on the oxide core materials with Si and Si$_3$N$_4$ cladding pairs.

Similar to the Asymmetric PC cladding waveguide, starting from 6-inch Si wafers, the 194nm Si$_3$N$_4$ layer is deposited at 775C by a Low Pressure Chemical Vapor Deposition (LPCVD) method, with a deposition rate at 23Å/min. The 110nm Poly-Si layer is
deposited at 625C by LPCVD method, with a deposition rate at 100A/min. The oxide core is deposited by LTO (Low temperature oxide), followed by 850C thermal annealing to form a stoimetric and solidified oxide. Different oxide thickness at 4μm, 5μm and 6μm are deposited by LTO followed by a thermal anneal. Chemical Mechanical Polishing is used to make the oxide core smooth to reduce the scattering loss by surface roughness. Then we spin a thick photo resist and do lithography to make the waveguide patterns. After lithography, we use high-density plasma etching to form the channel waveguide core by deep etching or the rib waveguide core by shallow etching. The etching profile is illustrated in Fig. 4-22.
Figure 4-22. The measurement of etching profile for the PC cladding channel waveguide using a P10 profilometer. SiO₂ core and Si/Si₃N₄ bottom cladding pairs are etched at the same time.

After etching, we repeat the same Si and Si₃N₄ cladding deposition process and finish the whole fabrication process.
Fabrication results of PC cladding channel waveguide and step coverage test by Si and Si$_3$N$_4$ layers

As we use LPCVD Si and Si$_3$N$_4$ film as cladding layers, the conformal step coverage on the sidewall of the waveguide is very important. To know whether the LPCVD method can

![SEM picture](image)

**Figure 4-23.** The SEM picture of step coverage test for the LPCVD Si layer and Si$_3$N$_4$ layer. The trench is made by KOH etching on the Si (100) surface. We can see the conformal step coverage.
lead to good step coverage, we made a trench on a bare silicon wafer and use LPCVD method to deposit Si and Si$_3$N$_4$ layers. The SEM pictures are shown in Fig. 4-23&24. We can see that the film step coverage is good.

Figure 4-24. SEM picture of the sidewall step coverage test by LPCVD methods.
For the fabricated PC cladding waveguide, we deposit 6 and half Si/Si$_3$N$_4$ pairs as cladding layers for both the bottom and top cladding. The number of layers on the chip is 27 layers. Film stress is induced due to the huge number of layers on the chip.
Figure 4-25. (a) an SEM cross-section picture of the PC cladding channel waveguide on a silicon substrate for a 4μm core thickness. (b) The measured guided spot at 1550nm by coupling the light to the PC cladding channel waveguide.
Figure 4-26. An SEM picture of the bending of the PC cladding channel waveguide on a silicon substrate for a 4μm core thickness.

Fig. 4-25a shows the SEM image of the fabricated PC cladding channel waveguide cross section, which demonstrates the realization of this kind of waveguide by silicon based materials and a CMOS compatible process. We also measured that the light at 1550nm is truly guided in the waveguide; the guided spot is illustrated in Fig. 4-25b. In fig. 4-26, we also illustrate the 90-degree bending of the PC cladding channel waveguide. The waveguide loss is measured as 6dB/cm – 10dB/cm and the bending loss is measured as 5dB/turn for our first generation waveguide.
PC cladding waveguide coupling and bending for future applications

We have discussed the characteristics of a single, straight PC cladding waveguide, for future applications, especially when many single waveguide devices need to be integrated on a chip to realize useful functions, coupling between them and sharp bending are very important points to be addressed. In this section, we will do an exploratory study on these functionalities, the design and simulation results will be discussed and the challenge for realizing these functions will be briefly discussed.

Based on the coupling mode theory, the basic principle to govern the coupling of the two PC cladding waveguides is:

\[
\frac{da}{dz} = i\beta_a a + iK_{ab} b
\]

\[
\frac{db}{dz} = iK_{ba} a + i\beta_b b
\]

where \( K_{ab} \) is the coupling coefficient between the two waveguides, \( a \) and \( b \) are the amplitude of the electromagnetic field in waveguide a and b, and \( \beta_a \) and \( \beta_b \) are the effective propagation mode constant for waveguide a and b, respectively.
Figure 4-27. The dispersion relations of a PC cladding waveguide with different core materials and their coupling. SiO$_2$ core with thickness 0.64um and Air core with thickness 1.5um and 1.2um, respectively.

As an example, we simulate two PC cladding waveguides, one with an oxide core and the other with a hollow core, clad by Si and SiO$_2$ dielectric layers. The dispersion relations are illustrated in Fig. 4-27, which shows the dispersion relations around 1.55um wavelength for a single mode waveguide with both an oxide core and a hollow core. According to the above equations, when there is mode matching between the two waveguides, the EM power can be transferred from one waveguide to another completely. The coupling scheme is illustrated in Fig. 4-28.
Figure 4-28. The coupling between a SiO$_2$ core PC cladding waveguide and an air core PC cladding waveguide.

One interesting characteristic is that for the PC cladding waveguide we are studying, the effective mode index is less than 1. Here, we want to emphasize that this doesn’t mean the light speed will be larger than $c$. Instead, the meaningful speed is the group velocity, not the phase velocity. In our case, quite oppositely, the group velocity, which represents the information transportation speed, is far less than $c$. This is the one of the most important characteristics for photonic band gap guiding and quite interestingly, we expect to use this point to make slow photon devices on chip in the future.
Waveguide bending is another important issue, which needs to be addressed, if we want to utilize light propagation in low index core materials. It has been shown that a constant cross-section waveguide with a bend maps onto a 1-D quantum problem with a potential well. In one dimension, an arbitrarily weak attractive potential will always create a bound state. It is easy to show that a resonance will occur when a half-integer number of wavelengths are contained within the potential well. In principle, this leads to perfect transmission. Of course, this analysis ignores factors important for a bend in a dielectric waveguide, such as mode mixing and losses due to a finite number of layers.

**Figure 4-29.** Cut away view of a 3-D bend, which locally has an on-chip PC cladding channel waveguide C cross-section everywhere.
Our system is based on a straight on-chip PC cladding waveguide C, but with a smooth ninety-degree bend, as illustrated in Fig. 4-29. The transmission is calculated by comparing the total integrating Poynting flux going into the bend, which is compared to the total coming out, for a Gaussian pulse centered around \( \omega = 0.203(2\pi c/a) \) and \( k_z = 0.191(2\pi a) \), with a core of 10a by 10a, which is meant to correspond to the parameters for the TM11 mode. The calculation was done for inner turning radii of 8a, 15a, and 22a. The results were a transmission of 91.6% for the smallest inner radius, corresponding to a value of 2.4 \( \mu \)m for \( a = 0.3 \mu \)m, and 92.9% for the largest inner radius, corresponding to a value of 6.6 \( \mu \)m. Despite our attempt to choose a k-vector corresponding to a resonant mode in the waveguide, it is found that the transmission as a function of frequency is relatively flat around the central pulse frequency.

