3103

Winter School on Optical Core Network Technologies,
Aveiro, 23-25 February, 2005, Portugal

Non-silica highly nonlinear holey fibers for telecommunications applications

S. Asimakis, P. Petropoulos, H. Ebendorff-Heidepriem, J. Leong, V. Finazzi, F. Koizumi, K. Frampton, R.C. Moore, T.M. Monro, D.J. Richardson

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom
sya@orc.soton.ac.uk

Abstract—**We report on recent development in the fabrication and characterization of small-core lead-silicate and bismuth-oxide glass holey fibers. These fibers exhibit an effective nonlinearity three orders of magnitude higher than standard silica fibers, offering the prospect of compact, nonlinear devices operating at low powers.**

Index Terms—**Fiber characterization; Nonlinear optics, fibers; Pulse propagation and solitons**

I. INTRODUCTION

HOLEY Fibers (HFs) have generated great interest over the past few years, growing from a research-oriented field to a commercially available technology. The optical properties of holey fibers rely on the specification of the size, shape and arrangement of the holes that surround a solid core and form the cladding. These parameters can easily be tailored according to the desired application, thus leading to unique features that are difficult to achieve using conventional fibers. Some of the most impressive properties of HFs are the possibilities to achieve endlessly single mode guidance [1], unique dispersion properties [2, 3, 4] and extreme values of Numerical Aperture (NA) [5] and fiber nonlinearity [6,7].

A particularly promising application of HFs concerns their use in nonlinear devices. HFs with very small core dimensions and relatively large holes, hence a very large NA, can tightly confine the light in the small core and exhibit a very high effective nonlinear coefficient γ. This is a measure of the strength of the nonlinear characteristics of a fiber and is defined as $\gamma=2\pi n_2/(\lambda A_{eff})$, where n_2 is the nonlinear refractive index, λ is the wavelength of operation and A_{eff} is the effective mode area [8]. For HFs made in silica, the maximum value of γ that can be achieved is 70 $W^{-1}km^{-1}$ [5,9]. Note for comparison, that the typical value for standard telecommunications fibers is 1 $W^{-1}km^{-1}$.

A range of important applications in telecommunication systems that have used highly nonlinear, small core HFs have already been demonstrated. These applications include wavelength conversion [10,11], demultiplexing [12] and 2R regeneration [13]. To date, most applications have been demonstrated in silica-based HFs. However, silica is not a particularly nonlinear material. Clearly, the use of compound glasses with higher nonlinear refractive indices than silica can lead to a further drastic increase in the achieved nonlinearity. Moreover, in general such glasses also have a relatively high linear refractive index, which leads to a further increased index contrast between the glass core and the holey cladding (and therefore the NA of the fiber), hence providing tighter mode confinement and smaller effective mode area (A_{eff}). Furthermore, compound glasses have in general lower softening temperatures compared to silica, thus allowing simpler approaches to be used for the fabrication of the HF preforms, such as the extrusion technique, which can also yield designs that cannot be created with the usual stacking techniques.

Among the various high-nonlinearity soft glasses, lead-silicate and bismuth-oxide glasses are particularly promising [7,14,15,16]. Both glasses exhibit a similar nonlinear refractive index, and exhibit a good thermal and mechanical stability, therefore allowing HF fabrication via the extrusion process. Additionally, bismuth-oxide glasses offer the great advantage of being compatible with silica fibers for fusion-splicing, and they also do not contain any toxic elements. With regard to commercially available lead-silicate glasses, their comparatively smooth temperature-viscosity-curve and higher crystallization stability are major assets, which allow for relatively easy fiber fabrication.

Here we report on recent progress in the fabrication of HFs made from both bismuth-oxide and lead-silicate glasses. We have focused on a fiber design that is targeted to achieving the maximum γ value possible. Excellent progress has been made and unprecedented levels of nonlinearity have been reached in the fibers we have fabricated. We also discuss the impact of this extreme design on the dispersion properties of the fibers resulting from the strong waveguide dispersion contribution for these structures.

II. FABRICATION PROCESS

For the fabrication of the HFs, we followed a simple approach, which consisted of three steps. First, the structured preform and the jacket tube were produced by extrusion from bulk glass billets [14,16]. Then, the structured preform was reduced in scale on a fiber-drawing tower to a cane of about 1.6 mm in diameter. Finally, the cane was inserted within the jacket tube and this assembly was drawn to the final fiber.

