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Self Similar Optical Fiber

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Abstract

This research proposes Self Similar optical fiber (SSF) as a new type of optical fiber. It has a special core that consists of self similar structure. Such a structure is obtained by following the formula for generating iterated function systems (IFS) in Fractal Theory. The resulted SSF can be viewed as a true fractal object in optical fibers. In addition, the method of fabricating SSF makes it possible to generate desired structures exponentially in numbers, whereas it also allows lower scale units in the structure to be reduced in size exponentially. The invention of SSF is expected to greatly ease the production of optical fiber when a large number of small hollow structures are needed in the core of the optical fiber.

This dissertation will analyze the core structure of SSF based on fractal theory. Possible properties from the structural characteristics and the corresponding applications are explained. Four SSF samples were obtained through actual fabrication in a laboratory environment. Different from traditional conductive heating fabrication system, I used an in-house designed furnace that incorporated a radiation heating method, and was equipped with automated temperature control system. The obtained samples were examined through spectrum tests. Results from the tests showed that SSF does have the optical property of delivering light in a certain wavelength range.

However, SSF as a new type of optical fiber requires a systematic research to find out the theory that explains its structure and the associated optical properties. The fabrication and quality of SSF also needs to be improved for product deployment. As a start of this

extensive research, this dissertation work opens the door to a very promising new area in optical fiber research.

Self Similar Optical Fiber

by

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Chapter 1   Introduction

Optical fibers are widely used in the world today, playing important roles in the areas of telecommunications, fiber lasers, sensors, lighting and so on. In general, optical fibers consist of a glass core and a glass cladding as shown in Figure 1.1. The refractive index of the core is higher than that of the cladding, making it possible for the fiber to retain light travelling through the fiber with little loss.[1] One limit in traditional optical fibers is that, due to the glass materials, the minimum attenuation is only obtained when the light is delivered at about 1550nm in wavelength. For light with other wavelengths such as ultraviolet and infrared, the attenuation is very large. As a result, applications of traditional optical fiber in UV and infrared areas are limited.
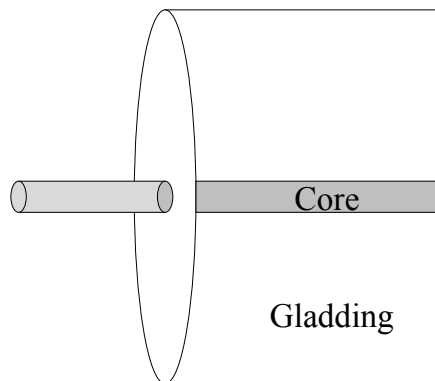
Figure 1.1 Traditional optical fiber

Among the various types of optical fibers, there is one that uses the photonic bandgap effect from the periodic hollow structures in the core to guide a specific wavelength of light. It is the Photonic Crystal Optical Fiber (PCF) [2]. This type of fiber relies on the structure to overcome the aforementioned limit of traditional optical fiber, and it has advantages in applications for high energy laser use and quantum communications where

transmission loss is required to be low. In addition, PCF can also guide UV or infrared light, which is difficult to do in traditional optical fiber.

But the development of PCF is limited by its fabrication. In general, there are two PCF fabrication methods. One is the stack and draw method, and the other is the casting. The stack and draw method can fabricate good quality PCF when there are less than a few hundred tunnels included. However, it is difficult to fabricate a PCF that needs to have a thousand tunnels inside. For the casting method, it requires high temperature and a quality die, which is not easy to obtain. Although PCF has been around 20 years, limitations in PCF fabrication have prevented it from being widely applied as expected. In a laboratory environment, we developed a new optical fiber that has self similar structures in the core. This new optical fiber is called Self Similar Optical Fiber (SSF). The self similar structures are made by iterating a fixed pattern scale by scale following fractal theory. This method of fabricating SSF is called self similar fabrication. We believe this is the first time that such a method of generating self similar structures is used in the fabrication of optical fibers. With this method, a large number of the hollow structures are fabricated inside an optical fiber. It enabled the self similar structures to not only generate exponentially in number, but also reduced exponentially in size.
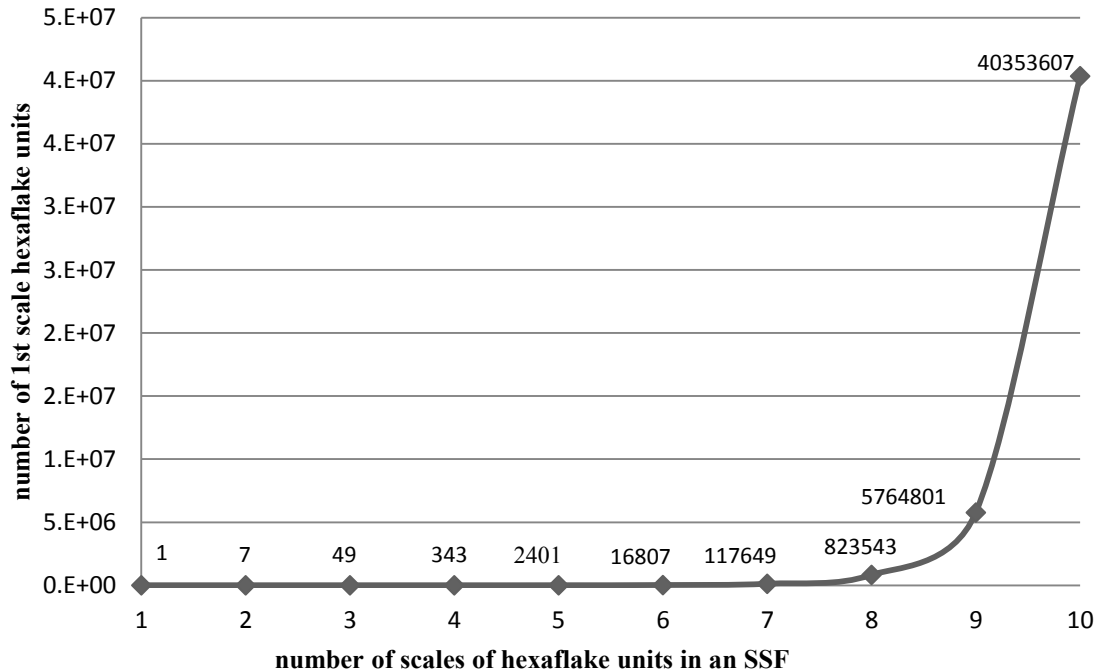
Figure 1.2 Number of 1st scale hexaflake unit(s) in an SSF with different numbers of scales of hexaflake

units

For example, Figure 1.2 shows the number of 1st scale fractal hexaflake units when SSF

is made with different numbers of scales of a hexaflake fractal unit. For SSFs with the

hexaflake units, each of these units consists of seven lower scale units. Therefore, for

SSF with 1 (one) scale of such structure, the number of 1st scale hexaflake unit is 1 (one).

But for SSF with 2 (two) scales of such structures, the number of 1st scale hexaflake units

becomes 7 (seven). When the number of scales is 3 (three), the number of 1st scale

hexaflake units turns out to be 49 (=7×7). If we keep this going, an SSF with 5 scales of

hexaflake structures will have 2401 (=7×7×7×7) 1st scale hexaflake units. And an SSF

with 10 scales of hexaflake structures will have over forty million (=7^9) 1st scale

hexaflake units. This clearly demonstrates that for each additional scale in SSF, the total

number of the smallest structures is increased exponentially. Such SSF fabrication

technology makes it possible to produce a mass of desired hollow structures inside one optical fiber.
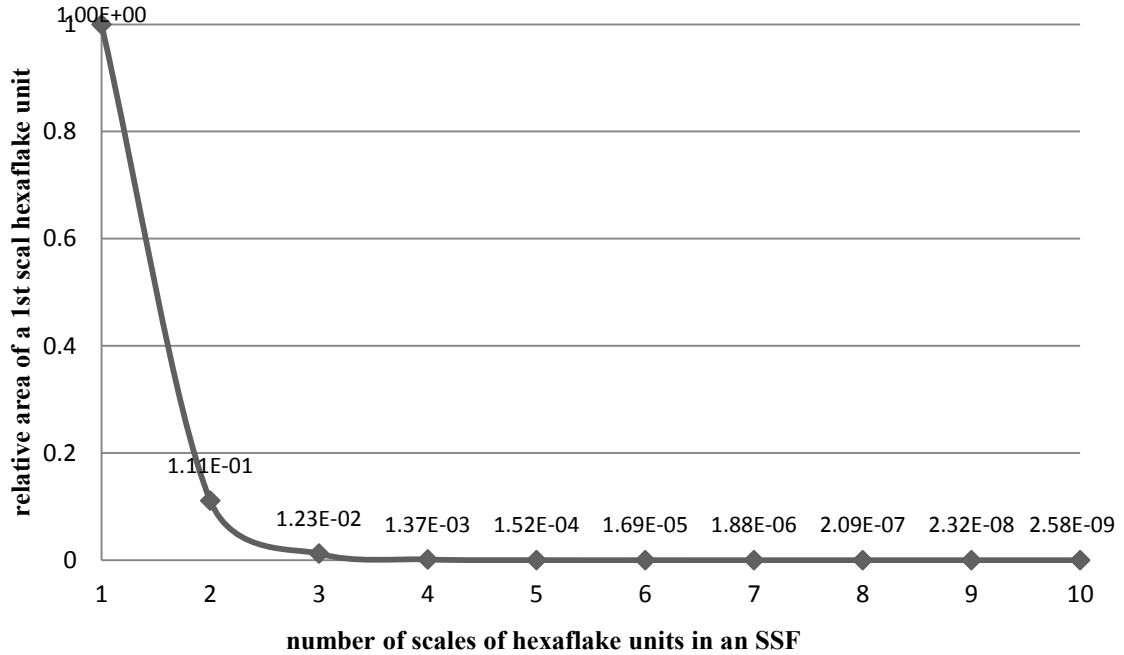
Figure 1.3 Relative area of a 1st scale hexaflake unit in an SSF with different numbers of scales of hexaflake structures

On the other hand, if we assume the core area of an SSF is always constant as 1 (one), as the number of scales increases, the area that each 1st scale hexaflake unit takes will decrease. For example, when there is only 1 (one) scale of hexaflake structure in an SSF, the area for a 1st scale hexaflake unit is exactly the total area of the core (=1). When there are two scales of hexaflake structures in an SSF, each 1st scale hexaflake unit takes an area of $0.111(= (1/3)^2)$. And for SSF with 10 scales of hexaflake structures, the area of each 1st scale hexaflake units drop dramatically to $2.581 \times 10^{-09} (=(1/3)^{18})$. Figure 1.3 shows the curve for area change of 1st scale hexaflake units when the number of scales in an SSF changes. This again indicates an exponential change (negatively) in the size of

lower scale structure units. Such features could be very useful for optical applications when there is a need for optical fibers with a large number of hollow structures that are small in size. The following chapters will discuss the concept of SSF, its possible applications, the SSF fabrication in our laboratory, and tests and analysis on the fabricated SSF samples.

Chapter 2   The concept of SSF

Self Similar Optical Fiber (SSF) is named on the basis of its structural pattern in the core.

Compared to traditional optical fiber, the core of an SSF consists of some base pattern

being repeated at different scales (See Figure 2.1(b)). At each scale, the newly formed

pattern is an iteration of the base one, which results in a self similar unit. In this chapter,

details about the self similar structure in SSF and its potential applications will be

discussed as well as the classification of SSF in the optical fiber family due to its

structural property.
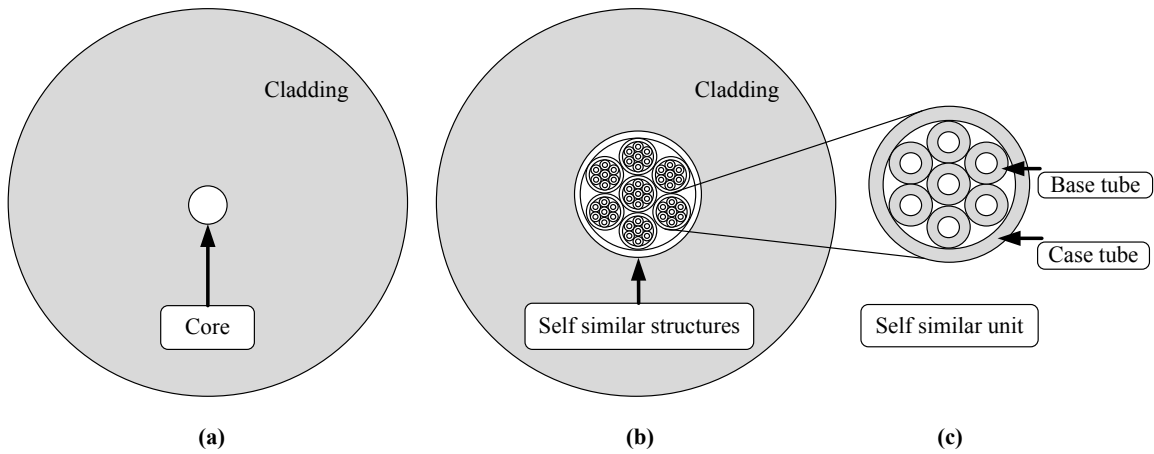
Figure 2.1 (a) Cross sections of traditional optical fiber, (b) Self Similar optical fiber with a two-scale

hexaflake unit, and (c) an enlarged self similar unit (or a one-scale hexaflake unit)

2.1   Self similar unit and self similar structure

A self similar unit is one with a particular structural pattern iterated. Figure 2.1(b) shows

an example SSF with a self similar structure in the core. This structure is formed with

hexaflake set iterations that are made in two steps: seven glass tubes, called base tubes,

were loaded into a case tube in Figure 2.1(c). Such an arrangement is called a hexaflake

unit. A hexaflake unit was drawn into a preform. Seven of these preforms were then fit

into a second case tube as a new "hexaflake unit" and again drawn into a preform.

Through this process, the original seven tube pattern was repeated at two scales. Since the

same geometric structure is self repeated in appearance, it can be called self-similar.

Accordingly, the formed unit is called self similar unit; and the structure that consists of

these formed units is self similar structure.

Many geometric patterns can be iterated to make the self similar units. Both the

geometric pattern and the ultimate size of the individual glass tubes will determine the

optical performance of the SSF. In this research, discussion will be focused on Cantor

Dust set and Hexaflake set to explain the idea of SSF. Hexaflake set is used for actual

SSF fabrication and test.

2.1.1 Cantor Dust set

d_1 $d_2 = \frac{1}{4}*d_1$ $d_3 = \frac{1}{4}*d_2$

(a) Base unit   (b) One-scale unit   (c) Two-scale unit
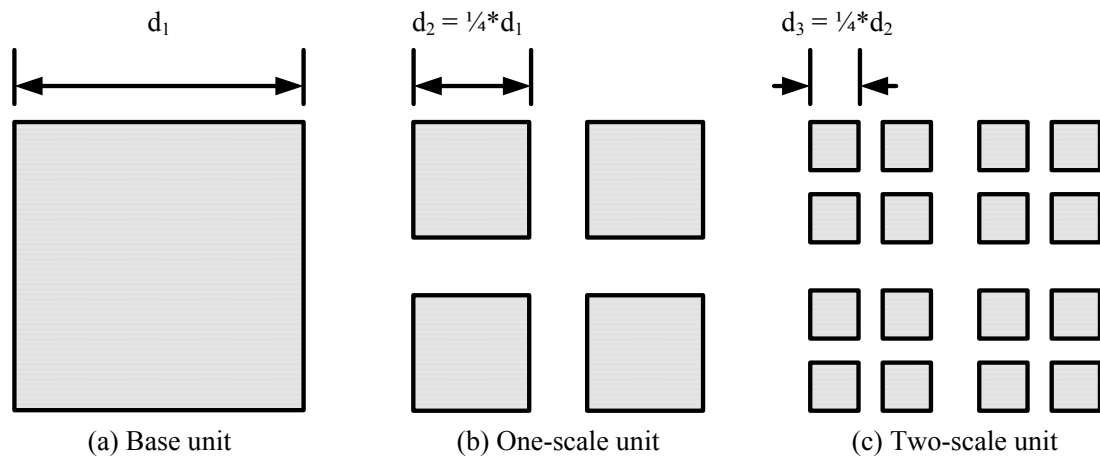
Figure 2.2 Cantor Dust set

Cantor Dust set uses a square object as the base unit in Figure 2.2(a). A recursive

function with two rules needs to be followed to develop this pattern. First, the unit of the

next scale iterates the one of the pervious scale. Second, the scaled ratio of a unit in the

next scale unit is one-fourth, and each upper scale Cantor Dust unit consists of four units

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from a lower scale. Figure 2.2 graphically shows how Cantor Dust set is developed. A square with side d_1 is used as the base unit. The next scale unit is formed by iterating the square structure with four scaled base units. If a two-scale unit is to be formed, a one-scale unit becomes the new 'base unit'. And four one-scale units make a two-scale unit. In this way, a Cantor Dust set can be developed with as many scales as needed.

2.1.2 SSF with Cantor Dust set

d_1 $d_2 = 1/4*d_1$ $d_3 = 1/4*d_2$

(a) One-scale unit   (b) Two-scale unit   (c) Three-scale unit
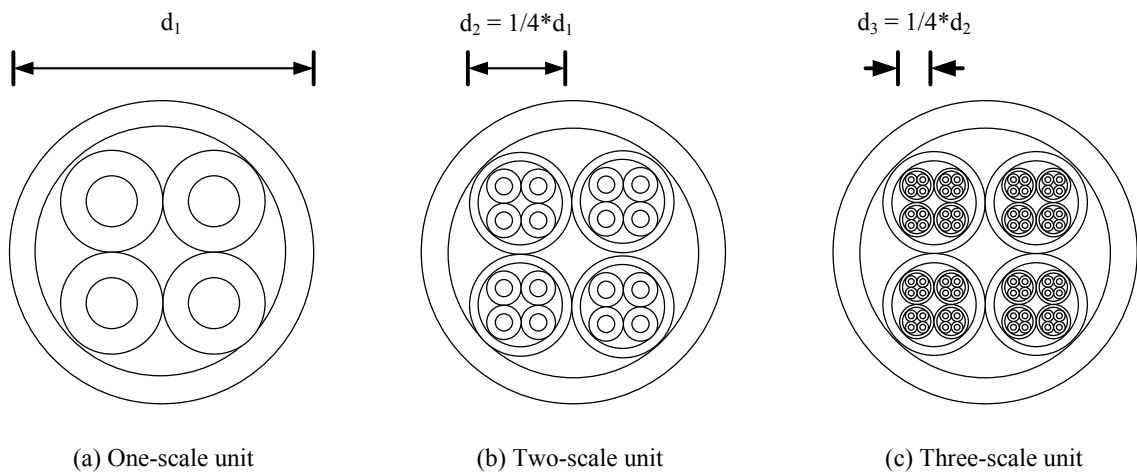
Figure 2.3 Cross section of Cantor Dust set units

