# DESIGN AND SIMULATION OF LOW POWER CONSUMPTION POLYMERIC BASED MMI THERMO-OPTIC SWITCH

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# ABSTRACT

In optical communication system, optical cross connect devices particularly an optical switch has become the main attraction for research due to its ability to route optical data signals without the need for conversion to electrical signals. Thus, it is important to develop optical devices such as optical switch with low power consumption and crosstalk for Wavelength Division Multiplexing (WDM) lightwave communication system. This project aims towards the design and simulation work of a polymeric based thermo-optic switch using Multimode Interference (MMI) structure to achieve low switching power capability and reduce crosstalk figure. The optical switch is designed on the 2x2 MMI cross coupler architecture of optical switch based on the general interference mechanism. Light propagation and thermal distribution through the optical switch is modeled using Finite Difference Beam Propagation Method (FD-BPM). Photosensitive SU-8 epoxy polymeric based waveguide material at core layers with PMGI at upper and lower cladding layer were chosen due to its low thermal conductivity and high thermo-optic coefficient. Further analysis has been performed by exploring the effect of heater's structure and its placement in order to reduce switching power. It is observed that by applying well-designed of heater's structure and suitable placement of heater, low power consumption as low as 9.05 mW with crosstalk level of -36.52 dB can be achieved.

# ABSTRAK

Di dalam sistem perhubungan optik, peranti perhubungan silang optik seperti suis optik menjadi tarikan utama dalam bidang penyelidikan kerana kebolehannya menghalakan isyarat data optik dari masukan ke keluaran yang dikehendaki tanpa perlu melibatkan penukaran ke isyarat elektrik. Sehubungan itu, adalah penting untuk membina satu peranti optik seperti suis optik yang mempunyai penggunaan kuasa pensuisan dan cakap silang yang rendah dalam multipleks pembahagi panjang gelombang (WDM) bagi sistem perhubungan gelombang cahaya. Projek ini bermatlamat untuk mereka bentuk dan membuat simulasi suis optik berasaskan bahan jenis polimer melalui kaedah kesan kawalan haba dan menggunakan struktur pengganding gangguan berbilang mod (MMI) bagi mencapai penggunaan kuasa pensuisan yang rendah serta mampu mengurangkan kadar cakap silang. Suis optik ini direka bentuk di atas senibina 2x2 pengganding silang MMI berasaskan mekanisma gangguan umum. Perambatan cahaya dan taburan haba menerusi suis optik telah dimodelkan menggunakan kaedah perbezaan terhingga-perambatan alur (FD-BPM). Bahan pandu gelombang yang berasaskan polimer peka cahaya, SU-8 epoxy di lapisan teras manakala PMGI di lapisan pelindung atas dan bawah dipilih bersesuaian dengan kekonduksian habanya yang rendah dan pekali termalnya yang tinggi. Analisis lebih lanjut telah dibuat dengan mengkaji kesan struktur pemanas dan kedudukannya bagi mengurangkan kuasa pensuisan. Dapat diperhatikan bahawa melalui penggunaan rekabentuk struktur pemanas yang baik dan kedudukannya yang sesuai, penggunaan kuasa serendah 9.05 mW dengan cakap silang -36.52 dB dapat dicapai.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| TEM | - | Transverse electromagnetic |
| TE | - | Transverse electric |
| TM | - | Transverse magnetic |
| MMI | - | Multimode interference |
| WDM | - | Wavelength division multiplexing |
| MPA | - | Mode propagation analysis |
| TO | - | Thermo-optic |
| FDM | - | Finite difference method |
| FEM | - | Finite element method |
| DC | - | Directional coupler |
| MZI | - | Mach-Zehnder interferometer |
| CT | - | Crosstalk |
| IL | - | Insertion loss |
| ER | - | Extinction ratio |
| EIM | - | Effective index method |
| BPM | - | Beam propagation method |

# LIST OF SYMBOLS

| SYMBOLS | | DESCRIPTION |
|---|---|---|
| $\boldsymbol{R}$ | - | Resistance |
| $\boldsymbol{E}$ | - | Electric field |
| $\boldsymbol{H}$ | - | Magnetic field |
| $\boldsymbol{J}$ | - | Current density |
| $\boldsymbol{\rho}$ | - | Charge density |
| $\boldsymbol{\sigma}$ | - | Conductivity |
| $\boldsymbol{D}$ | - | Electric flux density |
| $\boldsymbol{B}$ | - | Magnetic flux density |
| $\boldsymbol{\varepsilon}$ | - | Dielectric permittivity of the medium |
| $\boldsymbol{\mu}$ | - | Magnetic permeability of the medium |
| $\boldsymbol{n}$ | - | Refractive index |
| $\boldsymbol{\lambda}$ | - | Wavelength |
| $\boldsymbol{k}$ | - | Wave number of a medium |
| $\boldsymbol{N}$ | - | Effective index of the mode |
| $\boldsymbol{\beta}$ | - | Wave propagation constant |
| $\boldsymbol{\omega}$ | - | Angular frequency |
| $\upsilon$ | - | Wave velocity |
| $\boldsymbol{v}$ | - | Mode number |
| $\boldsymbol{T}$ | - | Waveguide thickness |
| $\boldsymbol{L_{\pi}}$ | - | Beat length of the two lowest-order modes |
| $\boldsymbol{c_{v}}$ | - | Field excitation coefficient |
| $\boldsymbol{E(y,z)}$ | - | Field profile |
| $\boldsymbol{L_{MMI}}$ | - | Multimode waveguide length |

| | | |
|---|---|---|
| $W_{MMI}$ | - | Multimode waveguide width |
| $p$ | - | Periodic number of the imaging along the multimode waveguide |
| $\dot{Q}'''$ | - | Distributed thermal source per unit volume |
| $C$ | - | Specific heat |
| $t$ | - | Time |
| $k$ | - | Thermal conductivity |
| $P$ | - | Supply power |
| $w$ | - | Heater width |
| $h$ | - | Heater length |
| $I$ | - | Current through the heater electrode |
| $dn/dT$ | - | Thermo-optic coefficient |
| $\Delta n$ | - | Refractive index difference |
| $\Delta T$ | - | Temperature rise |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Project

