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High Power chirped pulse all-fibre amplification system based on large mode area fibre components

N. G. R. Broderick, D. J. Richardson, D. Taverner,* J. E. Caplen, L. Dong, M. Ibsen

Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK.

Phone: +44 (0)1703 593144, Fax: +44 (0)1703 593142, email: ngb@orc.soton.ac.uk

Abstract

The fabrication of large mode-area single mode fibres are crucial to developing high power all-fibre lasers and amplifiers. We report the amplification of picosecond pulses to microjoule energy levels and pulse peak powers in excess of 500kW in an all fiber Chirped Pulse Amplification (CPA) system based on novel large mode area fiber components.

1. Introduction

Chirped pulse amplification (CPA) is a well known technique for producing high power short optical pulses[1,2] suitable for a wide range of applications including nonlinear experiments and time resolved spectroscopy. Using such techniques with bulk amplifier systems it is possible to produce femtosecond optical pulses with terawatts of peak power[3].

In a CPA system a short transform limited optical pulse is first chirped by a highly dispersive element and thereby temporally stretched by factors of up to 10000. The pulse is then amplified to a high energy before being recompressed back to its initial duration at the system output by a device of opposite dispersive characteristics to the pulse stretcher.

*Present Address:3M Bragg Grating Technologies, 206 West Newberry Road, Bloomfield, CT 06002-1331 USA.

In this manner low peak powers are maintained, avoiding the limiting effects of nonlinearity within the amplifier, thus massively extending the peak powers attainable. Pulse stretching and compression is usually performed using bulk optic devices such as a diffraction grating pair. However in order to obtain the temporal stretching factors required grating separations of order 1 m are required, making such systems large and cumbersome to use.

Recently the CPA technique has been applied to pulse systems based on erbium doped fibre amplifiers opening up the possibility of robust, compact CPA systems based on linearly chirped fibre Bragg gratings (FBGs). FBGs are highly dispersive and can thus provide suitable time-delays in only centimetre lengths of fibre. For example using a 12 cm grating Galvanauskas *et al.*[4] demonstrated a CPA scheme capable of producing 2 ps pulses with energies of 300 nJ (corresponding to a peak power of 150 kW). One drawback to the use of FBGs is that they are intrinsically nonlinear and at high powers this nonlinearity degrades the pulse quality. The power level at which this occurs clearly depends on the mode area of the fibre and hence it is advantageous to use fibres with large mode areas but which are still single-mode at the operating wavelength. Recently such a fibre was developed for use in high power amplifiers in order to reduce the effect of the nonlinearity as well as allowing for more efficient energy extraction[5]. By slightly modifying the composition of this fibre we are able to fabricate photosensitive large mode area fibres suitable for grating writing. These gratings were then used as the compressor for a CPA system based around an erbium fibre amplifier chain to produce an all-fibre based source of high power (> 500 kW) short pulses.

2. Experimental Results

The schematic of our experimental setup is shown in Fig. 1. The pulse source is a passively mode-locked erbium fibre ring laser producing transform limited 1.5 ps soliton pulses at a repetition rate of 1.67 MHz at (tuneable) central wavelengths around 1534 nm. The soliton pulse energy is 10 pJ. The pulses were then stretched to a duration of $\approx$ 600 ps after reflection from a 20 cm linearly chirped grating FBG1 (described below). After being stretched the resulting pulse train was amplified in an EDFA to an average power of 10 dBm and then passed through a pulse selection system based on an AOM with fast 100 ns rise and fall times. The pulse selector could be used to step down the repetition rate of the pulse train to a user definable subharmonic of the laser repetition frequency. In the experiments described herein we selected a pulse repetition rate of 10 kHz. The selected pulses were then amplified in a 3m long, low noise optical preamplifier to an energy of ≈ 100 nJ before being launched through a second gated AOM (used to reduce the affect of ASE induced gain saturation) into a final stage, double pass amplifier of 80cm length constructed from large mode area erbium doped fiber which allowed for efficient energy extraction and low optical nonlinearity[5]. The energy of the pulses at the amplifier system output was $\approx 15\,\mu$J. By appropriate polarisation control the pulses were then launched onto grating FBG2, recompressed and output from the system. Note that the pulse energy launched into FBG2 could be controlled by rotation of a half wave plate (see Fig.1). The coupling efficiency from the final stage amplifier output to compressor output was around 45%.

