国防科学技术大学
National University of Defense Technology

COMSOL CONFERENCE
2014 SHANGHAI

Simulation of Negative Curvature Hollow-core Fiber

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Excerpt from the Proceedings of the 2014 COMSOL Conference in Bangalore

INTRODUCTION

- Background
- Theory
- Results
- Summary

INTRODUCTION

- Background

1. Characteristics and applications of HCF

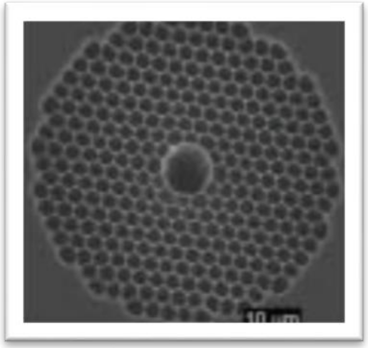
Characteristics

1） Low loss

HC-PBG

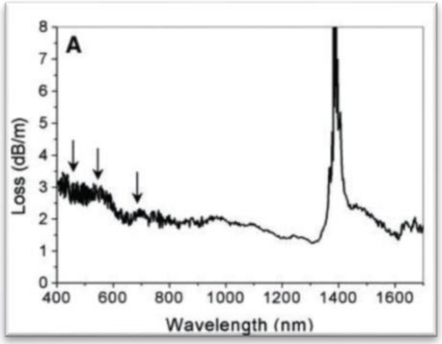
1.2dB/km @ 1620nm

50±30dB/km @ 3.33μm



2）Broad Bandwidth

Kagome fiber:
a few hundred nm



3） High threshold

Applications

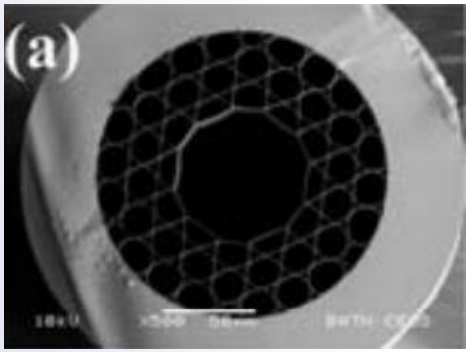
1） interaction between light and gases

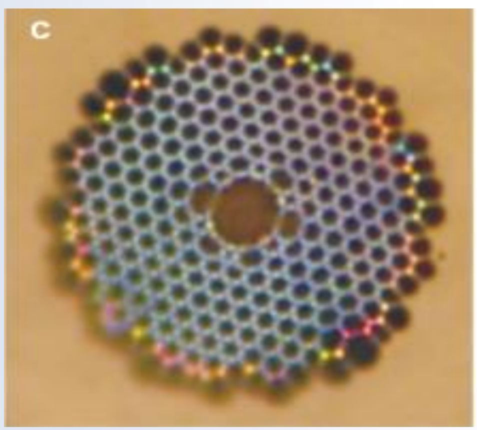
2） high-power laser transmission

3） ulterfast laser delivery

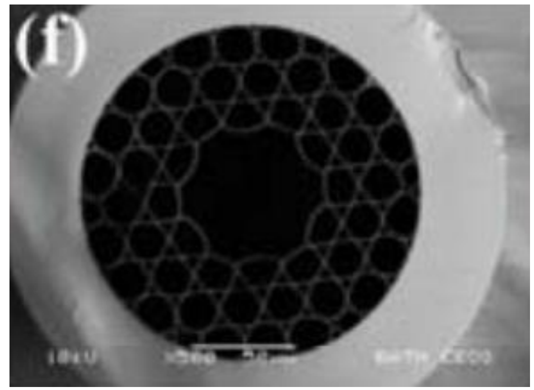
2. Negative Curvature Hollow-core Fiber

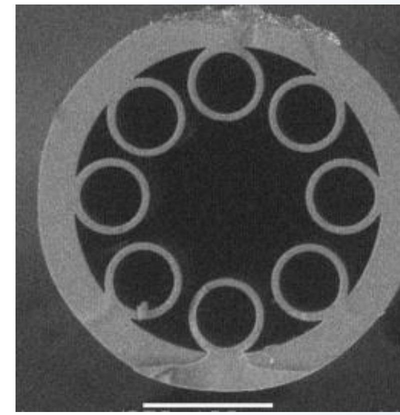
Normal Curvature

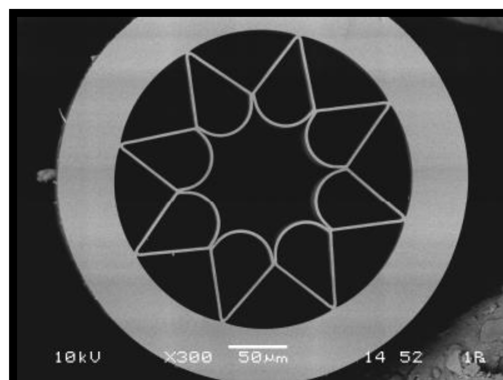


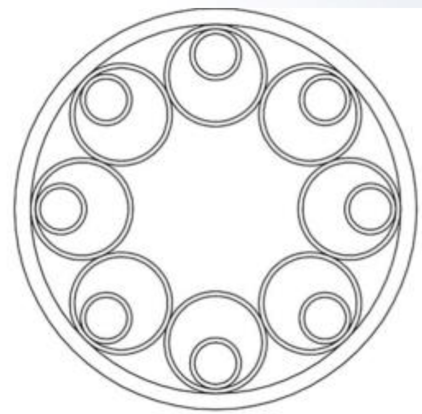


Negative Curvature









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3. Research Institutes

(1) UK	University of Bath
(2) France	Université de Limoges
(3) Italy	University of Modena and Reggio Emilia
(4) Russia	Russian Academy of Science