As developments in optical fiber communications and integrated optical electronics scale up, the popularity for research work in this area increased as well. The enhancement in telecommunication system leads to the demand for increasing bandwidth capacity. Besides that, the world needs telecommunications system that can fit on the flexibility and re-configurability. Therefore, the implementation of optical communication system as a medium to transmit data signal has become major concern in telecommunication field due to its remarkable advantages on the performance.

The transmission and processing of signals carried by optical beams has been a topic of great interest since the early 1960s, when the development of first laser provided a stable source of coherent light for such application. Thus, the concept of integrated optics emerged in which the conventional electric integrated circuits are replaced by the Photonic Integrated Circuits (PIC). Photonics Integrated Circuit (PIC) has its own significant advantages such as low power consumption, low transmission loss, higher bandwidth and immunity to electromagnetic interference.

Consequently, the field step forward onto the development of semiconductor optical devices which permitted very efficient and compact optoelectronic devices. These developments yield a rich variety of passive or active components such as optical splitters, optical coupler, variable optical attenuator, waveguide cross-couplers, optical switches and modulators.

In order to accomplish the current world demand, Wavelength Division Multiplexing (WDM) system which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelength was introduced. In the WDM systems, signal routing and coupling devices such as optical switch are required to obtain large bandwidth.

Therefore, high speed and high capacity optical switch are crucially needed in current optical networks system. For this, it is necessary to research for good and tolerable performances of optical switch. Furthermore, it is important to develop optical devices that have low power consumption and crosstalk.

There are various optical switching technologies available today, such as Micro Electromechanical System (MEMs) (Dobbelaere et al., 2002, Leow et al., 2004), Electro optic switch (Lee et al.,2005, Wang et al., 2004 and Xiao et al., 2009), Thermo optic switch which originates from the temperature dependency of material's refractive index (Keil et al., 1996, Wu et al., 2006 and Al-Hetar et al., 2008) and Liquid Crystal Switch (Papadimitriou, 2003, Vazquez et al., 2003 and Shih et al., 2009). Thermo optic effects are one of the tuning effects that can change the refractive indices and modulate the propagation of light. Compared with electro optic effect, thermo optic effect is simpler and more flexible. Besides that, thermo optic effect can be found in all transparent materials (Nishihara et al., 1989)

There are also several types of structure for optical switch which have been developed such as Directional coupler (DC) based switch (Supaa'at, 2004, Beggs et al., 2009), Mach-Zehnder interferometer (MZI) based switch (Inoue et al., 1992, Wong et al., 2005), Y-branch based switch (Yeo et al., 2006), multimode interference (MMI) based switch (Wang et al., 2006, Al-Hetar et al., 2008, Yin, 2008 and Jia et al., 2007) and combination of MMI-MZI based switch. Among these technologies, an MMI based switch has its own popularity due to their excellent performance and more than that, MMI structure is the most fabrication tolerance device. In addition, MMI devices owing to its advantages such as ultra-compact size, low loss and polarization insensitive (Soldano and Penning, 1995). In this work, MMI optical switch based on thermo-optic (TO) control is proposed due to its simplicity and flexibility.

Material research for optoelectronic application has been started extensively few decades back since there is great demand for components that meet performance criteria as well as economic requirements. Few materials with different advantages have been explored and used for the fabrication of optical waveguides, as well as the integrated components. These materials include III-V compound semiconductors, silica, LiNbO3, sol-gel material and polymer. These materials have their own advantages and disadvantages as compared to their counterpart. For example, the III-V semiconductors are unique in monolithic integration among waveguides, light sources and detectors. However, the complexity of fabrication due to high cost of III-V growth technology, high fiber to chip coupling and waveguide loss are present challenges for its practical applications in OEICs. Polymeric materials in other hand have been extensively being used in optical switch development due to the potential of added optical functionality and able to be produce at low cost (Yao et al., 2002). Furthermore, polymeric devices have a potential of integrating multifunctional devices and cost effective mass production (Hida et al., 1993). It is believed that the combination of suitable material like polymer and superior type of structure like MMI structure will definitely lead to low power consumption and low crosstalk value. A review on published optical switches is listed in Table 1.1.

