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Hollow Core Antiresonant Fibres for Fibre Laser Applications

HUANG XIAOSHENG

School of Electrical & Electronic Engineering

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in fulfillment of the requirements for the degree of
Doctor of Philosophy

2017

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

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Date

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HUANG XIAOSHENG

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Abstract

Hollow core photonic crystal fibres (HC-PCFs) have promising applications in high power beam delivery, chemical sensing and gas-based nonlinear optics. According to the waveguide mechanisms they based on, HC-PCFs are typically classified into two kinds. One kind guide light via a two dimensional photonic bandgap while the other through anti-resonant reflection. The former one is so-called hollow core photonic bandgap fibres (HC-PBGFs) while the latter is commonly named hollow core anti-resonant fibres (HAFs). Compared to HC-PBGFs, HAFs can have much broader transmission windows and more flexible fibre designs. As a result, HAFs are currently more popular than HC-PBGFs. Hence the topic of this thesis is focused on HAFs.

HAFs have already been demonstrated to have potential on the application of gas filled fibre lasers. As early as 2002, the first demonstration of the Raman scattering emission had been observed with an H_2 filled HAF. During the past decades, a lot of efforts have been devoted into the gas filled HAF lasers. However, so far there is no demonstration of any all HAF based fibre laser because there exist two restrictions. The first restriction is that hollow core fibres are favoured in long wavelength regions where solid core glass fibres suffer high material loss, besides, a small cavity cross section (i.e., fibre core size) is preferred to reduce the lasing threshold. However, the confinement loss of a HAF (i.e., cavity loss) increases fastly when core size gets smaller or wavelength gets longer. The second restriction is there is no hollow core fibre based fibre coupler to build an all hollow core fibre based laser ring cavity. Therefore, the task of this thesis is to get rid of these two restrictions to make our contributions to all HAF based fibre lasers.

Firstly, I develop the hollow core fibre fabrication technique based on our local facilities. Secondly, I design, fabricate, and characterize a HAF which can have relatively low transmission loss in small core and long wavelength conditions. Thirdly, I design, fabricate, and characterize a HAF based fibre coupler whose power splitting ratio is tunable by adjusting the fibre strain. Thirdly, I use the HAF based fibre coupler to build a ring cavity in a fibre laser system, where the tunable feature of the fibre coupler helps to optimize the conversion efficiency. Moreover, the HAF based fibre coupler is experimentally proved to be able to split and deliver the ultra fast laser pulse without degradation.

Acronyms

HC-PCF	hollow core photonic crystal fibre
HC-PBGF	hollow core photonic bandgap fibre
HAF	hollow core antiresonant fibre
HCF	hollow core fibre
TLF	tube lattice fibre
1TLF	tube lattice fibre with one cladding layer
2TLF	tube lattice fibre with two cladding layers
WDM	wavelength division multiplexer
DCAF	dual core antiresonant fibre
SPARROW	stratified planar antiresonant reflecting optical waveguide
KF	kagome fibre
UV	ultra violet
IR	infra red
COFT	center for optical fibre technology
MCVD	modified chemical vapor deposition
VAD	vapor axial deposition
OVD	outside vapor deposition
RMM	reverse mould method
CL	confinement loss
FM	fundamental mode
OSA	optical spectrum analyzer
FOM	figure of merit

ACM1	airy cladding mode inside the first cladding layer
SMF	single mode fibre
FUT	fibre under test
FWHM	full width at half maximum
MMF	multi mode fibre

Contents

Acknowledgements	i
Abstract	iii
Symbols and Acronyms	v
List of Contents	vii
List of Figures	xi
List of Tables	xxi
1 Introduction	1
1.1 History of Conventional Optical Fibre	1
1.2 Development of Hollow Core - Photonic Crystal Fibres (HC-PCFs)	3
1.2.1 Guiding principles of HC-PBGFs	5
1.2.2 Guiding Principles of Hollow Core Antiresonant Fibres (HAFs)	6
1.2.3 Overview of Nano-void Fibre and Bragg Fibre	8
1.2.4 Conclusion	9
1.3 Motivations and Objectives	9
1.3.1 Limitation of 1TLF	9
1.3.2 Lack of Hollow Core Fibre Components	10
1.4 Main Contributions	11
1.5 Outline of the Thesis	11

2	Literature Review	15
2.1	Waveguide mechanism of HAFs	15
2.1.1	Anti-resonant reflection	16
2.1.2	Inhibited coupling effects	20
2.2	Classification of HAFs and Their Properties	21
2.2.1	Kagome fibres	21
2.2.2	One layer tube lattice fibre	23
2.2.3	Other HAFs	24
2.3	Applications of HAFs	25
2.3.1	Light and gas interaction	25
2.3.2	Beam delivery	28
2.4	Conclusion	29
3	Developing a method to fabricate the hollow core fibres	31
3.1	Preform fabrication and post processing	32
3.1.1	Conventional preform fabrication processes	32
3.1.2	Develop a method to fabricate preforms with micro structures	33
3.2	Cane drawing process	38
3.3	Fiber drawing process	40
3.3.1	Principal Processes in fibre Drawing	42
3.3.2	Failed Trials and Introspection	45
3.4	Conclusion	49

4	Novel Fibre Design: Tube Lattice Fibre with Two Cladding Layers	51
4.1	Simulation Tool: Polymode	51
4.2	Fiber Design and Theretical Verification	53
4.2.1	Designed Structure	53
4.2.2	Simulation Structure Simplification	54
4.2.3	Transmission Spectrum of 2TLF	56
4.2.4	Advantage of 2TLF Over KF	57
4.3	Capability of 2TLF for Overcoming Design Contradictions	57
4.3.1	First Contradiction: Low Confinement Loss and Small Core Size	57
4.3.2	Second Contradiction: Low Bending Loss and Low Confine- ment Loss	63
4.4	Conclusion	71
5	Dual Core Antiresonant Fibre	73
5.1	Fiber Coupler Review	73
5.1.1	Solid Core Fibre Based Coupler	74
5.1.2	HC-PBGF Based Dual Core Fibres	75
5.1.3	KF Based Dual Core Fibre	76
5.1.4	Dual Hollow Core Antiresonant Fibre Design	78
5.2	New Dual Core Antiresonant Fibre Design	79
5.2.1	Flexible Design via Stacking	79
5.2.2	Scalability of the Number of Cores	80
5.2.3	Strategy to Realize All Fibre Coupling	81

5.3	DCAF Characterization	82
5.3.1	Antiresonant Spectrum	83
5.3.2	Relationship Between Power Splitting Ratio and DCAF Length	85
5.3.3	Adjustable Power Splitting Ratio	88
5.3.4	Polarization Independent	89
5.3.5	Obsolete DCAF Design	91
5.4	Conclusion	92
6	DCAF Applications	93
6.1	Fiber Laser with DCAF Based Ring Cavity	93
6.1.1	Setup of 1.06 μm Yb-doped Fibre Laser	94
6.1.2	Experiment Results	95
6.2	Ultra-Fast Pulse Delivery and Splitting	99
6.2.1	Experiment Method	99
6.2.2	Experiment Results	100
6.2.3	Theoretical Estimation	102
6.3	Conclusion	105
7	Conclusion and Future Work	107
7.1	Conclusion	107
7.2	Future Work	108
	Appendix	111
	A Numerical Code for Pulse Evolution	111
	B Python Code for TLF Simulation	114
	Author's Publications	119
	Bibliography	121

List of Figures

1.1	(a) Illustration of John Tyndall's experiment to demonstrate the light can propagate via internal reflection. (b) Cited from [1] Bell's photophone.	2
1.2	Left: Peacock feather and its micro-structure captured by SEM (cite from [2]). Right: Butterfly wing and its micro-structure captured by SEM (cite from [3]).	4
1.3	Cited from [4], cross section of (a) a 19 cell hollow core photonic bandgap fibre (b) a 5-layer Kagome fibre (c) a tube lattice fibre (d) a nano-void fibre (e) a Bragg fibre.	5
1.4	(Cited from Ref. [5]) Evolution of the bandgap structure with different air-filling fraction (the air-filling fraction is deduced from $\pi(D/\Lambda)^2/2\sqrt{3}$).	7
2.1	Upper: Schematic of stratified planar anti-resonant reflecting optical waveguide, where $n_2 > n_1$. Lower: Refractive index profile of the model.	17
2.2	Upper: Schematic of 1-layer stratified planar anti-resonant reflecting optical waveguide. Lower: Transmission spectrum.	18
2.3	The illustration used to derive the cutoff wavelength at the high index layers.	19

2.4	Core and silica cladding modes at (a) high transmission bands and (b) low transmission bands. The inset is the zoom in view of the fast oscillating silica cladding mode at high transmission bands.	21
2.5	Cited from [6]. Scanning electron micrograph of the first Kagome fibre, with 15 μm core diameter and 170 μm outer diameter.	22
2.6	Cited from [7]. Shows the Kagome fibre with uniform structure. . . .	23
2.7	Left: cited from [8], 1TLF with touched cladding. Right: cited from [9], 1TLF with separate cladding.	24
2.8	Left: Structure of nested anti-resonant nodeless fibre. Right: cited from [10], YuFei's structure.	25
2.9	Cited from [11] Experiment Layout of the mixed laser cavity.	28
3.1	Schematic of preform fabrication process of MCVD.	34
3.2	Left: a bitmap image. Right: schematic of preform stacking method. . . .	35
3.3	Upper: HSQ 300 tubes with 20 mm diameter; Lower: small rods and capillaries.	36
3.4	(a)Home made preform stacking rig; (b)capillary arrays stacked by the stacking machine.	36
3.5	Graphic user interface of the stacking rig.	37
3.6	Schematic to show the post processing of stacked array.	38
3.7	A real stacked preform at stage 2 which is made to be as round as possible.	39
3.8	Final preform with gas pressure control instruction.	40
3.9	Schematic of the cane-drawing apparatus.	41
3.10	Cross section view of a cane with unique structure.	41
3.11	Micro image of the cane which is selectively sealed with UV glue. . .	42

3.12	Schematic diagram for optical fibre drawing system along with five principal zones. Here V_f and V_d are the preform feed speed and fibre drawing speed, respectively.	43
3.13	Schematic diagram of pressurized coating applicator.	45
3.14	Cross section view of a fabricated hollow core fibre.	46
3.15	A failed trial: gas pressure differential between core and cladding is too small.	47
3.16	A failed trial: gas pressure differential between core and cladding is too significant.	47
3.17	(a) A failed trial: no gas pressure difference between small gaps and cladding capillaries. (b) Both of capillaries and gaps are sealed by UV glue.	48
3.18	(a) Step 1: Pour the UV glue on the end face of the fibre, hence both capillary and gap are sealed, but the glue is not cured. (b) Step 2: Remove the glue in capillary holes with fibres, and cure the glue. (c) Step 3: Pour more glue on the end face than step 1, then cure the glue and cut the cane, make sure the facet is flat.	48
4.1	Inset: Fibre structure simulated in [12], with core radius $R = 15\mu m$, $t = 0.42\mu m$. The Red line shows the confinement loss of this fibre structure simulated by Polymode while blue dots are cited from [12].	52
4.2	(a) Novel fiber design: tube lattice fibre with two cladding layers. (b) Simplified structure of 2TLF for simulation.	54
4.3	Compares the CL of different structures (A to E) within the third transmission band ($2 < F < 3$, normalized frequency F is defined in the manuscript). All the structures have the same core diameter ($10.0\mu m$), capillary size ($14.3\mu m$) and wall thickness ($1.0\mu m$). . . .	55

- 4.4 Simulated CL of a 2TLF at different wavelengths. The fibre has core radius $R = 9.78\mu m$, $t = 1.00\mu m$. Black regions correspond to the high loss regions and red curve shows the CL of low loss regions. . . . 56
- 4.5 Simulated confinement loss of three different structures over several transmission bands. All the fibres have core radius $R = 9.78\mu m$, $t = 1.00\mu m$. Black regions correspond to the high loss regions. IKF denotes the structure of the Kagome fibre preform scale down to the fibre size, without any structural deformation. 58
- 4.6 Microscopic images of the cross-section of (a) 1TLF, with $32.4\mu m$ core diameter, $1.45\mu m$ wall thickness, $20.3\mu m$ capillary hole diameter and $220\mu m$ outer diameter, denoted as Fibre #1; (b) 2TLF, with $31.9\mu m$ core diameter, $1.96\mu m$ wall thickness, $20.9\mu m$ capillary hole diameter and $245\mu m$ outer diameter, denoted as Fibre #2. . . . 59
- 4.7 Microscopic images of a 1TLF, red circles match well with the capillary boundaries. 60
- 4.8 Schematic of the setup used to measure the transmission loss of the fundamental mode, based on the cut-back method. The fibre is first bent to a smaller circle with $d_b = 15cm$, in order to filter out the higher-order modes. P_A is the power at point A, P_B is the power at point B, l is the cut fibre length between point A and B. The fibre loss is then calculated as $\frac{P_B - P_A}{l}$. The inset shows the near field mode image at point B, a pure fundamental mode can be observed. SC400: supercontinuum laser source, L1: microscope objective, TLF: tube lattice fibre, OSA: optical spectrum analyzer. 61

- 4.9 (a) Simulated and measured loss evolution of Fibre #1 over three transmission bands (800 nm to 2100 nm), (b) simulated and measured loss curves of Fibre #2 over three transmission bands (850 nm to 1750 nm), black areas represent the high resonant regions; (c) average loss taken at different transmission bands over D/λ value. In all the figures, blue and red lines show the measured and simulated loss of Fibre #1 respectively, while black and magenta lines show the measured and simulated loss of Fibre #2 respectively. Here, simulated loss represents the CL only while the measured loss represents the total fibre loss including the CL and the fabrication induced loss. 62
- 4.10 Airy cladding mode at first cladding ring (ACM1). 64
- 4.11 (a) Schematic of the setup used to measure the bending loss, SC400: supercontinuum laser source, L1: microscope objective, RS: rotational stage, FA: fibre adapter, SMF: single mode fibre, OSA: optical spectrum analyser; Cross-section image of (b) Fibre #3 with core diameter $D = 32.0\mu m$, capillary hole diameter $d = 19.7\mu m$, $\frac{d}{D} = 0.62$; (c) Fibre #4, core diameter $D = 32.3\mu m$, capillary hole diameter $d = 16.0\mu m$, $\frac{d}{D} = 0.50$. Gaps in the cladding area are denoted with numbers in a yellow font. 65
- 4.12 (a) Schematic of the setup used to measure the bending loss, SC400: supercontinuum laser source, L1: microscope objective, RS: rotational stage, FA: fibre adapter, SMF: single mode fibre, OSA: optical spectrum analyser; Cross-section image of (b) Fibre #3 with core diameter $D = 32.0\mu m$, capillary hole diameter $d = 19.7\mu m$, $\frac{d}{D} = 0.62$; (c) Fibre #4, core diameter $D = 32.3\mu m$, capillary hole diameter $d = 16.0\mu m$, $\frac{d}{D} = 0.50$. Gaps in the cladding area are denoted with numbers in a yellow font. 67

4.13	Bending loss of (a) Fibre #3 and (b) Fibre #4 at 1200 nm ($F=3.5$) when bent to different directions; (c) The relationship between 3dB diameter and gap width (or azimuthal separation of cladding). Blue colors correspond to the Fibre #3 ($\frac{d}{D} = 0.62$) while red colors correspond to the Fibre #4 ($\frac{d}{D} = 0.50$). Dash lines are the average 3dB diameter values.	68
4.14	Shows the schematic to determine the bending direction of the fibre. The red arrow indicate the bending direction.	69
4.15	(a) Simulated confinement loss of the fundamental mode; (b) simulated refractive index of the fundamental mode and airy cladding mode. (c) All the structures have the same core size 32.0 μm and the same wall thickness 1.43 μm . The hole diameter of the cladding capillaries in structure A and C is 20.0 μm while that in structure B and D is 13.14 μm . The airy cladding mode inside the first cladding ring has the closest effective index to the core modes and is shown in the right side of the figure.	70
5.1	Schematic of a 2X2 fibre coupler made by fused tapered method. . . .	74
5.2	Left: Mode pattern of an odd mode. Right: Mode pattern of an even mode.	75
5.3	Cite from [13], scanning electron micrograph of the cross section of a dual core HC-PBGF.	76
5.4	(a) Cite from [14], scanning electron micrograph of the cross section of a polymer dual core KF. (b) Cite from [15], scanning electron micrograph of the cross section of a silica dual core KF.	77
5.5	Cited from [16] (a) The proposed elliptical dual-core HAF structure. (b) The proposed composite circular dual-core HAF structure. . . .	78
5.6	Designed structure of dual hollow core antiresonant fibre coupler, t is capillary wall thickness, g is channel gap width, D is core diameter. .	80

5.7	Three and four air core couplers to represent scalability of the number of cores.	81
5.8	DCAF connection by tapered fibres (a), and asymmetric core fibres (b) and (c).	82
5.9	Alternative DCAF design which has longer core separation distance. .	83
5.10	Cross section view of a fabricated hollow core antiresonant fibre coupler, in which $t = 1.21 \mu m$, $D = 35.2 \mu m$ and $g = 12.5 \mu m$	84
5.11	Schematic of the experiment setup used to measure the transmission spectrum of the fabricated DCAF. Where SC400 is a supercontinuum laser source, M1 and M2 are the reflective mirrors, L1 is a coupling lens, FUT is the DCAF under test, SMF is a single mode fibre, and OSA is an optical spectrum analyzer.	85
5.12	(a) Transmission spectrums at both port C and D of a HAFC with $1.21 \mu m$ wall thickness, demonstrating anti-resonant feature and 50:50 power splitting. (b) Transmission spectrum at port D of DCAFs with different fibre length. In all cases, light is coupled into port A.	86
5.13	Relationship between g/D and coupling length L_c . For all the cases, $D = 35.0 \mu m$, wavelength is $1060 nm$	87
5.14	(a) Shows the calculated and measured value of P_D over longitudinal length z . (b) near field mode images observed at output ports for different coupler lengths.	88
5.15	Schematic of the setup used to apply a longitudinal tension of DCAF.	89
5.16	Shows the relationship between P_D and the longitudinal tension applied to the fibre coupler when incident light is coupled into port A. Fibre coupler length is $40 cm$. Here, the unit of tension is μm because the tension is represented by the stretched length of the fibre coupler.	90
5.17	Schematic of the experiment setup used to measure the power at port C and port D at various polarization direction of incident light. . . .	91

5.18	Cross section of the obsolete structure. Inset: near field mode image.	91
6.1	(a) Setup schematic of the 1.06 μm Yb-doped fibre laser. (b) Setup schematic of the hollow core coupler by free space coupling.	95
6.2	(a) Cited from [17], Yb-doped fibre absorption and emission cross sections. (b) Cited from [18], transmission spectrum of the WDM. . .	96
6.3	(a) Evolution of signal power as launched pump power increases. (b) Output spectrum under 340 mW pump power, and 26 % output coupling ratio.	97
6.4	Plot the output coupling ratio over tension applied on DCAF. The tension is represented by the translation stage travel distance. . . .	98
6.5	Schematic diagram to show the evolution trend of output signal power over output coupling ratio.	99
6.6	Measured output signal power for various output coupling ratio at 1.06 μm . Pump power is 340 mW.	100
6.7	Schematic of experiment setup for femtosecond pulse delivery and splitting. L1 and L2 are focusing lens; FUT is the fibre under test, it can be a DCAF, or a multimode fibre (MMF). The internal structure of the femtosecond laser is illustrated in Fig. 1 in [19].	101
6.8	Measured and fitted pulse at (a) port C, and (b) port D when light is coupled into port A of a 40 cm DCAF. $P_C : P_D = 50 : 50$, where P_C and P_D are the power measured at port C and port D, respectively.	101
6.9	Original pulse from the laser source (blue, 47 fs), the transmitted pulse after propagating through a 40 cm MMF (black, 500 fs) and a 40 cm DCAF (purple and green, 75 fs and 70 fs, respectively). . . .	102
6.10	Transmitted pulse width keeps invariant as power splitting ratio varies.	103
6.11	Simulated and fitted value of effective index of DCAF.	104

6.12 Simulated pulse shape before and after propagating through a 40 cm MMF.	105
6.13 Simulated pulse shape before and after propagating through a 0.4 m DCAF.	106

List of Tables

5.1	Parameters and Simulation Results for Coupling Length Calculation.	85
5.2	Power splitting ratio at 980nm when polarization of incident light varies.	90
6.1	Cavity Loss Measurement.	95
6.2	Dispersion and Nonlinear Length Calculation	103

Chapter 1

Introduction

1.1 History of Conventional Optical Fibre

The recent award of the Nobel Prize in Physics 2009 to Professor Charles Kao underscores the tremendous changes that optical fibre has brought about in modern society. fibre optics has revolutionized the way I receive information and communicate with one another, and it has played a major role in ushering in the information era. Although fibre optics has incontrovertibly changed our life, its history is just around one century.

