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# Negative curvature fibers with reduced leakage loss

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**Abstract:** We describe improved designs for “negative curvature” hollow core anti-resonant fibers. Numerical simulations show that introducing additional silica rings into the cladding results in a major reduction in the fiber leakage losses, for realizable fiber structures.

**OCIS codes:** (060.2280) Fiber design and fabrication; (060.2400) Fiber properties; (060.4005) Microstructured fibers.

## 1. Introduction

Hollow core anti-resonant fibers with a “negative curvature” of the core boundary have been developed in recent years as a route for achieving reduced fiber losses, low mode-glass overlap and wide transmission spectra [1,2]. Negative curvature fibers (NCFs) with losses as low as 24dB/km at 2.4 $\mu$ m have been demonstrated [3] and the benefits of the negative curvature have been modeled numerically [4]. These fibers could be used to handle high optical powers [5], to access new wavelengths regimes [6, 7] and for studying light/gas interactions [8]. Reduction of attenuation in this type of fiber is a challenging problem that could benefit all of these applications.

The core wall of an NCF is a high refractive index (glass) region surrounding and defining the hollow core, whose thickness satisfies an anti-resonant condition [9]. We will show that modification of the region immediately outside the core wall has a major impact on the rate of leakage from the fiber core, while leaving the anti-resonant condition of the core wall unaffected. The modifications we propose to previously-reported designs are restricted to outside of the core wall, enabling us to make direct comparison with the existing proven designs.

In this work we first describe the idea from a theoretical point of view. Then we propose a realistic design for a practical fiber and use numerical simulations to evaluate the impact of this novel structure on the fiber performance.

## 2. Theoretical case

The design “A” depicted in Fig. 1 shows a fiber structure that has been thoroughly studied theoretically and experimentally in [3], [10] and [5]. The radius of the fiber’s hollow core  $R_c$  is 47 $\mu$ m, the thickness of the silica core boundary  $t$  is 2.66  $\mu$ m and the inner radius of the silica cladding tube  $R_T$  is 128.75 $\mu$ m. The spectral range of interest for these parameters is between 2.8 and 3.8  $\mu$ m, between the first and second core wall resonances. We choose this fiber as the starting point of our discussion because it gives us the possibility to relate our results directly to previous work which has been experimentally validated.

In structure “B” of Fig. 1 the same fiber core radius  $R_c$  and core boundary thickness  $t$  of structure “A” have been used but the cladding holes are circles of diameter  $d=58.27\mu$ m rather than “ice-cream cone” holes. The adoption of circular cladding holes removes the Fano resonances in the fiber transmission spectra [11]. As in [3], we used Comsol to perform all our numerical simulations. The calculated transmission spectra for structures “A” and “B” at wavelengths between 2.75 $\mu$ m and 4 $\mu$ m are shown in Figure 1 (purple line with dots and green full line respectively).

The field associated with the core mode is not completely confined within the hollow core, but extends beyond the silica core boundary into the cladding holes.. However if we modify the structure “B” by adding an additional ring of glass (structure “C” in Fig. 1) within the cladding holes of the fiber, we can exclude light from this area giving an improved confinement to the fiber core. We choose the outer diameter  $d_l$  of this new ring to be half of the outer diameter of the cladding holes  $d$ , and give it the same wall thickness. The transmission spectrum for this ideal design is also shown in Fig. 1 (dashed blue line). The leakage losses of the fiber have been dramatically reduced by the additional structures, by up to 3 orders of magnitude to well below 0.1dB/km, on the short wavelength side of the transmission window.

## 3. Practical case

The considered fiber structure “C” is not realizable because the internal silica ring is suspended in air. We now support this internal structure and thus design a similar fiber which is practical. The structure we have studied is shown in Fig. 1 (structure “D”). As we can see from the transmission spectrum in Fig. 1 (red dashed-dotted line) this practical structure should provide a reduction of leakage losses of 100 times compared to previously-reported designs (structure “B”), on the short-wavelength side of the transmission window to below 0.1dB/km.

