

Stretched pulse Yb³⁺ :Silica Fibre Laser

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Abstract

We report what we believe to be the first results on short pulse generation in Yb³⁺:silica fibre. By applying the stretched pulse technique in a unidirectional, polarisation-switch Yb³⁺ fibre laser incorporating a prism-based dispersive delay line, we obtain self-start mode-locking and 100 pJ pulses which can be compressed to give clean chirp-free <100 fs pulses. We believe such sources to have great potential for use in all solid-state, high power femtosecond pulse systems based on Yb³⁺:silica glass and as seeds for conventional Nd³⁺:glass amplifier chains.

Ytterbium doped silica fibre with its broad gain-bandwidth, high optical conversion efficiency and large saturation fluence represents an extremely attractive medium for both the generation and subsequent amplification of ultrashort optical pulses [1,2]. Moreover, such a Yb^{3+} :fibre system can be further power-scaled by the addition of diode-pumped waveguide or bulk glass amplifier stages making the construction of compact, all-solid-state, high power, short pulse systems an exciting possibility.

In order to realise such a system a robust and reliable Yb^{3+} :silica fibre based, femtosecond pulse seed source is required. However, before this work no reports of short pulse generation in the Yb^{3+} :silica system have been made. The majority of mode-locked fibre work to date has focused on erbium-doped silica fibre operating at 1550 nm with a number of mode-locking geometries successfully demonstrated operating in both the anomalous dispersion (soliton) [3,4] and dispersion compensated regimes [5,6,7]. Of particular note have been the results obtained using stretched pulse mode-locking based on nonlinear polarisation evolution in which fibre sections of large anomalous and normal dispersions are employed to periodically stretch and compress the pulse as it propagates within the cavity, thereby reducing the cavity nonlinearity and dispersive wave generation [6,7]. Reliable self-start mode-locking and pulses as short as 77 fs when compressed extra-cavity have been obtained from such systems based on Er^{3+} [6]. The principal difficulty associated with pulse generation within Yb^{3+} doped fibres results from the high value of normal material dispersion for silica around the 1030 nm gain peak. While waveguide dispersion can be used to offset material dispersion it does not appear feasible to achieve overall anomalous dispersion via this approach for such a short wavelength. Similar problems

have been experienced in Nd³⁺:silica fibre lasers, however a number of notable results including pulses as short as 38 fs [8] have been obtained by employing bulk/lumped dispersion compensating elements within the cavity. Unfortunately, the difficulty in obtaining self-start mode-locking within these lasers, which have typically been of a Fabry-Perot geometry, has required the use of either an intra-cavity modulator [8], a semiconductor saturable absorber [9], or mechanical perturbation of the system to initiate pulsed operation [10].

In order to obtain self-start modelocking, we decided to use a unidirectional ring (travelling wave) geometry for our laser cavity. Fig. 1 shows the set-up which comprises four principal components: a section of Yb³⁺:silica fibre which provides the gain, normal dispersion, nonlinearity and birefringence required within the cavity, a bulk DDL to provide anomalous dispersion, a polarising optical circulator to provide polarisation dependent loss and to ensure unidirectional operation of the cavity, and a simple extra-cavity fibre pulse compressor. Additional intracavity waveplates, mirrors and polarising beam splitters are included to (1) control the bias of the polarisation switch, (2) to adjust the laser output coupling (through PBS1), and (3) to allow for simultaneous closing of the cavity and launching of the 912 nm pump radiation. Despite the relative complexity of the cavity layout operational round-trip losses as low as 9.5 dB were obtained (measured at 1064nm).

In order to keep the prism separation in the delay line to a reasonable value (< 1m) we needed to minimise the length of active fibre within the cavity whilst simultaneously ensuring that we have sufficient gain, (>15 dB), around 1030 nm, and sufficient signal

re-absorption at 975 nm to frustrate lasing at this wavelength. With this in mind we used a high concentration (2300 ppm by weight), Yb^{3+} doped silica fibre (NA=0.21 and cutoff wavelength 940 nm), and pumped the system at 912 nm which offers higher gain per unit length around 1030 nm than pumping at the 975 nm absorption peak [1]. A length of 75 cm of fibre was found to give optimum performance and was used in all of the experiments described below. The second-order and third-order dispersions of the 75 cm of fibre were estimated to be $+2.6 \times 10^4 \text{ fs}^2$ and $+1.5 \times 10^4 \text{ fs}^3$, respectively, at 1030 nm. The birefringent beat-length of the fibre was measured to be 12 cm around 1030 nm.

