Characterisation of Nested Anti-Resonant Hollow Core Fibre for Ultrafast Synchronisation Applications

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Abstract

In this report, a new NANF-type HCF cable has been made and characterised for use in the Vulcan Petawatt Laser Facility. First measurements of the autocorrelation, spectrum and spectral interferogram of light directed through 50m of the fibre demonstrate its ability to distribute laser pulses with little change over distances relevant to the scale of the Vulcan 20-20 facility. The results support its use as a distributor of optical reference pulses for the Vulcan 20-20 timing system.

1 Introduction

Synchronisation of the petawatt laser systems for the Vulcan 20-20 project down to <2fs rms timing jitter will be a significant challenge for the project to overcome. Achieving this will require optical locking of the two petawatt lasers lines to the facility timing reference. A prerequisite to this is an ultra-low phase noise master oscillator (the timing reference) that can be distributed across the entire facility with sub-femtosecond timing stability.
This level of performance is achievable by use of a stabilised single mode fibre (SMF) optic link [1]. To date SMF links have been reported achieving <1fs jitter over distances of >1km [2]. However, it can be challenging to manage optical power budget, in addition to dispersion and modulation of the reference pulses in these systems. The diagram of a typical SMF link is shown in figure 1. One possibility for improving the performance of stabilised links is to replace the majority of the SMF with hollow core fibres (HCFs). HCFs exhibit novel characteristics that are difficult to achieve with single and multi mode fibre. They can be engineered for low dispersion, loss, material nonlinearity and thermal sensitivity simultaneously due to their largely hollow waveguide structure. In particular, nested anti-resonant nodeless (NANF) hollow core fibres exhibit all of these properties with remarkably low loss [3]. The combination of properties is ideal for the distribution of an optical reference and may offer performance improvement if integrated into a stabilised fibre optic link. In this report, we investigate the properties of a SMF-HCF hybrid cable, characterising it and evaluating its suitability for use in synchronisation systems in the Vulcan laser facility.

2 Optical Setup

A Michelson-type, double path interferometer, as shown in figure 2, was created to investigate the properties of the hybrid cable. Light from the source was split between the HCF and a reference arm, with a $\frac{\lambda}{2}$ waveplate providing control of the optical power entering the both arms of the interferometer. Control of the fraction of the return pulses from each arm reaching the common arm is provided by $\frac{\lambda}{4}$ waveplates. An autocorrelator, spectrometer, camera and power meter were placed at various points in the system to characterise the pulse duration, spectrum, power stability and pointing stability of light from the fibre as well as the dispersion and onset of nonlinearity in

