Nonlinear pulse compression, dispersion compensation, and soliton propagation in holey fiber at 1 μm

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Abstract: We fabricated a single mode, polarization maintaining, highly non-linear, 125 μm silica jacketed, holey fiber with anomalous dispersion at 1.06 μm. Nonlinear pulse compression and soliton propagation are demonstrated (1.06 μm, Yb³⁺ source) with just 1 mW average power.

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Soliton applications such as nonlinear pulse compression, and propagation without pulse broadening, are widely used at wavelengths above 1.3 μm, where standard single mode fiber has anomalous dispersion [1]. Sources of ultra short pulses operating at 1 μm have wide application in spectroscopy and materials processing, but until now, soliton applications have not been accessible because standard single mode fiber does not have anomalous dispersion below 1.3 μm. Holey fiber is a rapidly emerging fiber technology which, because of the increased range of fabrication parameters compared to standard fibers, can be designed and fabricated with dispersion and non-linear properties beyond those previously possible [2,3]. Indeed, holey fiber with anomalous dispersion at 850 nm has recently been demonstrated to support soliton propagation over short distances (~3 soliton periods) in a multimode fiber with 2 μm core diameter [4], and in another demonstration, visible continuum generation was produced in a single mode fiber at 800 nm in a 2 μm core diameter fiber [5]. Here we report fabrication of a pure silica holey fiber with a 1.5 μm diameter core, which has anomalous dispersion at 1.06 μm, and exceptional nonlinear characteristics. At only 1 mW average power, it supports both soliton compression, and propagation over 20 soliton periods without broadening. With its robust handling properties, this fiber should be suitable for wide use in practical soliton applications at 1 μm.

Fig. 1. is a scanning electron micrograph showing the fiber structure. The holey region (fabricated using standard techniques [6]) provides average refractive index guiding in the solid core, and supports strictly single mode propagation at 1.06 μm. The small 1.5 μm diameter core (A_{eff} = 3 μm² at 1.06 μm), is approximately one quarter the diameter of that in a standard fiber [2]. This gives rise to the increased power densities and hence a high effective nonlinearity in this fiber [1]. The large air fill fraction results in the anomalous dispersion, and combined with the small core ensures that the fiber remains strictly single mode. The fiber is highly suitable for applications requiring polarization maintaining fiber, having a birefringent beat length of just 1.15mm at 1.06 μm. This birefringence arises from the combination of core asymmetry, high refractive index contrast and small scale structure. The 125 μm silica jacket, makes the fiber easy to handle, and allows for ready integration with conventional fiber technology.

Fig. 1. Scanning electron micrograph of the fiber showing the silica jacket and the holey fiber core.
For the experimental demonstration we used an in house Ytterbium (Yb$^{3+}$) stretch-pulse mode locked fiber laser source. Yb$^{3+}$ doped silica fibers represent an attractive medium for both the generation and amplification of ultrashort pulses, and we demonstrated the first short pulse Yb$^{3+}$ silica fiber oscillator in 1997 [7]. We have now developed a more practical and stable diode-pumped system that we will report elsewhere. By suitable selection of output port from the laser, the output pulses were gaussian, positively chirped, 2.4ps (compressible to 108 fs with external diffraction grating pair), ~60 pJ, at 54 MHz repetition rate (~3 mW average power). We achieved approximately 30% coupling efficiency into the holey fiber, giving a maximum transmitted pulse energy of ~20 pJ.

To analyze the effects of propagation in the fiber, we measured autocorrelations and spectra of the transmitted pulses. We noted that the spectra of the 20 pJ transmitted pulses was significantly distorted, indicating that non-linear processes have occurred; so in order to demonstrate the purely linear effect of anomalous dispersion, we also characterized ~1 pJ pulses, obtained by attenuating the input pulses with a neutral density filter. Fig. 2. shows a plot of the pulse FWHM vs. fiber length. Fig. 3 shows the autocorrelation and spectrum of the shortest transmitted pulses, with attenuation prior to launch (linear regime) and without attenuation (non-linear regime).

In the linear regime, the launched input pulse energy was attenuated to ~ 1pJ (peak power of compressed pulse ~ 6 W) such that the spectrum remained undistorted after propagation. The pulse duration steadily decreased to a minimum as the fiber was cut-back, until the fiber dispersion just compensated for the initial chirp. Shorter fiber lengths did not completely remove the chirp, so the measured pulse duration again increased. The minimum duration of 170 fs compares with 108 fs when we compressed the pulses with a grating pair; and by fitting the data [1] we estimate the dispersion of the fiber to be ~150 ps/(nm.km). We believe that this is the first direct demonstration of linear dispersion compensation in a holey fiber with anomalous dispersion at wavelengths less than 1.3 μm.

![Plot of transmitted pulse FWHM vs. fiber length](image)

In the non-linear regime, Fig. 2. clearly shows that we have demonstrated soliton propagation without temporal broadening over 2.6 m of fiber, which we calculated to be 20 soliton periods. The symmetric spectrum in Fig. 3.b) (propagation through 1m of fiber) indicates the effects of SPM, whereas the spectrum in Fig. 3.c) (propagation through 2m of fiber) shows a distinct peak at 1.075 μm, which is evidence of Raman scattering. The power levels (average power 1 mW, peak power 130 W) and short fiber lengths reflect the very high nonlinearity of this fiber, and accessibility of these non-linear effects for practical applications. The shortest compressed pulse has a duration of 60 fs, compared to 108fs when compressed purely linearly with a diffraction grating pair. Again, the exceptionally non-linear behavior of the fiber makes it suitable for practical uses of non-linear pulse compression.
In conclusion, we have fabricated a physically robust holey fiber that we demonstrate can support nonlinear pulse compression, dispersion compensation, and soliton propagation at 1 μm with only 1mW of launched power and in 2m of fiber. With such desirable dispersion and nonlinear properties in a robust fiber, it should for the first time be practical to investigate all-fiber based soliton oscillators, amplifiers, pulse compressors, and soliton propagation based on Yb$^{3+}$ and Nd$^{3+}$ rare earth doped fibers at 1.0 – 1.1 μm wavelengths. We have recently reported the first demonstration of soliton mode-locking at 1.03 μm in a holey fiber with Yb$^{3+}$ doped core, and we will be investigating soliton propagation at 1.06 μm in longer lengths of this fiber using amplified pulses from our Yb$^{3+}$ mode-locked fiber laser.

References: