Design of a Hydrogen-Filled Hollow-core Fiber Raman Laser

Yangyang Qin
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DESIGN OF A HYDROGEN-FILLED HOLLOW-CORE RAMAN FIBER LASER

by

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B.E. Huazhong University of Science and Technology, 2015

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
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in the College of Optics and Photonics
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Orlando, Florida

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Major Professor: Rodrigo Amezgua Correa
ABSTRACT

The purpose of this study is to investigate the design of a Raman fiber laser based on a molecule hydrogen-filled hollow-core fiber with non-touching single ring of capillaries structure. O-hydrogen vibrational frequency shift of 4155 cm⁻¹ and rotational frequency shift of 587 cm⁻¹ were employed to generate Raman scattering from a 1064nm pump source.

A thorough exploration was made to show how all Raman fiber laser components made up: gas chamber, hollow-core fibers, windows. The whole process of chamber design, modification and fabrication were demonstrated. Besides, two kinds of anti-resonant hollow-core fibers were studied and tested. The transmission and loss spectrum of these fibers were measured thus it’s easier to make a choice. Through the whole thesis a Raman fiber laser can be set up and tested very soon.
Dedicated to my parents
ACKNOWLEDGMENTS

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LIST OF ACRONYMS/ABBREVIATIONS

ABS: Acrylonitrile Butadiene Styrene

AR-HCF: Anti Resonant Hollow-Core Fiber

FFF: Fused Filament Fabrication

HC-PCF: Hollow Core Photonic Crystal Fiber

HNF: Highly Nonlinear Fiber

IR: Infrared

SRS: Stimulated Raman Scattering

TIR: Total Internal Reflection

UV: Ultraviolet
CHAPTER ONE: INTRODUCTION

Since first invented in the late 1950s, laser have experienced its considerable development due to its properties: high power density, low divergence and high coherence. The first Raman laser, realized in 1962, used nitrobenzene as the gain medium, which was intra-cavity-pumped inside a Q-switching ruby laser [1]. Later, Raman laser in fibers and in silicon were reported.

In a long time, scientists and researchers are seeking for a waveguide to transport electromagnetic radiation with low losses and high stability. Then fibers appeared. Since “invented” in the 19th century, fibers developed with explosive growth until today. Fibers are almost perfect for energy and signal transportation in our current technology level for low losses and low cost energy and signal transportation compared to coaxial cables.

The development of optical fibers, to some extent, is a process of trying new medium as fiber core and cladding [2]. Scientists and researchers tried materials with good physical and mechanical properties we know to see whether they also have desired optical properties. For example, silica has low absorption from visible to the near infrared (IR) range, so it is a good choice of the fiber core material [1-3].

The whole thesis is divided into six chapters. Chapter one is the introduction. Chapter two introduce the fundamentals and development of hollow-core fibers. Chapter three tells the history and development of Raman scattering and Raman lasers. Chapter four tells about why hydrogen gas was selected. Chapter five focus on the design and development of the whole
setup, concentrate more on gas chambers design, windows, pump laser and fiber characterization. Then finally, Chapter six discuss about conclusion and future work of this design.
CHAPTER TWO: HOLLOW-CORE FIBERS

Actually, hollow-core fibers are first invented with the principle of specular reflection [4]. If the fiber core consists of air, reflecting light will reflect with the same angle to the surface normal as the incident light, thus the fiber cladding act as a “mirror” and light continues spread in fiber core [1]. Compared to solid medium, air has different optical properties and theoretically lower losses. It has been predicted that silica hollow-core fibers could reach 0.2dB/km, which is the extreme losses of solid silica fibers at λ=1550nm [5]. Also, we can avoid risk of damage using hollow-core fibers in high power cases.

2.1 Waveguide by Total Internal Reflection

Total internal reflection (TIR) fibers are the most simple and common fibers. It was first made 1950s [4]. It happens when the refractive index of the incident side is larger than the other side. According to Snell’s law:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \] (1)

then the critical angle can be calculated as below:

\[ \theta_c = \sin^{-1} \frac{n_2}{n_1} \] (2)

If the incident angle greater than critical angle, then the wave vector will not have a component normal to the boundary, thus the optical wave will be totally reflected and propagate along the fiber.
For some certain frequency ranges, there are materials (e.g., sapphire at $\lambda=10.6\,\mu m$) that have a refractive index $n < 1$, therefore, it can serve as a suitable cladding for HCFs [6]. However, the choices of cladding materials with perfect properties limited the development of TIR fibers.