Each cane-jacket tube assembly could be drawn to more than 100m of fiber, consisting of bands with different core diameters. The fiber outer diameter, and hence the core diameter as well, was actively controlled during the fiber drawing stage by adjusting the tension applied to the pull.

Following the extrusion process described above, fibers with core diameters in the range of 1.1–2.1μm were produced. Applying scanning electron microscopy (SEM), the dimensions of the core and the struts were determined for each fiber band with high accuracy. A typical cross-sectional image of the fabricated fibers is shown in Figure 1. In our design, the core has a triangular shape and is supported by three fine struts at relative angles of 120°. The obvious advantage of this design is the combination of a high air-filling fraction coupled with a low value of confinement loss, which can be achieved for strut lengths of the order of 6-8μm.Below we compare the properties of small core HFs made of two different soft glasses, namely a commercial lead-silicate Schott glass (SF57) or a bismuth-oxide glass provided by Asahi Glass Company.

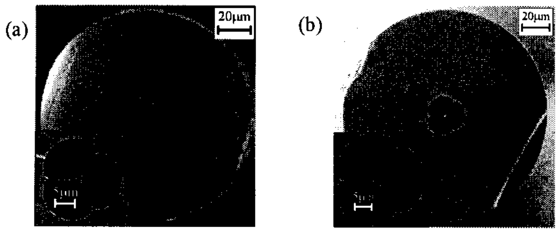

Fig. 1: SEM images of HF cross section for (a) lead-silicate and (b) bismuth - oxide fiber.

III. FIBER PROPERTIES

A. Propagation Loss

The propagation loss of the fibers was measured using free-space coupling from a laser diode at 1550nm and applying the cutback method. For the bismuth-oxide glass HFs, a 2.1μm core fiber exhibited a loss of 2.7dB/m, while a fiber with a smaller core of 1.8μm had a higher loss of 3.4dB/m. With regard to the lead-silicate HFs, a loss of 2.3dB/m was measured for a fiber with a core diameter as low as 1.1μm, and 2.0dB/m for a 1.4μm core fiber.

Useful conclusions regarding the impact of the holey structure on the propagation loss can be drawn by a direct comparison of the loss of the HFs with the corresponding propagation loss of bare fibers (i.e. heavily multimode uniform solid fibers without a core). Applying the cutback method we measured the loss of the bare fibers to be 0.9dB/m for the lead-silicate glass and 1.6dB/m for the bismuth-oxide glass. The notable increase in the propagation loss of the HFs relative to that of the bare fibers is due to the impact of surface roughness experienced by the signal at the air/glass boundaries [5]. We also note that the propagation loss of the HFs increases with a decrease in the core size. This behaviour also originates from the overlap of the modal field with the air holes of the HFs. The magnitude of this overlap increases with a decrease in the core size; hence the effect of surface imperfections becomes more significant, leading to a higher propagation loss [17].

The loss values reported here represent significant progress on the fabrication process of compound glass HFs (e.g. see [16]). The improvement in the levels of propagation loss as compared to previous attempts is attributed to improvements in the cleaning process of the fiber preform prior to caning. It is anticipated that further improvements in the fabrication process will result in even lower losses, ideally close to the loss of the bulk glass itself.

B. Effective Nonlinearity

The nonlinear behavior of the various small-core HFs at 1550nm was evaluated from a measurement of the nonlinear phase shift that was induced through self-phase modulation of a dual frequency, optical beat signal propagating through the fiber under test [18, 19]. The measured nonlinear phase shift per unit of effective length is plotted as a function of the input power for the smallest core bismuth-oxide and lead-silicate HFs in Figures 2a and b. The value of the effective nonlinear coefficient γ for each fiber was calculated from the slope of the corresponding linear fit to be ~1100W^{-1}km^{-1} for the case of the 1.8 μm core bismuth-oxide HF and ~1860W^{-1}km^{-1} for the 1.1μm core lead-silicate HF. To our knowledge, the effective nonlinearity of 1860W^{-1}km^{-1} is the highest value achieved in a HF to date.

