DRAL
Daresbury Laboratory
Rutherford Appleton Laboratory

RAL Report
RAL-95-031

VULCAN Ultra-short Pulse Development Fibre-Grating Pulse Compression

D C Wilson C J Mistry G Figueira and C Danson

March 1995

Rutherford Appleton Laboratory Chilton DIDCOT Oxfordshire OX11 0QX

VULCAN Ultra-short pulse development
Fibre-Grating Pulse Compression

[1]D C Wilson, C J Mistry, [2]G Figueira and C N Danson

Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon.

[1]Blackett Laboratory, Imperial College, Prince Consort Road, London

Current address: MRC Muscle and Cell Motility Unit, Randall Institute,

26-29 Drury Lane, London WC2 B5RL

[2]GoLP/Centro de Electrodinâmica, Instituto Superior Técnico,

Av. Rovisco Pais, 1096 Lisboa Codex, Portugal

Abstract

In this report we analyse the feasibility of implementing a fibre-grating compression scheme at the output of the Nd:YLF oscillator used in the VULCAN CPA Nd:glass laser. This process has previously demonstrated that it can efficiently compress pulses to a few tens of femtoseconds. Based on calculations, we determine the optimum parameters for our present system, and perform several experiments in order to measure the compressed pulse widths. The importance of achieving such short pulse lengths lies on the high peak powers that become available at the output of the system.

Introduction

The availability of high peak power pulses using the Chirped Pulse Amplification [1] (CPA) technique at the Nd:glass laser VULCAN is due both to the short pulse lengths attainable at the output of the oscillators, the existing high gain amplifier chain and the large aperture gratings in the interaction area. These pulses, when focused on target, allow high brightness operation in excess of 10^{19} W/cm^2 [2].

There are currently two short-pulse oscillators available for use on the VULCAN CPA scheme. The Nd:YLF additive pulse modelocked (APM) laser [3], generates 2-3 ps pulses of 1 nJ energy, and the Nd:LMA APM laser [4] generates 500 fs pulses of 0.5 nJ energy. The experiments that employ CPA would benefit from the availability of even shorter pulses, giving higher peak powers and intensities. It would also be advantageous to have an alternative source of ≤500 fs pulses to serve as a backup to the Nd:LMA oscillator. We propose to achieve these two goals by compressing the 2 ps pulses currently generated by the Nd:YLF oscillator.

Fibre-grating pulse compression provides a relatively straightforward means of obtaining good quality compressed laser pulses, from a standard short pulse oscillator. The technique has been used in the past to produce pulses as short as 30 fs [5], and in our case it should be possible to reduce the pulse duration of the Nd:YLF oscillator by an order of magnitude to around 200 fs-400 fs.

We start by presenting an outline of the theory of fibre-grating pulse compression, after which we perform calculations in order to determine the optimum values for our system parameters. Next we describe our experiments and present the results obtained. Finally, we discuss the implications of these results on the feasibility of the proposed pulse compressor.

Outline of Theory

The minimum final duration of a laser pulse is limited by its bandwidth, according to the well known time-bandwidth theorem $\Delta\omega\Delta t \geq k$, where $\Delta\omega$ is the frequency bandwidth, Δt is the pulse length and k is a number of the order of unity that depends on the shape of the pulse. When the expression is an equality, the pulse is said to be transform limited. For such a pulse, no reduction in duration can be achieved unless its frequency bandwidth is increased. Usually, the pulses delivered by oscillators are, or near to, transform limited. Therefore, there are two stages involved in the fibre-grating compression scheme, the first involving broadening of the frequency bandwidth of the pulse, and the second where temporal compression of the spectrally broadened pulse is performed.

Stage 1

The spectral broadening is achieved by passing the pulse down a length of optical fibre. Within this medium self-phase-modulation (SPM) [6,7] causes new frequencies to be added to the pulse spectrum. In the presence of an intense optical pulse, the refractive index of the fibre core is non-linearly modified via the Kerr effect and this leads to a phase shift of the light within the pulse. This phase shift translates into a frequency shift whose magnitude and direction depends on the rate of change of the pulse intensity according to

$$\Delta\omega(t) = -\frac{d[\Delta\phi(t)]}{dt} = -n_2 kL\frac{dI(t)}{dt} \qquad (1).$$

