POLYMER BASED OPTICAL WAVEGUIDES

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Specially dedicated to
my beloved grandmother, parents, sister, brother and my dear

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ABSTRACT

Optical waveguides are structures that confine and direct optical signals in a region of higher effective index than its surrounding media. For integrated optics and photonic applications, it is often of importance to prepare waveguides in the form of thin film structures. Polymeric materials are particularly attractive in integrated optics because of their ability to be processed rapidly, cost-effectively, and with high yields. Polymeric materials are allowed to form compact optical circuits by offering large refractive index contrasts. A new polymeric material: CYCLOTENE™ PhotoBCB 4024-40 from DOW® Chemical had been adopted in this study for the development of optical waveguides. The behavior of light propagation and the confinement of light in a polymer based optical waveguide had been investigated. The characteristics of the waveguide had been simulated by finite difference method in MATLAB programming environment to obtain the optimum structure for waveguide fabrication. Planar slab waveguides and single mode straight waveguides have been fabricated using low cost photolithographic techniques and wet chemical etching processes. The properties of the polymer material and the fabricated waveguides have been characterized. The experimental results have demonstrated optical waveguiding in the polymer material. Attenuation of single mode optical waveguides at 633 nm and 1550nm with waveguide losses of 1.62 dB/cm and 3.6304 dB/cm have been obtained respectively. Even though the losses are rather high, the polymer material is still suitable as a waveguiding material in the optical interconnect situations by optimizing the fabrication process.

ABSTRAK

Pandu gelombang optik adalah struktur yang membatas dan memandu tenaga optik dalam satu kawasan yang mempunyai index pembiasan yang lebih tinggi daripada medium yang mengelilingnya. Dalam aplikasi litar bersepadu optik dan fotonik, penyediaan pandu gelombang berbentuk struktur filem nipis adalah penting. Bahan polimer merupakan satu bahan yang menarik dalam litar bersepadu optik kerana keupayaannya yang boleh diproses dengan cepat, murah dan produktif. Litar optik padat boleh dibentuk dengan bahan polimer kerana ia menawarkan kontrast index pembiasan yang besar. Satu bahan polimer yang baru dari DOW® Chemical: CYCLOTENE™ PhotoBCB 4024-40 telah dikaji bagi pembinaan pandu gelombang optik. Sifat perambatan cahaya dan pembatasan tenaga optik dalam pandu gelombang polimer telah diselidik. Simulasi telah dilakukan dalam perkakasan MATLAB untuk mengetahui dan mengaji sifat pandu gelombang serta mendapatkan satu struktur yang optimum bagi fabrikasi pandu gelombang. Pandu gelombang planar dan pandu gelombang monomod lurus telah dibina dengan proses fotolitografi yang murah dan teknik hakisan kimia basah. Sifat bahan polimer dan pandu gelombang yang dibina telah dikaji serta parameter optik telah diukur. Keputusan yang diperolehi menunjukkan sifat perambatan optik dalam bahan polimer ini. Pelemahan kuasa sebanyak 1.62 dB/cm pada panjang gelombang 633 nm dan 3.6304 dB/cm pada panjang gelombang 1550 nm telah didapati dalam pandu gelombang monomod lurus. Walaupun pelemahan kuasa tersebut agak tinggi, bahan polimer ini adalah sesuai sebagai bahan perambatan optik dalam rangkaian optik dengan memperbaiki proses fabrikasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\mathrm{d}n/\mathrm{dT}$ - Thermo-optic coefficient
n - Refractive index
T - Thickness
$\mathbf{E}$ - Time dependent electric field
$\mathbf{H}$ - Time dependent magnetic field
$\mathbf{D}$ - Electric displacement
$\mathbf{B}$ - Magnetic induction
$\mathbf{J}$ - Current density
ρ - Charge density
TE - Transverse electric modes
TM - Transverse magnetic modes
k_0 - Vacuum wave vector
c - Speed of light
λ - Wavelength of the light source
β - Propagation constant along the z direction
θ - Angle
t_{co} - Cut-off thickness
m - Modes
Δx - Rectangular mesh size at the x direction
Δy - Rectangular mesh size at the y direction
b - Normalized propagation constant
L - Length
ε - Dielectric constant
μ - Permeability