**Table 1.1** Summarization of published optical switch

| Switch Configuration | Port N X M | Material | Technology | Power/ Voltage/ Current | CT (dB) | Switching Time | IL (dB) |
|---|---|---|---|---|---|---|---|
| MMI (Wu *et al.*, 2006) | 1×2 | Sol-gel | Thermo-optic | 84 mW | - | - | - |
| MMI (Wang *et al.*,2006) | 1×2 | Polymer | Thermo-optic | 22 mW | -20 | 4 ms | - |
| MMI-MZI (Gao *et al.*,2009) | 2×2 | Polymer | Thermo-optic | 7.5 mW | -37 | 400 µs | |
| MMI (Yin *et al.*, 2008) | 1×2 | GaAs/AlGaAs | Thermo-optic | 110 mA | -33 | - | - |
| MMI (Xie *et al.*,2009) | 2×2 | Polymer | Thermo-optic | 8.9 mW | -23 | - | 10 |
| MMI-MZI (Al-hetar *et al.*,2011) | 2×2 | Polymer | Thermo-optic | 1.85 mW | -28.6 | 0.7 ms | 0.88 |
| MZI-MMI (Xia *et al.*, 2004) | 2×2 | Silicon on insulator | Thermo-optic | 235 mW | - | 60 µs | 12 |
| MZI-MMI (Lai *et al.*, 1998) | 2×2 | Silica | Thermo- optic | 110 mW | - | 150 µs | 1 |

| Switch Configuration | Port N X M | Material | Technology | Power/ Voltage/ Current | CT (dB) | Switching Time | IL (dB) |
|---|---|---|---|---|---|---|---|
| MMI (May-Arrioja *et al.*,2006) | 2×2 | InGaAsp | Electro-optic | - | -20 | - | - |
| Y-branch (Yeo *et al.*, 2006) | 1×2 | Hybrid polymer-silica | Thermo-optic | 70 mW | -35 | - | - |
| MZI-MMI (Liu *et al.*,2005) | 2×2 | Silicon on insulator | Thermo-optic | 145 mW | - | 8 ± 1 μs | - |
| MZI with 3 dB DC (Sohma *et al.*, 2002) | 2×2 | Silica | Thermo-optic | 45 mW | - | 3 ms | - |
| MMI (Nagai *et al.*, 2002) | 2×2 | InGaAsP | Electro-optic | - | -13 | - | - |

**Notes:**

CT – Crosstalk

IL – Insertion loss

N – Number of input port

M – Number of output port

## 1.2 Problem statement

Optical switches are crucial components in optical networks. The ability to reconfigure optical switches with low power consumption has become a significant issue and is highly desirable. Furthermore switches with a small footprint are important for space, satellite and flight based applications. Therefore, the employment of Multimode Interference (MMI) thermo-optic switch in integrated optical circuit are required since they offer small size, robustness, good power balance, low polarization sensitivity, low insertion loss and ease of fabrication. In this project, the effect of single heater electrodes in terms of structure and placement will be analyzed to achieve low switching power consumption and crosstalk.

## 1.3 Objective of the project

This project aims to design a polymeric based thermal-optical switch using Multimode Interference (MMI) structure to achieve low switching power capability and reduce crosstalk figure. The optical switch will be designed on the 2x2 MMI cross coupler architecture of optical switch based on the general interference mechanism. The research objectives can be specified as follows:

1. To design a 2×2 MMI cross coupler as basic architecture of optical switch.
2. To implement a polymer based thermo-optic (TO) effect in designing MMI optical switch.
3. To investigate the effect of heater electrode in terms of structure and placement towards power consumption and crosstalk.

## 1.4 Scope of the project

In order to realize the research objectives which have been stated in previous sub section, the corresponding works to be carried out in this research have been identified as follows:

1. Design and optimization of MMI waveguide structure and dimension.
2. Design and optimization of heater electrode to the waveguide in terms of size and position to determine the optimum heater design for low switching power and crosstalk.

## 1.5 Project Methodology

This research begins with literature studies on MMI effect. The operation of optical MMI device is based on self-imaging effect principle. According to the self-imaging effect principle, an input field in a multimode waveguide is reproduced at periodic intervals along that waveguide. There are two types of interference mechanism, which are general interference and restricted interference. The restricted interference can be further divided into paired interference and symmetric interference. The optical switch in this project will be designed based on the general interference mechanism. Literature studies also included waveguide modeling techniques which are finite difference method (FDM), effective index method (EIM) and beam propagation method (BPM). These methods are adopted in solving the wave equation.

In order to develop MMI optical switch, a cross coupler has been adopted as the basic architecture of switch structure. The simulation work will be based on BeamProp™ platform for a single design with multiple width and length combination of cross coupler. Further refinement on the proposed MMI optical switch will be required in order to obtain a cross coupler structure with high extinction ratio, low insertion loss and polarization-insensitive.

The following phase of the project will be on the studies of thermo-optic (TO) effect. This phase is required to understand the relationship of the parameters that governing the functionality of the device. Thus, heat distribution in the optical waveguides can be obtained and eventually, better placement of heater electrodes can be designed in order to ensure excellent performance of the optical switch.

The crucial step in this project is to determine placement of the heater electrodes. It was found that optical switch with low power consumption can be achieved by considering the size, shape and number of the heating electrode, as well as the distance between heating electrode and core layer. In order to achieve the design objectives, which are low power consumption and wide attenuation range, further simulation will be based on BeamProp software from RSoft® due to its versatility. From the simulation result, analysis will be carried out to obtain low switching power capability and low crosstalk. The final stage of this project is thesis writing which include the findings, results and discussion. The methodology of this work is summarized in the following flow chart.

