
The objective of this research is to investigate the use of laser direct writing to micro-pattern low loss passive optical channel waveguide devices using a new hybrid organic/inorganic polymer. Review of literature shows previous methods of optical waveguide device patterning as well as application of other non-polymer materials. System setup and design of the waveguide components are discussed. Results show that laser direct writing of the hybrid polymer produce single mode interconnects with a loss of less 1dB/cm.
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LIST OF SYMBOLS

Å          Angstroms
AgNO₃      Silver nitrite
Ar         Argon
β          Propagation constant
BPM        Beam propagation method
CAD        Computer aided design
cm         Centimeter
Cu         Copper
dB         Decibels
E_D        Energy density
EMI        Electromagnetic interference
f          Focal distance
HeNe       Helium neon laser
KNO₃       Potassium nitrate
λ          Wavelength
LiO₂       Lithium dioxide
LiNbO₃     Lithium niobate
LiTaO₃     Lithium tantalate
mW         Milliwatts
ms         Milliseconds
μm         Micrometer
n₁         Cover layer index of refraction
n₂         Guiding layer index of refraction
n3  Substrate index of refraction
\( n_{\text{eff}} \)  Effective index
Ni  Nickel
nm  Nanometer
\( O_2 \)  Oxygen
OIC  Optical integrated circuit
PCB  Printed circuit board
P_D  Power density
P_I  Incident power
\( \psi_{10} \)  Fresnel phase shift at the film-to-air interface
\( \psi_{12} \)  Fresnel phase shift at the film-to-substrate interface
R  Radius
RF  Radio frequency
s  Seconds
\( \text{SiO}_2 \)  Silicon dioxide
SP  Scanning speed
t_D  Dwell time
\( \theta_2 \)  Angle of incidence of the guided wave
\( \theta_C \)  Critical angle
Ti  Titanium
UV  Ultraviolet
V  Vanadium
CHAPTER 1
INTRODUCTION

Since the early 1960s, during the development of stable laser systems, the processing and transmission of optical information has been a topic of interest in the arena of integrated circuits as opposed to using more familiar means of signal propagation such as electrical current or radio waves. This approach offers advantages in both performance and cost in the manufacturing of such devices. Additionally, as integrated systems are increasingly becoming faster and more efficient, some of the common problems of electromagnetic interference (EMI), crosstalk, and stray capacitances are eliminated in optical integrated circuits (OIC) [1]. As the frequency of an electrical signal propagating through a conductor increases, the impedance of the conductor increases as well, which causes the propagation properties of an electrical cable to have higher attenuations [1]-[10].

OICs have a number of advantages over electrical integrated circuit and conventional optical signal processing systems that are comprised of largely discrete components. These advantages include increased bandwidth, expanded frequency and wavelength division multiplexing, low-loss couplers, smaller size and weight, improved reliability, and lower power consumption [1] [2]. Naturally there are disadvantages to these systems which primarily center on the cost of developing new fabrication methods and technologies [7]. As the market and demand for OICs grows, low cost polymers are viewed as an attractive medium in which to create various optical components.

Even though the field of integrated optics is still fairly new there are currently many applications which involve the use of channel waveguides essential to the system’s operation. One of the first applications to implement OICs was a radio frequency (RF) spectrum analyzer.
used for military applications [1]. In telecommunications optical switches are in great demand for high-bit rate communication systems, and waveguide switches are desired because of their high speed capabilities [2]. Analog – to – digital converters are common applications which use optical interferometric modulators that are aligned in parallel to provide a specific bit conversion [9]. Additional implementations of OICs include waveguide temperature sensors, Doppler velocimeters, chemical sensors, as well as a myriad of telecommunication applications [3]-[8].

1.1 Purpose and Objectives of the Study

The purpose of the study is to make a contribution to the field of integrated optics technologies. Through the study of three i-line photosensitive polymers, optical properties are determined to find the suitability of these materials in the OICs. These properties include the index of refraction, the wavelength absorbance spectra, and the thickness of spin coated films. After these properties are obtained simulations using an optical waveguide computer aided design (CAD) and simulation software will be used to ensure a single mode waveguide can be produced with low propagation loss. A mask-less ultraviolet (UV) photolithographic method called laser direct writing will be used in the patterning of passive single mode integrated optical components. The relationship between the applied energy of the UV laser and the waveguide dimensions is investigated. Optical characterization of the propagation power loss of the resulting optical channel waveguide structures will be performed to ensure suitability for implementation in OIC applications.

The main objectives of the study are as follows:

- Characterize three different UV polymer photo resists, Norland Optical Adhesive 61 (Norland Products Inc.) [46], NR7-6000 (Futurrex, Inc.) [47], and Ormocer® (Micro
Resist Technology GmbH) inorganic-organic hybrid polymers, Ormocore and Ormoclad [49]. A spin-on coating thickness calibration curve will be measured, as well as the indices of refraction of all three materials at wavelengths of 633nm and 1550nm.

- Simulate waveguide properties, including power propagation loss measurement and verification of operation in a single mode, of a straight interconnect, y-branch, and a directional coupler using BeamPROP™ (RSoft Design Group, Inc.) [45], an integrated optical device simulation software.
- Investigate the method of laser direct writing for the micro-patterning of polymer single mode optical waveguide devices by measuring the propagation loss using the techniques of “end-firing” and the “cut-back method.”

1.2 Research Question

The research question associated with this study is stated below for hypothesis testing.

**Research Question**: Does laser direct writing micro-patterning produce single mode passive waveguide devices that show a significant loss in the output power due to increasing length?

- **Null Hypothesis**:
  
  There is no significant difference in output power means due to the length of the micro-patterned optical waveguide at a confidence level of 95%.
  
  \[ H_0: \mu_1 - \mu_2 = 0 \]

- **Alternative Hypothesis**:
  
  There is significant difference in output power means due to the length of the micro-patterned optical waveguide at a confidence level of 95%.
  
  \[ H_a: \mu_1 - \mu_2 > 0 \]
where

\( \mu_1 \) represents the shortest length of the optical waveguide and

\( \mu_2 \) represents progressively longer lengths of the optical waveguide.

1.3 Scope of the Study

This study focuses on the mask-less micro-patterning of passive optical waveguide channel components using laser direct writing that operate in a single mode. Three designed components will include optical interconnects, directional coupler, and y-branch structures. The waveguide materials are all photosensitive to wavelengths near 365nm. All of these devices are micropatterned in a normal atmospheric environment that does not require a clean room or vacuum equipment to process or polymerize the three negative tone resists.
CHAPTER 2
REVIEW OF LITERATURE

2.1 Waveguide Fundamentals

The most fundamental element in integrated optics technologies is the optical waveguide which is defined as a structure that allows the confinement of light within its boundaries by total internal reflection [6]. For example, in Figure 1, the indices of refraction for the shaded areas $n_1$ and $n_3$ need to be less than the index of $n_2$ to meet the total internal reflection requirements. Using Snell’s law, to find the minimum angle at which total internal reflection occurs, it is seen that the critical angle, $\theta_c$, at the $n_1,n_2$ boundary is:

$$\theta_c = \sin^{-1}(\frac{n_1}{n_2})$$

so, the allowable angles of $\theta_2$ for confinement within the waveguide boundary $n_1, n_2$ are

$$\theta_2 \geq \sin^{-1}(\frac{n_1}{n_2})$$

Additionally, $\theta_2$ for the $n_2, n_3$ boundary at which total internal reflection occurs is

$$\theta_2 \geq \sin^{-1}(\frac{n_3}{n_2})$$

Figure 1: Optical ray pattern for a guided mode.

