FULL PAPER

Fabrication of a tellurite hollow core optical fiber with six non-touching cladding air holes

Hoang Tuan TONG¹,², Nobuhiko NISHIHARAGUCHI¹, Takenobu SUZUKI¹ and Yasutake OHISHI¹

¹Research Center for Advanced Photon Technology, Toyota Technological Institute, 2–12–1 Hisakata, Tempaku, Nagoya 468–8511, Japan

We experimentally demonstrate for the first time a successful fabrication of a new tellurite hollow core optical fiber which has 6 non-touching air holes in the cladding. This is because it is known from the simulation that when the two nearby cladding air-holes connect to each other, the confinement loss in the core will be high. New tellurite glass is developed to improve the optical and thermal properties and the light transmission properties from 0.4 to 2.4 µm are studied experimentally. In addition, the calculation shows that high transmission bands and low transmission bands which locate alternately in the measured transmission spectrum correspond to the effects of resonant reflection and anti-resonant reflection.

Key-words: Hollow core fiber, Microstructured optical fiber, Fiber fabrication and characterization

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1. Introduction

Due to the air-guiding characteristics of the air-core, hollow core optical fibers (HCOFs) can give rise to many unique properties which cannot be realized by using conventional solid fibers such as high optical power delivery,¹ high damage threshold,¹ low loss levels²,³ and broad bandwidth from vacuum ultraviolet to the NIR⁴ up to the mid-IR region⁵ or even terahertz range.⁶ HCOFs can confine the electromagnetic field inside the central air-core⁷ where lights can be guided by photonic bandgap effect⁸ due to the presence of the periodic air-hole microstructure in the cladding or by antiresonant reflection effect⁹ which enables light confinement in a medium with a lower refractive index than that of its surroundings.¹⁰,¹¹

Recently, hollow core antiresonant fibers¹¹–¹⁴ have been widely studied because it is not necessary to have a complicated air-hole structure in the cladding but the first ring of air holes mainly determines the guiding properties.¹⁵ It is demonstrated that the antiresonant reflection mechanism allows a much broader spectral transmission than that achieved in photonic bandgap fibers¹⁶,¹⁷ and low loss transmission bands, even in a mid-IR wavelength region (λ > 4 µm), can be obtained by using one ring of air hole despite of very high material losses of silica.¹⁵ Due to their superior properties, HCOFs have many potential applications including data communications¹⁸,¹⁹ optical data transmission,²⁰ terahertz propagation,²¹ power beam delivery for industrial applications such as cutting, welding, and engraving,¹ medical applications²²,²³ and chemical sensing.²⁴

A tellurite HCOF with a large hexagonal hollow core in the center was demonstrated in our previous work.²⁵ However, the two adjacent air-holes in the cladding connected to each other. In this work, a new tellurite HCOF with 6 non-touching air holes in the cladding is realized. The fiber is successfully fabricated and its transmission spectrum is experimentally measured from 0.4 to 2.4 µm. By our calculation, it can be confirmed that high transmission bands and low transmission bands which locate alternately in the measured transmission spectrum are due to the effect of antiresonant reflection and resonant reflection, respectively.

2. Fiber development

2.1 Previous work

Figure 1 shows a tellurite HCOF which was demonstrated in our previous work.²⁶ The fiber had a large hexagonal hollow core surrounded by a microstructure of smaller air holes in the cladding.²⁷ The walls of two adjacent cladding air holes touched each other and the width of the touching area was about 1.2 to 1.5 µm. Although it was proved in our experiments that supercontinuum light can be propagated in the air-core of the fiber by the fundamental mode and the 1st order mode,²⁸ the measured output spectrum from 0.4 to 2.4 µm after a 7-cm-long fiber was narrow and noisy as shown in Fig. 2.

This feature can be attributed to the high transmission loss due to the existence of the touching area. The touching area between two cladding air holes can be considered as additional optical resonators.⁷ They make the density
of electromagnetic states in the cladding⁷) and the leakage loss of the propagating mode¹³) rapidly increase. Accordingly, they cause high optical loss in the transmission spectrum. To reduce this transmission loss, it is necessary to develop new tellurite hollow-core fiber whose structure does not include those touching area.

### 2.2 Glass material developments

New tellurite glasses based on TeO₂, ZnO, Li₂O and Bi₂O₃ were developed by systematically investigating the influence of the mole percentage of each component. Among them, the 76.5TeO₂–6ZnO–11.5Li₂O–6Bi₂O₃ (TZLB) glass was chosen as a potential glass material for the fiber fabrication because of its good optical and thermal properties. Its transmission spectrum from 0.2 to 10 µm was measured by an ultraviolet–visible spectrometer (Perkin Elmer, Lambda 900) and an fourier transform infrared spectroscopy spectrometer (Perkin Elmer, Spectrum 100) and was shown in Fig. 3. As compared to the result in our previous work,²⁸) the transmission spectrum in this work was improved and expanded further to long wavelength side although the same TZLB glass composition was used. The reason can be attributed to the modification of the melting process. In this work, the powders to make glass samples were preheated in an hour at 550°C and then were completely melted in one more hour at 850°C instead of 900°C in our previous work. The whole process took place inside an electric furnace purged by dried oxygen and argon gases to greatly suppress the effect of moisture contamination.

The refractive index dispersion of the developed TZLB glass from 0.5 to 4.1 µm was obtained by using a triangular TZLB glass prism and the minimum deviation method.²⁹) The measured refractive index was fitted to the Sellmeier equation³⁰),³¹) as given by Eq. (1). Both of them are plotted in Fig. 4 and the Sellmeier coefficients are shown in Table 1.

\[
n^2(\lambda) = 1 + \sum_{i=1}^{3} A_i \lambda^2 / (\lambda^2 - L_i^2) \tag{1}
\]

\begin{table}[h]
\centering
\caption{Sellmeier coefficients of the TZLB glass (76.5TeO₂–6ZnO–11.5Li₂O–6Bi₂O₃)}
\begin{tabular}{lccc}
\hline
Material & Sellmeier coefficients & \\
& $i = 1$ & $i = 2$ & $i = 3$ \\
\hline
TZLB & $A_i$ & 3.1773 & 0.0028 & 2.5571 \\
& $L_i$ & 0.1827 & 0.4015 & 16.7426 \\
\hline
\end{tabular}
\end{table}

About 20 mg powder of the developed TZLB glass was heated to 600°C in a platinum pan at a rate of 10 K/min under a nitrogen gas atmosphere by a differential scanning
calorimetry (DSC) system (Rigaku, Thermo Plus DSC 8270) to study glass thermal properties. The same amount of Al2O3 powder was used as the reference sample. The glass transition temperature (Tg) at 283.5°C can be calculated from the DSC curve shown in Fig. 5. During this heating process, crystallization did not occur as can be understood by the DSC curve. It can be mentioned that our developed TZLB glass has high thermal stability and is suitable for fiber fabrication.

In addition, the glass thermal expansion from 200 to 400°C was measured by a thermal mechanical analysis (TMA) system (Rigaku, Thermo Plus TMA 8310) and shown in Fig. 6. The softening temperature (Ts) was found about 320.9°C. Above this temperature, the developed TZLB glass becomes soft enough and can be drawn into fiber.

2.3 Fiber development

Figure 7 shows schematic images of tellurite HCOFs with non-touching air-hole structure in the cladding and different number of air holes (N = 5, 6 and 7). Multiphysics software, the finite element method (FEM) and the perfectly-matched (PM) boundary condition were used for the calculation of confinement loss and modal intensity distribution. The mesh resolution was automatically optimized to maintain the calculation accuracy and reduce the calculation time. However, the largest mesh size was equal to 0.25 μm which is equal to 1/1024 of the shortest wavelength of the wavelength range from 2 to 6 μm.

Figure 8 shows the N dependence of the confinement loss calculated for the fundamental modes in the tellurite HCOFs by the solid line (N = 5), the dashed line (N = 6) and the dotted line (N = 7). As can be seen, the confinement loss in four wavelength bands located from 2 to 6 μm was less than 10 dB/m. The confinement loss becomes much lower when N is larger than 5, but it slightly increases when N is larger than 6.

