Applicability of low macrobending loss hollow-core PCF to FTTH applications

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***Abstract*— Fiber-To-The-Home (FTTH) technology has been significantly implemented in access networks, providing very high data rates transmission and a variety of digital content to subscribers. It involves an optical cable link being installed between the building entry point and each subscriber with the Multiple Dwelling Units (MDUs), i.e. flats and apartments. In other words, optical cable has to lie fairly straight to carry a strong signal, since typically is necessary to bend, twist and turn the lines in and out of tight corners without degrading the link connection. In this paper we propose the use of Hollow-Core Photonic Crystal Fiber (HC-PCF) for FTTH applications. It is presented an experimental analysis of the macrobending effects in a HC-PCF based on a comparison with traditional fibers and by following the ITU-T G.657B standard recommendations. We observe this fiber, with only 6.5 µm core, is bending loss insensitive, even at extremely small bending radius of 2 mm, in which it presents a loss of only 0.58 dB.**

Index Terms—Fiber-To-The-Home, Photonic Crystal Fibers, Hollow-core (HC-PCF), Optical fibers and Bending loss.

I. INTRODUCTION

Photonic Crystal Fibers (PCFs),also known as microstructured fiber, has changed the ways of light guidance within the fibers and opened new perspectives in the optical fiber technology[1-3]. These fibers have a periodic wavelength-scale microstructure running along their length. Their core and two-dimensional photonic crystal can be made from several geometries and materials, allowing light to be guided thorough different mechanisms with a huge range of wavelengths, extending to the terahertz regions [1].

Hollow-Core Photonic Crystal Fibers (HC-PCFs) are based on a periodic array of air holes in silica glass cladding[4,5]. Unlike conventional fibers, in which light is guided by total internalreflection, in a HC-PCF light is confined into a hollow core with low loss due to Photonic Bandgap(PBG) effect[4]. HC-PCFs have been shown very interesting for several scientific and technological areas, such as development of gas-based devices [6], delivery of megawatt pulses [7], and generation of frequency

Brazilian Microwave and Optoelectronics Society-SBMO received 1 Sept. 2010; revised 6 June 2011; accepted 21 June 2011
Brazilian Society of Electromagnetism-SBMag ISSN 2179-1074

combs [8].Moreover, HC-PCFsallow light to be guided into core with low bending loss [9,10].In this work, we evaluate the applicability of these fibers to FTTH networks according to the ITU G.657B standard [11] by measuring its macrobending loss for very small bending radius and comparing its performance to traditional single-mode fibers.

II. Fiber-to-the-Home Applications

Nowadays, the networks traffic is growing at speed never seen before. Current technologies provide low cost solutions with high data rates that were previously not possible. However, most networks are based on Asymmetric Digital Subscriber Line (ADSL), Hybrid Fiber-Coaxial (HFC) and wireless technology. These technologies will not able to support future bandwidth demand due your physical limitations, such as higher attenuation as frequency increase for more bandwidth. In addition, the future broadband networks needs to offer triple-play solution.

The FTTH technology is becoming a reality for most people around the world, since it represents a cost-effective solution for providing broadband services using optical fibers. These networks achieve very high data rates with long distances, reaching up to20 km between customer and central office, delivering data service, voice and video [12].

The increase FTTH deployment around the world in last year’s creates a new optical fiber area: bend insensitive single-mode fiber [13]. These fibers are used to solve bending losses in installation process. Furthermore, they can reduce the network costs and improve system performance [14].The optical fiber experiences a series of bends during the installation process, mainly in Multiple Dwelling Units (MDUs) in-home wiring, in which bending radius could reach up to 5mm [14].

Recently reports shows that to offers a robust FTTH network with a satisfactory performance the bend insensitive fiber must accomplish 0.1dB/turn of optical loss at this bending radius [14]. However, standard single-mode fiber has an optical loss of 20dB/turn at this scenario, implying a reduction factor of 200 [15] and making it a real challenge.

Therefore, several fiber design shave been proposed in order to solve this problem, such as: reducing mode field diameter [16], depressed cladding [17], hole-assisted [18] and trench cladding [15, 19]. The reduce mode field design is inefficient showing an optical loss of 2 dB/turn at 5 mm bending radius [16]. Furthermore, the geometric change in core switches cutoff frequency, zero-dispersion wavelength and slope dispersion fiber parameters, not meeting the ITU-T G.652 requirements [15, 16]. F. Wu et al proposed to create a low index layer around the core, known as depressed cladding design [17].This design offers a quiet more flexibility in set the fiber parameters. However, it has the same performance as reducing mode field at 5 mm bending radius [17]. On the other hand, the hole-assisted technique provides better performance than previous ones, staying near the bending loss requirements. Otherwise, the most issue in this fiber design is the manufacturing process because it is not suitable for delivering high fiber volume for FTTH deployments [18].