In 1842, Jean-Daniel Colladon first demonstrated the "light pipe" experiment, in which he used a tube to collect and pipe sunlight to the lecture table. In 1870, the British Royal Society in London, England witnessed a similar demonstration given by natural philosopher, John Tyndall. Tyndall, using a jet of water that flowed from one container to another and a beam of light, demonstrated that light can propagate in a special waveguide and follow a specific path based on internal reflection. The illustration of the experiment is shown in Fig. 1(a). Ten years later, on February 1880, at Bell's laboratory in Washington, D.C, Alexander Graham Bell, together with his assistant Charles Summer Tainter, invented a telecommunication device named photophone, which allowed for the transmission of speech on a beam

Figure 1.1: (a) Illustration of John Tyndall's experiment to demonstrate the light can propagate via internal reflection. (b) Cited from [1] Bell's photophone.

of light. This is an early application of optical communication. The photophone consists of a transmitter and a receiver as shown in Fig. 1(b).

Several decades later, a renewed interest in optical communications was stimulated in the early 1960s with the invention of the laser. The earliest lasers were developed in late 1950s by Gordon Gould, Charles Towns, Arthur Schawlow, and other researchers [20]. A laser patent was first filed by Gordon Gould in April 1959. The invention of the laser stimulated a tremendous research effort into the study of optical components to attain reliable information transfer using a lightwave carrier. In 1961, the propagating modes inside a cylindrical dielectric waveguide were first studied [21] by Elias Snitzer who is thought to be the pioneer of optical fibre. Triggered by Snitzer's work, in 1966, an article titled as "Dielectric-fibre surface waveguides for optical frequencies" is published by Kao and Hochham in which they proposed that optical signals can propagate via dielectric waveguides or optical fibres fabricated from glass to avoid degradation by the atmosphere [22]. Once the optical fibre was proposed, it was regarded as a replacement for coaxial cable and was fast developed.

At beginning, the transmission loss of optical fibre was around 1000 dB/km [22], which was much higher than that of coaxial cable (5-10 dB/km). Within a decade, the optical fibre loss was reduced to below 5 dB/km [23]. Under the efforts of all the researchers, in early 1980s, the record loss of a single mode optical fibre was eventually reduced to 0.2 dB/km at 1.55 μm [24].

A transmission loss around 0.2 dB/km is almost the lowest loss a solid core optical fibre can ever reach due to the limitation of material absorption and Rayleigh scattering. The average loss of Corning ULL SMF-28 [25], one of the most popular commercial fibres for long-haul transmission is 0.17 dB/km. Although the conventional solid core fibres benefit from low transmission loss in near infrared and easy fabrication, they are limited by the solid core propagation, which induce low damage power, high absorption, high dispersion and high non-linearity. To overcome the drawbacks of conventional solid core fibres, hollow core fibres (HCFs) in which light propagates within the air were proposed [26]. The potential benefits of guiding light in air derive from lower nonlinearity, lower Rayleigh scattering and therefore, lower transmission loss compared to conventional solid core fibres.

1.2 Development of Hollow Core - Photonic Crystal Fibres (HC-PCFs)

In a HCF, the light field is confined inside the air core (low index) while the surrounding materials have higher index. Hence in the case of hollow core fibre, the total internal reflection could never occur and all the core modes are leakage modes. Obviously, if the surrounding cladding has no extra structure, the leakage loss of HCF should be extremely high. A special structure of cladding is necessary to reduce the leakage loss of core modes. Scientists then noticed the photonic crystal arrays from the nature. It was found that both butterfly and peacock have colourful feathers because their wings and feathers are composed of many regular photonic crystal arrays (Please, see Fig. 1.2).

Figure 1.2: Left: Peacock feather and its micro-structure captured by SEM (cite from [2]). Right: Butterfly wing and its micro-structure captured by SEM (cite from [3]).

Followed with this observation, in 1987, the conception of photonic bandgap is proposed by Yablonovitch [27] and John [28]. In 1995, the first theoretical demonstration of hollow core photonic crystal fibres (HC-PCFs, these fibres possess an airy core surrounded by a periodic array of holes) [29] is reported by Birks et. al, which is a remarkable milestone in fibre optics, making it possible to propagate light in the air filled hollow core. Thanks to this novel guiding property, HC-PCFs have the potentials of achieving lower Rayleigh scattering, higher damaging threshold and lower nonlinearity compared to conventional solid core fibres [30]. As a result, HC-PCFs have promising applications in areas such as ultrafast / high power laser beam delivery [31–35] , gas laser interaction [36–38] and even chemical sensing [39–41].

According to different waveguide mechanism, HC-PCFs are generally classified into two kinds, hollow core photonic bandgap fibres (HC-PBGFs) and hollow core antiresonant fibres (HAFs). Figure 1.3 present the most popular air core fibre structures.

Figure 1.3: Cited from [4], cross section of (a) a 19 cell hollow core photonic bandgap fibre (b) a 5-layer Kagome fibre (c) a tube lattice fibre (d) a nano-void fibre (e) a Bragg fibre.

1.2.1 Guiding principles of HC-PBGFs

Most HC-PBGFs consist of a honeycomb lattice with a small glass filling region (see Figure 1.3 (a)) and the rest areas are filled with air. One early low loss HC-PBGF was demonstrated by Charlene Smith and colleagues at Corning in 2003 [30]. After more than a decade study, the waveguide mechanism of HC-PBGF has an explanation.

Light confinement in the air-core is a result of anti-resonances of the resonators formed at the apices of the air-silica honeycomb lattice. By controlling the size of the struts that form the resonators, at a certain wavelength region (which is determined by the geometry parameters of the fibre) the cladding supports no cladding mode which has the similar propagation constant to that of the core modes, hence the core modes cannot be coupled into the cladding and will be confined inside the core area [5, 42–45].

An important parameter of a HC-PBGF is the air-filling fraction, it can determine the main properties such as the position and width of bandgap. The relationship of air-filling fraction and the bandgap character has already been studied [5]. Figure 1.4 shows the evolution of the bandgap structure with the increasing of air-filling fraction which is represented by D/Λ , where D corresponds to the hole diameter, Λ corresponds to the pitch (spacing between the air holes). In the figure, K corresponds to the vacuum wave vector and β denotes the wave vector component along the fibre axis. The colours indicate the density of optical states (DOS) of the modes supported by the structure. The DOS values are normalized according to DOS values of silica bulk material [46]. The bandgap depicted in white corresponds to DOS=0. According to Fig. 1.4, as the air-filling fraction increases, the bandgap shifted to higher frequency regions and gets wider and wider.

In the bandgap wavelengths, since the core modes cannot be coupled into the cladding, the confinement loss is negligible. The main factor that contributes to the fibre loss is the surface roughness due to structural distortion as well as frozen in capillary waves [47]. The record measured loss of HC-PBGFs is 1.2 dB/km at $1.62 \mu\text{m}$ [47]. However, HC-PBGFs suffer from narrow transmission bandwidth and single transmission band which limits their applications. For example, to demonstrate the lasing emission of acetylene, a hollow core fibre should have low loss at both $1.53 \mu\text{m}$ (pump light) and $3.12 \mu\text{m}$ (emission), which is impossible if using a HC-PBGF. Hollow core fibres with multiple and broad transmission bands are more competitive, and this calls for another kind of HC-PBGF, i.e., hollow core antiresonant fibres (HAFs).

1.2.2 Guiding Principles of Hollow Core Antiresonant Fibres (HAFs)

Different from HC-PBGF, a HAF doesn't exhibit full bandgaps around the air-line (effective refractive index = 1.0), which means some cladding modes do exist, with similar propagation constants to those of the core modes. Hence, the waveguide

Figure 1.4: (Cited from Ref. [5]) Evolution of the bandgap structure with different air-filling fraction (the air-filling fraction is deduced from $\pi(D/\Lambda)^2/2\sqrt{3}$).

mechanism of a HAF cannot rely on a "bandgap" as a HC-PBGF. Instead, it bases on the combination of both anti-resonance and inhibited coupling (for details please refer to section 2.1) to low density of states cladding modes [9, 48–50], which allows HAFs to have multiple and broad transmission bands. The first HAF, demonstrated in 2002 [6], has Kagome cladding feature (refer to Fig. 1.3 (b)). Limited by the flat core boundary, the fibre has a relative high transmission loss, i.e., 1 dB/m at 1307nm in experiment [6]. By implementing a negative curvature in the core boundary, a fibre loss of HAF with Kagome cladding has been greatly reduced to 0.1db/m level [51].

A Kagome cladding has multiple cladding layers with many vertices. Several years later, it was found that extra cladding layers have no contribution to the fibre per-

formance [52, 53]. Even worse, the vertices in the Kagome cladding can cause extra losses [54]. In order to simplify the structure without compromising performances, a HAF with simplified and modified cladding structure was proposed [9, 50, 55]. The cladding of modified HAF is composed of one layer of tubes, hence is named one layer tube lattice fibre (1TLF, as shown in Fig. 1.3(c)). 1TLF is much more competitive in aspects of cost, robustness, and performance than Kagome fibres and has become the dominant type of HAF. A record fibre loss of 8 dB/km at 750 nm in a 1TLF has been demonstrated which confirms that 1TLF could surpass Kagome fibres [56].

1.2.3 Overview of Nano-void Fibre and Bragg Fibre

There are other kinds of hollow core fibres, such as Nano-void fibre [4] and Bragg fibre [57]. The one shown in figure 1.3(d) is a Nano-void fibre. This fibre provides a strong light confinement within a central subwavelength sized hollow-core, which is a very extinctive feature. Here, the discontinuity in the electric field at the hollow core surface allows the formation of very intense evanescent fields [58], in that the light is confined in and close to the hollow region. Such strong confinement of light in a subwavelength hole, as well as long interaction lengths, are necessary for several applications such as gas light interaction, atomic waveguides [59], and group velocity dispersion control [60].

Bragg fibre was first proposed by Yeh *et al.* in 1970s [57, 61], and later developed by other researchers [62]. The Figure 1.3(e) shows a Bragg optical fibre which comprises of two chalcogenide glass compositions that are arranged in concentric layers [57]. This fibre is able to guide light via a photonic bandgap (similar to the HC-PBGF) over all the possible incident angles (which thus contributes propagation within the air core) with an appropriate choice of the layers' spacing and refractive indices. The drawback of Bragg optical fibre is that its preform is very difficult to make because it needs to deposit many alternating layers.

1.2.4 Conclusion

Although there are many kinds of HCFs, in the scope of this thesis, I will focus on HAF because it exhibits unique features over other HCFs. The record loss of HAF is very low (8 dB/km) which is comparable to that of the HC-PBGF while the transmission bands is much broader [56]. When compared to Nano-void fibre and Bragg optical fibre, HAF can achieve lower loss, broad and multiple transmission bands and is easier to fabricate.

1.3 Motivations and Objectives

Although HAF has seen a drastic progress, its applications are limited in lab demonstrations. Despite its popularity due to broad multiple transmission bands and small overlap between core modes and solid materials (hence less limited by the cladding material absorption), its applications have been hampered by its large core requirement and lack of supporting fibre components. Furthermore, there are only a small number of groups contributing to this important technology. Hence, this thesis is devoted to adding new advances that can address limitation and drawbacks of the HAF.

1.3.1 Limitation of 1TLF

”There are two design contradictions in a 1TLF. The first contradiction is that in a 1TLF, low fibre loss and small fibre core cannot be simultaneously achieved. The loss of 1TLF is limited by the value of D/λ , as D/λ gets smaller, the confinement loss (CL) is quickly increased [49,63], where D is the core diameter, λ is the wavelength. Hence, a large core is a typical feature in the TLF. Although the large core certainly helps to reduce the CL, it can sometimes contradict to other requirements. For instance, a small core can increase pump light intensity and ameliorate high power requirement to overcome a threshold in gas-filled TLF applications. Thus, a small

core TLF without compromising the CL could be a next important step to advance the gas-filled TLF technology.” [64]

”The Second contradiction is between the low bending loss and low transmission loss. With a determined core size, D , a 1TLF with smaller capillary hole size, d , experiences less bending loss. However, in the case of 1TLF, the reduced d increases the confinement loss that counteracts the bending loss improvement.” [64]

If the above contradictions could be addressed, the important properties such as a low fibre loss, a small hollow core and a low bending loss could be realized simultaneously. Then, the fibre design would not be limited by the aforementioned contradictions, hence promising more practical applications.

1.3.2 Lack of Hollow Core Fibre Components

Coherent and incoherent light sources were demonstrated in gas-filled HAFs. These include high efficient Raman emission at 1900 nm from a hydrogen filled HAF and laser at 3120 nm from an acetylene filled HAFs. All these gases can have long shift and are able to generate mid-infrared emission through down-conversion processes. Despite the successful demonstrations, the device design was limited by either single propagation through the gas-filled HAFs or a cavity including bulk optics. Therefore, the system is bulky and fragile, limiting its performance only in a lab.

An approach based on all-fiber structures could be a breakthrough. Currently, there is no available fibre coupler based on a HAF. This is the main motivation of this thesis. In order to realize air core fibre coupler, I set out the objective of this thesis as follows:

- Design, fabricate and characterize a novel hollow core fibre design whose contradicting requirements are lifted.
- New design to ease fabrication processes.
- Develop HAF based fibre coupler and apply them into real applications.

1.4 Main Contributions

The main contributions of the thesis are thus include:

- I proposed a novel design of HAFs, which is a tube lattice fibre with two cladding layers (2TLF). The cladding structure is renewed with solid rods for providing flexibility in design and fabrication.
- I established fabrication methods to produce the hollow core fibres by using our local facilities. The method is based on the stack and draw technique and can also be applied to fabricate the preform of other micro-structured fibres. By definition, micro-structured fibres are optical fibre waveguides where guiding is obtained through manipulation of waveguide structure rather than its index of refraction.
- I both theoretically and experimentally prove that transmission loss of 2TLF is less limited by the value of D/λ as well as the capillary hole size d , hence a 2TLF should have potential in small core applications.
- I designed, fabricated and characterized a dual hollow core anti-resonant fibre (DCAF) which can serve as a variable optical fibre coupler.
- I demonstrated the application of the DCAF as a fibre coupler by building a fibre laser ring cavity, and variable coupling strength by simply applying mechanical strain.

1.5 Outline of the Thesis

Chapter 2 reviews progress of a HAF, including the waveguide mechanism of the HAF (combination of antiresonant effects and inhibited coupling effects), classification of HAFs (Kagome fibres, 1TLF and fibres with Yufei's structure) and practical applications of HAF. Applications are focused on the gas filled fibre lasers that are

closely related to the motivation of this thesis. I have also discussed some open problems or those that still remained to be further studied. The subsequent chapters are focusing on solving these problems.

The following chapters that present the main contributions are divided into three parts: Part I (chapter 3) is on development of hollow core fibre fabrication technique. Part II (chapter 4) is on the hollow core fibre design and characterization to achieve a high figure of merit for gas fibre lasers. Part III (chapter 5 and 6) is on the design, characterization and the application of the DCAF (serve as the adjustable fibre coupler in a laser ring cavity).

In Chapter 3, a method (stack and draw process) to fabricate the designed 2TLF structure is introduced in detail. At first, the design of preform structure is explained. Then the preform with designed structure is stacked and fabricated. The preform is then drawn into canes and finally drawn into fibres. The purpose of two-step fabrication is to reduce the scale down ratio and alleviate structural deformation. The details about preform and cane preprocessing are also introduced in this chapter. Fabrication process to build desirable differential pressure among air core, capillary holes, and capillary gaps has been demonstrated. With the successful pressure building, a fibre with good structure is eventually obtained.

In Chapter 4, a 2TLF fibre design is proposed, fabricated and characterized. 2TLF is both theoretically and experimentally proved to be able to resolve the mentioned contradictions of a 1TLF:

- A 2TLF design benefits from low loss at long wavelength and small core conditions, hence is promising for the applications of fibre laser applications as well as mid-infrared transmission.
- A 2TLF design can achieve low bending loss without sacrificing the CL by enabling small capillary hole diameter requirement as well as separation of the core and the jacketing tube.

In Chapter 5, both solid core fibre coupler and hollow core fibre coupler and their drawbacks are reviewed. Hollow core fibre couplers based on HAF can reserve the advantages of HAFs, i.e., broad transmission band, low dispersion, low nonlinearity, and low absorption loss, however the current design is hard to fabricate. Therefore, the modified DCAF design is proposed, fabricated and characterized. The fabricated DCAF is characterized to have following properties:

- Spectral properties of DCAF are the same as a HAF.
- DCAF is able to work as a 2 x 2 fibre coupler. And all input ports and output ports of the multi-core coupler can be fiberized via tapered fibres or asymmetric core fibres, to fulfil all-fibre coupler with fibre extension.
- Power splitting ratio of the DCAF is variable by applying different tension.
- Performance of the DCAF is polarization independent.

As the DCAF has so many intriguing properties, it should has promising applications. Therefore, several applications of DCAF will be introduced in the next chapter.

In Chapter 6, I demonstrate two promising application of DCAF. The first demonstration is a ytterbium dope fibre laser. In this laser system, the DCAF plays a role as a variable coupler and the variable coupling feature helps to optimize the laser performance. The other demonstration is the application of DCAF in femtosecond pulse delivery as well as splitting. Both experimental results and theoretical analysis support that DCAF is able to deliver femtosecond pulse without significant broadening, which is much better than the solid core fibres.