To cope with the high energies in the final stage compressor a specially designed large mode area fibre was fabricated. The refractive index profile shown in Fig. 2 consists of a low index three layered core surround by a depressed index cladding. Note that the feature size of the layers in the core is too small to effect the fundamental mode profile. The core was co-doped with germanium and boron to increase the photosensitive whilst providing suitable control of the refractive index. The low refractive index difference between the core and the cladding ensured that the fibre remained single moded with a NA of ~ 0.05, a cutoff wavelength of 1300 nm and an estimated mode area of $450\,\mu m^2$, i.e. between 4 to 10 times that of fibre conventionally used to write FBGs. We therefore anticipated a corresponding increase in achievable output pulse energies and powers relative to previous all-fibre CPA systems[6].

This fibre was then hydrogen loaded to further increase the photosensitivity. Fig. 3 shows the reflection characteristics of the compressor grating (FBG2) written in this fibre. The compressor grating was 10 cm long with a bandwidth of 2 nm with a chirp of 439 ps/nm and 90% reflectivity. FBG1 (stretcher) was 20cm long with a bandwidth of 4nm and was linearly chirped with a slope of $-442\,\mathrm{ps/nm}$. The peak peak reflectivity of the grating was approximately 10%. FBG1 was mounted in a temperature controlled rig which allowed an arbitrary thermal gradient to be placed along its length in order to precisely control the chirp. Both gratings were written using a scanning phase-mask technique[7] and both gratings were apodised so as to reduce the ripples in the time-delay.

We first examined the quality of the pulse amplification and compression with low powers launched into the recompression grating FBG2, optimising the source wavelength for minimum linear distortion. With no thermal gradient on FBG1 pulse recompression to 4.0ps was readily achievable representing a pulse broadening by a factor of 2.7 due to spectral gain shaping, spectral filtering by the FBGs and the slight mismatch between the dispersions of FBG1 and FBG2. By adjusting the temperature gradient and hence the chirp on FBG1 it was possible to reduce the pulse width to 3.5ps. This pulse quality was maintained up to a reflected pulse energy of 900 nJ, corresponding to a peak power of $\approx 225\,\mathrm{kW}$ (see Fig. 4). At higher output pulse energies nonlinear pulse distortion became apparent as shown in Fig. 5 where we show the corresponding output autocorrelation function and spectrum for an output pulse energy of $2.5\,\mu\mathrm{J}$. Note that the pulse is much squarer due to nonlinear reshaping but that the pulse compression still appears to be reasonable. If we assume a $sech^2$ shaped pulse the pulse FWHM is 5.00 ps. The peak power of these pulses corresponds to 500 kW. The nonlinear distortion is more evident in the spectral domain where the side-lobes are more distinct and the onset of Raman scattering is observed

3. Conclusion

We have designed and fabricated photosensitive large mode area fibre Bragg gratings and demonstrated their use use in a compact, robust all-fibre based CPA system. We have obtained good quality picosecond pulses with pulse energies in the microjoule regime and peak powers as high as 500 kW. The results represent a significant advance upon previous all fibre

CPA systems and our simulations indicate that substantially higher pulse energies and powers should be achievable by further optimisation of the gratings. We believe such practical sources to have great potential for use in a wide range of nonlinear optics applications. This pulse source has already proved to be a convenient and efficient pump for optical parametric interactions in periodically poled lithium niobate. For example when pumping an optical parametric amplifier it gave record gains for a fibre laser pumped system[8]. Furthermore it is expected to find numerous other applications such as continuum generation or material processing.