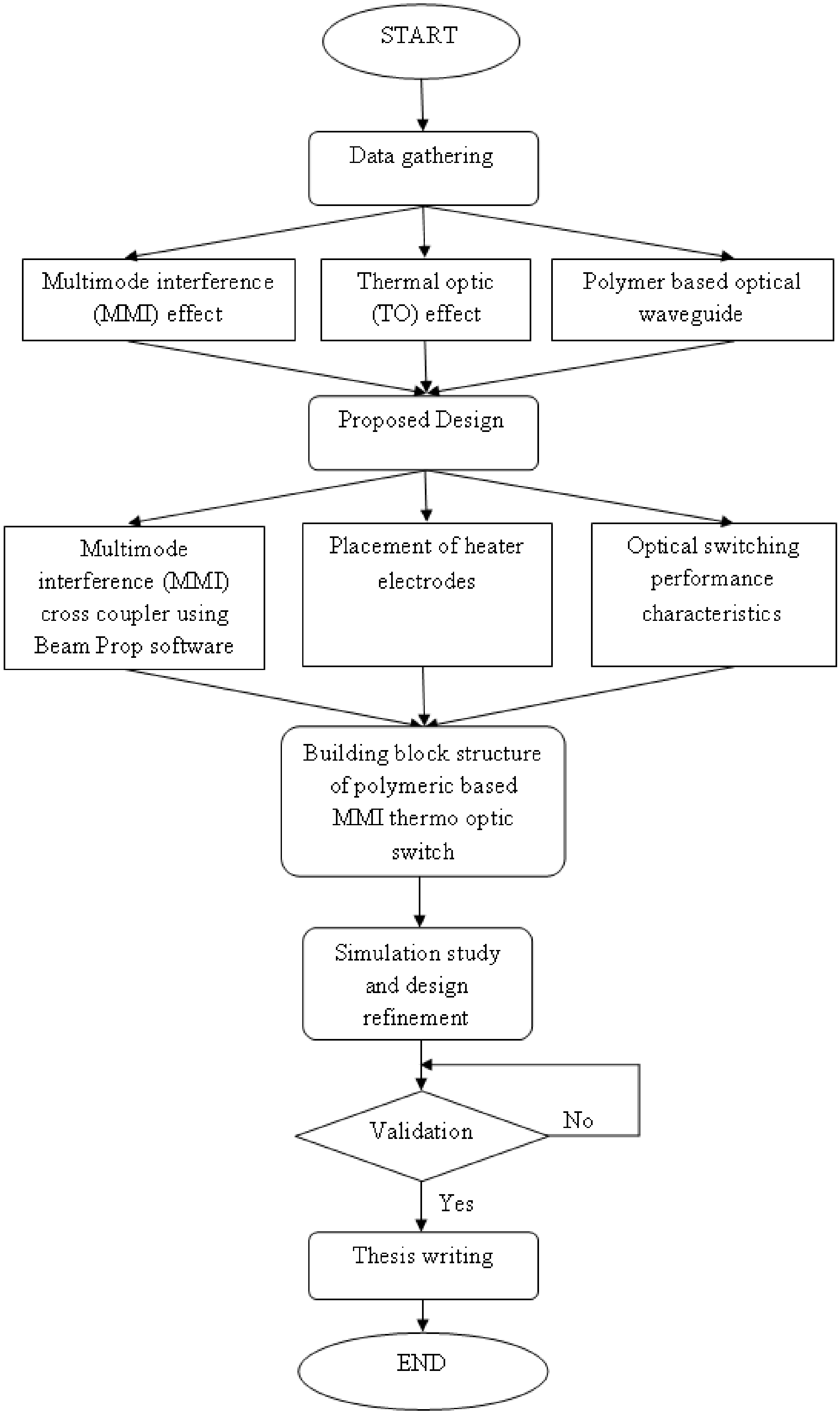



**Figure 1.1** Project methodology flow chart

## 1.6 Project outline

Chapter 1 presents an introduction of optical devices development in optical communication networking. The objective and the scope of this research study are presented as well.

Chapter 2 discusses the main principles of optical waveguide theory. The general wave equation which describes the propagation of light in the optical waveguide is derived using Maxwell's equation. The eigenvalue function for slab waveguide has been obtained using the ray-optics approach. The modeling techniques of channel waveguides have been discussed in detail, which include, the Effective Index Method, Finite Difference Method and Beam Propagation Method.

Chapter 3 explains the multimode interference (MMI) theory which is based on self-imaging principle. Classification on imaging mechanism into general interference and restricted interference has been explained in detail. The mathematical formulations that differentiate the properties of these interference mechanisms are briefly described. This chapter also covers the thermal analysis which is the fundamental aspect in designing the optimum heater structure. The temperature profiles of thermo-optic (TO) waveguides are analyzed by Finite Difference Method (FDM) and Finite Element Method (FEM).

Chapter 4 emphasizes on the simulation and optimization of the MMI TO switch. The optimization step starts from optimizing the MMI cross coupler. In order to design a TO switch and further analysis on heater's structure, the simulation was performed by employing BeamProp software from RSoft® due to its versatility.

Chapter 5 remarks the overall conclusions research contributions of this project and discuss possibilities for further development of this work.

# CHAPTER 2

# OPTICAL WAVEGUIDE THEORY

## 2.1 Introduction

This chapter presents the fundamental and the brief concepts of optical waveguide theory and techniques applied. The optical waveguide are defined using the electromagnetic theory of light from Maxwell's equation while the techniques that have been employed for optical waveguide modeling are based on Effective Index Method (EIM), Finite Different Method (FDM) and Beam Propagation Method (BPM).

## 2.2 Basic configuration of optical waveguide

Optical waveguide is a basic structure for confinement and transmission of light which light is guided into a specific direction.

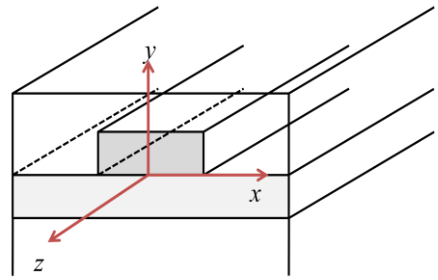



**Figure 2.1** Basic optical waveguide structures (Koshibu, 1992)

Figure 2.1 shows the basic structure of optical waveguide, where the thin film has higher refractive index than either substrate or the upper cladding. Basically, there are two basic configurations of optical waveguide which are planar slab optical waveguide and channel optical waveguide.