A further contribution to the overall normal GVD of the cavity was made by the optical circulator which contained a 2.54 cm YIG crystal. The two passes per round-trip through the isolator provided >30 dB discrimination between the two counter-propagating modes but resulted in an estimated further $+2 \times 10^4 \text{ fs}^2$ of normal second order dispersion that required cancellation within the DDL.

The DDL (similar to that used in Ref. [8]) comprised six, SF10 prisms. The total dispersion of the DDL could be adjusted by varying the separation of the prism triplet pairs. The DDL was estimated to provide $-4.4 \pm 0.5 \times 10^4 \text{ fs}^2$ and $-1.7 \pm 0.05 \times 10^5 \text{ fs}^3$ of second and third-order dispersion respectively at 1030 nm for our experimentally optimised prism separation of 75 cm. The estimated uncertainty in the dispersion values relates to issues of angular alignment and uncertainty in the exact amount of SF10 glass in the optical path through the DDL. Note that the third order dispersion of the DDL is also of opposite sign to those of the other dispersive elements within the

cavity and will also be partially compensated. The pulses have their minimum duration at the 85% reflectivity wedged mirror (WM in Fig. 1) but are spatially chirped at this point. Therefore we have chosen to extract the output pulses at PBS1 where they have only a linear temporal chirp that can be compressed simply by propagation in an appropriate length of normally dispersive fibre.

Self-starting modelocking was achieved for appropriate settings of the intracavity waveplates and overall cavity dispersion, with a self start threshold of ~ 700 mW incident (~ 350 mW launched) pump power. Mode-locked average output powers of upto 30 mW were obtained at the 15% wedged mirror (WM) output with typically 5mW of useful compressible output extracted at PBS1. Stable single pulse operation at a repetition rate of 50 MHz could readily be obtained although operation with multiple pulses in the cavity could also be observed for other wave plate settings. The typical output pulse energy at the variable output coupler was therefore ~ 100 pJ.

As mentioned before, the pulses at the output PBS1 have a strong temporal chirp. The duration was typically 0.5-1.5 ps (depending on the adjustment of the intracavity waveplates and dispersion), and the 3 dB spectral width varied between 10 nm and 50 nm. A typical background-free autocorrelation function (ACF) and spectrum are shown in Fig. 2 for a prism separation of 75 cm, corresponding to a small overall second-order cavity dispersion of $+1.5 \pm 5 \times 10^3$ fs².

In order to compress the pulses by eliminating their temporal chirp, we coupled the pulses of Fig. 2 into varying length of normally dispersive fibre and recorded the ACF

and spectra as a function of fibre length. The second-order and third-order dispersions of the fibre were estimated to be $+2.8 \times 10^4 \text{ fs}^2/\text{m}$ and $+2.0 \times 10^4 \text{ fs}^3/\text{m}$, respectively, at 1030 nm. Fig.3 shows the obtained pulses with halfwidths as short as 87 fs, indicating a compression factor of order 10. Fig. 4 contains a plot of the ACF and spectrum of the shortest pulses obtained and demonstrates the excellent quality of the pulses. The time bandwidth product was 0.44 as expected for transform-limited Gaussian pulses. Comparing Fig. 2 and Fig. 4 we see that the spectral bandwidth of the compressed pulses is slightly narrower than that of the input spectra. This is due to a slight residual spatial chirp of the output beam (caused by imperfect angular alignment of the DDL) which can lead to some spectral filtering when the pulses are coupled into the single-mode compressor fibre. By adjusting the focus of the coupling lense we could tune the effective peak wavelength of the pulses over $\sim 30\text{nm}$. Using this feature we were able to probe the effects of higher order dispersions within the system. The broadening we observed as a function of pulse bandwidth, peak wavelength and compressor length indicate that our pulse compression was currently principally limited by the third-order dispersion of the compression fibre, rather than by nonlinear chirp of the output pulses, implying that considerably shorter pulses should be achievable by further optimisation of cavity and/or compressor. The shortest pulse duration obtained so far is 65 fs.

