# Soliton transmission and supercontinuum generation in holey fiber, using a diode pumped Ytterbium fiber source

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**Abstract:** We report linear dispersion compensation, soliton pulse formation, soliton compression, and ultra-broad supercontinuum generation in a holey fiber with anomalous dispersion at wavelengths above 800nm. The holey fiber was seeded with ultrashort pulses from a diode pumped, Ytterbium (Yb)-doped fiber source operating at 1.06 µm. The results highlight the compatibility of the rapidly developing holey fiber technology with short pulse Yb-doped fiber lasers for wide application.

**OCIS codes:**(060.5530) Pulse propagation and solitons, (060.4370) Nonlinear optics, fibers

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## 1. Introduction

The use of soliton effects such as nonlinear pulse compression, propagation, and the soliton self-frequency shift (SSFS) in optical fiber have been exploited in a variety of sources operating at wavelengths above 1.3 µm, most commonly using lasers based on erbium doped fiber which operate around 1550nm [1]. However it has not been possible to exploit soliton effects within sources operating in the visible and near infrared regions of the spectrum, since conventional single mode fibers display normal dispersion at wavelengths below 1.3 µm. Holey fiber technology, which allows for a far broader range of fabrication parameters compared to conventional doped fiber fabrication techniques, means that it is possible to design and make fibers with dispersion and non-linear properties outside of the previously accessible parameter ranges[2, 3]. Indeed, holey fiber with anomalous dispersion at wavelengths as short as 500 nm has recently been demonstrated[3], and similar fibers have been shown to be capable of supporting soliton propagation over a distance of ~3 soliton periods when seeded from a Ti:Sapphire laser operating at 800nm. In addition to soliton effects, both holey fibers and tapered standard fibers have been demonstrated to generate broadband supercontinuum light when pumped with short pulses at around 800nm [4, 5], which has enabled significant new developments in spectroscopy [6] and metrology [7]. To date, supercontinuum spectra have been reported spanning from below 300nm in the UV[8] to wavelengths beyond 1600nm.

Whilst the bulk Ti:Sapphire systems used to seed the initial demonstrations of soliton and supercontinuum effects in holey fiber are suitable for research, they are far from ideal if one wishes to develop practical sources based on holey fiber technology. However, over recent years a number of practical, diode-pumped ultrafast laser and amplifier systems based on Yb-doped fiber have been developed. In this letter, we demonstrate that these systems are capable of achieving the pulse durations and energies required to exploit the unusual nonlinear properties of holey fibers. For example, the inherent normal dispersion of conventional fibers around 1µm means that it has previously been necessary to use bulk elements such as gratings/prisms in these systems to provide the required dispersion compensation. Working towards the possibility of replacing these bulk elements with more compact fiber-based dispersion compensation, we present the first direct demonstration of linear dispersion compensation using holey fiber. We also present results showing soliton formation and compression, soliton propagation without temporal broadening over 60m of fiber (corresponding to ~475 soliton periods), and SSFS wavelength tuning (1.06 - 1.1 µm). All of these experiments were seeded using the output from a practical, diode pumped, stretched-pulse, Yb-doped fiber laser operating at ~1.06µm. Finally, by amplifying the laser seed pulses using diode-pumped, Yb-doped fiber amplifiers, we generated ultra broadband visible supercontinuum in small core holey fiber.

