Towards zero dispersion highly nonlinear lead silicate glass holey fibres at 1550nm by structured-element-stacking

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Abstract We report the fabrication of lead-silicate holey fibres with a high nonlinearity up to 414$W^{-1}km^{-1}$ and low dispersion at 1550nm using a new fabrication technique based on the stacking of extruded structured elements.

Introduction

Holey Fibre (HF) technology offers great prospects for the development of high performance, high nonlinearity fibres for use in nonlinear devices such as all-optical switches, wavelength converters and supercontinuum generators. Nonlinearities approaching the maximum theoretical values possible in fibre have been achieved for several materials. For example a γ value at 1550nm of 70 $W^{-1}km^{-1}$ has been achieved in a silica HF [1] and 1860 $W^{-1}km^{-1}$ in a lead silicate HF [2]. Whilst this in itself is an impressive achievement, obtaining suitable dispersion properties is often of greater importance for many nonlinear device applications, necessitating a trade-off in magnitude of nonlinearity for dispersion control. Several design techniques to optimise this trade-off have been suggested and applied to silica HFs [3,4]. However, until recently the fabrication techniques for soft glass HFs were not sufficiently developed to allow consideration of the more complex fibre structures required. Consequently, work on high nonlinearity soft glass HFs has so far focused on maximising the γ value by fabricating suspended core structures with as small a core and as high an NA as possible. However, improvements in glass extrusion technology now allow the production of more complex preform stacking elements, providing far greater possibilities for producing dispersion tailored compound glass HFs. In this paper we demonstrate a new extrusion/stacking technique that has allowed the production of high nonlinearity soft glass holey fibres with a zero dispersion wavelength shifted to the 1.55µm regime.

Fabrication

Schott SF57 was selected as the glass host for this work. Fig. 1 illustrates the fabrication scheme of our fibre (we refer to this technique as the Structured Element Stacking Technique - SEST). First, we developed a new die design that allowed us to directly extrude 6- and 7-hole hexagonal preforms. The resulting structured preforms were then drawn to canes with an outer diameter of ~600 µm and stacked into an extruded jacketing tube, as illustrated in Fig.1. Finally, this assembled preform was drawn into >200m of fibre. Thus, with the SEST design we were able to fabricate HFs with an hexagonal arrangement of effectively 4 rings of holes (48 holes in total), by stacking together just 7 structured elements. Unlike our previously extruded suspended-core HFs [2], whose critical properties are determined primarily by just one parameter, the core diameter, our SEST fibres have two adjustable parameters: the hole-to-hole pitch Λ and the hole diameter d (or relative hole size d/Λ). Λ is adjusted by the scale of the microstructured region. Note that the core size of the SEST fibres depends on both d and Λ, and is about 2Λ-d. The core sizes of our fabricated HFs ranged between 2.4-4.5 µm and had a d/Λ ratio of 0.48 in the outer cladding region, and 0.55 in the region surrounding the core. A typical SEM image of the fibre cross-section is shown in Fig.2.

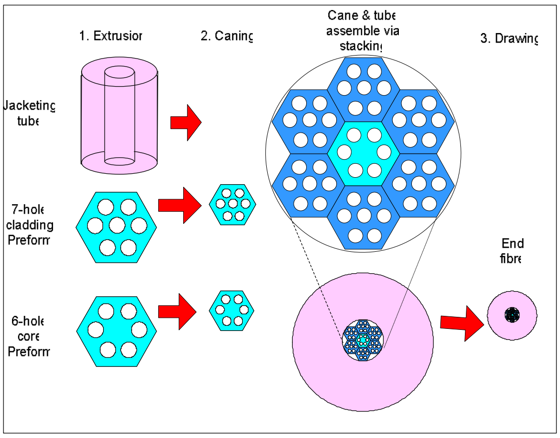

Fig.1: Fabrication scheme for the SEST fibre.

Fibre properties

We performed measurements on 3 different SEST fibres with core sizes of 4.2 µm (HF#1), 3.4 µm (HF#2) and 2.4 µm (HF#3). The spatial mode guidance characteristics of HF#1, #2 and #3 at 1.55 µm were investigated. The measured mode profile for all fibres exhibits the near hexagonal symmetry of the fibre core, which is in good agreement with the predicted fundamental mode profile (Fig.2). The propagation loss of the fibres was measured at 1.55 µm using free space coupling from a laser diode and the cutback method. A loss of 3.2±0.5 dB/m, 3.5±0.5dB/m and 4.3±0.3dB/m was measured for HF#1, #2 and #3 respectively.

