Highly nonlinear and anomalously dispersive lead silicate glass holey fibers

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

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

Abstract: In this paper we present significant progress on the fabrication of small-core lead-silicate holey fibers. The glass used in this work is SF57, a commercially available, highly nonlinear Schott glass. We report the fabrication of small core SF57 fibers with a loss as low as 2.6 dB/m at 1550 nm, and the fabrication of fibers with a nonlinear coefficient as high as 640 $W^{-1}km^{-1}$. We demonstrate the generation of Raman solitons at ~1550 nm in a short length of such a fiber which highlights the fact that the group velocity dispersion can be anomalous at these wavelengths despite the large normal material dispersion of the glass around 1550nm.

OCIS codes: (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication; (060.2290) Fiber materials; (060.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and solitons.

References and links

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. 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), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-10-25-1520.
3. K. M. Kiang, K. Frampton, T. M. Monro, R. Moore, J. Tucknott, D. W. Hewak, D. J. Richardson, and H. N. Rutt, "Extruded singlemode non-silica glass holey optical fibres," Electron. Lett. **38**, 546-547 (2002).
4. P. Petropoulos, T. M. Monro, H. Ebendorff-Heidepriem, K. Frampton, R. C. Moore, H. N. Rutt, and D. J. Richardson, "Soliton-self-frequency-shift effects and pulse compression in an anomalously dispersive high nonlinearity lead silicate holey fiber," presented at OFC 2003, Atlanta, Georgia, paper PD03 (Postdeadline).
5. H. Ebendorff-Heidepriem, P. Petropoulos, V. Finazzi, K. Frampton, R. Moore, D. J. Richardson, and T. M. Monro, "Highly nonlinear bismuth-oxide-based glass holey fiber," presented at OFC 2004, Los Angeles, California, paper ThA4.
6. V. Kumar, A. K. George, J. C. Knight, and P. S. Russell, "Tellurite photonic crystal fiber," Opt. Express **11**, 2641-2645 (2003), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-20-2641.
7. 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).
8. S. R. Friberg and P. W. Smith, "Nonlinear Optical-Glasses for Ultrafast Optical Switches," IEEE J. Quantum Electron. **23**, 2089-2094 (1987).
9. G. P. Agrawal, Nonlinear Fiber Optics, 2nd ed. (Academic Press, Inc., 1995).
10. T. M. Monro, K. M. Kiang, J. H. Lee, K. Frampton, Z. Yusoff, R. Moore, J. Tucknott, D. W. Hewak, H. N. Rutt, and D. J. Richardson, "High nonlinearity extruded single-mode holey optical fibers," presented at OFC 2002, Anaheim, California, 19-21 March 2002, paper FA1-1 (Postdeadline).
11. E. M. Vogel, M. J. Weber, and D. M. Krol, "Nonlinear Optical Phenomena in Glass," Phys. Chem. Glasses **32**, 231-254 (1991).
12. S. Fujino, H. Ijiri, F. Shimizu, and K. Morinaga, "Measurement of viscosity of multi-component glasses in the wide range for fiber drawing," J. Jpn. Inst. Met. **62**, 106-110 (1998).
13. Schott Glass Catalogue, 2003.

#3473 - $15.00 US Received December 01, 2003; Revised December 12, 2003

14. L. Poladian, N. A. Issa, and T. M. Monro, "Fourier decomposition algorithm for leaky modes of fibres with arbitrary geometry," Opt. Express **10**, 449-454 (2002), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-10-10-449.
15. T. M. Monro, D. J. Richardson, N. G. R. Broderick, and P. J. Bennett, "Holey optical fibers: An efficient modal model," J. Lightwave Technol. **17**, 1093-1102 (1999).
16. 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).