In conclusion, we have presented the first experimental results for mode-locking of an Yb^{3+} silica fibre laser. The laser is self-starting, potentially diode pumpable and has produced high quality pulses as short as 65 fs. Compressible pulses of 100 pJ energy have been obtained with peak wavelengths tuneable in the range 1030-1060 nm. 1nJ

pulse energies should be achievable with optimized output coupling prior to the DDL at PBS2 and the use of an appropriate anomalously dispersive compression scheme. We believe such sources to have great potential for use in all solid-state, high power femtosecond pulse sources based on Yb^{3+} :silica glass.

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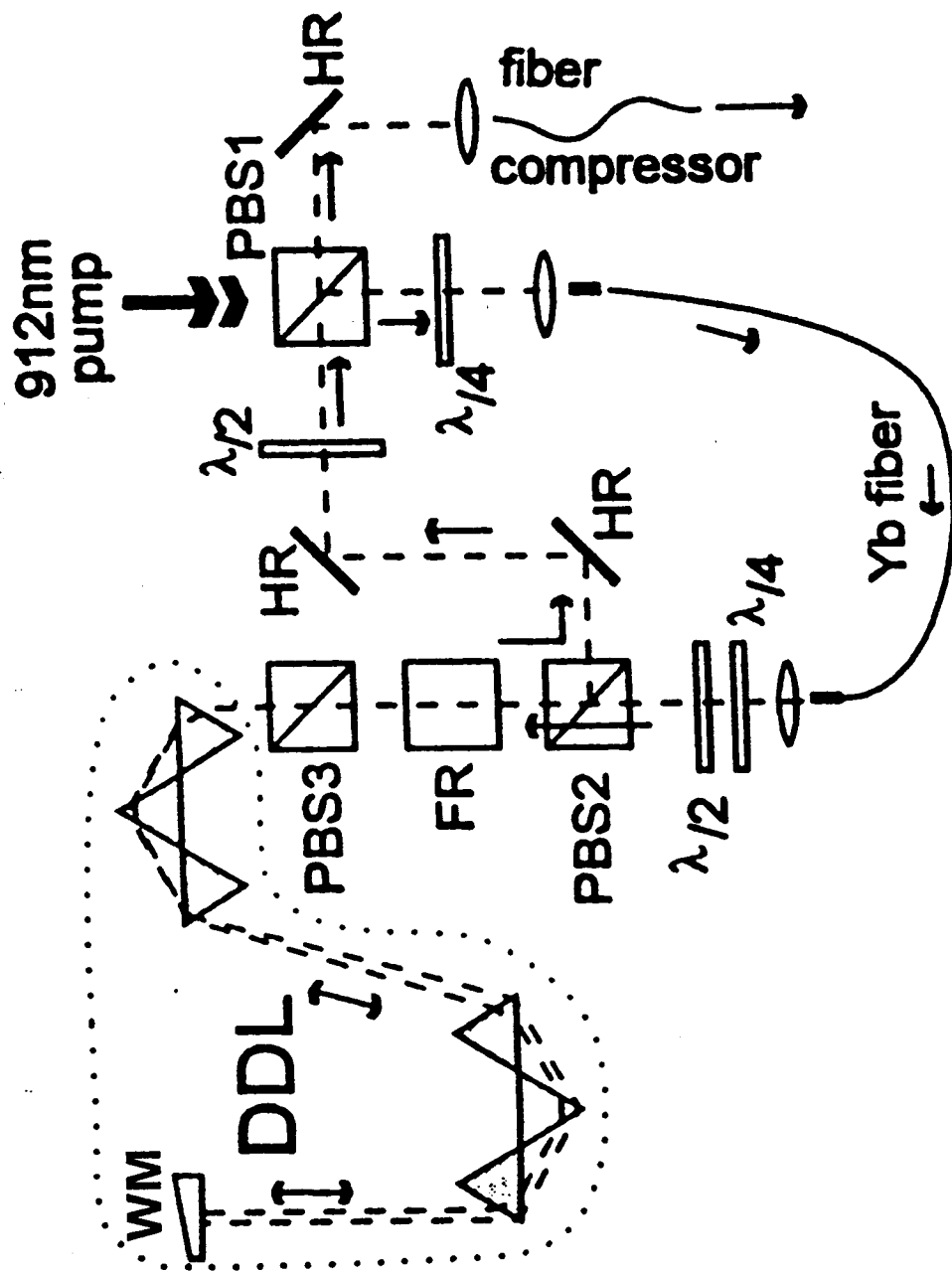


Fig. 1 The experimental configuration. PBS= polarisation beam splitter, HR= high reflectivity mirror, DDL= Dispersive Delay Line, WM= 85% reflectivity wedged mirror.