In Chapter 7, I conclude the thesis and highlight some potential future research directions.

Chapter 2

Literature Review

Hollow core anti-resonant fibre (HAF) is one of the most dominant HC-PCFs. It was first demonstrated in the form of Kagome fibre in 2002 [6]. So far, the waveguide mechanism of HAFs hasn't been clearly studied yet, although quite a part of researchers think it should base on the combination of inhibited coupling between core and cladding modes and the anti-resonant effects [65, 66]. HAFs can achieve relative low transmission loss even at mid-infrared (record loss is 34 dB/km at 3.05 μm [10]) while having multiple and broad transmission windows. Based on these properties, HAFs have many promising applications especially on mid-IR emission generation.

2.1 Waveguide mechanism of HAFs

The waveguide mechanism of the HAFs has already been detailedly discussed in my Ph.D qualification examination report [67]. The contents of section 2.1 are cited from my Ph.D qualification examination report while having some minor revision.

Different from conventional solid core fibres, HAFs cannot guide light via total internal reflection because the air core has a low refractive index. As mentioned, the waveguide mechanism of HAFs is related to both anti-resonant reflection and the

inhibited coupling effects. To study the anti-resonant reflection the Stratified Planar Anti-resonant Reflecting Optical Waveguide (SPARROW) model will be introduced [68]. This SPARROW model can describe and predict the transmission property of the HAFs. However, this model cannot explain why a leaky guided mode can coexist with cladding modes with similar effective refractive index (or propagation constant). This question can be answered by introducing the inhibited coupling effects between core and cladding modes.

2.1.1 Anti-resonant reflection

”Figure 2.1 depicts the geometry of a SPARROW, which is a planar waveguide with a low index (n_1) core surrounded by alternating layers of high (n_2) and low (n_1) indices. The location of the resonances and anti-resonances regions in the transmission spectrum forms the multiple transmission bands and will be taken into consideration to analyze this planar structure. Every high index layer can be regarded as a Fabry-Parot (FP) like resonator. For narrow low index layers ($b \ll d$), they are always anti-resonant because they are too narrow to support any modes by themselves.” [67]

”To understand the principle in a SPARROW waveguide, the schematic of a one layer SPARROW structure is shown in Fig. 2.2. Upper plot illustrates propagation conditions of two different wavelengths. The wavelength which is corresponding to the transmission minimum is named resonant wavelength while the wavelength corresponds to the high transmission band of the spectrum is named anti-resonant wavelength. The ‘resonant’ and ‘anti-resonant’ here are named for high index layers. At resonant wavelengths, high index layers can serve as resonators, modes can propagate in high index layer, and transmission power in core area is minimized. In contrast, high index layers cannot satisfy the resonant condition at anti-resonant wavelengths and most of the light is confined in the core area via reflection (especially for the structure with more high-index layers). The lower plot in Fig. 2.2 shows the transmission spectrum of this waveguide. It can be observed that in the

Figure 2.1: Upper: Schematic of stratified planar anti-resonant reflecting optical waveguide, where $n_2 > n_1$. Lower: Refractive index profile of the model.

anti-resonant region losses still exist because of the imperfect reflections at the low-high index interfaces. Generally, transmission loss of low-order modes is much lower than that of higher-order modes because low-order modes propagate with higher propagation constant (or smaller incident angles).” [67]

”Figure 2.3 shows a simple model for deriving the cutoff wavelength at the high index layers, where k_1 and k_2 are the wave vectors in low index core and high index layer respectively, n_1 and n_2 correspond to the refractive index of low index medium and high index medium respectively, θ_1 and θ_2 are the incident angle and refractive angle respectively, d is the diameter of the low index core and t is the thickness of high index layer. For the geometry considered here, light is launched into the low index core.” [67]

For the lowest order core mode, according to Snell’s law and boundary conditions,

Figure 2.2: Upper: Schematic of 1-layer stratified planar anti-resonant reflecting optical waveguide. Lower: Transmission spectrum.

there is a relationship as:

$$\begin{cases} k_{2x} = k_2 \cos \theta_2 \\ k_2/n_2 = k_1/n_1 = 2\pi/\lambda \\ n_1 \sin \theta_1 = n_2 \sin \theta_2 \\ k_1 d = \pi \end{cases} \quad (2.1)$$

According to Fig. 2.1, the following equation is obtained:

$$k_{2x} = \frac{2\pi}{\lambda} \sqrt{n_2^2 - n_1^2 + \left(\frac{\lambda}{2d}\right)^2}, \quad (2.2)$$

Along with the cut-off condition:

$$k_{2x}t = m\pi, \quad (2.3)$$

Where $m=1, 2, 3\dots$ The cut-off wavelengths are given by:

$$\lambda_m = \frac{2t}{m} \sqrt{n_2^2 - n_1^2 + \left(\frac{\lambda}{2d}\right)^2}, \quad (2.4)$$

When $\lambda/d \ll 1$:

$$\lambda_m = \frac{2t}{m} \sqrt{n_2^2 - n_1^2}, \quad (2.5)$$

"From equation 2.5 it can be known that transmission property of SPARROW is determined by the thickness of high index layer once the materials are fixed. In the case of HAFs, t corresponds to the core wall thickness, equation 2.5 hence can be applied to predict the transmission spectrum of HAFs." [67] Moreover, the transmission condition of Fresnel fibres [69] and Bragg fibres can be deduced from Fresnel equations in a similar way.

Figure 2.3: The illustration used to derive the cutoff wavelength at the high index layers.

2.1.2 Inhibited coupling effects

”While a SPARROW model can accurately predict the optical spectrum of HAFs, it is unable to explain why a leaky core mode can coexist with cladding modes with similar propagation constant. A mechanism analogy to Von Neumann-Winger within a continuum [70] is proposed to answer this question. The core mode of HAFs is a quasi-localized guided mode whose effective index and frequency are within the cladding continuum (which means there exist cladding modes have similar propagation constant to that of the core modes). The main reason that the core mode can propagate in the core is attributed to the high degree of the transverse-field mismatch between the transversely fast-oscillating cladding modes and the slowly-varying air core modes. This transverse-field mismatch then induces the ”inhibited interaction” between the core modes and the silica cladding modes. As a result, core modes can coexist with cladding modes without notable coupling effects.” [67]

”Figure 2.4(a) shows the pattern of core mode and silica cladding mode at high transmission bands (anti-resonant wavelengths). The simulation results are obtained by using the open source software Polymode based on vector wave expansion method [71, 72]. From the simulated mode images, it is implied that the coupling between core mode and cladding modes is quite weak although they have very close propagation constant. These cladding modes exhibit fast phase oscillations and can be regarded as independent waveguide modes restricted in silica cladding because of rapid field decay into the air regions. The inhibited coupling between core and cladding modes is mainly attribute to the phase oscillations of the latter that deviates from resonances which occur near the resonant frequency. Another reason for the weak interaction is the strong transverse-field mismatch between the modes, as indicated by the fast intensity oscillations of the cladding mode (see the inset in Fig. 2.4), which causes the ”washing-out” of the overlap with the slowly varying core-field distribution. Figure 2.4(b) shows the core mode and cladding mode at low transmission bands (high resonant wavelengths). In this low transmission band, the interaction between core mode and cladding modes is no longer inhibited be-

Figure 2.4: Core and silica cladding modes at (a) high transmission bands and (b) low transmission bands. The inset is the zoom in view of the fast oscillating silica cladding mode at high transmission bands.

cause the phase match condition can be satisfied. The confinement loss of the fibre increases as quite a part of core mode energy is coupled into the cladding.” [67]

2.2 Classification of HAFs and Their Properties

The cladding lattice of HAF can be any shape as long as the core wall thickness can satisfy the anti-resonant condition. There are several types of HAFs, they have different features while the waveguide mechanism are the same (which is explained in section 2.1).

2.2.1 Kagome fibres

The first Kagome fibre was demonstrated in 2002 by F. Benabid *et al.*, the structure is shown in figure 2.5 which is cited from [6]. The name ”Kagome fibre” comes from the fact that the fibre has cladding lattices which look like a traditional Japanese woven bamboo pattern named ”Kagome”. The minimum loss of the fibre is around

1 dB/m at 1307 nm. As it's the first demonstration, there is notable distortion on the fibre structure due to the immature fabrication technique, which caused the relatively high loss. After 4 years' development, in 2006, the fabrication technique of Kagome fibre was greatly improved. As is shown in figure 2.6, which is cited from [7], the fibre structure is much uniform than the first Kagome fibre. However, the loss was still in dB/m level even the fibre structure looks good.

Figure 2.5: Cited from [6]. Scanning electron micrograph of the first Kagome fibre, with 15 μm core diameter and 170 μm outer diameter.

Later in 2011, the negative core curvature is found to play an important role in the reduction of fibre loss by enhancing the coupling inhibition between core and cladding modes [51]. By applying a negative core curvature, the fibre loss is reduced to 0.18 dB/m over a transmission bandwidth larger than 200 THz.

In the meantime, the function of multiple cladding layers was also studied in order to simplify the fibre structure. In 2007, a research group from Germany found that only the first two cladding rings play roles in confinement loss reduction through theoretical analyzation [52]. In 2013, another group experimentally proved this [73]. According to this finding, the simplified hollow core anti-resonant fibres, i.e., one layer tube lattice fibre (1TLF) is proposed [74].

Figure 2.6: Cited from [7]. Shows the Kagome fibre with uniform structure.

2.2.2 One layer tube lattice fibre

A 1TLF only has one layer of cladding ring [9, 50, 55, 75, 76]. By simplifying the cladding structure, there are only several capillaries in the cladding, which improves the fabrication efficiency and reduce the cost. At very beginning, the cladding capillaries of 1TLF are touched (as shown in the left of figure 2.7). Then the touching area was found to suffer the extra loss [9]. This extra loss is caused by the Fano resonance [54, 77–79] based on the fact that a round capillary suffers less Fano resonance [54] while the touched capillaries tend to be less round. In HAFs, Fano resonances occur between the core mode and some high order dielectric modes. The dielectric modes involved into the coupling mechanism are strictly related to the number of sides of the polygon which forms the cladding lattice [54]. The cladding capillaries of 1TLF is then designed to be separated in order to keep capillaries round and avoid the extra loss due to Fano resonance, as is shown in the right of figure 2.7.

Since its first demonstration in 2010, a lot of work has been done to optimize the performance of 1TLF. In 2014, it was found theoretically that the bending loss can be greatly reduced by making the capillary size smaller [55]. A reasonable explanation is by doing so, the effective refractive index of the core modes is far away from that of the airy cladding modes, which then weakens the coupling between core and airy cladding modes even the fibre is bent (For more details, please refer to section 4.3.2). In this way, the fibre with small bending loss (0.25 dB/turn) at mid-infrared ($3.35 \mu m$) was demonstrated. In 2016, researchers from Max Planck Institute found that the capillary size of cladding can be adjusted in order to filter out the second order mode, consequently, they demonstrated an endless single mode HAF with the loss less than 0.2 dB/m in the near infrared and a spectral flatness 1 dB over a >110 THz bandwidth [50]. The record transmission loss of 1TLF is 7.7 dB/km at 750 nm which is demonstrated recently in 2017 [56].

Figure 2.7: Left: cited from [8], 1TLF with touched cladding. Right: cited from [9], 1TLF with separate cladding.

2.2.3 Other HAFs

Besides the HAFs I introduced previously, there still are some other HAFs with special structures. The most popular two are the nested anti-resonant nodeless fibre (NANF) and YuFei's structure.

The structure of NANF is illustrated in the left of figure 2.8. Different from the 1TLF, it has a smaller capillary nested inside the outer capillary. The theoretical loss

of NANF can beat the conventional solid core fibre [12, 55, 80], however, so far there is no demonstration can reach the theoretical loss level limited by the immature fabrication technique [80].

Compared to HAFs, the core of YuFei's structure is farer away from the jacket, as is shown in the right of figure 2.8. In this way the confinement loss can be greatly reduced especially in longer wavelength regions. The record loss of YuFei's structure is 34 dB/km at 3050nm.

Figure 2.8: Left: Structure of nested anti-resonant nodeless fibre. Right: cited from [10], YuFei's structure.

2.3 Applications of HAFs

As was briefly mentioned in section 1.1, since the light propagate in the hollow core, HAFs have many promising applications based on this.

2.3.1 Light and gas interaction

The hollow core of HAF can serve as a small gas cavity which can enhance the gas light interaction. And when compared to the HC-PBGFs, the multiple and broad transmission properties of HAFs are more favored. There are two main kinds of applications of gas filled HAF, i.e., gas fibre laser and supercontinuum generation.

Fibre lasers have potential applications in many areas. Thanks to their compactness, good beam qualities, relatively high efficiency and convenient heat management, they can beat conventional gas and solid state laser from some aspects and are gradually replacing these lasers in many applications [81]. Compact mid-IR fibre lasers have attracted a lot of attentions for the reason that they have wide applications in atmosphere monitoring, medicine, security and defence [82–87]. For chemical gas lasers, their power level can reach as high as MW level [81], which is beyond the damage threshold of the solid core fibres. Besides, in glass fibres the spectral linewidth of emission light will broaden at high powers. As the kinds of available rare earth materials are limited, just certain emission wavelengths can be generated by solid core fibre lasers. For solid core fibre lasers, mid-IR laser are usually generated by using erbium doped or holmium doped fibres. To overcome the drawbacks of solid core fibre lasers, gas lasers has been proved to be a good way to generate the mid-IR emission [88–93].

However, the application of these gas lasers are restricted by the short interaction length of the traditional gas cells as well as the bulky and cumbersome systems. The advent of hollow core anti-resonant fibres which has long interaction length, relatively low transmission loss, and the multiple and broad transmission windows make it to be a good cavity for gas fibre lasers, which combines both the advantages of fibre and gas lasers [6, 45].

By simply adjusting the geometry of the HAFs, such as wall thickness and core diameter, fibre gas laser is able to demonstrate the emission from UV to the mid-IR. The spectral width of the fibre gas laser is very narrow due to the nature of transitions in atomic and molecular gases. In 2002, the first emission in H₂-filled HAFs via stimulated Raman scattering was demonstrated [6]. Since then, many emission based on gas filled HAFs have been demonstrated [65, 94–97]. A 1.9 μm emission was obtained by the stimulated vibrational Raman scattering in a hydrogen filled HAF in 2014, the conversion efficiency can reach as high as 48% [94]. So far, the gas fibre lasers introduced are based on the stimulated Raman scattering of gas molecules, there are another type of gas fibre laser based on the population inversion

of gas molecules such C_2H_2 and HCN which are able to generate mid-IR emission efficiently.

The efficiency of the first mid-IR fibre gas laser is only 1%, it is based on the population inversion of the acetylene gas filled in a Kagome fibre [97]. The high loss of the Kagome fibre is responsible for the low conversion efficiency. Later in 2014, as the HAF with negative curvature and 1TLF was proposed, the fibre loss of HAF was greatly reduced, the conversion efficiency is then improved to 30% [98].

However, according to the definition of the laser, all the above works just demonstrated the laser emission, but no resonant inside the cavity. In 2016, for the first time, a mid-IR gas laser using feedback in an optical cavity (a HAF) was demonstrated, the whole system has excellent potential for power scaling [11]. Nonetheless, the realization of the feedback is through the free space which means to make a compact gas fibre laser with feedback system is still not possible. As shown in the Fig. 2.9, because there is no optical fibre coupler that can work at mid-IR, the separation of the output and feedback light path has to rely on a half transmit and half reflect mirror.

From reviewing these works, I also found that the gases used to generate emissions are very active (H_2 , C_2H_2 and HCN), Raman emission in a HAF with gases such as oxygen filled HAFs hasn't been demonstrated yet. The reason is that the Raman threshold of oxygen and nitrogen is quite high. If there is a HAF can have relatively small core (small cavity cross section area) with low optical loss, the Raman threshold can be greatly reduced and it may be possible to observe the Raman emission with an oxygen (or nitrogen) filled HAF. And due to their long distance Raman shift (Oxygen: 1556 cm^{-1} , Nitrogen: 2331 cm^{-1}), both oxygen and nitrogen have potential to generate mid-IR emissions.

HAF is also a favorable cavity for supercontinuum generation because its dispersion curve is tunable by filling different gases and controlling the gas pressure [99, 100]. Enlighten by the work in [101], in which the researchers obtained extremely flat supercontinuum spectrum down to 150nm by launching TW laser pulse into noble

Figure 2.9: Cited from [11] Experiment Layout of the mixed laser cavity.

gases in multiple filaments, Belli *et al.*, generated a supercontinuum in hydrogen filled Kagome fibre, spanning from 124nm to 1200nm, which contains the vacuum ultraviolet, visible light and near-infrared [36].

2.3.2 Beam delivery

Hollow core anti-resonant fibres are considered to be suitable for the beam delivery for industrial laser machining applications and medical lasers.

For micromachining high energy and ultrafast lasers are favoured because their high efficiency and high quality. However, flexible beam delivery systems is hard to achieve which limits the fabrication of precision machinery. The advent of hollow-core antiresonant fibres is good news for micromachining. It may help to address this problem. Unlike conventional solid core fibres, which suffer from non-linear effects and core material damage, the hollow core anti-resonant fibres can get rid of these limitations. The capability of HAFs to deliver the ultrashort pulse from the regime of nanosecond to the sub-femtosecond has already been demonstrated [34,35]. Also, HAFs have been characterized to have good property in damage threshold,

dispersion and bending loss. In 2012, a modified KF with negative core curvature was demonstrated to have the ability to deliver ns pulses with 10mJ energy [31]. And delivery of 10.5 ps pulse with an average power of 5 W (97 μJ) is reported in their recent work [102]. Moreover, recently in 2016, an industrial fibre beam delivery system for ultrafast lasers has been invented based on HAFs [103]. To evaluate its performance, the delivery system has been tested with ultrafast laser beams with different parameters ranging from 3 to 200W average power, 300 fs to 10ps pulse width and 3 to 250 μJ pulse energy. The testing results reveal that the HAF based delivery system has an excellent potential for ultrafast laser delivery.

HAFs also have promising usage in power delivery for surgical applications. For the reason that the water in tissue can strongly absorb the mid-IR light, the Er:YAG laser whose wavelength is 2.94 μm is extensively used. Generally, the articulated arms which are bulky and cumbersome are used in order to precisely deliver the 2.94 μm laser beams and avoid damaging the surrounding tissues. This problem cannot be addressed by using the solid core fibres due to the high material absorption of silica in mid-IR region [104].

2.4 Conclusion

In this chapter, I have reviewed several existing results of HAF, including the waveguide mechanism of the HAF (combination of antiresonant effects and inhibited coupling effects), classification of HAFs (Kagome fibres, 1TLFs and fibres with Yufei's structure) and practical applications of HAF. One of a potential application of HAF is gas filled fibre laser. However, by reviewing the past works on gas fibre lasers I found there are two difficulties to be solved before the gas filled HAF lasers can be extensively used, the difficulties are:

- Lack of hollow core fibre coupler for mid-IR transmission and to make a compact gas fibre laser with feedback system.

