Final Report

Contract AOARD-05-4012,
"Novel fiber laser source for hyper-sensitive, long-range LIDAR system"

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14. ABSTRACT
A study of an innovative waveguide structure including hollow optical fiber (HOF) with a central hole and rare earth doped ring core is investigated. The HOGF serves as a novel fiber laser and amplifier gain medium. The central air hole and glass ring core gives an access to chromatic dispersion control, while the rare earth doped ring and its adiabatic taper endows a new degree of freedom to design clad pumped fiber laser gain medium that has not been available in the prior arts. The project encompasses the design of the HOF and its fabrication, then active device implementation and characterization. Optimal design parameters are obtained for applications for LIDAR systems and other optical applications.

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1. Introductions

The time frame of the project AOARD-05-4012 has been proposed in the contract as in the Table 1.

Milestones \ Months	1	2	3	4	5	6	7	8	9	10	11	12
HOF waveguide design	→	→										
Rare earth doped HOF fabrication		→	→									
Pumping Scheme study			→	→								
Laser cavity assembly				→	→	→						
Laser characteristics studies						→	→	→	→	→		
SBS study								→	→	→	→	
HOF structure optimization											→	→

In the past six months, we successfully accomplished the milestones in due time, along with journal and conference publications through research works.

As of September 30'th after six months of the project launch since February of 2005, we have achieved the following goals;

1) HOF (Hollow Optical Fiber) waveguide design
   - Modal intensity distribution for guided modes along the ring core
   - Dispersion control by HOF waveguide parameters
2) Rare earth doped HOF fabrication
   - Yb doping by solution doping technique along with modified CVD
   - Yb ion concentration estimation and measurements of transmission spectra of fabricated HOF
3) Pumping scheme study and laser cavity assembly
   - End-pumping scheme adopted
   - Fiber laser cavity assembled
   - Initial measurement of lasing performances
4) Related research and publications
   - Four papers accepted in journals

2. HOF waveguide design

The HOF is composed of three layers, central air hole with radius ‘a’, raised index ring core with thickness ‘d’, and the amount of refractive index contrast between the silica cladding and the ring core, Δ, as indicated in Fig. 1

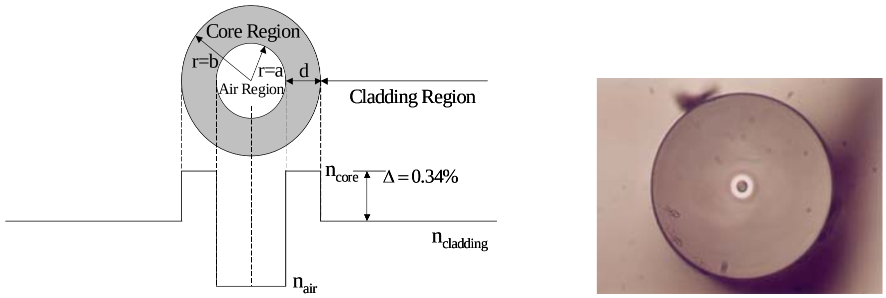

Figure 1 Schematic structure of HOF, on the left, and the cross section photograph of a fabricated HOF

Thus far the fundamental mode in HOF has been of main concern, yet in order to facilitate the HOF structure in a fiber laser cavity it is important to understand the optical properties of higher order mode. In this research, we have developed an analysis routine based on commercial vector waveguide analysis tool, “Mode Solver,” to investigate the modal properties of guided modes in HOF along both the ring core and the cladding.

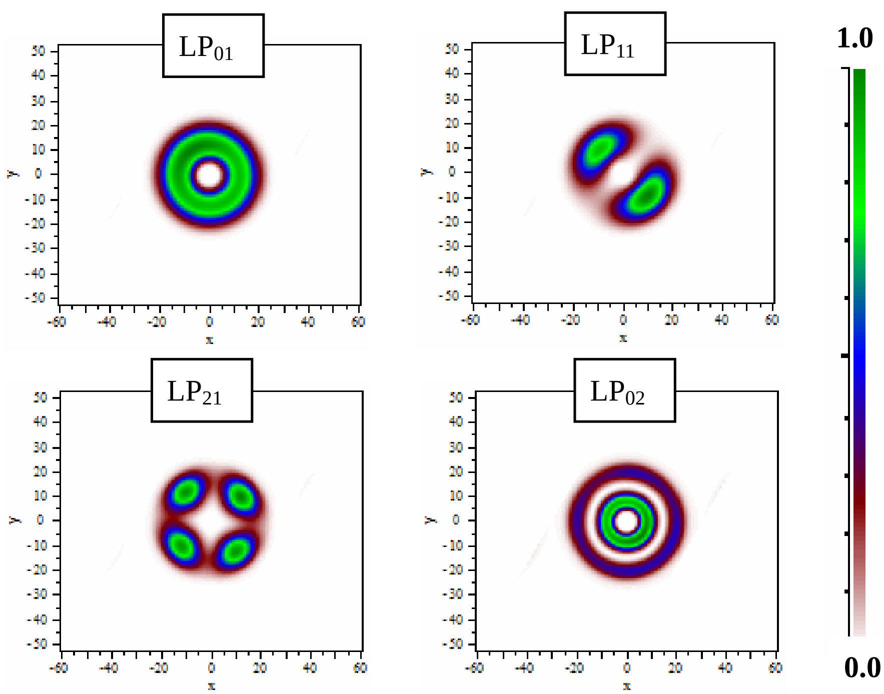

Figure 2. The intensity profiles of modes guided along the ring core of HOF

The intensity profiles of the guided modes along the ring core of HOF were calculated by solving wave equation and Maxwell's equation for the three layer boundary conditions. The results are summarized in Fig.2. It is noted that the guided high order modes are mainly confined in the ring core maintaining the characteristic annulus intensity distribution as the fundamental LP_{01} mode. The nodes of intensity are also located along the ring core as seen in the case of LP_{11} and LP_{21} modes.

We further apply the same routine to calculate the modal structure of cladding modes. The cladding modes are defined by the interface between the silica cladding and the air interface and due to high refractive index difference between silica and air the cladding modes are inherently multi-moded. The intensity distribution of the first two modes are shown in Fig. 3.

