LOW POWER POLYMERIC THERMO-OPTIC DIGITAL OPTICAL SWITCH

IAN YULIANTI

UNIVERSITI TEKNOLOGI MALAYSIA

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To

My parents, my husband and my children

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ABSTRACT

Optical switches are essential components in optical network. In order to improve the performance of optical network, the optical switch must address requirements, such as low crosstalk, high extinction ratio, low insertion loss, low power consumption, very fast switching time and insensitive to wavelength and polarization. Digital optical switch (DOS) has become a very attractive component for space switching in multi-wavelength optical communication system application due to its sensitivity for drive power fluctuations, polarization, wavelength, temperature and device geometrical variations. This thesis explores the design of new DOS in order to improve its performance especially in terms of crosstalk and power consumption. Polymeric thermo-optic effect DOS has been developed due to its high thermo-optic coefficient which can support low power consumption devices. Buried square core waveguide is used in this research due to its low fiber to chip coupling loss. In order to ensure the waveguide operates as a single-mode waveguide in the optical communication transmission window, the optimization was done using alternating direction implicit method, finite difference method (FDM) and effective index method. The simulation and optimization of the Y-branch shape are done using finite difference beam propagation method whereas the heater design was optimized by employing FDM to solve the steady state heat transfer equation and scalar Helmholtz equation. The Y-branch shape is a hybrid of modified cosine S-bend branch and linear branch. Effective waveguide heating has been done by using a parabolic heater. With branching angle of 0.299^{o} and device length of only 5 mm, the simulation shows that the device could exhibit crosstalk of -33 dB at heating power of only 26 mW. In order to further reduce the crosstalk, a variable optical attenuator (VOA) has been designed to be connected to the DOS. The VOA is constructed from cosine S-bend which has low loss (< 0.2 dB) at off state, thus it is suitable to be used in optical switch. The VOA design uses the same material as that of the DOS which is the photo-active ultra violet curable fluorinated resins based on acrylate in order to ensure compatibility. The thermo-optic coefficient of the material is $-1.7 \times 10^{-4}/^{o}C$ and thermal conductivity is $0.17\ W/m^{o}C$. The optimized DOS without VOA was fabricated. The crosstalk of -26 dB is achieved at electrical power of 32 mW, and the insertion loss is less than -2.5 dB. In terms of wavelength dependency, the device shows a good performance inside the C-band with fluctuation of the insertion loss value around 0.5 dB.

ABSTRAK

Suis optik merupakan komponen penting di dalam rangkaian optik. Bagi memperbaiki perlaksanaan rangkaian optik, suis optik mestilah memenuhi beberapa keperluan seperti cakap silang yang rendah, nisbah pemupusan yang tinggi, kehilangan sisipan yang rendah, penggunaan kuasa yang rendah, masa pensuisan yang pantas dan tidak peka terhadap panjang gelombang dan pengutuban. Suis optik digital (DOS) telah menjadi komponen yang sangat diminati dalam pengaplikasian sistem perhubungan optik berbilang panjang gelombang bersesuaian dengan kepekaannya terhadap pengutuban, panjang gelombang, suhu dan perbezaan bentuk geometri peranti. Thesis ini mengkaji rekabentuk DOS yang baru bagi memperbaiki perlaksanaannya terutamanya dari segi cakap silang dan penggunaan kuasa. DOS yang berasaskan bahan polimer dengan kesan kawalan haba telah dibangunkan bersesuaian dengan pekali termalya yang tinggi yang dapat memberikan penggunaan kuasa peranti yang rendah. Pandu gelombang dengan struktur teras segi empat tertanam telah ditetapkan untuk digunakan dalam penyelidikan. Bagi memastikan pandu gelombang dapat beroperasi sebagai pandu gelombang mod tunggal dalam kerangka penghantaran perhubungan optik, pandu gelombang yang optimum diperolehi menggunakan kaedah arah tersirat silih ganti, kaedah perbezaan terhingga (FDM) dan kaedah indeks effektif. Simulasi dan pengoptimuman bentuk cabang-Y dilakukan dengan menggunakan kaedah perbezaan hingga-perambatan alur, manakala rekabentuk pemanas dioptimumkan menggunakan FDM untuk menyelesaikan persamaan pindah haba keadaan pegun dan persamaan skala Helmholzt. Bentuk cabang-Y adalah campuran yang terbentuk dari cabang lengkuk-S kosinus yang diubah suai dan cabang linear. Pemanasan pandu gelombang yang berkesan dilakukan dengan menggunakan pemanas parabolik. Dengan cabang yang bersudut 0.229^{o} dan panjang hanya 5mm, simulasi menunjukkan alat ini mempamerkan cakap silang sebanyak -33 dB pada keperluan kuasa yang dikira hanyalah sebanyak 26mW. Bagi mengurangkan cakap silang, pelemah optik boleh ubah (VOA) telah direka untuk disambungkan kepada DOS. VOA dibina dari lengkuk-S kosinus yang mempunyai kehilangan yang rendah (< 0.2dB) pada keadaan padam menyebabkan kesesuiannya untuk digunakan bersama suis optik. Rekabentuk VOA menggunakan bahan yang sama seperti DOS iaitu acrylate polimer untuk memastikan keserasiannya. Pekali terma bagi bahan ini adalah $-1.7\times10^{-4}/^{o}C$ dan keberaliran terma adalah $0.17\ W/m^{o}C$. Fabrikasi DOS tanpa VOA telah dilakukan. Cakap silang sebanyak -26 dB dicapai pada kuasa elektrik sebanyak 32 mW dan kehilangan masukan adalah kurang dari -2.5 dB. Dari sudut kebergantungan terhadap panjang gelombang, alat ini menunjukkan perlaksanaan yang baik dalam lengkuk-C dengan perubahan nilai bagi kehilangan kemasukan adalah sekitar 0.5 dB.