- The core of current HAF is large in order to reduce the fibre loss, which makes it impossible to generate Raman emission with gases whose Raman gains are very low (such as oxygen and nitrogen).

The subsequent chapters are focusing on solving the above problems.

Chapter 3

Developing a method to fabricate the hollow core fibres

This chapter is devoted to develop the hollow core fibre fabrication technique. Without an advanced fibre fabrication technique, none fibre design can come true, no matter how superior it is. Thanks to my local facilities in Center for Optical Fibre Technology (COFT), I am able to develop my own fibre fabrication technique.

Since the topic of this thesis is about hollow core antiresonant fibres, I will focus on the fabrication of hollow core fibres (as well as some microstructured fibres which can be fabricated using the same method). The fabrication of HCFs is much more different from the fabrication of solid core fibres.

When drawing a solid core fibre from a preform, the most important two parameters are preform feed speed V_f and capstan drawing speed V_d because of mass conservation. And the longitudinal consistency of the solid core fibre should be good even when the draw down ratio ($D_{preform}/D_{fiber}$) is larger than 100. However, in the case of HAFs, it's much more difficult and complicated to maintain the longitudinal consistency of the fibre. Besides V_f and V_d , other parameters such as surface tension, temperature, glass viscosity and gas pressure difference between core and cladding also play an important role in the process of fibre fabrication, and this has so far

made it impossible to draw a long piece HAF with good longitudinal consistency directly from a preform [105]. Therefore, to make a HAF with good structure and uniformity is a challenging task and requires intensive process improvement from the solid core fibre fabrication techniques.

In this chapter, I divide the whole fabrication process into three separate processes: preform fabrication and postprocessing, cane drawing and fibre drawing.

3.1 Preform fabrication and post processing

The terminology "Preform" is commonly used among optical fibre manufacturers. It is either a glass rod (for conventional solid core fibres) or a tube with micro structures (for microstructured fibres) where the optical fibre is drawn from. A preform is a large scale version of the optical fibre with the same (or similar) waveguide structure as the target fibre. Typical size of a lab preform is in the range of 20 mm to 50 mm and its length is around 1 m. According to mass conservation, tens of kilometers' fibre can be drawn from a preform.

3.1.1 Conventional preform fabrication processes

In this section, I will briefly introduce one of dominant methods of conventional preform fabrication process: modified chemical vapor deposition (MCVD) [106–108]. The fundamental principle of chemical vaporization is controlling the vapor density difference between the desired precursor and the rest to realize highly selective vaporization of a certain precursor, thus to form a high purity material which is preferred by long distance optical transmission (good for loss and dispersion control).

In MCVD, the deposition is governed by the five key steps as illustrated by Fig. 3.1 (different steps are denoted by the numbers in red font).

The first process is vapor delivery. For the precursors which are in the liquid phase at room temperature can be delivered using the bubbler technology together with dry Oxygen.

The second process is chemical reaction of vapor. As the silica tube is heated by a high temperature torch, at a certain high temperature, precursors can have oxidation reaction with oxygen and transform into oxide glass and exist as a form of soot.

The third process is deposition of soot layer. The glasses formed by the reaction of precursor and oxygen are commonly in a size of tens of nanometers [109]. Then these glass particles come together to form a soot particle in the size of 0.1 to 0.5 μm . Finally, these soot particles deposit to form a soot layer due to the thermophoresis [110].

The fourth process is named sintering. After the previous processes, deposition of soot particles will form a silica particle layer on the inner surface of the jacket tube. And the purpose of this sintering process is to make the deposit glass layer optically transparent.

The last step is applying a negative pressure inside the substrate tube while keep heating it, hence the tube will collapse and becomes seal to form a solid rod which becomes a preform.

Besides, MCVD, there are other preform fabrication processes such as plasma chemical vapor deposition (PCVD) [111], vapor axial deposition (VAD) [112] and outside vapor deposition (OVD) [113–115]. Although these fabrication processes have different deposition mechanism and consolidation method, their fundamental principles are quite the same, i.e., first deliver high purity precursor vapor into a substrate tube (or rod), and then form the target glass layer by oxidation reaction and deposition. However, these conventional fabrication processes cannot be applied to fabricate a preform with micro structures.

3.1.2 Develop a method to fabricate preforms with micro structures

Similar to conventional fibre fabrication process, fabrication of microstructured fibres also relies on a preform. By the means of "stacking", I can manage to have a

Figure 3.1: Schematic of preform fabrication process of MCVD.

preform with the desired structure. The preform stacking is analogy to the imaging. In a bitmap image, pixel is the basic unit, by arranging the brightness of all the pixels, it forms an object with specific meaning. Similarly, by selectively placing different capillaries (rods or even vacant) at different position, I can eventually stack a preform with any structures. The schematic is shown in Fig. 3.2. In fact, a stack and draw process has already been applied in the fabrication of microstructured fibres silica [116,117]. However, the details of this technique have been kept confidentially and hence I have to develop my own facilities and techniques.

The whole preform fabrication process is divided into three steps.

3.1.2.1 Preparation of Capillaries and rods

As the fundamental unit in preform stacking process, capillaries (rods) commonly have a diameter in the range of 0.3 - 3 mm and with 1 m length. They are drawn from the commercial tubes/rods with larger size (10 - 40 mm, see Fig. 3.3) by using an optical fibre drawing tower (for details, please refer to section 3.2).

For rod drawing, according to mass conservation, the size can be accurately controlled by simply set the ratio between drawing speed V_d and feed speed V_f . For

Figure 3.2: Left: a bitmap image. Right: schematic of preform stacking method.

capillary drawing, the air filling ratio should be taken into consideration. By controlling the drawing temperature and inner tube gas pressure, the air fill fraction (area of air over area of the capillary) can be controlled, and hence the capillary thickness. The wall thickness of these capillaries cannot be either too thick or too thin, usually, the ratio of inner capillary diameter over outer capillary diameter is in the range of 0.8-0.95. In the case of thick capillary walls, the transmission window of the fibre will be narrow while the capillary with thin glass wall is fragile and too sensitive to the gas pressure difference.

3.1.2.2 Capillary/rod stacking

It's time-consuming, inefficient, and inaccurate to stack hundreds of capillaries/rods to form a certain structure by manual. Besides, capillaries/rods are easily get polluted during this manual process. To avoid these drawbacks of manual stacking, a preform stacking rig which can semi-automatically stack the capillaries is designed and fabricated. A picture of the preform stacking rig is shown in Fig. 3.4 (a).

The operation panel of the stacking rig is shown in Fig. 3.5 which is coded based on the Visual Basic language. The movement of the motor will adjust automatically

Figure 3.3: Upper: HSQ 300 tubes with 20 *mm* diameter; Lower: small rods and capillaries.

Figure 3.4: (a) Home made preform stacking rig; (b) capillary arrays stacked by the stacking machine.

Figure 3.5: Graphic user interface of the stacking rig.

according to the capillary diameter, hence the capillary can be aligned to the correct position. By clicking the button "Drop" and "Next", capillary is released and drops on the target position, and then the motor will go to the next position automatically. Figure 3.4 (b) shows a microstructured array stacked by the stacking machine. The stacking rig is just semi-automatic because I have to load the capillaries onto the hook manually. Even so, it has already greatly sped up the stacking process. It just takes around 1 hour to stack a preform with 150 capillaries.

3.1.2.3 Post processing of stacked array

As indicated by Fig. 3.5, the outer shape of the stacked array is a hexagon. There are a lot of work remain to do before obtaining a final preform with round shape. The whole post processing process is depicted in Fig. 3.6. An array directly stacked by the stacking rig is denoted as stage 1 whose outer boundary is a hexagon. To

Figure 3.6: Schematic to show the post processing of stacked array.

make it as round as possible, I need to remove some capillaries, then it becomes stage 2 (can also refer to Fig. 3.7). Now I can insert the capillary array into a jacket tube, as the array is made to be as round as possible, the gap area between the array and the jacket tube is small and hence the capillaries will not slip off, this comes into stage 3. To make it more stable, rods with smaller sizes are used to fill and minimize the gap area, and now it can be called a "preform".

3.2 Cane drawing process

Different from conventional fibre drawing process, in which a preform is directly drawn into fibre, the drawing process of fibres with micro structures are usually separated into two steps in order not to deform the micro structures. At first several

Figure 3.7: A real stacked preform at stage 2 which is made to be as round as possible.

canes with size in the range of 2.0-4.0 mm will be drawn from a preform, then use these canes to draw fibres with several hundred microns diameter. As a result, the drawing down ratio at each step is just around 10.

Figure 3.8 shows the final preform for cane drawing. The end of the preform is fused to collapse while one side of the preform has a small gap prepared by the glass cutting saw. During the cane drawing process, the gas inside the hollow core area can go out through the crack because there are inter-spaces between the capillaries while the gas inside the capillaries is unable to get out since the end of preform has been fused. This leads to the positive differential pressure between cladding and core area and the positive differential pressure makes it possible not just to counterbalance the effect of surface tension but also to achieve substantial expansion of the holey region, which is helpful to reduce the fibre core size and avoid the shrinking of capillaries.

Schematic of cane drawing process is illustrated in Fig. 3.9. The preform is controlled by a precision feed machine and is accurately fed into a circular heater called

Figure 3.8: Final preform with gas pressure control instruction.

the drawing furnace. Inside the drawing furnace, the preform end is heated and softened to the point where it can be drawn into a thinner preform, which is named as "cane".

To draw the cane with desired geometry parameters, preform feed speed, cane drawing speed, furnace temperature and cane puller tension should be correctly set. Furnace temperature and feed speed influence the softness of the preform and hence influence the tension and change the sensitivity to gas pressure differential. Increasing the temperature and slowing down the feed speed can increase the softness of the preform.

A cane of a hollow core fibre with unique structure is drawn in COFT. As shown in Fig. 3.10, the cane has a diameter around 2.5mm and is quite symmetrical.

As the cane drawing process is very similar to (but simpler than) the fibre drawing process, the details about the apparatus and the drawing parameter control will be introduced in next section which describes the fiber drawing process.

3.3 Fiber drawing process

For a cane in Fig. 3.10, there are a lot of hollow areas which make the whole structure very sensitive to the gas pressure. Such a cane needs to be preprocessed before drawing into the fibre. During the fibre drawing stage (draw cane into fibre), the gas pressure difference between core area and the cladding capillaries is necessary

Figure 3.9: Schematic of the cane-drawing apparatus.

Figure 3.10: Cross section view of a cane with unique structure.

Figure 3.11: Micro image of the cane which is selectively sealed with UV glue.

in order to maintain the structure, otherwise the cladding capillaries will shrink due to the surface tension. For this purpose, I blocked the capillaries by using UV glues while keep the core area unblocked (as shown in Fig. 3.11). As a result, once I apply the vacuum to the core area, there exist the positive pressure difference between capillary holes and the core area which then helps to maintain the structure. By increasing the pressure difference the separation between the cladding parts will get smaller. The small separation between the cladding parts is desired in order to reduce the transmission loss (for details, please refer to section 2.2.2).

Now the cane is ready for fibre drawing. In this section, I will focus on introducing my local fibre drawing facility and fibre drawing technique in terms of its principal constitutive processes.

3.3.1 Principal Processes in fibre Drawing

Our actual fibre drawing setup is composed of functionally different devices and instruments such as a precision feed motor, high temperature furnace, fibre thickness monitor, gas pressure controlling system, coating applicator together with coating bath, UV curing lamp, draw tension gauge, drawing capstan and take-up bobbin in

Figure 3.12: Schematic diagram for optical fibre drawing system along with five principal zones. Here V_f and V_d are the preform feed speed and fibre drawing speed, respectively.

an 10-meter-high mechanically stable tower. The main processes in fibre drawing can be classified into five major zones, which are: gas zone, heating zone, aligning zone, coating zone, and collecting zone, as shown in Fig. 3.12.

The gas zone includes three gas channels. One of the gas channel is used to control the cane gas pressure with argon. Users can manually set the volume of gas (cc/min), and by controlling the leakage valve in the pipeline, the pressure in the cane can be controlled accordingly. As many reactions will occur at high temperature, another argon channel is connected to the fibre drawing furnace to purge the furnace and keep it clean. The gas channel supplies nitrogen is connected to coating die to push the coating out. Moreover, there is also a compressed air channel used to drive the tension gauge which is not shown in the figure.

The heating zone is composed of a high temperature furnace (maximum value is 2500 °C) and a precision temperature controller with a resolution as precise as 0.5 °C. Usually, the temperature set to soften the solid preform to form a drop down shape is 2100 °C (and 2060 °C for a tube). And the process temperature (a temperature under which the fibre is stable drawn with proper tension) is a bit lower than the drop down temperature. From a drop down position, preform is tapered to a smaller size, and bare glass fibre is continuously drawn down. It takes 20 minutes for the furnace to warm up from room temperature to drop down temperature.

The major device in the aligning zone is a thickness monitor. It can not only measure the size of the drawn fibre, but also can be used to monitor whether the fibre is at the center or not. If the fibre is not at the center, I need to adjust it to the center with motors in horizontal plane, otherwise many problems will occur such uneven heating and uneven coating.

The coating zone is used to jacket the bare glass fibre with soft coating materials. Although pristine glass fibre has a very high strength, around $70,000 \text{ kg/cm}^2$ [109], it is easily broken due to surface damage when a bare fibre comes in contact with other objects. Hence, to surround a coating material on a bare glass fibre is imperative to protect its outer surface. There are mainly two kinds of coatings in my system for specific applications, which are low index coating and high index coating. The coatings are stored in a warm coating bath (above 30 °C) in order to increase the fluidity. The specifics of coating mechanics is shown in Fig. 3.13. As introduced previously, nitrogen is used to apply the pressure to push coating into the coating die. The die radius R_d is selective to determine the coated fibre radius R . The relationship among die radius R_d , coated fibre radius R , and bare fibre radius r is represented by the following equation:

$$R = (r + R_d)/2$$

The coated fibre is then go through a UV lamp and the coating attached on the fibre gets cured. The collecting zone is composed of a take-up capstan, a rotational

Figure 3.13: Schematic diagram of pressurized coating applicator.

winder with a bobbin and several pulleys. The capstan provides the force to pull down the fibre.

By controlling the differential gas pressure between the core and cladding, a 2 layers tube lattice fibre (a modified HAF, which will be introduced in Chapter 4) with good and symmetric structure is eventually obtained (as shown in Fig. 3.14).

3.3.2 Failed Trials and Introspection

As mentioned before, gas pressure differential is one of the most important parameters in fibre fabrication process. It is necessary to apply an accurate and stable gas pressure differential between core and cladding area to obtain a uniform fibre structure (as shown in Fig. 3.14). I learn to control this pressure differential in an empirical way. In fact, I have failed a lot of times before successfully controlling the gas pressure. I have encountered various problems which are enumerated below:

Figure 3.14: Cross section view of a fabricated hollow core fibre.

1. If the gas pressure inside the cladding capillaries is too small, hollow core area in the fibre will inflate and gaps between split claddings will get too wide (as shown in Fig. 3.15). In such fibres, the contents of higher order modes should be mighty high due to the large core size and wide gaps.
2. If the gas pressure inside the cladding capillaries is too big, hollow core area in the fibre will collapse and gaps between split claddings will disappear. As the cladding capillaries touch with each other, the fibre will suffer extra loss caused by Fano resonance. Besides, the comparable core size and cladding capillary size can induce the strong coupling between core and the capillary holes and reduce the fundamental mode content (see Fig. 3.16).
3. By properly controlling the gas pressure, the fibre structure in Fig. 3.17(a) seems to be much better than those in Fig. 3.15 and Fig. 3.16. However, the shape of cladding capillary is not round because the pressure in gaps (as pointed out by red arrow in Fig. 3.17(a)) is the same as that in the capillaries (in other words, there is no pressure difference between capillary and the gaps). The sealing scenario as shown in Fig. 3.17(b) accounts for this, in which both capillary holes and gaps are sealed by UV glue.

Figure 3.15: A failed trial: gas pressure differential between core and cladding is too small.

Figure 3.16: A failed trial: gas pressure differential between core and cladding is too significant.

Figure 3.17: (a) A failed trial: no gas pressure difference between small gaps and cladding capillaries. (b) Both of capillaries and gaps are sealed by UV glue.

However, it is not easy to seal the capillaries while keeping the gaps between them unblocked. Here, I achieve this via an approach I call it "reverse mould method" (RMM). The schematic of RMM is illustrated in Fig. 3.18. Eventually, the fibre as shown in Fig. 3.14 has been fabricated.

Figure 3.18: (a) Step 1: Pour the UV glue on the end face of the fibre, hence both capillary and gap are sealed, but the glue is not cured. (b) Step 2: Remove the glue in capillary holes with fibres, and cure the glue. (c) Step 3: Pour more glue on the end face than step 1, then cure the glue and cut the cane, make sure the facet is flat.

3.4 Conclusion

In this chapter, a method (stack and draw process) to fabricate the designed 2TLF structure is introduced in detail. At first, the design of preform structure is explained. Then the preform with designed structure is stacked and fabricated. The preform is then drawn into canes and finally drawn into fibres. The purpose of two-step fabrication is to reduce the scale down ratio and alleviate structural deformation. The details about preform and cane preprocessing are also introduced in this chapter. Fabrication process to build desirable differential pressure among air core, capillary holes, and capillary gaps has been demonstrated. With the successful pressure building, a fibre with good structure is eventually obtained. However, the fabrication induced losses do exist. A combination of viscosity of material along with surface tension and thermal instability during drawing can lead to undulating ripples in the capillary surface and these apparently give rise to the fibre loss which is discussed in section 4.3.1.

Chapter 4

Novel Fibre Design: Tube Lattice Fibre with Two Cladding Layers

As stated in section 1.3.1, there are two unsolved contradictions with current HAFs. The first contradiction is that shrinking the core size can induce the fast increasing of confinement loss. The other contradiction is that the low bending loss and low confinement loss cannot be achieved simultaneously. Nonetheless, in fibre laser applications, the hollow core fibre that serves as a laser cavity should have properties of small cavity cross section (or small effective mode area), small confinement loss, and small bending loss. Hence, for current 1TLF design, it is hard to optimize the structural parameters to optimize the fibre laser performance since there are contradictions between small fibre core & low confinement loss and low bending loss & low confinement loss. In this chapter, a novel fibre design: tube lattice fibre with two cladding layers (2TLF) specialized for fibre laser applications is proposed to solve the existing contradictions.

4.1 Simulation Tool: Polymode

Simulation works are necessary to theoretically verify the feasibility of the new fibre design. All the simulation results in this chapter are obtained with a free open source

software named Polymode based on the wave vector expansion method [72] and is compiled in python language [48, 71, 118]. Before proceeding to the fibre design, the accuracy and reliability of the Polymode should be examined first.