## 2. Experimental setup and results

A scanning electron microgram (SEM) image of the robust, jacketed, polarization-maintaining holey fiber used in our experiments is shown inset to Fig. 1. The fiber has a small ~1.6µm diameter core with an effective mode area ($A_{eff}$) ~3µm$^2$ at $\lambda$=1.06µm, approximately 20 times smaller than for conventional fibers at this wavelength. The small core also gives rise to the increased power densities and hence high effective nonlinearity of this fiber [1]. The dispersion of the fiber also differs from that of standard fiber because the small diameter core together with the large air fill fraction in the cladding results in an exceptionally strong (anomalous) waveguide contribution to the dispersion. This can dominate the (normal) material dispersion of silica to provide fiber with overall anomalous dispersion at wavelengths below 1.3 µm where all conventional fibers have normal dispersion. The fiber in Fig.1 has a zero dispersion wavelength ($\lambda_0$) of ~800nm (predicted with a full vector numerical model[2], using the SEM photograph of the fiber to define the transverse refractive index distribution). The high (measured) transmission loss of ~1dB/m is principally due to confinement loss, and can be greatly reduced by adding more rings of holey structure around the core. This was done to produce the fiber used for the supercontinuum demonstration reported in this paper, which had a much-reduced loss of 0.1dB/m, and similar fibers with losses as low as 0.01dB/m (at 1550nm) have been reported[11]. The fiber is rigorously single mode at wavelengths above 1µm, but will support higher order modes at shorter wavelengths. However, the confinement losses increase rapidly at shorter wavelengths, attenuating these higher order modes, so the fiber is effectively single mode down into the visible regions of the spectrum. The fiber is highly suitable for polarization maintaining applications, having a birefringence length of just 1.15mm at 1.06 µm wavelength (polarisation extinction ~21dB between fiber axes). This high birefringence arises from the combination of core asymmetry, high refractive index contrast and small-scale structure.

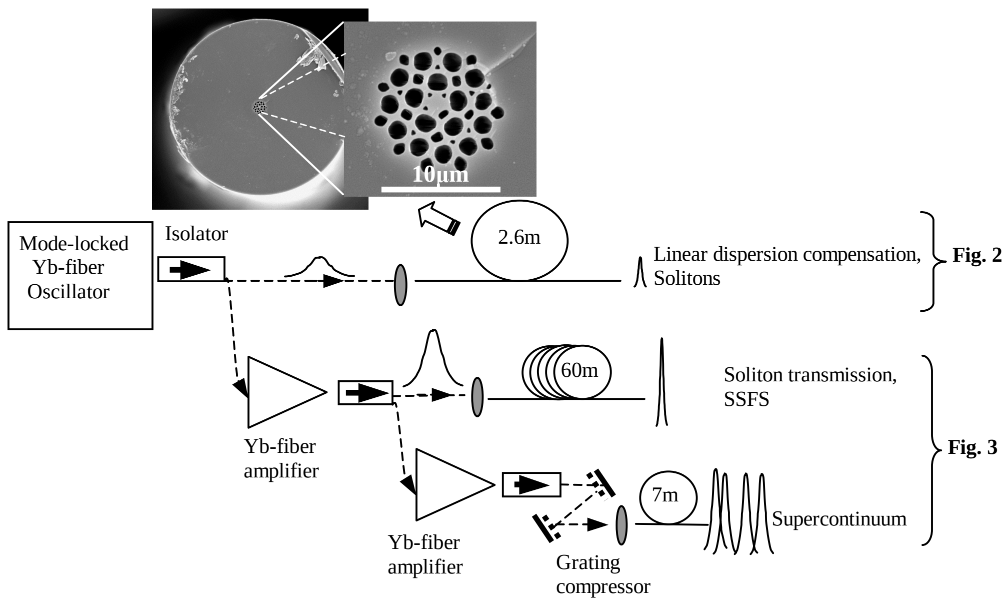


Fig.1. Experimental system configuration. Inset: SEM of holey fiber used for the pulse compression and preliminary soliton experiments.

### *2.1 Linear dispersion compensation and soliton formation*

The experimental setup of the mode-locked seed laser and launch arrangement are shown in Fig. 1. We used an Yb-doped, stretched pulse fiber laser that was developed in-house as our master oscillator [12]. For supercontinuum generation we amplified the pulses in diode-pumped Yb-doped fiber amplifiers. Mode-locked operation of the laser is based upon the stretched pulse principle[13] employing nonlinear polarisation rotation within the fiber as a fast saturable absorber mechanism. A semiconductor saturable absorber mirror (SESAM) is incorporated to ensure robust self-starting [14]. The laser is pumped with a telecommunications grade laser diode, which results in a highly reliable and stable oscillator. The measured amplitude noise is just ~0.05% (10Hz resolution bandwidth). The average laser output power was ~3 mW at a pulse repetition rate of 54 MHz (~60 pJ pulse energy). The laser produces positively chirped pulses at its output port with a FWHM duration of 2.4ps (see autocorrelation in Fig. 2.a), compressible down to ~110fs ($\Delta\nu\Delta\tau$~0.6) using a bulk grating pair.

