Extruded small-core bismuth oxide glass holey fibres

P. Petropoulos, H. Ebendorff-Heidepriem, S. Asimakis, R.C. Moore, K. Frampton, F. Koizumi, T.M. Monro, D.J. Richardson
Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom.
pp@orc.soton.ac.uk

Abstract: We report our progress on the fabrication and characterisation of highly nonlinear bismuth oxide glass holey fibres. The measured losses for these fibres were ~3 dB/m at 1.55 μm, and the effective nonlinearity of the smallest core fibre was as high as 1100 $W^{-1}km^{-1}$ at the same wavelength.

1. Introduction

Nonlinear effects can be very important for telecommunications, as they can be used to implement a variety of important functions directly in the optical domain, such as wavelength conversion, time-domain demultiplexing, signal regeneration and so on. There is therefore an increasing interest in the development of highly nonlinear fibres in order to reduce the operating powers and/or reduce the effective device lengths. The nonlinear behaviour of an optical fibre is characterised by the effective nonlinearity coefficient γ, which is proportional to the nonlinear refractive index of the fibre n_2, and inversely proportional to the effective mode area A_{eff}. The optimisation of both of these parameters can be employed in order to enhance the nonlinearity coefficient of the fibre. Microstuctured fibre technology allows the fabrication of fibres which exhibit a combination of small-core structures and an extremely high numerical aperture (NA), facilitated by the high refractive index contrast between the glass core and the surrounding air. This technique has been employed to demonstrate pure silica holey fibres (HFs) with an effective nonlinearity as high as ~70 $W^{-1}km^{-1}$ [1], this is to be compared to the effective nonlinearity of a standard telecommunications fibre of ~1 $W^{-1}km^{-1}$.

The use of compound glasses, which offer higher nonlinear refractive indices than silica, provides a route to even higher nonlinearity fibres [2-7]. Chalcogenide glasses for example, exhibit more than two orders of magnitude higher nonlinear refractive index than silica, and recently an extremely high nonlinearity conventional fibre (γ=1000 $W^{-1}km^{-1}$) has been reported [3]. However, due to the conventional solid cladding, the dispersion of this fibre was dominated by the high normal material dispersion of the glass, which can be detrimental for device functionality and performance. In this work, we seek to combine the advantages of HF technology with a high nonlinearity glass to achieve a record nonlinearity for a HF.

The material we are using here is a bismuth-oxide-based glass. This is an attractive novel material for nonlinear devices and compact Er-doped amplifiers. It shows a high nonlinearity without containing any toxic elements such as Pb, As, Se, Te [2]. It also exhibits good mechanical, chemical and thermal stability, which allows easy fibre fabrication process. It accepts high Er doping levels without suffering from concentration quenching and clustering effects [8], and the Er-doped glass exhibits broadband emission at 1550 nm. A nonlinear fibre [9] and a short Er-doped fibre amplifier with broadband emission [8] have already been developed from this glass. In addition, bismuth-oxide-based fibres can be fusion-spliced to silica fibres [10], offering thus easy integration to silica-based optical systems.

2. Fibre Fabrication

The bismuth-oxide-based glass we used has a low softening temperature of 550 °C, which allows use of the extrusion technique for perform production. The fibre fabrication consists of three steps. In the first step, the structured preform and the jacket tube are extruded. The cross-section of an extruded preform of 16 mm outer diameter is shown in Fig. 1a. In the second step, the preform is reduced in scale on a fibre drawing tower to a cane of about 1.6 mm diameter. In the last step, the cane is inserted within the jacket tube, and this assembly is drawn down to the final fibre. The core diameter is adjusted during fibre drawing by appropriate choice of the external fibre diameter (130-215 μm for our fibres). This fabrication technique allows us to continuously draw more than ~100 m of fibre from a single preform.

The dimensions of the structural features within the high nonlinearity HF we drew were measured using scanning electron microscopy (SEM). The core is optically isolated from the outer solid glass region by three fine supporting struts (Fig. 1b). It is evident that the geometry has been maintained well during the two-step reduction process from the structured preform down to the final fibre. Full collapse of the cane onto the jacket tube has been achieved without any decrease in the size of the air holes and struts relative to the core size. In the drawn fibres, the struts were about 5-8 μm long and 250 nm wide, which ensures that confinement loss is reduced to a negligible level [11]. The structural features of the bismuth-oxide glass HF are very similar to those of lead silicate glass HFs that have been produced by extrusion using the same die geometry [6]. We have used this fibre geometry, since it closely resembles an air-suspended rod - the idealised HF geometry that offers maximum NA. The reproducibility of the HF geometry using different glass materials and thus different glass viscosity behaviour demonstrates the excellent versatility and reliability of the extrusion technique for HF fabrication.