For Polymode, simulation parameters should be carefully determined as they can greatly influence the final results. To verify the accuracy of the software as well as the simulation settings, I used Polymode to simulate a HAF in a published literature. Comparison between the simulated CL in the literature (simulated by Comsol) and my simulation result (by using Polymode) is shown in Fig 3.2. My simulation results (red line) can reproduce CL (blue dots) of a 1TLF (Inset in Fig: 3.2) within 10% discrepancy at maximum.

It can be noticed that there exists a slight horizontal shift between red line and blue dots and this is ascribed to the mesh setting in Polymode. To speed up the simulation process, the resolution of the mesh cannot be set too high. This then influences the accuracy of wall thickness recognition. According to equation 2.5, the variation of wall thickness can induce the shift on transmission spectrum.

Figure 4.1: Inset: Fibre structure simulated in [12], with core radius $R = 15\mu m$, $t = 0.42\mu m$. The Red line shows the confinement loss of this fibre structure simulated by Polymode while blue dots are cited from [12].

4.2 Fiber Design and Theretical Verification

4.2.1 Designed Structure

As introduced previously, KF and 1TLF are two main kinds of HAFs. Although these fibres are popular, they both have some limitations respectively (refer to section 2.2). KF benefits from efficient fabrication, easy structure control and uniform structure along its length. But there are many vertices in KF's cladding which introduces Fano-resonance loss [54]. Moreover, the cladding lattice of KF is in hexagonal shape, which is reported to suffer higher loss than the ones with round cladding shape [119]. As for 1TLF, by simplifying the cladding to only one layer, the surface tension between cladding layers is eliminated. However, the CL of 1TLF is very sensitive to the cladding capillary size, transmission wavelength and core size. To have relatively low CL, usually, large cladding capillary size, a large D/λ value is preferred.

Aiming to overcome the forementioned limitations of KF and 1TLF, the modified fibre design should have following features:

1. Fewer vertices in the cladding in order to reduce the Fano-resonance loss.
2. Round cladding lattice.
3. Multiple layers, hence less limited by the cladding capillary size, application wavelength and core size.
4. Negative curvature core cladding boundary to enhance the inhibited coupling effects.

A 2TLF structure as shown in Fig. 4.2 (a) is finally determined to satisfy the above requirements. In the designed structure, the gap **2** between cladding capillaries **3** and jacket tube **4** is filled with solid rods. The rod filled area well supports the capillary cladding **3**, and reduce fabrication burden as compared to capillary layers.

In next subsection, it will be proved that this rod filled area almost has no influence on the light confinement, i.e., the area **2** can be regarded as a part of the jacket, and thus, a simplified structure is proposed for simulation. (see Fig.4.2 (b))

Figure 4.2: (a)Novel fiber design: tube lattice fibre with two cladding layers.(b)Simplified structure of 2TLF for simulation.

4.2.2 Simulation Structure Simplification

The designed fibres feature a peculiar structure of rods supporting the tubes (structure A in Fig. 4.3), which form an air-core area with antiresonant walls. However, articulating the structure in full becomes very heavy for simulation and attempt to simply the structure to structure D in Fig.4.3 for simulations in this chapter. We prove that the structure of rods (with small holes in-between) does not influence the airy modes and hence can be overlooked. Moreover, a small change on the inner jacket shape just slightly influences the simulation result. Eventually, we find that the performance discrepancy between structure A and structure D is acceptable.

Figure 4.3 presents a calculated confinement loss (CL) from structure A to structure D, with progressive simplification of the cladding structure. As shown, the performance of structures A, B and C are nearly the same. The structure D marks a bit

lower CL because the contacting area between the jacketing tube and the capillary holes is reduced from structure C to D. The reduced contact area helps to suppress the CL.

Figure 4.3: Compares the CL of different structures (A to E) within the third transmission band ($2 < F < 3$, normalized frequency F is defined in the manuscript). All the structures have the same core diameter ($10.0 \mu\text{m}$), capillary size ($14.3 \mu\text{m}$) and wall thickness ($1.0 \mu\text{m}$).

I further confirm this with the structure E where the touching area becomes larger. As expected, the CL of structure E is the highest while structure D offers the lowest CL thanks to the minimum touching area. As the CL discrepancy between structure A and D is marginal (within 25%), it's better to use structure D for simulation instead of A. And the designed 2TLF as shown in Fig.4.2(a) can be simplified to a structure as shown in Fig. 4.2(b) for the same reason.

4.2.3 Transmission Spectrum of 2TLF

Now that we have the reliable simulation tool, Polymode, as well as a simplified fibre structure for simulation, we are ready to do simulation works to test the properties of 2TLF before going ahead to fabrication.

As expect, 2TLF is a kind of HAF and its transmission spectrum should comply with the antiresonant mechanism (refer to section 2.1). The antiresonant feature is observed with the simulated spectrum of 2TLF. As shown in Fig. 4.4, black areas correspond to the high resonant regions (regions close to the resonant wavelength which can be calculated from equation 2.5). Between every two adjacent high resonant regions, there exists a low loss region whose confinement losses are plotted as red curve.

Figure 4.4: Simulated CL of a 2TLF at different wavelengths. The fibre has core radius $R = 9.78\mu\text{m}$, $t = 1.00\mu\text{m}$. Black regions correspond to the high loss regions and red curve shows the CL of low loss regions.

4.2.4 Advantage of 2TLF Over KF

Figure 4.5 shows the simulated transmission spectra of the different structures. All the fibres have the same silica wall thickness ($t = 1\mu m$) and core radius ($R = 9.78\mu m$). The local peak losses observed in the transmission windows in Fig. 4.5 are caused by coupling between the cladding mode and the fundamental mode [55]. The results show that the 2TLF can mark the same CL as the IKF that is the ideal form of KF when ignoring the structural deformation by surface tension during fibre drawing. Moreover, the transmission windows of 2TLF are broader. When taking the effect of the surface tension during the drawing process into consideration, the KF will better represent the realistic structures. It is indicated by Fig. 4.5 that the IKF shows better performance than the KF with obvious decrease in the CL. The transition from the IKF to the KF is accompanied with transforming round cladding walls to flat surfaces, hence including a large number of vertices. The vertices enhance Fano resonances between core and cladding modes and increase the transmission loss. As a result, the confinement loss of 2TLF is nearly one magnitude lower than that of the KF as implied in Fig. 4.5.

Besides the above simulation works, I also studied the relationship between confinement loss, bending loss and fibre core size by simulation, which is discussed in next section together with the experiment results.

4.3 Capability of 2TLF for Overcoming Design Contradictions

4.3.1 First Contradiction: Low Confinement Loss and Small Core Size

Based on the fibre fabrication technique introduced in chapter 3, two tube lattice fibres, a 1TLF and a 2TLF, are eventually fabricated and compared to demonstrate the role of the second cladding ring and explore the superiority of 2TLF over 1TLF.

Figure 4.5: Simulated confinement loss of three different structures over several transmission bands. All the fibres have core radius $R = 9.78\mu m$, $t = 1.00\mu m$. Black regions correspond to the high loss regions. IKF denotes the structure of the Kagome fibre preform scale down to the fibre size, without any structural deformation.

Figure 4.6 depicts the fabricated fibres. A 1TLF has a $32.4\mu m$ core diameter, a $1.45\mu m$ wall thickness and a $20.3\mu m$ capillary hole size is denoted as Fibre #1. A 2TLF has a $31.9\mu m$ core diameter, a $20.9\mu m$ capillary hole size and a $1.96\mu m$ wall thickness is denoted as Fibre #2 as shown in Fig. 5.1(b). The two fibres are made into the same core size in order to have a fair performance comparison.

The fibres are in good uniform structure although there still exists slight fabrication related deformation. However, the slight deformation does not interrupt our main conclusions. I provide our observation to confirm that all the capillaries are nearly round. This is supported by Fig. 4.7, in which the red circles match well with the capillary boundaries. It is true that the distances between the tubes forming the negative curvature are not the same as presented in Fig. 4.6. This fabrication limit has been taken into account in the discussion as in Fig. 4.13 The author also would like to note that such fabrication limit does not stop comparison with theoretical results as done in e.g. ref. [50].

The transmission loss of the fundamental mode (FM) of the fibres is then measured by conventional cutback method [120]. Figure 4.8 illustrates the measurement setup

Figure 4.6: Microscopic images of the cross-section of (a) 1TLF, with $32.4 \mu\text{m}$ core diameter, $1.45 \mu\text{m}$ wall thickness, $20.3 \mu\text{m}$ capillary hole diameter and $220 \mu\text{m}$ outer diameter, denoted as Fibre #1; (b) 2TLF, with $31.9 \mu\text{m}$ core diameter, $1.96 \mu\text{m}$ wall thickness, $20.9 \mu\text{m}$ capillary hole diameter and $245 \mu\text{m}$ outer diameter, denoted as Fibre #2.

configuration. The fibre (this part of fibre is not for loss test) is first bent to a circle with a diameter of 15 cm for the purpose to filter out the higher-order mode contents. Limited by the space, the fibre under test is bent to circles with a 2-meter perimeter, i.e., 32 cm bending radius, which should not introduce perceivable bending loss. Laser beam is coupled into one end facet of the TLFs by a flat-convex lens. The other facet of the TLFs is either connected to a CCD camera to monitor near field mode image or connected to an optical spectrum analyzer (OSA) to measure the optical spectrum of the transmitted signal. The measured near field pattern is shown in the inset of Fig. 4.8 which confirms the fundamental mode propagation. As a result, the transmission loss measurement only includes a robust FM.

To determine the cutback fibre length for loss measurement, I refer to ref. [80], in which the authors measure a HAF loss of 175 dB/km from 20 m and 5.1 m fibres. Although a longer fibre certainly helps to improve measurement accuracy, I believe the cutback fibre length around 15 m is enough to measure the loss at 100 dB/km level.

Figure 4.9 shows both the simulated and measured loss of the TLFs. The transmis-

Figure 4.7: Microscopic images of a 1TLF, red circles match well with the capillary boundaries.

sion loss of the Fibre #1 (1TLF) is measured by cutting a 20 m fibre to 3m and is represented by the blue curve in Fig. 4.9 (a). The transmission loss of the Fibre #2 (1TLF) is measured by cutting a 15 m fibre to 3 m and is represented by the black curve in Fig. 4.9 (b). The output spectrum was measured for multiple times over an hour and took the average to obtained P_A and P_B (measured power at point A and B in Fig. 4.8) excluding outliers. In this way, the measurement error is insignificant when comparing the similar lengths of fibres.

Simulated confinement losses of both fibres are also plotted as presented by the dotted curves in Fig. 4.9. The losses are plotted over both the wavelength and the normalized frequency. Please note that simulated loss only corresponds to the CL while the measured transmission loss is the total fibre loss including the CL and the fabrication induced loss. This is the reason why there is a discrepancy between the measured and simulated results. The speculation is further evidenced by the Fig. 4.9(a) that as the wavelength gets longer, CL becomes a dominant loss, the discrepancy between measured and simulated results becomes smaller.

The result in Fig.4.9 "The CL is determined by a fibre design, but there are other contributors to the loss introduced during fabrication such as a scattering loss [12,

Figure 4.8: Schematic of the setup used to measure the transmission loss of the fundamental mode, based on the cut-back method. The fibre is first bent to a smaller circle with $d_b = 15\text{cm}$, in order to filter out the higher-order modes. P_A is the power at point A, P_B is the power at point B, l is the cut fibre length between point A and B. The fibre loss is then calculated as $\frac{P_B - P_A}{l}$. The inset shows the near field mode image at point B, a pure fundamental mode can be observed. SC400: supercontinuum laser source, L1: microscope objective, TLF: tube lattice fibre, OSA: optical spectrum analyzer.

[47, 49] and an imperfection loss induced by structural variation across the fibre cross-section such as uniformity of capillary holes or hole distance [49]. We note that the fabrication induced losses reduce with increasing wavelength (thus, decreasing D/λ) [12, 49]. Consequently, it is the CL that contributes to the increasing measured loss when the value of D/λ gets smaller toward longer wavelength. At a short wavelength region, the fabrication related losses contribute more to the evolution of the total fibre loss than the CL [49]. This explains the insignificant loss difference between 1TLF and 2TLF at the short wavelength band in Fig. 4.9. This also explains the insignificant measured loss increment with the increasing of wavelength at short wavelength regions. When transmission band moves towards longer wavelength, the CL grows quickly and becomes a dominant factor to the total fibre loss. Such tendency is evident in 1TLF (Fig 4.9.(a)), but not in 2TLF (Fig 4.9.(b)) for both simulation and experimental results.” (cited from [64])

”The behaviors of the measured loss and the simulated CL over D/λ are summarized in Fig. 4.9(c). The presented loss at each band was obtained by taking an average of the loss curves in Fig. 4.9(a) and (b) excluding the sharp rises close to the inhibited regions. As demonstrated in Fig. 4.9(c), the second cladding layer slows

Figure 4.9: (a) Simulated and measured loss evolution of Fibre #1 over three transmission bands (800 nm to 2100 nm), (b) simulated and measured loss curves of Fibre #2 over three transmission bands (850 nm to 1750 nm), black areas represent the high resonant regions; (c) average loss taken at different transmission bands over D/λ value. In all the figures, blue and red lines show the measured and simulated loss of Fibre #1 respectively, while black and magenta lines show the measured and simulated loss of Fibre #2 respectively. Here, simulated loss represents the CL only while the measured loss represents the total fibre loss including the CL and the fabrication induced loss.

the loss increasing rate over the D/λ , and making the 2TLF as a promising design to applications benefiting from a small D/λ , or a small core. Apparently, the loss with a smaller D/λ , or in a longer wavelength, is lower in 2TLF. A quality of TLF for gas-light interaction applications can be determined by introducing a figure of merit (FOM) i.e., $f_{om} = \frac{\lambda}{\pi D^2 \alpha}$, where α is the exponential attenuation of a propagation light intensity [6]. From the measurement results in Fig 4.9(c), the FOM of both Fibre #1 and Fibre #2 is around 2500 when $D/\lambda = 27$. However, as the value of D/λ decreases to 20, the FOM of Fibre #2 maintains the same, whereas that of the Fibre #1 decreases to 1240. Thanks to the lower attenuation in the long wavelength band as well as the small core, the 2TLF could offer better performance in the gas-light interaction applications.” (cited from [64])

Therefore, such a 2TLF is no longer restricted by the contradiction between small core and low confinement loss and is good for fibre laser applications.

4.3.2 Second Contradiction: Low Bending Loss and Low Confinement Loss

In fibre lasers, the optical fibre serves as the laser cavity should be long enough, and thus, inevitably, has to be bent and will introduce a bending loss which then contributes to the cavity loss. Therefore, bending loss is an important character of the optical fibre in fibre laser applications, especially for HAFs, whose photonic crystal cladding supports many cladding modes which can couple with the core modes when fibre is bent. In this subsection, 2TLF is verified to possess the capability to achieve both low confinement loss and low bending loss at the same time by two steps: Firstly, a 1TLF with smaller capillary hole size is proved to suffer lower bending loss, however, high confinement loss. Secondly, a second cladding layer is found to significantly reduce the confinement loss in small capillary case.

Relationship between Capillary Size and Bending Loss

A cladding capillary of the TLF can also supports cladding modes because of the antiresonant reflection. The airy cladding mode whose effective refractive index is closest to that of the FM is the mode inside the first cladding layer (ACM1, see Fig. 4.10). When the fibre is kept straight the FM is tightly confined inside the hollow core area due to the waveguide principle of the HAF (section 2.1), and thus, the overlap between ACM1 and FM is negligible. However, once the fibre is bent to a certain critical bend radius, overlap and coupling effects between FM and ACM1 can no longer be overlooked and bending loss increases rapidly. The effective refractive index of ACM1 is directly related to capillary hole diameter d , while the effective refractive index of fundamental mode is determined by the hollow core diameter D . Hence the value of d/D may influence the coupling effects between fundamental mode and ACM1, and therefore influence the bending performance of a TLF.

Figure 4.10: Airy cladding mode at first cladding ring (ACM1).

The relationship between cladding capillary hole size and the bending loss in 2TLFs has already been studied in my previous work which was published on *Scientific Reports*:

”A prior theoretical study [55] also reported that a bending loss of 1TLF is greatly influenced by cladding hole size that a small hole size suppresses the bending loss at a given core size. The smaller tube hole size reduces an effective refractive index of a cladding airy mode [121], rendering coupling between core and cladding modes weaker [122,123], even in a bent fibre. We provide experimental evidences of this theoretical investigation. Bending losses in 2TLFs with various hole sizes are experimentally examined to confirm the relationship.” (cited from [64])

”The schematic of our bending loss measurement is depicted in Fig. 4.11(a). A fibre laser pumped supercontinuum source is coupled into the 2TLF which is bent to a half circle with diameter D_b . After the bending, only a core mode is guided. The core mode is coupled into a telecomm single mode fibre (SMF) and a transmission spectrum is recorded by an OSA. Because the bending loss can be subject to the bending direction in our 2TLF, 2TLFs under test are mounted on a rotational stage in order to align the bending direction to the split gap. The fibre #3 and #4 in Fig.

4.11(b) and (c) have a similar core size, D , around $32\ \mu\text{m}$, but different capillary hole diameters, d , of 19.7 and $16.0\ \mu\text{m}$, respectively. Thus, their D/d parameter is determined by d only. The wall thickness of both fibres is same at $2.0\ \mu\text{m}$. The two fibres are experimentally characterized with a similar background loss around $0.2\ \text{dB}/\text{m}$ at $1200\ \text{nm}$ because of the similarity in the core size and the wall thickness.” (cited from [64])

(a)

Figure 4.11: (a) Schematic of the setup used to measure the bending loss, SC400: supercontinuum laser source, L1: microscope objective, RS: rotational stage, FA: fibre adapter, SMF: single mode fibre, OSA: optical spectrum analyser; Cross-section image of (b) Fibre #3 with core diameter $D = 32.0\ \mu\text{m}$, capillary hole diameter $d = 19.7\ \mu\text{m}$, $\frac{d}{D} = 0.62$; (c) Fibre #4, core diameter $D = 32.3\ \mu\text{m}$, capillary hole diameter $d = 16.0\ \mu\text{m}$, $\frac{d}{D} = 0.50$. Gaps in the cladding area are denoted with numbers in a yellow font.