### 2.2 Waveguide by Reflection at a Conducting Boundary

This kind of waveguide is similar to TIR fibers. There is a conducting boundary around the fiber core, reflecting the light back to the core like a mirror [1]. If we have small incident angle to the boundary, there will be less reflections along the fiber direction, thus we can get a relatively low loss [1, 4]. More layers of conducting medium can significantly improve the performance of this kind of fiber. But the high absorption of light in conductors limits this kind of fiber from signal transportation. This kind of waveguide is not commonly used for its limit of high losses [1].
2.3 Waveguide by Photonic Bandgaps

Apart from what we mentioned above, there is another kind of waveguide that produces a reflecting boundary by photonic bandgap effect [7]. Photonic bandgap fibers have a cladding consist of two different optical materials, high-index by low-index periodically just like a grating [8]. For selected wavelength, the reflection wave phase of two neighbored interfaces differs $\pi/2$; in addition, the reflection coefficients for the interfaces have opposite signs. Therefore, all reflected components interfere, which results in a strong reflection [9].

Our desired wavelength is usually much greater than the period, as a result, light is unlikely to pass through the cladding and continue propagating along fiber core. Since the photonic bandgap prevent light from getting through, it is a perfect “mirror” for propagating light along the fiber [1, 2, 4].

Figure 2: (a) Example of a low-loss HC-PCF (b) Detail of the core region. [10]
CHAPTER THREE: RAMAN SCATTERING

Raman scattering is a special scattering effect. It was first discovered by C.V. Raman in 1928. Raman scattering is similar to Compton-Debye Effect in X-rays scattering. When photons interact with small particles (molecules or atoms), most photons will scatter elastically while a very small fraction of photons will scatter inelastically [11]. These photons will interact with molecules or atoms inelastically, exchanging momentum and energy, changing molecule vibrational or rotational mode with the help of phonons, thus produce photons with different frequency. Actually scattered photons usually have lower frequency compared to incident photons [11]. First the photon will excite molecule to a “virtual state”, which only exists while light is present, then the molecule relaxes and produces a new photon.

![Raman Scattering Diagram](http://www.horiba.com/es/scientific/products/raman-spectroscopy/raman-academy/raman-faqs/raman-scattering/)

**Figure 3:** Raman Scattering

**Source:** Horiba Scientific

3.1 Stokes shift and Anti-Stokes shift

When Raman scattering occurs, there will be a frequency (or wavelength) difference between absorption peak and emission peak [11, 12]. If absorbed photons have greater energy than emitted photons, this kind of frequency (or wavelength) shift called Stokes shift. On the contrary, if absorbed photons have lower energy than emitted photons, it is called Anti-Stokes shift [11].

The energy exchange between photons and molecules (or atoms) will generate new photons with different energy. In a spectrum, there would be lines shifted from absorption line: a lower frequency Stokes line and a higher frequency Anti-Stokes line [13]. Normally, Stokes line is much stronger than Anti-Stokes line [11, 13]. However, if the medium gets heated, later a stronger Anti-Stokes line can be observed compared with that cool medium.

![Stokes and Anti-Stokes Shift](image)

Figure 4: Stokes and Anti-Stokes Shift [13]
### 3.2 Raman Spectroscopy

Raman spectroscopy is a spectroscopy technique to analyze the vibrational and rotational modes for target molecules (or atoms) basing on Raman effect [11]. Specific molecule (or atom) has identical vibrational and rotational modes, by analyzing these modes using Raman spectroscopy it is easy to identify molecules [11, 12].

Actually Raman scattering is too weak to observe using traditional light source [13]. Lasers were used for Raman spectroscopy as a light source to enhance the scattering light.

Raman spectroscopy is highly selective and sensitive to identify similar molecules (or atoms) [11]. Raman spectroscopy can be used in chemistry for sample component analysis simply by comparing output spectrum to Raman spectral libraries [14].

### 3.3 Raman Laser

Raman laser is a specific new kind of laser that base on the fundamental of stimulated Raman scattering (SRS) [15]. As pump power increased, scattered Stokes photon can further more promote other pump photons, in which process the Stokes intensity grow rapidly; this process is called stimulated Raman scattering (SRS) [16]. Usually the stimulated Raman scattering (SRS) is determined by molecule vibrational modes. Then the stimulated Raman scattering stimulated Raman scattering (SRS) frequency can be written as:

\[ \omega_{SRS} = \omega_{pump} - \omega_{stokes} \] (3)
where $\omega_{\text{pump}}$ and $\omega_{\text{stokes}}$ are pump frequency and Stokes frequency respectively. When the frequency difference $\omega_{\text{SRS}}$ matches one of the molecule vibrational modes, vibrational transition process is excited [16, 17]. This is why stimulated Raman scattering (SRS) need a higher gas molecule density and generate stronger radiation.

