Simulation of the Structural Parameters of Anti-resonant Hollow-core Photonic Crystal Fibers

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Anti-resonant hollow-core photonic crystal fiber (AR-HCF) has unique advantages, such as low nonlinearity and high damage threshold, which make it a promising candidate for high-power laser delivery at distances of tens of meters. However, due to the special structure, optical properties such as mode-field profile and bending loss of hollow-core fibers are different from those of solid-core fibers. These differences have limited the widespread use of AR-HCF in practice. In this paper we conduct numerical analysis of AR-HCFs with different structural parameters, to analyze their influences on an AR-HCF’s optical properties. The simulation results show that with a 23-μm air-core diameter, the fundamental mode profile of an AR-HCF can well match that of the widely used Nufern’s 20/400 fiber, for nearly-single-mode power delivery applications. Moreover, with the ratio of cladding capillary diameter to air-core diameter ranging from 0.6 to 0.7, the AR-HCF shows excellent optical characteristics, including low bending sensitivity while maintaining single-mode transmission at the same time. We believe these results lay the foundation for the application of AR-HCFs in the power delivery of high power fiber laser systems.

Keywords : Bending loss, Effective mode area, High-power fiber lasers, Hollow-core photonic crystal fiber

OCIS codes : (060.2400) Fiber properties; (060.5295) Photonic crystal fiber; (140.3510) Lasers, fiber mode

I. INTRODUCTION

In recent years, significant progress in power scaling up to tens of kilowatts has been made for high-power fiber lasers [1–5]. Considering their simplicity, compactness, high efficiency and good beam quality, high-power fiber lasers are now widely used in industry and the military. With the rapid development of these high-power laser sources, the demand for flexible power delivery via optical fiber is also growing. Especially for narrow-linewidth nearly-single-mode laser sources, with flexible power delivery to a spectral or coherent beam combination system, output power can be further enhanced, with excellent beam quality [6, 7].

In power-delivery applications for these sources, traditional solid-core fibers transmit light through fused silica, which can hardly overcome their inherent nonlinear optical effects. Among these nonlinear effects, stimulated Brillouin scattering (SBS) generates backward-transmitted stokes light, causing damage to optical devices in the system, which limits the further output-power scaling of a fiber am-
plifier [8–10]. Self-phase modulation (SPM) causes spectral broadening during laser amplification [11–13]. Generally, to balance power scaling and nonlinearity suppression, the power-delivery distance for solid-core fibers is usually just a few meters, which is far from sufficient for large-scale beam combining applications.

Hollow-core photonic crystal fiber (HC-PCF), which emerged in 1999 [14], consists of periodically arranged air holes and silica capillaries forming a cladding around an air core at the center of the structure, where the propagation properties of light are similar to those in free space. Because the laser is confined within the air core rather than the silica base, the laser field has little overlap with the cladding material, resulting in simultaneously a reduction of the nonlinear coefficient by at least three orders of magnitude in HC-PCF plus a much higher laser damage threshold. Therefore, HC-PCF can break through the bottlenecks of conventional fused-silica fibers and provide an ideal optical environment with low nonlinear effects for lasers, nonlinear optics, and other fields. HC-PCFs are divided into two categories according to the guidance mechanism. One is the photonic band gap hollow-core fiber (PBG-HCF) [15], based on the “photonic band gap” effect, while the other is known as the anti-resonant hollow-core photonic crystal fiber (AR-HCF) [16]. Inspired by the concept of a negative-curvature core boundary [17], the negative-curvature anti-resonant hollow-core fiber was first proposed in 2011 [18]. The single-cladding design concept ensures excellent optical performance while simplifying the structure of the hollow-core fiber, for easy fabrication. Compared to PBG-HCF, single-layer AR-HCF has a larger core and mode field diameter, which is the key to reduce leakage loss. Meanwhile, the structure of AR-HCF also reduces the overlap between laser field and cladding material, which contributes to a much higher laser damage threshold, and also makes the surface scattering loss of AR-HCF at least one order of magnitude lower than that of PBG-HCF. Low loss combined with low optical nonlinearity and high damage threshold gives AR-HCF the potential to outperform solid-core fiber, meaning that these fibers hold great promise for applications where delivery of high power and high damage threshold gives AR-HCF the potential to transmit high-power fiber laser.

In this paper, we calculate the effective mode area and diameter of 20/400 fiber (NA 0.065) via numerical simulation, and derive the air-core diameter and other relevant structural parameters of the AR-HCF based on the condition of matching the effective mode-field diameter. Then we mainly illustrate the influence of bending on AR-HCF. Eventually, a set of optimized structural parameters for the AR-HCF is proposed, so that it can be coupled and matched to traditional solid-core fiber while maintaining good optical properties for subsequent practical applications.

II. METHODS AND RESULTS

In this work, mode profiles, effective mode area, and loss of the 20/400 fiber and AR-HCF are numerically simulated for different parameters. Using a full-vector finite-element mode solver and applying global integration calculations, we can obtain the electromagnetic field distribution of the modes in the air core and cladding capillaries of the AR-HCF.

2.1. The Effective Mode Area of 20/400 Fiber

The effective mode area of the 20/400 fiber (NA 0.065) is 232.7 μm², as computed by the formula of Eq. (1) [24]

\[
A_{\text{eff}} = \left( \frac{\int \int |F(x,y)|^2 \, dx \, dy}{\int \int |F(x,y)|^4 \, dx \, dy} \right)^2.
\]

where \( F(x, y) \) is the fundamental mode field distribution. Correspondingly, the effective mode field diameter is calculated to be 17.2 μm. Then the effective mode field diameter of the AR-HCF is specified based on the condition of matching effective mode field diameter, so that other structural parameters can be determined. Finally, according to the results of numerical simulation, the AR-HCF that can match the effective mode field diameter of the solid-core 20/400 fiber is obtained.

2.2. Independent Geometric Structural Parameters of AR-HCF

The number of independent parameters to identify an anti-resonant hollow-fiber is five: the number of cladding capillaries \( N \), the capillary wall thickness \( t \), the air core diameter \( D \), the capillary outer diameter \( d \), and the fiber outer diameter \( OD \), as depicted in Fig. 1.

In what follows, we mainly discuss and analyze the influence of four parameters other than \( OD \) on the optical properties of AR-HCF, focusing on the effective mode area, mode profile, and the bending effect.

2.2.1. The Number of Cladding Capillaries \( N \)

To achieve single-mode transmission in a hollow-core
The maximum value of the ratio $d/D$ is the maximum size of the capillaries, and is limited mostly by the capillary size [25]. Large numbers of capillaries inevitably limit their maximum size, and limit the maximum value of the ratio $d/D$, thus limiting the loss of modes in hollow-core fibers. This also greatly limits bending loss in such non-touching tubes AR-HCFs, as shown in [19]. The maximum ratio for a given AR-HCF is obtained when the capillaries touch, as expressed in Eq. (2) [25]

$$\left(\frac{d}{D}\right)_{\text{max}}(N) = \frac{\sin\left(\frac{\pi}{N}\right)}{1 - \sin\left(\frac{\pi}{N}\right)}, \text{ for } N > 3. \quad (2)$$

For a non-touching-tube AR-HCF, the ratio should be lower than the value calculated in Eq. (2). Mattia et al. [25] simulated the modes’ effective indices as a function of $d/D$. For $N \geq 8$, the difference in effective refractive index between the TM01, TE01, and HE21 core modes and the cladding modes is too large, where $d/D \leq 0.62$. Accordingly, it is impossible to resonantly couple the higher-order core mode to the cladding mode to realize HOM suppression. Therefore, there is strong demand to keep the number of capillaries below 7, as confirmed in previous publications [26, 27].

On the other hand, having fewer than 6 cladding capillaries leads either to a pronounced gap between capillaries, or too large $d/D$ values. Both of these situations would mainly affect the core fundamental mode loss. This point of view will also be demonstrated in our subsequent simulation work.

The 7-capillary design clearly offers an advantage compared to other values of $N$, in terms of the above reasons. Therefore, this paper considers one of the simplest designs of an anti-resonant hollow-core fiber, consisting of one layer of 7 non-touching capillaries as cladding.