Since there is total internal reflection for both the $n_1,n_2$ and $n_2,n_3$ boundaries, the light is now considered to be guided within the $n_2$ medium. It should be noted that this is an ideal situation. In practice, a small amount of the reflected light radiates in the cladding layer which is one cause
of propagation power loss. The propagation constant of light in a waveguide, often denoted with the parameter $\beta$, determines how the phase and amplitude of light with a given frequency varies along the propagation direction, and is given by:

$$\beta = kn_2 \cos \theta_2 ,$$

where $k=2\pi\lambda_0/c$ [1]. $\beta$ may actually be complex where its real part is the phase delay per unit propagation distance, while the imaginary part describes optical gain with a negative quantity or loss with a positive quantity [3]. The propagation constant can be expressed as the product of the effective refractive index and the vacuum wave number. The propagation constant depends on the frequency, or wavelength, of the light. This frequency dependency determines the group delay and the dispersion of the waveguide. Effective index is a number quantifying the phase delay per unit length of propagating light in a waveguide and can be calculated by [5]:

$$n_{\text{eff}} = \beta / k$$

A rectangular waveguide structure confines light in two dimensions, whereas the planar description provided above describes light that is only confined within one dimension. The waveguide region, shown as n1 in Figure 2, is surrounded on all sides by a medium with an index, n2, less than n1. The x and y axis represent the width and height respectively, and the z-axis represents the direction in which light is propagating down the channel. It is not necessary that the media surrounding the core waveguide, however, in this case the modes of the waveguide will not be exactly symmetric [2]. The channel style of waveguide is a popular method as it is generally easy to produce, as well as being cheaper because only two different indices of the confining media are required.
2.2 Optical Waveguide Materials

Many types of materials are used in the fabrication of optical waveguide structures. Crystalline structures such as lithium niobate are used as waveguide layers that have uses in both passive and active optical components. The most well know case of a special waveguide, fiber optics, uses glass materials as the core layer for light propagation. These ideas are implemented in the design of glass type waveguides in OICs. Photosensitive polymers are a popular cost effective material used in waveguide fabrication.

2.2.1 Lithium Niobate (LiNbO$_3$)

Fabricating waveguides using LiNbO$_3$ as a substrate is widely used in functional optical devices because of the excellent electro-optic and accousto-optic effects [7]. Additionally LiNbO$_3$ can provide an easy method of fabrication for low loss waveguides because the differences in index of the core and clad layers, as well as the thickness of the waveguides, are consistently produced. LiNbO$_3$ substrates are also commercially and readily available.

There are several methods of fabrication of LiNbO$_3$ waveguides which include growing a
single crystal of LiNbO₃ on a lithium tantalate (LiTaO₃) crystal with a similar crystalline structure, and also a sputtering method where a single crystal film of LiTaO₃ is deposited on a glass substrate [8]. These two methods are generally not used in functional waveguide devices because of the poor optical properties, specifically propagation losses of more than 3dB/cm [7]. Other techniques include lithium dioxide (LiO₂) out-diffusion, which involves heating LiNbO₃ substrate in a vacuum until the LiO₂ is diffused from the crystal which provides a higher index near the surface [1]. Transition metals such as Ti, V, Ni, and Cu have been used in the thermal in-diffusion method where a metallic film is deposited on a LiNbO₃ crystal in a high temperature flowing inert gas, such as Ar or O₂, resulting in Ti diffused waveguides providing the best optical properties [8]. Again as the transition metal is deposited on the crystal surface this provides a higher index for the core material of the waveguide on top of the LiNbO₃ cladding layer. The difference of index is determined by the thickness of the diffused layer.

Another method of LiNbO₃ fabrication is light ion implantation which offers the possibility of producing waveguides in photorefractive materials [38]. In this study they produce a planar waveguide, without a post annealing procedure in LiNbO₃, in which optical modes are excited. This method helps reduce the cost of typical LiNbO₃ methods as it does not require the extreme heat conditions involved in annealing. Channel waveguides have been successfully patterned by in-diffusing titanium on the surface of the crystal using a lift-off technique [39]. This includes application of a photoresist, contact exposure using a chromium mask, photoresist development, titanium evaporation and finally a lift-off procedure.

2.2.2 Glass Based Waveguides

One of the most well known uses of special waveguides is fiber optics, and the material
that is used as the core is generally a glass variant. Glass is typically used because of the ease of the fabrication process. Common optical waveguide fabrication techniques using glass include thermal ion exchange and RF sputtering [5].

Slab waveguides are produced by thermal ion exchange of a soda-lime glass substrate that is placed in a molten salt solution, typically silver nitrite (AgNO₃) or potassium nitrate (KNO₃), until ion exchange occurs. For Ag⁺ ions, the typical conditions to grow a 2.4μm thick layer required immersion in a temperature of 250°C for two hours, and for K⁺ ions a 3.52μm layer required a temperature of 370°C for four hours [7]. As a result the Ag⁺ solution produced optical losses at a high 4 to 5dB/cm whereas the K⁺ solution offered much better optical properties of 0.5dB/cm. Research done using this method of glass waveguides has been performed [41] where not only slab waveguides are fabricated, but channel waveguides and couplers. This study achieved single transverse electric (TE) and Transverse magnetic (TM) modes with dimensions of less than 5.3μm² with optical losses of between 0.1 and 0.2dB/cm.

RF sputtering provides an advantage as any dielectric film can be chosen as the waveguide layer [8]. Sputtering of glass is performed in an Ar atmosphere by applying power to the RF source and the target. Typically the sputtering process can be quite long as the rate of thickness deposited is about 0.57μm/hour, and it is common for the propagation loss to be as high as 3 to 4dB/cm [7]. However, when semiconductor material substrates are used, such as Si, a buffer layer of silicon dioxide (SiO₂), also know as silica, can be used in conjunction with the glass waveguide that is capable of producing results as low as 0.01dB/cm [40].

2.2.3 UV Photosensitive Polymers

Optical waveguides and devices using polymer materials is increasingly becoming an
attractive option because of their potential applications in optical communications, optical interconnections, and integrated optics [16]. Polymer materials provide well controlled refractive indices, good thermal stabilities, ease of processing, and good adhesion on a wide range of substrates [22]. Additionally polymer materials are better suited in board level electronics than, for instance, a LiNbO$_3$ substrate because of the lower dielectric constant [25] and overall lower production costs.

The curing of photosensitive polymers used in OIC’s exhibit high absorption of light in the UV spectrum. Conversely thin films polymers with very low absorption, especially in the common communications wavelengths between 633 and 1550 nm, are essential to providing a very low optical power propagation loss [25].

Norland Optical Adhesive-61 (NOA-61) is a clear, colorless, photopolymer that will cure when exposed to UV light. Since this polymer is a one part solution, there is no need for additional mixing or heat curing commonly required by various types of adhesives. The curing takes place within the range of 350-380nm where the material has high absorption [47]. NOA-61 is not inhibited by oxygen during curing, which means that all of the polymer will completely cross-link. Typically NOA-61 is used in applications such as bonding lens, aerospace and commercial optics, and for terminating and splicing optical fibers. A previous study has shown the ability to use NOA-61 in waveguide applications. However, it was shown that the optical losses of the material are very high for infrared wavelengths. So, the feasibility of this material acting as the core layer is low, however, it may still provide an effective cladding layer depending on NOA-61’s index of refraction relative to core material.

NR7-6000P is fairly new negative tone resist that is specifically designed for UV exposure at 365nm. An attractive aspect of this polymer is that it exhibit straight sidewall
profile. Additional features of NR7-6000P are the fast developing time, resistance to temperatures up to 180°C, and a long shelf life of over three year.

Some materials, in the case of Ormocer® inorganic-organic hybrid polymers, Ormocore and Ormoclad, are specifically engineered for use in integrated optics. Ormocore/ormoclad can be processed in a room temperature environment as well as in an open air environment. They are also photosensitive and are therefore directly photopatternable, which results in low roughness and low stress waveguides. Inorganic-organic hybrid polymers make possible the combination of useful organic and inorganic characteristics within a single molecular-scale composite [50]. They can be synthesized to have a controllable combination of the properties such as optical, electrical, and mechanical performances by combining the properties of both organic polymer and inorganic compound [51]. For example, inorganic material can increase the optical quality, scratch resistance, and hardness of organic polymers, while the organic polymer can improve the toughness of brittle inorganic materials.

Another advantage of using these materials is the ability to custom tune the indices of refraction. Figure 3 shows the linear relationship, at four different optical wavelengths, when blending Ormocore and Ormoclad at different ratios. For example, with a ratio of 80% Ormocore and 20% Ormoclad the resulting refractive index is approximately 1.550 using a wavelength of 635nm. This technique provides a precisely tunable range of approximately 0.0125 for the index difference between Ormocore and Ormoclad.

