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Coherent Widely Tunable Source of Sub-picosecond Pulses Using All-normal Dispersion Fiber Supercontinuum

L. E. Hooper, P. J. Mosley, A. C. Muir, F. Yu, B. J. Mangan, W.J. Wadsworth, J. C. Knight
Centre for Photonics and Photonic Materials
Department of Physics, University of Bath
Bath BA2 7AY, UK
L.E.Hooper@bath.ac.uk

J. M. Dudley
Laboratoire d'Optique P. M. Duffieux
Institut FEMTO-ST, Université de Franche-Comté
25030 Besançon, France

Abstract—**We describe supercontinuum generation using photonic crystal fibres with all-normal group velocity dispersion profiles, pumped at 1064 nm and 800 nm wavelengths. Highly coherent and stable continua are demonstrated experimentally. We present pulse duration measurements obtained when spectrally filtering the all-normal dispersion supercontinuum, and show that this method is an excellent candidate for use as a compact, low-noise, tunable ultrafast laser source. Experimental spectral and temporal measurements are interpreted using numerical simulations, and experiment and modeling are shown to be in very good agreement.**

Key words: Photonic Crystal Fibre, Supercontinuum Generation, Nonlinear Optics

I. Introduction

Supercontinuum (SC) generated using photonic crystal fibre (PCF) is a valuable tool for many imaging and metrology applications [1]. Current state-of-the-art PCF SC sources can span an octave or more, and can be generated by low energy pump pulses [2]. These PCFs are designed such that the zero-dispersion wavelength is just below the pump wavelength so the pump propagates in the anomalous group velocity dispersion (GVD) regime. In this case, spectral broadening is highly efficient, utilising multi-soliton break up and the Raman shift of solitons to longer wavelengths. However, this process is highly sensitive to pump pulse fluctuations and quantum noise, and so the resulting supercontinuum has unstable spectral intensity and phase from shot to shot, severely degrading the mutual spectral coherence of the supercontinuum pulse train. This can be a limiting factor in applications where time-resolved measurements or high coherence are necessary, for example in nonlinear microscopy [3] and ultra-short pulse generation [4]. Additionally, due to the presence of several Raman shifted solitons, each supercontinuum has a complex temporal profile, limiting applications as a tunable laser source.

One very effective way to reduce the noise in supercontinuum generation is to obtain spectral broadening in the normal GVD regime, where solitons do not form. In this case bandwidth is generated by self phase modulation and optical wave breaking [5]. By careful choice of design parameters, it is possible to fabricate PCF with an all-normal GVD profile, which ensures that the generated wavelengths never enter the anomalous GVD regime. In previous work we have reported an all-normal GVD PCF fabricated with low dispersion for pumping at 1064 nm [6]. We demonstrated broad, flat SC spectra spanning 800 nm bandwidth, and re-compression of a 200 nm wide self phase modulation SC to within a factor of 2 of the transform limit using only linear compensation. These types of PCF have also been a subject of recent research elsewhere [7, 8]. These highly stable and coherent supercontinuum sources are expected to have a range of applications, including optical coherence tomography, ultra-short pulse generation, frequency metrology and nonlinear microscopy.

In this paper we describe PCF which we have fabricated with all-normal GVD and almost zero dispersion at 800 nm. Furthermore we demonstrate of the use of a supercontinuum generated by a 1064 nm pump laser in all-normal dispersion fibre as a compact tunable sub-picosecond laser source.

II. All normal dispersion PCF

We have fabricated two different fibres with all-normal GVD profiles and low GVD at pump wavelengths of 1064 nm and 800 nm. The first of these has already been reported in [5]. They are both solid core PCFs with 8 rings of air holes, and were fabricated from fused silica glass using the stack and draw method. The 1064 nm PCF has measured pitch = 1.65 um and hole diameter/pitch ratio = 0.32, and the 800 nm PCF has a pitch = 0.95 um, and hole diameter/pitch ratio = 0.49. The measured dispersion profiles of these two fibres are shown in Fig. 1. Plotted on the same axes is the measured dispersion profile of a conventional SC PCF designed for pumping at 1064 nm [2]. This fibre is used for comparison in experimental and simulation results throughout this paper.

