610

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CW SOLITON TRAIN GENERATION IN THE REPETITION RATE RANGE 60-90 GHZ USING A DISPERSION DECREASING FIBRE.

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Abstract

We report the generation of stable, CW soliton trains at 1.551 μm using a technique based on the nonlinear propagation of a beat-signal in a dispersion-tailored fibre system. Repetition rates in the range 60-90 Gbit/s and mark-space ratios in the range 1:5 to 1:11 were obtained.

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Introduction

Ultra-high bit-rate sources of soliton pulses capable of operating in the gigahertz region are of considerable interest for the next generation of optical fibre telecommunication systems, as well as for optical signal processing. An all-optical method for ultra-high frequency soliton train generation has recently been suggested [1,2]. The technique is based upon the beating of two narrow-linewidth CW beams in an amplifying fibre. As the beat-signal propagates within a fibre which slowly amplifies it, the nonlinear and dispersive effects gradually transform the beat-signal into a soliton train. The propagation of solitons in a fibre of steadily decreasing dispersion is formally analogous to the propagation of solitons in an amplifying fibre. It is therefore possible to generate soliton trains using the same technique simply by replacing the amplifier fibre by a dispersion decreasing fibre (DDF) [1-3]. Fabrication technology for such fibres has been developed [3]. This method of soliton train generation permits one to generate high-quality trains of well separated, pedestal free, non-interacting solitons with no frequency modulation or cw background. The pulse repetition rate is determined simply by the frequency separation of the two source lasers. The technique permits the generation of soliton trains at repetition rates ranging from several tens of GHz to rates approaching the THz regime, providing appropriate beat-signal powers and suitable amplifying or, DDFs, can be obtained. The ratio of the pulse duration to the pulse separation (the Mark Space Ratio (MSR)), can be varied over a wide range from 1:5 to values in excess of 1:10. At these values of MSR the interaction between neighbouring solitons is reduced to a negligible level. The technique allows wide tunability of the soliton train repetition rate, the soliton duration, the MSR and also the soliton central frequency. Using a single DDF one can cover a wide range of operating requirements by simply tuning the signal power and input frequency separation.

In the first experimental demonstration of this technique [2] a parametric light source of optical pulses with an intra-cavity Fabry-Perot etalon was used to provide the input signal. The source produced two, time-coincident 25 ps pulse at central frequencies differing by 200 GHz. The resulting 25 ps, 200 GHz beat-signal pulse was then propagated in a 1 km fibre with decreasing dispersion and resulted in 25 ps long bunches of five solitons (200 GHz). In a second experiment two single frequency DFB laser diodes were used to create a beat-signal which was then amplified in an erbium-doped fibre amplifier and propagated in a 2.2 km DDF. The system generated 1 μs trains of identical solitons with durations in the range 1.5-3 psec at repetition rates in the range 80-130 GHz. Each train contained $\approx 10^5$ solitons and the train repetition rate frequency was $\approx$500 Hz. It was also shown that stimulated Brillouin scattering could hinder the generation of such long soliton trains. The problem was eliminated by suppression of the Brillouin scattering by weak modulation of the phases of the CW light beams by adding weak current modulation to the laser diode drive current.

In this paper we report the generation of a real CW train of solitons at repetition rates in the gigahertz range based on a slight variation of the above technique. In our experiments two CW DFB lasers operating around 1.55 μm were used to generate a beat-signal which was then amplified in an EDFA. The amplified beat-signal was first propagated in a 1 km section of dispersion-shifted fibre (DSF) and then transformed into a soliton train during propagation through a 1.6 km section of DDF. Repetition rates in the range 60-90 GHz with MSRs in the range 1:5 to 1:11 have been achieved. We describe and discuss the system behaviour with respect to the repetition rate and MSR tuning ranges and present theoretical results which clarify the role of the additional section of DSF.

Experiments.

The experimental configuration is illustrated in Fig.1. The two, pig-tailed, single frequency DFB lasers (DFB1 and DFB2) were combined using a 50:50 coupler. The resulting beat-signal was then passed through a polarisation sensitive isolator (isolator 1) and into an erbium-doped fibre amplifier (EDFA) with counter-propagating pump. The isolator not only isolated DFB1 and 2 but also served to ensure that the output from the two diodes was in the same polarization state. Polarization controllers were included in both input leads to the combining coupler in order to maximise and equalise the relative intensities of the input signals passing through isolator 1. A combined signal strength of 0.2 mW could be launched into the EDFA. A 980/1550 WDM coupler was placed just after isolator 1 to enable monitoring of the EDFA input signal and to protect this isolator from damage due to unabsorbed 980 nm pump. The temperature of the two diodes could be independently varied to an accuracy of 0.01 K over a range of 30 K about room temperature enabling the laser wavelength separation to be tuned between 0 and 2.5 nm. The EDFA was pumped using a Ti:Sapphire laser giving upto 3W of optical power at 978 nm. The 978 nm radiation was coupled into the EDFA via a second WDM coupler, the 978 nm tap port enabled the input pump power to be monitored and accurately stabilised using a servo-circuit and Bragg cell placed in front of the launch optics. The EDFA fibre was based on a silica-germano-alumina host, contained 160 ppm Er^{3+}, with an NA = 0.2, and a cut-off wavelength of 930 nm. The EDFA had a length of 35m. The amplified beat-signal was passed through a second polarisation-insensitive isolator (isolator2) which prevented feedback into the EDFA from the rest of the system. Up to 300 mW of amplified signal was available at the isolator output. A section of dispersion-shifted fibre (DSF) of 1 km length was then spliced to the isolator output. The fibre had a dispersion $|D| < 1.5$ ps/nm/km at 1551 nm. The DDF was spliced to the end of the DSF. The DDF fibre was fabricated using a recently developed technique [3]; whereby its external diameter was tapered down from 155 μm at the input to 112 μm over a length of 1.6 km. Thus, the dispersion at 1.55 μm varied between D = 10 ps/nm/km and D = 0.5 ps/nm/km at the input and output respectively. The dispersion-length profile was designed to be close to a hyperbolic form and to be suitable for soliton train generation at repetition rates > 130 GHz whn used without the DSF [3].

A 90:10 coupler was spliced to the DDF output to facilitate real-time monitoring of the pulse train by a scanning background-free autocorrelator, an optical spectrum analyzer and a calibrated average power meter.