TABLE OF CONTENT

LIST OF TABLE

LIST OF FIGURE

LIST OF SYMBOLS

n	-	Refractive index
k_o	-	Free space wave number
ω	-	Angular frequency
ε	-	Dielectric permittivity
μ	-	Magnetic permeability of the material
β	-	Wave propagation constant in an infinite medium
N	-	Effective refractive index
$\mathbf{E}$	-	Electric field
$\mathbf{H}$	-	Magnetic field
γ_c	-	Decay constant in cladding layer and substrate
γ_s	-	Decay constant in substrate
V	-	Normalized frequency
b	-	Normalized propagation constant
h	-	Offset in the lateral direction of S-bend waveguide
$R(z)$	-	Curvature radius of S-bend waveguide
T	-	Temperature
σ	-	Material density
η	-	Coefficient of volume expansion of material
Λ_0	-	Strain polarizability constant
ψ	-	Local normal modes
ϕ	-	Transverse field dependence of the modes
K	-	Coupling coefficient
D	-	Waveguide separation (inner separation)
A_o	-	Amplitude of the first orde system mode
A_1	-	Amplitude of the second orde system mode
χ	-	Mode coupling between the normal modes
u	-	slowly varying electric field

$\bar{k}$	-	Reference wave number
$\bar{n}$	-	Reference refractive index
q	-	Heat flux
k	-	Thermal conductivity of material
q_c''	-	Convective rate equation
h_c	-	Convection heat transfer coefficient
T_s	-	Surface temperature
T_∞	-	Approach fluid temperature
c_p	-	Specific heat
Q	-	Heat generation rate per unit volume
Δn	-	Refractive index difference between branches
ΔN_{eff}	-	Effective refractive index difference
A	-	Amplitude of the cosine function
l_c	-	Length of modified cosine bend
l_{ln}	-	Length of linear branch
ρ	-	Material electric resistivity
P	-	Applied electric power
B	-	Heater width
L_h	-	Heater length
g	-	Waveguide gap
d	-	Center to center heater-waveguide distance
W	-	Heater width
t	-	Heater thickness