Fig. 2. shows the results obtained by launching the ~2.4ps duration positively chirped Gaussian pulses directly from the laser into a length of the HF and recording the non-collinear second-harmonic-generation (SHG) autocorrelations and optical spectra of the transmitted pulses. We used a half wave plate at the launch to match the pulse polarisation to a principal axis of the highly birefringent fiber. Without taking this precaution, components of the pulses launched on to the orthogonal fiber axes were observed to walk-off temporally due to the difference in dispersion between the axes, complicating the interpretation of the experiments. We present data for two launched pulse energies: 1pJ, for which the propagation is close to linear over the propagation lengths considered, and 20 pJ, for which significant nonlinear effects become apparent. Starting with a fiber length of ~2.6m (estimated transmission loss ~2dB) we gradually cut back the fiber length to record the evolution of the pulses as a function of propagation distance.

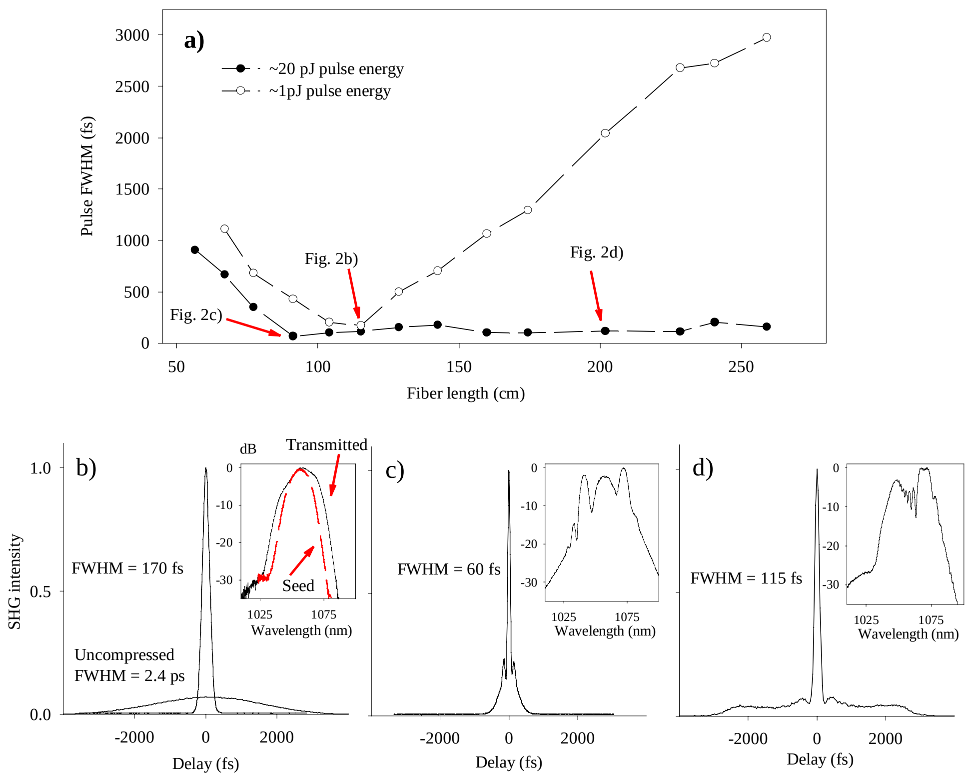


Fig.2. Results obtained launching pulses directly from the laser into 2.2 m length of holey fiber. a) Plot of transmitted pulse FWHM vs. fiber length. b)-d) Autocorrelation and inset spectra of pulses transmitted through holey fiber: b) linear regime (1pJ pulses), fiber length = 1.15 m c) non-linear regime (20pJ pulses), fiber length = 0.92 m , d)non-linear regime, Raman scattering, fiber length = 2.02m.