2.3 Methods of Waveguide Micro-patterning

In the fabrication of waveguides for use in OICs, initial start up and operating costs must be considered. Some systems can provide very high resolutions, whereas other systems may
Figure 3: Refractive indices of blended Ormocore and Ormoclad [49].

have lower resolution but are more cost effective and efficient. The techniques of UV photolithography, electron beam lithography, ion implantation, and laser direct writing are investigated.

2.3.1 Masked UV Photolithography

In the fabrication of integrated circuits (IC), photolithography is almost exclusively the process of choice when transferring patterns from a mask onto the targeted thin film [35]. Photolithography is a very mature technique that is continually improving to offer improved resolution to create smaller features. UV photolithography provides an efficient and reproducible approach when creating complex designs, and when many units are made.

There are several steps involved in the UV photolithography methodology. A silicon substrate, in the case of many IC applications, is coated with either a negative or positive tone resist. The thin film is then covered with a mask and exposed to UV light. Masks are flat
glasses or quartz plates that are transparent to UV light that have an absorber pattern metal which blocks the UV rays. They are placed in direct contact with the surface of the photoresist, in the case of hard contact masks, or placed within 10 to 20\(\mu\)m [35] above the surface for soft contact masks. After exposure, a developing solution rinses the uncured areas of the thin film off the substrate leaving a patterned photoresist on surface.

Photolithography has been used in waveguide fabrication using commercially available polymers [20][16][34][26]. Results of single mode waveguides with large cross-sections and a large index difference between the core and cladding layer have been achieved with optical losses of below 0.5dB/cm at a wavelength of 1.3\(\mu\)m [20]. In this study benzocyclobutene, a high temperature stable polymer is used as the core material of the channel waveguide, and SiO\(_2\) is thermally grown for the upper and lower cladding layers. Another study [16] shows optical losses of 0.62dB/cm and 0.77dB/cm at 1.3\(\mu\)m for TE and TM polarizations respectively in this implementation of channel waveguides as well as Y-branch power splitters with a 50:50 split.

One of the most common negative tone resists, Su-8, was used as the core waveguide material as it provides attractive characteristics in the 0.8, 1.3, and 1.55\(\mu\)m wavelengths. An optical epoxy, Norland 61, provides the upper and lower cladding layers, and is a cost effective UV sensitive optical epoxy. Four different polymer optical interconnects, saw-tooth, funnel connect, overlap, and straight tight-ended have been fabricated using large-area projection lithography equipment [34] using an inorganic-organic hybrid polymer that is capable of refractive index tuning. The polymer used, Ormocer, provides a very flexible option in customizing the difference of index between the core and cladding layers. The results of this study show that these waveguides were multimode and exhibited losses of 0.7dB/cm at 1.3\(\mu\)m wavelength. Methods have been explored using photolithography in the fabrication of photonics packaging [26] where flexibility is
demonstrated in the optimized partitioning between base-substrate with standard printed circuit board (PCB) low density interconnects and added thin films with high density interconnects. Their lithography equipment provided imaging of large-area panels (610mm x 610mm) with a throughput of 27 panels/hour at a resolution of 5μm using an Ormocer i-line sensitive and photopatternable resist.

For many years UV photolithography has shown to be an excellent method of fabricating microelectronic devices. A drawback however is time and money spent on creating a suitable mask especially in prototyping situations. Typically a mask is designed using an electron beam with much higher resolution than the actual photolithographic process can achieve [37] although techniques such as projection printing are being used to help reduce these costs [35]. Additional drawbacks of using masked pattern transfer are the probability of mask misalignment or errors in stenciling the mask which can cause extra resources to be wasted in making corrections. Masked photolithography is technically a two-dimensional process and has limitations when a non-planar topography is desired [36].

2.3.2 Electron Beam (E-beam) Lithography

When creating the stencil mask for photolithograph it is common to use E-beam lithography [35] to etch the pattern. This technique also provides a high resolution pattern in which high energy electrons (1 to 100keV) are focused to an extremely small beam [12]. Additionally, no mask is required for pattern transfer. Specialized electron sensitive tone resists are needed for curing to occur.

E-beam lithography can provide an attractive option over photolithographic techniques as it can precisely control the energy and dose to which the tone resists are exposed as well as
imaging the electrons to a small point ~100Å as opposed to a 5000Å spot of light [34]. Fabrication of integrated waveguide filters, based on Bragg gratings, by a single step E-beam writing process has been shown [12]. These filters were designed to operate in the common 1.55μm wavelength of telecommunications systems. Wavelength duplexers with different grating lengths [13], also for operation at 1.55μm are produced. Waveguide components with large radius curves, sub-micron period grating structures for advanced laser systems, and the fabrication of holographic elements for spatial optical systems [11] are explored using electron beam lithography.

With this high resolution technique, there is the disadvantage of having long production times of over 1 hour, and by nature of electron beams being charged particles there is a need for a vacuum which causes more complex and expensive imaging systems [36].

2.3.3 Ion Implantation Doping

Ion implantation doping is a waveguide fabrication method in which substitutional dopant atoms are created [1]. The ions of these atoms are accelerated through 20-300keV before contacting the target substrate. This results in a layer that has a higher index than the substrate and can exhibit losses as low as 0.2dB/cm [8]. Generally after the implantation process further annealing is needed to provide characteristically good waveguides. With an entire system containing an ion generator, an accelerator, an ion separator, and a raster-scan deflector [34] it is quite apparent that this technique is both expensive and quite large in size.

2.3.4 Mask-less Laser Direct Writing

Laser direct writing systems are increasingly becoming a popular solution in the
fabrication of waveguide components. This technique has been shown as an easier and more cost effective method because a photo mask is not required to polymerize desired patterns. The polymerization process is photon induced, or visible laser irradiation induced [19], which allows reaction to occur at room temperature [25]. Additionally clean rooms are not mandatory which allows samples to be created in a normal atmospheric environment [18]. The flexible nature of this system allows patterning of structures that prevent the need of mask contact printing and associated mask processing machinery as well as the ability to pattern long dimensions of waveguides over relatively large planar areas [22]. A further advantage of this system is the short process time which usually ranges from several seconds to several minutes, whereas a method such as reactive ion etching has shown to grow structures at the inefficient pace of 14 to 46nm/min [31].

Laser direct writing fabrication of planar waveguide power splitters and directional couplers on silicon are shown to be a favorable technique that requires less equipment and wafer processing [21]. They show that this method produced these optical components to have losses of less than 0.2dB/cm. Studies have also shown [22] that waveguide Y-branches and directional couplers using polymeric materials fabricated with laser direct writing produced very low losses of 0.03dB/cm at 840nm wavelength. Additionally, research shows single mode planar waveguides produced for applications in planar light wave circuits had losses of 0.67dB/cm at the 1.55μm wavelength [24].

Studies [15][42][43] have used pulsed lasers, or femtosecond lasers, for the polymerization of a photoresist in laser direct writing systems for microstructure fabrication. These types of lasers are desirable as the bandwidth of the laser pulse, generally less than 150ns, is used to probe fast chemical reactions, such as the breaking of bonds between atoms, or in the
case of a photosensitive resist the cross-linking of the polymer. Typical scanning speeds for femtosecond pulsed lasers is usually less than 100μm/s [42] which occasionally causes long processing times in complex patterns. A diode module laser however, is capable of producing patterns of with dwell times as high as 100mm/s depending on the input laser power. This allows for a shorter processes time. In addition to favorable time efficiency, diode module lasers usually range from 20-30 times less expensive then commercially available femtosecond lasers.
CHAPTER 3
METHODOLOGY

3.1 Research Design

The investigation into the micro-patterning by laser direct writing of polymer single mode passive channel waveguide devices occurs in three primary stages. The design and software simulation of the three different structures is first carried out (Section 3.2). Then after acceptable simulation results are obtained, the substrate is cleaned and the different core and cladding layers are deposited and patterned with the laser direct writing system (Section 3.3.2). After the multiple layers have been processed and patterned the resulting structures are placed within the optical loss characterization system (Section 3.3.3).