Planar slab optical waveguide or 2-dimensional (2D) optical waveguide has optical confinement in only one transverse direction of thickness (-*y* direction) in the thin film. On the other hand, channel optical waveguide or 3-dimensional (3D) optical waveguide allow the light propagate in both direction (–*x* and –*y* direction).

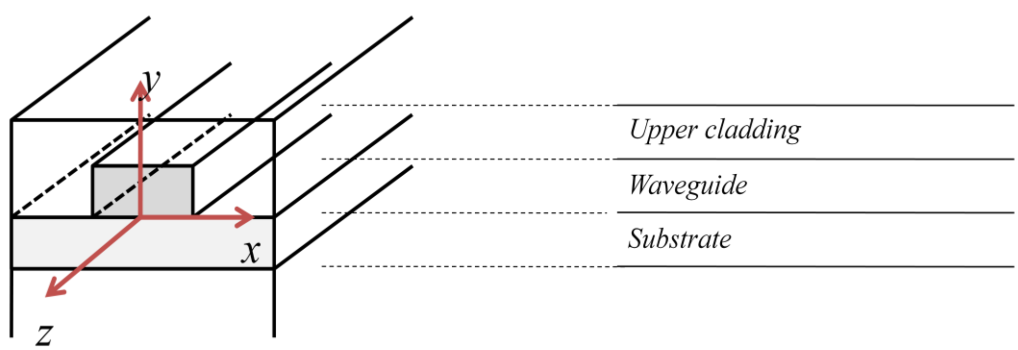



**Figure 2.2** Layers in planar slab optical waveguide (Koshibu, 1992)

Figure 2.2 shows the planar slab optical waveguide layer. The optical waveguide is called symmetric if the upper clad and substrate layer materials have the same refractive index. Otherwise the waveguide is called asymmetric optical waveguide. Further analysis on planar slab optical waveguide will be explained in Section 2.3.

Figure 2.3 below shows –*x* and –*y* view for the most common geometries for channel optical waveguide. Channel optical waveguide structures are usually analyzed with the approximate technique namely; *Effective Index Method (EIM)* which will be described further in Section 2.4.

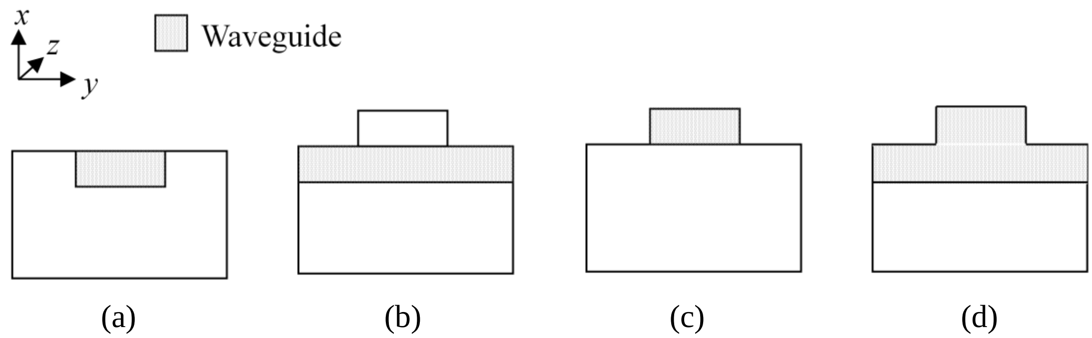



**Figure 2.3** –*x* and –*y* view for the most common geometries for channel waveguide (a) Buried channel waveguide (b) Strip-loaded waveguide (c) Ridge waveguide (d) Rib waveguide (Zappe, 1995).

## 2.3 Planar Slab Optical Waveguide

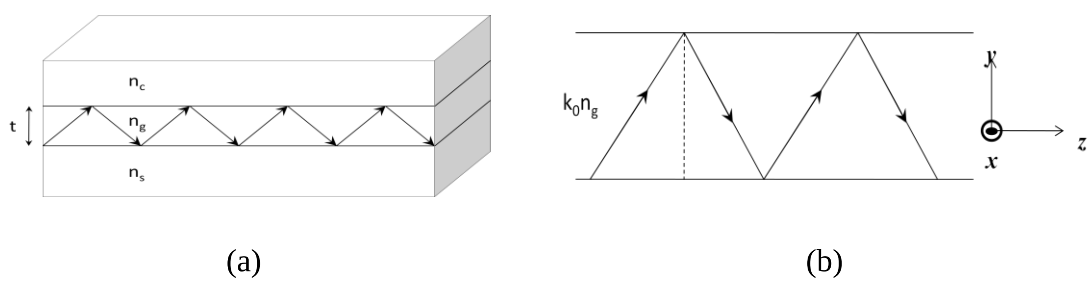



**Figure 2.4** Planar slab optical waveguide structure and guiding layer (a) Symmetric dielectric waveguide (b) Wave propagation in planar slab waveguide (Reed G. T. and Knight A. P., 2004)

Figure 2.4(a) shows the planar slab optical waveguide structure where the waveguide layer (or core layer) has a refractive index $n_g$, the lower cladding layer $n_s$ and the upper cladding layer is $n_c$.