LIST OF ABBREVIATION

IP	-	Internet Protocol
WDM	-	Wavelength division multiplexing
OADM	-	Optical add-drop multiplexer
F-OADM	-	Fixed optical add-drop multiplexer
ROADM	-	Reconfigurable optical add-drop multiplexer
DOS	-	Digital optical switch
CT	-	Crosstalk
VOA	-	Variable optical attenuator
FD-BPM	-	Finite difference beam propagation methods
ADI	-	Alternating direction implicit
FDM	-	Finite difference method
SOR	-	Successive over relaxation method
EIM	-	Effective index method
WDL	-	Wavelength dependence loss
PDL	-	Polarization dependence loss
O-E-O	-	Optical-electrical-optical
OSW	-	Optical switches
MZI	-	Mach Zhender Interferrometric
PLC	-	Planar lightwave circuit
PDL	-	Polarization-dependent loss
MEMS	-	Microelectromechanical system
DC	-	Directional coupler
LC	-	Liquid crystals
TE	-	Transverse electric
TM	-	Transverse magnetic
IL	-	Insertion loss
E	-	Extinction ratio

BSC	-	Buried Square Core
TBC	-	Transparent boundary condition
PR	-	Photoresist

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1. Research Background

Optical communication systems have been deployed worldwide since 1980 and have indeed revolutionized the technology behind telecommunications. Optical communication systems use high carrier frequencies (~100 THz) in the visible or near-infrared region of the electromagnetic spectrum (Agrawal, 2002). These high carrier frequencies make the optical communication very attractive for high bandwidth service which is highly demanded in today communication systems.

The explosion in demand for network bandwidth is largely due to the growth in data traffic, specifically Internet Protocol (IP) and the growth in wireless communications. The carrier bandwidth could be increased by installing new fiber or increase the effective bandwidth of existing fiber. However, laying new fiber is costly. Increasing the effective capacity of existing fiber can be done by increasing the bit rate of existing systems or increasing the number of wavelengths on a fiber. Wavelength division multiplexing (WDM) technology which transmits multiple optical channels at different wavelengths over a single optical fiber offers an attractive solution to increase network bandwidth without disturbing the existing embedded fiber, which populates most buildings and campuses, and continue to be the cable of choice for the near future. With the use of WDM, the capacity of a single strand of fiber, 250 microns in diameter, can carry between 10 and 80 Gbps; a typical cable of 18 millimeters in diameter contains up to 200 fibers (Kiniry, 1998). For long-haul fiber links forming the backbone or the core of a telecommunication network, the role of WDM is simply to increase the total bit rate. Dense WDM (DWDM) technologies with a channel spacing of 12.5 GHz for terrestrial point-to-point WDM transmission application has been developed by Suzuki et.al (Suzuki *et al.*, 2006).

One of the critical components for WDM routing networks is an optical add drop multiplexer (OADM) to add and drop a subset of wavelengths from the transmission system without full opto-electronic regeneration (Lo *et al.*, 2004). An OADM connect the core network to a smaller subnetwork or to individual users which is typically arranged in a ring topology. The OADM facilitates format and data rate transparency and management of fiber capacity by enabling the selective removing and adding of individual channels at intermediate sites in the system. In terms of wavelength routing functions, the OADM could be fixed (F-OADM) or reconfigurable (ROADM). An 8-degree ROADM using the wavelength selective switches for channel adding and optical splitters for channel dropping with node scalability to 256 degree and crosstalk-induced power penalties below 0.5 dB has been recently reported (Shankar *et al.*,2007).

Various technologies could be used to build OADM, such as fiber Bragg gratings (FBGs) combined with optical circulators (OCs) (Jones *et al.*,1995; Lauder *et al.* , 1998; Eldada *et al.*,1999; Liaw *et al.*,1999; Song *et al.*,2001; Leisching *et al.*,2000), combination of an arrayed waveguide grating (AWG) and optical switches (Ishida *et al.*, 1994; Hattori *et al.*, 1999; Saida *et al.*, 2000; Eldada *et al.*, 2006), FBGs with couplers (Mechin *et al.*, 2001; Riziotis and Zervas, 2001; Augustsson, 2000; Park *et al.*, 2001), FBGs in a Mach–Zehnder interferometer (Hibino *et al.*, 1996; Kashyap et al., 1993; Kuo *et al.*, 2001) and FBGs combined with optical switches and optical circulators (Lo *et al.*2004). Among them, the OADM with optical switches incorporated in a pair of AWG's has the advantage of being able to change the switch state, add/drop or pass through, in service without affecting the other wavelength channels (Hattori *et al.*, 1999). Therefore, for example, the OADM based system offers a minimum-start in an initial installation and can be expanded by increasing the number of wavelengths as the amount of traffic increases.

