Study of 2-D Square Rod-in-Air Photonic Crystal Optical Switch and Design of Fast Planar Laser Shutter

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STUDY OF 2-D SQUARE ROD-IN-AIR PHOTONIC CRYSTAL OPTICAL SWITCH
AND DESIGN OF FAST PLANAR LASER SHUTTER

By

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A Dissertation submitted to the
Department of Electrical and Computer Engineering
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Degree Awarded:
Fall Semester, 2009
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This manuscript is dedicated to my deceased grandparents, my parents, my cousin’s family and my sister’s family with my deepest love. I also give my appreciation to all those people who generously helped me before. Without their years of care and sacrifices, I wouldn’t have achieved my goal. I will continue to further my goal under their care.

This manuscript is also dedicated to my wife and my daughter. God bless them!
ACKNOWLEDGEMENTS

I would like to give my hearty gratitude to Dr. Jim P. Zheng for his teaching and advising me and in helping me to finish my dissertation. I would also like to sincerely thank Ms. Duo Liu for her help through the years. I would also like to thank my colleagues in the lab: Dr. Wei Zhu, Dr. Pedro Moss, Vivek Tiwari, Annadanesh Shelliikeri, and Michael Greenleaf for their generous assistance when writing my dissertation. Lastly, I again appreciate the inspiration, support and help from the above people, in particular Dr. Jim P. Zheng and Ms. Duo Liu.
TABLES OF CONTENTS

List of Tables .................................................................................................................... vii
List of Figures .................................................................................................................. viii
Abstract .............................................................................................................................. xi

PART I

CHAPTER 1 INTRODUCTION .........................................................................................2
CHAPTER 2 DEVELOPMENT AND APPLICATIONS OF PHOTONIC CRYSTALS .......9
CHAPTER 3 SIMULATION ............................................................................................16
CHAPTER 4 BASIC STRUCTURE AND ITS BAND GAP ...........................................25
CHAPTER 5 2-D SQUARE ROD-IN-AIR PHOTONIC CRYSTAL SWITCH ..............30
CHAPTER 6 FEATURE OF 2-D SQUARE ROD-IN-AIR PHOTONIC CRYSTAL SWITCH ............................................................................................................................34
CHAPTER 7 FUTURE RESEARCH ................................................................................53
APPENDIX A MPB PROGRAM ......................................................................................54
APPENDIX B MEEP PROGRAM ....................................................................................55

PART II

CHAPTER 8 INTRODUCTION ........................................................................................59
CHAPTER 9 STRUCTURE OF LASER SHUTTER .......................................................61
CHAPTER 10 MATHEMATICS OF LASER SHUTTER ...............................................71
CHAPTER 11 SIMULATION RESULTS AND ANALYSIS ..........................................86
LIST OF TABLES

PART I

Table 3.1 Computer information ........................................................................................................... 24
Table 4.1 Difference between TM and TE wave ..................................................................................... 29
Table 6.1 Source properties .................................................................................................................... 42
Table 6.2 The range of ratio of energy flow of the left, right, upper, and down channel in the cases of different diameter of single inserted rod .................................................................................. 48

PART II

Table 8.1 Summary of levels for single pulsed laser and laser system classification (ANSI Z316.1 Standard) .............................................................................................................................. 60
Table 10.1 Parameters of DKDP ........................................................................................................... 74
Table 10.2 Parameters of intrinsic semiconductor materials ................................................................. 75
Table 10.3 \( m \), \( V_{BR} \), and \( E_{BR} \) determined by fitting curve ................................................................. 79
Table 10.4 Comparison of laser shutter with Si and GaAs PCSS ............................................................. 84
Table 11.1 Parameters applied in the simulation of Figure 11.1 ............................................................. 87
Table 11.2 Dependence of laser shutter performance with Si PCSS geometry ................................. 91
LIST OF FIGURES

PART I

Figure 1.1 Scheme of distributed feedback laser .................................................................5

Figure 2.1 Cross section views of several PFCs designs ...................................................10

Figure 3.1 Yee lattice .........................................................................................................20

Figure 4.1 Cartesian coordinate system .............................................................................25

Figure 4.2 Top view of 2-D square rod-in-air photonic crystal structure .......................27

Figure 4.3 TM band gap diagram of 2-D square rod-in-air photonic crystal ....................28

Figure 4.4 TE band gap diagram of 2-D square rod-in-air photonic crystal ......................29

Figure 5.1 Top view of 2D square rod-in-air photonic crystal optical switch structure ....32

Figure 5.2 Snapshot of Ez at time 106 a/c during the simulation ........................................33

Figure 6.1 Relationship between ratio of net energy flow and position of single inserted rod in the case of Gaussian, point source ...............................................................34

Figure 6.2 Plot of Ez vs. time at the center of left detector (-7, 0) in the case of single rod at (0.1, 0.1) .........................................................................................................................39

Figure 6.3 Plot of Ez vs. time at the center of left detector (-7, 0) in the case of single rod at (-0.7, - 0.7) .....................................................................................................................40

Figure 6.4 Plot of Ez vs. time at the center of left detector (-7, 0) in the case of single rod at (0.6, 0.6) .........................................................................................................................41

Figure 6.5 Relationship between ratio of net energy flow and position of single inserted rod in the case of Gaussian, line source ........................................................................42

Figure 6.6 Relationship between ratio of net energy flow and position of single inserted rod in the case of continuous wave, point source .........................................................43

Figure 6.7 Relationship between ratio of net energy flow and position of single inserted rod in the case of continuous wave, line source .........................................................44
Figure 6.8 Comparison of ratio of net energy flow in the left channel under different
sources................................................................................................................................45

Figure 6.9 Comparison of ratio of net energy flow in the right channel under different
sources................................................................................................................................46

Figure 6.10 Comparison of ratio of net energy flow in the upper channel under different
sources................................................................................................................................46

Figure 6.11 Comparison of ratio of net energy flow in the down channel under different
sources................................................................................................................................47

Figure 6.12: Relationship between the ratio of net energy flow in each channel and the
position of single inserted rod (Ø = 0.3a) under the case of TM Gaussian point source.
The frequency is 0.35 c/a.................................................................48

Figure 6.13: Relationship between the ratio of net energy flow in each channel and the
position of single inserted rod (Ø = 0.5a) under the case of TM Gaussian point source.
The frequency is 0.35 c/a.................................................................49

Figure 6.14: Relationship between the ratio of net energy flow in each channel and the
position of single inserted rod under the case of TM Gaussian point source. The
frequency is 0.35 c/a. Note that diameter of rod at (1, 1) is 0.3a.................................50

Figure 6.15: Relationship between the ratio of net energy flow in each channel and the
position of single inserted rod under the case of TM Gaussian point source. The
frequency is 0.35 c/a. Note that diameter of rod at (1, 1) is 0.5a.................................51

Figure 6.16: Comparison of ratio of net energy flow entering the upper channel when
diameter of rod at (1, 1) is 0.3a, 0.4a, and 0.5a respectively.................................52

PART II

Figure 9.1 Polarization of light.................................................................62

Figure 9.2 Schematic of laser shutter..........................................................65

Figure 9.3 A stand-alone Pockels cell intensity modulator.................................66

Figure 9.4 Polarizer......................................................................................67

Figure 9.5 Semiconductor photon sensor......................................................68

Figure 9.6 Circuit model of laser shutter......................................................70

Figure 10.1 Pockels cell intensity modulator with longitudinal configuration........73
Figure 10.2 Measured drift velocity of carriers in high-purity Si and GaAs as a function of the applied electric field ..........................................................76

Figure 10.3 Multiplication factor versus reverse bias in GaAs intrinsic semiconductor...80
Figure 10.4 Relationship between length of intrinsic GaAs and: (a) breakdown electric field $E_{BR}$, and (b) factor $m$ ..................................................................................................81

Figure 10.5 Relationship of electric field and multiplication factor $M$ for GaAs PCSS with length of 1 mm. ..........................................................................................................82

Figure 11.1 Plots of laser shutter performance .....................................................................90

Figure 11.2: The relationship between the ratio of $I_0/I_i$ of the laser shutter and the carrier lifetime of the PCSS in the case of a fixed incident laser pulse. .........................92

Figure 11.3 Effect of peak intensity of an incident laser pulse on the laser shutter ..........94

Figure 11.4 Effect of pulse width of incident laser pulse on the ratio of $I_0/I_i$ ...............96

Figure 11.5 Effect of area of electrode of the Pockels cell on laser shutter ....................97

Figure 11.6 Effect of linear and nonlinear relationship of carrier velocity $v_d$ and electric field $E$ on laser shutter performance .................................................................99

Figure 11.7 The influence of avalanche effect of GaAs PCSS on laser shutter performance. .........................................................................................................................101
ABSTRACT

This dissertation is made of two parts. Part I, chapter 1 to chapter 7, is 2-D square rod-in-air photonic crystal optical switch; Part II, chapter 8 to chapter 12, is design of fast laser shutter.

Photonic crystal is a kind of materials with periodic structures. Moreover the lattice constant of photonic crystals is on the same scale as the wavelength of electromagnetic waves. One of photonic crystal’s specific properties is that only allowable electromagnetic wave states could propagate inside. This property presents a new way of controlling the propagation of light inside materials. In this paper, a 2-D photonic crystal optical switch is proposed. This is a rods-in-air structure device by removing two cross-lines of rods from a 2-D square-rod photonic crystal. The optical switch feature is achieved by inserting a single rod along the line segment from (-0.7, -0.7) to (0.7, 0.7) in coordinate. In fact, this line segment is the diagonal line of the intersection area of two removed cross-lines of rods. The position of the inserted single rod determines how much the total source energy propagates into the upper channel. In the case of transverse magnetic Gaussian point source, up to 41.38% of the total source energy goes into the upper channel and is shown by time domain simulation. It is also found that the magnitude of the reflected wave in the left channel varies greatly with spatial position of the single inserted rod. The larger the magnitude of the reflected wave in the left channel, the less energy goes into the upper channel. The time delay between the incident wave and the reflected wave in the left channel is also related to the position of the single inserted rod. In addition, the extremely large time delay between the incident wave and the reflected wave in the left channel shows that the reflected wave encounters many reflections with the walls of the left channel, instead of reflected back from the single inserted rod directly. Simulations also demonstrate that the control effect of this 2-D photonic crystal optical switch exists under the cases of Gaussian/continuous wave, point/line source. The advantage of this photonic crystal optical switch presented here is operational simplicity because the change of the position of only one rod is needed to finish the switching function. This operational simplicity is critical in
microoptoelectromechanical system (MOEMS) device. Consequently, this 2-D photonic crystal optical switch is an attractive design in the study of integrating optical circuit.

The goal of Part II is to design a laser shutter to protect eyes from fast laser pulse. The width of targeted laser pulse is $30 \text{ ns}$. It is proposed to apply Pockels cell intensity modulator with longitudinal configuration to block the laser pulse. The Pockels cell material is Deuterated Potassium Dihydrogen Phosphate $\text{KD}_2\text{PO}_4$ (DKDP) because its electrooptic parameter, $r_{63}$, is highest among popular nonlinear electrooptic materials. The laser shutter is controlled by a semiconductor photon sensor. When photon sensor probes laser pulse, laser shutter starts to block off the laser pulse. The performance of laser shutter is also investigated under variant conditions: laser pulse intensity, semiconductor carrier lifetime, size of Pockels cell.
PART I

2-D SQUARE ROD-IN-AIR PHOTONIC CRYSTAL OPTICAL SWITCH
CHAPTER 1
INTRODUCTION

1.1 Genesis of photonic crystal

People have been known the phenomena of electromagnetic since ancient times. However, the basic principles of electromagnetic wasn’t understood until 1861, when James Clerk Maxwell, a gifted Scottish physicist published his excellent works [1]. In his publications, Maxwell formulated the electromagnetic theory, which was later summarized as Maxwell’s equations. Maxwell’s equations in differential form are [2]:

\[ \nabla \cdot \mathbf{D} = \rho_v \] ...............................................................(1.1a)

\[ \nabla \cdot \mathbf{B} = 0 \] ...............................................................(1.1b)

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \] ...............................................................(1.1c)

\[ \nabla \times \mathbf{E} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \] ...............................................................(1.1d)

where \( \mathbf{D} = \varepsilon \mathbf{E} \) is electric flux density;
\( \mathbf{B} = \mu \mathbf{H} \) is magnetic flux density;
\( \mathbf{E} \) is electric field intensity;
\( \mathbf{H} \) is magnetic field intensity;
\( \rho_v \) is volume charge density;
\( \mathbf{J} \) is volume current density;
\( \varepsilon \) is permittivity of medium; It represents macroscopically electrical property of medium. In general, it is also represented as \( \varepsilon = \varepsilon_r \varepsilon_o \) in which \( \varepsilon_o \) is the permittivity of free space and \( \varepsilon_r \) is dielectric constant or relative permittivity. \( \varepsilon_o \) is a constant, \( \frac{10^{-9}}{36\pi} \) or 8.854x10^{-12} F/m. \( \varepsilon_r \) is a ratio without unit.

\( \mu \) is permeability of medium. It represents macroscopically magnetic property of medium. In general, it also represents as \( \mu = \mu_r \mu_o \) in which \( \mu_o \) is the
permeability of free space and $\mu_r$ is relative permeability. $\mu_0$ is a constant, $4\pi \times 10^{-7}$ F/m. $\mu_r$ is a ratio without unit.

Even though Maxwell’s theory is the rule governing all electromagnetic phenomena, electromagnetic phenomena appear before people in all possible forms. This variety of electromagnetic phenomena has been the driving force behind human being’s research activities since foundation of Maxwell’s equations. For this reason study of electromagnetic phenomena is not a closed book.

Among all electromagnetic phenomena is photonic crystal (PhC) a new one. It was proposed in 1987, twenty years ago. The first road to find photonic crystal is the investigation of spontaneous emission by atoms. Spontaneous emission in atoms is a process in which an excited electron stayed at the higher energy state jumps down the lower energy state with emission of a photon. It was Albert Einstein who started to study spontaneous emission in 1917 [3]. Edward Purcell Later discovered that spontaneous emission in atoms could be modified by surrounding electromagnetic field [4]. This controlled spontaneous emission is very attractive phenomenon in solid state physics. This is because spontaneous emission which, in semiconductors, is in the form of electron-hole recombination has a major contribution on the behavior of electrons. Spontaneous emission in solid state physics was inhibited in a cavity in 1985 [5, 6]. After two years Eli Yablovitch, one of pioneers in the photonic crystal community, proposed that inhibited spontaneous emission could be achieved three-dimensionally by periodic dielectric structures [7].

Another important milestone was PhC hill which is the study of Anderson localization [8]. Anderson localization is named after Philip Warren Anderson who is one of the first scientists to study wave function of electrons in semiconductors with random doping and non-crystalline materials. His conclusion is that, under strongly disordered potential wells, which models the real situation inside random doped semiconductor or non-crystalline materials, wave function of electrons could not expand into entire the materials. This means that electrons are constrained in local areas if conditions are satisfied, and this phenomenon is called Anderson localization. Since Anderson localization was predicted in 1958, it has been successfully used in research of disordered systems. In the mid 1980s’ Sajjev John [9] and Philip Warren Anderson [10] suggested
that Anderson localization could be realized in optical systems more easily than in solid state materials. Finally, Sajjey John, another pioneer of PhC society, proposed in 1987 [11] that Anderson localization could be materialized in a carefully prepared three dimensional dielectric structure.

After four years of effort since the birth of PhC proposal, the first experimental three dimensional PhC structure with full band gap was fabricated by Eli Yablonovitch and his coworkers in Bell Lab in 1991 [12]. It is a face centered cubic (fcc) structure. Its band gap of this fcc PhC structure is ~ 20% of its center frequency. Any light with a frequency within the band gap could not propagate this fcc PhC structure no matter what incident direction light takes.

1.2 Definition of photonic crystal

Photonic crystals are, by definition, structures with periodic dielectric constant ($\varepsilon_r$) in which the lattice constant is comparable with wavelength of specified electromagnetic wave ($\lambda$). This unique property allow for the control of the propagation of a specified electromagnetic wave in corresponding photonic crystal. When the structure of the photonic crystal and properties of electromagnetic wave satisfy, propagation of electromagnetic wave is forbidden in photonic crystal. This is probably the most striking characteristic of photonic crystals. This means that not all electromagnetic wave could go through photonic crystal. From this point of view, photonic crystal likes a frequency filter. But this is not all. It has been found that photonic crystal displays more special features. Photonic crystals are made from dielectrics, metals, and polymers at this present time. Photonic crystals are artificially designed and fabricated using modern microscopic technology since lattice constant is requested to be comparable with wavelength of specified electromagnetic wave. If the requirement is not held, photonic crystal never expresses distinguishing properties.

It is frequently seen another term, photonic band gap (PBG), in the literatures. Generally, photonic crystal and photonic band gap have the same meaning. They may be used interchangeable without lost in generality. For the consistency, only photonic crystal is used in this study.
Electromagnetic wave represents all waves which propagate by interaction of variable electric field and variable magnetic field. It includes x-rays, ultraviolet radiation, visible light, infrared radiation, microwave, and so on. The focus of this document is photonic crystal switch which is mainly about visible light. For this reason, the term, light, is used in most sections. However, the term electromagnetic wave is also used in some sections in order to better express intentions. In general, they can be used interchangeable.

