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An extruded single-mode, high-nonlinearity, tellurite glass holey fibre

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We report fabrication of the first single mode tellurite glass holey fibre produced from an extruded preform. Robust single mode guidance was observed at 1047nm in the fabricated small core holey fibre. An effective mode area of 2.6μm^2 and high effective nonlinearity of 580W^{-1}km^{-1} at 1047nm were predicted. The fibre loss was measured to be 3.5dB/m at 1050nm, and 5.8dB/m at 1550nm.

Introduction: The demonstration of first silica glass holey fibre (HF) [1] and more recently non-silica glass holey fibre [2], have generated widespread interest due to the unique optical properties that these novel waveguides can provide. These properties result form the wavelength-scaled features of the microstructured cladding and the large index-contrast between the air and the background material. Non-silica glasses offer numerous interesting opportunities for many HF types relative to silica due to their substantially different material properties. For example, non-silica glasses offer much high linear and nonlinear refractive indices than silica glass. Moreover, non-silica glasses such as chalcogenide glasses, tellurite glasses, and other heavy-metal oxide glasses can offer high transparency in the mid-infrared (mid-IR) region

(2.5-25μm), while the transparency of silica glass decreases rapidly at wavelengths beyond ~2.2μm. Additionally the high solubility of the rare-earth ions (up to 10,000 to 100,000 weight ppm) in non-silica glasses permits the development of practical short fibre based device with high gain.

Tellurite glasses [3] appear particularly attractive for HF fabrication combining amongst others the key attributes of: good thermal and chemical stability; reasonably broad transmission windows (0.35-6μm); high linear and nonlinear refractive indices, and relatively low phonon energies. Conventional solid core/cladding tellurite fibres have already been produced and have been used in a number of interesting device demonstrations including broadband amplification from 1535nm to 1610nm in an Er doped fibre amplifier [4], and from 1490nm to 1650nm in a tellurite fibre Raman amplifier [5]. These results highlight the usefulness and practicality of the tellurite glass system. Fabrication of the first tellurite HF was reported in 2003. This fibre was highly multimoded with an effective mode area A_{eff} of 21.2μm^2 and a calculated effective nonlinearity γ of 47.8$W^{-1}km^{-1}$ [6]. More recently workers at NTT reported a high nonlinearity tellurite HF fabricated using a preform casting technique with a calculated effective mode area A_{eff} of 3.54μm^2, calculated γ of 675$W^{-1}km^{-1}$ and low propagation loss of 0.4dB/m at 1550nm [7]. However, from the core geometry, and effective mode area reported [7], it would appear that this fibre would still have been multimoded and significantly no clear statement of the fibre being single moded was provided in this paper. However, single-mode operation is a pre-requisite for many applications. In this Letter, we present what we believe to be the first successful fabrication of an extruded single-mode tellurite holey fibre with small effective mode area and high effective nonlinearity. Reasonable propagation losses of 3.5dB/m and 5.8dB/m were measured at 1050nm and 1550nm, respectively.

Fabrication: Sodium-zinc-tellurite glass ($75TeO_2$-$20ZnO$-$5Na_2O$, mol.%) [3] was selected and prepared in-house for use as the background material of our tellurite HF. Fig.1 shows the measured Differential Thermal Analysis (DTA) and the measured glass viscosity curves, in which Tg and Tx are the temperatures of glass transition and the onset of crystallization respectively. Since the usable viscosity range for fibre drawing is between $10^{6.5}$ and 10^4 poise, and the crystallization onset temperature of this tellurite glass is far away from the temperature corresponding to the low viscosity limit, this glass exhibits excellent thermal stability during fibre drawing.

Just as in our previous compound glass work [8], our holey preform was made by an extrusion technique. The holey inner preform element that defines the core structure was first extruded and then drawn into cane with 1.2mm outer-diameter (OD). The cane was then inserted into an extruded jacket tube with 8.6mm OD and 1.2mm inner-diameter (ID), and the resulting assembly drawn into fibre of 250μm OD. The total fibre yield was ~45m. Fig.2 shows Scanning Electron Microscope (SEM) micrographs of the cross-section, and the magnified central region of the fibre. The triangular core is isolated from the outer glass jacket by three

7.4±0.2 µm long and 180±20 nm thin supporting struts. The fibre exhibited extremely good structural uniformity along its full 45m length.

Since the three thin supporting struts have a width that is much less, and a length that is much greater than the wavelength of light, the core can be considered as essentially an air-suspended high-index glass rod. The extremely high index-contrast between the core and the cladding, leads to (1) high confinement of light and (2) single mode guidance at infrared wavelengths due to the extremely small core.

