3D Printed Hollow Core Fiber with Negative Curvature for Terahertz Applications

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***Abstract*—In this paper we demonstrate the terahertz propagation in hollow core fiber with negative curvature core, manufactured through rapid prototyping technique using low cost 3D printer. The fiber was numerically and experimentally characterized using finite element software and a terahertz time domain spectrometer (THz-TDS). The results indicate that the fiber guides at least until 1.1 THz, covering spectral range with extremely high loss materials. The guidance is supported by antiresonant effect. The fiber was printed with low resolution 3D printer leading to hollow-core structure with several surface modes.**

***Index Terms*—**Hollow core fiber, Terahertz, microstructured fiber, 3D printer.

I. INTRODUCTION

Generation and detection technology of terahertz signals (THz) with frequency range of THz ~0,1 and ~10 THz, has experienced strong growth in recent years, leading to intense research activity associated with waveguides development for millimetric waves propagation [1]. Although metal guides have been proposed and used, the finite conductivity of metals limits their applications [2]. Recently, interesting results have been reported on terahertz waveguides, based on manufacture technology of polymer optical fibers [3]. Terahertz fibers with simple design, such as a rod or a dielectric tube, were investigated and also microstructured fibers with reduced signal attenuation and high terahertz evanescent field [3]-[4].

Terahertz waves are strongly absorbed in water and in several polymeric and vitreous materials. The high absorption loss requires a special design of the terahertz fibers for propagating most energy in the air region surrounding the fiber (evanescent field), in the microstructured air regions of the porous fiber or in the core of hollow core fibers.

The hollow core fibers have been extensively studied for the near infrared to visible range (typical range of ~0,6 µm to ~3,0 µm) [5] and now are a practicable option to develop low attenuation terahertz waveguides, since most signal propagates in the dry air within the core region of the fiber and minimizes the energy fraction into the polymer or glass structure [6]-[7]. Although polymers have reduced attenuation in the THz range compared to glasses usually used for optical fibers, they have losses with typical values from ~1 dB/cm (Zeonex®-Cyclic Olefin Polymer) to ~60 dB/cm (PMMA-

Brazilian Microwave and Optoelectronics Society-SBMO *received March 2015; for review April 2015; accepted June 2015*
Brazilian Society of Electromagnetism-SBMag *ISSN 2179-1074*

Polymethyl methacrylate) [3]. A proper design of polymer fiber with high porosity reduces the effective absorption loss up to 1/10 of the typical material loss used in the fiber manufacture. However, hollow core fibers can improve the reduction of effective absorption loss, because about 95% of the modal energy is at air-core resulting a reduction in the absorption to less than 1/20 of the characteristic loss of the host material. Despite intense research in fibers for terahertz waves, only few designs have simultaneously broadband transmission up to the range of 1 THz, low absorption, low bending loss, ease cutting and splice techniques, and available in long lengths [3]-[4],[8]-[10].

A new design for optical hollow core silica fiber was recently presented [11]-[12]. Its main characteristics are cladding microstructured with few holes around the hollow core and a polymer ring that defines the core diameter. The polymer ring has several sections with negative curvature (curves facing the interior of the core). Projects of hollow core fiber with negative curvature were also previously investigated in fibers formed by arrangements of tubes [13]. The main feature of this kind of design is the optical propagation by antiresonant effect and a reduced confinement loss [14]-[15].

In this work we numerically investigate the wave propagation properties of polymer terahertz hollow core fiber with negative curvature (HCNC) and the influence of the core's shape on propagation and the confinement losses. Additionally, the modal coupling of core modes and the cladding gallery modes were numerically investigated. We also report the manufacture of polymeric HCNC through rapid prototyping technique using low cost 3D printer. The fiber was experimentally characterized on a terahertz time-domain spectrometer.

Considering the high absorption of dielectric materials in terahertz range [16], it is essential to confine major part of modal energy at the air core. This way the hollow-core fiber with negative curvature core has great potential to be a low loss terahertz waveguide capable to support modes in large frequency range.

