DESIGN AND FABRICATION OF A POLYMER BASED DIRECTIONAL COUPLER THERMOOPTIC SWITCH

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DEDICATIONS

Especially dedicated to my beloved parents, my wife, my children, my siblings and all my friends for their support, confidence and understanding with love and respect.

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PUBLICATIONS, AWARDS AND PATENT

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1. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Digital electrooptic modulators synthesized from directional couplers. *Proceedings 5th. IEEE Malaysia International Conference on Comm. and 2nd. East Asean Conference Lightwave System Lasers Optoelectronics (MICC 2001 & LISLO 2001)*. 376-379. Oct. 2001.

2. Mohd Supa'at, A. S., Mohammad, A. B., Mohd Kassim, N. and Omar, R. Analysis of mode fields in optical waveguides. *International Conference on Computers, Comms., Control and Power Engineering. IEEE TENCON '02*. Oct. 2002.

3. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Design of buried type polymer based waveguide optical directional coupler. *IEEE International Conference on Semiconductor Electronics. ICSE 2002 Proceeding*. 397-401. December 2002.

4. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Fabrication of Thermooptic Switch Using Polymers. *IEEE National Symposium on Microelectronics. NSM 2003*. 8-11. September 2003.

5. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Design of parallel waveguide using electrooptic effect in controlling the coupling of light. *Journal Institution of Engineers, Malaysia. Special Issue ELECTRICAL*. 63(1). 33-36. March 2002.

6. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Modelling techniques for rectangular dielectric waveguides-ribs waveguides. *Jurnal Teknologi. 36(D).* 29-143. Jun 2002.

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2. Special Jury's Award:- 2X2 Thermooptic Polymer based Optical Switch. Industrial Art and Technology Exhibition (INATEX). Universiti Teknologi Malaysia. Johor Bahru. 17-19 September. 2003.

3. Gold Medal:-Thermooptic Photonic Switch. 32nd. International Exhibition of Invention, New Techniques and Products of Geneva. 30 March – 4 April. 2004.

Patent:

1. Patent Pending:- Thermooptic Photonic Switch.

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1. A. S. M. Supa'at, A. B. Mohammad and N. M. Kassim. Thermal analysis: Induced temperature profiles of polymer waveguide. *Submitted for Journal Institute of Engineers Singapore. IES.*

2. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Polymer based directional coupler thermooptic optical switch. *Submitted for Jurnal Teknologi*.

3. A. S. M. Supa'at, A. B. Mohammad and N. M. Kassim. Low Cost Waveguide based Switch using all polymers with Low Power Consumption. *Submitted for Journal on Wireless and Optical Communications*.

4. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Low power consumption thermooptic switch using polymers. *Submitted for Journal of Industrial Technology, SIRIM*.

5. Abu Sahmah Mohd Supa'at, Abu Bakar Mohammad and Norazan Mohd Kassim. Design of polymer based directional coupler thermooptic optical switch. *Submitted for ICECE, 2004.*

6. Abu Bakar Mohammad, Abu Sahmah Mohd Supa'at and Norazan Mohd Kassim. Development of 2x2 asymmetrical thermooptic switch. *Submitted for ICECE, 2004* .