1.3 Physics of photonic crystal

Photonic crystal is very complicated topic in physics. It is not possible to completely discuss photonic crystal in this single section; however it is necessary and possible to give a clear and simple physical explanation about the principles of photonic crystal. Both Eli Yablovitch and Sajjev John discussed Distributed feedback (DFB) laser in their original papers. The structure of distributed feedback laser is actually a one dimensional photonic crystal. This one dimensional photonic crystal is the simplest case and consequently is also a good starting point to discuss the physics of photonic crystal.

Distributed feedback laser was manufactured in 1971 [13, 14] and was then given a complete theoretical explanation in 1972 [15] by H. Kogelnik and C.V. Shank of Bell lab. The structure of distributed feedback laser is a one dimensional periodic structure. When an incident light meets it at normal angle from the left side, reflection phenomenon happens at each interface of the layer of media [Figure 1.1]. In fact, there is also
reflection phenomenon occurring when light propagates from medium 1 to medium 2. However, this reflection wave is absurdly omitted here in order to providing a simple physical reason. Each reflection wave lags by a phase of $ka$, where $k$ is average wave vector in one layer of media and $a$ is lattice constant which is the total width of medium 1 and medium 2. Here, the intensity of light is represented by the electrical field intensity $E$ in order to simplify the discussion. Finally, the electrical field intensity at left side is expressed as:

$$E = E_o + E_o e^{-j2ka} + E_o e^{-j4ka} + E_o e^{-j6ka} + ... + E_o e^{-j(2n)ka} + ...$$

where $E$ is the electrical field intensity after superposition of incident wave and all reflected waves:

- $E_o$ is the electrical field intensity of incident wave;
- $E_o e^{-j2ka}$ is electrical field intensity of reflection wave at the first interface ($z = a$);
- $E_o e^{-j4ka}$ is electrical field intensity of reflection wave at the second interface ($z = 2a$);
- $E_o e^{-j(2n)ka}$ is electrical field intensity of reflection wave at the nth interface ($z = na$);

For above equations, the total reverse wave is comparable to the incident wave when $n$ is larger and $2ka$ is an integer number of $2\pi$. This shows that the incident wave is totally reflected when the frequency satisfies condition, $2ka = 2n\pi$, here $n$ is an integer number. The above deduction is only the zeroth-order approximation. The real situation is more complex because light experiences multiple reflections, even though the above equation displays the characteristic of this periodic layer structure. In real cases, there exists a range of frequency for distributed feedback laser for which light in this range could not propagate the distributed feedback structure. This range of frequency is termed as “stop band”. Exhaustive discussion of distributed feedback laser is presented in textbooks [16, 17].

The situations of electromagnetic wave in two and three dimensional photonic crystals are more difficult to explain than one dimensional photonic crystals, like distributed feedback laser. But the basic characteristic of photonic crystals and fundamental physics reason are same for 1D, 2D and 3D photonic crystals.
I could not end this section without commenting on the difference between the classical optical materials and photonic crystal materials. The phenomena of reflection and refraction of light are mentioned in textbooks. The related physical laws, reflection law and Snell’s law, are well known. But they are classic optical phenomena. Photonic crystal is totally different from them. The fundament difference is that lattice constant of photonic crystal is comparable with the wavelength of light. The wavelength of visible light extends from $400 \text{ nm}$ of red light to $700 \text{ nm}$ of violet light. However, common optical materials either are not crystal materials, like glass, or crystal with lattice constants much less than wavelength of light, like SiO$_2$.

### 1.4 Photonic crystals in nature

It was two twenty years ago when people began to study photonic crystal. But photonic crystal has existed for millions years on earth. As early as the 19$^{th}$ century, physicists and biologists started investigating the colors of living systems. It was not concluded, until 1970s, that color phenomena in animals and plants originates from not only pigments but also structures [18]. Color phenomena due to structures of biology were entitled as structural colors whereas those due to pigments were named as pigmentary colors. Although peoples realized structure is a major reason of colors in biology, physical explanation of structural colors was based on classic optics: reflection, refraction, scattering, diffraction, interference, etc.

It was not until this century when biologists began to study the structural colors of nature from the point view of photonic crystals. At first, it was found that there is photonic crystal in the wings of papilio palinurus butterfly in 2000 [19]. The subtle photonic crystal in the wings helps butterflies to produce extraordinary optical phenomena: polarization conversion [19], bright iridescence without large wing movement [20], etc. Photonic crystal in wing of the butterfly wings is a tilted multiple layer structure. Later, it was also found photonic crystals in other butterflies [21], beetles [22], plants [24, 25], and aquatic systems [26].

Even though natural photonic crystal has existed for over 500 million years, most unbelievable fact is the high quality of natural photonic crystal. Such natural elegant photonic crystal structures are far beyond the ability of modern advanced technology.
Images of the natural photonic crystals under scanning electron microscope and transmission electron microscope are nearly perfect. Such perfect structures in living system attract us to understand them and design and manufacture similar structures. For example, the size of photonic crystals in papilio palinurus wings is about $4 – 6 \mu m$ [19] which is nearly ten times the wavelength of visible light. For this case, photonic crystal phenomenon logically shouldn’t exist however it does in butterflies wings. To consider interesting biology phenomena gives more help to development of science and engineering.
CHAPTER 2
DEVELOPMENT AND APPLICATIONS OF PHOTONICS CRYSTALS

2.1 Photonic crystal fiber

Photonic crystal fiber (PCF) is the most successful practical application of photonic crystals. This striking development of PCF was mainly contributed to Philip Russell and his coworkers at the University of Bath, UK. It was as early as 1991 when Philip Russell proposed the idea of PCF. Conversional fiber operation is based on the principle of Total Internal Reflection (TIR), by which light propagates from a higher index medium to a lower index medium, would totally reflected back when the incident angle is larger than the critical angle, which is determined by Snell’s law:

$$\theta_{\text{critical}} = \sin^{-1}\left(\frac{n_{\text{low}}}{n_{\text{high}}}\right)$$

where $n_{\text{high}}$ represents higher index medium; $n_{\text{low}}$ represents lower index medium. All conventional fibers are solid core fibers. This is because TIR only happens when light goes from a high index medium to a low index medium. Moreover, no material has the index less than 1, which is the index of air. Thus, there is solid core within conventional fibers. When light propagates in solid materials, as well known, there is always loss due to absorption, scattering, etc which result from interaction between light and materials. Consequently, for all conventional fibers, there is a limitation of loss. This limitation is the minimum loss of light when it goes through materials.

In PCFs, a 2-dimensional photonic crystal lattice is suitably designed so that light is trapped inside 2-dimensional photonic crystal. For PCFs, the core could be hollow [Figure 2.1 (b) & (d)], just air inside. Under such hollow core environment, the loss of light could be lower in PCFs than that of conventional fibers. The reason is, when light propagates in air, loss is lower than that in solid materials. The ultra-low loss in hollow core PCFs is the most attractive feature and strongest motivation behind research activities of PCFs.
Since PCF was proposed, Philip Russell and his coworkers had spent five years exploring and manufacturing the first PCFs. The first PCF was successfully fabricated in 1996 which is a solid core PCF [27]. The first hollow core PCF in the world appeared in 1999 by stack-and-draw approach [28]. Even though the features of PCFs were not as good as commercial conventional fibers at that time, successful fabrication of PCFs showed that light could be confined within this new of fiber, PCF.

Years later, the features of PCFs have been improved to a large extend through development of fabrication technique and proper design. In 2003, Corning company, which is one of leading optics companies in United States, successfully manufactured hollow-core silica/air PCF with several hundred meters length and minimum loss of 13 dB/km at 1500 nm [29]. This is probably the first PCF whose features were published in details. The longer and better PCFs is expected to been manufactured soon. In 2004, the loss of PCF reduced to 1.2 dB/km at 1620 nm [30]. Since then, the progress of achieving
less loss PCFs has been limited. For conventional fibers, the loss of SMF-28e fiber of Corning Company is 0.2 dB/km at 1550 nm [31]. The loss of PCFs is six times higher than that of commercial conventional fibers. The roughness of inner wall of PCFs is believed to be the major reason resulting in somewhat large loss [30]. The existence of roughness of inner walls of PCFs leads to changes of lattice in a local scale. And geometry of PhC is tightly related with the features of PhC, for example, loss of fiber. Improving the technique and fabrication of PCFs with smoother inner walls is the key to reducing loss of PCFs.

Although the loss of PCFs is still higher than that of commercial conventional fibers, promising PCFs’ applications on other engineering realms have launched in the last two years. In telecommunication, people used PCFs to implement all-optical 80 Gb/s Time-Division Demultiplexing [32], Full-Duplex Radio-on-Photonic transport system [33], and 4 X 10 Gb/s over 5-km-long [34]. The application of PCFs in sensors has been studied [35, 36]. Other appealing applications of PCFs include laser tweezers, high power transmission, nonlinear effects, etc.

2.2 Photonic crystal cavity

Cavity is a device or, strictly speaking, a structure in which only resonance state exists. In optics, the resonance state is named mode terminologically, which is specified by frequency and polarization of light. Cavity is a common and important structure in optics. The resonator of laser, for example, is indeed a cavity. The quality of output coherence light of laser is largely determined by the quality of the cavity. The primary standard of evaluating a cavity is quality factor, Q, which, in optics, is defined as below:

\[ Q = \frac{f_0}{FWHM} \]

where \( f_0 \) is resonant frequency and \( FWHM \) is the full width at half of maximum. A cavity with higher \( Q \) indicates a better characteristic of resonance. Physically speaking, quality factor is strongly related to several broadening processes occurred within the cavity. For example, due to interactions among atoms, molecules, electrons, frequency of output coherence light of laser varies from resonant frequency. Such varied frequency of output
coherence light deteriorates quality factor of the laser, $Q$. The broadening process is a complicated topic. More details can be found in reference [37].

The higher quality factor is a desirable goal of cavity. Another goal of cavity studies is manufacturing nano-size cavity in order to apply cavity or laser into micro scale fields. The potential to achieving both goals, however, is limited in conventional cavity. This is because conventional cavities are realized by reflection approach. When the size of the cavity is scaling down, it is very difficult to confine light in a small volume by the method of reflection. As a result, leakiness of light becomes relatively larger, and consequently quality the factor is deteriorated. If conventional cavity keeps still in large size, there are more matters within cavity volume. More matter leads to abounding collisions among atoms, molecules, etc. Finally, it is not possible to improve the quality to a great extent due to abounding broadening process within the cavity. Based on the above discussions, realizing cavities with higher quality factor and ultra-small size is really a challenging issue in conventional cavity studies.

The discovery of photonic crystals in last century brought a new approach to overcome this difficult problem of conventional cavity studies. In 1991, the possibility of realizing cavity of photonic crystals was first explored theoretically [38, 39, 40]. When periodic property of a bulk photonic crystal is broken, for instance removing a rod from a bulk of two dimensional photonic crystal, a defect is formed locally. In this local defect, it is possible to confine light with to a specific mode. This local defect inside a photonic crystal structure is indeed a cavity. Most research focused on proposal, design, simulation, and analysis of varied cavity structures in the following years [41, 42]. The first real photonic crystal cavity appeared in 1997 [43, 44]. The first real photonic crystal cavity was called air-bridge microcavity. Its quality factor is only 265 at wavelength of 1560 nm and volume is $0.055 \mu m^3$.

In 2001, two research groups successfully fabricated similar structured photonic crystal cavities which demonstrates a quality factor higher than $10^3$, one 1500 [45] and another 1900 [46]. This astonishing progress, at first, is attributed to a new cavity structure which firstly appeared in 1998 [47]. Then Through optimization of design and refinement of technology, the potential of this new structured cavity was shown fully.
Another new structured cavity with quality factor $4.5 \times 10^4$ was fabricated in 2003 [48]. This is the first photonic crystal cavity which has a quality factor in excess of $10^4$. This new structure of photonic crystal cavity is called “L3” because three rods are removed in a bulk hexagonal air-hole PhC. In 2006-2007, photonic crystal cavity with heterostructure expresses better quality factor above one million. To date, quality factor of this kind of cavity reaches $1.28 \times 10^6$ [49]. This kind of heterstructure photonic crystal cavity was also analyzed that and the loss of light is mainly due to imperfection design and technique [50]. The better photonic crystal cavity will appear through optimization of and refinement of technology. In 2005, a double-heterostructure cavity was fabricated. Even though its quality factor was $6 \times 10^5$, it was theoretically predicted that quality factor could be up to $2 \times 10^8$ if the real cavity structure is perfect as designed. This is the best prediction of quality factor thus far [51]. All cavities discussed above are single layer structures. In 2006, a double layered structure photonic crystal cavity was fabricated [52]. Its quality factor was up to $6 \times 10^7$ which has been the highest quality factor until to date. With the surprising advance in the studies of photonic crystal cavity, the research of their potential applications has been moving forward simultaneously and quickly. In fact, the quality factor of $10^5$ is enough for most applications of photonic crystal cavity [53]. These applications include laser, filter, quantum computing, cavity quantum electrodynamics, and so on. It is not possible to cover all respects of these applications of photonic crystal cavities. Only the photonic crystal cavity’s application on laser is summarized below.

In conventional laser, spontaneous emission is dominant when current is small. When the current is larger than the threshold current, typically in the order of mA, simulated emission is dominant in the cavity. For conventional laser, the threshold current exists because spontaneous emission exists. Recently, was proposed that it is possible to construct thresholdless laser by embedding quantum dots in photonic crystal cavities [54 - 56]. This thresholdless laser does not have threshold current because spontaneous emission is suppressed in the cavities to a large extent.

In summation, the research in the area of photonic crystal cavities is very active now. To date, most photonic crystal cavities are two dimensional planer hexagonal structures and are fabricatd in semiconductor materials: silicon (Si), indium gallium
arsenic phosphide (InGaAsP), gallium arsenic (GaAs). The fabricating technologies to manufacture photonic crystal cavities are metal organic chemical vapor deposition, electron beam lithography, and etching. The quality factor is related to the structure of photonic crystal cavity. Thus, the first thing in realizing a photonic crystal cavity is to do simulation and then find the optimal structure. Most simulations used FDTD method. So far, quality factor has reaches $6 \times 10^7$ experimentally. Moreover, higher quality factor will be obtained with optimizing design and improving technique.

### 2.3 Photonic crystal switch

The research of PhC optical switch has been carried out using several approaches. The first approach is to change the material’s index by utilizing the Kerr effect [57]-[61]. The index of some materials is dependent of the applied electrical field. The relation of index’s change and applied electrical field is $\Delta n = \lambda K E^2$, where $\lambda$ is the wavelength of the light, $K$ is the Kerr constant, and $E$ is the amplitude of the electric field. By increasing the input power of light, the index of the materials in PhC structures is varied large. As a result, the cavity is in an on or off resonance state and then the switching is implemented. These types of optical switch are popularly named all-optical switch because they are controlled by input light intensity.

The second approach is to change the material’s index by heating [62, 63]. This approach is similar to the first approach. This is because that material index is related to the applied electrical field but also temperature. By heating the PhC structures, the index of material is changed and the switching feature is realized.

The third approach is to insert different PhC structures into optical the network with microelectromechanical (MEMS) technology [64]-[67]. When different PhC structures are inserted between input waveguide port and output waveguide port, the coupling between input port and output port is changed. The input light is coupled to the output port in the case of “on” coupling.

In addition, other approaches were used to implement the PhC switches, for example: changing the conductance of the semiconductor in PhC structure [68], changing design parameters of PhC structure [69], changing incident light angle [70], utilizing the
self-imaging phenomena in multi-mode interface PhC [71]. To date, the investigation of PhC optical switches is not a full-fledged area. Many designs have been proposed and compared. The basic ideal of realizing switching feature is to change the properties of the materials of PhC structures (for example, index) or the PhC geometry structures. The 2D PhC optical switch proposed in this paper achieves the switching function by changing the geometry structure of PhC.
CHAPTER 3
SIMULATION

3.1 Block-iterative frequency domain Methods for Maxwell’s equations

The static properties of electromagnetic wave inside PhC structure is provided by frequency vs. wave vector diagram (ω-k diagram). The method which was used to find this ω-k diagram in this prospectus is Block-iterative frequency domain Methods [72-75]. In this method, the motion of electromagnetic wave in a PhC structure is described by an eigenvalue equation which is derived from Maxell’s equations. The matrixes in this eigenvalue equation are determined after a plane wave basis is selected. So the electromagnetism problem is treated as an eigenvalue problem. The eigenvectors of this eigenvalue equation represents the electromagnetic wave which is allowed to propagate in PhC structure.

