Fabrication and supercontinuum generation in a tellurite hybrid microstructured optical fiber with near-zero and flattened chromatic dispersion control

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Supercontinuum (SC) generation in tellurite hybrid microstructured optical fibers (HMOFs) whose refractive index difference between core and cladding materials was as large as 0.49 was demonstrated for the first time. The fiber was successfully fabricated and its chromatic dispersion was tailored to be near-zero and flattened with three zero-dispersion wavelengths at 1270, 1973 and 3627 nm. A broad SC generation was experimentally demonstrated with 5-dB spectral flatness over a 1060-nm spectral bandwidth by using a 20-cm-long section of the fabricated tellurite HMOF.

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1. Introduction

Supercontinuum (SC) generation in optical fibers has been a topic of great interest because it can provide multiwavelength optical sources with high coherence and brightness. The spectral bandwidths of SC generation can be expanded from the ultraviolet to mid-infrared (mid-IR) regions which are useful for many potential applications such as wavelength division multiplexing transmission, optical frequency combs, spectroscopy and optical coherence tomography. However, SC spectra can also suffer from significant fluctuations in amplitude, which translate to a poor signal-to-noise ratio and can limit its utility. For some applications such as frequency metrology, telecommunications, pulse compression, and coherent spectroscopy, it is important that the SC source is generated with low noise and with high spectral flatness.

Since an SC with broad bandwidth was first reported using silica microstructured optical fiber (MOF), the use of MOFs for SC generation is particularly attractive because tight mode confinement can be realized, fiber nonlinearity increases and the zero-dispersion wavelength can be tailored to improve the performance of SC generation. Recently, tellurite glasses have been employed for MOFs instead of silica glasses due to their high nonlinearity, wide transmission in the mid-IR region, low fiber attenuation and high thermal stability. Tellurite MOFs have been widely studied for telecommunications and mid-IR applications. However, SC generation in tellurite MOFs by using common and commercial pump sources in the near-infrared region has faced many difficulties because the material zero-dispersion wavelengths (ZDWs) of these glasses generally locate at long wavelengths around 2.0–2.3 μm. Several efforts have been devoted to control the chromatic dispersion for tellurite MOFs. It is expected that MOFs with flattened dispersion profiles and can enhance the nonlinear spectral broadening and the spectral flatness of SC generation. But, these properties require very complex fiber structures and tapered fibers which are difficult to be fabricated.

In order to tailor chromatic dispersion profile of tellurite fibers in higher extent but simplify their fiber structure, our group proposed a tellurite hybrid microstructured optical fiber (HMOF) in which there is a refractive index difference (Δn) between core and cladding materials. An SC generation was demonstrated experimentally in our tellurite HMOF whose Δn is 0.11 at 1544 nm. Moreover, it is also reported in our calculation that by using larger value of Δn, chromatic dispersion profiles of tellurite HMOFs can be much more flattened which are favorable for a broad and flat spectrum of SC generation. However, such a tellurite HMOF with large Δn has not been experimentally realized yet.

In this work, we demonstrated a successful fabrication of a new tellurite HMOF whose Δn is as large as 0.49. The calculated chromatic dispersion profile was near-zero and flattened in the wavelength range from about 1200 to 3600 nm with 3 ZDWs at 1270, 1973 and 3627 nm. For the first time, we observed a flattened SC spectrum with 5-dB spectral flatness over 1060 nm spectral bandwidth generated in a 20-cm-long section of the new tellurite HMOF with large Δn.

2. Fiber fabrication

2.1 Material developments

In practice, a successful fiber fabrication requires core and cladding glasses to have similar thermal properties such as transition and softening temperatures (Tg and Tc), thermal expansion coefficients (CTE) and high thermal stability (ΔTf). A large difference in those parameters obstructs fiber fabrication process by residual stress or crystallization which make fibers easy to be damaged. Glass materials in the same glass system usually have similar thermal properties which can meet the requirements of fiber fabrication. However, the refractive index difference

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WO3 and Nb2O5 are more than 48 times larger than those of silica. et al., the Raman gain coefficient of tellurite glasses doped with WO3 and Nb2O5 are more than 48 times larger than those of silica glasses while those of other common tellurite glasses are just about 30 times higher. Therefore, the 70TeO2–8Li2O–17WO3–3MoO3–2Nb2O5 mol% glass (TLWMN) has been developed by our group as a promising core glass material for tellurite optical fibers. A systematic investigation on glass formation, optical and thermal properties of phosphate-tellurite glasses was carried out to develop suitable cladding materials for TLWMN-based HMOFs. Among them, the 10TeO2–30ZnO–15Na2O–45P2O5 mol% (TZNP) glass was the most suitable. The thermal properties (Tg, Tc, and CTE) of TZNP glass are close to those of the TLWMN glass as shown in Table 1.