1. Introduction

Microstructured fiber technology has enabled significant progress in the development of fibers with high effective nonlinearity. This is achieved by combining a small core design with a high numerical aperture (NA) to yield tight mode confinement. Using such a technique, pure silica holey fibers (HFs) with an effective mode area as small as 1.3 μm^2 have successfully been fabricated, exhibiting effective nonlinearity coefficients as high as 70 W^{-1} km^{-1} at 1550 nm [1], i.e. around 70 times more nonlinear than standard single mode fibers. In contrast to conventional fibers, HFs can be made from a single material, which eliminates the problems induced by the core/cladding interface of two different glasses. This allows a broader range of glass compositions to be used for fiber devices. Using microstructured fiber technology, the fabrication of compound glass HF has been demonstrated for lead silicate glasses [2-4], heavy metal oxide glasses [5, 6] and lanthanum-gallium-sulfide glass [7]. The material nonlinearity of compound glasses [8] can be more than one order of magnitude larger than that of silica [9]. The combination of highly nonlinear glass composition and small core/high NA HF geometry allows a further dramatic increase of the fiber nonlinearity. Recently, a lead silicate HF with an effective nonlinearity ~550 times larger than that of standard silica fibers has been demonstrated [10]. Most nonlinear/high-index glasses have a high normal material dispersion at 1550 nm, which dominates the overall dispersion of fibers with conventional solid cladding. However, for many nonlinear device applications, anomalous or near-zero dispersion is required. Fortunately, the HF geometry affects drastically the waveguide dispersion, allowing the highly normal material dispersion to be overcome. Indeed lead silicate HFs showing anomalous dispersion at 1550 nm have been demonstrated [2].

Due to their suitable combination of properties, lead silicate glasses are promising materials for highly nonlinear HFs. Although their material nonlinearity is lower than in chalcogenide and heavy metal oxide glasses [11], they offer higher thermal and crystallization stability and less steep viscosity-temperature-curves, while exhibiting low softening temperatures [12]. This opens up the use of extrusion as an alternative technology for fiber preform fabrication [2, 3, 6]. Compared with the stacking technique, which is used typically for silica HFs, extrusion is less labor-intensive and allows good reproducibility of the preform geometry.

Among commercially available lead silicate glasses, SF57 exhibits the highest nonlinearity. The nonlinear refractive index of this glass was measured to be $4.1 \cdot 10^{-19}$ m^2/W at 1060 nm [8]. The linear refractive index of SF57 is 1.8 at 1550 nm [13], which is quite high when compared to that of pure silica. At the same time the zero-dispersion wavelength for the glass is 1970 nm and the material dispersion is strongly normal at 1550 nm. However, compared with chalcogenide and heavy metal oxide glasses (n~2.4 at 1550 nm), the significantly lower refractive index of SF57 enables more efficient integration with conventional fiber systems. In addition, it facilitates the design and fabrication of HFs with near-zero and anomalous dispersion at 1550 nm.

In this paper we present recent progress that has been achieved in the fabrication of SF57 small-core HFs. Fibers with varying core diameters between 1.7 and 2.9 μm have been

#3473 - $15.00 US Received December 01, 2003; Revised December 12, 2003

fabricated, exhibiting the highest effective nonlinearity coefficients ever reported for a HF. Numerical simulations have shown that the chromatic dispersion of these fibers can be anomalous at ~1550 nm. This was verified through a soliton experiment, which showed that just a short length of HF was capable of giving rise to Raman solitons, even for moderate input pulse energies. ~80 nm wavelength shifts were observed for a gigahertz repetition rate pulsed input, accompanied by significant pulse compression.

2. Fiber fabrication and structure

The fiber fabrication process followed three steps. First, the structured preform and jacket tube were produced from bulk glass billets using the extrusion technique. The structured preform (Fig. 1a), which had an outer diameter of about 16 mm, was reduced in scale on a fiber drawing tower to a cane of about 1.7 mm diameter (Fig. 1(b)). In the last step, the cane was inserted within a jacket tube, and this assembly was drawn to the final fiber (Fig. 1(c)). From each assembly, we have drawn more than 200 meters of fiber. We produced fibers with core diameters in the range 1.7-2.9 μm from four different assemblies. The core diameter was adjusted during fiber drawing by an appropriate choice of the external fiber diameter (130-190 μm). Note that the ratio between core size and fiber diameter can be changed via the choice of jacket geometry and corresponding cane size, which allows the fiber diameter for a certain core size to be set to a desired value.

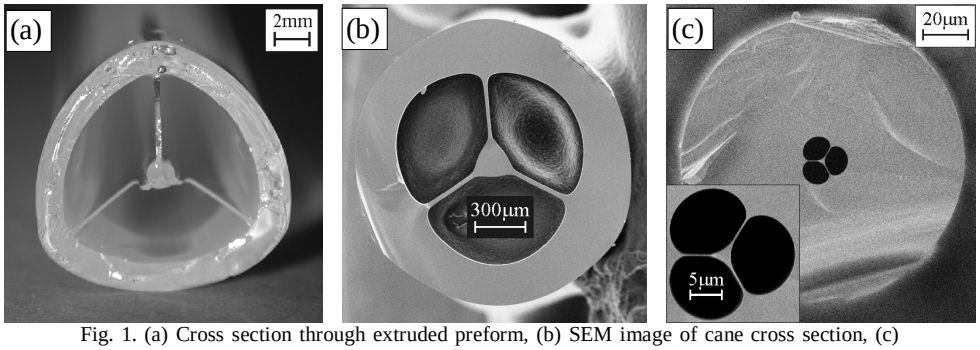

Fig. 1. (a) Cross section through extruded preform, (b) SEM image of cane cross section, (c) SEM image of holey fiber cross section.