When Cantor Dust set pattern is used in the core of an optical fiber, the circle shape of the cross section of four round glass tubes replace the four square base units in the set, and an out-layer *case tube* is used to bundle the tube set. The scaled ratio of glass tubes still keeps being one-fourth for the two scales next to each other. The structure in appearance is self-similar. Iteration of the original pattern can be made as many times as needed to obtain the preform. Then the preform is put into a cladding glass case tube that fits its sizes, and drawn into SSF. As an example, Figure 2.3 shows the Cantor Dust set units formed using glass tubes. The preform has the unit iterated at three scales. With a

cladding layer around the Cantor Dust set in Figure 2.4, an SSF with a three-scale Cantor Dust unit is made.
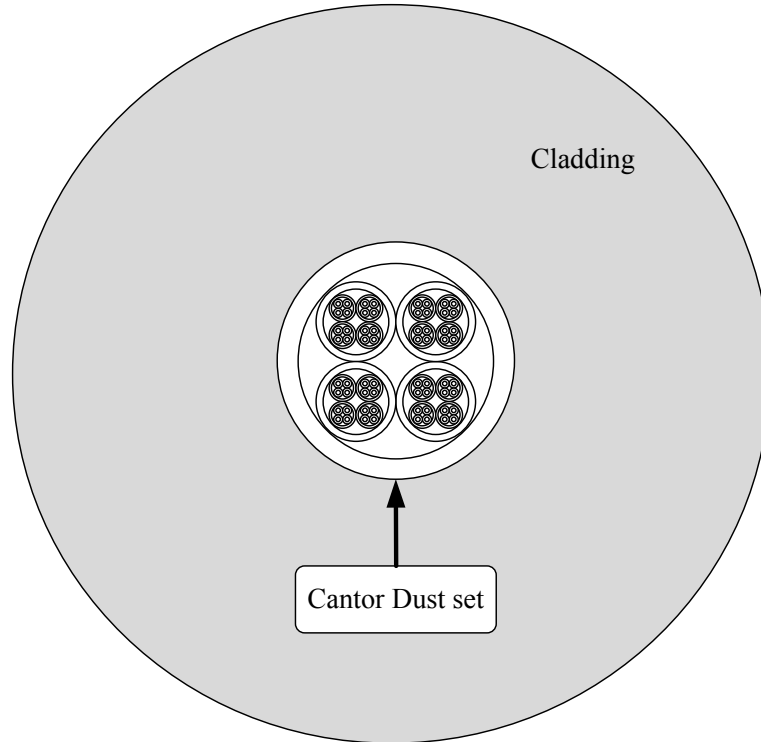
Figure 2.4 Cross section of SSF with a three-scale Cantor Dust unit

2.1.3 Hexaflake set

(a) Base unit   (b) One-scale unit   (c) Two-scale unit
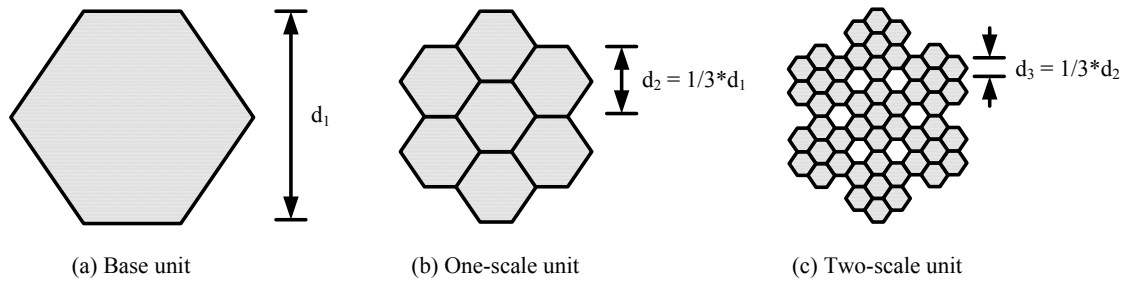
Figure 2.5 Hexaflake set

In a Hexaflake set, a hexagon object as shown in Figure 2.5(a) is used as the base unit. A recursive function specifically for Hexaflake set should be followed. The two rules in this recursive function are that the unit of upper scale iterates the unit of the lower scale next

to it; and the scaled ratio of a base unit in the next upper scale is one-third. The formation

of a Hexaflake set is demonstrated in Figure 2.5. A hexagon base unit has its opposite

sides being d_1 apart. The next (2nd) scale unit consists of seven base units. And at this

scale, the two opposite sides in the original base unit becomes $1/3d_1$ apart. If repeating

this pattern using one-scale units as the new base unit, a two-scale unit can be generated.

Similar to Cantor Dust set, a Hexaflake set can be made with as many scales as wanted. It

also has the property of self-similarity.

2.1.4   SSF with Hexaflake set

(a) One-scale unit   (b) Two-scale unit   (c) Three-scale unit
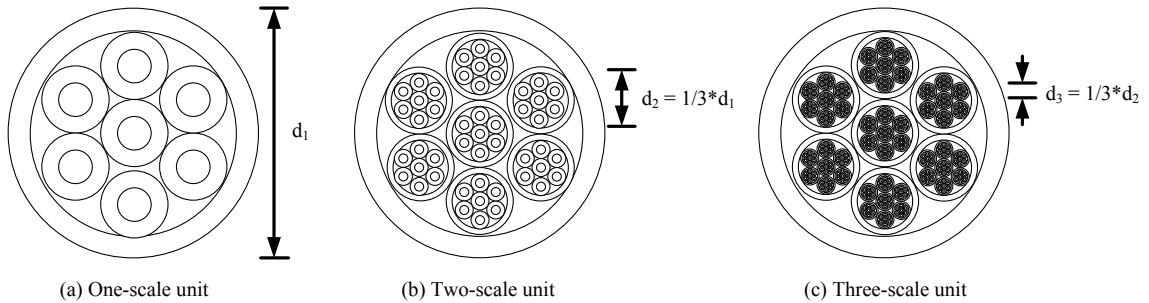
Figure 2.6 Cross section of Hexaflake set units

Using Hexaflake set in the core of an optical fiber will create an SSF. Given that glass

tubes are round in shape, circles replace the hexagon objects in the structure as the base

unit. As shown in Figure 2.6(a), seven small base glass tubes (the base units) are bundled

in a case glass tube in to make an one-scale unit. Following the recursive function, seven

one-scale units are bundled in a case glass tube again to form a two-scale unit in

Figure2.6(b). After this iteration, the diameter of each glass tube is now 1/3 of its original

size in a one-scale unit. The iteration can be repeated to any scales as desired. Figure 2.6

has an example of Hexaflake set up to three scales. If using the three-scale unit product as

the preform, a cladding glass tube will be used with it to make the ultimate SSF (shown in Figure 2.7).
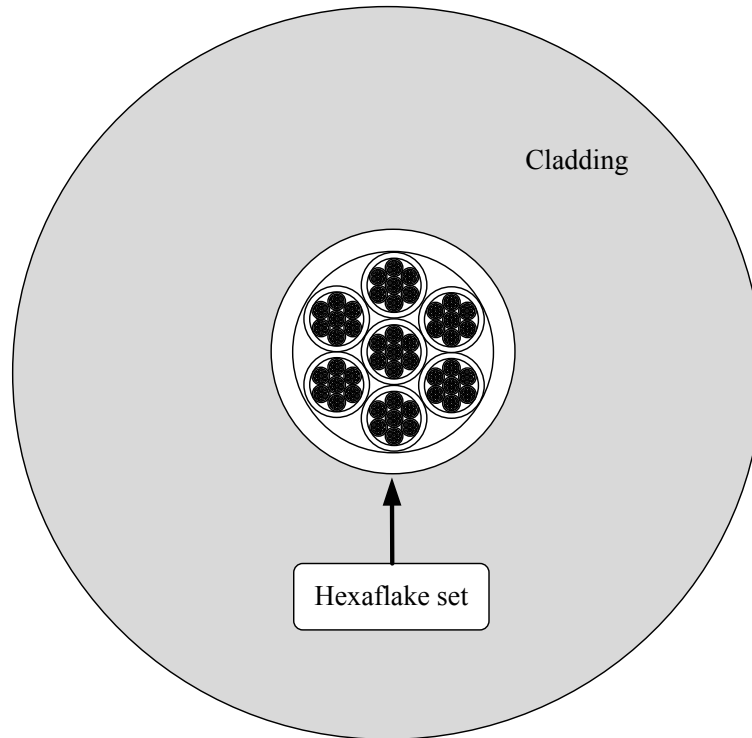
Figure 2.7 Cross section of SSF with a three-scale hexaflake unit

2.1.5   Possible structures with multi fractal pattern(s) and functional unit(s)

The structure of an SSF core is not limited to single pattern fractal layout or with glass tubes of single sizes. Multiple fractal patterns can be used to develop a hybrid structure in the core. Figure 2.8 shows an example of SSF with a hybrid structure. The hybrid structure consists of both hexaflake units and Cantor Dust units.
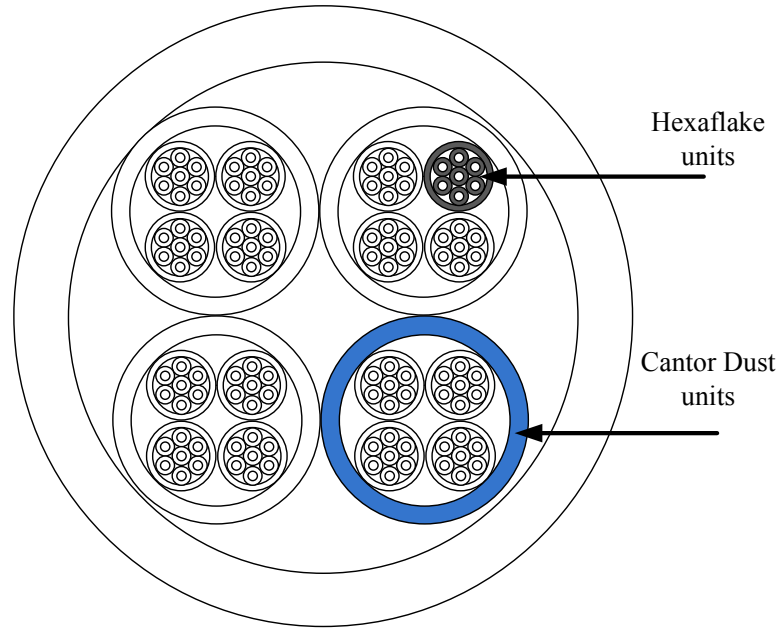
Figure 2.8 A possible hybrid structure consists of Cantor Dust units and Hexaflake units

In addition, similar to PCF [2], there could be SSF with functional hollow or solid unit(s). The functional unit(s) can be one or more at any scale in the self similar structure. The position(s) of the functional unit(s) can be arranged randomly or purposefully. Figure 2.9(a) is an example SSF with a hollow unit at the center. It can be viewed as the hollow-core SSF (HC-SSF). On the other hand, Figure 2.9(b) shows an example SSF with multiple hollow units at a lower scale. If the hollow unit(s) is/are replaced by solid unit(s) as demonstrated in Figure 2.9(c) and Figure 2.9(d), a self similar structure with functional solid unit(s) can be developed.
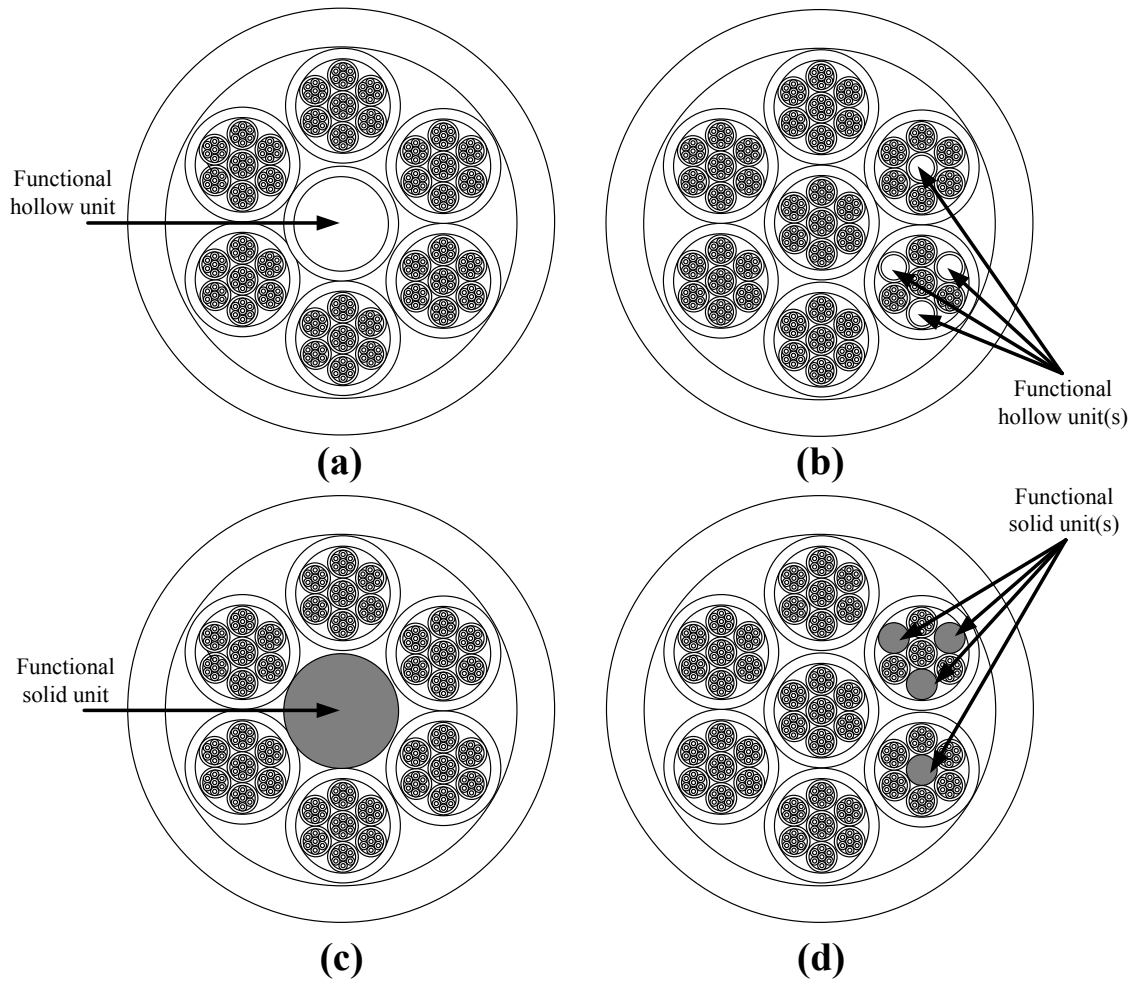
Figure 2.9 Self similar structures with possible functional unit(s)

2.2 Theoretical Classification of SSF

Cantor Dust set and Hexaflake set are only two examples demonstrating the formation of the core structure inside an SSF. For all other SSF, the structure of the core is generated in the same manner by iterating the same structure to a desired scale. Since Cantor Dust set and Hexaflake set are both fractal, it is reasonable to propose that the geometrical structures of SSF can be viewed as fractal in theory.

2.2.1 What is fractal?

In fractal geometry, a fractal object often has the following characteristics[1]:

"When we refer to a set F as a fractal, therefore, we will typically have the following in mind.

1. F has a fine structure, i.e. detail on arbitrarily small scales.

2. F is too irregular to be described in traditional geometrical language, both locally and globally.

3. Often F has some form of self-similarity, perhaps approximate or statistical.

4. Usually, the 'fractal dimension' of F (defined in some ways) is greater than its topological dimension.

5. In most cases of interest F is defined in a very simple way, perhaps recursively."

As demonstrated in Cantor Dust set and Hexaflake set, the two structures are built with base units such as squares or hexagons. As the iteration repeated, base units can become very small. Although the base units can be described in traditional Euclidean geometric language, the resulted iterated structures are so fine that they cannot be described using the same language. However, the formation of a fractal object is very simple in a recursive way. The ultimate structures are obtained by repeating the very original structure from the beginning scale, which can be viewed as self-similar. The *self-similarity* is an important property that makes fractal object different from others in geometry. Other than that, the *fractal dimension[2]* is also evaluated along with the self-similarity feature to determine if an object is fractal.

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[1] Fractal definitions are in [3].
[2] Fractal dimension is used to describe the dimension of a fractal object in fractal geometry. Unlike the traditional Euclidean dimension which is only the integer, it could be a fraction or constant. Fractal dimension is determined based on the relation between units in the two scales next to each other. Hence, the fractal dimension cannot be used to

2.2.2 SSF - An optical fiber with true fractal structure?

To determine if SSF is fractal, the two properties, self-similarity and fractal dimension, have to be examined. These two properties can be looked at together with the ways that a fractal structure is created.

In the world of fractals, there are five ways that fractal objects they are formed, resulting in five types of fractals: escape-time fractals, iterated functions systems (IFS), random fractals, strange attractors, and L-systems[3] [4]. The fabrication process of SSF follows the rules for generating iterated function systems (IFS) among the five varieties. In other words, the core structure of an SSF is a representation of IFS. Since the geometrical structure of an IFS at different scales is similar, SSF with IFS structure meets the requirement of self-similarity for fractals.

As for the other property for determining fractal, the fractal dimension for SSFs can be calculated once the structure pattern is determined. For example, SSF with Cantor Dust set core structure has the fractal dimension as 1 (see Figure 2.10). And SSF with Hexaflake set core structure has the fractal dimension being 1.7712 (see Figure 2.11). The dimension of neither of these two sets can be described using traditional topologic dimension. Especially, given that the dimension of Hexaflake set structure is a fraction, describing it using topological dimension is impossible. Therefore it can be claimed that SSFs with Cantor Dust set structure and Hexaflake set structure are fractal.

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describe the dimension of the first scale unit of fractal objects. The fractal dimension of a fractal object can be calculated from the equation - log m / log r, where m is the repeated number of the previous unit, and r is the scaled ratio. The fractal dimension calculated from this equation is also referred to as the similarity dimension of a fractal set [3].

[3] *Time-escape fractals* are defined by a formula or recurrence relation at each point of a space. *Iterated functions systems* have a fixed geometric replacement rule to build the system with the same unit structure. *Random fractals* are generated by stochastic rather than deterministic process. *Strange attractors* are generated by iteration of a map or the solution of a system of initial-value differential equations that exhibit chaos. And *L-systems* are generated by string rewriting and are designed to model the branching patterns of plants.

For other SSF, the core structure is always generated in the way that IFS is developed. Hence, theoretically, their fractal dimension should meet the requirement for fractal objects. Although this has not been proved through mathematical verification, before any exception is found, it is very reasonable to view SSF as fractal.

Fractal dimension of Cantor Dust set structures
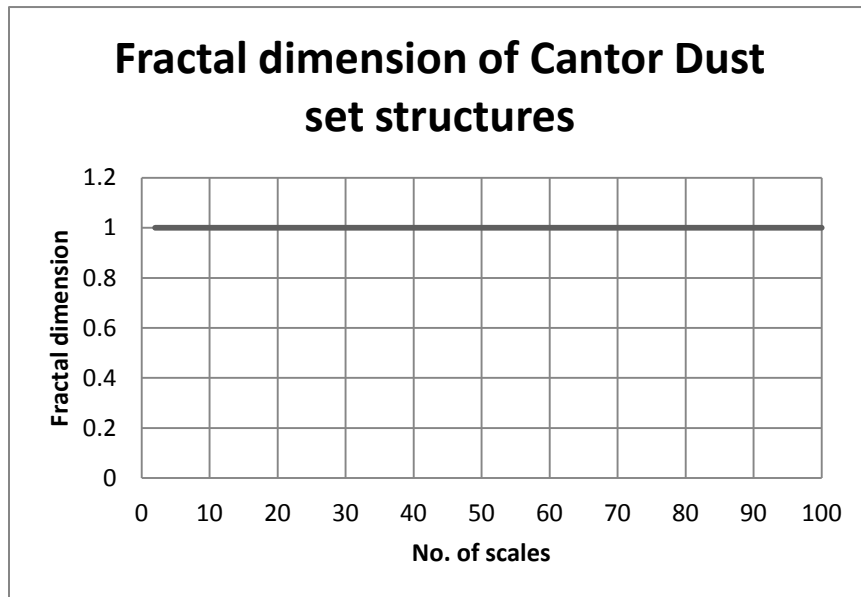
Figure 2.10 Fractal dimension of Cantor Dust set structures with 2 to 100 scales

Fractal dimension of hexaflake set structures
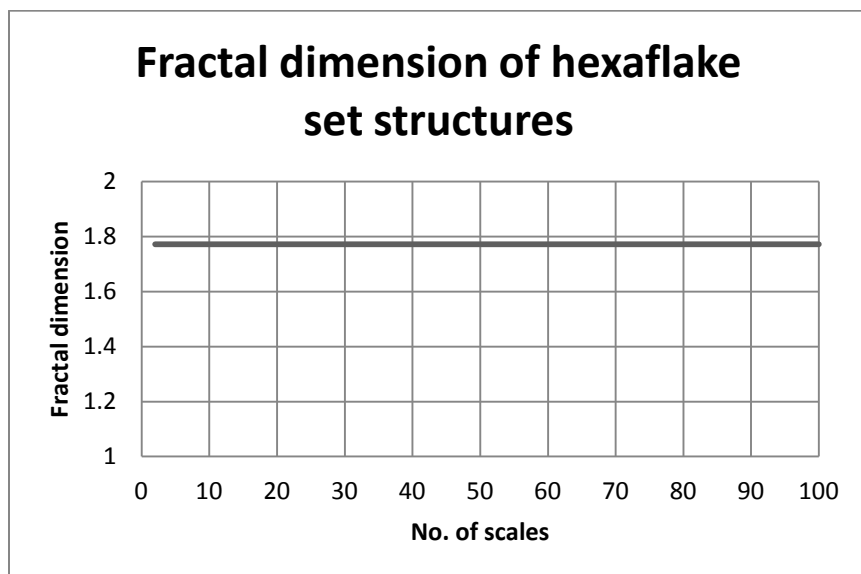
Figure 2.11 Fractal dimension of Hexaflake set structures with 2 to 100 scales

It needs to be noted that, there have been two very related research studies on fractal fiber products [5][6][7]. But they either did not fabricated optical fibers, or only made optical fibers with a simple fractal structure that contained a limited number of tunnels in the core. For example, Lee M. Cook is the first person that made a fractal faceplate using optical fibers [5]. This research aimed at creating engineered fractal objects with optical fibers as the materials. It is fractal related. But the resulted product is not a fractal optical fiber. On the other hand, S.T. Huntington et. al. made a kind of fractal-base optical fiber successfully [6][7]. They used an adjusted "stack and draw" method to fabricate fractal-based optical fiber. The resulted structure of their products was very simple.