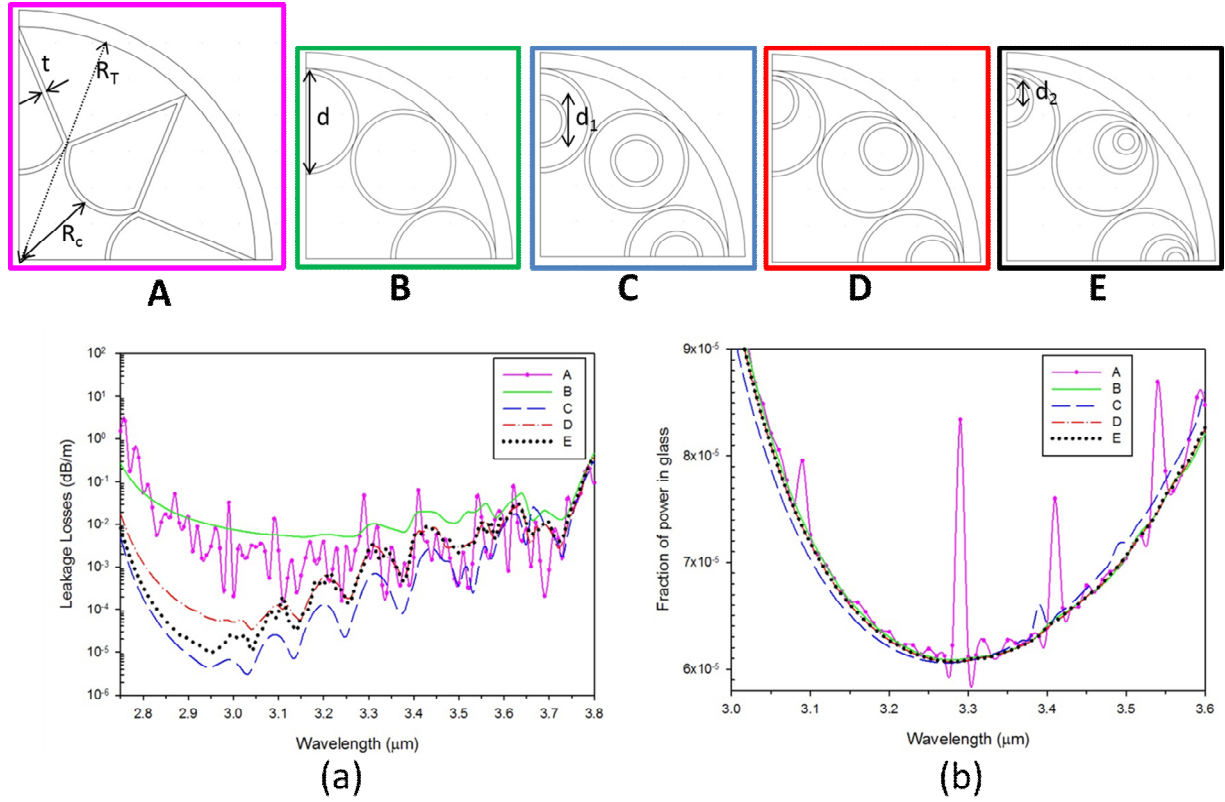


Fig. 1: (a) Calculated leakage losses for the different structures depicted above: A (purple line with dots), B (green full line), C (blue dashed line), D (red dashed-dotted line), E (black dotted line). The insertion of additional silica rings within the cladding structure of the NCF can substantially reduce the fiber leakage losses ; (b) Calculated fraction of power in glass for all the different structures A,B,C,D,E. The additional silica rings within the cladding structure leaves the overlap between the optical mode and the silica almost unaltered.

In principle, further reduction in the leakage losses can be achieved by adding extra rings within the fiber cladding. As an example, the structure “E” of Fig. 1 has three nested rings (the diameter  $d_2$  of the most internal circle is equal to  $d/2$ , the thickness of the silica layer is the same of that of all other layers  $t$ ). As we can see in Fig. 1(a) (black dotted line) the addition of a third nested ring would reduce the confinement by 5 times as compared to the previous fiber structure (“D”).