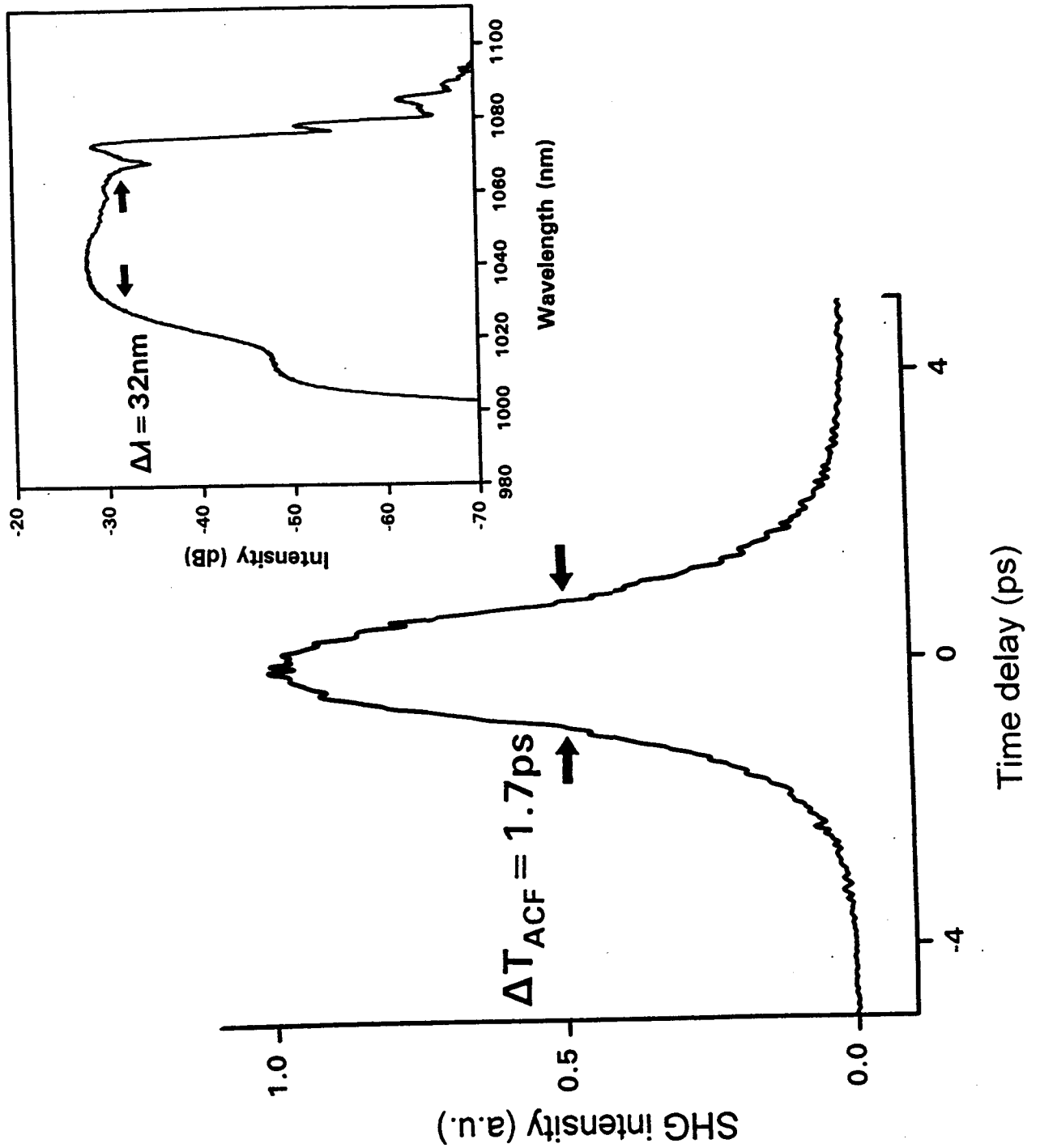


Fig. 2 Autocorrelation trace and spectrum of chirped output pulses prior to compression with the fibre compressor. Actual pulse width is 1.2 ps assuming a Gaussian pulse form.