Here $\Delta\omega$ is the frequency shift, $\Delta\phi$ the phase shift, n_2 is the non-linear refractive index of the fibre core, L is the length of fibre, k is the wavenumber of the light and I is its intensity. At the leading and trailing edges of the pulse the intensity is changing rapidly, causing new frequencies to be generated, thus broadening its spectrum. At the leading edge of the pulse the intensity is increasing, causing the spectrum to broaden towards longer wavelengths, and at the trailing edge, where the intensity is decreasing, the spectrum is broadened towards shorter wavelengths. The overall effect of SPM is to produce a pulse with the same temporal shape as the original input one but with a broader spectrum. Group velocity dispersion (GVD) limits the length of fibre that can be used as in most cases it is positive and causes the pulse to spread out in time, with the lower frequency components travelling faster than the high frequency ones. As a result of GVD the pulse intensity drops and the spectral broadening effect of SPM becomes less significant. These two effects can nevertheless be suitably combined to make the pulse develop a linear frequency chirp in time, which is required for compression purposes.

Stage 2

In the second stage of the fibre-grating compression technique a pair of diffraction gratings is used. For a linearly chirped pulse, the distance between the two gratings can be chosen such that the chirp is almost exactly cancelled out by the compressor and the pulse emerging from the grating pair will be close to transform limited with the same temporal shape as the original one, but with a broader bandwidth and a correspondingly shorter duration. Further parameters are the incidence angle on the first grating and the number of grooves per millimetre.

A detailed analysis of fibre-grating compression has been performed by Tomlinson *et al.* [8]. In their work they calculate, for several example input pulses of different peak powers, energies and durations, the optimum fibre length and grating separation required to compress the pulse to its minimum duration. A useful tutorial paper on this subject is that of Gomes *et al.* [7], and the original paper on optical pulse compression using a pair of diffraction gratings, by Treacy [9], is also interesting. A very understandable non-technical description of the process is given by New [6].

Calculations

Using the formulae of Tomlinson *et al.*, calculations were performed to estimate the optimum length of fibre, the type of grating that should be used, the grating spacing, and the minimum pulse duration that could be expected.

In these calculations, a normalised length Z_0 is defined as

$$Z_0 = 0.322\pi^2 c^2 \tau_0^2 / |D(\lambda)|\lambda \qquad (2),$$

and a normalised amplitude as

$$A = (P / P_1)^{1/2} \qquad (3),$$

where

$$P_1 = (nc\lambda A_{eff} / 16\pi Z_0 n_2) \times 10^{-7}\ \text{W} \qquad (4).$$

Here τ_0 is the intensity FWHM duration of the input pulse, $|D(\lambda)|$ is the group delay dispersion `in dimensionless units, λ is the vacuum centre wavelength, and P is the peak power of the input pulse, n is the refractive index of the fibre core and n_2 its nonlinear coefficient in electrostatic units, A_{eff} is its effective area (square centimetres) and c is the velocity of light in centimetres per second. These parameters need not be discussed here, being enough to mention that Z_0 represents the length of fibre required for GVD approximately to double the pulse and P_1 is the peak power for SPM approximately to double the spectral width of a pulse in a fibre of length Z_0. The following expressions for pulse compression ratio, optimum fibre length and centre to centre grating separation were obtained by Tomlinson *et al.* who solved the non-linear Schrödinger equation for input pulses of the form $V(0,t) = A\,\mathrm{sech}(t/t_0)$:

$$\tau_0 / \tau \approx 0.63A \qquad (5)$$

$$Z_{opt} / Z_0 = 1.6 / A \qquad (6)$$

$$b \approx \frac{6.4\pi c^2 d^2 \cos^2\gamma}{\lambda^3}\left(\frac{t_0^2}{A}\right) \qquad (7).$$

Here τ is the pulse duration after compression, Z_{opt} is the optimum fibre length, b is the grating separation, d is the groove spacing and γ is the angle of diffraction at the first grating at λ.

