Hollow antiresonant fibers with low bending loss

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Abstract: We first use numerical simulations to show that bending losses of hollow antiresonant fibers are a strong function of their geometrical structure. We then demonstrate this by fabricating a hollow antiresonant fiber which presents a bending loss as low as 0.25dB/turn at a wavelength of 3.35μm and a bend radius of 2.5cm. This fiber has a relatively low attenuation (<200dB/km) over 600nm mid-infrared spectral range.

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1. Introduction

Applied research on hollow core optical fibers [1] includes various applications such as gas, liquid and chemical sensing [2, 3], optical data transmission [4], terahertz propagation [5], power beam delivery for industrial or medical applications [6, 7], and others. The adoption of a hollow core can allow more than 99.99% of the travelling light to be concentrated in air rather than in glass. This characteristic allows the use of these optical fibers in the mid-infrared wavelength regime [8–10] where silica absorption becomes high.

Two different technological approaches are arising in this novel spectral domain for silica-based fibers. The first is hollow antiresonant fibers (ARFs) of the type of [8], which have been demonstrated with a loss as low as 34dB/km at 3.05 µm and attenuation less than 200dB/km over a mid-infrared transmission bandwidth of about 900 nm [9]. The second is hollow core photonic bandgap fibers (HC-PBGFs) which have recently been reported with an attenuation of 50 ± 30dB/km at 3.33 µm and an attenuation less than 200dB/km over a mid-infrared transmission bandwidth approaching 200nm [10]. Despite the fact that ARFs have been demonstrated with lower attenuation and wider transmission bandwidth than HC-PBGFs, until now the latter have had the great advantage of having a much lower bending loss. In [10] Wheeler and colleagues reported a HC-PBGF with a 50 µm core diameter and bending losses of 0.25 dB/turn for a bend radius of 2.5 cm and wavelengths greater than 3.35 µm. In contrast, in [9], Yu et al. reported around 5.5dB/turn for a 10 cm bend radius at a wavelength of 3.35 µm, in an ARF with a 94 µm core diameter. Even given that bending losses of the fundamental mode may depend strongly on core size (as in the case of solid core optical fibres [11, 12]), it is obvious that bending loss results reported from HC-PBGFs are superior to those reported in ARFs. In [10] the lower bending loss of HC-PBGFs in comparison to ARFs was attributed to their fundamentally different guidance mechanism [13–15]. Due to the crucial importance of the bending loss for the practical use of hollow core fibers in the mid-infrared regime, this aspect is of particular interest.

In this work, we demonstrate that the bending loss of ARFs can be greatly reduced below those reported in [9]. Indeed, it has been recently observed that the bending loss of ARFs evolves in a more complicated fashion than that of conventional fibers [7, 16]. In particular, in [16] it was shown that coupling between silica cladding modes and the fundamental-like mode of ARFs greatly affects fiber bending losses. The objective of this work is to explore the bend characteristics of a different fiber design as reported in [17].

The design investigated here is based on cladding tubes which are not in contact with one another [17], so that each tube is “free” of its neighbours. This structure has already been investigated [17] as a possible way to reduce the overall fiber attenuation. In this work we intend to further investigate this same type of structure with a “free” core boundary in order to assess its benefits in terms of bending loss reduction. In section 2, we first evaluate the impact of the separation of the cladding tubes on the transmission and bending losses. Then, in section 3, we report on the fabrication of an ARF and on the attenuation and bending loss measurements. Finally in section 4 we draw some conclusions.

2. Numerical analysis

Figure 1(B) shows the typical structure of an ARF. As in [16], we use Comsol to perform our numerical simulations and we adopt a core diameter $D_c = 110\mu m$ and silica wall thickness $t = 2.66\mu m$. The cladding tube diameter $d$ for structure B (Fig. 1) is $d_0 = 68.19\mu m$ and inner diameter of the outer jacketing tube is $D_T = D_c + 2d_0 = 246.38\mu m$. As in [16], the wavelength used in our simulations is 3.05 µm.