The Maxwell’s equations under the condition with zero charge (ρ = 0) and zero current (J = 0) are rewritten below:

\[ \nabla \cdot \mathbf{D}(\mathbf{r}, t) = 0 \] .......................................................... (3.1a)

\[ \nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t} \] .................................................. (3.1b)

\[ \nabla \cdot \mathbf{B}(\mathbf{r}, t) = 0 \] .......................................................... (3.1c)

\[ \nabla \times \mathbf{H}(\mathbf{r}, t) = \frac{\partial \mathbf{D}(\mathbf{r}, t)}{\partial t} \] .......................................................... (3.1d)

The qualities $\mathbf{E}$ and $\mathbf{H}$ of electromagnetic field are written as harmonic modes as follow:

\[ \mathbf{H}(\mathbf{r}, t) = \mathbf{H}(\mathbf{r})e^{-i\omega t} \] .......................................................... (3.2a)

\[ \mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r})e^{-i\omega t} \] .......................................................... (3.2b)

So the equation (3.1b) is transformed as:

\[ \nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \left( \mu_r \mu_o \mathbf{H}(\mathbf{r}, t) \right)}{\partial t} \]

\[ \nabla \times \mathbf{E}(\mathbf{r}) = \mu_r \mu_o (i\omega) \mathbf{H}(\mathbf{r}) \] .................................................. (3.3a)

Similarly, the equation (3.1d) is transformed as:
\[ \nabla \times \mathbf{H}(\mathbf{r}, t) = \frac{\partial (\varepsilon, \varepsilon_o \mathbf{E}(\mathbf{r}, t))}{\partial t} \]

\[ \nabla \times \mathbf{H}(\mathbf{r}) = -\varepsilon, \varepsilon_o (i\omega) \mathbf{E}(\mathbf{r}) \]  

(3.3b)

Divided by \( \varepsilon(\mathbf{r}) = \varepsilon,(\mathbf{r})\varepsilon_o \) and take the curl of equation (3.3b)

\[ \frac{1}{\varepsilon, \varepsilon_o} (\nabla \times \mathbf{H}(\mathbf{r})) = (-i\omega) \mathbf{E}(\mathbf{r}) \]

\[ \nabla \times \left( \frac{1}{\varepsilon, \varepsilon_o} (\nabla \times \mathbf{H}(\mathbf{r})) \right) = (-i\omega)(\nabla \times \mathbf{E}(\mathbf{r})) \]  

(3.4)

Substitute \( \nabla \times \mathbf{E}(\mathbf{r}) \) of the right side of equation (3.4) with equation (3.3a)

\[ \nabla \times \left( \frac{1}{\varepsilon, \varepsilon_o} (\nabla \times \mathbf{H}(\mathbf{r})) \right) = \omega^2 \mu_o \mu, \mathbf{H}(\mathbf{r}) \]

\[ \nabla \times \left( \frac{1}{\varepsilon, } (\nabla \times \mathbf{H}(\mathbf{r})) \right) = \omega^2 \varepsilon_o \mu_o \mu, \mathbf{H}(\mathbf{r}) \]  

(3.5)

In this prospectus, it was only considered the case of periodic change of dielectric constant \( \varepsilon(\mathbf{r}) = \varepsilon,(\mathbf{r})\varepsilon_o \). The permeability in this study is the same as that of free space, i.e. \( \mu_r = 1 \). In addition, due to \( c^2 = \frac{1}{\varepsilon_o \mu_o} \), the equation is reduced to compact form as follow:

\[ \nabla \times \left( \frac{1}{\varepsilon, } (\nabla \times \mathbf{H}(\mathbf{r})) \right) = \left( \frac{\omega}{c} \right)^2 \mathbf{H}(\mathbf{r}) \]  

(3.6)

According to the Bloch’s theorem, \( \mathbf{H}(\mathbf{r}) \) is represented as \( e^{ik \cdot r} \mathbf{H}_k(\mathbf{r}) \) in a periodic PhC structure, where \( \mathbf{k} \) is the Bloch wavevector and \( \mathbf{H}_k(\mathbf{r}) \) is a periodic vector function. Equation (3.6) is then reduced as an eigenvalue equation:

\[ \hat{A}_k \mathbf{H}_k(\mathbf{r}) = \left( \frac{\omega}{c} \right)^2 \mathbf{H}_k(\mathbf{r}) \]  

(3.7)

where \( \hat{A}_k \) is the positive semi-definite Hermitian operator:

\[ \hat{A}_k = (\nabla + i\mathbf{k}) \times \frac{1}{\varepsilon, } (\nabla + i\mathbf{k}) \times \]  

(3.8)

Indeed, the eigenvector \( \mathbf{H}_k(\mathbf{r}) \) in equation (3.7) is the electromagnetic wave which could propagate in a PhC structure. Of course, the complete expression is
$e^{i(k \cdot r - \omega t)} \mathbf{H}_k(r)$. In order to find the eigenvector $\mathbf{H}_k(r)$, a set of basis is selected, say \( \{ b_m \} \), so the eigenvector is written as:

$$
\mathbf{H}_k(r) = \sum_{m=1}^{N} h_m |b_m \rangle \tag{3.9}
$$

Next, build up corresponding to the matrix eigenvector equation which has the same physical meaning as equation (3.8). The matrix eigenvector equation is:

$$
\mathbf{A}_{NN} h = \left( \frac{\omega}{c} \right)^2 \mathbf{B}_{NN} h \tag{3.10}
$$

where $h$ is a column vector of the basis coefficients $h_m$, i.e. $h = [h_1, h_2, \ldots, h_N]^T$; $A$ and $B$ is matrices with entries $A_{nm} = \langle b_n \mid \hat{A}_k \mid b_m \rangle$ and $B_{nm} = \langle b_n \mid b_m \rangle$.

The block-iterative frequency domain Methods for Maxwell’s equations is introduced above. This method was proposed by an MIT research group. They also implemented this method as software: MIT Photonic Band (MPB). MPB is an open code software and run on the Unix-like systems. In MPB, the planewave basis was selected i.e. $|b_m \rangle = e^{i k \cdot r}$, where $k$ is Bloch wavevector which is determined by a PhC structure. For a 3 dimensional PhC structure, the primitive lattice vectors are $\{ \mathbf{R}_1, \mathbf{R}_2, \mathbf{R}_3 \}$ and its primitive reciprocal lattice vector are $\{ \mathbf{G}_1, \mathbf{G}_2, \mathbf{G}_3 \}$. They are related by equation $\mathbf{R}_i \cdot \mathbf{G}_j = 2\pi \delta_{ij}$. The Bloch wavevector $k$ is $l\mathbf{G}_1 + m\mathbf{G}_2 + n\mathbf{G}_3$ in which $l$, $m$, and $n$ are integer numbers.

### 3.2 Finite-difference time-domain (FDTD) method

The FDTD was used to study the dynamic properties of electromagnetic wave in this study. The FDTD is a widely used numerical technique to solve electromagnetic questions. This method was proposed in 1966 by Kane Yee [76] and also called Yee algorithm in literatures. In 1980, FDTD was, at the first time, used to describe Yee algorithm [77]. The fundamental idea of FDTD is presented here. First, let’s rewrite equation (3.1b) of Maxwell’s equations, $\nabla \times \mathbf{E}(r,t) = -\frac{\partial \mathbf{B}(r,t)}{\partial t}$, as three equations in the forms of x, y and z components:
\[-\frac{\partial B_z}{\partial t} = \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial z} \] ....................................................(3.11a)

\[-\frac{\partial B_y}{\partial t} = \frac{\partial E_z}{\partial z} - \frac{\partial E_z}{\partial x} \] ....................................................(3.11b)

\[-\frac{\partial B_z}{\partial t} = \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \] ....................................................(3.11c)

In the same way, equation (3.1d) of Maxwell's equations, \( \nabla \times \mathbf{H}(\mathbf{r}, t) = \frac{\partial \mathbf{D}(\mathbf{r}, t)}{\partial t} \), is rewritten as:

\[\frac{\partial D_x}{\partial t} = \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \] ....................................................(3.11d)

\[\frac{\partial D_y}{\partial t} = \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \] ....................................................(3.11e)

\[\frac{\partial D_z}{\partial t} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \] ....................................................(3.11f)

Second, a grid system of space is constructed in order to replacing differential equations with difference equations [Figure 3.1]. In the x axis, the distance of two adjacent points is \( \Delta x \). Similarly, this distance between two adjacent points is \( \Delta y \) for y axis and \( \Delta z \) for z axis. As a result, any point of this grid system in space is denoted as \((i, j, k) = (i \Delta x, j \Delta y, k \Delta z)\), where \( i, j \) and \( k \) are integer numbers. Such a grid system of space is termed as Yee lattice. In order to achieve second-order accuracy, the \( \mathbf{E} \) components are in the middle of the edge and \( \mathbf{H} \) components are in the center of the faces in Yee lattice.

Since electromagnetic wave is function of time, another grid system of time is also constructed in the same method. Any point on this grid system of time is denoted as \((n) = (n \Delta t)\), where \( n \) is an integer number. So, any function \( F \) of space and time could be written as \( F(i \Delta x, j \Delta y, k \Delta z, n \Delta t) = F^n(i, j, k) \).
Third, use difference equations to replace differential equations in the above grid system of space and time. In calculus, the approximation relationship $\frac{df(x)}{dx} \approx \frac{\Delta f(x)}{\Delta x}$ exists when $\Delta x$ is small. In numerical mathematics, there are three alternative ways to implement the transformation from differential equation to difference equation:

$$\frac{\Delta f}{\Delta x} = \frac{f(x + \Delta x) - f(x)}{\Delta x} \quad \text{(forward difference)}$$

$$\frac{\Delta f}{\Delta x} = \frac{f(x) - f(x - \Delta x)}{\Delta x} \quad \text{(backward difference)}$$

$$\frac{\Delta f}{\Delta x} = \frac{f(x + \Delta x/2) - f(x - \Delta x/2)}{\Delta x} \quad \text{(central difference)}$$

Because the central difference has second order accurate, which is higher than first order accurate of the forward difference method and backward difference method, it is usually used in FDTD [78]. In fact, the selection of $E$ and $H$ components in Yee lattice
is the central difference method. For the differential equation (3.11a), its corresponding difference equation is:

\[
\frac{B_{x}^{n+1/2}(i, j + \frac{1}{2}, k + \frac{1}{2}) - B_{x}^{n-1/2}(i, j + \frac{1}{2}, k + \frac{1}{2})}{\Delta t} = \frac{E_{y}^{n}(i, j + \frac{1}{2}, k + 1) - E_{y}^{n}(i, j + \frac{1}{2}, k)}{\Delta z} - \frac{E_{z}^{n}(i, j + 1, k + \frac{1}{2}) - E_{z}^{n}(i, j, k + \frac{1}{2})}{\Delta y}
\]

Generally, in FDTD algorithm, the space grid displacement is identical, i.e. \(\Delta x = \Delta y = \Delta z = \delta\), the above equation is reduced as:

\[
H_{x}^{n+1/2}(i, j + \frac{1}{2}, k + \frac{1}{2}) = H_{x}^{n-1/2}(i, j + \frac{1}{2}, k + \frac{1}{2}) + \frac{\Delta t}{\mu(i, j + \frac{1}{2}, k + \frac{1}{2})} [E_{y}^{n}(i, j + \frac{1}{2}, k + 1) - E_{y}^{n}(i, j + \frac{1}{2}, k)] - ..............(3.12a)
\]

\[
E_{x}^{n}(i, j + 1, k + \frac{1}{2}) + E_{x}^{n}(i, j, k + \frac{1}{2})
\]

Similarly, differential equations of (3.11b) ~ (3.11f) could be transformed to corresponding difference equations:

\[
H_{y}^{n+1/2}(i + \frac{1}{2}, j, k + \frac{1}{2}) = H_{y}^{n-1/2}(i + \frac{1}{2}, j, k + \frac{1}{2}) + \frac{\Delta t}{\mu(i + \frac{1}{2}, j, k + \frac{1}{2})} [E_{z}^{n}(i + \frac{1}{2}, j + 1, k) - E_{z}^{n}(i, j, k + \frac{1}{2})] - ..............(3.12b)
\]

\[
E_{y}^{n}(i + \frac{1}{2}, j, k + 1) + E_{y}^{n}(i + \frac{1}{2}, j, k)
\]

\[
H_{z}^{n+1/2}(i + \frac{1}{2}, j, k + \frac{1}{2}) = H_{z}^{n-1/2}(i + \frac{1}{2}, j, k + \frac{1}{2}) + \frac{\Delta t}{\mu(i + \frac{1}{2}, j, k)} [E_{y}^{n}(i + \frac{1}{2}, j + 1, k) - E_{y}^{n}(i + \frac{1}{2}, j, k)] - ..............(3.12c)
\]

\[
E_{z}^{n}(i + 1, j, k + \frac{1}{2}) + E_{z}^{n}(i, j + 1, k)
\]
All preparatory works prior to FDTD’s launch are finished, thus far. When an initial condition is given, $E$ and $H$ components at any point in space and time could be known by solving the above difference equations (3.12a – 3.12f) using iteration. In FDTD, the grid of discretion of space and time are required to be small in order to get an accurate solution. The smaller the grids of space and time, the more computational work needed. Consequently, the extremely large amount of computation works is an apparent disadvantage of using FDTD, particularly when computers were not affordable research devices. This was one reason why FDTD was not popular numerical technique before 1980’s. From the above explanations of the basic principles of FDTD, it is well known that FDTD approach is a simple and easily understood and implemented computational tool. However, it was not safe to conclude that FDTD method is a practical and a robust technique when it was proposed. Many problems were open at that time, for instance, stable criterion [79], numerical dispersion and anisotropy errors [80], and absorbing boundary conditions [81]. This is another reason that FDTD didn’t become an active tool...
in electromagnetic simulation after its proposal immediately. It took decades to make FDTD a major numerical method in the simulation community.

FDTD was applied to investigate photonic crystals in 1990s’ [82-86]. The existence of periodic boundary conditions in photonic crystals is a new question to FDTD algorithm. In order to overcome this challenging question, several approaches were added into FDTD, for example: normal incident method, sine-cosine method, and multiple unit cell methods [87]. After years of adjustments, FDTD has been well used in the simulation of photonic crystals. Generally, FDTD method is used to study transmission and reflection spectra of photonic crystals. By FDTD, the variation of E and H of computational area during test time is calculated. Based on these raw data (E and H), advanced processing is undertaken to deeply analyze the properties of photonic crystal structures. In order to shorten simulation time, hardware devices have been utilized with FDTD algorithm. From the prospective of computer science, the implementation of algorithm based on hardware devices is faster than that based on software. Recently, several hardware approaches have been investigated, for example, PC cluster and field-programmable gate arrays (FPGAs). Because the simulation time is exponentially dependent on the size of the photonic crystal structures, the implementation of the algorithm using hardware device also meets the requirement of future applications.

Many software of FDTD algorithm are available. The FDTD software used in this prospectus is called MIT Electromagnetic Equation Propagation (MEEP) [88]. MEEP has been developed by a research group at MIT. This free software becomes a popular FDTD simulation tool, particularly at universities, since it is an open-coded tool. It is possible and easy to modify it to meet variant requirements in research.

### 3.3 Computer information of simulation

Both MPB and MEEP need a Unix-like operating system. Among many selective operating systems, Debian GNU/Linux was applied in this prospectus. Debian GNU/Linux is an operating system designed for Personal Computer. It is a good choice for my research because all simulations run on a Personal Computer. Like all Unix-like operating systems, Debian GNU/Linux is also a free and open-coded operating system.
All information regarding computer, both hardware and software, is presented in Table 3.1. The codes (MPB and MEEP) were edited by text editor Emacs. Emacs is editor software under Unix-like systems. Emacs has similar features as Notepad software of Microsoft XP operating system.

<table>
<thead>
<tr>
<th>Hardware Environment</th>
<th>Dell Inspiron 2650</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPU: Intel Pentium 4, mobile 1.70G Hz</td>
</tr>
<tr>
<td></td>
<td>Memory: 512 MB RAM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Software Environment</th>
<th>Operating system: Debian GNU/Linux 3.1, sarge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulation program (frequency domain): MPB 1.4.2</td>
</tr>
<tr>
<td></td>
<td>Simulation program (time domain): MEEP 0.10</td>
</tr>
</tbody>
</table>

Table 3.1 Computer information
CHAPTER 4
BASIC STRUCTURE AND ITS BAND GAP

4.1 Cartesian coordinate system and its unit

The coordinate system of this study, see Figure 4.1, is first demonstrated in order to prevent misunderstanding. What unique about this coordinate system is that the Y axis points downward. Additionally, this coordinate system is also under right-hand rule. This means that the Z axis points inward toward the paper. The reason why this special coordinate system was applied in this study is that simulation tools, MPB and MEEP, use this Cartesian coordinate system. The unit length is a, i.e. one lattice constant.

