Heterogeneous Gas-filling in Anti-resonant Hollow Core Fibers

Wentong LI
Department of Information Engineering
The Chinese University of Hong Kong
Shatin, N.T., HONG KONG
lw018@ie.cuhk.edu.hk

Calvin Chun-Kit CHAN
Department of Information Engineering
The Chinese University of Hong Kong
Shatin, N.T., HONG KONG
ckchan@ie.cuhk.edu.hk

***Abstract*—We show reduction in confinement loss in an anti-resonant hollow core fiber by heterogeneous gas-filling which introduce differences in refractive indices between its core and cladding parts.**

Keywords—anti-resonant hollow core fiber, gas-filling

I. INTRODUCTION

Conventional solid core fiber confines and guides light by total internal reflection (TIR). With better design and manufacturing, its loss keeps decreasing, and the cutting-edge result shows a loss level as low as ~0.14 dB/km [1]. However, it is difficult to further reduce the loss, due to the fundamental limit posed by Rayleigh scattering and fused silica's intrinsic absorption. Early attempts have tried to guide and confine light in air, via a cylindrical Bragg structure, inside a Bragg fiber [2]. Since photonic crystals were introduced, research on photonic crystal fiber (PCF) has grown rapidly. It was shown that hollow core PCF, which has an air core by removing the central glass tube during fiber drawing, can confine light by the periodic cladding tubes. It has a low confinement loss (CL) but a relatively high surface scattering loss (SSL), due to the large overlap between the mode and the glass. The best reported result to date is 1.7 dB/km [3]. Besides, these one-dimensional and two-dimensional periodic structures, anti-resonant reflection can also confine light in air core with a low refractive index. Unlikely PCF, the modes in the anti-resonant hollow core fiber are leaky in nature, thus its CL is high, while its SSL is low, due to its simple structure. Recent works focus on decreasing its CL. Various geometrical fiber designs, as well as optimization of parameters, have been extensively studied. The cladding has been changed from a single layer of tubes to nested and conjoined tubes, and the tubes are avoided to touch each other so as to further suppress the CL [4]. With these efforts, the best reported performance to date is 0.65 dB/km [5]. Although the loss level is still higher than that of the conventional fiber, hollow core fibers still show some advantageous features. For example, the hollow core region can be fulfilled by gas or liquid so as to generate high nonlinearity or other interaction between light and matters [6].

Hollow core fibers have to realize a smaller loss level before they can serve as an alternative to conventional ones deployed in telecommunication. While better fabrication and advanced design may help, in this paper, we show that by filling the core and cladding with different type of gases, so as to introduce differences in the refractive indices between the core and the cladding, the CL can be reduced. It is effective for a wide range of fiber designs, and is also fully compatible with current fabrication process. The simulation shows that, compared with Argon-only fiber, the CL of the Argon-Helium (Ar-He) filled fiber can be reduced to 60%.

II. HETEROGENEOUS GAS-FILLING

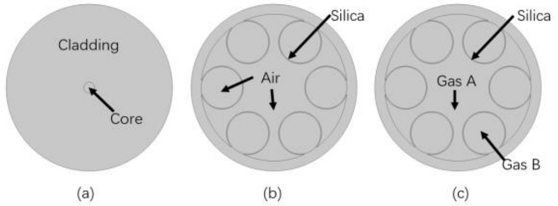

Figure 1: Different designs of optical fibers. (a) Conventional fiber has a high-index core and low-index cladding, and guides light by TIR. (b) Anti-resonant hollow core fiber guides light in air core by anti-resonant reflection induced by glass tubes. (c) Our proposed scheme fills the core and the cladding parts of anti-resonant hollow core fiber by different gas, while n(Gas A) > n(Gas B).

Optical waveguides can be realized via various physical principles, as illustrated in Fig. 1. Light guiding in the widely used solid core fiber, as shown in Fig. 1(a), is based on total internal reflection (TIR), owing to the high refractive index material in the core region and the low refractive index material in the cladding part. In contrast, light in the anti-resonant fiber is "loosely" confined in the core area and the modes are leaky. Despite the nature, the leakage can be significantly suppressed by the glass wall around the core when the anti-resonance condition is satisfied [7]. The hollow part is filled by the inert gas used during fiber drawing, though the gas is air mostly [8], as depicted in Fig. 1(b). Here, we propose to employ heterogeneous gas-filling to such anti-resonant fibers, in which the core is filled with the gas with high refractive index, say Gas A in Fig. 1(c), while the cladding tubes are filled with another type of gas, say Gas B in Fig. 1(c) with low refractive index. Such heterogeneous gas-filling induces TIR, thus can further suppress the leakage, in addition to anti-resonance. This can reduce the confinement loss of the anti-resonant fiber.

