Simulations of Negative Curvature Hollow-core Fiber

Jiangbin Zhang, Zefeng Wang* and Jinbao Chen
College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha, P.R.China, 410073
*Corresponding author: 47 Yawachi Street, Changsha City, Hunan Province, P.R.China, 410073
hotrosemaths@163.com

Abstract: COMSOL Multiphysics was used to simulate and analyze the transmission attenuation spectra of negative curvature hollow-core fiber (NCHCF) over the wavelength from 2.7 μm to 4.2 μm. Effect of the thickness of capillaries and the distance between capillaries on confinement loss spectra was studied, which agreed well with the high-loss and low-loss bands predicted by the ARROW model. Based on mode confinement factor, a criterion for selecting the fundamental mode was proposed. Theoretical analysis has shown that the integral coefficient of 0.5 could effectively distinguish fundamental modes from high-ordered ones. This method was easy and accessible, and the error rate was fractional. This research could offer useful theoretic guidance for the design and fabrication of negative curvature hollow-core fiber.

Keywords: microstructured fiber, mid-infrared, hollow-core fiber

1. Introduction

Hollow-core fiber (HCF) has wide applications in light-gas interaction, high-power laser transmission and ultrafast laser delivery[1]. In recent years, HCF with negative curvature of the core boundary has exhibited an unexpected lower attenuation than regular ones and performs well in mid-infrared wavelength region[2]. Modeling the negative curvature hollow-core fiber and optimizing the parameters are of great importance for fiber fabrication.

In 2010, Y.Y.Wang et al. firstly discovered the importance of curvature of the core boundary in HCF[3]. An attenuation as low as 0.18 dB/m could be achieved in Kagome fiber with negative curvature of the core boundary[4]. Gérôme et al. illustrated that the complex cladding structure had negligible effect on the loss of Kagome fiber, which means that the fabrication process could be easier and quicker[5]. Numerical analyses were done by Vincetti and Setti using a simplified cladding and showed that the high-loss spectral regions were determined by the coupling interaction between the core mode and cladding modes[6]. In 2011, Pryamikov et al. fabricated the first silica NCHCF without lattice structure in the cladding[7] and Kosolapov et al. demonstrated that using chalcogenide glass instead of silica as the fabrication material could extended the transmission window to 10.6 μm for CO_2 laser in a similar structured NCHCF[8]. In 2013, Kosolapov et al. reported that non-touching capillaries could reduce the confinement loss compared to touching capillaries and the measured attenuation at 5.8 μm and 7.7 μm were 30 dB/m and 50 dB/m, respectively[9]. Recently, Walter et al. fabricated the NCHCF with a low bending loss 0.25 dB/turn at a wavelength of 3.35 μm and a bend radius of 2.5 μm[10]. He also proposed an improved structure with extra anti-resonant glass elements in the air cladding. According to the numerical analysis, the new structure greatly improved performances in confinement loss and bending loss[11].

In this paper, the mode analysis in RF module is chosen as the electromagnetic model to study the transmitting light in the fiber. Setting the proper boundary conditions and meshing are key to the accuracy of the confinement loss. We mainly study the confinement loss spectra which is affected by many factors, including the size of the core, thickness and ratio of the capillaries, number of capillaries. Due to low efficiency and high error rate by manual decision of the fundamental mode, we propose an automated method based on the mode distribution characteristics to reduce the human participation in the calculating process. We extend the concept of mode confinement factor (MFC) into a more general one and find that the parameter set to 0.5 can efficiently select fundamental mode from high-ordered modes.

2. Theory

In conventional fiber, refractive index in the core is higher than that in the cladding. Thus, according to total internal reflection (TIR), light can be totally confined in the fiber core. Mode theory mathematically is based on solving the Bessel equation, a singular Sturm-Liouville boundary value problem. Nevertheless, as for the leaky fiber, the propagating phenomenon cannot be explained by TIR. Despite the band-gap fiber which has photonic band gap in the cladding, loss is the intrinsic property of the leaky fiber. The mode theory should be modified to be used in this kind of fiber, but still faces many challenges.

We should introduce complex propagating constant

$$\beta = \beta_r + i\alpha \qquad (2.1)$$

where β_r and α are both real numbers and α is the attenuation constant.