![Cartesian coordinate system](image)

Figure 4.1: Cartesian coordinate applied in this prospectus

4.2 2-D square rod-in-air PhC structure

In this study, 2-D PhC structure has been selected to for investigation. There are three reasons for this selection: (1) simulation of 2-D PhC structure does not need more time and advanced computer system. Roughly, the amount of time domain simulation (FDTD) is proportional to the product of numbers of grid points along each dimension of the entire computational area, i.e. \( \prod_{i=1}^{4} N_i \), where \( N_i \) is the number of grid points along each dimension (3-D space and 1-D time). In this study, the computational size is \( 20a \times 40a \) and the resolution is 10. The number of grid points along x and y axis is 200 and 400
respectively. Using a computer it took about 20 minutes for most time domain simulations [Table 3.1]. If running the 3-D time domain simulation, with the length of the third dimension is assumed 1, the amount of simulation time should be enlarged by 10 because the resolution is 10. As a conclusion, simulation of 2-D PhC structure is a feasible topic for the present conditions; (2) to this date, fabricating of 3-D PhC structure is still a challenging issue, therefore, 2-D PhC structure has been investigated much more than 3-D PhC. The study of 2-D PhC structure has rather practical meaning; (3) simulation of 2-D PhC structure has more general conclusions which are also valid for 3-D PhC structure. In other words, study of 2-D PhC structure is a quick method to understand the entire properties of 3-D PhC structures.

Because our photonic crystal optical switch is constructed on 2-D square rod-in-air PhC, it is necessary to find the band gap of such PhC structure. The parameters of 2-D square rod-in-air PhC structure are shown below [Figure 4.2]: the diameters of rods are 0.4a (a is the lattice constant of the square PhC structure), relative dielectric constant of rods, εr, is 12 which corresponds to silicon at 1500 nm wavelength. The dielectric constant εr of air is 1.
After running MPB code (see Appendix A), band gap diagrams of TM [Figure 4.3] and TE [Figure 4.4] are presented. For TM wave, there is only non-zero component of electric field along z axis [Table 4.1]; For TE wave, only no-zero component of magnetic field along z axis. The simulation results clearly show there is a complete TM wave band gap. But there is not a complete band gap for TE wave. This TM band gap has frequency range from $0.28 \, c/a$ to $0.42 \, c/a$. This band gap means that any TM light with frequency inside band ($0.28 \, c/a \sim 0.42 \, c/a$) could not propagate in the bulk square rod-in-air PhC structure.
Figure 4.3: TM band gap diagram of 2-D square rod-in-air photonic crystal. The lattice constant of PhC is $a$, diameter of high index rod is $0.2a$. Point $\Gamma$, $X$, and $M$ on $x$ axis corresponds to $(0, 0)$, $(0.5, 0)$ and $(0.5, 0.5)$ in Brillouin zone respectively. For square lattice crystal, the unit of Brillouin zone is $(2\pi/a, 2\pi/a)$. Band gap $0.28~0.42~c/a$ for $\phi=0.4a$. 
Figure 4.4: TE band gap diagram of 2-D square rod-in-air photonic crystal. The lattice constant of PhC is $a$, radius of high index rod is $0.2a$. Point $\Gamma$, $X$, and $M$ on x axis corresponds to $(0, 0)$, $(0.5, 0)$ and $(0.5, 0.5)$ in Brillouin zone respectively. For square lattice crystal, the unit of Brillouin zone is $(2\pi/a, 2\pi/a)$.

Table 4.1 Difference between TM and TE wave

<table>
<thead>
<tr>
<th></th>
<th>Electric field (E)</th>
<th>Magnetic field (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TM</strong> Transverse Magnetic wave</td>
<td>$E_x = 0$</td>
<td>$H_x \neq 0$</td>
</tr>
<tr>
<td></td>
<td>$E_y = 0$</td>
<td>$H_y \neq 0$</td>
</tr>
<tr>
<td></td>
<td>$E_z \neq 0$</td>
<td>$H_z = 0$</td>
</tr>
<tr>
<td><strong>TE</strong> Transverse Electric wave</td>
<td>$E_x \neq 0$</td>
<td>$H_x = 0$</td>
</tr>
<tr>
<td></td>
<td>$E_y \neq 0$</td>
<td>$H_y = 0$</td>
</tr>
<tr>
<td></td>
<td>$E_z = 0$</td>
<td>$H_z \neq 0$</td>
</tr>
</tbody>
</table>

Electric field and magnetic field are always vertical each other. This is what Maxwell’s electromagnetic theory tells us.
CHAPTER 5
2-D SQUARE ROD-IN-AIR PHOTONIC CRYSTAL OPTICAL SWITCH

5.1 Geometric structure

The 2-D square rod-in-air photonic crystal optical switch structure [Figure 5.1] is produced by removing two vertical lines of rods from a bulk square rod-in-air PhC. After removing two lines of rods, two channels with $2a$ width appear in the bulk of PhC.

5.2 Simulation design in time domain

The time domain simulation was designed as shown below: a point source was positioned in the left channel at (-8, 0), and light emitted uniformly in x-y plane. It sent a TM Gaussian pulse with center frequency of $0.35 \ c/a$ and pulse width of $20 \ a/c$. Four detectors with length of $2a$ were vertically positioned at four channels. The centers of the four detectors respectively are (-7, 0) for left detector, (7, 0) for right detector, (0, -7) for upper detector and (0, 7) for down detector. Each detector accumulates the total net energy flow in the corresponding channel, i.e. poyting vector $\mathbf{P} = \mathbf{E} \times \mathbf{H}$. Each detector has a direction which indicates the direction of positive energy flow accumulated by it. If the energy flow passes through a detector in the opposite direction of the detector, this energy flow is counted as negative energy flow. When reflection phenomena exist during the simulation, light passes through a detector from different directions. By the end of simulation, a detector accumulates the total net energy along detector’s direction, i.e. the sum of positive energy flows minus that of negative energy flows. The directions of four detectors are as follow: positive direction of x axis for the left and right detectors, negative direction of y axis for the upper detector, and positive direction of y axis for the down detector. All detectors are transparent to light, i.e. no influence on the propagation of light. An additional high-index ($\varepsilon_r = 12$) single rod with same geometry property (radius = $0.2a$) was inserted along the diagonal line segment of the intersection area of two removed cross-lines rods. This diagonal line segment starts at (-0.7, -0.7) and ends at
The simulation results illustrate that the position of the single inserted rod controls the quantity of light entering the different channels. The entire simulation area is 20a by 40a. A perfectly matched layer (PML) with thickness of one lattice constant was the inside wall of entire simulation area. In simulations, application of PML boundary condition absorbed numerical reflections at the boundary of computational area and consequently provided an accurate solution [89]. The simulation ran 500 time unit (a/c) in order to make the light disappear by the end of simulation.

Figure 5.2 shows a snapshot shoot of electric field intensity (E_z) distribution in the 2D PhC optical switch at time of 106 a/c. This snapshot shows that most energy goes into the upper channel. Even though only E_z is illustrated in Figure 5.2, this snapshot also represents the energy flow. At first, this is because the energy flow of EM wave is expressed by poynting vector \( \mathbf{P} = \mathbf{E} \times \mathbf{H} \). Moreover, light propagation is the result of interaction between electric and magnetic fields. So electric field \( \mathbf{E} \) and magnetic field \( \mathbf{H} \) overlap in space and time. The ratio of energy flow shown in Figure 5.2 was normalized by the total source energy. It should be pointed out that about 50% of the energy from the light source never get into the PhC. Add the reflection by PhC, the energy flowed into the PhC is always less than 50%. Figure 5.2 also demonstrates that some light propagates inside the PhC rather than inside the channels. The energy flow which propagates inside PhC couldn’t be counted by the detectors since the length of detectors is 2a.
Figure 5.1: Top view of 2D square rod-in-air photonic crystal optical switch structure. Areas around source and inserted rod are separately enlarged as two small figures on the right side. Circles represent high-index material ($\varepsilon = 12$). The entire simulation area is $20a$ by $40a$. Note that the x axis is toward to left, the y axis down, and the z axis vertically to paper with pointing away from readers. The origin is located at the center of cross area, as indicated.
Figure 5.2: Snapshot of $E_z$ at time $106 a/c$ during the simulation under the case of single inserted rod coordinate position (-0.5, -0.5). The red color represents positive $E_z$, the blue color negative $E_z$. The deeper the color means the larger magnitude of $E_z$, i.e. $|E_z|$. Some light (indicated by dotted circles) apparently detours the detectors and couldn’t be accumulated by the detectors. Point source is also clearly seen as small blue point.
CHAPTER 6

FEATURES OF 2-D SQUARE ROD-IN-AIR PHOTONIC CRYSTAL SWITCH

6.1 The ratio of net energy flow in each channel

![Graph showing the relationship between the ratio of net energy flow in each channel and the position of a single inserted rod under the case of TM Gaussian point source. The center frequency is 0.35 c/a and pulse width is 20 a/c. The curve labeled right+up+down represents the sum ratio of net energy flow in the right, upper, and down channels.]

Figure 6.1: Relationship between the ratio of net energy flow in each channel and the position of a single inserted rod under the case of TM Gaussian point source. The center frequency is 0.35 c/a and pulse width is 20 a/c. The curve labeled right+up+down represents the sum ratio of net energy flow in the right, upper, and down channels.

The relationship between net energy flow in each channel and the position of a single inserted rod is shown in Figure 6.1. Where, the x axis is the position of the single inserted rod, the y axis represents the ratio of net energy flow in channels after unified with total source energy. In Figure 6.1, the ratio of net energy flow of the upper channel follows the ratio of net energy flow of the left channel. When the position of the single inserted rod is far away from the center (0, 0), much of the incident light along the left
channel goes into the upper channel. When the single inserted rod is near to the center \((0, 0)\), less of the incident light enters into the upper channel. Indeed, much of the incident light from the left channel is reflected back into the left channel under such case. The similarity of the net energy flow ratio in both left channel and upper channel indicates the control effect of this 2D rods-in-air PhC structure on the incident light from the left channel. The maximum net energy flow ratio of the upper channel, \(41.38\%\), occurs when the distance is \(2.12a\). Except of the maximum net energy ratio of the upper channel, there is a maximal net energy flow ratio of the upper channel, \(24.91\%\), when distance is \(0.71a\). The minimal energy ratio of the upper channel is only \(1.15\%\) corresponding to distance of \(1.56a\).

It is also shown in Figure 6.1 that the curves of the net energy flow ratio of the left channel and upper channel are very close, with less than 2\% difference in the net energy flow ratio, in the distance ranges of \(0.8a\sim1.0a\) and \(1.8a\sim2.0a\). This demonstrates that more light from the left channel goes into the upper channel when a single rod was inserted in the range \(0.8a\sim1.0a\) and \(1.8a\sim2.0a\). Consequently, the switching efficiency of optical switch in the range of \(0.8a\sim1.0a\) and \(1.8a\sim2.0a\) is the highest among the entire distance ranges. However, it is noted that the maximum switching ratio, \(41.38\%\), and maximal switching ratio, \(24.91\%\) are not in the ranges with the highest switching efficiency. In other words, both the maximum switching ratio and switching efficiency could not coexist in our 2D rods-in-air square-rod PhC optical switch.

From the simulation results in Figure 6.1, it can be concluded that not all light propagates inside channels. This is because the sum of net energy flow ratio of the upper, right, and down channels is always a little more than that by the left channel. This difference of the net energy flow is associated with the position of the single inserted rod. Its range is from \(0.94\%\) (corresponding to the distance of \(0.85a\)) to \(0.20\%\) (corresponding to the distance of \(1.56a\sim1.70a\)). It is also shown in Figure 5.2 that not all light propagates inside the channels. This conclusion is easily understandable because property of light in the band gap cannot be absolutely excluded from the PhC. For light whose state is in the band gap of a bulk of PhC, it is safe to conclude that it could not pass through the bulk of PhC. It, however, must enters into a small depth within the PhC when it meets a bulk of PhC. From simulations a small amount of light always propagates inside the PhC rather
than inside the channels [Figure 5.2]. Because the detectors’ length is $2a$, the detectors only count the energy flow inside channels. This means that detectors do not count all energy flow into optical switch. A small amount of light detours the detectors without leaving any trace on the detectors.

The simulation result that indicates the net energy flow accumulated by the upper, right, and down channels is always more than that by the left channel also indicates that the small amount of light, which detours the left detectors, flows into the channels from PhC during propagation. Because the light that detours the left detector flows back into the channels and is accumulated by the upper, right, and down detectors, the left detector counts less net energy flow than that by the upper, right and down channels in total. The amount of light which returns from the PhC to the channels is small and its maximum amount is only 0.94%. The left detector is only one lattice away from the point source. This is a possible reason why net energy flow that detours the left channel is a bit more than those that detour the upper, right, and down detectors.

### 6.2 The reflected wave in the left channel

The ratio of net energy flow of the left channel is valley-shape due to the variant reflection in the left channel [Figure 6.1]. In our simulations, it is the net energy flow that is collected by the directional detectors. The left detector, whose direction is the positive direction of x axis, counts the energy flow of the reflected wave as negative energy flow because the reflected wave passes through the left detector along negative x axis. The more powerful the reflected wave, the more negative energy flow the left detector collects. Assuming that the incident wave is same, the left detector consequently counts the less amount of net energy flow. The most powerful reflected wave is in the left channel when a single inserted rod locates at $(0.1, 0.1)$. As a result, the minimum ratio of net energy flow of the left channel, 7.85%, corresponds to the location of the single inserted rod $(0.1, 0.1)$. When the single inserted rod is far away from the location $(0.1, 0.1)$, there is a weak reflected wave in the left channel. So, the left detector counts more of net energy flow since a weak reflected wave has a less negative energy flow. This variable reflection of light is the reason for the valley-shape of energy flow ratio of the left-channel. Obviously, this alterable reflection results from different position of the
single inserted rod. The plots of $E_z$ vs. time at position (-7, 0), which is the center of the left detector, under different positions of the single inserted rod are shown in Figure 6.2 - Figure 6.4. They clearly show the existence of the reflected wave in the left channel. With the change in location of the single inserted rod, the reflected wave are changed to a large extend.

It is assumed that the Gaussian TM point source sent one half of the total source energy along the negative x axis and another half of the total source energy along the positive x axis in the left channel. The first half of the total source energy, heading in the negative x axis, is absorbed by the PML boundary condition when it impinges the boundary of simulation area. The total source energy that did not pass the left detector is beyond the discussion. Another half of the total source energy, which propagates along the positive x axis, is the incident wave of the left channel. The incident wave passed the left detector as positive energy flow and impinged the single inserted rod. As a result of collision with the single inserted rod, the incident wave with half the total source energy was divided into four waves, each of them respectively entered into four channels: the left, upper, right and down channel. The wave which entered the left channel is indeed the reflected wave of the left channel. The reflected wave propagated along the left channel in the negative x axis direction, passed the left detector as negative energy flow, and was finally absorbed by the PML boundary condition. The net energy flow of the left channel is the difference between the negative energy flow of the reflected wave from the positive energy flow of the incident wave. The strongest reflected wave happens at a distance of $1.56a$ (correspond to the position of the single inserted rod (0.1, 0.1)) in this case, the ratio of the net energy flow of the left channel is the minimum, 7.85%. Based on the assumption that the positive energy flow of the incident wave in the left channel is one half of total source energy, the energy flow of the reflected wave is 50% - 7.85% = 42.15% at a distance of $1.56a$. The weakest reflected wave in the left channel has the energy flow 50% - 44.81% = 5.19% at a distance of 2.26a because the maximum ratio of net energy flow of the left channel, 44.81%. The maximal ratio of the net energy flow of the left channel is 30.14% at a distance of 0.42a where the ratio of energy flow of the reflected wave is 50% - 30.14% = 19.86%. Although the above reasoning is a simple approximation, not strictly theoretical analysis, the results, which the ratio of energy flow
of the reflected wave in the left channel varies in the range of 5.19% to 42.15%, show that the position of a single inserted rod affects greatly the reflection wave of the left channel in our 2D rods-in-air square-rod PhC optical switch. In other words, the effect of a single inserted rod on the reflection wave of the left channel is very sensitive. This is because the ratio of energy flow of the strongest reflected wave, 42.15%, is eight times larger than that of the weakest reflected wave, 5.19%.

The plots of Ez vs. time at point of (-7, 0), which is the center of the left detector, is evidence that reflection wave exists [Figure 6.2 - Figure 6.4]. Figure 6.2 corresponds to the case of distance of 1.56a, in which the energy flow of the reflected wave of 42.15% exists, based on above analysis. In Figure 6.2, the amplitude of the reflected wave is nearly the same as that of the incident wave, both 0.6 a.u.. Both the incident wave and reflected wave are clearly separated by a time delay of 50 a/c. In Figure 6.3, the case for distance 0.42a, the reflected wave is mixed together with the incident wave. According to the previous analysis of this case, the energy flow of the reflected wave is 19.86%, which is smaller than that of the case for distance 1.56a. In the case of distance 0.42a, the amplitude of the reflected wave is about 0.4 a.u. which is also smaller than that of distance 1.56a (0.6 a.u.). In Figure 6.3, both the incident and reflected waves are not clearly separated and the reflected wave delayed 30 a/c after the incident wave. Figure 6.4 shows the case of distance 2.26a, in which the energy flow of the reflected wave is 5.19% and smaller than those of distance 0.42a and 1.56a, from the previous analysis. In Figure 6.4, the amplitude of the reflected wave is 0.2 a.u., which is also the smallest among Figure 6.2 - Figure 6.4. However, in the case of distance 2.26a, the time delay between the incident and reflected waves, 130 a/c, is the largest among Figure 6.2 - Figure 6.4. It can be concluded that the reflected wave was changed with respect to both amplitude and time delay in the cases of variant position of a single inserted rod. As a result, the change reflects how the reflected wave affects the net energy flow ratio counted by the left detector. The more powerful the reflected wave, the less net energy flow counted by left detector. It is noted that Figure 6.2 - Figure 6.4 are plots at one point (-7, 0). However, the energy flow collected by the left detector is a line integral from (-7, -1) and (-7, 1). Ez plots vs. time at one point in Figure 6.2 - Figure 6.4, only provide a
valuable and reasonable, but not strict, explanation to the valley-shape net energy flow ratio of the left channel.