Fig. 2 shows typical spectra generated in 1 m of each all-normal dispersion PCF. The PCF for 1064 nm was pumped

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using 400 fs full-width half-maximum (FWHM) $sech^2$ pulses, 400 mW average power at 20 MHz, centered at 1075 nm. The PCF for 800 nm was pumped using 200 fs FWHM pulses from a mode-locked Ti:Sapphire laser, with 120 mW average power at 76 MHz, centered at 800 nm. The spectrum generated in the 1064 nm PCF is extremely flat, whereas the spectrum generated in the 800 nm PCF has a central dip of approximately 13 dB. This effect is due to the proximity of the maximum of the dispersion curve to zero dispersion, as described in [9].

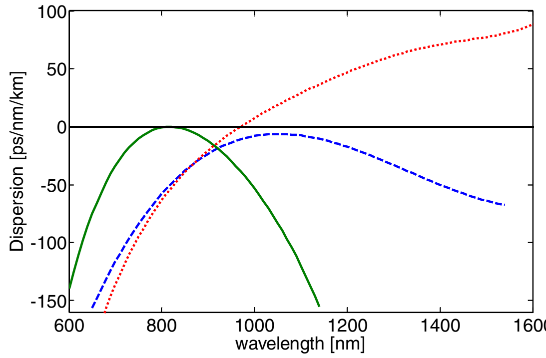

Figure 1. Measured fibre dispersion profiles of all-normal dispersion PCFs for pumping at 800 nm (solid green), and 1064 nm (dashed blue), and a conventional SC PCF [2] (dotted red)

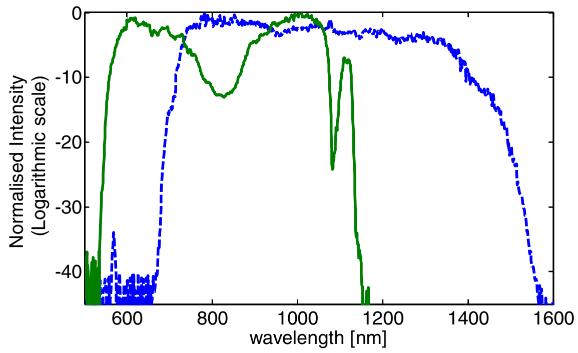

Figure 2. Spectrum generated in 1 m 1064 nm PCF using 400 fs, 400 mW 20 MHz pump centred at 1075 nm (dashed blue), and 1 m 800 nm PCF using Ti:Sapphire pump, 200 fs, 120 mW, 76 MHz, centred at 800 nm (solid green)

III. SIMULATIONS

The supercontinua generated in all-normal dispersion fibres are expected to exhibit a much higher level of pulse-to-pulse spectral coherence compared with conventional supercontinuum fibre, because self phase modulation and optical wave breaking are coherent processes. We have carried out simulations in order to demonstrate the significant differences between the two types of supercontinuum. For this we use a numerical model which implements the split step Fourier method to solve the generalized nonlinear Schrödinger equation (GNLSE) [10]. We model two different PCFs; the all-normal dispersion fibre for 1064 nm, and the conventional supercontinuum fibre designed for pumping at 1064 nm, both described in the previous section. The input pulse parameters were chosen to be similar to those used in the experiment described later in section IV. The PCFs are both 20 cm in length and pumped with 200 fs FWHM $sech^2$ pulses centered at 1064 nm, with an average power of 0.36 W at 20 MHz. For each PCF an ensemble of 20 single shot simulations, each with a random quantum noise seed, were calculated. This models fundamental noise, and disregards any technical noise. The modulus of the complex degree of first order coherence $|g_{12}^{(1)}|$ was calculated over the ensemble using

$$\left|g_{12}^{(1)}(\lambda,t_1-t_2)\right| = \left|\frac{\left\langle E_1^*(\lambda,t_1)E_2(\lambda,t_2)\right\rangle}{\sqrt{\left\langle\left|E_1(\lambda,t_1)\right|^2\right\rangle\left\langle\left|E_2(\lambda,t_2)\right|^2\right\rangle}}\right| \quad (1)$$

where the angle brackets signify an ensemble average over independently generated SC pairs. The resulting mean spectra and average spectral coherence are shown in Fig. 3 for the all-normal GVD PCF and the conventional PCF respectively.

