January 2015

INDIUM TELLURIDE (In2Te3) SEMICONDUCTOR CYLINDER FIBER SENSOR

Xun Huang
Syracuse University

Abstract

Sensors play a very important role in control, monitor and security system. More and more novel technology has been used on a variety of sensors. This thesis investigates using semiconductor cylinder fiber as a new kind of fiber sensor.

Our main motive to do this research is based on my interest in optical fiber. After I did some experiments on the semiconductor cylinder fiber, I found some interesting characteristics. When we changed some environmental conditions around the fiber, the output light from it would change accordingly. So I did a systematic research on it.

This project uses In_2Te_3 as a coating layer between the glass core and glass cladding boundary. The layer is a few microns thick and deposited in vacuum. The fiber is industry-standard 125 µm in dimension and with ±5 µm tolerance. Some experiments have been conducted on a 2.5 inches long semiconductor cylinder fiber. As the surrounding temperature changes, the light output would change linearly in log scale. And different magnetic fields also change the light output. These characteristics provide a good potential for the fiber to function as a fiber sensor.

Another experiment was conducted to see if there was an amplification or laser effect on this kind of fiber. Wide-spectrum light pumps were used to shine light on the side of this piece of fiber, and so far no obvious amplification was observed.

INDIUM TELLURIDE (In_2Te_3) SEMICONDUCTOR CYLINDER FIBER SENSOR

by

Xun Huang

Master Degree
B.S., Hohai University, 2013
M.S., Syracuse University, 2015

Thesis

Submitted in partial fulfillment of the requirements for the degree of

Master of Science in *Electrical Engineer*.

Syracuse University

August 2015

Acknowledgements

The author expresses sincere gratitude to my dear advisors Dr. Qiwang Song and Dr. Philipp Kornreich. They give me many invaluable advices during the course of research and experiments, and at the same time led me to the gate of optical science.

Many thanks are given to my lab colleague, Abhinay Sandupatla, who offered a lot of help and knowledge in the process of research.

Many thanks are given to the lab manager, James Flattery, who offered great help in the lab equipment and thesis writing.

CONTENTS

List of Figures

List of Tables

Chapter 1 Basics of Optical Fiber Sensor (Literature Review)

1.1 Basics of Optical Fiber

1.1.1 Refractive Index

Refractive Index is an essential parameter in optical system. When light travels in free space, its speed is $c \approx 3 \times 10^8$ m/s. The speed of light varies when it goes through different kinds of medium, which would be *v,* less than *c*. [1]The ratio of the speed of light travels in free space to that in matter is the index of refraction *n* of the material and is given by

$$n = \frac{c}{v} \tag{1-1}$$

1.1.2 Total Internal Reflection

Reflection and refraction happens when light encounters the boundary of two different media. One part of the light is reflected into the first medium, and the other part is bent (refracted) into the second medium. The sum of the refracted light power and the reflected light power should equal to the power of the incident light (Figure 1-1).

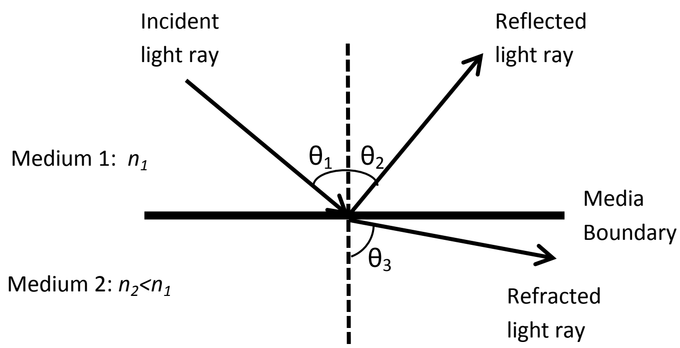


Figure 1-1 Reflection and refraction of a light ray at a medium boundary

According to Snell's Law and the law of reflection,

$$\frac{n_1}{n_2} = \frac{\sin\theta_3}{\sin\theta_1} \tag{1-2}$$

$$\theta_1 = \theta_2 \tag{1-3}$$

The total internal reflection happens when $\theta_3 = 90^\circ$,

$$\sin \emptyset_c = \frac{n_2}{n_1} \tag{1-4}$$

$\emptyset_c$ is the critical angle of the total reflection. If $\theta_1 \geq \emptyset_c$, then total internal reflection happens[1],[14].

1.1.3 Multimode Fiber

An optical fiber consists of two parts: core and cladding. Core is the solid glass rod in which light propagates through, while cladding is the glass surrounding the core. Usually the refractive index of core glass n_1 is larger than n_2, in order to obtain total reflection inside the core.

Multimode fiber is one kind of fiber that there is more than one mode traveling within the core. *Mode* can be described as the pattern that light propagates along a waveguide. If the diameter of the fiber is large enough, it would be possible that multiple modes travel in the fiber at the same time.

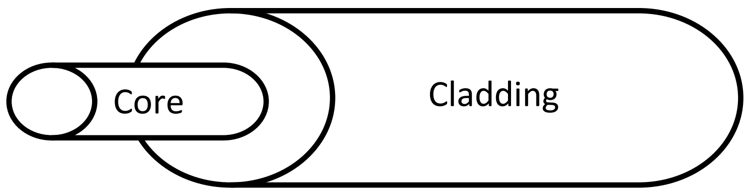


Figure 1-2 Diagram of multimode fiber

1.1.4 Step-Index Fiber

There are two generally used fiber types. One is step-index fiber, and the other is graded-index fiber. For step-index fiber, there's an abrupt change of the refractive index at the boundary; for graded-index fiber, the refractive index varies as a function of radial distance from cladding to core.

My project is working on the multimode step-index fiber. [1]Figure 1-3 shows the structure of multimode step-index fiber, and how light travels through the fiber.

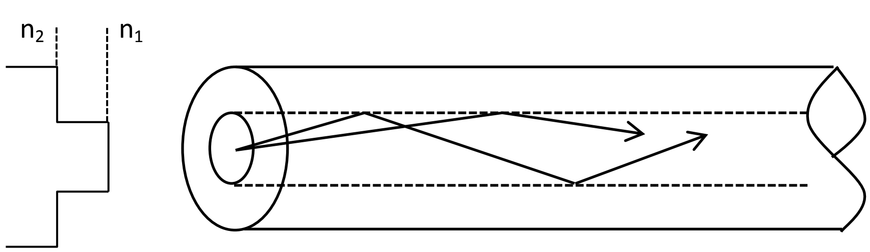


Figure 1-3 Structure of Multimode step-index fiber

1.2 Basics of Fiber Optics Sensor

1.2.1 Fiber Optics Acoustic Sensor

The principal of fiber optics acoustic sensor is that the acoustic wave gives pressure to the sensing fiber, resulting a phase change in the fiber. Usually, Mach-Zehnder interferometer[2] is employed as part of the set-up in the sensing system.

In Mach-Zehnder interferometer, a laser beam is split. Part of it is transmitted by a reference fiber, and other part transmitted in a sensing fiber which is exposed to the acoustic field. The sensitivity of this kind of sensor is shown in Figure 1-4.

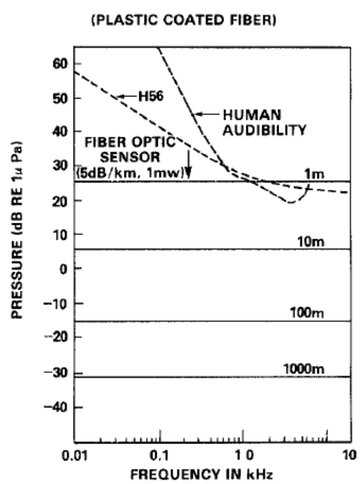


Figure 1-4 Minimum detectable pressure for a shot noise-limited fiber optic acoustic sensor for various lengths of coated optical fiber

1.2.2 Fiber optic magnetic sensor

Fiber optic magnetic sensor[2] has three types of approach to realize it. First is to coil fiber around a nickle tube or rod to measure the direction of linear polarization due to the external magnetic field.

Second is to take advantage of the Magnetostrictive material, which is a material whose shape or dimension would change when it is placed along the axis of an applied magnetic field. It is bonded to or jacketed by a magnetostrictive material. The sensitivity of this sensor is reported as high as $8*10^{-8}$ Gauss ($8*10^{-12}$ Tesla)/m.

Last approach recommended by Giallorenzi is to use a metallic stripline under the fiber. The principal of third kind of sensor is also using the magnetistctive material, but with a perfect zero bias field operation.

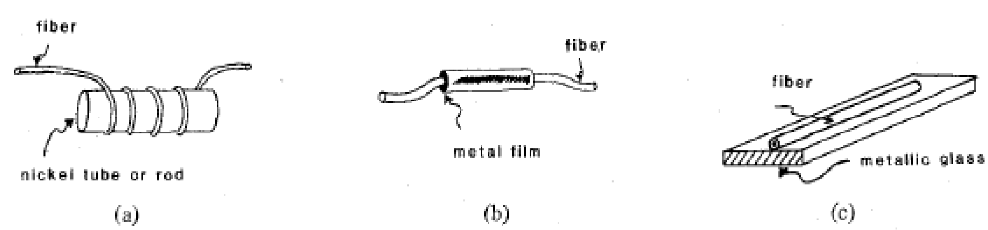


Figure 1-5 Three types of magnetic fiber sensor: (a) Mandrel sensor (b)coated sensor (c)stripline sensor

1.2.3 Fiber Optic Gyros

Fiber optic gyros are now widely used in vehicle, aircrafts and navigation system. It has been a good substitution for the mechanical gyroscope. The principal of this sensor is based on Sagnac Interferometer.

Sagnac Interferometer[4] works like this: two light sources with same phase and wavelength go into the same light path but with opposite direction, and at the output there's a detector that measures the interference fringe. Due to the invariance of the speed of light, when the apparatus rotates, two lights would experience different distance, which results in different phase change and different interference fringe.

Fiber optic gyro works in the same way. Through two opposite light traveling in the rotating fiber, the sensor can measure the rotating speed from the interferometer.[3]In Figure 1-6, the fiber coil is rotating in the clockwise (CW) direction. The CW and counter-clockwise (CCW) rotating lights meet at the same exit point to interfere with each other.

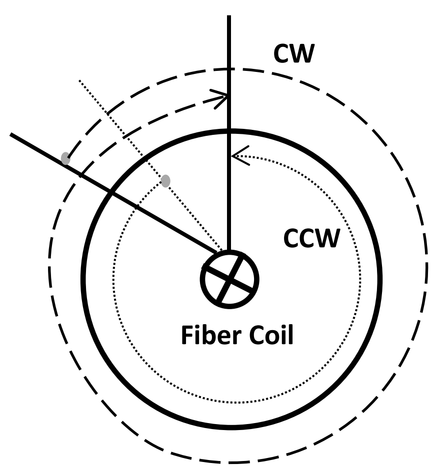
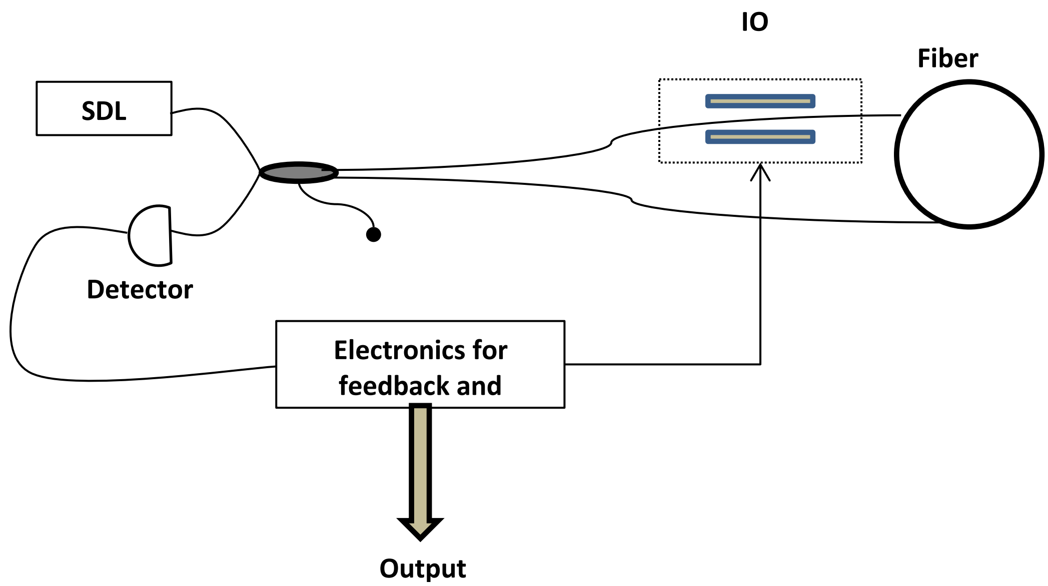


Fig. 1-6 Principle of the fiber-optic gyroscope.