For our calculations it was assumed that the output of the Nd:YLF oscillator is a sech^2 pulse having an intensity FWHM duration of 2.5 ps, which is consistent with scanning autocorrelator measurements [10]. From average power measurements an average pulse energy of approximately 1.2 nJ was calculated, indicating a peak power of about 420 W. For silica fibre, $n_2 \approx 1.1\times10^{-13}$ esu, and for single mode fibre at 1.053 μm, A_{eff} is approximately 4.6×10^{-7} cm^2 and $|D(\lambda)| = 9.5\times10^{21}$. This gives $Z_0 \approx 180$ m, $P_1 \approx 2.11$ W and $A \approx 14.1$. Therefore, from equations (5) and (6) we obtain the following:

$$\tau \approx 0.28 \text{ ps}$$

$$Z_{\mathrm{opt}} \approx 20.4 \text{ m}$$

If gratings with 600 lines/mm are used at a diffraction angle close to zero degrees with a double passed geometry, the required spacing to achieve optimum compression will be, from Equation 7, approximately 0.31 m. Our calculations suggest then that with a combination of about 20 m of single mode silica fibre and two 600 l/mm gratings, the 2.5 ps output of the Nd:YLF oscillator should be compressed to around 280 fs.

In the above calculation, no account has been taken of loss due to poor coupling efficiency into the fibre. In reality, only 60% of the oscillator energy may be coupled into the single mode fibre. This in turn means that the peak power will be reduced to around 250 W, leading to a value for A of about 11. With these considerations the following was obtained:

$$\tau \approx 0.358 \text{ ps}$$
$$Z_{opt} \approx 26 \text{ m}$$
$$b \approx 0.39 \text{ m.}$$

In a length of fibre as short as 26 m, losses due to stimulated Raman scattering and other effects should be negligible.

Experimental results

After performing the above calculations to estimate optimum fibre length, compression ratio and grating separation, measurements were made to investigate the amount of spectral broadening that could be achieved by passing the output of the Nd:YLF oscillator along an optical fibre.

Initially a 20 m length of fibre was used. The spectrum of the Nd:YLF oscillator pulse was measured before the fibre input using a 600 lines/mm grating spectrometer and the pulse duration was measured simultaneously with a scanning autocorrelator. The spectral width (FWHM) was measured to be ≈ 0.55 nm, and the pulse duration ≈ 2.5 ps, which indicates, assuming a sech^2 pulse shape, that the oscillator pulse was close to transform limited. The oscillator pulse spectrum is shown in Figure 1.

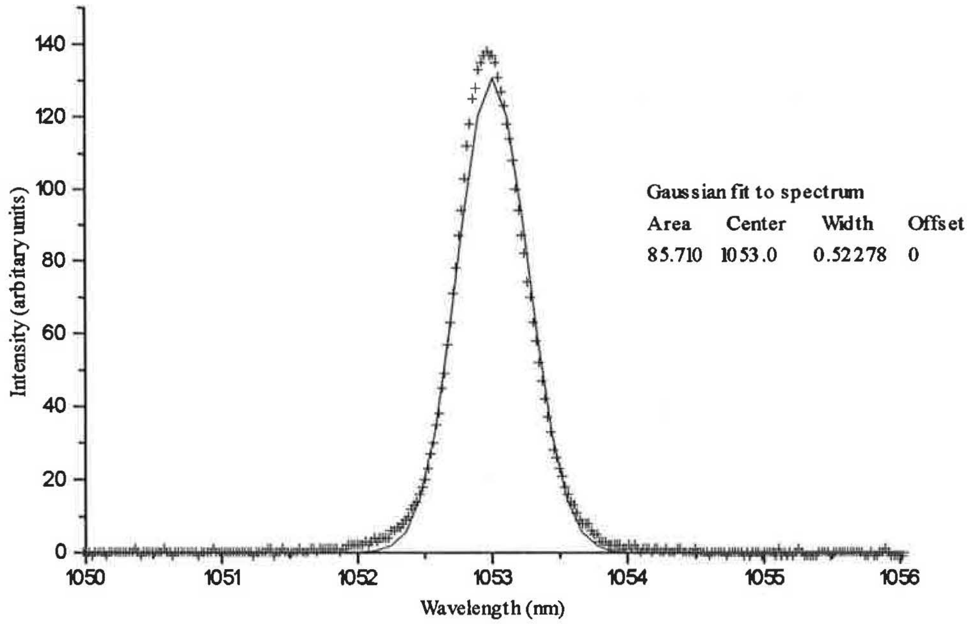

Figure 1. The oscillator pulse spectrum

The output of the oscillator was coupled into the fibre using a Newport FL10-B laser diode objective. Optical isolation from the oscillator was ensured by a Faraday rotator. The average power into and out of the fibre was measured with a power meter and a coupling efficiency of 50-60% was achieved. The maximum input power was about 160 mW which gave an output of about 90 mW. In order to investigate the dependence of spectral broadening on pulse power, a variable neutral density filter was placed between the oscillator output and the fibre input. This allowed the input power to be varied continuously between 0 and 160 mW.