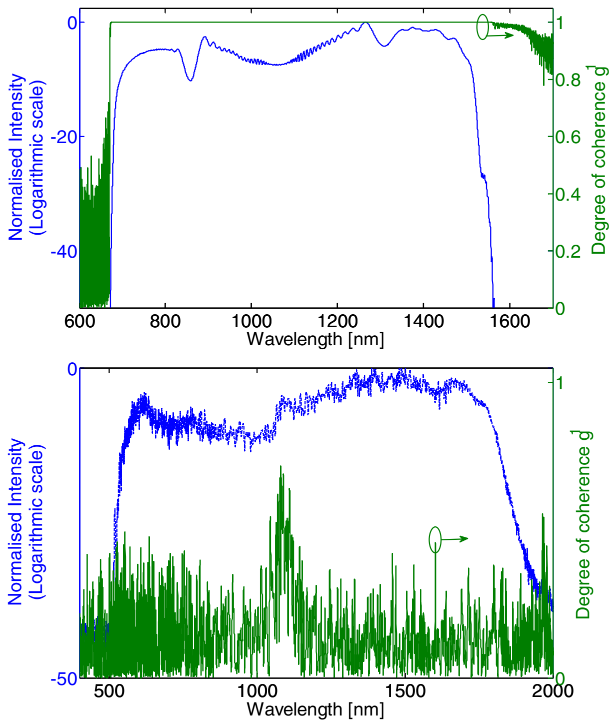

Figure 3. Simulated average spectrum and mutual degree of coherence after propagation in 20 cm all-normal dispersion PCF (above) 20 cm conventional PCF (below)

The simulated all-normal dispersion SC spectrum shows characteristic self phase modulation peaks in the centre, and side lobes at the short and long wavelength edges which are new frequencies generated by optical wave breaking [5]. The fibre length was chosen as the shortest length required to produce the maximum spectral bandwidth. A flatter and smoother spectrum is obtained when using longer lengths of fibre. The calculated coherence is exactly unity across the whole spectral bandwidth. In contrast, the SC generated in conventional PCF is spectrally broader, has a fine and complex structure, and poor spectral coherence, which is practically zero across most of the spectrum.

The temporal characteristics of the simulated supercontinua are shown in Fig. 4. Each of the 20 single-shot results is plotted along with the resulting average intensity. The all-normal dispersion SC has a single pulse in the time domain, which remains stable from shot to shot. The conventional SC however contains many temporal peaks, which shift relative to one another by differing amounts from shot to shot. When averaged, this results overall in a broad pulse with a complex structure.

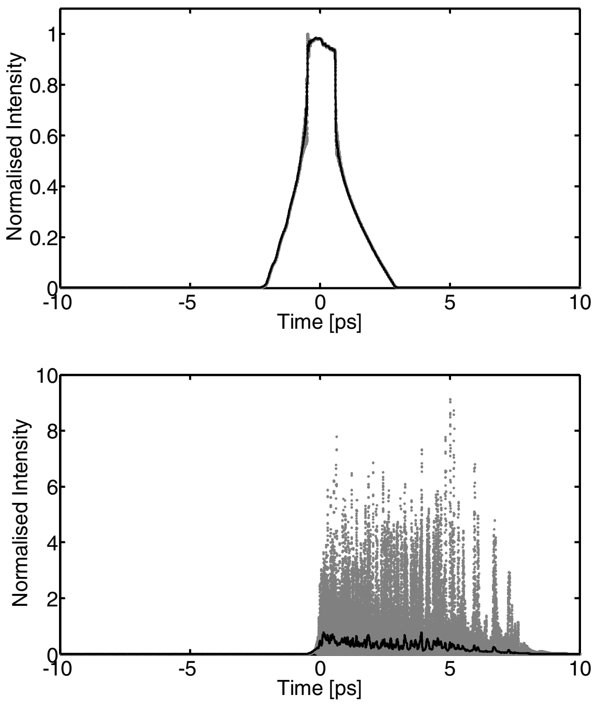

Figure 4. Temporal profile after propagation in 20 cm all-normal dispersion PCF (above) and 20 cm conventional SC PCF (below). 20 single shot simulations are plotted in grey, and the average of these is shown in black.