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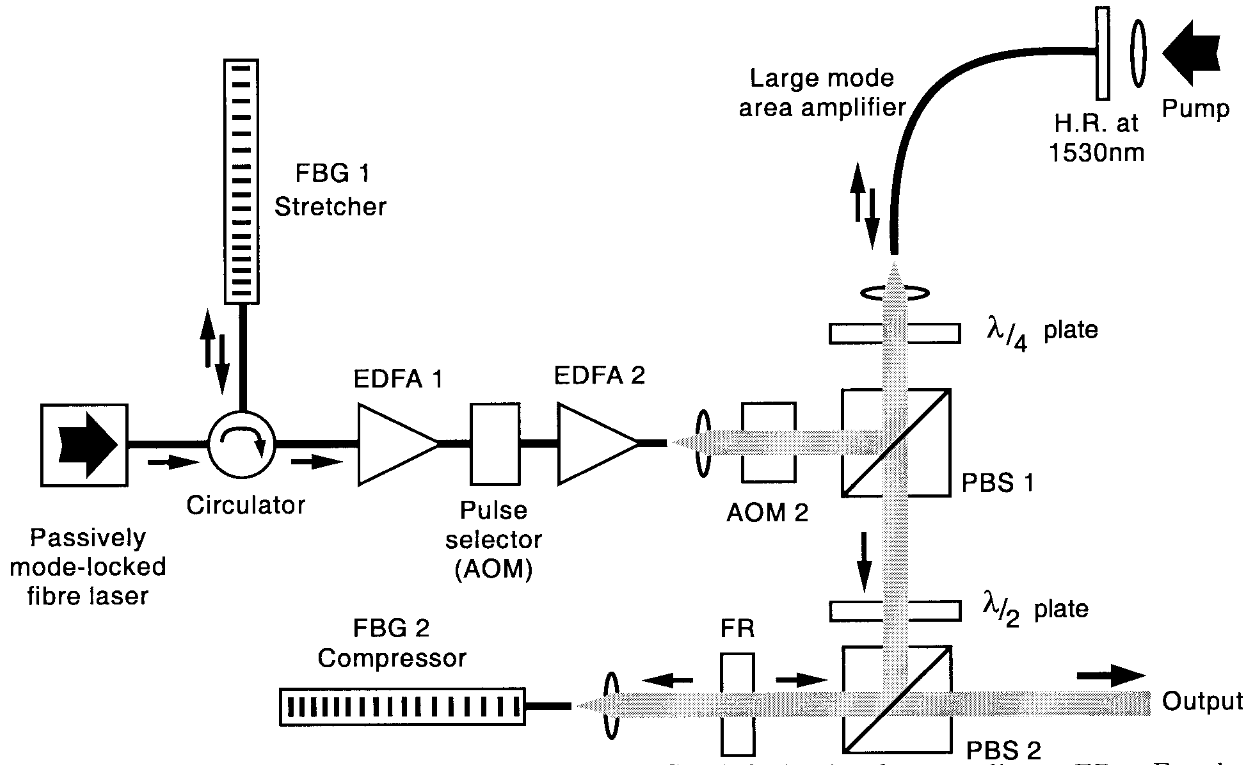

Fig. 1. Schematic of the experimental setup, PBS - Polarisation beam splitter, FR – Faraday rotator. See text for more details.