It is noted that the central air hole of HOF structure also affect the cladding modes and cladding modes are also showing annulus distribution. Note that pump photon in a clad pumped fiber laser cavity will be guided by these cladding modes. Therefore the modal overlap between the core mode and the cladding mode would be an important barometer to predict and assess the fiber laser pumping efficiency. Another spatial overlap between the cladding mode and the rare earth ion distribution would also play a critical role in pumping efficiency.

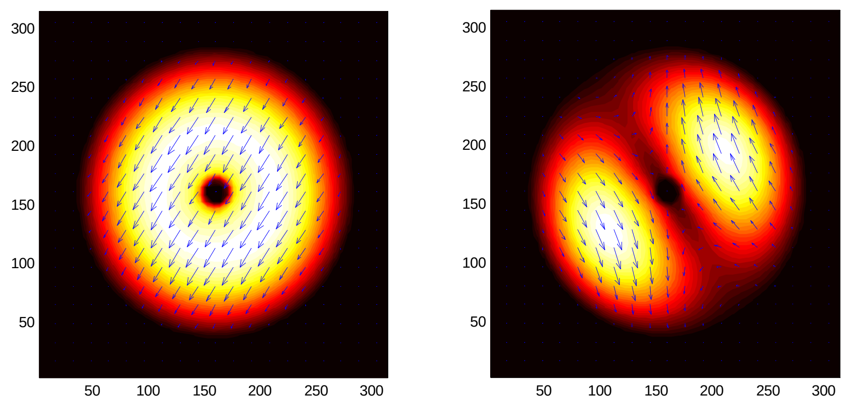

Figure 3. The intensity distribution of the first two cladding modes of HOF

For the core modes shown in Fig.2, we further investigated their chromatic dispersion as a function of HOF waveguide parameters. In this case we have assumed the waveguide parameters as in Fig. 4-(a) and the chromatic dispersion was calculated as a function of air hole size, a_{hole}.

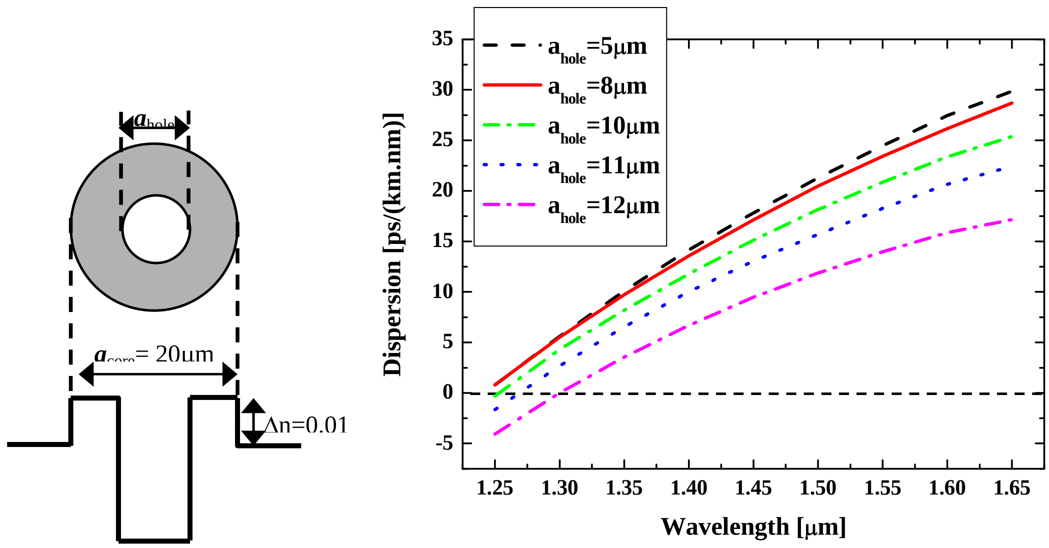

Figure 4. Waveguide parameters used in the analysis and the chromatic dispersion

In order to achieve polarization maintenance in HOF, asymmetry in the waveguide should be introduced. We have investigated elliptical ring core whose structure is shown in Fig. 5.

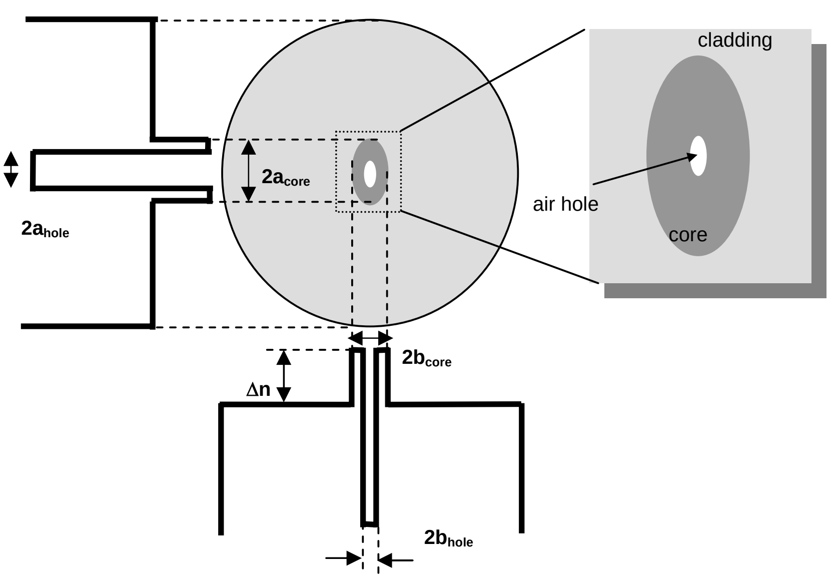

Figure 5. Waveguide parameters for elliptical ring core HOF

Note that in the elliptical ring core HOF, ellipticity, a/b, has been newly introduced as a waveguide design parameter to signify the amount of asymmetry in the core. The birefringence, n_{eff_y}-n_{eff_x}, has been evaluated and the results are summarized in Fig. 6. It is observed that there exists an optimal range of the hole size for high birefringence, whilst Δn monotonically increases the birefringence.