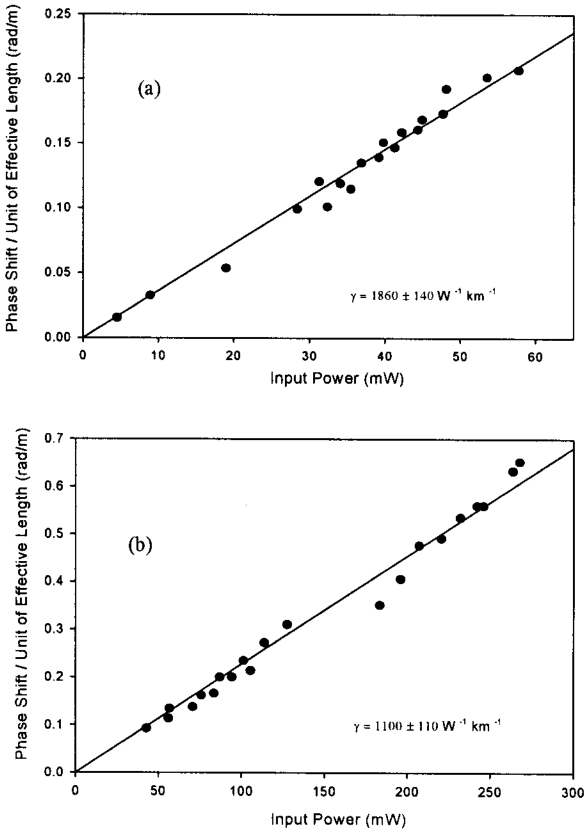

Fig. 2: Nonlinear Phase Shift per unit of effective length for the (a) 1.1 μm core lead silicate HF and the (b) 1.8 μm core bismuth HF

The performance of a fiber-based nonlinear device depends on both the effective nonlinearity and the effective length of the fiber used [18]. Since the effective length of a fiber is determined by the propagation loss it exhibits, it becomes apparent that fibers for nonlinear devices are required to have a high effective nonlinearity and a low propagation loss. To date, small-core soft glass HFs have a nonlinearity that is three orders of magnitude greater than that of standard optical fibers, nevertheless they exhibit much higher propagation loss. A very high propagation loss can greatly deteriorate the nonlinear performance. However, for short devices in the order of 1m, fiber losses of ≤2dB/m can be readily tolerated, since in this case the effective fiber length is over 80% of the physical fiber length. Furthermore, the unprecedented nonlinearity of soft glass HFs can outweigh the decrease of the effective fiber length caused by their higher propagation losses compared to standard optical fibers. Thus, compound glass HFs offer the prospect of compact nonlinear devices operating at very low powers.

C. Dispersion Properties

In conventional single-mode optical fibers the waveguide dispersion contribution is relatively small, however the extreme waveguiding conditions in small-core, high NA HFs can strongly affect the overall dispersion characteristics of these fibers [20]. As far as the two materials we have used in this work are concerned, it is known that high refractive index glasses exhibit zero group velocity dispersion at long wavelengths. In particular, the zero group velocity dispersion is at 1970nm for the lead silicate glass and at 2310nm for the bismuth glass we used. Hence, both glasses have a strong normal dispersion at 1550nm. However, HF designs that combine a small-core with a large air-filling fraction can effectively shift the overall dispersion curve towards shorter wavelengths to such an extent that anomalous dispersion can be achieved at 1550nm [16].

The group velocity dispersion of the fabricated compound glass HFs was calculated from the index profile of the fibers using a commercial full-vector modal solver. The predicted dispersion profiles are presented in Figure 3.

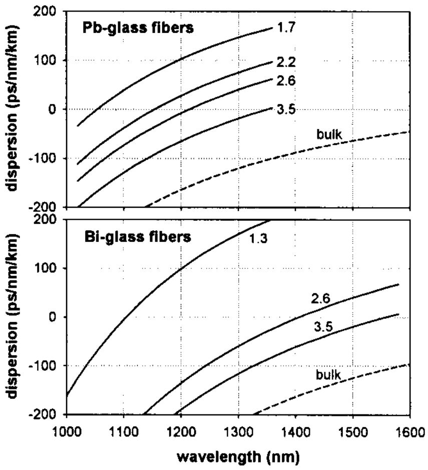

Fig. 3. Dispersion of bulk glass and predicted dispersion for HFs with different core diameters (numbers in μm in the graph).

The numerical simulations predict that, for a specified wavelength, the dispersion of both lead-silicate and bismuth-oxide HFs increases with decreasing core size, due to enhanced waveguide dispersion. As a result, the zero-dispersion wavelength is shifted towards shorter wavelengths.