3.2 Design of Waveguide Structures

3.2.1 BeamPROPTM Waveguide Simulation Software

BeamPROP is a design tool that is part of the Rsoft Photonics Component Design Suite. BeamPROP is based on the beam propagation method (BPM) for the design and simulation of integrated and fiber-optic waveguide devices and circuits. The BPM incorporates techniques that utilizes an implicit finite-difference scheme, however it is only suited for a planar topology [6].

The flexibility of the software allows users to create systems for the design of waveguide devices, optical circuits, and other photonic devices as well as fundamental objects such as straight, tapered, curved, y-branched waveguide segments and lenses. Each individual component has its own set of properties that can be accessed include shape information, such as taper or bend type and magnitude, and optical properties, such as refractive index profile type
and value. BeamPROP allows the user to manually create photonic structures, but it also contains several built-in utilities to automatically create complicated structures. Utilities are available for common periodic structures, grating structures, and arrayed waveguide grating (AWG) structures. Rsoft CAD with related utilities also allows for the creation of customized components using mathematical equations or data files. BeamPROP includes BPM-based mode solvers which allow the calculation of modal propagation constants and profiles of both guided and radiation modes for any arbitrary 2D or 3D geometry [45].

3.2.2 Interconnects

The most fundamental building block of optical integrated circuits is a channel waveguide interconnections. This element serves to optically connect two points within an OIC. The straight channel waveguide is the simplest structure for guiding light. Interconnects also act as a spatial filters which maintains a Gaussian mode [2] throughout the OIC architecture. The width and height dimensions are to be determined in the simulation results in Section 3.3. The length of the interconnection waveguide will be patterned to allow ample space to perform the “cut-back” loss measurements detailed in Section 3.4.3. Once the width and height dimension are determined to provide a single mode, low loss, waveguide, they can be applied to the Y-branch and directional coupler described below.

BeamPROP is used as the waveguide simulation software. All waveguide structures that were simulated are 3D channel waveguides that uses a Gaussian shaped beam with a wavelength of 1550nm. The launch beam has a width and height with the same dimensions of the waveguide under test. To excite multimode propagation, if applicable, the input source is place slightly off center. Initially to discover the number of modes in the interconnection structures, mode
calculations are performed on width and height waveguide dimensions of 2µm x 2µm up to 15µm x 15µm. The core index of refraction used is 1.5251 and the cladding index of refraction is 1.5149. These numbers are from the prism coupler measured values (Section 4.1). Figure 5 shows the number of modes and effective index of refraction of each mode. From this data, it can be seen that from heights of 2.5µm to 6.5µm a single mode can be achieved. For heights greater than 6.5µm multiple modes will start propagating.

Figure 4: RSoft CAD schematic of an interconnection device.

Figure 5: Mode calculation of rectangular interconnects.
Figure 6 provides an XY cross section of four modes and their profiles. Dimensions with a 15μm width and 15μm height were used to illustrate the shape and peak intensity of the output for four modes of a multimode waveguide. Red shows lobe where the maximum output power of each mode occurs; pink denotes cladding layer with the least amount of light is propagating.

Figure 6: Computed mode profiles for modes 0, 1, 2, and 3.
However, as the modes increase radiation into the cladding layer increases as well, a factor which causes higher propagation power loss. This is seen as the blue shaded areas “bleeding” into the pink cladding layer.

For a comparison of 2D Gaussian profiles, a fundamental mode and multimode distribution curve is illustrated in Figure 7. The x-axis is the waveguide width in micrometers (0 is the waveguide center), and the y-axis is the intensity (arbitrary units) of the waveguide power. Again, the same waveguide dimensions were used as in the previous figure. As can be seen in the difference of the maximum intensity between the two modes, the multimode (M1) has nearly 30% less peak power than that of the fundamental mode (M0). This further illustrates why it is desired to operate a passive optical device with a single mode.

![Figure 7: 2D Gaussian profile of the fundamental mode M0 and M1.](image)

3.2.3 Y-branches

A branch in a wave guide consists of a single input wave guide, a short tapered section, and two output waveguides. Y-branches, or sometimes referred to as power splitters, equally divide the power between two output waveguides. Y-branches are frequently used for this function
as they are easy to design and are fairly insensitive to patterning tolerances [4]. This design is symmetric, so for two output arms the power is split 50\%. Additionally power splitters can be fabricated with multiple output waveguides which provide for even distribution of the signal on the output arms. For this study, a Y-branch is designed with an input waveguide that splits into two arms that have angles, \( \theta \), of 0.5 to 8\(^{\circ} \) that stretch until the parallel distance between the two waveguides is 80\( \mu \)m. This distance is chosen to ensure the split signals will not encounter any coupling effects that are discussed in the next section. Figure 8 shows the Y-branch schematic.

Studies have been performed [22] showing the relationship between the angle of the bend and the losses encountered. Bends of less than 3\(^{\circ} \) exhibited losses of less than 1dB, while bend angles 4\(^{\circ} \) and higher showed exponentially growing losses of greater than 1dB. Similar results are achieved in the simulation of the splitters. The same input power parameters of the interconnection simulation are used here as well. The simulation for a 2\(^{\circ} \) angle for a y-branch is shown in Figure 9. The left half shows a top-down view of the device with the y-axis providing
the direction (Z) the light propagates and the x-axis is the waveguide width. The power probes are displayed in the right half of Figure 9. The input power and the power of the left are denoted with the blue waveform, and the right arm is displayed as the green signal. The remaining simulations of this structure using different branching angles are located in Appendix B.1.

![Figure 9: Simulation of a 50/50 2° Y-branch.](image)

Even though the input power is set to 1, the waveguide power probes will show the effects of the input coupling loss, hence the blue power monitor shown at approximately 0.75 units of the total input power of 1 unit.

Figure 10 shows the simulations of the propagation power loss as a result of the bending angle. Simulated angles that are less than 3° have loss of less than 1.5dB, while angles greater than 6.5° experience total waveguide power loss.
3.2.4 Directional Coupler

The directional coupler component has two input and two output ports, and is comprised of two closely separated waveguides. The basic principle governing this coupling technique is based on the periodical optical power exchange that occurs between two parallel waveguides through the overlapping of the evanescent waves in a mode [2]. The dimensions are similar to the Y-branch, however there is a spacing between the two merging branches that are aligned parallel to each other instead of the two branches combining together as discussed above. The basic shape of the coupler is displayed in Figure 11.

By adjusting the coupling width, the distance between the closely spaced parallel sections, and coupling length, the ratio of coupling power can be adjusted from 0 to 1 to suit application specific needs. Figure 12 is a directional coupler that was simulated to illustrate the coupling interaction between the two waveguides. The blue signal represents the left side of the
structure while the green signal represents the right side. Because a very nice sinusoidal wave is plotted it is quite easy to calculate the minimum coupling distance with near 100% power transfer.

![Figure 11: Directional coupler CAD schematic.](image)

In addition to the coupling length, the distance between the two parallel waveguides plays an important role. Figure 13 illustrates the minimum coupling length with respect to the width.
between coupling waveguides. The remaining directional coupler simulations used to populate this plot are located in Appendix B. As can be seen, when the coupling width increases the minimum distance for complete coupling to occur increases. The simulation in Figure 14 is an optimized directional coupler with 3µm coupling width and a minimum coupling length of approximately 800µm for which there is complete coupling. This illustrates the ease at which design dimensions can be constructed.

![Figure 13: Plot of coupling width and the effect on coupling length.](image)

![Figure 14: An optimized direction coupler with minimum coupling length.](image)
3.3 Instrumentation

A listing of the equipment required for this proposal is provided in Table 1. All of the equipment cataloged below is readily available in the Optics Research Laboratory, with exception to the scanning electron microscope (SEM) and Fourier transform infrared spectroscopy (FTIR) equipment is available in the Department of Materials Science and Engineering with limited access and availability. Both facilities are located in the UNT Discovery Park building.

Table 1: Instrumentation for waveguide patterning and analysis.