The system implementation we adopted is different to previously published techniques [1,2,4] in that we added a section of DSF before the DDF. The DSF was used to spectrally enrich the beat-signal through four-wave mixing prior to soliton formation and compression in the DDF. The basic mechanism of soliton train generation remains the same (the details will be considered in the next section). However, the modification permitted us to extend the range of applications of the DDF to both lower repetition rate trains and lower input beat-signal powers than could be obtained with the single DDF fibre section.

Results

The spectrum of a 300 mW beat-signal from the laser diode/EDFA combination after propagation in the 1km DSF is shown in Fig.2. The intensities of the sidebands generated by four-wave mixing are approximately 10 dB below the main spectral components and do not depend on wavelength separation over the range 0 - 0.8 nm. Autocorrelation functions measured at the input and output of the DSF were identical and were fitted by a sinusoidal beat-signal of the form $G(\tau) = 1 + 2\mathrm{Cos}^2(\pi R\tau)$, where R is the repetition rate and τ is the time delay, leading to a 3:1 ratio between the maximum to minimum SHG autocorrelation intensity (Fig.2). Following spectral enrichment in the DSF the soliton train was generated in the DDF. Fig.3 shows the spectrum and corresponding background-free autocorrelation function measured at the output of the DDF for a launch power of 300 mW and DFB wavelength separation of 0.57 nm (70 GHz). The autocorrelation trace shows that we have generated a periodic train of well separated identical pulses at a repetition rate of 70 GHz. There is no background signal on the autocorrelation function and the trace is flat between pulses. The individual pulses have a good sech^2 form with no pedestal. The half-width of the autocorrelation function corresponds to a soliton duration of 1.3ps. The optical spectrum is enriched by many additional spectral components. It contains a discrete number of equally separated lines corresponding to a 70 GHz periodic signal. The peaks of the discrete spectral lines can be fitted by a continuous envelope which corresponds to the optical spectrum of the individual pulses forming the train. The autocorrelation function and spectrum provide a good fit for a train of 70 GHz solitons with durations of 1.3 ps and a corresponding MSR of 1:11. Figs.4,5 show background-free autocorrelation traces and corresponding optical spectra obtained for two other settings of the input beat-signal as indicated. In Fig.4 the DFB lasers had a separation of 0.62 nm (77GHz) and the input beat-signal power was 270 mW. In this case we have obtained a 77 GHz train of solitons with durations of 1.8 ps, this corresponds to a MSR of 1:7. Fig.5 illustrates the generation of a 90 GHz train of 2 ps solitons (MSR = 1:5.5) obtained for an input beat-signal power of 270 mW. These results demonstrate the wide tuning potential (with regard to the repetition rate, soliton duration and MSR) offered by this configuration with only the simple variation of power and frequency of the input beat-signal. Analysis of the full range of input beat-signal parameters investigated indicate that generation of high-quality solitons trains in the repetition rate range of 60-90 GHz and solitons durations in the range 1.3-4 psec was possible with our configuration.

It is also of significance to note that stimulated Brillouin scattering (SBS) which had proved problematic in previous experiments [4] was not encountered during the course of these experiments. The relatively high SBS threshold is thought to be due to the use of two different fibre sections [5]. In addition, the linewidths of the DFB lasers are slightly broader and the launched powers slightly lower than those used in [4].

Discussion.

The soliton train generation techniques which have been considered previously based on the effect of transformation of a beat-signal in a single DDF show that for a particular fibre design there exists a well defined range of repetition rates, soliton durations and corresponding MSR over which high-quality soliton trains can be generated. The principal parameters which define the DDF performance are the fibre length, the dispersion profile and the ratio of the input to output dispersion. In turn, the possible repetition rate and soliton duration ranges coupled to the value of the output dispersion dictate the input power required for effective system operation. For instance, the shorter the length of the DDF the higher the pulse repetition rates that can be generated and consequently the higher the input powers required. However, it is possible to extend the range of application of the available DDF by using a section of a DSF prior to the DDF as illustrated by our experiments and shown theoretically below. This permits one to generate soliton trains with lower repetition rates and powers than possible simply with the DDF fibre alone. To support this idea we theoretically consider the modified case. The theory is based on the numerical simulation of the nonlinear Schrodinger equation and is similar to the analysis undertaken in [1,2]. The propagation of the light in the fibre system can be described by the following dimensionless equation for the electric field envelope $\Psi(\tau, \xi)$

$$i\frac{\delta\Psi(\tau,\xi)}{\delta\xi}-\frac{1}{2}D(\xi)\frac{\delta^2\Psi(\tau,\xi)}{\delta\tau^2}+|\psi(\tau,\xi)|^2\Psi(\tau,\xi)+i\gamma(\xi)\Psi(\tau,\xi)=0$$

where $D(\xi)$ and $\gamma(\xi)$ are the dimensionless chromatic dispersion and losses, respectively. The initial signal $\Psi(\tau,0)$ is a beat-signal

$$\Psi(\tau,0)=aSin(\pi\tau/2)$$

The dispersion of the first section of fibre is taken to be zero (DSF), followed by the DDF which is characterised by a hyperbolic decrease in dispersion along its length. To take into account the system losses we simply include a step loss of 1 dB at the DSF/DDF splice. Expressed mathematically the fibre dispersion and loss are represented by

$$D(\xi)=\begin{cases}0, & 0<\xi\leq\xi_1\\ 0.9(1+12(\xi-\xi_1))^{-1}, & \xi_1<\xi<\xi_2\end{cases}$$

$$\gamma(\xi)=\alpha.\delta(\xi-\xi_1)$$

The parameters used in the numerical simulation $a=1.3$, $\alpha=1.1$, $\xi_1=0.7$, and $\xi_2=1.7$ correspond to those of the experimental system described in this paper. The results of the simulation are presented in Figs.6 and 7.

In Fig.6 we present both temporal and spectral characteristics of the pulse train as calculated at the input, at the end of the DSF and at the DDF output. It can be seen that four wave mixing during propagation in the DSF leads to spectral enrichment. Comparing Figs.6b and d it is found that the amplitude of the generated sidebands are 10dB down relative to the source signals, as observed experimentally. Note that the temporal form of the beat-signal is unaffected (see Figs.6a and c). However, the small four wave mixing enhances the compression stage of the soliton formation in the DDF. As a result high quality soliton trains can be generated in this modified configuration at lower repetition rates and powers than possible with the single DDF stage. Figs.6e,f and Fig.7 show the linear temporal, spectral and logarithmic temporal characteristics respectively at the DDF ouput as obtained from the simulation and clearly demonstrate pedestal free pulse formation. In Fig.8 data comparing the evolution of the pulse peak power and width along the DDF fibre with and without prior spectral enrichment of the beat-signal in the DSF is presented. Note that soliton formation is not possible at these input beat-signal parameters without the DSF.

