Exploring the Effect of the Core Boundary Curvature in Hollow Antiresonant Fibers

Lieke D. van Putten, Eric Numkam Fokoua, Seyedmohammad A. Mousavi, Walter Belardi, Subhasis Chaudhuri, John V. Badding, Francesco Poletti

Abstract— **Through numerical simulations, we systematically study the leakage loss properties of a simplified novel hollow antiresonant fiber in which the core is surrounded by semi-elliptical elements. These studies lead to new insight into the effect of the curvature of the core boundary in antiresonant fibers. We observe in particular that in our design, there exists an optimum curvature of the elements - which we quantify simply through the aspect ratio of the ellipses – for which the fiber's leakage loss is minimized. Furthermore, it is shown that elliptical elements can lead to orders of magnitude loss reduction as compared to similar fibers with circular ones.**

Index Terms—**Optical Fibers, Optimization Methods**

I. INTRODUCTION

HOLLOW antiresonant fibers (ARF) are emerging as attractive candidates for low-loss light guidance at near and mid-infrared wavelengths [1, 2]. Their low optical nonlinearity and ultralow fraction of power carried in the glass result in a high damage threshold for ultrashort pulse delivery applications, while also placing less stringent demands on the transparency of the materials employed [3]. Recent research is focusing on optimizing their structure in order to reduce the total loss. In Kagome-type hollow core fibers with a hypocycloid core surround, several studies have shown a dependency between the leakage loss of the fiber and its cladding structure [4, 5], and recent works have already established that leakage loss can be significantly reduced when the curvature of the arcs forming the core boundary is increased [6-8], although no clear physical explanation has been provided for this behavior. A more recent family of hollow antiresonant fibers, already highlighted for its low loss in the infrared [2] and for its relatively low bending loss at large mode field diameters [5], consists of a simpler design in which the air-core is surrounded by a number of touching or non-touching circular capillaries [1, 9]. These fiber types offer a better platform to try to understand the effect that the curvature of the membranes surrounding the core has on the overall loss, since different curvatures can be obtained while keeping unchanged key geometrical parameters [5, 10]. In a more recent study, a fiber featuring elliptical elements was shown to further reduce the leakage loss while offering effectively single-mode guidance [11].

L.D. van Putten, E. Numkam Fokoua, S.A. Mousavi, W. Belardi and F. Poletti are with the Optoelectronics Research Centre, Southampton, United Kingdom.
S. Chaudhuri and J.V. Badding are with Department of Chemistry, Pennsylvania State University, University Park, PA 16802, USA

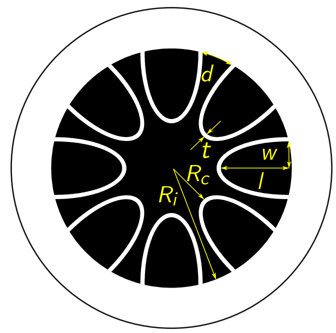

Fig. 1. Geometrical parameters of the fiber under study, here with 8 half elliptical strands. The core radius is R_c, the major semi-axis l, the minor semi-axis w, wall thickness t, cladding radius R_i and separation d.

In this work, we further explore the relationship between the curvature of the cladding elements and the optical properties of the fiber. We also suggest a possible interpretation of the physical principle leading to loss variation for a change in curvature. To this end, we also opt for elliptical cladding elements as they offer the flexibility for a systematic and gradual change of the core boundary curvature while maintaining other design parameters, such as the separation between the elements, constant. However, we choose instead half ellipses as they allow us to study the effect of core surround curvature and have the prospect of increased structural stability during fabrication since they have two anchor points rather than one for full ellipses.

II. STRUCTURAL DEFINITION AND SIMULATIONS

Figure 1 illustrates the geometry of the cross-section of the structure we study, along with the definition of the main design parameters that may be modified. We quantify the curvature c of the elements through the aspect ratio of the elliptical elements surrounding the core, that is, c = l/w, and can modify it in several ways. To enable the fairest possible comparison between fibers with different values of c, we chose to fix the core radius R_c and the inner cladding radius R_i (hence also the major semi-axes of the ellipses), and to keep the separation d between the anchor points of neighboring elliptical elements along the inner cladding boundary also constant.