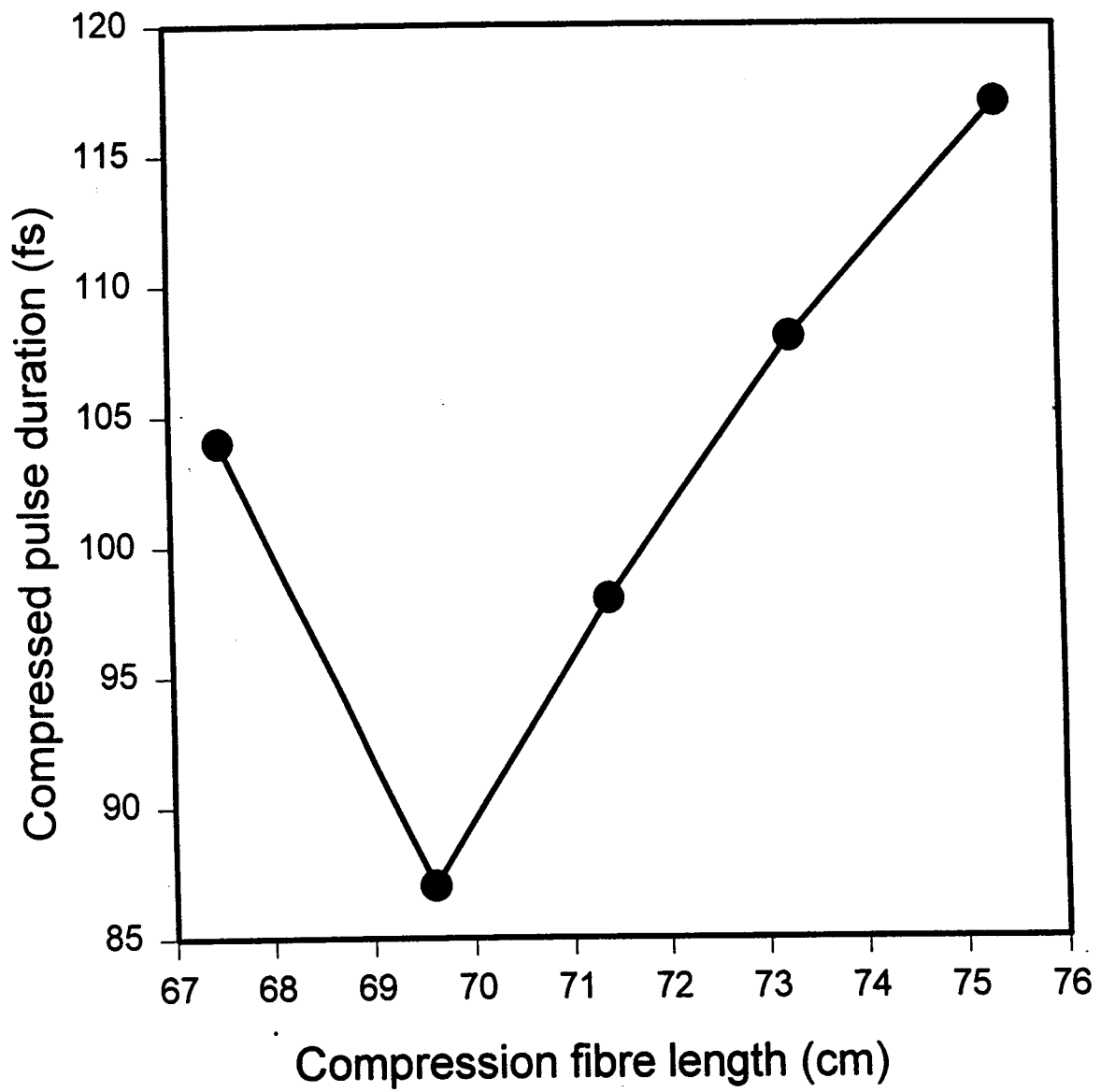


Fig.3 Output pulse duration as a function of the compression fibre length for the pulses shown in Fig. 2.

