PDMS based waveguides for microfluidics and EOCB

Weiping Qiu
Louisiana State University and Agricultural and Mechanical College

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PDMS Based Waveguides for Microfluidics and EOCB

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Mechanical Engineering
in
The Department of Mechanical Engineering

by
Weiping Qiu
B.S., Zhejiang University, 2004
M.S., Zhejiang University, 2006
August 2012
Acknowledgments

I would like to take this opportunity to sincerely thank my major advisor, Dr. Wanjun Wang, for his continuous guidance, encouragement and support. Without Dr. Wang’s devoted time and effort, this research work and thesis would not be completed progressively.

I am also obliged to my committee members: Dr. Su-Seng Pang and Dr. Ashok Srivastava, for their professional advices and guidance.

I want to express my appreciation to my group fellows, Guocheng Shao, Yuxuan Zhou, Zhengyu Miao and Ziliang Cai for their help and discussions on the research.

Last, and most importantly, I wish to thank my parents. Their endless love and support made every single progress in my life possible.
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Abstract

Due to the low cost, fast and ease of molding, PDMS has become one of the most popular materials for microfluidics devices, bioMEMS applications. Meanwhile, the integration of different functional components on to one single chip (or Lab on a Chip) is the dream for many scientists and engineers in the related area. In addition to the necessary mechanical components for accommodating the reactions, such as pumps, valves, mixers and so on, optical components such as waveguides, lens, interferers are all desired to be lumped into such a system.

The waveguide for such a system requires the material to have good transparency, and more importantly, compatibility with the materials and current fabrication technique. PDMS is the candidate which fits all the requirements. But, for a waveguide to function, refractive index difference must be fulfilled that is the refractive index of the core material should be higher than the cladding material.

In this thesis, a PDMS waveguide using different mixing ratios of base and curing agent of Sylgard 184 is fabricated. The main aspects of this thesis work includes: (1) Refractive indices of a series of Sylgard 184 PDMS with base to curing agent ratio have been measured. Different mixing ratios of the base and curing agent mixture were found to have different refractive index which indicates its potential in waveguide application. (2) A prototype of the waveguide with different mixing ratios for the core and cladding part respectively is fabricated. The idea of the realization of this approach is confirmed.
Chapter 1
Introduction

1.1 MEMS and ‘Lab on a Chip’

Micro-Electro-Mechanical Systems (MEMS) are integrated devices which nominally couples different functional components with small feature size usually in the range of 100 nm — 10 cm. In the early stage of MEMS history, researches have been mainly focused on the integration of mechanical parts and electrical parts, and based on silicon materials[17]. Several successful commercial products were developed with MEMS technology such as ink-jet printers by IBM[16] and micro-mirror array projectors by Texas Instruments[25]. With the expansion needs of the miniaturization of devices in different application fields, MEMS has been quickly extended into areas like chemical and biomedical reactions and detections which are microfluidics manipulation related.

Modern microfluidics can be traced back to the development of a silicon chip based gas chromatograph at Stanford [23] and the ink-jet printer at IBM [16] in the late 1970s. Since then, major components for the microfluidics system, such as micro-scale channels, valves, pumps and mixers has been developed and modified[15]. With significant decreasing in size, the microfluidics system shows significant advantages over its macro-scale counterpart: minimized consumption of reagents, increased automation, reduced manufacturing costs, and improved efficiency.

One of the long term goals of microfluidics system is the fulfilling of the concept of ‘lab on a chip’. This is a dream for many researchers from different fields, especially for chemical and biomedical analysts. Two major function parts should
be included in this ‘lab on a chip’: (1) one is a microfluidics manipulation system, including chemical transportation reaction separation and so on. (2) the other part is the sensing and characterization system. Enormous effort on the development of microfluidic functional elements has built the foundation for the microfluidics manipulation[14].

