Optimizing the Curvature of Elliptical Cladding Elements to Reduce Leakage Loss in Antiresonant Hollow Core Fibres

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Abstract *We study systematically the effect of the curvature of glass membranes on the confinement loss of an antiresonant negative curvature hollow core fibre. Optimum curvatures are found that can reduce the fibre loss by orders of magnitude.*

Introduction

Hollow core antiresonant fibres, where light is confined in an air core through antiresonances in dielectric membranes surrounding the core, are a newly emerging family of fibres with great potential for short-reach and device applications[1]. Due to the very small fraction of optical power carried in the glass, these fibres have a low optical nonlinearity and a high damage threshold, making them attractive solutions for high peak power ultrashort pulse delivery applications[2], for transmission at wavelengths where glass is opaque[1] and for short reach data transmission[3].

One important line of investigation concerns the development of novel structures that allow optical guidance at the lowest possible loss. Recent studies in the so-called Kagome-lattice fibres have shown that by having a core surrounding membrane with a negative curvature, the resulting leakage loss –the dominant source of loss in these fibres– can be reduced.[4] More recent works have shown that such leakage loss can be further decreased by increasing the curvature of the arcs that surround the core.[5,6] An interesting antiresonant fibre design offering low loss guidance is that of an air-core surrounded by a number of touching or non-touching dielectric tubular elements[1,7]. This fibre provides a good basis to study the effect of the curvature of the cladding elements, since this can be changed independently of other parameters, which makes fair comparisons possible. In this work, a systematic study of the relationship between the leakage loss and the curvature of the cladding elements of an antiresonant fibre with half-elliptical elements is presented. We find that significant loss reduction is possible by optimising the curvature, and propose some initial understanding of why this happens.

Modelled fibres

To study the effect of the curvature on the leakage loss, we propose a novel hollow core fibre design with half-elliptical cladding elements. Elliptical membranes offer design flexibility, as their curvature can be changed by varying the ratio between major and minor-axis, as already studied recently[8]. In this work we focus on half-elliptical elements (see Fig.1), which due to the presence of two anchoring points rather than just one benefit from an increased stability of the shape of the fibre during the drawing process.

In order to enable a fair comparison between fibres with different curvatures, in this study we consider fibres with the same core radius, *Rc*, ellipse length, *l,* and azimuthal separation between the elements, *d*, as shown in Fig. 1. The curvature, defined as $c = l/w$, can be changed by simply varying the number of half-elliptical cladding elements in the structure (increasing the number of cladding elements leads to a larger curvature). In this way, the effect of different curvatures can be studied without modifying other loss-influencing structural parameters.

In this study, a set of fibres with 4, 6, 8, 10, 12 and 14 half-ellipses are studied (some examples in fig.1). The inner fibre radius, R_i, is chosen to be nearly twice the length of R_c, while the thickness

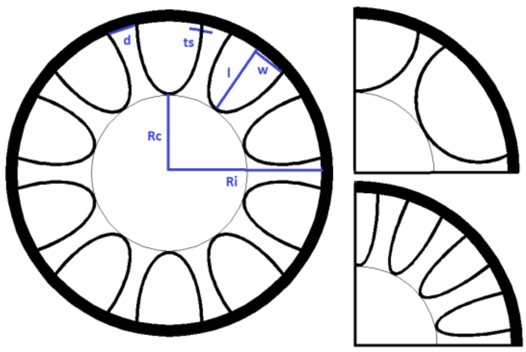

Fig. 1:(left)Geometrical parameters in the studied fibre with core radius Rc, inner fibre radius Ri, major-axis of the ellipse l, minor-axis w, thickness of the elements t and separation between the elements d.
(right) Simulated structure with 6 and 14 cladding elements.

