Additive Manufactured and Laser Enhanced Optical Fiber on Flexible Kapton Substrate

Dianhao Hou
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Additive Manufactured and Laser Enhanced Optical Fiber on Flexible Kapton Substrate

by

Dianhao Hou

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Materials Science and Engineering Department of Chemical and Biomedical Engineering College of Engineering University of South Florida

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Keywords: Micro-dispensing, Fused Deposition Modeling, Surface Flatness, Transmission Loss

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Dedication

I dedicate this work to my dear parents who always support and love me. I also want to dedicate it to my friends who always help and accompany me. Finally, I want to dedicate my work to my favourite show *Running Man* which brings me happiness every weekend for almost ten years.
Acknowledgments

I would like to thank my co-major professors Dr. Venkat Bhethanabotla and Dr. Tom Weller for their encouragement, support, care and guidance, and my committee member Dr. Zhimin Shi for his knowledge and time provided to my thesis, and Dr. Wang for his support to our 3D-printing group, and Dr. Emirov for his contribution on the SEM characterization, and my mentor Roger Tipton for his kind and wise suggestions both on my work and life, and Carlos, Mohamed, Omer, Vishu, Ryan and Merve in printing group for all their help during experiments, and my families and friends for their accompany.
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Abstract

This thesis mainly focuses on the realization of laser enhancing additive manufactured optical fibers on the flexible substrate based on previous work on the rigid surface, and the exploration of their loss at different bend status by optical transmission test. Optical fibers are successfully fabricated using polymethyl methacrylate by fused deposition modeling technology within Norland Optical Adhesive 1369 which is chosen as the cladding material and micro-dispersed on the Kapton substrate. The Laser cutting technology and scanning electron microscope have been used to enhance and characterize the flatness of two end facets of samples, respectively. The optical adhesive and PMMA core are perpendicularly cut by the Lumera Super-Rapid industrial high repetition rate picosecond laser with a wavelength at 355 nm using the different number of cut times and output power. The flatness of these end facets is compared after observation under SEM and the optimum laser-cut parameters for our fibers on the flexible substrate have been found as cutting 2 times with power output at 1400 mW. The fibers are cut to be 50 mm long and tested to see their properties against loss while undergoing different bend angles. As the bend radius decreases, the loss is found slowly increasing from approximate 0.4 – 0.8 dB/cm which represents the straight situation for different samples. And a bend radius range from 30 to 80 mm is found that loss will dramatically climb to around 2.5 – 3.2 dB/cm.
Chapter One: Introduction

1.1 Motivation

As technologies being updated faster and faster in the modern world, the requirement for stable and rapid communication has raised much more attention than before especially to adapt to the big data era. In order to better transfer information and data while reacting to the tenser space situation, optical fibers are introduced to replace the traditional wires which connected with bulky and slow characteristics. At the meantime, artificial intelligence has been developed a lot during the last decades. Different types of functions have been derived from that and the need for information transfer on the non-solid surface such as artificial skin was also brought on the table. Getting promoted by this trend, we have investigated a fast and convenient method to realize the fabrication of optical fiber within cladding material on the flexible substrate. This thesis will mainly demonstrate the laser enhancement and transmission property of the novel prototype.

1.2 Outlines

In this paper, the motivation of the thesis and background of 3D printing particularly FDM are introduced in chapter one. The four steps experimental method and equipment involved within fabrication processes are illustrated in chapter two. In chapter three, details of the laser cutting process are discussed, which includes the focus point locating method and realization and
characterization of different cutting with a various number of laser cut and power output. With the result of laser cutting showed in chapter three, finalized optical fibers are fabricated and the transmission test is demonstrated from its preparation and test aspects which included in chapter four. According to the result got in both chapters three and four, a general discussion is summarized in chapter five and the potential development of this thesis in the future is analyzed in chapter six.

1.3 Background

The most crucial and basic technology for this needs to be introduced starting from 3D Printing, which also known as the Additive manufacturing technique, is used for making the product in a consecutive layering sequence. Highly complex and precise structures that are relatively difficult realized by conventional methods can be achieved easily using 3D printing technologies. It has witnessed explosive growth in the research domain during the past three decades and its application has covered in consumer durables, medical, manufacturing, transportation, and many different fields. The predefined user design in 3D printing techniques has shortened the manufacturing time with respect to a variety of materials. For a large amount of different input material, commonly, 3D printing can be classified into solid, liquid and powder-based techniques. Solid-based techniques are comprised of Fused Deposition Modeling (FDM), liquid-based techniques are comprised of stereolithography (SLA), Digital Light Processing (DLP), and Direct Ink Writing (DIW), and powder-based techniques are comprised of Selective Laser Sintering (SLS), and Selective Laser Melting (SLM) [7]. Among different kinds of 3D printing, FDM is one of the most frequently used technologies.
Considering the utilization of FDM realistically, although it has to replace the print head frequently, FDM machines are still believed to be the most needed equipment among all types of 3D printers which may due to mainly its low cost in setting up and maintenance and ease in use and design [7]. Another important advantage is the precise control over the temperature systems which can effectively protect the solidified layers from impairing by the temperature fluctuation during the solidification that may cause the delamination with the neighboring printed layers and showcase unexpected porosity. This may lead to a rapid decrease in mechanical strength. Also, the mechanical properties of the final print are a function of the interface between the print layers, which is a function of interaction, thickness, and gap, etc.. The surface quality and appearance of the product is highly determined by the printing parameters including printing speed, extrusion speed, nozzle temperature and work platform temperature, etc..

Figure 1-1. Schematic of FDM process

For the FDM process, in general, filaments should be thermoplastics in which their polymer chains can be mobilized with ease on heating above their glass transition temperature Tg or
composite materials. ABS (Acrylonitrile Butadiene Styrene), PA (Polyamide) and PC (Polycarbonate) are the most commonly used feedstock due to their lower costs [7]. Filaments are supplied to the heater by two rollers to get semi-molten inside and then can be pushed to the nozzle connected with it. Then it can be easily extruded out from the nozzle as more and more semi-liquid feedstock accumulate inside. The work platform will be preheated to the proper temperature for targeted feedstock. During the printing process, it will be moved following the script programmed before which can be derived from tomography scans, magnetic resonance imaging scans, or CAD model data and get the feedstock from the nozzle onto the top surface of the aimed area. The layer by layer construction can be achieved by movement of the module along with the Z direction.
Chapter Two: Experimental Equipment and Methods

During our research on additive manufactured optical fibers on the flexible substrate, there are mainly four steps include micro-dispensing optical adhesive as the cladding material on the flexible substrate by the nScrypt smart pump system, UV curing the cladding material by a black-ray UV lamp, printing extruded filament into the cured cladding material utilizing the nFD system, and the last step is laser cutting the two end facets of the optical fiber making use of the Lumera super rapid laser.

Figure 2-1. The main work station of nScrypt 3Dn Table-Top
2.1 Fused Deposition Modeling System

The nFD module is controlled by the highly precise computer system which can realize accurate movement along the XYZ axes correct to 0.001 mm. It is consists of a filament feeding section, liquefier with temperature control and changeable tip set that the removing and installing of tips is quite convenient. Printing with different thermoplastic materials at various sizes for specific requirements is achievable by switching to the proper nozzle.

![Image of nFD printing on a circuit board](image)

**Figure 2-2. Illustration of nFD printing on a circuit board**

Two thermocouple slots are equipped with the nFD module for temperature control and safety limiter, respectively. Common thermoplastic materials such as ABS and PMMA involved in this thesis are compatible with this nFD system due to its wide operating temperature range which makes it a really powerful tool.
2.2 Smart Pump System

The Micro-Dispensing process is possessed by the SmartPump system which is equipped with a pump that can achieve releasing or terminating materials dispensing precisely with no tailing. There is a large range of viscosity that starts from 1 cP but no limit to 1 million cP can be operated by this system due to its strong compatibility. It is able to deal with over 10,000 kinds of commercial material and features volumetric control correct to 20 picoliters.

As shown in figure 2-3, the syringe with optical adhesive inside is connected to the mount of the micro-dispensing system and linked with pressure supply from the other side. Our optical adhesive will be pushed into the mount and driven down to the top surface of the workpiece passing through the nozzle used for dispensing.

Figure 2-3. Illustration of micro-dispensing on a printed ABS substrate
2.3 Lumera Picosecond Laser

The laser used in this thesis is the Lumera Super Rapid laser which can achieve an industrial grade and has a pulse width at the picosecond level. It has mainly three components including laser head, control units and chiller as shown in figure 2-4.

![Figure 2-4. Components of the laser system](image)

For this laser, pulses can be emitted with energy higher than 120 μJ and length within a range from 7 to 10 picoseconds. The repetition rates of pulses can reach to 1MHz and the normal wavelength locates at 1064 nm. It has three achievable spectral regions including visible green spectral region (second harmonic, 532 nm), non-visible UV region (third harmonic, 355 nm) and non-visible UV region (fourth harmonic, 266 nm) which can be converted from the infrared pulses [23].
Here in our laser end facet process, we mainly use the wavelength at 355 nm which is the third harmonic generation produced by frequency tripling the fundamental beam (1064 nm) with a nonlinear crystal being integrated which converts the doubled radiation and the residual infrared radiation (1064 nm) to ultraviolet laser radiation to achieve the wavelength of 355 nm by sum-frequency-mixing [23]. Figure 2-5 is made by nScrypt® for explaining how this Lumera super rapid laser has been connected with the nScrypt® Table Top set. Figure 2-6 has illustrated the alignment of the dielectric monochrome mirrors for conversion to 1064 nm and 355 nm.
The quality of the area after laser machining can be very high due to the short pulse width which leads to the process with a relatively low temperature that would not introduce thermal side effects such as microcracks, recast or burr. This laser has a quite high resolution and wide compatibility with various materials that different operations like scribing or cutting can be achieved correct to the \( \mu \text{m/nm} \) range.