2.3　The possible properties of SSF and its applications

2.3.1　Determinants of the overall optical performance of SSF

In appearance, the hollow self similar structure looks similar to the hollow structure in another type of optical fiber – the photonic crystal optical fiber (PCF). The hollow structures in both types of optical fibers share a basic light guiding property[4]. However, the self similar structure in SSF is fractal, but not periodic as that in PCF[5] [8]. Such a fundamental difference is that optical fibers with self similar structures have two structure properties: self similarity and symmetry. These two determine the possible optical performance of SSF.

2.3.1.1　Self Similarity of a fractal pattern

Research studies have found that fractal optical products, such as fractal optical plate, not only has the self similarity in structures, but also has the self similarity in optical

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[4] The light properties of SSF will be presented in Chapter 4.
[5] See section 2.2 in Chapter 2.

performance [8][9][10][11]. These studies indicated that the optical properties of a higher

scale iterate those of a lower scale next to it, and the overall optical properties of the

fractal optical product are all-inclusive with optical properties from all scales. Although

these research studies were based on one dimension fractal structure, it is reasonable to

hypothesize that SSF has the self similarity in overall optical performance because of self

similarity in structure.

Based on our understanding, the self similarity in optical performance of SSF means that

its overall optical performance is due to a collection of the guided modes[6] of the

structures at all scales. For example, the overall optical performance of an SSF with a 10-

scale hexaflake unit is due to the collection of the guided modes for units from the first to

the tenth scales. With this in mind, the difference in the number of scales of different SSF

determines their differences in the overall optical performance. In addition, the guided

modes of an SSF with fewer scales are reflected in those of an SSF with more scales. For

example, when an SSF with a 5-scale hexaflake unit is compared with one that has a 10-

scale hexaflake unit, their overall optical performances will be different. But the guided

modes of a 5-scale SSF can be found in those of a 10-scale SSF.

2.3.1.2   Symmetry of a fractal pattern

When different self similar structures are used in SSF, the overall optical performances

will differ. We used the point symmetry group [12] to determine the differences between

fractal patterns. For example, a Cantor Dust set structure (Figure 2.3) and a hexaflake set

structure with the same number of scales (Figure 2.6) have two different structure

symmetries. In Figure 2.6(c), we assume a three-scale hexaflake unit consisting of

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[6] The guided modes are TE, TM and hybrid modes from the transverse modes for electromagnetic waves.

identical glass tubes, and all lower scale units in it are aligned in the same orientation. The symmetry of such a three-scale hexaflake unit approximates that of a hexagon shape. According to group theory [12], the symmetry of a hexagon is a C_{6v} point symmetry group. Hence, an ideal three-scale hexaflake unit (shown in Figure 2.6(c)) can be considered as a C_{6v} point symmetry group. Following the same logic, a same scale Cantor Dust unit (shown in Figure 2.3(c)) can be viewed as a C_{4v} point symmetry group. The different structure symmetries can make a difference in overall optical performances such as the guided modes in the corresponding SSFs.

For the two determinants explained above, the self similarity can be expressed using self similar group, which is a matrix for the self similarity from a fractal pattern's recursive function. The symmetry of a fractal pattern is expressed using point symmetry group. Hence, the overall optical performance of an SSF can be viewed as the product group from its self similar group and point symmetry group. The irreducible representations of the product group are the guided modes. The reason the irreducible representation corresponds to the guided modes is that the elements of the product group commute with Maxwell equations.

Although additional research is needed to build the theoretical ground for SSF and verify the arguments made above, one thing about SSF is true – its fabrication is not difficult[7] regardless of various design factors such as single or multi geometrical patterns, scale of self similar structure, units alignment, and scale ratio. These variations in SSF would extensively increase the possible areas where it can be applied.

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[7] Chapter 3 will demonstrate how the fabrication is done.

2.3.2 Possible properties of SSF and its applications

There are four possible optical and physical properties[8] that we expect SSF to have:

- Light guiding at specific wavelength

- Enabling light to interact with gas or liquid

- Capillary action

- nonlinear optical effect from nano thin film semiconductor or metal coating

The first property comes from the self similar structure. The second and third properties are in common with those of PCF, as they both have hollow structures. The last one could be generated from nano thin film semiconductor or metal coated inside the optical fiber. These properties have great potential use in many areas, including telecommunications, UV and infrared carriers, sensors, medical applications, chemistry analysis, fiber lasers, etc. Details about the properties and corresponding applications of SSF are provided below.

2.3.2.1 Light guiding at specific wavelength

Different from traditional optical fiber, the light guiding property of SSF comes from self similar structure instead of the refractive index difference between glass materials[9]. As mentioned earlier, the overall optical performance of an SSF is due to a collection of guided modes from all scales. Since the self similar structure units at different scales have different sizes, different wavelengths of light can be expected to be delivered in an SSF parallel. In application, it means that the information that can be carried by SSF would be

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[8] Several properties have not been verified yet, but are viewed as possible.
[9] Theoretical explanation for this property is not fully developed. However, tests on fabricated samples have revealed that SSFs do guide light with certain wavelength.

higher information carrier ability than current optical fibers. It can be deployed in telecommunications which always needs large bandwidth capacity.

Another advantage that SSF may have is that the self similar structure allows light in a wider range of wavelengths to get through than traditional optical fiber, including UV and infrared light. Several researches indicated that hollow-core PCF (HC-PCF) can work well in the UV and infrared light [13][14] [15][16]. Such light was found delivered through the hollow core structure. It is reasonable to consider that SSF with a center hollow unit (hollow-core SSF) in Figure 2.12 or any other appropriate fractal patterns can guide UV or infrared light. Such an advantage, if verified, would help overcome the limit that traditional optical fiber has in UV and infrared applications.
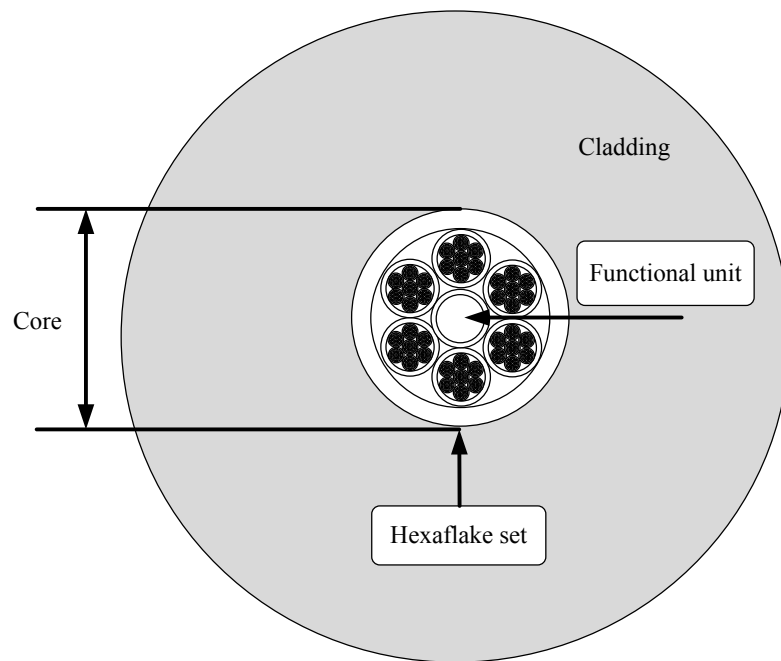
Figure 2.12 Hollow-Core SSF (HC-SSF)

For photolithography in VLSI manufacturing, SSF can be used to guide UV light and work in an area as small as the cross section of a human hair or micro dimensions. In medical areas, SSF can be deployed in treatment devices, making it possible to guide UV

light into the human body to destroy cancer cells or bad DNA with minimum physical damage. In a similar manner, HC-SSF can also be used as an infrared light carrier for alternative medical operations and imaging.

2.3.2.2 Enabling light to interact with gas or liquid

The hollow structure in SSF can be filled with gas or liquid, so that light is possible to interact with the gas or high refractive index liquid to generate certain optical effects. Similar optical effects have been found in PCF [2][17][18][19], which also has hollow structure to be filled with gas or liquid. These effects can be used in fiber based lasers, biosensors, and many other applications that are still being developed. Although this property has not been verified in SSF, SSF does appear to be promising in this aspect.

2.3.2.3 Capillary action

With self similar fabrication method, it will be possible to fabricate SSF that contains over a thousand small hollow structures in the core. Such structures could have capillary action. By controlling the hollow tunnel size, SSF can be used to capture certain liquids, or small elements such as cells or molecules. It hence can be applied in the areas of chemical, medical, or biological analysis.

2.3.2.4 Coated with nano thin semiconductor or metal film

With current coating techniques in optical fiber fabrication [20][21], it is possible to coat the self similar units with nano thin films in an SSF to achieve special optical properties. It has been found that a regular optical fiber with about 15~20nm Cadmium Phosphide (Cd_3P_2) film can amplify light in a range of wavelength [22][23]. Also, a 5~10nm gold alloy film inside a regular optical fiber was observed having optical responses with DNA

liquids [24]. When these semiconductor or metal thin films are coated around self similar

units[10] or individual glass tubes in an SSF, the obtained SSF would have multiple layers

of dielectric material. It is expected that SSF coated with Cd_3P_2 can be used as optical

amplifiers or in fiber laser stimulations. SSF coated with gold alloy thin films would have

the potential use in biosensors.

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[10] The self similar units can be at selective scale(s) or all scales.

Chapter 3   Fabrication of SSF

Although the discussed advantages of SSF are appealing, they can only be obtained after SSF is fabricated. This chapter will explain the fabricating technique for SSF, including the process that was taken, challenges encountered, and solutions.

3.1   Overview of fabricating SSF

In this research, Hexaflake set is chosen as the base unit structure in constructing the SSF. It approximates an ideal circle in shape, and is symmetric in geometrical arrangement. Compared to the other patterns such as Cantor Dust set, Hexaflake set would have less deformation when glass tubes are pulled to be rescaled, hence making the fabrication easier. For the purpose of testing the fabrication technique of SSF, Hexaflake set thus turns out to be the best choice for the base unit structure.

The SSF to be fabricated is iterated to the third scale. This is the highest scale that can be reached given the equipment capability in the laboratory. As described in Chapter 2 (see Figure 2.7), an SSF with three scales hexaflake iteration in the core would have 49 one-scale hexaflake units, 7 two-scale hexaflake units, and 1 three-scale hexaflake unit.

The development of an SSF involves three steps as shown in Figure 3.1: selecting glass materials, making core with hexaflake units, and fabricating SSF using the core.

```
                    ┌─────────────────────────────┐
                    │           Step 2            │
                    │     Making hexaflake units  │
                    │   ┌───────────────────────┐ │
                    │   │  One-scale hexaflake  │ │
                    │   │        units          │ │
                    │   └───────────┬───────────┘ │
┌────────────────┐  │               ▼             │  ┌────────────────┐
│    Step 1      │  │   ┌───────────────────────┐ │  │    Step 3      │
│Choosing glass  │─▶│   │  Two-scale hexaflake  │ │─▶│Fabricating SSF │
│   material     │  │   │        units          │ │  │                │
└────────────────┘  │   └───────────┬───────────┘ │  └────────────────┘
                    │               ▼             │
                    │   ┌───────────────────────┐ │
                    │   │ Three-scale hexaflake │ │
                    │   │        unit           │ │
                    │   └───────────────────────┘ │
                    └─────────────────────────────┘
```
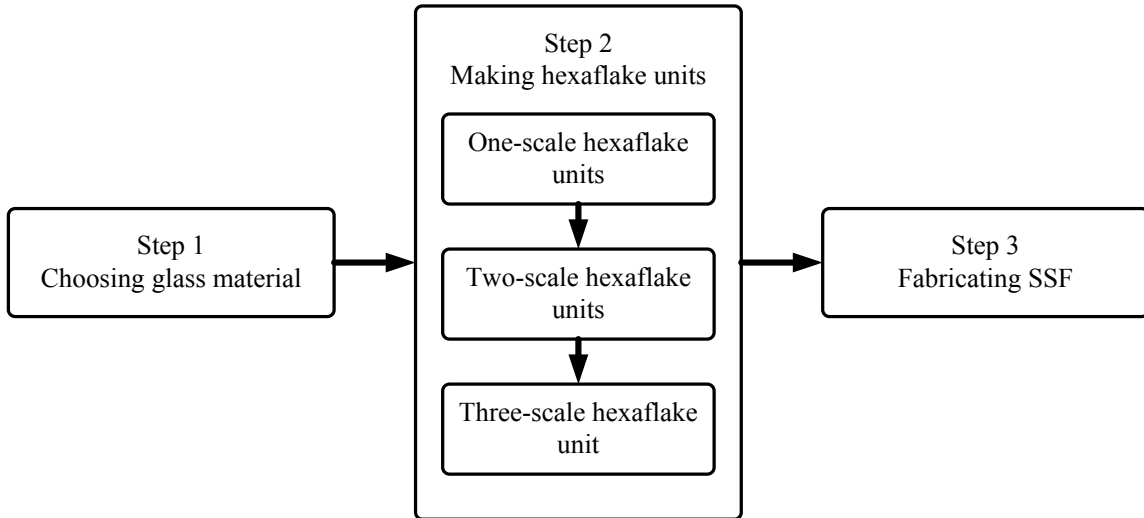
Figure 3.1 Developing processes of SSF with a three-scale hexaflake unit

3.1.1   Step 1: Selecting glass material

For test sample preform fabrication of SSF in a laboratory environment, the glass
materials should be easy to acquire; have various tube sizes to meet the need of fitting
tubes to make the fractal patterns; and have the softening temperature range from 800 to
900 Celsius. Corning Pyrex (Corning 7740) meets these requirements well. Therefore, it
is selected for the test in the fabricating process in our laboratory.

As shown in Table 3.1, three sizes of Corning 7740 glass tubes were used in the test
sample fabrication. GT1 and GT2 were used for making the hexaflake units in the
preform of the SSF core, with GT1 tubes bundled in a GT2 tube. GT3 is the cladding
layer of an SSF. Dimension errors were observed in the glass materials to be used.
However, these errors can be neglected because they will become minor as the tubes are
rescaled.

Glass tube Type	Inside Diameter (ID) (unit: mm)	Outside Diameter (OD) (unit: mm)
GT1	0.5	1
GT2	6	8
GT3	1.5	6.5

Table 3.1 Specifications of glass tubes

3.1.2   Step2: Making core with the hexaflake units

The SSF core making starts with the one-scale hexaflake unit, including seven base tubes

(GT1) bundled in a case tube (GT2)(shown in Figure 2.1(c)). This one-scale unit is pulled

to about 1mm diameter, so that seven of these rescaled one-scale units can be packed into

a GT2 to make the two-scale hexaflake unit. These two-scale units then can be rescaled

and packed again into a GT2 to make a three-scale hexaflake unit. And this process can

be repeated until a hexaflake unit with desired scales is obtained to be used as the core. In

our test fabrication, we only want the hexaflake units to be made with three scales. Figure

3.1 briefly describes our fabrication process.

3.1.3   Step 3: Fabricating SSF

Once a core with hexaflake units with the desired scale is obtained, it can be rescaled as

desired, and put into a cladding glass tube to be pulled into an optical fiber. GT3 is used

as the cladding outer shell in this test.

3.2   The fabrication system

Given the complexity of the layered structure and the strict requirement on the rescale

ratio, an optical fiber fabrication system that can evenly heat the glass materials with

good control is essential for success. Such a system should consist of two main sub-

systems: pulling temperature control sub-system that softens the glass materials and a

fiber dimension pulling ratio control sub-system that determines the dimension of the pulled preform or optical fibers.

There had been an existing pulling furnace in the laboratory. It however could not provide good control over temperature and pulling ratio. There were three main drawbacks that prevented it from fitting the need of fabricating SSF. First, it used traditional heat conduction method to heat the glass tubes. Such heating method could cause non-uniform distribution of the heat in the glass tube layers. Second, the temperature control had to be done manually, which had delay in response to the temperature change. And third, the scale ratio circuit can only provide a fixed pulling ratio. It did not meet the need of changing ratio in making the fractal structure core and the ultimate SSF.

To resolve these problems, a new optical fiber fabrication system was developed on the basis of the existing pulling furnace. Development of the new system will be introduced against the drawbacks in the existing one.

3.2.1 New optical fiber fabrication system – uniform heat distribution

Like most optical fiber fabrication systems, the existing pulling furnace in our laboratory uses heat conduction method to soften glass material. A characteristic of this heating method is that the heat takes time to be transferred from an object's surface to the inside, hence making the subject unevenly heated. If temperature is measured in different depth of the heated subject, it will be highest at the surface, decreasing all the way down to the center.

The same heating phenomenon was also observed when some optical fibers were fabricated in our laboratory before. It can lower the quality of preforms, which are pulled

into optical fiber later. Each preform has a cladding layer and a core that needs to be

bound. The temperature difference prevented the core and cladding layers from being

bound well, hence the obtained preform would have a considerable amount of air gaps.

Even if a well bound preform was made, success in optical fiber making is not guaranteed.

Sometimes the surface of the preform was heated to a temperature that it made soft

enough to be pull. But, the center of the preform did not receive sufficient heat to become

soft. There were other times that the center area of the preform was soft enough, while

the surface had become too soft, leading the preform to easily break during fabrication.

For a standard optical fiber, the core is solid. Since heat will be conducted faster in a

solid piece than a hollow object, the outside/center temperature difference is not very

different and therefore less problematic in a regular optical fiber preform during

fabrication. It is usually less than 10 ~ 15 Celsius degrees, which is not a serious problem.