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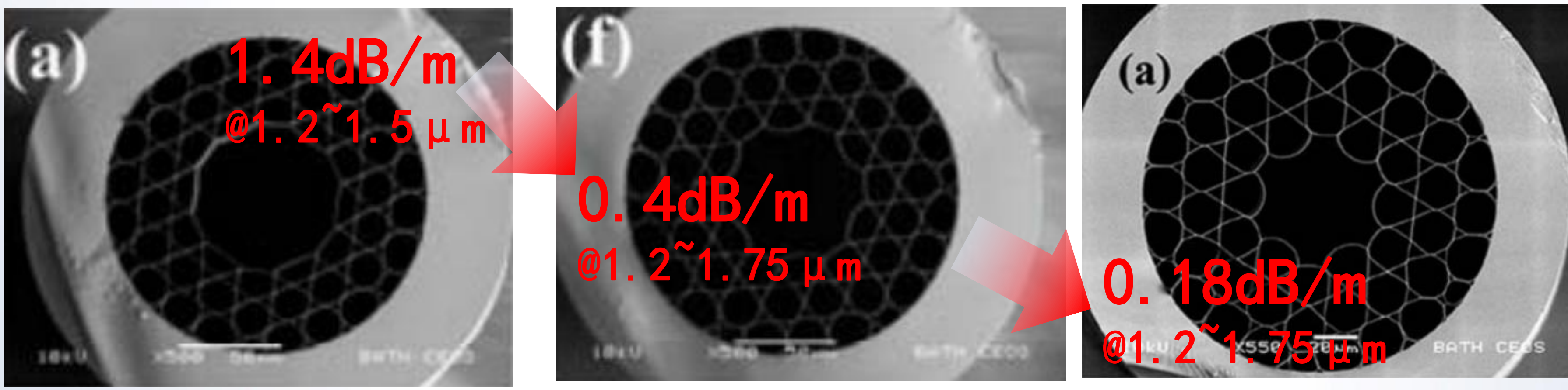
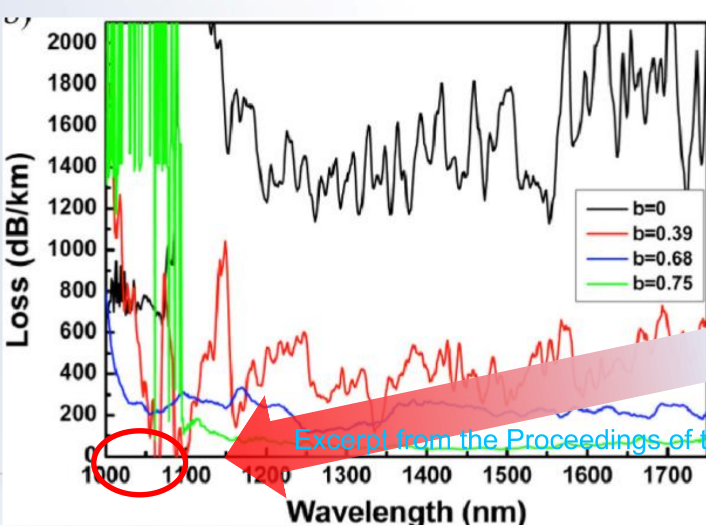
4. Review of NCHCF

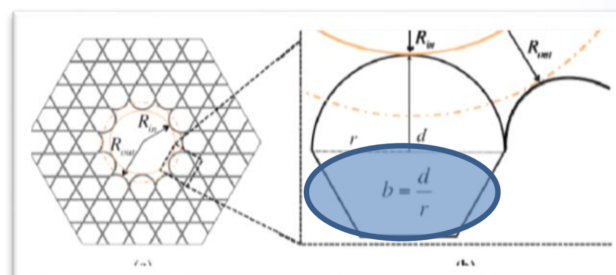


CLEO, 2010: CPDB4.

Opt. lett., 2011, 36(5): 669-671.

Kagome fiber with negative curvature of the core boundary achieved lower loss

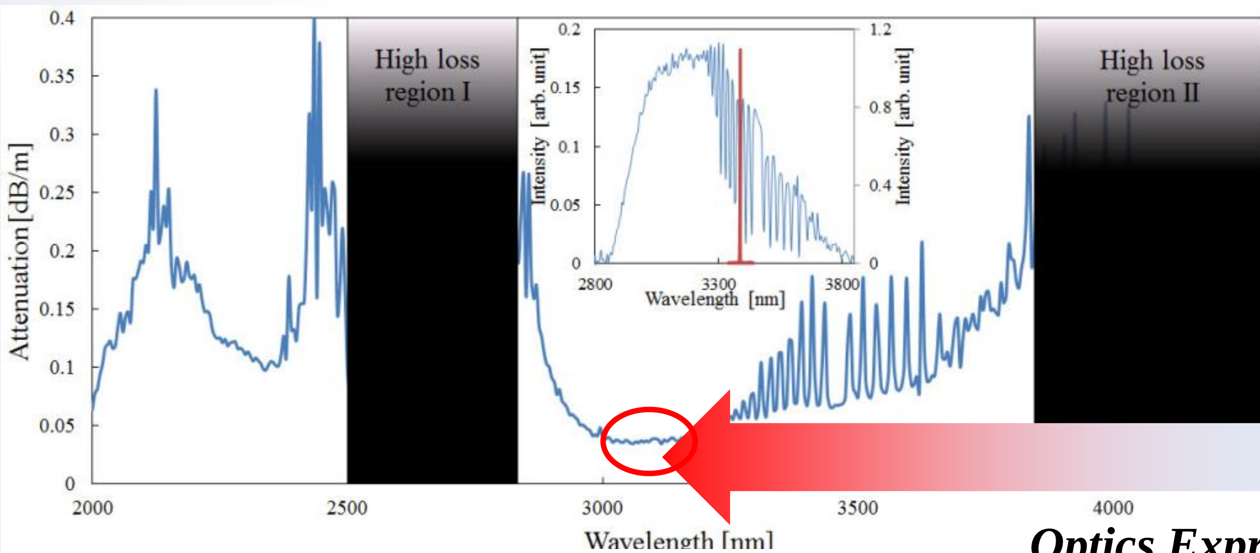


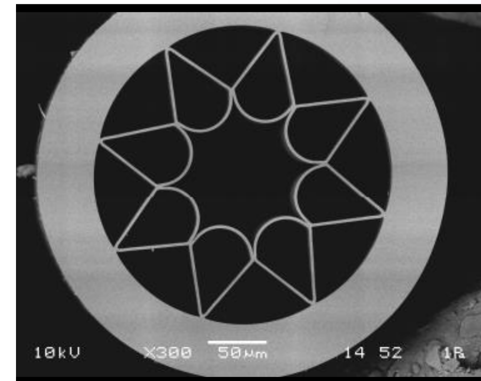


0.017dB/m @ 1.06μm

Optics Express, 2013, 21(23): 28597-28608.

