High birefringence hollow core with nested anti-resonance nodeless fibers for terahertz guidance

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Abstract

Recently, hollow-core fibers have been brought to the attention of the photonics research community because of their capability of very high transmission capacity. Several fiber parameters regarding the transmission capacity have been extensively studied. Loss is the first and foremost parameter that was examined. Equally important parameter and still in an early stage of the investigation is the birefringence of the hollow-core fibers. In this study, the high birefringence in the hollow core with nested antiresonance nodeless fibers (HC-NANF) is proposed for the investigation. This model is specifically designed for terahertz guidance made from TOPAS copolymer. Using finite element method (FEM), the initial simulation results reveal that a number of the inner tubes and tube thickness play an important role in the loss at the operating frequency around 1 THz. However, the tube separation has no significant effect on the effective material loss. In addition, there is no birefringence existing in the straight fiber model. In order to achieve high birefringence, the proposed fiber is bended at a particular radius. The result shows that the bending gives rise to the changes of the effective refractive indices in the horizontal and vertical directions of the core leading to a significant birefringence in the hollow-core fiber. Finally, the orthogonal birefringence obtained from HC-NANF design is found to be higher than 10^{-4}.

Antiresonant reflecting guidance mechanism

Hollow core antiresonant fibers consisting of a single layer or multiple layers of cladding tubes are devices that use antiresonant reflecting guidance mechanism to confine light or electromagnetic wave in the fiber. This fiber uses air as the core material and uses an appropriate material as the cladding material. The primary key of this mechanism is the thickness of the tubes; the cladding part. With a particular thickness, some wavelengths (called "antiresonant wavelength") can be confined in the fiber due to antiresonant reflecting guidance mechanism.

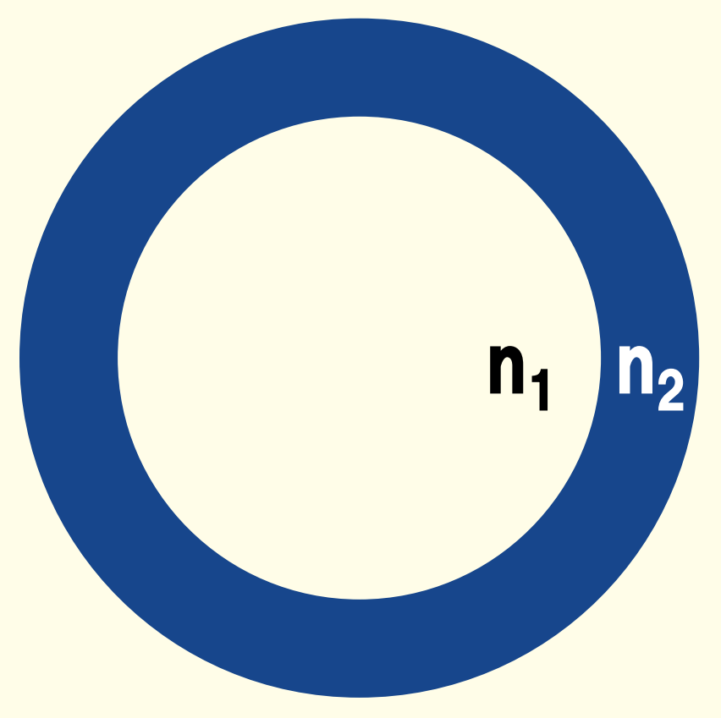

Figure 1 Schematic diagram cross-section of a hollow core fiber.