2.4 Black-Ray UV Lamp

The ultraviolet lamp we used to cure our samples after the micro-dispensing process is Black Ray long wave ultraviolet lamp from UVP company which belongs to model B-100 AP/R.
It comes with the special heat-resistant plastic Cool-TouchTM housing which allows users to handle the lamp head regardless of how long the lamp has been operating. These rugged lamps can be placed face down on a working surface without damage to the filter. A 100-watt spot bulb is equipped and rated at 5000 hours.

Figure 2-7. The realistic and schematic model of Black-Ray ultraviolet lamp
Chapter Three: Laser End Facet

For samples after fused deposition modeling process, the status of the sample now becomes layered form which is composed of an aluminum flat plate at the bottom, the flexible substrate (Kapton) fixed around four edges by one side adhesive Kapton on the plate, the Norland optical adhesive micro-dispensed on the flexible substrate and PMMA fiber as core material printed into the optical adhesive but also covered by it because of reflowing during the temperature drop period.

![Figure 3-1. Printed fibers inside cladding on the flexible substrate before laser cutting](image)

Considering the final utilization of this research, the sample which more specifically the core fiber should be extremely flat and smooth on the cross-section at the two ends. The method used to be applied by manually cut with a razor blade and mechanical polishing after that. But we found the roughness on the two cross-sections are not good enough, moreover, the shape of the fiber apparently deformed due to the mechanical stress applied during the process. Thus, we decided to first use a novel approach of laser cutting the PMMA core fiber to get the desired cross-section without obvious deformation and more importantly, the roughness of the surface which
would be the inlet and outlet of light gets decreased. Besides, the nScrypt 3D tabletop we are using has three modules (nFD, micro dispenser and lumera picosecond laser) installed together which coincidently help us realize the integration of all fabrication processes.

3.1 Focus Point Locating

With respect to the laser cutting, the laser comes out from the objective lens and hit onto the position we want it to cut at. But it has a very small range along its path that only the sample is moved into this range can realize the cut by the laser. That is the so-called focal range and in the middle of this range should be the focus point which has the highest energy and works the best for cutting.

![Schematic of laser focus point](image)

**Figure 3-2. Schematic of laser focus point**

Our samples are quite difficult to find the exact focus point due to their colors. The optical adhesive and the PMMA core are transparent. Although the Kapton substrate below has a red color, it is also relatively transparent. These factors tremendously decrease the possibility of
distinguishing whether the laser cut mark is at the PMMA core which is our final aim of this process.

In lieu of cutting the fibers, we decided to concentrate on locating the focus point of the Kapton substrate. Its red color can give us a relatively more obvious sign of laser-cut area.

![Figure 3-3. Schematic of focus point locating](image)

The principle for confirming the focus point of our laser beam is to cut and move the “beam” both along the X and Z axis, or Y and Z axis at the same time. The beam movement is realized by the work stage movement along the X or Y axis and objective lens movement along the Z axis.

![Figure 3-4. Traces on the silver layer after focus point locating program](image)
The cutting trace on the Kapton substrate in this case will be more obvious focusing on only a specific short part of the whole movement, which particularly refers to the period when the top surface of the Kapton substrate is involved in the range of good focus. The middle point of this trace should be the focus point we are looking for. But what we need for the focus point is the exact position along the Z axis. Here we are using the relation between movements along the X/Y axis and Z axis to calculate this height. Expressed as the equation:

\[ z_f = z_i + \frac{(x_m - x_l)z_\omega}{x_\omega} \]

where \( z_f \) refers to the position of focus point along the Z axis, \( z_i \) and \( x_l \) refer to the initial position of the movement along the Z and X axis set in the script illustrated in figure 3-5, respectively. \( z_\omega \) and \( x_\omega \) refer to the whole distance of the movements along the Z and X axis which also have been set in the script, respectively. \( x_m \) is the value we measure from the middle of the cutting trace.

In order to make it more accurate, normally we ran this focus point locating program and repeated the steps above several times. After every round, the value for the focus point used in the script will be replaced and the routine range around it will get reset. Before laser cutting, this process will be done for accurately locating the focus point for that position at that time of using.