With these constraints, an increasingly larger value of c can

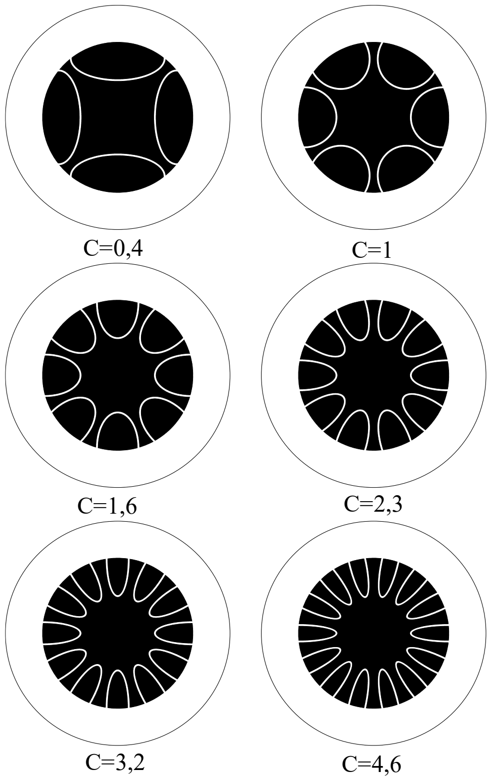

Fig. 2. Simulated structures with increasing aspect ratio. The case with 6 half ellipses corresponds to unit aspect ratio (c=1).

be achieved by increasing the number of elements, as can be seen in Fig. 2. For a fiber with a core radius of R_c we chose an inner cladding radius R_i =1.98Rc. By choosing a separation d of 0.424 R_c we obtain unit aspect ratio or semi-circular elements when exactly six elements are included. By changing the number of elliptical elements from 4 to 14 we obtain aspect ratios c ranging from 0.4 to 4.5. In the study the wall thickness t was chosen to be 0.036 R_c.

Using a commercially available finite element solver, COMSOL Multiphysics, we solved for the core-guided modes of these fibers, focusing primarily on the leakage loss properties of the fundamental HE11 mode. The perfectly matched layers were optimized using the same parameters as Ref. [1], which were validated in Ref. [12,13]. We used a refractive index n = 1.49 for the cladding material typical of a polymer (but the results would be almost identical for silica) and did not include the negligible material dispersion or absorption.

III. Results and Discussion

In Figure 3 the leakage loss and fraction of optical power in the dielectric for the six different structures are plotted as a function of normalized frequency, $f=2t/\lambda\times\sqrt{(n^2-1)}$, for f in the range 0.7-3.1. In the three antiresonance windows covered by our simulations, the structure with 10 ellipses and a corresponding c of ~2.3 is found to have a considerably lower value of leakage loss than the others. In the second antiresonance window, the minimum loss for this structure (black curve) is nearly two orders of magnitude lower than the corresponding value for the structure with semi-circular elements (yellow curve) despite both having identical core and cladding dimensions. To test the reliability of this conclusion we repeated these simulations with different core sizes and inner cladding radii. In all cases the results indicate that in structures with semi-elliptical elements with fixed major axis, fixed core size and fixed azimuthal gap between elements' anchor points, there exists an optimum curvature c for which the loss is minimized, and either side of which the loss increases. Table 1 summarizes the optimum aspect ratios found for a range of design parameters, which was always in the region of ~2.1-2.4. Our simulations were also repeated for cases where we fixed instead the absolute minimum distance between neighboring elements and yielded again, similar results. In our simplified design, the simulated minimum loss for the optimum curvature is of the order of 1 dB/km. We found however that replacing the circular arcs in fiber designs such as in ref. [7] with elliptical ones could further reduce the loss by an order of magnitude approximately.