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Optoelectronic technology and optical networking will become the key enablers of the future communications infrastructure through the elimination of the severe restrictions of bandwidth and bit-error rate inherent in traditional electromagnetic signal-based communications. Electromagnetic signals carried over copper (or coaxial) wires suffer attenuation (loss of strength) and are subject to errors due to noise and hence such systems have limited data rates (the upper bound given by Shannon's theorem). When copper or coax is replaced by fiber technology, the achievable bandwidth is in excess of 50 Terabps with an almost zero bit-error rate. The birth of optical communications occurred in the 1970's with two key technology breakthroughs [1]. The modern era of optical communication may be said to have originated with the invention of the laser in 1958, and early developments soon followed the realization of the first laser in 1960. The second breakthrough happened in September 1970, when a glass fiber with an attenuation of less than 20dB/km was succeeded developed by Corning in the USA. With the development of optical fibers with an attenuation of 20dB/km, the threshold to make fiber optics a viable technology for telecommunications was crossed. The first field deployments of fiber communication systems used Multimode Fibers (MMFs) with lasers operating in the 850 nm wavelength band. These systems could transmit several kilometers with optical losses in the range of 2 to 3 dB/km. A second generation of lasers operating at 1310 nm enabled transmission in the "second window" of the optical fiber where the optical loss is about 0.5dB/km in a Single-Mode-Fiber (SMF).

In the 1980's, the British Telecom carriers started replacing all their MMFs operating at 850 nm. Another wavelength window around 1550 nm was developed where a standard SMF has its minimum optical loss of about 0.22dB/km [2].

The development of fiber based telecommunication systems in the 1990's focused on increasing their transmission capacity. This was done first by increasing the signal modulation speed from 155 Mbps to 622 Mbps, to 2.5 Gbps, and finally to 10 Gbps. The total available bandwidth of standard optical fibers is enormous; it is about 20 THz. Optical networks have recently moved from being a research curiosity to becoming a billion-dollar business [3]. A few important applications that will be enabled by high speed optical networks are internet and web browsing, graphic visualization, medical image access and distribution, multimedia conferencing, and broadband services to the home (Fiber to the home, FTTH). Optical networks will change the paradigms possible for tomorrow's information systems designers by increasing the viability of network-reliant applications. For business organizations, the availability of high capacity, low-cost networking promises to address today's business needs as well as effectively eliminate geographic boundaries for the business systems of the future. The increased demand for bandwidth by business needing support for digital commerce, remote workers, and client intranet applications is straining current network capacities and IT budgets. By providing unprecedented low cost telecommunications capacity, all-optical networks have the potential to address these critical business issues.

The demand in optical networking for photonic components that meet performance criteria as well as economic requirements has opened the door for novel technologies capable for high yield low cost manufacturing while delivering high performance and enabling unique functions. The most promising new technologies are integrated optics. Integrated optics made its appearance in the late 1960s [4]. It was an exciting technology because it offered the promise of compact, environmentally stable micro-optical systems that would replace bulk optical systems. The planar geometry of integrated optical devices and interconnects made them attractive candidates for hybrid or monolithic integration with electronic systems. Integration permits the parallel production of complex multi-function photonic circuits on a planar substrate. Photonic integrated circuits (PICs) are the monolithic integration of two or more integrated optical circuits (IOCs) on a single substrate. They are the photonic equivalent of microelectronic chips. The market for these devices has reached a critical commercial threshold. According to a study from Business Communication Company, Inc. [5], the market for photonic integrated circuit subsystems and components is currently estimated at $4.3 billion. It is expected to grow at an average annual rate of 20.5% to reach almost $11 billion by 2006.