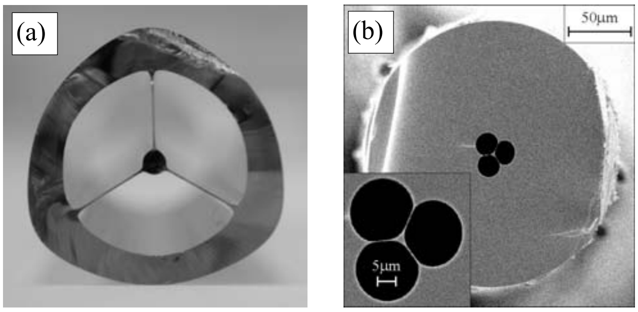

Fig. 1. (a) Cross section through the extruded perform and (b) SEM image of the holey fibre.

3. Fibre properties

Recent progress on the fabrication process of the fibres has allowed for a significant reduction of the fibre propagation losses, as well as an improvement in the quality of the fibre structure. We characterised some of our most recent fibres in terms of loss and effective nonlinearity. The core diameters of these fibres ranged between 1.6 and 2.1 μm. The propagation losses were measured at 1550 nm using the cut-back method. The fibre with 2.1 μm core exhibited a loss of 2.7 dB/m. The fibre with a smaller core of 1.6 μm had a higher loss of 3.4 dB/m. We also produced a bulk unstructured fibre to determine the impact of the microstructure on the propagation loss. The bulk fibre was made from the same glass batch using a similar extrusion process and fibre drawing conditions and exhibited a loss of 1.65 dB/m. The predicted mode profiles of fibres reveal that the modal field overlaps with the air holes. As a result, the light interacts with the air/glass boundaries near the core, and so the effect of surface roughness on fibre loss becomes significant. The higher loss in the HF compared with the bulk fibre is likely to be due to surface imperfections within the structured preform. Simulations have shown that the magnitude of the overlap and thus the impact of surface roughness increases with decreasing core size [12]. This is in agreement with the higher loss value measured for the fibre sample with the smaller core size. However, we expect that further improvements in the fabrication process will decrease the losses to values near the bulk fibre. The bismuth-oxide-based glass used in this study was melted in an ambient atmosphere. It is anticipated that the use of dehydrated glass will result in a further reduction of the loss down to values close to those previously reported for bismuth-based conventional fibre (<0.8dB/m) [9].

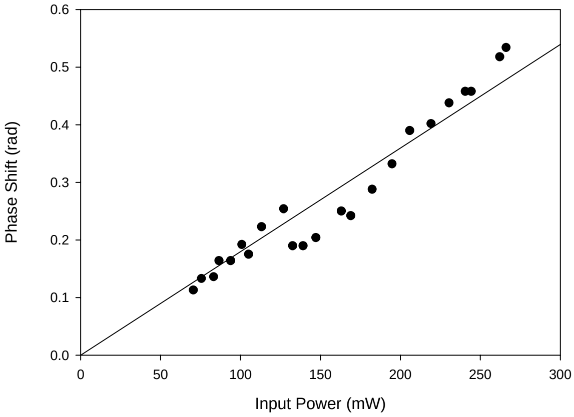

Fig. 2. Measurement of the nonlinear phase shift as a function of the input power for a 1.28 m long bismuth-oxide-based glass HF.

The measurement of the effective nonlinearity and mode area at 1550 nm was based on a measurement of the nonlinear phase shift induced through self-phase modulation, with a dual frequency beat signal propagating through the fibre [13]. The nonlinear phase shift measured for the 1.6 μm core fibre is plotted in Fig. 2 as a function of the input power. From the slope of the linear fit and taking into account the effective length of the test fibre, the value of the effective nonlinear coefficient γ was estimated to be 1100±110 $W^{-1}km^{-1}$. Given the nonlinear refractive index of the glass, our measurement yields an estimate of A_{eff}=1.2 μm^2.

We have also experimented with splicing these HFs to conventional single-mode fibre (SMF). The fibre we used for these experiments had a core diameter of 2.0 μm. In order to reduce the losses due to mode mismatch we employed two conventional small-core buffer fibre stages to reduce the mode area at the immediate interface to the HF. Typical total splice losses of ~5.8 dB were achieved, which although quite high, were nevertheless still 0.9 dB lower those achieved by butt-coupling to the bismuth-oxide HF. Mode mismatch and Fresnel reflections accounted for 4.0 dB of the total loss. We believe the additional excess loss of 1.8 dB to be due to the fact that some higher order modes that were evident at the fibre output during free-space coupling disappeared after splicing the fibre (Fig. 3).

Fig. 3 IR image of the near-field pattern of the spliced bismuth-oxide-based glass HF.