Utilizing the focus point of the Kapton substrate got from the process discussed before, we can calculate the focus point for our core fiber with help from SEM characterization discussed later in chapter 3.2. Taking the diameter of our additively manufactured fibers measured by the SEM imaging as a reference, with the distance between the nozzle of FDM and the top surface of
Kapton substrate also taken into account, we can obtain the value for how high the focus point of the laser beam should be over the Kapton substrate to cut right in the middle of our PMMA fiber.

```plaintext
; DOG.X = 0; // Air off
; DOG.X = 0; // A up
; DOG.X = 0; // B up
; DOG.X = 1; // Enable shutter open.

incremental
G1 X=-188.094 Y=-68.159 F50 //moving from the camera (starting point)

// Move to focal point
absolute
G1 Z=48.42 F50 // Focus -48.42 (for 127 um kapton on the metal sheet)

// Draw starting and ending marks
absolute
; DO4.Y = 1; // open electro-optic modulator (EOM) (turn on light)
; DO4.Y = 0; // close electro-optic modulator (EOM) (turn off light)
incremental
G1 X=5 F50
; DO4.Y = 1; // open electro-optic modulator (EOM) (turn on light)
; DO4.Y = 0; // close electro-optic modulator (EOM) (turn off light)
G1 Z=3 F50

// focal point routine
absolute
G1 Z=49.17 F50 // focal point (-48.42) + 0.75 mm
incremental
; DO4.Y = 1; // open electro-optic modulator (EOM) (turn on light)
G1 X=21.5 F50
; DO4.Y = 0; // close electro-optic modulator (EOM) (turn off light)
G1 X=3

incremental
G1 X=-188.094 Y=-68.159 F50 //moving to the camera (starting point) // Laser to Camera Vector (188.094, 68.159) in
absolute
G1 Z=22.296 F20 // Focus Camera
```

**Figure 3-5. Script for laser focus point locating**

### 3.2 Laser Cut Parameters

For laser cutting, even the focus range is properly located and adjusted to the desired position. The final effect will still be influenced by a couple of very complex factors including beam traverse speed, laser power output and beam paths. There is plenty of research focused on this area in order to achieve the best cut.

In our case, the end facets should be as smooth and flat as possible to meet the requirement for light transmission with less reflective and diffractive loss. Considering the property of our
optical adhesive and PMMA fiber which could be easily deformed by the thermal effect of the laser beam, the heat transfer time during this cutting process should be decreased to the lowest that finally directs to the maximum traverse speed allowed for our 3D Table Top equipment. This speed of 50 mm/s will be used within all the laser cutting programs.

Table 3-1. Exploration of power output (mW) and laser cutting times

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Power Output</th>
<th>Cutting Times</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>2</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>3</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>2</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>3</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>7</td>
<td>300</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>8</td>
<td>300</td>
<td>2</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>9</td>
<td>300</td>
<td>3</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>10</td>
<td>400</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
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<td>11</td>
<td>400</td>
<td>2</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>12</td>
<td>400</td>
<td>3</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>13</td>
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<td>1</td>
<td>Partially Cut</td>
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<td>500</td>
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<td>Partially Cut</td>
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<td>3</td>
<td>Partially Cut</td>
</tr>
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<td>16</td>
<td>600</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>17</td>
<td>600</td>
<td>2</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>18</td>
<td>600</td>
<td>3</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>19</td>
<td>700</td>
<td>1</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>20</td>
<td>700</td>
<td>2</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>21</td>
<td>700</td>
<td>3</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>22</td>
<td>800</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>23</td>
<td>800</td>
<td>2</td>
<td>Partially Cut</td>
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<tr>
<td>24</td>
<td>800</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>25</td>
<td>900</td>
<td>1</td>
<td>Partially Cut</td>
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<tr>
<td>26</td>
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<td>2</td>
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</tr>
<tr>
<td>27</td>
<td>900</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>28</td>
<td>1000</td>
<td>1</td>
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Table 3-1. (Continued)

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<th>Results</th>
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<tbody>
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<td>1000</td>
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<td>Fully Cut</td>
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<tr>
<td>30</td>
<td>1000</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>31</td>
<td>1100</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>32</td>
<td>1100</td>
<td>2</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>33</td>
<td>1100</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>34</td>
<td>1200</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>35</td>
<td>1200</td>
<td>2</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>36</td>
<td>1200</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>37</td>
<td>1300</td>
<td>1</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>38</td>
<td>1300</td>
<td>2</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>39</td>
<td>1300</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>40</td>
<td>1400</td>
<td>1</td>
<td>Partially Cut</td>
</tr>
<tr>
<td>41</td>
<td>1400</td>
<td>2</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>42</td>
<td>1400</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>43</td>
<td>1500</td>
<td>1</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>44</td>
<td>1500</td>
<td>2</td>
<td>Fully Cut</td>
</tr>
<tr>
<td>45</td>
<td>1500</td>
<td>3</td>
<td>Fully Cut</td>
</tr>
</tbody>
</table>

Before we explore the best combination for our fiber cut, we need to find out the real power output in order to acquire more precise data.