In order to obtain the mode propagation, the total internal reflection (TIR) is required and for this it needs any angle greater than critical angle, $\theta_c$. For the two borders, $\theta_c$ are;

$$\theta_{c(substrate)} = sin^{-1}\left(\frac{n_s}{n_g}\right) \quad (2.1\text{ -a})$$

$$\theta_{c(upper)} = sin^{-1}\left(\frac{n_c}{n_g}\right) \quad (2.1\text{ -b})$$

Thus, the propagation can be described as the direction of wavenormal where the waves propagate along the *z*-direction with wavevector *k* where $k = k_0 n_1$ as illustrated in Figure 2.4 (b). The wavevector *k* can be divide in *y* direction and *z* direction component particularly which gives;

$$k_z = n_g k_0 \sin\theta_1 \quad (2.2\text{ -a})$$

$$k_y = n_g k_0 \cos\theta_1 \quad (2.2\text{ -b})$$

As can be seen above, the wavevector in *z* direction indicate the rate at which the wave propagates. The wavevector $k_z$ is frequently replaced by the variable $\beta$. By defining the effective refractive index of the mode is N, thus gives;

$$N = n_g sin\theta_1 \quad (2.3)$$

Therefore the equation (2.2-a) becomes;

$$k_z = \beta = Nk_0 \quad (2.4)$$

The guided modes that propagate along the z direction without ‘zig-zag’ back and forth with refractive index, N make the corresponding range of N is

$$n_c < \mathrm{N} < n_s \quad (2.5)$$

## 2.4 Channel Optical Waveguide

A channel waveguide or 3D confinement waveguide is the most practical structure for integrated optics. This type of structure allows the flexible routing of light around the waveguide surface (Zappe, 1995). Mathematical analysis has been performed in order to find the propagation constants and field profiles of all the modes in the waveguide. Nevertheless, it is complex matter to define the intended solution for channel waveguide compared with slab waveguide. Therefore, there are few methods that exist to simplify the calculations such as, Effective Index Method (Knox, 1970) and Method of Field Shadows (Zappe, 1995). The effective index method is simple and fast approach to determine the propagation constant and effective index channel (3D) waveguide (Zappe, 1995). The work conducted for this research, implement an effective index method.

## 2.5 Wave equation in optical waveguide

The optical waveguide are defined using wave equation which is origin from the Maxwell's equation. Maxwell's equations are set of four partial differential equations to show an electromagnetic wave. The following equations are simplified sets of Maxwell's equation (Sadiku, 2001);

$$\nabla \cdot D = \rho \tag{2.6-a}$$

$$\nabla \cdot B = 0 \tag{2.6-b}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.6-c}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2.6-d}$$

where,

| | | |
|---|---|---|
| $E$ | = | Electric field (V/m) |
| $H$ | = | Magnetic field (A/m) |
| $\rho$ | = | Charge density (C/m$^3$) |
| $J$ | = | Current density (A/cm$^2$) |

Assuming that dielectric slab waveguide is formed from materials which are linear, isotropic and source free; the current density, *J* and charge density, $\rho$ will equal to zero. In order to apply Maxwell's equation into wave equations analysis, it is necessary to specify the relations between *D*, *E*, *H* and *B*. The basic relation of electromagnetic theory for both electric and magnetic field states that;

$$B = \mu H \tag{2.7}$$

$$D = \varepsilon E \tag{2.8}$$

where **ε** and μ are the permittivity and permeatibility of the waveguide medium. Both define as;

$$\mu = \mu_R \mu_O \tag{2.9}$$

$$\varepsilon = \varepsilon_R \varepsilon_O \tag{2.10}$$

where,

| | | |
|---|---|---|
| $\mu_O$ | = | permeability of free space |
| $\mu_R$ | = | relative permeability of medium |
| $\varepsilon_O$ | = | permittivity of free space |
| $\varepsilon_R$ | = | relative permittivity of medium |

In order to derive the wave equation from Maxwell's equation, take the curl of equation (2.6-c) which then gives;

$$\nabla \times \nabla \times E = -\mu \frac{\partial}{\partial t}(\nabla \times H) \tag{2.11}$$

Equation (2.11) can be rewrite by plugging into equation (2.6-d) which will express the equation as follows;

$$\nabla \times \nabla \times E = -\mu \left[ \frac{\partial J}{\partial t} + \frac{\partial^2 D}{\partial t^2} \right] \tag{2.12}$$

By applying the vector identity,

$$\nabla \times \nabla \times E = \nabla(\nabla \cdot E) - \nabla^2 E \tag{2.13}$$

to the left hand-side of equation 2.12, where $\nabla \cdot E = 0$ , which gives;

$$\begin{aligned} \nabla^2 E &= \nabla \times \nabla \times E \\ &= \mu \left[ \frac{\partial J}{\partial t} + \frac{\partial^2 D}{\partial t^2} \right] \end{aligned} \tag{2.14}$$

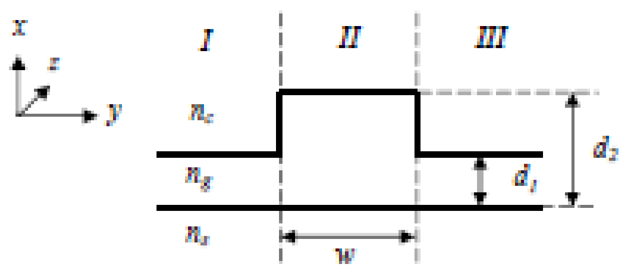
By assuming the moment of **J** = 0 and by substituting equation 2.8 into equation 2.14 yields the wave equation;

$$\nabla^2 E = \varepsilon\mu \frac{\partial^2 E}{\partial t^2} \tag{2.15}$$

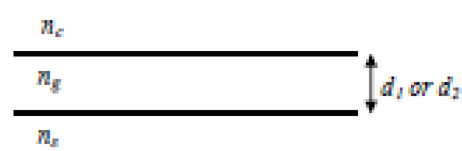
The derivation of wave equations is formulated by equation 2.15 which is required to be solved, subject to the requirements that fields decay away from the guiding region and satisfy appropriate boundary conditions at any discontinuity interface.