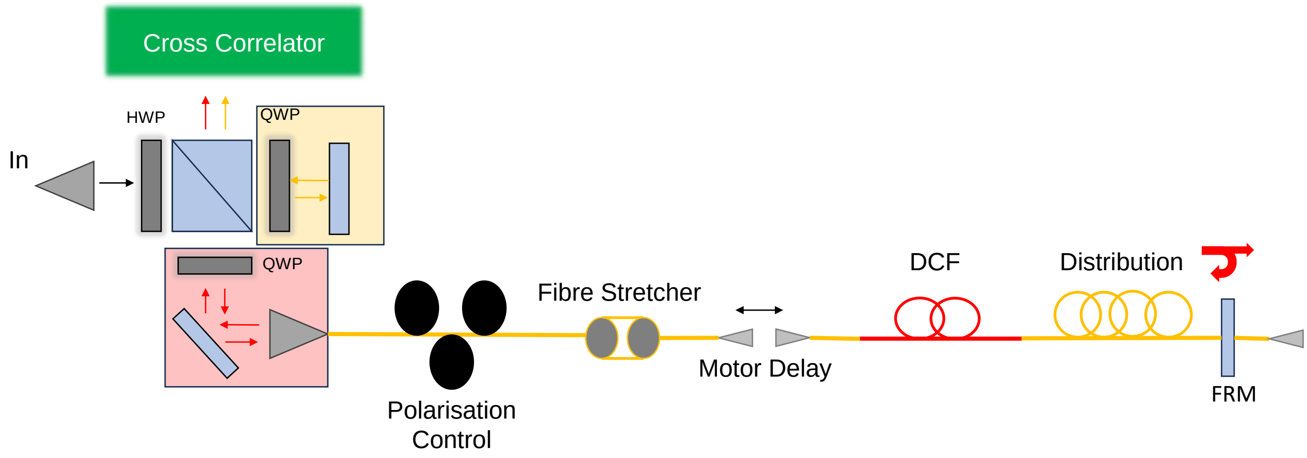

Figure 1: Single mode stabilised fibre optic link including an in line polarisation controller, fibre stretcher for fast stabilisation, motor delay to keep the stretcher within range, dispersion compensating fibre (DCF) to maintain short pulse duration at the output of the link and a Faraday rotator mirror (FRM) before the output. Light reflected from the FRM travels back through the link into a cross-correlator where a path-length sensitive signal is generated.

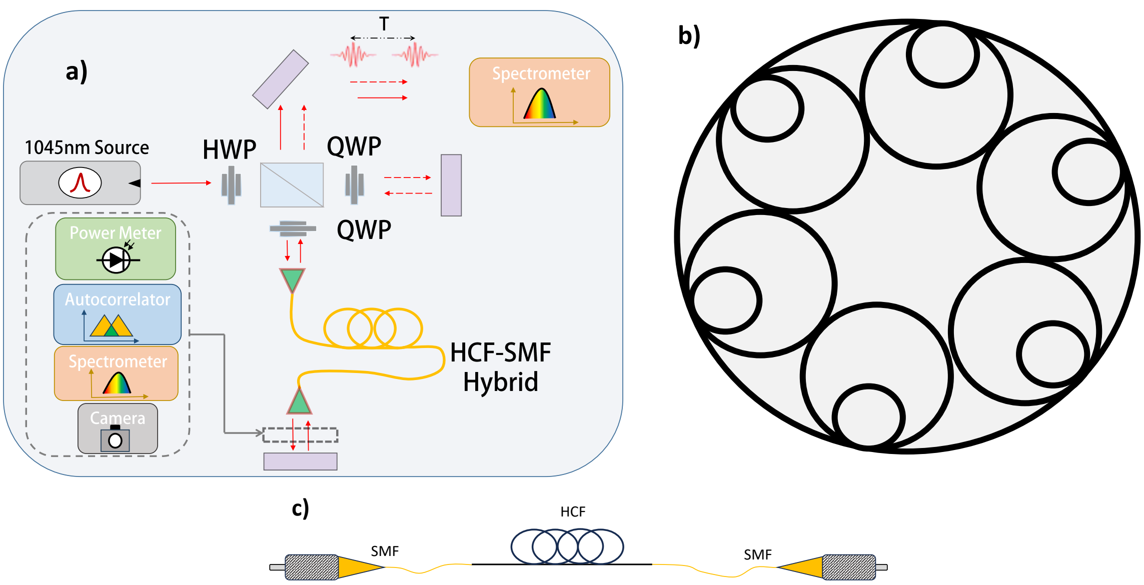

Figure 2: a) Michelson interferometer setup to characterise the >50m hybrid cable. b) 'Revolver' design of typical nested anti resonant nodeless hollow core fibre. c) Hybrid cable design, HCF terminated by two SMF pigtails of differing length that cancel the dispersion in the 50m of HCF

the fibre. The experiment utilised a Spectra Physics Insight DeepSee unit, a Ti:Sapphire system producing 200fs (10nm bandwidth typ.) pulses at an operating wavelength of 1045nm.