<table>
<thead>
<tr>
<th>Prism Coupler</th>
<th>XY Translation Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoresist spinner</td>
<td>Spatial filter</td>
</tr>
<tr>
<td>375nm UV laser diode module</td>
<td>Collimating lens</td>
</tr>
<tr>
<td>633nm HeNe laser module</td>
<td>Polarizing lens</td>
</tr>
<tr>
<td>1550nm fiber coupled laser</td>
<td>Charged Coupling Device Camera</td>
</tr>
<tr>
<td>Beam shutter and controller</td>
<td>Hotplate</td>
</tr>
<tr>
<td>Neutral Density (ND) filters</td>
<td>UV exposure chamber</td>
</tr>
<tr>
<td>5x beam expander</td>
<td>SEM</td>
</tr>
<tr>
<td>90° Mirror</td>
<td>Optical Microscope 10x-40x magnification</td>
</tr>
<tr>
<td>10x Objective Lens</td>
<td>Laser beam profiling software</td>
</tr>
<tr>
<td>Iris Diaphragm</td>
<td>LabVIEW</td>
</tr>
<tr>
<td>FTIR</td>
<td>PC</td>
</tr>
</tbody>
</table>

3.3.1 Laser Direct Writing System

The laser direct writing system used in this study is illustrated in Figure 15. Very few components are required in the construction of this system which lends itself to inexpensive initial setup costs. A personal computer (PC) running a LabVIEW Virtual Interface by National Instruments Corporation controls the motion of the precision translational stages and the triggering of the shutter controller. A 10X objective lens is fine tuned with a manual actuator so that the spot size, or focal waist, is as small as possible to provide the best pattern resolution.
Controlling velocity, or dwell time, of the substrate moving under the laser beam alters the dose of energy thin films are exposed causing a greater command of the physical dimension, especially the width of the waveguide structure and depth of penetration of the laser spot. Dwell time, measured in milliseconds, is determined by

$$t_D = \frac{2R}{SP}$$  \hspace{1cm} (6)

where R is the radius of the laser spot and SP represents scan speed (mm/s), and the spot diameter(μm) is expressed as

$$2R = \frac{4\lambda f}{\pi D}$$  \hspace{1cm} (7)

with λ being the wavelength of the UV laser, f and D are the focal length and diameter of the focusing lens [18]. The effective width of laser beam is also determined by viewing the Gaussian power intensity profile of the UV writing beam. The full width of the 1/e intensity (approximately 36.7% of the total beam width) of the profile is shown in Figure 16. Because of limits to the resolution of the charged coupling device (CCD) detection camera, the beam that was captured has not been passed through the 10X objective lens. When the beam had been
passed through the objective lens the display showed a total of 5 pixels which did not provide an accurate means of measuring the beam width. These figures show the shape of the writing laser has a near Gaussian profile. However, using Eq. 7 the width of the spot size is calculated to approximately 3.3μm, which will be used to pattern the waveguide devices.

Figure 16: 2D and 3D power intensity profiles of the 375nm direct writing UV laser.
3.3.2 Sample Preparation

The process in which the channel waveguides are to be fabricated includes four primary steps that are illustrated in Figure 17. The substrate is cleaned to ensure maximal adhesion of the polymers. A first layer of lower cladding material is deposited on the substrate and cured. Next, the application, UV patterning by direct laser writing, and the development of the core layer material. Finally, in the cases where air is not the upper cladding layer, a third layer is deposited and cured in the same process as the lower cladding layer.

![Figure 17: Channel waveguide fabrication method.](attachment:image)

Adhesion of the film to the substrate and the uniformity of the film depend in large on the cleanliness of the substrate. Therefore, substrates need to be cleaned with great care. First, substrates are immersed in a beaker containing acetone for 3 minutes in an ultrasonic bath followed by 3 minutes ultrasonic bath in isopropyl alcohol. Substrates are then blow dried with compressed nitrogen, followed by baking in an oven at 100°C for four hours (Figure 17a). The substrates are deemed ready for further fabrication processes. A negative photoresist layer is deposited to the cleaned silicon substrate by spin on coating. This produces a film that is uniform across the substrate. Thin film thickness is depends on the viscosity of the material, the spin speed and the ramping acceleration of photo resist spinner. After the cladding layer is spun on to the substrate, it is placed in a UV chamber which emits a peak wavelength at 365nm for rapid
curing. The energy requirements for curing vary with the materials, however for this study the exposure time is in the range of 1-5 minutes. The cladding layer is then baked on a hotplate to ensure maximum adhesion to the substrate as well as bake out any remaining solvents (Figure 17b). The cured cladding layer remains on the substrate and ready for the core layer that will be waveguide patterned. After the core material is spin coated on top of the cladding layer, the laser direct writing system is used to pattern the waveguide. The traveling speed of the substrate is determined by the power of the laser source and the energy requirements of the individual polymers. For this study the waveguide dimensions are five centimeters in length, and 5.5µm of width and height to produce single mode waveguides. Once exposure is completed the core patterned waveguides on the substrate is again placed on a hotplate for a post bake. After post bake, the uncured material is developed by rinsing with developer until only the cured core waveguides remain on top of the cladding layer (Figure 17c). The process for the upper cladding layer coating is identical to that for the lower cladding layer. A final hard bake may be performed at temperatures of 150-240°C for up to three hours depending on final application for the waveguides (Figure 17d).

3.3.3 Waveguide Characterization

The low loss waveguide is an essential requirement for implementing high performance OIC. Propagation losses are measured using the cut-back method [15] because of its simple configuration. A laser beam for visible (633nm) and infrared (1550nm) wavelengths is focused into the channel waveguide, and the result power loss is captured with a CCD camera. The cut-back loss measurements are taken under the identical conditions on the same substrate by cleaving off a portion of the waveguide after each measurement. As the remaining waveguide is
reduced in size the loss for the waveguide is determined as the slope of a linear fit for the power transmission versus device length.

For the characterization of the channel waveguide’s optical properties the cut back method including end fire coupling is implemented. Laser sources of 633nm and 1550nm are required to measure the optical loss of a waveguide structure in typical communication wavelengths. A source helium-neon (HeNe) laser is used for 633nm wavelength emits a power of 2mW to a laser spot of 0.8mm in diameter. For the infrared spectrum a fiber coupled laser source with a maximum output of 1.5mW is inserted in place of the HeNe laser. The beam from the individual sources passes through a polarizing lens which is set to allow only the horizontal TE mode. Next a spatial filter is required so that variations in intensity are filtered out of the Gaussian beam profile. Additionally the beam is collected by a collimating lens to prevent the spread of the power spectrum before entering a 20X objective lens. This objective lens will produce a laser spot size which is smaller than the end of the waveguide structure allowing all the power to enter. After the light has passed through the waveguide the resulting beam is collected by another 20X objective lens which expands the light so it may be measured by the photodetector. In this study the photodetector is the Spiricon CCD that is connected by a coaxial cable to a PC that has a video capture graphics card. Spiricon’s laser beam diagnostics software captures the images and performs calculations of the detected power, beam dimensions, as well as controlling the camera. This system is illustrated in Figure 18.

![Figure 18: Schematic of waveguide characterization system.](image-url)
CHAPTER 4

RESULTS

4.1 Spin-On Coating Thin Film Characterization

To measure the thickness and refractive index of the proposed thin films, the Metricon® Corporation 2010 Prism Coupler is employed. This prism coupling system contains several measurement functions which are important in characterizing thin films. A laser beam of individually selectable 633nm and 1550nm wavelengths strikes the base of a prism that has a high index (n>1.9) which is reflected to a photodetector (Figure 19(a)). A thin air gap occurs when the thin film touches the prism base by means of a pneumatic coupling head. These components are then rotated by use of a stepper motor while the laser beam is stationary to provide an output illustrating the mode angle, which occurs when the light exceeds the total internal reflection criterion, causing the intensity of light collected by the photodetector to decrease. This is seen in Figure 19(b) as the dips, or valleys, in the output wave form. The y-axis is the reflected intensity captured by the photodetector, and the x-axis is the angle of incidence, $\theta_0$, of the light entering the prism. Each step represents an angle of 0.015°. The leftmost valley in the output waveform is the fundamental mode of the thin film, and each additional valley is a subsequent mode.