The normalized Bessel equation is[1]

$$\left(d_R^2 + R^{-1}d_R + 1 - m^2R^{-2}\right)\psi\left(R\right) = 0 \qquad (2.2)$$

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

The complex number β turns the equation into a complex Bessel equation, and the solution is in complex domain.

In leaky fibers, due to the failure of TIR, a complex propagating constant is introduced which extends real domain into complex domain. In addition, cladding mode does not simply attenuate along the radius direction, but transmits transversely. Modified Bessel function of the second kind should be replaced by Hankel function to describe the field outside the core region. Meanwhile the fine structure of cladding makes the boundary conditions more complex. These new changes make the mode theory of leaky HCF more challenging.

Anti-Resonant Reflecting Optical Waveguide (ARROW) model is widely used to explain the properties of hollow core photonic band-gap fiber and other hollow-core fiber. In this model, the high refractive index layer is regarded as a Fabry-Perot cavity. The light goes out of the high refractive index layer when the wavelength is close to the resonant wavelength. However, when the propagating wavelength is far away from the resonant wavelength, the light should be reflected back, resulting in good confinement. Therefore the matching condition of wavelength determine the band edges of high-loss and low-loss regions.

The resonant wavelength can be expressed as below.

$$\lambda_{res} = \frac{2d}{m}\sqrt{n_2^2 - n_1^2} \qquad (2.3)$$

where λ_{res} is the resonant wavelength, d is the thickness of high refractive index layer, n_1 is the smaller refractive index, n_2 is the bigger refractive index and m is an integer starting from 1.

ARROW model uses ray theory to explain the properties of the waveguide, so it is effective when $d/\lambda \gg 1$ and may fail in long wavelength region.

3. Use of COMSOL Multiphysics

3.1 Geometry structure of NCHCF

The COMSOL Multiphysics finite element software[12] is used to simulate the eigen-modes of the micro-structured fiber. We select **2D** as the space dimension, then in the list of **Add Physics**, the following menu is selected: **Radio Frequency** > **Electromagnetic Waves, Frequency Domain(emw)** > **Preset Studies** > **Mode Analysis**. We fill in the **Global Parameters** with Table.1 and build the geometry structure of NCHCF with the parameters in Table.1, see Figure.1.

Table.1 Global parameters set in COMSOL

Name	Value	Expression
D_core	119[um]	Diameter of the fiber core
N	8	Number of capillaries
eta_t	sin(pi/N)/(1-sin(pi/N))	Structure coefficient
d_0	eta_t*D_core	Outer diameter of capillary when tangent
delta	8[um]	Change of outer diameter of capillary
d_out	d_0-delta	Actual diameter of capillary
eta_c	0.8	Capillary coefficient
d_in	d_out*eta_c	Inner diameter of capillary
t	(d_out-d_in)/2	Thickness of capillary
T	10[um]	Thickness of jack tube
D_f	D_core+2*(d_out+T)	Diameter ot the fiber

From Figure.1, when the capillaries in the cladding are tangent with the adjacent ones, we have

$$\sin\left(\frac{1}{2}\times\frac{2\pi}{N}\right)=\frac{d_{out}/2}{(D_{core}+d_{out})/2} \quad (3.1)$$

Then, we can get

$$d_{out}=\frac{\sin(\pi/N)}{1-\sin(\pi/N)}\times D_{core} \quad (3.2)$$

Let us define the structure coefficient,

$$\eta_t\equiv\frac{\sin(\pi/N)}{1-\sin(\pi/N)} \quad (3.3)$$

As η_t is only determined by N, some typical values are in Table.2.

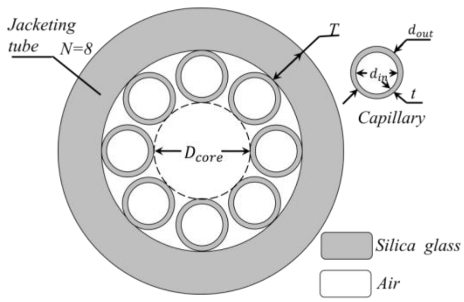

Figure.1 Cross section of NCHCF

Table.2 Some typical values between the number of capillaries and the structure coefficient

N	η_t	N	η_t
3	6.464	8	0.620
4	2.414	9	0.520
5	1.426	10	0.447
6	1.000	11	0.392
7	0.766	12	0.349

To precisely describe the relationship between capillaries, we introduce the symbol δ to describe the changed quantity of the outer diameter of the capillary

$$\delta = d_0 - d$$

Consequently there are mainly three cases. When $\delta = 0$, capillaries are tangent; when $\delta > 0$, capillaries are apart and have air gaps just as Figure.1; when $\delta < 0$, capillaries are overlapped due to the thickness of the capillary.

