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High Nonlinearity Holey Fibers: Design, Fabrication and Applications

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Abstract

We describe our recent progress in the development of next-generation small-core holey fibers (HFs) with unique dispersive and nonlinear properties. We report the use of Genetic Algorithms to optimize the dispersion characteristics of silica-based HFs, and report progress in soft-glass HF fabrication which has resulted in fibers with record values of nonlinearity.

The field of HF technology has enjoyed tremendous progress over recent years spurred on by an ever increasing demand for specialty fibers and devices for a growing range of applications. The main advantage of HFs lies in the fact that the fundamental guidance mechanism allows for extremely flexible engineering of the waveguide properties through appropriate design of the solid core and the air-filled cladding. At the same time HF technology eliminates the requirement for a two-material core-clad system for fiber fabrication, thereby allowing the use of glasses which would otherwise present major challenges for conventional fiber manufacturing processes.

High nonlinearity per unit length in HFs ($\gamma = 2\pi n_2/\lambda A_{eff}$) can most readily be achieved by ensuring a small effective area A_{eff}. By incorporating a large air-fill fraction (d/Λ) in the HF cladding, and using a small core size, it is possible to achieve extremely tight mode confinement (here d is the hole size and Λ the hole spacing as used to specify uniform hexagonally stacked HF structures). This approach can be used to produce fibers with nonlinearities per unit length approaching the maximum theoretical value possible for the host material [1]. Moreover, due to the strong wavelength dependence of the effective cladding index in this design regime, it is possible to control the overall dispersion characteristics of the fiber over an extended wavelength range – allowing for example anomalous dispersion at wavelengths that would otherwise be precluded by the material dispersion of the glass, or multiple zero dispersion wavelengths within technologically important spectral regions. A further obvious means to enhance the nonlinearity is to use materials with an intrinsically higher value of n_2.

The majority of work to date has focused on developing silica HFs and many of the basic theoretical predictions concerning control of nonlinear and dispersive fiber characteristics have been experimentally demonstrated in this material system. Early experiments demonstrated the high values of nonlinearity that are possible, and showed that it is possible to shift the zero dispersion wavelength for silica HFs into the near IR/visible regions of the spectrum. This is technologically significant since it allows supercontinuum (SC) generation over extremely broad bandwidths at very modest pump powers using convenient pump sources such as Ti: Sapphire laser [2]. SC sources based on this approach are now finding widespread use in applications such as metrology and Optical Coherence Tomography (OCT). From the perspective of telecommunications at 1550 nm, early work focused on exploiting the high effective nonlinearity of HFs to reduce the power-length product of fiber based nonlinear devices including various optical switches [3], wavelength converters [4,] and Raman based devices [5]. However, for many such applications dispersion is often a major issue and, whilst dispersion-shifted and dispersion-flattened HF variants have been demonstrated (see e.g. [6]), it is still not clear whether silica HF technology can offer improved performance relative to the highly optimized conventional dispersion-shifted high nonlinearity fibers that are already commercially available. The focus in this area is thus to establish whether HFs with improved combinations of nonlinearity, dispersion and dispersion slope characteristics can be designed and fabricated.

Recently we have begun to theoretically explore the possibility of using Genetic Algorithm (GA) approaches to search for and optimize complex HF designs with interesting combinations of nonlinear and dispersive properties, and to establish the fabrication tolerances associated with these designs. As means of an example we illustrate use of the technique to optimize fiber designs providing ultra-flat dispersion at telecommunication wavelengths. We used the GA to minimize the integrated chromatic dispersion value over the wavelength range 1500nm to 1600 nm for various generic hole structures such as the one shown inset in Fig.1 (which is characterized by 6 structural parameters). We restricted the parameter space to only those designs offering relatively high effective nonlinearity. The results we obtained demonstrate that ultra-flat dispersion profiles can be achieved, whilst maintaining a reasonably high effective nonlinearity (γ=10.4 $W^{-1}km^{-1}$ for the case shown in Fig.1). Average dispersion slopes of less than $3\cdot10^{-3}$ ps/nm^2/km were achieved. Our tolerance analysis showed that for this design a precision of less than 1% in hole size and position are necessary to control the dispersion characteristics with suitable accuracy. The GA approach represents a powerful design tool and can be used to optimize the design of many HF types. Further examples will be presented at the conference.