Optical guidance: A ~30-cm long piece of fibre was mechanically cleaved at both end facets. Laser radiation at various wavelengths was respectively launched into one facet and the spatial mode guidance characteristics of the fibre investigated by imaging the output mode onto a CCD camera. Several different single transverse mode lasers were used in these experiments, including an Argon ion laser capable of operating at a wavelength of either 488nm or 514.5 nm, a LD operating at 635nm, and a Nd:YLF laser operating at 1047nm. It is observed that, at the shorter wavelength of 488nm, the fibre core is capable of supporting a few higher-order modes. The core appears to support less fewer modes at 514.5nm and 635nm. Robust single-mode guidance is observed at 1047nm. It can therefore be deduced that the effective cut-off wavelength for single-mode operation of this fibre is between 635nm and 1047nm, and that this fibre should be single mode in use for all wavelengths longer than 1047nm. Figs.3(a)&(c) show the observed guidance of this fibre at 488nm and 1047nm.

Using the SEM photos shown in Fig.2 to define the microstructure parameters, the predicted high-order mode profiles at 488nm and the fundamental mode profile at 1047nm are shown in Fig.3(b)&(d), respectively. It can be seen that the geometrical shapes of the predicted modes are in good agreement with the measured mode profiles. Although our modeling work indicates that the fibre should still be slightly multimoded at 1047nm, we found that in practice it was impossible to observe anything other than the fundamental mode at 1047nm at the fibre output, meaning that the fibre can be considered effectively single mode. This is, to the best of our knowledge [6, 7], the first observation of single-mode operation of a tellurite HF.

Using the predicted intensity profiles, the effective mode area A_{eff} ($=(\iint I(x,y)dxdy)^2/\iint I^2(x,y)dxdy$) [9]) were calculated as 3.0±0.1 μm^2 at 488nm and 2.6±0.1 μm^2 at 1047nm, respectively. Using the A_{eff} value at 1047nm and $n_2=2.5\times10^{-19}$ m^2/W [6], we calculated the effective nonlinearity γ ($=2\pi n_2/(\lambda A_{eff}$) [9]) of this fibre as $580W^{-1}km^{-1}$ at 1047nm, which is around 580 times higher than the conventional silica fibre.

The propagation of this holey fibre was measured by the cut-back technique, using a white light source ranging from 0.25µm to 2.5µm. The loss was measured to be 5.8±1.0 dB/m at 1.55µm and 3.5±1.0 dB/m at 1.05µm, which is substantially higher than the lowest loss in NTT's tellurite multimode HF of 0.4dB/m at 1.55µm [7] (see Fig.4). Fig.4 also illustrates the intrinsic V curve (wavelength versus loss) of this tellurite fibre [3], and the low losses which have been achieved by NTT in a tellurite fibre Raman amplifier fibre [5]. It is seen that tellurite glass based fibre possesses the potential to for the applications in the NIR and mid-IR region (1-4μm). The main origins of the loss in our fibre are attributed to the OH absorption, surface roughness at the air-glass interface, and scattering centres formed in the glass during heating in the extrusion and fibre drawing processes. The minimum propagation loss of our tellurite fibres at 1.05μm increased from 0.7dB/m in an unstructured/unclad fibre, which was drawn from an extruded rod, to 3.5dB/m in the final HF, due to the multi-step thermal processing. Note that although the extrusion technique may lead to slightly higher fibre losses than direct casting it is better suited for producing fibre with fine features for the majority of non-silica glasses since it is difficult to fill small voids in casting moulds for typical glass viscosities at melting. Tellurite glass is unusual in that it has a very low viscosity and is thus a very good glass for casting complex structures. Further work to reduce the fibre loss is underway.

Conclusion: We have reported what is to the best of our knowledge the first observation of single-mode operation in tellurite HF. The fibre provides effective single-mode guidance at wavelengths of ~1μm and beyond, and is predicted to have a small effective mode area of $2.6\mu m^2$ and a large effective nonlinearity per unit length γ of $580W^{-1}km^{-1}$ at 1047nm. The measured losses of the fibre are 3.5dB/m at 1.05μm and 5.8dB/m at 1.55μm. Further reductions in both mode area and loss are to be anticipated in the near future.

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Figure captions:

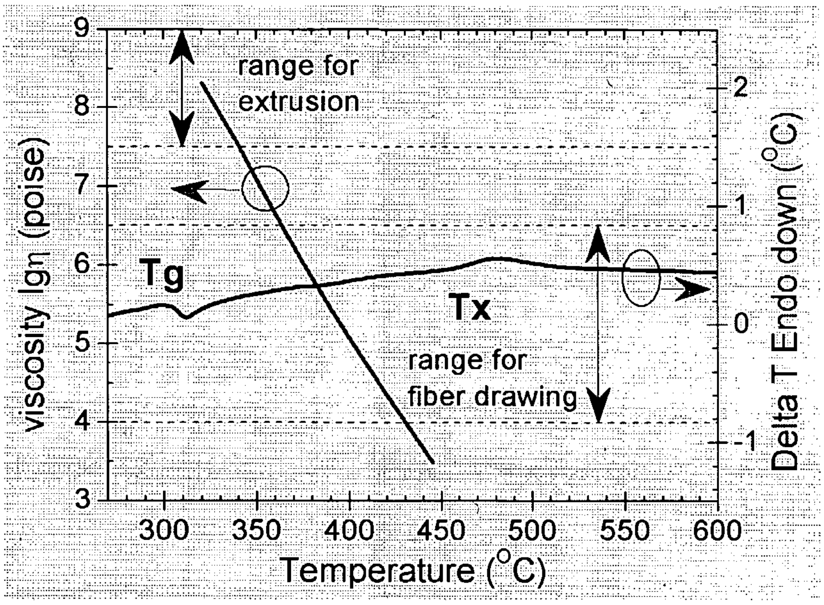
Fig. 1. DTA curve and viscosity curve of the selected tellurite glass.

Fig. 2. SEM photographs of cross-section and the magnified centre of the fabricated tellurite holey fibre with 250µm OD.

Fig. 3. (a)&(c) Observed near-field images of the guidance at 488nm and 1047nm. (b)&(d) Predicted high-order modes at 488nm and fundamental mode at 1047nm. (The contours on the intensity profiles have a spacing of 1dB).

Fig.4. Comparison of reported losses of tellurite fibres. (1) intrinsic loss of $75TeO_2$-$20ZnO$-$5Na_2O$ (mol.%) [3]; (2) NTT tellurite fibre Raman amplifier [5]; (3) NTT tellurite holey fibre [7]; (4) this work.

FIGURE 1



range for extrusion
Tg
Tx
range for fiber drawing
viscosity lgη (poise)
Delta T Endo down (°C)
Temperature (°C)
9
8
7
6
5
4
3
2
1
0
-1
300
350
400
450
500
550
600

FIGURE 2

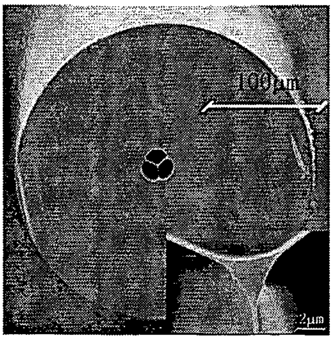


FIGURE 3

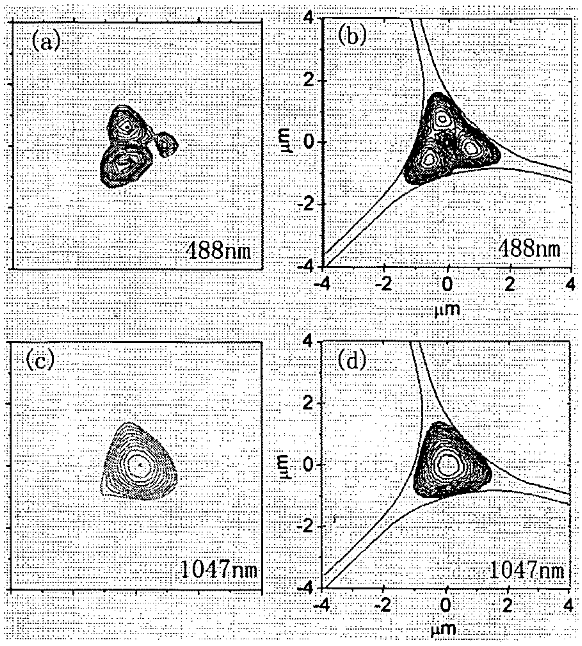
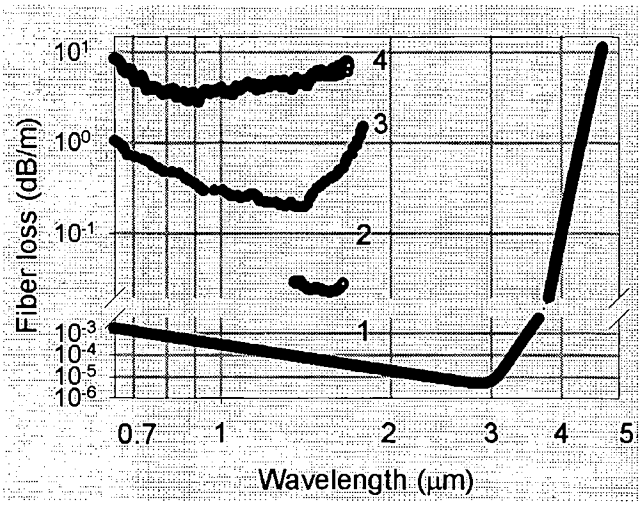


FIGURE 4



Fiber loss (dB/m)
10^1
10^0
10^{-1}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
4
3
2
1
0.7
1
2
3
4
5
Wavelength (μm)