

Non-silica highly nonlinear holey fibers for telecommunications applications

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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 $70 \text{ W}^{-1}\text{km}^{-1}$ [5,9]. Note for comparison, that the typical value for standard telecommunications fibers is $1 \text{ W}^{-1}\text{km}^{-1}$.

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 1.1–2.1 μm 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 6–8 μm . Below we compare the properties of small core HF's made of two different soft glasses, namely a commercial lead-silicate Schott glass (SF57) or a bismuth-oxide glass provided by Asahi Glass Company.

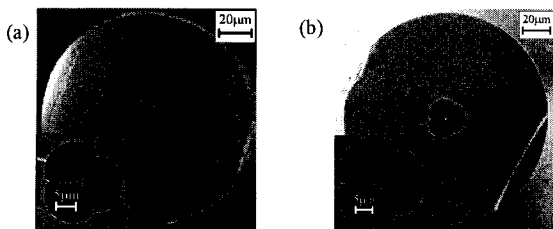


Fig. 1: SEM images of HF cross section for (a) lead-silicate and (b) bismuth-oxide fiber.

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 HF's, a 2.1 μm core fiber exhibited a loss of 2.7dB/m, while a fiber with a smaller core of 1.8 μm had a higher loss of 3.4dB/m. With regard to the lead-silicate HF's, a loss of 2.3dB/m was measured for a fiber with a core diameter as low as 1.1 μm , and 2.0dB/m for a 1.4 μm 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 HF's 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 HF's 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 HF's 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 HF's. 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 HF's (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 HF's 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 HF's 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 $\sim 1100\text{W}^{-1}\text{km}^{-1}$ for the case of the 1.8 μm core bismuth-oxide HF and $\sim 1860\text{W}^{-1}\text{km}^{-1}$ for the 1.1 μm core lead-silicate HF. To our knowledge, the effective nonlinearity of $1860\text{W}^{-1}\text{km}^{-1}$ is the highest value achieved in a HF to date.

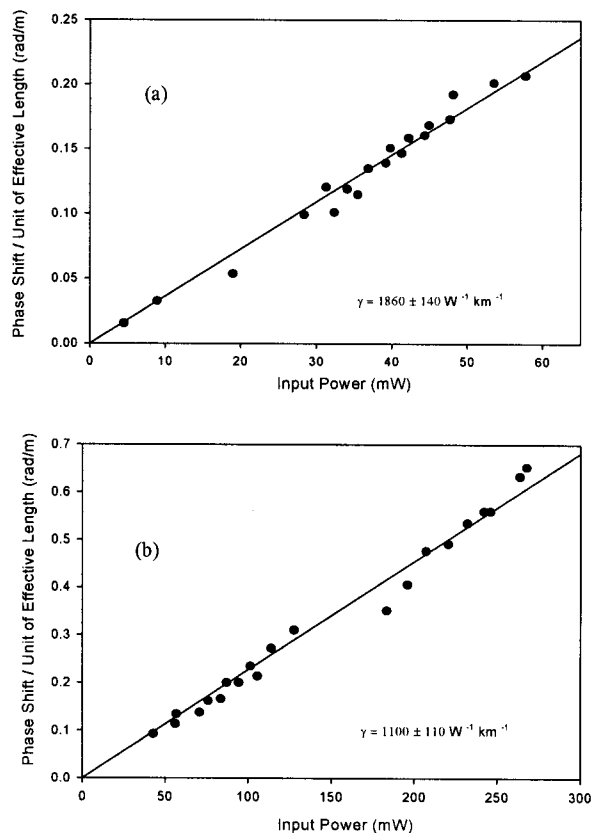


Fig. 2: Nonlinear Phase Shift per unit of effective length for the (a) 1.1 μm core lead silicate HF and the (b) 1.8 μm core bismuth HF

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 HF's 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 $\leq 2\text{dB/m}$ 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 HF's can outweigh the decrease of the effective fiber length caused by their higher propagation losses compared to standard optical fibers. Thus, compound glass HF's 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 HF's 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 HF's 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.

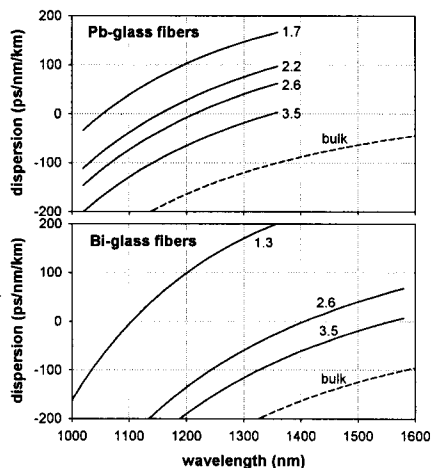


Fig. 3. Dispersion of bulk glass and predicted dispersion for HF's with different core diameters (numbers in μm in the graph).

The numerical simulations predict that, for a specified wavelength, the dispersion of both lead-silicate and bismuth-oxide HF's 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 ($\sim 2.0\text{ps}$), 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 1.8 μm 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 $\sim 40\text{nm}$ for a moderate input pulse energy of $\sim 18\text{pJ}$. 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.

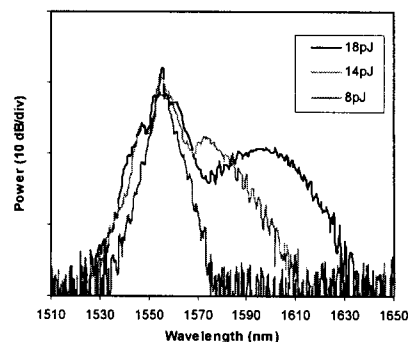


Fig. 4. The Raman soliton spectra at the output of 53cm of the 1.4 μm enclosed core diameter, bismuth-oxide HF for different levels of input pulse energy

IV. CONCLUSIONS

Small core HF's 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 – 2.1 μm for the bismuth-oxide glass and 1.1 – 1.4 μm 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 HF's 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 HF's for achieving a very high nonlinearity per unit length of fiber has been clearly demonstrated. In particular, a 1.8 μm core HF made from

bismuth-oxide based glass exhibited a nonlinearity of about $1100\text{W}^{-1}\text{km}^{-1}$, while a $1.1\mu\text{m}$ core lead-silicate fiber had a record-high nonlinearity of $\sim 1860\text{W}^{-1}\text{km}^{-1}$. We believe that compound glass HF's provide a real prospect towards the realization of sub-meter long nonlinear devices operating at milliwatts of optical power.

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