Bismuth glass holey fibers with high nonlinearity

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

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

Abstract: We report on the progress of bismuth oxide glass holey fibers for nonlinear device applications. The use of micron-scale core diameters has resulted in a very high nonlinearity of 1100 W^{-1} km^{-1} at 1550 nm. The nonlinear performance of the fibers is evaluated in terms of a newly introduced figure-of-merit for nonlinear device applications. Anomalous dispersion at 1550 nm has been predicted and experimentally confirmed by soliton self-frequency shifting. In addition, we demonstrate the fusion-splicing of a bismuth holey fiber to silica fibers, which has resulted in reduced coupling loss and robust single mode guiding at 1550 nm.

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.

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1. Introduction

Highly nonlinear holey fibers (HFs) have attracted growing attention in recent years because they promise the development of compact nonlinear devices operating at low powers [1]. The wavelength-scale features and design flexibility of HFs allow a broader range of optical properties than is possible in conventional fibers. In particular, the effective fiber nonlinearity and the sign and magnitude of the group velocity dispersion can be tailored in small-core HFs. The effective fiber nonlinearity at a given wavelength (λ) is defined as [2]

$$\gamma = (2\pi/\lambda) \times (n_2 / A_{\mathrm{eff}}). \quad (1)$$

Thus, the effective fiber nonlinearity can be tailored via the nonlinear refractive index, n_2 of the material and the effective mode area, A_{eff}, which is determined by the HF design. The combination of small hole-to-hole-pitch and large air-filling fraction results in tight mode confinement due to the high glass/air index contrast and thus in a small effective mode area. For pure silica HFs, the lower limit for A_{eff} is 1.5 μm^2, which corresponds to an effective nonlinearity of γ~70 W^{-1} km^{-1} [3] (70 times the nonlinearity of conventional fibers).

The use of compound glasses with higher nonlinear refractive indices allows a further drastic increase of the fiber nonlinearity. To date, highly nonlinear compound glass HFs have been demonstrated for lead silicate [4,5], tellurite [6] and bismuth silicate [7] glasses. The highest nonlinearity of a HF achieved previously is 675 W^{-1} km^{-1} for a HF made from tellurite glass [6]. The highest nonlinearity reported for a conventional fiber made from a bismuth borate glass is 1360 W^{-1} km^{-1} [8]. Although this is significantly higher than results reported in HFs to date, note that the large normal fiber dispersion resulting from the large normal material dispersion of this material restricts the applicability of this fiber. In contrast, the novel waveguiding properties of HFs offer the possibility of overcoming the large normal material dispersion of high-index glasses. Indeed, lead silicate and bismuth silicate HFs with near-zero or anomalous dispersion at 1550 nm have been demonstrated [4,5,9].

In this paper, we describe progress in the development of low-loss high-nonlinearity HFs based on bismuth-oxide glass. In contrast to other highly nonlinear compound glasses, bismuth glasses do not contain toxic elements such as Pb, As, Se, Te [10], and fibers made from bismuth silicate glass can be fusion-spliced to silica fibers [11], which allows easy integration with silica-based systems. In addition, bismuth silicate glass exhibits good mechanical, chemical and thermal stability, which allows low-loss fiber fabrication as demonstrated for a nonlinear fiber [12]. The nonlinear performance of the fibers is evaluated and compared with other highly nonlinear fibers using figure-of-merit considerations. We demonstrate a HF with a very high nonlinearity of 1100 W^{-1} km^{-1} and with anomalous dispersion at 1550 nm. In addition we report on soliton self-frequency shifting and fusion-splicing of bismuth HFs to silica fibers.