The output from the fibre was directed to the grating spectrometer allowing the width of the broadened spectrum to be measured. Figure 2 shows a schematic of the experimental set-up.

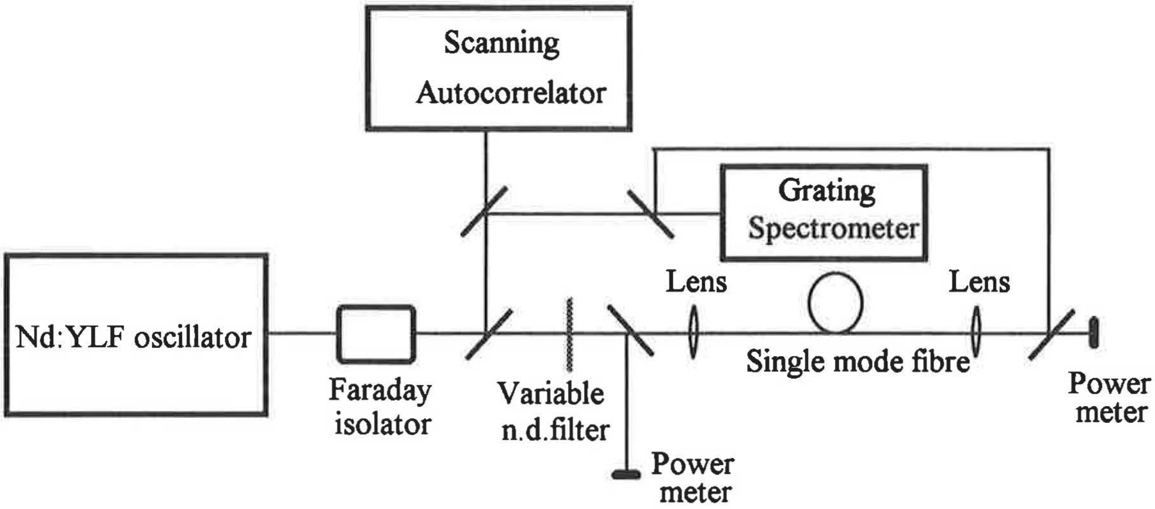

Figure 2. Schematic of experimental arrangement

Readings were taken of the spectral broadening as a function of the input power to the fibre, which was varied by adjusting the variable neutral density filter. The output power was monitored to ensure that the transmission of the fibre was not power dependent. Figure 3 shows the width of the broadened spectrum as a function of input power for the 20 m fibre. As expected, the graph shows a linear dependence. Also shown is the data obtained when this procedure was repeated for an 11 m length of fibre. Again a linear dependence of spectral width on power is demonstrated, but the gradient for the shorter fibre is shallower than for the 20 m fibre. As well as being linearly dependent on power, the spectral width was expected to vary linearly with fibre length.

From Equation 1, the spectral width should be proportional to the input power multiplied by the fibre length. This result is confirmed by combining the data from figure 3 for both fibre lengths in Figure 4.

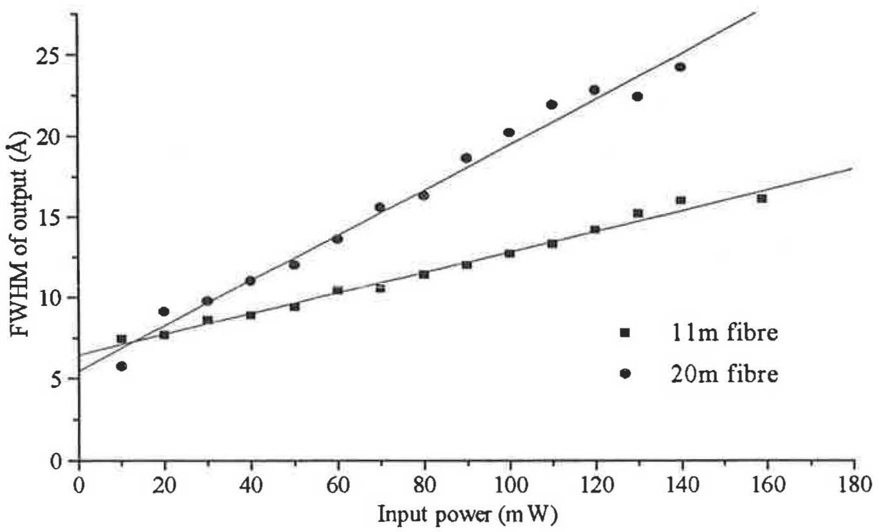

Figure 3. Width of the broadened spectrum versus input power for two fibre lengths.