When two or more optical propagation modes are observed thin film thickness and index are capable of being calculated using the mode equation [44]:

$$\left(\frac{2\pi}{\lambda}\right)^* n \cos \theta * T + \Psi_{10} + \Psi_{12} = m \prod (m = 0,1,2,...)$$

(8)

where $\lambda$ is the laser wavelength, $\theta$ is the angle of incidence between the thin film and substrate, $n$ is the thin film index, and $\Psi_{10}$ and $\Psi_{12}$ are the Fresnel phase shifts at the film-air and film-
substrate interfaces. Solving the eigenvalue equation simultaneously for two or more modes produces the values of thin film thickness and refractive index [30].

Figure 19(a) Schematic of primary prism coupling components. (b) Typical prism coupler output intensity graph.

An additional measurement which is suitable in the characterization of the thin films is the waveguide optical loss option. This technique implements a moving fiber which scans the length of the substrate to detect the exponential decay of the light streak on the propagating mode. However, this technique can only be used in a slab waveguide structure as the dimensions of the
intended optical channel components will be too small to form an adequate coupling point with the coupling prism.

In the case where only one mode is resolved, the index of refraction of the measured material is manually entered or “assumed” to allow calculations to be performed for thickness. For films that were too thin to allow at least one mode to propagate, an Alpha Step surface profiler was implemented to measure the thickness. The results of the spin speed vs. thickness curves for Norland Optical Adhesive 61 (Figure 20), Ormocer®s inorganic-organic hybrid polymers (Figure 21), and NR7-6000 (Figure 22) all show that a faster spin speed results in a thinner application of the thin film to the substrate. Error bars express potential error amounts that are graphically relative to each data point in a data series. For Figures 20-24, 5 percent positive and negative potential error amounts are used for the results of this experiment.

Figure 20: Calibration curve for Norland 61 optical adhesive.
Figure 21: Calibration curve for Ormocore positive photo resist.

Figure 22: Calibration curve of NR7-6000 positive photo resist with five different ratios of NR7: cyclohexanone.
In addition to providing thickness measurements of thin films, the prism coupling unit also calculates the index of refraction of each material at wavelengths of 632.8nm and 1550nm. For convenience these results are listed in Table 2. The raw data measurements for index of refraction are located in Appendix A.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Index @ $\lambda=632.8$nm</th>
<th>Index @ $\lambda=1550$nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norland NOA-61</td>
<td>1.5564</td>
<td>1.5408</td>
</tr>
<tr>
<td>Futerrex NR7-6000</td>
<td>1.5997</td>
<td>1.5774</td>
</tr>
<tr>
<td>Micro Resist Ormocore</td>
<td>1.5438</td>
<td>1.5329</td>
</tr>
<tr>
<td>Micro Resist Ormoclad</td>
<td>1.5299</td>
<td>1.5149</td>
</tr>
<tr>
<td>Ormoclad/Ormocore 50% Mix</td>
<td>1.5392</td>
<td>1.5251</td>
</tr>
</tbody>
</table>

4.2 Waveguide Dimensions

To determine the energy density of the laser spot the dwell time and the power density of the writing laser parameters are required. The input power must first be found. Using a light power meter the objective lens was focused so the spot is in the photodetector surface which provided an incident power of 21μW. Since the spot size diameter is found from Eq. 7, the power density is the incident power divided by the area of the laser spot:

$$P_D = \frac{P_I}{\pi r^2},$$

(9)

Once power density is determined the energy density is simply found by:

$$E_D = P_D \cdot t_D,$$

(10)

where $t_D$ was found in Eq. 6. For example, when a $t_D$ of 2ms is used, the resulting energy density is 214mJ/cm².
The physical dimensions of the Ormocore channel waveguide width (Figure 23) are shown as a function of laser spot dwell time. In both illustrations is apparent that the longer exposure to the energy dose of the laser spot will result in a wider width and a deeper penetration through the polymer. Faster dwell times, lower values of \( t_D \), will have less exposure to the laser power energy and therefore will have a smaller waveguide width, while longer exposure results in larger waveguide widths. The penetration depth (Figure 24) can also be controlled by the energy density. For the laser beam energy to penetrate all the way to the substrate with a thickness of 60\( \mu \)m, the dwell time must be greater than 4ms. Otherwise, if the laser did not penetrate to the substrate patterned structures will be washed away during the development procedures listed in Section 3.3.2.

![Image of waveguide width as influenced by laser dwell time.](image)

*Figure 23: Waveguide width as it is influenced by laser dwell time.*
4.3 Waveguide Optical Characteristics

The full testing length of the waveguide is approximately 33 mm so as to allow ample length for measuring optical losses. The cut-back loss measurements are taken over a group of four single mode waveguides, using Ormocore as the cladding layers and a 50% blended ratio of Ormoclad and Ormocore is the core material, which are spun-on and micro-patterned under identical conditions on the same substrate by cleaving off strips after each measurement. The loss for the waveguide is determined as the slope of a linear fit for the power transmission versus device length is 0.79dB/cm as depicted in Figure 25. The prism coupler was also used to characterize the power loss of the Ormocore material. Figure 26 shows a result of 0.84dB/cm for the measurement. It should be noted in the prism coupling measurement, air is used as the upper cladding ladder, thus the difference in loss values compared to the end fire technique.
Figure 25: Optical loss of interconnect using the end fire-cut back method [50].

Figure 26: Prism coupler loss measurement of Ormocore at 1550nm wavelength.
4.4 Micropatterned Components

Fully fabricated interconnection waveguides using the aforementioned processing and microfabrication technique are illustrated in the SEM micrographs of Figure 27. The distance between waveguides is 80μm, and has channel widths of approximately 5.5μm.

![SEM micrograph of parallel waveguides with 80μm separation and width of 6μm.](image)

(a) SEM micrograph of parallel waveguides with 80μm separation and width of 6μm.
(b) SEM micrograph of a cross sectional profile view of a single waveguide [50].

Because of cost limitations of the Ormocer polymers, only the interconnection structures were characterized for loss measurement. Since the patterned interconnects exhibited propagation losses of less than 1dB/cm, any losses seen in the simulations above 1dB/cm of the y-branch and directional coupler are due to bends within the structure. However, the Y-branch and directional coupler components were fabricated with NR7-6000 to show the capabilities of the laser direct writing technique. Figures 28, 29, and 30 are optical micrographs of the Y-branch components with angles of 2, 4, and 8°. Each of the branch extend until the parallel separation between waveguides is 80μm to avoid the evanescent wave coupling effects discussed in Section 3.2.3. The width of the waveguides at any point is measured to 5.46μm.
Figure 28: Y-branch shown with a 2° splitting angle.

Figure 29: Y-branch shown with a 4° splitting angle.

Figure 30: Y-branch shown with an 8° splitting angle.
Directional couplers that were micropatterned are found in Figures 31 and 32. Again the width of the waveguide is 5.5μm as in the previous designs. The coupling length highlighted in Figure 31, and the coupling width along with the waveguide width is shown in Figure 32.

![Figure 31: Directional coupler shown with a coupling length of 800μm.](image1)

![Figure 32: Directional coupler shown with a magnified view of the coupling width.](image2)

In an effort to show that more complex designs are feasible using laser direct writing a 1 x 8 power splitter is micropatterned (Figs. 33 and 34). Even though angles of 8° were shown to have high losses they are used so that the entire structure may be viewed at a higher
magnification. The consistency of the direct writing technique is again apparent, as accurate angles and desired waveguide dimensions are easily reproduced.

Figure 33: 1 x 8 power splitter.

Figure 34: 1 x 8 splitter with measurement overlay.

4.5 Hypothesis Testing

As was discussed in Chapter 1, the research question is formulated as a null hypothesis and alternate hypothesis. The stated hypotheses are:
• **Null Hypothesis:**

There is no significant difference in output power means due to the length of the micro-patterned optical waveguide at a confidence level of 95%.

\[ H_0: \mu_1 - \mu_2 = 0 \]

• **Alternative Hypothesis:**

There is significant difference in output power means due to the length of the micro-patterned optical waveguide at a confidence level of 95%.

\[ H_a: \mu_1 - \mu_2 > 0 \]

Testing at a standard confidence level of 95% (\( \alpha = 0.05 \)) for 3 degrees of freedom (df), the critical value of “t” for a one tailed test is 2.35336343 [52].

Statistical analysis methods are performed, as well as the generation of tables, using the Data Analysis function within Microsoft Excel. To test the difference of means between samples a t-Test for paired samples is utilized on the data in Table 3.