3.2 Materials

We should choose **Electromagnetic Waves, Frequency Domain(emw) > Electric Displacement Field > Refractive Index,** then the calculation is based on the refractive index.

The NCHCF are composed of two types of materials, silica and air. In this simulation, we regard air as a non-dispersive media and have a constant refractive index equal to 1. The refractive index of silica is affected by the wavelength. We use Sellmeier function[13] to approximate it,

$$n^2(\lambda)=1+\sum_{j=1}^{m}\frac{B_j\lambda^2}{\lambda^2-\lambda_j^2} \quad (3.4)$$

where λ_j is the j-th resonant wavelength and B_j is the strength of the j-th resonant wavelength. We normally take first three items, and the parameters are shown in Table.3.

Table.3 Parameters in Sellmeier function

$B_1=0.6961663$	$B_2=0.4079426$	$B_3=0.8974794$
$\lambda_1=0.0684043\mu m$	$\lambda_2=0.1162414\mu m$	$\lambda_3=9.0896161\mu m$

As material absorption is a constant value, it is not considered in the simulation.

3.3 Basic fiber parameters

In finite element method, the eigenvalue equation is

$$\nabla\times(\varepsilon_r^{-1}\nabla\times\overrightarrow{H})-k_0^2\overrightarrow{H}=0 \quad (3.5)$$

where $\varepsilon_r = n^2$ is the relative permittivity, n is the refractive index of the material, k_0 is free space wave vector and $\vec{H}$ is the magnetic field.

The eigenvalue is

$$eval=-j\beta \quad (3.6)$$

where β is the complex propagating constant and j is the imaginary unit.

So the effective refractive index is

$$n_{eff}=\frac{\beta}{k_0}=\frac{eval}{k_0}j \quad (3.7)$$

The attenuation of fiber is defined as

$$\alpha_{dB}=-\frac{10}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \quad (3.8)$$

where L is length of the fiber, P_{in} and P_{out} are the input and output power respectively.

3.4 Boundary Conditions

Proper boundary condition is vital to simplify the problem and enhance the efficiency.

In order to calculate the confinement loss of NCHCF, Perfectly Matched Layer (PML) is utilized. There are mainly two kinds of PML, rectangular PML and circular PML. In this paper, we use circular PML which is more convenient. We should choose **Definitions > Perfectly Matched Layer**, and set **Geometry > Type > Cylindrical**. The region is the outer jacketing tube.

3.5 Meshing

The speed and accuracy are determined by the meshing. In general, the finer the meshing is, the higher accuracy can be achieved with longer calculation time and larger amount of memory. Actually, it also increases the degree of freedom and more quasi-solutions are obtained. Therefore choosing a proper meshing degree is a very practical problem.

As the thickness of NCHCF is several micrometers, which is comparable to wavelength of the light. In the silica region of the cladding, we manually set **Maximum element size** to 1 μm, **Resolution of narrow regions** to 5 in **Element Size**. In other regions, **Maximum element size** is set to 2 μm.

3.6 Communicate COMSOL with MATLAB

COMSOL Multiphysics develops from a toolbox in MATLAB. LiveLink™ for MATLAB® module, based on Client-Server framework, is to realize the communication between COMSOL and MATLAB[14]. When COMSOL with MATLAB is launched, we open the MATLAB and then it loads the library which we have built. Every action in COMSOL Desktop has code lines corresponding to it in MATLAB Server. Also, we can import the model from the server as well as export the model into the server. The bidirectional data flow provides the simulation with more flexibility. See Figure.2.