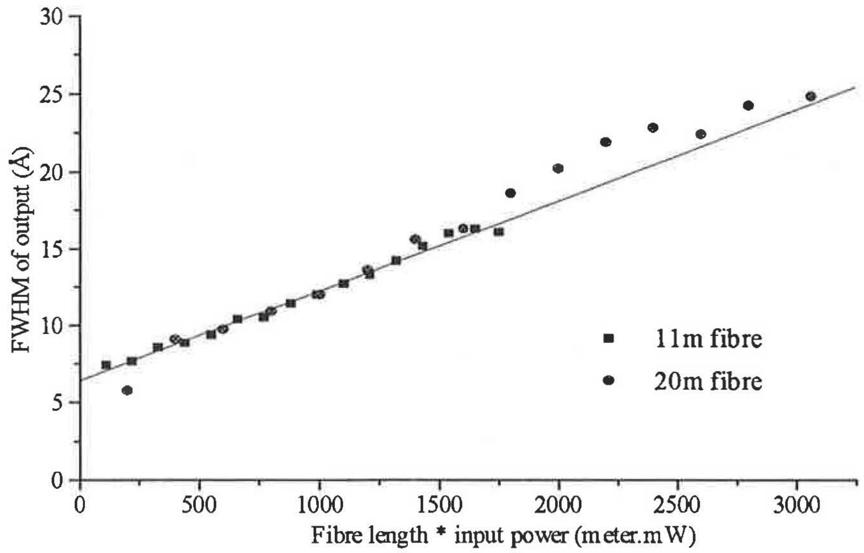

Figure 4. Width of the broadened spectrum versus (power multiplied by fibre length) for the two fibre lengths.

While the measurements demonstrated the predicted linear relationships between spectral width and power, and between spectral width and fibre length, it was clear that the degree of broadening was not as large as had been expected or predicted by the earlier calculations, and was not large enough to give the order of compression desired. For a 2 ps transform limited $sech^2$ pulse, the spectral width is about 0.6 nm. Therefore, in order to produce a compressed pulse of 200 fs duration, we required a spectral width of at least 6 nm. The maximum width that was achieved with 20 m of fibre was about 2.5 nm. As the maximum power available was limited to 160 mW, it was necessary to increase the fibre length in order to generate a larger spectral broadening. Extrapolation of the graph in Figure 4 showed that for an input of about 160 mW, a 50 m length should be sufficient to generate the required bandwidth. A fibre that long was then used with the corresponding results shown in Figure 5.