1.2 Optical Sensing and Detection of ‘Lab on a Chip’

In the sensing system, the detection issues will arise when the whole system is scaled down. Beside all kinds of advantages it has, the reduced dimensions means smaller analysis volumes, but also means a reduction in detection volumes, decreasing the number of chemicals available for detection, hence making them more difficult to be detected. Thus, the two main factors that affect the choice of the detection method for microfluidic devices are sensitivity and scalability to smaller dimensions. Regular electro-chemical detection does not fulfill all these conditions, where sensitive portable systems are required. Optical sensing shows great sensitivity. Coupling or integrating optical components into microfluidic devices is a popular choice. Depending on the existence form of the optical sensing system, optical sensing systems are divided into two categories: (a), Out of chip sensing, in which optical sensing system is coupled to microfluidic devices; (b), On chip sensing, in which micro-optical components are integrated into microfluidic devices as a whole. Figure 1.1 shows an out of chip optical sensing system, in which optical system is not integrated into the reaction chip, only optical fibers used to guide the excitation light are inserted to the sensing area.

Different from out of chip sensing, optical components in the on chip sensing system are integrated into the substrate chip to fulfill both reaction and detec-
tion functions on the same single chip. The optical components used in these detectors are mainly light emitting diodes (LEDs) or laser diodes as light sources, optical fibers, gradient refractive index lenses, and diffractive elements. These are assembled into compact detectors to develop a portable instrumentation based on microfluidic devices. From both the materials and technology standpoint, the integration of optical functions into a microchip is very promising. Optical components like micro-lens and waveguides have been integrated into system by different research groups [8, 21, 22, 29].

1.2.1 Absorbance Based Sensing

UV/Vis absorbance detection is the most widely used detection method in common macro-structure sensing systems. However, due to the significant decreasing of the dimensions of the detection area, usually the micron sized channels, the sensitivity of the detection becomes a big issue. Incorporation of optical fibers into the detection region is a simple approach[12]: the chip is positioned between the ends of two optical fibers facing one another. One fiber was connected to a light
source and the other collects the transmitted light and guided it into a CCD array. As light from an optical fiber is highly divergent, both excitation and detection fibers usually need to get very close to yield sufficient irradiance. To overcome this problem, a cylindrical micro-lens at the end of the excitation fiber has been added [19].

1.2.2 Fluorescence Based Sensing

Laser-induced fluorescence detection is the most widely used optical method for micro-sensing systems, due to its superior selectivity and sensitivity [18]. The integration of micro-lenses and planar waveguides in microfluidic devices is useful for improvement of the detection in sensing systems. For instance, by using a planar waveguide the optical path length can be increased for absorbance measurements, or by focusing the light in the channel to increase the excitation power for fluorescence measurements. Out of plane lens has been into a microfluidics cytometer system by double exposure lithography of SU-8 process [22]. Roulet et al. fabricated micro-lenses directly into a glass chip for the collection of fluorescence light, by melting islands of photoresist into a hemispherical shape [20]. In another approach, a microfluidic device in PDMS contained an insertion channel to accommodate an optical fiber for fluorescence excitation [7]. Multiple 2D planar micro-lenses have been used to focus the light from a LED into a microfluidic channel [21]. This design enabled a reduction in the spot size and a seven fold increase of the fluorescence signal.

1.2.3 Waveguides for On Chip Sensing

Optical waveguides are used for guiding electromagnetic waves in the optical spectrum. The basic principle of optical waveguides is the total internal reflection. Total internal reflection happens on the boundary of two medium materials if the inci-
dent angle of the light beam is greater than the critical incident angle, $\Phi_c$, which is determined by the refractive indices of the two materials. Figure 1.2 shows the total reflection of light in a fish tank.

Optical glass fiber is the ideal waveguides for long distance telecom application with broad bandwidth and very low attenuation loss. However, optical glass fiber is not compatible with current microfluidics system fabrication process. PDMS based polymer materials have attracted more attention because of their ease in fabrication and compatibility with substrate materials, thanks to the vastly use of PDMS in microfluidics devices [8, 9].

1.3 PDMS Based Waveguides in EOOCB

Other than optical MEMS applications, PDMS based waveguides have drawn plenty of attentions in substituting copper based waveguides in data and telecommunication [4, 6, 13, 28]. The increasing speeds being seen for optical communications are increasing the speed and frequencies being used in telecom and datacom
equipment, which is causing electrical interconnection to be pushed to its limits. A new concept of embedded optical waveguides in conventional printed circuit board technology has been proposed (See Figure 1.3). The final product will be the Electrical-Optical-Circuit-Board (EOCB)[5]. The polymer waveguide structure that integrated in the EOCB system consists of three layers, i.e. top cladding layer, core layer and bottom cladding layer.