![Graph](image.png)

**Figure 4-30.** Transmission spectrum around a ninety-degree bend for a PC cladding channel waveguide C structure with an inner radius of 8a.
One way we propose to improve this structure is to introduce a mirror plane symmetry, which will remain unbroken at the bend. It has already been shown that 100% transmission can be achieved in 2-D photonic crystals at multiple wavelengths within the photonic band gap. The advantage of 2-D structures is that they automatically have a mirror plane symmetry which gives rise to TE and TM modes, which transform in opposite ways under the symmetry, thus preventing mode mixing. This idea can then be extended to 3-D photonic crystals. It was shown that the dispersion relation could then be tailored to create equivalent dispersion relations for both polarizations. An improved structure was thus designed with mirror plane symmetry. The core was chosen to have a width of 8a and a height of 12a in an effort to have a relatively close inner and outer radii at the bend (which improves the validity of approximating the turn as a perturbation to the straight waveguide), while still choosing relatively large core radii to ensure low losses. The source was improved to include almost 12 half-periods of source. The target $k_z = 0.182(2\pi/a)$, with $\delta k_z \approx 0.011$ (6%), a relatively narrow spread. This prediction is borne out qualitatively in the uniform spatial variation seen along the waveguide direction. The frequency peak was $\omega = 0.1995$, with a width of $\delta \omega \approx 0.006$ (3%), as can be seen in the raw frequency spectrum. The total transmission was found to be 96.8%, but with peaks in the transmission frequency spectrum in excess of 99%. Very little light leaks out over these distances, due to the fact that the straight and bend guiding modes are high-quality resonators with $Q$'s of order 1000s, so most of the loss must be due to reflection. Also, it is clear that this structure effectively decouples TE and TM modes –
the input ratio of TM/TE is effectively infinite (over 1 billion), while the output ratio is still high: over 1800.

Figure 4.31. Distribution of electric field power for light being guided around a ninety-degree bend. The source is the narrow array of bulges in the lower right. Virtually no power is observed to leak from the waveguide, suggesting most losses about the bend are a result of reflection.

On a related note, we can exploit the success of the bent on-chip PC cladding channel waveguide C to create a practical ring resonator cavity. Unlike the ring-resonator proposed, materials with a constant period and dielectric constant are utilized to make a simple yet relatively high-performance device. For instance, a structure with 6 bilayers
and a core of 10a by 10a, a Q of 7740 can be achieved for a TM$_{12}$-like mode; Q of 2560 for a TE$_{23}$-like mode. This possibility will be explored in greater detail in a future work.

In summary, we have developed a new type of silicon waveguide – a PC cladding waveguide based on a Photonic Band Gap (PBG) principle. Light propagation in a low index core (e.g. SiO$_2$) or a hollow core waveguide can be realized with our PC cladding waveguide structure. The fabrication of the waveguide is compatible to standard silicon CMOS process. We utilized prism coupling to the asymmetric PBG waveguide and the effective index of the propagation mode is measured directly, which demonstrated the photonic band gap guiding mechanism. The loss for the asymmetric PC cladding waveguide is measured as 0.5dB/cm for both TE and TM modes. We also fabricated and measured a PC cladding channel waveguide. The light is measured to be nicely guided in low index core materials. PC cladding waveguide coupling and bending are also discussed and it is promising for integration.
Chapter 5

Silicon based multi-channel optical filter and tunability

A Si-based multi-channel optical filter based on an omnidirectional reflecting photonic band gap structure with a relatively large air gap defect is fabricated and measured. Using only one device, a multichannel filter with tunability around the two telecom wavelengths 1.55μm and 1.3μm by an electrostatic force is realized. Four widely spaced resonant modes within the photonic band gap are observed, which is in good agreement with numerical simulations. The whole process is at low temperature (~80°C) and compatible with current microelectronics process technology. There are several potential applications of this technology in wavelength division multiplexing devices. The electrical tunability through free carrier injection is simulated and a prototype device is measured.
Introduction to optical filters and their application to WDM

In future telecommunication systems, optical filters will be very important components for wavelength division multiplexing (WDM) applications. How to route different wavelengths depends on optical filter functionality. Fig. 5-1 shows how optical filters can be used to route the carrier information.

Figure 5-1. Illustration of the Multiplex/Demultiplex in WDM system.
Fig. 5-2 shows fiber Bragg grating filters, which use UV light to define the grating patterns; and thin film filters, which have been widely used in the photonics field. These kinds of filters normally have a small index contrast between different layers. Recently, microcavity (with cavity layer thickness of integer half wavelength) filters based on photonic band gap structures have also been proposed to realize compact and integrated filters on chip, as shown in Fig. 5-3. In this chapter, we will focus on 1D photonic crystal structures with large index contrast dielectric layers, which lead to large photonic band gap properties. By engineering the microcavity size inside the periodic structures, we can achieve multi-channel filters.
Figure 5-3. An optical filter and switching based on 3D photonic crystals.

Multichannel filter by engineering the cavity layer size

A large amount of research in recent years has focused on periodic dielectric materials possessing a photonic band gap (PBG), a range of frequencies within which the propagation of light is forbidden. PBG materials offer an unprecedented degree of control over light, which gives rise to a wide range of device applications in telecommunications and optoelectronics. Specific applications proposed to date include but are not limited to waveguide with sharp turns, channel drop filters, microcavity waveguide, and photonic crystal fibers [19-25, 99-129]. However, the functionality of
many of these devices is limited by the fact that they must be manufactured to operate at a specific wavelength. Applications in telecommunications, such as WDM, require the flexibility to operate at a large number of neighboring wavelengths. One promising strategy to address this problem is to create multiple channel PBG devices. Several groups have already proposed, and in some cases, begun designing and testing such devices. Fabrication of a bulk three-dimensionally periodic structure on the appropriate lengths scales with sufficient accuracy to retain a full PBG is a well-known, highly non-trivial experimental problem in its own right, let alone with the additional problem of introducing multi channel functions and tunability -- even though theoretical solutions to the latter have already been proposed. Fortunately, it has recently been demonstrated that one-dimensionally periodic dielectric structures are capable of reflecting light from all incident angles and polarizations, under proper conditions. Clearly, a beam of light confined between two such perfect omnidirectional mirrors separated by a fixed distance could only exist at certain discrete wavelengths, if its wavelength were within the range of omnidirectional reflection. If the separation between these two mirrors could subsequently be adjusted, then the allowed wavelengths could be adjusted, as well.
Photonic localized states and electromagnetic field enhancement inside a cavity

Figure 5.4. (a) a single channel optical filter with half wavelength cavity layer thickness and (b) a two channel optical filter with three wavelength cavity layer thickness.
Figure 5-5. The reflectivity spectrum of the multichannel filters based on one-dimensional dielectric layers with high index contrast and cavity thickness 3λ.