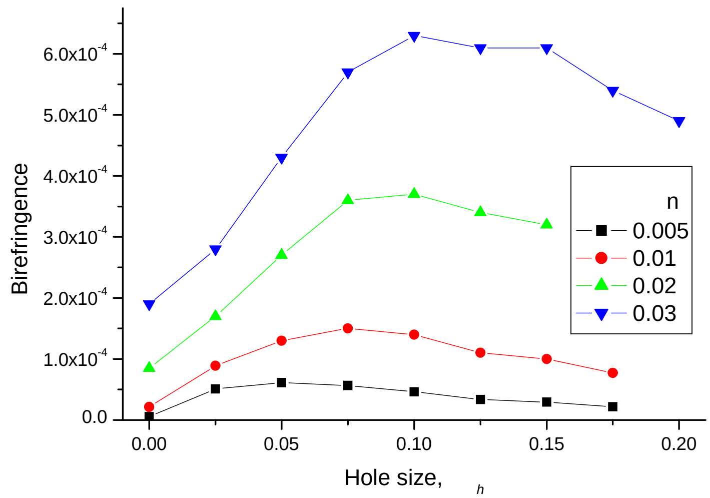

Figure 6 Birefringence of elliptical ring core HOF for various waveguide parameters

3. Rare earth doped HOF fabrication

1) Yb doping by solution doping technique along with modified CVD

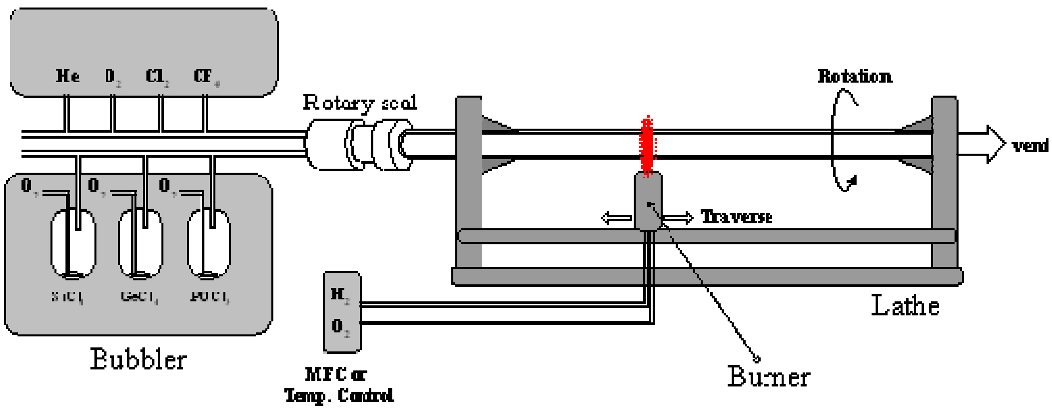

Figure 7. Schematic setup for perform fabrication

After deposition of silica soot layer by appropriate flow of $SiCl_4$ with O_2 carrier, the tube was soaked with a alcoholic rare earth solution to impregnate rare earth halides into the silica soot layer. The composition of the solutions used in the experiments are shown in Table 1. We have chosen Yb as the primary dopant due to its high efficiency in fiber laser.

Table 1. The composition of the solution used in perform fabrication

Solution	Yb^{3+}(I)	Yb^{3+}/Er^{3+}(II)
Al nitrite(g)	10	10
Yb_2Cl_3 (g)	1	1
Er_2Cl_3 (g)	0	0.1
HCl or ethanol (mL)	200 mL	200 mL

After soaking of the soot layer, the solution was dried up and the soot layer was sintered in an oxygen rich environment at a high temperature to result in Yb doped silica layer to form the core. After collapsing the doped tube into a solid perform, fiber was drawn from the perform utilizing the drawing tower shown below.

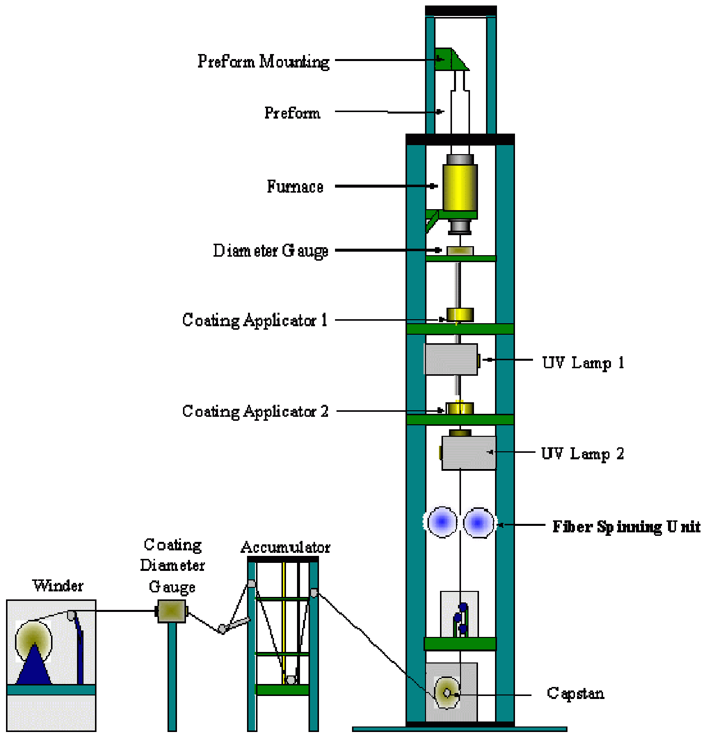

Figure 8. Drawing tower schematics

In order to keep the hollow region intact, lower temperature and higher tension have been employed. The final fiber diameter was 125μm with acrylate polymer jacketing over it.

2) Yb ion concentration estimation and measurements of transmission spectra of fabricated HOF

The transmission through the fabricated Yb doped fiber was carried out using a white light source and an optical spectrum analyzer for different lengths of fiber. The absorption spectrum was measured as shown in Fig. 8, where we could identify the characteristic absorption bands of Yb ion in silica. For 5cm long fiber the absorption was 5.25dB at 915nm and 7.9dB at 979nm. The concentration of Yb was estimated as 2000 ppm.