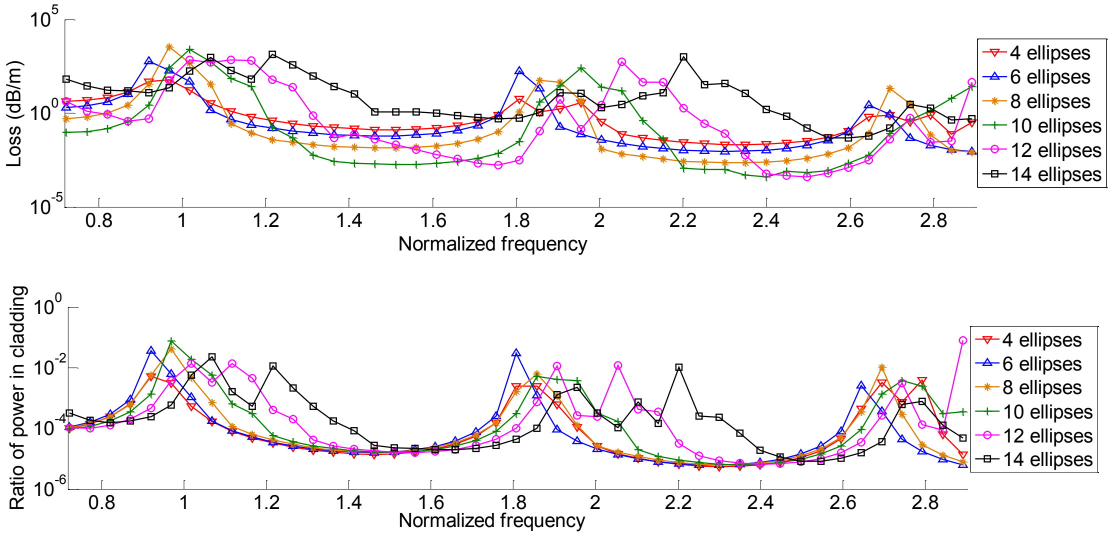

Fig. 2: (top) Leakage loss of the fibre for six different curvatures. (bottom) Ratio of power in the cladding membranes for all six different curvatures.

of the cladding elements is set to $R_c/28$. To include the case where the curvature equals unity (i.e. half circle), the parameters are chosen so that for six ellipses *c* equals 1. This forces the separation *d* between the ellipses to be 0.424 R_c. This set of parameters enables the test of curvatures ranging between 0.4 (4 ellipses) and 4.5 (14 ellipses). Due to the small fraction of power in the cladding elements, material absorption is not included in these simulations[9]. The material dispersion is also neglected (with a dielectrics refractive index of 1.49), which makes it convenient to represent spectral results as a function of normalised frequencies, $f = \frac{2\pi}{\lambda}\frac{Rc}{100}\sqrt{n^2-1}$.

Results

The leakage loss of the core-guided modes in these structures have been calculated using a finite element solver with optimized perfectly matched layers[10]. In Fig.2a the leakage loss and the fraction of optical power guided in the dielectric cladding is plotted for all six fibres. Interestingly, at antiresonance (i.e. frequencies of ~1.5, ~2.5 etc.) the loss of the various fibres first decreases (4 → 10 elements) and then rapidly increases (10 → 14). Despite the fact that the fibres have the same core and cladding size, remarkably the overall loss values differ by as much as 4 orders of magnitude. The structure with the lowest leakage loss corresponds to the one with 10 ellipses, i.e. with a curvature of ~2.3. Its loss is two orders of magnitudes lower than the corresponding value for the structure with c=1. These simulations have been repeated fibres with smaller and larger R_c/l and the optimum curvature was always found to lay in the 2-2.5 range, as shown in Table 1.

As the number of elements increases, we also note a decrease in the width of the antiresonance windows, as can be seen more clearly in Fig. 2b. Even though all structures exhibit a very similar minimum value of fractional power in the dielectric (~10^{-5}), the higher curvatures produce resonance produce wider and more blue-shifted peaks, likely due to the slightly increased optical thickness at some point along the membrane.

The same six structures have also been studied with glass-filled ellipses instead of air-filled elements. Due to the absence of antiresonance elements in the cladding, the fibres with glass-filled elements have a leakage loss more than three orders of magnitude higher than in the structure with air-filled cladding element, and it is almost independent on the curvature. This leads us to conclude that only the combination of curvature and antiresonance is responsible for the effect seen in Fig.2.

Examining the field distributions in the fundamental mode shows that at lower curvatures the power leaks preferentially through the elliptical element. At large enough curvatures a large fraction of power becomes guided within the membranes of the cladding elements, through which it leaks out to the fibre jacket and contributes to the loss. In Figure 3 this is shown quantitatively. The integral of the radial Poynting vector along the boundary is calculated and the

Tab. 1: Optimum curvature for simulations with different Rc/l ratios

Rc/l	Optimum number of ellipses	Corresponding curvature
0.9	8	2.13
1.18	10	2.36
1.67	12	2.13

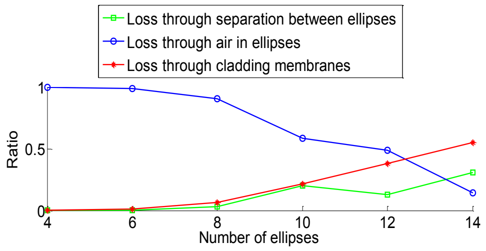

Fig. 3: Ratio of leakage loss through each section of the fibre structure

contributions are divided into three different parts: the fractional power flowing radially through the elliptical elements, through the gaps between elements and through the glass of the membranes. It can be seen that the ratio of loss through the air surface in the ellipses decreases for an increasing curvature, while the loss through the membranes increases. This can be explained by realizing that at higher curvature the light rays for the guided mode strike the surface of the elements at an angle that leads the refracted ray to be totally internal reflected. The combination of these two effects leads to the observed optimum loss for a fibre with 10-12 ellipses, where both contributions are similar in size.

This understanding can be also applied to the loss reduction in other types of antiresonant fibres, for example those in ref. [6] that are formed by expanding preforms with touching circular tubes and produce touching 'ice cream cone' shapes. If instead of circular elements the curved core boundary is replaced by half-ellipses as in Fig.1, the loss can be further reduced. Using an ellipse with a curvature of C=1.9, the leakage loss of the structure can be further decreased by more than one order of magnitude, i.e. from $3.3*10^{-4}$ dB/km to $4.34*10^{-5}$ dB/km for a 47 um core size.

Conclusions

We have systematically studied the influence of the curvature of the cladding elements in hollow core antiresonant fibres. We have found that in fibres with the same core and cladding size the leakage loss can decrease by several orders of magnitude by simply changing the curvature of the half-elliptical elements in the cladding. This very significant reduction could be a way to achieve low loss hollow core fibres with a small core and cladding size, which would be better matched to the mode field diameter of solid fibres and more easily spliceable to them.

We have investigated the physical origin of this loss and found that such a dependence of the loss from the curvature of the elements does not occur when solid cladding elements are used instead of air-filled ones, indicating that it is the combination of curvature and antiresonance that plays a role.

The decrease in loss seems correlated with a decreased leakage through the glass membranes. However, this loss decrease does not continue indefinitely. When the curvature is increased beyond a given optimum value, c~2, the core mode begins to couple efficiently (thanks to total internal reflection) to glass guided modes in the elliptical elements.

Whilst fabricating structures with membranes of curvature higher than 1 makes the fabrication process more complex since simple cylindrical glass tubes cannot be used, extrusion or 3D printing/additive manufacturing processes might be used to produce preforms with the desired c>1 structure. Sufficiently 'cold' draws might then in principle prevent surface tension and pressure forces from restoring the c=1 condition, eventually leading to fabrication of the desired fibres.

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