Summary.

In conclusion, we have experimentally generated stable, CW trains of high purity, fundamental solitons at repetition rates in the range of 60-90 GHz and Mark-Space Ratios as high as 1:11, using the technique of soliton train formation from nonlinear dual-frequency, beat-signal propagation in a dispersion decreasing fibre. We have demonstrated the suitability of an all-fibre, DFB, EDFA combination for the generation of the required beat-signal in such experiments. In addition, we have demonstrated both experimentally and theoretically that by adding a section of DSF prior to the DDF can extend the operating repetition rate range of a given DDF.

We believe that this highly stable, all-fibre scheme for generating high purity soliton pules with its wide wavelength, repetition-rate and MSR tuning range has great potential as a stable source of ultra-high repetition rate soliton pulses for use in future ultra-high bit-rate telecommunication systems.

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Figure captions

Fig.1. Experimental configuration.

Fig.2. Spectrum (a) and autocorrelation function (b) of the amplified beat-signal at the end of the 1.0 km DSF. The input beat-signal power was 300 mW.

Fig.3. Spectrum (a) and autocorrelation functions (b) of a 70 GHz soliton train at the output of the DDF. The input beat-signal power was 300 mW.

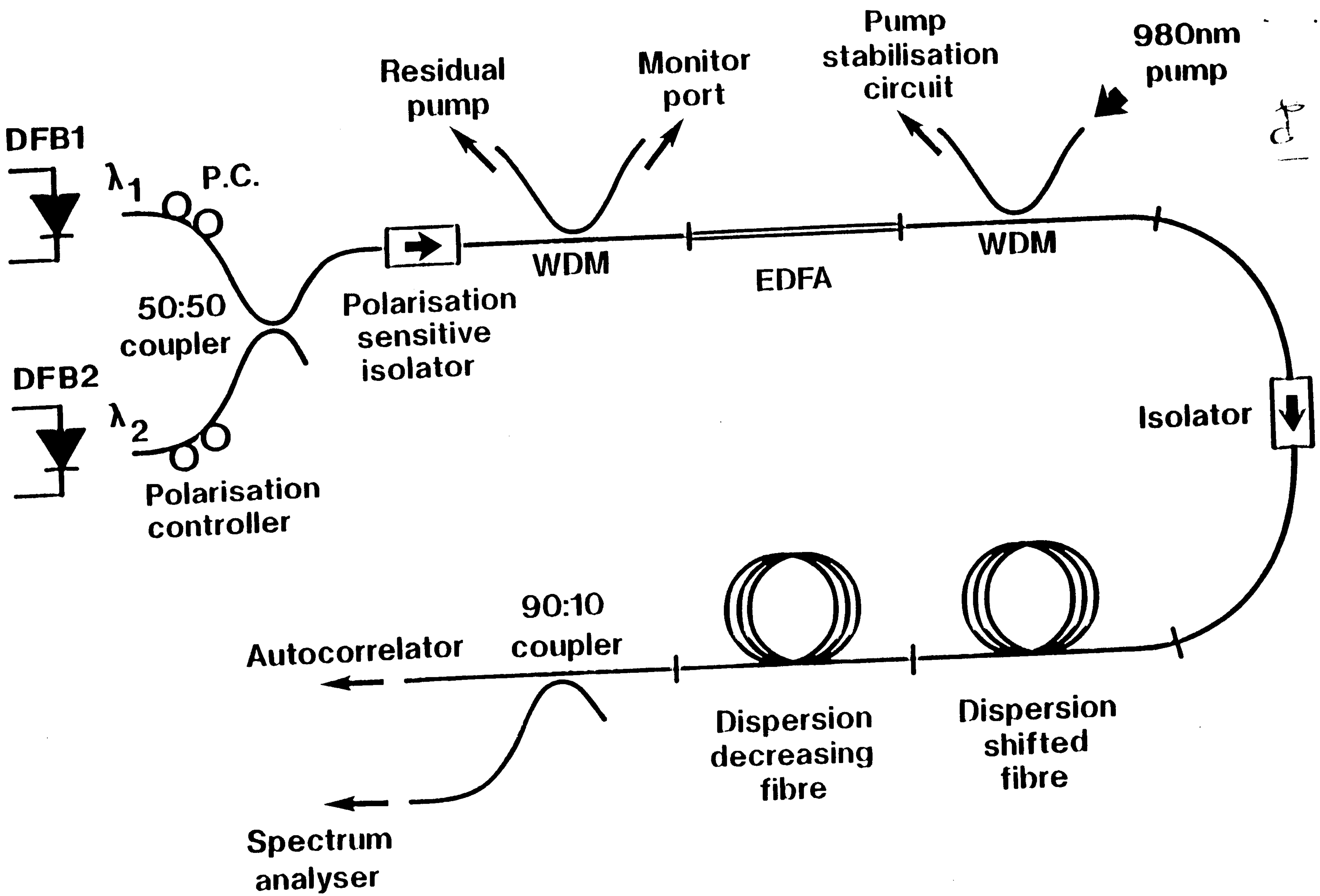
Fig.4. Spectrum (a) and autocorrelation function (b) of a 77 GHz soliton train at the output of the DDF. The input beat-signal power was 270 mW.