Recently, low index trench design has attracted attention since it is a commercial solution that

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achieves 0.1dB/km optical loss at 5 mm bending radius [19]. Additionally, it is compatible with the ITU-T G.657and G.652standards and can be manufactured using standard Outside Vapor Deposition (OVD) [15].

Finally, the photonic crystal design uses 2D periodic array of air holes to allow light guidance with especial properties that is impossible to obtain in conventional fibers, such low attenuation, bending insensitive, high power levels and flat dispersion [1]. Moreover, up to date, there is no experimental results showing Hollow-Core Photonic Crystal Fiber (HC-PCF) performance for FTTH applications.

For effectively employ HC-PCF in FTTH networks is also important that splice loss between it and already installed optical fiber kept as low as possible. Theoretically, SMF-28 and HC-PCF splicing could reach up to 0.48 dB [20]. Although, using a conventional splicer and optimized parameters optical loss of 1.48 – 2.01dB were obtained with only one arc discharge [20]. However, these values can be improved by mitigating splice parameters, multiple discharge arcs and combining fibers with same core diameters [20].

FTTH applications use the Wavelength Division Multiplexing (WDM) technology. WDM technology implies multiple channels in a single fiber, in which combined to optical amplifiers results in extremely high optical powers, generally located at MDUs [14]. In these installations, as the level of optical power and the radius of curvature increases a fiber degradation effect occurs, as know fusion effect, in which optical power is converted in thermal heat, reducing network lifetime. It was also observed that for 5 mm bending radius in SMF-28 the maximum optical power where fusion effect does not overcome bending loss is 1.7W [21]. However, HC-PCF will not suffer this problem due your PBG guidance, in which can works with power levels up to megawatts [7].

III. Hollow-core fiber

Hollow-core PCFs [1, 4] rely on a 2D photonic crystal formed by an array of air holes, which are generally present at as high as 90% air-filling factor. Total Internal Reflection (TIR) is not possible in this case, since the cladding index (mixture of pure silica and air) is higher than the air core index [5]. Light guidance is attained by coherent Bragg scattering, where light at wavelengths within well-defined stop bands is prohibited from propagating in the photonic crystal cladding and is confined to a central defect. Only certain wavelength bands are confined and guided down the fiber. Each band corresponds to the presence of a full two-dimensional PBG in the photonic crystal cladding. For this reason, these fibers are called Photonic Bandgap Fibers (PBGFs), in which light is guided in a low-index core by the PBG effect.In PBGFs, the photonic crystal cladding acts as a mirror and more than 99% of the optical power is located in the air and not in glass [5]. Therefore, light with wavelengths corresponding to the bandgaps cannot escape the core and so is guided along the fiber with low loss [1]. Theoretically, the minimum attenuation in conventional optical fibers is 0.15dB/km, whereas in HC-PBGF is only 0.1dB/km, making it strong candidate to future telecommunication networks. Currently, the lowest attenuation obtained in HC-PCF ii 1.2dB/km [5]. Furthermore, novel process

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eases production of hollow-core fiber [21].

We have used a HC-PCF with a core formed by the omission of seven unit cells which presents no sign of surface modes interactions within the bandgap. The photonic crystal cladding of this thin core wall fiber has a pitch Λ = 6.7 μm and an air filling fraction of ~ 96%, giving rise to a photonic bandgap centered approximately at 1550 nm [22]. Furthermore, this fiber has a very low nonlinear coefficient than conventional solid fibers,approximately three orders of magnitude less [23], due the nonlinearity index of air is lower than silica or doped silica. This low nonlinearity combined with low dispersion makes it ideal fiber to deliver and manipulate ultra-short pulses [24, 25] or optics sensorial applications [26]. A scanning electron microscopy (SEM) image of fiber with thin core wall is shown in Fig. 1.

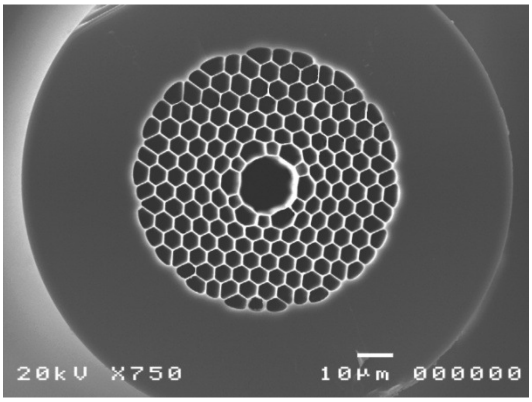

Fig. 1. Hollow-core PCF.