Hollow-core fibers with high transmittance in the optical regime were reported using fibers with negative curvature core [11]-[12]. The proposed hollow-core terahertz fibers, however, are based on conventional fiber optic manufacture technique or based on high-resolution high-cost 3D printing (thickness layer of ~16 μm to ~28 μm) [17]. In this work, 3D printed terahertz hollow-core fiber is numerically and experimentally characterized taking into account the guidance by antiresonant effect and the strong coupling between core and cladding modes. The dispersive properties of fundamental modes were investigated and the spectral transmission was measured in terahertz time domain spectroscopy (THz-TDS) setup.

II. TERAHERTZ HOLLOW CORE FIBER

The hollow core fiber guides of electromagnetic waves using one of the three physical phenomena: the photonic bandgap effect, the Bragg reflection or the antiresonant effect.

The bandgap effect occurs in hollow core fiber when the fiber has a microstructured cladding with appropriated air holes distribution, so that region does not guide transversal modes in a range of frequencies. In this case, if the terahertz wave is launched into the core it is not possible to couple it to the cladding modes, thus allowing the signal propagation in the core with low confinement loss in this frequency range. A special category of hollow core fibers have a microstructure cladding called Kagomè [18]. This type of fiber has a high air-filling fraction in the cladding region, resulting in a low density of guided modes. Consequently only a weak coupling between the core and cladding modes is possible, allowing propagation in the core with low losses and in broad spectral bands.

Another category of hollow core fiber is based on cladding formed by the succession of high and low refractive index material layers, giving rise to a kind of Bragg reflector. Such fibers are known as OmniGuide or Bragg fibers [19].

The hollow core fiber, proposed in this work, has the core surrounded by a single air holes layer and the core is delimited by a ring of polymer material. The predominant guiding mechanism in this case is the antiresonant effect as in the arrangement of fibers with tubes [15], [20]-[22]. At antiresonant condition, the core mode (CM) and the modes guided by the polymer ring structure (PM) are decoupled. The resonant condition occurs in certain frequency ranges, and in this case, CM and PM modes couples increasing the confinement losses. The frequency at which the resonant condition occurs can be found analytically, by a simple model for tubes. The main frequencies at which there are coupling between the CM and PM modes can be approximately determined using (1) [14]:

$$f_R = \frac{m\ c}{2\ e\sqrt{n_H^2 - n_L^2}}\ ,\ m \in \mathbb{N}, \tag{1}$$

where f_R indicates the frequency which occurs the phase matching between the core mode and the modes at the polymer ring surrounding the core, m is an integer, c is the speed of light in vacuum, e is the thickness of the polymer ring, n_H indicates the polymer refractive index and n_L represents the core material refractive index (in our case, n_L= 1) [20]-[21].

III. Geometric Model of Terahertz Hollow Core Fiber

The polymer terahertz fiber investigated here is based on silica optical fiber recently presented [11]-[12]. In order to make it possible to manufacture the polymer terahertz fiber in a low cost 3D rapid prototype printer, the walls which defining the air holes in the microstructure were thickened. For manufacturing it was used a 3D printer model Orion Delta from SeeMeCNC. The printer has ~400 µm effective resolution in the transverse print plane defined by the hole in the extruder nozzle and deposited polymer layers with thickness from 50 µm to 100 µm. Taking into account the different printing resolution in transversal plane and longitudinal plane, a proper planning of rapid prototyping allows orient the model to be printed prioritizing manufacture with higher resolution. This manufacturing technique allows build fiber with a good repeatability. The terahertz waveguides manufacturing by rapid prototyping technique was recently presented in the literature for fabrication of hollow core terahertz fiber [22].

Figs. 1(a)-(b) show the cross section geometric model of two terahertz hollow core fibers. Fig. 1(a) shows the fiber with planar core (HCr), while Fig. 1(b) shows fiber with negative curvature core (HCc).