ABSTRACT

This thesis is concerned with the development of optical switches, which are essential components for wavelength division multiplexed optical networks. A waveguide type 2X2 thermooptic polymer optical switch based on generalized directional coupler interferometer operating at 1550 nm for singlemode operation has been designed and fabricated. Three research topics in the development of optical switches were unified through the use of polymer materials in photonic devices. The topics are; a unique formulation of two and three dimensional model of planar dielectric waveguide using MATLAB for accurate simulation of straight waveguides and waveguides bend. Secondly, a thermal analysis used for the calculation of the temperature profile and the resulting phase shift due to thin film heater electrodes in polymers using MATLAB for switching functions and finally, the design, fabrication and measurement of 2X2 thermooptic polymer based optical switch. Optical propagation in dielectric waveguides has been analyzed using the semi analytical effective index method and numerical method based on finite difference approach. The iterative solution and successive over relaxation method have been sought for better results of the criterion of sufficient accuracy and improvement of speed of convergence respectively. A description of thermal analysis used for the calculation of the temperature profile and the resulting phase shift in polymer optical waveguide has been investigated. The resulting phase shift due to the induced temperature as a function of the thin film electrodes heater configuration and the applied power have been determined for future device implementation between two adjacent polymer waveguides. The device uses symmetrical and asymmetrical modes interference couplers to perform necessary passive power splitting operations. Electrically controlled gold heater electrodes and chromium heater pads for adhesion were used to perform the switching operation by altering the refractive index of the coupler arms. The new asymmetric structure in terms of index contrast difference between the cladding and waveguiding layers of 2X2 polymer switch was fabricated using ultraviolet curable acrylate adhesive polymers on silicon substrate using photolithography process. A switching time of 7 ms and a crosstalk value of -30 dB were measured. The insertion loss measured was 2 dB. It also has the advantage of being a low cost optical switch with a very low power consumption of 12.26 mW.

ABSTRAK

Tesis ini adalah berkaitan dengan pembangunan suis optik, di mana ia merupakan komponen penting dalam rangkaian pemultipleks pembahagi panjang gelombang. Suis optik 2X2 jenis pandu gelombang berasaskan pengganding berarah interferometer am beroperasi dalam mod tunggal pada panjang gelombang 1550 nm telah direkabentuk dan dibikin menggunakan termooptik polimer. Tiga topik penyelidikan telah disepadukan melalui penggunaan bahan-bahan polimer dalam peranti-peranti fotonik. Topik tersebut adalah, satu perumusan unik bagi model dua dan tiga dimensi pandu gelombang satah menggunakan MATLAB untuk penyelakuan jitu pandu gelombang yang lurus dan bengkok. Keduanya, analisis terma digunakan bagi penghitungan susuk suhu dan keputusan anjakan fasa akibat dari pemanas elektrod filem nipis ke atas bahan polimer menggunakan MATLAB bagi tujuan fungsi pensuisan dan akhirnya, rekabentuk, pembikinan dan pengukuran suis optik 2X2 berasaskan termooptik polimer. Perambatan optik dalam pandu gelombang dielektrik telah dianalisa menggunakan kaedah indek berkesan separuh beranalisis dan kaedah berangka berasaskan pendekatan perbezaan terhingga. Penyelesaian berlelar dan kaedah santaian berturutan telah digunakan untuk mendapatkan keputusan yang lebih baik bagi kriteria kejituan dan kelajuan penumpuan penyelesaian tersebut. Perihalan analisis terma yang digunakan untuk penghitungan susuk suhu dan keputusan anjakan fasa dalam pandu gelombang polimer telah diselidiki. Keputusan anjakan fasa akibat suhu teraruh sebagai fungsi tatarajah elektrod pemanas filem nipis dan kuasa kenaan telah ditentukan bagi tujuan pelaksanaan di masa hadapan antara dua pandu gelombang polimer yang bersebelahan. Peranti ini menggunakan gangguan pengganding mod simetri dan tak simetri untuk melakukan operasi pemisahan kuasa secara pasif. Elektrod pemanas diperbuat dari emas dan pad diperbuat dari kromium bagi tujuan rekatan yang dikawal secara elektrik digunakan untuk melakukan operasi pensuisan dengan mengubah indek biasan lengan pengganding. Satu struktur tak simetri dengan perbezaan indek biasan di antara lapisan penyalutan dan pandu gelombang bagi suis optik 2X2 telah dibikin menggunakan acrylate polimer rekatan terawet ultraungu di atas substrat silicon menggunakan proses fotolitografi. Masa pensuisan 7 ms dan cakap silang -30 dB telah diukur. Kehilangan masukan yang telah diukur adalah 2 dB. Ia juga mempunyai kelebihan sebagai suis optik yang murah dengan penggunaan kuasa yang sangat rendah sebanyak 12.26 mW.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