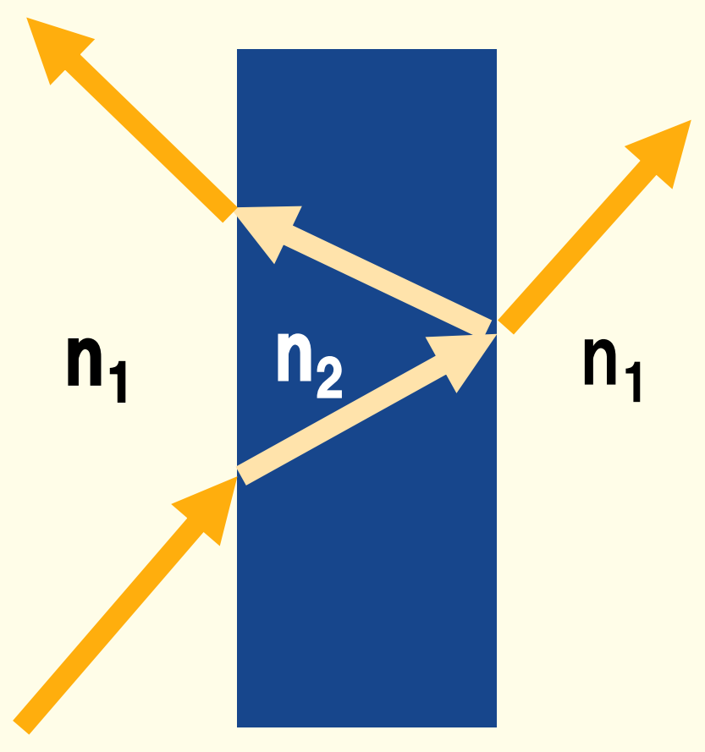

Figure 2 Optical pathways at the hollow core fiber interface.

The higher refractive index cladding can be considered as Fabry-Perot resonator. At a particular wavelength matching to the antiresonant condition, the fiber experiences low leakage because of destructive interference of Fabry-Perot resonator. For multiple layers, each layer can be considered as an individual Fabry-Perot resonator and the leakage is lower when having a single cladding layer. To confine electromagnetic wave, the thickness is the most accessible parameter for adjusting a propagating wave at a particular wavelength. The resonance wavelength can be expressed as

$$\lambda_r = \frac{2d}{m}\sqrt{n_2^2 - n_1^2}$$

where m is an integer beginning with 1
d is the thickness of cladding
n is refractive index

Note that, the confined electromagnetic wave in the fiber must be far away from the resonance wavelength.

Modeling

In this research, a hollow-core fiber was designed and its performance was investigated by way of simulation. We chose a core diameter (d_c) to be 1.6 mm, outer capillary diameter (d_1) as 3.3 mm, inner capillary diameter (d_2-d_3) depending on the tube separation distance (z), and for a single circular nested tube diameter of inner capillary tube $d_1 = d_o - z - 2t$ with the capillary tube thickness (t) in a range form 0.09 mm to 0.20 mm.

The fiber material in this model is TOPAS copolymer with a refractive index (n) of 1.5258. The bulk material loss of TOPAS is α_{mat} = 0.36 (f-0.4) + 0.06 [dB/cm], where f is in THz. While the core is designed by using air with refractive index of 1.

The total loss comes from two dominant sources of loss that are effective material loss (or material absorption loss) and confinement loss (α_{cl}). The effective material loss (α_{eff}) can be calculated by the following equation