The dimensions of the structural features within the HFs were measured using scanning electron microscopy (SEM). The four different HFs have very similar cross-sectional profiles. The core is optically isolated from the outer solid glass region by three fine supporting struts (Fig. 1(c)). For cores of 1.7-2.3 μm diameter, the struts are ≈5 μm long and 250 nm thick. The four HFs, made from different starting preforms, vary only slightly in the strut length and thickness relative to the core size, which demonstrates the excellent reproducibility possible using this technique.

The fibers presented here have an improved structure as compared with previous fibers of this type [3]. Full collapse of the canes onto the jacket tubes has been achieved without decreasing the size of the air holes and length of struts relative to the cores. The struts of the fibers presented here are more than two times longer and almost two times thinner, which ensures that the core is optically isolated from the external environment, and thus that confinement loss has been reduced to negligible levels [14]. In addition, the core dimensions have been reduced to increase mode confinement.

3. Basic fiber properties

Here we report on the basic properties of the two fibers that demonstrate the most exceptional properties among all the fibers produced - specifically the fiber with the smallest core and thus highest nonlinearity, and the fiber with the lowest loss.

#3473 - $15.00 US Received December 01, 2003; Revised December 12, 2003

The propagation loss of the fibers was measured at 1550 nm using free space coupling from a laser diode and the cut-back method. The first fiber produced, which has the smallest core of 1.7 μm, exhibits an average loss of ~9 dB/m, however several localized sections with losses ranging from 5 to 18 dB/m were found along the length of fiber drawn. These large variations of loss values indicate localized losses, possibly due to defects in the preform. Improvements in the fiber fabrication procedures have allowed us to produce a fiber with reduced losses of 2.6 dB/m. To our knowledge the losses of this fiber, (hereafter referred to as the second fiber), are the lowest reported for a compound glass HF at 1550 nm. For lead silicate glasses the losses are expected to be even lower at wavelengths between 550 and 1300 nm [2]. In addition, the low-loss values have been measured to be consistent over tens of meters of fiber. Note that the loss of bulk SF57 at 1550 nm is 1.6 dB/m [13].

In the first fiber, which has a 1.7 μm core, robust single-mode guidance was observed at 1550 nm. The mode profile of this fiber has been predicted using the SEM image of the fiber structure and a full-vectorial implementation of the orthogonal function method [15]. The predicted mode profile at 1550 nm is superimposed on the index profile in Fig. 2(a) (inset). The predicted effective mode area, A_{eff}, for the 1.7 μm core is 2.6 μm^2.