”The evolution trend in bending loss of Fibre #3 is shown in Fig. 4.12 when the

fibre bending direction is aligned to a split gap. The bending loss curve is divided into three parts according to the evolution trend. When the bending diameter is large (region **I**), the bending loss is too low to be accurately measured. However, prior simulation works reported the bending loss at this region increases exponentially [55]. When the bending diameter enters region **II**, its bending loss grows enough to be detected by the OSA. An exponential increase of the bending loss with tighter bending is apparent in this region as shown in Fig. 4.12. As we further reduce the bending diameter (region **III**), the behavior dramatically changes. Instead of the exponential growth, the bending loss oscillates in an irregular manner. This behavior was already predicted in simulation with an explanation of the bending dependence of the Fano resonances [53, 54]. Our experimental observation confirms the theoretical results. We also note that a similar behavior was observed regardless of the bending direction to different split gaps. As our main interest is to attain experimental evidences of the bending loss dependence on the hole size, the experiments were carried out in the Region **I** and **II** only. To evaluate the bending loss, we introduce a 3 dB diameter, i.e., a bending diameter at which a bending loss becomes 3 dB/round . Thus, the smaller the 3 dB diameter, the lower the bending loss.” (cited from [64])

”Figure 4.13(a) and (b) represent measured bending losses of Fibre #3 and Fibre #4 respectively at different bending directions. The tested fibres were bent to different split gaps as labeled from 1 to 6 in anti-clockwise direction in Fig. 4.11. The bending performances are then summarized in Fig. 4.13(c). The average 3 dB bending diameter of Fibre #3 with $d/D = 0.62$ is measured as 10.1 cm , which is 60% larger than Fibre #4 ($d/D = 0.50$) whose 3 dB bending diameter is averaged to 6.3 cm . Since the two fibres have similar core size (around $32.0\text{ }\mu\text{m}$) and consequently the same loss around 0.2 dB/m at 1200 nm , the only variable in d/D becomes the hole size, d . We note that the hole size of Fibre #3 and Fibre #4 are measured as 19.7 and $16.0\text{ }\mu\text{m}$ respectively. Therefore, the result clearly demonstrates that the fibre with a smaller hole diameter indeed enjoys lower bending loss.” (cited from [64])

”We now clarify the bending loss dependence on the bending directions in Fig. 4.13

Figure 4.12: (a) Schematic of the setup used to measure the bending loss, SC400: supercontinuum laser source, L1: microscope objective, RS: rotational stage, FA: fibre adapter, SMF: single mode fibre, OSA: optical spectrum analyser; Cross-section image of (b) Fibre #3 with core diameter $D = 32.0\mu m$, capillary hole diameter $d = 19.7\mu m$, $\frac{d}{D} = 0.62$; (c) Fibre #4, core diameter $D = 32.3\mu m$, capillary hole diameter $d = 16.0\mu m$, $\frac{d}{D} = 0.50$. Gaps in the cladding area are denoted with numbers in a yellow font.

(a) and (b). Compared to Fibre #3 (Fig. 4.13(a)), the bending direction dependence is more significant in Fibre #4 (Fig. 4.13(b)). This is caused by asymmetric nature of fibre structure. While the split gaps are only varied within $2.0\mu m$ in Fibre #3, the gap size in Fibre #4 exhibits wider variation of $4.0\mu m$. As a consequence, the bending loss in Fibre #4 becomes subjective to the bending directions. Bending to a wider gap suffers larger bending loss as found in Fig. 4.13(c) (red dots). Our observation suggests the wider gap can bridge the mode index difference between the core and the cladding modes and increases the bending loss [123].” (cited from [64])

The method to determine which direction the fibre is bent to is illustrated in Fig. 4.14. The top side of the fibre is marked with red marker for reference. As the bending direction (red arrow) is perpendicular to the marked position, under the microscope we can know which gap the fibre is bent toward. When the fibre is rotated, the bending direction will also change accordingly. To ensure the fibre is not twisted, every time we rotate the fibre, we release another side and re-bend the

Figure 4.13: Bending loss of (a) Fibre #3 and (b) Fibre #4 at 1200 nm ($F=3.5$) when bent to different directions; (c) The relationship between 3dB diameter and gap width (or azimuthal separation of cladding). Blue colors correspond to the Fibre #3 ($\frac{d}{D} = 0.62$) while red colors correspond to the Fibre #4 ($\frac{d}{D} = 0.50$). Dash lines are the average 3dB diameter values.

fibre.

Relationship Between Capillary Size and Confinement Loss

In last part, simulation results show that 2TLF with smaller capillary size suffers lower bending loss. In this part, I'm going to show the impact of shrinking capillary size on the CL which has been presented in my prior publication [64].

"Transmission performance of TLF is mainly determined by a core size (to determine the CL) and a wall thickness (to determine the transmission band) while the bending

Figure 4.14: Shows the schematic to determine the bending direction of the fibre. The red arrow indicate the bending direction.

loss is controllable by a hole size. Hence, the characteristics of TLF can be tailored by adjusting the independent design parameters toward bending insensitive low loss design. In the 1TLF design, however, there is a trade off between low bending loss and low transmission loss [55]. As confirmed, a smaller cladding hole size is desired to achieve a low bending loss. However, the small cladding hole effectively reduces a distance between a core and a fibre jacket tube, resulting in a leakage loss increase. The 2TLF structure is not bound to this trade-off. The second cladding layer keeps the distance large enough to avoid the excess leakage loss without sacrificing the capillary hole size, hence promising better bending performance.” (cited from [64])

”We confirm this additional benefit of 2TLF in Fig. 4.15. We theoretically compare 4 fibre designs with various hole sizes. The first two structures represent 1TLF, and the others 2TLF. All the structures have the same core diameter $32.0\ \mu\text{m}$ and same wall thickness $1.43\ \mu\text{m}$, to make a fair comparison. The only difference between structure A and B, and structure C and D is the capillary hole diameter. The hole diameter in structure A and C is $20.0\ \mu\text{m}$ while that in structure B and D is reduced to $13.2\ \mu\text{m}$. Figure 4.15(b) illustrates effective index of the airy cladding mode in the first cladding ring (ACM1). A beam profile of ACM1 is shown in Fig. 4.15(c). The index gap between the ACM1 and the core mode can represent the coupling strength, hence a transmission loss. The core mode effective index is nearly same for

the all fibres because of the same core diameter. In addition, the effective refractive index of ACM1 in structures A and C are much larger than structures B and D as shown in Fig. 4.15(b). Consequently, the coupling between core modes and the ACM1 in structure A and C are stronger. This explains why shrinking the cladding capillary hole can reduce the bending loss.” (cited from [64])

Figure 4.15: (a) Simulated confinement loss of the fundamental mode; (b) simulated refractive index of the fundamental mode and airy cladding mode. (c) All the structures have the same core size $32.0 \mu m$ and the same wall thickness $1.43 \mu m$. The hole diameter of the cladding capillaries in structure A and C is $20.0 \mu m$ while that in structure B and D is $13.14 \mu m$. The airy cladding mode inside the first cladding ring has the closest effective index to the core modes and is shown in the right side of the figure.

”Subsequently, it can be expected that both structure B and D would have lower bending loss than fibre A and C, respectively due to the smaller hole size. However, Fig. 4.15(a) shows the CL of structure B is much higher than that of structure A. This high CL accounts for close proximity of core to the jacket tube. In 1TLF, the attained low bending loss from the small hole size is compensated by the high CL. Fortunately, 2TLF is free from this constraint as indicated in Fig. 4.15(a). The second layer provides a sufficient distance between core modes and fibre jacket to

prevent the undesired leakage. Hence, 2TLF provides a highly engineerable platform, with freely adjustable individual design parameters of D , t and d without trade-offs. Besides, the bending loss of 2TLF should not be higher than their 1TLF counterpart because adding the second cladding layer does not increase the bending loss [53].” (cited from [64])

4.4 Conclusion

The most important structural parameters in a TLF design include core diameter, wall thickness and capillary hole diameter. They are always interlinked, inducing trade-offs in fibre performances and provoking the two existing contradictions in a TLF design (section 1.3.1).

In this chapter, a 2TLF fibre design is proposed, fabricated and characterized. It is indicated by Fig. 4.6 that 2TLF tends to have thicker glass wall than 1TLF, which may do harm to the transmission bandwidth and transmission loss [49]. However, the glass wall thickness of 2TLF can be further reduced by using capillaries with thinner walls in the stacking process. Therefore, 2TLF is both theoretically and experimentally proved to be able to resolve the mentioned contradictions:

1. A 2TLF design benefits from low loss at long wavelength and small core conditions, hence is promising for the applications of fibre laser applications as well as mid-infrared transmission.
2. A 2TLF design can achieve low bending loss without sacrificing the CL by enabling small capillary hole diameter requirement as well as separation of the core and the jacketing tube.

Chapter 5

Dual Core Antiresonant Fibre

In last chapter, we have designed, fabricated and characterized a 2TLF which can serve as a hollow laser cavity with extremely long interaction length. However, to build a hollow core fibre laser, we still need a hollow core fibre based optic coupler to realise an all hollow core fibre based ring cavity. Therefore, in the scope of this chapter, we focus on the design, fabrication and characterization of such a hollow core fibre based coupler.

5.1 Fiber Coupler Review

Fiber based optic elements (such as fibre couplers, fibre grating, fibre polarizer and fibre amplifier) are important components for integration in fibre laser delivery systems and fibre laser sources. Among them, a fibre optic coupler, which is defined as "*a device used in optical fibre systems with one or more input fibres and one or several output fibres*" [124], is the most basic fibre components for directing, combining or splitting powers. Analogy to optical fibres, the classification of fibre couplers also depend on their core material, and hence are divided into either solid core or hollow core fibre based coupler. Among all the couplers, a 2X2 (two input ports and two output ports) fibre coupler is the most popular one, and hence we focus on reviewing the 2×2 fibre couplers.

5.1.1 Solid Core Fibre Based Coupler

Most of the solid core fibre couplers are fabricated by a fused tapered method. Schematic of a 2X2 fibre coupler fabricated by this method is shown in figure 5.1. L in the figure is the actual length of the fibre coupler. The length L of the fibre coupler is determined according to the coupling length L_c in order to achieve a target energy splitting ratio P_3/P_4 , where P_3 and P_4 are the output power at port 3 and port 4, respectively.

Figure 5.1: Schematic of a 2X2 fibre coupler made by fused tapered method.

The coupling length is a minimum length at which the light launched into one core can be totally coupled into another core, and can be calculated according to the following equation [125]:

$$L_c = \frac{\lambda}{2(n_e^i - n_o^i)}, i = x, y, \quad (5.1)$$

Where n_o^i and n_e^i are the effective refractive indices of i-polarized odd and even modes, respectively. The even mode and the odd mode are resulted from the modal coupling which turns one individual core mode into a pair of supermodes [126], as shown in Fig. 5.2. The energy is transferred between two cores in a sinusoidal way along the fibre coupler, with a period of $2L_c$. Hence, the splitting ratio of the coupler is a sin function of the coupler length L . When the light is generated into port 1, the light come out at port 3 can be determined by the following function:

$$P_3 = 0.5 + 0.5 \sin\left(0.5\pi + \frac{L}{L_c}\pi\right), \quad (5.2)$$

Due to the mature fabrication technology, solid core fibre couplers have extensive applications, especially in wavelength division multiplexing telecom systems and in fibre laser systems [124].

Figure 5.2: Left: Mode pattern of an odd mode. Right: Mode pattern of an even mode.

5.1.2 HC-PBGF Based Dual Core Fibres

Although solid core fibre couplers take advantage of mature fabrication technology, they suffer from the drawbacks of solid core such as high absorption loss at mid-IR, low damage threshold and high nonlinearity. In order to get rid of the limitations of the solid core, in the past decade, HC-PBGF based dual-core fibres were theoretically and experimentally studied [13, 125, 127]. Figure 5.3 shows one of the dual core HC-PBGF, which has a central core accompanied with a smaller side core. The central core is for the low loss guidance while the side core is implemented to filter out the higher order modes through coupling from the central core to the side core, to ensure the single mode transmission in the central core.

As the structure is based on HC-PBGF, the dual core HC-PBGF suffers from relative narrow and single transmission wavelength when compared to HAFs. Besides, the silica struts between the cores will impose material limitations on the coupler. Moreover, as indicated by Fig. 5.3, the separation distance between the cores is too

Figure 5.3: Cite from [13], scanning electron micrograph of the cross section of a dual core HC-PBGF.

small (around $5 \mu m$), which makes it difficult to separate the modes in two cores. Hence, such a dual core HC-PBGF is not suitable to serve as a fibre coupler.

5.1.3 KF Based Dual Core Fibre

The HAF offers more intriguing properties than HC-PBGF including multiple and much broader transmission bands, and more flexible cladding structures. Consequently, dual core fibres were investigated based on the HAF design. However, the result is quite disappointing.

In 2009, a polymer dual core kagome fibre was demonstrated to study the coupling phenomenon [14]. The cross section of the fibre is shown in Fig. 5.4 (a). From their experiment results, no coupling effect between the two cores was observed for the transmission wavelengths. The explanation is that the high core mode confinement feature of antiresonant fibre results in the low overlap between core modes and the cladding (as introduced in section 2.1) which inhibits the formation of supermode

and coupling. Instead, it is shown that light is able to couple between the cores through coupling to cladding struts in the resonant (or high loss) wavelengths. Thus, its coupling performance is poor.

Later in 2016, another group from Southampton attempted a similar structure (see Fig. 5.4 (b)) by using silica as the cladding material [15]. As indicated in the figure, in order to observe the coupling effects in transmission wavelength, the core boundary was made to be flat to reduce the confinement of core modes and increase the overlap areas between core modes and the silica cladding area. Moreover, the struts width between the two cores was narrowed to merely $4.5 \mu m$ to enhance the coupling effects. However, even for the structure with flat core boundary and $4.5 \mu m$ core separation, the overall power transfer is $< 30\%$. What's more, the KF based fibre coupler is polarization dependent and it suffers from material limitations due to the silica struts between the cores.

Figure 5.4: (a) Cite from [14], scanning electron micrograph of the cross section of a polymer dual core KF. (b) Cite from [15], scanning electron micrograph of the cross section of a silica dual core KF.

In conclusion, the prior KF based dual core fibres have following drawbacks which make them unsuitable to serve as a fibre coupler:

- Flat core cladding boundary weakens the core mode confinement and introduces higher transmission loss.

- Separation distance between the cores is too small (around $5 \mu m$) to divide the light into two paths.
- Light coupled via the silica struts, unable to take advantages of hollow cores.
- Weak coupling effects between air cores even in the case of flat core cladding boundary and small core separation distance.
- Polarization dependent.

5.1.4 Dual Hollow Core Antiresonant Fibre Design

For the above dual core hollow core fibre designs, although their core modes are confined inside the hollow cores, their coupling region is via the silica cladding areas, hence inducing extra background loss. Recently, in 2016, two dual core HAF design was proposed as an alternative design [16]. The dual core HAF designs are shown in Fig. 5.5. In both dual core fibre designs, there is an air gap which connects the two cores, hence the modal coupling between the core modes thoroughly occurs in air. According to their simulation results, both designs can have short coupling length as short as several centimeters and are polarization independent.

Figure 5.5: Cited from [16] (a) The proposed elliptical dual-core HAF structure. (b) The proposed composite circular dual-core HAF structure.

However, according to our experience and knowledge on fibre fabrication, both the designed structures cannot be practically come true. For the structure in Fig. 5.5, it is hard to control the wall thickness of the elliptical capillaries which is critical to an antiresonant waveguide. As for the structure in Fig. 5.5(b), there is no way to combine two antiresonant waveguide without deforming the cladding structure. And for this reason, there has not been any demonstration of the HAF based dual core fibre so far to the best of our knowledge.

5.2 New Dual Core Antiresonant Fibre Design

As discussed in section 5.1, a dual core hollow antiresonant fibre which couples via the air channel can work normally as a fibre coupler while inheriting the advantage of hollow core antiresonant fibre. However, the former designs are not practical.

5.2.1 Flexible Design via Stacking

Based on our unique preform stacking method (as introduced in section 3.1.2), we are able to propose a new dual hollow core antiresonant fibre (DCAF) and fabricate this design. Our DCAF design is shown in Fig. 5.6. It composes of two hollow cores **1** which are connected to each other through an air gap **3**. One layer of cladding capillaries **2** surrounds the hollow cores to form an antiresonant waveguide.

Because all the capillaries are round and with the same size, the wall thickness remains the same. Such a DCAF design is easy to stack and fabricate by using our stack and draw method. Rods are used to fill the gap areas between capillary cladding and the jacket tube because the solid rods suffer no deformation caused by the gas pressure difference. Hence our DCAF design is less influenced by the variation of the gas pressure difference between fibre core and the cladding holes.

Besides, for this DCAF design, the core separation can be as large as $20\ \mu m$ when core diameter is $D = 30\ \mu m$. This large core separation distance allows us to direct

Figure 5.6: Designed structure of dual hollow core antiresonant fibre coupler, t is capillary wall thickness, g is channel gap width, D is core diameter.

individual core beam to two separate paths using external fibres (which we will discuss later in section 5.2.3) or free space optics. Using equation 5.1, one practical design can be represented with $12\ \mu m$ gap (g) at 1000 nm wavelength. With this structure, the coupling length, $L_c = 25cm$, which indicates the relatively strong coupling between the cores.

5.2.2 Scalability of the Number of Cores

Another advantage of this kind of stacking design is it is very flexible. Based on this stacking method, we can even extend the number of cores to as more as we want for specific applications. Both designs possess 3 and 4 cores are shown in Fig. 5.7 to represent scalability of the number of cores. Since a dual core fibre can serve as a 2×2 coupler, similarly, a three core and a four core fibre can work as a 3×3 and 4×4 fibre coupler, respectively.

Figure 5.7: Three and four air core couplers to represent scalability of the number of cores.

5.2.3 Strategy to Realize All Fibre Coupling

The DCAF can be connected directly to other fibres or fibre components via fibre extension. The extension can be achieved by splicing or butt-coupling between the coupler and extension fibres. Figure 5.8 represents fibre connections to the coupler to provide direction connection to other fibres or fibre components. The fibre coupler can consist of 2 air cores (but not limited) as illustrated in Fig. 5.6. The two cores provide 2 x 2 ports as input (Port A and B) and output ends (Port C and D). Each port is accessible via free space or connection fibre.

In the air core fibre coupler, the neighbouring two cores are placed very closely in order to realise the coupling, and this may imply limitation of using conventional fibres as a connection fibre. Adaptation of connection fibre is required. fibre tapering is one example of such adaptation. A tapered end can be placed at one of the air cores for a coupling purpose. Such connection is illustrated in Fig. 5.8(a). Because of the small diameter of the tapered end, two tapered fibres can be placed side by side, exactly matched to the air core location. This allows 2 x 2 connection in full. Alternatively, an asymmetric core fibre (as shown in Fig. 5.8(b)) can be used as a connection fibre as shown in Fig. 5.8(c). The asymmetric core fibre possesses an off-centred core that can be connected to one of the cores in the coupler. Because the wall thickness closed to the core is small, two of such asymmetric core fibre can be placed side by side at the exact location of air cores in the coupler. Hence, the air core coupling can be fully all-fiberized.

Figure 5.8: DCAF connection by tapered fibres (a), and asymmetric core fibres (b) and (c).

To make this all-fiberized process easier, we can even adjust the design to increase the core separation. The alternative design is shown in Fig. 5.9. However, increasing the core separation can induce the longer coupling length. Hence there is a trade off between core separation distance and the coupling length which should be determined according to the specific situations.

5.3 DCAF Characterization

A DCAF fabricated by the stack and draw technique is shown in Fig. 5.10. The fabricated DCAF has a good structure which verifies the superiority and feasibility of our design. In this section, properties of fabricated DCAF are characterized. At first, the transmission spectrum of the DCAF is measured to show it still keeps

Figure 5.9: Alternative DCAF design which has longer core separation distance.

the feature of the HAF. The DCAF is then proved to be polarization independent, which can reduce the azimuthal alignment requirements for connecting the DCAF with single core fibres. Then the coupling features of the DCAF are studied and the power splitting ratio is found to be tunable as the tension is applied to the fibre. At last, an obsolete structure which tried previously is presented.