[3]Figure 1-7 Basic configuration Fiber Optic Gyro used nowadays (SLD: superluminescent diode IOC: integrated optics chip modulator)

1.2.4 Fiber Temperature Sensor

There are several types of sensors to measure the temperature. Currently, the sensor modulated with fiber Fabry–Perot interferometer (FFPI) has more sensitivity in temperature measuring, [5]which is around 0.025 ˚C. The principle of this sensor is comparing the phase change, which is dependent on temperature. The sensitivity of the sensor is dependant on the length of the Fabry-Perot Cavity, which means the larger the cavity, the more sensitive it will be.

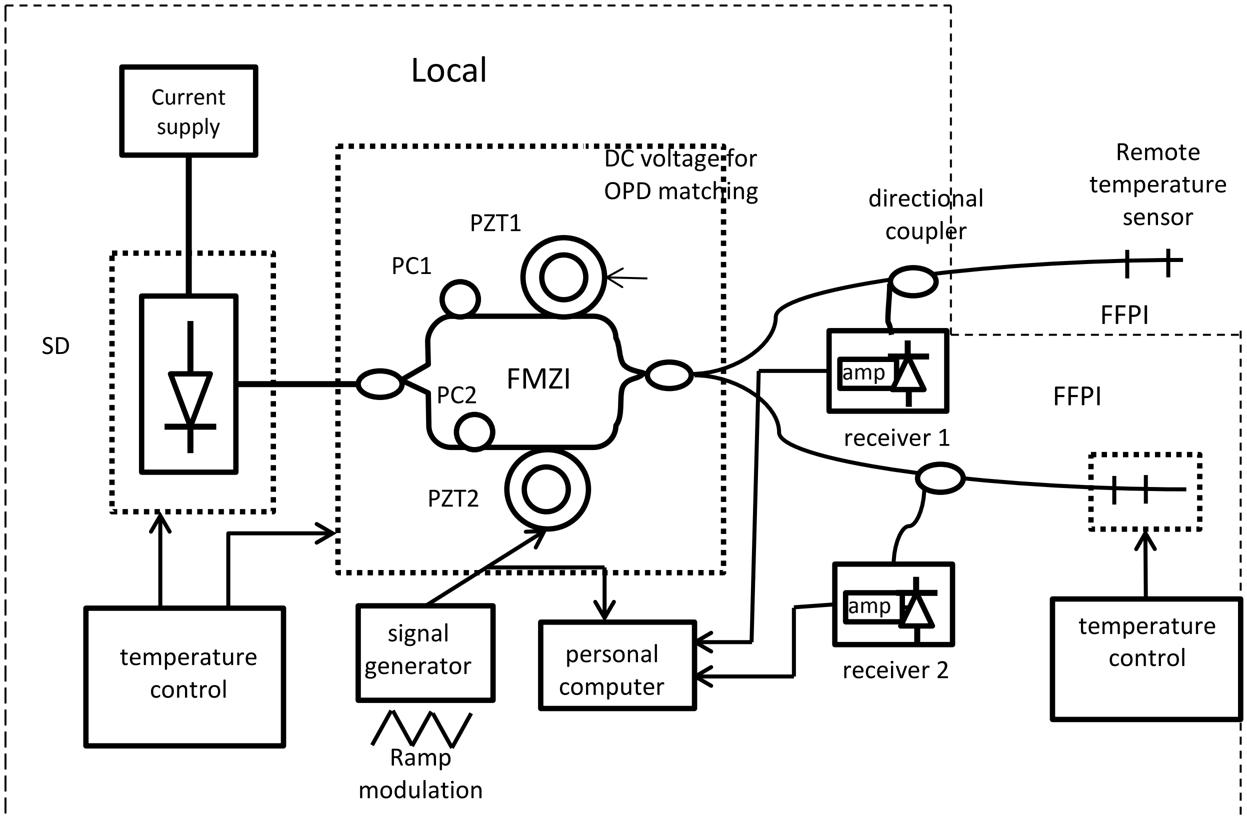


Fig 1-8 [5]Experimental configuration: SLD, superluminescent diode; OPD, optical path difference; PZT 1, PZT 2, piezoelectric transducer tubes; PC 1, PC 2, polarization controllers.

[3]Brillouin fiber sensor is another type of temperature sensor which basically applies the principle of stimulated Brillouin scattering. An acoustic wave couples two counter-propagating beams, which are frequency-shifted by an amount that is dependent on temperature or strain. This kind of sensor has a spatial resolution around 1 meter. [6]So it's suitable for temperature monitor in civil construction. There are already commercial uses in a dam project.

[7]Semiconductor temperature fiber sensor is a sensor which uses semiconductor as a light absorber. The absorption rate is dependent on the temperature. Its basic structure is placing a small piece of semiconductor between two fiber terminals. Measure the input and output light

power and determine the temperature as a function of absorption rate. Its resolution is 1 ˚C ranging from -10 ˚C to 300 ˚C.

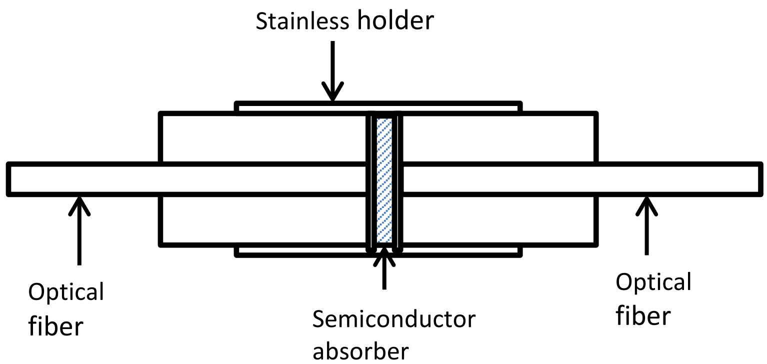


Figure 1-9 Configuration of optical-fiber sensor using semiconductor

Above I gave a brief idea of the optical fiber sensors and semiconductor material, which showed that various types of fiber sensors have been used in measuring the magnetic field, temperature etc. The contribution of my thesis is that I made a new kind of fiber sensor which is coated with In_2Te_3 semiconductor material. And I tested this fiber with the change of the temperature and magnetic field. I also tested it with the pump light to see if there's laser effect happen.

This thesis is organized as follows: Introduction of basics of semiconductor material is in Chapter 2; Fiber fabrication process is in Chapter 3; Experimental setup is in Chapter 4; Test result is in Chapter 5; Conclusion and Future work is in Chapter 6.

Chapter 2 Basics of Semiconductor Material

[1]Energy Band

The conduction properties of a semiconductor can be interpreted with the aid of the energy-band diagrams. In a semiconductor the valence electrons occupy a band of energy levels called valence band. This is the lowest band of allowed states. The next higher band of allowed energy levels for the electrons is called the conduction band. These two bands are separated by an energy gap, in which no energy level exists. As temperature is raised, some electrons are thermally excited across the bandgap.

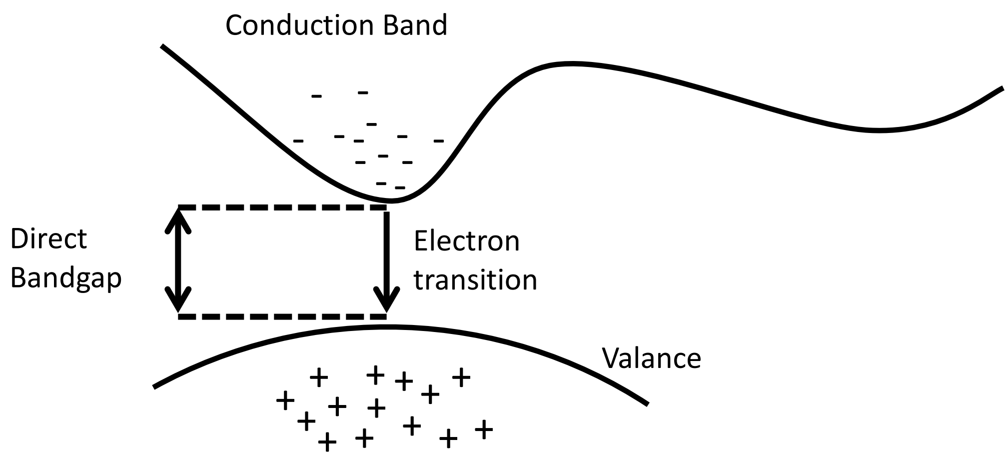


Figure 2-1 Electron recombination and the associated photon emission for a direct-bandgap material

Light Source Semiconductor Material

The semiconductor material that is used for the active layer of an optical source must have a direct bandgap (which means the most probable recombination process where electrons and holes have same momentum value). In a direct-bandgap semiconductor, electrons and holes can recombine directly across the bandgap without needing a third particle to conserve momentum. Only in direct-bandgap material is the radiative recombination sufficiently high to produce an adequate level of optical emission. Although none of the normal single-element semiconductors are direct-gap materials, many binary compounds are. The most important of these compounds are made from III-V materials (In, Ga, Al). Various ternary and quaternary combinations of binary compounds of these elements are also direct-gap material and are suitable candidates for optical source.

Conditions for Laser Effect

Three keys for laser action are photon absorption, spontaneous emission and stimulated emission. These three processes are represented by the simple two-energy-level diagrams, where E_1 is the ground-state energy and E_2 is the excited-state energy. According to Planck's law, a transition between these two states involves the absorption or emission of a photon of energy $\mathrm{h}v_{12} = \mathrm{E}_2 - E_1$. Normally, the system is in the ground state. When a photon of energy $\mathrm{h}v_{12}$ impinges on the system, an electron in state E_1 can absorb the photon energy and be excited to state E_2. Since this is an unstable state, the electron will shortly return to the ground state, thereby emitting a photon of energy $\mathrm{h}v_{12}$. This occurs without any external stimulation and is called spontaneous emission. These emissions are isotropic and of random phase, and thus appear as a narrowband Gauss (10^{-4} Tesla) output.

Stimulated Emission

The electron can also be induced to make a downward transition from the excited level to the ground-state level by an external stimulation. If a photon of energy $h\nu_{12}$ impinges on the system while the electron is still in its excited state, the electron is immediately stimulated to drop to the ground state and give off a photon of energy $h\nu_{12}$. This emitted photon is in phase with the incident photon, and the resultant emission is known as stimulated emission.

Pumping Technique

In thermal equilibrium the density of excited electrons is very small. Most photons incident on the system will therefore be absorbed, so that stimulated emission is essentially negligible. Stimulated emission will exceed absorption only if the population of the excited state is greater than that of the ground state. This condition is known as population inversion. Since this is not an equilibrium condition, population inversion is achieved by "pumping" techniques. In a semiconductor laser, population inversion is accomplished by means of externally injected photons.

Chapter 3 Fabrication Process

3.1 Fiber Parameters

First, we chose the rod as 7056 Corning, cladding as 7052 Corning. Following are the properties of these two types of glass:

Type	Thermal Expansion×10-7 cm/cm/˚C 0~300˚C	Annealing point,˚C	Strain Point, ˚C	Softening Point, ˚C	Refractive Index % 589.3nm	Density g/cc	ID, mm	OD, mm	Length, mm
7052 Corning	47.0	484	440	712	1.484	2.29	2.0	9.0	152.4
7056 Corning	51.5	512	472	718	1.486	2.27	1.8	N/A	101.6

Table 3-1 Glass Parameters

We need to match physical thermal and optical requirement,

1. Softening Point of rod and cladding should be within 50˚C.
2. $n_{cladding}$(refractive index) should be smaller than n_{rod}, in order to have total inner reflection.
3. Inner diameter (ID) of the rod should be less than Inner diameter (ID) of the cladding, meet the requirement of $ID_{core}<ID_{cladding}<2\times ID_{core}$

According to the format, all the requirements are met.

We use Indium Tellurium In2Te3, whose melting point is 667˚C, as the coating. Following is the data:

Material	***Weight(mg)***
In_2Te_3	47.8
Rod	623.1
coated rod	623.4

/	**Density(mg/cm3)**
In2Te3	5750

Table 3-2 Fiber Ampoule Parameters

Volume of film:

$$\frac{Weight\ of\ coated\ rod - Weight\ of\ rod}{Density\ of\ material} = \frac{623.4-623.1}{5750} = 52.17 \times 10^{-6} cm^3 \quad (3\text{-}1)$$

Film thickness:

$$\frac{Volume\ of\ film\ (cm^3)}{Area\ of\ film (cm^2)} = \frac{52.17 \times 10^{-6}}{\pi * 15.24(length) * 0.18(diameter)}$$

$$= 6.054 \times 10^{-6} (cm) = 6.054(\mu\text{m}) \quad (3\text{-}2)$$

3.2 Redrawing

The Redrawing tower is used to make small diameter glass core rod from the commercially available large diameter glass stock. It's shown in Figure 3-1. Its principle is that a system of pulleys guide the thicken glass rod until the softening point is reached. Detailed procedures are as followed:

1. Cut a piece of chosen thicker rod which can properly fit into the tower (around 27cm)
2. Make two small hooks on both ends of the rod that we are going to redraw
3. Install it in the redrawing tower
4. Add 100 grams weight on the hook(Determined by experience to maintain desired diameter ratio before and after redrawing and speed of process)
5. Turn on furnace
6. Set temperature as 10 degrees below melting point (690̊C) (Determined by experience to maintain desired diameter ratio before and after redrawing and speed of process).
7. Wait until redrawing procedure completes. It took about 30 minutes.
8. Turn off furnace
9. Carefully take off the rod after cooling down.
10. The rod after redrawing is two-thirds of the original one in diameter. The specific rate depends on the weight and temperature set.

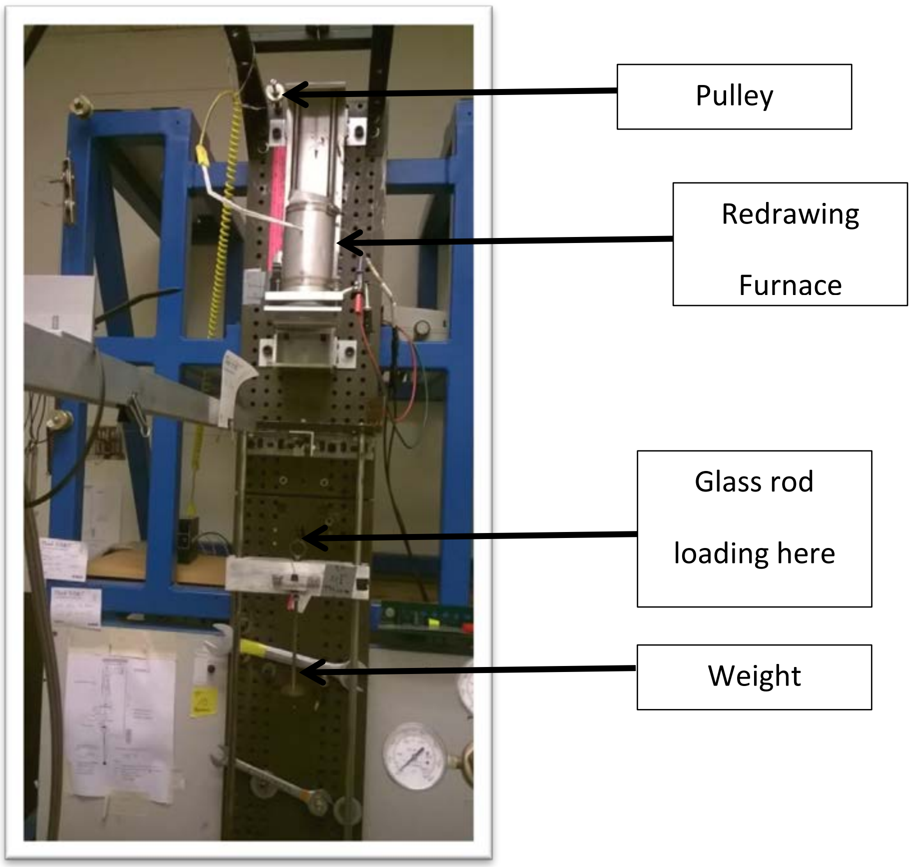


Figure 3-1 Photo of Redrawing Tower

As shown in Figure 3-1, when the weight is added, the redrawing furnace would go up while the weight is going down. So the glass rod would be stretched into smaller diameter.

3.3 Coating

We then use a resistive vacuum deposition system equipped with a rotating fixture, to coat the fiber a thin film of metal alloy. The following steps are used：

1. Turn nitrogen pressure vent on
2. Turn nitrogen cylinder valve on
3. Turn nitrogen vent off
4. Turn nitrogen cylinder valve off

The purpose of the steps above is to make the pressure inside and outside of the covering same.

5. open the bell jar
6. Install the rod and alloy
7. Close bell jar
8. close Foreline valve
9. open Rough valve
10. Wait until the pressure of TC1(thermocouple) & TC2 same
11. close Rough valve
12. Open Foreline valve and Hi-vac valve
13. Pour liquid nitrogen into vacuum machine
14. Turn ionization gauge on
15. Turn rotating machine on
16. Set heating machine to 20Volts A.C.

17. Gradually increase input voltage from 20V to 40V in 20 minutes and record voltage& current
18. after In_2Te_3 source material has fully evaporated, turn down heating machine
19. Keep rotating for 15min until cooling down
20. Turn rotating machine off
21. Turn ionization gauge off
22. close Hi-vac valve
23. Open vent valve
24. Turn cylinder pressure valve on
25. Take out the fiber[13]

Time	**Voltage A.C.**	**U(V)**	**I(A)**
11:20	10	0.36	28
11:25	30	1.1	114.7
11:30	40	1.5	142
11:32	15	0.3	41.4

Table 3-3 Coating Processing Data

From the data, we see that voltage and current increase gradually when we increase the value of Voltage.

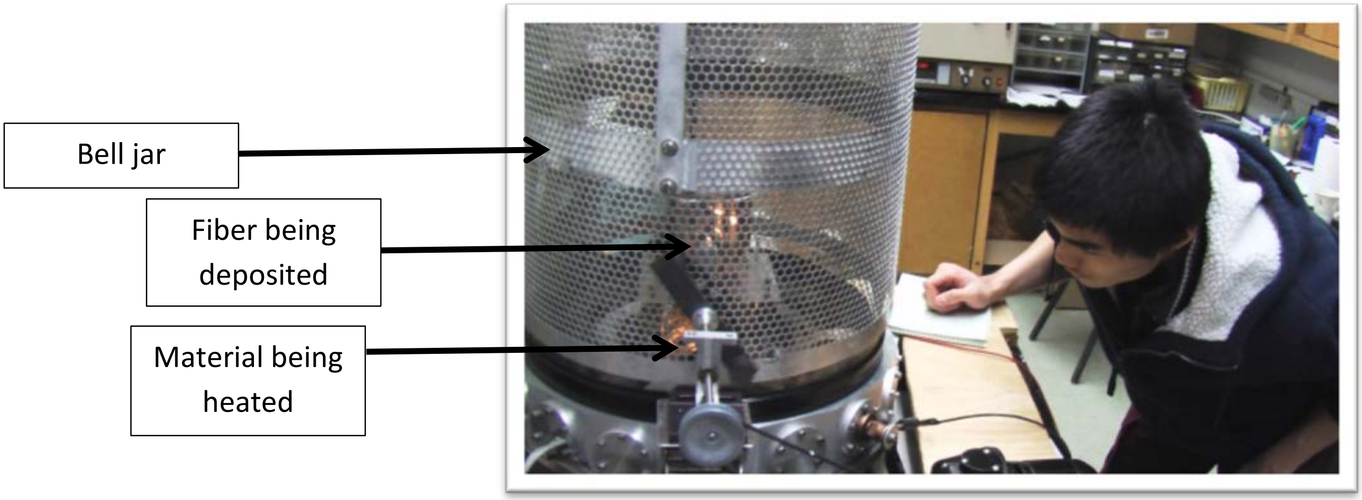


Figure 3-2 Photo of thin film vacuum deposition machine

Figure 3-2 shows the process of deposition. The material is heated and vaporized by the heater and fiber is coated with the material on top. The bell jar is to make sure that the whole process is in a vacuum environment.

3.4 Vacuum Sealing

Next, we seal the coated rod in the cladding tube to make an ampoule. Steps are the following:

1. Pinch off the cladding tube from one end
2. Place the coated fiber rod in the tube
3. Make sure that one end of the rod is at the end of the tube
4. Place the tube inside the furnace
5. Make sure that center of the rod should be in the center of furnace
6. Mark the other end of rod on the tube
7. Turn on vacuum pump and wait till pressure reach 10-3 Torr(0.13Pa)(TC#2)
8. Slowly open the vacuum value, wait until pressure in gauge reach 10^{-3} Torr(TC#1)
9. Switch ON the turbo pump and wait till pressure 10^{-6} Torr($1.3*10^{-4}$Pa)
10. Quickly pinch off the other end about 2cm before the mark on the tube. The 2cm is to leave some space for the rod inside the cladding.
11. Close the vacuum valve
12. Switch off-turbo pump
13. Switch off-vacuum main
14. Switch off-vacuum pump

Figure 3-3 Photo of vacuum Sealing Process

Figure 3-3 shows the vacuum sealing process. The ampoule is installed in the system and being sealed by the torch.