As depicted in Fig. 1, we modify the design B by slightly changing the outer diameter $d$ of the tubes used to form the cladding and keeping $D_c$ and $t$ unchanged. We quantify the extent of this modification by adopting the parameter $\delta$, which is the difference between the cladding
tube diameter $d_0$ of the original structure B and the cladding tube diameter $d$ in the modified structures (see Fig. 1). At the bottom of Fig. 1 are some magnifications of certain areas of the considered structures (those in the dashed rectangles). As we can see, structure A is an ARF in which the silica cladding tubes penetrate into one another ($\delta<0$), structure B is an ARF in which the cladding tubes touch each other at a single point ($\delta=0$), and structure C is an ARF in which the cladding tubes are detached ($\delta>0$). Note that for all the simulated structures we have included a small penetration of 0.1 $\mu$m of all cladding tubes into the outer jacket tube, in order to make our simulations closer to the real case. This is illustrated in the magnification at the bottom of structure C.

![Fig. 1. Structure B is a typical ARF design. This is modified by changing the parameter $\delta$ (the difference between the new and the original cladding tube diameter: $\delta = d_0 - d$). The core diameter $D_c$ and the wall thickness $t$ are fixed for all structures while the cladding tube diameter $d$ changes. Structure A has $\delta<0$. B is an imaginary structure with $\delta = 0$. C is a structure with a “free” core boundary ($\delta>0$).](image)

### 2.1 Transmission losses

We have evaluated the impact of the separation of the cladding tubes in the structure of Fig. 1 on the fiber transmission losses. The results are shown in Fig. 2. The red dashed curve represents the leakage losses of the fundamental-like mode while the blue full line is obtained by including the effects of silica absorption from [18] in our numerical simulations. The minimum leakage loss is obtained for $\delta = 0$. However for $0<\delta<12$ $\mu$m (separated holes) the leakage loss of the fundamental-like mode of the ARF increases of only a small amount. In the case of $\delta <0$ (inter-penetrating holes), the amount of leakage rapidly increases. We can then conclude, as in [17], that the case of $\delta > 0$ (ARF with a “free” core boundary) is advantageous in terms of leakage losses (red dashed line) as compared to the realistic case of an ARF in which $\delta <0$. 

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However, when including the effects of silica attenuation (full blue line), using the “C” design is advantageous in terms of propagation loss over the “A” design only when the degree of penetration is quite substantial (in our designed case, for $\delta < -1 \mu m$). This would also depend on the amount of the silica material absorption and therefore on the particular wavelength range that it has been considered. Nevertheless the advantage of the structure “C” in terms of attenuation is likely to be greater in the near infrared spectral range. Indeed in this case we can neglect the impact of silica absorption.

2.2 Bending losses

We explored the impact of the separation of the cladding tubes on the bending losses of ARFs. The bending losses are calculated as in [16]. The results are shown in Fig. 3 for values of $\delta$ equals to 0, 8, 12 and 20$\mu m$. 

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Fig. 2. Impact of the modification of the $\delta$ parameter on the losses of ARFs. The red dashed line represents the leakage losses. The blue full line shows the losses when the silica material absorption is included in our simulations.

Fig. 3. Bending losses for different ARFs with $\delta > 0$. The bending losses of the considered ARFs can be greatly reduced by increasing the cladding tube separation. Note that all considered structures have the same core radius $R_c = D_c/2$ and the same wall thickness $t$. 

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In the original structure with $\delta = 0$ (black dashed line) bending losses are strongly affected by the coupling between the fundamental-like mode and the cladding silica modes [16]. This is visible from the local peaks present in the plots of Fig. 3. However we can also notice that the bend radius corresponding to these peaks is pushed towards smaller values when the cladding tube separation (and thus $\delta$) is increased. Eventually, when considering bend radii greater than 2 cm and $\delta = 20\mu m$ the local peaks completely disappear and no longer affect the evolution of the bending losses with the bend radius. We conclude that the adoption of an ARF with $\delta > 0$ would be extremely beneficial in terms of bending losses, particularly when the cladding tube separation is relatively large. Since the amount of leakage increases with $\delta$ (Fig. 2), a correct balance is required to produce a fiber with both low bending loss and low transmission losses.