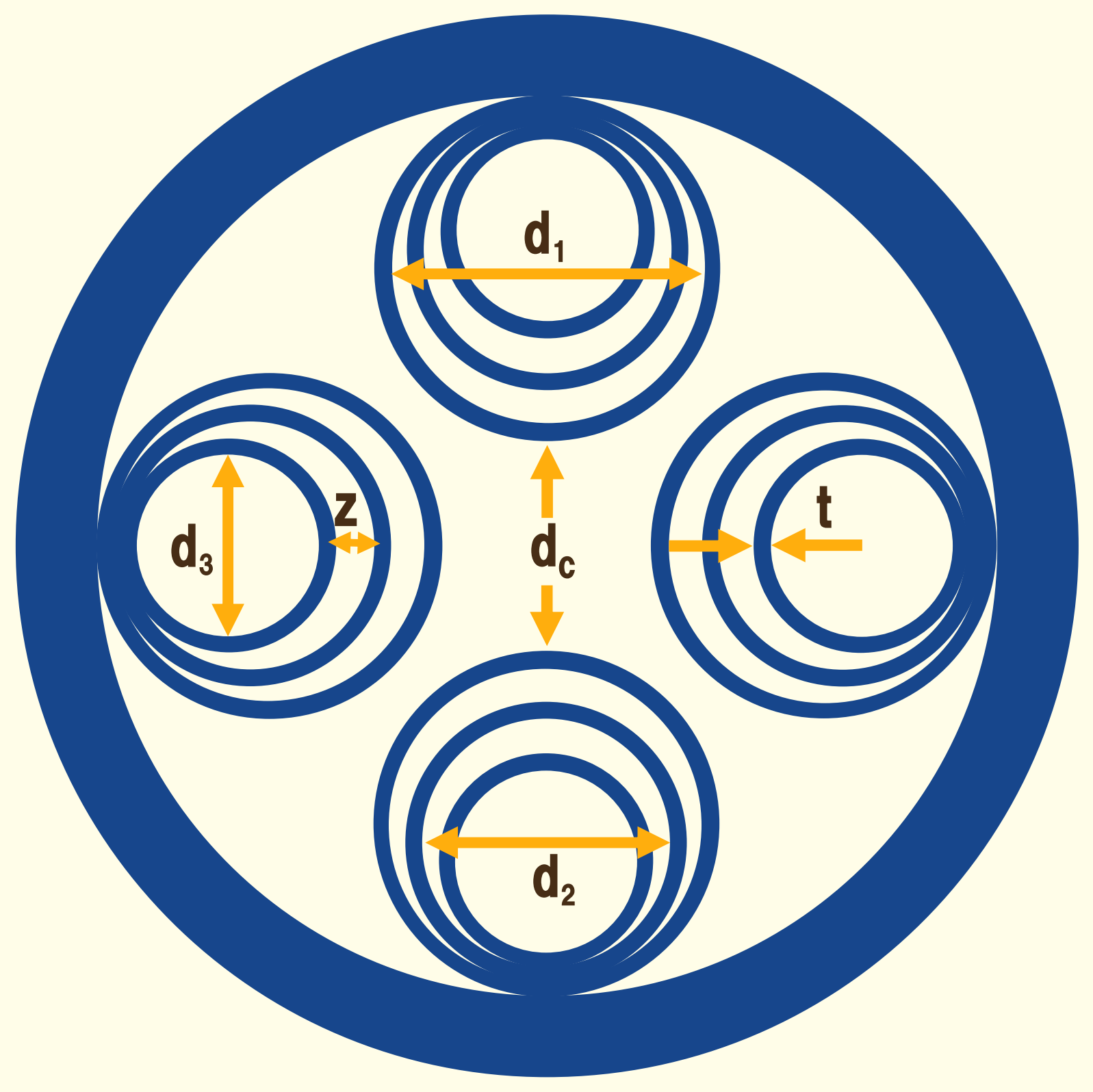

Figure 3 Geometry of hollow core nested anti-resonant node free fiber.

$$\alpha_{eff} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\frac{\int_{mat} n\alpha_{mat}|E|^2 dA}{2\int_{all} S_z dA}\right)$$

where ε_0 is the relative permittivity
μ_0 is the relative permeability
n is the refractive index of material
α_{mat} is bulk absorption loss
S_z is the Poynting vector in the direction of propagation

In this case, the electromagnetic wave propagate along the z-axis, the Poynting vector is defined as $S_z = (E \times H^*)$z, where *E* is the electric field and *H* is the magmatic field.

The confinement loss (α_{cl}) can be calculated by the following equation

$$\alpha_{cl} = 8.686\left(\frac{2\pi f}{c}\right)Im(n_{eff})$$

Where c is the speed of light and
$Im(n_{eff})$ represents the imaginary part of the complex effective refractive index.