Table 3-2. Real power output (mW) at different power settings and repetition rates (kHz)

<table>
<thead>
<tr>
<th>Power Setting</th>
<th>100 kHz</th>
<th>250 kHz</th>
<th>500 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>22.00</td>
<td>7.22</td>
<td>4.14</td>
</tr>
<tr>
<td>1.0</td>
<td>77.90</td>
<td>33.40</td>
<td>16.44</td>
</tr>
<tr>
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Figure 3-6. The function of real power output and power level

We measured the real power output at different power levels and repetition rates indicated on the Lumera equipment as shown in table 3-2.

The readings were inserted into Microsoft Excel and constructed the function between real power output and power levels at different repetition rates illustrated in figure 3-6 to help set the power level corresponding to the real output we want.

Samples were cut with the designed power output and paths and images were captured utilizing the main camera of the 3D Table Top and optical microscope as examples exhibited in figure 3-7. Under the main camera: a. 400 mW 1/2/3 cuts. b. 1000 mW 1/2/3 cuts. c. 1400 mW 1/2/3 cuts. Under the optical microscope: d. 400 mW 1/2/3 cuts. d. 1000 mW 1/2/3 cuts. e. 1400 mW 1/2/3 cuts. As we can see from these pictures, there are only shallow traces on the optical adhesive shown in the picture a. Picture b illustrates the cutting with some depth into the adhesive and the fiber but not separated completely. The thoroughly cut-off can be found in the picture c.
that the fiber is obviously divided. We also tried an optical microscope utilizing its higher magnification. The observation did not give us much useful information because of our transparent fiber and adhesive. Too much light passes through and only the metal sheet beneath can be well observed. However, we can see that the traces are wider and deeper at higher power output and numbers of cut. Unfortunately, none of these pictures were clear enough for our end facets flatness exploration due to the relatively lower resolution and drove us to make use of SEM characterizing our surfaces.

![Figure 3-7. Laser cutting images under the main camera and optical microscope](image_url)

The low vacuum scanning electron microscope in the nanotechnology research & education center was used to observe the end facets. The reason for choosing a low vacuum SEM is that water molecules will be spread on the surface to overcome the lack of conductivity of our samples.
Figure 3-8. SEM images: a. 400 mW 3 cuts. b. 1000 mW 3 cuts. c. 1400 mW 3 cuts.

The SEM images were taken from the top view of the cutting which means that we were looking from where the laser comes. As shown in figure 3-8, basically, the gray background represents the optical adhesive with fiber coated inside which is not visible. Fibers go from top to bottom and the laser cuts transversely which left the cracks quite obvious in the pictures. Although the adhesive will reflow back after laser cutting, the covering on the fiber end facets will be decreased to the least due to the mechanical tension between fiber and adhesive. The results shown in table 3-2 are acquired using both images taken by the main camera and SEM. Our fiber and adhesive are transparent and only the substrate is almost transparent but has a little red color which allows the laser to leave a black cutting trace. Furthermore, we used the scale bar to measure the cutting edge in the SEM image and compared with the known diameter at 70 microns of our fibers. Only cuttings above this length with black trace could be recognized as fully cut.

All the images got from SEM will then be analyzed using the processing tool ImageJ to profile the end facets and compared to acquire the optimum combination of power output and paths. Several representative data points are selected that their SEM images and related end facets profiles are illustrated in figure 3-9.
3.3 Result

According to images after SEM, fibers can be clearly recognized whether they have been cut off and this range is located from power output at 1000 milliwatt to 1500 milliwatt. There is no doubt that power output higher than 1500 milliwatt could definitely be able to cut it off. But the damage to the metal sheet under the flexible substrate needs to be considered as well which limits the upper limit. As shown in figure 3-9, cuttings at 1200 and 1400 milliwatt and three images related to different numbers of cut for each power output are listed. 1400 milliwatt is the optimum.

Figure 3-9. End facets profiles at different power levels and cut numbers
option and we selected 1200 milliwatt as a comparison because it has a very clear view of unsuccessful cutting. Using the method mentioned before which includes the scale bar of SEM and trace color from main camera images, we are able to obtain the results shown in table 3-2 and apparently, the picture of one time cutting at 1200 milliwatt gives us a more direct feeling of it. By transferring these images into the 8-bits color mode, the cutting area can be chosen and plotted by recognizing the grey value. The shape of the separated edge will then be profiled and shown in the graph under each parameter combination. The dimension here is pixels which could be transferred to microns by setting scale function. All the SEM images have the same format and dimension that the ratio is about 3.1 pixels to 1 micron.