SYMBOL		DESCRIPTION
β	-	Propagation constant
ε_r	-	Relative permittivity
ε_0	-	Free space permittivity
μ_0	-	Free space permeability
λ	-	Optical wavelength in free space
c	-	Speed of light in free space
k	-	Thermal conductivity
k_0	-	Free space wave number
k_T	-	Wave vector transverse component
$\Delta\beta$	-	Propagation constant difference
Δn	-	Refractive index difference
σ	-	Stefan Boltzmann constant (5.669×10^{-8} W/m^2K^4)
Q	-	Radiated power of the black body
Q_{gen}	-	Power generated per unit volume
T	-	Temperature
E	-	Electric field
H	-	Magnetic field
ε_e	-	Radiation coefficient emissivity of the surface
α	-	Thermal diffusivity
h	-	Convection heat transfer coefficient
κ	-	Coupling coefficient
L_c	-	Coupling length
$\partial n / \partial T$	-	Thermooptic coefficient

n	-	Refractive index
n_{TE}	-	TE mode refractive index
n_{TM}	-	TM mode refractive index
n_{eff}	-	Effective refractive index
O	-	S-bends offset
R_c	-	Curvature radius
η_i	-	Effective impedance of the *i-th* mode
$A_s(z)$	-	Amplitude of the symmetric mode
$A_a(z)$	-	Amplitude of the asymmetric mode
t	-	Thickness of the structure
t_{uc}	-	Upper cladding thickness
t_{lc}	-	Lower cladding thickness
w	-	Waveguide width
ω	-	Angular frequency
D	-	Electrode heater thickness
B	-	Electrode heater width
L	-	Electrode heater length
g	-	Waveguide spacing
P	-	Applied heating power
d	-	Center-to-center distance between electrode heater and the core
N_{sym}	-	Effective index of lowest order system mode referred as symmetric mode
N_{asym}	-	Effective index of lowest order system mode referred as asymmetric mode

LIST OF ABBREVIATIONS

AOS	-	Acoustooptic switch
ADM	-	Add-drop multiplexer
OOO	-	All optical cross connect
AC	-	Alternating current
ATM	-	Asynchronous transfer mode
BOE	-	Buffered oxide etchant
BSC	-	Buried square core
CCM	-	Chip-to-chip module
CTE	-	Coefficient of thermal expansion
DI	-	Deionized
DWDM	-	Dense wavelength division multiplexing
DUT	-	Device under test
DOS	-	Digital optical switch
DC	-	Directional coupler
DCTOPS	-	Directional coupler thermooptic polymer switch
EI	-	Effective index
EIM	-	Effective index method
EO	-	Electrooptic
FD	-	Finite difference
FDM	-	Finite difference method
FHD	-	Flame hydrolysis deposition
FVFD	-	Full vectorial finite difference
ICP	-	Inductively coupled plasma
IR	-	Infrared
IL	-	Insertion loss
IC	-	Integrated circuit
IP	-	Internet protocol
IDFT	-	Inverse discrete Fourier transform

ISFD	-	Iterative scalar finite difference
LD	-	Laser diode
LANs	-	Local area networks
MZ	-	Mach-Zehnder
MZI	-	Mach-Zehnder interferometer
MEMS	-	Micro-electro-mechanical system
MBOA	-	Modified bifurcation optically active
MCM	-	Multichip-to-multichip
OADM	-	Optical add-drop multiplexer
OXC	-	Optical cross connect
OE	-	Optical-to-electrical
OEO	-	Optical-to-electrical-to-optical
PR	-	Photoresist
PLC	-	Planar lightwave circuit
PDL	-	Polarization dependent loss
KLTN	-	Potassium lithium tantalite niobate
PL	-	Propagation loss
RIE	-	Reactive ion etching
SVFD	-	Semi vectorial finite difference
SOA	-	Semiconductor optical amplifier
TO	-	Thermooptic
TOC	-	Thermooptic coefficient
3D	-	Three-dimensional
TIR	-	Total internal reflection
TE	-	Transverse electric
TM	-	Transverse magnetic
TLS	-	Tunable laser source
2D	-	Two-dimensional
UV	-	Ultraviolet
VFE	-	Vector finite element
VCS	-	Vertical coupling switch
VLSI	-	Very large scale integrated
WDL	-	Wavelength dependent loss
WDM	-	Wavelength division multiplex

