Chapter 1 Introduction

1-1 Background

Photonic crystals (PCs) arise from the cooperation of periodic scatters thus, they are called "crystal" because of their periodicity and "photonic" because of their action on light.[1] The concept behind these materials stems from pioneering work of Yablonovitch [2] and John [3]. Of particular interest is a photonic crystal whose band structure possesses a complete photonic band gap (PBG) [4]. A PBG defines a range of frequencies for which light is forbidden to propagate inside the crystals. As a result of the existence of photonic band gaps and their unusual dispersion properties, photonic crystals can sustain various light wave, pulse, and beam propagation regimes which are of physical interest and important for numerous applications, such as perfect reflector.

Recently, the research in 2-D PC slab waveguide is focused on the following topics: (1) Photonic crystal waveguides: By making a line defect, an extended mode that can be used to guide light is created. When we bend the waveguide sharply (90-degree), 100% transmission can be achieved for specific frequencies.[5] (2)Bound states at waveguide bends and constrictions: Jaffe and Goldstone[6] proved that bends, which behave like local bulges in the guide, always support bound states in constant cross-section quantum waveguides under the condition that the wave function vanishes on the boundary. In particular, photonic crystal waveguides can be designed to possess mode gaps in their spectrum and these mode gaps make it possible for bound states to exist in bends, bulges, and even constrictions, both above and below the cutoff frequency for guided modes. (3) Photonic crystal micro-cavities: In addition to making line defects, we can also create local imperfections that trap light at the imperfections within the crystal. (4) Waveguide crossings: The waveguide intersections in integrated optical circuits have lacked general principles that could be applied a priori to diverse systems. The perpendicular crossings in such systems exhibit negligible crosstalk is close to 10% when the waveguide width is on the order of a wavelength. The design in PC waveguide permitting single-mode waveguides with optimal miniaturization falls as low as 10^{-9}. [7] (5) Waveguide branches: An idea waveguide branches is a device that splits the input power into two output waveguides without significant reflection or radiation losses. (6) Channel drop filters: Channel dropping filters are devices that are necessary for the manipulation of Wavelength Division Multiplexed (WDM) optical communications. PCs present a unique opportunity to investigate the possibilities of miniaturizing such a device to the scale of the wavelength of interest --- 1.55 μm. (7) Input / Ouput coupling: Because of the different underlying physics of traditional index guiding and PC guiding, coupling of light into and out of PC waveguides is not a trivial problem. There are large insertion losses. One way to achieve coupling is to use a resonant mode to couple the modes in the two types of waveguides. (8) Radiation losses: In general, we deal a 2-D periodic PC slab or a 1-D periodic bar in 3D, coupling to radiation modes can occur, resulting in "leaky" behavior of photon fields. A way to reduce the radiation loss is to exploit the symmetry properties of the defect-state in order to introduce nodes in the far-field pattern that could lead to weak coupling with the radiation manifold.

Besides the design PC waveguide, the fabrication of photonic crystal structure in semi-conductors has been gaining increased attention since their theoretical prediction and experimental realization. [8] In particular, photonic crystal structures can be used to solve various fundamental problems associated with controlling spontaneous emission [9], reducing the group velocity of light [10] and also problems associated with increasing the efficiency of nonlinear optical interactions and possible methods of controlling phase locking in these interactions [11-14].

In simulation, early work in this area employed the "scalar wave approximation" which assumed the two polarizations of the EM waves can be treated separately. [15][16] The results showed that the band gap does not agree with experiment. The vector wave solution of Maxwell's equation for PCs was carried out independently by several groups. [17-19] All of the methods employ a planewave expansion of the electromagnetic field and use Bloch's theorem to reduce the problem to the solution of a set of linear equations. Recently, Pendry and MacKinnon [20] introduced transfer matrix method (TMM) for studying photonic crystal structure. Using the TMM, the band structure of an infinite periodic system can be calculated. The main advantage of this method is the calculation of the transmission and reflection coefficients for EM waves of various frequencies incident on a finite thickness slab of the PBG material. The TMM has been applied in studies of defects in 2-D (metallic) PBG structures [21] [22], of PBG materials in which the dielectric constants are complex and frequency dependent [23], of 3-D layer-by layer PBG material[24] and metallic structures.

The usefulness of K.P formalism in describing the motion of electrons in semiconductors has led to its extension to treat light in PBG materials. [25][26] But they derived from scalar Maxwell's equation. The first time vector K.P approach for photonic band structure is mentioned by Jonhson, et al. [27][28] They used Konh-Luttinger as basis to expand the magnetic field and derived a analytical solution to describe bulk PCs. In 2000, Sipe pointed out that the K.P treatments of PBG materials based on the usual mater equation must employ not only the physical photonic band solution of that equation, but also unphysical solution, in order to form a complete set. [29] Recently, the envelop function approximation is applied to photonic crystal in a manner similar to K.P theory in semiconductor. [30][31] They derived the "mater equation" from Maxwell Equation and expanded by electric mode, i.e.,

$\vec{\nabla}\times\vec{\nabla}\times\vec{E}_{nk}(\vec{r})=\frac{w_n^2}{c^2}e(\vec{r})\vec{E}_{nk}(\vec{r})$. Applying the method to PC waveguide, the frequencies of guided mode in heterostructures can be obtained correctly.

1-2 Motivation

In photonic crystals with defect, there is a phenomenon that in 1-D no mater how small the defect is, there always allows a bound state in the forbidden gap but in 2-D or 3-D, it always needs finite defect to trap photon in the band gap. [32] This is similar to the comparison between the 1-D and 2-D (3-D) potential well in quantum mechanics. In one dimension even an infinitesimal well will bind a state. In two (three) dimensions, a finite depth potential is required to produce a bound state.

If we introduce Kohn-Luttinger functions as the basis of **H**(r) and derive by K.P theory, we find the photon excites a massive quasi-particle in photonic crystals. The quasi-particle possesses rest mass so that it can be trapped in the defect resulting from the attractive potential which is defined as the product of rest energy and index disorder. We will introduce one-band model and two-band model of K.P theory to explain the phenomenon in one and two dimensional cases, and then applying the two models to several structures.

With the development of fabrication techniques of the photonic crystals, the modeling theory for the localized mode in photonic crystals has also developed. We try to develop the transfer matrix method (TMM) and finite difference time domain (FDTD) method to realize the electric field distribution and the localized defect mode in PCs. Recently, Villeneuve, Fan, and Joannopoulos use smoothing sharp varying dielectric constant boundary to solve eigen energy in PCs. [33] We will also introduce this method to FDTD method.

1-3 Organization of the thesis

In chapter one, we introduce the brief review of photonic crystal and its applications. We also talk about the simulation method and the development of K.P theory in photonic crystals. In chapter two, we introduce K.P theory into Maxwell's equation to derive mater equation in bulk PCs. From the equation we get the effective dielectric constant no master in one band model or two bands model. Then, we add a defect into PCs, and derive the master equation with similar method. At last, we introduce the transfer matrix method and finite difference time domain method in calculating field distribution and transmittance and dispersion relation.

In chapter three, we use TMM and FDTD to study basic concept of 1-D and 2-D PCs and then use K.P method to solve the defect structure and compare with TMM. Because the K.P method needs the larger width of defect, we put the K.P theory in hetero-structure in 1-D and 2-D case. We conclude our result in the last chapter.