IV. TUNABLE SOURCE

The superior temporal characteristics of the SC generated in all-normal dispersion PCF make it an attractive candidate as a broad band, compact tunable laser source. For such a source to be useful, it should span a broad bandwidth and each spectral slice should contain a single ultra-short pulse. Using conventional PCF SC for such a source is not ideal because of the temporal structure on the SC pulses. On the other hand, the all-normal GVD SC maintains a single pulse in the time domain. In this section we investigate experimentally the temporal properties of both conventional and all-normal dispersion PCF SC when spectrally sliced.

The experimental set up is shown in Fig. 5. An amplified mode-locked fibre laser emits 5 ps chirped pulses, with bandwidth 14 nm, centered at 1064 nm. These were compressed using an external grating compressor to 200 fs FWHM. After compression a pedestal remained from the higher order dispersion in the laser and grating pair, but this did not make a significant contribution to spectral broadening in the SC PCF. To reduce the total dispersion we chose a 0.2 m length of all-normal dispersion PCF, which is the shortest length required to produce the maximum bandwidth. After 0.2 m no further broadening occurred, only smoothing of the spectral structure, and broadening in the time domain. The average power at the fibre output was 0.36 W, corresponding to an input pulse energy of 18 nJ. The resulting spectrum spanned from 700 nm to 1450 nm, and had an average spectral power density of approximately 0.5 mW/nm. The generated SC pulses were then spectrally sliced using a 4-f filter consisting of an SF11 prism, adjustable slit and mirror. The temporal profile of the filtered supercontinuum was then analysed using a commercial autocorrelator (APE). The measured values of root mean square (RMS) autocorrelation time for various RMS bandwidths and central wavelengths are shown in Fig. 6. The autocorrelation traces obtained are consistently clean, short and pedestal free. As a reference, the RMS autocorrelation width of the input pulses is 0.6 ps.

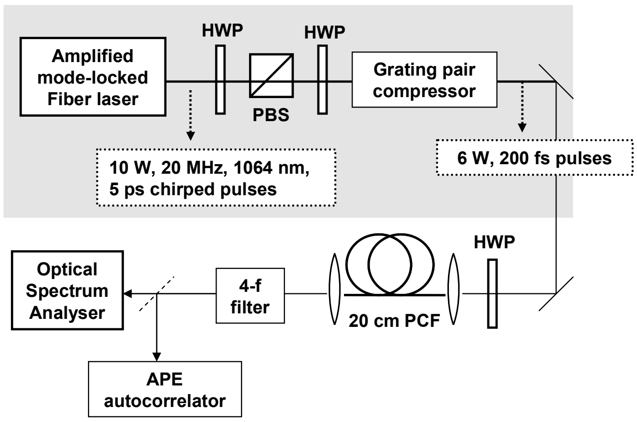

Figure 5. Experimental set up for filtering supercontinuum. HWP = half wave plate, PBS = polarizing beam splitter.

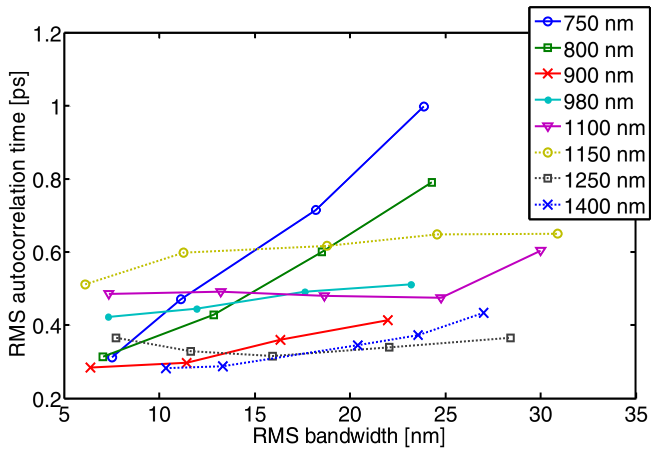

Figure 6. RMS autocorrelation pulse widths of spectral slices from the all-normal dispersion PCF SC, and their dependence on central wavelength, and RMS bandwidth.