Some of the key qualitative properties for waveguide materials are listed below:

1. Good refractive index control

2. Intrinsic absorption loss, low optical scattering loss, and low polarization dependent loss

3. Low cost and environmental friendly material and low material processing loss

4. High thermal stability, good environmental stability and good mechanical strength

5. Similar coefficient of thermal expansion (CTE) value as the other materials in use
1.4 Scope of the Research

The research work presented in this thesis is focused on PDMS based waveguides for microfluidics system and EOCB. PDMS elastomers with different compositions have been investigated.

In chapter 2, refractive indices of different composition combinations of Sylgard 184 will be given out. Mixtures ratios of 20 : 1, 10 : 1, 5 : 1, and 2.5 : 1 for base and curing agent of Sylgard 184 were prepared. Refractive indices for all mixture ratios were measured to find out the proper core and cladding materials matchup.

In chapter 3, the design and fabrication process of the PDMS based waveguides will be discussed. Because of low Young’s modulus of PDMS, misalignment frequently happens when interfacing PDMS base waveguide devices to optical glass fiber by inserting fibers into the holder channels. 20 : 1 and 5 : 1 mixture ratio Sylgard 184 were chosen as cladding and core material respectively. Lithography of SU-8 mold, together with PDMS molding process will also be given in detail.

In Chapter 4, preliminary results will be given out. The intensity at the receiving end of both with and without the waveguide core are measured to confirm the effectiveness of the waveguide fabricated by using different mixing ratios of base and curing agent of Sylgard 184.
Chapter 2
Refractive Indices of Sylgard 184 PDMS with Different Base and Curing Agent Mixing Ratios

2.1 Introduction

PDMS based waveguides show its inherent advantage in compatibility with the widely used PDMS substrate in microfluidics applications, comparing to other polymer based waveguides, such as PMMA or SU-8 [3, 11]. In a PDMS microfluidics system, the relative stiff and brittle SU-8/PMMA waveguides are prone to breakage upon handling when embedded into the flexible PDMS substrate. Another advantage of PDMS is its broader transparency spectrum, down to 300 nm, into the UV band.

However, the key reason for PDMS being used as waveguide materials is the easy access to the modification of refractive indices by different fabrication process or composition modification. For a core/cladding structured waveguide, refractive index of core material is required to be higher than the cladding material so that the light is confined inside the waveguide by total internal reflection. So far, different refractive indices of PDMS materials have been reported. David A. Chang-Yen et al has reported their PDMS waveguides by curing the core and cladding part of the waveguides at different temperatures[8]. Their research indicated that crosslinking degree of PDMS material depends on the curing temperature and time. The curing of core PDMS at an elevated temperature leads to a higher refractive index compare the cladding PDMS curing at room temperature with extended curing time. The waveguide fabricated by this method showed moderate temperature and humidity sensitivity but without temporal variation over a 30 day period. However, the intrinsic temperature instability causes a big concern since the core and cladding
materials were cured at different temperature [13]. To avoid this, PDMS based waveguides comprises of two distinct materials for core and cladding parts was proposed by Stefan Kopetz and his colleagues [13]. In their work, the core materials is using a special development by Wacker Chemie with the provisorial product name SLM 77522 while the cladding material is a standard commercial PDMS material (Wacker ELASTOSIL RT 601). In the core materials, a few methyl groups were substituted by phenyl groups for obtaining a higher refractive index[5]. Both high temperature stability($> 29^\circ C$) and low attenuation loss were achieved with the specialized core part materials. However, the modification of the core material by replacing methyl groups by phenyl groups may not only change the optical properties, the materials properties and compatibility problem may arise at the mean time. Hence, PDMS based waveguides made of cheaper and handy commonly used commercial products with good materials compatibility is highly favored.

2.2 Sylgard 184 PDMS

The curing of PDMS is a process where crosslinking of the PDMS chains happens when two components mixed with each other with certain ratio. Cross-linking is achieved using vinyl ended polymers with Si-H groups carried by functional oligomers.

The addition occurs mainly on the terminal carbon and is catalyzed by Pt. As illustrated in Figure 2.1, the crosslinking process is made of three steps: oxidative addition of the Si-H on the Pt, H transfer on the double bond, and reductive elimination of the product.

