An experimental study of the primary parameters that determine the temporal compression of CW Nd:YAG laser pulses

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An experimental study of temporally compressed CW Nd:YAG laser pulses using an optical fibre and diffraction grating pair technique has been carried out. The relevant experimental parameters have been varied so that a better insight into the physical processes could be gained and to enable some comparisons to be made with theory. Under optimum conditions an overall \(47 \times\) pulsewidth compression and \(10 \times\) enhancement in peak power have been achieved. Changes in fibre length, peak power and grating separation gave rise to outputs which showed good qualitative agreement with theoretical predictions.

1. Introduction

The temporal compression of ultrashort pulses by means of self-phase-modulation (SPM) induced chirp during propagation in a monomode optical fibre in the regime of positive group velocity dispersion (GVD) and subsequent de-chirp using a suitable dispersive delay line has proved to be a powerful technique in shortening picosecond and femtosecond laser pulses [1-7]. The use of a grating pair as the delay line has been demonstrated to be more effective than other schemes [1]. Several authors have reported successful attempts to compress laser pulses in the picosecond regime [1,2] as well as in the femtosecond regime [3-5] and more recently, relatively "long" (30-100 ps) pulses from a CW mode-locked Nd:YAG laser have been compressed both at the fundamental frequency [6] and when frequency doubled [7]. Theoretical treatments for optical pulse compression have also been reported [8] and an extensive article containing normalised expressions has been published recently [9].

In this letter, we report a study relating the dependence of the compression characteristics of the pulses from a CW mode-locked Nd:YAG laser on several of the primary parameters involved; notably fibre length, input pulsewidth and grating separation. Nonlinear (second-order autocorrelation) and linear (Synchroscan streak camera) measurement techniques were employed in order to provide complementary diagnostics. An overall \(47 \times\) pulse shortening and \(10 \times\) enhancement in peak power have been achieved, in good agreement with other reported results [7].

2. Experimental

The experimental arrangement is shown schematically in fig. 1. The CW mode-locked Nd:YAG laser (Quantronix model 116) has already been described [10] and it suffices to mention here that it produces \(\approx 80\) ps pulses at a repetition rate of 100 MHz with an average power of 7 W. The non-polarisation maintaining monomode optical fibre had a 7 \(\mu\)m core diameter, 1 dB/km loss at 1.06 \(\mu\)m and 35 ps/km nm group velocity dispersion. To establish optimum conditions for compression, various lengths of fibre from 200 to 125 m in steps of 25 m were used. Part of the laser output was directed via beam splitter BS3 to a Photocron II streak camera with an extended S1 photocathode [11] which, as well as being used "in-line" to measure the input pulsewidth to the fibre, also displayed any feedback features caused by reflection at the input face of the fibre. The remainder of the laser beam was focused into the fibre by a X20 uncoated microscope objective. At the output end of the fibre,
a similar X20 microscope objective was used to collect and recollimate the light (use of a X10 objective at this position had no effect on the results). The collimated beam was directed through the delay line consisting of two 1800 l/mm holographic gratings with a 90% diffraction efficiency for 1.06 μm at a 75° angle of incidence. A double pass scheme of the gratings was used with mirror M1 retroreflected the input beam through the delay line at an optical height slightly below that of the input. (The advantages of this scheme are discussed later.) For the most part a constant total grating separation of 1 m was maintained. The compressed output pulses were directed off mirror M2 onto a Photochron HA Synchroscan streak camera with an S20 photocathode which has a measured time resolution of 1 ps [12]. Alternatively a non-background free autocorrelation using a 5 mm long crystal of KDP was used to measure the pulse durations with a higher temporal resolution.