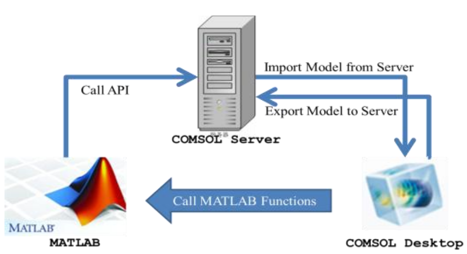

Figure.2 Schematic diagram of communication between COMSOL and MATLAB

We should build the model before exporting the model into a m-file. It is modified into a function with some parameters and then we can call it in repetition. In addition, we could build the model once, and repeatedly modify some values and call the solver. The latter method is more efficient but requires more programming technique. The Sellmeier function could be inserted into the m-file considering dispersion property of silica.

3.7 Select the fundamental mode

Near the refractive index of the fiber core, fundamental mode generally can be found. Nevertheless, if every time we manually decide the fundamental mode, although the accuracy can be guaranteed, it does not take advantage of computers.

In single mode fiber, MFC is used to describe the capability of confining light. In photonic crystal fiber, we can imagine a round rod as the fiber core in the core region with the same refractive index of the center. Similarly, we define the shortest distance between the opposite capillaries as the diameter of the fiber core, and MFC can be calculated. But as most energy is confined in the fiber core for many modes, it is not ideal for mode selection.

We define integral coefficient $c_p \in (0,1]$, which is the ratio of the diameter of integral area to the diameter of fiber core. We can get energy confinement ratio η_p,

$$\eta_P = \frac{P_c}{P_{total}} = \frac{\iint_{S_c} |P_z|^2 \, dxdy}{\iint_{S_f} |P_z|^2 \, dxdy} \qquad (3.9)$$

where P_z is z component of energy density vector, S_f is the whole cross section region, S_c is the calculated cross section region.

We select four typical modes at 1.55 μm and calculate the energy confinement factor as below.

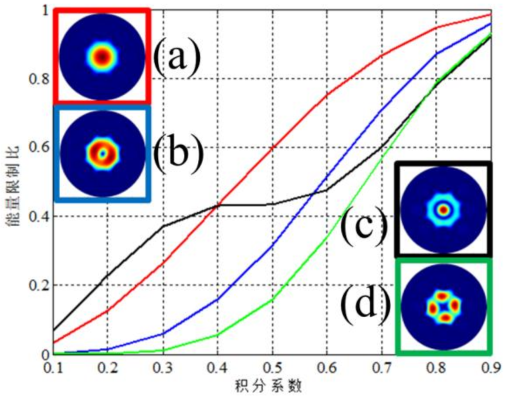

Figure.3 the relationship between energy confinement factor and integral coefficient (a)LP_{01} (b)LP_{11} (c)LP_{02} (d)LP_{21}

It should be noticed that we use a named method regarding linear polarization mode theory with the assumption of weak guiding condition. But it roughly works for NCHCF.

From Figure.3, when $c_p > 0.9$, η_P exceeds 90%. It is also evident that when $c_p = 0.5$, different modes have separated η_P, which is advantagous for selecting mode.

4. Results and Discussion

We calculated the spectra between 2.7 μm and 4.2 μm with $D_{core} = 119$ μm, $d_{out} = 63$ μm, $d_{out} = 51$ μm, $T = 20$ μm. The result is shown in Figure.3.

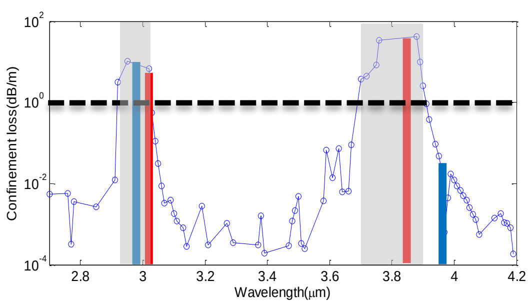

Figure.3 Confinement loss spectral using parameters in reference [9]

The black line is a reference line where the loss is 1 dB/m. We define the high-loss region where loss is larger than 1 dB/m and low-loss region smaller than 1 dB/m. Therefore in Figure.3, two high-loss regions and three low-loss regions can be observed. We take the middle wavelength 3.4 μm where the refractive index of the silica is 1.4088, into the ARROW formula and the resonant wavelengths are 2.9770 μm and 3.9693 μm, marked with blue lines in Figure.3. In order to improve the accuracy, we again substitute these two wavelengths into ARROW formula, and the iterated results are marked with red lines, which fall in high-loss regions, and is in good agreement with the simulation.