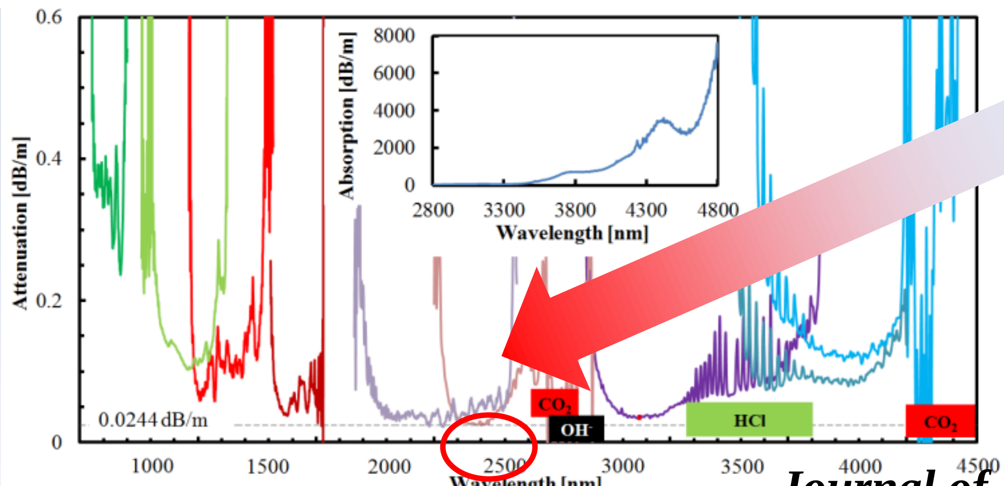
4. Review of NCHCF





34dB/km@3.05μm

Optics Express, 2012, 20(10): 11153-11158.



24dB/km@2.4μm

Successful applications:

1. 0.06dB/m@2.94μm Surgery
2. 0.23dB/m@1.030μm

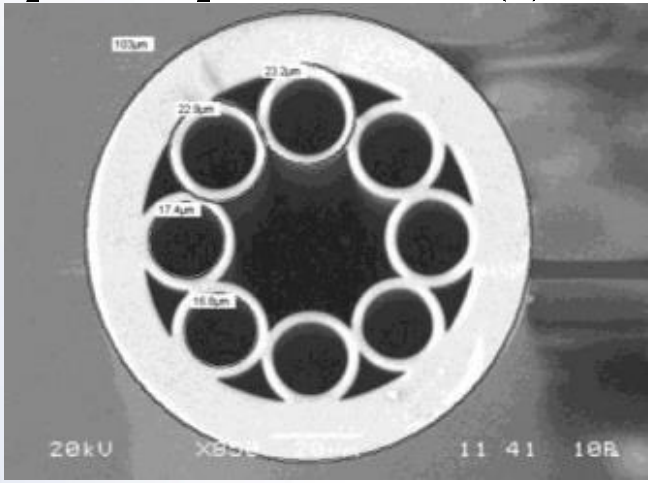
   0.16dB/m@1.064μm Micro-machining

Journal of Non-Crystalline Solids, 2013, 377: 236-239.

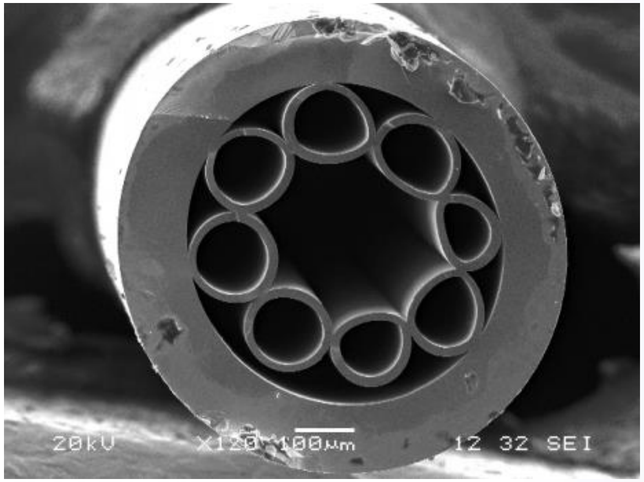
Optics Express, 2013, 21(18): 21466-21471. *Optics Express*, 2013, 21(19): 22742-22753.

4. Review of NCHCF

Optics Express, 2011, 19(2): 1441-1448.



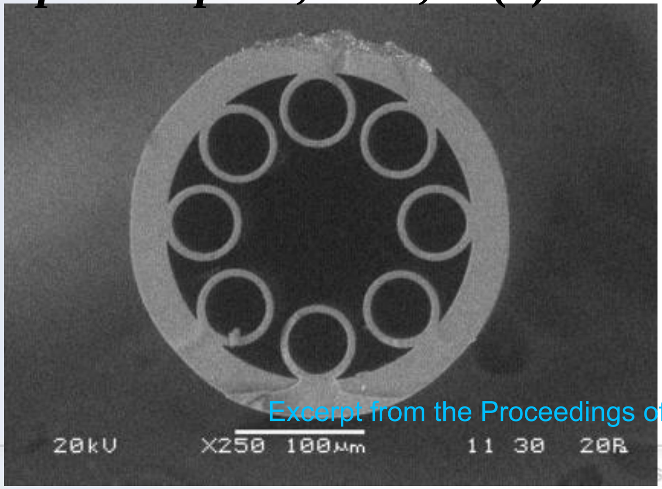
Optics Express, 2011, 19(25): 25723-25728.