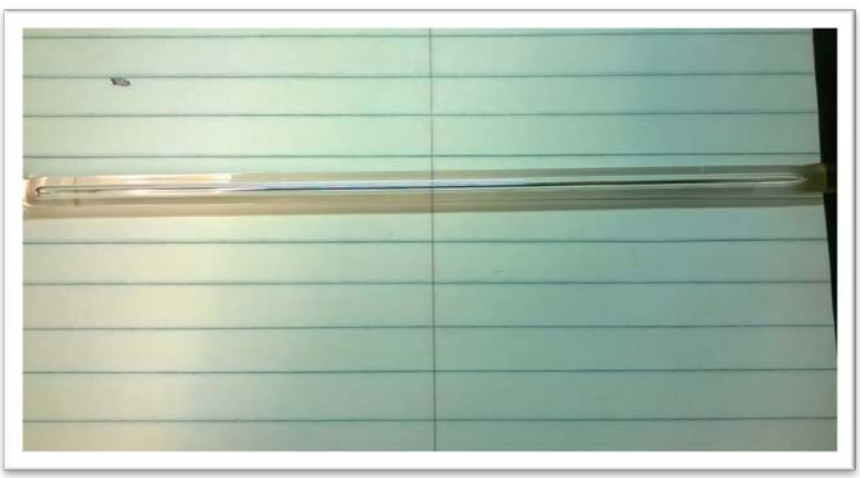


Figure 3-4 Photo of ampoule before collapsing

Figure 3-4 shows the fiber ampoule that is before collapsing, we can still see the black coating around the fiber from the picture.

3.5 Collapsing

After that, we need to collapse the ampoule. It takes around 4 hours. Following are the steps:

1. Turn on the furnace
2. Clean the boats and caps of the railcar
3. Apply anti-sieze mixture on the screws and caps
4. Melt the tin in the boat to make it liquid
5. Place ampoule in the boat and tighten the caps
6. Place boat on the rails carefully
7. Move the boat to the ‘start point’ mark
8. Set the collapse temperature for 710˚C
9. Wait until temperature in the boat reaches 380˚C
10. Move boat to an area between Zone 1 and Zone 2
11. Wait for T.C. (thermocouple) to reach 600˚C
12. Move boat to collapse zone
13. Open the valve of nitrogen
14. Wait until temperature reach 720˚C
15. Move back to the ‘annealing point’ mark
16. Close the valve of nitrogen
17. Wait until temperature reaches 560˚C
18. Move back to ‘start point’ mark
19. Turn off the furnace & take it out the next day

Time	***Temperature(°C)***
11:50	381
move to place between Zone 1 (High Temperature Zone) and Zone 2 (Low Temperature Zone)	
12:25	597
Move to Zone 1	
12:35	714
Open liquid nitrogen valve, let air pressure goes to 550 psi	
12:41	718
12:43	655
Close liquid nitrogen valve, open baffle, move to middle of Zone 1 and Zone 2	
13:33	508
Close baffle	
14:32	490
16:43	446

Table 3-4 Collapsing Processing Data

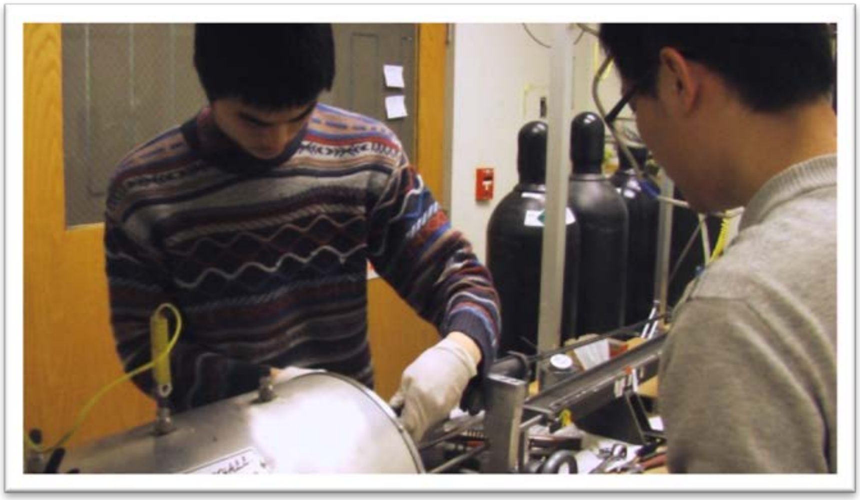


Figure 3-5 Photo of collapsing process

Figure 3-5 shows the process of collapsing. The ampoule is put in the steel boat and moved into collapsing furnace.

3.6 Pulling

We observe the following steps,

1. Make two handles(10 inches) for the ampoule, one end has a J hook
2. Turn on the main board power
3. Set Preform power source as 5Hz, Vpp 3V, Square wave
4. Set capstan power source as 50Hz, Vpp 3V, Square wave
5. Move the preform holder up until it just barely touches the cut-off switch.
6. Install the fiber, make sure that the ampoule part is in the heating furnace
7. Attach the weights to the end of ampoule.(200 gram)
8. Make sure that ampoule does not touch the side walls of furnace.
9. Turn on furnace, make voltage supply to 70V
10. Turn on the capstan
11. Set the temperature as 690˚C
12. Wait until heated ampoule almost drops to the ground
13. Break off the end of fiber& pull it with hand (Careful)
14. Move down the furnace
15. Connect the end of the fiber to the capstan
16. Check the thickness monitor and adjust speed setting to match 125 µm.
17. When finished, turn off heater
18. Turn off main board power

3.7 Cleaving & Polishing

This is the last step I did before testing the final fiber. Usually these two steps are done by high precision factory machine. But due to equipment limitation, I did it manually.

For cleaving, the steps are as followed:

1. Prepare a tape, house water and a cleaving pen
2. Break off a fiber 0.5 inch longer than what I need, which is 2.5 (2+0.5) inches
3. Tape one end of fiber on desk
4. Measure the fiber and mark the place you want to cleave. (leave some length for the other end, for we need to cleave both ends)
5. Hold the end by hand and slightly pull it
6. At the same time, use the cleaving pen cleave the marking spot perpendicularly
7. Finish cleaving, apply house water on the tape and take off the fiber from tape
8. Use the same way cleave the other end

For polishing, the steps are:

1. Prepare three polishing pads (1250 grits, 2500 grits, 6000 grits)
2. Prepare a bare fiber terminator(BFT) and a polishing adapter
3. Insert fiber into BFT carefully (easily breaks)
4. Put adapter on the first polishing pad (1250 grits),then apply BFT to the adapter
5. Gently circle the adapter on the pads for 10 to 20 seconds with a little push on the BFT
6. Do the same way on 2500 grits pad and 6000 grits, accordingly.
7. Observe the cross section of fiber through microscope.

These are all the steps dealing with the fiber fabrication, from picking up material to final polishing. The process may differ from what is usually done in the factory, but with this fiber we can still observe the typical optical characteristics of the fiber and quantum effect of the semiconductor. In the next few chapters, we will talk about these characteristics and its correlating experiment setup.

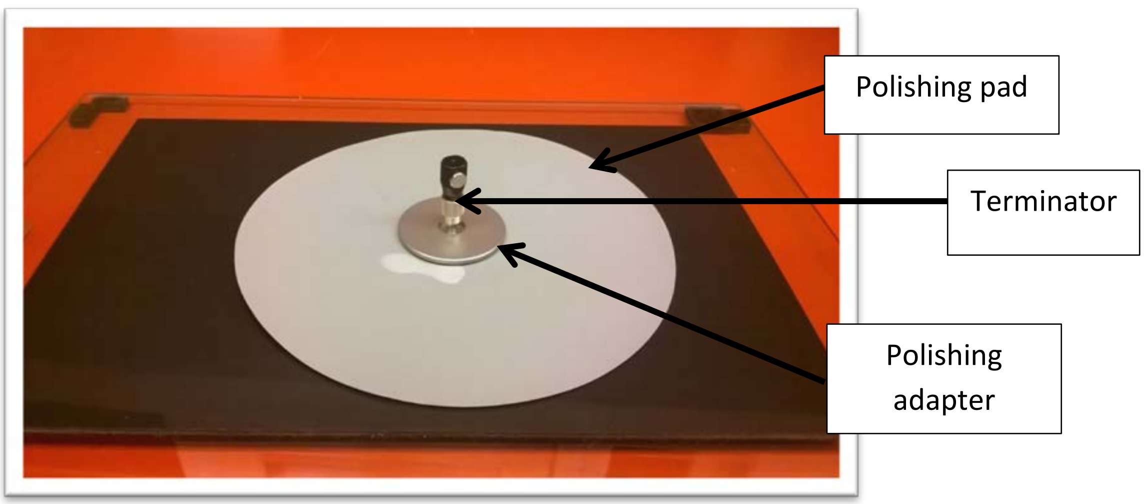


Figure 3-6 Setup of polishing pad, adapter and terminator

Figure 3-6 is the setup of polishing process. The fiber is inserted in the terminator, below it is adapter, and the polishing pad is in the bottom.

3.8 Final Semiconductor Coated-Fiber Sample

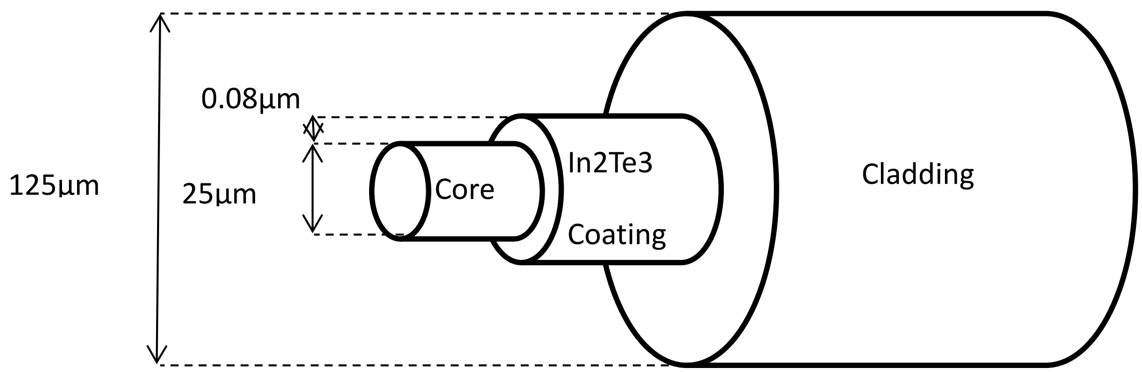


Figure 3-7 In2Te3 Cylinder Fiber consisting of a glass core covered with a thin In2Te3 semiconducting film and a glass cladding

As shown in Figure 3-7, the final coated core fiber is with one thin film layer coated between the glass cladding and core layers.

Figure 3-8 Photo of Test Fiber

Figure 3-8 shows the final test fiber after polishing. It’s as thin as one human hair.

Chapter 4 Experiment Setup

4.1 General experiment setup

In order to examine the characteristics of this coated fiber, we coupled it with two different CW (Continuous Wavelength) light sources, and then focused the output light into spectrum analyzer. The setup (figure 4-1) is as follows:

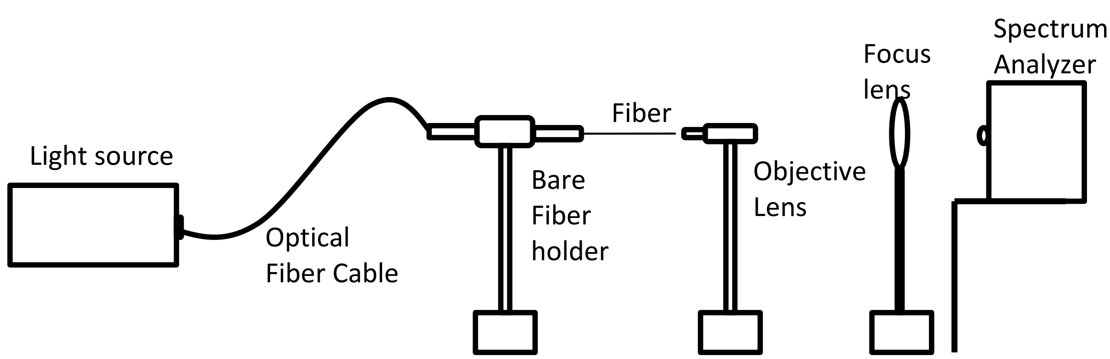


Figure 4-1 General setup for testing semiconductor coated fiber

4.2 Equipment chosen

4.2.1 Light source

- Light source 1

Figure 4-2 Photo of light source 1

This device is Light Source 1, whose spectrum is 424nm~681nm and 1117nm~1294nm. The source power is strong at -6.79dBm (209.5µw) but its spectrum is not flat, it has two peaks at 400nm and 600nm as shown in Figure 5-8.

- Light Source 2

Figure 4-3 Photo of light source 2

This device is white light source, from Ando Electric Co. , LTD. The series number is AQ-4303B. Its wavelength can be switched in three options: 400nm~1800nm, 700nm~1800nm, 1000nm~1800nm. The source can be either CW (continuous wave) or 270Hz pulse light. The output light (after fiber cable connection) of this device is around -45dBm/10nm.[10]

We chose 400nm~1800nm CW light as our experiment setup, because this is the widest spectrum range we can choose from this device.

4.2.2 Pump Light Source

This device is a light source is Pump Light Source. It has a wide range of spectrum from 400nm to 1700nm, most power rest in the range of visible light spectrum 610nm~750nm. This device has two long fiber bundle cables, each has a power of -5.15dBm(304.9µW).

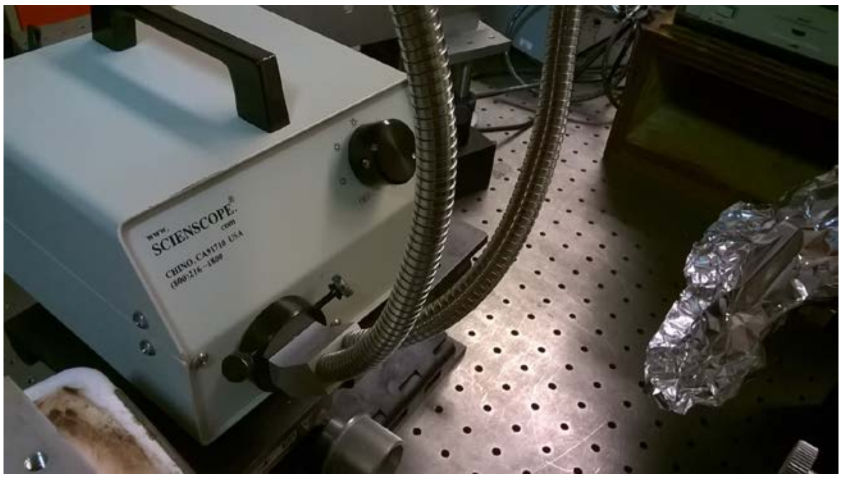


Figure 4-4 Photo of pump light source

4.2.3 Objective Lens & Focus Lens

This objective lens is a ten times (10X) magnification lens and its N.A(Numerical Aperture) is 0.3 with T.L(tube lens) of 170. The coated fiber can be seen on the left of objective lens.

Figure 4-5 Photo of 10X objective lens

This focus lens is a fixed-focus biconvex lens. Its focus length is around 2 inches. As the picture shown, it’s used for focus light into analyzer.

Figure 4-6 Photo of biconvex Focus Lens

4.2.4 Spectrum Analyzer

This device is a spectrum analyzer, from Ando Electric Co. LTD. The series number of it is AQ-6315E. It can detect the wavelength from 300nm~1750nm with the accuracy of ±0.5nm. The intensity ranges from -90dBm to +20dBm, with accuracy of ±0.3dB. The data and graph can be either exported to floppy disk or to laptop[11].

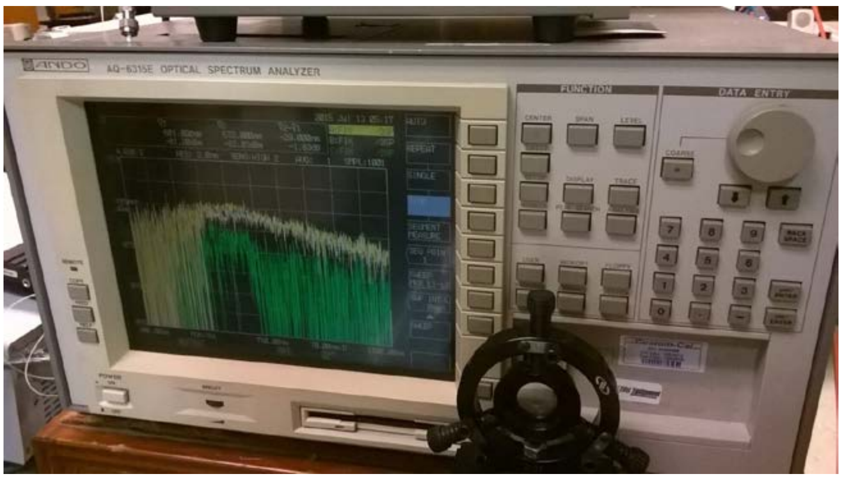


Figure 4-7 Photo of AQ5315E spectrum analyzer

4.2.5 Thermometer

This device is a thermometer from OMEGA, the serial number is HH-2001KL. Its range is from -199.9°C to 199.9°C, and resolution is 0.1°C. The accuracy is 0.1% reading ±0.2°C. [12]

Figure 4-8 Photo of Thermometer

4.3 Experiment setup with pumping light

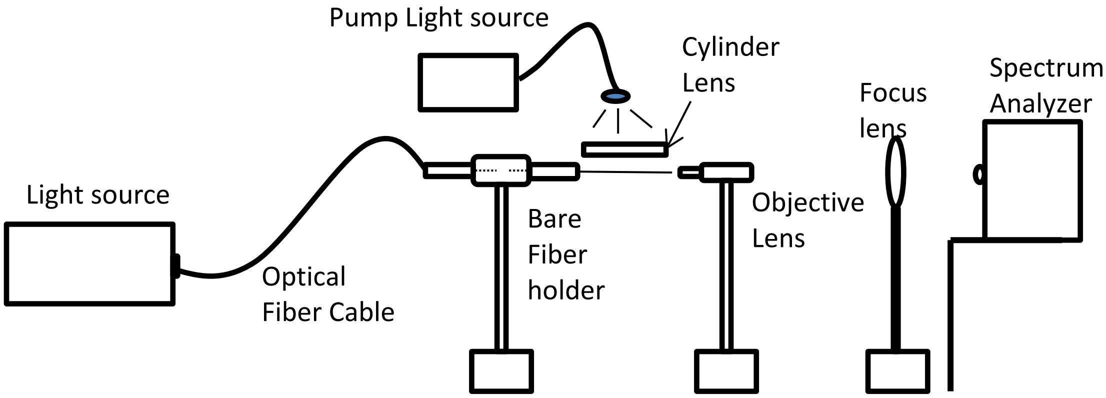


Figure 4-9 Experiment setup with pumping light

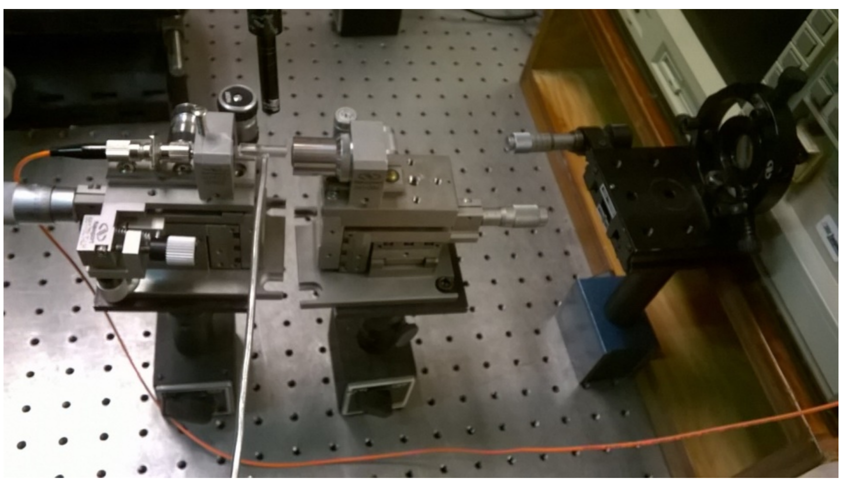


Figure 4-10 Lab setup with pumping light

Purpose of Experiment

The purpose of this experiment is to check if there's laser effect happen in this semi-conductor coated fiber.

Experiment Setup

As shown in figure 4-9, the experiment adds one extra light source as the pumping light. A glass rod replaces a cylinder lens, with focus length of 1/8 inches.

According to the quantum theory, population inversion is one of key requirements for laser. To let population inversion happen, pumping light is necessary. This setup is to examine whether there's amplification or laser emission with the semi-conductor coated fiber.

4.4 Experiment setup with temperature change

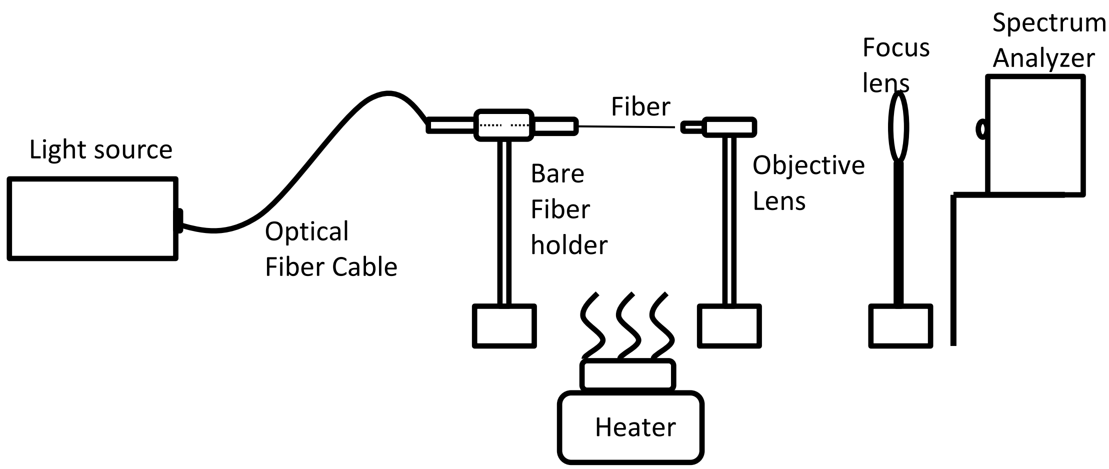


Figure 4-11 Experiment setup with temperature change

Figure 4-12 Lab setup with temperature change

Purpose of Experiment

The purpose of this experiment is to check if there's temperature sensitivity of this semiconductor-coated fiber and what the sensitivity is.

Experiment Setup

As shown in Figure 4-11, there's a heater beside the whole fiber setup. Because it's in an open space, so the temperature range has an upper limit of 100 ˚C and a lower limit of room temperature (around 20˚C). One temperature probe is attached on the top of the setup to do the measurement.