The OADM-based system requires two functions for the optical switch in the OADM node (Hattori *et al*., 1999). One is high-isolation switching for the add/drop operation and the other is channel-by-channel level equalization. A high extinction ratio is essential for the switch in order to avoid the degradation of a bit error rate caused by a crosstalk. If the crosstalk in the switch cannot be ignored, the system scale, which is determined by the transmission characteristics of the WDM signals, might be limited severely. Beside high extinction ratio, the optical switches to be deployed in OADM should have low insertion loss, low power consumption and switching time in the order of millisecond and especially, they should be insensitive to wavelength and polarization, in other words they should be invisible to the network.

There are various optical switching technologies available today, such as Micro-electromechanical System Devices (Dobbelaere *et al*., 2002), Electro-optic Switches (Lee *et al*., 1997), Thermo-optic Switches (Interferometric switches and Digital optical switches) (Keil *et al*., 1996) and Liquid-Crystal Switches (Papadimitriou, 2003). Each technology has its own advantages and disadvantages and therefore research still continues. Waveguide based digital optical switch (DOS) which operating through modal evolution has become a very attractive component on optical communication system due to their digital response against applied power. The DOS is useful in the sense that additional applied power, beyond the switching power, does not degrade the crosstalk (CT). This characteristic enables the device to be insensitive to electrical power applied, polarization, wavelength, temperature and geometrical variations (Silberberg, 1987). Various DOS have been developed using silica on silicon (Hoffmann *et al*., 1998), silicon resin (Toyoda *et al*., 1999), polymers (Hauffe, 2001), $LiNbO_3$ (Krahenbuhl *et al*., 2002) and the most recently is amorphous silicon (Sirletto et al., 2006).

The DOS can be realized by using either electro-optic effect or thermo-optic effect. An electro-optic DOS based on $LiNbO_3$ has high performance such as able to change its state extremely rapidly (less than nanosecond) and reliable. Nevertheless, it has high insertion loss and possible polarization dependence. Polarization independence is possible but at the cost of a higher driving voltage, which in turn limits the switching speed. Meanwhile, thermo-optic switches are generally small in size and the optical parameters, such as crosstalk and insertion loss, are acceptable for many application. Polymer waveguide thermo-optic switches have been investigated from early time due to the potential of integrating multifunctional devices and cost effective mass production (Hida *et al*., 1993). Compared to the silica, though the absorption loss is higher, the polymer waveguide has strong competitiveness when optical signal controlling is needed (Noh *et al*., 2004a). Furthermore, due to the high thermo-optic coefficient and the low thermal conductivity of the polymer, it enables highly efficient thermo-optic index modulation and low operating power. Therefore, due to its attractive properties, polymeric thermo-optic DOS are chosen to be developed in this research so that it will exhibits low CT and low power consumption.

1.2. Problem Statement

The main advantages of DOS technology is that it provides high wavelength and polarization insensitivity which is crucial properties for optical switch to be adopted in optical network. However, DOS have the drawback of having high switching power. Moreover, the DOS performance is also limited by the crosstalk. Conventional DOSs generally have a relatively high crosstalk in the region of -20 dB. Considering that a crosstalk of approximately -25 dB in optical switch generally induces a 1 dB power penalty in all-optical communication networks, the crosstalk of a DOS should be, at minimum, lower than -30 dB (Yeo and Shin, 2006). To improve the CT, several methods have been proposed. W-DOS has been developed by Siebel *et al* (2000) but the CT achieved is still high (-30 dB), meanwhile Noh *et al.* (2004b) developed asymmetric DOS and achieved CT value less than -40 dB with very high power consumption (350 mW). Conventional DOSs also have a problem in terms of fabrication due to their very small branching angle of the Y-branch. Initially, this small branching angle is intended to minimize mode coupling between the local system modes; nevertheless it causes difficulty in fabrication process. Further more, this small branching angle leads to long interaction lengths (Hoekstra, 2000) thus it is not sufficient for large switching matrix which requires cascading many stages of switches. Various larger branching angle DOS have been proposed. Siebel *et al* (2001), Noh *et al.* (2006), Jiang *et al.* (2006) developed DOS with integrated attenuator to enhance the CT by attenuating the remained light on the switch-off branch. However, the devices mentioned above still consume high electrical power. Reducing the supplied power is important as it will result in a lowering power density in the heating elements which benefits the lifespan and the reliability of the heater and the switch itself. A low driver power is also very important for larger-scale switching matrix as it reduce the cost. Thus, a research needs to be carried out to improve the DOS performance.