>3.5μm Silica < 1 dB/m

10.6μm chalcogenide glass~13.5dB/m

Optics Express, 2013, 21(8): 9514-9519.



0.05dB/m @ 3.39μm Silica

Non-touching capillaries results in lower loss

INTRODUCTION

Theory

1. Failure of conventional mode theory

Eigenvalue Equation

$$\nabla^2 \vec{E} + k^2 \vec{E} = 0$$

$$\nabla^2 \vec{H} + k^2 \vec{H} = 0$$

↓

Standard Bessel Equation

$$(d_R^2 + R^{-1} d_R + 1 - m^2 R^{-2}) \psi(R) = 0$$

where $R^2 = r^2 U^2$

↓ $\beta = \beta_r + i\alpha$

Complex Bessel Equation

↓

Leaky Modes

$K_m(R)$ → $\boldsymbol{H_m(R)}$

$$\psi_{leaky} = \begin{cases} AJ_m, & \text{in the core} \\ BH_m, & \text{in the cladding} \end{cases}$$

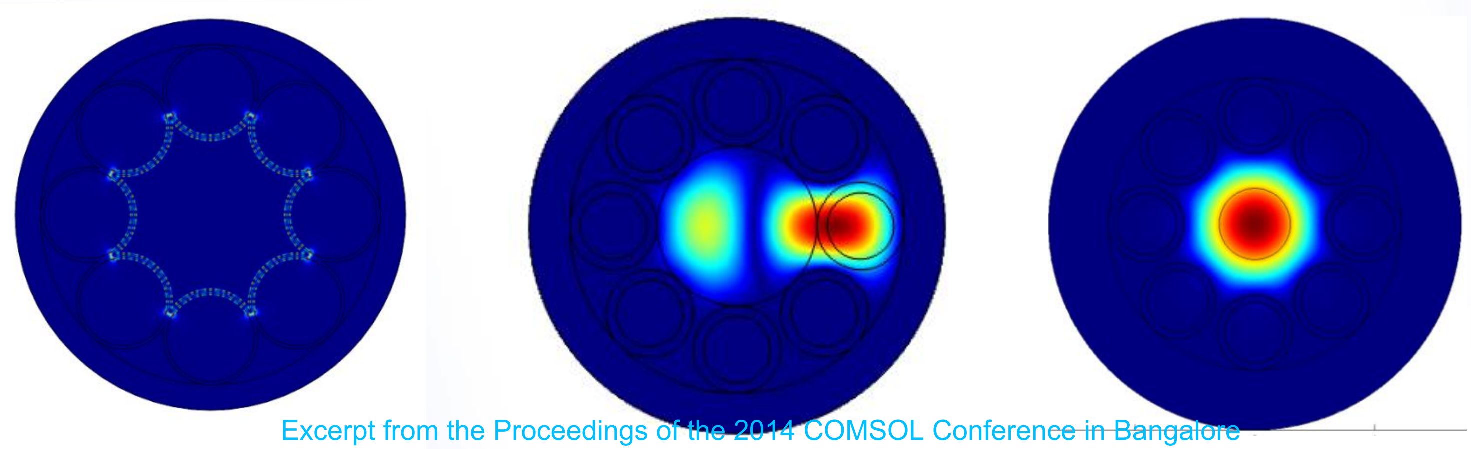
Mode theory of leaky fibers is under development!

2. Two common models

1. ARROW model

$$\lambda_{res} = \frac{2d}{m}\sqrt{n_2^2 - n_1^2}$$

2. Cladding leaky mode coupling model



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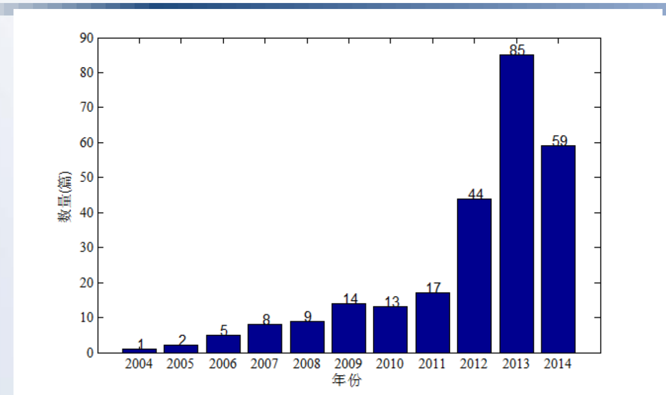
INTRODUCTION

Results

1. COMSOL Multiphysics



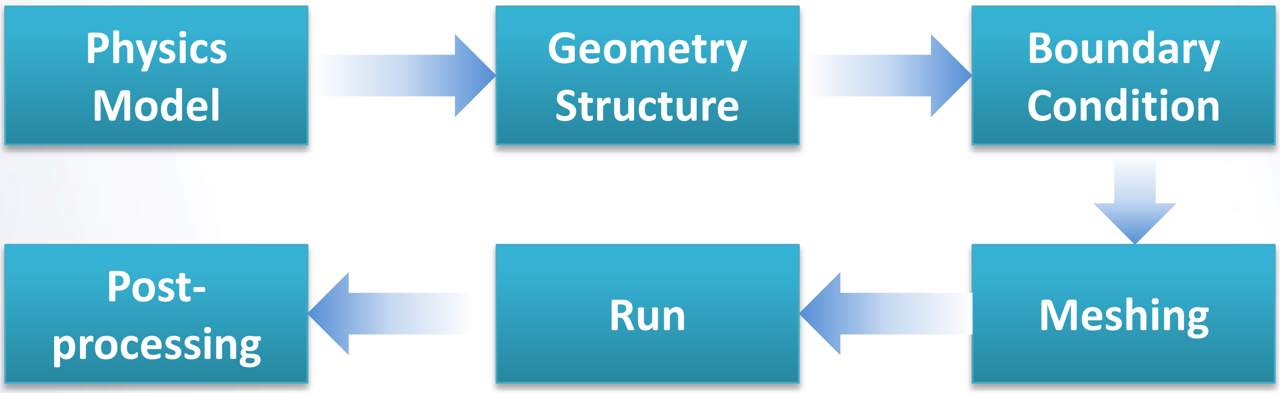
Number of COMSOL related articles in some journals of Nature Group(To 2014, May 20th)