The dimensions of the fiber geometric models were adjusted to propagate signals in the terahertz range. Figs. 1(c) and 1(d) show a quarter of the geometric models used in a finite element modeling software and the geometrical parameters of the investigated fibers. For both fibers the diameter (D) is 25.0 mm and the thickness (e) of the walls between air holes is 0.5 mm. The fiber in Fig. 1(c) has core with inner radius R_c=4.19 mm, curvature radius r_r=0.51 mm and r_s=0.50 mm, the last two radii define how the walls surrounding the polymeric core and the triangular holes are joined.

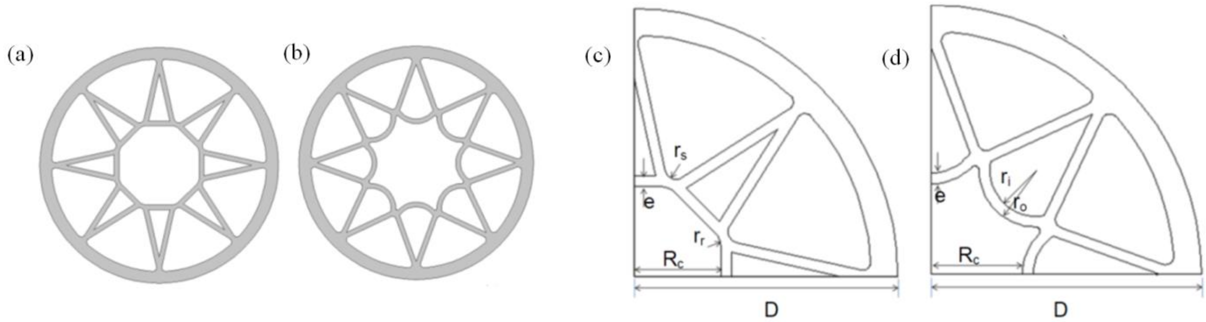

Fig. 1. Geometrical model of hollow core terahertz fibers. (a) Hollow core fiber with core defined by planar boundary. (b) Hollow core fiber with core defined by a negative curvature core. (c) and (d) Geometrical parameters of hollow core terahertz fibers.

The fiber shown in Figs. 1(b) and 1(d) has core boundaries with negative curvature, radii curvature R_c=4.20 mm, r_i=4.26 mm and r_o=5.26 mm. The fiber shown in Fig. 1(d) was manufactured with a length of 10 cm, using a rapid prototyping technique with ABS polymer (acrylonitrile butadiene styrene) and e=0.54 mm. For the numerical analyzes the refractive index of the polymer was consider constant, equal to 1.52, what is an index equivalent to the Zeonex® polymer, but without considering the absorption losses.

IV. NUMERICAL TRANSMISSION EVALUATION

The numerical analyzes were performed using commercial software based on the vector finite element method (Comsol®). Figs. 2(a)-(d) show the modal power distribution in the core and in the polymer region. Figs. 2(a) and 2(b) show the mode confined in the air-core of the terahertz fiber with planar boundaries, and core with negative curvature boundaries, respectively. Figs. 2(c) and 2(d) illustrate modes confined in the air holes surrounding the core and at high refractive index regions, respectively.

Fig. 3(a) shows the numerical values of fundamental core mode effective index as a frequency function. Black symbols denote the results to the fiber with planar core (HCr), while the red symbols show the results to the fiber with negative curvature core (HCc). It can be seen that to the HCr fiber there is a strong variation in the effective indices values arising from the intense coupling between the core mode (CM) and polymer modes (PM) [23]. The fiber with negative curvature core has fewer disturbances in the dispersion curve, which is related to a smaller number of modes coupled with the

 ISSN 2179-1074

core mode. The strong slope of the dispersion curves indicates that the effective index of the mode guided by the polymer changes rapidly as a frequency function.