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

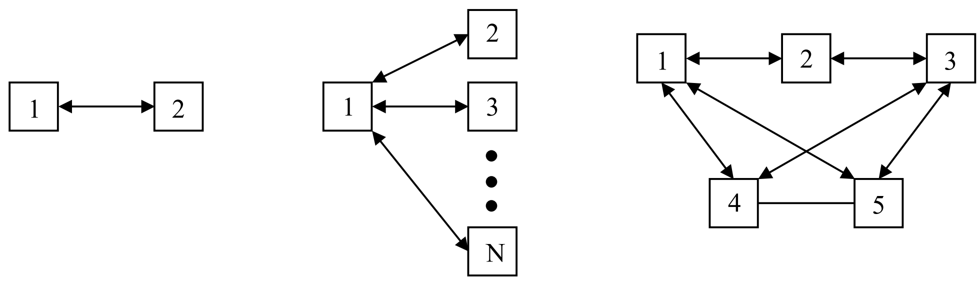
The world we live in today requires communication on many levels, the most basic of which is human to human. Indeed the invention of the telegraph and the telephone were the answers to this need that irrevocably changed our world and resulted in the creation of widespread telecommunication networks. A similar revolution has occurred in electronics computing devices that has resulted in the need for communication from computer to computer. An ever increasing demand for the acquisition, processing and sharing of information concerning the world and its future course, today, these needs are echoed in the demand for higher bandwidth in telecommunications networks and similarly in computing as a demand for higher processing speeds.

Computing devices for example, may experience a revolution in the near future as processing speed place higher demands on conventional electronics. Communication inside a computer on a board-to-board or perhaps chip-to-chip level may benefit from the implementation of optical interconnection because as frequency increase electrical interconnections experiences higher losses and crosstalk. Optical interconnection provides a means to achieve the same function while consuming less power, which alleviates some of the problems of heat dissipation in integrated circuits. In addition the higher integration densities can be achieved in optical interconnects because of the reduced electromagnetic coupling between adjacent channels compared to electrical connections.

Similarly, in telecommunication networks, the tremendous achievements in optical data transmission have resulted in a massive global deployment of optical fiber transmission lines, spanning a total distance that is be measured in the hundreds of millions of kilometers. Up until recently, the story of the progress made in point to point optical fiber transmission has sufficed to capture all the interesting developments in modern optical communications.

As optical comunication technology advances, electronic circuits increase in complexity and performance. This increase also requires an increase in the number of interconnection per chip and in the interconnection speed, otherwise the bottlenecks due to electrical connections created, will limit the overall system performance. The interconnections include: chip-to-chip module (CCM) on a common multichip module, multichip-to-multichip (MCM) module and board-to-board communication through a back plane. The increasing cost in terms of power, size, component count weight and reliability of implementing the required interconnects electrically has motivated serious consideration of replacing electrical interconnects with optical interconnects in optical communication network.

In the last decade, however an interesting evolution has been occurring in the world of optical communication. The major technology issues are now shifting from those of optical links to that actively control over signal paths through various information distribution topologies as depicted schematically in Figure 1.1. This interest has been triggered by the explosive growth in high data rate multimedia traffic over the past few years. Increasing user demands for high performance connections and expanding number of user have initiated the development of fiber to the home or fiber to the hub systems and local area or metropolitan area network systems.



(a) Link (b) Hub (c) Network

Figure 1.1: Basic information distribution topologies

The link topology in Figure 1.1(a) represents the simplest use of optical technology in a communication system. The nodes transmit and receive optical signal and perform all other functions electronically. In a hub design, information is distributed to multiple nodes from a single transmitter. Optical technologies are now being deployed to realize such hubs and a good example of this hub type passive optical network emerging for the distribution of cable television services. In this configuration, fiber is used as the transmission medium, however some optical function such as passive signal distribution and wavelength multiplexing are beginning to permeate into the nodes. Similarly in full network structure shown in Figure 1.1(c), optical technologies provides the links between the nodes, but within the nodes they are utilized for signal processing functions such as protection switching, add-drop multiplexer (ADM) and also provides some switching capability.