In order to measure the fiber PBGs, a white light source with tungsten filament, has been coupled to the HC-PBGF and the output was analyzed using an Optical Spectrum Analyzer (OSA). Fig. 2 shows its transmission spectrum for a fiber length of 200 m. One can observe there are three well-defined transmission bands with low loss. In this work we concentrate our analysis in the range of 1535-1575 nm, which corresponds to C-Telecom band.

The minimum attenuation of HC-PCF is 15dB/km and remains below over 50 db/km more than 300 nm [4]. It has been used a piece of 1m-long to evaluate the macrobending effects.

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Brazilian Society of Electromagnetism-SBMag ISSN 2179-1074

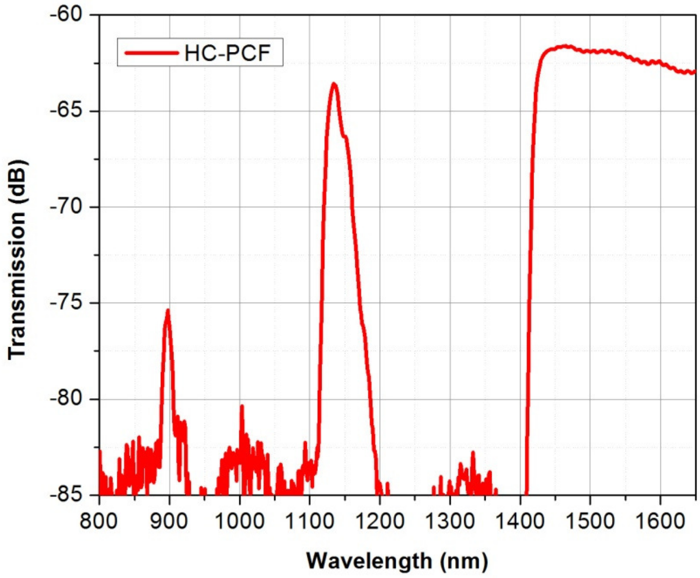

Fig. 2. Transmission Spectrum.

IV. EXPERIMENTAL SETUP

The experimental setup, shown in Fig. 3, was based on the following pieces of equipment: a tunable External Cavity Laser (ECL), XYZ positioners, some objective lenses, tubes of different diameters and a powermeter. The opticaloutput power from ECL source was 9 dBm.

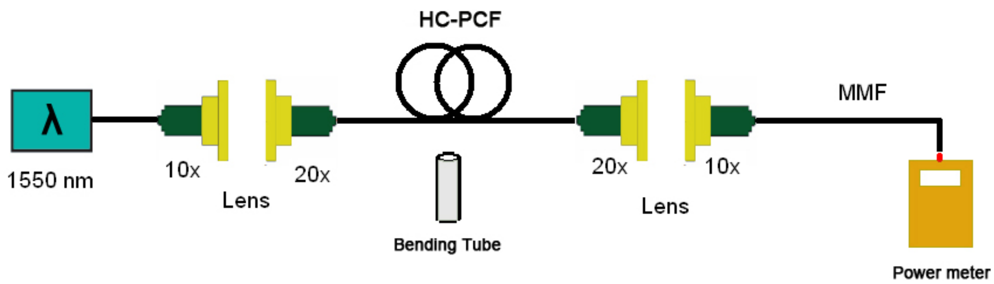

Fig. 3. Experimental setup for measuring macrobending loss.

In order to measure the macrobending loss, we have twisted our fiber around some glass tubes and observe the measured at the power meter before and after the bending. The tube diameters used for this experiment were: 32, 20, 15, 12, 10, 7 and 4 mm. It was not possible to analyze the macrobending loss for diameter of less than 4 mm because of the vey fiber air-filling fraction that usually leads to break it. With the purpose of comparison, curves with the same diameter were made using a standard SMF-28 fiber.

V. RESULTS

Initially, ECL wavelength was set to 1550 nm; the measurements of bending loss shown in Fig. 4. For SMF-28 fiber, we observe there is a minimum curvature radius that allows light guidance into the fiber core. When the critical radius is overcome, the guided mode escapes to the cladding in conventional single mode fiber. Unlike, HC-PCF has a cladding photonic crystal which enables light

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guidance even for a very small bending radius, giving rise to extremely low macrobending loss.