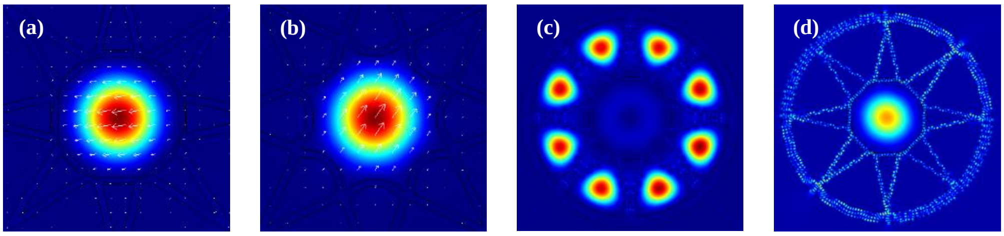

Fig. 2.(a)Fundamental mode of HCr. (b) Fundamental mode HCc. (c) and (d) higher modes in the air-holes and polymer.

When the effective index of both, core and polymer modes reach very close values, a phase match occurs establishing a resonant condition in which there is a strong exchange of energy between modes, leading to increased confinement losses and the abrupt variation in the dispersion curve. This undesirable mode coupling condition can be reduced fabricating terahertz fiber with thinner polymer web structure.

In Figs. 3(a) and 3(b), the studied frequency range corresponds to a small part of a wavelength band (496-500 GHz) in which there is antiresonant effect, favoring the terahertz signal propagation with low losses. The sharp variations in transmission are related to the core and cladding mode coupling observed in Fig. 3(a) and so complex coupling characteristic occurs because the ticker polymeric structure supports many high order modes. These analyzes demand extra computational time to converge to the fundamental mode. In Fig. 3(b) the spectral transmittance for both hollow core fibers are analyzed, considering the fundamental optical mode and fibers with one meter long.

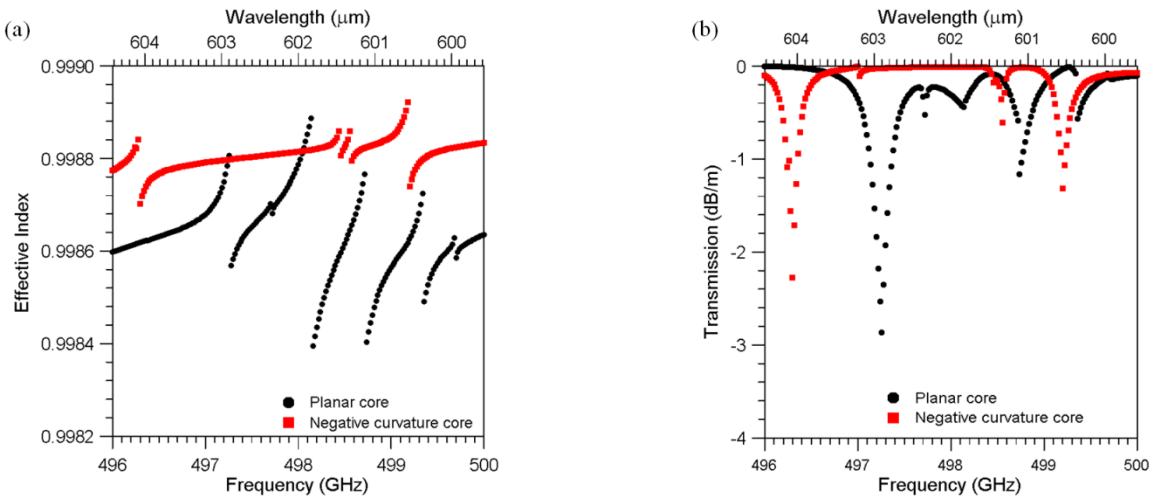

Fig. 3. Effective index and transmission spectrum of THz HCr and HCc fibers. (a) Effective index as frequency function. (b) Transmission spectrum as frequency function considering fibers with one meter long.

The transmission curve for the HCr fiber indicates coupling with six modes supported by the polymer while the result for the HCc fiber (red symbols) indicates coupling with four polymer modes. The transmission curve of HCc fiber is higher and cleaner than that for HCr fiber.