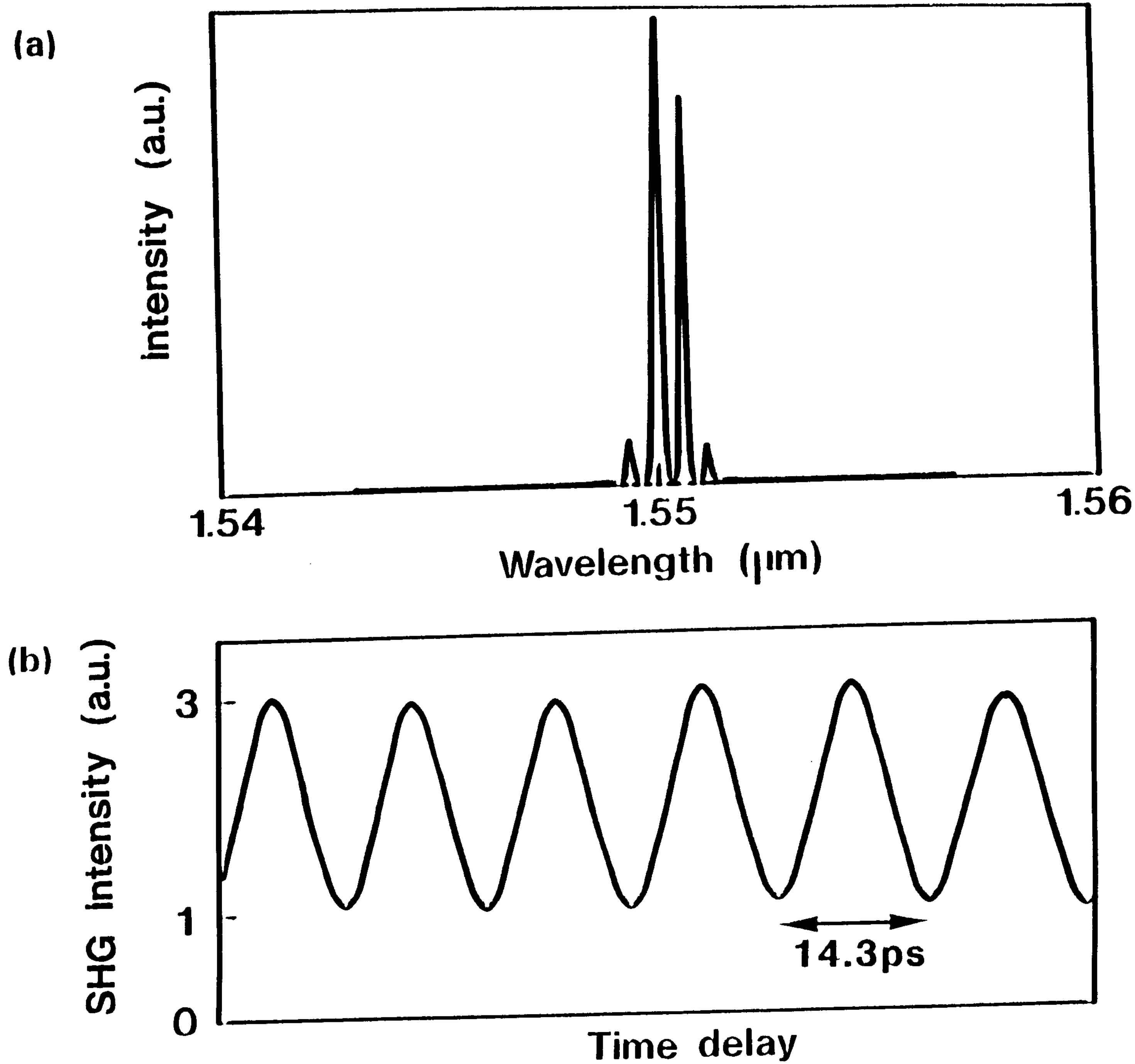
Fig.5. Spectrum (a) and autocorrelation function (b) of a 90 GHz soliton train at the output of the DDF. The input beat-signal power was 270 mW.

Fig.6. Results of the numerical simulations: Temporal intensity profile (a) and spectrum (b) of the initial beat-signal; Temporal intensity profile (c) and spectrum (d) at the output of the DSF; soliton train (e) and spectrum (f) at the DDF output.

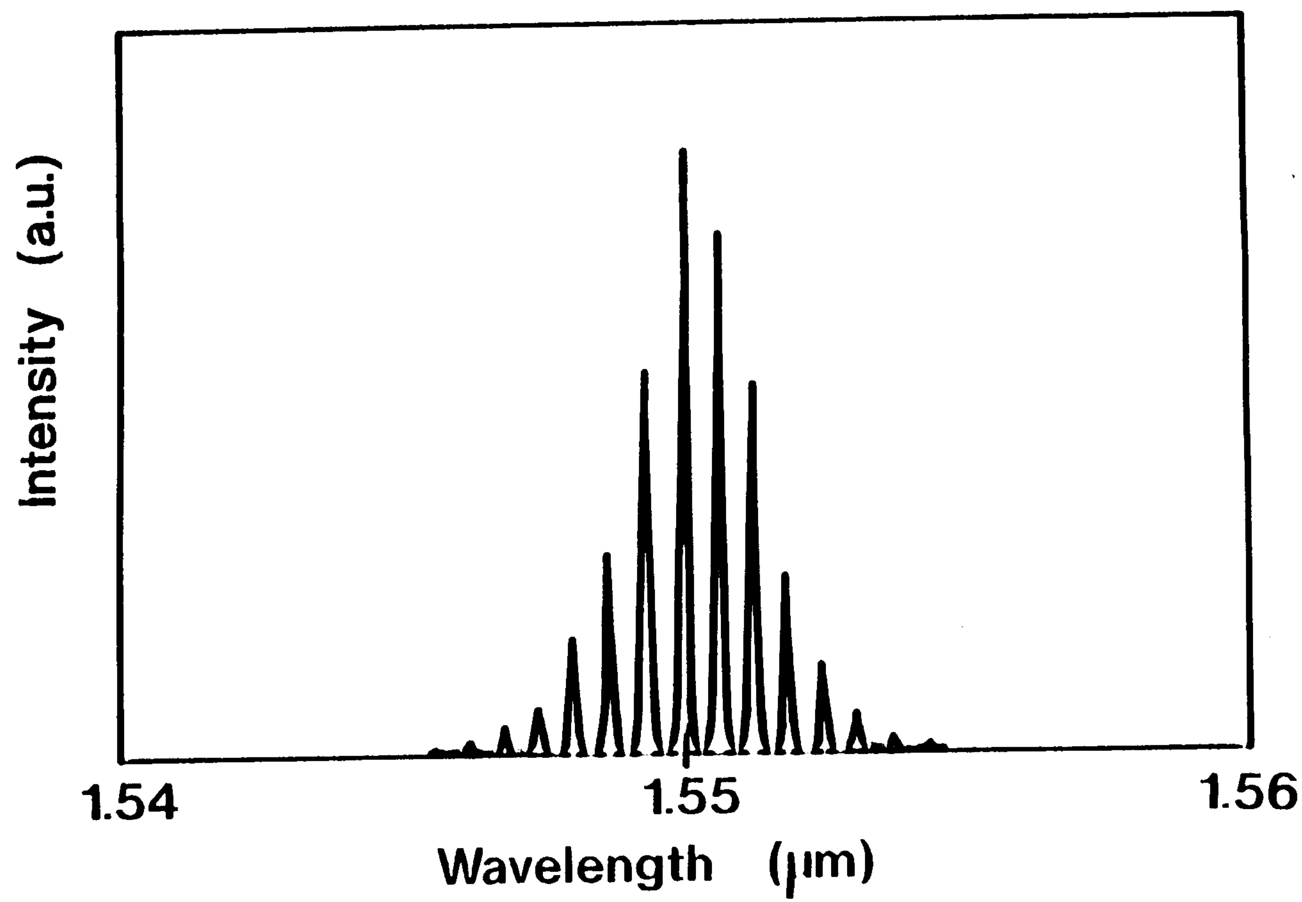
Fig.7. Logarithic plot of the soliton train at the DDF output clearly demonstrating the pedestal-free, pulse formation process.