Features：

1. Full vector finite element method, high precision
2. Multiphysics model coupling, wide application
3. Communication with MATLAB

flexibility development

Flow Chart



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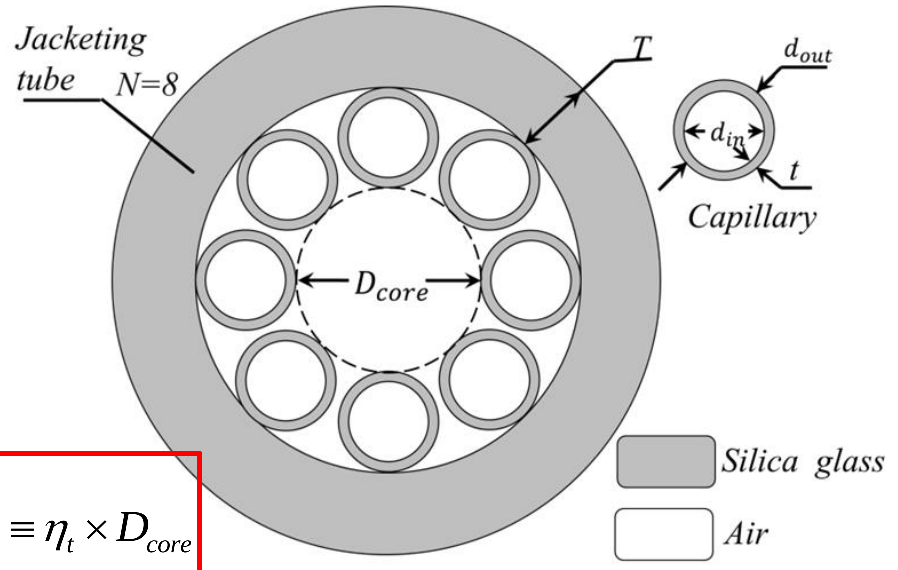
2. Geometry Structure



$$\eta_c = d_{in}/d_{out}$$

$$d_{out} = \frac{\sin(\pi/N)}{1-\sin(\pi/N)} \times D_{core} \equiv \eta_t \times D_{core}$$

Name	Symbol	Value
Diameters of the fiber core	D_{core}	119[um]
Number of capillaries	N	8
Outer diameter of the capillary	d_{out}	63[um]
Inner diameter of the capillary	d_{in}	51[um]
Thickness of the capillary	t	6[um]
Thickness of the jacketing tube	T	10[um]

3. Study

1. COMSOL GUI

2. LiveLink™ for MATLAB®

3. COMSOL Script

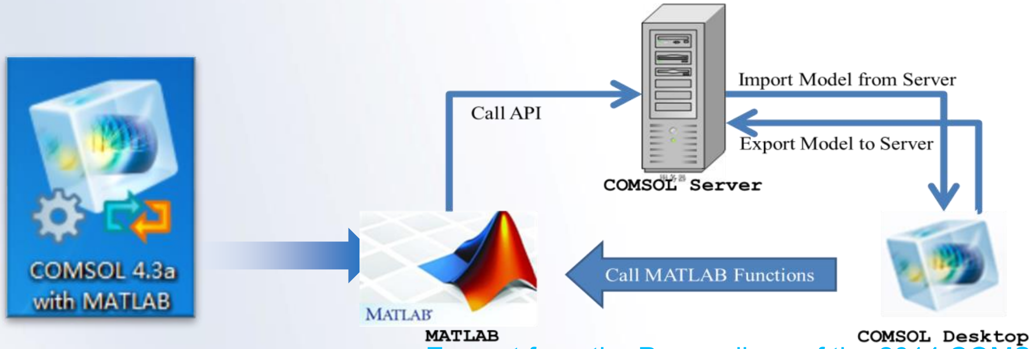
Wavelength

Separated distance

Thickness of jacket tube

Capillary coefficient

# of capillaries



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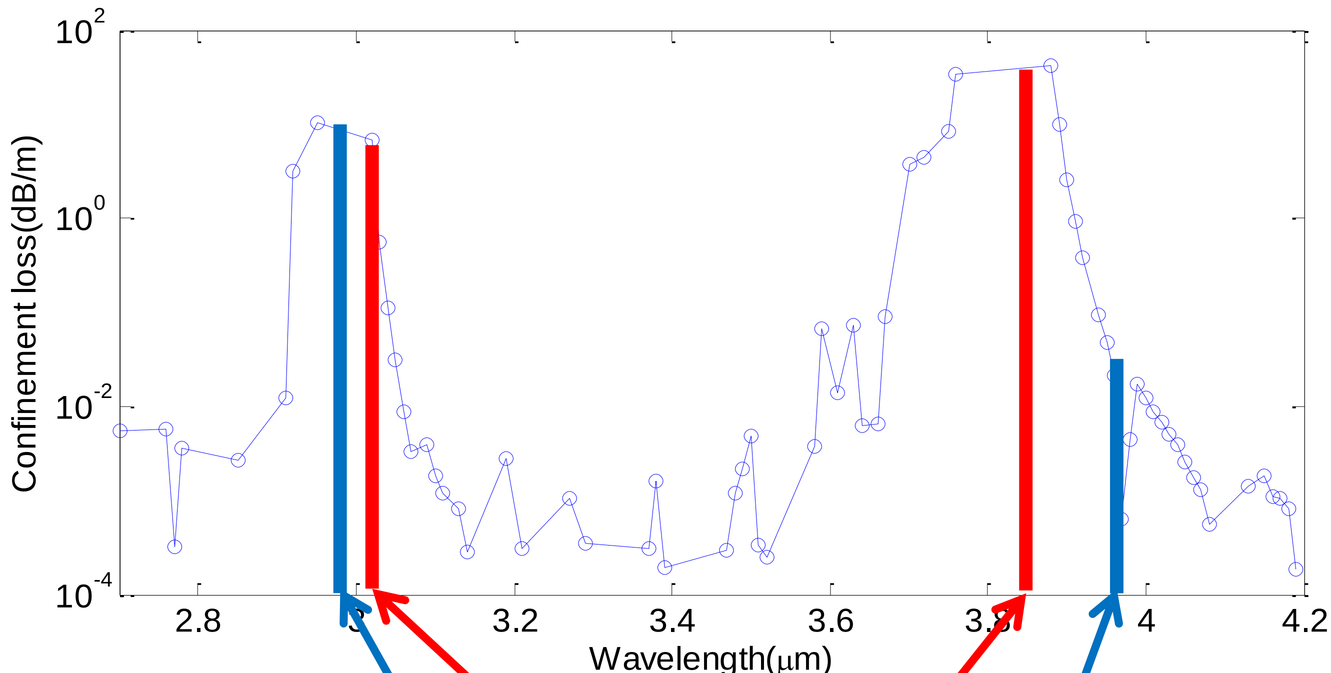
4. Results