<table>
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<tr>
<th>Distance</th>
<th>Sample #1</th>
<th>Sample #2</th>
<th>Sample #3</th>
<th>Sample #4</th>
</tr>
</thead>
<tbody>
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<td>6mm</td>
<td>0.0185</td>
<td>0.0180</td>
<td>0.0170</td>
<td>0.0179</td>
</tr>
<tr>
<td>10mm</td>
<td>0.0160</td>
<td>0.0158</td>
<td>0.0157</td>
<td>0.0156</td>
</tr>
<tr>
<td>16mm</td>
<td>0.0140</td>
<td>0.0132</td>
<td>0.0133</td>
<td>0.0134</td>
</tr>
<tr>
<td>23mm</td>
<td>0.0135</td>
<td>0.0128</td>
<td>0.0130</td>
<td>0.0129</td>
</tr>
<tr>
<td>26mm</td>
<td>0.0120</td>
<td>0.0121</td>
<td>0.0120</td>
<td>0.0128</td>
</tr>
<tr>
<td>33mm</td>
<td>0.0110</td>
<td>0.0115</td>
<td>0.0116</td>
<td>0.0107</td>
</tr>
</tbody>
</table>

For the first segment, the means of the 6mm and the 10mm interconnects are compared (Table 4), and the calculated t-value is 7.80798321. This value is greater than the 95% significance calculated t-value of 2.35336343. Therefore, the null hypothesis (\( H_0 \)) is rejected.
Mathematically:

\[ t_{\text{Stat}} > t_{\text{Critical}} \]

7.80798321 > 2.35336343

Therefore,

Reject \( H_0 \), Accept \( H_a \)

\[ \mu_1 - \mu_2 > 0 \]

Table 4: Paired two sample \( t \)-test for means for 6mm and 10mm optical interconnects.

<table>
<thead>
<tr>
<th>Significance Level ( \alpha = 0.05 )</th>
<th>6mm</th>
<th>10mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.01785</td>
<td>0.015775</td>
</tr>
<tr>
<td>Variance</td>
<td>3.9E-07</td>
<td>2.9167E-08</td>
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<td>4</td>
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<tr>
<td>Pearson Correlation</td>
<td>0.64070322</td>
<td></td>
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<tr>
<td>Hypothesized Mean Difference</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>( t ) Stat</td>
<td>7.80798321</td>
<td></td>
</tr>
<tr>
<td>( P(T\leq t) ) one-tail</td>
<td>0.00218653</td>
<td></td>
</tr>
<tr>
<td>( t ) Critical one-tail</td>
<td>2.35336343</td>
<td></td>
</tr>
</tbody>
</table>

The next segment, the means of the 6mm and the 16mm interconnects are compared (Table 5), and the calculated \( t \)-value is 18.549963. This value is greater than the 95% significance calculated \( t \)-value of 2.35336343. Therefore, the null hypothesis (\( H_0 \)) is rejected. Mathematically:

\[ t_{\text{Stat}} > t_{\text{Critical}} \]

18.549963 > 2.35336343

Therefore,

Reject \( H_0 \), Accept \( H_a \)

\[ \mu_1 - \mu_2 > 0 \]
Table 5: Paired two sample t-test for means for 6mm and 16mm optical interconnects.

<table>
<thead>
<tr>
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<th>6mm</th>
<th>16mm</th>
</tr>
</thead>
<tbody>
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<td>Significance Level α</td>
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</tr>
<tr>
<td>Mean</td>
<td>0.01785</td>
<td>0.013475</td>
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<tr>
<td>Variance</td>
<td>3.9E-07</td>
<td>1.2917E-07</td>
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<td>Pearson Correlation</td>
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<tr>
<td>Hypothesized Mean Difference</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>t Stat</td>
<td>18.549963</td>
<td></td>
</tr>
<tr>
<td>P(T&lt;=t) one-tail</td>
<td>0.000171</td>
<td></td>
</tr>
<tr>
<td>t Critical one-tail</td>
<td>2.35336343</td>
<td></td>
</tr>
</tbody>
</table>

The next segment, the means of the 6mm and the 23mm interconnects are compared (Table 6), and the calculated t-value is 17.7251747. This value is greater than the 95% significance calculated t-value of 2.35336343. Therefore, the null hypothesis (H₀) is rejected. Mathematically:

\[ t_{\text{Stat}} > t_{\text{Critical}} \]

\[ 17.7251747 > 2.35336343 \]

Therefore,

Reject H₀, Accept Hₐ

\[ \mu_1 - \mu_2 > 0 \]

Table 6: Paired two sample t-test for means for 6mm and 23mm optical interconnects.

<table>
<thead>
<tr>
<th></th>
<th>6mm</th>
<th>23mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance Level α</td>
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<td>4</td>
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</tr>
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<td>df</td>
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<td></td>
</tr>
<tr>
<td>t Stat</td>
<td>17.7251747</td>
<td></td>
</tr>
<tr>
<td>P(T&lt;=t) one-tail</td>
<td>0.00019576</td>
<td></td>
</tr>
<tr>
<td>t Critical one-tail</td>
<td>2.35336343</td>
<td></td>
</tr>
</tbody>
</table>
The next segment, the means of the 6mm and the 26mm interconnects are compared (Table 7), and the calculated t-value is 15.870276. This value is greater than the 95% significance calculated t-value of 2.35336343. Therefore, the null hypothesis (H₀) is rejected.

Mathematically:

\[ t_{\text{Stat}} > t_{\text{Critical}} \]
\[ 15.870276 > 2.35336343 \]

Therefore,

Reject H₀, Accept Hₐ

\[ \mu₁ - \mu₂ > 0 \]

Table 7: Paired two sample t-test for means for 6mm and 26mm optical interconnects.

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<td>df</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>t Stat</td>
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<td></td>
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<tr>
<td>P(T&lt;=t) one-tail</td>
<td>0.000272</td>
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<td>t Critical one-tail</td>
<td>2.35336343</td>
<td></td>
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</table>

The final segment tested, the means of the 6mm and the 33mm interconnects are compared (Table 8), and the calculated t-value is 14.2590967. This value is greater than the 95% significance calculated t-value of 2.35336343. Therefore, the null hypothesis (H₀) is rejected.

Mathematically:

\[ t_{\text{Stat}} > t_{\text{Critical}} \]
\[ 14.2590967 > 2.35336343 \]

Therefore,
Reject $H_0$, Accept $H_a$

$\mu_1 - \mu_2 > 0$

Table 8: Paired two sample $t$-test for means for 6mm and 33mm optical interconnects.

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<th>Significance Level $\alpha=0.05$</th>
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<th>33mm</th>
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<td></td>
</tr>
<tr>
<td>df</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>t Stat</td>
<td></td>
<td>14.2590967</td>
<td></td>
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<td>$P(T&lt;=t)$ one-tail</td>
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<td>0.0003737</td>
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<td>2.35336343</td>
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CHAPTER 5

CONCLUSIONS

An efficient and cost effective method of mask-less UV photolithography micropattering of all polymer single mode passive optical components for the use in OICs is shown. Three different types of negative photo resists thin films were characterized to find index of refraction at wavelengths of 633nm and 1550nm and to acquire photo resist spinner calibration curves with various spin rates for determining thin film thickness. Simulations were preformed to determine dimensions for single mode optical channel waveguide components. Simulations also predicted the loss of y-branches bends, as well as the determining the optimal width and length for full coupling to occur in an evanescent wave directional coupler. Characterization of the resulting interconnection components tested shows the micropatterned waveguides to be single mode and have losses of 0.79dB/cm which achieves the goal of having less that 1dB/cm loss which integral for use in OICs. Waveguide width and the depth dimensions are shown graphically to be dependent on the energy density of the writing laser. Laser direct writing provides a promise of future trends in micro miniaturization fabrication especially in prototyping optical systems where turn around time and low operation cost is vital.
APPENDIX A

PRISM COUPLER INDEX OF REFRACTION MEASUREMENT DATA
Futurrex NR7-6000

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### Ormocore

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<td>140</td>
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</tr>
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55
### Ormoclad