However, SSF has fractal iterations in the core, all consisting of hollow glass tubes,

making the heat conduction less efficient. Depending on the fractal structure in the core,

the temperature difference between the surface and center of an SSF preform could be as

high as 50 ~ 100 Celsius degrees. Figure 3.2 shows the ideal and actual temperature

distribution in preforms of a regular optical fiber vs. an SSF with a hexaflake core. The

dotted lines are the ideal temperature distribution, which is the same at different depth

from the surface. The solid curves are the actual temperature distribution for both types

of optical fibers. The span of the temperature difference from preform surface to the

center is much larger in SSF (Figure 3.2(b)) than in regular optical fiber (Figure 3.2(a)).
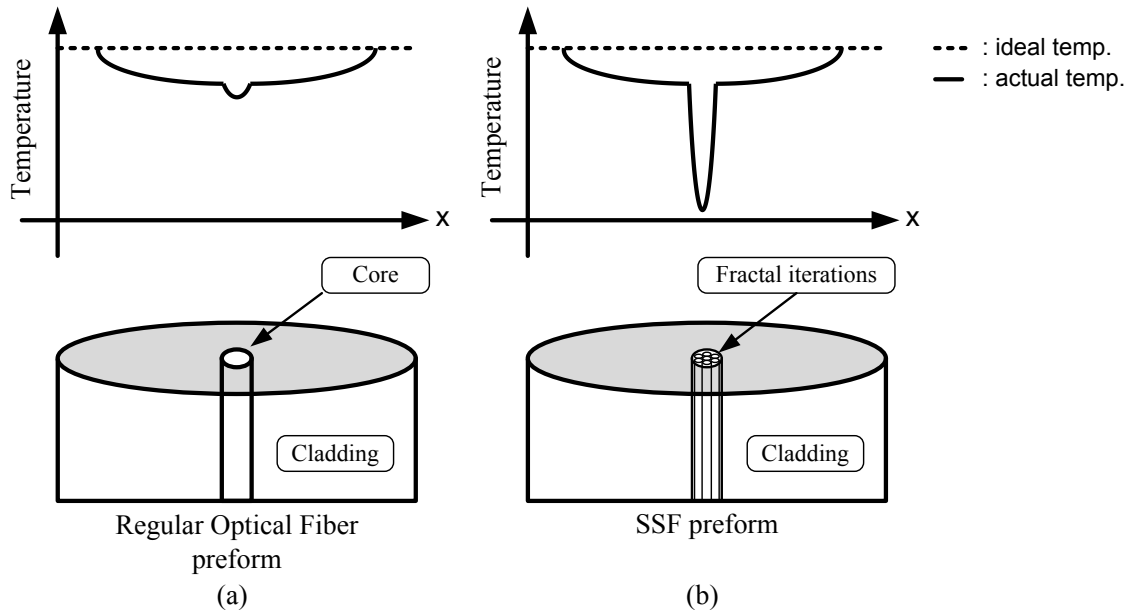
Figure 3.2 Temperature distributions for normal preform and SSF preform in the heat coil based fiber

pulling furnace

Such a large temperature cannot be ignored. This means that the existing optical fiber

pulling furnace is not suitable for SSF fabrication. One of my original one-scale

hexaflake unit samples using the existing pulling furnace confirms that this equipment

cannot meet the needs of making SSF. The obtained sample was easily broken.

3.2.2   Solution: Radiation furnace

A radiation based furnace seems to be a good alternative for SSF fabrication. It has

several advantages over the conduction method in optical fiber fabrication.

First, energy can easily pass through the glass material by radiation to reach the center of

the glass preform. The uneven heat (hence temperature) distribution is therefore

minimized.

Second, the heat from the radiation source can be turned on or off instantly. This is a very important attribute to help keep the working temperature constant in the process of optical fiber making.

Third, it can be used to selectively heat different materials when needed. When using the radiation method, energy is delivered as light waves. Such a feature makes it possible to control the wavelength of light, from 200nm (ultraviolet) to 3000nm (infrared), to heat different materials effectively and efficiently. For example, when a piece to be heated has both glass and semiconductor materials, long wavelength light (over 2000nm) can be used to heat the glass while having little effect on the semiconductor material. However, when short wavelength light is used (less than 600nm), the semiconductor material is heated efficiently, while the glass material remains unaffected. Selectively using light with different wavelengths enable the heating of different materials to be done without interference to the other materials.

Optical fiber pulling furnaces using radiation heating methods are not new. They are available commercially. For the purpose of making SSF in the laboratory, a commercial pulling furnace is not only expensive; it also lacks the flexibility in fabrication control that is often needed in the development of new products. Given these concerns, an in-house radiation furnace was developed. The development was conducted in two phases: a furnace solely heated by radiation, and an improved hybrid furnace using both radiation and filaments for heating.

3.2.2.1 A furnace solely relying on radiation

The first version of the radiation furnace[11] was built using a copper furnace frame

covered with an aluminum reflector. Eight 300 watts Quartz Halogen bulbs were installed

in the furnace frame as the radiation source. Theoretically, the furnace should work well.

But some problems showed up after a few uses.

First, the furnace was designed too large, leaving a considerable space between the

heating lamps and the targeted material. Such a flaw in design caused the heating

efficiency to be lower than expected.

Second, although the total output power from the eight halogen bulbs could be as high as

2400 watts; the working load limit of the general electrical outlets in the laboratory was

1850 watts, making it impossible to take full advantage of the radiant output. This limited

the working temperature inside the furnace.

Third, as mentioned above, there needed to be a protection circuit connected to the

furnace, so that a threshold could be set to avoid overloading the general circuit in the

laboratory. Such a protection circuit was made with an isolator transformer, a Varac

transformer, and a specially designed fuse circuit. It was noticed that when a high

electrical current was passing through the two transformers, a lot of heat was generated,

causing resistance of the transformers to increase. The two transformers now looked like

two heat resistors. The increased resistance lowed the output power. As a result, in the

pulling process, the power delivered to the radiation furnace would vary from 1100-1200

watts to 800 watts throughout the fabrication.

Before these problems were identified, I was able to overcome these problems. The one-

scale hexaflake units were able to be made successfully. However, the two-scale

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[11] The elements and specifications of the optical fiber fabrication furnace are in Appendix A.

hexaflake units could not be made due to the reasons above. Before the SSF fabrication could continuous, improvements had to be made to the radiation furnace. This led to the creation of a hybrid furnace.

3.2.2.2   A hybrid furnace

The hybrid furnace has an eight inch coil of filament wire. This addition of this heat source helped provided sufficient energy to successful fabricate an SSF. In actual use, the power from the lamp radiation was about 1200 watts, and the power from the heat coil was about 800 watts. Even though there was some energy decay caused by the protection circuit, the overall power provided by both together could still deliver 1600 – 2000 watts. The addition of the heating coil did not affect the unique heating properties found in radiation furnace: glass materials could still be easily heated; the heat delivery could be turned on or off with a fast response; and wavelength of the light source could be controlled to efficiently heat the target materials. Lastly, the hybrid provided three different heating modes: conduction only, radiation only, or both. These different modes could be used to meet the different heating needs of various other fabrication tasks.

3.3   New optical fiber fabrication system – accurate temperature control

The fabrication of self similar optical fiber requires that the heating temperature be constant. Unfortunately, our existing optical fiber pulling furnace relied on manual operation to maintain the working temperature. Not only was there a delay in the human response to temperature changes, but the actual temperature obtained through human control was not accurate. To ensure the SSF can be made successfully and with good quality, a temperature control system with accurate temperature adjustment is needed. A

proportional-integral-derivative (PID) feedback temperature controller that can

manipulate the furnace power through AC phase control turned out to be an ideal solution.

In the newly designed optical fiber fabrication system, an Arduino microprocessor board

was used as the PID feedback controller. It monitors temperature, detects AC phase

signal, and triggers the power control. Through the program embedded in Arduino, each

half AC cosine cycle can be divided into 256 phases. In other words, the power output

control could be as accurate as 0.39% (=1/256) of the total power. On the other hand,

since the power control can be triggered once in each AC cosine cycle, it means the

response time to any detected temperature can be as short as a half AC cosine cycle,

which is 8 milliseconds. Such a short response time ensure that any temperature change

can be adjusted in a timely manner to help maintain a constant temperature in the furnace.
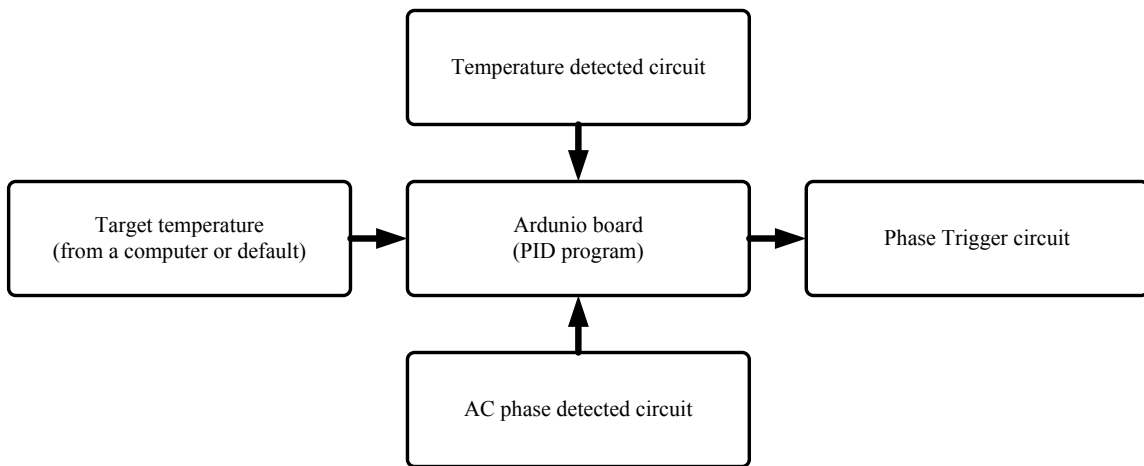

Figure 3.3 Overview of temperature control system

The temperature control realized through the PID controller is demonstrated in Figure 3.3.

A target temperature is entered into the Arduino board program. Two detector circuits

send the measured temperature and AC phase signals to the board program. A PID

feedback control program compares the difference temperature and adjusts the AC phase

to regulate the power for temperature control. If needed, this PID controller can be connected to a computer. Equipped with a user interface (UI) through Labview, these three elements together form a temperature control system that can define target temperature, monitor real time furnace temperature, and also record the temperature history throughout the optical fiber pulling process. The working flow chart of the PID control program is presented in Appendix B.

3.3.1 A potential problem with the temperature control system

It was later found that there could be a triggering problem in the actual control circuit. Due to the physical thresholds of the chips in the AC trigger circuit, each AC phase zero cross point had a mis-triggering area next to it (see Figure 3.4). If power trigger signals are sent from the Arduino board when AC phase enters these mis-triggering areas, the power delivered to the furnace could be either zero or full. The radiation furnace flickers randomly when the power output is close to zero. When the power output is full (or near full), the resulted high temperature can damage the furnace. In both situations, the temperature control system would fail to maintain the furnace at a stable temperature.
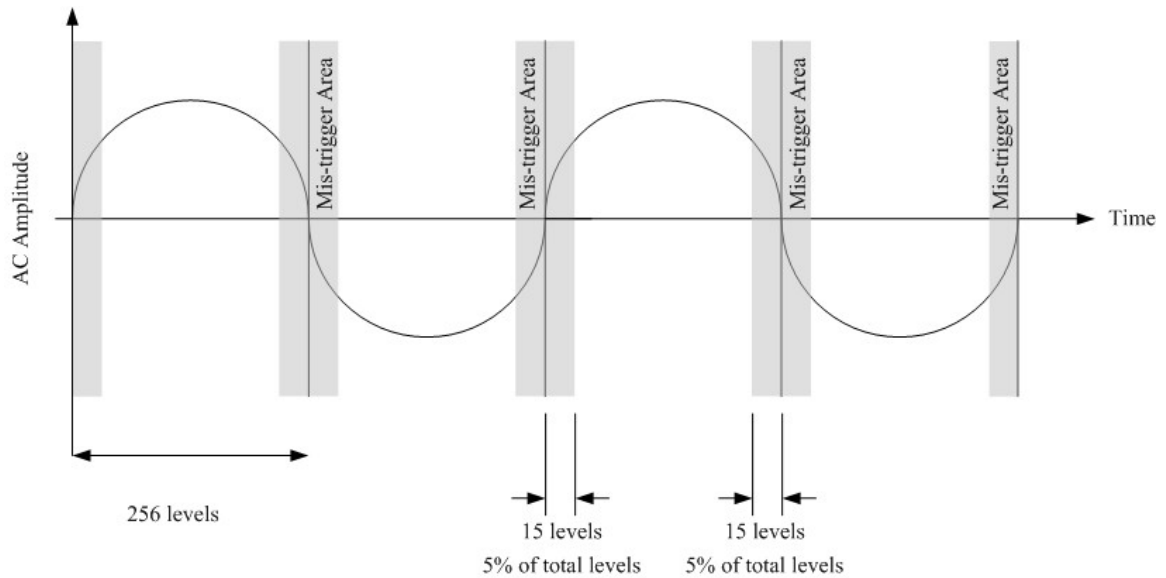
Figure 3.4 Mis-triggering areas in AC phases

Tests were conducted to identify the mis-triggering areas. The test results reveal that a mis-triggering area was about 10% of the duration of a half cosine waveform, with 5% at both the beginning and end of the half waveform. The controlling program in the Arduino was then revised to skip these mis-triggering areas. Since power delivery cannot be triggered in the first and last 5% of every half AC cosine waveform, the available power sent to the furnace was changed between 5% and 95% of the total AC outlet power.

3.4   New optical fiber fabrication system – flexible pulling scale ratio control

In the existing laboratory furnace, the pulling scale ratio was controlled through a control circuit that could only provide a fixed ratio. When a different scale ratio was needed, the only solution was to build a new circuit. In SSF fabrication, the scale ratio would change frequently. For example, the scale ratio for units at different scale levels could be different. Also, different fractal patterns would have different scale ratio requirements. It was not practical to keep building a new circuit whenever a new scale ratio is needed. A

seamless pulling scale ratio control system was therefore developed to meet the need in SSF fabricating.

3.4.1 A seamless pulling scale ratio control system

The new scale ratio control system (see Figure 3.5) consists of two step motors, with a motor driver connected to each of them. One driver drives a step motor to control the feed speed of the preform glass materials by applying a vertical force. This speed control is called preform feed speed control. The other driver drives a step motor that is connected to a capstan. This motor is used to pull the finial processed glass materials down from the optical fiber fabrication tower, where a horizontal force is applied. The speed controller is called the capstan speed control. For both step motors, square waves are used to control their speed. A high frequency of square wave will drive the step motor moving fast. Whereas the step motor will move slowly when the low frequency square wave is applied. These two speeds can be regulated to produce diameters needed for hexaflake units and final optical fibers.
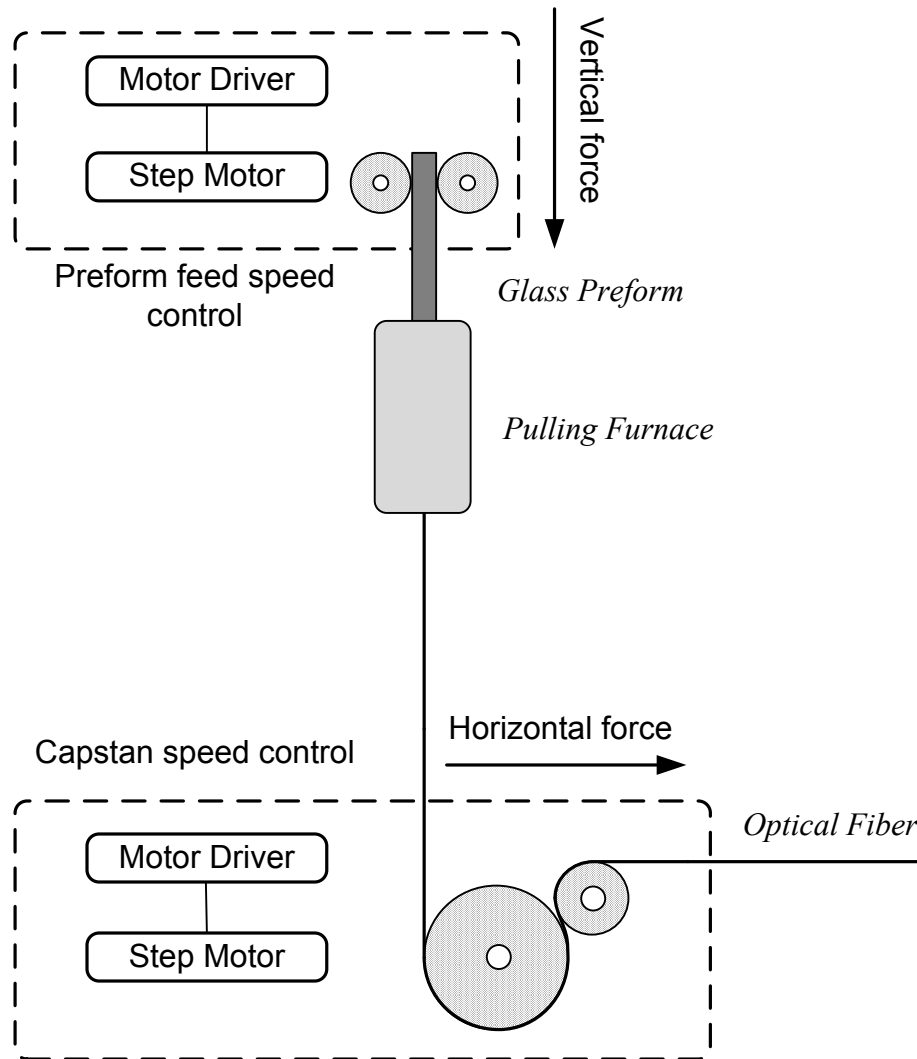
Figure 3.5 Scale ratio control system

3.5   Actual SSF fabrication

The new heating furnace, temperature control system, and scale ratio control system form

the new fabrication system. Actual SSF fabrication was successfully conducted. These

were made to the third scale level.

The one-scale hexaflake units were made using the radiation furnace only. The

fabrication worked well yielding 181 one-scale hexaflake units. These units were similar

in size, and were about 1mm in diameter and 30cm in length.

Seven similar one-scale units were then packed into a fitting glass case tub to make a two-scale hexaflake pre-unit. The true two-scale hexaflake units were obtained after the pre-units were rescaled. This was originally done using the radiation furnace. But serious pattern defects were observed in the first two finished two-scale units. After the furnace was improved into a hybrid one, 23 two-scale units were successfully made with it.

On the basis of the two-scale units, efforts were taken to make three-scale hexaflake units. Two three-scale units were made. However, the effort of making SSF from them failed. The main reason was that the three-scale units contained too many sub-scale units. Even though the improved hybrid furnace had higher power, it still could not provide sufficient heat to soften the inner hexaflake units.