The hub and network topologies need not be mutually exclusive and can be combined and be referred to optical network. As optical networks develop, an increasing need for such vital functions as signal distribution, switching, protection and reconfiguration is evident, due to the volume and complexity of network traffic and the high cost of lost high throughput links. In the first generation of optical networks, these functions have been implemented electronically, with optical fiber simply replacing the old copper lines as transmission medium. It is rapidly becoming apparent, however, that the information throughput of the network is limited by bottlenecks at the network nodes where the electronic functions are performed.

The second generation of optical networks is currently under active development and aim to achieve optically transparent paths through a network by removing the electrical components and exploiting the unique properties of optics. This interest has been triggered by current evolving telecommunication networks focusing on network flexibility and transmission capacity, which requires enhanced functionality of photonics integrated circuits for optical communications. In addition, for example, modern wavelength division multiplex (WDM) system (Kaminow *et al.,* 1996; Koga *et al.,* 1996), requires signal routing, coupling and switching devices having large optical bandwidth and to be polarization insensitive.

According to these functionality of photonic integrated circuits for optical communications, optical switch, attenuator, optical modulator, multiplexers and wavelength filter are investigated actively (Kaminow *et al.,* 1996). In these devices, optical switch plays a role of basic device in high bit rate optical network by means of integration with ADM or optical cross connector (OXC) (Brackett, 1990; Borella *et al.,* 1997). Moreover it is used to implement redundant path protection to provide economical protection against fiber cuts and failures for asynchronous transfer mode (ATM), internet protocol (IP) and dense wavelength division multiplexing (DWDM) transmission systems. These are the basic premise of optical switching that by replacing existing electronic network switches with optical ones the need for optical to electronic to optical (OEO) conversion is removed. Clearly the advantages of being able to avoid the OEO conversion stages are significant.

1.2 Optical switching

Lightwave transmission via low-loss, low-dispersion single mode fiber has become the choice for high capacity point-to-point communication systems. From the viewpoint of transmission, fiber offers the potential of enormous information bandwidth. To preserve this advantage in future lightwave networks, it is important that the total information capacity of the network not be limited by the switch that provides connectivity. The current optical cross connect (OXC) uses an electrical core for switching, where the optical signals are first converted to electrical signals, which are then switched by electronic switch and finally converted back to optical signals or in other word, optical to electrical to optical switching (OEO) for further transmission. Therefore, electronic switching devices have limitations on both the data rate that they will handle and the switching reconfiguration rates achievable.

The main attraction of optical switching is that it enables routing of optical data signals without the need for conversion to electrical signals or sometimes referred to all optical cross connect (OOO). In contrast to OEO, when the data rate increases, an expensive transceivers and electronic switch core have to be replaced. The OOO is independent of data rate and ready for future data rate upgrades. Since, there is no need for expensive and power hungry high speed electronic switches, transmitters and receivers, the system becomes less expensive. In addition, the reduction of complexity improves reliability of the OOO crossconnect compared to OEO solutions.

The key component for OOO crossconnect is an optical switch. Optical switches are attractive components for routing of high bit rate optical signals in all optical networks, for circuit protection switching to by-pass a faulty system or cable and for the space stage of transparent OXCs. Switching of cable TV in local area networks (LANs), high bit rate data in optical backplanes of a computer and optical signals in sensors may be further applications in the telecommunications area. Optical switches suitable for the above mentioned application could be implemented at low cost by using polymer waveguide technology.