In Fig. 5-4, a single channel filter based on a 1D microcavity is shown in (a). By engineering the cavity size, we can have two resonances within the photonic band gap, which is shown in (b). The reflectivity spectrum over a wide range of wavelength is illustrated in Fig.5-5. Here we can see resonance at the two wavelengths of 1.55μm and 1.3μm for the same device. As we have discussed in Chapter 3, when the cavity length is $L = n\lambda/2$ (n>2), there are more resonance states with high $Q$ ($Q = n\pi R^{1/2}/(1 - R)$). The localization properties of the resonance states are shown in Fig. 5-6. The photonic density of states is plotted in Fig. 5-7, which shows the 3-like densities of states for the three resonance states in the photonic band gap.
Figure 5-6. The electric field distribution at the microcavity states at 1.54μm, the strong localization of E-field intensity inside the microcavity is shown here, the cavity thickness is 3λ.

Figure 5-7. The density of states in the band gap range, which shows the δ-like photonic density of states at the localized states.
In this chapter, we demonstrate a multichannel one-dimensional PBG structure with a large air defect size and tunability in silicon-based materials with an omnidirectional photonic band gap. Using only one device, a multichannel filters around two telecom wavelength 1.55µm and 1.3µm is realized, which is important for multiple wavelengths demultiplexing around both 1.55 and 1.3µm. To realize this function, relatively large defects are required which can induce multiple localized states within the PBG and still keep large Free Spectral Range (FSR) features. High index contrast materials are necessary to have an omnidirectional band gap.

![Diagram of photonic band gap structure](image)

**Figure 5-8.** Illustration of the one dimensional photonic band gap structure with a large air cavity. The two quarter-wave stacks are composed of Si/SiO₂ pairs, which are separated by an air gap with a thickness 4.8µm.

The device studied here comprises two quarter-wave stacks consisting of alternating layers of Si and SiO₂, separated by a tunable air gap. Each stack is theoretically predicted
to have an omnidirectional reflecting frequency range between twenty and thirty percent of the midgap frequency. The period of the dielectric stack was chosen to create a band gap at the telecom wavelengths of 1.3 and 1.55μm. A schematic illustration of this tunable PBG device is given in Fig. 5-8.
Figure 5-9. The SEM image of the multichannel filter with tunability based on Si/SiO₂ 1D photonic band gap micro cavities. (a) is the top view and (b) is the side view.

It is fabricated, layer-by-layer, using the following procedure: first, a 260 nm-thick ($\lambda/4n_{SiO₂}$) SiO₂ layer is deposited atop a (100) Si substrate by plasma enhanced chemical vapor deposition (PECVD). A 110 nm-thick ($\lambda/4n_{Si}$) amorphous Si layer is then deposited on top by e-beam. Two more identical bilayers are then added, followed by another identical layer of SiO₂. The reflectivity of the stack is 99%. Next, a sacrificial layer of polyimide is spin-coated on top with $3\lambda$ ($\lambda = 1.55\mu m$) thickness. The entire structure made up to this point is cured at a relatively high temperature, and then cooled.
After cooling, the top dielectric stack is deposited on top of the polyimide with the same specifications as for the bottom dielectric stack with 99% reflectivity.

![Figure 5-10](image.png)

**Figure 5-10.** The TEM cross-section picture of the multichannel filters.

Next, a film with a low Young's modulus is deposited opposite the Si substrate to serve as a supporting membrane. Lithography is used to pattern the resulting structure and form the air gap in selected areas. It is important to note that a CMOS-compatible low-temperature process is used, because it allows polymeric materials to be incorporated into the structure, and it reduces the film stress -- that is important to ensure that each layer of dielectric remains relatively flat. After the removal of the sacrificial layer of polyimide, a
typical microelectromechanical system (MEMS) method is used to adjust the size of the air gap. The membrane with low Young's modulus is suspended by supporting beams. Application of a voltage between the membrane and substrate can tune the cavity thickness.
Figure 5-11. (a) The measured reflectivity spectrum by FTIR. Four resonance modes within the photonic band gap at 1.402μm, 1.582μm, 1.792μm, and 2.072μm are seen. The PBG range is from 1.19μm to 2.18μm according to simulation. The shorter wavelength spectrum is not shown here because of the weak FTIR photodetector responsivity. (b) A numerical simulation of the reflectance, showing resonance modes within the photonic band gap at 1.415μm, 1.581μm, 1.793μm and 2.074μm, which is in good agreement with measurements in the FTIR measurement wavelength range.
Silicon based multi channel filter at telecom wavelength at 1.55μm and 1.3μm

The reflectivity spectrum of this device was measured using a Nicolet 860 Fourier transform infrared spectrometer (FTIR) at room temperature. A sample measurement of this device, taken with a mirror separation of 4.8μm, is shown in Fig. 5-11(a). The results were unchanged under small temperature variations of about 5 degrees, up to experimental resolution. The FTIR was calibrated relative to the reflectivity of Au at that wavelength. The photonic band gap at normal incidence is very large, extending from 1.19 to 2.18 μm. Four dips in the reflectivity spectrum falling within the PBG were observed to be centered at the wavelengths 1.402, 1.582, 1.792 and 2.072 μm. The positions of these dips are in good agreement with two independent numerical calculations. First, a finite-difference time-domain (FDTD) simulation of Maxwell's equations was performed in order to produce the reflection spectrum shown in Fig. 5-11(b). Second, eigenmodes of Maxwell's equations with periodic boundary conditions were computed by preconditioned conjugate-gradient minimization of the block Rayleigh quotient in a plane wave basis, using a freely available software package. This calculation was used to create a projected band structure for both TM and TE modes (left and right-hand sides, respectively), which is shown in Fig. 5-12. It was confirmed that the modes at zero transverse wave vector, corresponding to normal incidence, are centered at the same wavelengths as the results from the time-domain simulation. The dips in the reflectance can then be understood as resonant modes, analogous to the defect modes of a doped semiconductor.
**Figure 5-12.** The projected band structure of the one-dimensional photonic crystal with an air cavity with the light line ($\omega=c\kappa_z$), showing an omnidirectional reflectance range for both TM and TE modes (left and right-hand sides, respectively) and multiple localized states within the band gap.

**MEMS Tunability through the cavity size change**

The tunability through the cavity size change is calculated in Fig.5-13:

$$\frac{\Delta\lambda}{\lambda} = \gamma \frac{\Delta d}{L_{eff}} = \frac{\Delta d}{d}$$  \hspace{1cm} (5.1)

which shows the almost 100nm tuning range can be achieved by a 9% cavity size change.
**Figure 5-13.** The numerical simulation on the tuning of the resonance states with a change in the cavity size change. Almost 100nm range can be tuned by a 9% cavity size change.

Application of a voltage also allows for tuning of the resonant modes, as illustrated in Fig. 5-14, where the spectra resulting from two different applied voltages are superimposed. For an applied voltage of 0V, two resonant modes are observed at the wavelengths 1.402 and 1.582 μm. Application of 4V shifts these modes to the wavelengths 1.392 and 1.568 μm. The wavelength shift is plotted against the applied voltage squared. The observed linear relationship between these two quantities is consistent with the mechanism of electrostatic tuning of the localized modes:

\[
F_{el} = \varepsilon_0 AV^2/2d^2 = k \Delta d
\]  
(5.2)

where \( F_{el} \) is the electrostatic force, \( V \) is the voltage, and \( k \) is the spring constant.
The figure also shows that an applied voltage of 10V can produce a shift of nearly 60 nm for the 1.582 μm resonances. A shift of this order of magnitude should be sufficient to enable switching and modulation in telecommunication devices.