## 2.6 Effective Index Method (EIM)

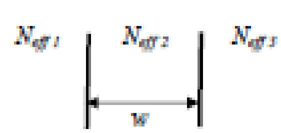
Consider the channel (3D) waveguide with the rib type as shown in Figure 2.3(d). In effective index method, 3D optical waveguide is divided into region I, II and III as shown in Figure 2.5(a). Each region is then considered as 2D slab waveguide homogeneous in the y direction as shown in Figure 2.5(b). The effective index is then obtained by solving the eigenvalue function in x direction to produce Neff 1, Neff 2 and Neff 3 for region I, II and III, respectively. Using the obtained effective index, the system can be further modeled as new 2D slab waveguide homogeneous in x direction as shown in Figure 2.5(c). By solving the eigenvalue function in y direction, the final effective index, N can be obtained. The propagation constant, β can be calculated by using equation (2.4).




(a) Rib waveguide structure




(b) 2D slab waveguide homogeneous in the y direction




(c) 2D slab waveguide homogeneous in the x direction

**Figure 2.5** Effective index method diagram (Reed G. T. and Knight A. P., 2004)

## 2.7 Finite Difference Method (FDM)

Waveguide modeling can be divided into analytical and numerical technique. One of numerical technique is finite difference method (FDM). This method is popular due to its simplicity in the discretization procedure and the relative ease of implementation into a computer code. In the finite difference method, the governing equations are approximated by a point-wise discretization scheme where derivatives are replaced by deference equations that involve the value of the solution at the nodal point (Majumdar, 2005). Finite different method illustration can be seen in Figure 1-A (Appendix A). Finite difference equation can be derived by using several approaches, which include Taylor series method or control volume method. The three point finite difference formula for the second derivatives can be state as follows:

$$\frac{d^2E}{dx^2} = \frac{E(i+1,\, j) - 2E(i,\, j) + E(i-1,\, j)}{\Delta x^2} \tag{2.16}$$

By adopting equation (2.16), the scalar wave equation (2.15) can now be written in basic discretized form as (Ibrahim, 2007)

$$E(i,\, j) = \frac{E(i+1,\, j) + E(i-1,\, j) - 1}{2\left(1 + \left(\frac{\Delta x^2}{\Delta y^2}\right)^2\right) - \Delta x^2\left(k_0 n^2(i,\, j) - \beta^2\right)} \tag{2.17}$$

where *i* and *j* represent the mesh point corresponding to *x* and *y* direction respectively.

If Equation (2.17) is multiplied with *E* and operating double integration towards *x* and *y*, the Rayleigh Quotient will be obtained (Ibrahim, 2007)

$$\beta^2 = \frac{\iint Ey\left(\left(\frac{d^2E_y}{dx^2} + \frac{d^2E_y}{dy^2}\right) + k_0 n^2 E_y\right)dxdy}{\iint E_y{}^2 dxdy} \tag{2.18}$$

Thus, the propagation constant of the mode and electric field distribution in the waveguide can then be solved using numerical method based on equation (2.18).

## 2.8 Beam Propagation Method (BPM)

The Beam Propagation Method (BPM) has been one of the most popular methods used in the modeling and simulation of electromagnetic wave propagation in dielectric waveguide. The advantages of BPM methods are (Baets *et al.*, 1990);

(a) Optical field can be propagated over a large distance (thousands of wavelengths) with negligibly small errors,

(b) The computer code is simple and can be adapted to more complex simulation problem

Then considering the 3-D scalar wave equation;

$$\frac{\delta^2 E}{\delta x^2} + \frac{\delta^2 E}{\delta y^2} + \frac{\delta^2 E}{\delta z^2} + k^2 n^2 (x,y,z)E = 0 \tag{2.19}$$

The TE field will then separated into two parts; the axially slowly varying envelope term of $\Phi(x,y,z)$ and another one is the rapidly varying term of exp(- $jk_{n0}z$). Thus $E(x,y,z)$ can be expressed by,

$$E(x,y,z) = \Phi(x,y,z)\ \exp(-\ jk_{n0}z) \tag{2.20}$$

By substituting equation (2.20) in equation (2.19) gives;

$$\nabla^2 \Phi - j2kn_0 \frac{\delta \Phi}{\delta z} + k^2(n^2 - {n_0}^2)\Phi = 0$$

where;

$$\nabla^2 = \frac{\delta^2}{\delta x^2} + \frac{\delta^2}{\delta y^2} \qquad (2.21)$$

Assume the weakly guiding condition, we can approximate *($n_2$ – $n_0^2$) ≈$2n_0$ (n - $n_0$)*, in equation 2.21, that would result the equation to be as follows;

$$\frac{\delta \Phi}{\delta z} = -j \frac{1}{2kn_0} \nabla^2 \Phi - jk(n - n_0)\Phi \qquad (2.22)$$

When $n=n_0$, the first term will remain in right hand side of the above equation. Therefore, it is known that the first term of equation 2.22 represents free space propagation in the medium have refractive index of $n_0$. While the second term of 2.22 represents the guiding function or influence of the region having refractive index *n (x,y,z).* Both side of equation 2.22 affect the light propagation simultaneously. In spite of this, for BPM analysis, the two terms are assumed can be separated and that each term affects the light propagation separately and alternately in the axially small distance in *z*-direction (Feit *et al*, 1978).