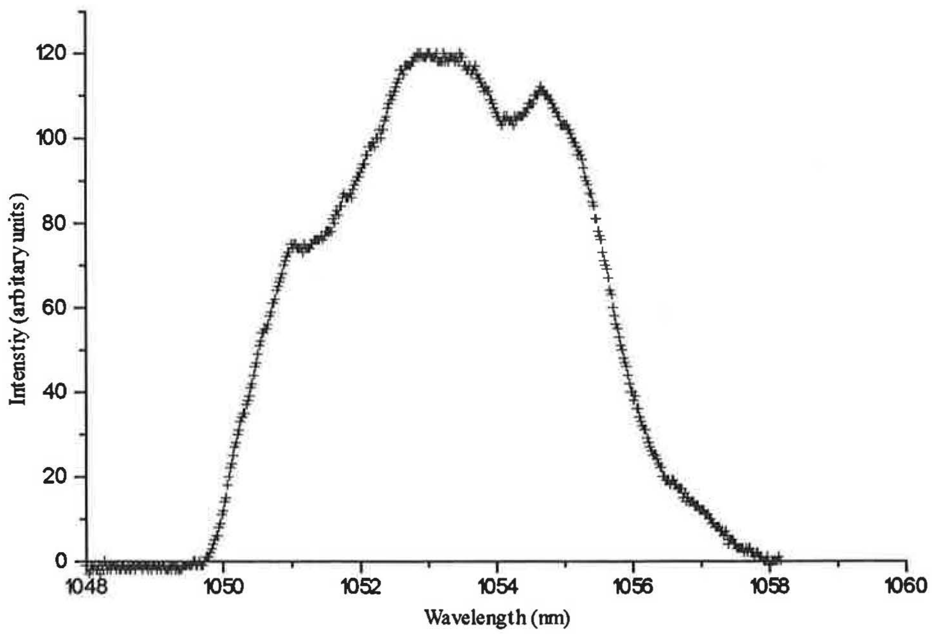

Figure 5. Spectrum of pulse after travelling through 50m of fibre.

The bandwidth has increased to 5 nm FWHM (this should be compared with the unbroadened spectrum of Figure 1). If ideal compression were possible, this value could be expected to give a minimum compressed pulse duration of around 240 fs. Once the pulses had been spectrally broadened through this last fibre, they could then be compressed temporarily using a grating pair. A schematic of the whole set-up used to compress the pulses is shown in Figure 6.

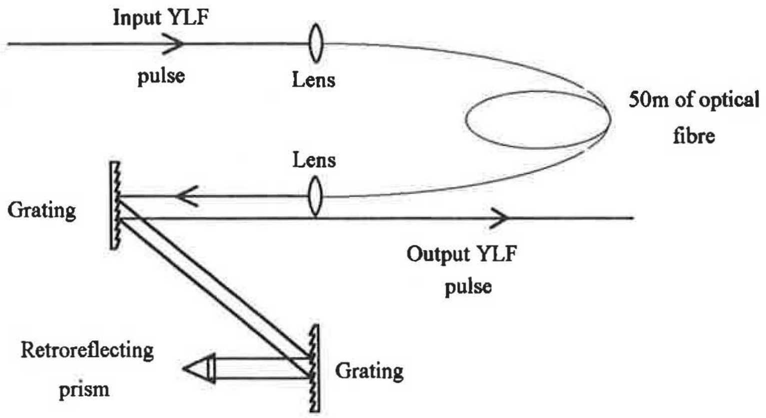

Figure 6. Schematic of compression set-up

Two 1200 lines/mm gratings were used in a double pass configuration. The equations for pulse compression derived by Treacy, were used to make an initial estimate of the required grating separation. The gratings were used in first order with a diffraction angle close to zero degrees. The results of Tomlinson *et al.* could not be used to determine the grating separation as those results assume the use of an optimum fibre length and the fibre used in this case was twice as long as the theoretical optimum length. However, using Treacy's equations it was possible to estimate the required grating separation. According to these, the wavelength dependent delay introduced by a pair of gratings in single pass is given by

$$\delta T = \frac{b\left(\lambda/d\right)d\lambda}{cd\left[1-\left(\lambda/d - \sin\theta\right)^2\right]} \tag{8}$$

where b is the grating separation, d the line spacing of the grooves, $d\lambda$ the spectral width, c the speed of light and θ is the angle of incidence on the first grating. In this case the initial pulse had a duration of approximately 2.5 ps and a bandwidth of approximately 5 nm, with a wavelength of 1.053 μm. The angle of incidence used was approximately 80°, thus giving $b \approx$ 10 cm. In the set-up used, the grating pair was double passed so a grating separation of approximately 5 cm was expected. The gratings were therefore set to that separation in the configuration shown in Figure 6, and the output pulse duration was measured with the scanning autocorrelator. At a separation of 5 cm no compression of the pulse was observed and so the grating separation was adjusted until a degree of compression was observed. Finally, at a separation of approximately 17 cm, a minimum pulse duration of approximately 400 fs was measured. (The minimum pulse duration measured to date is 370 fs.) The pulse duration displayed a quadratic dependence on grating separation and this is shown in Figure 7.