To verify our proposed idea, we perform numerical simulations of the air-resonant fiber. We consider a single tube anti-resonant fiber, as depicted in Fig. 1(c). The core radius is 20 μm, the outer radius of each silica cladding tube is 14μm, and the thickness of tubes is 500 nm, so that the conventional telecommunication band locates in its first anti-resonant window. The core is assumed to be filled with Gas A with a refractive index of 1.0005. The CL of the fundamental mode at λ = 1.55 μm is simulated when the refractive index of the cladding (filled with Gas B) changes from 1 to 1.001. Simulation results show that the CL decreases significantly when the refractive index of the cladding part, n(cladding), decreases, as shown in Fig. 2. For example, when n(cladding) is 1.0002, the value of CL is just half of that when n(core)=n(cladding)=1.0005.

978-1-7281-5445-9/20/$31.00 ©2020 IEEE

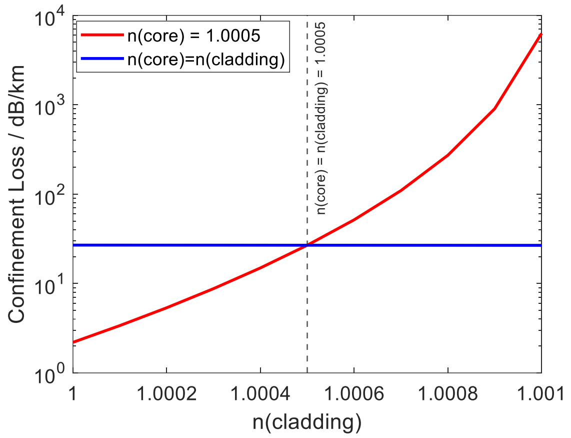

Figure 2: The CL varies significantly when the balance between the core's and the cladding's refractive indices are broken (red line). Meanwhile, varying both refractive indices simultaneously almost has no effect on the confinement loss.

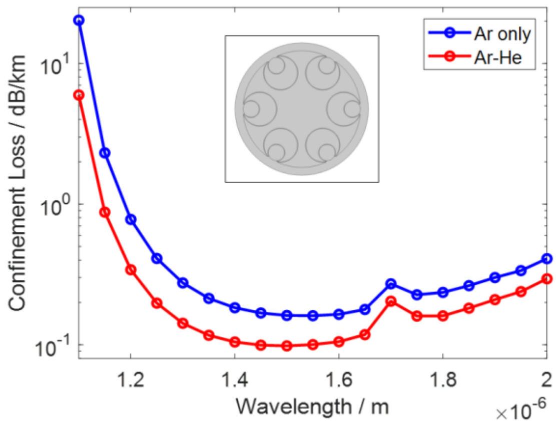

Figure 3: The CL of the two types of fibers. The curves exhibit similar shapes, but the CL of the Ar-He fiber is lower than that of the Ar-only fiber. Inset: the geometry of the hollow core fiber used in the simulation.

In order to show that it is the relative difference, instead of the absolute values of the refractive indices in the hollow parts that cause the change of the CL, we also simulate the cases when the hollow parts have their refractive indices varying from 1 to 1.001, while keeping the condition of n(core) = n(cladding). It is shown in Fig. 2 that the CL almost remains constant when the refractive index of the cladding changes.

III. Characterization of Heterogeneoud Gas-filling

In this section, we analyze the effect of heterogeneous gas-filling on a state-of-the-art hollow-core fiber design, named nested anti-resonant nodeless fiber (NANF). It has been well-recognized for its lowest reported loss among all fabricated hollow-core fibers. Recent work has achieved an impressive loss level as low as 0.65 dB/km in C-band [5]. Finite element method is used to search for the modes in the given fiber. In our numerical simulation, the core radius is 20 µm, the outer radius of each outer cladding tube is 14 µm, the outer radius of each inner cladding tube is 7 µm, and the tube thickness is 500 nm. The fiber is filled by Argon (Ar) gas in the core region and Helium (He) gas in the cladding region, and it is labelled as Ar-He fiber. The refractive index of Argon is 1.00026, while that of Helium is 1.00003. Another case with the fiber filled with Argon gas only, labelled as Ar-only fiber, is used as the reference. In order to calculate the wavelength-dependent refractive index of the used silica, the Sellmeier equation [9] is used:

$$n^2(\lambda) - 1 = \sum_{i=1}^{n} \frac{B_i \lambda^2}{\lambda^2 - l_i^2} \qquad (1)$$

where $n = 3$, $B_1 = 0.6961663$, $B_2 = 0.4079426$, $B_3 = 0.8974794$, l_1 = 0.0684043, l_2 = 0.1162414, l_3 = 9.896161, are the Sellmeier coefficients, λ is the wavelength, and $n(\lambda)$ is the refractive index of the fused silica.