Wavelength



After iteration

Mid-wavelength 3.4μm

$$\lambda_{res} = \frac{2d}{m}\sqrt{n_2^2 - n_1^2}$$

Loss peaks agreed well with ARROW model

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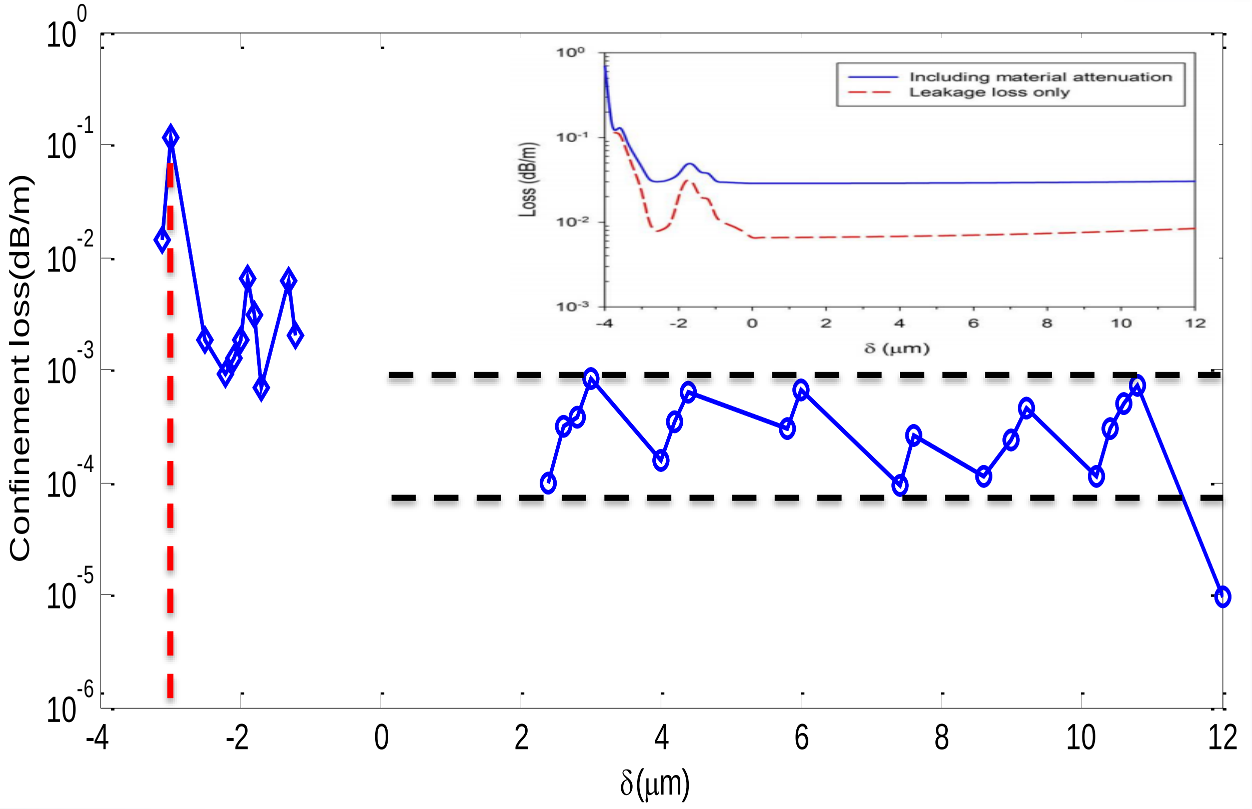
4. Results