Images of the fundamental mode in tellurite HCOFs with non-touching and touching air-hole structure were simulated and shown in Fig. 9(a). In addition, it can be seen that when the gap between two adjacent air holes disappears, their walls connect to each other forming nodes where the mode field can reside.7)33),34) Due to these coupling modes, the confinement loss is large and the transmission spectrum is degraded. The calculated intensity distribution of the leaky mode in the glass wall for touching air-hole structure is also plotted in Fig. 9(a). To quantitatively show that non-touching air-hole structure has lower loss than touching air-hole structures, the confinement loss spectra for the fundamental modes of those structures were calculated when N = 6 and they are shown in Fig. 9(b). It can be understood clearly from Fig. 9(b)
that the confinement loss of the touching air-hole structure is very high as compared to that of the non-touching structure, especially in the long wavelength range over 5.0 μm.

2.4 Fiber fabrication

Following the finding of the above numerical analysis, a tellurite HCOF with 6 non-touching air holes in the cladding was fabricated by using the stack-and-draw technique. Its fiber fabrication process is illustrated as the schematic diagram in Fig. 10. A cylindrical TZLB tube was first prepared by using rotational casting method.35) Its outer and inner diameters were 15 and 10 mm, respectively. The outer of the tube was polished so that its wall thickness was controlled to be as thin as 1 mm. Then, it was elongated to obtain TZLB capillary tubes which have 0.25-mm wall thickness. The length of each tube was about 15 cm. A hexagonal air-hole structure in the cladding was formed by stacking and soldering a set of 6 capillary tubes inside a cylindrical TZLB jacket tube. Finally, they were drawn into fiber whose diameter was about 150 μm. Experimental capillary tubes and the fiber cross-sectional image which was taken by a scanning electron microscope are shown in Figs. 11 and 12, respectively.

3. Results and discussions

A supercontinuum light source (Fianium SC450) was coupled into the central hollow core of a 20-cm-long fabricated tellurite HCOF by the butt-joint method. The images of propagated modes at the output facet of the fiber segment were captured by a near-infrared CCD camera as shown in Fig. 13.

By carefully controlling the coupling conditions such as the incident angle of light beams and incident intensity, the light can be coupled successfully into the hollow core of the fiber as the fundamental mode. Besides, the 1st order mode can also be found. The captured images of the modes propagated in the fiber were shown in Fig. 14. They are consistent with images which were obtained by the numerical calculation using the Comsol Multiphysics software as shown in Fig. 15.
To analyse the transmission properties of the fabricated tellurite HCOF, the objective lens and the CCD camera in Fig. 13 were replaced by a ZBLAN single mode fiber (Fiber Lab ZSF-6) which connected to optical spectrum analyzers (OSA) as shown in Fig. 16.

The transmission spectrum at the output end of the fiber was captured by two OSA (Yokogawa AQ6373 and AQ6375) whose working ranges were from 0.4 to 1.2μm and from 1.2 to 2.4μm, respectively. The results were combined and plotted in Fig. 17. It can be seen that the spectrum included high transmission bands and low transmission bands, alternately. A close correspondence was found between our experimental transmission results and the antiresonant reflecting optical waveguide model. It is explained that when antiresonant reflection takes place, the light is confined in the core forming high transmission bands. Contrarily, the minimum of the narrow low transmission bands correspond to resonant wavelengths. The resonant reflection wavelength, $\lambda_{RR}$ can be calculated by using Eq. (2) where $t$ is the wall thickness, $n_{glass}$ is the refractive index of tellurite glass and $m$ is the integer.

$$\lambda_{RR} = \frac{2(n_{glass}^2 - n_{air}^2)^{1/2}}{m}$$ (2)

Vertical dashed lines in Fig. 17 represent the position of resonant reflection wavelengths calculated by Eq. (2). At those wavelengths, the transmission drastically reduces and the transmission minima are found.

4. Conclusions

In this work, new tellurite HCOF which has 6 non-touching air holes in the cladding was studied. It is realized that when the two nearby cladding air-holes connect to each other, the confinement loss in the core will be high. The fiber fabrication of a tellurite HCOF with 6 non-touching cladding air holes was successfully carried out and the light propagation and transmission properties from 0.4 to 2.4μm were demonstrated experimentally for the first time. The transmission spectrum included high transmission bands and low transmission bands alternately due to the effect of resonant reflection and anti-resonant reflection. The measured results are consistent with the calculation. The results at longer wavelengths are expected in our future work, especially in the mid-IR region, in order to exploit this hollow core fiber for many potential applications.

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