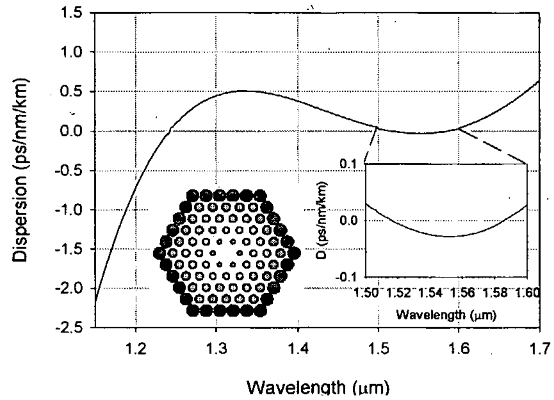

Fig.1 Calculated dispersion profile for the radially chirped pure-silica HF shown in the Inset, optimized using the GA. (Λ=1.516µm, d_1, $d_2..d_5$=0.317, 0.484, 0.571, 0.632, 0.667 µm).

Rapid progress is also being made towards making HFs from compound glasses offering values of n_2 that are 1-2 orders of magnitude higher than that of silica, and has resulted in the production of fibers with record levels of nonlinearity. Examples of glasses currently under investigation include chalcogenides, lead silicates and heavy metal oxides such as tellurite and Bismuth oxide based glasses. To date the record nonlinearity in a HF at 1550 nm is 1860 $W^{-1}km^{-1}$ (Fig.2) and which was achieved using lead silicate glass. The preform used to make this fiber was fabricated using an extrusion process, which is well suited to compound glasses due to their low melting temperatures. The preform was then drawn into a cane and in a third stage into a fiber with a core diameter of ~1.0 µm. The fiber cross-section is shown in Fig.2 (inset). The core is supported by three long thin struts, providing a high NA that approaches that of an air-suspended rod. The fiber exhibited robust single-mode operation and a loss of 2.1 dB/m@1.06 µm and 2.3 dB/m@1.55 µm. The zero-dispersion wavelength of this fiber was calculated to be around 900 nm. However, by increasing slightly the core diameter we were able to shift the zero-dispersion wavelength to ~1 µm making it suitable for efficient SC pumping with Nd^{3+}, and Yb^{3+} based lasers. This was later verified in SC experiments at these wavelengths which yielded spectral bandwidth in excess of 600 nm for input pulse energies of just a few tens of pJ. These fibers are extremely attractive for Yb^{3+}-fiber laser pumped SC generation [7].

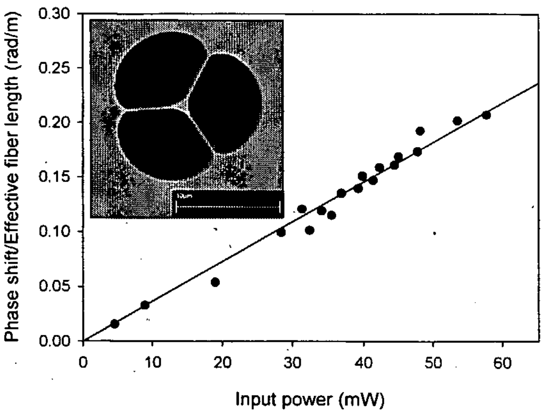

Fig.2 Measurement of the nonlinear phase shift as a function of power for the lead silicate fiber, an SEM image of which is shown in the Inset.

In conclusion, small-core HFs represent extremely interesting and flexible media for nonlinear optics. The use of new design tools and algorithms, coupled with the use of new materials and fabrication approaches, promises great scope for compact, efficient NL devices capable of operating within a broad range of wavelengths in the visible and NIR.

References

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