1.3 Motivation

There is an increasing need for optical switch matrices for routing, switching, protection switching, cross connection and add-drop multiplexing. The recent progress in WDM lightwave communication system will further increase the necessity of optical switch modules. Several optical switch architectures have been proposed and implemented in silica on silicon or glass substrates (Shibata, 2002; Syahriar *et al.,* 1998), Ti-$LiNbO_3$ (Lu *et al.,* 1994; Krahenbuhl *et al.,* 2002) and semiconductors (Hamamoto *et al.,* 1993; Kang *et al.,* 2000). The planar lightwave circuit (PLC) technology has been used to develop large scale matrix switches with good performance, however these switches are slow due to the intrinsic optical coupling efficiency resulting from a mismatch of the mode field between the PLC and the optical device (Nakagawa *et al.,* 1998). Ti-$LiNbO_3$, on the other hand is fast but they have large polarization dependence, and are impossible to monolithically integrate with active devices. As for semiconductor based switches, various types have been proposed. Semiconductor optical amplifier gate type switches (Hamamoto *et al.,* 1996) exhibit low insertion loss and quite high extinction ratios. However, they have the disadvantage of switching speed, which is limited by the carrier lifetimes. This will causes the pattern effect, which result in signal degeneration (D'Alessandro *et al.,* 2001).

On the other hand, polymeric optical devices have attracted large attention recently, because of low costs and high-speed possibilities as well as fabrication flexibility (Pun and Wong, 2002). High speed Mach-Zehnder (MZ) modulator (Wang *et al.,* 1999; Spickermann *et al.,* 1996) and polarization control devices (Lee and Shin, 1997a; Oh *et al.,* 1997a) have been demonstrated using polymers. Since the polymer can be dissolved, it can be cast into almost any shape. Polymers have an additional degree of freedom, the poling field defines the direction of the optic axis. Unique devices having twisted optic axes have been demonstrated by Oh and Shin (1996), a possibility of which did not exist before polymers. Furthermore the polymer devices can be fabricated directly on electronic substrates and assembled with integrated circuits (ICs) to create a hybrid optoelectronic package (Ermer *et al.,* 1992; Oh and Shin, 1996). The performance comparison of different technologies given by Lytel (1994) is shown in Table1.1.

Table 1.1: A comparison of polymers with other common inorganic materials for photonic devices (Lytel, 1994)

Figure of merit	**GaAs**	**Ti:LiNbO$_3$**	**Polymers**
Dielectric constant, ε	12	28	3.5
Refractive index, n	3.5	2.2	1.6
Loss (dB/cm @ $\lambda = 1.3\mu m$)	2	0.2	0.5
BW-length product (GHz-cm)	>100	10	>150

There are various factors to determine whether the material is suitable for making high speed devices. The most important of these factors are (i) speed match (ii) dielectric constant and (iii) index change per unit electric field. For high speed devices a good speed match between the traveling electric signal and optical signal is very important. The speed of the electric signal is $\frac{c}{\sqrt{\varepsilon_r}}$ and that of optical signal is $\frac{c}{n}$ where c is the speed of light in the free space and ε_r and n are the dielectric constant and the refractive index of the material, respectively. The closer the two speeds are the longer the interaction length and the more effective the modulation. Large bandwidth-length product is required for material to be used for fabricating high speed switches. Low dielectric constant is desirable for high speed devices because it reduces the response time of the device by reducing the capacitance of the electrode. As the polymer has higher thermooptic coefficient (TOC) of typical value in the order of -10^{-4} $^{o}C^{-1}$, compared with inorganic materials of typical value in the order of 10^{-5} $^{o}C^{-1}$, it also reduces the driving power required for the modulator or switch (Toyoda *et al.,* 2000) and suitable for larger switching matrices. Thin film of polymer devices can be easily fabricated on virtually any smooth substrates. Monolithic integration of polymer devices with very large scale integrated (VLSI) circuitry can be realized with less technical complexity. The virtually unlimited variations of molecular design make it possible to tailor the optical and other properties of polymers to meet specific requirements. Therefore, it is the goal of this work to continue to expand the knowledge and applicability of integrated optical devices by proposing a new optical switch configuration using all polymer materials.

1.4 Statement of the problem

Polymer integrated optical devices have great potential for applications in high speed optical interconnects due to their microelectronics processing compatibility, their multilevel high density feasibility and ultra high speed operation capability. However, the fabrication of polymer integrated optical devices is still done through trial and error due to inaccurate design schemes and insufficient characterization of materials and processing steps. Furthermore, the device components should meet practical requirements such as low optical losses, polarization insensitivity, low crosstalk, low power consumption, small size, cost effective manufacture and reproducibility, low insertion loss, wavelength dependence and reliability issues. These are the unsolved problems that motivated this research work.