Simulation results

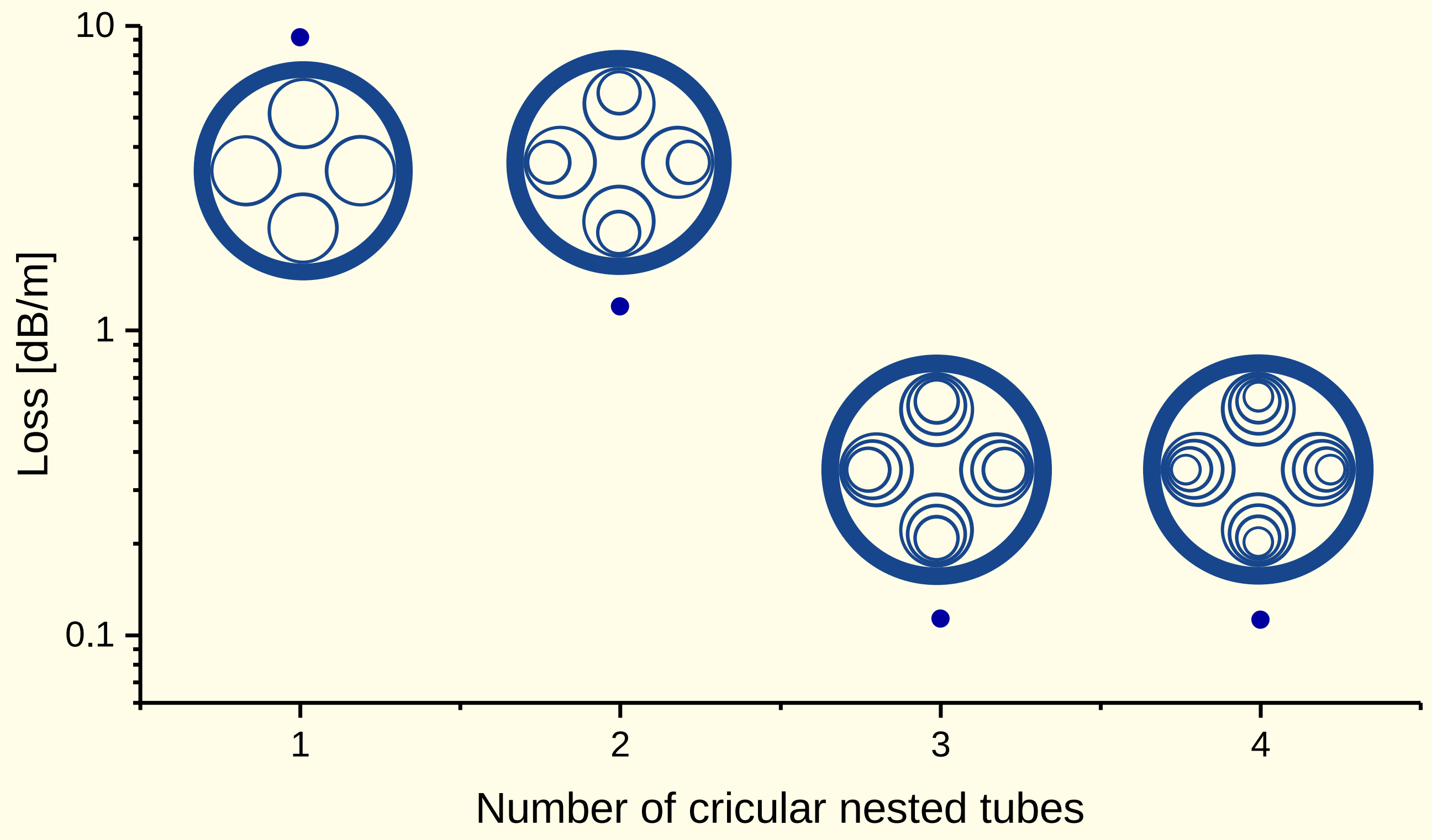

Figure 4 The loss of 1-4 circular nested tube anti-resonant fiber.