Figure 5-14. The resonance wavelength shift with applied voltage square at 1.582μm and 1.402μm, the relationship between the wavelength shift and voltage squared is $\Delta \lambda \sim V^2$.

For resonant modes observed around the wavelengths 1.402 and 1.582 μm, the quality factors ("Q's") were measured to be approximately 94 and 79, respectively. The Q's found in the FDTD simulation were considerably higher, 943 and 988, respectively. The Q of the fabricated structures can be degraded by: 1) mirror reflectivity; 2) mirror absorption, (there is no absorption in the air gap); 3) deviations from parallel mirrors with no curvature. Here, the main contribution to making the fabricated Q less than the theoretical Q is the mirror curvature. This diagnosis is evident in the resonance signal
asymmetry on the long wavelength side, suggesting a convex curvature, resulting from a compressive stress. Using a staircase correlation function, we estimate the radius of curvature of the mirror from the broadening at the resonance wavelength around 1.582 \( \mu m \), which is about 20nm, to be 0.7cm.

It is interesting to note that two of these resonances are within the standard telecommunications wavelength spectrum. Additionally, the free spectral range of this PBG device (more than 100nm) is very large. The tuning is coupled and not independent for the two wavelengths, so only one of the two wavelengths is expected to be used in a basic deployment. One might envision an array of identically fabricated devices functioning in several wavelength regions.

In summary, Si-based multichannel, tunable and omnidirectional photonic band gap devices were designed, fabricated and measured. This is the first time multiple resonant modes created by omnidirectional PBG materials have been studied experimentally. The large 1 \( \mu m \) band gap at normal incidence served to allow for widely spaced resonant modes, with one near the 1.3 and one near 1.55 \( \mu m \), two wavelengths of interest in telecommunications.

**Electrically Tunable Silicon Photonic Band Gap Materials Based on multiple Smart-Cut Transfers**
In this section, electrically tunable multiple layer Photonic Band Gap materials are proposed and analyzed. Based on multiple silicon-on-insulator (SOI) layers and a smart cut transfer method, single crystalline silicon as a PBG defect layer between oxide silica layers is possible. Fast electrically tunable PBG devices are designed in which nanosecond (ns) and low voltage tuning can be realized based on multiple layers using a smart-cut method. Prototype multiple SOI layers is fabricated. Reflectivity measurements show good agreement with the simulation, and the SEM picture shows good materials quality. Fast electrically tunable PBG materials based on this method are very useful potential devices for switching, modulation and wavelength conversion for WDM applications.

In future telecommunications, WDM is becoming a standard for handling the rapidly increasing data traffic. Silicon microphotronics has received more and more attention recently, which will integrate all the functional micro-scale optical devices on chip, much similar to the microelectronics today. Tunable photonic crystals are key devices for microphotonics, especially for future WDM applications [23-26]. Since the first introduction of Photonic Band Gap structures (PBG), also known as photonic crystals, new concepts and designs have been proposed, which could be building blocks for the next generation photonic integrated circuits. There have been many ideas to realize tuning of PBG structures, such as the optical Pockel effect, the nonlinear optical effect, the electro-optic effect and the MEMS method. Unfortunately, for silicon based PBG structures, the above methods are not suitable to realize fast tuning as silicon is center symmetric, so the Pockel effect vanishes, and since Si is an indirect band gap material,
nonlinear optical effects are very weak compared to those in III-V based materials. MEMS provides an effective method for Si based materials, but it is slow in terms of speed. Electrically tuning the Si PBG devices remains challenging until silicon-on insulator (SOI) technology appeared recently.

Here we propose using a multiple SOI layer transfer method to realize the electrical tuning of Si-based PBG materials by free carrier injection (plasma effect). In Si PBG structures, it is impossible to incorporate single crystalline silicon between SiO₂ layers using conventional deposition techniques. As is essential for free carrier injection tuning, a multiple smart-cut SOI process is used to make stacking single crystalline silicon onto silicon substrate with a oxide layer in between possible. Based on a smart-cut process, fast electrical tuning can be realized.

**Figure 5-15.** Illustration of the schematic fabrication process for a multiple smart-cut SOI stack structure realization.
The schematic fabrication process is illustrated in Fig. 5-15. The multiple smart-cut SOI process includes two basic techniques: hydrogen implantation and wafer bonding. The hydrogen implantation defines how deep the fragilized buried layer will be. Realizing multiple SOI layers based on a layer transfer process can be achieved in many ways: repeating a single layer transfer several times onto a SOI wafer, transferring onto a single substrate or a SOI wafer where whole SOI layers stack already formed.
Figure 5-16. The Silicon based Photonic Band Gap structure; the single-crystalline silicon defect layer is the active layer with a p-i-n diode to realize the free carrier injection.

The proposed Si-PBG device is illustrated in Fig.5-16. The p-i-n diode in the single crystalline defect layer (active layer) is used to achieve electrical tuning. When a voltage is applied between the contacts, the free carriers are injected into the intrinsic part; hence the refractive index is changed. Based on the two-carrier injection into semiconductors, which has been studied by Lampert and Mark [36]. The injected carriers are as follows:

\[ n = \frac{(3 \mu_n (n_0 - p_0) V)^{1/2}}{(2(b+1) B_r L^2)^{1/2}} \quad (5.3) \]

where \( B_r \) is the recombination rate, \( \mu_n \) is the electron mobility in Si, \( n_0-p_0 \) is the thermal equilibrium density for the intrinsic part of the p-i-n diode, \( V \) is the applied voltage, \( b \) is the ratio \( b=\mu_n/\mu_p \), and \( L \) is the channel length for the intrinsic part. To estimate the free carrier injection, we use \( \mu_n=1450 \text{cm}^2/\text{Vs} \), \( \mu_p=450 \text{cm}^2/\text{Vs} \), considering bimolecular recombination centers only for single crystalline Si, and taking \( B_r=2.68 \times 10^{-15} \text{cm}^3 \text{s}^{-1} \), we get:

\[ n = 4.4 \times 10^8 \times (n_0 - p_0)^{1/2} V^{1/2} / L \quad (5.4) \]
Figure 5-17. The reflectance of the Si-PBG structure under different bias voltages: 0V, 1.5V and 5V. The defect mode is shifted when the voltage is applied.
Figure 5-18. The resonance mode shift as a function of voltage. A 4nm (400GHz) shift can be realized by an applied voltage of 5V.