3 Results and Discussion

In order to act as a distributor for optical reference pulses, the change in the pulse duration and spectrum of the light output from the fibre should be minimal. To investigate this, the autocorrelation and spectrum were measured at the input and output of the fibre as shown in figure 3. A single pass of the cable resulted in <40fs increase to the FWHM pulse duration, an increase of 20%. Measurements of the spectrum show an unexpected increase in the post HCF FWHM bandwidth of 0.4nm, around 6%. There are two possible for this. First is a slight misalignment

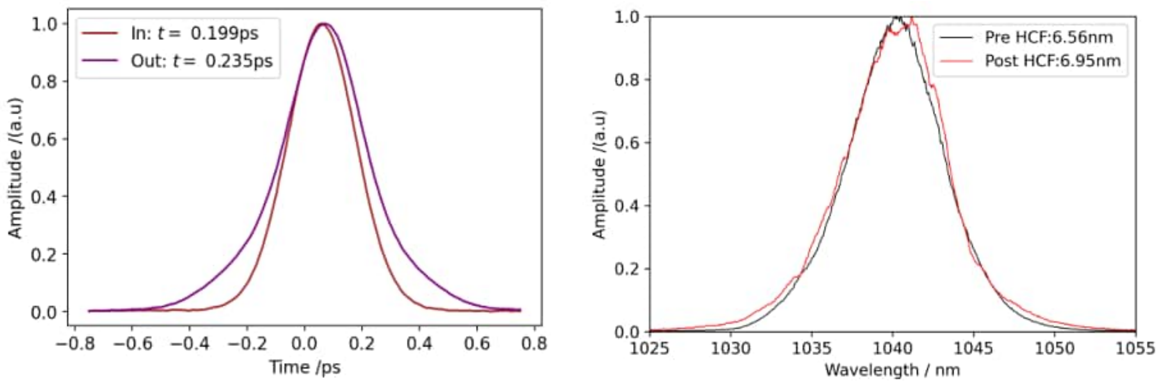

Figure 3: Measurements of the pulses autocorrelation and spectrum after a single pass of the 50m fibre.

of the light into the spectrometer in one of the two positions for the test. The other possibility is the coupling of a large amount of light into the fibre causing slight spectral broadening through self phase modulation. This would also explain the small envelope modulation around the centre wavelength. Regardless of the cause, the spectrum and autocorrelation envelopes remain gaussian-like with only small changes in width, suggesting the fibre can be used to distribute optical reference pulses.

Spectral interferometry (SI) was used to characterise the dispersion introduced by the SMF-HCF fibre. The extra spectral phase imparted to the light propagating through the fibre is contained within the spectral interferogram of the two arms of the interferometer. The spectral phase can be described as a polynomial expansion about the central frequency ω_0 of the laser pulse:

$$\varphi(\omega) = \varphi_0 + \varphi_1(\omega-\omega_c) + \varphi_2\frac{(\omega-\omega_c)^2}{2} + \varphi_3\frac{(\omega-\omega_c)^3}{6}... \tag{1}$$

where the coefficients contain a full description of the fibre dispersion. In ascending order, the coefficients correspond to a phase constant (φ_0), group delay (GD, φ_1), group delay dispersion (GDD, φ_2), third order dispersion (TOD, (φ_3) followed by higher order dispersions. The spectral interferogram of the reference and HCF transiting pulses produces a signal on the spectrometer given by equation 2:

$$S(\omega) = |E_0(\omega)|^2 + |E_U(\omega)|^2 + 2|f(\omega)|cos(\Delta\varphi(\omega) + \omega\tau) \tag{2}$$

where $E_0(\omega)$ and $E_U(\omega)$ are the respective electric fields of the reference and fibre arm pulses. This function describes an envelope being modulated (see figure 4) according to the spectral phase difference, $\Delta\varphi(\omega)$, between the pulses. Fourier transforming, filtering and inverse transforming the measurement back to the spectral domain allows the term containing the spectral phase difference, $|f(\omega)|cos(\Delta\varphi(\omega)+\omega\tau)$, to be isolated. Taking the argument of this term, followed by a polynomial fitting yields the coefficients of the spectral phase expansion described in equation 1. Thus the various orders of dispersion in the system can be measured.

This procedure was applied to interferograms of the round trip and reference pulses giving the spectral phase measurement in figure 4. A cubic fitting is sufficient to match the measured spectral phase difference, indicating that dispersion terms higher than third order can be neglected. The spectral phase coefficients of the fit are provided in overview table 1.