Separated distance



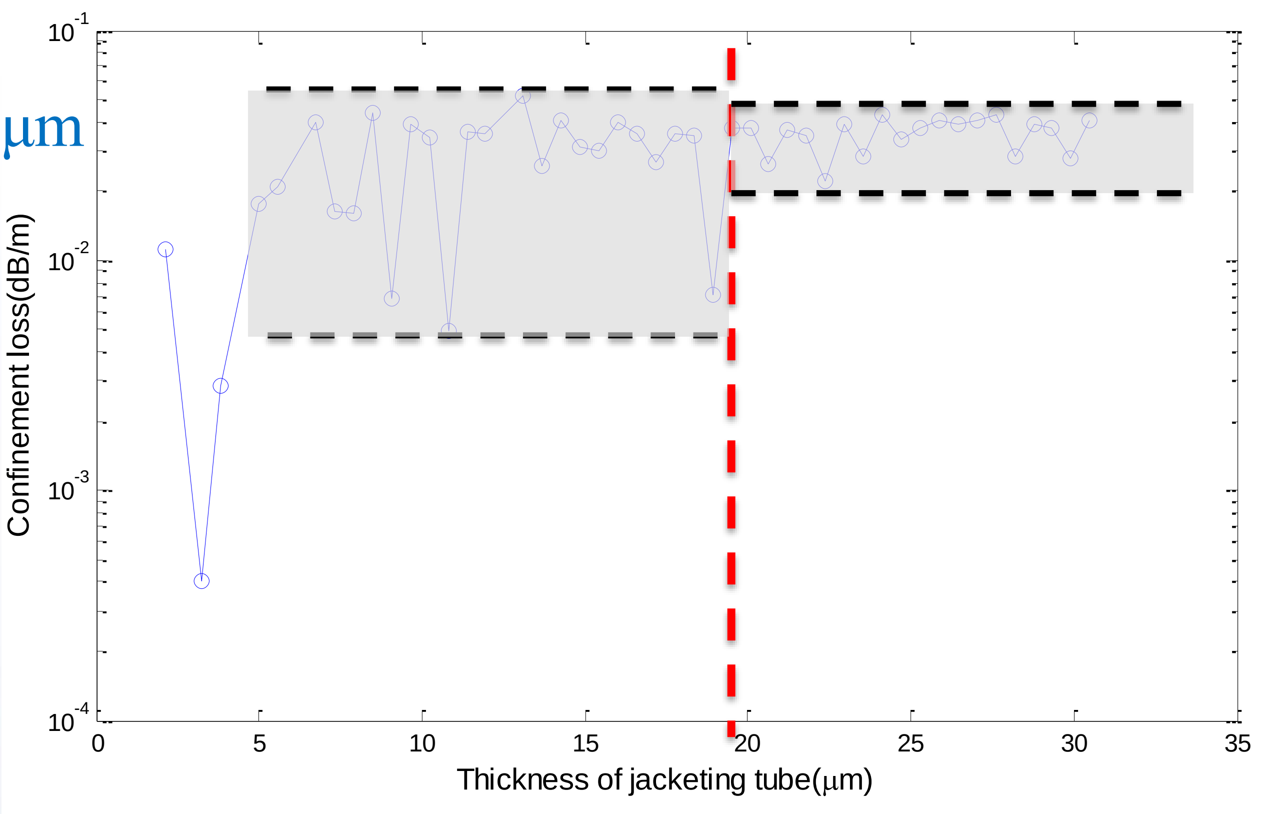
Non-touching capillaries resulted in lower loss

Optics Express, 2014, 22(8): 10091-10096.