1.3. Objective of Research

This research aims to develop 1×2 thermo-optic DOS with low CT and low power consumption to be used in optical network, but generally as a building block for larger switching matrix. The research objective can be further specified as:

- To design 1×2 DOS geometry which appropriate to be used in optical network.
- To gain an optimum heater electrode design and optimum heater electrode position for low power consumption.
- To design an optimum variable optical attenuator (VOA) to be implemented in DOS to reduce crosstalk.

1.4. Scope of Research

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

- Design and optimization of waveguide structure and dimension.
- Design and optimization of Y-junction geometry with compromise branching angle to make the fabrication less difficult while the switching functions still perform properly.
- Investigation of temperature profiles induced by heater electrode to the waveguide in order to determine the optimum heater design.
- Simulation and optimization of variable optical attenuator to be used in DOS.
- Fabrication and characterization of the optimized DOS.

1.5. Research Methodology

The research methodology was separated into eight main phases as shown in Figure 1.1. The first phase is literature review to understand the problem, research requirement, related current technology especially digital optical switch technology. Through the literature review, the related theory and published works were overviewed. The findings were used to define the objectives, scopes, and design requirements for solving the problem of optical switch. The second phase is to select the material and optimize the waveguide structure and dimension to be single mode in the transmission window for today optical communication system. The modal analysis was done using finite difference beam propagation methods (FD-BPM) utilizes alternating direction implicit (ADI) method and finite difference method (FDM) utilizes successive over relaxation (SOR) method. Semi-analytical method was also done as comparison using effective index method (EIM). The third phase is to simulate the structure of Y-junction using FD-BPM. The fourth phase is to simulate and design the heater electrode to find the best position, dimension and material to minimize the switching power using FDM which was accomplished by MATLAB. The next phase is to design VOA in order to decrease the crosstalk. The optimized design was then fabricated using coating, photolithography technique and dry etching. Optical parameters which include crosstalk, insertion loss and sensitivity to the input power of the fabricated devices were then measured to investigate the device characteristics. The fabrications of the devices were done by outsourcing.