In these profile graphs, X-axis represents the length chosen to be analyzed, the Y-axis represents the length along the direction of fiber which has some peaks describing the topography of the end facets. The flatness of the end facets can be characterized by the fluctuation range of these peaks which illustrates the surface height variety and we can find that most peaks are located within a range about 20 microns and relatively more stable or flat areas can be found for some cuttings fluctuating within about 5 microns. The proportion of these flat areas will then be compared and the result for the optimum parameters is given by 1400 milliwatt for power output and 2 times for the number of cuts. From the profile graph of this data point, we can obtain that the relatively flat area with value difference along Y-axis less than 5 microns is around 30 microns long which almost achieves half of the fiber diameter.
Chapter Four: Bend Fibers

In chapter three we talked about optimizing the parameters for laser cutting on the two end facets of each sample. With this combination, we will be able to laser cut our samples smoothly and decrease the effect of deformation. Then a razor blade is needed to cut off the connected substrate. Although the laser can cut on the whole width of the substrate, the stainless steel plate beneath could be cut as well and will influence being used next time due to the superficial crack. After the sample is separated on both sides, the transmission test can be processing then.

4.1 Sample Preparation and Components Alignment

For the transmission test, samples after laser cutting at the two ends will be separated by two cutting traces at 1 mm length whose middle points are located right on the fiber. Hence, only the optical adhesive and substrate around the sample are still connected at this moment. The razor blade will then be used to cut off the rest adhesive and substrate along the two ends of the cutting trace. Moreover, the razor blade will be used to cut parallelly to the fiber with some margin that left for sample mount and the samples should be pulled away from the needless substrate. In this way, our prototype will be acquired with a rectangular substrate beneath.

A HeNe laser with the wavelength at 632.8 nm has been used. Mirrors and lenses are used to direct the laser to the sample on the test platform. All the components need to be adjusted one by one to make sure that the laser is hitting right on the center of each component and finally get
directed into the center of the objective lens. Once all the components except the lens next to the objective are fixed, the distance between two lenses needs to be decided by moving that lens along the line connecting the mirror and objective. Normally it should be the value marked on that lens, but this step is to better confirm that the power output to the objective and sample is the highest without much loss across the system. This lens will then be fixed as well. The whole layout of transmission test components is exhibited in figure 4-1

![Figure 4-1. The layout of transmission test components observing from the top view](image)

As you can see in figure 4-1, the sample actually is not tested in a normal way due to our flexible substrate and bend requirement. The sample mount has to enable two operations. Considering the bending step during the test, the sample or the flexible Kapton substrate has to be mounted perpendicular to the top surface of the test platform which means the bending movement should only happen in the plane that horizontal to the platform. In other words, the fiber should be kept at the same height no matter how it is bent to align the lenses, pinhole and detector.
Figure 4-2. The side view of the sample mount and sample length

The other requirement for the sample mount is the movement along three axes and satisfaction with angle adjustment. The common test platform has equipped rails along three axes that could make the sample moveable spatially. A circular test base was found which can realize the rotation of 360 degrees. So, the circular test base was mounted on the common test platform and an optical breadboard was ordered and mounted on the circular test platform. The threaded holes on the optical breadboard enabled us to fix several accessories including plates, pedestals and a cylindrical supporter on it. In this case, the flexible Kapton substrate was clamped on the close side to the objective lens by the cylindrical supporter and the lower part of the pedestal. The circular base under the breadboard can help us adjust the fiber to be accurately connected with the
laser coming out from the objective lens. During the test, we can manually push the far side of the substrate to realize the different bend radii using a U shaped part which can push the substrate without touching the optical adhesive and fiber because of its hollow appearance.

### 4.2 Transmission Test

![Figure 4-3. The measured result of straight length using ImageJ](image)

After the sample well mounted (The inlet of fiber should be as close to the outlet of the objective lens as possible), the alignment of the objective lens, fiber, pinhole and detector needs to be checked again. Moving to the top view and adjusting the circular test base until the inlet of fiber is perpendicular to the laser light. This operation needs to be done every time after changing the position of the sample. The normal incident light is extremely important for achieving the highest power output.
Another thing crucial to the whole transmission test is the curved length during bending. Although each sample is controlled to be fifty millimeters long, the sample was found curving unthoroughly due to its fixed situation between cylindrical supporter and pedestal. It is quite important to acquire the real curved length which will decide the final bend radius. Pictures were taken from the top view and ImageJ was used here to analyze it to measure the straight length. The difference between straight length and sample length is the curved length.