3. Results and discussion

3.1. Input peak power variation

For a fixed fibre length, the spectral broadening obtained is dependent on the peak power in the fibre. Consequently, the degree of pulse compression will be power dependent, provided that the other competing nonlinear processes such as stimulated Raman scattering can be eliminated [13]. We have examined the power dependence for various fibre lengths and the results shown in fig. 2 are representative of the qualitative behaviour irrespective of fibre length. In this case, the input pulsewidth was 100 ps and the fibre length was 125 m. By varying the input focus condition, the power in the fibre could be conveniently altered. At low powers of 700 mW average power the pulses had durations ≈29 ps with quite wide wings (fig. 2a). On increasing the power, the pulses narrowed noticeably, the wings became less pronounced and the pulse profile sequence obtained on increasing the input power from 700 mW to 1.4 W in steps of 100 mW is illustrated in fig. 2. For the pulsewidths quoted, gaussian profiles have been assumed, but a sech² pulse shape might be more representative, especially for the more compressed examples. A minimum pulsewidth of 2.8 ps (fig. 2g) was obtained for an input average power of 1.3 W but it is clear from the autocorrelation traces (e.g. figs. 2f and 2g) that the pulse compression was incomplete in the extremes of the pulse profile. Moreover, for average powers exceeding 1.3 W the compressed pulses became much more noisy and had increased durations (see fig. 2h). This was due mainly to losses introduced by stimulated Raman scattering, which we have examined in some detail and this will be reported in another publication [13].

3.2. Fibre length variation

We have carried out pulse compression measurements in the regime where the actual length (Z) of
fibre used was very much less than the value \( Z_0 \) calculated from the theory [9]. In keeping with the notation of Tomlinson et al. [9], \( Z_0 \) was determined to be 322 km, so, although operating in the regime \( A^2Z/Z_0 > 10 \) (\( A \) is a normalising amplitude) where calculations do not strictly hold [9], it was expected that qualitative trends in the compression with system parameters should give reasonable agreement with experiment. In practice, we have found that the best compression factors were achieved where the power in the fibre was such that the output pulse prior to traversing the gratings developed a “rectangular” profile [13]. Previous theoretical considerations [8] of this dispersed self-phase-modulated pulse predict spectra and pulse shapes that agree qualitatively with our experimental data and we found that at the power level where this rectangular pulse evolves, the maximum compression was observed for a given fibre length, and grating separation and noise-free compressed pulses were reliably produced. In most cases a repetitively operating streak camera was used to monitor the output pulse from the fibre, such that the critical power level for pulse compression was achieved [13]. Complementary autocorrelation measurements of the compressed pulses were taken to optimise the parameters of the compression. Maintaining a fixed input pulsewidth and grating separation, the fibre length was changed and the power varied to obtain maximum compression, increased power levels being necessary for shorter fibre lengths. As can be seen from table 1 the pulsewidths achieved were essen-

![Fig. 2. (a)-(h) Autocorrelation traces of the dependence of the compressed pulsewidth versus input peak power for a fixed fibre length (125 m) and grating separation (1 m).](image)

**Table 1**

<table>
<thead>
<tr>
<th>Fibre length ( z ) (m)</th>
<th>Input peak power ( P ) (W)</th>
<th>Calculated compressed pulsewidth ( r_{th} ) (ps)</th>
<th>Measured compressed pulsewidth ( r_{exp} ) (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>40</td>
<td>4.3</td>
<td>2.9</td>
</tr>
<tr>
<td>175</td>
<td>55</td>
<td>3.5</td>
<td>2.1</td>
</tr>
<tr>
<td>150</td>
<td>100</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>125</td>
<td>130</td>
<td>2.1</td>
<td>2.8</td>
</tr>
</tbody>
</table>

\( a^o \) Input pulsewidth \( r_0 = 100 \) ps, grating separation \( b = 100 \) cm.
3.3. Input pulsewidth variation