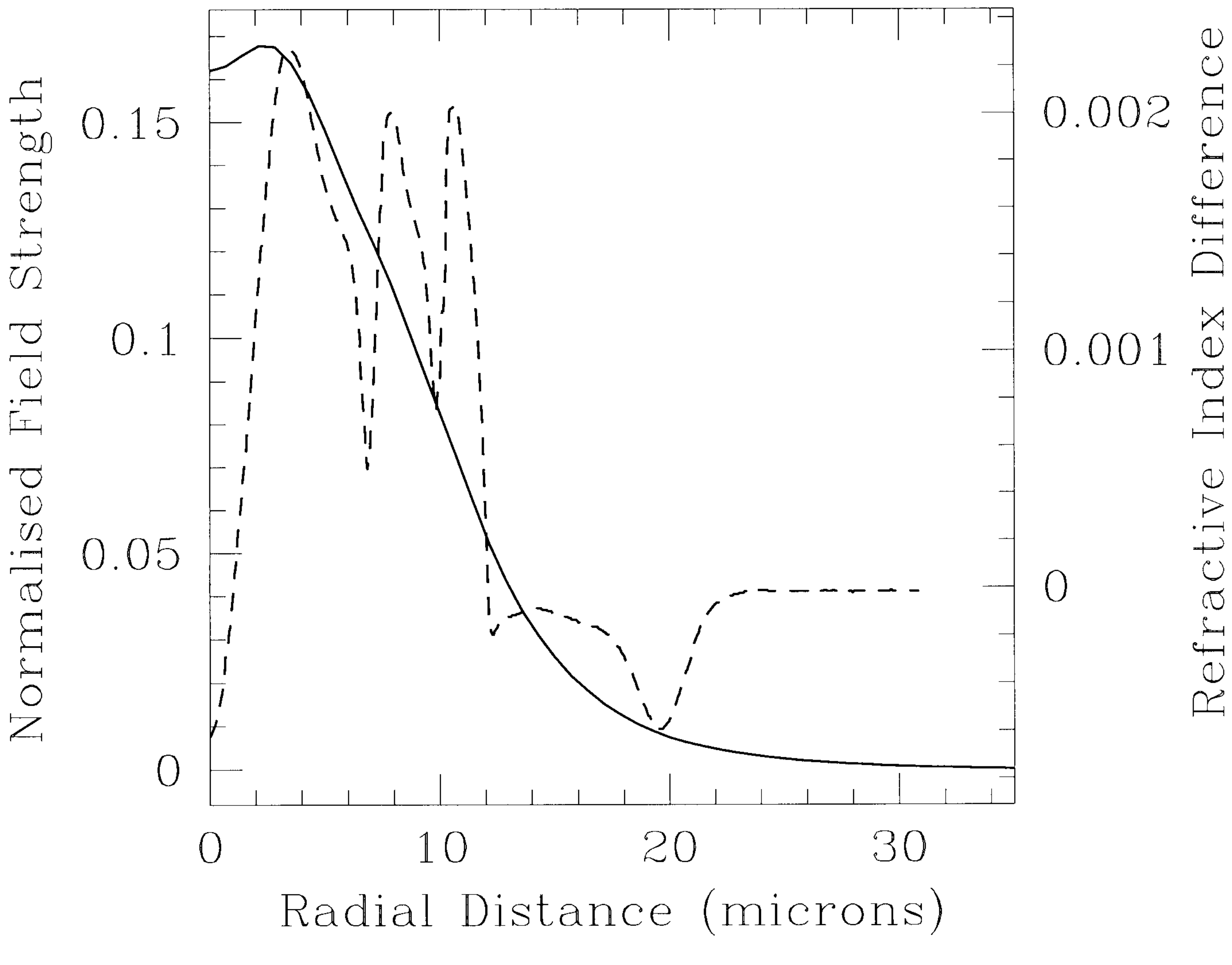

Fig. 2. Theoretical mode profile (solid line) and measured refractive index profile (dashed line) for the large mode area photosensitive fibre.