V. Experimental Results

The HCc fiber transmission spectrum was measured using the THz-TDS setup presented in the Fig. 4(a) and the inset shows the THz emission spectrum for this setup covering a range from 0.1 THz to 1.2 THz. The terahertz signal generation is achieved by using a femtosecond laser focused on the semiconductor material with suitable antenna that emits a wide THz spectrum. The terahertz fibers are arranged between two s-p lenses [24] which delimit a test region. The detection occurs in the optical spectrum after the terahertz signal modulates the properties of an electro-optic crystal that is crossed by a time synchronized second femtosecond laser pulse. This allows transferring the THz information (field amplitude and phase) to a second optical signal and be efficiently detected. This THz spectroscopy technique allows determining the refractive indices of dielectric materials, measures the time domain absorption and resonant effects in complex molecular reaction dynamic, and evaluates the transmission of filters, polarizers, and metamaterials, as well to characterize the propagation properties of dielectric and metallic guides.

We determined the refractive index of the polymeric material (ABS) used for printing the fiber in the terahertz range. The refractive index is approximately a constant value around 1.6 as previously presented in the literature [25]. The melting temperature of ABS is around 110-125°C, thus the waveguide should work under 110°C to maintain proposed form [26,27].

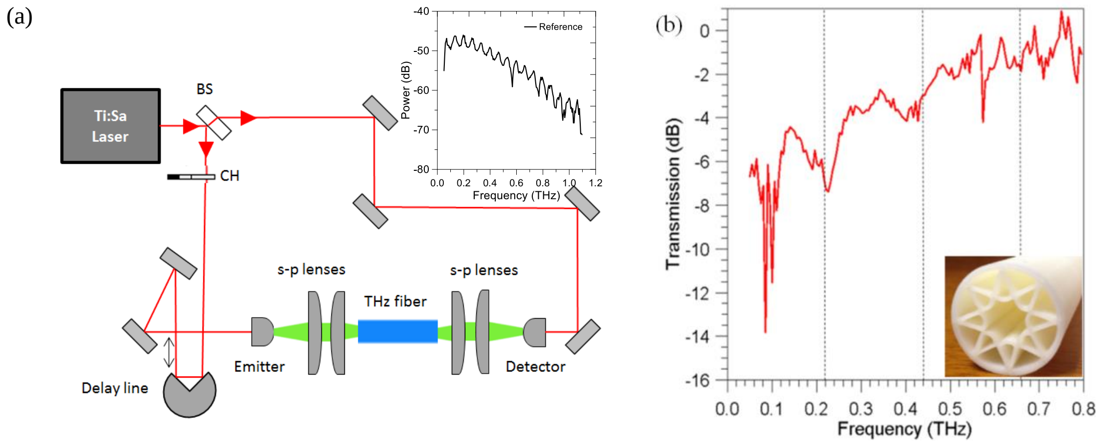

Fig. 4. (a) Terahertz time domain spectrometer setup to characterize fibers. Inset Transmission spectrum reference. (b) Experimental transmission spectrum of HCc fiber with 10 cm long. Inset printed HCc fiber.

The transmission spectrum of the 3D printed HCc fiber, with 10 cm long, is shown in Fig. 4(b). The transmission spectrum was obtained by normalizing the fiber results with that obtained without sample (reference scan). As mentioned previously this fiber guides THz modes by antiresonant effect, thus in Fig. 4(b) the black dotted lines indicate the central resonant frequencies, evaluated with equation (1), considering the fiber to be formed just by a single core ring around the air-core. This resonant condition can be seemed as dips in the transmission spectrum. Outside these frequencies, the fiber guides with relatively low losses. Besides the resonant dips, several other low transmission dips are present and can be attributed to the several couplings between the core and polymer modes, caused by the thicker wall of the fiber, as presented in Fig. 3(b).