Fig.8 Dynamics of the peak intensity and pulse duration (solid lines) in the DDF during formation of the soliton train shown in Figs.6 and 7. The dashed curves demonstrate the behaviour of the peak intensity and pulse duration for the same input signal parameters neglecting prior propagation in the DSF.

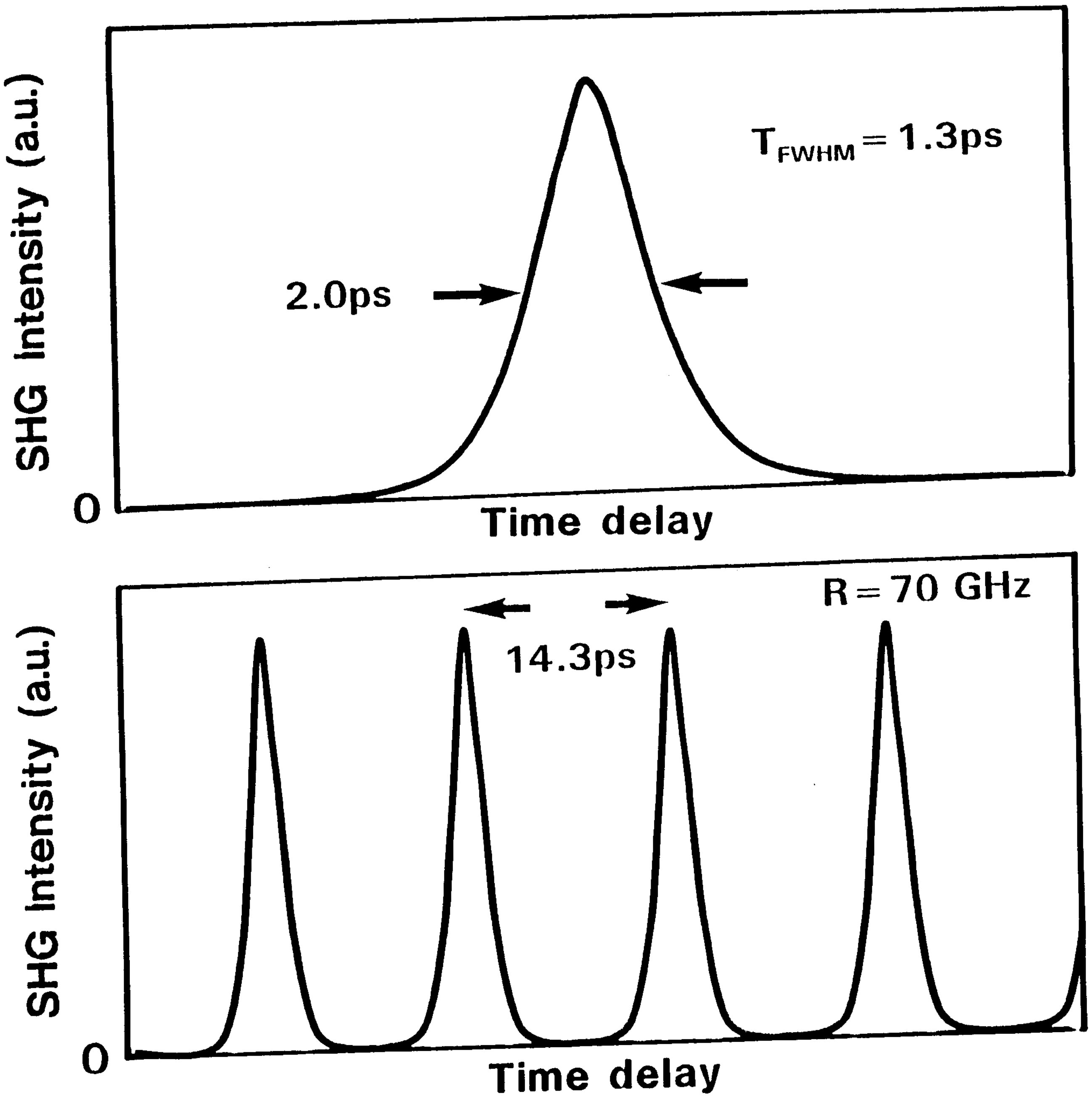

DFB1
λ1
P.C.
50:50
coupler
DFB2
λ2
Polarisation
controller
Polarisation
sensitive
isolator
Residual
pump
WDM
Monitor
port
EDFA
Pump
stabilisation
circuit
WDM
980nm
pump
Isolator
Autocorrelator
90:10
coupler
Spectrum
analyser
Dispersion
decreasing
fibre
Dispersion
shifted
fibre