In 1976, the first Raman laser in an optical fiber was reported by K. O. Hill. Raman laser is pumped with optical energy, which is different from conventional lasers [15, 16]. Once we choose a pump laser wavelength, the output Raman laser wavelength is determined by rotational and vibrational frequency of the gain medium. This differs from conventional lasers whose output wavelengths are determined by energy states of gain medium [15].

It is a great advantage that these unusual wavelengths can be obtained using Raman laser while they are not easy for conventional lasers. Raman lasers based on waveguides in silicon on a chip (silicon lasers) have been demonstrated [17]. Gases are also potential medium for Raman lasers. The only problem is that the high pump power threshold of gases lasers limits its development; however, the increase of gas pressure will significantly reduce the desired pump power until a certain threshold of pressure [18, 19].
CHAPTER FOUR: HYDROGEN MOLECULE

Among dozens of Raman materials, high pressure hydrogen gas is widely used [16, 20]. There are several advantages using hydrogen gas. First of all, hydrogen gas is cheap, that makes it economic. It is gas at room temperature so it is easy to design the gas cell and to increase the gas pressure, thus the density of medium can be easily controlled. Hydrogen molecule has a large Stokes shift frequency in Raman mediums [11, 12, 15]. Finally, the absorption near infrared (NIR) spectrum for hydrogen molecule is relatively low, that makes it easier to get Raman gain [15, 20].

4.1 Vibrational modes

For a linear molecule the vibrational degrees of freedom are 3N-5 [13]. The vibrational modes can be simplified to oscillation modes, thus the vibrational energy can be present as:

\[ E_{vib} = \left( n + \frac{1}{2} \right) \hbar \omega \]  

(4)

here, \( n \) is a non-negative integer, \( \hbar \) is reduced Planck constant and \( \omega \) is the angular frequency of hydrogen molecule [13,15,19]. Then we can calculate that the vibrational frequency shift of \( \text{o-} \) hydrogen molecule is \( \omega_v = 4155cm^{-1} \) [21,24]. For the pump laser at a wavelength of 1064 nm, the expect vibrational Stokes line in hydrogen gas will be 1907 nm.
4.2 Rotational Modes

For a linear molecule the rotational degrees of freedom are 2 [13]. Actually, the kinetic energy of rotation can be written as:

\[ E_{\text{rot}} = \frac{l(l+1)\hbar^2}{2\mu r_0^2} \]  

(5)

here, \( l \) is a non-negative integer, \( \hbar \) is reduced Planck constant, \( \mu \) is the reduced mass of hydrogen molecule and \( r_0 \) is the average distance between the two hydrogen atoms [20,21]. And the o-hydrogen molecule rotational frequency shift is proved to be \( \omega_r = 587 \text{ cm}^{-1} \) [22-24]. For the pump laser at a wavelength of 1064 nm, the expect rotational Stokes line in hydrogen gas will be 1135 nm.
CHAPTER FIVE: SETUP

In a Raman scattering system, Raman scattering is always so weak compared to Rayleigh scattering [13]. In order to get sufficient Raman scattering intensity, there are two options to make the improvement. The first solution is to increase the peak pump power so the final Raman scattering intensity will be large enough for our observation; the second option is to increase the medium gas density, a higher pressure will lead to more interaction, therefore the output Raman scattering power can be raised to a detectable level [18]. However, it is always easier to increase gas pressure than to increase the pump power.

For this case of a hydrogen-filled Raman fiber laser system, the design of the gas chamber is super important due to the desire of high pressure of gas. For this system, a hydrogen pressure level not less than 10 atm is needed to achieve the stimulated Raman scattering (SRS) threshold, which is the minimum pressure to see stimulated Raman scattering (SRS) at a relatively low pump power level [18]. And to seek the minimum power for a stimulated Raman scattering (SRS), the cell pressure need to be raised to a higher level: in this system a hydrogen gas pressure of 30 atm was set as a maximum, which is a risky task for the experiment.