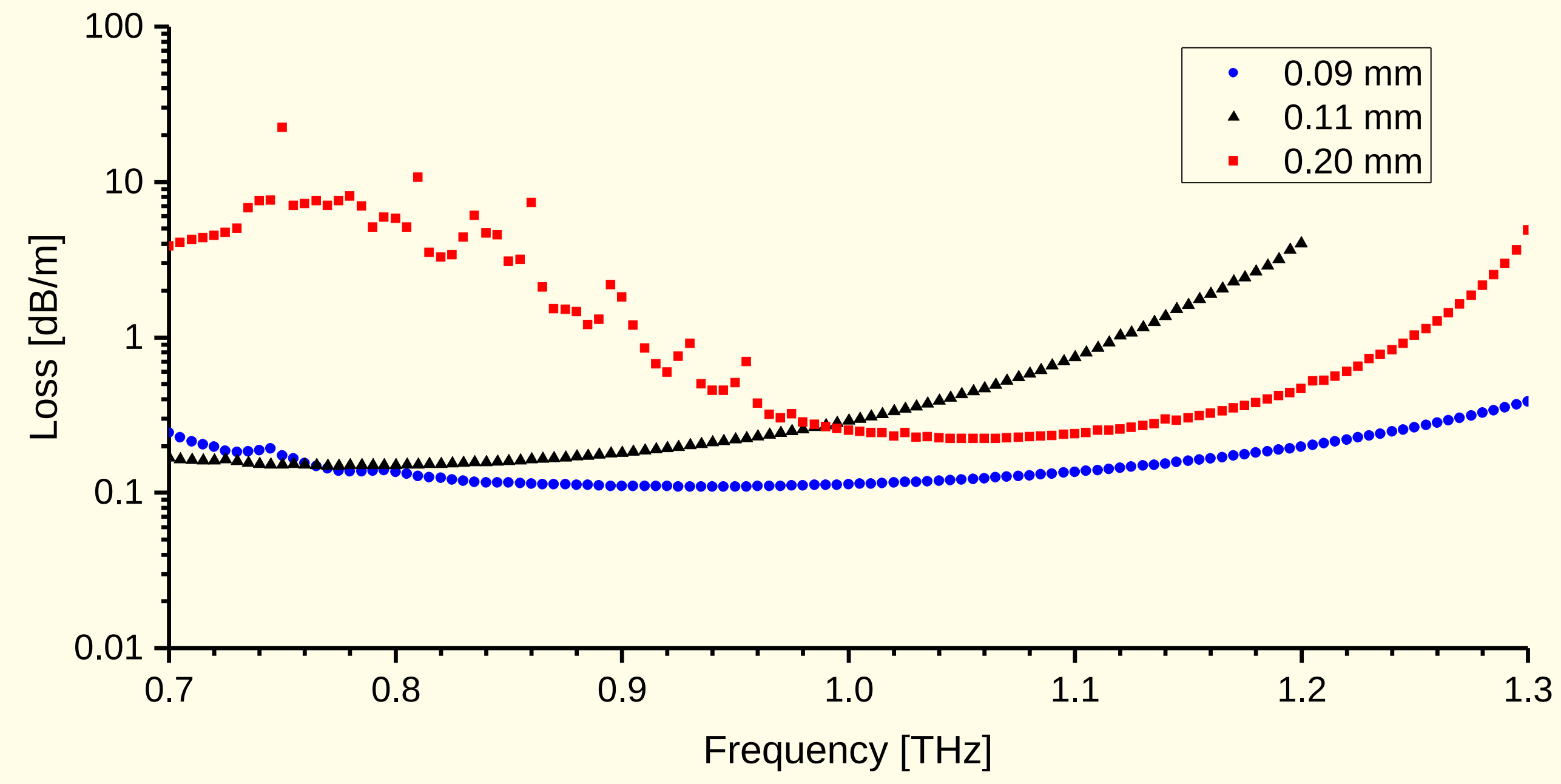

Figure 5 The loss profile of hollow core nested anti-resonant node free fiber at different thickness.

In order to obtain the birefringence, the proposed fiber is bended at different bending radii. A larger birefringence can be achieved when reducing the bending radius as shown in figure 6.