In order to verify the correctness of the simulation, we also simulate the same structure in reference[10] to analyze the effect of gap distance on the confinement loss. The diameter of fiber D_f is constant, and thickness of capillary T is changed with the variant δ. The result is shown in Figure.4.

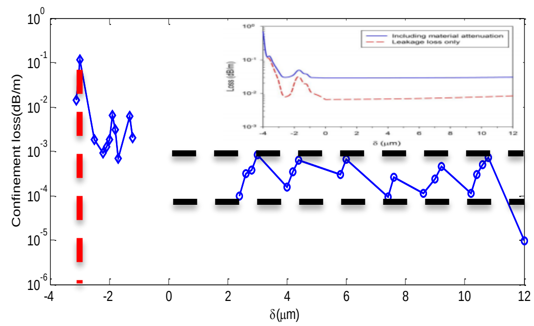

Figure.4 Effect of gap distance on confinement loss

According to Figure.4, when $\delta > 0$ and it varies between 2 μm and 10 μm, the confinement loss fluctuates slightly between 10^{-4} dB/m ~ 10^{-3} dB/m. When the capillaries are overlapped $\delta < 0$, a peak can be found at $\delta = -3$ μm. Compared with these cases, we can conclude that distant capillaries contributes to reducing the overall confinement loss. The inset in Figure.4 is the result of Walter et al[10].

ARROW model has pointed out that the transmission band is decided by the thickness of capillary, so it is necessary to investigate further in which degree the results of simulation fit with the ARROW formula. Let outer diameter of capillary be constant, and change the thickness of capillary. Thus, capillary coefficient η_c is changed. As shown in Figure.3, we have investigated the confinement loss where the thickness of capillary is 6 μm. We also calculate the case in which the thickness of capillary is 3 μm and 15 μm respectively, between 2.7 μm and 4.2 μm. The result is shown in Figure.5.

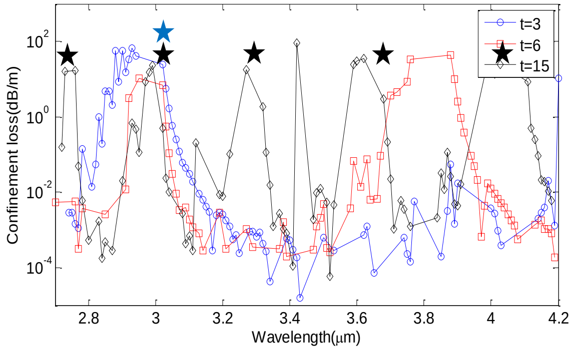

Figure.5 Confinement loss spectra with different thickness of capillary

Blue, red and black lines represent 3 μm, 6 μm and 15 μm respectively. The blue star represents the resonant wavelength after iteration when $T = 3\ \mu\text{m}$, and black stars when $T = 15\ \mu\text{m}$. The specific values are shown in Table.4.

Table.4 Resonant wavelengths predicted by ARROW formula

T/μm	ARROW-3.4 μm	ARROW-iteration
3	2.98	3.02
6	3.97, 2.98	3.86, 3.02
15	4.25, 3.72, 3.30, 2.98, 2.71	4.07, 3.67, 3.32, 3.02, 2.77

According to Figure.5, it is obvious that the results of simulation fit well with the predicted values of ARROW formula. What's more, we can find that thinner capillary can have less confinement loss. The reason could be that thinner capillary supports less cladding modes, then the coupling between the fiber core and cladding is weaker, resulting in less confinement loss.

5. Conclusions

In this paper, we have demonstrated the flexibility of COMSOL Multiphysics used to simulate and analyze the confinement loss spectra of negative curvature hollow-core fiber. The effects of the thickness of capillaries, the number of capillaries, the diameter of fiber core on the confinement loss are also investigated. The proposed criterion based on a mode confinement factor to judge the fundamental mode is illustrated. Results of this work could help design NCHCF with specific transmitting windows and give useful guidance for fiber fabrication.

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