Sylgard 184 PDMS is a Dow Corning Corporation elastomer product kit based on addition cross-linking. The kit contains two chemicals: Base (part A) and Curing Agent (part B).
FIGURE 2.1. PDMS polymerisation scheme based on a two-component set (courtesy of Dow Corning)

The Base (part A) contains the followings[1]:

1. Dimethyl siloxane, dimethylvinyl terminated - 68083-19-2
2. Dimethylvinylated and trimethylated silica - 68988-89-6
3. Tetra (trimethoxysilox) silane - 3555-47-3
4. Ethyl benzene - 100-41-4

The Curing Agent (part B) contains the followings:

1. Dimethyl, methylhydrogen siloxane - 68037-59-2
2. Dimethyl siloxane, dimethylvinyl terminated - 68083-19-2
3. Dimethylvinylated and trimethylated silica - 68988-89-6
4. Tetramethyl tetravinyl cyclotetra siloxane - 2554-06-5

5. Ethyl benzene - 100-41-4

2.3 Varying Refractive Indices by Changing Base and Curing Agent Ratio

As mentioned in Section 2.1, the refractive index of PDMS could be modified either by curing at different temperature or by introducing different branch groups to the polymer chain.

The curing temperature matters sound intuitive because reaction molecules are more active at an elevated temperature. The refractive index of the cured PDMS is dependent on its curing degree, which well explains the refractive indices variation between materials cured at different temperatures because the PDMS chains tend to be more active at higher curing temperature.
2.4 Refractive Indices Measurement

In order to testify the idea of fabricating a waveguide with the same PDMS products but different compositions for its core and cladding parts, PDMS with different base and curing agent ratio were mixed and cured, for further refractive indices measurement. Since the commercial Sylgard 184 silicone elastomer is supplied to be mixed at a ratio of 10 : 1 (base: agent), four different mixing ratios were chosen around this standard point from 2.5 : 1 to 20 : 1. For each composition, about 0.5 g of curing agent (Sylgard 184 part B) was poured into a small plastic beaker on an electronic weighing scale. Too small amount of the curing agent may lead to an unpredictable real mixing ratio, considering the factors like container wall stripping and the uncertainty of the measurement itself. Then, the base part (Sylgard 184 part A) was gradually added into the beaker very carefully according to get desired mass mixing ratios at 2.5 : 1, 5 : 1, 10 : 1, and 20 : 1. The mixture was then stirred with a clean plastic stick for about 2 minutes. Air bubbles were generated and gradually broken down in the stirring process. Uniformly distributed enormous tiny air bubbles indicate the well mixing of the two parts. The mixture with bubbles was then vacuumed by VT5042EK500 Vacuum Oven at room temperature for 10 minutes to eliminate the bubbles. The de-aerated mixture was then poured onto a clean and dry 4 inch diameter silicon wafer surface, and then cured in M326 Mechanical Convection Oven at 65°C for 2 hours.

The refractive indices of the 4 different compositions of the cured PDMS were measured by ellipsometry method. Figure 2.3 showed the ellipsometric data of the four different compositions of the cured Sylgard 184 PDMS. The refractive index of each composition decreases with the increasing wavelength which follows the trend of Sellmeier formula. The refractive index difference between 20 : 1 and 5 : 1 should
FIGURE 2.3. Refractive index for different mixing ratio of Sylgard 184. (a) Sylgard 184(20 : 1), (b) Sylgard 184 (10 : 1), (c) Sylgard 184(5 : 1), and (d) Sylgard 184(2.5 : 1) be good enough for them to be used as cladding and core part of the waveguide respectively. This composition combination is suggested for further test.
Chapter 3
Design and Fabrication of the PDMS Based Waveguides with Modified Mixing Ratio of Sylgard 184

3.1 Introduction

PDMS is a soft and flexible elastomer making it a very excellent soft lithography material [2, 26]. The highly hydrophobic surface of the cured PDMS makes the de-molding process very easy when PDMS is involved either on the mold side or on the device material side. PDMS polymer has been widely used in the replica molding applications with very high fidelity achieved[26]. The feature size of the structures down to nanometers could be replica molded with PDMS[27].