For a typical example, consider a n-doped Si wafer as the initial substrate, with $n_0-p_0=4 \times 10^{16} \text{cm}^{-3}$, and a channel length $L=100\mu m$. According to the refractive index change with the free carrier injection and using the transfer matrix method, we simulated the resonance mode shift with the applied voltage in Fig.5-17 and Fig.5-18. Here Fig.5-17 shows the Si-PBG reflectance under different applied voltages, 0V, 1.5V and 5V (the relationship between voltage and injection level can be found in eq.5.4), and the resonance wavelength shift is clear seen and it is shown that a 4nm (400GHz around 1.55\mu m) mode shift can be achieved. In Fig.5-18, we plot the corresponding resonance wavelength shift with applied voltage.
There are many applications associated with the resonance mode shift, such as optical switching, optical modulation and wavelength conversion devices with electronical tunability. Since the lifetime of the free carriers range from $10^{-6}$-$10^{-9}$s, the switching and modulation speed ranges from nanosecond (ns) to microsecond ($\mu$s), faster than a mechanical switch. Another important application is for a tunable Si light emitter if the defect layer (active layer) is doped with rare earth elements such as Er. The design is very similar to the VCSEL laser in a III-V material system. Here we emphasize that, with the multiple SOI layer transfer method, an electronically tunable, active Si-based device can be realized. This is very important as current Si-microelectronics process can be utilized to make useful optical devices.

![Layer Diagram](image)

**Figure 5-19.** Illustration of the fabricated prototype multiple SOI stack structure (left part) and an SEM picture of the fabricated structure (right part).
Figure 5-20. The measured reflectance spectrum (a), and the simulated reflectance spectrum based on the real structure. The defect mode is at 1.61μm.

The prototype multiple SOI stack structure is fabricated based on the methods described above. Fig.5-19 is an SEM view of the multiple SOI layers with sharp interfaces and perfect intra-layer insulation. The optical reflectivity is measured by Fourier Transform Infrared Spectroscopy (FTIR), with resonance at 1.61μm and Q=38, which shows good agreement with the numerical simulation in Fig.5-20, with resonance wavelength at 1.61μm and Q=40, further confirming the superior materials quality of the multiple SOI stacks.
In summary, an electrically tunable Si-PBG device based on a multiple SOI layer transfer method is designed and simulated, which can be fully CMOS compatible and can be integrated into current Si microelectronics technology. Potential applications include optical switching, optical modulation and tunable Si light emitters. The prototype multiple SOI stack structure has been fabricated and reflectivity measurements have been made showing superior materials quality. Future study of the designed structure is in progress and the preliminary results appear to be promising.

In conclusion, a Si-based multi-channel optical filter based on an omnidirectional reflecting photonic band gap structure with a relatively large air gap defect is fabricated and measured. Using only one device, a multichannel filters with tunability around two telecom wavelength 1.55µm and 1.3µm by an electrostatic force is realized. Four widely spaced resonant modes within the photonic band gap are observed, which is in good agreement with numerical simulations. The electrical tunability through free carrier injection is simulated and a prototype device is measured.
Chapter 6

**Silicon based Photonic Quasicrystal Structures**  
- Photonic band gap properties and omnidirectional reflectance in Si/SiO$_2$ Thue-Morse quasicrystals

We study photonic quasicrystal structures and their properties in this chapter, especially with regard to fractal band gap properties and transparent resonant transmission states. The Fibonacci structure is introduced and discussed at first and then we discuss in detail the Thue-Morse structures. A-periodic Si/SiO$_2$ Thue-Morse (T-M) multilayer structures have been fabricated, for the first time, to investigate fractal photonic band gap properties and omnidirectional reflectance. Variable angle reflectance measurements demonstrate a large photonic band gap in the T-M structure, which is in good agreement with transfer matrix simulations. The physical origin of the T-M omnidirectional band-gap has been explained as a result of periodic spatial correlations in a complex T-M structure. The flexibility of T-M systems can provide an attractive alternative to photonic crystals.
Introduction to photonic quasicrystal structures

Since the pioneering work by Yablonovitch and John [5,6], much attention has been focused on periodic photonic crystals, like the electronic band gap in semiconductors, where there are certain frequency ranges that inhibit the propagation of light. When a defect is made and the periodic symmetry is broken, a resonant transmission is induced, which has many important characteristics and make the photonic crystal promising to realize integration with the integrated circuits in the future on a chip. Therefore, the study of photonic crystal has been extended to photonic quasicrystal structures, where more structural parameters can be tuned in these quasiperiodic systems, thus opening a way to a wide range of technological applications to many fields [40-63].

Photonic quasicrystals (QPX’s) are deterministically generated dielectric structures with non-periodic refractive index modulation. QPX’s represent intermediate photonic structures between periodic dielectric materials, namely photonic crystal structures, and random media. By stacking together layers of different dielectric materials, A and B, according to simple rules, we can generate 1D QPX’s. QPX’s show peculiar physical properties like the formation of multiple frequency band gap regions called pseudo band gaps, the presence of fractal transmission resonances and the occurrence of critically localized states (field states that decay weaker than exponentially, typically by a power law, and have a rich self similar structure). Since the first experimental realization by Gellermann et al. of an optical Fibonacci quasicrystal [50], the Fibonacci system has been predominantly investigated leading to the experimental demonstration of transmission scaling, symmetry-induced resonance, complex light dispersion and strong band-edge
group velocity reduction. Fibonacci quasicrystals are an example of quasi-periodic
structures with delta-like Fourier power spectrum (FPS) characterized by non-periodic
self-similar Bragg peaks, which are responsible for the location, and width of the energy
pseudo-gaps. However, there are other classes of quasicrystals that exhibit a “more
complex” structure than the Fibonacci ones. In particular, deterministic aperiodic
structures are characterized by singular continuous Fourier spectrum.

In this chapter, we will discuss the Fibonacci structures and their properties, the current
progress with this structure, which has been studied as an example for quasi-photonic
crystals by many groups. Then we will mainly discuss our work and the first fabrication
of high index contrast Si/SiO$_2$ Thue-Morse structures. The Fibonacci structures are quasi
crystal structures, which are close to periodic structures, while Thue-Morse structures are
aperiodic structures, which are more close to random structures.

**Fibonacci photonic quasicrystals**

The Fibonacci sequence is one of the first examples in the family of quasi-periodic
structures and has been studied by many groups all over the world. The first Fibonacci
lattice is made by Merlin, considerable efforts has been focused on the peculiar wave
properties of Fibonacci structures. Since Kohmoto, etc. proposed the photonic Fibonacci
structures, most of the studies have concentrated on the localization properties of photons
[48]. The localization for electrons in the solid state system has been studied for decades,
such as disorder-induced Anderson localized states, within gap localized states induced
by defects, these two types of localized states has the same exponential decay behaviour.
For example, the microcavity state inside periodic photonic crystals belongs to defect-induced localized states. Another localized state, which has power law decay behavior instead of exponential decay, has bulk localized properties. The resonant transmission states in the quasi-periodic structures, including Fibonacci system, belong to the bulk localized states.

