Fusion-Spliced Highly Nonlinear Soft-glass W-type Index Profiled Fibre with Ultra-flattened, Low Dispersion Profile in 1.55µm Telecommunication Window

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Abstract: We report arc fusion splicing of highly nonlinear soft glass fibre with a flattened, near-zero dispersion profile at 1.55µm to conventional silica fibre. Reasonable splice loss values and watt-level power handling are demonstrated.

OCIS codes: (060.0060) Fibre optics and optical communications; (190.4370) Nonlinear optics, fibres

1. Introduction

In the past decade significant work on non-silica glass based highly nonlinear fibre (HNLF), including microstructured optical fibre (MOF) [1,2] and conventional step-index fibre [3] has been undertaken demonstrating several potential benefits as compared to their silica counterparts. These include shorter device lengths due to the increased nonlinearity per unit length (and hence more stable, lower latency devices) and fibre with improved resilience to Stimulated Brillouin Scattering (SBS). HNLF with a high nonlinearity and a flat near-zero dispersion profile is especially desirable for many nonlinear applications such as four-wave mixing based parametric processes including frequency conversion, parametric generation, oscillation and amplification [4]. Unfortunately, all earlier reported non-silica glass HNLFs have possessed either a dispersion shifted profile [2] or a highly normal dispersion profile [3], either due to an inadequate index-contrast between the core and the cladding [3], or difficulty in controlling the dimensions of a holey cladding with adequate precision [2]. We previously reported fabrication of the first single-mode non-silica glass HNLF with flatted, near-zero dispersion profile at 1.55µm [5]. The fibre had an all-solid W-type index profile (see Fig.1(a)) with a high index contrast. Three types of commercial Schott lead silicate glasses, i.e., SF57 with refractive index at 1.55µm n_{1550nm} of 1.80, LLF1 with n_{1550nm} of 1.53, SF6 with n_{1550nm} of 1.76, were used as the core, the first cladding and the second cladding respectively. With a core diameter of 1.63µm, the fibre showed high nonlinearity γ of $820W^{-1}km^{-1}$ at 1.55µm and a normal dispersion profile across all wavelengths. At ~1.52µm the dispersion slope DS of the fibre was zero and the dispersion D was -2.6ps/nm/km [5]. Whilst, this work was highly encouraging, two important technical issues remained to be resolved. Firstly, a HNLF with a dispersion profile with two zero dispersion wavelengths (ZDWs) in 1.55µm region is more desirable than that with a normal dispersion profile for many applications. Secondly, it in order to be able to integrate such fibres within systems it is is important to be able to splice such fibres to standard silica fibre types. In this work, we report, for the first time, the fabrication of non-silica glass HNLF with an ultra-flattened dispersion profile and two ZDWs in 1.55µm region (with a maximum dispersion value ≤2.0ps/nm/km). Moreover, we report successful arc-fusion splicing to conventional single mode fibre using an offset-heating and bridge-fibre method. Reasonably low splicing loss (given the large mode mismatch) has been achieved. Power tests on the spliced fibres shows that the splice between the lead silicate glass HNLF and silica fibre can resist watt-level powers and stable optical performance.

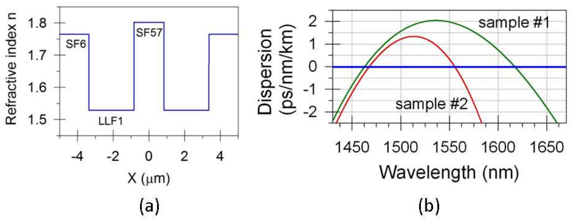

Fig.1 (a) W-type index profile of lead silicate glass HNLF; (b) measured dispersion profiles of two samples of lead silicate glass HNLFs

2. Fibre fabrication and characterization

According to the numerical simulation [5], in order to achieve both near-zero dispersion (D) and dispersion slope (DS) at 1.55µm in a W-type index profiled fibre based on SF57/LLF1/SF6 glasses, the optimized core diameter d_{core}

should be between 1.64-1.66µm. This means that the fibre core diameter and correspondingly the fibre outer-diameter (OD) should be precisely controlled within a range of ±0.6%. This is a challenging task, because this requirement is very close to the accuracy of the commercial silica fibre drawing tower, i.e., ±0.5-1.0µm for a 125µm OD fibre. In our fabrication, the fibre diameter is intentionally controlled with a deliberate diameter variation is achieved between adjacent bands of drawn fibre so that fibre with close to zero dispersion at 1.55µm can be obtained within the draw (along with fibre exhibiting other interesting dispersion profiles). Two separate fibre draws were made under the same drawing conditions and more than 400 meters of fibre was obtained.