3.2 Design

Since the aim of this thesis is to investigate the potential of fabricating the PDMS based waveguides with modified mixing ratio and further verify it by introducing a prototype, a multimode waveguide of 125 microns in width to match up with 125 microns in diameter optical fiber is designed. The core/cladding structured optical waveguides consist of two parts, the core with a relative higher refractive index, and the cladding with a relative lower refractive index. The core is either fully surrounded or half surrounded by its cladding. The latter is using air as part of its cladding since refractive index of air is considered to be 1 which is always lower than the core. The half surrounded core/cladding configuration such as planar waveguides, usually takes less fabrication steps. Although, the half surrounded waveguide is proven to work and has been used in many real applications, the fully surrounded core is preferred to investigate the optical property where a symmetrical structure is believed to simplify the analysis and some unnecessary concern
FIGURE 3.1. A 2D schematic diagram of waveguide design

could be ignored. The fabrication of a fully surrounded core taken by our method is just as simple as the fabrication of a planar PDMS waveguide.

Figure 3.1 shows the 2D schematic diagram of the waveguide design. The core with its two ends connected to two optical fiber insertion holders where the optical fibers could be interfaced for attenuation test.

Figure 3.2 gives the flow chart of the fabrication procedure. Generally the whole fabrication is made of three steps. The first step is to fabrication of the SU-8 mold by UV lithography. The second step is the casting of the cladding part of the PDMS waveguide and a permanent bonding of the top and bottom layer of the cladding. The third step is the casting of the core part.

3.3 Fabrication of the PDMS Based Waveguides with Modified Mixing Ratio of Sylgard 184

3.3.1 Fabrication of SU-8 Mold by UV Lithography

UV Lithography has been widely used in fabricating structures with feature size in microns. It is a cheaper technique comparing to X-ray lithography. SU-8 is a negative tone photoresist that the UV exposed area will be cross-linked after the exposure through a patterned mask. As illustrated in Figure 3.1, a hollow channel
is desired just before filling it up with the high refractive index PDMS, to make a fully wrapped waveguide core. With this in mind, protruded SU-8 strips on silicon wafer is the goal in this mold fabrication step. The desired thickness of the SU-8 strips is 125 microns to matchup the 125 microns in diameter optical fiber for interfacing reason. A layer of SU-8 100 photoresist was spun coated to a clean and dry 4 inch silicon wafer by a PWM101 Light-duty Spinner at 2000 rpm for 25 seconds. The soft bake was taken at 95°C for 2 hours to evaporate off the solvent on the hotplate. The exposure dosage was 400 mJ/cm². A 30 minutes post bake was taken for the fully cross-linking of the exposed area. Throughout the soft and post bake process, care was taken in both the heating and cooling to avoid the over stressed structure.

Figure 3.3 gives the soft bake process of the SU-8 mold fabrication. The post bake process is similar but with a peak temperature of 95°C and dwelled for 30 minutes. The dwell step at 65°C for 15 minutes at both heating and cooling routes is necessary to release the stress introduced in the phase transformation process.

3.3.2 Casting of the Cladding of the PDMS Waveguides with Modified Mixing Ratio of Sylgard 184

Two casting steps were involved in this waveguides fabrication process. The first step was the casting of the cladding part which consists of two PDMS pieces. In this step, the mixing ratio of base to curing agent is chosen to be 20 : 1 as the lower refractive index is required. The bottom piece of the cladding is just a negative structure of the SU-8 mold. Micro-channels are obtained in reverse to the protruded strips on the SU-8 mold. The well mixed and de-gassed liquid state PDMS was poured into the as-prepared SU-8 mold. The mixing and de-gassing process was just the same as mentioned in Chapter 2. Then the PDMS liquid together with SU-8 was then placed into Mechanical Convection Oven (M326 Mechanical Convection
Oven in CAMD cleanroom, LSU) for 2 hours at 65°C for curing. The casting of the top cladding PDMS piece is very similar to the bottom piece. The only difference is that the top piece is mold on a clean and non-structured silicon wafer.