1.5 Objective of the research

The problem being addressed by the present research work, is therefore the main nobjective of the research and is stated as follows:

To provide accurate model and design schemes for polymer based optical switch. The then polymer based optical switch will be fabricated and tested. The performance of the fabricated polymer based optical switch should give low switching power, low crosstalk, polarization independent and low insertion loss operated at the third telecommunication window with a central wavelength of 1550 nm.

1.6 Scope of the research

It is too vast for any single research work under a given time frame to cover all topics broadly related and yet separable to realize TO polymer based optical switch. As research is a continuing effort, the present research will focus specifically on the following:

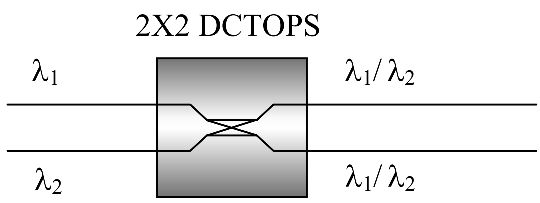
1. To choose the TO polymer materials for waveguides core, cladding and the substrate to fabricate an optical switch.
2. Modeling and simulation of low loss waveguides structure including straight, bend, parallel and the device configuration compatible with singlemode fiber core dimension for monomode operation at the third telecommunication window, with a central wavelength of 1550 nm.
3. Determination of the coupling length variations as a function of waveguide dimension, waveguide gap and effective index difference between the two identical and parallel waveguide branches.
4. Calculation of the optimum position of the heater electrodes due to the heater electrodes placed alongside the branch relative to the waveguides core to reduce switching power consumption.
5. Design of masks. Three different types of masks need to be designed, one for definition of waveguides, one for the heater electrodes and one for the heater pads.
6. Fabrication of TO optical switch with low switching power, low crosstalk, polarization independent and low insertion loss.
7. Measurement and characterization of the realized device.

1.7 Directional coupler thermooptic polymer switch

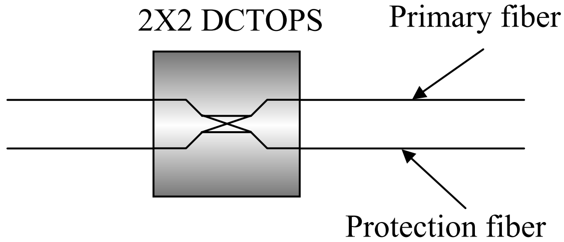
The focus of the work is the development of 2X2 directional coupler thermooptic polymer switch (DCTOPS), specifically using of all TO polymer material. The advantage of investigating a 2X2 DCTOPS is that it can perform a number of useful functions in thin film devices. These functions include power division, modulation, switching, routing and protection switching without the optical-electrical-optical (OEO) conversion. Additionally, the DCTOPS uses less switching power and small in size, which implies low propagation loss and insertion loss, which is suitable for large switching matrices devices for OXC applications. Furthermore, by using ultraviolet (UV) curable acrylate adhesive polymers instead of their inorganic counterparts such as $LiNbO_3$ to make these devices will have the following advantages:

1. Closer index of refraction match to the optical fibers and polymer waveguides.
2. Potential for working with wavelengths from visible to IR region.
3. Can be fabricated directly on electronic substrates and assembled with integrated circuits (ICs) to create a hybrid optoelectronics package.
4. Ease of fabrication using standard optoelectronics technology.
5. Feasibility of large scale integration.
6. Suitable for mass production.

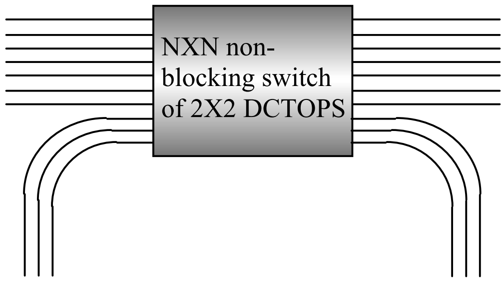
In this research, the feasibility of 2X2 DCTOPS has been investigated in detail and mathematical models were developed to predict its behavior. This has led to the development of efficient 2X2 DCTOPS with functions expected to find various uses in the emerging generation of optical networks. Three possible applications of these devices are shown in Figure 1.2.