As the number and curvature of the elements increase, we note a distinct narrowing of the antiresonance window. This is more apparent when examining plots of the fractional power guided in glass shown in Fig. 3b. It is clear from the plots that an increase in the curvature of the elements results in an increasingly large blue shift of the low frequency edge of the antiresonance window, leading to its narrowing. A qualitatively similar behavior was recently observed in fibers with circular cladding elements as their refractive index increased, and was attributed to changes in the cutoff frequency of the modes guided within the thin elements [14].

Interestingly, the minima of the fractional power carried in the solid material are rather similar for all structures, indicating that the aspect ratio of the ellipses cannot be used to enhance transmission where the material is highly absorbing [15].

To verify whether the decrease in loss can be explained by the curvature alone, we have also studied the same 6 structures in which the semi-ellipses are solid, i.e. completely filled with the dielectric material. Fig. 4 shows a comparison between these and the air filled (antiresonant) case at the fixed normalized frequency of 1.55. Two observations can be readily made from the plot: (i) the antiresonance of the strands provide more than three orders of magnitude improvement in the loss compared with the solid structure; and (ii) for solid elements, in striking contrast to the membrane case, no noticeable change occurs to the loss as a function of the curvature of the elements. This indicates that both antiresonance and element curvature play a role in the observed loss reduction. Antiresonance dictated by the thickness of the elements determines the spectral window where light confined in the core are effectively reflected and experiences little leakage, whereas the curvature, by determining which modes are guided within the thin elements also plays a role in determining wavelengths at which significant coupling with core guided modes is possible.

It is interesting to examine the field distributions of the modes guided in the different structures simulated. Figure 5 shows the contour plot of the z-component of the time-averaged Poynting vector for the six structures at a normalized frequency of 1.55. The contour lines cover a 60dB range and are 2dB apart. For structures in which the elements have a low c value, significant leakage occurs through the curved elements, and the field intensity near the inner jacket boundary is relatively

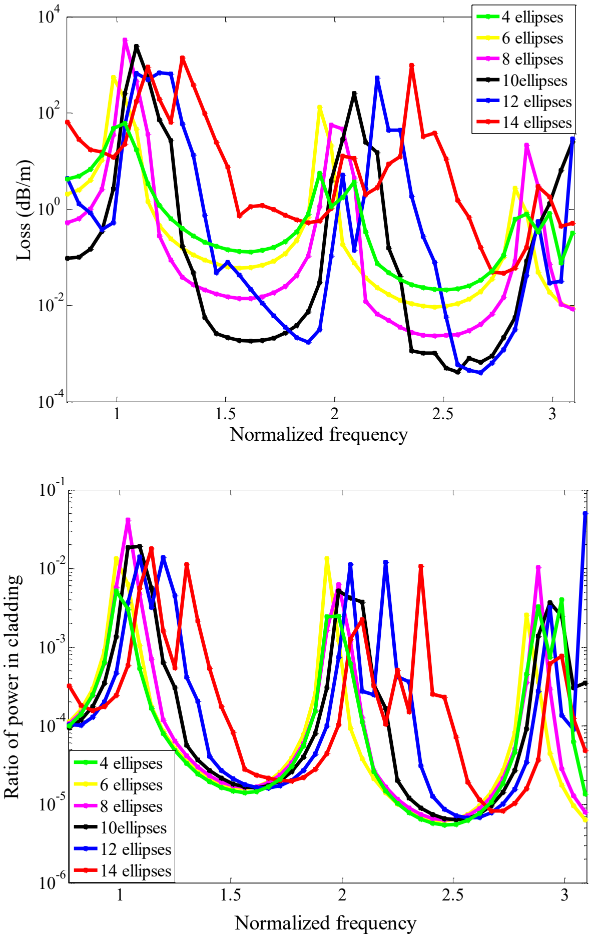

Fig. 3. (top) Leakage loss of the fibers in Fig. 2. The structure with 6 ellipses corresponds unit aspect ratio of a circle or semi-circles. (bottom) Fraction of power in glass for the fundamental mode for each structure.