4.5 Experiment setup with magnetic field change

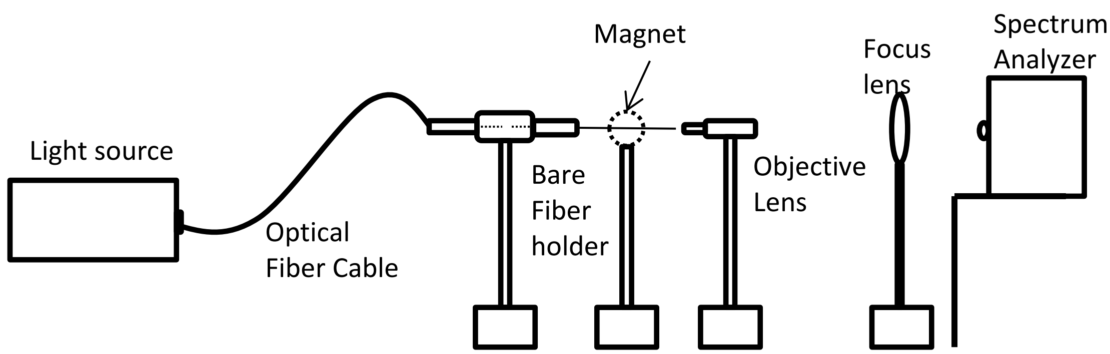


Figure 4-13 Experiment setup with magnetic field change

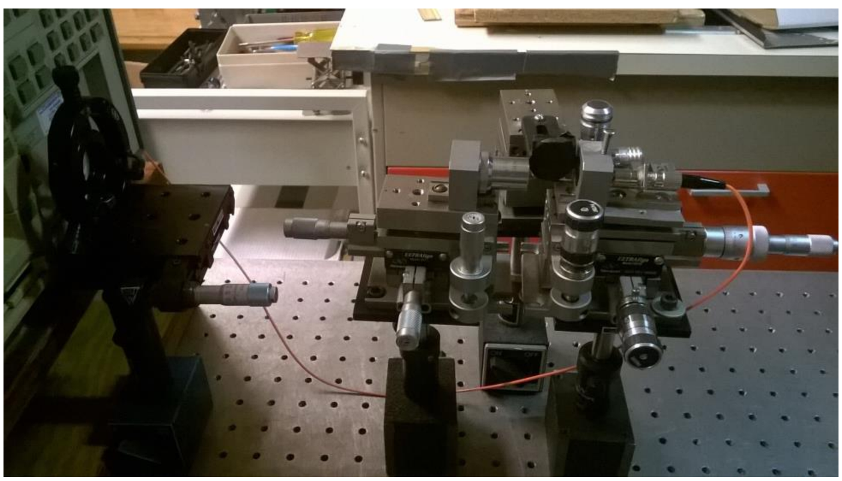


Figure 4-14 Lab setup with magnetic field change

Purpose of Experiment

The purpose of this experiment is to check if there's magnetic sensitivity of this semiconductor-coated fiber and what the sensitivity is.

Experiment Setup

As shown in Figure 4-13, a set of magnets are used to apply a magnetic field around the fiber. The change of the field is realized by adding numbers or flipping the magnet. Several tests have been done to measure the light output in accordance to the magnetic field change.

Chapter 5 Test Result

5.1 Fiber cross-section image

Figure 5-1 and Figure 5-2 are the cross-section images of two ends of the test fiber, whose coating material is In_2Te_3. As shown in the figure, the vertical line on the far right is the cursor which detects light intensity along it. The line in the middle is the base (reference) cursor. And the curve and line on the most left shows the intensity according to the detect cursor.

We can see from the image that it's dark in the middle core and bright in the cladding. The regular uncoated factory fiber should have a bright core and less-bright cladding, as in the figure 5-3. The result means that the semiconductor has a high absorption over the light transmitted in the fiber core, so there's a steep drop between the core and the cladding.

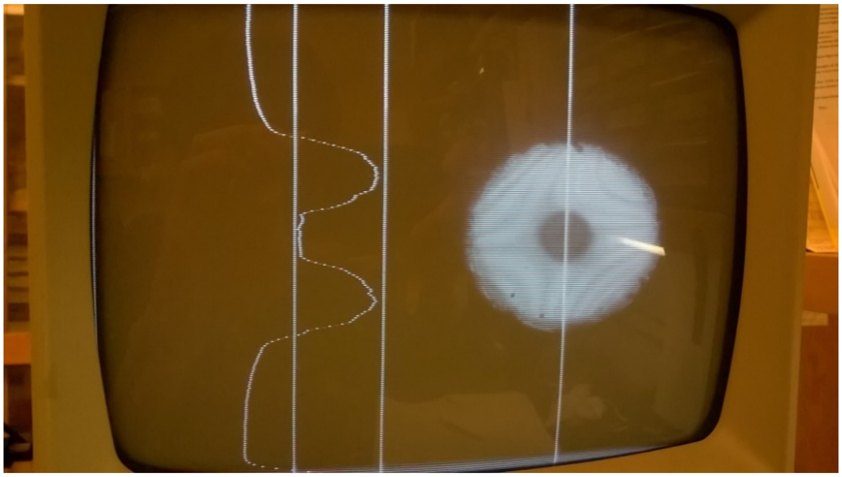


Figure 5-1 Cross-section image of one end of test fiber (In_2Te_3 coated)

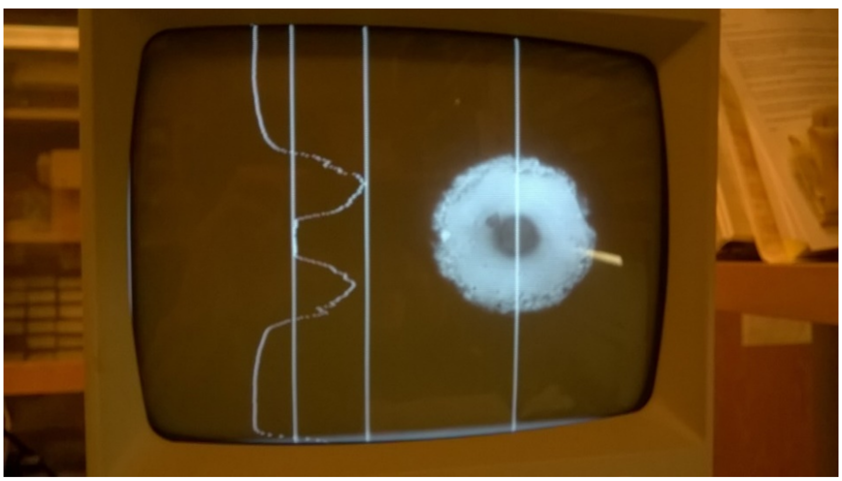


Figure 5-2 Cross-section image of the other end of test fiber (In_2Te_3 coated)

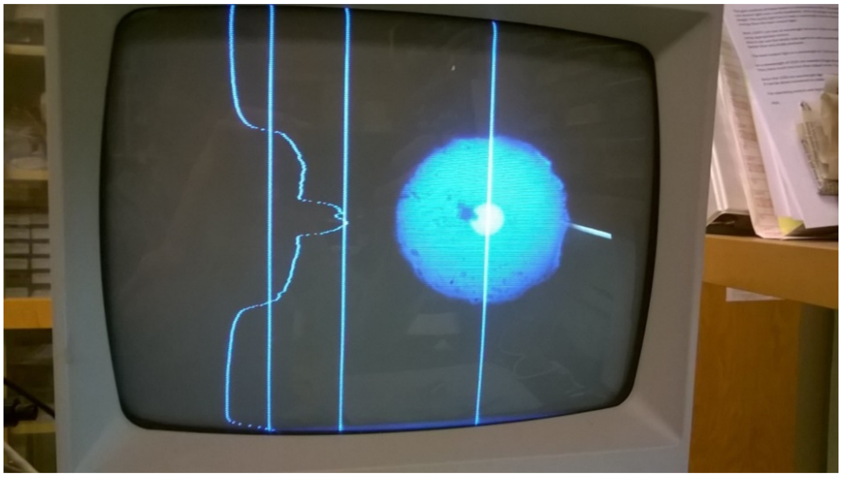


Figure 5-3 Cross-section image of one end of blank fiber

5.2 Temperature Sensitivity of fiber

We set up the experiment as Figure 5-4. There's an obvious power shift detected in the graph below:

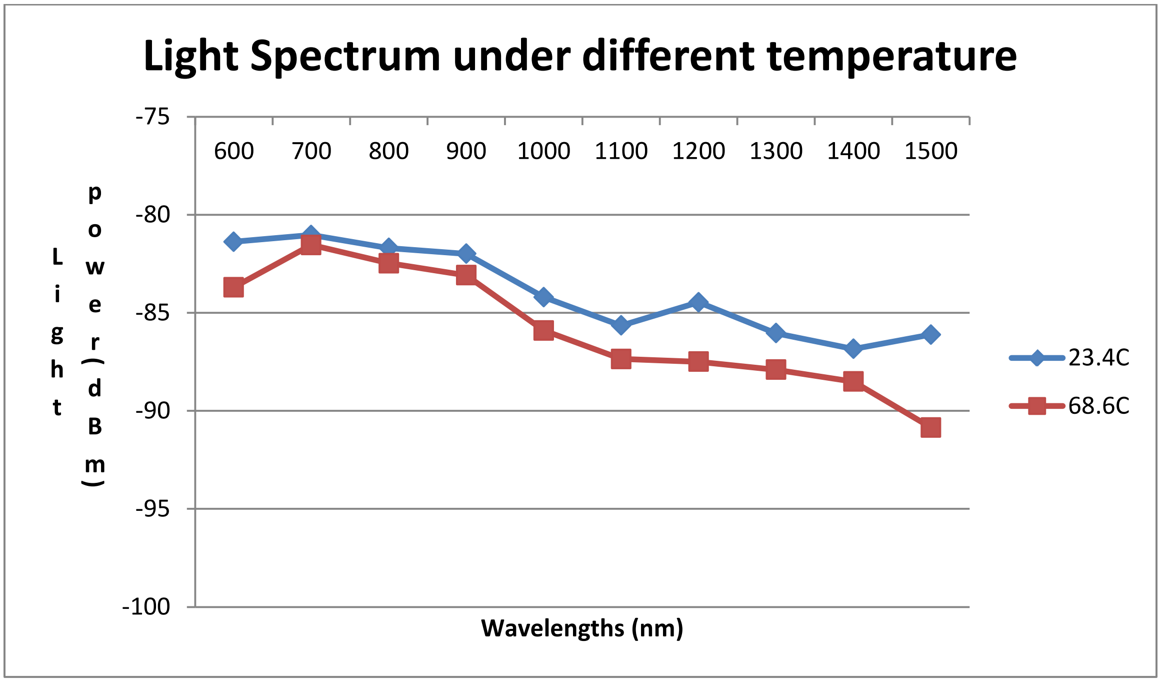


Figure 5-4 Comparison of spectrum with temperature of 20˚C (upper trace) and 68˚C (lower trace)

Figure 5-4 shows that there's a difference of the output light power when the temperature changes. For the accuracy of spectrum analyzer is ±0.3dB, the average difference of 1.2dB is larger than the 0.6dB. So it indicates that a power shift actually happens when temperature changes which made it possible for this kind of fiber to be a sensor. More experiment data are presented in the following Table,

Temperature ˚C	Total Power between 500nm~1500nm (dBm)	Power in nanowatts nW
23.4	-57.71	1.69
30	-57.85	1.64
39.2	-58.15	1.53
49.6	-58.36	1.46
60	-58.84	1.31
68.6	-58.99	1.26
76.7	-59.47	1.13