Assuming that the reflected wave is produced by a single inserted rod, which position is $(0, 0)$, the time delay between the incident and reflected waves at point $(-7, 0)$ should be $2(0 - (-7))a/c = 14 a/c$ in the point view of classic optics. However, the time delays in Figure 6.2 - Figure 6.4 are much greater than $14 a/c$. It shows that the reflected wave was not directly produced by the single inserted rod. Before the reflected wave returns back to the left detector, it encountered more reflections with PhC walls of the left channel, which consequently increases the delay time of reflection wave at a large extent.

![Figure 6.2: Plot of $E_z$ vs. time at the center of the left detector $(-7, 0)$ under the case of single inserted rod at $(0.1, 0.1)$. The incident wave and reflection wave with same amplitude are illustrated even though part of them is overlapped in time.](image)
Figure 6.3: Plot of $E_z$ vs. time at the center of the left detector (-7, 0) under the case of single inserted rod at (-0.7, -0.7). The weakened reflection wave is mixed with incident wave.
Figure 6.4 Plot of $E_z$ vs. time at the center of the left detector (-7, 0) under the case of single inserted rod at (0.6, 0.6). The smaller reflection wave appears after a period of time.

6.3 The ratio of net energy flow under different kinds of source

Simulations have been carried out when the properties of source was changed [Table 6.1]. The results demonstrate that similar switching feature exists under source with different properties [Figure 6.5 - Figure 6.7]. In other words, this 2-D square rods-in-air PhC optical switch can be applied in general conditions, Gaussian or CW, point source or line source. This is one of its advantages.
Table 6.1 Source properties

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Gaussian</th>
<th>Continuous wave (cw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point source</td>
<td>Center freq $0.35 \ c/a$, pulse width $20 \ a/c$; source center (-8, 0)</td>
<td>Freq. $0.35 \ c/a$; Source center (-8, 0)</td>
</tr>
<tr>
<td>Line source</td>
<td>Center freq. $0.35 \ c/a$, pulse width $20 \ a/c$; source location from (-8, -1) to (-8, 1)</td>
<td>Freq. $0.35 \ c/a$; source location from (-8, -1) to (-8, 1)</td>
</tr>
</tbody>
</table>

Figure 6.5: Relationship between the ratio of net energy flow in each channel and the position of single inserted rod under the case of TM Gaussian line source. Center frequency is $0.35 \ c/a$ and pulse width is $20 \ a/c$. The curve labeled right+up+down represents the sum ratio of net energy flow in the right, upper, and down channels.
Figure 6.6: Relationship between the ratio of net energy flow in each channel and the position of single inserted rod under the case of TM continuous wave point source. The frequency is $0.35 \, c/a$. The curve labeled right+up+down represents the sum ratio of net energy flow in the right, upper, and down channels.
Figure 6.7 Relationship between the ratio of net energy flow in each channel and the position of single inserted rod under the case of TM continuous wave line source. The frequency is $0.35 \frac{c}{a}$. The curve labeled right+up+down represents the sum ratio of net energy flow in the right, upper, and down channels.

After exhausted comparison, it is found that the ratio of net energy flow in the right, upper and down channel under the cases of Gaussian point and line sources are same [Figure 6.9 - Figure 6.11]. In addition, the ratio of net energy flow in the right, upper, and down channel under the continuous wave point and line source are same [Figure 6.9 - Figure 6.11]. It is shown that the ratio of net energy flow in the right, upper, and down channel is only related with the frequency property of source. The geometry of source does not affect the ratio of net energy flow in the right, upper, and down channel. This conclusion is still valid for the ratio of net energy flow in the left channel only when the distance is larger than $1.56a$ [Figure 6.8]. In the distance less than $1.56a$, the ratio of net energy flow in the left channel is related with not only the frequency property of source but also the geometry of source. In the point view of Fourier Transform, a Gaussian pulse includes many frequency components and a CW source sends out light with one frequency. In addition, the properties of PhC are related with the frequency of
light. So, the ratio of net energy flow in the right, upper, and down channel is only related with the frequency property of source.

For Gaussian source, the maximal switching ratio is $41.4\%$ at the distance $2.12a$; for the CW source, the maximal switching ratio is $40.8\%$ at the distance $2.26a$. The maximal switching ratio of both Gaussian source and CW source are nearly same, but the corresponding distance shifts $0.14a$.

Figure 6.8: Comparison of ratio of net energy flow in the left channel under different sources.
Figure 6.9: Comparison of ratio of net energy flow in the right channel under different sources.

Figure 6.10: Comparison of ratio of net energy flow in the upper channel under different sources.
Figure 6.11: Comparison of ratio of net energy flow in the down channel under different sources.

6.4 Effect of diameter of single inserted rod on the distribution of energy flow

When diameter of single inserted rod is $0.3a$, distribution of energy flow of Gaussian point source is shown in Figure 6.12; when diameter of single inserted rod is $0.5a$, distribution of energy flow of Gaussian point source is shown in Figure 6.13. It is shown, when diameter of single inserted rod is changed from $0.3a$ to $0.5a$, ratio of energy flow entering the upper channel follows that of the left channel, but, to different extent. Besides, ratio of energy flow entering the right and down channels changes to a great scale. It is difficult to exactly describe the effect of diameter of single inserted rod on the distribution of energy flow among channels. The Table 6.2 gives an over simple description.
Table 6.2: The range of ratio of energy flow of the left, right, upper, and down channel in the cases of different diameter of single inserted rod

<table>
<thead>
<tr>
<th>Diameter of inserted rod</th>
<th>Left channel (%)</th>
<th>Right channel (%)</th>
<th>Upper channel (%)</th>
<th>Down channel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø (0.3a)</td>
<td>11.75 ~ 44.60</td>
<td>0.43 ~ 8.47</td>
<td>0.96 ~ 42.65</td>
<td>0.60 ~ 3.01</td>
</tr>
<tr>
<td>Ø (0.4a)</td>
<td>10.37 ~ 44.97</td>
<td>0.42 ~ 7.96</td>
<td>1.03 ~ 40.69</td>
<td>0.19 ~ 4.89</td>
</tr>
<tr>
<td>Ø (0.5a)</td>
<td>20.02 ~ 44.89</td>
<td>0.80 ~ 18.75</td>
<td>0.45 ~ 37.68</td>
<td>0.21 ~ 8.72</td>
</tr>
</tbody>
</table>

Figure 6.12: Relationship between the ratio of net energy flow in each channel and the position of single inserted rod (Ø = 0.3a) under the case of TM Gaussian point source. The frequency is 0.35 c/a.
Figure 6.13: Relationship between the ratio of net energy flow in each channel and the position of single inserted rod ($\varnothing = 0.5a$) under the case of TM Gaussian point source. The frequency is $0.35 \, c/a$.

### 6.5 Effect of diameter of rod at $(I, I)$ on the distribution of energy flow

When diameter of rod is at $(I, I)$ is $0.3a$, distribution of energy flow of Gaussian point source is shown in Figure 6.14; when diameter of rod at $(I, I)$ is $0.5a$, distribution of energy flow of Gaussian point source is shown in Figure 6.15. It is demonstrated that, when diameter of rod at $(I, I)$ is changed from $0.3a$ to $0.5a$, ratio of net energy flow entering upper channel follows that of the left channel. It is shown, in Figure 6.16, that the relationship between ratio of net energy flow and the position of single inserted rod ($\varnothing = 0.4a$) varies in a little scale, when the diameter of rod at $(I, I)$ changes from $0.3a$ to $0.5a$. In other words, the effect of diameter of rod at $(I, I)$ on the ratio of net energy flow entering the upper channel is very small.
Figure 6.14: Relationship between the ratio of net energy flow in each channel and the position of single inserted rod under the case of TM Gaussian point source. The frequency is $0.35 \frac{c}{a}$. Note that diameter of rod at $(1, 1)$ is $0.3a$. 
Figure 6.15: Relationship between the ratio of net energy flow in each channel and the position of single inserted rod under the case of TM Gaussian point source. The frequency is $0.35 \frac{c}{a}$. Note that diameter of rod at $(l, l)$ is $0.5a$. 
Figure 6.16: Comparison of ratio of net energy flow entering the upper channel when diameter of rod at \((1, 1)\) is \(0.3a\), \(0.4a\), and \(0.5a\) respectively.
CHAPTER 7
FUTURE RESEARCH

6.1 Future researches

After many simulations, the feature of 2-D square rod-in-air photonic crystal optical switch becomes clear. Its switch features were shown in the simulations of net energy flow ratio under different kinds of sources, Gaussian or continuous wave, point source or line source. It is also demonstrated that this switch feature exits when varying the diameter of single inserted rod and the rod at \((1, 1)\).

Even though many simulations have been done, there still remain many questions. For instance, how does this switch feature happen? It has just been recently determined that this feature results from the many reflections that light encounters in this 2-D PhC structure. It is possible to find deeper physical reasons and explain the switching phenomenon with more details? If the physical reasons can be understood the design better switching structures can be achieved.

Second, in order to better understand the influence of the source on the energy ration curves, it is necessary to do simulations under other kinds of source conditions. For example, if the frequency was fixed at \(0.35 \ c/a\) in all finished simulation. This frequency, \(0.35 \ c/a\), is at the middle position of first TM band gap of square rod-in-air photonic crystal \((0.28 \sim 0.42 \ c/a)\). What would happen if frequency of the source changes to another frequency of the band gap?

Third, in previous simulations, just a single rod is inserted at the cross section area. If this pattern of single inserted rod is changed, what would happen? There are many possible patterns, for example: two inserted rods, single rods with different radius and/or different geometry shape. In this respect, it is also needed to do more simulation to find a better pattern with higher switching ratio.
APPENDIX A

MPB PROGRAM

Below is MPB code of computing band gap of 2-D squared rod-in-air photonic crystal.

;;;------basic configuration
(define filename-prefix "cup0008a-")
(set! num-bands 8)
(set! resolution 32)

;;;------configure k, wave vector
(set! k-points (list (vector3 0 0 0)
  (vector3 0.5 0 0)
  (vector3 0.5 0.5 0)
  (vector3 0 0 0)))
(set! k-points (interpolate 4 k-points))

;;;------configure geometry
(set! geometry (list (make cylinder
  (center 0 0 0) (radius 0.2) (height infinity)
  (material (make dielectric (epsilon 12)))))
(set! geometry-lattice (make lattice (size 1 1 no-size)))

;;;------run
(run-tm)
(run-te)
APPENDIX B

MEEP PROGRAM

Below is MEEP code of computing the propagation of TM wave in 2-D square rod-in-air photonic crystal optical switch. In the code, single inserted rod position at (-0.5, -0.5).

; the first part is about the geometry
(define filename-prefix "mug0059d")
(define-param resolution 10)
(define-param x-width 20)
(define-param y-width 40)
(define-param w 1);width of bar

(set! geometry-lattice (make lattice
   (size x-width y-width no-size)))

(define wvga-ctr (vector3 0 0))
(define wvgb-ctr (vector3 0 0))

(define silicon (make dielectric (epsilon 12)))
(define dot (make cylinder
   (center 0 0)(radius 0.2)(height infinity)
   (material silicon)))
(define dot1 (shift-geometric-object dot (vector3 -1 -1)))
(define dot2 (shift-geometric-object dot1 (vector3 0.5 0.5)))

(define dot-matrix (geometric-objects-lattice-duplicates (list dot)))

; horizontal waveguide
(define wvga (make block
   (center wvga-ctr) (size infinity w infinity)
   (material air)))

; vertical waveguide
(define wvgb (make block
   (center wvgb-ctr) (size w infinity infinity)
   (material air)))

(define stru-type-a (append dot-matrix (list wvga)))
(define stru-type-b (append stru-type-a (list wvgb)))

(define-param type 2); 1 is for one waveguide, 2 is for two waveguide
(if (= type 1) (set! geometry stru-type-a))
(if (= type 2) (set! geometry (append stru-type-b (list dot2))))
;the second part is about source
(define-param fcen 0.35)
(define-param src-wid 20); for source, smoothing property of src,
(define-param src-ctr (vector3 -8 0)); source center
(define src1 (make continuous-src (frequency fcen)(width src-wid)))
(define src2 (make gaussian-src (frequency fcen)(width src-wid)))
(set! sources (list (make source
  (src src2)
  (component Ez);TM source
  (center src-ctr)
  (size 0 0)))); point source
(set! pml-layers (list (make pml (thickness 1.0))))

;the part below is about flux1, which collect total energy of source

(define left-src-ctr (vector3 -8.5 0))
(define right-src-ctr (vector3 -7.5 0))
(define up-src-ctr (vector3 -8 -0.5))
(define down-src-ctr (vector3 -8 0.5))
(define-param flux1-df 0.05); for flux1, fcen-df/2 ~ fcen+df/2
(define-param flux1-size 1);size of flux1
(define flux1-nfreq 100);number of freq. points of flux1

(define left-src (add-flux fcen flux1-df flux1-nfreq
  (make flux-region
    (center left-src-ctr) (size 0 flux1-size) (weight -1.0)))))
(define right-src (add-flux fcen flux1-df flux1-nfreq
  (make flux-region
    (center right-src-ctr) (size 0 flux1-size)))))
(define up-src (add-flux fcen flux1-df flux1-nfreq
  (make flux-region
    (center up-src-ctr) (size flux1-size 0) (weight -1.0)))))
(define down-src (add-flux fcen flux1-df flux1-nfreq
  (make flux-region
    (center down-src-ctr) (size flux1-size 0)))))

;the part below is about flux2, which collect energy through each channel

(define left-ch-ctr (vector3 -7 0))
(define right-ch-ctr (vector3 7 0))
(define up-ch-ctr (vector3 0 -7))
(define down-ch-ctr (vector3 0 7))
(define-param flux2-df 0.05); for flux2, fcen-df/2 ~ fcen+df/2
(define-param flux2-size 2);size of flux2
(define flux2-nfreq 100);number of freq. points of flux2
(define left-ch (add-flux fcen flux2-df flux2-nfreq
  (make flux-region
    (center left-ch-ctr) (size 0 flux2-size))))
(define right-ch (add-flux fcen flux2-df flux2-nfreq
  (make flux-region
    (center right-ch-ctr) (size 0 flux2-size))))
(define up-ch (add-flux fcen flux2-df flux2-nfreq
  (make flux-region
    (center up-ch-ctr) (size flux2-size 0) (weight -1.0))))
(define down-ch (add-flux fcen flux2-df flux2-nfreq
  (make flux-region
    (center down-ch-ctr) (size flux2-size 0))))

;run
;just run epsilon when run type is 1, run util 500 when run type is 2

(define-param run-type 2)
(if (= run-type 1) (begin
  (output-epsilon)
  (quit)))
(if (= run-type 2) (begin
  (run-until 500 (at-beginning output-epsilon))
  (print "Gaussian source freq 0.35 width 20 TM(Ez) run 500\n")
  (print "source center (-8 0) source size (0 0) point source\n")
  (print "single-rod (0.5 0.5)\n")
  (print "source-flux-box-center = source center source-flux-size 1 x 1\n")
  (display-fluxes left-src right-src up-src down-src)
  (print "left-channel-center (-7 0) left-channel-size (0 2)\n")
  (print "right-channel-center (7 0) right-channel-size (0 2)\n")
  (print "up-channel-center (0 -7) up-channel-size (2 0)\n")
  (print "down-channel-center (0 7) down-channel-size (2 0)\n")
  (display-fluxes left-ch right-ch up-ch down-ch)))
PART II

DESIGN OF FAST PLANAR LASER SHUTTER
CHAPTER 8
INTRODUCTION

8.1 Motivation

The goal of the proposed laser shutter is to protect eyes from hazard caused by a short intensive laser pulse. The width of targeted laser pulse is in the order of tens of nanosecond. There are four fundamental requirements for the laser shutter:

- The response time of the proposed laser shutter is in the order of 1 ns in order to successfully block the short intensive laser pulse. A typical width for Q-switching laser pulse is about 30 ns.
- The proposed laser shutter must block the laser pulse with various frequencies. It is noted that optical coatings and filters can only block the light with a fixed frequency or a certain band. So, it is not an appropriate approach to achieve the goal of blocking the laser pulse with various frequencies. Besides, the protective goggle, regularly used in laser lab, only reduces the intensity of incident light in some extent. It, however, could not block off the incident laser pulse completely.
- The proposed laser shutter is a planar device. Because the laser shutter is designed to protect human eyes, it is better to fabricate it on the surface of goggle. If the laser shutter is used in vehicles or aircrafts to protect the eyes of drivers or pilots, it is also to be fabricated on the surface of windows.
- The laser shutter is triggered by the incident laser pulse automatically. When a laser pulse hits the laser shutter, the laser shutter blocks the laser pulse. In the case of no laser pulse, the laser shutter is in normal state and does not reduce the intensity of the incident light which is more moderate than the laser pulse.