5.1 Chamber Design

As the chamber should sustain a high gas pressure up to 30 atm [18], plastic materials are not good choices, metal materials like aluminum and stainless steel have been chosen for the gas cell materials.
There should be a window in the chamber in order that lase from the pump source can get through and enter the chamber. A cap is used to keep the chamber in high pressure. Also, in the other side of the chamber, there should be a tiny hole for the hollow-core fiber. Fiber insert from the tiny hole until near the window. And a golden rod fitting is used to connect the chamber body and the fiber hole. Thus pump laser can coupled into the hollow-core fiber. Both the window and the fiber hole are sealed with rubber O-rings near the gap.

To put the chamber in a stable environment, the bottom of the chamber should be the same as a V-shape fiber holder so it can be screwed in a Thorlabs XYZ stage. Also, the Thorlabs XYZ stage can be adjusted for 3 degrees of freedom, that makes it is easy to change the position of the chamber and then correct the position of the hollow-core fiber when the beam coupling process needs to be done.

The metal gas cell takes long time to fabricate with metalworking technology so it is not convenient to adjusted and modified. However, 3D printing technology can be a perfect solution for this concern. Once the gas cell is designed, it can be printed by the 3D printer. The plastic gas cell can be easily fabricated and is about the same size and detail to a real metal gas cell for the experiment.

To design the gas chamber, an efficient computer aided design (CAD) software is needed. Here the free CAD software Autodesk 123D design by Autodesk, Inc. was used for model design.
The principle of the chamber design process is to create a high pressure sustainable gas cell with gas inlet and a fiber inlet. A Creator Pro 3D printer from Flashforge Corporation was used for 3D printing.

![Creator Pro 3D printer](image)

Figure 5: Creator Pro 3D printer

This 3D printer is a 3D printer using Fused Filament Fabrication (FFF) technology: materials were added from the bottom layer by layer. Some key technical specifications are showed in table.

<table>
<thead>
<tr>
<th>Layer Resolution</th>
<th>Precision</th>
<th>Filament Type</th>
<th>Filament Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1~0.5mm</td>
<td>XY</td>
<td>Z</td>
<td>ABS, PLA,</td>
</tr>
<tr>
<td></td>
<td>11µm</td>
<td>2.5µm</td>
<td>1.75mm</td>
</tr>
</tbody>
</table>

So the resolution of this 3D printer is high enough for the desired chamber model. Here the 3D printer use Acrylonitrile butadiene styrene (ABS) as filament. Acrylonitrile butadiene
styrene (ABS) is a thermoplastic polymer with good properties of impact resistance and toughness [25].

5.1.1 Gas Hole at Surface

For this scheme the gas hole at the chamber was put at one surface, that is the same side as the fiber hole. This is the first plan for the chamber.

Figure 6 shows the initial chamber design with gas hole and fiber hole at one surface and the window at another surface.

![Figure 6: Chamber with Gas Hole on Surface](image)

The cap is design to fix the window and to seal the whole chamber in order that high pressure will not escape.

Figure 7 shows the front side and back side of the cap. Six screw holes were applied to fix the cap with chamber.
Figure 7: Cap design (a) Front of the cap (b) Back of the cap

The whole printing process takes several hours under standard resolution, that is a layer height of 0.18mm. This is high enough for a tested plastic chamber although the support portion of the chamber printed with low quality.

Figure 8 shows the printed chamber sample with gas hole and fiber hole at one surface and the window at another surface.

Figure 8: Printed Chamber 1

However, it is crowd for the two connection fittings at one surface. More important is that it is difficult to adjust the connection tubing system with current gas hole design when the
chamber is fixed on a stage; the design should be changed in order that fittings between the chamber and tubing system can be adjusted easily.

5.1.2 Gas Hole on the Top

To improve and modify the previous chamber, a new chamber was designed. This chamber was designed with fiber hole at one surface, window at another surface and gas hole on the top. Compare with the previous design, the gas hole moves from a surface to the top of the chamber.

Figure 9 shows the new chamber design with gas hole on the top.

![Figure 9: Chamber with Gas Hole on the Top](image)

For the new design, the advantage is that gas inlet fittings can be easily adjusted and fixed when the chamber is screwed firmly in the stage. Furthermore, the fiber hole diameter was increased to adjust a new fitting while the old fitting option cannot seal the gap between fiber hole and fiber very well.
Figure 10 shows the modified chamber printed by 3D printer. This is the best design so far and is ready to be manufactured.

Figure 10: Printed Chamber with gas hole top

Figure 11 shows the real metal chamber fabricated CREOL machine shop. To seal the fittings and connections polytetrafluoroethylene (Teflon) was used.