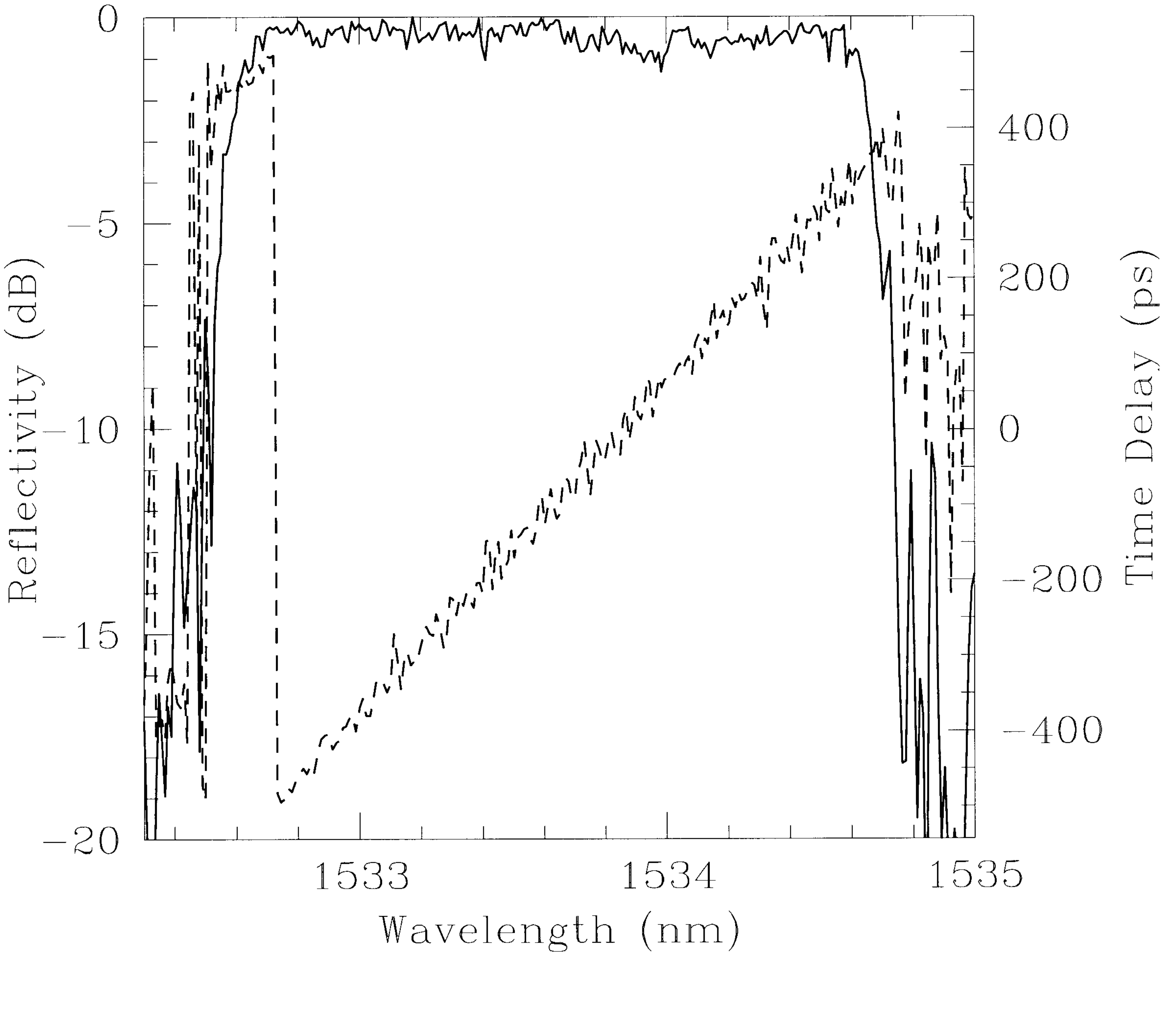

Fig. 3. Reflection spectrum of the 2nd chirped grating (FBG2). The solid line shows the reflectivity while the dashed line indicates the delay.