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### Data Table

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</table>

### Graph

The graph shows a spectral analysis with peaks at various wavelengths and intensities.
**Ormocore/Ormoclad 50%/50% Mixture**

![Graph of Ormocore/Ormoclad 50%/50% Mixture](image)

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**Ormoclad/core**

![Graph of Ormoclad/core](image)

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<th>Intensity:</th>
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</thead>
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<tr>
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<th>555</th>
<th>315</th>
<th>75</th>
<th>-165</th>
<th>Step</th>
<th>0</th>
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APPENDIX B

WAVEGUIDE SIMULATION RESULTS
Y-branch Simulation for 0.5-8° bends

0.5° Y-branch

1° Y-branch
1.5° Y-branch

2° Y-branch
2.5° Y-branch
3° Y-branch

3.5° Y-branch
4° Y-branch
4.5° Y-branch

5° Y-branch
5.5° Y-branch

6° Y-branch
6.5° Y-branch

- Pathway
- Monitor
1. Power
2. Power

Monitor Value (a.u.) vs. Propagation Direction (μm)
7° Y-branch

7.5° Y-branch
$8^\circ$ Y-branch
Directional Coupler

1μm Coupling Width

1.5μm Coupling Width
2μm Coupling Width

2.5μm Coupling Width
3 μm Coupling Width
3.5μm Coupling Width

4μm Coupling Width
5 μm Coupling Width
6μm Coupling Width

7μm Coupling Width
APPENDIX C

TRANSLATION STAGES G-CODE FOR WAVEGUIDE STRUCTURES
Interconnection Code

;Brad Borden
;Dr. Shuping Wang, Advising Professor

; This program writes 20 straight interconnection waveguides
; with a separation of 80um and width of approx. 5.5um

DVAR $fil
$fil = FILEOPEN "COM1", 2
COMMINIT $fil, "baud=9600 parity=N data=8 stop=1" ;initialize COM port
COMMSETTIMEOUT $fil, -1, 0, 0 ; Define timeout for data at serial port
ENABLE X Y
; turn on servo loop control for the axes
METRIC
; set to use metric programming units
SECONDS
; speeds interpreted as units / second
ABSOLUTE
; set absolute programming mode

; Starting location
LINEAR X30 Y80 F20
DWELL 0.1

; Interconnects
REPEAT 20
   FILEWRITENOTERM $fil, "ens\x0D" ; shutter open
   LINEAR Y-40 F1
   FILEWRITENOTERM $fil, "ens\x0D" ; shutter closed
   DWELL 0.1
   LINEAR X0.08 Y40 F10
   DWELL 0.1

ENDRPT

FILECLOSE $fil
DWELL 0.1
HOME X Y ; Program end
Y-branch Code

; Brad Borden
; Dr. Shuping Wang, Advising Professor

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;; These program writes Y-branches with angles of 2°, 4°, and 8° and has a waveguide width of approximately 5.5um
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

DVAR $fil
$fil = FILEOPEN "COM1", 2
COMMINIT $fil, "baud=9600 parity=N data=8 stop=1" ; initialize COM port
COMMSETTIMEOUT $fil, -1, 0, 0 ; Define timeout for data at serial port
ENABLE X Y ; turn on servo loop control for the axes
METRIC ; set to use metric programming units
SECONDS ; speeds interpreted as units / second
ABSOLUTE ; set absolute programming mode

; Starting Position
LINEAR X30 Y80 F40

; 2° Y-branch
; Upper Arm
INCREMENTAL ; set to incremental programming mode
FILEWRITENOTERM $fil, "ens\x0D" ; shutter open
LINEAR Y-2 F1 G8
CCW X-0.02 Y-0.573075 I-16.41819 J0 F1 G8
CW X0.02 Y-0.573075 I-16.37819 J-1.146148 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ; shutter CLOSED
DWELL 0.2

ABSOLUTE
LINEAR X30 Y80 F40
DWELL 0.2

; Lower Arm
INCREMENTAL
FILEWRITENOTERM $fil, "ens\x0D" ; shutter open
LINEAR Y-2 F1 G8
CW X-0.02 Y-0.573075 I-16.41819 J0 F1 G8
CCW X-0.02 Y-0.573075 I16.37819 J-1.146148 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ; shutter CLOSED

ABSOLUTE
LINEAR X29.5 Y80 F40
DWELL 0.2

; 4° Y-branch
; Upper Arm
INCREMENTAL
FILEWRITENOTERM $fil, "ens\x0D" ; shutter open
LINEAR Y-2 F1 G8
CW X0.02 Y-0.286013 I4.107677 J0 F1 G8
CW X0.02 Y-0.286013 I-4.067677 J-0.572026 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ;shutter CLOSED
DWELL 0.2

ABSOLUTE
LINEAR X29.5 Y80 F40
DWELL 0.2

;Lower Arm
INCREMENTAL
FILEWRITENOTERM $fil, "ens\x0D" ;shutter open
LINEAR Y-2 F1 G8
CW X-0.02 Y-0.286013 I-4.107677 J0 F1 G8
CCW X-0.02 Y-0.286013 I4.067677 J-0.572026 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ;shutter CLOSED

;8° Y-branch
;Upper Arm
ABSOLUTE
LINEAR X29 Y80 F40
DWELL 0.2

INCREMENTAL
FILEWRITENOTERM $fil, "ens\x0D" ;shutter open
LINEAR Y-2 F1 G8
CCW X0.02 Y-0.142307 I1.031803 J0 F1 G8
CW X0.02 Y-0.142307 I-0.991803 J-0.284615 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ;shutter CLOSED
DWELL 0.2

ABSOLUTE
LINEAR X29 Y80 F40
DWELL 0.2

;Lower Arm
INCREMENTAL
FILEWRITENOTERM $fil, "ens\x0D" ;shutter open
LINEAR Y-2 F1 G8
CW X-0.02 Y-0.142307 I-1.031803 J0 F1 G8
CCW X-0.02 Y-0.142307 I0.991803 J-0.284615 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ;shutter CLOSED

FILECLOSE $fil
DWELL 0.1
HOME X Y ; Program end
Directional Coupler Code

; Brad Borden
; Dr. Shuping Wang, Advising Professor
; This program writes a directional coupler with a coupling
; width of approx. 3um, coupling length of 800um, and bends
; of 4°
;
DVAR $fil
$fil = FILEOPEN "COM1", 2
COMMINIT $fil, "baud=9600 parity=N data=8 stop=1"
COMMSETTIMEOUT $fil, -1, 0, 0 ; Define timeout for data at serial port
ENABLE X Y
; turn on servo loop control for the axes
METRIC
; set to use metric programming units
SECONDS
; speeds interpreted as units / second
ABSOLUTE
; set absolute programming mode
; Directional coupler 4°
; Starting position
LINEAR X28 Y80 F40
DWELL 0.2

; Upper Segment
INCREMENTAL
FILEWRITENOTERM $fil, "ens\x0D" ; shutter open
LINEAR Y-2 F1 G8
CW X-0.02 Y-0.286013 I-4.107677 J0 F1 G8
CCW X-0.02 Y-0.286013 I4.067677 J-0.572026 F1 G8
LINEAR Y-0.8 F1 G8 ; Coupling Length of 800um
CCW X0.02 Y-0.286013 I4.107677 J0 F1 G8
CW X0.02 Y-0.286013 I-4.067677 J-0.572026 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ; shutter CLOSED

ABSOLUTE
LINEAR X27.91 Y80 F40
DWELL 0.2

; Lower Segment
INCREMENTAL
FILEWRITENOTERM $fil, "ens\x0D" ; shutter open
LINEAR Y-2 F1 G8
CW X-0.02 Y-0.286013 I-4.107677 J0 F1 G8
CCW X-0.02 Y-0.286013 I4.067677 J-0.572026 F1 G8
LINEAR Y-0.8 F1 G8 ; Coupling Length of 800um
CW X-0.02 Y-0.286013 I-4.107677 J0 F1 G8
CCW X-0.02 Y-0.286013 I4.067677 J-0.572026 F1 G8
LINEAR Y-2 F1 G8
FILEWRITENOTERM $fil, "ens\x0D" ; shutter CLOSED

FILECLOSE $fil
DWELL 0.1
HOME X Y ; Program end
REFERENCES


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