4. Results

Thickness of jacketing tube

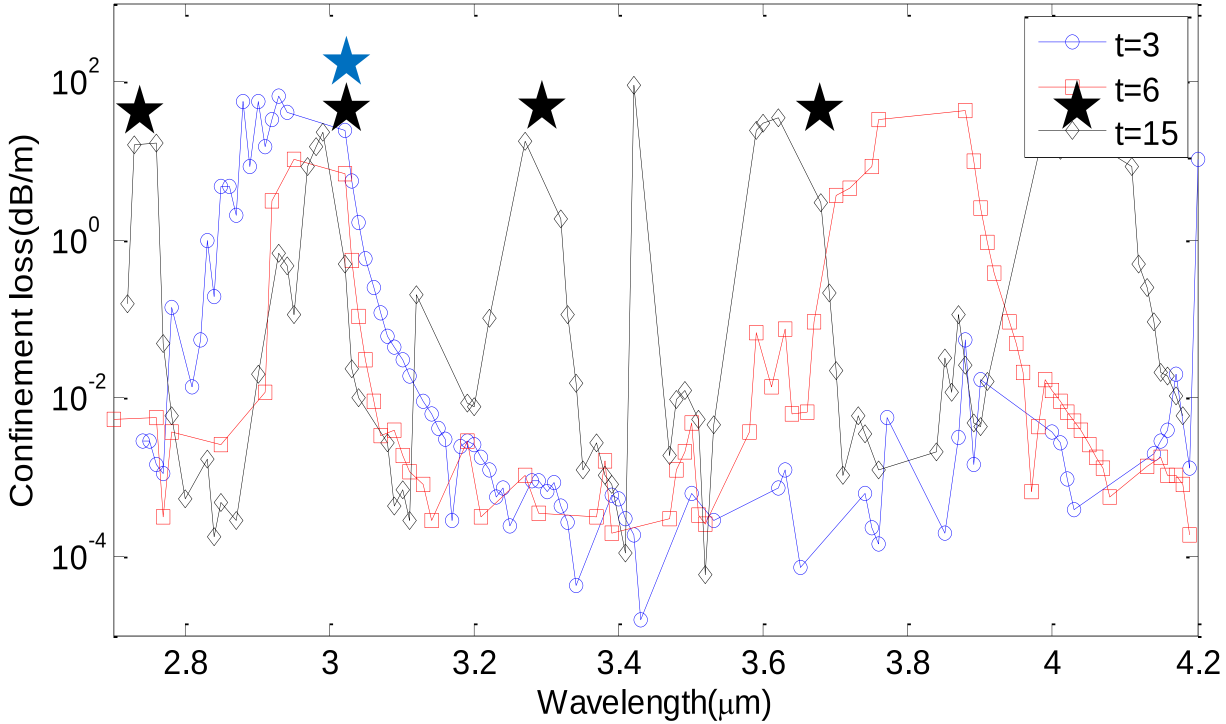
λ=3.05μm



Thickness of 20μm led to steady results

4. Results

Capillary coefficient



Thinner thickness of capillaries resulted in lower, wider and flatter spectral

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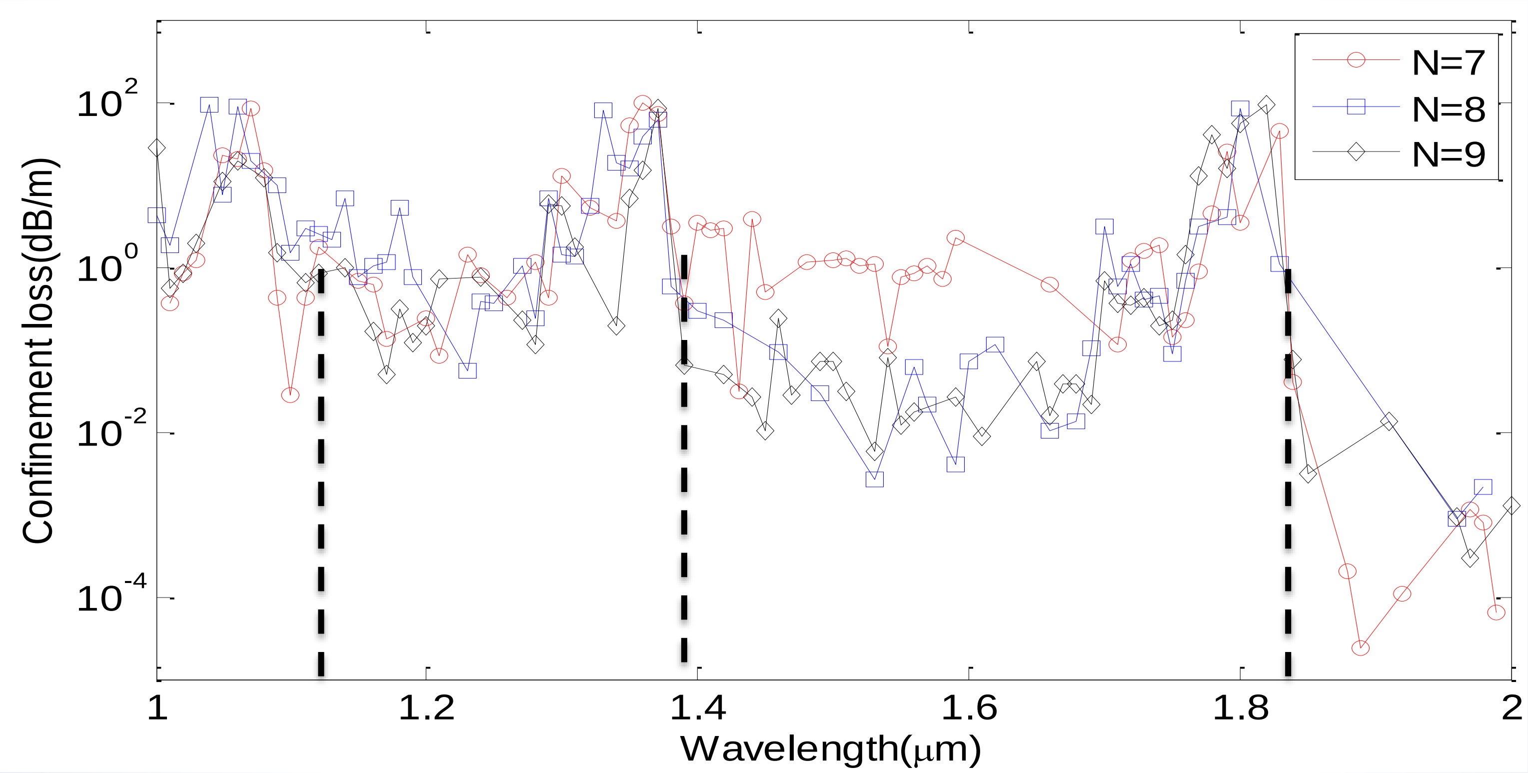
4. Results



# of capillaries

Number of capillaries had little effect on loss peaks in given thickness of capillaries

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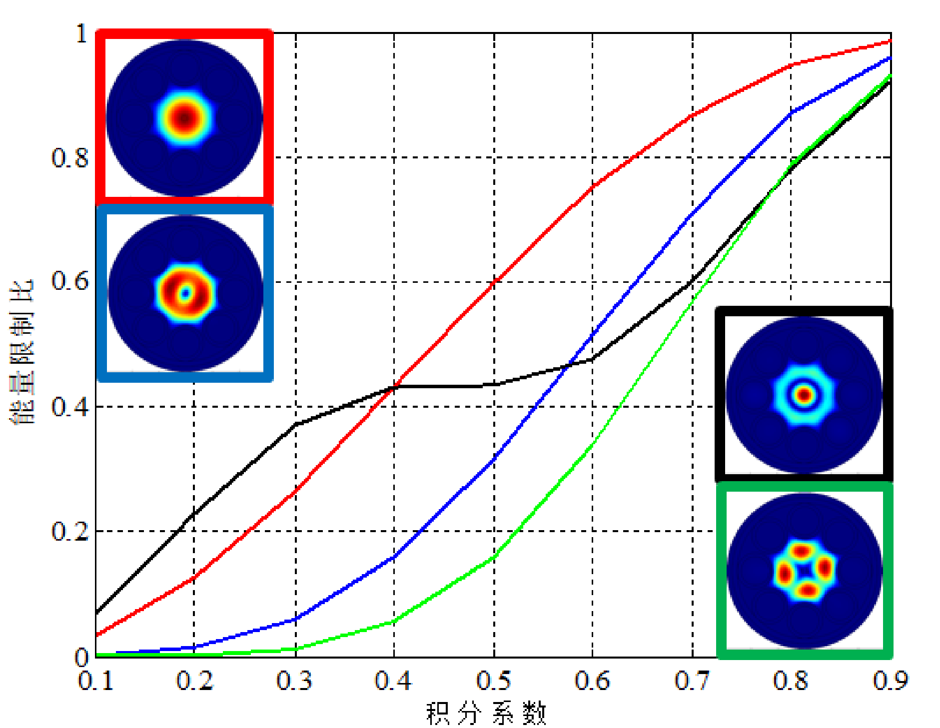
5. New criterion for mode selection

New idea

Mode confinement factor $\eta = \dfrac{P_{core}}{P_{total}}$

Energy confinement factor $\eta_P = \dfrac{P_c}{P_{total}} = \dfrac{\iint_{S_c} |P_z|^2 \, dxdy}{\iint_{S_f} |P_z|^2 \, dxdy}$

Integral coefficient $c_P = \dfrac{r_c}{r_{core}}$



MFC could effectively distinguish **core modes** from cladding modes

When C_p=0.5, ECF could distinguish **fundamental mode** from high-ordered modes

Conclusion

- ARROW model agreed well with the simulation results;
- Non-touching capillaries result in lower confinement loss;
- Specific geometry structure has a proper thickness of jacketing tube;
- Thinner thickness of capillary resulted in lower, wider and flatter spectral;
- ECF could effectively distinguish fundamental mode from high-ordered modes.

Acknowledgement

Acknowledgement

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Thanks COMSOL, for an excellent simulation platform

Thank you for your attention!