The Fibonacci sequence can be generated in the following deterministic way:

\[ S_{j+1} = \{S_j, S_j\}, \text{ for } j \geq 1; \text{ with } S_0=\{B\} \text{ and } S_1=\{A\}. \]  

So this generation leads to:

\[ S_0 = \{B\}; \]
\[ S_1 = \{A\}; \]
\[ S_2 = \{BA\}; \]
\[ S_3 = \{ABA\}; \]
\[ S_4 = \{BAABA\}; \]
\[ S_5 = \{ABABAABA\}; \]

\[ \ldots \ldots \ldots \]

For the Fibonacci structures, it has been shown that the wave function is not exponentially localized but rather it is bulk localized (less than exponential decay at large distance). These structures have a rich scaling behavior. Now we consider the optical propagation through a Fibonacci lattice. The transfer matrix method can be used to simulate the transmission behavior and the following matrix form gives the transmission through the interface A – B:
\[ T_{AB} = T_{B/A}^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & r \end{bmatrix} , \]

where \( r = n_B/n_A \). The wave propagation in a layer A or B is described by a matrix:

\[ T_{A(B)} = \begin{bmatrix} \cos \delta_{A(B)} & -\sin \delta_{A(B)} \\ \sin \delta_{A(B)} & \cos \delta_{A(B)} \end{bmatrix} , \]

where the phase factor is given by \( \delta_{A(B)} = n_{A(B)} k d_{A(B)} \), and \( k \) is the wave vector in vacuum.

The whole system can be described by a matrix \( M_j \), which is a multiplied by the above matrices. From the final matrix and their matrix elements, we can calculate the transmission properties and other related properties, like reflectance \( R \) and resonance states \( Q \).
Figure 6-1. The transmission spectrum for a TiO$_2$/SiO$_2$ Fibonacci structure. (a) and (b) show the $S_5$ structure with 16 layers, (c) and (d) shows the $S_6$ structure with 26 layers, and (e) and (f) shows the $S_8$ structure with 68 layers; (a), (c), and (e) shows the measurement results, (b), (d) and (f) shows the simulation results based on above transfer matrix form. We can see fractal behavior of the resonant transmission with increasing layers.

Fig. 6-1 shows the transmission properties of Fibonacci structure $S_i$ for TiO$_2$/SiO$_2$ multilayers. As a general trend, it can be seen that, with an increasing number of layers, more and more resonant transmission peaks appear, which is due to the inherent nature of the quasi-photonic structures, namely fractal behaviour. We also observe that, with an
increasing number of layers, there are certain range of frequencies with zero transmission
– one dimensional photonic band gap.

**Thue-Morse photonic quasicrystals**

The principal example of an aperiodic structure is given by the Thue-Morse (T-M) sequence, generated by the simple inflation rule $\sigma_{T,M}$: $A \rightarrow AB$, $B \rightarrow BA$. The strings give the lower order T-M sequences:

\[ S_0 = A, \]
\[ S_1 = AB, \]
\[ S_2 = ABBA, \]
\[ S_3 = ABBABAAB, \]
\[ S_4 = ABBABAABBAABBAABBA, \]
\[ S_5 = ABBABAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBAABBA, \]

.................................
Figure 6-2. The fabrication process for the Thue-Morse structures on substrate.

An extensive theoretical literature describes both the localization and the intriguing scaling of T-M resonant transmission states in terms of a generalized trace map approach, originally introduced by Kohmoto et al. [62] to explain the Fibonacci case.

Self-similar pattern of the resonant transmission states for T-M structures

Electron scattering from aperiodic potentials has been investigated by Fourier transform methods showing close relationships between the geometry of the potential and the physical properties of the corresponding energy spectra. One of the most important properties of the quasi-photonic structures is the fractal behaviour with increasing layers. We will discuss the fractal transmission states for T-M structures. Similar to the transfer matrix method, we can calculate the completely transparent states for different order quarter wavelength T-M systems. Fig. 6-3 shows the complete transmission states and
self-similar pattern.

Figure 6-3. The self-similar pattern for a Thue-Morse system, which shows the fractal behaviour with the increasing layers.

From Fig.6-3, the self-similar pattern of the complete transparent states is clear, with
increasing orders, one transparent state becomes three, three becomes five, and so on. When the number of layers is large enough, the complete transparent states tend to become discontinuous bands, but not continuous, and this is the central point for the photonic quasicrystals. The fractal behaviour of the transparent states is very important for the dense multi-frequency filter applications. As we know from the microcavity states in a periodic photonic crystal, a large size defect state is necessary to generate multiple states within the band gap, but it is not realistic for dense frequency applications. The complete transparent transmission states in photonic quasicrystals, like T-M structures, provide us with a deterministic way to generate a dense frequency pattern. The localized behaviour of the transparent states is illustrated in Fig. 6-4
Figure 6-4. The electric field distribution in the TM multilayers for a completely transparent frequency at order 5 (32 layers), 6 (64 layers) and 7 (128 layers).

For the completely transparent electromagnetic state, the wave function is similar to the T-M lattice structures. This EM wave distribution is also similar to the electronic wave function in the T-M lattice system.
In the above, we have briefly discussed the fractal behaviour of the complete transparent states in a T-M system. However, the band-gap properties of T-M structures are still under debate and the problem has not been investigated experimentally. We will discuss in detail the photonic band gap and fractal band gap behaviour in the following.

Fractal photonic band gap properties and omnidirectional reflectance in Si/SiO₂ Thue-Morse quasicrystals

T-M optical quasicrystals have not been fabricated previously. In this section we report on the first experimental realization and study of the optical band-gap properties of Si/SiO₂ T-M quasicrystals up to 32 layers thick. For simplicity, the thickness $d_{A,B}$ of the two materials, SiO₂ (layer A) and Si (layer B), has been chosen to satisfy the Bragg condition, $d_{A} n_{A} = d_{B} n_{B} = \lambda_0 / 4$, where $n_{A}$ and $n_{B}$ are the respective refractive indices and $\lambda_0 = 1550\text{nm}$. The samples were fabricated on transparent fused silica substrates through RF-magnetron sputtering in a Kurt J. Lesker CMS 18 UHV sputtering system using Si and SiO₂ targets. The Si and SiO₂ were sputtered in an Ar plasma at a power of 300 W and a deposition pressure of $3\times10^{-3}\text{Torr}$. The reflectance measurements were performed using a Nicolet Magna 860 Fourier Transform Infrared (FTIR) spectrometer coupled to a Nic-Plan IR Microscope for better spatial resolution. For variable angle measurements we used the main chamber of the same FTIR equipped with a VeeMax variable angle specular reflectance accessory and a ZnSe polarizer. In Fig. 6-5 (a) we show the TEM picture of the 32 layers T-M structure ($S_5$). In Fig. 6-5 (b-d), we report the measured and
calculated reflectance spectra of three T-M samples with different sizes. The 8 layer T-M sample (S₃), Fig.6-5 (b), has a large photonic band-gap around 2300nm. The 16 layer T-M sample (S₄), Fig.6-5 (c), has the original band-gap of Fig. 6-5 (b), split into two distinct adjacent band-gaps, separated by a narrow transmission band. The S₃ case, Fig. 6-5 (d), has three adjacent band-gaps (numbered 1,2,3) separated by two distinct narrow transmission regions.
Figure 6-5. (a) Transmission Electron Microscope (TEM) cross-section of the 32 layer (S_3) T-M structure. The light and dark layers correspond to SiO_2 and Si respectively. The letters on the different layers indicate all the components of the S_3 sequence. (b) Experimental (dash-dot line) and calculated (solid line) reflectance for the 8 layer (S_3) T-M structure. (c) Experimental (dash-dot line) and calculated (solid line) reflectance for the 16 layer (S_4) T-M structure. (d) Experimental (dash-dot line) and calculated (solid line) reflectance for the 32 layer (S_3) T-M structure. For all the simulations we have considered $n_A=1.46$ (SiO_2), $n_B=3.63$ (Si) and an incidence angle $\theta=30^\circ$, which approximately compensates for the large microscope objective numerical aperture (N.A.=0.6). The layer thickness is defined by the Bragg condition at $\lambda_0=1.55\mu$m.
Figure 6-6. Simulation of the reflectivity spectrum for a 32-layer Si/SiO₂ Thue-Morse structure at different angle of incidence for both TE and TM polarization.
Figure 6-7. Simulation of the omnidirectional band gap range for a 32-layer Si/SiO₂ Thue-Morse structure, which is marked by shaded area.
Figure 6-8. The FTIR reflectivity measurement at normal incidence. The solid line is the FTIR measurement, and the dashed line is the simulation based on the transfer matrix method.
Figure 6-9. The FTIR reflectivity measurement at 45-degree incidence. The solid line is the FTIR measurement, and the dashed line is the simulation based on the transfer matrix method.
Figure 6-10. The FTIR reflectivity measurement at 70-degree incidence. The solid line is the FTIR measurement, and the dashed line is the simulation based on the transfer matrix method.