Theoretical considerations of the compression [8,9] imply a strong dependence on the initial pulsewidth. This aspect was examined experimentally by slightly detuning (differential micrometer movement on the 100% reflector) the cavity length of the mode-locked laser away from optimum, such that the output pulses increased in duration. A variation of 80–150 ps was available in this way, and these pulses were then directed into the fibre in the usual manner. The measurements were carried out for two different fibre lengths, 150 and 125 m, and the results are listed in Table 2. As the input pulsewidth increased, the peak power decreased and consequently it was necessary to increase the average power to achieve optimum compression. Within the experimental error, no substantial variation was detected in the observed compressed pulsewidths. It was not possible to usefully employ input pulsewidths much greater than 110 ps for the lengths of fibre used, because for longer pulses than this it was necessary to increase their power to achieve maximum compression. However, for the higher powers associated with these longer input pulses, stimulated Raman scattering became evident through the appearance of the first Stokes radiation at 1.12 μm. Because no significant variation in the duration of the compressed pulses was observed, it would appear that there is a trade-off between the parameters of input pulsewidth, fibre length and/or input peak power. Provided the SPM spectrum broadens enough to support the short compressed pulses and the power in the fibre is below that at which Raman scattering losses are present (transmission losses can be neglected), then it

<table>
<thead>
<tr>
<th>Fibre length (m)</th>
<th>Input pulsewidth (ps)</th>
<th>Optimum input peak power (W)</th>
<th>Measured compressed pulsewidth (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>82</td>
<td>48</td>
<td>3.3</td>
</tr>
<tr>
<td>150</td>
<td>100</td>
<td>100</td>
<td>2.5</td>
</tr>
<tr>
<td>150</td>
<td>110</td>
<td>127</td>
<td>3.0</td>
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<tr>
<td>125</td>
<td>86</td>
<td>93</td>
<td>3.1</td>
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<tr>
<td>125</td>
<td>100</td>
<td>130</td>
<td>2.8</td>
</tr>
</tbody>
</table>
should be possible to operate with the condition of highest average power (shorter fibre lengths). Thus, for compressed pulses having approximately equal durations, higher average and peak powers for the compression can be achieved. For most applications this is the most important parameter.

3.4. Variation of grating separation

Compression of a spectrally dispersed phase-modulated pulse in a linearly dispersive delay line is most conveniently carried out using a grating pair. With long input pulses (>60 ps) to the fibre it is predicted [9] that the grating separation is impractically large and as pointed out previously, although the expressions used to determine the compression are approximate they should be "expected" to apply in this regime [9]. However, it has already been shown [6,7] that by using the grating pair at grazing incidence angles, the dispersive effect is increased and reduced separations (<1 m) of the gratings can be used for compression of "long" input pulses. In our arrangement the angle of incidence was approximately 75° and a double pass of the gratings enhanced the beam quality of the output (maintaining a well defined circular profile) while effectively doubling the grating separation.

We have also examined the compression achieved for various overall grating separations when the fibre length was fixed at 125 m and input pulses had durations of 85 ps. The results of this are listed in table 3 and at each grating separation a pulse duration versus power dependence similar to fig. 2 was obtained. From table 3 it can be seen that as the grating separation was increased the power required for optimum compression decreased as would be expected [9]. For the shortest grating separation, stimulated Raman scattering prevented further increase in the peak power necessary (>150 W) to achieve shortening comparable to that at the larger grating separations. With grating separations of more than 1 m the peak power necessary for best compression appeared to saturate at a value ≈94 W.

4. Conclusion

In summary, we have performed a series of experimental measurements on the optimisation of the parameters involved in the single-stage shortening of 1.06 μm pulses from a CW mode-locked Nd:YAG laser. A maximum compression factor of 47 times was achieved, with an associated 10 times enhancement in peak power. The effects of varying the fibre length, peak power, input pulsewidth and grating separation were characterised. An overall coupling efficiency through the system of ≈20% in average power was achieved, but this could be increased by using polarisation retaining fibre. The results are in good qualitative agreement with theoretical predictions despite the fact that the experiments were performed in a pulse duration range outside that for which the theoretical considerations strictly apply [9]. With the introduction of the fibre/grating pair as a standard laboratory instrument for pulse compression the above characterisation and experimental trends may be useful to the users of such systems. It is possible that with suitable optimisation, compression of the 100 ps pulses from the mode-locked Nd:YAG laser to subpicosecond durations could be achieved.

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References