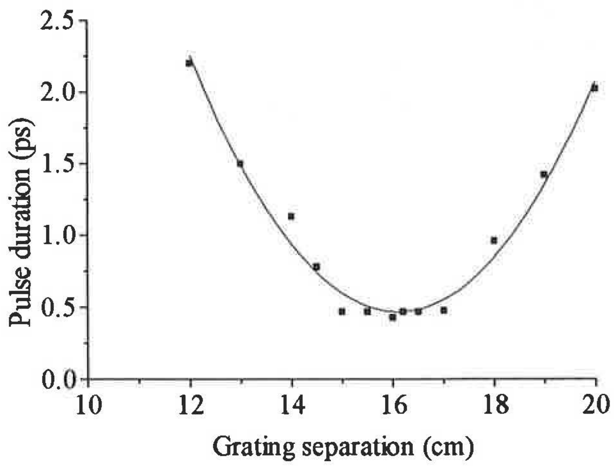

Figure 7. Dependence of pulse duration on grating separation

The disagreement between the predictions made by Treacy and the experimental results may be due to the fact that the pulse emerging from the fibre was not exactly linearly chirped (Treacy's calculations were applied to a linearly chirped pulse), and in addition, the pulse may have been lengthened by group velocity dispersion in the fibre, so that the pulse duration at the input to the grating compressor was actually greater than 2.5 ps. One other factor may be that in the above calculations by Tomlinson *et al.* the pulse had a sech profile, and our primary assumption on the profile was that it displayed a $sech^2$ profile.

Figure 8 shows the autocorrelation trace of a 480 fs pulse. No noticeable 'shoulders' are seen on this pulse, so any background pedestal must be at the <10% level.

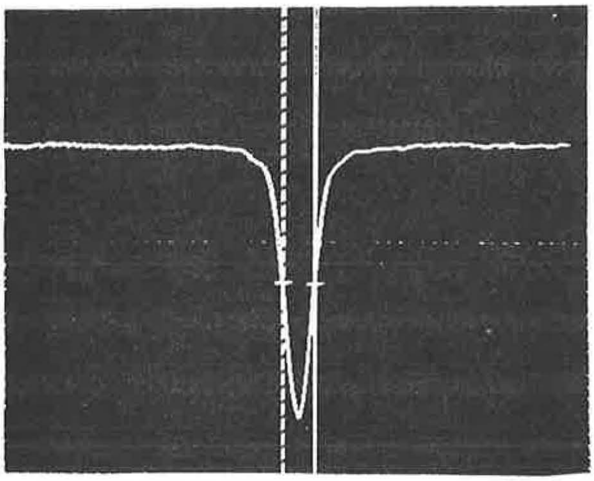

Figure 8. Autocorrelation of compressed pulse

Conclusions

It has been demonstrated that the 2 - 3 ps output pulses of the Nd:YLF oscillator can be compressed to <400 fs using 50 m of single mode fibre and a pair of 1200 lines/mm diffraction gratings in double pass configuration. The compressed oscillator output will be used as an upgraded short pulse source for the VULCAN CPA system and demonstrates the possibility of using this technique to compress the output of the Nd:LMA oscillator to generate seed pulses of <200 fs. Further experiments are required to investigate why both the fibre length and the grating separation needed to achieve a good compression ratio differ from the predicted theoretical values.

Acknowledgements

We wish to acknowledge the fruitful discussions with members of Professor A I Fergusons's group in the Department of Pure and Applied Physics at the University of Strathclyde, Glasgow and with Microlase Optical Systems Limited.

References

1. P Maine, D Strickland, P Bado, M Pessot, G Mourou., IEEE J Quantum Electronics **24** (1988), 398.
2. C B Edwards *et al.*, in press.
3. I P Mercer, Z Chang, C N Danson, C B Edwards, M H R Hutchinson and M R G Miller, Optics Communications **107** (1994), 77.
4. M W Phillips, J R M Barr, D W Hughes, D C Hanna Z Chang, C N Danson and C B Edwards, Optics Letters, **17** (1992), 1453.
5. C V Shank, R L Fork, R Yen, R H Stolen and W J Tomlinson, Applied Physics Letters **40** (1982), 761.
6. G New, Physics World 7 (1990), 33.
7. A S L Gomes, A S Gouveia-Neto and J R Taylor, Quantum Electronics **20** (1988), 95.
8. W J Tomlinson, R H Stolen and C V Shank, J. Opt. Soc. Am. B **1** (1984), 139.
9. E B Treacy, IEEE J. Quant. Elec. **QE-5** (1969), 454.
10. Z Chang *et al.*., CLF Annual Report 1992, **RAL-92-020,** 101.