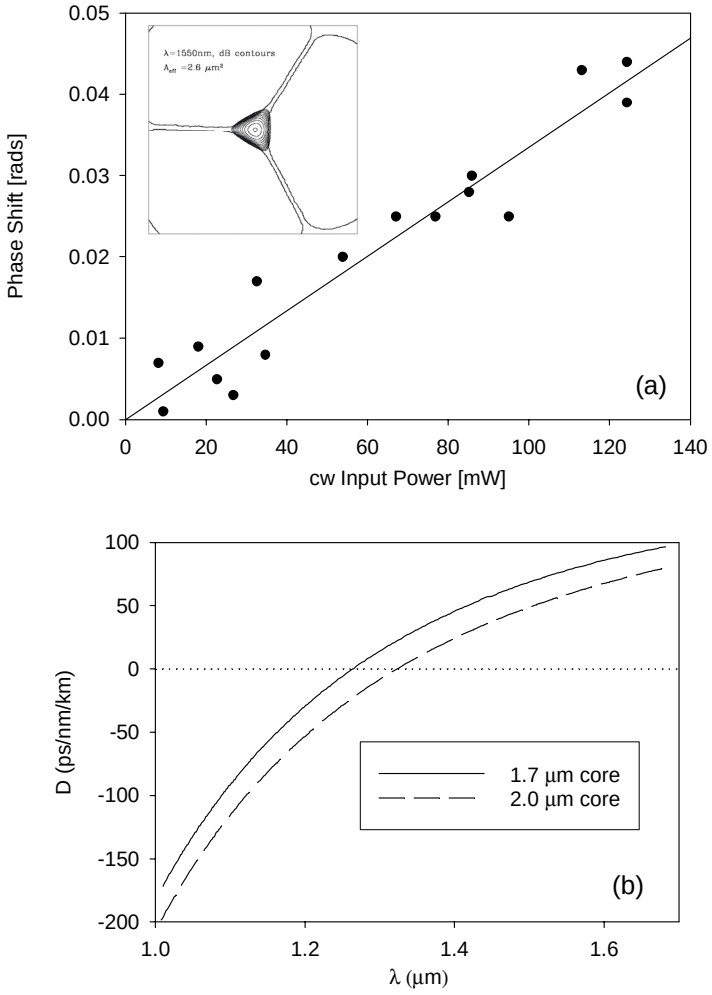

Fig. 2. (a) Nonlinearity measurement over 0.37m of the first fiber; inset shows the mode profile of this fiber; (b) dispersion profile of the SF57 HFs with core diameters of 1.7 μm and 2.0 μm.

#3473 - $15.00 US Received December 01, 2003; Revised December 12, 2003

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 fiber [16]. The nonlinear phase shift measured for the first fiber is plotted in Fig. 2(a) as a function of the input power. From the slope of the linear fit and taking into account the effective length of the fiber under test, an average value of the effective nonlinear coefficient γ of the first fiber was estimated to be 640 ± 60 W^{-1} km^{-1}. Assuming the value of n_2 from Ref. [8], our measurement yields an estimate of $A_{eff} \approx 2.6 \pm 0.3$ μm^2, in excellent agreement with the numerical prediction (Fig. 2(a) - inset). For the second fiber, which has a core of 2.0 μm, we measured a nonlinear coefficient of 440 ± 60 W^{-1} km^{-1}. Compared with the first fiber, the lower nonlinearity of the second fiber is commensurate with the larger core size and thus larger effective mode area of this fiber. However, it should be noted that more than one transverse mode could be supported in the larger-core second fiber.

The zero dispersion wavelength of bulk SF57 is ~1970 nm. However, numerical predictions have shown that the extreme waveguide properties of the particular design have significantly altered the overall dispersion characteristics of the fibers (Fig. 2(b)). For the first fiber with 1.7 μm core, the zero dispersion wavelength is shifted to 1280 nm, whereas the dispersion at 1550 nm is +88 ps/nm/km. The fact that fiber dispersion is anomalous at these wavelengths enables us to investigate higher order soliton effects in this fiber [4].

4. Raman soliton experiments

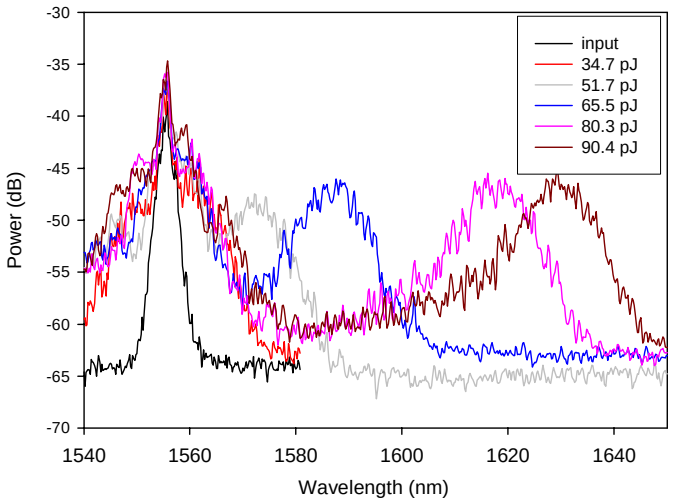

Fig. 3. Traces of the Raman soliton spectra at the output of the HF for various levels of input pulse energies.