To test the contribution of the waveguide dispersion in the overall dispersion properties of the fabricated fibers, we studied the self-phase modulation (SPM) spectra of short soliton pulses (~2.0ps), coming from a mode-locked fiber ring laser (1556nm, 9.95GHz repetition rate), that were amplified using a high-power, erbium doped fiber amplifier, and free-space coupled to 0.53m of the 1.8μm core bismuth HF.

Figure 4 shows the optical spectra obtained at the output of the fiber for various input optical power levels. The main feature observed in the figure is a wavelength shift of the original signal, which is strongly dependent on the energy of the incoming pulses. The shift increases as the energy of the input pulses is increased, becoming as high as ~ 40nm for a moderate input pulse energy of ~ 18pJ. The shapes of these SPM-broadened spectra confirm the presence of higher order soliton effects in the form of soliton self-frequency shifting, the manifestation of which requires anomalously dispersive media. Therefore, it can safely be concluded that the dispersion of the fiber is indeed anomalous at these wavelengths.

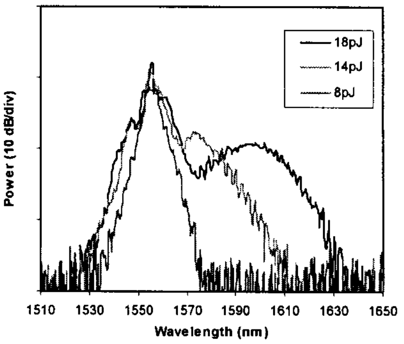

Fig. 4. The Raman soliton spectra at the output of 53cm of the 1.4μm enclosed core diameter, bismuth-oxide HF for different levels of input pulse energy

IV. CONCLUSIONS

Small core HFs made of bismuth-oxide and lead-silicate glasses have been fabricated and characterised in terms of loss and nonlinearity. We fabricated fibers with core diameters ranging from 1.8 – 2.1μm for the bismuth-oxide glass and 1.1 – 1.4μm for the lead-silicate glass. All fibers exhibited losses ranging between 2 - 3.5dB/m, with the bismuth-oxide fibers being somewhat lossier. We found that the propagation loss increased for smaller core diameters, which we attribute to a more pronounced effect of surface roughness. It is anticipated that improvements in the fabrication of compound glass HFs will lead to a further reduction in the propagation loss, ideally down to the loss-limit imposed by the bulk glass itself.

The potential of compound glass HFs for achieving a very high nonlinearity per unit length of fiber has been clearly demonstrated. In particular, a 1.8μm core HF made from bismuth-oxide based glass exhibited a nonlinearity of about $1100W^{-1}km^{-1}$, while a 1.1μm core lead-silicate fiber had a record-high nonlinearity of $\sim1860W^{-1}km^{-1}$. We believe that compound glass HFs provide a real prospect towards the realization of sub-meter long nonlinear devices operating at milliwatts of optical power.

ACKNOWLEDGMENT

We wish to thank Asahi Glass Company for the fabrication of the bulk bismuth glass. S.Asimakis is supported by the Greek State Scholarships Foundation. J.Leong is supported by a scholarship by Malaysia Government.

H. Ebendorff-Heidepriem and T.M. Monro are currently with the School of Chemistry and Physics, University of Adelaide, Australia.

REFERENCES

[1] T.A. Birks, J.C. Knight, P.St.J.Russel, "Endlessly single-mode photonic crystal fibre", *Optics Letters*, 22: 961-963,1997.

[2] J.C. Knight, J. Arriaga, T. A Birks, A. Ortigosa-Blanch, W.J. Wadsworth, P.S.J Russell, "Anomalous dispersion in photonic crystal fiber", *IEEE Photonics Technology Letters,* 12: 807-809,2000.

[3] T.M. Monro, D.J. Richardson, N.G.R. Broderick, P.J. Bennett, "Modeling large air fraction holey optical fibers", *IEEE Journal of Lightwave Technology*, 18:50-56,2000.

[4] W.H. Reeves, J.C. Knight, P.S.J. Russell, P.J. Roberts, "Demonstration of ultra- flattened dispersion in photonic crystal fibers", *Optics Express*, 10:609-613,2002.