2.2.2. The Capillary Wall Thickness $t$

The guidance mechanism of the HC-ARF can be explained by the principle of the anti-resonant reflecting optical waveguide (ARROW). The ARROW works in a way analogous to a Fabry-Perot cavity. The guided modes in the air core are mainly determined by the wall thickness of the quartz capillaries in the cladding [28]. The light will strikingly leak into the capillaries only if the wall thickness satisfies the resonance condition, which is similar to the coherent subtraction in F-P cavity. In contrast, the other light will be reflected and confined within the air core as guided modes. The resonance wavelength can be expressed as in Eq. (3) [28]

$$\lambda_r = \frac{2t}{m} \sqrt{n_2^2 - 1}, \quad (3)$$

where $t$ is the wall thickness of the capillary. In this work, the material of the capillaries is assumed to be fused silica, with a refractive index $n_2 = 1.45$. Here $m$ is a positive integer indicating the resonance order. When $m$ equals 1, the corresponding wavelength $\lambda_r$ is the first-order resonance wavelength. Theoretically, any light with a center wavelength greater than the first-order resonance wavelength can be transmitted in the AR-HCF. For a wider transmission band, the thickness $t$ should be as small as possible. However, small $t$ could lead to fabrication problems. Balancing fiber transmission bandwidth and fabrication operability, the thickness $t$ is chosen to be 405 nm in our simulations, which corresponds to a first-order resonance wavelength of 850.5 nm, allowing the propagation of a 1064 nm laser in the first-order optical transmission band.

2.2.3. The Influence on the Effective Mode Area of $D$ and $d$

After specifying the number of cladding capillaries $N$ and the capillary wall thickness $t$, we determine the air core diameter $D$ and capillary diameter $d$ through simulating the properties of the AR-HCF.

The maximum value of $d/D$ is 0.7664 as the Eq. (2) expressed, for an AR-HCF with 7 non-touching capillaries. To achieve mode-field matching to solid-core fiber with a core of 20 μm, the air core diameter $D$ of the AR-HCF is set from 20 to 25 μm, and $d/D$ is set as 0.4, 0.5, 0.6, and 0.7 in the following simulations. The electric and magnetic field components of the optical modes in the fiber are obtained through a general finite-element solver. By solving the eigen equation, the profiles for the guided mode with the corresponding eigen value $n_{\text{eff}}$ can be obtained, from which the fundamental mode profile can be distinguished. With the corresponding fundamental mode profile, the effective mode area for the AR-HCF is calculated according to Eq. (1). The results are shown in Fig. 2(a): For different $d/D$ values, the effective mode area increases with increasing $D$. More specifically, for a change of only 5 μm in $D$, the effective mode area changes from 180 μm² to about 280 μm², a 56% increase. The horizontal line in Fig. 2(a) represents the ef-

![Cross section of an anti-resonant hollow-core photonic crystal fiber (AR-HCF) with $N = 7$.](Image)
The effective mode area of solid-core fiber with a 20-μm core, which is 232.7 μm$^2$. It is clear that, regardless of different $d/D$ values, for $D$ around 23 μm the effective mode area of an AR-HCF is right around the value we need for good matching to a 20/400 solid-core fiber.

In addition, for different $d/D$ values (different $d$, actually) the difference in effective mode area is minimal, as can be seen in Fig. 2(b). To roughly match the solid-core fiber, the air-core diameter $D$ remains constant at 23 μm; with increasing $d$, the effective mode area decreases. To be more exact, compared to Fig. 2(a) the value of the effective mode area experiences a slight decline from 256 to 235 μm$^2$, a change of only 8.2%, while $d$ increases by 183% (from 6 to 17 μm).

The numerical simulations indicate that the effective mode area of an AR-HCF mostly depends on the air-core diameter $D$ rather than the cladding capillary diameter $d$.

As a consequence, considering the above factors, we determined that the value of the air core diameter $D$ should be 23 μm to match a solid-core fiber with a core of 20 μm.

### 2.2.4. The Cladding Capillary Diameter $d$ and the Bending Effect

In this section we investigate the influence of bending on the loss and effective mode area of a fiber with $D = 23$ μm. To study the bending characteristics, a second-order mode analysis is performed on the two-dimensional axisymmetric finite element model of the AR-HCF; the analytical diagram of a bending fiber is shown in Fig. 3. The blue dashed line represents the bending plane, which is parallel to the $y$ axis and aligned with the fiber structure.