TABLE 1
OPTIMUM ASPECT RATIO FOUND FOR DIFFERENT GEOMETRY PARAMETERS

R_c (μm)	R_j(μm)	Optimum aspect ratio	Number of ellipses at optimum
10	19	2.13	8
13	23	2.36	10
15	24	2.13	12

high. In the structure with the lowest loss, the curved elements are more effective at repelling the field which has vanishingly small intensity near the inner jacket boundary, and this results in the observed reduced leakage loss. Further curvature beyond this optimum point produces a strong field localization within the thin dielectric membranes. This indicates a stronger coupling between membrane guided modes below cut-off and air-guided core modes, and clearly represents an additional pathway for the guided light to leak out to the increase in the jacket and increase the loss of the fiber. We examined this mechanism more quantitatively by calculating the relative contributions to the overall loss arising from leakage of the electromagnetic field through: i) the elliptical elements; ii) the gaps between the elements; and iii) the glass membranes. We do so by calculating the outward flux of the radial Poynting vector along the inner jacket boundary. This flux taken along the outer cladding boundary gives the total leakage loss. If we decompose this integral along specific segments on the solid clad boundary, as shown in the inset of Fig. 6, we can calculate the relative contributions to the loss.

The gaps between elements are shown in green, the glass membranes in red and the contribution due to leakage through the elliptical elements in blue. These contributions, normalized to the total integral along the inner boundary (i.e. the confinement loss), are plotted in Fig. 6 as a function of the number of elliptical elements in the fiber. It can be seen that for the smaller values of curvature, i.e. for structures with 4, 6 and 8 elements, leakage through the elliptical elements is the dominating contribution. Interestingly, this contribution decreases monotonically with increased curvature. What makes the total loss increasing after 10 elements is the combined contribution of leakage through the gaps and along the membranes. Leakage through the gaps increases both as a result of the slightly increasing minimum distance between the elements, and the increasing number of gaps (In simulations where this minimum distance was kept constant and the inner cladding radius slightly decreasing instead, we obtained similar results in optimum curvature and leakage contributions).

For 12 elements, the leakage through the thin membranes is similar in magnitude to the leakage through the elliptical elements, and it becomes the dominant contribution for the structure with 14 elements. The decrease of some contributions and increase of others as a function of aspect ratio explains the presence of an optimum curvature for which the loss is minimized, as shown in Fig. 3.

Leakage through the membranes can be understood from the viewpoint of geometrical optics by realizing that when the aspect ratio of the elements is very high, light rays forming the guided core-guided mode strike the curved elements at shallow angle with the local normal. Because of the curved nature of the elliptical strand, the refracted ray may become trapped in the membrane via total internal reflection and guided this way to the outer jacket. This effect becomes increasingly dramatic

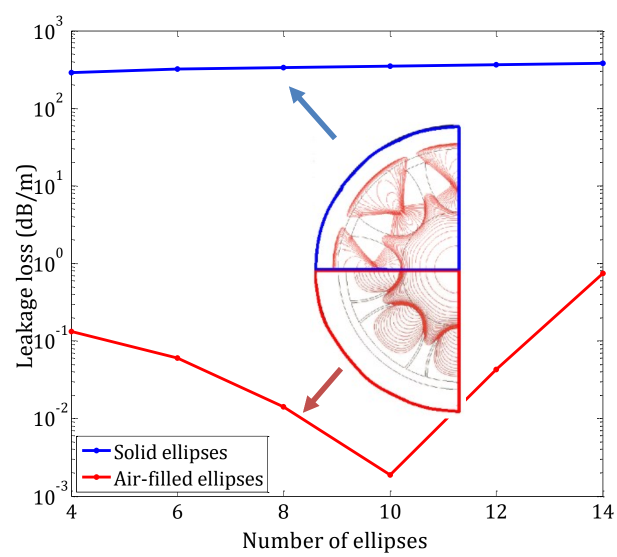

Fig. 4. Loss comparison for structures with solid ellipses and air-filled ellipses as a function of the number of ellipses in the cladding. All simulations at f=1.55.