2. Fiber fabrication, structure and modal properties

The fibers were made from bismuth silicate glass developed at Asahi Glass Company. Due to the high bismuth content, the glass exhibits a high linear and nonlinear refractive index of 2.02 and 3.2×10^{-19} m^2/W at 1550 nm, respectively [12]. Note that the bismuth borate glass in [8] has higher indices due to higher bismuth content. The fabrication process followed three steps. First, structured preform and jacket tube were produced from bulk glass billets using the extrusion technique [13]. Then, the structured preform of about 16 mm diameter was reduced in scale on a fiber drawing tower to a cane of about 1.7 mm diameter. In the last step, the cane was inserted within the jacket tube, and this assembly was drawn to the final fiber of more than 100 m length with core diameters in the range 1.8–2.7 µm. The core diameter was adjusted during fiber drawing by appropriate choice of the external fiber diameter (130–210 µm). We produced a range of HFs from three individual preforms using this approach.

The dimensions of the structural features within the HFs were measured using scanning electron microscopy (SEM). The core is optically isolated from the outer solid glass region by three 5-8 µm long and ~250 nm thick supporting struts (Fig. 1(a)), and thus confinement loss is negligible [3]. To derive a useful core diameter from the triangular core shape, we define as the core diameter the diameter of the circle that has the same area as the regular triangle that fits just inside the core region. The modal properties at 1550 nm were calculated for the HF #1 with 2.7 µm core diameter using the SEM image of the fiber and a commercial beam propagation package (BeamPROP by RSoft Design Group). The predicted mode profile has a triangular shape (Fig. 1(b)) and the predicted effective mode area is 3.1 µm^2. Note that simulations demonstrate that this fiber is not strictly single-mode. Indeed, the V-number of an air-suspended rod of bismuth glass equivalent to this HF is equal to ~10 and also free-space coupling experiments revealed that the fiber guided more than one mode. Simulations show that core sizes <1 µm would be required for this fiber type to be strictly single-mode. However, effectively single-mode guidance has been observed for the fiber with 1.8 µm core.

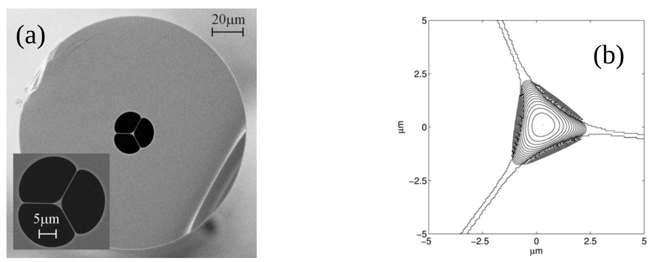

Fig. 1. (a) SEM image of HF #3 with 2.1 µm core and (b) predicted mode profile superimposed on the index profile of HF #1 with 2.7 µm core.

Modeling of idealized HFs with circular air holes arranged on a hexagonal lattice has shown that the fiber dispersion can be anomalous when sufficiently large air-filling fraction and small core size are used. For example, when the core size is 2.4 µm and the air-filling fraction is 60%, we calculated anomalous dispersion of +40 ps/nm/km at 1550 nm. Note that the material dispersion is –107 ps/nm/km, which demonstrates that the air/glass microstructure allows the high normal material dispersion of the bismuth glass to be overcome. We anticipate anomalous dispersion for the HFs described in this paper, since these fibers have similar core sizes but even larger air-filling fractions than the modeled fibers.

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 losses of the HFs (2.7–4.7 dB/m) (Fig. 2(a)) are higher than the loss of a corresponding unstructured extruded fiber (1.6 dB/m). Since the modal field overlaps with the holes within the HF (Fig. 1(b)), one likely cause of this additional loss is scattering due to surface imperfections (roughness and contamination) at the air/glass interface around the core. For each preform, the fiber loss increases with decreasing core size, which is consistent with the predictions that the impact of surface imperfections becomes more pronounced as the core size decreases [14]. The lower losses of HFs #2 and #3 are attributed to a lower degree of surface contamination resulting from ultrasonic cleaning of the preforms prior to caning. This demonstrates that further improvement in the surface quality is a promising route to decrease the losses of HFs. In addition, the use of dehydrated glass with lower bulk loss due to lower OH content (0.5 dB/m for an unstructured extruded fiber) promises the fabrication of bismuth glass HFs with losses lower than 1 dB/m.