Usually a perfectly matched layer (PML) is applied around the core as the exterior boundary condition, to calculate the loss of fiber. When the fiber is bent, the effective index turns complex, and its imaginary part is used to estimate the bending loss. Different from a solid-core fiber, there is a layer of periodically arranged capillaries between the air core and the silica-based outer cladding, forming the inner cladding in AR-HCF (marked in Fig. 4). According to the guidance mechanism in an anti-resonant hollow-core fiber and subsequent simulation works, when bending resonant coupling occurs, the light coupling into a cladding capillary quickly resonates to the outer coating cladding. In that way, the light can hardly continue to propagate in the core and capillary along the fiber, which results in loss. In other words, the optical power coupled into the cladding capillary is almost completely depleted over a very short distance. As a consequence, the percentage of the optical power that leaks into capillaries is hereby calculated to represent the concept of bending loss. So, in this paper we mainly focus on the percentage of power in capillaries before and after bending the fiber, by integrating for the electric field distributions of the air core and cladding capillaries respectively, with the integral domain shown in Fig. 4.

The bending loss increases as bending radius decreases, due to the reduced reflectivity from the cladding [25], which is seen in following simulations.

To investigate the principle of the bending loss of the fundamental mode, the bending radius is set from 5 to 45 mm for different $d/D$ values (0.35, 0.52, 0.61, 0.69, and 0.74). The results are shown in Fig. 5.
It is noted from Fig. 5 that the proportion of power in the capillaries shows fluctuations. Generally, too small a bending radius (near 5 mm) leads to excessive bending loss, as shown in the Fig. 5. To be more precise, the bending loss stabilizes at a rather low level, except for several maxima. Of particularly note here is that the bending-loss peaks occur when the fundamental mode in the air core is resonantly coupled to the leakage modes propagating in the air holes of individual cladding capillaries. Moreover, these couplings occur only at specific, critical bending radii. When $d/D = 0.74$, the percentage of power in capillaries shoots up to 25% at $R_b = 22$ and 30 mm. Then the bending loss plunges to only 2% when the bending radius is greater than 35 mm, while the critical bending radii are reduced to 17 and 23 mm respectively when $d/D = 0.69$. As $d/D$ continues to decrease to 0.52, the resonant bending radius reduces to 8 mm and only one loss peak remains. Eventually there are no resonant coupling loss peaks caused by bending, when $d/D$ is reduced to 0.35. It is clear that the positions of resonant coupling loss peaks depend on the ratio between cladding capillary and core sizes. Overall, the position of the resonant-loss peak gradually shifts to smaller bending radius until it disappears, with the value of $d/D$ varying from 0.74 down to 0.35.

The mode profiles of bending-induced resonant coupling are shown in Fig. 6. As Fig. 6(a) indicates, for an AR-HCF with $d/D = 0.69$, at bending radius $R_b = 23$ mm there is strong resonant coupling between the fundamental mode in the air core and leakage modes propagating in the cladding capillaries, by which a cladding capillary mode is excited. On the basis of the simulation results shown in Fig. 5, it is possible to significantly suppress the resonant coupling loss associated with a bending AR-HCF by reducing the $d/D$ value. However, as shown in Fig. 6(b), for small $d/D$ the core fundamental mode could be transmitted in the gap when bending the fiber. This mode profile, then, can be suppressed by reducing the $d/D$ value.

**FIG. 4.** Schematic diagram of the inner and outer cladding layers, and the integral domains.

**FIG. 5.** Simulated dependence of the bending loss of the air core fundamental mode on bending radius, for $\lambda = 1064$ nm.

**FIG. 6.** The modal distribution of the fundamental mode, (a) for $R_b = 23$ mm and $d/D = 0.69$, and (b) for $R_b = 5$ mm and $d/D = 0.35$. 
far from Gaussian, which is the profile of the fundamental mode in a typical solid-core fiber. Generally, the critical bending radii vary with the size of the air core, even if the value of \(d/D\) remains the same.

In the previous part, we focused on resonant-coupling-induced loss. For the no-resonance bending radius, e.g. \(R_b = 60\) mm, we conduct further simulations with different \(d/D\) values. The results are shown in Fig. 7. As \(d/D\) rises from 0.35 to 0.74, the proportion of power in capillaries increases by approximately 285%, although the overall loss level stays low.

From all of the results above, we can conclude that for small \(d/D\) the power in the capillaries can be well suppressed while bending the fiber. However, to avoid the fundamental mode being transmitted in the gap, which causes the mode profile distortion shown in Fig. 6(b), extremely small \(d/D\) values are also not preferable. In practice, we seldom bend a fiber to a radius below 25 mm; a reduction of \(d/D\) to 0.61 is sufficient to avoid resonant-coupling-induced loss, and there is no need to keep reducing it.