The Fig. 5 presents a comparison between numerical and experimental data from 0.1 to 0.5 THz for the HCc fiber with one meter long. The numerical curve (black plot) describes a general behavior compatible with two high transmission frequency range (transmission bands). The region around 0.24 THz present low transmission and corresponds to the region where the phase matching between core and polymer modes occurs. This coupling can be observed in the Fig. 5(a) that shows the effective index of fundamental core mode as function of frequency. Around 0.24 THz the core fundamental mode couples with one of the polymer ring modes, causing a very abrupt variation of the effective index and increasing the confinement loss. In Fig. 5(b) it is observed that numerical data correctly represent the regions with high transmission and also the coupling region of core and polymer modes around 0.24 THz. The numerical and experimental spectral transmission have differences in both frequency and amplitude probably because the numerical model is based on an idealized fiber and the high polymer absorption was not considered.

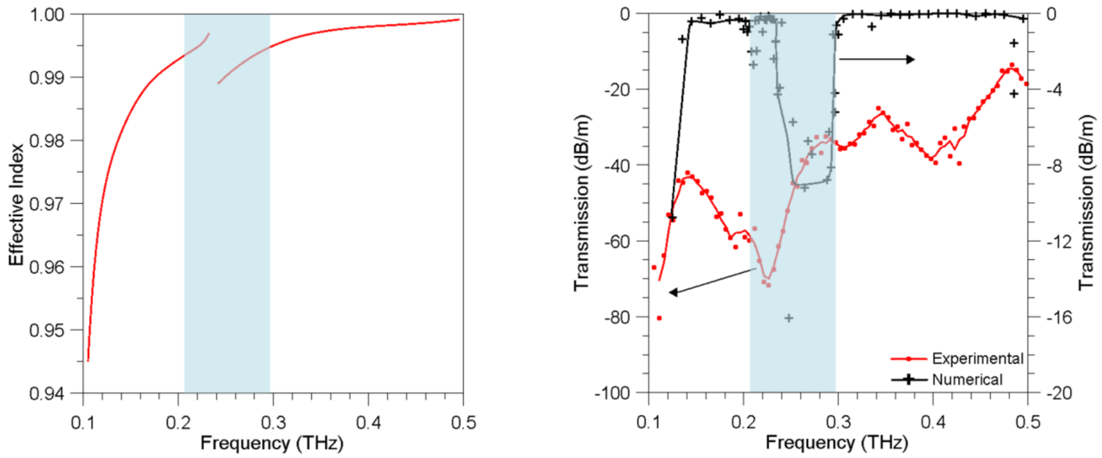

Fig. 5. (a) Numerical effective index of HCc fiber with oscillations around 0.24 THz. (b) Numerical (black curve) and experimental (red curve with symbol) transmission of HCc fiber with low loss transmission around 0.21-0.3 THz, considering a fiber with one meter long. The lines connecting the data are to guide the eyes.

VI. CONCLUSION

In this paper, the propagation properties of terahertz hollow core fiber and the influence of negative curvature in the core geometry were numerically studied. The production of terahertz polymer fibers has been demonstrated, using 3D rapid prototyping technique in polymer using a low cost printer. The accuracy of impression allowed manufacturing fibers with mode guidance from 0.1 THz to at least 1.1 THz.

The numerical and experimental results indicate that the fiber, when operating in about 500 GHz, is guiding in an antiresonant condition which reduces the confinement loss. However, to enable the manufacture with low-cost low-resolution 3D printer the polymer regions were thickened, causing an excessive increase of surface modes in the region with high refractive index. These modes eventually couple to the air-core fundamental mode causing changes in the dispersion properties as well as increasing the confinement losses at specific frequencies. The numerical results demonstrate that negative curvature core is able to reduce these undesirable coupling modes.

Considering the high material absorption of dielectric materials in terahertz range [16], it is essential to confine major part of modal energy at the air core. This way the hollow-core fiber with negative curvature core, confining about 95% of modal energy at the air-core, has great potential to be a low loss terahertz waveguide capable to support modes in large frequency range and promote applications such as sensors (gas or liquid filled core) and imagers (evaluating transmission or reflection in small devices with high intensity THz signal and small focal point).

ACKNOWLEDGMENT

This Work was partially supported by CNPq and FAPESP by the project INCT-Fotônica para Comunicações Ópticas (Fotonicom), and CAPES.

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