The experiment was repeated using the conventional PCF, and in this case a broad pedestal was observed, implying that much of the pulse energy is contained in the ejected solitons which have been Raman shifted to different wavelengths and therefore dispersed different amounts. Some example autocorrelation results are presented in Fig. 7, which are typical of autocorrelation traces seen at all wavelengths. They each correspond to a spectral slice with RMS bandwidth 10 nm, centered at 1250 nm. The simulated autocorrelation traces are calculated over an ensemble of 20 single shots, as in the previous section except with 5% intensity noise added, which we estimate to be the intensity noise on our laser source. There is excellent agreement between our simulations and the experiment.

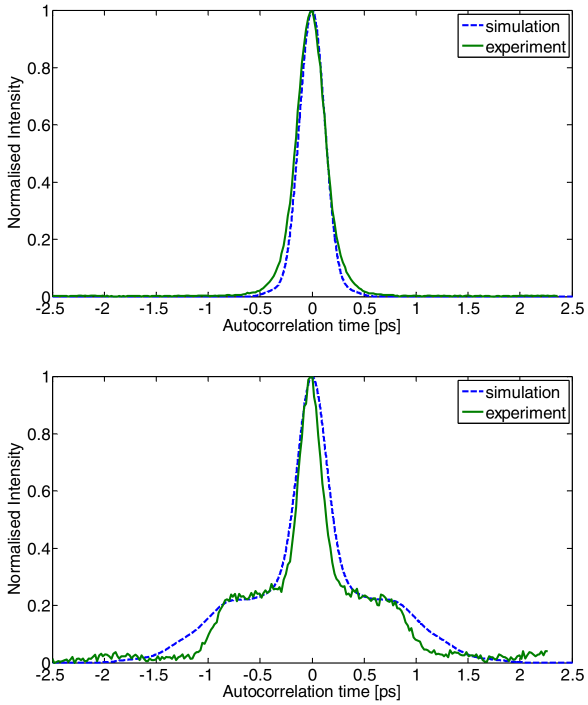

Figure 7. Measured and simulated autocorrelation traces of spectral slices centered at 1250 nm, with RMS bandwidth 10 nm, for all-normal dispersion SC (above) and conventional SC (below)

V. Conclusions

We have demonstrated the advantages of using all-normal dispersion PCF for coherent supercontinuum generation. It is possible to fabricate all normal dispersion PCFs with low dispersion for pumping at different pump wavelengths. In this paper we presented two all-normal dispersion PCFs which we have fabricated, for pumping at commonly used wavelengths 1064 nm and 800 nm. These have both been demonstrated to produce typical self phase modulation and optical wave breaking spectra, and in previous work we demonstrated the compressibility of such a continuum [6].

We have demonstrated the advantages of using all-normal dispersion PCF for coherent supercontinuum generation. The spectra generated in all-normal dispersion PCF are significantly more stable and spectrally coherent than in anomalously pumped SC PCF. Additionally, the temporal properties of the all-normal dispersion SC pulses make them an ideal candidate to combine with spectral filtering for use as a low-noise, ultrafast tunable laser source. In this paper we experimentally demonstrated such a source, and compared the results with those obtained from a SC PCF pumped in the anomalous dispersion regime. It is clear that all-normal dispersion SC PCF produces much cleaner and shorter pulses, with all the energy contained within a single sub-picosecond pulse. This is in contrast to the conventional PCF which yielded pulses with complex and fluctuating temporal structure distributed over several picoseconds.

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