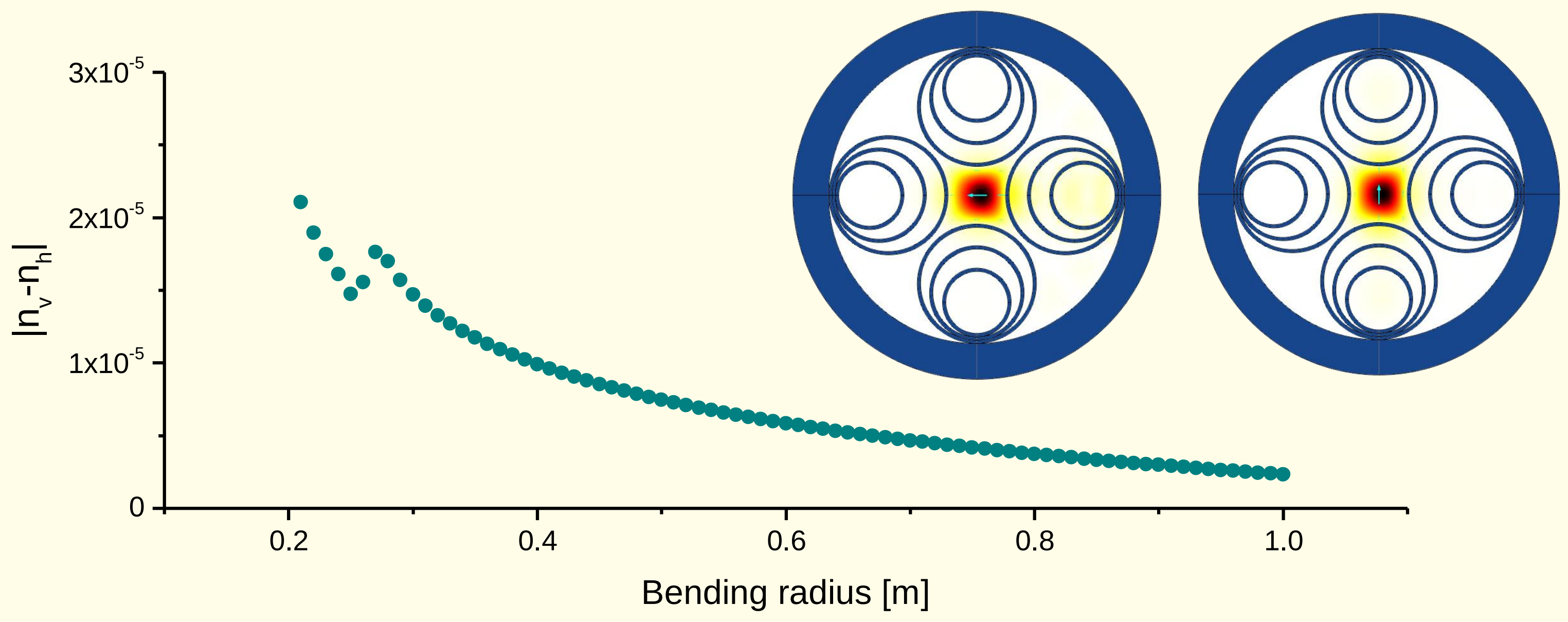

Figure 6 Birefringence as a function of bending radius at 1 THz with d_c = 1.6 mm, d_1 = 3.3 mm, t = 0.09mm and z = 0.52

Conclusions

The proposed fiber design is suitable for operating in THz regime. The numerical results shows that the cladding consists of four circular anti-resonant tubes and each anti-resonant tube consists of 3 circular nested tubes, the proposed fiber was optimized provide the acceptable loss. The thickness of circular nested tubes which matched to the resonance frequency is 0.09 mm. To achieve the birefringence, this fiber was bended. The result shows that the birefringence can be changed by varying the bending radius of the fiber.

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References

G. K. M. Hasanuzzaman, S. Iezekiel, C. Markos, and M. S. Habib, "Hollow-core fiber with nested anti-resonant tubes for low-loss THz guidance," Opt. Commun., vol. 426, no. March, pp. 477-482, 2018.

S. A. Mousavi, S. R. Sandoghchi, D. J. Richardson, and F. Poletti, "Broadband high birefringence and polarizing hollow core antiresonant fibers," Opt. Express, 2016.

S. A. Mousavi, D. J. Richardson, S. R. Sandoghchi, and F. Poletti, "First design of high birefringence and polarising hollow core anti-resonant fibre," in European Conference on Optical Communication, ECOC, 2015.

F. Poletti, "Nested antiresonant nodeless hollow core fiber," Opt. Express, 2014.

M. Hou et al., "Antiresonant reflecting guidance mechanism in hollow-core fiber for gas pressure sensing," Opt. Express, vol. 24, no. 24, p. 27890, 2016.