The proposed laser shutter operates in a manner similar to a Liquid Crystal Display (LCD) [1, 91]. The LCD is a spatial light modulator. There are many pixels on a LCD and the brightness of a pixel of a screen is regulated by the voltage applied on the pixel. The light source of a LCD is at the back of planar display. When the pixel is dark, light is totally blocked. Actually, this is the objective that the laser shutter should achieve.
But the shortest response time of LCD is approximately 10 ms, and then it could not meet the first requirement of laser shutter, even though it can block the light with various frequencies.

In order to meet the requirement of short response time, the electro-optic materials are used to replace the liquid crystal. The response time of the electro-optic materials is in the order of 10 ns, shorter than that of the liquid crystals.

The photoconductive semiconductor switch (PCSS) is designed as the trigger of laser shutter. When a laser pulse impinges the PCSS, the PCSS initiates the laser shutter to block the incident laser pulse. Both the electro-optic materials and the semiconductor materials can be manufactured on the surface of glass by the planar technology.

### 8.2 Laser safety classifications

The national laser safety standards, ANSI Z136 series, catalogs laser into four classes according to the potential hazards on human body occurred by laser. The Table 8.1 is a summary of classes for a single pulsed laser. Class I lasers are absolutely safe and Class 3 and 4 lasers are dangerous for eyes. Class 2 lasers can cause damage to eyes when viewing directly for a long period of time. Unfortunately, there is no specification of class 2 for single pulsed laser in ANSI Z316.1 Standard. It is noted that the performance of the laser shutter is the focus of this work at the present stage. The laser safety for eyes will be the main topic in the future research.

Table 8.1 Summary of levels for single pulsed laser and laser system classification (ANSI Z316.1 Standard). There is no Class 2 for single pulsed laser in ANSI Z316. [92]

<table>
<thead>
<tr>
<th>Wavelength range (μm)</th>
<th>Class 1</th>
<th>Class 3</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible, 0.4 ~ 0.7</td>
<td>≤ 0.2 × 10⁻⁶ J</td>
<td>&gt; Class 1 but ≤ 31 × 10⁻³ J·cm⁻²</td>
<td>&gt; 31 × 10⁻³ J·cm⁻²</td>
</tr>
</tbody>
</table>

60
CHAPTER 9

STRUCTURE OF LASER SHUTTER

9.1 Polarization of light

The propagation of light is a result of interaction of electric and magnetic fields. Light propagates along the direction of cross product of electric field \((E)\) and magnetic field \((H)\), i.e. \(\vec{E} \times \vec{H}\). For a beam of light propagating in a fixed direction, there are many possibilities of oscillation direction of electric field and corresponding magnetic field [Figure 9.1]. In academics, only the vibrating direction of electric field is used to distinguish among these possibilities. This is because the electric field and magnetic field are always perpendicular with each other when a beam of light propagates. In the case of both the oscillation direction of electric field \((E)\) and propagation direction of light \((k)\) being known, the oscillation direction of magnetic field \((H)\) can be determined. The oscillation direction of electric field of light is named polarization of light in optics literatures.

Polarization of light is a common applicable property in the optics engineering. The laser shutter application discussed in this document is actually one of the optics polarization applications.
Figure 9.1: When a beam of unpolarized light propagates along the z axis in vacuum, the electric field $E$ (red color curve) and the magnetic field $H$ (blue color curve) possibly oscillate in any direction in the plane perpendicular to propagation direction. Two cases are illustrated as the examples.

### 9.2 Schematic and principle of the laser shutter

The proposed laser shutter is made of three parts: Pockels cell intensity modulator, PCSS, and bias resistor [Figure 9.2]. In the normal condition in which there is no intensive laser impinging on the laser shutter, the Pockels cell intensity modulator, consisting of a Pockels cell and two optical polarizers aligned perpendicular to each other, does not affect the incident light. When an intensive beam of laser pulse impinges the laser shutter, the Pockels cells intensity modulator of the laser shutter will be triggered by the PCSS to block off the incoming intensive laser beam in a short period of time. As a consequence, the intensity of the transmitted laser beam, which passes through the laser shutter, could be reduced to a lower level which is safe to naked eyes. Whether the Pockels cell intensity modulator takes effect depends on the applied voltage across it. When a high DC voltage is applied on the Pockels cell intensity modulator, for a random polarization incident light, approximate 50% of incident light passes through the intensity modulator. When there is no voltage on the Pockels cell intensity modulator, the incident light is totally blocked out of the laser shutter. The voltage on the Pockels cell is regulated by a charging-discharging circuit, in which a PCSS functions as a switch. When
the intensive laser stops impinging on the PCSS, applied voltage on the Pockels cell modulator would return to its normal value, i.e. the high DC voltage. There are two configurations of the Pockels cell intensity modulator according to the relation between the direction of the applied electric field and the light propagation direction. In the longitudinal Pockels cell intensity modulator depicted in Figure 9.2(a), an external electric field is applied along the propagation direction of light, whereas, in the transverse Pockels cell intensity modulator of Figure 9.2(b), an external electric field is applied perpendicular to the direction of propagation of light. In this dissertation, only the longitudinal Pockels cell intensity modulator is investigated because it is suitable for fabrication on a planar structure. Of course, when compared with the transverse Pockels cell intensity modulator, the longitudinal Pockels cell intensity modulator has its disadvantage, for example its high half-wave voltage $V_{\pi}$. This detailed discussion about half-wave voltage is provided in section 10.1.
(a)
Figure 9.2: Schematic of laser shutter with (a) longitudinal configuration and (b) transverse configuration. HV represents high DC voltage source; P1 and P2 represent two polarizers, the angle of their polarization directions is 90°; PC represents Pockels cell; PCSS represents a photoconductive semiconductor switch; R represents a bias resistor. The components inside dashed line are called Pockels cell intensity modulator.

### 9.3 Pockels cell intensity modulator

The Pockels cell intensity modulator is made of two polarizers and a Pockels cell [Figure 9.3]. When a beam of incident light hits the Pockels cell intensity modulator, the intensity of the transmitted light is regulated by the applied voltage on it. The operation method of the Pockels cell intensity modulator is briefly discussed below.
A polarizer is a kind of polarization optics device. Each polarizer has a polarization direction. A non-polarized beam of light can be decomposed into two polarized beams, whose polarization directions are perpendicular with each other. When an unpolarized incident light passes through a polarizer, the light with the same polarization as the polarization direction of the polarizer can go through [Figure 9.4]. The light with other polarization component will be filtered out. There are two polarizers in the Pockels cell intensity modulator and the angle between their polarization directions is 90° [Figure 9.3].
The Pockels cell is another kind of polarization optics device [Figure 9.3]. When a beam of polarized light goes through the Pockels cell, the polarization of the incident light could be modulated with an angle by the external applied voltage on the Pockels cell. This modulation effect of the Pockels cell results from the optically anisotropic materials, of which the Pockels cell is made. This is because the speed of light in optically anisotropic materials is related with the polarization of light. In other words, the speed of light in optically anisotropic materials is not a constant, but a variable associated with the polarization of light. Moreover, the speed of light in optically anisotropic materials is related with the external electric field. In the Pockels cell intensity modulator, an external electric field is applied along certain directions, which is uniquely associated with the crystalline structure of optically anisotropic materials. When the polarized incident light propagates through the Pockels cells, the polarization of light is controlled by the external electric field on the Pockels cells.

9.4 Photoconductive semiconductor switch (PCSS)

The PCSS is made of an intrinsic semiconductor, i.e. pure semiconductor without intended doping [Figure 9.5]. In an intrinsic semiconductor, most electrons are bonded. The resistivity of an intrinsic semiconductor, $\rho$, is very high due to lack of carriers inside
it. Under this situation, the intrinsic semiconductor is in the off state since current is not allowed to pass. Strictly, there are a few carriers in an intrinsic semiconductor due to thermal excitement. But, the carrier concentration generated by thermal excitement is much lower than that generated by intensive laser pulse in an intrinsic semiconductor. However, when a beam of intensive light hits an intrinsic semiconductor, more carriers (electron-hole pairs) are generated inside. This is because the bonded electrons in an intrinsic semiconductor absorb the energy of photon and consequently are excited as free electrons and free holes. As a result, resistivity of an intrinsic semiconductor decreases to a large extent.

![Figure 9.5: An intrinsic semiconductor in off-state (left figure) and on-state (right figure).](image)

- represents free electrons and ○ represents free holes. The default size of PCSS is indicated.

**9.5 Circuit model of the laser shutter**

In the circuit model of the laser shutter, a variable resistor $R_s(t)$ simulates the effect of the PCSS and a constant capacitor simulates the effect of the Pockels cell [Figure 9.6]. When the laser shutter is in the normal state, the PCSS is in “off state” and
its resistance is much larger than that of the bias resistor, i.e. $R_{S(\text{off})} >> R$. From the circuit model, it is known, when the PCSS is in “off-state”, that a high DC voltage is applied on the Pockels cell, i.e. $v_c \approx V_H$. From the previous discussion, we know that an incident light can go through the Pockels cell without being blocked when the Pockels cell is under a high DC voltage. However, when a beam of intensive laser pulse is coming, the laser shutter should transfer from the normal state to the “off state” in a short time. When the laser shutter is in the block-off state, no incident light can go through the laser shutter. The entire description of transfer process is as follows: under the effect of the intensive incident laser pulse, the PCSS is transferred from “off-state” to “on-state” because many carriers (electrons and holes) are generated in the PCSS. From the circuit model, it can be seen that the Pockels cell would be discharged through the PCSS. In the choice of suitable parameters, it makes sense that the resistance of the bias resistor is much higher than that of the PCSS, i.e. $R >> R_{S(\text{on})}$. So, the voltage of the Pockels cell can nearly drop to zero, i.e. $v_c \approx 0$. When there is no voltage on the Pockels cell, the incident light would be blocked out of the laser shutter. The PCSS functions as a channel to transport the charges of the Pockels cell, and it is expected to behave as a smaller resistance in order to shut down the laser shutter quickly. The resistance of the PCSS depends on the carrier concentration, carrier mobility, carrier lifetime, and geometry of the PCSS.
Figure 9.6: Circuit model of laser shutter. $v_c(t)$ represents the voltage applied on the Pockels cell; $R_s(t)$ represents the resistance of the PCSS.
CHAPTER 10
MATHEMATICS OF LASER SHUTTER

10.1 Incident laser pulse

The intensity of an incident laser pulse, $P_{in}(t)$, is described as a Gaussian function of time:

$$P_{in}(t) = P_0 e^{-\left(\frac{t-t_0}{\Delta t}\right)^2}$$

where $P_0$ is the peak intensity and its unit is $W/m^2$, $\Delta t$ is the pulse width and its default value is $30 \text{ ns}$, $t_0$ is the center time of the laser pulse and its value is three times of the pulse width, i.e. $3 \cdot \Delta t$. The flux of the incident laser pulse, $I_i$, is defined as the integral of $P_{in}(t)$ over time $t$:

$$I_i = \int_0^\infty P_{in}(t) \, dt$$

The unit of $I_i$ is $J/m^2$. The wavelength of the incident laser $\lambda$ is set to $532 \text{ nm}$ and the corresponding frequency is $5.64 \times 10^{14} \text{ sec}^{-1}$.

10.2 Longitudinal Pockels cell intensity modulator

For a longitudinal Pockels cell intensity modulator, common electro-optic crystals are those which have point-group symmetry of $42m$. The correct arrangement of $42m$ electrooptic crystals in the longitudinal Pockels cell intensity modulator is shown in Figure 10.1. The popular $42m$ electrooptic crystals are Potassium Dihydrogen Phosphate $\text{KH}_2\text{PO}_4$ (KDP), Deuterated Potassium Dihydrogen Phosphate $\text{KD}_2\text{PO}_4$ (DKDP), and Ammonium Dihydrogen Phosphate $\text{NH}_4\text{H}_2\text{PO}_4$ (ADP).

Assuming that a beam of unpolarized light is normally impinging the longitudinal Pockels cell intensity modulator, the relation between the incident intensity $P_{in}$ and the transmitted intensity $P_{out}$ of modulator is [93]:

$$\frac{P_{out}}{P_{in}} = \frac{1}{2} \sin^2 \left( \frac{V}{V} \right)$$

................................................... (10.3)
\[ V_\pi = \frac{\lambda}{2n_0^2 r_{63}} \] ................................................................. (10.4a)

where \( V \) is the applied voltage on the Pockels cell, \( \lambda \) is the wavelength of the incident laser in free-space, \( n_0 \) is the index of the Pockels cell material along optic axis, and \( r_{63} \) is an element of electrooptic tensor of the Pockels cell material. The parameter, \( r_{63} \), represents the electro-optic effect of materials. The materials with a larger \( r_{63} \) have a larger electro-optic effect than those with small \( r_{63} \). When the applied voltage \( V \) is equal to the half-wave voltage \( V_\pi \), the transmitted intensity \( P_{out} \) is equal to the incident intensity \( P_{in} \). In the popular electrooptic materials with ponit-group symmetry \( \bar{4}2m \), the \( r_{63} \) of DKDP is the larger than those of other popular materials (KDP and ADP). Hence, DKDP is applied in the proposed laser shutter. From equation (10.4a), it is known that the half-wave voltage \( V_\pi \) is independent of the geometry of the longitudinal Pockels cell intensity modulator.

In the case of the transverse Pockels cell intensity modulator, the transmitted intensity is also calculated from equation (10.3), but the equation (10.4a) is replaced by:

\[ V_\pi = \frac{\lambda}{2n_0^2 r_{22}} \cdot \frac{d}{L} \] ................................................................. (10.4b)

where \( \lambda \) is the wavelength of the incident laser in free-space, \( n_0 \) is the index of the Pockels cell material along optic axis, and the \( r_{22} \) is an element of electrooptic tensor of the Pockels cell material, \( d \) is the distance between electrodes of the transverse Pockels cell intensity modulator and \( L \) is the distance between two polarizers of the transverse Pockels cell intensity modulator. Unlike the longitudinal Pockels cell intensity modulator, it is shown in equation (10.4b) that the half-wave voltage \( V_\pi \) of the transverse Pockels cell intensity modulator is related with the geometry of the Pockels cell intensity modulator. It is possible to designate \( V_\pi \) by changing the geometry of the transverse Pockels cell intensity modulator. This is an advantage of the transverse Pockels cell intensity modulator.

Similar to the definition in the equation (10.2), the transmitted flux of the laser shutter \( I_o \) is:

\[ I_o = \int_0^\infty P_{out} (t) dt \] ................................................................. (10.5)

In the circuit model of the laser shutter, the Pockels Cell is treated as a capacitor. Its capacitance is:
\[ C = \varepsilon_r \varepsilon_0 \frac{A}{d} \] (10.6)

Where \( \varepsilon_r \) is relative permittivity of the Pockels cell electrooptic material, the constant \( \varepsilon_0 \) is permittivity of free space and its value is \( 8.854 \times 10^{-12} \, \text{F/m} \), \( A \) is the area of capacitor, i.e. area of the electrode of the Pockels cell, \( d \) is the thickness of capacitor, i.e. distance between the electrodes of the Pockels cell. The default values of \( A \) and \( d \) are \( 1 \, \text{cm}^2 \) and \( 5 \, \text{mm} \). The properties of the DKDP are in Table 10.1. Given the properties of the DKDP, the voltage of DC source is set to \( 3340 \, \text{vol} \). from the equation (10.4a).