## 2.9 Previous works of MMI Thermo-optic switch

There is increasing work for optical switch design due to its demand for low power consumption and crosstalk figure. Xie *et al*. (2009) demonstrates a compact, very low power consumption, and low crosstalk of multimode interference 2x2 coupler-based polymer thermo-optic photonic switch.

The fabricated thin-film small-area heater confirmed the simulation results with operating power consumption as low as 8.9 mW. The switching crosstalk obtained was less than -23 dB.

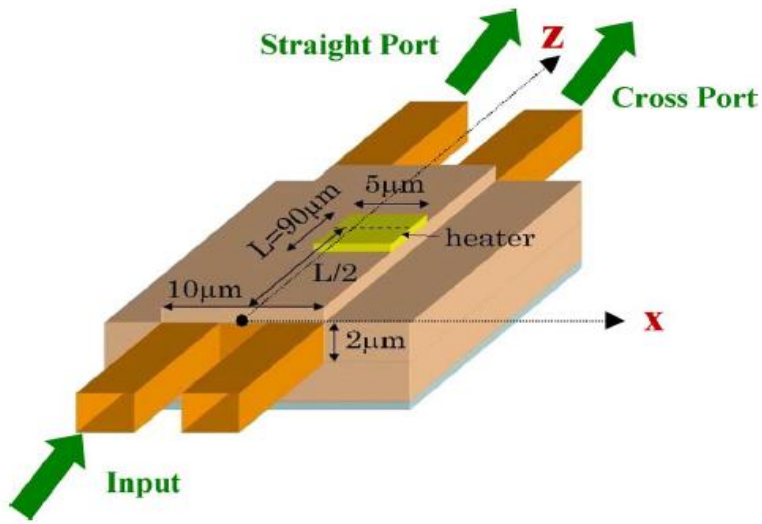



**Figure 2.6** Schematic of the MMI optical switch (Xie *et al.*, 2009)

The polymer switch consists of thin polymer core/cladding layers, commercially available standard SU-8 epoxy/polymethyl-glutarimide (PMGI), coated on top of Si substrate with a thin-film heater placed above the device. The polymer refractive indexes are 1.575 and 1.480, respectively, at a wavelength of 1550 nm. A schematic structure of the MMI polymer switch is illustrated in Figure 2.6.

An optical switch based on the multimode interference (MMI) coupler is also demonstrated by Wang *et al.* (2006). The device is designed and fabricated on polymeric materials. Thermo-optic (TO) effect of polymers with negative TO coefficient is employed to change the self-imaging effect of a side-heated MMI coupler and realize optical switching.

The polymeric materials used in the experiments are ZPU series from Zen Photonics, Inc. The refractive index of the polymers used for the core and cladding are 1.464 and 1.459, respectively. The size of the single-mode channel waveguide is $7x7\mu m^2$. The width and length of the MMI region are 48 μm and 3.6 mm, respectively. To realize the 250-μm separation at the input–output ends of the device chip, bends are designed in the input–output access sections, as shown in Figure 2.7.

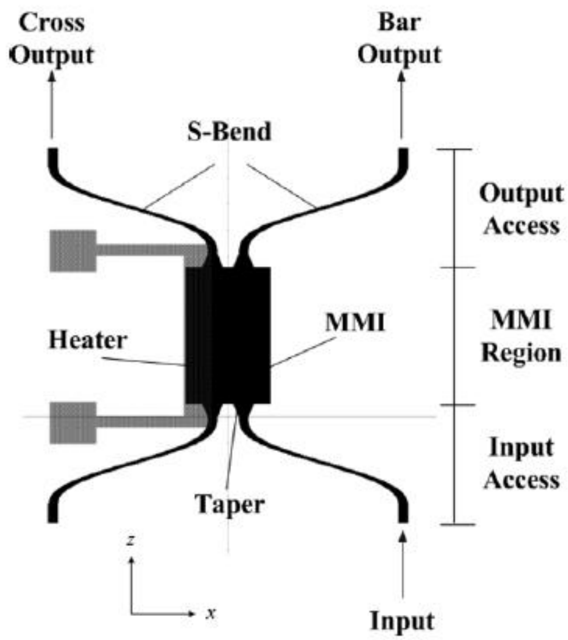



**Figure 2.7** Schematic diagram of the MMI based optical switch (Wang *et al.*, 2006)

A glass wafer is used as the substrate. After a 20-μm-thick polymer film is coated on the substrate as the lower cladding layer, a 7-μm-thick film is spun, patterned and then etched to form the core structure of the component, which is then coated by an upper cladding layer with a thickness of 15 μm. The switching power is about 22 mW and the measured crosstalk is about -20 dB.

The 2x2 MMI-MZI polymer thermo-optic switch in a high refractive index contrast (0.102) with a new structure design is realized by Al-hetar *et al*. (2011). A strongly guiding ridge waveguide with deep etching in the lower cladding has been used. In addition, ridge silicon is extended from the silicon substrate to the lower cladding and between heater electrodes. The main purpose behind this change in substrate layer is to localize the heating at a heated region and limit the heat diffusion elsewhere.

The experimental results show that the 2x2 MMI-MZI polymer thermo-optic switch has low switching power of less than 1.85 mW, a crosstalk at two states of less than -28.6 dB. The core and cladding are ZPU12-480 and LRF378 with their refractive indexes are 1.48 and 1.378, respectively at a wavelength of 1550 nm. Figure 2.8 shows the structural schematic of 2x2 MMI-MZI thermo-optic switch that has been proposed.

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