The effective nonlinearity of the fabricated fibres was measured to be $820W^{-1}km^{-1}$ at 1.55µm using the Boskovic method. The propagation loss of the samples from both draws was measured to be 2.0±0.2 dB/m, using the cutback method. A low-coherence interferometric technique [7] was employed to characterise the dispersion profile of the fibre from 1300nm to 1700nm, using a broadband polarized supercontinuum source. The measured dispersion curves for selected fibre samples from the two different draws are illustrated in Fig.1(b). It is seen that both fibre samples have a dispersion profile exhibiting two ZDWs around 1.55µm and an absolute dispersion value of no more than 2ps/nm/km over a wavelength range of no more than 100nm. To the best of our knowledge, this is the first report of the fabrication of a non-silica glass HNLF with two ZDWs and such low dispersion values.

3. Arc fusion splicing

In any real practical telecommunications application the ability to integrate fibre components with silica based optical fibres is likely to be essential. Arc fusion splicing is a quick and efficient method to connect two fibres together with good mechanical strength and low splice loss. In order to form a fusion splice, the glass fibre must be softened with the corresponding viscosity reduced down to a level of 10^5 poise [6]. This means that during the splicing the silica fibre should be heated to above 2000^oC whilst the lead silicate glass HNLF described above should be heated to just $700\text{-}800^oC$. Consequently, the normal symmetric splicing configuration (i.e. applying the arc across the ends of the two fibres to be spliced) cannot be used to splice a silica fibre and a lead silicate glass fibre together as the lead silicate glass fibre with lower viscosity will be less resistant to surface tension forces. Instead, offset heating, i.e., moving the heat source (the arc electrodes), away from the lead silicate glass fibre and closer to the silica fibre, is necessary for fusion-splicing these two dissimilar glass fibres together. Secondly, the mode field diameter (MFD) of the lead silicate glass HNLF is calculated to be 1.6µm at 1.55µm, while that of conventional single mode silica fibre (Corning SMF28) is 10.5µm. Such a big MFD mismatch will result in an intrinsic splice loss of ~10.5dB if the fibres are spliced directly. Use of a bridge fibre, which has an intermediate MFD between the SMF28 fibre and the lead silicate glass HNLF is necessary to minimize the total splicing loss between SMF28 and the lead silicate glass HNLF. A commercial Ericsson FSU975 arc fusion splicer is used in the experiment. Two commercial high numerical-aperture (NA) silica fibres, Nufern UHNA3 and UHNA7, with an MFD of 4.1µm and 3.2µm respectively at 1.55µm, are chosen in this work as the bridge fibres between the SMF28 fibre and the lead silicate glass HNLF. Note that the core of both UHNA3 and UHNA7 are doped with high content of germanium. In splicing the bridge fibre with lead silicate glass HNLF, first the lead silicate glass HNLF is manually aligned with the bridge fibre using a butt-coupling method, ensuring that all the light from the silica bridge fibre is launched into the core of lead silicate glass HNLF (as shown in Fig.2(a)). Fig.2(b) illustrates one of the lead silicate glass HNLF samples spliced with a silica bridge fibre. The central vertical dash line represents the position of the arc electrodes of the splicer. The splice position is offset from the arc electrodes by a distance that is typically between 300-500µm. The best experimental splice loss between UHNA3 and lead silicate glass HNLF is 3.2dB, in good agreement with the calculated splice loss due to the MFD mismatch. However, the splice loss between UHNA7 and HNLF is 3.7dB, in comparison with the calculated splice loss of 2.0dB from the MFD mismatch. This could arise from the core misalignment of the two fibres during the manual butt-coupling; more experiments will be carried out to lower the splice loss and to understand the nature of the loss.