5.3.1 Antiresonant Spectrum

As DCAF is based on hollow core antiresonant fibres, the parameter that determines its transmission spectrum should be capillary wall thickness t . How the capillary wall thickness t can influence the transmission property has been explained in section 2.1. Figure 5.11 is the schematic of the experiment setup used to measure the transmission spectrum.

As is shown in Fig. 5.11, the laser beam is coupled into port A. The SMF is mounted on a 3 axis translation stage. By aligning the SMF to either port C or port D, the output spectrum of different core is obtained. The measured output spectrum of both port C and port D are shown in Fig. 5.12 (a), the port A is served as an input

Figure 5.10: Cross section view of a fabricated hollow core antiresonant fibre coupler, in which $t = 1.21 \mu m$, $D = 35.2 \mu m$ and $g = 12.5 \mu m$.

port and the transmission is measured at port C and D for a 50:50 coupling setting. F in the figure is normalized frequency as defined in equation 2.5. In a HAF, when F closes to an integer, there is a high loss region, and a low loss transmission band exists between every adjacent high loss regions. This is also true for the DCAF as is indicated by Fig. 5.12 (a). Both the measured spectrum of port C and port D show this kind of antiresonant feature. Therefore, we can conclude that the coupling between the cores does not change the waveguide mechanism of the DCAF, i.e., a combination of antiresonant reflection and inhibited coupling between core modes and silica cladding modes.

The interference pattern of the transmission spectrum in Fig. 5.12 (b) can be explained by the modal interference between the first order and second order super-modes, which has also been observed with other fibre optic couplers [128]. Both the period and strength of the sinusoidal modulation in the transmission spectrum increase as the coupler length gets shorter as indicated by Fig. 5.12(b), which follows the regular of modes interference.

Figure 5.11: Schematic of the experiment setup used to measure the transmission spectrum of the fabricated DCAF. Where SC400 is a supercontinuum laser source, M1 and M2 are the reflective mirrors, L1 is a coupling lens, FUT is the DCAF under test, SMF is a single mode fibre, and OSA is an optical spectrum analyzer.

5.3.2 Relationship Between Power Splitting Ratio and DCAF Length

Besides antiresonant transmission spectrum, another important feature of a DCAF should be coupling effects between hollow cores. The coupling property of a DCAF is highly influenced by the value of g/D , where g is the gap width and D is the averaged core diameter. This value determines the coupling length, L_c . In a fibre coupler, the coupling ratio between cores varies sinusoidally as the coupler length varies, and a coupling length is the shortest distance at which input power is totally transferred from one core to the other. Therefore, it is necessary to explore the relationship between g/D and L_c to exactly predict the coupling length from coupler geometry, so as to determine the coupler length for certain applications.

Table 5.1: **Parameters and Simulation Results for Coupling Length Calculation.**

g/D	$g(\mu m)$	$D(\mu m)$	n_{odd}	n_{even}	$\Delta n_{eff}(\times 10^{-6})$	$L_c(cm)$
0.268	9.4	35.0	0.999709370	0.999710062	0.692	76.6
0.313	10.95	35.0	0.999725401	0.999726495	1.093	48.5
0.327	11.45	35.0	0.999730565	0.999731900	1.335	39.7
0.343	12.0	35.0	0.999736251	0.999737944	1.693	31.3
0.357	12.5	35.0	0.999741415	0.999743623	2.208	24.0

I use Comsol Multiphysics (RF Module) to simulate the effective refractive indices of the even and the odd mode at different g/D , the structural parameters used and

Figure 5.12: (a) Transmission spectrums at both port C and D of a HAFC with 1.21 μm wall thickness, demonstrating anti-resonant feature and 50:50 power splitting. (b) Transmission spectrum at port D of DCAFs with different fibre length. In all cases, light is coupled into port A.

the simulation results are shown in table 5.1. According to formula 5.1, coupling length at different g/D can be obtained and the results are shown in Fig. 5.13. From the 5.13, L_c decreases linearly as g/D becomes larger [129]. For the DCAF shown in Fig. 5.10, g varies at different longitudinal position z while D keeps invariant. If we use function $g(z)$ to represent the relationship between gap width g and longitudinal position z , then we have:

$$L_c(z) = -16.25g(z) + 229.75, \quad (5.3)$$

Where the unit of $L_c(z)$ is cm , and the unit of $g(z)$ is μm . According to formula 5.2, when the light is coupled into port A, the power at port D, $P_D(z)$, is a sinusoidal function over z , and can be set as:

$$P_D(z) = 0.5\sin(\varphi(z) - \pi/2) + 0.5, \quad (5.4)$$

Figure 5.13: Relationship between g/D and coupling length L_c . For all the cases, $D = 35.0\mu m$, wavelength is 1060 nm .

Where $\varphi(z)$ is the accumulated phase:

$$\varphi(z) = \int_0^z \frac{\pi}{L_c(z)} dz, \quad (5.5)$$

As is depicted in Fig. 5.14 (a), at first, $g(z)$ along a 86 cm fibre has been measured. To obtain this $g(z)$, the gap widths at several positions ($z=0,40,65,86\text{cm}$) are measured, and then assume gap width in each two adjacent positions changes in a linear manner. Based on formulas 5.3, 5.4 and 5.5, the calculated value of P_D is plotted over z as shown by the solid line in Fig. 5.14(a). The blue dots in Fig. 5.14 (a) correspond to the measured value of P_D . The tendency of measurement result matches well with the calculation. When $z = 40\text{ cm}$, more than 90% of input power can be coupled into port D.

Figure 5.14 (b) shows the near mode image patterns at different longitudinal positions. It seems the DCAF is not single mode, it also supports the second order mode (LP₁₁).

In conclusion, in this subsection, I prove that the power ratio in each hollow core varies along the fibre length in a sinusoidal manner which is consistent with the performance of conventional fibre optic coupler.

Figure 5.14: (a) Shows the calculated and measured value of P_D over longitudinal length z . (b) near field mode images observed at output ports for different coupler lengths.

5.3.3 Adjustable Power Splitting Ratio

We then found that the power ratio at the output port is adjustable as we applying longitudinal tension. The coupler is mounted on translational stages as illustrated in Fig. 5.15. Incident light at $1\mu\text{m}$ wavelength is launched into the port A, and output light from port C and D is monitored with a CCD camera to evaluate the coupling performance. The coupler length is chosen at 40 cm, matched to L_c . The tension applied on the fibre can be represented by the travelling length of the translation stage.

Fig. 5.16 shows the evolution of power at the port D, P_D , and the port C, P_C , at different tension. At low tension, the coupling ratio $P_D/(P_C + P_D)$ is small while the ratio gradually increases with higher tension (fiber gets tighter and tighter). The coupling ratio is variable from 5% to 95%. This is a striking difference from

Figure 5.15: Schematic of the setup used to apply a longitudinal tension of DCAF.

the conventional fibre coupler that has to be cut for a desired coupling ratio, thus invariant once its length is fixed. Our air core coupler offers a variable coupling ratio at a single fibre length. Moreover, the variable coupling does not compromise the fibre performance in that the fibre insertion loss or total output power, $P_C + P_D$, is not sacrificed over the entire coupling ratio as shown in Fig. 5.16. In addition, the anti-resonant transmission bands are well preserved at the different coupling ratios. Near field mode patterns from the output ports at different tension are shown in Fig. 5.16, evidencing the variable coupling ratios.

The tension dependent coupling ratio has been explained in one of my recent publication [129], "I speculate that the dependence of the coupling ratio on the longitudinal tension is related to phase sensitivity of the fundamental mode to strain. As reported in [130], longitudinal strain can induce structural deformation of the hollow core fibre, resulting in fundamental mode effective index change. Moreover, in our DHAF, the strain induced structural deformation can change the gap width, which would greatly influence the coupling length as indicated in Fig. 5.13." (Cited from [129])

5.3.4 Polarization Independent

The experiment setup used to prove the polarization independence of the DCAF is shown in Fig. 5.17. In the setup, the polarized direction of the beam from 980 nm laser is controlled by a linear polarizer (LP), the transmitted light through the fibre under test (FUT) is split into two paths and are selectively measured with a power meter (PM) by using a barrier to block the other path.

Figure 5.16: Shows the relationship between P_D and the longitudinal tension applied to the fibre coupler when incident light is coupled into port A. Fibre coupler length is 40 cm. Here, the unit of tension is μm because the tension is represented by the stretched length of the fibre coupler.

The results are recorded in table 5.2. As the polarized direction changes, the power splitting ratio of the FUT almost keeps invariant, which verifies the performance of DCAF is polarization independent. This is also in accordance with the simulation, in which the effective refractive index difference between x and y polarization components is smaller than 10^{-6} .

Table 5.2: **Power splitting ratio at 980nm when polarization of incident light varies.**

$\Delta\theta$	0°	30°	60°	90°	120°	150°	180°
$P_C(mW)$	31	43	29	7	-	13.5	31
$P_D(mW)$	19	26	19	4	-	8.5	19
$P_C : P_D$	62.0:38.0	62.3:37.7	60.4:39.6	63.6:36.4	-	61.4:38.6	62.0:38.0

$\Delta\theta$: Angle difference between the directions of the linear polarizer and the incident light polarization.

Figure 5.17: Schematic of the experiment setup used to measure the power at port C and port D at various polarization direction of incident light.

5.3.5 Obsolete DCAF Design

Figure 5.18 shows an obsolete design. In this obsolete design, the air cores have large diameters ($> 50\mu m$) in order to maintain the air gap between the air cores to enable the inter-core mode coupling. Result from the large core, the higher order mode contents significantly increased and the fundamental mode content could not be observed, which is implied by the inset in Fig. 5.18.

Figure 5.18: Cross section of the obsolete structure. Inset: near field mode image.

5.4 Conclusion

In this chapter, both solid core fibre coupler and hollow core fibre coupler are reviewed. Hollow core fibre couplers based on HAF can reserve the advantages of HAFs, i.e., broad transmission band, low dispersion, low nonlinearity, and low absorption loss, however the prior design is hard to fabricate. Therefore, new DCAF design is proposed, fabricated and characterized in-house. The fabricated DCAF is characterized to have following properties:

1. Spectral properties of DCAF are the same as a HAF.
2. DCAF is able to work as a 2 x 2 fibre coupler. And all input ports and output ports of the multi-core coupler can be fibreized via tapered fibres or asymmetric core fibres, to fulfil all-fibre coupler with fibre extension.
3. Power splitting ratio of the DCAF is variable by applying different tension.
4. Performance of the DCAF is polarization independent.

As the DCAF has so many intriguing properties, it should has promising applications. Therefore, several applications of DCAF will be introduced in the next chapter.

Chapter 6

DCAF Applications

In this chapter, the fabricated DCAF will be used in practical applications, which include laser ring cavity and ultra fast beam delivery and splitting. The works in this chapter have been published [129].

6.1 Fiber Laser with DCAF Based Ring Cavity

As mentioned in section 2.3.1, the unavailability of mid IR fibre coupler forces the mid-IR fibre laser to be built with free space optical components [11] to realize a laser ring cavity. In this section, I demonstrate the robust coupling performance and applicability of the DCAF in forming a fibre laser ring cavity. Although the working wavelength of the built Yb-doped fibre laser is around $1.06\ \mu m$ in near infrared region, it does imply the capability of DCAF in building a mid-IR laser ring cavity. The reason is that a DCAF complies with antiresonant waveguide mechanism and have similar performance in near infrared and mid-IR because the light is confined inside and coupling via the airy areas.

Moreover, one of the main difficulties for a fibre laser to achieve maximum signal power output is the requirement for a fibre optic element with various output coupling ratio. DCAF makes the optimization easier because the output ratio of DCAF is variable.

6.1.1 Setup of 1.06 μm Yb-doped Fibre Laser

Yb-doped fibre lasers benefit from high output power and good efficiency [131]. They have extensive applications in medicine, micro-machining, marking, and scribing. The emission wavelengths of Yb doped fibre lasers are mostly in a range of 1050-1120 nm [132]. Especially, one of the most successful wavelength in this wavelength range is 1.06 μm . A 1.06 μm laser is critical for both pumping and second harmonic generation (or frequency doubling) [133]. In this subsection, a 1.06 μm Yb-doped fibre laser with relatively narrow spectral linewidth (2 nm) is demonstrated with a DCAF to build a ring cavity.

The fibre laser configuration is depicted in Fig. 6.1. Pump light from the diode laser around the wavelength 0.98 μm is coupled into the ring cavity by a bandpass (with central wavelength at 980 nm and 1060 nm, respectively) wavelength division multiplex coupler (WDM). The WDM has a low loss and is polarization independent helps to realize the wavelength selection (see Fig. 6.2 (b)). The optical isolator has an insertion loss smaller than 1.5 dB, isolation of 30 dB and return loss better than 50 dB. The optical isolator can not only hinders bidirectional lasing in the loop, inhibiting hole burning effect in the gain medium, but also protects the pump laser against back reflections. The signal is coupled out from the ring cavity by a piece of DCAF serves as a variable coupler, allowing the optimization of the output coupling ratio.

The laser ring cavity is built with a DCAF through free space coupling as shown in Fig. 6.1 (b). Table 6.1 records the transmitted power at different positions (as denoted in red font) to test the cavity loss. In the case, $P_C : P_D = P_4 : P_{Output} = 90:10$, the cavity loss $\alpha = -10\log(41/112) = 4.36\text{dB}$, with most of the losses induced by the lens absorption. This cavity loss can be greatly reduced by using lenses with proper anti-reflection coating. Moreover, all fibre coupling (refer to section 5.2.3) could significantly reduce the cavity loss which should be an important part of the future work.

Figure 6.1: (a) Setup schematic of the $1.06 \mu\text{m}$ Yb-doped fibre laser. (b) Setup schematic of the hollow core coupler by free space coupling.

Table 6.1: **Cavity Loss Measurement.**

Position	a	1	2	3	4(b)	5(c)	6	d	Output
Power(mW)	112	105	96	85	79	71	67	41	8

Under a certain length of YDF (i.e., fixed quantity of gain medium), as the pump power increases, the cavity gain can eventually overcome the cavity loss and the lasing output is achieved [134].

6.1.2 Experiment Results

Figure 6.3 (a) plots the signal power (central wavelength at $1.06 \mu\text{m}$) over different pump power (980 nm). Black curve and right curve correspond to the results measured at different output coupling ratio, $OC = 0.26$ and $OC = 0.16$, respectively, where $OC = P_D / (P_C + P_D)$ is determined by the tension applied on the DCAF as shown in Fig. 6.4.

Figure 6.2: (a) Cited from [17], Yb-doped fibre absorption and emission cross sections. (b) Cited from [18], transmission spectrum of the WDM.

The output spectrum as well as the output beam profile are also measured as shown in Fig. 6.3 (b). The linewidth of the output signal is as narrow as 2 nm with a central wavelength at 1057 nm. The signal-to-noise ratio is higher than 40 dB. The output of the laser is a single mode gaussian-like beam as indicated by the near field mode pattern.

By increasing OC from 0.16 to 0.26, the cavity loss increases, which then induces a higher threshold (see the inset in Fig. 6.3 (a)) but improves the slope efficiency. This is reasonable as the increasing of OC also increases the cavity loss. The influence of output coupling ratio OC on the signal power P_s is then studied.

The output signal power P_s in a single-mode ytterbium doped fibre laser can be estimated according to conservation of the total photon number [135,136]:

$$P_s = \eta_{cav} \times [P_p \xi (1 - A) - P_{th}] \frac{h\nu_s}{h\nu_p}, \quad (6.1)$$

Where ξ is a factor which represents the coupling efficiency from the pump source to the YDF, P_p is the launched pump power, $h\nu_s$ and $h\nu_p$ are the energies of signal and pump photons respectively. These parameters are constants. The variables in equation 6.1 are pump threshold power P_{th} , single pass pump loss A ($1 - A$ represents relative amount of the absorbed pump power) and cavity efficiency η_{cav} . The cavity efficiency is defined ratio of output power over the power feedback to the YDF:

Figure 6.3: (a) Evolution of signal power as launched pump power increases. (b) Output spectrum under 340 mW pump power, and 26 % output coupling ratio.

$$\eta_{cav} = \frac{(1 - L_{ab})OC}{1 - (1 - L_{ab})(1 - OC)(1 - L_{cd})(1 - L_{de})}, \quad (6.2)$$

Where L_{ab} , L_{cd} , and L_{de} , are relative losses between a and b, c and d, d and e in anticlockwise direction in the configuration and can be calculated according to table 6.1. Locations of a to e are pointed out in Fig.6.1 with red fonts. From this expression it is indicated that the position of lossy components (such as optical isolator) are very important: the cavity efficiency will be maximized when lossy components are placed between c and d in anticlockwise direction. It can be calculated that $\eta'_{cav}(OC) > 0, \eta''_{cav}(OC) < 0, OC \in (0, 1)$. Hence as T increases, the first term in

Figure 6.4: Plot the output coupling ratio over tension applied on DCAF. The tension is represented by the translation stage travel distance.

equation 6.1, i.e., η_{cav} also gets larger but with a decreasing growing rate. On the other hand, the value of the second term in equation 6.1, i.e., $[P_p \xi(1 - A) - P_{th}]$, becomes smaller as OC increases, the reason is that the increasing cavity loss enlarges the value of single pass pump loss A and pump threshold power P_{th} . The physical meaning of term $[P_p \xi(1 - A) - P_{th}]$ relates to the absorbed pump power by YDF.

When, OC becomes smaller, the increasing rate of the first term is larger than the decreasing rate of the second term [136], hence P_s grows with the increasing OC . Once the value of OC is large enough, the increasing rate of the first term begins to be slower than the decreasing rate of the second term, and as a result, the value of P_s decreases. Therefore, there exists a optimized OC value under which the signal power P_s reaches its maximum. The sketch diagram of this process is illustrated in Fig.6.5.

In this presented work, the optimized output coupling ratio can be easily obtained due to the variable coupling feature of the DCAF. As is shown in Fig. 6.6, the maximum output signal power can be achieved as the output coupling ratio is optimized to around 0.27, with a maximized slope efficiency around 15.4 %.

Figure 6.5: Schematic diagram to show the evolution trend of output signal power over output coupling ratio.

6.2 Ultra-Fast Pulse Delivery and Splitting

Since the conventional solid core fibres are limited by the dispersion and high non-linearity for ultrafast pulse delivery, free space transmission has been the only way to deliver ultra fast laser pulses for a long time [137], until the emerge of hollow core fibres. Hollow core fibres have been demonstrated to realize the high energy ultra fast pulse delivery and generation for the reason that hollow core fibres can get rid of the limits induced by core materials such as dispersion and nonlinearity [44, 103, 138]. Although fibre based ultra fast beam delivery has been come true with hollow core fibres, to the best of my knowledge, there is no demonstration of fibre based splitter for ultra fast pulses. In this section, a piece of DCAF is proved to be able to deliver and split the femtosecond pulse without notable degradation, hence has the potential to serve as a fibre optic splitter for ultra fast pulses. DCAF can work together with hollow core fibres to realize all fibre-based delivery systems with multiplexing function for ultra fast pulses.