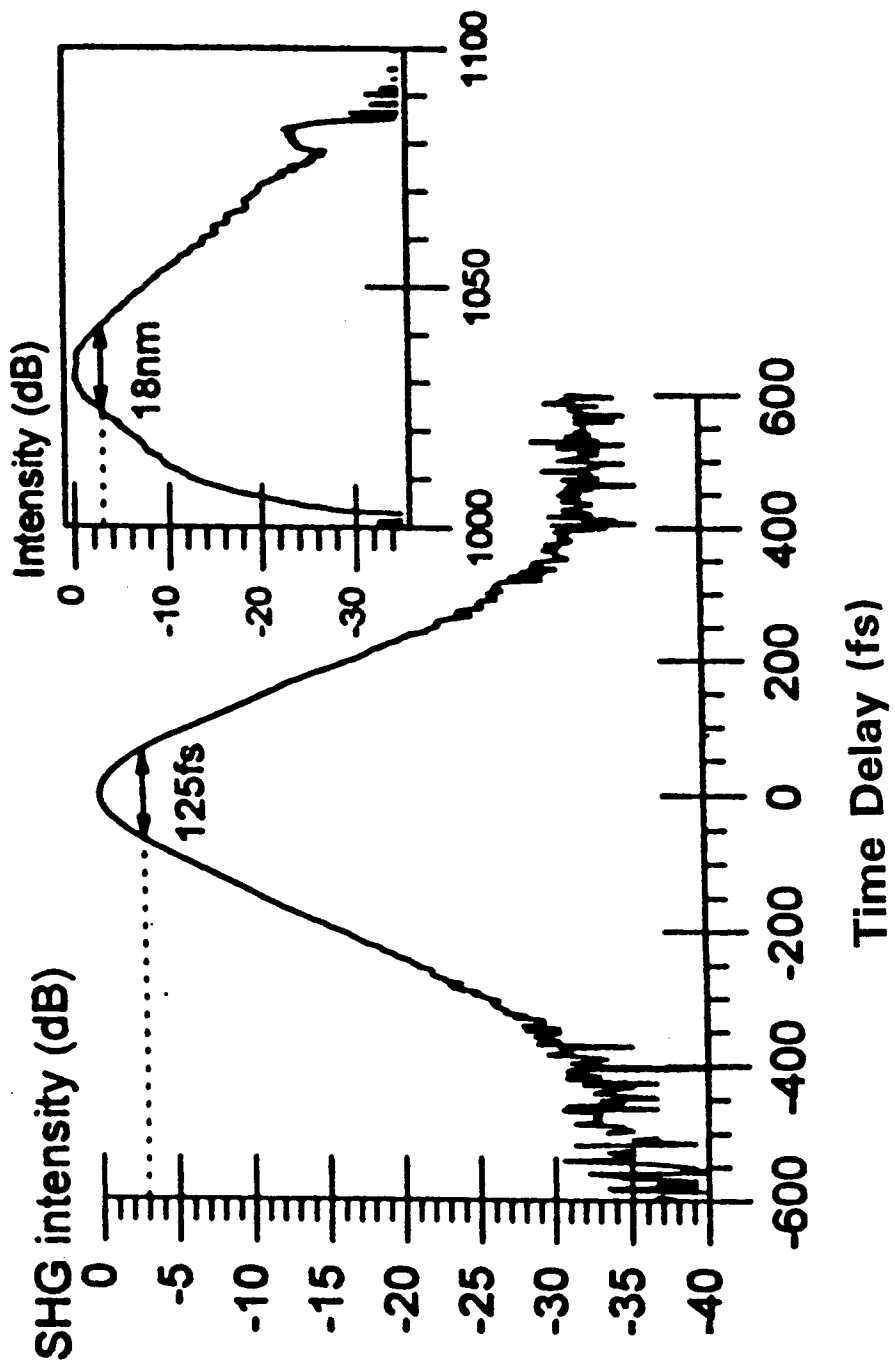


Fig.4 Autocorrelation and spectrum of the pulses obtained after the external cavity pulse compressor. The pulse width is calculated to be 87 fs, assuming a Gaussian pulse shape.