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The measurement of the effective nonlinearity and mode area at 1550 nm was based on measurement of the nonlinear phase shift induced through self-phase modulation [15]. In Fig. 2(b), the nonlinear phase shift measured for the HF #3 with 1.8 μm core diameter is plotted as a function of the input power. The nonlinear coefficient γ was determined from the slope of the linear fit and taking into account the effective length of the test fiber. Depending on the core size (2.7-1.8 μm), we measured effective nonlinearities in the range of 460-1100 W^{-1} km^{-1} (Fig. 2(c)). To our knowledge, the effective nonlinearity of 1100 W^{-1} km^{-1} is the highest value achieved in a HF to date. It is almost two times higher than the nonlinearity attained recently in a tellurite HF [6]. Given the nonlinear refractive index of the bismuth glass [12], the measured γ value yields the effective mode area according to equation (1). For the HF #1 with 2.7 μm core, the A_{eff} value of 2.8±0.3 μm^2 derived from the measured γ value of 460±50 W^{-1} km^{-1} is in good agreement with the predicted A_{eff} value of 3.1 μm^2, which demonstrates the reliability of our measurement of the effective nonlinear coefficient.

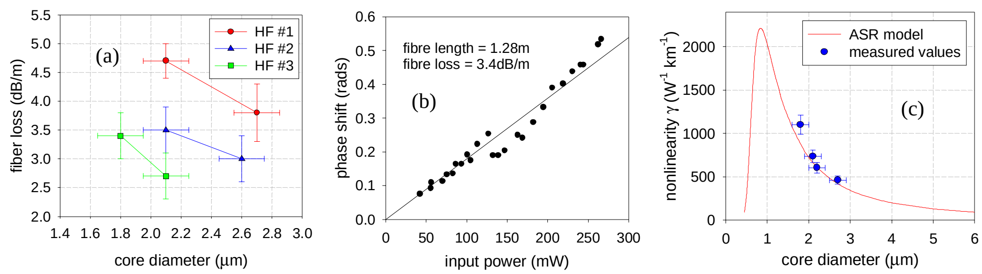

Fig. 2 (a) Measured propagation loss of the HFs made from three individual preforms, (b) measured nonlinear phase shift as a function of input power yielding $\gamma = 1100$ W^{-1} km^{-1} from the slope of the linear fit for HF #3 with 1.8 μm core, and (c) calculated nonlinearity for a bismuth glass air-suspended rod and measured fiber nonlinearities.

The impact of the core size on the effective fiber nonlinearity was explored by modeling an air-suspended rod (ASR) of bismuth glass, which represents the fundamental limit in the mode area / nonlinearity that can be achieved in an air/glass microstructured fiber made from this material. For a given core diameter, the measured γ values are in good agreement with the γ values predicted by the ASR model (Fig. 2(c)). This demonstrates that the simplified ASR model is a reliable approach to estimate the nonlinearity that can be achieved by our HF geometry. The ASR model predicts that the fiber nonlinearity can be enhanced drastically by decreasing the core diameter (Fig. 2(c)). The ultimate limit is 2200 W^{-1} km^{-1} for a 0.8 μm core.

3. Figure-of-merit for nonlinear performance

Based on their high effective nonlinearities, the small-core HFs described in this paper are aimed at compact nonlinear devices operating at low input powers. To evaluate the nonlinear performance of our HFs, we have derived figure-of-merits (FOMs) based on the required input power, P_{in}, to achieve a certain nonlinear phase shift, $\Delta\varphi$, [15]

$$\Delta\varphi / (2\, P_{in}) = \gamma \times L_{eff} \quad , \tag{2}$$

where L_{eff} is the effective fiber length, which is determined by the propagation loss, α, and the physical length, L, of the actual fiber [2].