The glass-transition temperature (Tg) and crystallization temperature (Tc) were determined by a differential scanning calorimeter (Rigaku, Thermo Plus DSC 8270). About 30-mg powder of sample placed in a platinum pan was heated from room temperature to 800°C at the rate of 10°C/min under a nitrogen atmosphere. The same amount of Al2O3 powder was used as a reference sample. A thermal mechanical analysis (TMA) (Rigaku, Thermo Plus TMA 8310) was employed to measure the thermal expansion coefficient (CTE). Cylindrical-rod samples whose diameters were 5 mm were prepared. Their lengths were 15 mm. The value of CTE was determined from the TMA curve which was obtained by heating the glass sample from the room temperature to the softening temperature (Tg) at the rate of 10°C/min. The CTE was defined by α in Eq. (1)

\[
\alpha = \frac{1}{l_0} \times \frac{l_0 - l_i}{T_f - T_i}
\]

where \(l_0\), \(l_i\) and \(l_f\) are sample length at room temperature, at temperature \(T_i\) and at temperature \(T_f\), respectively.

The wavelength-dependent refractive indices of TLWMN and TZNP glasses were measured by the minimum deviation method. The uncertainty of the measurement is as low as ±10⁻⁴. The measured refractive indices were used to determine the Sellmeier equation given by Eq. (2) where \(\lambda\) is the wavelength, \(n\) is the wavelength-dependent refractive index, \(A_i\) and \(L_i\) are Sellmeier coefficients. The Sellmeier-fitting refractive indices of TLWMN and TZNP glasses are plotted in Fig. 1. At 1544 nm, their refractive index difference is as large as 0.49.

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

Because thermal and optical properties of TLWMN and TZNP glasses can well satisfy the requirements of fiber fabrication, they were proposed as appropriate glass materials for tellurite HMOFs in which flattened chromatic dispersion profiles are expected.

### Table 1. Thermal and optical properties of TLWMN and TZNP glasses

| Glass  | Transition temperature Tg (°C) | Softening temperature Tc (°C) | Thermal stability ΔTc (°C) | Coefficient of thermal expansion α (1/°C) | Refractive index at 1544 nm |
|--------|-------------------------------|-----------------------------|---------------------------|------------------------------------------|-----------------------------|
| TLWMN  | 349                           | 373                         | NA                        | 2.08 × 10⁻⁵                              | 2.058                       |
| TZNP   | 341                           | 370                         | NA                        | 2.17 × 10⁻⁵                              | 1.565                       |

\(\alpha\) is the wavelength-dependent refractive index, \(A_i\) and \(L_i\) are Sellmeier coefficients.

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### 2.2 Fabrication process

In this work, tellurite HMOFs were successfully fabricated based on the rotational casting and rod in tube method. The commercial pure reagents (99.99%) were used as raw materials. The fibers were constructed with a solid core and a cladding in which a microstructure of six air holes was placed. The core and cladding were made of TLWMN and TZNP glasses, respectively.

A schematic diagram which illustrates the fiber fabrication process was shown in Fig. 2. Hexagonal and cylindrical cladding tubes were prepared by the rotational casting method. Their inner and outer diameters were 3 and 12 mm, respectively. A small and uniform core rod obtained from the first elongation was inserted into a hexagonal cladding tube. They were elongated to obtain a hexagonal cane whose diameter was around 3 mm. The hexagonal cane was inserted into a cylindrical cladding tube and elongated again to obtain a cylindrical cane. By this step, a structure of 6 air holes surrounding the core was formed in the cladding area of the cylindrical cane. Finally, the fiber drawing process was performed with a positive pressure of nitrogen gas introduced into the air-hole microstructure to maintain this pattern. During fabrication process, the interstitial gap between canes and...
cladding tubes was evacuated by a vacuum pump. The air-hole microstructure of tellurite HMOFs was finely controllable by tuning the nitrogen gas pressure from 1 to 10 kPa with the accuracy of 0.1 kPa.

2.3 Fiber characterization

Image of fiber cross sections are shown in Fig. 3. Figure 3(a) shows cross-sectional image of the fiber taken by an optical microscope. Figure 3(b) shows a scanning electron microscopy (SEM) image of the fiber whose core diameter is about 1.16 µm. The SEM measurement showed that the diameters of air holes in Fig. 3(b) were from 4.8 to 7.2 µm.

A full-vector mode solver (Mode Solution software) based on the finite difference method and the perfectly matched layer boundary condition was used for the calculation of chromatic dispersion. The calculated chromatic dispersion of the fabricated tellurite HMOF in Fig. 3(b) was compared to the material dispersion of the core material as shown in Fig. 4. It was also compared to the calculated chromatic dispersion of the tellurite HMOF whose $\Delta n = 0.49$ as shown in Fig. 5. By increasing $\Delta n$ to 0.49, three ZDWs can be obtained at 1270, 1973 and 3627 nm whereas there is only one ZDW in case of the core material dispersion or in case of the tellurite HMOF with $\Delta n = 0.11$. At 1550 nm, the calculated dispersion D was 57.841 ps/nm-km, the calculated dispersion slope was 0.014 ps/nm²-km, the calculated effective mode area $A_{eff}$ was 0.591 µm², the calculated nonlinear refractive index $n_2$ was $1.17 \times 10^{-19}$ m²/W and the calculated nonlinear coefficient $\gamma$ was 8.01 m⁻¹ W⁻¹.