Fig. 6-6 and Fig. 6-7 show the reflectivity simulation for the 32 layers Si/SiO₂ Thue-Morse structures for incident angle from zero degree to 89 degree for both TE and TM polarization. The shaded region is the omnidirectional photonic band gap range. It can be seen from the simulation that the left band edge of the omnidirectional band gap range is
determined by the left band edge of the zero degree, while the right band edge of the omnidirectional band gap range is determined by the right band edge of the TM polarization at 90 degree. So in the experiment, we only need to measure the reflectivity of the TM mode from 0 degree to 90 degree.

Fig. 6-8 to Fig. 6-10 shows the reflectivity measurement of the TM mode from 0 degree to 70 degree as in our experimental set up, as large as 70 degree can be measured. We see good agreement between theory and experiment for the fundamental band gap, which demonstrates clearly the omnidirectional band gap range for the Si/SiO₂ high index contrast 32 layers Thue – Morse structure. Because we can only mechanically measure the angle of the VeeMax variable angle specular reflectance accessory, we see some shift with the simulation for the fundamental band gap.
Figure 6-11. (a) Normalized frequency plot of the calculated transmission spectra of $S_3$ (dot-line), $S_4$ (dashed-line) and $S_5$ (solid-line) T-M structures. The numbers in the three band-gap regions of the $S_5$ structure correspond to the band-gap nomenclature shown in Fig. 6-5 (d). (b) Normalized frequency plot of the calculated transmission spectra of $U_3$ (dot-line), $U_5$ (dashed-line) and $U_{11}$ (solid-line), the periodic approximate units for the fundamental band-gaps of the T-M structures. (c) Rescaled (horizontal scale in the phase plots of (a) and (b) has been rescaled by the constant factor of 50) transmission spectrum of a 256 (solid line) layer ($S_8$) and 32 (dashed line) layer ($S_9$) T-M structure respectively. (d) Fourier Power Spectra (FPS) of the associated T-M strings with 32 ($S_3$) and 256 ($S_8$) characters respectively. The FPS of the $S_5$ string has been expanded by a factor of 2.
The peculiar band-gap scaling is reproduced in the simulations, Fig. 6-11 (a), where we show the calculated T-M transmission spectra versus the normalized frequency from 0 to 2 for the S₃, S₄ and S₅ generations, respectively. The three band-gaps in S₅ are labelled as the experimental data in Fig 6-5 (d). At the normalized frequency around 0.3, the smaller adjacent band-gaps of S₅ split into two separate band-gaps following the same pattern occurring at the two fundamental band-gaps in the T-M generation S₄ (see dashed line, central band-gaps). The observed band-gap scaling is a result of the self-similar (fractal) character of an ideal, infinite T-M structure, reflecting the enormous complexity of the associated string geometry. To achieve a phenomenological understanding of the T-M optical properties, we performed discrete Fourier analysis on a T-M string with 256 characters (S₈) assigning the numerical value 1 and 0 to the A and B symbols respectively. The FPS of S₈ and S₅ are plotted in Fig. 6-11 (d), as a function of the percentage of sampling frequency. The FPS of the S₈ contains a hierarchy of frequency peaks connected by “small bands” of secondary frequency contributions (see Fig. 6-11 d). Comparing the two spectra in Fig. 6-11 (d), the FPS of the short S₅ string collapses for the S₈ case into a rich structure of narrow frequency peaks realizing a fine triplication pattern around the broader S₅ bands. Since all the information contained in the optical transmission of Fig. 6-11 (a) falls between 0 and 2 in a normalized frequency scale and reflects all the frequencies in the associated FPS, we can establish a natural correspondence between Fig. 6-11 (d) and Fig. 6-11 (a) by rescaling the transmission data, as shown in Fig. 6-11 (c). After normalized frequency rescaling, a nice correlation
appears between the Fourier peaks of the $S_8$ string and the position and width of the corresponding optical band-gaps. Within this approach, the band-gap properties of the T-M structures can be understood as the result of local correlations (frequency peaks) in the associated T-M string. In particular, the physical origin of the fundamental T-M band-gaps can be attributed to local correlations in the form of periodic strings with the corresponding frequency ($\sim 30\%$) in the associated FPS (see Fig. 6-11 (d)). As an example, we consider the periodic approximant for the T-M structure, strings of the kind $U_n=(ABB)^n$, ($U_n=ABBABBABB\ldots n$ times). The calculated transmission for $U_3$, $U_5$ and $U_{11}$, shown in Fig. 6-11 (b), qualitatively reproduces the two T-M fundamental band-gaps.
Figure 6-12. (a) Calculated reflectance of the 32 layer (S₃) T-M structure for both TE (solid line) and TM (dashed-dot line) modes at different incidence angles specified in the Figure. (b) Measured variable angle reflectance data (thick solid line) and transfer matrix simulation (thin solid line) for the TM polarization and incidence angles specified in the figure. At the incidence angles θ=0° and θ=70°, the calculated reflectance of the periodic U₁₁ T-M approximant is also shown for comparison.

As we have found in previous sections that the T-M central band-gaps also share the
distinctive band-gap physical properties of their periodic approximants, in particular the omnidirectional reflectance. We compare the 32-layer T-M structure with the periodic U_{11} structure. In Fig. 6-12 (a) we show the calculated reflectance spectra for both the Transverse-electric (TE) and Transverse-magnetic (TM) modes versus wavelength for different incidence angles up to 89°. The grey shaded area shows unambiguously the occurrence of a large omnidirectional band-gap region corresponding to the central band-gap and determined only by the TM polarization. The experimental variable angle reflectance data is plotted in Fig. 6-12 (b) along with the calculated variable angle reflectance of the U_{11} approximant structure up to 70° incidence for the TM polarization. A large region of wide-angle reflectivity is experimentally demonstrated at the central band-gap of the T-M structure, which corresponds with the angular behaviour of the periodic U_{11} structure. The comparison with the simulation data in Fig. 6-12 (a) demonstrates the omnidirectional reflectivity of the experimental T-M structure.