(a)



(b)



(c)

Figure 1.2: Optical network applications of the devices investigated in this work, indicating (a) optical switching functions (b) optical protection switching and (c) optical add-drop multiplexing (OADM)

In Figure 1.2(a), the 2X2 DCTOPS is used to perform optical switching functions for two different wavelengths consecutively. In Figure 1.2(b), the 2X2 DCTOPS is used as a protection switch, when a primary optical link is severed. An OXC is NXN non-blocking optical switch composed of 2X2 DCTOPS as in general a building block, allows a traffic stream to be modified at a network node as depicted in Figure 1.2(c). The NXN switch is set in a state such that desired data streams are added and dropped at a given node.

1.8 Thesis outline

Much of this work is devoted to the study of the integrated optical 2X2 directional coupler thermooptic polymer switch (DCTOPS). As introduction in Chapter 1, the motivation and reasoning of polymer device research for integrated optical devices are discussed. The objective and the scope of the research study with possible applications of the research device are presented.

Chapter 2 extends the discussion and provides a more detailed reviews of optical switches, which have been developed and related published work by other researchers.

In Chapter 3, the theoretical foundations and mode analysis upon which the integrated optical components in this work are based is discussed. The basic relations and definitions concerned with mode propagation of straight and bend waveguides channel were emphasized. The intent is to produce a detailed mathematical description of optical waveguides as the key elements in the implementation of any waveguide based thermooptic (TO) switch. Next, the numerical simulation is presented. This will serve to provide a proper foundation of understanding of the concepts described in the subsequent chapters.

In Chapter 4, a thermal analysis of the design 2X2 DCTOPS due to the deposition of thin film heater electrodes on top of the device structure is discussed. First, the design consideration and characterization of the thin film heater electrodes is described. The temperature profiles of thermooptic (TO) polymer waveguides are analyzed by inverse discrete Fourier transform method (IDFT). The resulting phase shift due to the induced temperature as a function of the thin film heater electrodes configuration and the applied power have been studied and determined for 2X2 DCTOPS devices implementation.

In Chapter 5, the design considerations that have been made in realizing 2X2 DCTOPS using polymer materials are discussed. The design switch is based on the theory of optical waveguides as the key elements of 2X2 DCTOPS and the thermal analysis for heater electrodes and heater pads discussed in Chapter 3 and Chapter 4 respectively. Two devices switch structures have been designed and simulated, those are symmetrical and asymmetrical. All these consideration will lead to final design of the masks, which will be used for the fabrication of the devices.

In Chapter 6, the details of the cleanroom processing steps for realization of the devices are discussed. The realization of the devices can be divided into two parts: First is the fabrication of the devices in the cleanroom and second is the packaging of the devices. Both the fabrication and packaging have been done during a period as a visiting researcher in the fabrication and packaging laboratories respectively, at Zenphotonics Co. Ltd. of Korea.

In Chapter 7, the measurement results for each step taken during fabrication process in realization of the 2X2 DCTOPS are presented. The 2X2 DCTOPS, which have been realized, is then characterized.

Finally in Chapter 8, a concluding remarks and recommendations for future prospects for this work are given.

implemented to provide mode matching conditions to standard singlemode optical fiber, thereby allowing the integrated devices to be easily packaged.

Employing many of these suggested improvements may improve the switch performance characteristics to a level where the 2X2 DCTOPS presented in this thesis become practical for commercialization. The above description of areas for continuation of this work is not exhaustive, but is designed to convey a flavor of the many doors of investigation, which have been opened. Finally, in addition to the principal application of optical networking, it is hoped that the devices described will find a wider and more far reaching applicability, thereby furthering the dream of integrated optic and fueling the evolution of communication.

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