In transmission measurement experiments, we found that the HOFs were very sensitive to bending unless waveguide parameters are well optimized. As shown in Fig. 9, the transmission on the longer wavelength significantly differs among three types of fabricated fibers, whose parameters are shown in Table 2. The loss at the longer wavelength indicates the cut-off of the fundamental mode in HOF. It is, therefore, highly important to adjust the hole diameter and ring thickness during the design and fiber drawing process to secure good guiding properties at the lasing wavelength range.

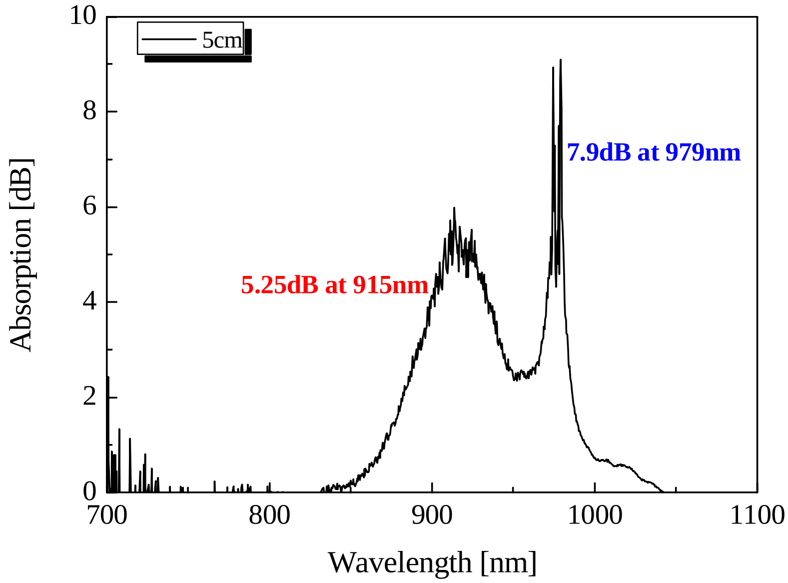

Figure 9. Absorption spectrum of fabricated Yb doped fiber

Table 2 Parameters of drawn fibers with different geometries

Fiber types	Hole diameter(μm)	Core thickness(μm)
Fiber 4	10.5	1.9
Fiber 5	9.2	1.7
Fiber 6	7.1	1.3

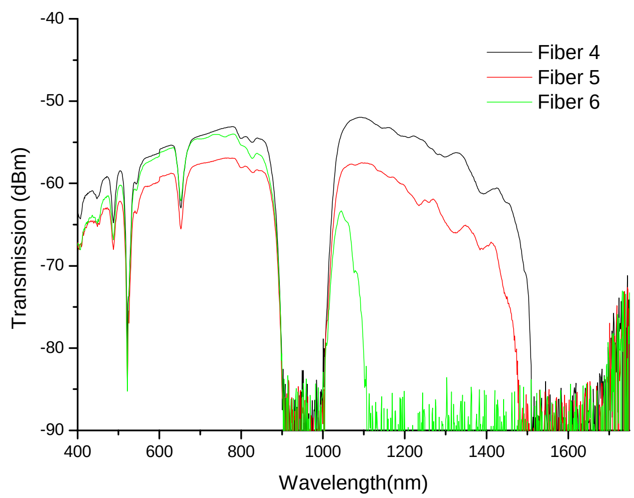

Figure 10. Transmission spectra for different fiber types

4. Pumping scheme study and laser cavity assembly

In the clad pumped fiber laser cavities, a good spatial overlap between the cladding modes and rare earth doped region should be secured for high slope efficiency. There have been several attempts to reduce the skew rays in the cladding to enhance the overlap. The cross-sections of those attempts are summarized in Fig. 11 and can be categorized into circular symmetric, off centered core, rectangular cladding, and D-shaped cladding. The absorption of pump photon along the fibers with these cross-sections have been obtained by researchers in Fredrich Schiller University at Jena, (http://www.iap.uni-jena.de/fawl/rdtfawl.html) and the results are shown in Fig. 12.

In future experiments we will adopt D-shape cross-section and its modification for further improvements in fiber laser performances.

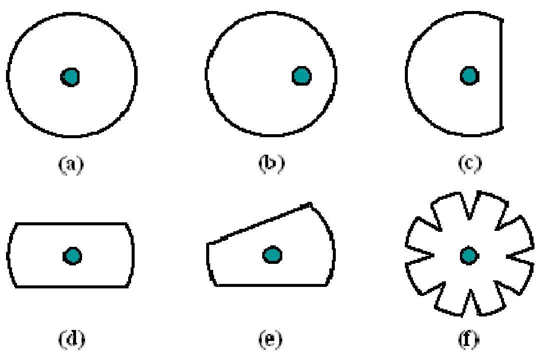

Figure 11. Cross-sections of various clad pumped fiber lasers

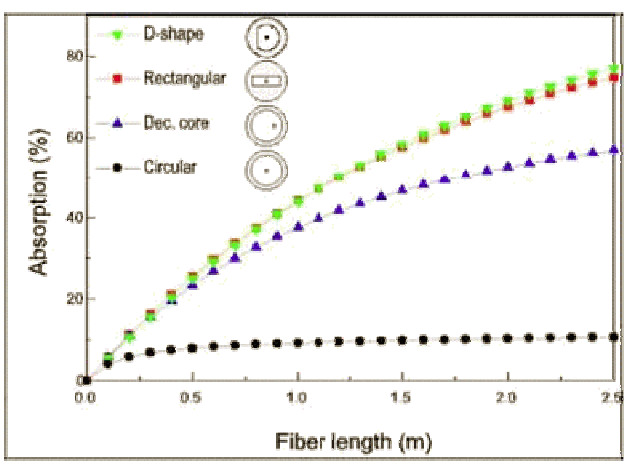

Figure 12. Pump absorption for various clad cross-sections.

In order to investigate the lasing characteristics, we have assembled a clad-pump fiber laser cavity as shown in Fig. 13. Here the cavity was closed with 4 % fresnel reflection at the silica fiber ends. Special care was given to cleave the fiber ends at right angle. Pump laser at 915 nm was firstly coupled to multimode fiber and then the output was further collimated and focused to optical fibers through a pair of dichroic mirrors. The laser output from the fiber end was then fed into an optical spectrum analyzer to investigate the lasing characteristics. The lasing spectrum of the fabricated fiber is shown in Fig.12. Due to broadband low reflectivity in fresnel reflection at the fiber ends, we could observe multiple lasing wavelengths across the gain region of Yb ions.