To help reduce the layers so that heat can be transferred to the center better, another three-scale unit was made without being bound in a case tube. Instead, it was placed into the cladding tube directly. An SSF with an adjusted three-scale hexaflake unit was made.
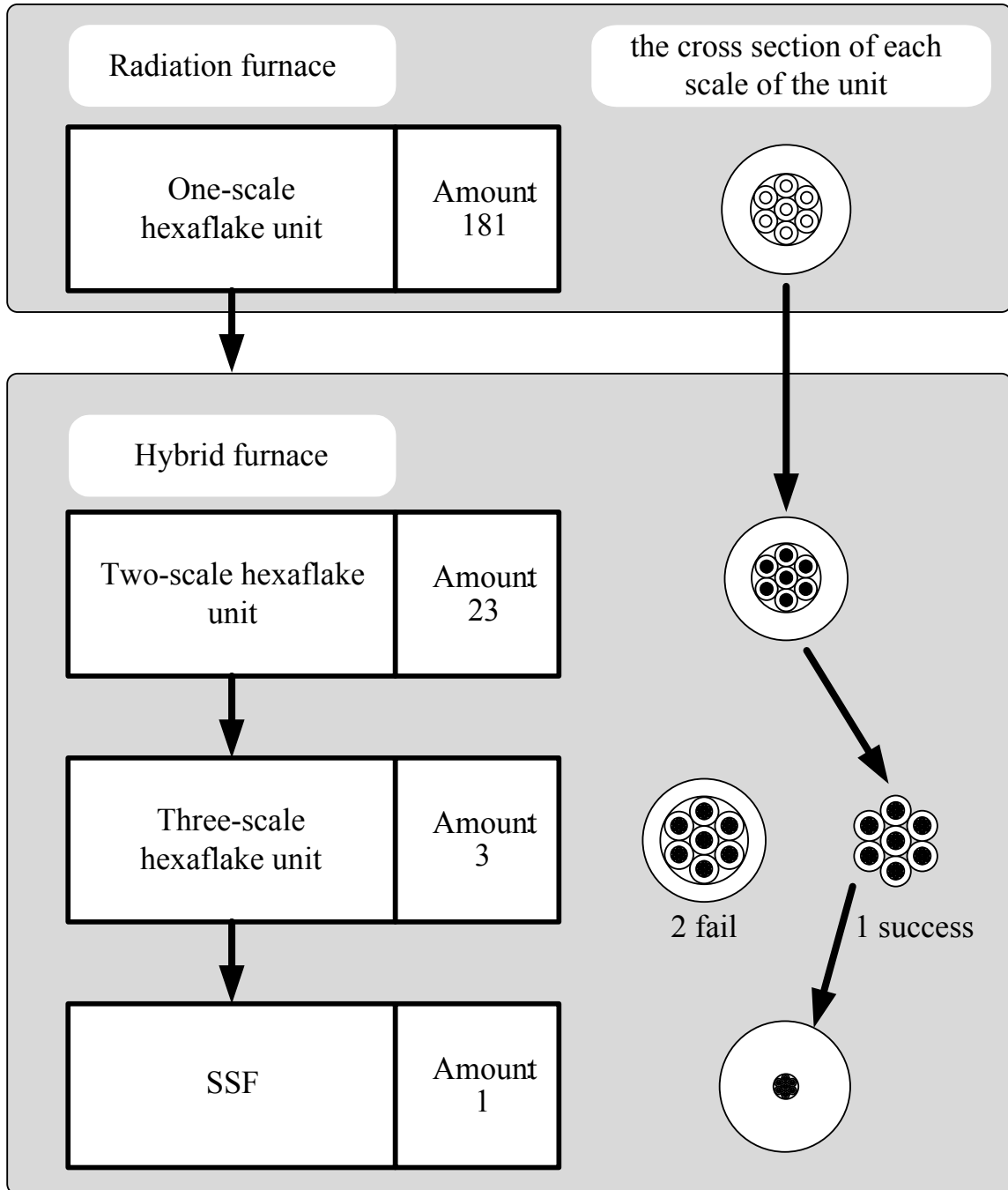
Figure 3.6 Fabrication process of SSF with an adjusted three-scale hexaflake unit

Figure 3.6 briefly shows the steps in making the SSF with an adjusted three-scale

hexaflake unit. The number of samples obtained for each scale is also listed. As noted,

the hybrid furnace was used after the fabrication of the one-scale hexaflake units.

In addition to the SSF sample with an adjusted three-scale hexaflake unit, other samples with lower scale hexaflake units were also made. These SSF samples were then tested for its optical properties. Details about the actual structure of the units at each scale and results from tests on the obtained SSF are included in Chapter 4.

Chapter 4   Analysis of SSF

The SSF fabrication described in Chapter 3 yielded four SSF samples, including one with a one-scale hexaflake unit (Sample A), two with two-scale hexaflake units (Sample B and C) and one SSF with an adjusted three-scale hexaflake unit without the case glass tube (Sample D). These samples were examined on the fabricated hexaflake units in the core. A spectrum analysis test was done later on each of the samples using light from 500 nm to 1000 nm in wavelength. Results from the examination and test are included in this Chapter.

4.1   Exanimate the fabricated hexaflake units of SSF samples

To examine the units in the obtained samples, an optical microscope was used. Samples were checked under this microscope at four different magnification rates: 50x, 100x, 200x, and 400x. The size of the actual hexaflake units in SSF samples was determined in two ways. Diameters of the hexaflake units were measured with the built-in microscope scale. There were some cases where the diameters of the lower scale units were too small to be measured. In these situations, calculation on the basis of the units' original size before being pulled and their pulling ratio[12] were used.

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[12] The pulling ratio is a ratio between the outside diameter (OD) of the perform before pulling SSF and the OD of the pulled SSF.
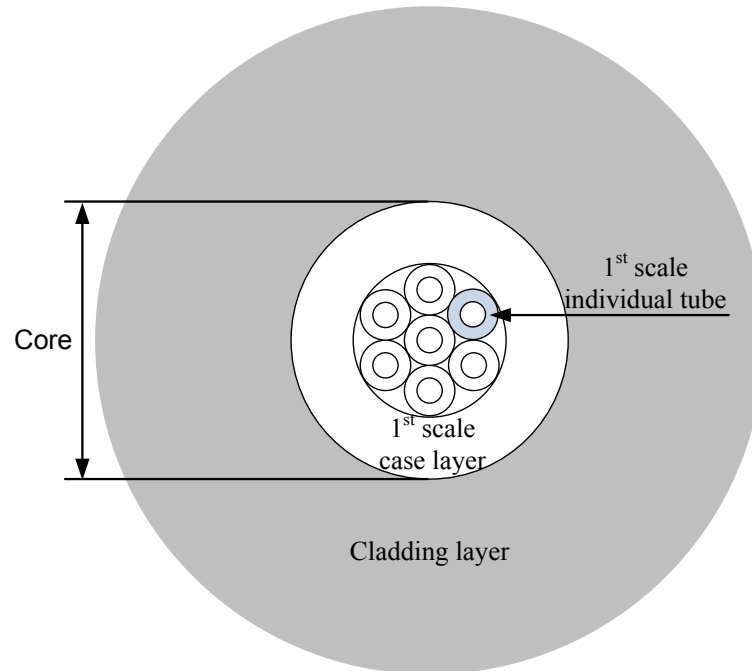
4.1.1 SSF with a one-scale hexaflake unit – Sample A

Figure 4.1 Ideal SSF with a one-scale hexaflake unit[13]

An ideal SSF with a one-scale hexaflake unit should have seven 1st scale individual tubes bound in one case layer in the core (see Figure 4.1). In the fabrication, the core unit was first made, with its outside diameter being 1mm (see Figure 4.2). The core unit was then put into a cladding glass tube to make an SSF preform. The ultimate SSF product is shown in Figure 4.3.

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[13] The core area is enlarged for demonstration. It does not reflect the actual ratio.
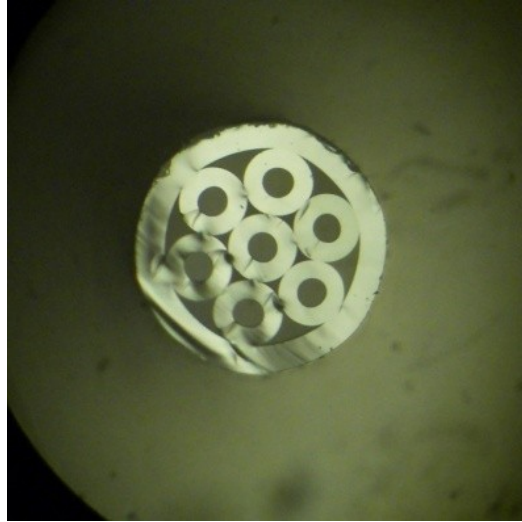
Figure 4.2 Core of Sample A (one-scale hexaflake unit) before fabrication (magnification: 50x)

Figure 4.3 Sample A - SSF with a one-scale hexaflake unit (magnification: 400x)

Figure 4.3 shows the completed one-scale hexaflake unit from Sample A. Unfortunately, a gap was found between the case layer for the core and the cladding layer. A possible reason is that the fabrication furnace could not provide enough power to fully soften the core and cladding tube, so that the two parts did not collapse perfectly.

In addition to examine the hexaflake unit in the core of Sample A, measurements of glass

tubes were accomplished. Results from the measurement are listed in Table 4.1.

Unit / Layer	Parameter	µm
1st scale hexaflake unit	*ID*	*1.413 µm*
- individual tube	*OD*	*5.65 µm*
1st scale hexaflake unit	*ID*	*20 µm*
- Case layer	*OD*	*22.6 µm*
Cladding layer	*ID*	*28 µm*
	OD	*164 µm*

Table 4.1 Sample A - the results of SSF with a one-scale hexaflake unit[14]

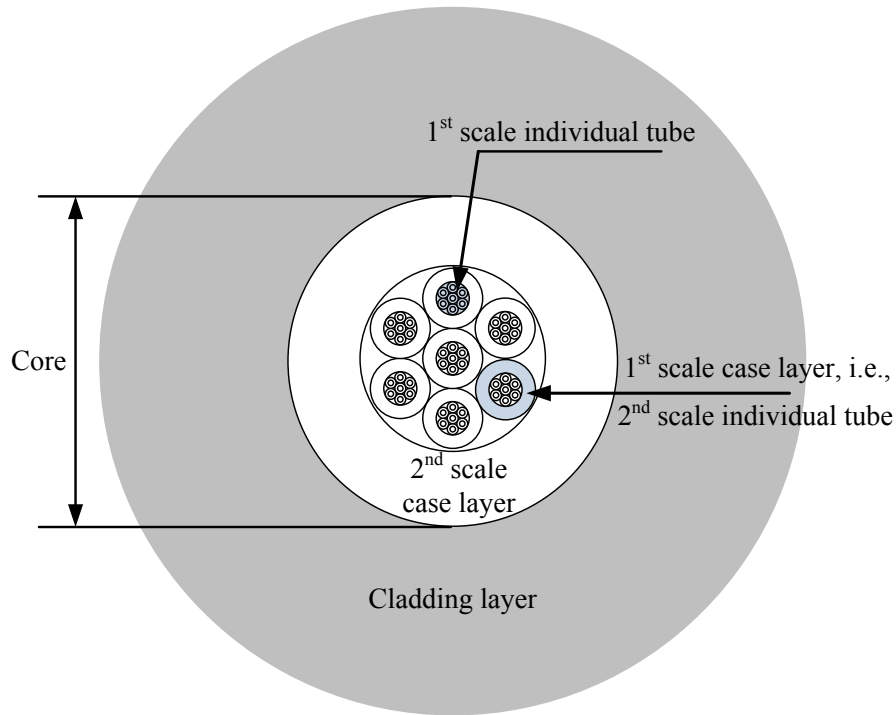## 4.1.2 SSF with a two-scale hexaflake unit – Sample B and Sample C

Figure 4.4 Ideal SSF with a two-scale hexaflake unit[13]

The ideal cross section of an SSF with a two-scale hexaflake unit is shown in Figure 4.4.

The complete hexaflake unit from 1st scale is now viewed as the unit element to form the

hexaflake at the 2nd scale. Seven of such 1st scale hexaflake units were bound in a fit case

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[14] All parameters were determined using the scaling ruler in the microscope.

tube (2nd scale case layer), yielding the hexaflake unit for the 2nd scale. This unit is then put into a cladding glass tube (as cladding layer in Figure 4.4) to make the SSF with a two-scale hexaflake unit.

Two SSF samples (Sample B and Sample C) having two-scale hexaflake units were fabricated. Their cores were prepared separately as shown in Figure 4.5 and Figure 4.7.

4.1.2.1   SSF with a two-scale hexaflake unit – Sample B

Sample B was made with the core as shown in Figure 4.5. The cross section shows that the seven 1st scale hexaflake units were compact and well made with almost identical size.
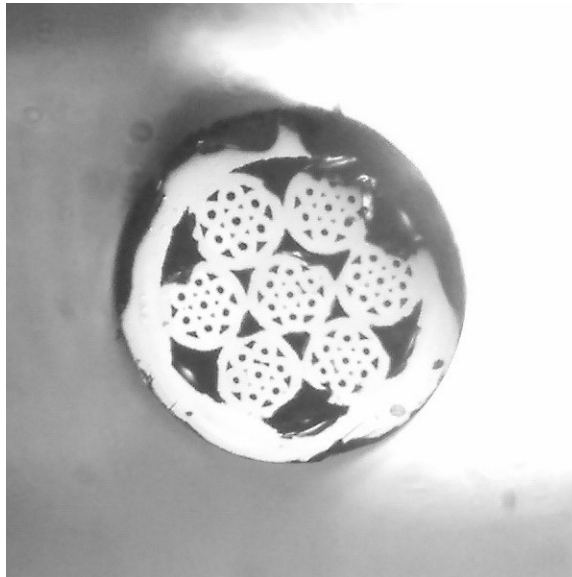

Figure 4.5 Core of Sample B (with a two-scale hexaflake unit) before fabrication (magnification: 100x)

The core shown in Figure 4.5 was put in a cladding glass tube to make a preform, and was then pulled into an SSF (Sample B). The cross section of Sample B is shown in Figure 4.6. Similar to Sample A, there is still a gap between the core and cladding layer in Sample B. This was due to insufficient power in the fabrication furnace.
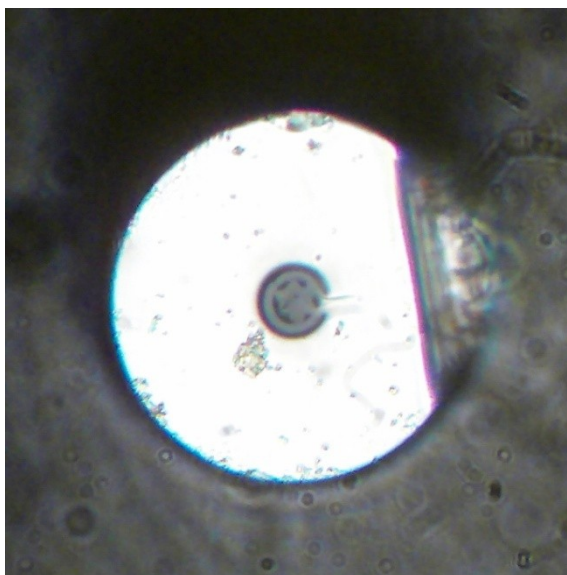
Figure 4.6 Sample B - SSF with a two-scale hexaflake unit (magnification: 400x)

Sample B was examined under the microscope for quality control. Table 4.2 has detailed size information about these elements. All other layers other than the base tubes in the 1st scale unit were measured using the built in microscope scale. The base tubes were too small to be measured. Their size was calculated based on their original size and the pulling ratio[12].

Unit / Layer	Parameter	μm
1st scale hexaflake unit - individual tube	ID	0.312 μm
	OD	0.938 μm
1st scale hexaflake unit - case layer (2nd scale hexaflake unit - individual tube)	ID	2.812 μm
	OD	3.75 μm
2nd scale hexaflake unit - case layer	ID	12.5 μm
	OD	17.5 μm
Cladding layer	ID	22.5 μm
	OD	125 μm

Table 4.2 Sample B - the results of SSF with a two-scale hexaflake unit[15]

---

[15] The parameters of the individual tube and case layer of the 1st scale hexaflake unit were calculated by the pulling ratio. The parameters of the 2nd scale hexaflake unit and cladding layer were determined using the scaling ruler in the microscope.

4.1.2.2 SSF with a two-scale hexaflake unit – Sample C

Sample C was made from another core (see Figure 4.7). The core of sample C is compact and uniform. The fabricated SSF (Sample C) (see Figure 4.8) still had a gap between the core and the cladding layer. Measurement of the core elements was done in the same way that Sample B was measured. Results showed that the scaled ratio of Sample C is 3.5.[16]
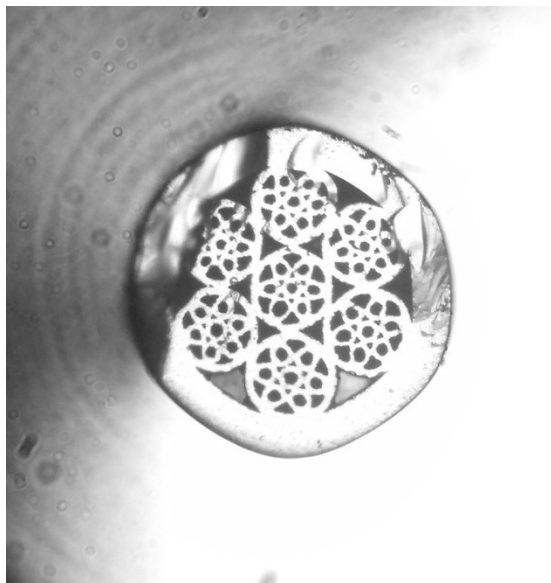

Figure 4.7 Core of Sample C (with a two-scale hexaflake unit) before fabrication (magnification: 100x)

---

[16] With the measured results, the ratio that the 1st scale unit was scaled in this 2nd scale unit is 4.667. In figure 2.8 of Chapter 2, this ratio should be d1 over d2, which is 3. Limited by the available equipment in the laboratory, the scaled ratio could not be controlled perfectly as desired.
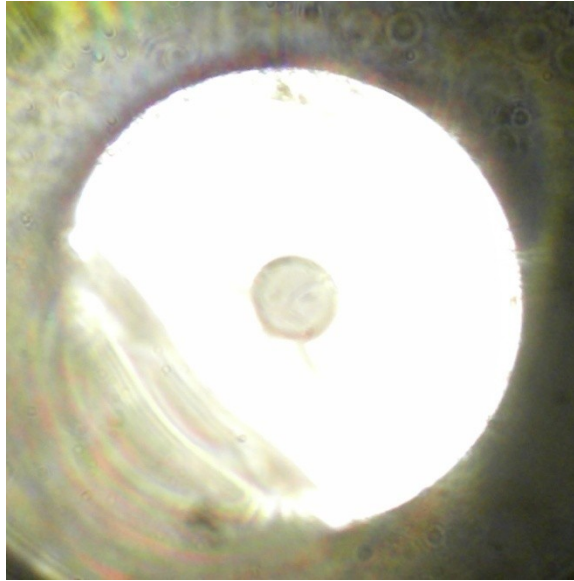
Figure 4.8 Sample C - SSF with a two-scale hexaflake unit (magnification: 400x)

Unit / Layer	Parameter	μm
1st scale hexaflake unit - individual tube	ID	0.709 μm
	OD	1.419 μm
1st scale hexaflake unit - case layer (2nd scale hexaflake unit - individual tube)	ID	4.61 μm
	OD	5.32 μm
2nd scale hexaflake unit - case layer	ID	13.3 μm
	OD	18.62 μm
Cladding layer	ID	18.62 μm
	OD	125 μm

Table 4.3 Sample C - the results of SSF with a two-scale hexaflake unit[17]

---

[17] The parameters of the individual tube and case layer of the 1st scale hexaflake unit were calculated by the pulling ratio. The parameters of the 2nd scale hexaflake unit and cladding layer were determined using the scaling ruler in the microscope. There were errors in the calculation of the 1st scale case layer and in the measurement of the ID of the 2nd scale case layer. So ID of the 2nd scale case layer is not three times of the OD of the 1st scale case layer.

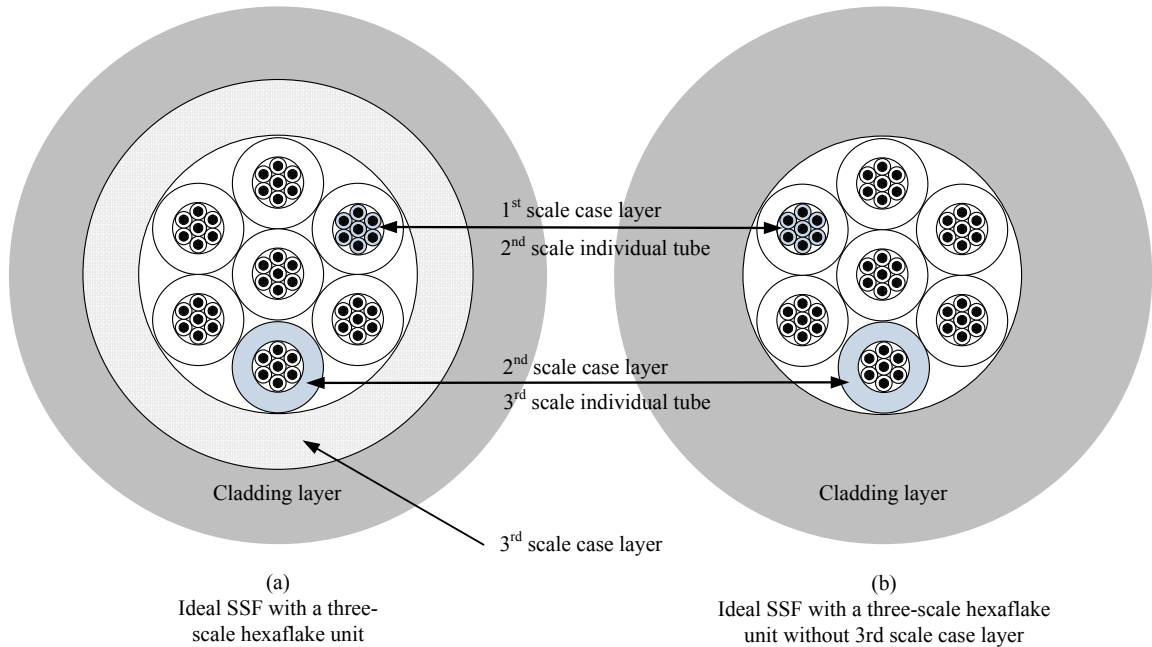### 4.1.3   SSF with a three-scale hexaflake unit - Sample D

1st scale case layer

2nd scale individual tube

2nd scale case layer

3rd scale individual tube

Cladding layer

Cladding layer

3rd scale case layer

(a)
Ideal SSF with a three-scale hexaflake unit

(b)
Ideal SSF with a three-scale hexaflake unit without 3rd scale case layer

Figure 4.9 Ideal SSFs with three-scale hexaflake units[13]

The ideal unit of an SSF with a three-scale hexaflake unit is as shown in Figure 4.9(a). It shows that seven 2nd scale hexaflake units are loaded in a case tube to make the core. Then the core is put into a cladding glass tube and pulled into an SSF. Efforts were taken to form the core as seen in Figure 4.9(a), but were not successful. The reason was that the output power of the hybrid furnace was not enough to soften all layers in the core, making the glass materials easy to break while being pulled.