Table 5-1 Total power-temperature data chart

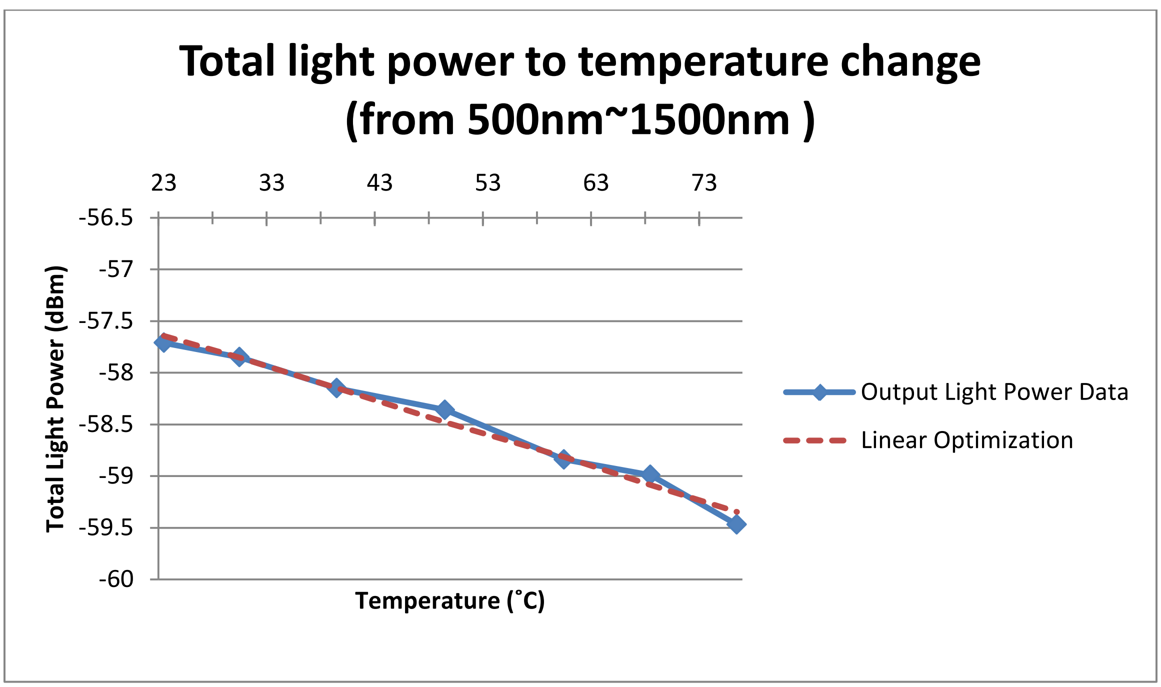


Figure 5-5 Total optical power vs. temperature

According to Figure 5-5 and Table 5-1, due to the experiment setup limitation, the temperature range reachable in this experiment is from 20˚C to 80˚C. But still we can observe the output power linearly decreased in log scale through the increase of temperature. The sensitivity in temperature is -0.03 dBm/˚C and the linearity is 7.21%. If we develop this characteristic more, it can be used as a potential temperature sensor in the future.

5.3 Magnetic Field Sensitivity of Fiber

According to the setup in Figure 4-13, when the surrounding magnetic field changes, light power output would change with it. Following is the data,

Magnetic field **Gauss($*10^{-4}$ Tesla)**	**Light power output** **dBm**	**Power in nanowatts** **nW**
-5	-57.89	1.62
-260	-59.31	1.17
-400	-57.82	1.65
-600	-58.31	1.47
-400	-57.66	1.71
-260	-57.67	1.71
-5	-57.54	1.76
+260	-56.90	2.04
+400	-58.16	1.53
+600	-58.56	1.39
+400	-58.06	1.56
+260	-57.81	1.66
-5	-57.65	1.71

Table 5-2 Total Power-Magnetic Field data chart

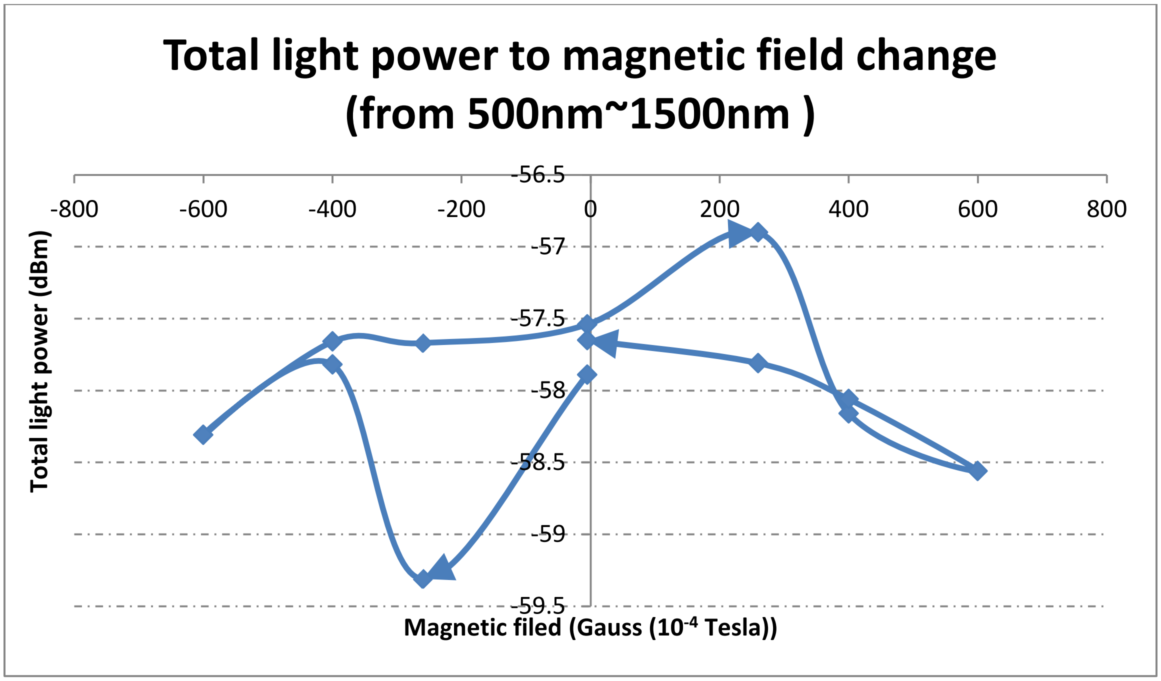


Figure 5-6 Total optical power vs. magnetic field

From Figure 5-6 and Table 5-2, we can see that the graph is like a loop and data is different when we have same magnetic field. The graph is like a hysteresis loop in magnetic field. We can also observe that at the point of ±260 Gauss, the light intensity is way low as -59.3dBm and high as -56.9dBm.

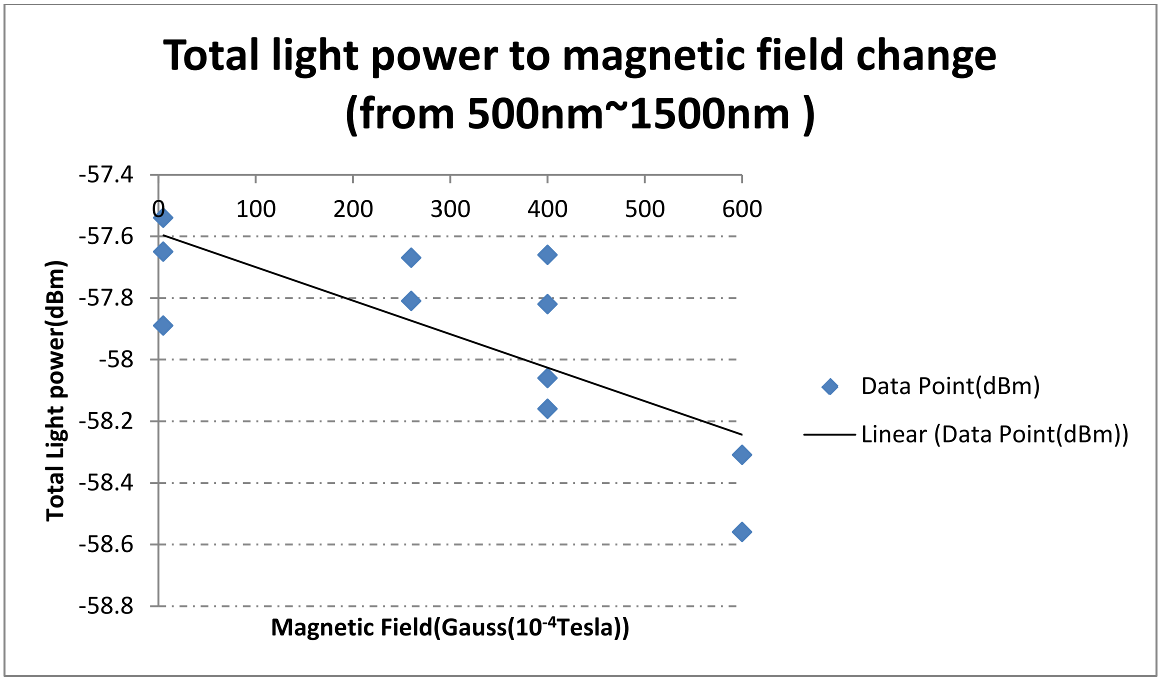


Figure 5-7 Refined graph of total optical power vs. magnetic field

Since we don't put any dipoles in the coating material and In_2Te_3 is not a ferromagnetic material, so we tried doing linear optimization of this graph. We first eliminate the highest and the lowest data point of -59.3dBm and -56.9dBm. And then flip the X-Axis around due to the symmetry. Then from Figure 5-7, we get the sensitivity is -0.0011 dBm/Gauss.

5.4 Laser property of fiber

According to the setup in Figure 4-9, we first use light source 2, the result from the spectrum analyzer is as below:

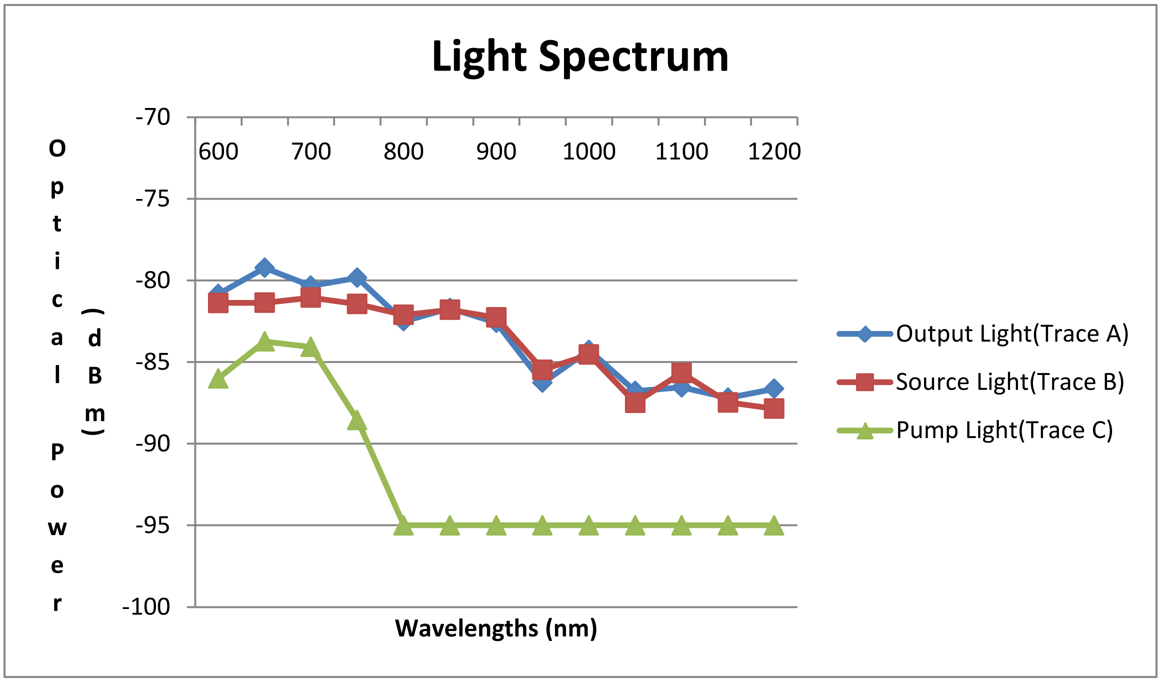


Figure 5-8 With light source 2, spectrum of a) output with pump light& coupling light b)output with coupling light c)output with pump light (-95dBm means no optical power detected)