[5] T.M. Monro, D. J. Richardson, "Holey optical fires: Fundamental properties and device applications",*C.R. Physique*, 4:175-186, 2003.

[6] W. Belardi, J.H. Lee, K. Furusawa, Z. Yusoff, P. Petropoulos, M. Ibsen, T.M. Monro, D.J. Richardson, "A 10 Gbit/sec tuneable wavelength converter based on four-wave mixing in highly nonlinear holey fibre",*Proc. European Conference on Optical Communications (ECOC '02)*,Copenhagen, paper PD1.2, 2002.

[7] H. Ebendorff-Heidepriem , P. Petropoulos, S. Asimakis, V. Finazzi, R. C. Moore, K. Frampton, F. Koizumi, D.J. Richardson, T.M. Monro, "Bismuth glass holey fibers with high nonlinearity " *Optics Express*, 12: 5082-5087,2004.

[8] G. P. Agrawal, *Nonlinear Fiber Optics, 3rd ed.* (Academic Press, 2001).

[9] V. Finazzi, T.M. Monro,D.J. Richardson, "Small-core silica holey fibers: nonlinearity and confinement loss trade-offs," *Journal of Optical Society of America B,* 20 :1427-1433, 2003.

[10] J.H. Lee, Z. Yusoff, W. Belardi, M. Ibsen, T.M. Monro, B. Thomsen, D.J. Richardson, "A holey fiber based WDM wavelength converter incorporating an apodized fiber Bragg grating filter", *Proc. Conference on Lasers and Electro-Optics (CLEO '02),* Long Beach, postdeadline paper CPDB5, 2002.

[11] J.H. Lee, P.C. Teh, W. Belardi, M. Ibsen, T.M. Monro, D.J. Richardson, "A tunable WDM wavelength converter based on cross-phase modulation effects in normal dispersion holey fiber*", IEEE Photonics Technology Letters*, 15:437-439,2003.

[12] A. I. Siahlo, L. K. Oxenløwe, K. S. Berg, A. T. Clausen, P. A. Andersen, C. Peucheret, A. Tersigni, P. Jeppesen, K.P. Hansen, J. R. Folkenberg, "A high-speed demultiplexer based on nonlinear optical loop mirror with a photonic crystal fiber", *IEEE Photonics Technology Letters*., 15:1147-1149,2003.

[13] P.Petropoulos, T.M. Monro, W. Belardi, K. Furusawa, J.H. Lee, D.J. Richardson, "2R-regenerative all-optical switch abased on a highly nonlinear holey fiber", *Optics LetterS,*26:1233-1235, 2001.

[14] K.M. Kiang, K. Frampton, T. M. Monro, R. Moore, J. Trucknott, D. W. Hewak, D. J. Richardson, H. N. Rutt, "Extruded single-mode non-silica glass holey optical fibres," *Electronics Letters,*. 38:546-547,2002.

[15] V. Kumar, A. K. George, W. H Reeves, J. C.Knight, P. S Russell, F. G. Omenetto, A. J. Taylor, "Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation",*Opics Express*, 10:1520-1525, 2002.

[16] P. Petropoulos, T.M. Monro, H. Ebendorff-Heidepriem, ,R.C. Moore, K. Frampton, D.J. Richardson, "Highly nonlinear and anomalously dispersive lead silicate glass holey fibers", *Optics Express,*11: 3568-3573, 2003.

[17] L. Farr, J.C. Knight, B.J. Mangan, P.J. Roberts, " Low loss photonic crystal fibre, *Proc. European Conference on Optical Communications (ECOC '02)*,Copenhagen , PD1.3 (Postdeadline),2004.

[18] A. Boskovic, S.V. Chernikov, J.R. Taylor, L. Gruner-Nielsen, O.A. Levring, "Direct continuous-wave measurement of n_2 in various types of telecommunication fiber at 1.55 μm", *Optics Letters*, 21:1966-1968, 1996.

[19] N.G.R. Broderick, T.M. Monro, P.J. Bennett, D.J. Richardson, "Nonlinearity in holey optical fibers: measurement and future opportunities", *Optics Letters*, 20:1395-1397, 1999.

[20] J. C. Knight, J. Arriaga, T.A Birks, A. Ortigosa-Blanch, W.J. Wadsworth, P.S.J. Russell, "Anomalous dispersion in photonic crystal fiber", *IEEE Photonics Technology Letters*, 12:807-809,2000.