6.2.1 Experiment Method

The schematic of the experiment setup for femtosecond pulse delivery is shown in Fig. 6.7. I used a homemade femtosecond laser built by Dr. Ma Jie at Prof.

Figure 6.6: Measured output signal power for various output coupling ratio at $1.06 \mu m$. Pump power is 340 mW.

Tang Dingyuan's group [19] as the light source. The femtosecond pulses have a spectral bandwidth of 26 nm with central wavelength at 1055 nm, a pulse repetition frequency of 113.5 MHz, a pulse duration of 47 fs, a single pulse energy of 2 nJ, and a pulse peak power of 43 kW. The light is coupled into the fibre under test (FUT) using a plane-convex lens with 30 mm focal length (L1). The transmitted beam is then collimated by another plane-convex lens with 8 mm focal length and then launched into an auto correlator for pulse width measurement. FUT in the setup can either be a DCAF (to evaluate the performance of DCAF) or a multimode fibre (MMF, for comparison).

6.2.2 Experiment Results

As is depicted in Fig. 6.7, the ultra fast laser beam with 47 fs pulse width is coupled into port A of a 40 cm DCAF, the power splitting ratio $P_C : P_D = 50 : 50$, where P_C and P_D are the power measured at port C and port D, respectively. The measured

Figure 6.7: Schematic of experiment setup for femtosecond pulse delivery and splitting. L1 and L2 are focusing lens; FUT is the fibre under test, it can be a DCAF, or a multimode fibre (MMF). The internal structure of the femtosecond laser is illustrated in Fig. 1 in [19].

pulse shape of port C and D are illustrated by the black curves in Fig. 6.8 (a) and (b), respectively. Red curves in Fig. 6.8 are the fitted curves with sech^2 shape. The measured pulse width of port C and port D are 75 fs and 70 fs respectively, which are almost the same (Please note to obtain the real pulse width, the measured width of the fitted curve should be divided by 1.543 which is the autocorrelation factor for sech^2 pulse). The output pulses from both port C and port D only suffer slight broadening compared to the 47 fs incident pulse. Moreover, the insets in Fig.6.8 show the beam profile of the output beam which indicate the single mode transmission.

Figure 6.8: Measured and fitted pulse at (a) port C, and (b) port D when light is coupled into port A of a 40 cm DCAF. $P_C : P_D = 50 : 50$, where P_C and P_D are the power measured at port C and port D, respectively.

To further verify the superior of hollow core waveguide over solid core, in the same setup as shown in Fig. 6.7, a 40 cm MMF is used instead of a 40 cm DCAF. The measured pulse after propagating through the 40 cm MMF is then compared with

the original pulse and the transmitted pulse after going through the 40 cm DCAF, as shown in Fig. 6.9. It is obvious that the DCAF can deliver and split the ultra fast laser beam without apparent degradation while the MMF suffers severe pulse broadening of 500 fs.

Figure 6.9: Original pulse from the laser source (blue, 47 fs), the transmitted pulse after propagating through a 40 cm MMF (black, 500 fs) and a 40 cm DCAF (purple and green, 75 fs and 70 fs, respectively).

I then study the effects of various tension (or different power splitting ratio) on the transmitted pulse widths. From Fig. 6.10, we can notice that transmitted pulse width of port C keeps invariant for various power splitting ratio. The same effect has also been observed with port D. Therefore, it can be concluded that the transmitted pulse width of the DCAF is independent with the power splitting ratio.

The results in Fig 6.10 can also be theoretically estimated, the process is the following subsection.

6.2.3 Theoretical Estimation

Pulse broadening is mainly induced by group velocity dispersion (GVD) and nonlinear effects [139]. The dispersion length L_D and the nonlinear length L_{NL} indicate

Figure 6.10: Transmitted pulse width keeps invariant as power splitting ratio varies.

the distance scales over which dispersive or nonlinear effects become important for pulse evolution. L_D and L_{NL} are defined as:

$$L_D = \frac{T_0^2}{|\beta_2|}, L_{NL} = \frac{1}{\gamma P_0}, \quad (6.3)$$

Where T_0 is full width at half maximum (FWHM) of incident pulse, β_2 represents dispersion of the group velocity and is responsible for pulse broadening, P_0 is peak power of the incident pulse, and γ is the nonlinear coefficient and can be calculated by the following equation:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \quad (6.4)$$

Where n_2 is the nonlinear index of fibre core material, A_{eff} is the effective mode area, and λ is the central wavelength of the pulse.

In my case, $P_0 = 43$ kW, $T_0 = 47$ fs, $\lambda = 1055$ nm, the following table is obtained according to equation 6.3 and 6.4.

Table 6.2: Dispersion and Nonlinear Length Calculation					
Fiber Type	$n_2(10^{-20}cm^2/W)$	$A_{eff}(\mu m^2)$	$ \beta_2 (ps^2/km)$	$L_{NL}(m)$	$L_D(m)$
MMF	2.8×10^4 [139]	655	23.3 [140]	0.087	0.095
DCAF	8.0 [141]	210	1.75	97.0	1.262

The effective mode areas in table 6.2 are the simulated values by using Polymode assuming that the beam is guided in the fundamental mode. Effective refractive index around 1055 nm of the DCAF has also been simulated and fitted into the curve: $n(\lambda) = -1.768 \times 10^{-12}\lambda^3 + 5.175 \times 10^{-19}\lambda^2 - 5.599 \times 10^{-6}\lambda + 1.002$, as is plotted in Fig. 6.11. β_2 of DCAF is then calculated according to the formula $\beta_2 = \frac{\lambda^3}{2\pi c^2} \frac{d^2 n}{d\lambda^2}$ [139].

Figure 6.11: Simulated and fitted value of effective index of DCAF.

In both cases, fibre length L is set at 0.4 m. For MMF, since $L_D < L, L_{NL} < L$, dispersion and nonlinearity act together as the pulse propagates along the fibre [139]. The code in Appendix B in [139] based on split-step method is used to simulate the pulse evolution. The simulated results are shown in Figure 6.12, the pulse broadening factor (output pulse width over input pulse width) is around 6.4, which is comparable to the measured pulse broadening factor (around 10) of the 40 cm MMF. The discrepancy is attributed to the error between actual and estimated value of A_{eff} , β_2 and n_2 .

For DCAF, since $L_D > L, L_{NL} \gg L$, neither dispersive nor nonlinear effects play an important role in pulse propagation, and the pulse will not suffer notable degradation [139]. This prediction is then verified by the simulation results in Figure 6.13 which indicates a pulse broadening factor as small as 1.15 while the measured pulse broadening factor is 1.6. This discrepancy is acceptable and reasonable. In theoreti-

Figure 6.12: Simulated pulse shape before and after propagating through a 40 cm MMF.

cal analysis, the overlap between core modes and silica walls has not been taken into consideration. In fact, since the nonlinear index of silica is four magnitudes higher than that of air [139,141], even 0.5 % percentage light in silica can significantly enhance the nonlinear effects. And this should be responsible for the discrepancy between the simulation and experiment results.

6.3 Conclusion

Overall, in this chapter, I demonstrated two promising applications of DCAF. The first demonstration is a ytterbium doped fibre laser. In this laser system, the DCAF plays a role as a variable coupler and the variable coupling feature helps to optimize the laser performance. The other demonstration is the application of DCAF in femtosecond pulse delivery as well as splitting. Both experimental results and theoretical analysis support that DCAF is able to deliver femtosecond pulses without significant broadening, which is much better than the solid core fibres. To the best of my knowledge, this is the first demonstration of ultra-fast pulse delivery and power splitting with dual hollow-core fibre.

Figure 6.13: Simulated pulse shape before and after propagating through a 0.4 m DCAF.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

As a novel fibre design which enables the light guidance in the air with broad transmission windows, HAF has attracted attentions of many researchers in the past decade. In this thesis, I manage to improve the applicability of HAFs, especially in fibre laser applications. The contributions of the thesis can be summarized as below:

- I have developed the fabrication technique for PCFs with local facilities. The fabricated HAFs are in good uniform structure and suffers low transmission loss over multiple transmission bands.
- I have proposed a 2TLF design. The 2TLF has been fabricated and characterized and has been proved to allow independent control of key structural parameters to achieve the design purposes without compromise. Therefore, 2TLF can have small core size, low confinement loss and low bending loss simultaneously and is promising for gas light interaction applications.
- I have proposed, fabricated and characterized the DCAF. The DCAF works stably as a fibre coupler and shows a variable coupling feature by applying

different mechanical tension. The application of HAFs, especially the mid-IR laser application, must benefit from the invention of such a hollow core fibre coupler.

- I have demonstrated the robust coupling performance and applicability of the DCAF in forming a fibre laser ring cavity. The various coupling feature of the DCAF is demonstrated to be helpful to the laser performance optimization.
- I have realized the femtosecond pulse delivery and power splitting without notable pulse broadening with a DCAF. The capability of the DCAF in ultra fast pulse delivery is verified by both numerical calculation and experiment.

7.2 Future Work

I list some possible directions for future studies.

- Figure 4.13 only provides measurement results. It would be more persuasive if simulation results can be provided. However, memory errors arise when trying to simulate the bent fibre model and the problem hasn't been solved yet. Therefore, one of my future work is to simulate the bending loss to support the measurement results.
- In Chapter 4, it is proved that the CL of 2TLF grows slowly with the increasing of D/λ , hence a 2TLF should have good performance in both the cases of small core and mid-IR. However, a small core ($D < 15\mu m$) means extremely great cane to fibre draw down ratio which may induce significant structural deformation. As a result, limited by the fibre fabrication technique, in the current stage, I cannot fabricate the 2TLF with a core diameter $D < 15\mu m$. Therefore, in the future, I am going to improve our art of fibre fabrication to draw the small core 2TLF with good structure, which will benefit the applicability of 2TLF in terms of fibre laser applications. In addition, the characterization

of fibre performance in mid-IR ($\lambda > 2.9\mu m$) region is restricted by the scarcity of light source and optical detector. Therefore, in the next stage, I also plan to cooperate with other groups who possess mid-IR light source and mid-IR detector, to characterize the mid-IR performance of 2TLF.

- In Chapter 5, a DCAF has been proposed. A DCAF can work as an optical coupler but through free space coupling without additional fibre connections. The strategy to realize all fibre coupling has already been proposed in section 5.2.3 but has not yet been demonstrated. Hence, to demonstrate the all fibre coupling with a DCAF is also one of my future plan.
- One of the most promising application area of the air core guidance is mid-IR. Scarcity of mid-IR fibre coupler is an unsolved problem for the realization of mid-IR fibre laser. Efforts on developing a mid-IR fibre coupler were attempted via fusing ZBLAN or chalcogenide fibres [142] as well as via dual hollow core silica fibres (please refer to section 5.1). Despite the prior efforts, challenges still remain in obtaining reliable coupler due to weak physical strength of soft glass fibres and limited coupling effects in the dual hollow core fibre. In the work of this thesis, I have designed and fabricated the DCAFs and demonstrated a near-IR fibre laser with the DCAF (section 6.1) to verify the applicability of DCAF in fibre laser systems. Besides, a DCAF which complies with the antiresonant waveguide mechanism (see section 5.3.1) should work normally even at mid-IR wavelengths. Thus, another future work is to build an all hollow core fibre based mid-IR laser with 2TLF and DCAF.
- In Chapter 4, the second cladding layer of a TLF is proved to reduce the CL in small core and long wavelength conditions. One of the future directions is adding a second cladding layer to the current DCAF design (which has only one cladding layer) to improve the performance of DCAF in mid-IR applications.

Appendix A

Numerical Code for Pulse Evolution

```
% This code solves the NLS equation with the split-step method
% This code is compiled by Matlab, based on the code written by Govind P. Agrawal
%  $idu/dz - \text{sgn}(\beta_2)/2 d^2u/d(\tau)^2 + N^2|u|^2u = 0$ 

%—Specify input parameters
clear all; %
distance = input('Enter fiber length (in units of L_D) = '); %
beta2 = input('dispersion: 1 for normal, -1 for anomalous'); %
N = input('Nonlinear parameter N = '); % soliton order
mshape = input('m = 0 for sech, m>0 for super-Gaussian = ');
chirp0 = 0; % input pulse chirp (default value)
%—set simulation parameters
nt = 1024*20; Tmax = 32*10; % FFT points and window size
step_num = round(20*distance*N^2); % No. of z steps to
deltaz = distance/step_num; % step size in z
dtau = (2*Tmax)/nt; % step size in tau
%—tau and omega arrays
```

```
tau = (-nt/2:nt/2-1)*dtau; % temporal grid
omega = (pi/Tmax)*[(0:nt/2-1) (-nt/2:-1)]; % frequency grid
%—Input Field profile
if mshape==0
uu = sech(tau).*exp(-0.5i*chirp0*tau.^2); % soliton
else % super-Gaussian
uu = exp(-0.5*(1+1i*chirp0).*tau.^(2*mshape));
end
%—Plot input pulse shape and spectrum
temp = fftshift(iff(uu)).*(nt*dtau)/sqrt(2*pi); % spectrum
figure; subplot(2,1,1);
plot(tau, abs(uu).^2, '-b'); hold on;
axis([-10 10 0 inf]);
xlabel('Normalized Time');
ylabel('Intensity (a.u.)');
title('Input and Output Pulse Shape and Spectrum');
subplot(2,1,2);
plot(fftshift(omega)/(2*pi), abs(temp).^2, '-b'); hold on;
axis([-0.5 0.5 0 inf]);
xlabel('Normalized Frequency');
ylabel('Spectral Power');
%—store dispersive phase shifts to speedup code
dispersion = exp(i*0.5*beta2*omega.^2*deltaz); % phase factor
hhz = 1i*N^2*deltaz; % nonlinear phase factor

%*****[ Beginning of MAIN Loop]*****
% scheme: 1/2N -> D -> 1/2N; first half step nonlinear
temp = uu.*exp(abs(uu).^2.*hhz/2); % note hhz/2
for n=1:step_num
f_temp = ifft(temp).*dispersion;
```

```
uu = fft(f_temp);
temp = uu.*exp(abs(uu).^2.*hhz);
end
uu = temp.*exp(-abs(uu).^2.*hhz/2); % Final field
temp = fftshift(iff(uu)).*(nt*dtau)/sqrt(2*pi); %Final spectrum
%*****[ End of MAIN Loop ]*****
%—Plot output pulse shape and spectrum
subplot(2,1,1)
plot(tau, 1*abs(uu).^2, 'r')
subplot(2,1,2)
plot(fftshift(omega)/(2*pi), abs(temp).^2, 'r')
%—Plot input pulse shape and spectrum
```


Appendix B

Python Code for TLF Simulation

```
# This code is used to simulate the confinement loss of tube lattice fiber  
# This code is compiled by python, written by Huang Xiaosheng in 2015
```

```
from pylab import * # module plot graphs  
from numpy import * # module about numerical  
from Polymode import * # PCF modules
```

```
# ——Set Parameters——
```

```
# Materials
```

```
air = Material.Air()
```

```
SiO2 = Material.Silica()
```

```
SiO2.color='orange'
```

```
sym = 6 # symmetry class of structure
```

```
Ny = (600,140) # resolution used to calculate mode
```

```
Nx =(800,200) # resolution used to plot the mode
```

```
m0=1
```

```

wlscan=arange(1.06,1.07,0.02) #wavelength scanning
neff=0.9997 # search mode around this effective index

layer = 1 # number of cladding layers
a=16.2 # inner core radius
t=1.45 # wall thickness
p=20.3 # capillary size

# Create jacket tube
wg = Waveguide.Waveguide(material=SiO2,rmax=p+a+t*4, symmetry=sym)
s0=Waveguide.Circle(air,center=(0,0),radius=p+a)
wg.add_shapes(s0)

# Create cladding capillaries
s0=Waveguide.Circle(SiO2,center=(a+p*0.5,0),radius=p*0.5)
wg.add_shapes(s0)
s0=Waveguide.Circle(air,center=(a+p*0.5,0),radius=p*0.5-t)
wg.add_shapes(s0)

# create lists to store relevant data
wls=[]
neffs=[]
losses=[]
Aeffs=[]

for wl in wlscan:
    modes=[] # store mode
    solver = NLSolver.DefaultSolver(wg,Ny)
    Plotter.figure()
    # wg.plot() # plot waveguide structure

```

```
# Plotter.show()
# print the settings print wl
print neff
print Ny
modes=solver(wl,m0,neff,number=2)# find the 2 modes around neff
# plot modes and find out the fundamental mode
for j in xrange(0,len(modes)):
    subplot(2,1,j+1)
    temp='wl=%f'%wl
    temp2='neff=%f '%real(modes[j].neff)
    title=temp2+temp
    #modes[j].plot(wg=wg,Nx=Ny,title=title)
    print modes[j].info()
    if abs(imag(modes[0].neff))<abs(imag(modes[1].neff)):
        neff=real(modes[0].neff)
    if abs(imag(modes[1].neff))<abs(imag(modes[0].neff)):
        neff=real(modes[1].neff)
    # Plotter.show()
    loss=4*pi*abs(imag(modes[0].neff))*4.343*0.001/(wl*1e-9)
    neff=real(modes[0].neff)
    Aeff=real(modes[0].effective_area())
    neffs.append(neff) # record neff
    wls.append(wl) # record group velocity
    losses.append(loss)# record loss
    Aeffs.append(Aeff)# record effective mode area

# print results
for i in range(0,len(wls)):
    print "wl:",wls[i]
    print "neff:",neffs[i]
```

```
print "loss",losses[i]  
print "Aeff",Aeffs[i]
```


Author's Publications

Journal papers:

1. Huang X, Qi W, Ho D, Yong KT, Luan F, Yoo S. "Hollow core anti-resonant fiber with split cladding", *Optics Express*. 2016 Apr 4;24(7):7670-8.
2. Huang X, Yoo S, Yong K. "Function of second cladding layer in hollow core tube lattice fibers", *Scientific Reports*. 2017;7.
3. Huang X, Ma J, Tang D, Yoo S. "Hollow-core air-gap anti-resonant fiber couplers", *Optics Express*. 2017 Nov 13;25(23):29296-306.

Conference papers:

1. Huang X, Qi W, Ho D, Yong KT, Luan F, Yoo S, "Hollow core anti-resonant fibres with split cladding", Proc. SPIE 9728, *Fiber Lasers XIII: Technology, Systems, and Applications*, 972821 (March 11, 2016); doi:10.1117/12.2213902
2. Huang X, Luan F, Yoo S, and Yong KT, "High Efficiency Mid-infrared Acetylene Filled Fiber Laser", *The 9th International Conference on Nanophotonics (ICNP 2016)*, P-04-02.
3. Huang X, Ho D, Qi W, Yoo S. "Double layer hollow core anti-resonant fiber for small core and low loss characteristics", *InCLEO: Applications and Technology* 2017 May 14 (pp. JW2A-95). Optical Society of America.

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