Figure 11: Final Metal Chamber
5.1.3 Pressure Test

To make sure there is no leak at the chamber and tubing system, a long time pressure test is needed to be done. The leakage test begins with a gas pressure of 400 psi (about 27 atm). And the final pressure after 6 hours is 374 psi (about 25.5 atm).

![Figure 12: Pressure Leakage Test](image)

This figure demonstrated that the whole gas system sealed very well. The small leakage here will not matter because the experiment will not last for such a long time like 6 hours. Actually optical measurement can be done in just one hour so pressure for this system can be treat as a constant.

5.2 Pump Laser

A Teem Photonics MNP-06E-000 solid-state Nd: YAG laser is used as a pump source with a wavelength of 1064 nm. This laser works at a repetition rate of 9.59 kHz, a single output
pulse energy of 7.9 μJ, pulse duration of 0.62 ns, maximum peak output power of ~12 kW and maximum average output power of ~80 mW.

5.3 Windows

To launch light into the hollow-core fiber in the gas cell a high transmission window is needed. The window should be stable enough for high gas pressure case and should be with high rigidity thus it will not break between the cap and the chamber when they are fixed with screws.

Here a Thorlabs WG41050-C UV fused silica high-precision window is selected. It is made of silica with high transmission from UV until near IR portion of the spectrum. The diameter of this window is 1 inch (25.4mm) with a thickness of 5 mm. Besides this window is coated with anti-reflective coating with the range of 1050 -1070 nm. The window transmission at the pump laser wavelength of 1064 nm is more than 99.8%.

Compared to N-BK7 glass, UV fused silica provide a high transmission into deeper UV, lower refractive index, better homogeneity and lower coefficient thermal expansion [26].

5.4 Fibers

To generate ‘white light’ from the 1064 nm wavelength pump laser, a highly nonlinear fiber (HNF) is used to launch 1064 nm pump light into hollow-core fiber. Basing on nonlinearity properties of this highly nonlinear fiber (HNF) a broadening spectrum will be generated and applied to hollow-core fiber. That’s how the transmission spectrum was measured.
Among series of hollow-core fibers, there are two kinds that are more potential for Raman fiber laser: ice-cream shape fiber and capillaries fiber. Here some work about these fibers were done to discover their properties.

Figure 13: Highly Nonlinear Fiber

Figure 14: Images of Anti-Resonant Hollow-core Fibers (a) Ice-cream Shape in Cladding; (b) Revolver Fibers with Nontouching Capillaries in Cladding
Actually, anti-resonant fibers are designed with anti-resonant core walls which can guide light into the mid-infrared spectrum [27]. Anti-resonant reflecting guidance model was used to explain how light transmits in anti-resonant hollow-core fibers (AR-HCF). There are some specific wavelengths that can be low-loss depending on the core wall thickness [28]. These resonance wavelengths can be described by:

$$\lambda_{re} = \frac{2t}{n} \sqrt{n_{clad}^2 - n_{air}^2}$$  \hspace{1cm} (6)

where $t$ is the thickness of core wall, $n$ is a positive integer, $n_{clad}$ and $n_{air}$ are refractive indexes of the cladding material and core filled with air respectively [24]. So transmission bands can be controlled just modifying the wall thickness.

5.4.1 Transmission and Loss Spectrum

Transmission spectrum is important in fiber characterization. By analyzing the transmission spectrum of the fiber the loss profile can be obtained, thus its potential in telecommunication can be considered.

To select a fiber for Raman Laser the transmission and absorption spectrum are also important and should be demonstrated to see whether there is a transmission band at desired wavelength. For this experiment two different structures of fibers were supposed to use in generating Stimulated Raman Scattering (SRS).

Table 2 shows some parameters of ice-cream fibers. They have the same structure in cross section but with different parameters.
Table 2: Parameters of ice-cream Fibers

<table>
<thead>
<tr>
<th></th>
<th>Draw 360</th>
<th>Draw 363</th>
<th>Draw 364</th>
<th>Draw 370</th>
<th>Draw 371</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_in (μm)</td>
<td>191</td>
<td>185</td>
<td>174</td>
<td>223</td>
<td>113</td>
</tr>
<tr>
<td>D_core (μm)</td>
<td>89.4</td>
<td>82.9</td>
<td>63.9</td>
<td>117</td>
<td>51.1</td>
</tr>
<tr>
<td>D_node (μm)</td>
<td>6.25</td>
<td>6.15</td>
<td>8.45</td>
<td>4.49</td>
<td>1.11</td>
</tr>
<tr>
<td>t (nm)</td>
<td>807</td>
<td>861</td>
<td>715</td>
<td>979</td>
<td>517</td>
</tr>
</tbody>
</table>

Designation $D_{in}$ corresponds to the inner diameter of the fiber, $D_{core}$ is the diameter of the circle inscribed into the core region, $D_{node}$ is the touching length of two neighbor ice-cream shape, $t$ is the thickness of the ice-cream walls.

