Fabrication of a Novel Tellurite Hollow Core Optical Fiber and Supercontinuum Light Propagation in Its Hollow Core

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Abstract: For the first time, we experimentally demonstrated the fabrication of a tellurite HC-PCF which has a large hexagonal hollow core in the center. The tellurite glass was developed by our group based on TeO_2, ZnO, Li_2O and Bi_2O_3 oxides. The fiber was successfully obtained by using rotational casting and rod in tube methods. A supercontinuum light source from 500 nm to more than 1500 nm was launched into the hollow core of the fiber. The result shows that the light beam can be coupled and propagated in the hollow core by the fundamental mode.

1 INTRODUCTION

After the first practical demonstration of single-mode hollow-core fiber in 1999 (Cregan, 1999), hollow-core photonic crystal fibers (HC-PCFs) has attracted huge interest of scientists and researchers due to their unique optical properties which are not possible to obtain by using conventional solid-core optical fibers. In general, a HC-PCF consists of a central hollow core surrounded by an array of hollow channels formed in the cladding running along the entire length of the fiber (Cubillas, 2017). Because the hollow-core region has low refractive index than that of the surrounding photonic crystal cladding, light is confined to the central hollow-core by photonic bandgap or anti-resonant reflection mechanisms which are different from the total internal reflection in solid-core fibers (Poli, 2007). Thus, HC-PCFs have the potential to overcome some of the fundamental limitations of solid fibers (Poletti, 2013).

HC-PCFs exhibit a number of intriguing optical properties including ultra-low optical nonlinearity, excellent power handling capabilities, high damage threshold, low latency and ultra-low losses at both conventional wavelengths around 1550 nm and longer wavelengths in the mid-IR region where conventional solid silica fibers effectively cease to transmit light (Poletti, 2013). In addition, they have low sensitivity to macro-bending (Hansen, 2004) and even for small bending diameter value (Poli, 2007).

The air-guiding properties of HC-PCFs offer significant advantages for the delivery of pulsed laser beams with high optical power and energies. They are needed in diverse applications ranging from industrial materials processing to biology and medicine such as laser marking, machining and welding, laser-Doppler velocimetry, multi-photon microscopy, treatment of various skin conditions and laser surgery (Poli, 2007; Poletti, 2013).

Recently, it has been demonstrated that a gas-filled HC-PCF can provide high conversion efficiency and signals detectable down to the deep-UV range (200 nm) (Joly, 2011) or even to the vacuum-UV range (less than 200 nm) (Mak, 2013). The ability to quickly adjust the gas species and gas pressure inside the fiber core results in a new degree of freedom for the control of the nonlinearity and the group velocity dispersion (GVD) which cannot be easily accessed by conventional optical fibers. These gas-filled HC-PCFs can offer broadband transmission from the deep UV range to the near-IR range which is a unique light source for metrology and spectroscopy (Travers, 2011) and gas sensing such as ammonia (Cubillas, 2008), methane (Cubillas, 2009) and carbon-dioxide (Nwaboh, 2013).

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Another important feature of HC-PCFs is that their excellent guidance properties are preserved even when both core and cladding channels are filled with liquid, provided that the liquid index n_L is less than the index of the glass n_G (Birks, 2004; Cox, 2006). These liquid-filled HC-PCFs are favourable for chemical sensors and efficient micro-reactors for photochemistry and catalysis applications (Cubillas, 2013; Schmidt, 2013). However, most of HC-PCFs are based on fused silica material (Poletti, 2013) which limits the choice of liquids because their refractive indices must be less than that of silica (n_G = 1.45 at 600 nm) to preserve the benefits of single-mode guidance. To overcome this issue glasses with higher refractive index are highly required. Moreover, another key difference between HC-PCFs and solid fibers is that the minimum loss transmission window of HC-PCFs is shifted from 1.55 µm to the spectral region around 1.9–2.1 µm (Lyngso, 2009) and the low loss transmission range can be extended to the mid-IR region (Wheeler, 2013). In order to take advantages of this low loss spectral range, glasses with broader transmission spectrum than that of silica are necessary.

Among several non-silica glasses, tellurite glasses can be considered as promising candidates as they exhibit not only wide transmission regions from 0.35 to 6 µm, but also large refractive index (n_G > 2.0 up to 3000 nm), high nonlinearity, high thermal stability and good corrosion resistance (Mori, 2008). In this work, we demonstrated for the first time the fabrication of tellurite HC-PCF and the propagation of a supercontinuum light source in its central hollow core. By controlling the coupling conditions, a fundamental mode can be transmitted.