$$L_{eff} = [1 - \exp(-\alpha \times L)] / \alpha \tag{3}$$

Thus, the nonlinear performance, $\Delta\varphi / (2\, P_{in})$, depends on both effective nonlinear coefficient and propagation loss. For optimal performance, i.e. large phase shift and/or small input power, both effective fiber length and nonlinearity should be as large as possible. The maximum effective fiber length is the reciprocal of the propagation loss, $L_{eff,max} = 1/\alpha$, and thus the term γ/α describes the FOM when using long fiber lengths. However, short fiber lengths are desirable to allow the realization of compact devices, and thus the term γ/α is not an appropriate FOM for such devices. To derive a FOM for this case, we choose to fix the real fiber length to 1m, which is a reasonable length for compact fiber devices, and use the effective fiber length for 1m real fiber length, $L_{eff,1m}$, in equation (2). Thus, the term, $\gamma \times L_{eff,1m}$, serves as a reasonable FOM for fibers aimed at compact nonlinear devices.

Table 1. Fiber loss, effective nonlinear coefficient γ and effective fiber lengths at 1550 nm for highly nonlinear dispersion-shifted silica fiber (HN-DSF); for silica, lead silicate (SF57) and bismuth glass HFs and for conventional fibers (CFs) from bismuth glasses.

fiber	**fiber loss (dB/m)**	**γ (W^{-1} km^{-1})**	**$L_{eff,max}$ (m)**	**$\gamma \times L_{eff,max}$ = γ/α (W^{-1})**	**$L_{eff,1m}$ (m)**	**$\gamma \times L_{eff,1m}$ (10^{-3} W^{-1})**
silica HN-DSF [16]	0.0005	20	8680	174	1.00	20
silica HF [17]	0.19	70	23	1.6	0.99	70
tellurite HF [6]	0.4	675	11	7.4	0.96	640
bismuth CF [12]	0.8	64	5.4	0.3	0.91	60
bismuth* CF [8]	1.9	1360	2.3	3.1	0.81	1100
bismuth HF#3	2.8	735	1.6	1.1	0.74	540
bismuth HF#3	3.4	1100	1.3	1.4	0.69	760
SF57 HF [5]	2.6	640	1.7	1.1	0.75	480
theoretical limit for bismuth silicate HF	1.0	2200	4.3	9.6	0.89	1970

* The bismuth borate glass of this fiber has a ~3 times higher nonlinear refractive index than the bismuth silicate glass used for our HFs and for the CF with nonlinear coefficient of 64 W^{-1} km^{-1}.

In Table 1, the FOMs for nonlinear performance of highly nonlinear bismuth HFs are compared with other nonlinear fibers. The silica state-of-the-art highly nonlinear dispersion-shifted fiber (HN-DSF) shows the highest γ/α FOM despite lowest nonlinearity due to the very low propagation loss. However, note that for the same nonlinear performance a much longer HN-DSF is required than for the other nonlinear fibers. The tellurite HF demonstrates the highest γ/α among the HFs due to both low loss and high nonlinearity. The conventional fiber made from bismuth borate glass (see footnote of Table 1) has a higher γ/α value than the bismuth HFs produced to date due to the very high nonlinear refractive index of this glass. As a result of their clearly higher losses, all the bismuth and SF57 HFs produced so far have lower γ/α values than the tellurite and silica HF. However, note that in principle both SF57 and bismuth glass HFs can have clearly higher γ/α values when low-loss fibers near the theoretical limit for the nonlinearity can be produced. The $\gamma \times L_{eff,1m}$ FOM increases in proportion to the nonlinear coefficient γ, which demonstrates that the propagation loss of the fibers considered here has only small impact on the nonlinear performance due to the short fiber length.