3.3.3 Bonding of the Cladding parts of PDMS Waveguides with Modified Mixing Ratio of Sylgard 184

In PDMS based microfluidics where multilayers of structure units are assembled together to function as a system, the bonding between different PDMS layers or some times PDMS/glass affects the functionality of the system [10]. It is more important in some specific application requiring a strong strength, such as the famous two cross channel pneumatic valve system [24]. Different bonding techniques, such as Oxygen plasma, corona discharge, partial curing, cross-linker variation and uncured PDMS adhesive have been investigated through many years. In our fabrication process, oxygen plasma bonding as the most widely used bonding method has been adopted for the two cladding pieces. Both the top and bottom piece of the cladding were treated by oxygen RF plasma for 30 seconds using the Bransen Plasma Asher (CAMD cleanroom, LSU). The fresh treated surfaces should be bonded to each other as soon as possible before the new generated O-H groups reacting with the oxygen in the air.

Figure 3.4 showed the failure surface of the bonded two cladding pieces after being forcibly pulled off. The newly created surface indicated a very good PDMS/PDMS bonding result.

3.3.4 Casting of the Core of the PDMS Waveguides with Modified Mixing Ratio of Sylgard 184

Generally two approaches could be adopted to fabricate a core fully wrapped core/cladding structured waveguide. The first approach is by casting the core first
and wrapping the core with cladding later. It is generally three steps fabrication process: core, bottom cladding, and top cladding. Since the core of the waveguide must be casted in a single step and tools such a doctor blade were applied to obtain the desired core structure, co-fabrication of other functional units together with the PDMS optical waveguides on the same layer seems difficult. The second approach is casting the cladding first instead and core later which is adopted by our fabrication process. The major advantage of this approach is that the external optical fibers could be interfaced with the fabricated waveguide with a seamless connection. The fibers were inserted into the hole created by the bonding of the two cladding piece before the 5 : 1 Sylgard 184 (core material) was filled. The core is filled up using a vacuum suction phenomenon. 5 : 1 Sylgard 184 PDMS liquid mixture is dropped only at two ends of the core channel to block the exits of the channel. Then the whole setup was placed into the vacuum oven to be vacuumed for 15 minutes. During the vacuum process, the liquid material at the two ends slowly fills the channel when the air inside were gradually pumped out. The main filling takes place when the air was re-entering the vacuum oven, where the higher oven air pressure pushing the liquid mixture into the vacuum channel. After the core channel was fully filled with the 5 : 1 Sylgard 184 PDMS, the whole setup was then placed into the convection oven to cure at 65°C for 2 hours.

Figure 3.5 shows the waveguide configuration before and after the curing of the core part. Pictures on the left are the middle part of the waveguide and the pictures on the right side are the waveguide/optical fiber interfacing structures. As marked in the picture, the optical fiber and waveguide core are not perfectly aligned as the intended design. This was probably because the optical fiber was not in a uniform contact with the channel side walls which caused the distortion or twist of the inserted optical fiber. As a result, tip of the distorted fiber leaned against on
one side of the soft channel wall. This misalignment greatly reduces the intensity of the signal on the receiving end. The degree of this misalignment is dependent on the handling of the insertion process making the attenuation measurement unpredictable.
FIGURE 3.2. Flowchart of fabrication
Dwell for 2 hrs
Ramp to 65 °C in 30 min
Dwell for 15 min
Ramp to 65 °C in 30 min
Relax at 25 °C for 30 min
Ramp to 100 °C in 30 min
Relax at 25 °C for 30 min
Dwell for 15 min
Ramp to 65 °C in 30 min
Relax at 25 °C for 30 min

FIGURE 3.3. Soft bake process for the SU-8 mold fabrication

FIGURE 3.4. The failure surface of the bonded PDMS cladding pieces
FIGURE 3.5. Core part of waveguide and core/optical fiber interface before and after core curing. (a) waveguide core before heating, (b) core/optical fiber interface before heating, (c) waveguide core after heating, and (d) core/optical fiber interface after heating
Chapter 4
Insertion Loss of the PDMS Based Waveguides Made of Modified Mixing Ratio Sylgard 184

4.1 Introduction
For microfluidic sensing and detection components, low insertion loss is desired. For the PDMS based waveguide, two parts contributes to the total insertion loss, the intrinsic loss and extrinsic loss. The intrinsic loss is caused by the absorption due to the molecule vibrations. It is found out that the harmonic vibrations of O-H and C-H bonds are the major contributors to the PDMS intrinsic loss [4, 5]. The extrinsic loss may due to parts, the scattering on the core and cladding boundary due to the roughness surface, deviation of the total internal reflection on the boundary due to materials diffusion in boundary region. The insertion loss is represented as the following formula:

\[ L = -10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \]  \hspace{1cm} (4.1)

Where \( L \) is the insertion loss of the device, \( P_{\text{in}} \) is the input signal intensity, and \( P_{\text{out}} \) is the output signal intensity on the receiving end.