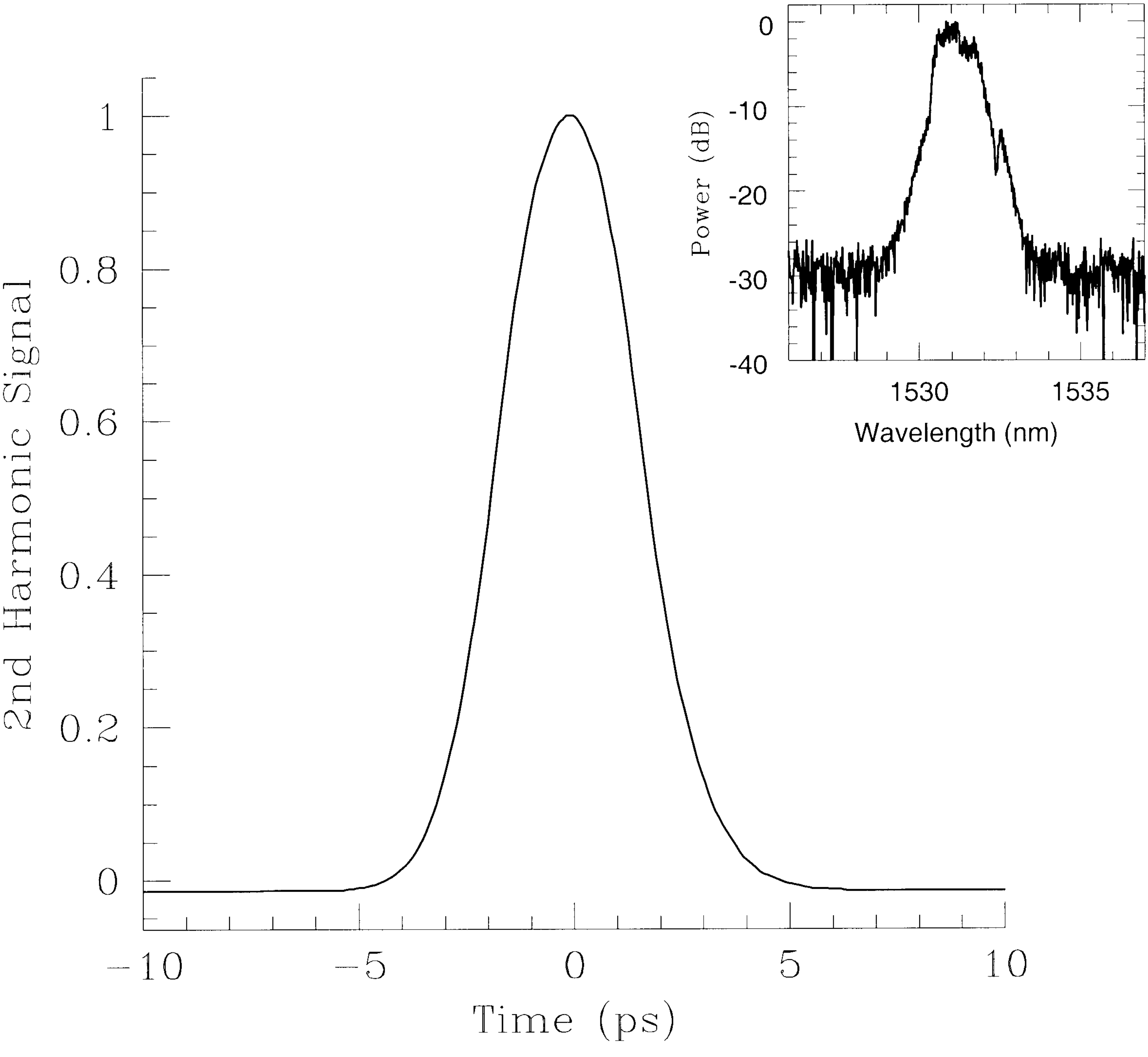

Fig. 4. Low power (900nJ) pulse autocorrelation trace (pulse width 3.5 ps). The measured pulse width is for an assumed $sech^2$ shape. The insert show the measured pulse spectra.