An adjustment was made to soften all the elements of the core. As seen in Figure 4.9(b), this was done by removing 3rd scale case layer. The remaining seven 2nd scale hexaflake units were added directly into the cladding tube. The obtained SSF was named Sample D (see Figure 4.10, Figure 4.11, and Figure 4.12[18]).

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[18] The seven 2nd scale units are found clear in Figure 4.10. Since Figure 4.11 and Figure 4.12 were photos taken under the microscope with higher magnification that has smaller focus area, only five of the seven 2nd scale units are visible.

From observation, the three-scale adjusted hexaflake unit was not as compact as those in the other samples. A case tube bounding the hexaflake units appears to be necessary to keep the unit in shape. In addition, the outside diameter of Sample D (370 µm) is over three times the size of a traditional optical fiber (125 µm), which still needs to be improved. On the other hand, the fabricated Sample D verified that an SSF with three or more scales of hexaflake units is possible to fabricate. This however requires a powerful optical fiber fabrication system and furnace.
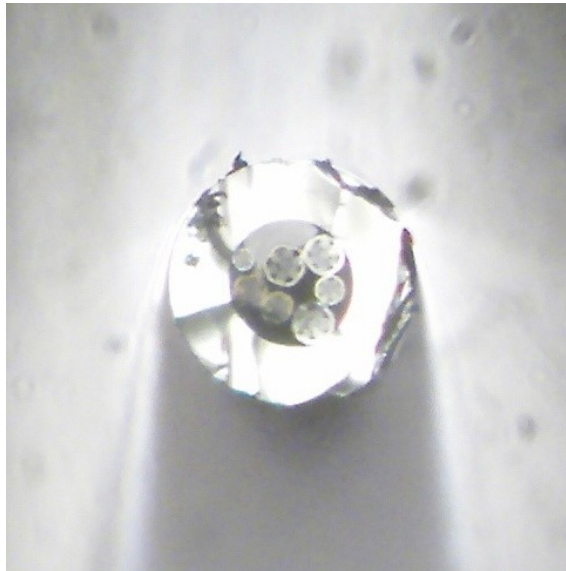

Figure 4.10 Sample D - SSF with a three-scale hexaflake unit (magnification: 200x)
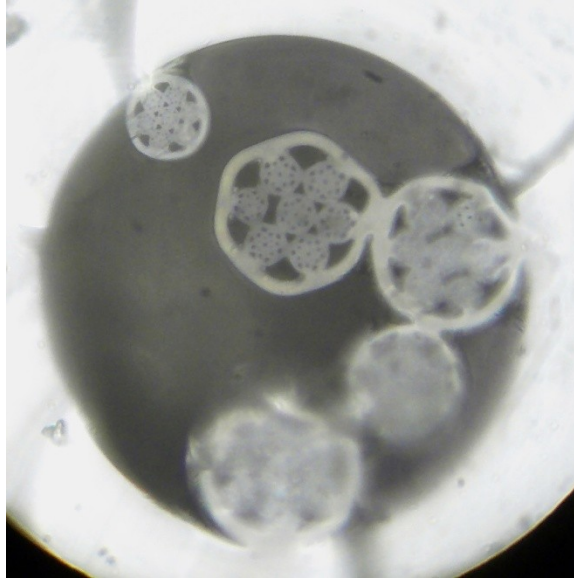
Figure 4.11 Sample D - First focus - SSF with a three-scale hexaflake unit (magnification: 400x)
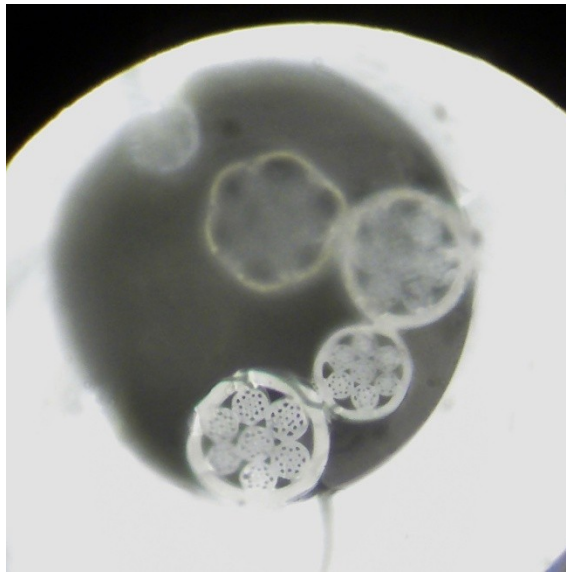

Figure 4.12 Sample D - Second focus - SSF with a three-scale hexaflake unit (magnification: 400x)

The results of Sample D are in Table 4.4. Since the case layer that holds the 2nd scale hexaflake units were removed in making Sample D, these 2nd scale units were rescaled to different sizes. The ID and OD of the 1st scale case layer were measured for three of these units. The average size of these three units estimates the sizes of the other four units.

Given that Sample D has not the case layer for 3rd scale hexaflake unit including, its scale ratio[3] was not able to be calculated.

Unit / Layer	Parameter	μm
1st scale hexaflake unit - individual tube	ID	2.125 μm
	OD	4.25 μm
1st scale hexaflake unit - case layer (2nd scale hexaflake unit - individual tube)	ID1	6.375 μm
	OD1	8.5 μm
	ID2	8.5 μm
	OD2	10.625 μm
	ID3	10.625 μm
	OD3	12.75 μm
2nd scale hexaflake unit - case layer (3rd scale hexaflake unit - individual tube)	ID	51 μm
	OD	68 μm
Cladding layer	ID	170 μm
	OD	340 μm

Table 4.4 Sample D - the results of SSF with a three-scale hexaflake unit[15]

4.2   Optical analysis test of SSF samples

Limited by the available equipment in the laboratory, some of the possible optical properties of the proposed in Chapter 2[19] were not able to be tested or verified. A monochromator was used to test the samples optical performance. A spectrum analysis test on their ability of delivering light was done.

The samples were first cut into lengths of 1.5 meters. In the spectrum analysis test, light was sent into sample fibers, and the intensity of light received at the other end was measured to find the fibers' transmittance property.

The equipment setup used in the test is shown in Figure 4.13. Light was generated by an Acton light source (1). A chopper (2) was used to reduce noise generated by the source. A microscope objective (3) focused the light from the chopper into the optical fiber sample (4). A 2nd microscope objective (5) is used to minimize light loss due to

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[19] See section 2.3.2 in Chapter 2.

scattering. After being separated by a monochromator (6), the light reached an optic

detector (7), where its intensity was detected. The light intensity was amplified by lock-in

amplifier (8), and at the end recorded by a computer.

1. Acton 250 watts Tungsten-Halogen light source (Model: TS428)
   (effective wavelength: 350nm ~ 2500nm)
2. Acton Chopper (Model: SR-540)
3. One microscope objective (20x/ 0.4)
4. 1.5 meter long SSF samples and commercial optical fiber
5. One microscope objective (10x/ 0.3)
6. Acton Spectra Pro 300i Monochromator (Model: 300i)
7. Silicon photo detector
   (effective wavelength: 400nm ~ 1100nm)
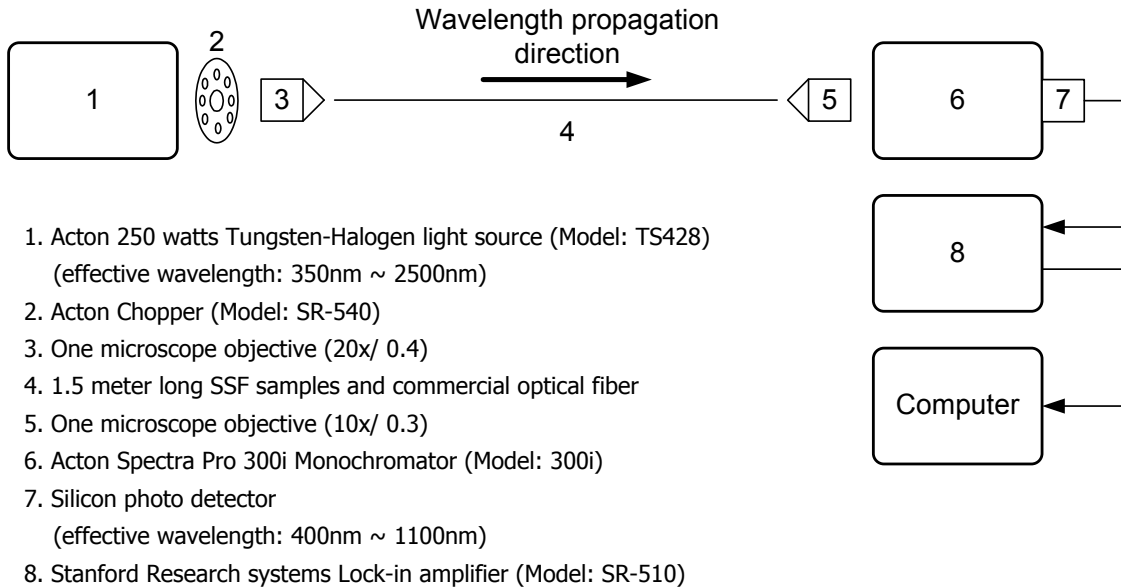8. Stanford Research systems Lock-in amplifier (Model: SR-510)

Figure 4.13 Equipment setup for testing SSF's transmittance performance

In the test, the monochromator (6) separates light through two diffraction gratings[20].

Since each grating corresponds to a specific wavelength range, testing a fiber at different

gratings would provide a more thorough performance test. The samples were all tested

using the 1st and 4th gratings. When the monochromator (6) was set to a specific grating, a

sample was tested with light throughout a given spectrum[21]. For each of the two

diffraction gratings, a sample was tested five times. The average of these five test results

was taken as the performance of that sample. All results were normalized as a ratio of the

---

[20]A diffraction grating is an optical component with a periodic structure in the monochromator. It splits and diffracts light into several beams travelling in different directions. The directions of these beams depend on the spacing of the grating and the wavelength of the light [25].
[21] For the 1st grating, the spectrum is from 400nm to 2400nm. For the 4th grating, the spectrum is from 200nm to 1200nm.

sample results to the contrast fiber's results under the same setting. The test results for each sample at each diffraction grating are presented below.

4.2.1 SSF with a one-scale hexaflake unit - Sample A

With two gratings used, Sample A was tested using wavelength from 500nm to 1000 nm. Figure 4.14 and 4.15 show the normalized results from tests using the 1st and 4th gratings. They share a similar pattern in the wavelength range between 500nm and 700nm, with apparent optical amplifying gain. The gain was over 1 when the 1st grating was used, and over 1.5 when the 4th grating was used.
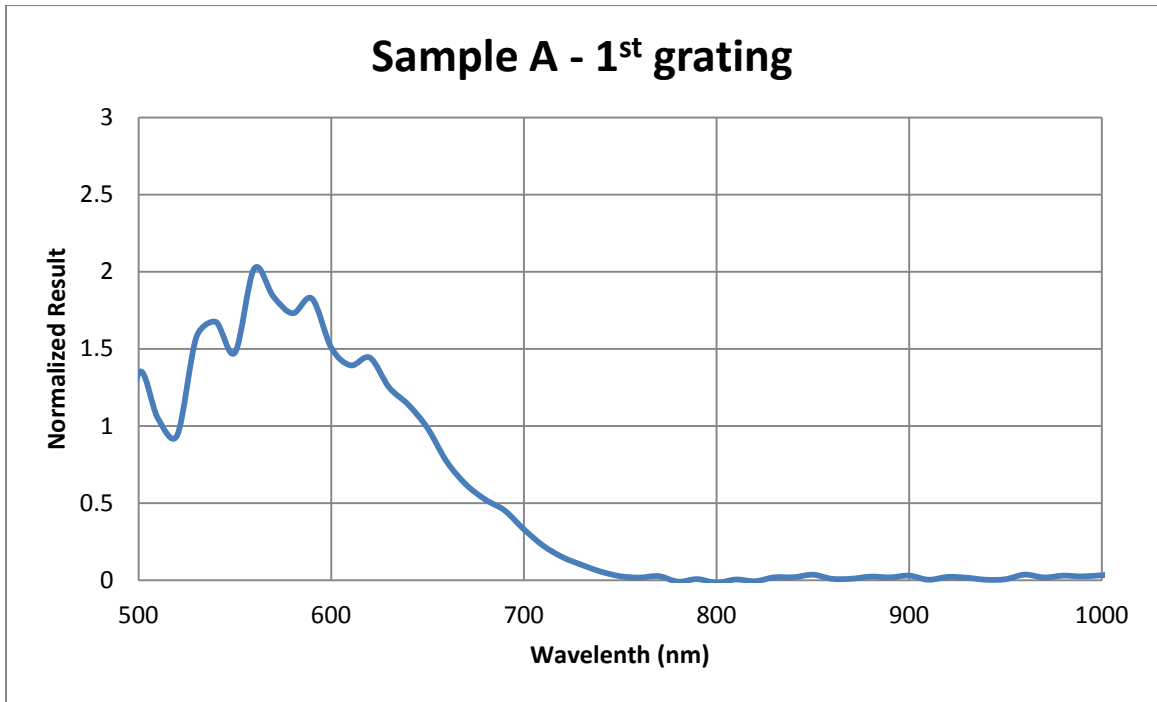

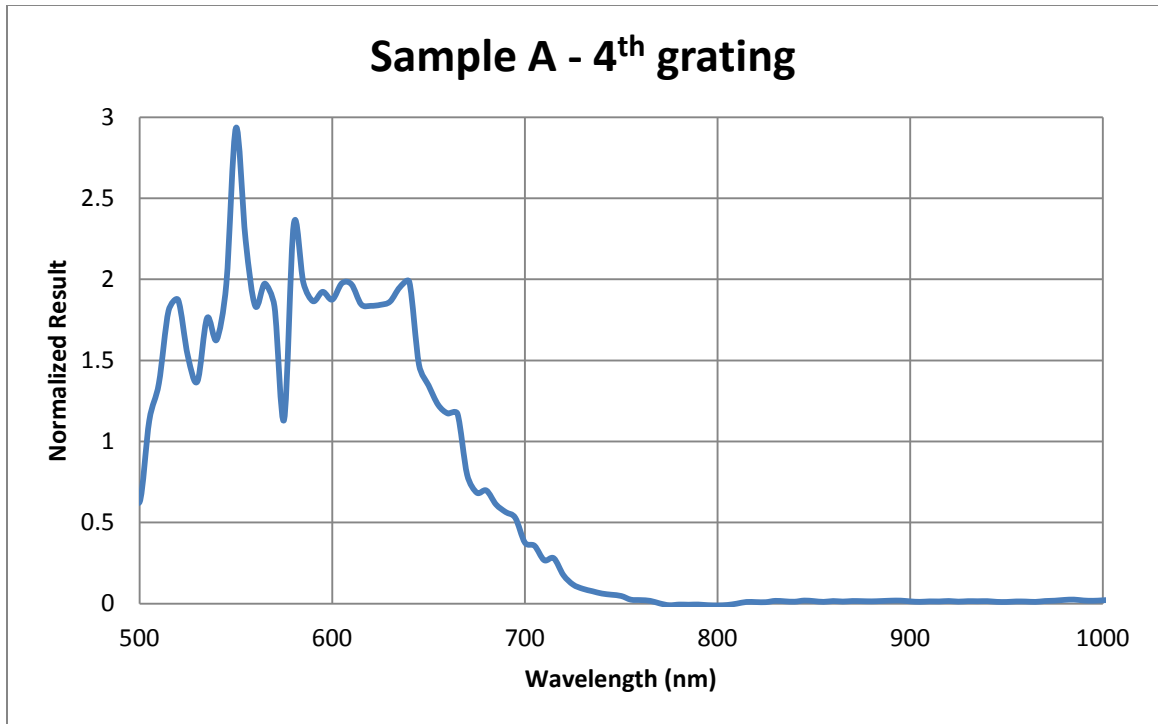Figure 4.14 Normalized test results of Sample A – 1st grating (500nm – 1000nm)

Figure 4.15 Normalized test results of Sample A – 4th grating (500nm – 1000nm)

4.2.2 SSF with a two-scale hexaflake unit - Sample B

Sample B was tested in the same way as Sample A. As shown in Figure 4.16 and 4.17,

Sample B performed well in the wavelength range between 500nm and 700nm. Whereas,

the curves approach zero for wavelengths over 700nm. Similar to Sample A, such results

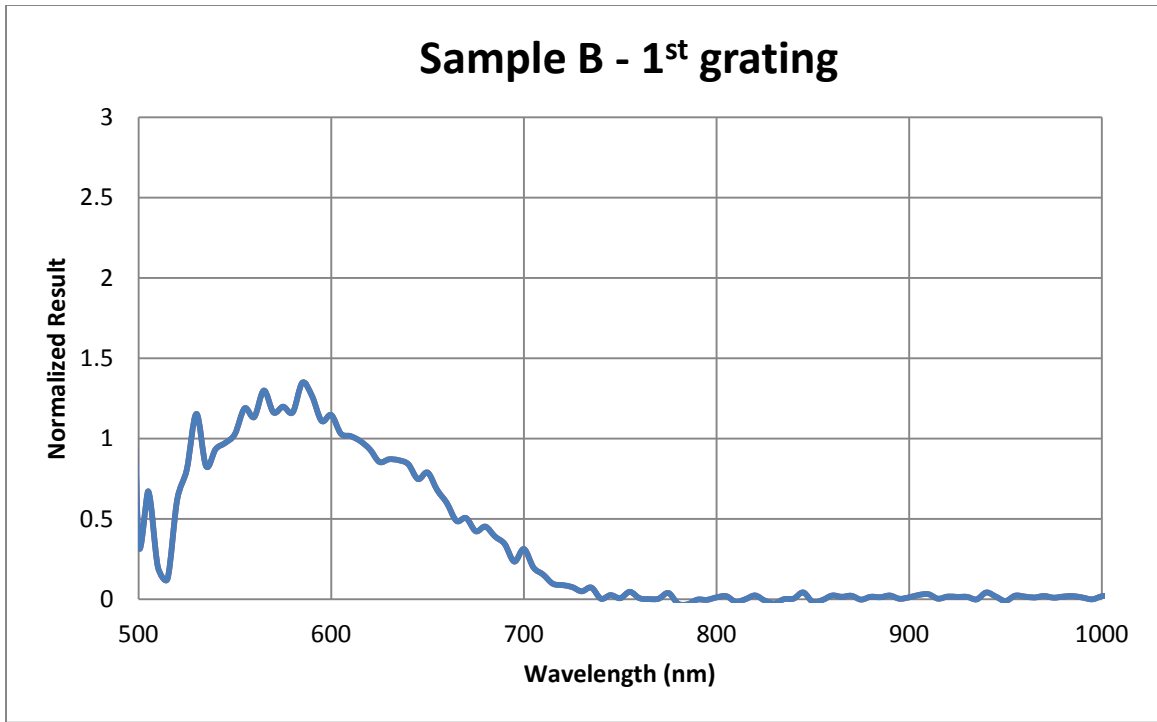indicate that Sample B worked like a light filter.