Meanwhile, we compute the effective mode area and bending loss at different bending radii for \(d/D = 0.61\), with the results shown in Fig. 8. For AR-HCF with \(D = 23\) \(\mu\)m and \(d/D = 0.61\), the effective mode field area increases from 208 to 236 \(\mu\)m² when the bending radius increases from 15 to 70 mm. To some extent, when the bending radius is large enough (greater than 35 mm), the influence of bending on the effective mode area is almost negligible. The percentage of power in the capillaries experiences a sharp fall from 5.3% to 0.3%, with the bending radius increasing from 15 to 35 mm, and from this point onward the bending loss levels off at 0.3%.

Bending the fiber distorts the air-core mode-field profile and reduces the effective mode area. These facts show that for practical applications attention must be paid to the design of the fiber structure, to limit the impact of bending and resonant coupling.

Based on the factors above, controlling the ratio between cladding capillary diameter \(d\) and core structure diameter \(D\) from 0.6 to 0.7 is a suitable choice of parameters, and we must ensure that the bending radius is greater than 35 mm to avoid resonant-coupling bending loss in practical applications.

The transmission loss of the air core fundamental mode of the AR-HCF with \(N = 7\), \(t = 405\) nm, \(D = 23\) \(\mu\)m, and \(d = 14\) \(\mu\)m is calculated to be about 0.12 dB/m, based on the effective refractive index of the fundamental mode. The loss of the fiber can be expressed as in Eq. (4):

\[
\text{Loss\[dB/m\]} = \frac{20}{\ln(10)} \frac{2\pi}{\lambda} \text{Im}\{n_{\text{eff}}\},
\]

where \(n_{\text{eff}}\) stands for the effective refractive index of the air core fundamental mode.

**III. CONCLUSION**

For an AR-HCF, whether it can be applied in practice is

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**TABLE 1.** The parameters and corresponding optical properties of the designed Anti-resonant hollow-core photonic crystal fiber (AR-HCF)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Number of Cladding Capillaries</td>
<td>(N)</td>
<td>7 High HOMs Suppression</td>
</tr>
<tr>
<td>The Capillary Wall Thickness (t)</td>
<td>405 nm</td>
<td>The First-order Transmission Band (&gt;850.5) nm</td>
</tr>
<tr>
<td>The Air Core Diameter (D)</td>
<td>23 (\mu)m</td>
<td>The Effective Mode Area (= 232) (\mu)m²</td>
</tr>
<tr>
<td>The Capillary Outer Diameter (d)</td>
<td>14–16 (\mu)m</td>
<td>Low Bending Sensitivity</td>
</tr>
<tr>
<td>Bending Radius (R_b)</td>
<td>(&gt;35) mm</td>
<td>No Bending Resonant Coupling Loss</td>
</tr>
</tbody>
</table>

- | - | Transmission Loss is 0.12 dB/m
an important factor for its subsequent development. From the perspective of demand for flexible power delivery, the coupling between a hollow-core fiber and a solid-core fiber must be taken into consideration. In conclusion, we have proposed an anti-resonant hollow-core fiber with 7 non-touching capillaries that offers high HOMs suppression and matches to Nufern’s 20/400 solid-core fiber (NA 0.065). For matching, the air core diameter \( D \) is set to 23 \( \mu m \), with the effective mode area calculated as 232 \( \mu m^2 \). According to the anti-resonant reflecting optical waveguide model, the cladding capillary thickness \( t \) is set to 405 nm, to transmit a laser of 1064 nm in the near infrared. It is possible to avoid resonant coupling loss and reduce bending sensitivity by keeping the ratio of cladding capillary diameter \( d \) to air core diameter \( D \) between 0.6 and 0.7. The parameters and corresponding optical properties of the AR-HCF are summarized in the following Table 1.

It is known that AR-HCFs with a capillary wall thickness greater than 200 nm could be easier to manufacture. Overall, the simulation results show great potential for AR-HCF applications in power delivery for high-power fiber laser systems.

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**DISCLOSURES**

The authors declare no conflicts of interest.

**DATA AVAILABILITY**

Data underlying the results presented in this paper are not publicly available at the time of publication, which may be obtained from the authors upon reasonable request.

**REFERENCES**