![Figure 4-4. Light shining through the fiber and pinhole detected by the detector](image)

When doing the transmission test, in other words, after the laser being turned on, several steps are required to ensure the accuracy of the measurements. The sample should be moved along axes perpendicular to the light path until a focused light shining in the adhesive on the substrate. During the period for our earlier attempts, it was extremely difficult to find this focused shining line. Not only because of the much smaller diameter for our PMMA core compared with
commercial fibers, but also the lack of power output from the objective lens. The situation got better after the realignment of components and readjustment of the distance between two lenses. Even working with our thinner fiber that the diameter is around seventy microns, the power output from the objective lens is high enough to show a clear shining line which means the incident light is shining through the fiber instead of passing through the optical adhesive. Another easier method to examine whether the light is well located is using a piece of paper blocking in front of the pinhole, a focused point reflects to shining through the fiber. Not focused light on the paper represents missing the fiber. This has to be used for status close to straight because a short line may show up on the paper due to diffraction caused by the optical adhesive when dealing with curved angles.

![Logging Chart](image)

**Figure 4-5. Real-time power plotting result and the highest reading**
For this optical transmission test, the most important thing is addressing the light path which begins from the laser source, passes through mirrors, lenses, the testing fiber and pinhole, finally goes into the detector. So, the pinhole is the last point that its center has to be precisely aligned with the light coming out from the fiber. It has to be adjusted to the smallest status with a diameter at 200 microns and placed as close to the outlet of fiber as possible in order to decrease the diffractive distance but block all the diffracted light out at the same time which will significantly increase the difficulty of their connection in the air. The minimum distance between the pinhole and the outlet of fiber is around 1 cm to 2 cm due to the limitation of our test platform. The pinhole can not be moved closer because its cylindrical supporter is already touching the edge of the platform. In this case, a useful function of the Thorlab Optical Power Monitor software was found not only to record the power detected on the detector but also to plot the real-time value changing trend. The pinhole was first moved to a position that roughly perpendicular to the outlet of the testing fiber with a ruler. Then the plotting function was started while the pinhole was slightly moved around that position including movement along the horizontal normal of light path and rotation. The curve illustrated in figure 4-5 clearly shows that the highest value detected represents the desired position and vertical angle needed for the pinhole. The detector does not need to be moved like pinhole because it should always be close to the latter with the parallel relation which can completely receive the light penetrate the center of pinhole and indicate the power reading detected. This highest value shown in the curve plotted which also represents the power at that bend angle will be collected with a picture of that bend status taken from the top
view. The pictures will then get analyzed by ImageJ to measure the exact angle bent correspondingly.

The data processing was done by Microsoft Excel with power and angle inserted. Angles need to be transferred to bend radii utilizing the equation:

\[ R = \frac{360L_c}{2\pi\theta} \]

which \( L_c \) represents the curved length measured for each fiber by ImageJ before, \( \theta \) represents the angle bent.

The dB Loss is derived from power changing ratio utilizing the equation:

\[ Loss_{dB} = -10 \log_{10} \frac{P_m}{P_R} \]

here \( P_m \) refers to measured power, \( P_R \) refers to reference power, the negative sign is used for our power decreasing trend.

Figure 4-6. The dB loss vs. bend radius curves for different samples.
By using the loss equation, we are able to calculate the loss related to each measured power at a particular bend radius for that prototype. The power measured for each particular sample initially without any bending was considered as the reference power of that sample in the equation. The power at each bend radius was measured ten times with the sample been released to straight and bent back to that marked position. The measured power then was taken from the arithmetic mean of those ten values.

4.3 Result

The data shown in figure 4-6 comes from the test of fibers being processed with the best parameters combination mentioned in chapter three. Loss calculated at different bend radii with individual reference power was plotted and the dimension dB/cm was used to explain the transmission loss per unit length of our fibers. The loss on Y-axis was divided by 5 cm which is the length of our prototype to generate this dimension. From the data, the loss starts from 0.4 – 0.8 dB/cm which refers to the initial position without bending. It begins to increase at a relatively small slope as the bend radius decreases until a particular range which is found to be 30 to 80 mm. The loss shows a rapid climb trend that the exact value jumps from about 0.8 dB/cm to a range within 2.5 and 3.2 dB/cm for different samples which means the power measured smaller than this bend radius range has reached 1% to 1‰ of the reference power.

During the test, the influence of all kinds of environmental light was decreased as much as possible by blocking or turning off. The power reading with laser off was shown at 0.09 microwatt which approximately equals to 2‰ to 10‰ of the value with the laser turned on. However, the
loss is still high compared with commercial fibers which might due to some reasons discussed and illustrated below.