3. Experimental results

We have fabricated an ARF with $\delta > 0$, to demonstrate the theoretical finding of Sect. 2. A scanning electron micrograph (SEM) of the fabricated fiber is shown on the left hand side of Fig. 4. The fiber has an outer diameter of 233$\mu m$. The core diameter is 109$\mu m$, the average cladding tube diameter is 27.9 $\mu m$ and the silica wall thickness is 2.4 $\mu m$. Over 200 meters of this fiber were drawn.

Fig. 4. On the left hand side is shown a SEM of the fabricated ARF. The measured fiber attenuation is shown on the right hand side. The minimum loss is around 100dB/km at 3.1$\mu m$. The inset on the right shows the simulated optical mode travelling into the fiber at 3.1$\mu m$.

3.1 Fiber attenuation

The attenuation of the fiber was measured by the cut-back method using a tungsten halogen bulb as broadband light source and a Bentham TMe300 monochromator, as in [9]. The resolution was 5 nm. We first purged 50 meters of the fiber with Argon for 2 days (at a net pressure of about 5 bars) in order to remove HCl gas [10], and then cut off 21m of the fiber to make our attenuation measurement. The residual length of 29m was chosen in order to minimize the influence on the loss measurement of higher order modes [17]. The measured loss is shown on the right hand side of Fig. 4. The minimum attenuation was measured to be 100dB/km at 3.1$\mu m$ and the loss was below 200dB/km over a bandwidth of about 600nm. The estimated maximum error of the measurement was less than 5% over the entire transmission bandwidth. The inset on the right of Fig. 4 shows the simulated fundamental-like optical mode at 3.1$\mu m$.

3.2 Bending losses

We measured the bending losses of the fabricated ARF by using 8.5 meters of the fiber in two different configurations. Firstly, as in [9], we measured the attenuation induced by bending
the fiber of half of a full turn (180 degrees) with a bend radius R. The result is shown on Fig. 5(a) and is directly comparable to that shown in Fig. 5 of [9]. As we can see, we can only observe a slight decrease of the light intensity for a bend radius of 2.5cm (blue full line) on the shorter wavelength edge.

![Diagram](image)

Fig. 5. Bending loss measurements: on the left hand side (a), the fiber transmission spectrum obtained by bending the fiber half a full turn, as in Fig. 5 of [9]; on the right hand side (b), we have adopted a different configuration by measuring the net fiber attenuation obtained by bending our fabricated fiber by 5 full turns. As in Fig. 3 of [10], bending losses are lower than 0.25dB/turn for wavelengths longer than 3.35μm and a bend radius of 2.5cm. The measured bending losses are lower than 0.5dB/turn over more than 450 nm bandwidth.

We adopted a second configuration for further bending loss measurements to be able to compare our results to those reported in Fig. 3 of [10]. As shown in Fig. 5(b), we measured the attenuation induced by bending the fabricated ARF by five full turns at different bend radii R. For a bend radius of 2.5cm (blue full line) the bending loss is lower than 0.5dB/turn across a bandwidth of 450nm, a much broader range than that reported in [10]. As in the reported HC-PBG [10], the bending loss of our ARFs is lower than 0.25dB/turn (1.6dB/m) for a bend radius of 2.5cm and wavelengths longer than 3.35μm. On the same figure we can observe that if the fiber is coiled on a standard fiber spool with a bend radius of 7.96cm (black dashed-dotted line), the bend loss is of about 0.15dB/turn (0.3dB/m) over the minimum attenuation region between 3.1 and 3.2μm (Fig. 4), a relevant wavelength range for the implementation of acetylene gas lasers [19].

4. Conclusion

We have demonstrated theoretically and experimentally that mid-infrared silica-based antiresonant fibers with low bending losses can be realized. The fabricated fiber with a free core boundary has relatively low attenuation and bending loss over an extended wavelength range.

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