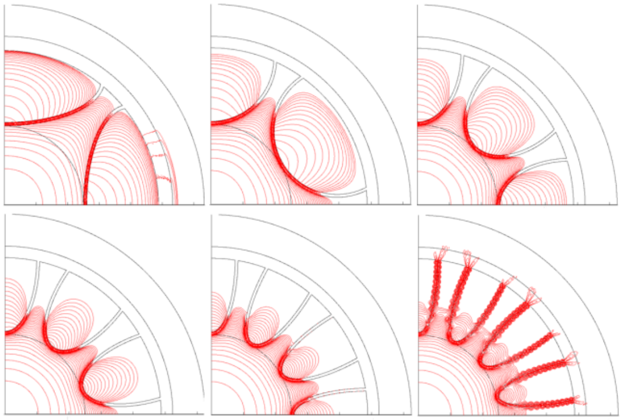

Fig. 5. Mode profile for studied structure at f=1.55.

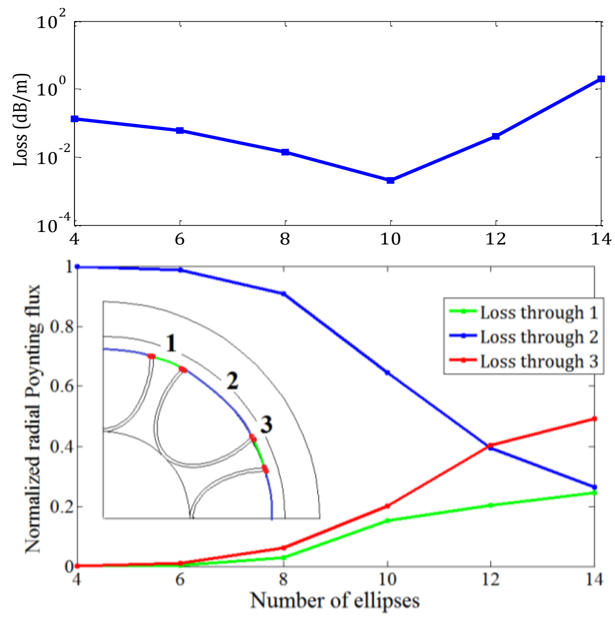

Fig. 6. Graph showing the ratio of the contribution to the leakage loss for the different boundary areas on the fiber.

when the curvature of the elements is increased, and it leads to the observed increase in leakage loss.

IV. Conclusion

We have systematically studied the influence of the curvature of core surrounding glass membranes in a simplified hollow core antiresonant fibers in which the core is surrounded by half elliptical membranes. We have found that by changing the curvature or aspect ratio of the elliptical elements, one may obtain a fiber in which the leakage loss is up to two orders of magnitude lower than in fibers with similar core and cladding radii, but having circular elements. We have also presented new insight into the role played by the curvature in the loss reduction. In general, the larger the curvature the lower the leakage through the antiresonant elements. However, the leakage through gaps between elements and along the dielectric membranes is seen to increase. For this reason, an optimum aspect ratio value for the elliptical elements c~2.3 has been observed for the several structures we analyzed, for which the leakage loss of the structure is minimized.

We have found that an optimum aspect ratio exists for any given set of fixed parameters such as core size, major axis of the ellipses and gap between the elements. The ability to reduce the loss of the fiber by changing the curvature for a fixed core size, or to reduce its core and cladding size for a given loss might find application in those areas where the fiber cross-section needs to be minimized, e.g. in the development of flexible Terahertz waveguides.

Whilst achieving membrane curvatures significantly greater than 1 might be complex for preform fabrication processes based on the stacking of circular capillaries, alternative processes based on extrusion or additive manufacturing techniques might provide a way to achieve the fibers proposed in this work, combined with a high tension, low temperature drawing process to minimize structural deformations during the fabrication of the fiber.

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