Figure 4.16 Normalized test results of Sample B – 1st grating (500nm – 1000nm)
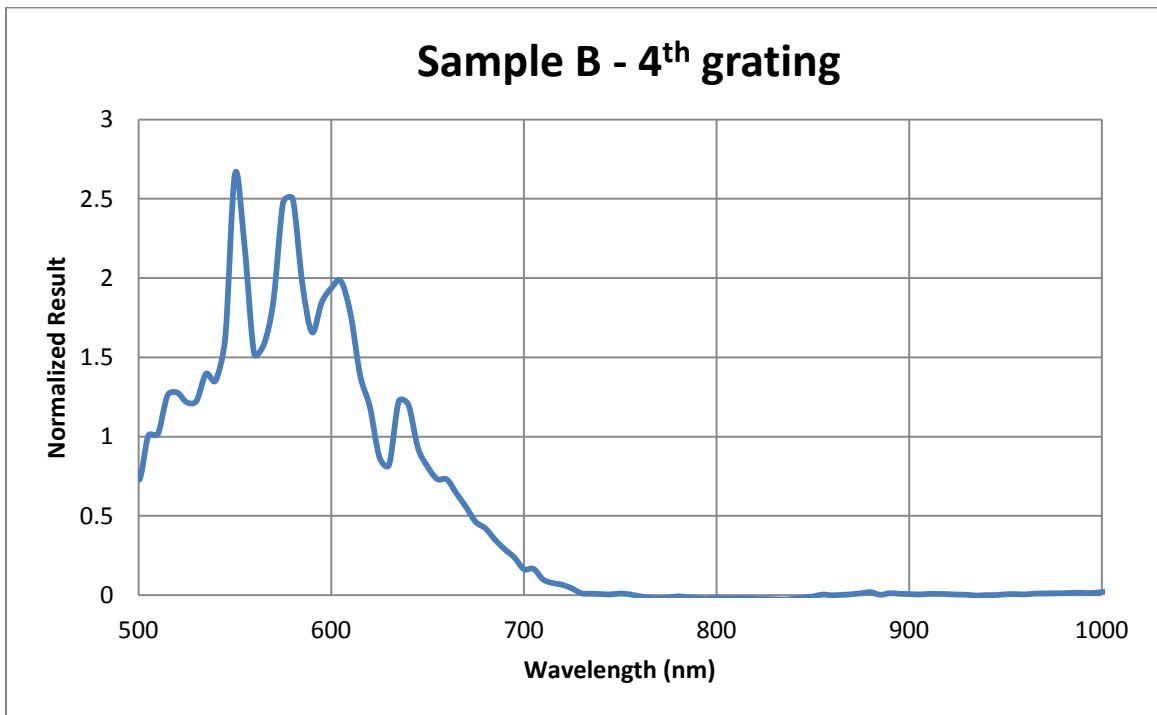

Figure 4.17 Normalized test results of Sample B – 4th grating (500nm – 1000nm)

4.2.3 SSF with a two-scale hexaflake unit - Sample C

The normalized results for Sample C are in Figure 4.18 and 4.19. Compared with Sample B, Sample C's ability of delivering visible light between 500nm and 700nm seemed to be weaker. The possible reason for this result is that the fabricated self similar structure of Sample B is better than Sample C.
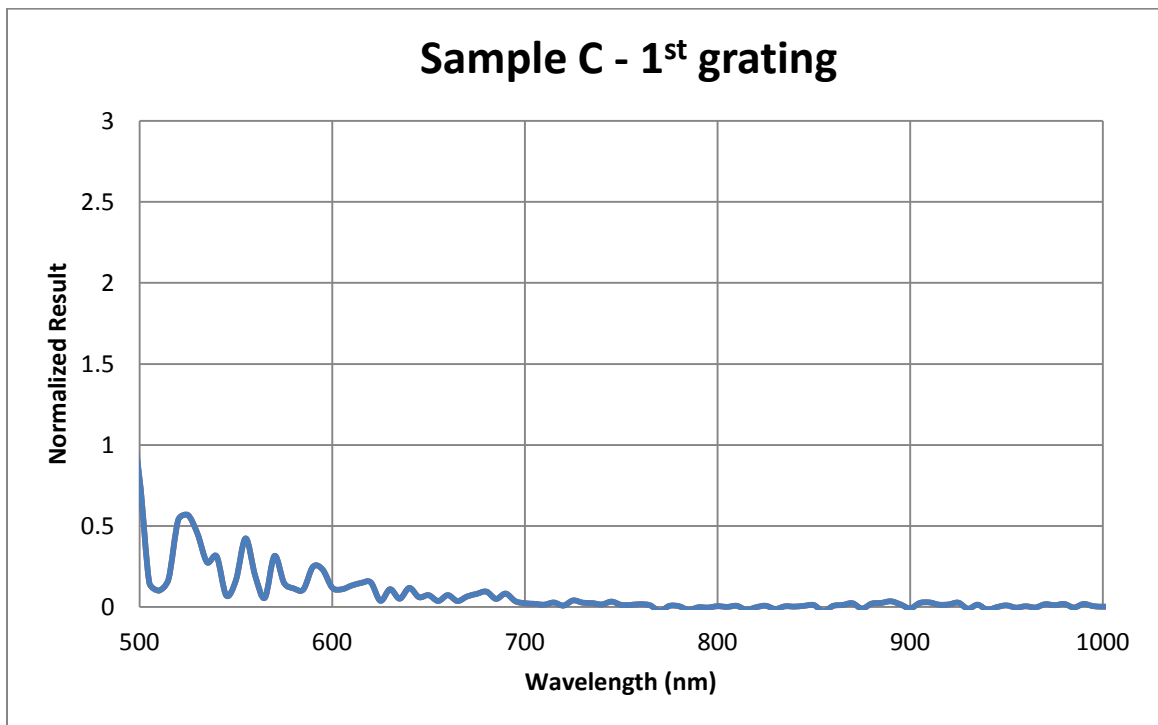

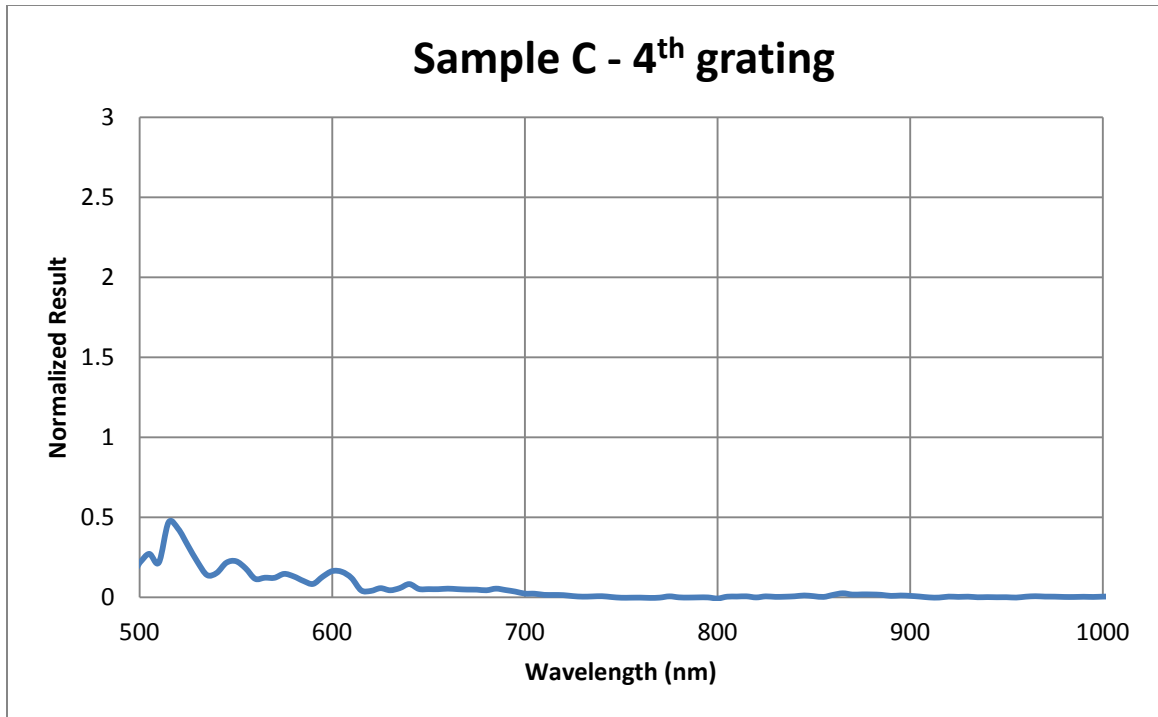Figure 4.18 Normalized test results of Sample C – 1st grating (500nm – 1000nm)

Figure 4.19 Normalized test results of Sample C – 4th grating (500nm – 1000nm)

The overall performances of Sample A, B and C in the test showed that the self similar structure filters light[22]. It could be viewed as a light filter that passes visible light between 500nm and 700nm, and blocks light of other wavelengths. From the measurement of Sample A, B, and C, it was found that the first scale unit of Sample A and the second scale units of Sample B and C had areas close in size. In addition, they also share the same structure. These could be the reason that Sample A, B, and C had similar optical test results. It should be mentioned that, although these results are encouraging, they still need to be further verified using better fabricated samples. Current measurements were based on the non-perfect self similar structures in the obtained samples.

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[22] Sample D is not included in the comparison. This is because Sample D had a modified structure without the case layer for the 3rd scale. It did not have a complete self similar structure as the two lower scales.

4.2.4 SSF with a three-scale hexaflake unit - Sample D

Test results for Sample D using the 1st and 4th gratings are shown in Figure 4.20 and Figure 4.21. The normalized values are apparently larger than those for other samples. In other words, Sample D allowed more light to pass through than other samples. One possible reason could be that there was a big space between the seven 2nd scale hexaflake units and the cladding layer. In addition, Sample D had a larger outside diameter than other samples after scaling. Both factors could contribute to that fact of allowing more light to go through.
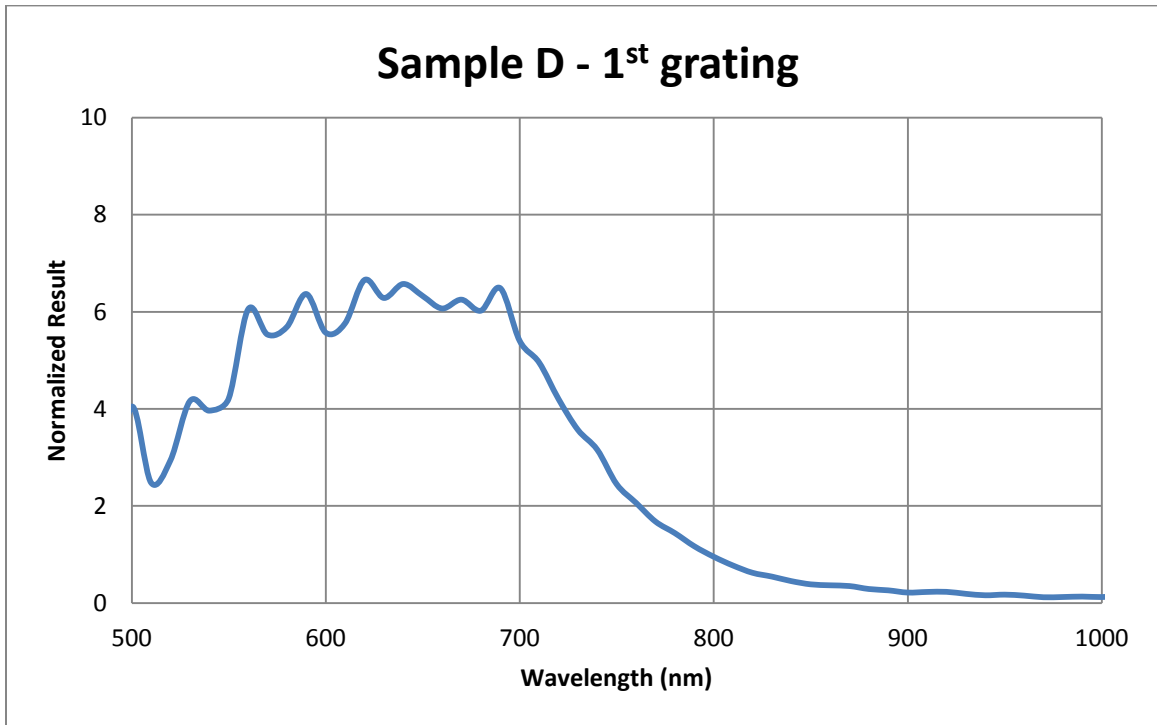

Figure 4.20 Normalized test results of Sample D – 1st grating (500nm – 1000nm)
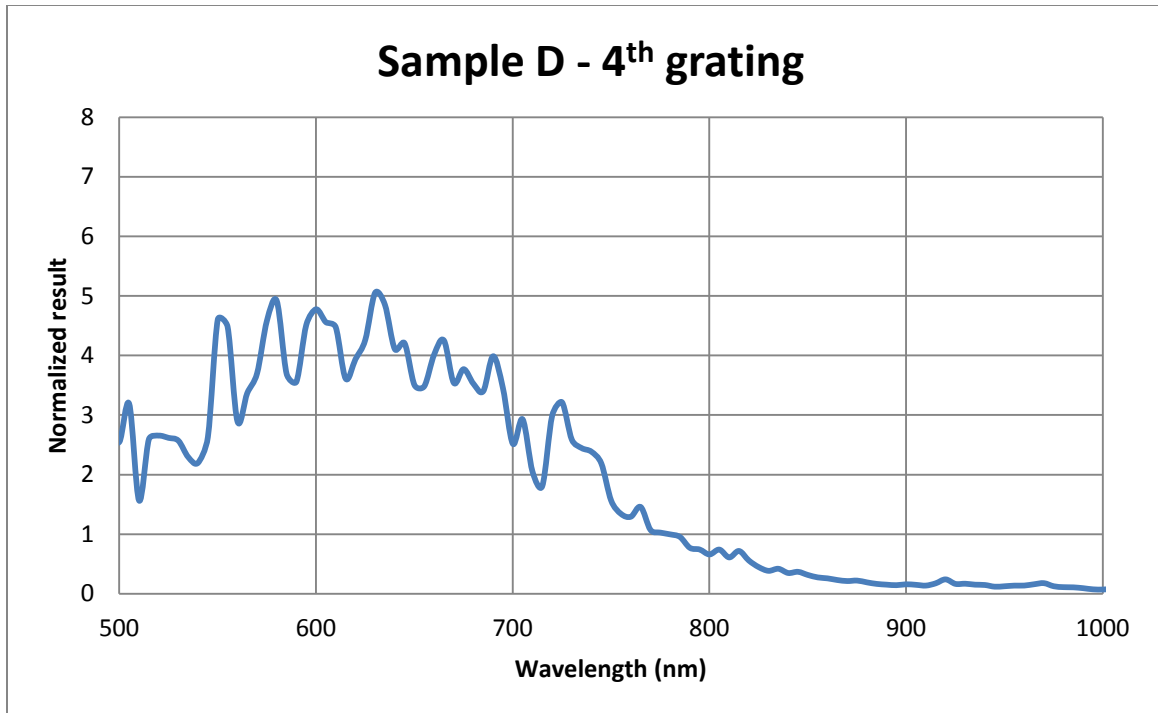
Figure 4.21 Normalized test results of Sample D – 4th grating (500nm – 1000nm)

4.3 Light leaking from the SSF samples

Light leaking was observed in the test on all four samples. The level of the leaking was different. Figure 4.22 is an example of the leaking from Sample D. One possible explanation for the leaking could be that the hexaflake units of these samples were not perfect.
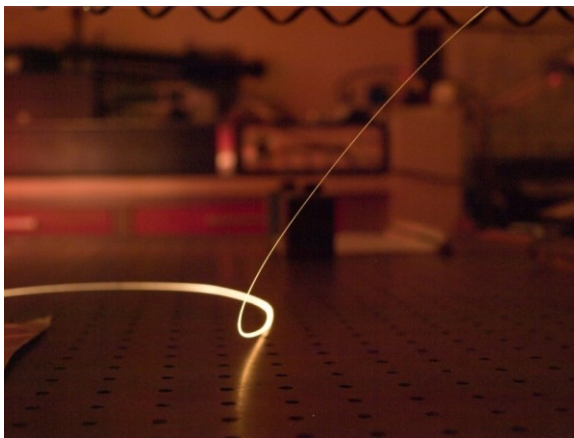
Figure 4.22 Light leaking from Sample D[23] (Exposure time: 1min)

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[23] Sample D was bent for the purpose of taking picture. The actual intensity of light leaking of Sample D is less than that shown in the picture.

Chapter 5   Conclusions

This dissertation has proposed Self Similar optical fiber (SSF) as a new type of optical fiber. To fabricate SSF, the self similar fabrication method was used in optical fiber production for the first time. Throughout this research, SSF has been found with many advantages in properties and the ease of fabrication. However, there are still challenges to overcome to make SSF possible to be massively produced and widely applied.

5.1   What is learnt about SSF

SSF is a kind of fractal optical fiber consisting of non-periodic self similar structures in an optical fiber. The overall optical performance of SSF is determined by the scale of the self similar structure and the symmetry of the fabricated fractal pattern. The more scales that a self similar structure has, the more guided modes from lower scale units will be included in the overall optical performance of the entire self similar structure. In addition, the fractal pattern has an impact on the overall optical performance of SSF.

The fabrication of SSF used a newly designed method called self similar fabrication method. Because of this new method, a new direction in the technique of fabricating optical fiber was developed. To implement it, a low-cost fabrication system was developed in-house. It indicates that such a fabrication method can be applied with minimum equipment requirements.

Limited by the available resources, samples obtained in this research were not as good as expected; even though, visible examination verified that fabricating SSF with the desired self similar structure is possible. Further optical tests also indicated that SSF does have light guiding property that can be used for light filtering.

5.2   Challenge and improvement

There are still challenges to overcome before mass production of such optical fiber is possible. Many problems were encountered during the fabrication, such as shape distortion in the core, gaps between the core and cladding layer and failure in making the core with 3rd scale hexaflake structure using the original case layer. All these problems can be traced to the lack of heating efficiency in the fabrication furnace.

Two improvements can be made to enhance the heating efficiency of the fabrication furnace. First, the structure of the furnace can be changed by reducing the distance between radiation sources and the targeted materials. Heat can be delivered to the materials better with less loss. Second, the radiation source can be changed from Quartz Halogen bulbs to high energy solid state power laser. The latter one is able to provide more power. With the two improvements made, the inner structures of the heated glass can be softened more thoroughly. As a result, the quality of preform collapsing or SSF pulling will be better.

5.3   Future work

Improvements in the fabrication furnace are needed to accomplish future work. Regardless, this dissertation has opened areas of exploration where future research can be done. SSF has materialized fractal objects that previously only existed in theory. It thus provides a means to test fractal theory.