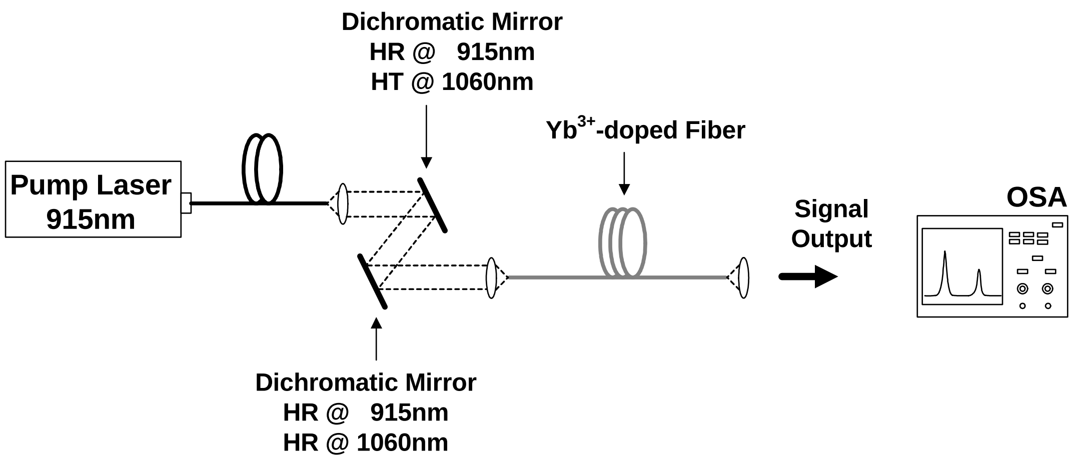

Figure 11. Schematic of clad pumped fiber laser cavity and experimental set-ups

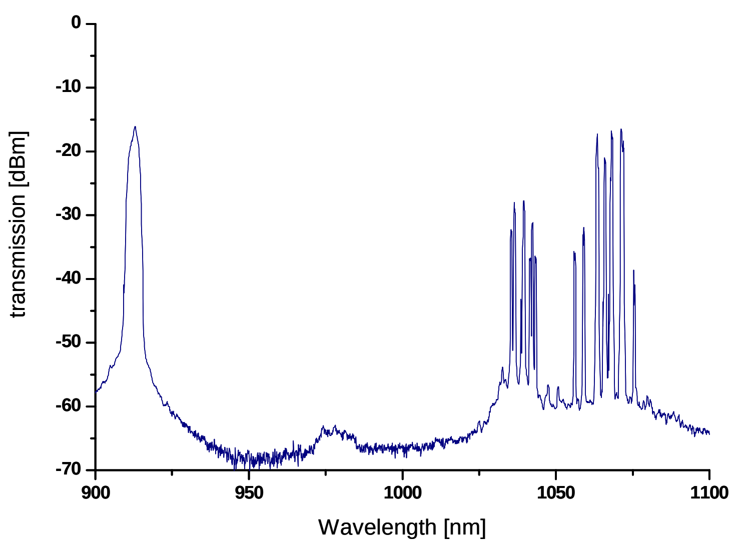

Figure 12 Lasing spectrum of Yb doped circular fiber laser

The peak around 915 is from the pump and multiple lasing lines near 1030, 1060nm were observed

5. Laser Characteristics

Fabricated fibers, as shown in Table 2, were further analyzed for laser characteristic analysis, in terms of Numerical Aperture (N.A.)

Table 3. Fiber Parameters that were used in laser characterization experiments

Fiber No.	Diameter (μm)	Hole diameter(μm)	Core thickness(μm)	NA
Fiber 4	125	10.5	1.9	0.19
Fiber 5	110	9.2	1.7	0.19
Fiber 6	85	7.1	1.3	0.19

In the laser experiments, the set-up was maintained as in Fig. 11, where the laser output coupling was made by 4% Fresnel reflection at the fiber end. The HOFs were spliced at both ends to single mode fiber, whose LP_{11} mode cut-off wavelength was 950nm. This special cut-off shifted fiber was used to ensure single mode guidance of the lasing wavelength. The splice preparation is schematically shown in Fig. 13.

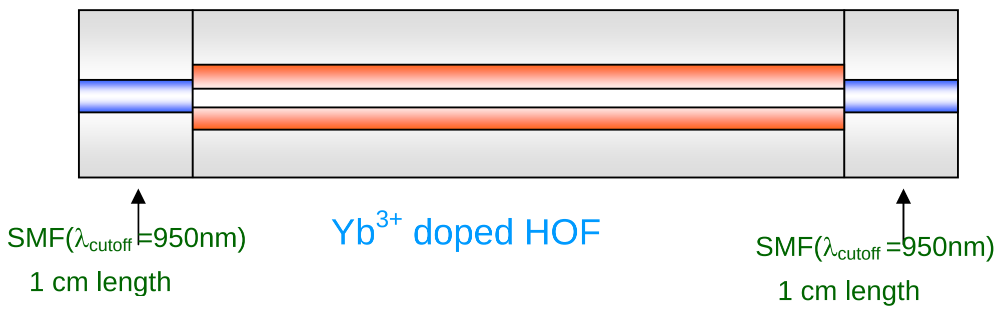

Fig. 13 Schematic diagram of fusion spliced HOF for laser characterization

The laser output power was measured as the 915nm pump power increased. For three types of fibers as shown in Table 3, the fiber lasers showed different lasing behavior in terms of the output power and slope efficiency. The laser characteristics are summarized in Fig. 14 for the three types of HOFs. The HOFs showed more or less similar lasing thresholds, about 1 Watt launched pump power at 915nm. However the output power and slope efficiency was quite different depending the types of HOF. For HOF type 4, the largest hole diameter and thinnest ring thickness, the maximum output laser power was less than 500mW for 8.0 W of pump. The slope efficiency was 8, and 10% in terms of launched and absorbed pump power, respectively.