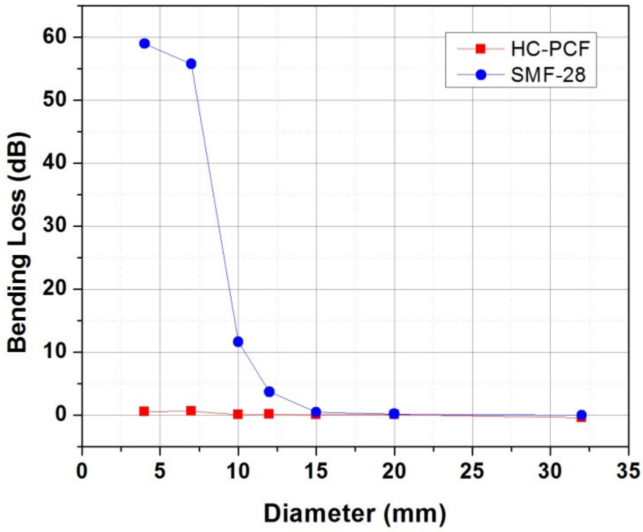

Fig. 4. Measurmeents of macrobending losses.

HC-PCF has overcome the performance of SMF-28 for all bending diameters bellow 15 mm. For instance, for a diameter of 12 mm, SMF-28 presents a bending loss of 3.7 dB, whereas the proposed HC-PCF provides a loss of only 0.11 dB. Furthermore, it was a loss of only 0.58 dB for a bending diameter of 4 mm, bending radius of 2 mm, whereas in SMF-28 loss reached up to 58.98 dB. A CCD camera has also been used to optimize the fiber coupling and obtain near field image of hollow-core fiber output at 1550 nm with minimum bending radius of 2 mm, as shown in Fig. 5. It is clear that the light is entirely confined to PCF core.

Fig. 5. Near field at 1550 nm for 2 mm bendingradius.

Finally, it was used an Amplified Spontaneous Emission (ASE) from an Erbium-Doped Fiber Amplifier, as a broadband source to evaluate possible bandgap variations due to macrobends in HC-PCF. These results are displayed in Fig. 6.The induced macrobends on the fiber can causes changes in the photonic crystal. We observed as the bending diameter increase, insignificant shift appears on the spectrum, since the guidance is slightly affected at certain wavelengths by only a few dBs in power. Such power variations is more sensitive at the center bandgap edges, where the highly loses are located. On the other hand, wavelengths around PBG center, such as 1550 nm, have nearly-zero loss.

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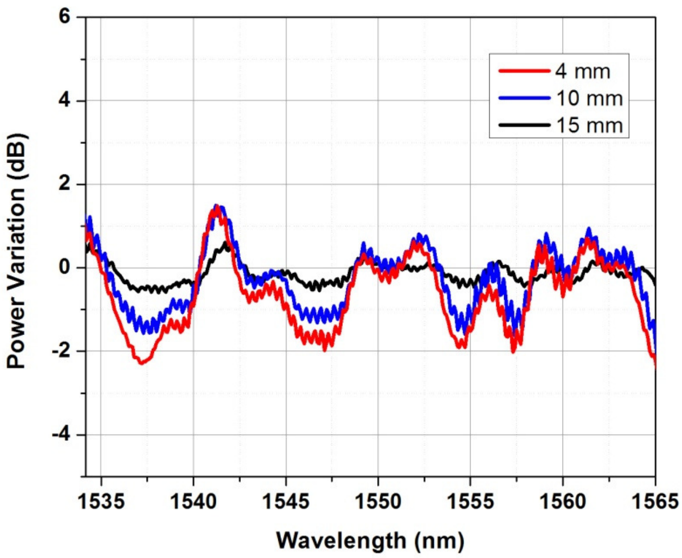

Fig. 6.Power variation for different bending diameters.

VI. CONCLUSIONS

According to ITU-T G.657 standard, developed by Study Group 15, approved and introduced in December 2006 there are two categories in single-mode optical fiber design for access networks, which are the G.657A and G.657B [11]. The G.657B pattern is the most strictness; so we used it to evaluate the performance of the proposed fiber. In this standard, the minimum loss acceptable is 0.15 dB at 10 mm bending diameter at 1550 nm. Under these conditions, the proposed hollow-core fiber showed a loss of only 0.09 dB. Furthermore, a bending loss of only 0.58 dB at 4 mm was reached and for values more than 12 mm there were not significant losses.

As conclusion, the HC-PGBF can be applied for FTTH solutions since it overcoming the straight requirements from ITU-T G.657B. Moreover, this fiber demonstrated power penalties below 3 dB over 1535-1575 nm range even at strictness bends and showed that can be a solution for fusion effect at MDUs. This fiber also can also be efficiently applied in tiny sensing devices with multiple radius of curvature [10].

ACKNOWLEDGMENT

The authors would like to thanks Jonathan Knight from the University of Bath for providing the fiber used in the experiments. Moreover, the authors also wish to acknowledge the financial support from CAPES and FAPESP under CePOF and FOTONICOM contracts.

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