Fig. 2.a) shows a plot of the pulse FWHM vs. fiber length for pulses in both the linear (1pJ) and nonlinear (20 pJ) regime. As expected for linear compression of an initially chirped pulse, the 1pJ pulses are seen to initially compress, reach a minimum duration after ~1.2m,

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and then to broaden again. The linearity of the compression process is confirmed by the inset spectrum Fig. 2b) in which only a modest spectral broadening is observed at the point of maximum linear pulse compression. Compression by a factor of ~14 to a minimum duration of 170 fs is observed, with some higher order phase distortion remaining when compared with the minumum duration of 108fs obtained when we compressed the pulses with a grating pair. Fitting the data of Fig. 2a)[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 below 1.3 μm.

In the non-linear regime (20pJ pulses), Fig. 2.a) indicates soliton propagation with minimal temporal pulse broadening over ~2.6 m of fiber. We calculate this to correspond to ~ 20 soliton periods (as defined by the minimum compressed pulse width and the above estimated HF dispersion). The shortest compressed pulses have a duration of 60 fs (see autocorrelation shown in Fig. 2.c). The symmetric spectrum inset to Fig. 2.c) (propagation through 0.92m of fiber) indicates the effects of SPM, whereas the spectrum in Fig. 2.d) (propagation through 2.02m of fiber) shows a distinct peak at 1.075 μm, which is evidence of the soliton self-frequency shift. The low pulse energies (20pJ, 200 W typical peak power) and ~1m lengths of this fiber required to form solitons[4, 9, 10], are at least an order of magnitude lower than those previously required for similar experiments in conventional fiber at 1550nm[1], making these nonlinear effects readily accessible for practical applications.

*2.2 Soliton transmission and supercontinuum generation*

To achieve higher pulse energies we amplified the laser pulses using parabolic amplification in diode pumped Yb doped fiber amplifiers. Parabolic amplification occurs in fiber amplifiers with normal dispersion and relies upon the progressive evolution of an initial short pulse towards an asymptotic parabolic temporal and spectral shape with a significant linear chirp[15]. Parabolic pulses are of immediate practical application because the linear positive chirp, permits the use of a simple diffraction grating compressor to produce high quality <300fs, multi-nJ pulses. The SEM of the small core, anomalously dispersive holey fiber used for the higher pulse energy experiments is shown in Fig. 3.a). Although not identical to the fiber used in the earlier experiments, the fiber in Fig. 3.a) has very similar construction (core diameter, air fill fraction), and experimentally measured parameters ($A_{eff}$, $\lambda_0$) compared to the previous fiber. We believe the processes of linear and non-linear pulse compression are acting similarly in both experiments. The key difference is that by incorporating more rings of holes, the fiber shown in Fig. 3.a) has much lower confinement losses (~0.1dB/m).

Launching the uncompressed amplified parabolic pulses (strong positive chirp, FWHM~6ps) directly into a 60m length of the holey fiber shown in Fig. 3.a), we observed dramatic temporal pulse compression and SSFS wavelength tuning. For low launched pulse energies (below ~10pJ), we again observed that the transmitted spectrum was undistorted but the pulses were temporally broadened (beyond the ~50ps measurement capability of our autocorrelator) due to the excess anomalous dispersion of the fiber. However, on increasing the launched pulse energy above ~20pJ, the FWHM of the transmitted pulses reduced to below 1ps, and for launched pulse energies around ~70pJ, the FWHM remained constant at ~400fs. Fig. 3.b) shows the SHG autocorrelation of the 400fs transmitted pulses (solitons), and of the 6ps launched pulses. This corresponds to transmission over ~475 soliton periods, which we believe is the longest transmission distance recorded for solitons at this wavelength. The spectrum shown in Fig. 3.c) clearly demonstrates single colour Raman solitons, which were tunable with increasing launched pulse energy out to a maximum wavelength of ~1.12μm. This complements our recent work on SSFS in an active Yb-doped HF where we achieved a much broader tuning range 1.06 – 1.33 μm [16].