For HOF type 6, with the smallest hole diameter, the slope efficiency and output power both increase by several folds in comparison to HOF type 4. The output power exceeds 1.5 Watt for 8 Watt of pump at 915nm. The slope efficiency also increases to 25 and 29% in terms of launched and absorbed pump power, respectively.

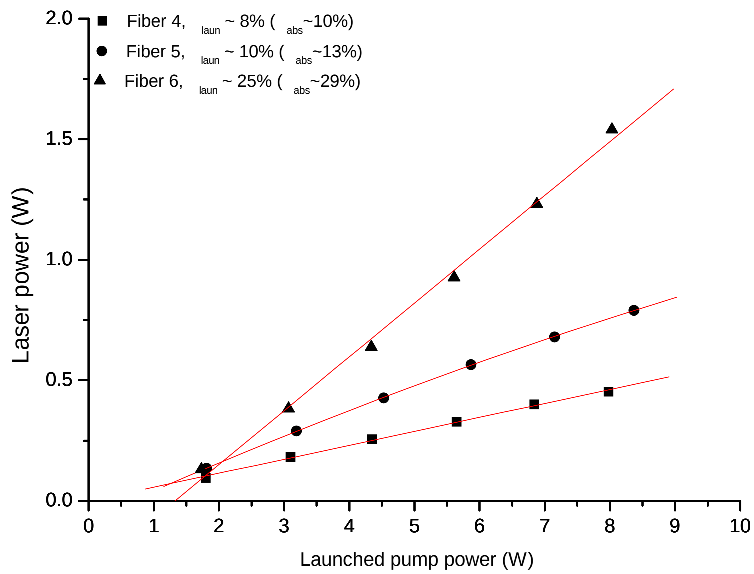

Fig. 14. Comparison of laser characteristics for HOFs

In the case of HOF type 6, the spectrum of laser output was also different from others and the laser output showed multiple lasing lines as shown in Fig. 15. The effects of fiber etalon as in Fig. 13 were attributed to this multi-line lasing.

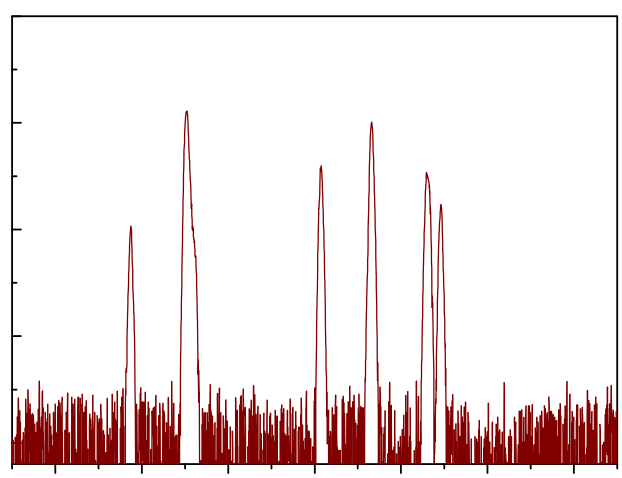

Fig. 15. Spectrum of laser output for HOF type 6, pumped at 2Watt

6. Brillouin Scattering studies,

Brillouin Scattering in optical fiber results from the interaction of acoustic wave and optical wave guided along the optical fiber. The structures of optical fiber does change both acoustic and optical mode propagation properties and resulted in different Brillouin frequencies. In the case of HOF, the central air hole drastically changes the acoustic mode and the dispersion of optical mode such that HOF will have different Brillouin frequency. In this study, we have collaborated with Prof. K. Hotate in the electrical engineering department, the University of Tokyo, in the analysis of Brillouin frequencies for different HOFs.

In order to understand the role of the central air hole, we have prepared three types of HOF with air hole diameter of 2, 4, and 6 μm. The outer diameters were all 125μm and the ring thickness was conformed to match single mode fiber (Corning SM 128), when they were collapsed to the solid core.

The experimental set-up to measure the Brillouin frequency and the gain spectra are shown in Fig. 16

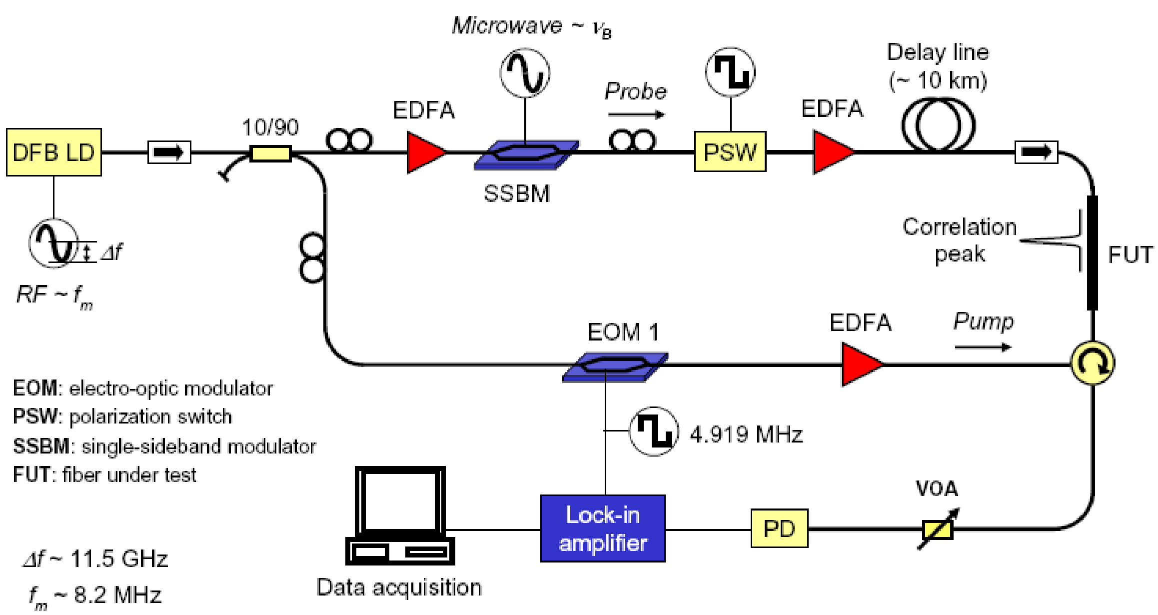

Fig.16. Experimental setup for the Brillouin Optical Correlation Domain Aanlysis system using double lock-in amplifiers and an SSB modulator. PSW: polarization switch.

[K. Song, K. Hotate, IEEE, Photon. Technol. Lett. Vol. 18, 499 (2006)]

The fiber under test (FUT) in Fig. 16 is composed of single mode fiber-HOF-single mode fiber segments as shown in Fig. 17. and the length of HOFs were about 10cm long.

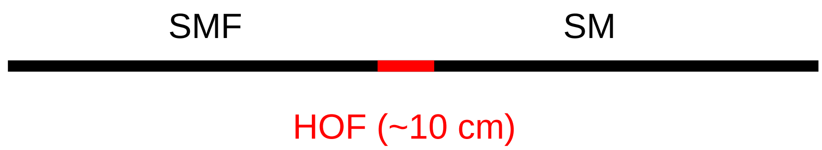

Fig. 17. Fiber uncder test

The Brillouin spectra measured by the system are summarized in Fig. 18. It is noted that as the central air hole diameter increases from 2, to 4, and 6 mm, the peak gain decreases along with blue-shift.

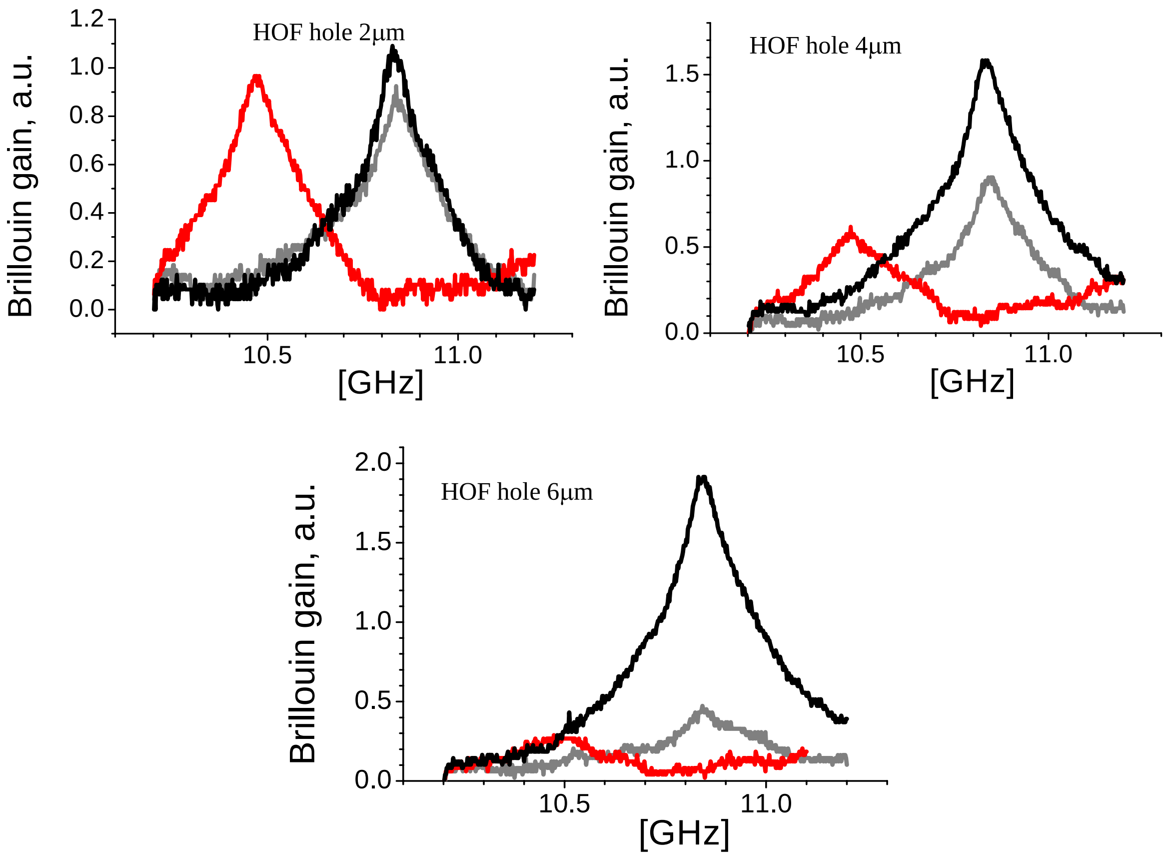

Fig.18. Brillouin gain spectra of HOF. The black line is for conventional single mode fiber (Corning SMF28) and Red line is for HOF. Grey line is normalized SMF referenced to HOF

The results are summarized in Table 4. Here the Brillouin frequency, ν_B , and the peak gain, C_B, of HOFs are compared with those of SMF.

Fiber Types	ν_B	*Normalized* C_B
SMF	~ 10.838 GHz	1
HOF – 2 μm	~ 10.468 GHz	~ 0.96
HOF – 4 μm	~ 10.479 GHz	~ 0.52
HOF – 6 μm	~ 10.495 GHz (+/- 5 MHz)	~ 0.30

7. HOF Optimization

HOF, thus far, has been a three-layered structure, the central air hole, high index ring core, and cladding, as shown in Fig. 1.

This structure, however, showed the cut-off of the fundamental LP_{01} mode cut-off at long wavelength. The cut-off can be blue-shifted when the fiber is bent and can induce additional loss. Especially when the ring core thickness decreases, the cut-off wavelength rapidly shifts below 1.0 μm as shown in Fig. 19, which will significantly reduce the laser performances.