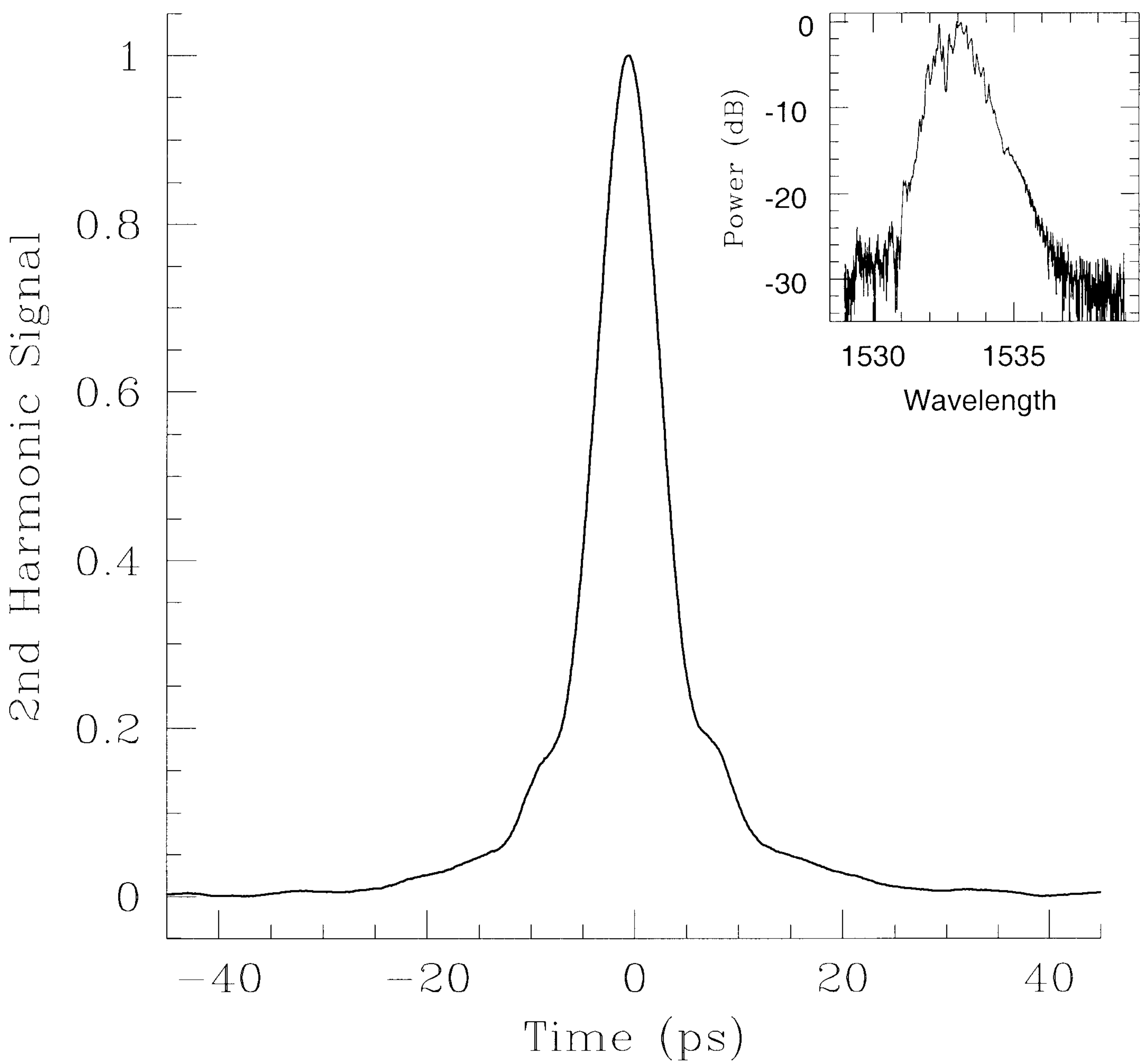

Fig. 5. High Power (2.5 μJ) autocorrelation trace (pulse width 4.98 ps). Insert show the measured pulse spectra.