2.4 SC generation

Figure 6 shows the experimental setup for SC generation in the fabricated tellurite HMOF with $\Delta n = 0.49$. A commercial 1550-nm femtosecond pulsed fiber laser (Alnair-Labs) was used as the pump source. The pulse width was 200 fs and the repetition rate was 40 MHz. The output of the pump source was coupled into the tellurite HMOF by a focusing lens with a numerical aperture of 0.47. The transmission of the lens at 1550 nm was higher than 90% and the coupling efficiency was about 10%. The output end of the tellurite HMOF was mechanically spliced with a silica single-mode fiber (SMF) by using the butt-joint method. The end of the silica SMF was connected to an optical spectrum analyzer (OSA).

Figure 7 shows the pump-power dependent SC spectra experimentally obtained from a 20-cm-long section of the fabricated tellurite HMOF. The average pump power shows in Fig. 7 was measured in front of the focusing lens by a laser power meter (Coherent-FieldmaxII-PowerMax PM10). The SC spectrum obviously broadened when the average pump power varied from 2.5 to 12.5 mW. The SC generated by 12.5-mW pump power could span from 800 to 2400 nm. A 5-dB spectral fluctuation was obtained in the wavelength ranges from 890 to 1425 nm and from 1875 to 2400 nm (totally about 1060-nm spectral span) as shown in Fig. 8. This spectral flatness level has not been realized before for SC spectra generated in tellurite HMOFs. In order to highlight the advantage of tellurite HMOFs with large $\Delta n$, SC spectrum obtained in this work was compared to the SC spectrum generated in a tellurite HMOF with low $\Delta n$ of 0.11.
which was reported in our previous work.\textsuperscript{22} The average power of the pump was converted into the peak power of the pump pulse for comparison. By using tellurite HMOF with low $\Delta n$ of 0.11, a peak power of 3833 W was required to generate an SC spectrum extending from 800 to 2400 nm.\textsuperscript{22} But, as shown in Fig. 8, a peak power of 1560 W which is equal to 12.5-mW peak power of pump pulse of 1560 W.

In addition, SC spectra obtained by using the same peak power of 1560 W in these two tellurite HMOFs were shown in Fig. 9 for comparison. It is shown that the SC spectrum generated in the tellurite HMOF with $\Delta n = 0.49$ extended from about 1300 to 2400 nm, whereas the SC spectrum spanning from about 800 to 1425 nm and from 1875 to 2400 nm (about 1060 nm of spectral span). This SC spectrum was extended from ~800 to 2400 nm (~1600 nm bandwidth) by using a low pump power of 12.5 mW and a short fiber length of 20 cm. As compared to the reported tellurite HMOF with low $\Delta n$ of 0.11,\textsuperscript{22} the generated SC spectrum in the new tellurite HMOF with high $\Delta n$ of 0.49 has broader spectral bandwidth and higher spectral flatness. In addition, it was obtained by using lower pump power and shorter fiber length. With these promising features of SC generation, tellurite HMOF with high $\Delta n$ will be benefit to many potential highly nonlinear applications in telecomunication system, frequency metrology, pulse compression, and coherent spectroscopy.

3. Conclusions

In summary, a novel tellurite HMOF with high freedom in tailoring chromatic dispersion due to large refractive index difference was demonstrated to improve the performance of SC generation. A new cladding material (TZNP) was chosen from a systematic material development in order that the core and cladding materials have similar thermal properties and high thermal stability but their refractive index difference is as large as 0.49. The tellurite HMOF with large $\Delta n$ of 0.49 was successfully fabricated for the first time and the generated SC spectrum was obtained with 5-dB spectral flatness in the wavelength ranges from 890 to 1425 nm and from 1875 to 2400 nm (about 1060 nm of spectral span). This SC spectrum was extended from ~800 to 2400 nm (~1600 nm bandwidth) by using a low pump power of 12.5 mW and a short fiber length of 20 cm. As compared to the reported tellurite HMOF with low $\Delta n$, the generated SC spectrum in the new tellurite HMOF with high $\Delta n$ of 0.49 has broader spectral bandwidth and higher spectral flatness. In addition, it was obtained by using lower pump power and shorter fiber length. With these promising features of SC generation, tellurite HMOF with large $\Delta n$ will be benefit to many potential highly nonlinear applications in telecommunication system, frequency metrology, pulse compression, and coherent spectroscopy.

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