Basic soliton propagation experiments at 1.55 μm with this 2.0 μm spliced fibre have confirmed that the chromatic dispersion is anomalous at these wavelengths. This is despite the fact that the zero dispersion wavelength for the bulk glass lies at ~2 μm. It is anticipated that smaller core fibres should be even more anomalously dispersive.

4. Conclusions

We have fabricated and characterised fibres with core diameters ranging between 1.6 and 2.1 μm in terms of their loss and effective nonlinearity at telecommunication wavelengths around 1.55 μm. Losses as low as ~2.7 dB/m were measured. The effective nonlinearity coefficient for the smallest core fibre was ~1100 $W^{-1}km^{-1}$. To the best of our knowledge this represents the highest nonlinearity yet reported for a HF and is three orders of magnitude higher than that of standard single-mode fibre. It is worth noting that the use of even higher nonlinearity glasses based on bismuth oxides, as was recently used to fabricate the record-high nonlinearity conventional fibre described in Ref. 14, should lead to yet further increases in HF nonlinearity.

The bulk glass used in this work was fabricated by Asahi Glass Company, whose technical contribution and funding for this work is greatfully acknowledged.

5. References

1. J. H. Lee, W. Belardi, K. Furusawa, P. Petropoulos, Z. Yusoff, T. M. Monro, and D. J. Richardson, "Four-wave mixing based 10-Gb/s tunable wavelength conversion using a holey fiber with a high SBS threshold," IEEE Photon. Technol. Lett. **15**, 440-442 (2003).
2. N. Sugimoto, H. Kanbara, S. Fujiwara, K. Tanaka, Y. Shimizugawa, and K. Hirao, "Third-order optical nonlinearities and their ultrafast response in Bi2O3-B2O3-SiO2 glasses," J. Opt. Soc. Am. B **16**, 1904-1908 (1999).
3. R. E. Slusher, J. S. Sanghera, L. B. Shaw, and I. D. Aggarwal, "Nonlinear optical properties of As-Se fiber," in OSA Topical meeting on Nonlinear Guided Waves and their Applications, Stressa, Italy, 1-4 Sept 2003.
4. T. M. Monro, Y. D. West, D. W. Hewak, N. G. R. Broderick, and D. J. Richardson, "Chalcogenide holey fibres," Electron. Lett. **36**, 1998-2000 (2000).
5. V. Kumar, A. K. George, W. H. Reeves, J. C. Knight, P. S. Russell, F. G. Omenetto, and A. J. Taylor, "Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation," Opt. Express **10**, 1520-1525 (2002).
6. P. Petropoulos, H. Ebendorff-Heidepriem, V. Finazzi, R. Moore, K. Frampton, D. J. Richardson, and T. M. Monro, "Highly nonlinear and anomalously dispersive lead silicate glass holey fibers," Opt. Express **11**, 3568-3573 (2003).
7. V. Kumar, A. K. George, J. C. Knight, and P. S. Russell, "Tellurite photonic crystal fiber," Opt. Express **11**, 2641-2645 (2003).
8. N. Sugimoto, Y. Kuroiwa, K. Ochiai, S. Ohara, Y. Furusawa, S. Ito, S. Tanabe, and T. Hanada, "Novel short-length EDF for C+L band amplification," in Optical Amplifiers and their Applications, Quebec City, Canada, 9-12 July 2000.
9. K. Kikuchi, K. Taira, and N. Sugimoto, "Highly nonlinear bismuth oxide-based glass fibers for all-optical signal processing," Electron. Lett. **38**, 166-167 (2002).
10. Y. Kuroiwa, N. Sugimoto, K. Ochiai, S. Ohara, Y. Furusawa, S. Ito, S. Tanabe, and T. Hanada, "Fusion spliceable and high efficient Bi2O3-based EDF for short length and broadband application pumped at 1480 nm," in OFC 2001, Anaheim, USA, 2001, paper TuI5.
11. L. Poladian, N. A. Issa, and T. M. Monro, "A Fourier decomposition algorithm for leaky modes of fibres with arbitrary geometry," Opt. Express **10**, 449-454 (2002).
12. L. Farr, J. C. Knight, B. J. Mangan, and P. J. Roberts, "Low loss photonic crystal fibre," in ECOC 2002, Copenhagen, Denmark, 2002, paper PD1.3.
13. A. Boskovic, S. V. Chernikov, J. R. Taylor, L. GrunerNielsen, and O. A. Levring, "Direct continuous-wave measurement of n(2) in various types of telecommunication fiber at 1.55 mu m," Opt. Lett. **21**, 1966-1968 (1996).

14. N. Sugimoto, T. Nagashima, T. Hasegawa, S. Ohara, K. Taira, and K. Kikuchi, "Bismuth-based optical fiber with nonlinear coefficient of 1360 W-1km-1," in OFC 2004, Los Angeles, USA, 2004, paper PDP26.