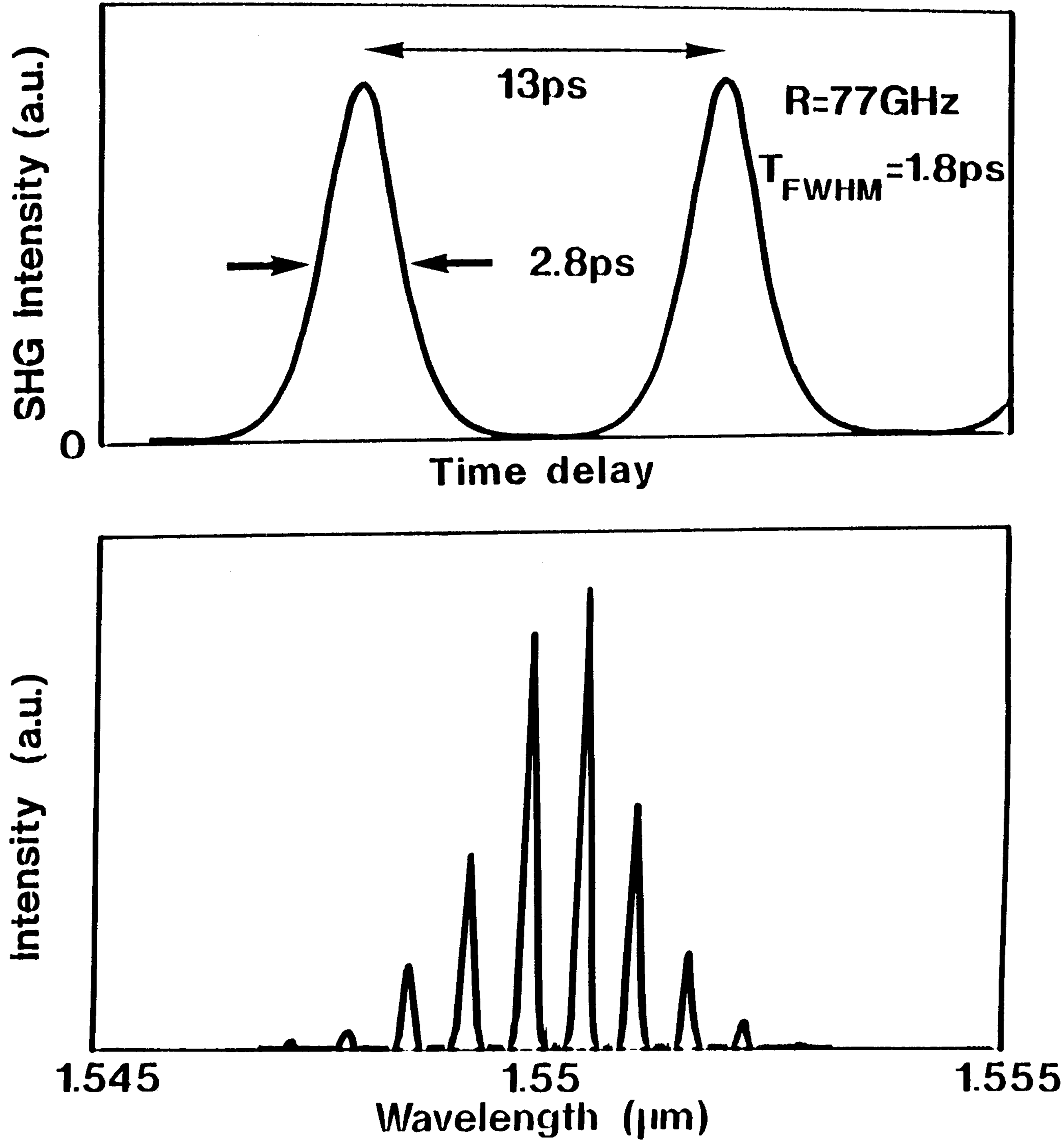

(a)
Intensity (a.u.)
1.54
1.55
1.56
Wavelength (μm)
(b)
SHG Intensity (a.u.)
3
1
0
14.3ps
Time delay

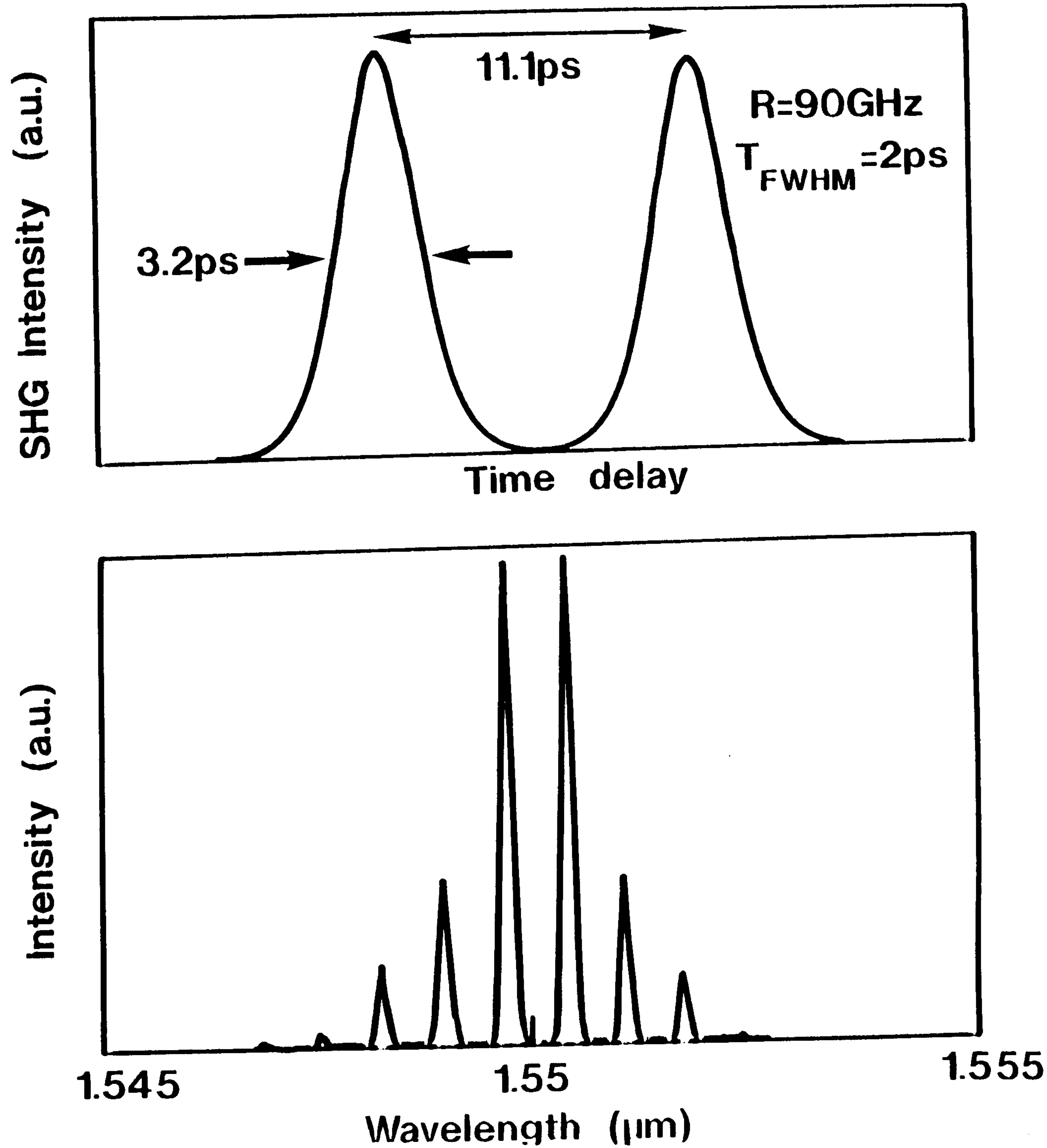
(a)