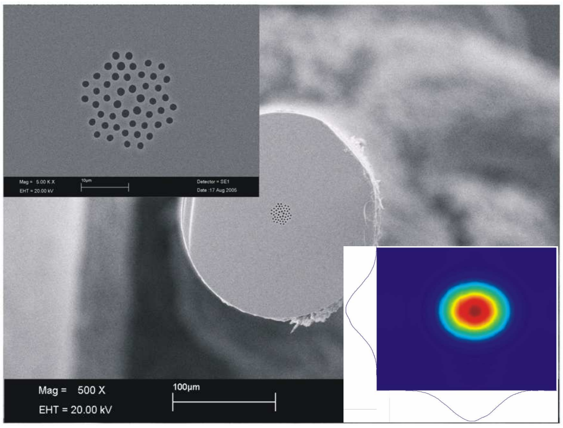

Fig.2: SEM image and measured mode profile of the SEST fibre at 1.55µm (HF#1)

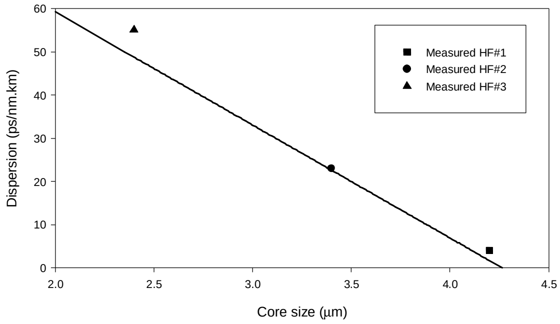

Fig.3 GVD at 1.55 µm as a function of core diameter for our SEST HF design with superposed experimental data for the 3 fibre samples.

We next evaluated the effective nonlinear coefficient for the fibres at 1.55 µm using a measurement based on the nonlinear phase induced through self-phase modulation of a continuous wave, dual-frequency, optical beat-signal propagated through the fibre. Our measurements were in excellent agreement with our modelling, which predicted γ values of ~170, 250 and 410 $W^{-1}km^{-1}$ for HF#1,#2 and #3 respectively.

The great advantages of SEST HFs though can be appreciated when the fibre dispersion is considered. We have performed numerical simulations using a full vector model to calculate the group velocity dispersion (GVD) profiles of the 3 fibres. The model used refractive index profiles based on SEM images of the real fibre structure. In Fig.3 we plot the predicted variation of GVD at 1.55µm with core size where it is seen that very low values of dispersion can be expected for core diameters of ~4µm. Superposed on the plot are experimentally determined dispersion values at 1.55µm measured for our samples using a low-coherence spectral interferometry technique [5]. The results are seen to be in very good agreement with our theoretical expectations. In Fig.4 we plot the theoretical variation of dispersion with wavelength for our three fibre samples. HF #2 and #3 are seen to exhibit anomalous GVD throughout the C-band due to an excess of waveguide dispersion in this region. However, for HF #1 the effects of material and waveguide dispersion oppose each other in such a way that the zero-dispersion wavelength is shifted to the region between 1530-1540nm, as intended from our design calculations. We also plot in Fig.4 the theoretical dispersion profiles of several extruded SF57 suspended-core fibres previously fabricated with maximum nonlinearity in mind [2]. The primary ZD wavelength for these fibres lies around 1µm. The figure shows that the SEST designs offer far greater control and flatter dispersion profiles in the 1.55µm region compared to the suspended-core structures previously fabricated. (Note that it is possible to envisage suspended-core fibres with primary ZD-wavelengths within the C-band however these designs are heavily multimode). The figure also shows the dispersion profile of a theoretical SEST design optimised for flattened dispersion at 1.55µm which highlights the excellent properties that should ultimately be achievable using the SEST approach.

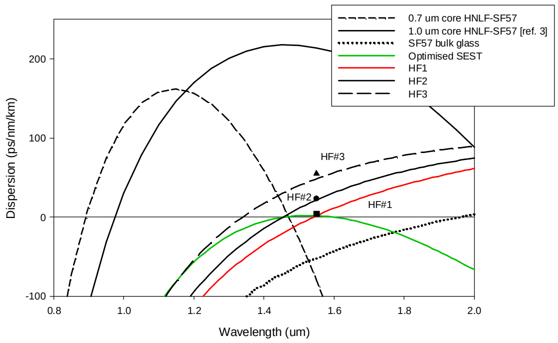

Fig.4 Comparison of dispersion profiles of our previous work on suspended-core HFs with different core sizes and various SEST fibres.

Conclusions

High nonlinearity, lead silicate HFs with ZD wavelengths around 1.55 µm have been fabricated using a combination of extrusion and stacking techniques. This fabrication approach combines the versatility of capillary stacking with the simplicity of extrusion to achieve greater freedom in dispersion control. We have confirmed that we have achieved a zero-dispersion wavelength within the C-band, in a fibre with a 3.2 dB/m loss and a γ value of 170 $W^{-1}km^{-1}$. Further improvements in dispersion flatness, loss and nonlinearity are to be anticipated in the near future.

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