Different draws of fibers were measured during that time with a length of 4 m.

Figure 15: Draw 360 Transmission Spectrum
Figure 16: Draw 363 Transmission Spectrum

Figure 17: Draw 364 Transmission Spectrum
By comparing transmission profiles of those different draws of fibers it is observed that Draw 360 has the maximum transmission at 1100-1300 nm band. For a rotational Raman scattering case with present pump laser wavelength of 1064 nm, a Stokes line is expected to be
observed at 1135 nm. Then this Stokes wavelength is on the transmission band with low loss and makes this fiber potential for 1135 nm Raman generation.

In the other hand, 3 draws of capillaries fibers were also tested to get their transmission spectrum and loss profile at desired wavelength. The tested length of those fibers were 10 m.

Table 3: Parameters of capillaries Fibers

<table>
<thead>
<tr>
<th></th>
<th>D_{out} (μm)</th>
<th>D_{in} (μm)</th>
<th>D_{core} (μm)</th>
<th>D_c (μm)</th>
<th>t(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draw 659</td>
<td>173</td>
<td>83.8</td>
<td>41.6</td>
<td>20.3</td>
<td>449</td>
</tr>
<tr>
<td>Draw 668</td>
<td>193</td>
<td>96.9</td>
<td>40.4</td>
<td>27.2</td>
<td>474</td>
</tr>
<tr>
<td>Draw 689</td>
<td>174</td>
<td>84.2</td>
<td>42.2</td>
<td>23.8</td>
<td>628</td>
</tr>
</tbody>
</table>

Designation D_{out} corresponds to the outer diameter of the fiber, D_{in} is the inner diameter of the fiber, D_{core} is the diameter of the circle inscribed into the core region, D_c is the diameter of such small capillaries rings, t is the thickness of the rings walls.
Figure 20: Draw 659 Transmission Spectrum

Figure 21: Draw 668 Transmission Spectrum
By comparing transmission profiles of those different draws of fibers it is observed that Draw 659 has the maximum transmission at 1100-2000 nm band. For a rotational Raman scattering case with present pump laser wavelength of 1064 nm, a Stokes line is expected to be observed at 1135 nm. For a Vibrational case the Stokes line should be at 1907 nm. Then this Stokes wavelength is on the transmission band with low loss and makes this fiber potential for both 1135 nm and 1907 nm Raman generation.

Figure 22: Draw 690 Transmission Spectrum
Figure 23: Draw 659 Loss Spectrum

Figure 24: Draw 668 Loss Spectrum
By comparing loss profiles of those different draws of fibers it is observed that Draw 689 has the minimum loss at 1400-2000 nm band. For a rotational Raman scattering case with present pump laser wavelength of 1064 nm, a Stokes line is expected to be observed at 1135 nm. The calculated loss is ~0.6dB/m. For a Vibrational case the Stokes line should be at 1907 nm. The calculated loss is ~0.2dB/m. Then this Stokes wavelength is on the low loss band makes this fiber potential for 1907 nm Raman generation.
CHAPTER SIX: SUMMARY AND OUTLOOK

In this investigation, it was successfully demonstrated that how a Raman fiber laser is made up of. All the components were studied and tested to see whether they suit this Raman fiber laser system. Chambers for the gas pressure system were first designed, then fabricated, finally tested during this discovery. Two kinds of anti-resonant hollow-core fibers (AR-HCFs) were potential for this system so they were tested at selected expected Raman scattering wavelength. The transmission and loss profiles of these two kinds of fibers were recorded maybe for later study and experiment.

The outlook for this investigation is to launch light into the fiber to analyze those fiber modes. And the coupling efficiency of this system is also super important. Also, it can be done very soon that light can be launched into the fiber under high hydrogen gas pressure to get Raman generation. Furthermore, more fiber structures can be tested later to see their potential for Raman fiber laser, as well as different gases.
REFERENCES