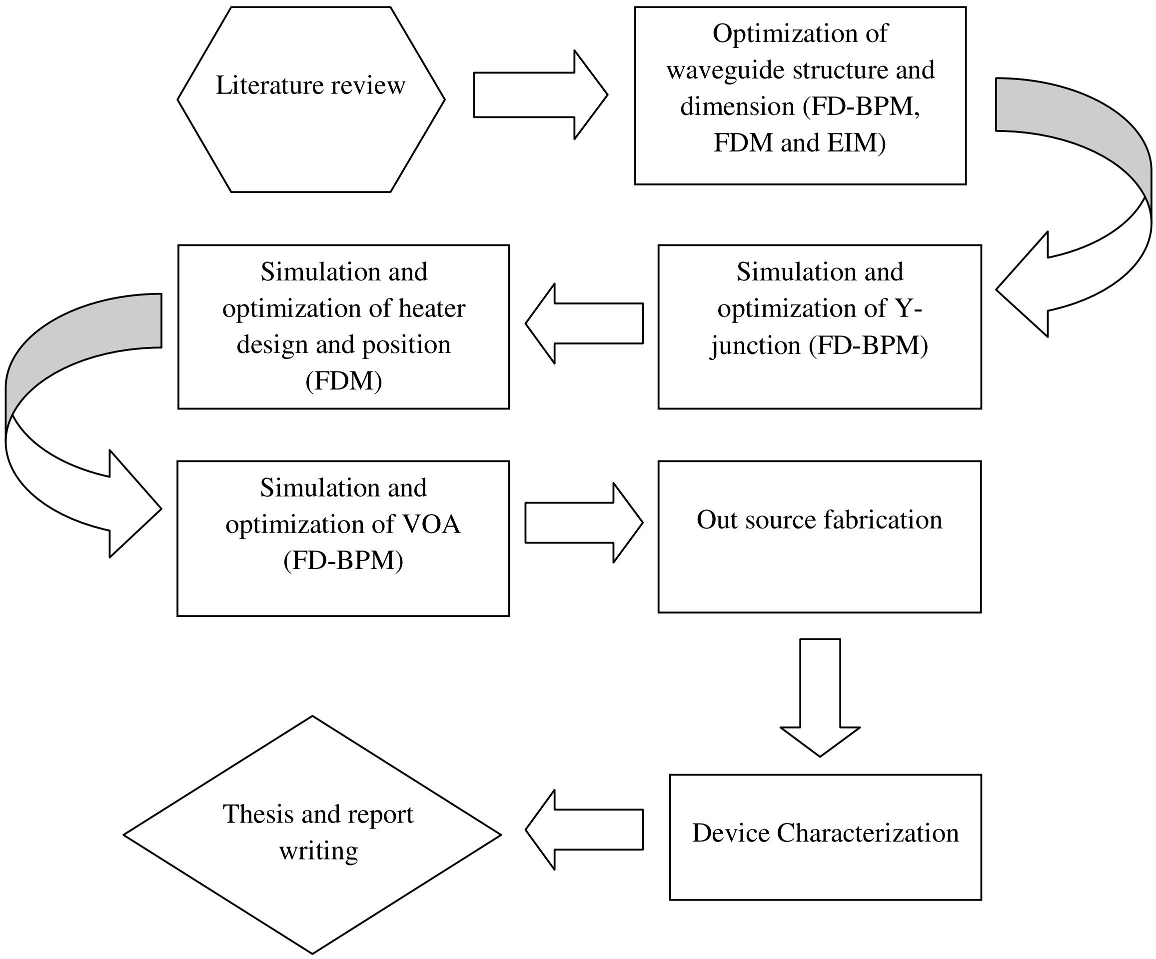

Figure 1.1 Flowchart of research methodology

1.6. Thesis Overview

As mentioned in Section 1.3, this work is devoted to the study and development of 1×2 thermo-optic DOS. The problem rose in this technology such as a limited crosstalk performance, high power consumption and a small branching angle which leads to the difficulty in fabrication process has been highlighted.

Discussion about optical switches technologies is presented in Chapter 2. First, the optical switch parameters are described. Then, optical switches as an important component in optical network, is discussed. The discussion is done by dividing optical switches technologies into two major categories, namely interferometric switches and non-interferometric switches. A review on published DOS is also presented.

In order to gain sufficient information to define the design requirements for solving the problem in DOS, fundamental theory of thermo-optic DOS is explained in Chapter 3. The discussion starts from the optical waveguide technologies available today and the light propagation in the waveguide. The modal analysis methods such as EIM and FDM are briefly discussed. The behavior of light propagation in Y-branch is discussed using coupled mode theory. An overview of beam propagation method (BPM) is discussed briefly as the design and optimization in this thesis is mainly accomplished by employing this method. At the end, thermal analysis which is the fundamental in designing the optimum heater structure is discussed.

Chapter 4 explains the simulation and optimization of the digital optical switch. The optimization step starts from optimizing the waveguide structure. The waveguide structure and dimension is optimized to be single mode in today optical communication window (1.3 μm to 1.55 μm). The optimization of a Y-branch constructed from the optimized waveguide was done by utilizing 3D BPM simulations accomplished by BPM-CAD software from OptiWave. A new method of heater design optimization was proposed. The optimization was then continued to the optimization of VOA by employing BPM.

Based on the optimized design resulted in Chapter 4, the 1×2 Y-branch waveguide and DOS without VOA was fabricated. The fabrication technique and characterization of the fabricated devices are explained in chapter 5. The fabrication technique includes coating, photolithography, dry etching and lift-off technique. The measurement was done for crosstalk values, insertion loss and device sensitivity to the input power.

Finally in Chapter 6, a concluding remarks and recommendations for future prospects for this work are given.

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