The end facets are not clean enough. The whole process does not have an environment like the cleanroom and it is sufficient to have some dirt sticks on the surface which enable diffraction and reflection of light.

The end facets are not flat enough. Although they are processed by the laser cut and the fluctuation of flatness is at the micron level, light could still be weakened when passes through two surfaces.

The fibers have cracks inside somewhere. The transmission test requires plenty of bend operation which can crack the fibers and weaken the light transported inside.
Chapter Five: Conclusion

5.1 Contributions

This thesis has realized the fabrication of the optical fiber coated by cladding material on the flexible surface using additive manufacturing method which includes fused deposition modeling and micro-dispensing. Direct printing PMMA fiber inside optical adhesive is achieved. This is the first time that laser cutting has been used for PMMA fiber end facets machining. Integrating the laser module with nFD and smart pump modules, we are able to complete the whole fabrication of this novel prototype within the 3D Table-Top system which is fast, convenient and low-cost.

Laser cutting at different power outputs from 100 mW to 1500 mW and the number of cuts from 1 to 3 have been done and the low vacuum SEM has been used for characterizing the end facets. Using ImageJ we are able to compare the flatness of all the surfaces and the optimum combination of laser cut times and power output has been found for PMMA fiber cleavage to be 1400 mW and 2 times.

By designing and constructing the transmission test circuit, we are able to acquire the transmission ability of our prototype at different angles from 0 degrees to 90 degrees which represents the range of bend radii from infinity to 26 mm. Our data indicate that prototypes have a critical bend radius within the range from 30 mm to 80mm, in which loss stays almost as low
as straight at 0.4 to 0.8 dB/cm when higher than this critical point, but rapidly increases 4 to 8 times reaching 2.5 to 3.2 dB/cm when bend radius goes lower than that point.

5.2 Future Work

The work introduced in this paper has several aspects that could be improved in the future. From the fabrication aspect, the final flatness of end facets will be tremendously influenced by heat transfer from laser to fiber, mechanical tension from the adhesive and fiber, and the reflow phenomenon of adhesive during the laser cutting process. Thermal, force and fluid analysis need to be done to better understand and improve the quality.

From the testing aspect, it is divided into two directions. The first direction is the accuracy of the test especially refers to the connection between pinhole and fiber which has been limited by distance and angle. Potential improvement might be the application of extra tools like a hollow cylinder with the same diameter as the outer diameter of pinhole which can be connected with it. The sample should be prepared to have the fiber right in the middle and fixed in the cylinder. The light coming from the objective lens will be aligned with the inlet of fiber that close to the other end of the cylinder. In this case, we can ensure the light passes through the objective lens, fiber and pinhole properly. The second direction is about the test variety. So far the fiber on the flexible substrate has only been tested within zero to ninety degrees towards the backside or bottom side. The other side bending should also be taken into account to see the potential comparison. Furthermore, the fiber undergoes a large amount of mechanical bending may be not able to transport light as well as before due to fatigue which probably requires a test on it.
References


Appendix A:

Differences between Printing on the Solid Surface and Flexible Substrate

Table A-1. Specifications comparison

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<tr>
<td>Additional Procedure</td>
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<td>ABS “juice”</td>
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</table>

Printing on the flexible substrate requires a metal sheet as an extra support structure. Unlike solid surface, the flexible substrate has relatively severe thermal deformation which will bend along its texture when being heated. The support structure is introduced to offer substrate stability during the fabrication at a higher temperature. Considering the heat transfer and flatness requirements, we finally chose the aluminum flat sheet from McMASTER-CARR. (Lowest thickness 0.25”)

This is the first step of all the fabrication process. Put the metal sheet on the table and Kapton substrate on the sheet. Turn on the heater and wait for them to be heated. The substrate will curve during this period due to a lack of fixation. When the temperature reaches the setpoint, use the other type of Kapton tape which has adhesive and can be utilized at high temperatures up to 300 °C to mount the four edges of the substrate one by one. Keep using wipes to wipe out the air between sheet and substrate to achieve the best flatness.
The additional procedure needs to be done to ensure printing on the flexible substrate. The solid surface we dealt with was ABS and it has very good stickiness with PMMA which is our core material. By contrast, the Kapton substrate does not stick well with PMMA which can be solved by increasing the table temperature. But temperature higher than 95 ℃ will destroy the optical adhesive we are using. In order to keep the PMMA on the substrate, the solution called ABS juice is utilized. (ABS dissolved in the acetone)

This step should be dealt with after curing the optical adhesive micro-dispersed before. Dissolve some ABS in the acetone and use swabs to spread it onto the substrate. The concentration of this ABS juice does not matter because that acetone will evaporate finally. The position of ABS juice should be two areas on the substrate close to the two ends of the adhesive which will be the start point and endpoint of core printing.