2 FIBER FABRICATION

A tellurite glass composed of TeO_2, ZnO, Li_2O and Bi_2O_3 (TZLB) was developed by our group aiming at their high thermal and mechanical stability. These two properties are very necessary for the fiber fabrication process because the hollow core fiber has a complex structure of micro-scale air holes. This microstructure is easily to be deformed or damaged by residual stresses and cracks which are caused by the unstable thermal and mechanical properties of the host glass.

An UV/VIS/NIR spectrometer (Perkin Elmer, Lambda 900) and an FT-IR spectrometer (Perkin Elmer, Spectrum 100) were used to measure transmission spectrum of the TZLB glass. The thickness of glass sample was about 1 mm. The transmission spectrum is shown in Fig. 1 with a broad transmission range covering from about 0.4 µm up to 6.0 µm.

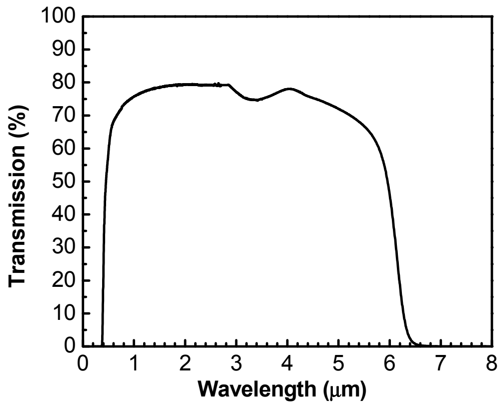

Figure 1: Transmission spectrum of the TZLB glass.

The refractive index of the TZLB glass was measured at different wavelengths from 0.5 to 4.6 µm by using a glass prism and the minimum deviation method. The uncertainness of the measurement is as low as $\pm 10^{-4}$. The measured refractive indices were fitted to the Sellmeier equation and were plotted in Fig. 2.

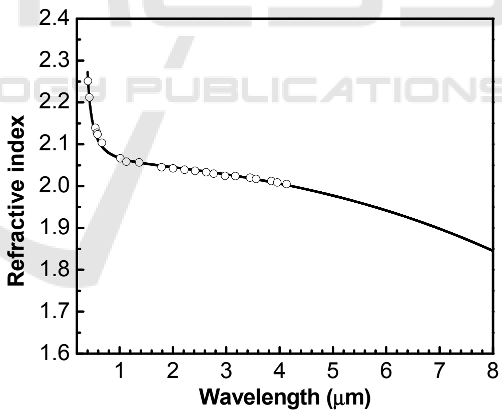

Figure 2: Wavelength-dependent refractive index of the TZLB glass.

In this work, the tellurite HC-PCF was successfully fabricated based on the rotational casting and rod in tube methods. The commercial pure reagents (99.99%) were used as raw materials. The fiber was constructed with a large hexagonal hollow core in the center which was surrounded by a microstructure of smaller air holes in the cladding. A schematic diagram which illustrates the fiber fabrication process was shown in Fig. 3.

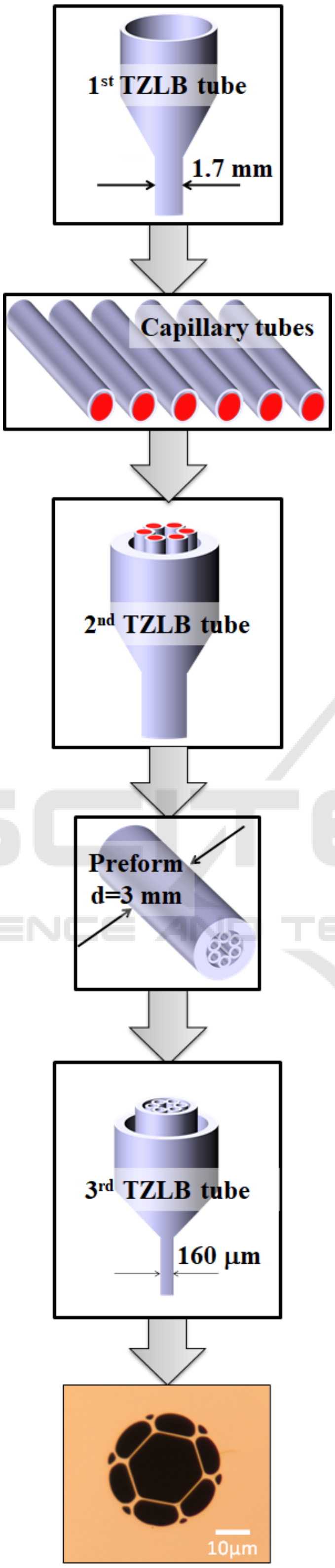

Figure 3: Schematic and experimental images of the fabrication of a TZLB HC-PCF.