Given a mode, its confinement loss is calculated from its effective refractive index [10]:

$$CL(dB/m) = 40\pi * Im(n_{eff})/(\ln(10)\,\lambda) \qquad (2)$$

where n_{eff} is the effective refractive index, and λ is the wavelength in vacuum.

Fig. 3 shows the simulated confinement loss of the fundamental mode. We can see that over the whole window, the CL decreases with the wavelength value, even if the difference of the refractive indices is very small. For example, the CL of the Ar-only fiber is 0.162 dB/km at λ = 1.5 µm, while that of the Ar-He fiber decreases to 0.098 dB/, thus the proposed scheme of Ar-He gas-filling reduces the CL to about 60% of original level of that of the Ar-only case.

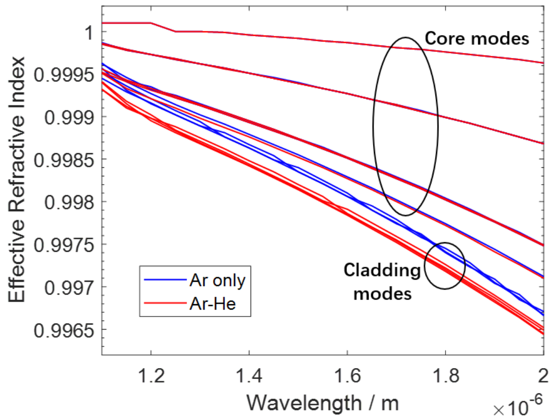

Figure 4: The modal profiles of the Ar-only and Ar-He fibers. Their effective refractive indices of the core modes are almost the same, but the cladding modes in the Ar-He fiber exhibit smaller refractive indices, due to its smaller material's refractive index.

With heterogeneous gas-filling, the modal profile of the fiber is also changed. From Fig. 4, we can notice that the core modes in both Ar-only fiber and Ar-He fiber exhibit almost identical effective refractive index profile over the wavelength, as they share the same refractive indices in the core region. However, the cladding modes in the Ar-He fiber exhibit smaller effective refractive index profile than that in the Ar-only fiber. This can be attributed to its smaller material's refractive index. The larger difference between its core's and cladding's refractive indices brings benefit. When the geometry changes, due to bend or imperfect manufacturing, larger refractive index difference suppresses the mode coupling, making the transfer of energy from FM to HOMs more difficult. As a result, the fiber is more robust against fluctuation of structure.

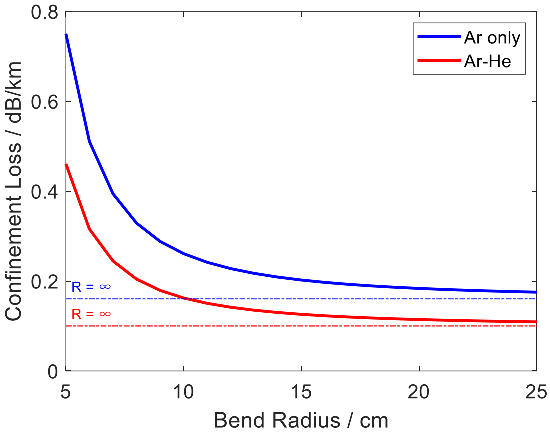

Figure 5: The bending loss of both Ar-only and Ar-He fibers. Two curves exhibit similar shape, but the Ar-He fiber has a lower loss level.

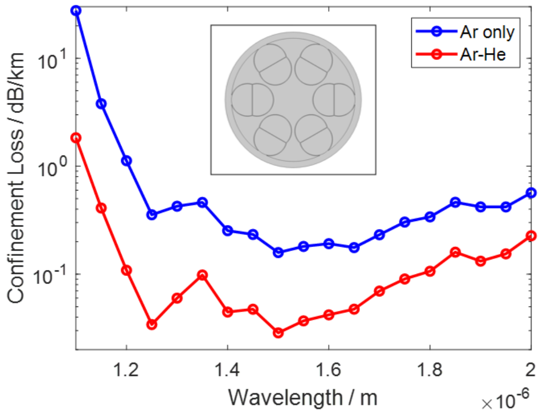

Figure 6: The confinement loss of the fundamental mode in the conjoined tube hollow-core fiber. Inset: the geometry of the conjoined tube fiber used in the simulation. Core radius: 20 μm, outer radius of tubes: 14 μm, distance of the centers of two tubes: 10 μm.