Planar lightwave circuits (PLCs) based on layers of glass, polymers, or other materials deposited on a planar substrate are a low-cost manufacturing and high integration density by using well-established fabrication technologies from the silicon industry. Wafer-scale processing enables automation, integration of multiple functions, and customization to individual requirements. In PLCs, optical waveguides, the fundamental components act as the photonic analog of copper circuits serving as interconnects among various discrete components on a chip. Optical waveguides are structures that confine and direct optical signals in a region of higher effective index than its surrounding media. Optical energy is confined in the substrate and superstrate has the highest index of refraction, thus providing the guiding region. The index profile is primarily the result of the waveguide fabrication process. Starting with simple waveguide structures, very complex optical circuits can be fabricated. Waveguides devices in photonic integrated circuits contain different shapes and sections with various functions. They can be classified into 2 categories: passive devices, which exhibit static characteristics for optical waves, and functional devices for optical wave control. Many optical functions have been demonstrated in PLC form such as splitting and combining of light, switching of channels in the space domain, multiplexing and demultiplexing of channels in the wavelength domain, and filtering. They are very important building blocks toward the construction of all-optical networks. The advantage of these fully transparent optical networks is that the signals stay in the optical domain without the need to convert them from the optical to the electrical domain and back to perform switching operations electrically [6].

With the proper design, PLC can replace the current bulk-optics hermetical packages, save costly alignment hours, simplify production processes, utilize wafer level semiconductors production techniques, miniaturize dimensions and improve performance. Throughout the latest decade, a number of PLC technologies have been explored. The common to PLC technologies lay at the design of accurate mask and using photolithographic techniques in a clean room. Once the proper mask for lithography is designed, the production can be done in wafer-scale methodologies, rather than costly chip-level production.

Today there are several technologies in different stages of development, ranging from research prototypes to field-proven devices. Amongst PLC technologies are [7] III-V semiconductors (InP, GaAs), silica-on-silicon, SiON (Silicon oxynitride)-on-silicon, silicon on insulator, polymeric waveguides, lithium niobate ($LiNbO_3$) and ion-exchange. Each of these material systems has advantages and disadvantages [8]. Lithium niobate modulators capable of 2.5 and 10Gbit/sec data rates have been commercialized and are deployed in the backbones of optical transmission networks worldwide. But lithium niobate is difficult to process and therefore costly. Furthermore, its crystalline structure prohibits monolithic integration of laser sources and detectors. The mismatch between the velocity of the light traveling in the lithium niobate waveguide and the microwave used to modulate the device limits the upper modulation frequency to about 40 GHz. Moreover, as a crystalline material, lithium niobate shows high birefringence that leads to high polarization-dependent losses. Another drawback is that lithium niobate has a considerable refractive-index mismatch with silica fiber, which leads to high coupling losses of about 1.5dB per fiber attachment point.

The silica on silicon system has the advantage that its index of refraction is perfectly matched to silica fiber. But the only active devices demonstrated to date are thermo-optic switches with modulation frequencies that are inherently limited to the millisecond range [9]. The silicon system also has the advantage of using the manufacturing process that has been optimized in the semiconductor industry. On the other hand, because of its high absorption in the 830 nm window, silicon is limited to applications in the 1310 and 1550 nm transmission windows.

Polymer optical devices have attracted a lot of attention with regard to applications in the all-optical network, basically, because they have the potential of added optical functionality and because they may be producible at low cost [10-13]. An important property of polymers is that they have a large negative thermo-optic coefficient ($dn/dT = -1\times10^{-4} \sim -4\times10^{-4}$) that is ten to forty times larger (in absolute value) than that of others conventional optical materials, resulting in low power consumption thermally-actuated optical elements. Polymers offer a wide range of refractive indexes closely matched to that of silica fiber, and therefore it is possible to optimize the material sets for different applications in all three transmission windows of silica fiber. Others advantages and the properties of polymer will be discussed in Chapter 3. Optical polymers were engineered in many laboratories worldwide and some are available commercially. Classes of polymers used in integrated optics include acrylates, polyimides, polycarbonates and olefin (e.g., cyclobutene). Several researchers had fabricated optical devices based on polymeric materials and proved its feasibility [14-23]. In this work, polymer olefin, the B-staged bisbenzocyclobutene (BCB) was adopted as the raw material of the research.