In summary, we have reported the first experimental study of the band-gap properties in Si/SiO₂ T-M quasicrystals, showing remarkable scaling properties of the transmission spectra and omnidirectional reflectance in a 32-layer structure. We have related the physical properties of the T-M optical spectrum with the complex geometry of its generating sequence, suggesting that ‘accidental’ periodic correlations are the origin of the T-M optical band-gaps. The presence of a fractal distribution of sharp band-edge states with resonant transmission and the unprecedented degree of structural flexibility of T-M systems can provide an attractive alternative route to photonic crystals for the fabrication of multi-frequency laser cavities (fractal cavities), sensors and dense optical
filters.

**Thue-Morse structure by PECVD deposition and results**

We have discussed the transparent transmission states and photonic band gap properties of Thue–Morse structures for a high index contrast Si/SiO$_2$ system. From the fabrication and materials choice requirement, the above discussion is based on Si and SiO$_2$ films using a sputtering method. As discussed in the fabrication process for the sputtering, the time and film thickness control are very important for the performance of quasi photonic crystals, especially for the sensitive transparent transmission states, which have novel localization properties.

To make a better sample for the Thue–Morse structures, we also used PECVD tool to deposit Si$_3$N$_4$ and SiO$_2$ as A and B films. The index contrast is smaller for these film choices, but for the PECVD tool, which is a state-of-the-art system and made by Applied Materials, it not only has better control of the refractive index and thickness for the films, but also the whole process can be programmed so that it can be an automatic deposition process, and thereby reduce the error related to by hand operation. We deposited the 32 layers Si$_3$N$_4$ and SiO$_2$ Thue–Morse structures by this PECVD tool, and Fig. 6-13 shows the results. From these results, we can see that this approach is very promising to push the high order T-M structures.
Figure 6-13. Reflectivity measurements and simulation of a 32 layer SiO₂ and Si rich nitride Thue-Morse structure.
Summary

In conclusion, we have studied photonic quasicrystal structures and their properties in this chapter, especially for their fractal band gap properties and the transparent resonant transmission states. A-periodic Si/SiO$_2$ Thue-Morse (T-M) multilayer structures have been fabricated, for the first time, to investigate both the scaling properties and the omnidirectional reflectance at the fundamental optical band-gap. Variable angle reflectance data have experimentally demonstrated a large reflectance band-gap in the optical spectrum of a T-M quasicrystal, in agreement with transfer matrix simulations. The physical origin of the T-M omnidirectional band-gap has been explained as a result of periodic spatial correlations in the complex T-M structure. From the comparison between the Si/SiO$_2$ and Si$_3$N$_4$/SiO$_2$ system, we can see the large index difference ($\Delta n$) leads to larger band gap for Si/SiO$_2$ than Si$_3$N$_4$/SiO$_2$ system, which is as same as periodic structures.
Chapter 7

Summary and future works

We have studied silicon-based photonic structures in this thesis; the photonic band gap materials and quasi-photonic band gap materials using CMOS compatible materials and processes have been studied in detail. Potential applications based on high index contrast dielectric layers on the integrated microphotonics field are also discussed, which is a very promising approach for next generation technology.

We focus on silicon-based PC clad waveguides, multichannel optical filters with tunability, and quasi-photonic band gap structures, as well as their applications. All are based on high index contrast Si/SiO₂, Si/Si₃N₄ and Si₃N₄/SiO₂ dielectric pairs.

**On-chip silicon based PC clad waveguide** We developed a new type of silicon waveguide: PC clad waveguide based on the PBG principle. Light propagation in a low index core (e.g. SiO₂) or hollow core waveguide can be realized with our PC clad waveguide structure, which is compatible with the CMOS process. We utilized prism coupling to the asymmetric PC clad waveguide to demonstrate the PBG guiding mechanism. The transmission loss of the asymmetric PC cladding waveguide was
measured as 0.5dB/cm for both TE and TM modes. We also fabricated and measured the PC clad channel waveguide. Measurements show that light is guided in low index core materials, and waveguide bending was demonstrated. PC clad waveguide coupling was also discussed. The material challenge is reduction of stress induced in the multilayer stacks.

**Multichannel optical filter with tunability** We developed a Si-based multi-channel optical filter based on omnidirectional reflecting photonic band gap structure with a relatively large air gap defect. A multichannel filter at two telecom wavelengths 1.55μm and 1.3μm with electrostatic force tuning was realized in a single device. Four widely spaced resonant modes within the photonic band gap were created. Electrical tunability through free carrier injection was simulated and a static prototype device was measured. The fabricated devices are far from ideal. The surface curvature induced by stress in the dielectric stacks is the main reason for the low Q at the resonance wavelength, and this problem needs to be solved to realize practical applications.

**Quasi-photonic band gap structures** We studied the quasi-photonic crystal structures and their properties in this thesis, especially for their fractal band gap properties and their transparent resonant transmission states. A-periodic Si/SiO₂ Thue-Morse (T-M) multilayer structures were fabricated to investigate both the scaling properties and the omnidirectional reflectance at the fundamental optical band-gap. Large angle reflectance data experimentally demonstrate a large reflectance band-gap in the optical spectrum of a T-M quasicrystal. The physical origin of the T-M omnidirectional band-gap has been
explained as a result of periodic spatial correlations in the complex T-M structure. The photonic quasicrystals can provide an alternative to photonic crystals for future multi-wavelength applications.

**Future works**

Looking forward, there are many challenging problems remaining to be solved. The silicon-based photonic structures depend critically on the qualities of dielectric layers, especially when many layers are stacked together, for example, in the PC clad waveguide, there are 27 dielectric layers, with different film of Si, Si₃N₄ and SiO₂ on a silicon substrate, which are deposited on each other. The stress induced by the multi-layer stacking is enormous, and it changes with the deposition method and conditions. The film thickness control is also another important parameter. Precise control is required, especially for microcavity structures. Due to the indirect band gap of silicon, it is very difficult to make active silicon-based devices on a silicon substrate, that are very critical in order to realize the ultimate goal on functional microphotonics circuits. Recently, there are many new ideas and fabrication methods, that are emerging and allow more materials to be integrated on a silicon substrate. For example, it is found that many polymer materials have very good optical properties, like large nonlinear optical coefficients, that can be used to make active optical devices on a silicon chip. Many polymer materials also have good emission properties, that can be used to make light emitting diodes, even lasers [130-152].
The future of silicon microphotonics is promising, as larger bandwidth requirements and fundamental physical limits are emerging for current electronics technology. The push for new materials, processes and CMOS compatibility with a silicon substrate will make the integrated photonic circuits based on silicon photonic structures developed in this thesis reach a new high level.
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