We have also investigated the CL due to bending of the two types of fibers. We consider an equivalent straight fiber model with modified refractive index:

$$n(x) = n * \exp\,(x/R) \tag{3}$$

where n is the refractive index of the material, R is the bend radius, and x is the coordinate of the x-axis. The loss of this equivalent fiber is regarded as the loss of fiber under bending. As shown in Fig. 5, the CL due to bending of both types of fiber exhibits similar profile against bend radius, though the Ar-He fiber shows a relative lower CL. For example, the CL of the Ar-only fiber is doubled that of the Ar-He fiber when the bend radius is within 8 cm.

Furthermore, the proposed heterogeneous gas-filling method can be applied to many other hollow-core fiber designs. Fig. 6 shows the CL of the fundamental mode in the conjoined tube fiber with and without heterogeneous gas-filling. This fiber core geometry is also well-known to realize low confinement loss [12]. From the simulation results, it is obvious that our proposed scheme can also effectively reduce the CL in this kind of hollow-core fiber, owing to the TIR induced by the heterogeneous gas-filling.

Besides, the proposed heterogeneous gas-filling scheme is compatible with current fabrication technique very well. In the fiber drawing process of common hollow-core fibers, the hollow part is usually filled with some types of inert gases for two reasons. First, this can prevent contamination by water vapor or other particles. Second, this can help to induce pressure inside the glass tubes so as to prevent them from collapse, due to surface tension [8]. The gas filling for the core region and the cladding parts can be performed independently so as to generate different levels of pressure. Therefore, the implementation of the proposed heterogeneous gas-filling scheme for hollow-core fibers is very compatible to the current fiber drawing process.

IV. Summary

In this paper, we introduce a novel yet effective method to reduce the confinement loss of the anti-resonant hollow core fibers by filling the core and cladding parts with different types of gases so as to make the refractive index at the core region higher than that of the cladding parts. Numerical simulations have showed that the confinement loss is reduced. owing to TIR brought by the difference of the refractive indices. The proposed scheme is effective in many geometrical designs of hollow-core fibers and is compatible to the current fiber drawing process. It is expected that proper choice and combinations of gases can bring new properties and applications to the hollow core fibers.

References

[1] Y. Tamura *et al*, "The first 0.14-dB/km loss optical fiber and its impact on submarine transmission," *J. Lightwave Technol.*, 36, 44-49 (2018).

[2] P. Yeh and A. Yariv, "Bragg reflection waveguides," *Opt. Commun.*, 19, 427–430 (1976).

[3] B. J. Mangan *et al*, "Low loss (1.7 dB/km) hollow core photonic bandgap fiber," in *Optical Fiber Communication Conference* Los Angeles, California, USA, paper PD24, (2004).

[4] F. Poletti, "Nested antiresonant nodeless hollow core fiber," *Opt. Express*, 22, 23807-23828 (2014).

[5] T. D. Bradley *et al.*, "Antiresonant hollow core fibre with 0.65dB/km attenuation across the C and L telecommunication bands," in *European Conference on Optical Communication (ECOC)*, Dublin, Ireland, pp. 1-4.(2019).

[6] J. C. Travers, W. Chang, J. Nold, N. Y. Joly, and P. St. J. Russell, "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers [Invited]," *J. Opt. Soc. Am. B*, 28, A11-A26 (2011).

[7] N. M. Litchinitser, A. K. Abeeluck, C. Headley, and B. J. Eggleton, "Antiresonant reflecting photonic crystal optical waveguides," *Opt. Lett.*, 27, 1592-1594 (2002).

[8] G. T. Jasion *et al*, "Fabrication of tubular anti-resonant hollow core fibers: modelling, draw dynamics and process optimization," *Opt. Express*, 27, 20567-20582 (2019).

[9] I. H. Malitson, "Interspecimen comparison of the refractive index of fused silica," *J. Opt. Soc. Am.*, 55, 1205-1209 (1965).

[10] T. P. White, B. T. Kuhlmey, R. C. McPhedran, D. Maystre, G. Renversez, C. Martijn de Sterke, and L. C. Botten, "Multipole method for microstructured optical fibers. I. Formulation," *J. Opt. Soc. Am. B*, 19, 2322-2330 (2002).

[11] M. Heiblum and J. Harris, "Analysis of curved optical waveguides by conformal transformation," *IEEE J. of Quant. Electron.*, 11, no. 2, pp. 75-83, (1975).

[12] S. Gao, Y. Wan, W. Ding, et al. "Hollow-core conjoined-tube negative-curvature fibre with ultralow loss," *Nat Commun*, 9, 2828 (2018).