To investigate the onset of nonlinear optical effect in the hybrid cable, a power scan of the spectrum was taken at the fibre output. The evolution of the spectral envelope is given in figure 5. The onset of self phase modulation is evident from the modulation of the pulse spectrum envelope for input powers greater than 60mW. This is comparable to the optical power that can be coupled into an all glass fiber before observing SPM. The SMF pigtails therefore provide a limit on the light that can be coupled into the fibre without degradation of the reference pulses.

4 Conclusion

Characterisation of the hybrid cable has shown good preservation of the pulse duration and spectrum at the output. The material dispersion has also been measured with third order dispersion shown to be the dominant effect in the transmission of ultrashort reference laser pulses through the waveguide. Due to the SMF pigtails, the effective nonlinearity of the hybrid cable is similar to an all SMF cable. Power scans of the pulse autocorrelation and spectrum show self-phase modulation degrading the reference pulse envelope for input coupling powers exceeding >50mW. These observations indicate that the cable is suitable for use in optical reference distribution however the timing stability has not yet been measured. Future efforts are now focused on measuring the passive path length stability in the HCF-SMF cable, comparing these an all SMF link, and moving towards active stabilisation of a stabilised fibre optic connection based on the hollow core fibre.

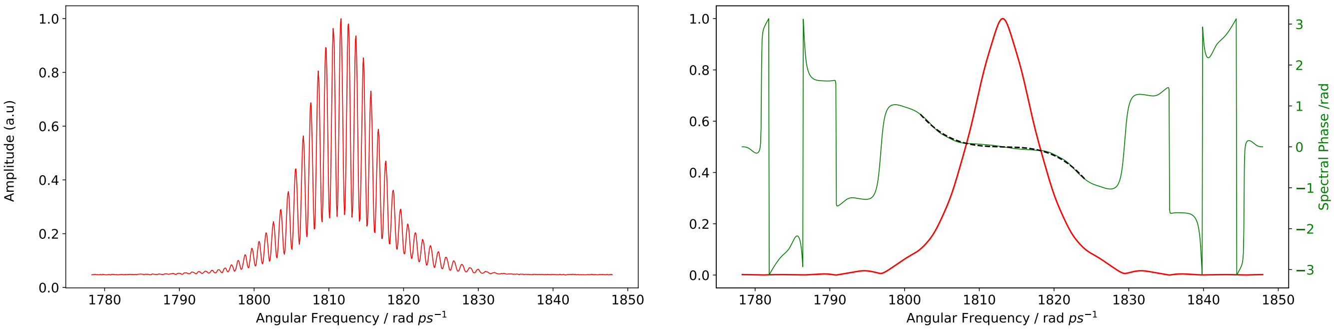

Figure 4: (Left) Spectral interferogram measured via michelson interferometer setup. (Right) Extracted modulation term (red) with measured spectral phase difference (green) and corresponding cubic polynomial fit (black). The relevant fit coefficients are given in table 1

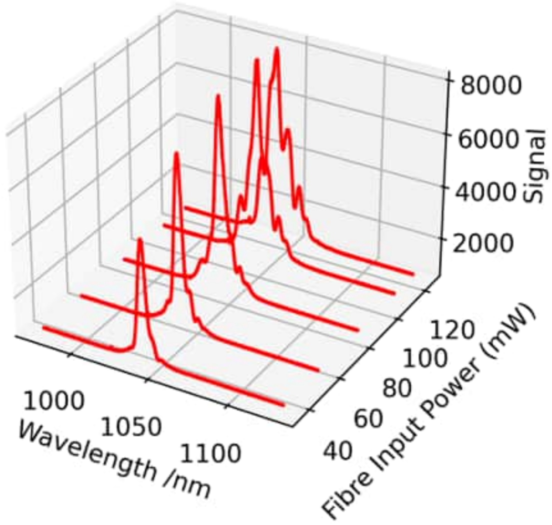

Figure 5: Evolution of the spectral envelope of the light with increasing power coupling into the fibre.