Figure 10.1: The Pockels cell intensity modulator with longitudinal configuration. The Pockels cell is made with DKDP. The external electric field is applied along the optic axis of DKDP, represented as z axis. Two polarizers are along the two principal axes of DKDP, i.e. x and y axes. Under an external voltage \( V \), two principal axes of DKDP become \( x' \) and \( y' \) and optic axis of DKDP remains along z axis. The angle of x and \( x' \) is \( 45^\circ \). The angle between y and \( y' \) is also \( 45^\circ \).
Table 10.1 Properties of some electro-optic materials [93]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>KDP(KH₂PO₄)</td>
<td>$\varepsilon_r = 20$; $n_0 = 1.51$; $r_{63} = 10.6 \times 10^{-12} \text{ m/V}$;</td>
</tr>
<tr>
<td>DKDP(KD₂PO₄)</td>
<td>$\varepsilon_r = 50$; $n_0 = 1.50$; $r_{63} = 23.6 \times 10^{-12} \text{ m/V}$;</td>
</tr>
<tr>
<td>ADP(NH₄H₂PO₄)</td>
<td>$\varepsilon_r = 12$; $n_0 = 1.52$; $r_{63} = 8.5 \times 10^{-12} \text{ m/V}$;</td>
</tr>
</tbody>
</table>

10.3 Resistivity of PCSS under a low electric field

Under a low electric field, the relation between carrier drift velocity $v_d$ and electric field $E$ of semiconductor materials is linear:

$$v_d = \mu E \quad \text{.................................................................(10.7)}$$

where the coefficient $\mu$ is the mobility of carriers. Then, under a low electric field, the current ($I$) and voltage ($V$) of the PCSS is:

$$I = q (\mu_n n + \mu_p p) \cdot E \cdot wd \quad \text{...........................................(10.8)}$$

where $q$ is electric charge and equal to $1.60 \times 10^{-19} \text{coul.}$, $w$ and $d$ are the parameters of size of the PCSS and are pictured in Figure 9.5, $\mu_n$ and $\mu_p$ are mobility of free electrons and free holes respectively, $n$ and $p$ are concentrations of electrons and holes respectively, $\mu_n n$ and $\mu_p p$ represent the contribution of electrons and holes to entire current $I$ respectively. In an intrinsic semiconductor, $n = p$ because a free electron and a hole are excited simultaneously when a photon is absorbed by a bonded electron. In addition, $\mu_n$ is much larger than $\mu_p$ in Si and GaAs [Table 10.2]. For simplicity, the contribution of holes to current is omitted in simulations. Additionally, in the PCSS, the electric field $E$ is equal to the ratio between the applied voltage $V$ and the length $l$:

$$E = \frac{V}{l} \quad \text{.............................................................................(10.9)}$$

Consequently, the equation (10.8) is simplified as:

$$I = q \mu_n n \cdot E \cdot wd = q \mu_n n \cdot \frac{V}{l} \cdot wd = q \mu_n n \frac{wd}{l} V \quad ....(10.10)$$

From the equation (3.10), the resistance of the PCSS, $R_S$, is:
\[ R_S = \frac{1}{q\mu_n n} \cdot \frac{l}{w \cdot d} \] (10.11)

It is noted that electron concentration \( n \) changes when the PCSS transfers from “off state” to “on state”. So, the electron concentration and resistance of the PCSS are expressed as functions of time, \( n(t) \) and \( R_S(t) \), in the below sections.

Table 10.2 Parameters of intrinsic Si and GaAs

<table>
<thead>
<tr>
<th></th>
<th>Parameters @ room temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>( \mu_n = 1420 \text{ cm}^2/\text{V} \cdot \text{sec}; \mu_p = 450 \text{ cm}^2/\text{V} \cdot \text{sec}; n_i = 8.60 \times 10^9 \text{ cm}^3. )</td>
</tr>
<tr>
<td>GaAs</td>
<td>( \mu_n = 8200 \text{ cm}^2/\text{V} \cdot \text{sec}; \mu_p = 400 \text{ cm}^2/\text{V} \cdot \text{sec}; n_i = 1.85 \times 10^6 \text{ cm}^3. )</td>
</tr>
</tbody>
</table>

Note: \( \mu_n \) and \( \mu_p \) are the mobilities of electrons and holes under low and moderate electric field, respectively; \( n_i \) is the carrier concentration at room temperature. [94]

10.4 Carrier motion in PCSS under a high electric field

Under a low electric field, the relationship between carrier drift velocity and electric field is linear, whereas this linear relationship does not hold under a high electric field [Figure 10.2]. In previous section 10.3, the DC source voltage is set to 3340 vol., and, from equation (10.9), the corresponding electric field of the PCSS is \( 3.34 \times 10^4 \text{ vol/cm} \), which is also the maximum electric field withstood by the PCSS. Under such high electric field, the linear relationship between carrier drift velocity and electric field is not held after inspecting Figure 10.2. It is necessary to take into account the nonlinear relationship between the carrier drift velocity and the electric field.

For Si material, the complete precise description of relationship between the electron velocity \( (v_d) \) and the electric field \( (E) \) is:

\[ v_d = \frac{\mu_n E}{1 + \left(\frac{\mu_n E}{\nu_{sat}}\right)^{\gamma/\beta}} \] (10.12)
When $E$ is low, $v_d \approx u_n E$; when $E$ is high, $v_d$ is close to saturated velocity $v_{sat}$. By fitting the Equation (10.12) with measured data in Figure 10.2, the parameters of the equation (10.12) are set as: $\mu_n = 1420 \text{ cm}^2/\text{V} \cdot \text{sec}$, $\beta = 1.4$, and $v_{sat} = 10^7 \text{ cm/sec}$. Considering the nonlinear relationship between electron velocity ($v_d$) and electric field ($E$), the current ($I$) and voltage ($V$) of Si sensor becomes:

$$I = q \cdot n \cdot v_d \cdot wd = q \cdot n \cdot \frac{\mu_n E}{1+(\frac{\mu_n E}{v_{sat}})^\beta} \cdot wd \quad (10.13)$$

where $q$ is electric charge and equal to $1.60 \times 10^{-19} \text{coul}$, $n$ is the electron concentration, $l$, $w$ and $d$ are the parameters of size of the PCSS and are pictured in Figure 9.5.

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Figure 10.2: Measured drift velocity of carriers in high-purity Si and GaAs as a function of the applied electric field. [95]
10.5 Carrier concentration of the PCSS

Another mathematical question associated with the PCSS is the function of electron concentration, \( n(t) \). The concentration of electrons in the PCSS is affected by two processes: generation of electrons due to absorption of photons and recombination of electrons in which electrons and holes are annihilated. The mathematical description of the processes of both generation and recombination is:

\[
\frac{dn}{dt} = G_0 - \frac{n - n_0}{\tau_n}
\]

where \( n \) is concentration of electrons, \( G_0 \) is the generation rate of carrier-electrons, i.e. how many electrons are excited as carriers in unit time by photons, \( \tau_n \) is the lifetime of free electrons, and \( n_0 \) is the concentration of free electron under the equilibrium state. Since the PCSS is made of intrinsic semiconductor, \( n_0 = n_i \). When the PCSS is in “on state”, \( n_0 \) is only small portion of the \( n \). So, for the mathematical simplicity, \( n_0 \) is omitted in the simulations. The lifetime of free electrons \( \tau_n \) can be set a value when fabricating the PCSS. For the Si PCSS, \( \tau_n \) is modulated from 1 ns ~ 1 ms by doping technology. However, for the GaAs PCSS, \( \tau_n \) can only be increased up to 1 ns in fabrication.

When the thickness of the PCSS (\( d \)) is less than the optical depth (1/\( \alpha \)), where \( \alpha \) is the optical absorption coefficient of the PCSS, the \( G_0 \) can be described as:

\[
G_0 = \eta \frac{P_{in}(t)/h\nu}{d}
\]

where \( P_{in}(t) \) is the intensity of the incident laser pulse, \( \eta \) is the efficiency of laser energy absorbed by the PCSS, \( h \) is Planck constant and \( \nu \) is frequency of light in free space, \( h\nu \) is the energy of each photon. Finally the equation describing the concentration of electrons is arranged and then written as:

\[
\frac{dn(t)}{dt} + \frac{n(t)}{\tau_n} = \frac{1}{h\nu d} P_{in}(t)
\]

10.6 Avalanching of PCSS under high electric field

In previous section 10.5, it is assumed that each photon generates one electron-hole pair when it is absorbed by the PCSS. After generation, electrons are swept away from the PCSS under the applied voltage. When free electrons move inside the PCSS, they must undergo collisions with other bonded electrons. Under a low electric field,
these collisions are not too sufficient to turn bonded electrons into free electrons. However, when the applied electric field increases to a level that the collisions are extremely intense and additional free electrons are generated. This phenomenon is called avalanching. When avalanching occurs, the current through the PCSS, $I$, is increased by a multiplication factor $M$, i.e.:

$$M = \frac{I}{I_0} \quad \text{................................................................. (10.17)}$$

where $I_0$ is the current under low electric field. It is found in experiments that the relationship between $M$ and applied electric field $E$ is described as [94]:

$$M = \frac{1}{1 - \left(\frac{E}{E_{BR}}\right)^m} \quad \text{................................................................. (10.18)}$$

where both factor $m$ and breakdown electric field $E_{BR}$, are involved. Both $m$ and $E_{BR}$ are determined experimentally and depends on device parameters such as dopants in the PCSS and geometry of the PCSS.

In the investigations of multiplication factor $M$, the choice of $m$ and $E_{BR}$ is based on the experiment data in Figure 10.3. First, through fitting solid curves of Figure 10.3 with the equation (10.17), $m$ and $E_{BR}$ are found for various thicknesses of the intrinsic GaAs samples and listed in Table 10.3. It is noted that only solid curves in Figure 10.3 are fitted because only contribution of electrons is taken into accounted in simulations. Then, for the second time, the fitting technology is applied to the values of $m$ and $E_{BR}$ in Table 10.3 in order to find the effect of the thickness of the GaAs sample on $m$ and $E_{BR}$. The resultant fitting curves are shown in Figure 10.4. The solid curve in Figure 10.4(a) is the relationship between $m$ and the thickness of the intrinsic GaAs sample and is expressed as:

$$m = 7 \cdot \left(1 - \exp\left(-\frac{l_{\text{cm}}}{h}\right)\right) \quad \text{.............................. (10.19)}$$

The solid curve in Figure 10.4(b) is the relationship between $E_{BR}$ and the thickness of the intrinsic GaAs sample and is expressed as:

$$E_{BR}(V/cm) = 2.6 \times 10^5 \exp\left(-\frac{0.1(\mu m)}{l_{\text{cm}} h}\right) \quad \text{.............................. (10.20)}$$

where the unit of $E_{BR}$ is $V/cm$. Given the default length of PCSS $l = 1 \text{ mm}$ in Figure 9.5, for the GaAs PCSS, $m = 7$ and $E_{BR} = 2.6 \times 10^5 \text{ V/cm}$. Consequently, for the GaAs PCSS,
the relationship between the multiplication factor $M$ and the applied electric field $E$ is described as:

$$M = \frac{1}{1 - \left(\frac{E(V/cm)}{2.6 \times 10^5(V/cm)}\right)^7} \quad \text{................................................ (10.21)}$$

Under the maximum electric field $3.34 \times 10^4 V/cm$, the maximum $M$ is almost one. It is concluded, for the GaAs PCSS, that the electric field is not too high to consider avalanching effect. The equation (10.21) is depicted in Figure 10.5.

Table 10.3 $m$, $V_{BR}$, and $E_{BR}$ determined by fitting solid curves of Figure 10.3 with the equation (10.17).

<table>
<thead>
<tr>
<th>Intrinsic GaAs Length ($\mu m$)</th>
<th>factor $m$</th>
<th>$V_{BR}$ (V)</th>
<th>$E_{BR}$ (MV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.7</td>
<td>6.80</td>
<td>1.36</td>
</tr>
<tr>
<td>0.10</td>
<td>2.1</td>
<td>7.23</td>
<td>0.72</td>
</tr>
<tr>
<td>0.20</td>
<td>3.0</td>
<td>10.15</td>
<td>0.51</td>
</tr>
<tr>
<td>0.28</td>
<td>3.1</td>
<td>12.35</td>
<td>0.44</td>
</tr>
<tr>
<td>0.49</td>
<td>3.5</td>
<td>17.00</td>
<td>0.35</td>
</tr>
<tr>
<td>0.57</td>
<td>4.0</td>
<td>19.90</td>
<td>0.35</td>
</tr>
<tr>
<td>1.13</td>
<td>6.1</td>
<td>34.50</td>
<td>0.31</td>
</tr>
<tr>
<td>2.61</td>
<td>6.6</td>
<td>71.56</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Figure 10.3: Copy of Fig. 1 of reference 96. Multiplication factor versus reverse bias in GaAs intrinsic semiconductor, solid lines represent multiplication factor of electrons, $M_e$, in the GaAs p$^+$-i-n$^+$ structures from left to right: $l = 0.05$, 0.10, 0.20, 0.28, 0.49, 0.57, 1.13, and 2.61 $\mu$m. Broken lines represent multiplication factor of holes $M_h$ in the GaAs n$^-$-i-p$^+$ structures from left to right: $l = 0.05$, 0.10, 0.21, 0.36 $\mu$m. [96]
Figure 10.4: The relationship between the length of intrinsic GaAs and: (a) breakdown electric field $E_{BR}$, and (b) factor $m$. 

\[ m = 7 \cdot \left(1 - \exp\left(-\frac{\text{length(\mu m)}}{0.5(\mu m)}\right)\right) \]
Figure 10.5: The relationship of electric field E and multiplication factor M for the GaAs PCSS with the length of 1 mm.

10.7 Bias resistor

When the laser shutter is in the normal state, nearly 100% of DC voltage should apply on the Pockels cell. In order to meet this requirement, \( R_S(\text{off}) \gg R \), where \( R_S(\text{off}) \) is the resistance of the PCSS when it is in “off state”. When the laser shutter is in “off state”, nearly 100% of DC voltage should be withstood by the bias resistor, \( R_S(\text{on}) \gg R \), where \( R_S(\text{on}) \) is the resistance of the PCSS when it is in “on state”.

When the size and material of the PCSS are given, the \( R_S(\text{off}) \) can be calculated from equation (10.11). For the Si PCSS, \( R_S(\text{off}) = 5.12 \times 10^9 \Omega \) and for the GaAs PCSS \( R_S(\text{off}) = 4.12 \times 10^{12} \Omega \), where the default size parameters of the PCSS are used, i.e. \( l=1\text{mm}, \ w=1\text{mm}, \ d=1\mu\text{m} \) and intrinsic carrier concentration of Table 10.2 is used.
The choice of \( R_s(\text{on}) \) is not easily treated as \( R_s(\text{off}) \) since the carrier concentration of the PCSS is a variable when the intensive laser pulse impinges on it. After a few initial trials, the bias resistor is finally set to \( 10^7 \, \Omega \).

Since the resistance of the bias resistor is much lower than \( R_s(\text{off}) \) of the PCSS, when the laser shutter is in the normal state, the high DC voltage source provides the laser shutter a small dark current which can be roughly calculated from the equation \( \frac{V}{R_s(\text{off})} \). For a laser shutter with the Si PCSS, the dark current is \( 652.34 \, nA \) and power consumption is \( 2.18 \, mW \); for a laser shutter with the GaAs PCSS, the dark current is \( 0.81 \, nA \) and power consumption is \( 0.003 \, mW \). Comparably, power consumption of the laser shutter with the Si PCSS is about 726 times of that of GaAs PCSS.

The comparison of the laser shutter with the Si and GaAs PCSS is summarized in Table 10.4. The Si PCSS is more easily to fabricated than the GaAs PCSS. However, the power consumption of the laser shutter with the Si PCSS is a disadvantage itself. The comparison of the transmitted flux \( I_o \) of the laser shutter with Si and GaAs PCSS is a difficult task since two factors are involved with the issue: free electron lifetime \( \tau_n \) and free electron mobility \( u_n \). Even though, under a low electric field, free electron mobility \( u_n \) of the Si PCSS is only \( 17\% \) of that of the GaAs PCSS, the free electron lifetime of the Si PCSS can be modulated up to \( 1 \, ms \), which nobly suppresses free electron lifetime of GaAs PCSS, the maximum value of which is \( 1 \, ns \). The higher mobility and longer lifetime of free electrons of the PCSS definitely decreases the transmitted flux \( I_o \) of the laser shutter. Unfortunately, either Si or GaAs PCSS can express advantages in both respects.
### Table 10.4 Comparison of laser shutter with Si and GaAs PCSS

<table>
<thead>
<tr>
<th></th>
<th>Si PCSS</th>
<th>GaAs PCSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>fabrication</td>
<td>easily</td>
<td>comparably difficult</td>
</tr>
<tr>
<td>power consumption</td>
<td>2.18 mW</td>
<td>0.003 mW</td>
</tr>
<tr>
<td>of laser shutter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>free electron lifetime</td>
<td>1 ns ~ 1 ms</td>
<td>up to 1 ns</td>
</tr>
<tr>
<td>free electron mobility</td>
<td>1420 cm²/V·sec</td>
<td>8500 cm²/V·sec</td>
</tr>
<tr>
<td>under low electric</td>
<td></td>
<td></td>
</tr>
<tr>
<td>field (u_n)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 10.8 Equations of the circuit model

The circuit model of the laser shutter is a one-order differential circuit [Figure 9.6]. According to the Kirchhoff’s voltage law and current law, the circuit model equation is written as:

\[ V_H = v_c(t) + (i_c(t) + i_s(t)) \cdot R \] .................................(10.22)

where \( V_H \) is the voltage of DC source, \( v_c(t) \) and \( i_c(t) \) are the voltage and current on capacitor, i.e. the voltage and current on the Pockels cell, \( i_s(t) \) is the current through the PCSS, and \( R \) is the bias resistor. For capacitor, the relation between voltage and current is:

\[ i_c(t) = C \frac{dv_c(t)}{dt} \] .................................................................(10.23)

where \( C \) is the capacitance of the Pockels cell and calculated from equation (10.6). The current \( i_s(t) \) is expressed in the equation (10.10) when only considering linear relationship between the carrier drift velocity \( v_d \) and the electric field \( E \), whereas it should be calculated by equation (10.9) and (10.13) when nonlinear relationship between the carrier drift velocity \( v_d \) and the electric field \( E \) is taken into account.