(b)


SHG Intensity (a.u.)
0
T_{FWHM} = 1.3ps
2.0ps
Time delay
SHG Intensity (a.u.)
0
R = 70 GHz
14.3ps
Time delay


13ps
R=77GHz
T_FWHM=1.8ps
2.8ps
SHG Intensity (a.u.)
0
Time delay
Intensity (a.u.)
1.545
1.55
1.555
Wavelength (μm)


11.1ps
R=90GHz
T FWHM =2ps
3.2ps
SHG Intensity (a.u.)
Time delay
Intensity (a.u.)
1.545
1.55
1.555
Wavelength (μm)

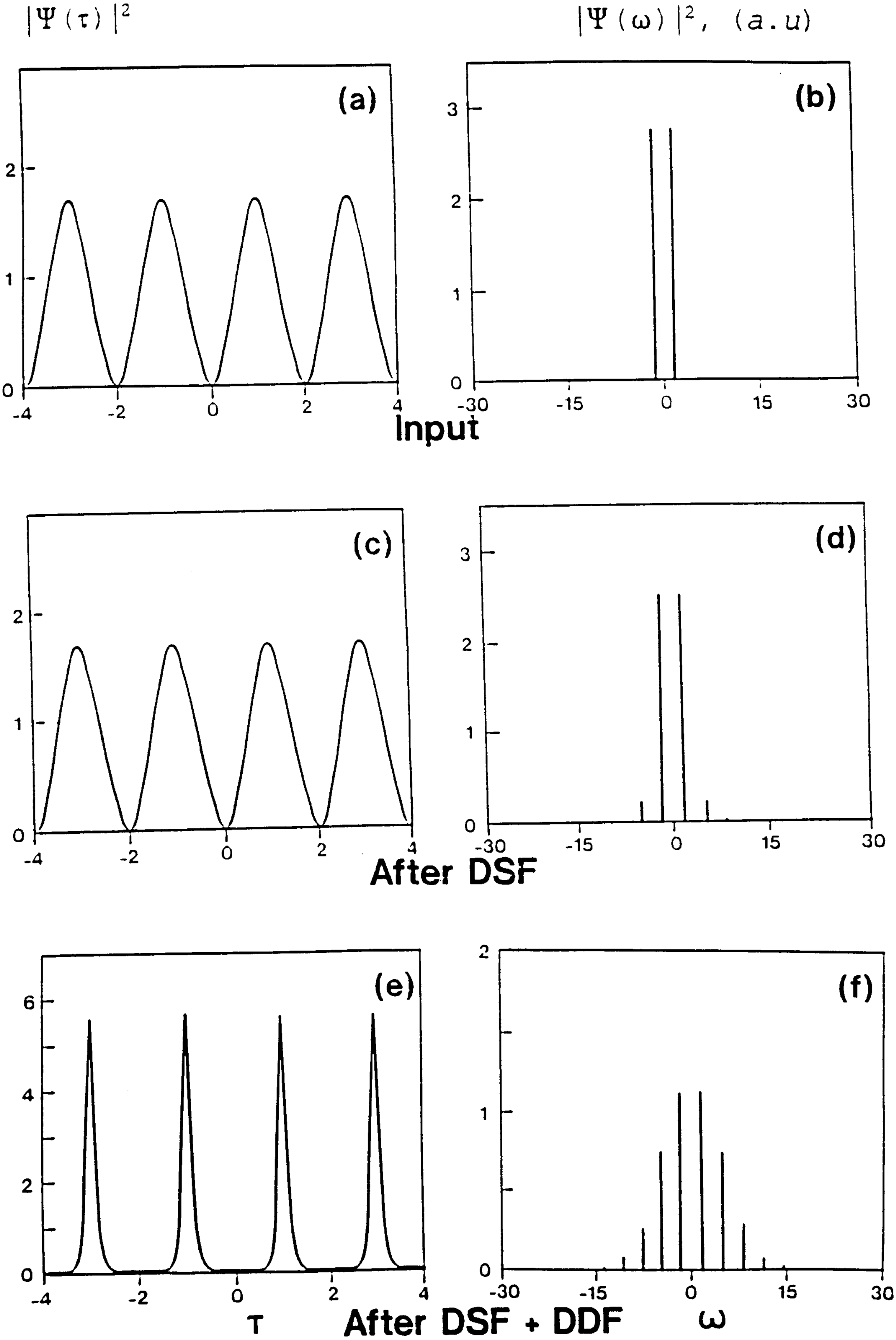
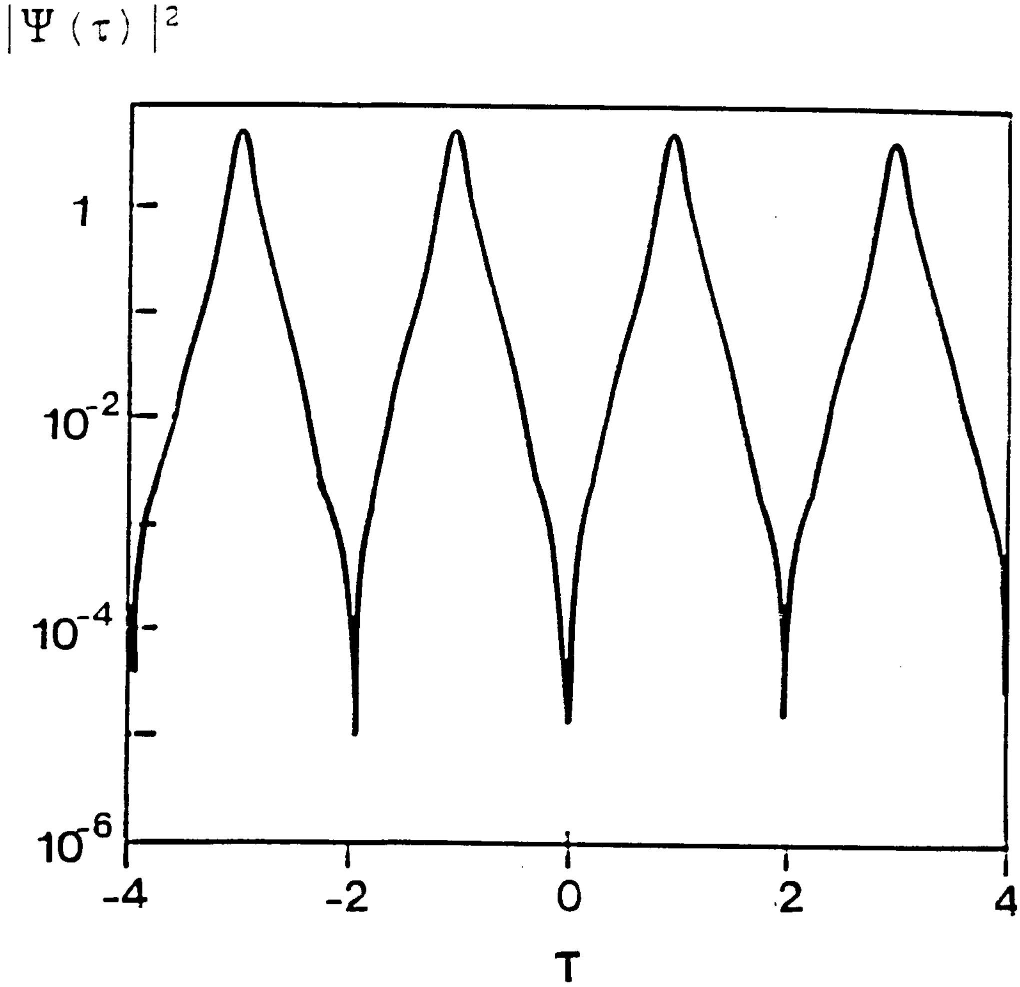