4. Soliton self-frequency shifting and splicing

To test the anomalous dispersion of the HFs produced, we have experimentally studied the self-phase modulation (SPM) spectra of soliton pulses (~2.0 ps, 1556 nm, 9.95 GHz repetition rate) from a mode-locked erbium fiber amplifier that were free-space coupled to a short piece (0.53m) of the 1.8 µm core HF #3 with highest nonlinearity. The main feature of the optical spectra obtained at the output of the fiber (Fig. 3(a)) is a wavelength shift of the original signal, which increases as the energy of the input pulses is increased, becoming as high as 40 nm for a moderate input pulse energy of 18 pJ. The shapes of these SPM-broadened spectra suggest the presence of higher order soliton effects in the form of soliton self-frequency shifting, the manifestation of which requires anomalously dispersive media.

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To make practical fiber-connectorized devices, splicing of nonlinear HFs to silica fibers is important. For the first time, we have spliced a compound glass HF to a silica SMF28 patchcord using a conventional mechanical cleaver and fusion splicer [9]. We used the bismuth HF #2 with 2.6 µm core. To reduce the overall mode-mismatch loss, two intermediate fiber buffer stages were used. Due to the much lower melting temperature of the bismuth glass relative to silica glass, very small values for the fusion time and current were used. The splices achieved were mechanically strong, especially with respect to applied strain in the axial direction (Fig. 3(b)). In order to reduce the losses due to mode mismatch we employed two conventional small-core buffer fiber 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 than those achieved by butt-coupling to the bismuth HF. Mode mismatch and Fresnel reflections accounted for 4.0 dB of the total loss. The introduction of an additional silica HF based buffer stage should help to considerably further reduce the mode-mismatch. 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 fiber output during free-space coupling disappeared after splicing the fiber. An IR image of the far end of the connectorized HF, when laser pulses at 1558 nm were launched into the fiber, showed that only the fundamental mode was excited (Fig. 3(c)). The image also demonstrates that the fundamental mode of the HF has a triangular mode shape, in agreement with the predicted mode profile.

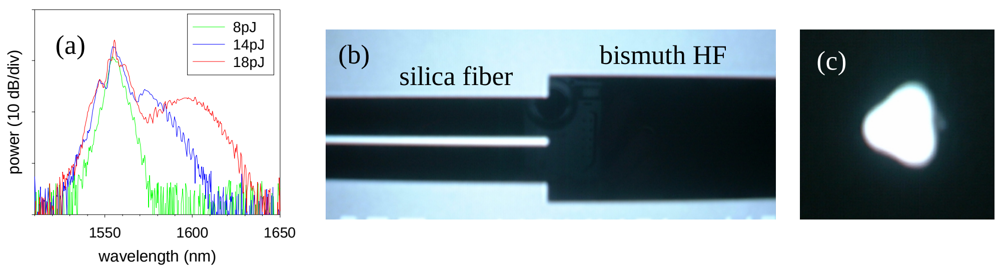

Fig. 3 (a) Raman soliton spectra at the output of 53cm of the 1.8 µm core HF with γ=1100 W^{-1} km^{-1} for different input pulse energies, (b) optical microscope image of bismuth HF to silica fiber splice and (c) IR image of the near field pattern of the connectorized HF.

5. Conclusions

We have produced bismuth glass HFs with <3 dB/m propagation loss and very high nonlinearity up to $\gamma = 1100\ W^{-1}\ km^{-1}$. FOM considerations have revealed that the bismuth HFs offer better performance in compact nonlinear devices than highly nonlinear silica fibers due to their clearly larger effective nonlinearities, which allows to minimize the required operating power. The higher loss of the bismuth HFs compared with silica HFs can be readily tolerated when only short fiber lengths <1 m are used. The nonlinearity can be enhanced further by decreasing the core size or using bismuth glasses with higher nonlinearities such as the bismuth borate glass with 3 times higher nonlinear index than the bismuth silicate glass used in this work. Future work is necessary to develop optimized methods to minimize splicing and coupling losses of highly nonlinear fibers with very small effective mode areas. Improvement in the surface roughness and contamination of HF preforms is anticipated to decrease the fiber losses even for small-core HFs. Both higher nonlinearities and lower losses together with progress in the splicing of highly nonlinear HFs to silica fibers should ultimately result in practical nonlinear devices using very short fiber lengths and operating at low powers.

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