#### 10.9 Program design

The program design is made of three sequential parts:

- Given the intensive incident laser pulse \( P_{in}(t) \), find the incident flux \( I_i \) from the equation (10.2) and the carrier concentration \( n(t) \) from the equation (10.16);
- Find the voltage on the Pockels cell \( v_c(t) \) from the equation (10.22);
- Calculate the transmitted intensity \( P_{out}(t) \) by the equation (10.3), then the transmitted flux \( I_o \) by the equation (10.5), and the ratio of \( I_o/I_i \);
The programming language is MATLAB and the finite difference time domain (FDTD) is used to solve the equations (10.16) and (10.22). FDTD is discussed in chapter 3 when solving the Maxwell’s equations.
CHAPTER 11
SIMULATION RESULTS AND ANALYSIS

11.1 Performance of laser shutter

The simulation results, shown in Figure 11.1, are carried out under the conditions of Table 11.1. In the simulation of Figure 11.1, a Si sensor and a DKDP Pockels cell are investigated. The incident laser pulse intensity, $P_{in}(t)$, is shown in Figure 11.1(a) and its total incident flux $I_i$ is $0.532 \text{ J/m}^2$, where $I_i$ is defined in equation (10.2), i.e. $\int_0^\infty P_{in}(t)dt$.

The center time $t_0$ and pulse width $\Delta t$ of incident laser pulse are 30 ns and 90 ns respectively and its peak power $P_0$ is $10 \text{ MW/m}^2$. Under the effect of the incident laser pulse, carriers are generated in the Si sensor and the plot of carrier concentration vs. time is shown in Figure 11.1(b). Since the lifetime of carrier of Si PCSS is set to 10 ns in the simulation, less than the pulse width of the incident laser pulse 30 ns, the plot of carrier concentration has similar shape with that of the incident laser pulse intensity $P_{in}(t)$. The maximum carrier concentration of the Si sensor $2.3 \times 10^{17} \text{ cm}^{-3}$, which is roughly $10^7$ times higher than that of the intrinsic Si at room temperature, $10^{10} \text{ cm}^{-3}$, appears at 100 ns, which delays a carrier life time ($\tau = 10 \text{ ns}$) after center time of incident laser pulse ($t_0 = 90 \text{ ns}$). The voltage on the Pockels cell, shown in Figure 11.1(c), dramatically drops from 3340 V to zero V during the time period of 40 ns (from 30 to 70 ns). This is because, during this period of time (from 30 to 70 ns), charges on electrodes of the Pockels cell are quickly removed through the PCSS. After 400 ns, the voltage on the Pockels cell increases slowly due to charging. During the time (after 400 ns), the carrier concentration of the PCSS is very low and hence charges on the Pockels cell could not be removed through the PCSS. The change of the voltage of the Pockels cell [Figure 11.1(c)] corresponds with the change of carrier concentration of the PCSS [Figure 11.1(b)]. The curves of intensity ($P_{in}$ and $P_{out}$) and flux ($I_i$ and $I_o$) of the laser shutter vs. time are shown in Figure 11.1 (d) and (e), respectively. It is calculated that transmitted flux $I_o$ is $0.0133 \text{ J/m}^2$, only 2.51% of total incident flux $I_i$. 

86
Table 11.1 Parameters applied in the simulation of Figure 11.1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser pulse</td>
<td>$P_0 = 10 \text{ MW/m}^2$; $\lambda = 532 \text{ nm}$; $t_0 = 90 \text{ ns}$; $\Delta t = 30 \text{ ns}$.</td>
</tr>
<tr>
<td>Pockels cell</td>
<td>DKDP: $\varepsilon_r = 50$; $n_0 = 1.5$; $r_{63} = 23.6 \times 10^{-12} \text{ m/V}$; Area = 1 cm$^2$; Thickness = 5 mm.</td>
</tr>
<tr>
<td>PCSS</td>
<td>Si: $\mu_n = 1420 \text{ cm}^2/\text{V} \cdot \text{sec}$; $\tau_n = 10 \text{ ns}$; $\eta = 0.9$; Length = 1 mm; Width = 1 mm; Depth = 1 $\mu$m.</td>
</tr>
<tr>
<td>Voltage source</td>
<td>3340 V</td>
</tr>
<tr>
<td>Bias resistor</td>
<td>10 $M\Omega$</td>
</tr>
</tbody>
</table>
Figure 11.1: (a) incident laser pulse intensity $P_{in}$; (b) carrier concentration of the Si PCSS; (c) voltage of the DKDP Pockels cell; (d) incident laser pulse intensity $P_{in}$ and transmitted laser intensity $P_{out}$ of the laser shutter; (e) incident laser flux $I_i$ and transmitted flux $I_o$ of the laser shutter. The incident laser pulse intensity $P_{in}$ is redrawn in (d) as a black curve in order to make a comparison with the transmitted intensity $P_{out}$.

The dependence of the PCSS geometry on the laser shutter performance is listed in Table 11.2. It is demonstrated that the transmitted flux $I_o$ is only related with the ratio of length and width of the PCSS, i.e. $l/w$, not with the depth of PCSS. This is because, from equation of (10.16), the free electron concentration $n$ is inversely proportional with depth of the PCSS, $(d)$. Consequently, the equation (10.11) is rewritten as $R_S = \frac{1}{q\mu_nnd} \cdot \frac{l}{w}$.

From this rewritten equation, it is concluded finally that the PCSS resistance is proportional with the ratio of $l/w$ because the term of $n \cdot d$ is independent with the PCSS geometry.
Table 11.2 Dependence of the laser shutter performance with the Si PCSS geometry

<table>
<thead>
<tr>
<th>Depth (μm)</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Length/Width</th>
<th>$I_0$ (J/m²)</th>
<th>$I_o/I_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.0133</td>
<td>2.51%</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
<td>0.0071</td>
<td>1.33%</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.0133</td>
<td>2.51%</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>4</td>
<td>0.5</td>
<td>0.0071</td>
<td>1.33%</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.0133</td>
<td>2.51%</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
<td>0.0071</td>
<td>1.33%</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.0133</td>
<td>2.51%</td>
</tr>
</tbody>
</table>

11.2 Effect of carrier lifetime of the PCSS on the laser shutter performance

The carrier lifetime of the PCSS $\tau_n$ is directly related with the carrier concentration of the PCSS. The longer carrier lifetime of the PCSS results in both higher carrier concentration and conductance of the PCSS. Under the help of the PCSS with higher conductance, the charge on electrodes of the Pockels cell could be removed more quickly. The Figure 11.2 is the relation between the ratio of $I_o/I_i$ of the laser shutter and the carrier lifetime of the PCSS under a fixed incident laser pulse. The parameters of the PCSS, the Pockels cell and the incident laser pulse in the simulation of Figure 11.2 are listed in Table 11.1, but the carrier lifetime of the PCSS varies from 1 ns to 1 ms. It is shown that the ratio of $I_o/I_i$ of the laser shutter decreases from 10%, corresponding to $\tau_n = 1$ ns, to 1.2%, corresponding to $\tau_n = 100$ ns. The ratio of $I_o/I_i$ of the laser shutter remains at 1.2% in the case of $\tau_n$ larger than 100 ns.
Figure 11.2: The relationship between the ratio of $I_o/I_i$ of the laser shutter and the carrier lifetime of the PCSS in the case of a fixed incident laser pulse.

11.3 Effect of the peak intensity of an incident laser pulse on the laser shutter performance

The response of the laser shutter to the peak intensity of an incident laser pulse is investigated in this section. Because the incident flux of a laser pulse $I_i$ is defined as $\int_0^\infty P_{in}(t)\,dt$, the incident flux $I_i$ is directly proportional with the peak intensity $P_o$ of the incident laser pulse. Then a higher $I_i$ results in a higher transmitted flux of the laser shutter $I_o$. However, the change of $I_o$ is not strictly linear to that of $I_i$ when the peak intensity of an incident laser pulse $P_o$ changes. This is because the carrier concentration of the PCSS becomes higher when an incident laser pulse with higher $I_i$ impinges it. The existence of higher carrier concentration decreases the discharging time of Pockels cell because the resistance of the PCSS decreases. Instead, according the above reasoning, the change of $I_o$ is slower than that of $I_i$ in the case of changing peak intensity of an incident laser pulse. It shows, in Figure 11.3(a), that the ratio of $I_o/I_i$ decreases with the increasing
of peak intensity of an incident laser pulse $P_o$. In Figure 11.3(b), the maximum carrier concentration of the PCSS linearly increases with the increasing of peak intensity of an incident laser pulse $P_o$.

In Figure 11.3, the effect of the carrier lifetime of the PCSS on both the ratio of $I_o/I_i$ and the maximum carrier concentration of PCSS is also illustrated. With the increasing of carrier lifetime $\tau_n$, the ratio of $I_o/I_i$ becomes lower and the maximum carrier concentration of the PCSS becomes higher. This conclusion is as same as that discussed in the previous section.
Figure 11.3: Effect of the peak intensity of an incident laser pulse on the ratio of $I_o/I_i$ of the laser shutter (a) and the maximum carrier concentration of the PCSS (b) in the cases of various carrier lifetime $\tau_n = 1, 10, \text{ and } 100 \text{ ns}$.

11.4 Effect of the pulse width of an incident laser pulse on the laser shutter performance

The effect of the pulse width of an incident laser pulse on the laser shutter is complicated since the incident flux $I_i$ is a function of both the peak intensity $P_o$ and the pulse width $\Delta t$, i.e. $I_i(P_o, \Delta t)$. For a given $I_i$, the peak intensity of a laser pulse decreases with the increasing of its pulse width. Graphically, for a given $I_i$, the incident laser pulse becomes flat when its pulse width increases. It is shown in Figure 11.4 that the shape of the incident laser pulse $P_{in}(t)$, whether it is flat or steep, affects the ratio of $I_o/I_i$ of the laser shutter when the $I_i$ is fixed. In Figure 11.4(a), a minimum ratio of $I_o/I_i$ of the laser shutter appears when the pulse width of the incident laser pulse increases from one value much less than $\tau_n$ to another value much larger than $\tau_n$, where $\tau_n$ is the lifetime of the PCSS. The minimum ratio of the $I_o/I_i$ of the laser shutter corresponds to the pulse width
of the incident laser pulse, which is approaching to carrier life time. When the pulse width is far away the carrier life time $\tau_n$, the ratio of $I_o/I_i$ increases. The Figure 11.4(b) provides the same conclusion as Figure 11.4(a). However, they do from different perspectives. In Figure 11.4(a), the carrier life time $\tau_n$ of the PCSS is fixed at 100 ns, whereas, in Figure 11.4(b), $I_i$ is a fixed number. In summary, under the condition of a fixed $I_i$, a minimum ratio of $I_o/I_i$ appears when the pulse width of the PCSS is comparable with the carrier lifetime of the PCSS.

It is noted that, in the previous section 4.3, the $I_i$ is changing. This is because the pulse width of the incident laser shutter $\Delta t = 30$ ns and the peak intensity $P_o$ of the incident laser pulse is a variable in Figure 11.3. The section 11.3 and 11.4 discuss about the performance of the laser shutter under different conditions.
11.5 Effect of area of electrode of the Pockels cell on the laser shutter performance

In the circuit model of the laser shutter, the Pockels cell is treated as a capacitor. The capacitance of the Pockels cell is proportional to its electrode area. When the Pockels cell electrodes expand, there are more charges on the electrodes of the Pockels cell before the coming of the incident laser pulse. When the laser shutter is triggered by an incident laser pulse, it would take more time to remove charges before the voltage of the Pockels cell decreases to zero. During the discharging time of the Pockels cell, part of the incident laser goes through the laser shutter and becomes the transmitted light of the laser shutter. It can be inferred from this that the longer the discharging time, the more transmitted flux there is. As a conclusion, the ratio of $I_o/I_i$ increases with the increasing of electrode area of the Pockels cell. The simulation of Figure 11.5 shows the linear relationship between
the area of the Pockels cell’s electrode and the ratio of $I_o/I_i$ of the laser shutter. The parameters of Figure 11.5 are listed in Table 11.1 but the area of the Pockels cell varies from 0.1 to 10 cm$^2$, and the incident flux $I_i$ varies from 1 to 10 J/m$^2$.

![Figure 11.5: Relation between area of the Pockels cell’s electrodes and the ratio of $I_o/I_i$ of the laser shutter under the cases of variant flux of incident laser pulse $I_i = 1, 2, 5, \text{ and } 10 \text{ J/m}^2$.](image)

11.6 Effect of nonlinear relationship between $v_d$ and $E$ on the laser shutter performance

In the simulation of Figure 11.6, the incident laser pulse is same as that of the simulation of Figure 11.1. When the nonlinear relationship between electron drift velocity $v_d$ and electric field $E$ of the PCSS is taken into account, the ratio of $I_o/I_i$ of the laser shutter is 7.52\%, nearly three times of that in the case of linear relationship between $v_d$ and $E$. During the entire simulation time, the maximum electric field $E$ appears at the launch time ($t = 0$) when the PCSS withstands the whole voltage of DC source. Given the voltage of DC source is 3340 V and length of the PCSS is 1 mm, it is calculated that the
maximum electric field is $3.3 \times 10^4 V/cm$. It is demonstrated in Figure 10.2 that the
electron drift velocity is already saturated under the maximum electric field $3.3 \times 10^4 V/cm$. In other words, the nonlinear relationship between $v_d$ and $E$ is very strong at
the starting time of the simulations. Under the same electric field $E$, the electron drift
velocity of the PCSS under the nonlinear relationship between $v_d$ and $E$ is slower
[Equation (10.7)] than that under the linear relationship between $v_d$ and $E$ [Equation
(10.12)]. The slower the electrons of the PCSS drift, the smaller the current of the PCSS;
the smaller the current of the PCSS, the more time it takes to discharges the charges on
the electrodes of the Pockels cell; the more time it takes to drop the voltage of the
Pockels cell to zero, the more incident light can pass through the laser shutter and then
becomes transmitted light. Finally, the ratio of $I_o/I_i$ of the laser shutter increases. In
summary, the nonlinear relationship between $v_d$ and $E$ gives a negative influence on the
laser shutter performance, since it takes more time to move the charges on electrodes of
the Pockels cell.
Figure 11.6: Effect of linear and nonlinear relationship of electrons drift velocity $v_d$ and electric field $E$ on the laser shutter performance: (a) intensity and (b) flux.
11.7 Effect of avalanching in the GaAs PCSS on the laser shutter performance

As discussed in section 10.6, the influence of the avalanche effect of the GaAs PCSS on the laser shutter performance is too small to be omitted. The simulation results provide the same conclusion. In Figure 11.7, it is shown that the transmitted intensity and flux of the laser shutter are identical before and after the avalanche effect is considered. The parameters of Figure 11.7 are listed in Table 11.1 except that the GaAs PCSS is applied in simulation of Figure 11.7.
Figure 11.7: The influence of the avalanche effect of the GaAs PCSS on the laser shutter performance. The legend of (a) is as same as that of (b).
CHAPTER 12

FUTURE RESEARCH

12.1 Future research

The simulation results illustrate that the proposed laser shutter can protect the eyes from the intensive laser pulse with pulse width $\Delta t \sim 30 \text{ ns}$. However, many extensive investigations are needed to carry out to improve its performance. First, the operation voltage of proposed laser shutter is too high to limit its real applications. The fundamental reason of such high operation voltage is the optical-electrical coefficient of most nonlinear optical materials is too small, usually in the range of $10^{-12} \text{ m/V}$. Finding a kind of nonlinear optical material with high coefficient is a good approach to decrease the operation voltage; Another question related with the optics material is the dielectric constant. The charge on the electrodes of the Pockels cell is proportional with the dielectric constant of the Pockels cell. The larger dielectric constant means longer time to discharge and then response time becomes longer. In summary, the dielectric constant of optics material is a major factor of response time of laser shutter. A kind of optics materials with high coefficient and low dielectric constant must improve the performance of the laser shutter in a larger extent.

Second, it is needed to take into account the properties of absorption and reflection of the Pockels cell material (DKDP).

Third, it is needed to consider the effect of spectra of the incident laser pulse on the laser shutter. In the present simulations, the frequency of the incident laser pulse is set to $532 \text{ nm}$. For the laser pulse with other frequencies, the performance of the laser shutter should change.
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PART I


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88. Homepage of free software MIT Electromagnetic Equation Propagation http://ab-initio.mit.edu/wiki/index.php/Meep, this is a free software to do simulation of PhC in time domain.


PART II


BIographyal Sketch

Huazhong Wang

Huazhong Wang was born at Shenyang City, Liaoning Province, the People’s Republic of China in 1972. He received his bachelor’s degree of Science at the Department of Electrical Engineering, Liaoning University in the spring 1993. Since fall 2001, he has studied for the Master degree at the Department of Electrical and Computer Engineering, FAMU-FSU College of Engineering, Florida State University. He received his Master degree in summer 2004 and PhD degree in fall 2009. During his master graduate study, he was a research assistant in the field of insulation materials and optics simulation and conducted research under Dr. Jim P. Zheng’s supervision.

John's research interests include simulation of optics device, photonic device, scientific programming, electrical and optical properties of materials.