With the rapid of the advance of integrated optics, the importance of optical waveguides, which are the fundamental elements of optical integrated circuits, has been widely recognized. Polymeric materials are particularly attractive in integrated optics because of their ability to be processed rapidly, cost-effectively, and with high yields. From this research, the knowledge and hand-on skill gained is needed for future development of polymer based active optical device.

1.2 Problem Statements

The importance of the optical waveguides as the fundamental components in the optical telecommunication networks, optical interconnections and devices has motivated us to carry out this research. For understanding the concept of the optical waveguides, a suitable mathematical model and simulation program for waveguide analysis will be studied. As previously reported in the section 1.1, the polymer based optical waveguides are attractive as a newly material in the advance development in the integrated optics. The chosen of a polymer which conforms to the equipments available for in-house fabrication is needed. Through the practical hands-on work, the waveguide fabrication processes should be managed and controlled. The polymer material should be characterized to verify its usage in the optical waveguides fabrication.

1.3 Research Objectives

In this research, the work was concentrated on the modeling, fabrication and characterization of polymer based optical waveguides. The first objective of the project is to investigate the behavior of light propagation in a polymer based optical waveguide. Through simulations the characteristics of optical waveguides could be understood. After the simulations, passive optical waveguides will be fabricated and the polymer based optical waveguides will be characterized.

1.4 Project Scope

It is too vast for any single research work under a given time frame to cover all the topics broadly related. As research is a continuing effort, the present research was focused on the scope as determined.

The literature review was done for understanding the research requirement, and finding out the related technology and tools. Through this, the related theory and technology were overviewed. The concept and analysis method of optical waveguide were studied. A mathematical approach was applied in order to model the waveguide structure and its ability to confine the light. Through this, the behavior of light propagation in a polymer based optical waveguide could be investigated and the characteristics of the optical waveguide could be simulated in order to obtain an optimum design.

In the first stage of the development of optical waveguide, a suitable polymeric material which conforms to the equipments available were studied and chosen for in-house waveguide fabrication. The waveguide fabrication process of the polymeric material was studied. Equipment for the fabrication processes has been set up for in-house fabrication. Several parameters need to be controlled during the fabrication processes. For example, thickness of the coated film could be controlled by varying the spin coating speed. The refractive index of the material is the most important parameter in the waveguiding material, which is controlled in the curing process. The conditions of the photolithography and etching processes were studied in order to obtain a better resolution of the waveguide. Passive optical waveguides were fabricated and characterized. Geometrical inspections, measurement of refractive index, waveguide excitation and loss measurement were done. The polymeric material has demonstrated the waveguiding properties through the performance analysis of the waveguides been carried out.

1.5 Thesis Outline

As an introduction (Chapter 1), the motivations of this research on the polymer based optical waveguides were discussed. The overview and goals for the research were presented.

Chapter 2 explains the basic concept and theory of optical waveguide and the analysis methods. Several parameters in waveguiding materials were discussed. A simple modeling technique for optical waveguide was developed.

In Chapter 3, several materials which are under intensive investigations as integrated optics and waveguide materials were discussed. This chapter extends the discussion in the research material, polymer, by providing a more detailed literature review and related works published by other researchers. The properties of the polymer material, Cyclotene™ PhotoBCB 4024-40 which is the research material in this work were presented.

The fabrication procedures of polymeric optical waveguide are described in Chapter 4. The conditions required for the fabrication processes were discussed. Problems and precautions needed to be taken during the fabrication process were presented.

Simulation and fabrication steps can only be validated when experimental results match with those of the simulations. Thin film optical characterization is needed in order to determine the suitability of the material as an optical waveguide material. In Chapter 5, several optical waveguide characterization methods and important parameters of optical waveguide are discussed.

Results of the research are shown in Chapter 6. Data verifications were done in the sense of comparing our modeling and simulation result with model developed by other researchers. Measurement results of fabricated waveguides are shown in this chapter.

Finally in Chapter 7, a concluding remarks and suggestions for future work are given. Modeling technique and fabrication skill obtained through this research could be applied for the future development of active optical devices.

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