To demonstrate self-frequency shifting of soliton pulses we used the first fiber. The small core size of this fiber ensured effective single-mode guidance, anomalous fiber dispersion and the highest effective nonlinearity of the fibers we fabricated. The pulse source for our experiments was an actively mode-locked erbium fiber ring laser operating at 1556 nm. We could choose the repetition rate of the source to be either 1.25 or 2.5 GHz by externally gating down the pulses by means of an electro-optic modulator. The pulses were amplified using an erbium doped fiber amplifier and free-space coupled onto the fiber, taking care that the signal polarization was aligned on the primary birefringence axis of the fiber. The maximum average power launched into the fiber was 110 mW. We first used a fiber length of 2.2 m which, when the fiber loss of ~9 dB/m is taken into account, corresponds to an effective length of 0.47 m. The repetition rate of the source was set at 1.25 GHz, and the pulse duration at the input of the

#3473 - $15.00 US Received December 01, 2003; Revised December 12, 2003

fiber was ~2.0 ps. For an input pulse energy of ~88 pJ (corresponding to the maximum average power) we could observe a wavelength shift of the original pulses by ~80 nm. The 3 dB bandwidth of the wavelength shifted signal was ~13 nm, which corresponds to the bandwidth of ~215 fs transform-limited solitons. This shift was dependent on the energy of the input pulses, confirming self-frequency-shifting of the soliton pulses, an effect which requires anomalous dispersion for its manifestation. In order to demonstrate this point, we measured the spectrum of the output signal as we varied the power launched into the fiber. These measurements are shown in Fig. 3. However, we were not able to autocorrelate these pulses. We believe that this was due to the fact that, since the fiber used was significantly longer that the effective nonlinear interaction length, the pulses lost their soliton nature early on in the fiber and broadened out due to dispersion thereby reducing the peak power at the end of the fiber below that required for the autocorrelation measurement.

We therefore cut the fiber down to a length of 0.37 m. The effective length in this case was just 0.26 m. We also changed the repetition rate of the source to 2.5 GHz and measured a pulse width of ~1.5 ps at the input of the HF. For full power at the amplifier, the energy of the input pulses was ~45 pJ. For this power level we obtained a wavelength shift of ~45 nm (Fig. 4(a)). This is close to the shift obtained with the longer piece of fiber for similar pulse energies, a fact which confirms our previous assumption about the effect that the extra length of fiber had on the pulses. The spectral bandwidth of the wavelength-shifted pulses was 21.2 nm. Indeed, in this instance we could readily measure the autocorrelation of the pulses, which showed a pulse width of ~190 fs (Fig. 4(b)). The time-bandwidth product was therefore 0.48, indicating almost transform-limited pulses.

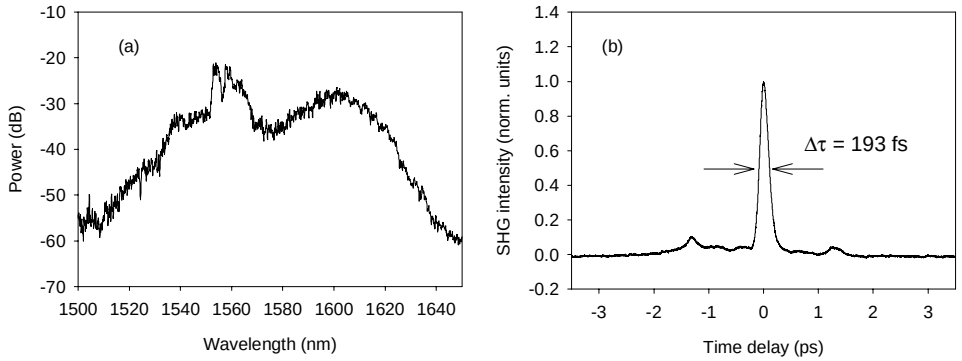

Fig. 4. (a) Optical spectrum and (b) autocorrelation trace of the 2.5 GHz wavelength-shifted pulses measured at the output of the 0.37m of SF57 HF.

5. Conclusions

This paper presents progress on the fabrication, characterization and application of lead silicate HFs. Fibers with both extremely high nonlinearity and a low loss at 1550 nm have been demonstrated. We used a HF with effective nonlinearity of ~640 $W^{-1}km^{-1}$ to generate Raman solitons from a telecommunications laser. Wavelength shifts of up to 80 nm and a 10-fold pulse compression in 0.37 m of this fiber were observed.

Further work on improving on the design of such fibers as well as developing techniques that will allow more efficient coupling is currently under way. Nevertheless, we envisage that the combination of high nonlinearity provided by compound glasses and the flexibility offered by microstructured fiber technology for engineering the fiber parameters should lead to the development of truly practical, compact nonlinear fiber devices.

#3473 - $15.00 US Received December 01, 2003; Revised December 12, 2003