|Ψ(τ)|²
|Ψ(ω)|², (a.u)
(a)
(b)
Input
(c)
(d)
After DSF
(e)
(f)
τ
After DSF + DDF
ω

Fig 7



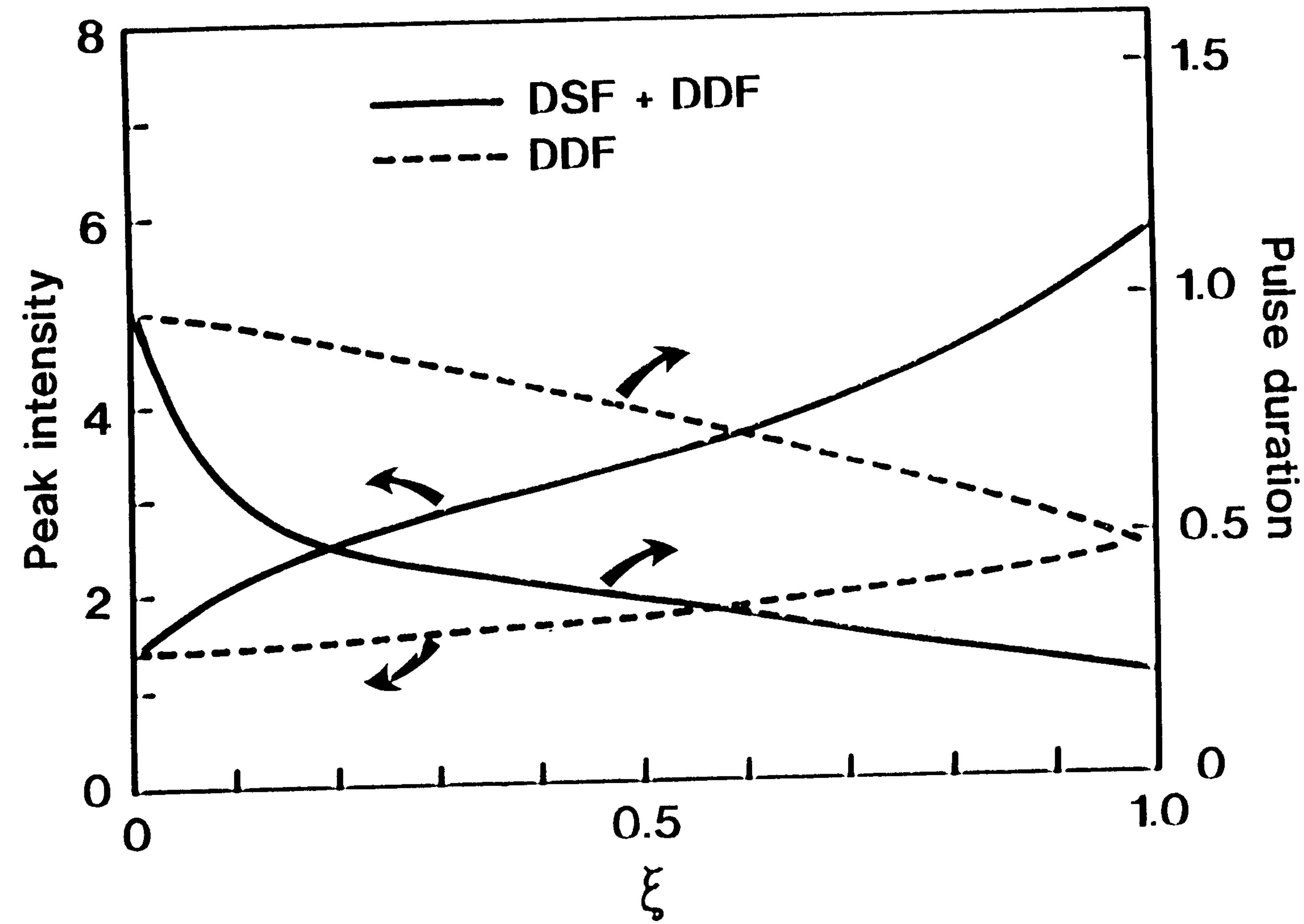


Fig 2