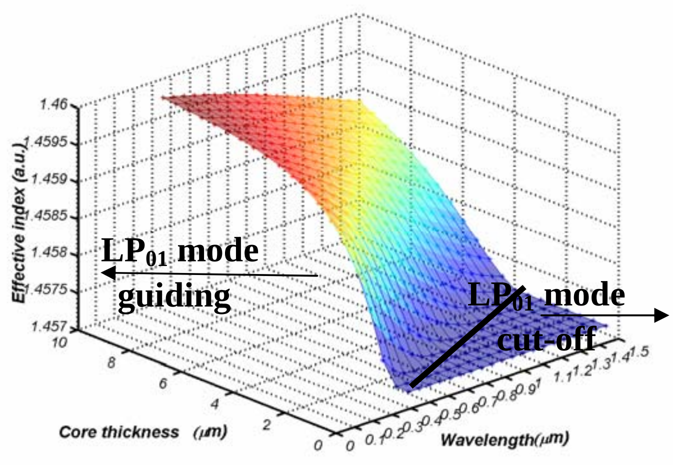

Fig. 19 The correlation of the LP_{01} mode cut-off and the core thickness.

This LP_{01} mode cut-off and bending sensitivity should be improved to sustain laser performances.

It is well-known that depressed inner cladding in single mode fibers can improve the bending performances and effectively control the cut-off wavelength. The depressed inner cladding is introduced in HOF structure as below

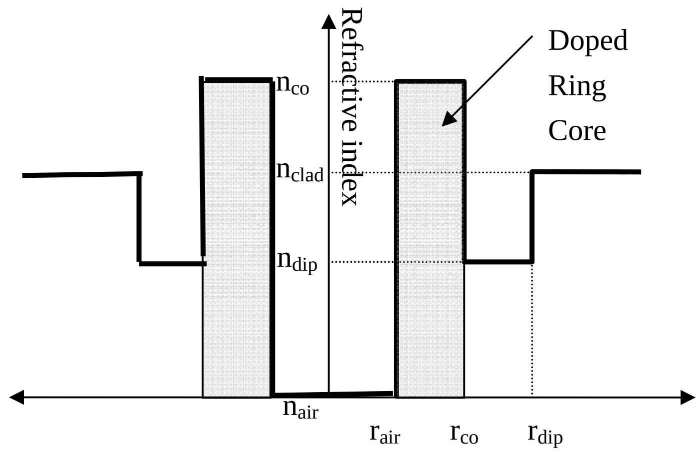

Fig. 20 Depressed inner cladding in HOF

For this structure, the requirement of ring core thickness is significantly relieved such that thicker ring can hold single mode with less bending sensitivity as shown in Fig. 21.

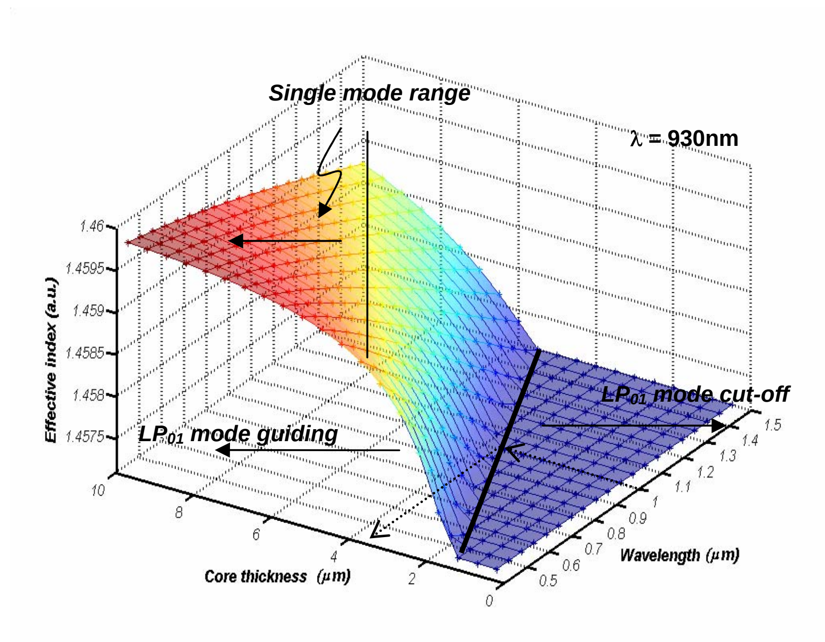

Fig. 21. The correlation of the LP_{01} mode cut-off and the core thickness for depressed inner cladding

Summary

In summary we have achieved the following goals

A. HOF (Hollow Optical Fiber) waveguide design
  - Modal intensity distribution for guided modes along the ring core
  - Dispersion control by HOF waveguide parameters

B. Rare earth doped HOF fabrication
  - Yb doping by solution doping technique along with modified CVD
  - Yb ion concentration estimation and measurements of transmission spectra of fabricated HOF

C. Pumping scheme study and laser cavity assembly
  - End-pumping scheme adopted
  - Fiber laser cavity assembled
  - Lasing performances

D. Laser Characterization
  - Three types of Yb doped fibers employed in fiber lasers
  - Laser threshold, slope efficiency were characterized as a function of hole diameter
  - Multiple lasing was observed in 1.0 μm range

E. Brillouin scattering studies
  - Shift in Brillouin Frequency was observed as a function of hole diameter
  - Decrease in Brillouin gain for larger hole diameters was observed

F. HOF optimization
  - LP_{01} mode cut-off in HOF was analyzed
  - Depressed inner cladding was introduced in HOF and its impact over LP_{01} mode cut-off was analyzed.

G. Related research and publications

S. Kim, Y. Jung, **K. Oh**, J. Kobelke, K. Schuster, J. Kirchhof, “New defect and lattice structure for air silica index guiding holey fiber,” , OSA Optics Letters, accepted for publication, 2005.

D. Lee, Y. Jung, Y. S. Jeong, and **K. Oh**, J, Kobelke, K, Schuster, J. Kirchhoff, “Highly polarization-dependent periodic coupling in mechanically induced long period grating over air-silica fibers,” OSA Optics Letters, accepted for publication, 2005

Y. Kim, Y. Jeong, **K. Oh**, J. Kobelke, K. Schuster, J. Kirchhof, “Multiport NXN multimode air-clad holey fiber coupler for high power combiner and spliiter”, OSA Optics Letters, accepted for publication, 2005

S. Kim, U. C. Paek, and **K. Oh**, “New defect design in index guiding holey fiber for uniform birefringence and negative flat dispersion over a wide spectral range,” OSA Optics Express, vol.13, no.16, pp.6039-6050, Aug.5 2005.