4.2 Measurement Setup
As mention in Chapter 3, optical fibers were directly inserted into the waveguide channel in the fabrication process. A 460 nmm LED was used as the light source. The output signal was received by USB 4000 Spectrometer from Ocean Optics. Figure 4.1 shows the fabricated waveguide ready for the insertion loss test.

Waveguides with different effective length has been designed. They are 5 mm, 10 mm, 20 mm, 30 mm, and 50 mm respectively. To exclude the interfacing loss in-
fluence, output intensity of two different length waveguides is required to determine the insertion loss. A 5 mm waveguide insertion loss could be determined as

$$L_{5\text{mm}} = -10 \log \left( \frac{P_{\text{out}}^{10\text{mm}}}{P_{\text{out}}^{5\text{mm}}} \right)$$

(4.2)

where $P_{\text{out}}^{10\text{mm}}$ is the output of the light intensity behind a 10 mm long waveguide channel, and $P_{\text{out}}^{5\text{mm}}$ is the output intensity behind a 5 mm long waveguide.

### 4.3 Results Discussion

Figure 4.2 shows the light intensity of the 460 nm LED light source after passing through the 5 mm PDMS waveguide. A relative strong signal was detected by the spectrometer which confirms the working of the PDMS waveguide by our method. In order to further confirm this, the inserted optical fibers were slightly pulled off to check the signal strength change.

Figure 4.3 showed the signal strength with 1 mm pulled off on each side. A dramatic decrease was observed with more than 30 folds as only a very weak signal peak was detected at 460 nm wavelength. When the optical fibers pulled further away, only about 2 mm from the waveguide interface, the output signal dies off. It
FIGURE 4.2. Intensity of the 460 nm LED light behind a 5 mm long PDMS Waveguide is interesting because the signal decrease faster than in the air medium. This could be due to two reasons. The first one is the alignment problem the optical fiber and the waveguide. When the optical fiber and the waveguide directly contact each other, there is no problem for the signal light entering into the waveguide path. However, when there is a gap between the optical fiber and the waveguide, slightly misalignment could cause severe deviation of the signal light off the track of the waveguide.

In order to further verify the effect of the waveguide, a contrast test with no core filled was carried out. Two optical fibers were inserted into a bonded cladding channel without core filled. Figure 4.5 shows the measured spectrum at the receiving end, the signal is about 10 fold lower than the one using a waveguide. Again, this
could be explained by the misalignment of the fibers facing each other. Without guiding, the light travels in straight line in space. The fibers facing each other in a channel can’t be guaranteed in the same line even if the channel itself is designed to be straight and fit perfect with the fiber, because any stress introduced in the handling process could cause the distortion of the optical fiber.

4.4 Summary
This thesis is focused on fabricating the PDMS based waveguides with different mixing ratios of the base and curing agent.
FIGURE 4.4. Intensity of the 460 nm LED light behind a 5 mm long PDMS Waveguide plus a 2 mm off interface

(1) Refractive indices of a series of Sylgard 184 PDMS with base to curing agent ratio have been measured. The refractive index variation with the mixing ratio suggested the application potential as waveguides in microfluidics system.

(2) A prototype of the waveguide with different mixing ratios for the core and cladding part respectively is fabricated. The idea of the realization of this approach is confirmed.
FIGURE 4.5. Intensity of the 460 nm LED light behind a 5 mm long air channel
References


Vita

Weiping Qiu was born in 1981, in Changxing, Zhejiang province, China. He finished his undergraduate studies at Zhejiang University in 2004. After that he earned a master of science degree in materials science from Zhejiang University in 2006. In August 2006 he came to Louisiana State University towards a degree of Master of Science in Mechanical Engineering.