HCF Length (m)	50
Insertion Loss (dB)	2.1
Group Delay (ns)	-5.552
Group Delay Dispersion (ps^2)	1.531
Third Order Dispersion (fs^3)	-93822
SPM Threshold (mW)	$\sim$ 50
Broadening per pass (fs)	$\sim$ 40
Output Beam	Gaussian
Output Power Stability (%)	<0.5

Table 1: Hybrid cable summary table

5 Supplementary Results

5.1 Spatial Profile

At the laser operating wavelengths, the hybrid cable should be in single-mode operation, acting as a spatial filter for the input light at the expense of some insertion loss. Camera images of the input and output, as in figure 6, confirm the output to be Gaussian-like, characteristic of the output from SM fibre. The insertion loss of the fibre was measured to be 2.1dB. By comparison to an dispersion compensated SMF system, this particularly low loss (>3 dB is common in a single pass).

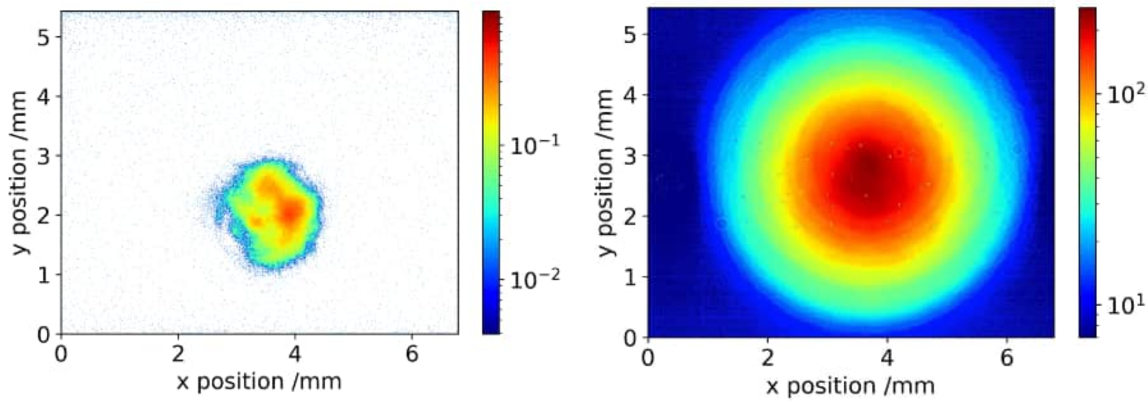

Figure 6: (Left) Spatial profile of the Insight DeepSee prior to the fibre input. (Right) Spatial profile at the output of the fibre. Image colour scales are arbitrary.

5.2 Power Stability

Stable optical output from the fibre is of importance if the hybrid cable is to be used in an optical cross correlator oscillator locking scheme. Optical power before and after the fibre was monitored over 30 minutes. Both scans, shown in figure 7, indicated a standard deviation of <0.5%. The hybrid cable is sufficiently stable for use in a laser-laser locking scheme. For polarisation sensitive cases, such as EOM-based arrival monitors, polarisation drift of light out of can be problematic. This effect has not yet been characterised in the hybrid cable and would make for a useful future measurement.

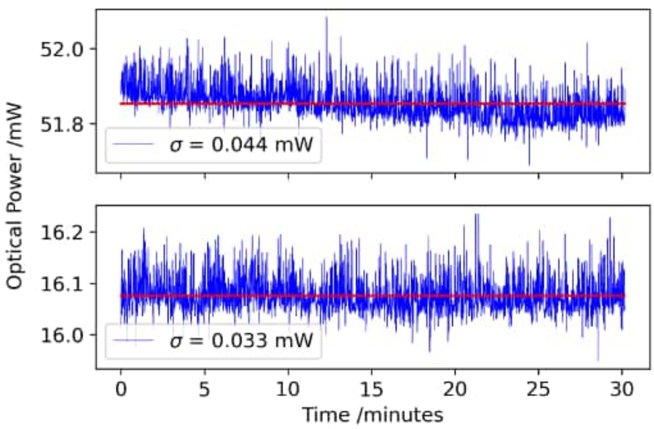

Figure 7: (Top) Input optical power measured over 30 minutes, (Bottom) Output optical power measured over 30 minutes.

6 References

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