With regard to fabrication, what has been done in the dissertation only verified that fabricating SSF is possible. The SSFs test samples were only made to 2 scales[24]. The fabrication of SSF with more scales of self similar structures and different fractal patterns
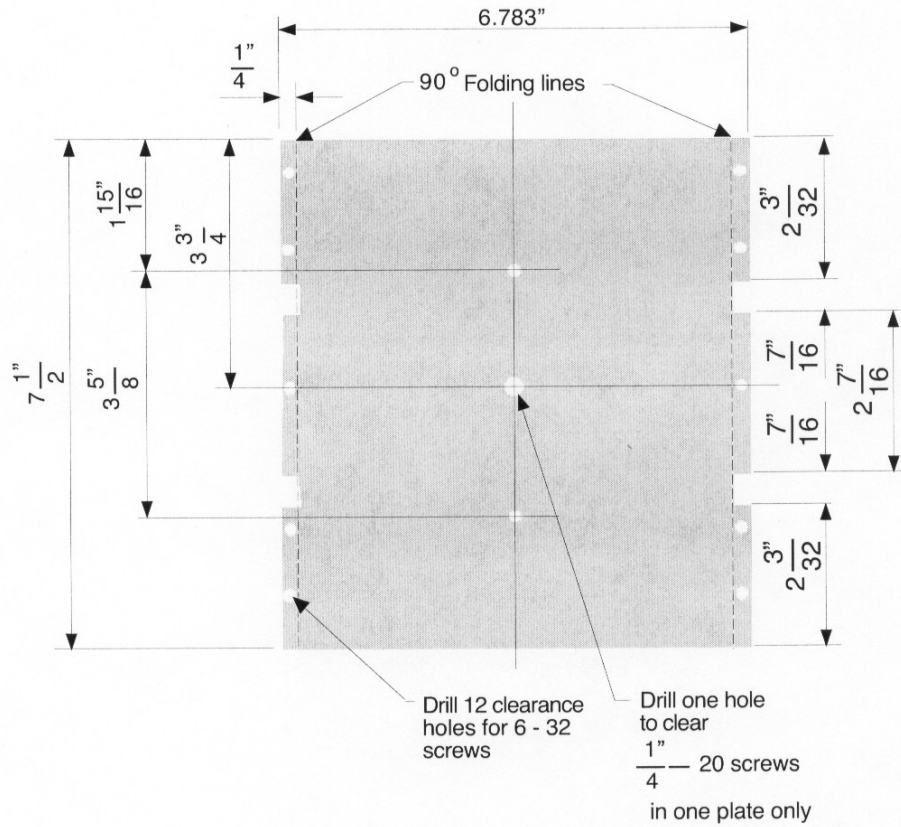
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[24] The SSF with an adjusted three-scale hexaflake unit did not follow the ideal structure. And the fabricated SSF was not satisfactory with a lot of distortion.

that have a denser core will require lab facilities and equipments to be better designed. After that, efforts can be taken to fabricate with over three scales of fractal structures.

In applications, based on possible properties, SSF could be applied to areas such as guiding, selective attenuation, filtering and generating nonlinear optical effects. These however are proposed according to current understanding to this new type of optical fiber. Verification of the possible properties would need future work. This should be done only after the SSF at the desired scales are fabricated with good quality.

To summarize, the SSF was proposed in concept, and tested preliminarily after flawed fabrication. There is still a long way to go to better understand the new being and its properties, and improve it into a mature product.
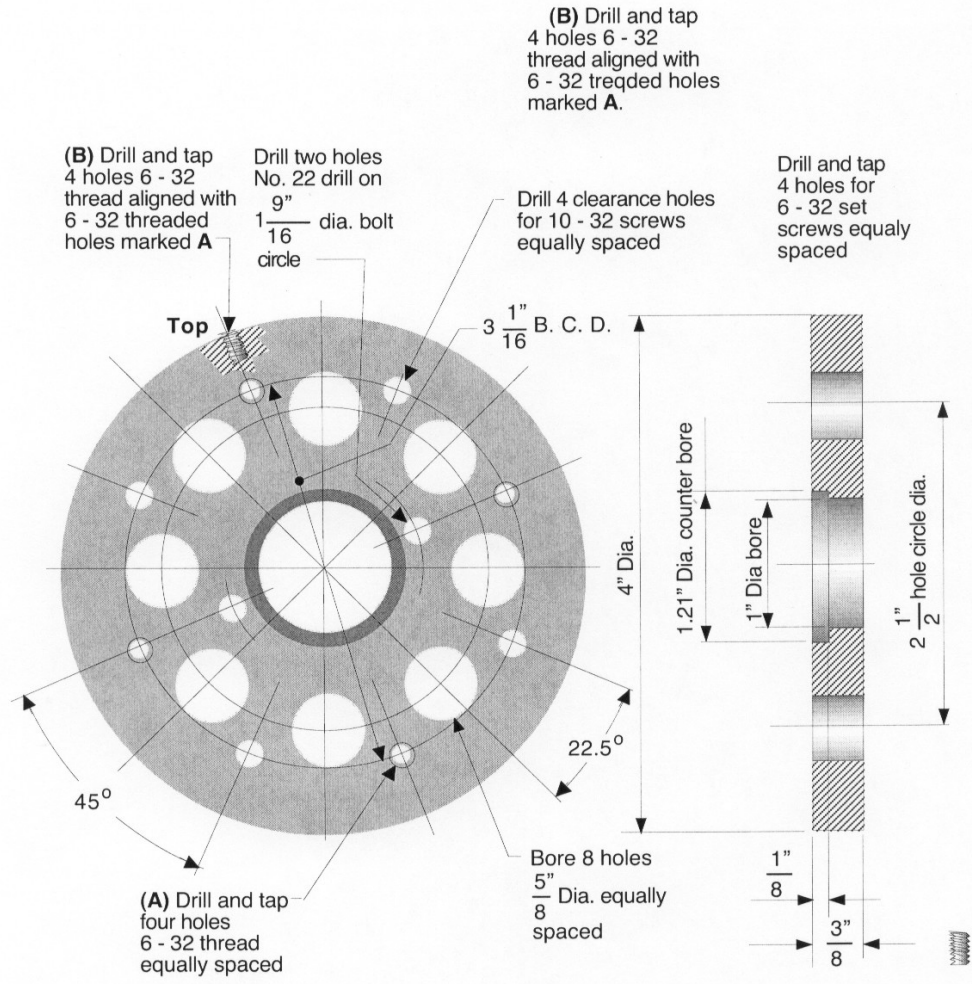
Appendix A - Components of radiation furnace

RADIATION FURNACE
COVER

2 Required

Material: Aluminum
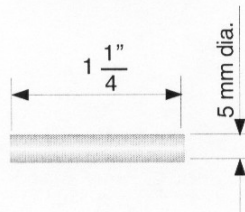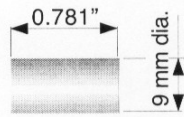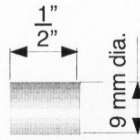
Figure A.1: Radiation furnace cover

(B) Drill and tap 4 holes 6 - 32 thread aligned with 6 - 32 treqded holes marked **A**.

(B) Drill and tap 4 holes 6 - 32 thread aligned with 6 - 32 threaded holes marked **A**

Drill two holes No. 22 drill on $1\frac{9"}{16}$ dia. bolt circle

Drill 4 clearance holes for 10 - 32 screws equally spaced

Drill and tap 4 holes for 6 - 32 set screws equaly spaced

Top

$3\frac{1"}{16}$ B. C. D.

1.21" Dia. counter bore

1" Dia bore

$2\frac{1"}{2}$ hole circle dia.

4" Dia.

22.5°

45°

(A) Drill and tap four holes 6 - 32 thread equally spaced

Bore 8 holes $\frac{5"}{8}$ Dia. equally spaced

$\frac{1"}{8}$

$\frac{3"}{8}$

FIBER PULL RADIATION FURNACE ENDS

2 Required

Material: Brass

Figure A.2: Radiation furnace ends

$\dfrac{1"}{2"}$

9 mm dia.

0.781"

9 mm dia.

$1\dfrac{1"}{4}$

5 mm dia.

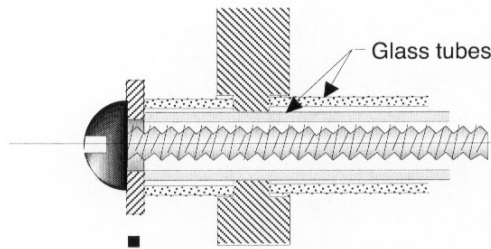6 - 32 round head screws $1\dfrac{3"}{4}$ long, 8 required

Washers, 8 required

RADIATION FURNACE GLASS INSULATORS

8 Required of each

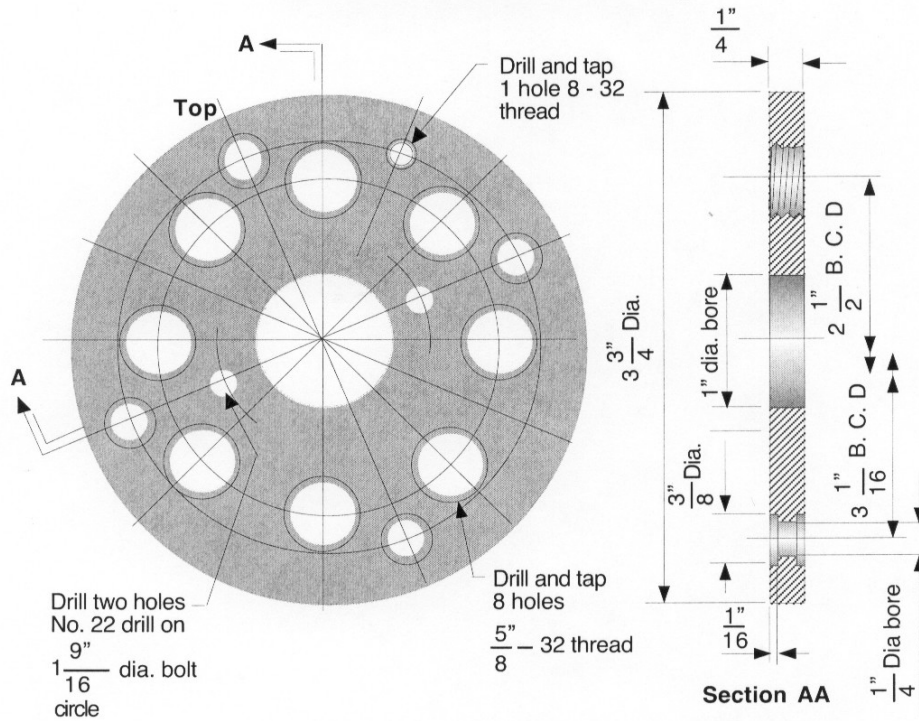## Material: Fused Quartz or Pyrex tubes

Figure A.3: Radiation furnace glass insulators

Figure A.4: Radiation furnace left contact plate

RADIATION FURNACE
LEFT CONTACT

8 Required

Material: Brass

Figure A.5: Radiation furnace left contact

Bottom   Contact detail   Electrical insulation mounting

Glass tubes

Top

A

A

Drill and tap
1 hole 8 - 32
thread

Drill two holes
No. 22 drill on
$1\frac{9"}{16}$ dia. bolt
circle

Bore 8 holes
0.188" dia. equally
spaced

$3\frac{3"}{4}$ Dia.

1" dia. bore

$3\frac{3"}{8}$ Dia.

$\frac{1"}{16}$

Section AA

$\frac{1"}{4}$

$2\frac{1"}{2}$ B. C. D

$3\frac{1"}{16}$ B. C. D

$\frac{1"}{4}$ Dia bore

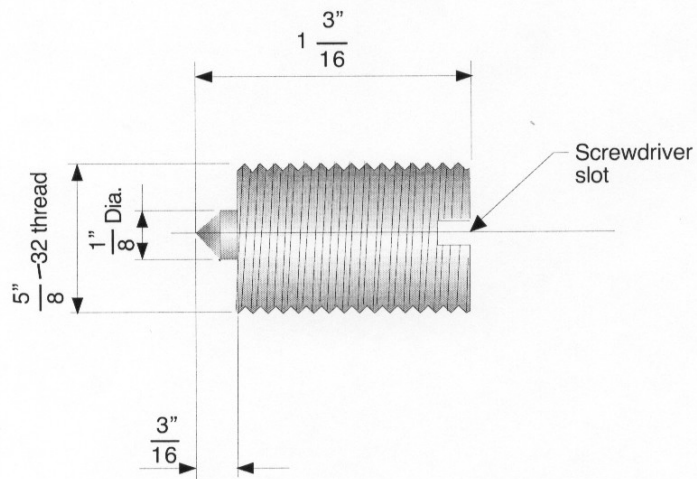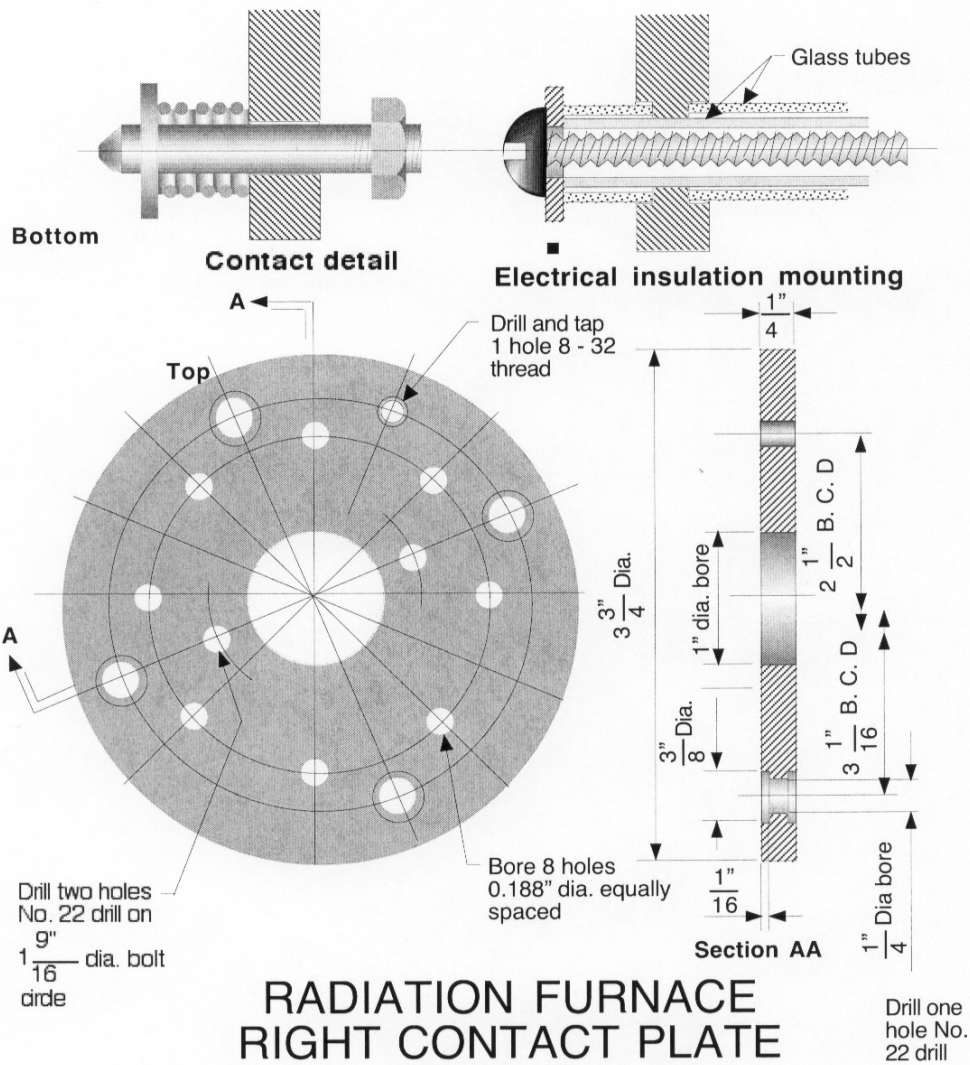Drill one
hole No.
22 drill

RADIATION FURNACE
RIGHT CONTACT PLATE

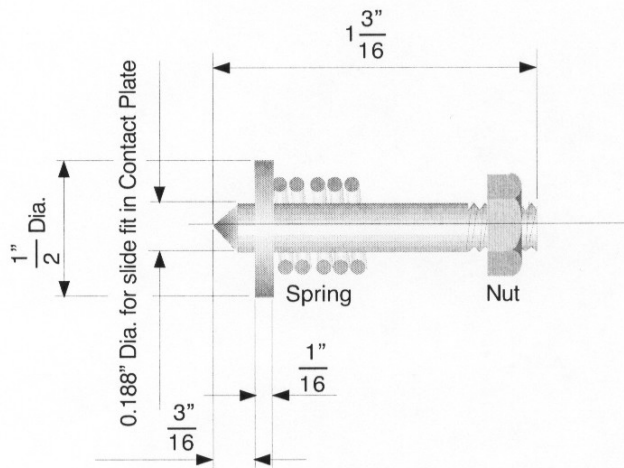## 1 Required
Material: Brass or copper

Figure A.6: Radiation furnace right contact plate
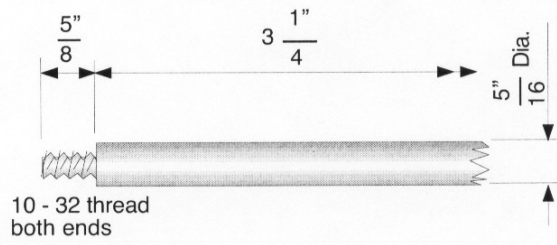
70

RADIATION FURNACE
RIGHT CONTACT

8 Required

Material: Brass

Figure A.7: Radiation furnace right contact

Figure A.8: Radiation furnace spacer rod
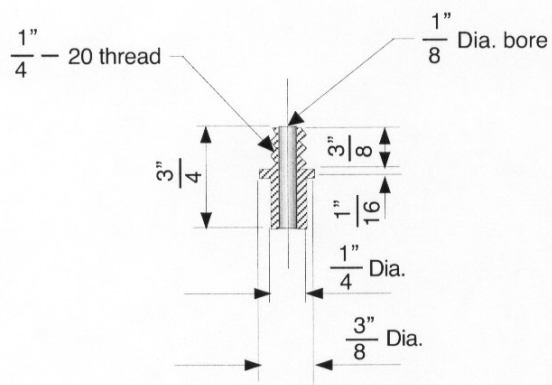
RADIATION FURNACE
THERMOCOUPLE HOLDER

Two required

Material: brass

Figure A.9: Radiation furnace thermocouple holder

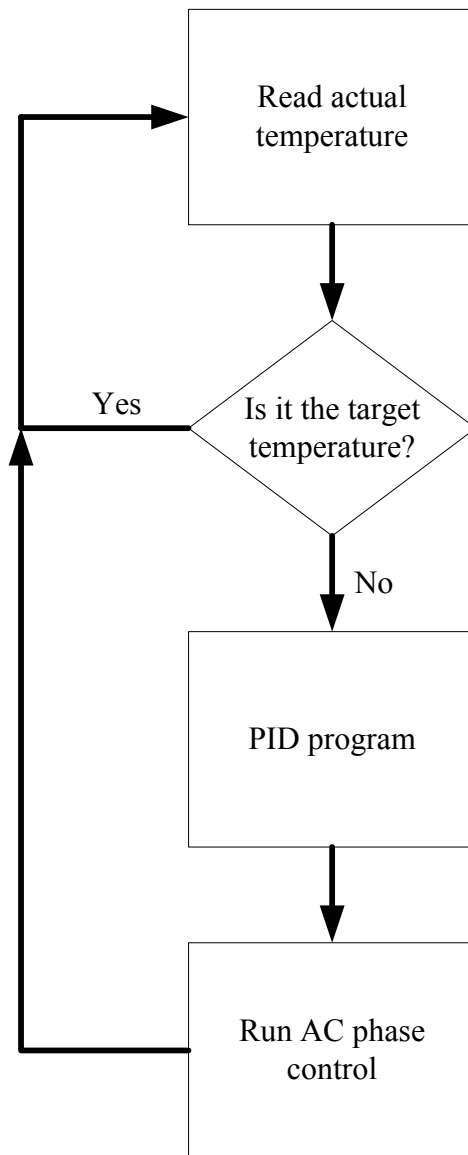# Appendix B - Working flow chart of PID temperature control

Figure B.1: Working flow for PID temperature control

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[5]   Lee M. Cook, "Fractal fiber optics," Applied Optics, Vol. 30, No. 36, pp.5220-5222

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