At first, a cylindrical TZLB tube was prepared by using rotational casting method. The outer diameter of this tube was 12 mm and its wall was controlled to be as thin as 1 mm. An elongation process was carried out to reduce the outer diameter from 12 mm to 1.7 mm and the product was called as TZLB capillary tube. Each of them was 15 cm long. A set of 6 capillary tubes was used to form a hexagonal close-packed structure by stacking them together. In order to form the large hollow core in the final fiber, the central capillary tube was absent. This hexagonal structure of TZLB capillary tubes was inserted into the second cylindrical TZLB jacket tube and was elongated to obtain a preform whose outer diameter was 3 mm. Finally, the preform was inserted into the third cylindrical TZLB jacket tube and was drawing into fiber whose diameter was about 160 µm. The cross-sectional image of the fiber was taken by an optical microscope and was shown in Fig. 3.

3 MODE CONFINEMENT PROPERTIES

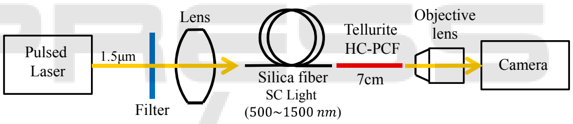

Figure 4: Experimental setup to investigate the characteristic of light propagation in the tellurite HC-PCF.

An experimental setup shown in Fig. 4 was used to study the mode confinement of the light beam propagated in the fabricated tellurite HC-PCF. A supercontinuum light source generated in a step-index silica fiber was launched into a 7-cm-long tellurite HC-PCF. The image of the propagated mode at the output facet of the tellurite HC-PCF was captured by a near-infrared CCD camera (Thorlabs-DC1240C). Figure 5 shows the images of different modes which were able to propagate in the tellurite HC-PCF. By controlling the coupling conditions, a fundamental mode was successfully coupled into the fiber. The captured images of the propagated modes are consistent with those can be obtained from our numerical calculation as shown in Fig. 6.

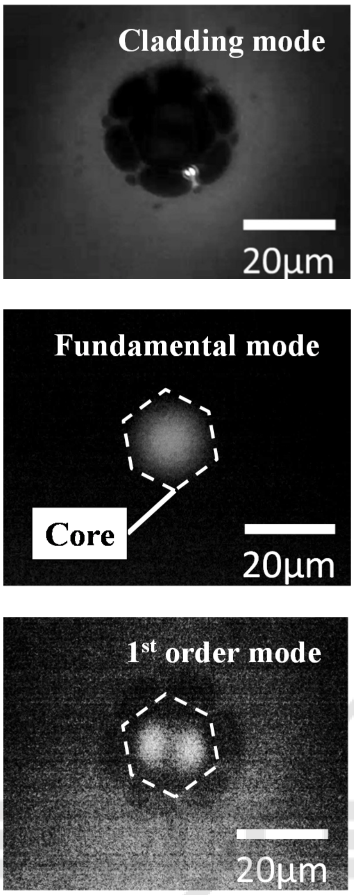

Figure 5: Images of different modes which were able to propagate in the tellurite HC-PCF.

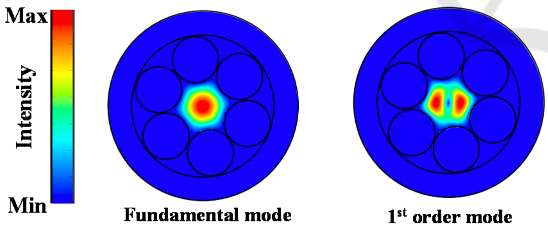

Figure 6: Calculated results of modes which can be confined in a tellurite HC-PCF.

4 CONCLUSIONS

For the first time, we experimentally demonstrated the fabrication of a tellurite HC-PCF which has a large hexagonal hollow core in the center. A supercontinuum light source from 500 nm to more than 1500 nm was launched into the fiber. The result shows that the light beam can be coupled and propagated in the hollow core with the fundamental mode. With the advantages of using tellurite glass such as high refractive index and broad transmission spectrum, it is expected that tellurite HC-PCF will be a good candidate for many interesting applications which are not possible to obtain by using silica-based HC-PCFs.

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