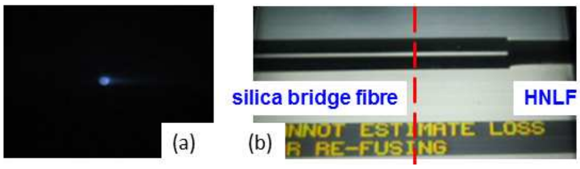

Fig.2 (a) Near-field image of 1.55µm laser guiding from output end of lead silicate glass HNLF butt-coupled with silica bridge fibre on splicer. (b) Photograph of spliced lead silicate glass HNLF sample with silica bridge fibre.

A splice loss of 0.2-0.3dB was achieved between the chosen high-NA silica bridge fibres and the SMF28 fibre using the multiple arcing method. The splicing loss due to the MFD mismatch between SMF28 and UHNA3 (or

UHNA7) should be 3.4dB (or 5.1dB). It is believed that thermal diffusion of the dopant in the fibre core is responsible for the observed large reduction splicing loss of the bridge fibre and the SMF28 here.

In many nonlinear applications such as fibre parametric amplification, watt-level CW pump power is required within the HNLF. The 3dB-level loss here will attenuate almost 50% of the pump power at the splice position and such wasted power will be converted to heat very locally around the splice. Whether this will cause a degradation of the optical performance is an obvious concern. In order to investigate the optical performance of the spliced lead silicate glass HNLF under watt-level operation two fibre samples were prepared and tested. Fig.3(a) illustrates the configuration of the spliced fibre samples. A 1550nm CW laser with a maximum output power of 5W was launched into the spliced fibre sample through a fibre connector. The output power from the end of the lead silicate HNLF was recorded by a power meter. Table 1 summarizes the optical properties of the spliced HNLF samples in the power test. As can be seen from Fig.3(b), when the power directly attenuated on the splice A in Sample #1 is 1.8W, i.e., the power launched into HNLF is 1.65W, the splice loss of splice A is almost constant within the 10-minute test. Note that each splice was sleeved with a polyethylene splice protector after splicing and no active cooling was adopted on the splices during the power test. This indicates the excellent stability of the splice between lead silicate glass HNLF and the bridge fibre. As also seen in Table 1, the splice A of the Sample #2, which uses UHNA7 as the bridge fibre, was damaged with 1W power on the splice A. A core-misalignment between UHNA7 and HNLF may be responsible for the damage.

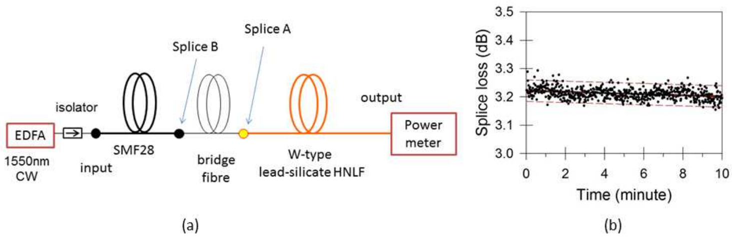

Fig.3 (a) Schematic of power test on spliced fibre sample. Note that length of HNLF is no more than 1meter to minimize nonlinear effect. (b) Stability of splice loss of splice A (between HNLF sample 1 and bridge fibre UHNA3) when 1.8W power is directly attenuated on splicer A.

Table 1 Summary of optical properties of spliced samples in power test

Lead-silicate glass HNLF	Loss at 1550 nm (dB/m)	Bridge fibre	MFD (μm)	loss of splice A (dB)	loss of splice B (dB)	Total splice loss of A&B (dB)	Net power on splice A to damage splice
Sample #1	2.0	UHNA3	4	3.2	0.2	3.4	>1.8W
Sample #2	2.0	UHNA7	3	3.7	0.3	4.0	~1W

4. Conclusion

We report the fabrication of non-silica glass HNLF with a two-ZDW flattened dispersion profile at 1.55μm for the first time. The dispersion is within ±2ps/nm/km over a bandwidth of more than 100nm around 1.55μm. An arc fusion splicing technique combined with offset-heating and a bridge-fibre for better mode matching was used to splice this soft glass HNLF with conventional silica fibre. A total splice loss between conventional silica fibre and non-silica glass HNLF of 3.4 dB was achieved. Power handling at the Watt-level and stability of the splice between the soft glass fibre and silica fibre at these power levels open the possibility of directly integrating this non-silica glass fibre within silica fibre systems. It is anticipated that further reduction in losses will be possible with further optimisation of the bridging fibres. This work is funded by European Communities Seventh Framework Programme FP/2007-2013 (224547, PHASORS).

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