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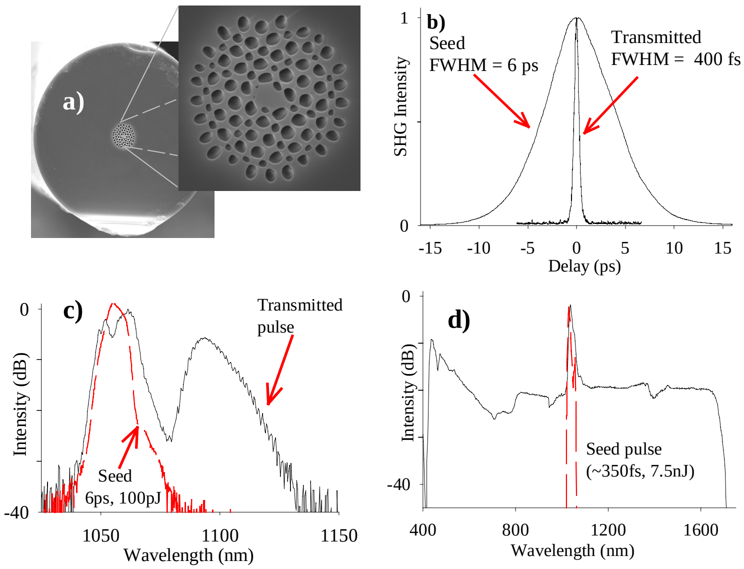


Fig. 3. Results obtained using amplified pulses. a) SEM of the holey fiber used for amplified pulse experiments. b) Autocorrelation of 70 pJ pulses; at the input (positively chirped, FWHM 6ps), and after transmission through 60m of fiber (FWHM ~400fs). c) Spectra of input pulses (FWHM 6ps, 100pJ) and wavelength shifted (SSFS) pulses after transmission through 60m of fiber. d) Broadband continuum obtained by launching 20kW peak power pulses (FWHM~350fs, 7.5nJ) into 7m fiber length. The chirp of the input pulses was removed using a diffraction grating compressor.

Finally, we increased the peak power of the launched pulses to ~20kW (350fs FWHM, 7.5nJ) by adding a higher power cladding pumped Yb-doped fiber amplifier, a modulator to reduce the pulse repetition rate, and a diffraction grating compressor to remove the chirp. The output of the fiber became a spectacular blue/white colour and the ultra-broad supercontinuum spectrum in Fig. 3.d) shows the enormous broadening into the visible region, especially compared to previous supercontinuum demonstrations from all fiber systems[17]. We report elsewhere[8] related evidence suggesting that the increase in spectral conversion at blue wavelengths is due to phase matching to a higher order spatial mode. As the pulse energy was increased, the spectrum first formed a broad continuum across the infrared spectrum, and only at the highest powers did the spectrum move into the visible range. The fiber length was 7m, but we note that visible blue light was seen towards the launch end of the fiber indicating that a substantially shorter fiber length could have been used. Using an oscilloscope and detector with ~2GHz bandwidth, the input pulses were jitter free with FWHM duration of 0.5ns (true pulse width of ~6ps), whereas the transmitted pulses were smeared across a 2ns (FWHM) time window with significant jitter, which we interpreted as break-up into multiple pulses.

## 3. Conclusion

In conclusion, we have directly demonstrated, for the first time to our knowledge, linear dispersion compensation in a holey fiber with anomalous dispersion at wavelengths less than 1.3 µm. At only 1 mW average power (peak power ~200W), the fiber supports both soliton compression, and pulse propagation without temporal broadening, and using pulses with higher peak power, we generated supercontinuum spectra spanning from below 400nm to above 1750nm. All experiments were seeded using a diode-pumped Yb-doped fiber source.

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