#### 4. Percentage of optical power in glass

The overlap of the core mode with the silica structure is a critical parameter, determining the NCFs performance in mid-infrared applications (where silica material absorption is a limitation) [4, 6] as well as its nonlinearity and power handling characteristics. It may also be relevant for the ultimate achievable fiber attenuation. Therefore we have studied the overlap of the optical power with the silica glass for the various fiber structures described above. The results are shown in Fig. 1(b). As we can see, despite adding additional silica to the structure, the minimum overlap of the guided mode with the glass remains almost exactly the same at around  $6 \times 10^{-5}$ .

#### 5. Design tolerances

We have performed a numerical analysis of structure “D” of Fig. 1 by changing first the inner hole diameter  $d_1$  and then the inner hole thickness  $t_1$  (keeping all other parameters unchanged) in order to evaluate the design tolerances of this structure. The calculation of the leakage losses is made at the specific wavelength of  $3.05 \mu\text{m}$ . The results are shown in Fig. 2.

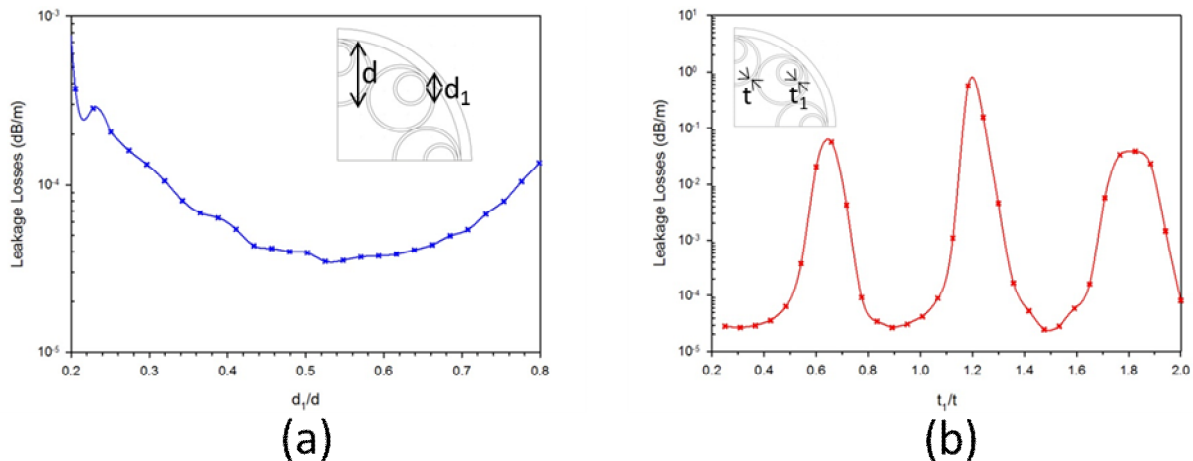


Fig. 2. (a) The calculated leakage losses for the structure depicted in the inset are almost identical for variations of  $d_1/d$  between 0.5 and 0.6; (b) The variation of the inner ring thickness has little effect on the fiber leakage losses for values of  $t_1/t$  between 0.8 and 1, between 0.2 and 0.4 and around 1.5.

The tolerances of this design are quite large. In Fig. 2(a) we can clearly see that the leakage losses have minor changes for values of  $d_1/d$  between 0.5 and 0.6. In Fig. 2(b) we can observe minor variations of the fiber performances for change of  $t_1/t$  between 0.8 and 1 as well as between 0.2 and 0.4 or around 1.5. The large tolerances allowed confirm that our design should be amenable to fabrication.

## 6. Conclusions

We have presented a novel and practical design improvement for hollow core anti-resonant fibers based on the use of additional silica rings in the cladding. We have investigated the potential benefit of this fiber structure in terms of leakage losses.

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