As we can see from Figure 5-7, spectrum of the pump light ranges from 610nm to 750nm. And accordingly, there's a difference between Trace A and Trace B in that spectrum period. Moreover, addition of average light intensity of Trace C and Trace B in that spectrum period is,

$$-81.01\text{dBm}(\text{Source1}) + -90.63\text{dBm}(\text{Pump}) \approx -79.87\text{dBm}(\text{Output Light}) \qquad (5\text{-}1)$$

We also change the light source to repeat the experiment,

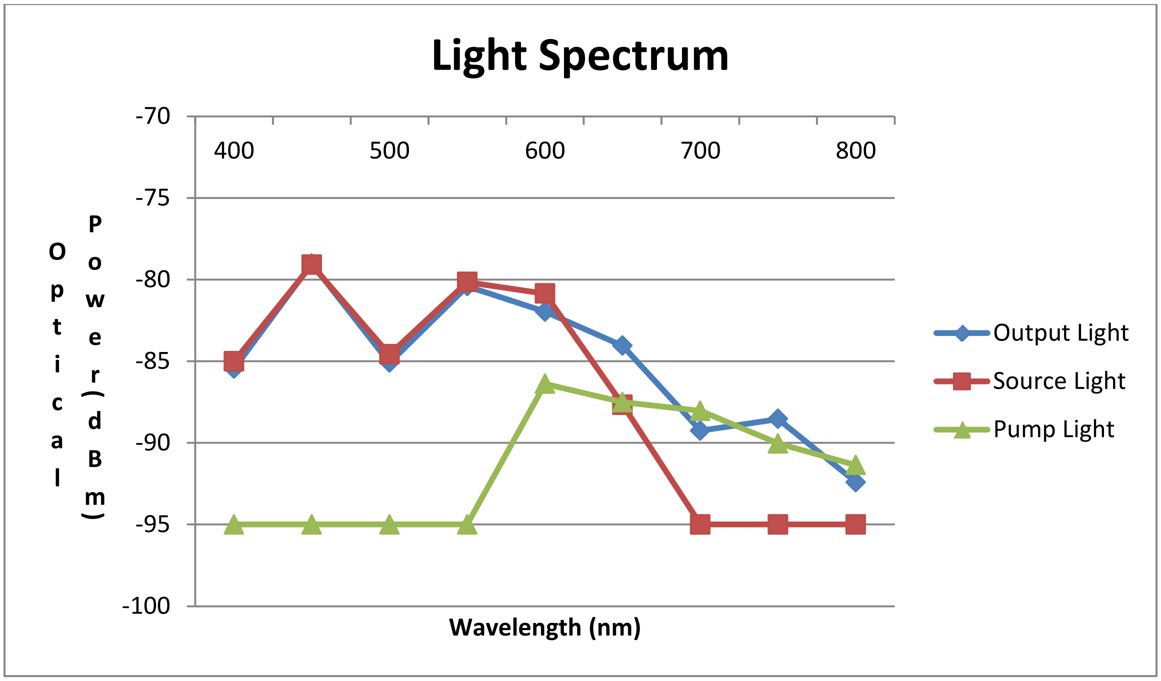


Figure 5-9 With light source 1, spectrum of a) Output with coupling light& pump light b) Output with coupling light c) Output with pump light

Between 610nm~750nm, the average intensity of three traces satisfies

$$-91.01\text{dBm(Source2)} + -91.14\text{dBm(Pump)} \approx -87.95\text{dBm(Output Light)} \tag{5-2}$$

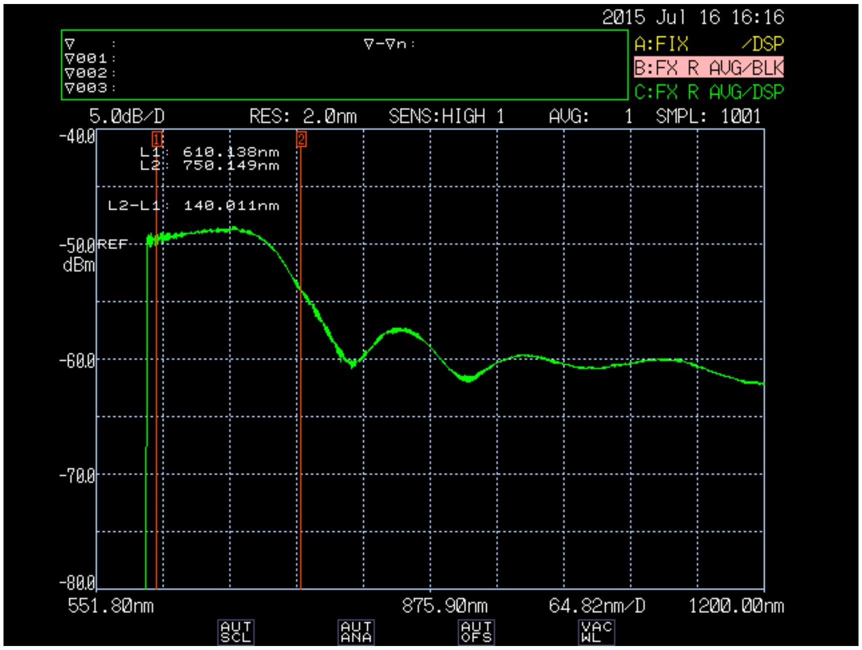


Figure 5-10 Spectrum of pump light shined on the fiber (600nm~1200nm)

From Figure 5-9, we pick the wavelength range from 610nm to 750nm. Then calculate the average light intensity ratio between Input pump light and output light

$$-91.14\text{dBm}(\text{Output})/-49.74\text{dBm}(\text{Input}) = -41.4\text{dB} \qquad (5\text{-}3)$$

$$41.4\text{dB}(\text{Loss})/5.334(\text{cm, fiber length}) = 7.762\text{dB/cm} \qquad (5\text{-}4)$$

The light decreases by 41.1dB through the semiconductor coated fiber and 7.762dB per centimeter.

So we can conclude from two experiments above that there occurs no amplification or laser effect between 400nm to 1100nm when there’s an external pump light(610~750nm). The output is linear to the input light sources.

5.5 Advantages and Disadvantages

Advantages

1. Simple structure and power-efficient

Fiber sensors have an obvious advantage that the fiber itself is a sensor. So unlike other bulky electrical sensors which need power supply, this kind of sensor only needs light to be transmitted in it. It is power-efficient. And because the structure is simple, it brings convenience in repairing or replacing the sensor if it is mal-functioned.

2. Applicable to many small and hard-reached places

Another merit fiber sensors have is that they're tiny and are able to reach many areas which normal sensors can hardly reach. This characteristic is quite important in many industry work[6]. Fiber sensor makes this possible.

3. Cost-efficient for measurement

Unlike other fiber sensors which may needs lots of expensive equipment to analyze received data, semiconductor cylinder sensor only needs optical power meter to measure the change of total optical power. The cost would be less.

Disadvantages

1. Measurement range is small in this work

Given the experimental data collected, the range being measured is limited. The temperature range is from 20 to 80˚C in this work and the magnetic field from -600 Gauss ($6*10^{-4}$ Tesla) to 600 Gauss ($6*10^{-4}$ Tesla). So it is still unknown what the characteristics would be in the bigger range. More data needs to be collected in a better experiment setup.

2. Sensor in the magnetic field need further study

The data collected in the magnetic field doesn't seem to be easily formulated. Improved data collection analysis is needed

3. Limitation of proper fiber glass

Each semiconductor has a specific melting point, which must match on the glass parameters for coating. So this kind of sensor is restricted by the glass type, which also means it cannot be used in an environment that exceeds the melting point of the semiconductor.

Chapter 6 Conclusion & Future Work

From the test results in Chapter 5, we can state that the In_2Te_3 semiconductor cylinder fiber would respond to the temperature and magnetic field change. And also, responding curve during temperature change seems linear in log scale as shown in Figure5-5, which reveals a good potential for being a sensor. At the same time, the responding curve during magnetic field change acts like a hysteresis loop, but we don't add dipoles or ferromagnetic material in the coating, so further study need to be done on this. We observe no laser or amplification effect between the wavelength of 400nm to 1100nm,

More future work can be done on a wider data range. Due to the restrictions of this experimental setup, now we only measured limited data: temperature from 20˚C to 80˚C and magnetic field from -600 Gauss (10^{-4} Tesla) to +600 Gauss (10^{-4} Tesla). Wider range of data could be collected by testing the fiber in a closed environment and with device of adjustable magnets. Test work also could be done on the electric field, to see how fiber characteristics respond to electric field change. Different semiconductor material could be tried in the cylinder fiber to see the difference between different materials.

Reference

[1]Keiser, Gerd. *Optical fiber communications*. John Wiley & Sons, Inc., 2003.

[2]Giallorenzi, Thomas G., et al. "*Optical fiber sensor technology*." *Microwave Theory and Techniques*, IEEE Transactions on 30.4 (1982): 472-511.

[3]Lee, Byoungho. "*Review of the present status of optical fiber sensors*." Optical Fiber Technology 9.2 (2003): 57-79.

[4]Anderson, Ronald, H. R. Bilger, and G. E. Stedman. *"" Sagnac" effect: A century of Earth-rotated interferometers."* American Journal of Physics 62.11 (1994): 975-985.

[5]Choi, Han-Sun, Henry F. Taylor, and Chung E. Lee. "*High-performance fiber-optic temperature sensor using low-coherence interferometry.*" Optics letters22.23 (1997): 1814-1816.

[6]Thévenaz, Luc, et al. "*Monitoring of large structure using distributed Brillouin fibre sensing*." 13th International Conference on Optical Fiber Sensors. Vol. 3746. No. THEVE-CONF-1999-006. Society of Photo-Optical Instrumentation Engineers, 1999.

[7]Kyuma, Kazuo, et al. "*Fiber-optic instrument for temperature measurement*."*Microwave Theory and Techniques*, IEEE Transactions on 30.4 (1982): 522-525.

[8]R Nave, http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html

[9] Sandupatla, Abhinay, "*Indium Telluride Cylinder Fiber Laser*" (2014). *Theses - ALL.* Paper 82. http://surface.syr.edu/thesis/82

[10] ANDO Electric Co. LTD, Instruction Manual For AQ-4304B White Light Source

[11] ANDO Electric Co. LTD, AQ-6315E Optical Spectrum Analyzer Instruction Manual

[12] Omega, HH-2000 Series Logging Thermometer Operation Instruction

[13] Installation, operation and maintenance manual for VHS-6 Pumping Stack model number

3352-L5035-30X

[14] Adams, Arlon and Lee, Jay K, Electromagnetics, Section 10, 4, Cognella, 2012

Vita

Xun Huang was born in Shanghai, China, in 1990. He received the B.S. degrees in Electrical Engineering from Hohai University, Nanjing, in 2013 and the M.S. degree in Electrical Engineering from Syracuse University, Syracuse, NY, in 2015

In 2015, he was a Teacher Assistant with Specialty Fiber Laboratory. His research interest includes fiber optics and semiconductor coatings.