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# Soliton interaction in the presence of a weak non-soliton component

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**Abstract**

We study both experimentally and theoretically soliton interaction in the presence of a weak non-soliton component and show that the existence of a frequency shifted cw wave results in a temporal shift of the soliton.

In ultralong distance soliton transmission the limit to the single channel bit rate is defined by jitter in the pulse arrival time. The fundamental origin of the time jitter is the change of the soliton central frequency due to perturbations experienced by the propagating soliton [1]. Such perturbations can arise from spontaneous emission noise in optical amplifiers (the Gordon-Haus effect) [2], partial overlapping of adjacent pulses ("classical" soliton- soliton interaction effect) [3] or excitation of a weak acoustic wave [4]. Another wide spread source of perturbations is a weak cw component, accompanying almost any propagating soliton. There are several origins for the formation of such a non-soliton component: periodic soliton amplification in fibre soliton lasers [5], variation of pulse envelope from $\mathrm{sech}^2$-shape as occurs in gain-switched semiconductor lasers [6], or residual cw radiation from sources based on electroabsorption modulators [7].

In this Letter, we consider both experimentally and theoretically this practical important source of perturbation and study soliton interaction in the presence of the dispersive wave.

The experimental configuration is shown in Fig.1. As a master source, we used a passive harmonic mode-locked fibre soliton laser (FL) which produced pulses with $\tau_0$ =2.5 ps FWHM at a repetition rate of 200 MHz [8]. By changing the position of the polarization controller PC1, we were able to change the fraction of the non-soliton component energy from less than 1% to 20%. Pulses from the laser were first passed through a Michelson interferometer to convert them into pulse pairs. A micrometer screw adjustment of the length of one interferometer arm allowed the pulse separation to be varied continuously from zero to a few tens of picoseconds while piezoelectric transducer control of the other arm allowed for the precise adjustment of the relative optical phase. The pulses were amplified after the interferometer with an $Er^{3+}/Yb^{3+}$ codoped fibre amplifier to maintain fundamental soliton propagation in the transmission fibre, which consisted of 2 km of standard telecom fibre (D=17 ps/nm$\cdot$ km) making the propagation distance of the order of 20 dispersion lengths with negligible losses. The soliton pulse pairs were detected with an autocorrelator and optical spectrum analyzer.

PC1 was first adjusted to set the laser mode-locked with a minimal fraction of non-soliton component. Fig.2 shows the experimental result for soliton-soliton interaction in which output pulse separation $\tau_{out}$ is plotted as a function of input pulse separation $\tau_{in}$ for both in-phase (relative soliton phase $\theta = 0$) and opposite phase ($\theta = \pi$) cases, which fitted well with theoretical predictions (dotted lines) based on Eq.1 in [9]. However, by increasing the fraction of the non-soliton component we observed significant changes in the soliton behaviour, with a strong dependence of $\tau_{out}$ on $\theta$ being observed for $\tau_{in}$ exceeding even $5\tau_0$, where "classical" soliton interaction forces should be very weak. We found a well-defined oscillatory dependence of $\tau_{out}(\tau_{in})$ with a period T= 6$\pm$0.5ps. The phase of the oscillation was dependent on $\theta$. Fig.3(b and c) show the deviation of the output pulse separation from that expected by Eq.(1) in [9] for the cw component having 10% and 20% of the average power respectively. Corresponding optical spectra are shown in the insets. Fig.3a shows the case, corresponding to Fig.2. Note that at certain delays there were no deviations of $\tau_{out}$ regardless of the phase $\theta$.

To consider the influence of the non-soliton component on soliton parameters, we apply perturbation theory, based on the inverse scattering transformation [1] and present initial conditions for the nonlinear Schrödinger equation in the form of a one-soliton solution $\psi_S(t)$ and a small finite perturbation

$\delta\psi(t)$ i.e.

$$\psi_0(t) = \psi_S(t) + \delta\psi(t), \tag{1}$$

where $t$ is the retarded time and the soliton is motionless (velocity V $= 0$) and its pulsewidth is normalized to 1 (soliton amplitude $\eta = 1$).

If we consider the case where the input separation $\tau_{in}$ between two solitons is large enough to make perturbations of the soliton parameters due to soliton-soliton interactions negligibly small and assume that both soliton and non-soliton component are mutually coherent waves having a phase difference $\phi$, then the perturbation of the soliton parameters may be expressed in the form

$$\delta\psi(t, \tau_{in}) = \mathrm{A}\exp j\phi[\exp j\Omega t + \exp(j\Omega(t - \tau_{in}) - \theta)] \tag{2}$$

and the change of soliton parameters are

$$\delta\eta(\tau_{in}) = A\pi\mathrm{sech}\frac{(\pi\Omega)}{2}[\cos\phi + \cos(\Omega\tau_{in} - \phi + \theta) \tag{3.a}$$

$$\delta V(\tau_{in}) = \Omega\delta\eta \tag{3.b}$$

where A is amplitude of the cw component and $\Omega$ is the frequency difference between the soliton and non-soliton component.

From Eq.(3) we can conclude that non-soliton component causes negligibly small perturbations of the soliton amplitude, while the change of the soliton central frequency results in a noticeable temporal shift of the soliton. Note also that there is no change of soliton parameters for a frequency unshifted non-soliton component and there is a frequency difference $\Omega_m$ resulting in maximum perturbation of the soliton parameters. From Eq.(3.b) we obtain $\Omega_m \approx 0.764$.

Throughout the experiment we kept $\theta = 0$ or $\pi$ and thus we can express the variation in the soliton separation time in the form

$$\tau_{out}(\tau_{in}) = \tau_{in} + z[\delta V(0) - \delta V(\tau_{in})] = \tau_{in} \pm Az\Omega\pi\mathrm{sech}\frac{(\pi\Omega)}{2}\sin(\Omega\tau_{in}) \tag{4}$$

(for simplicity we put $\phi = \pi/2$, because the particular value of $\phi$ does not affect the basic conclusion in any significant way). In our case, z=20, $\Omega$=1.1 and A=$6\cdot10^{-3}$ and $9\cdot10^{-3}$ for cases (b) and (c) respectively, giving a theoretical oscillation period of 6 ps and maximum deviation of 0.25ps for case (b) and 0.4ps for case (c). There is good agreement between the experimental and theoretical results for the period of the oscillations while the theoretical value of the oscillation amplitude is approximately 10 times smaller. A possible reason for this is that the non-soliton component generated by the FL is not a truly cw wave, as it was assumed in the theoretical consideration but a rather long ($\sim$ 500 ps) dispersive pulse. But this assumption remains to be verified.

In conclusion, we have studied both experimentally and theoretically a practically important case of soliton interaction in the presence of a cw component. It has been shown that the existence of a frequency shifted non-soliton component results in a temporal shift of the soliton. This effect may have applications in optical processing where modulation of a weak cw signal results in a temporal modulation of the soliton position. In addition, the effect of third order dispersion results in the spectral separation of linear and nonlinear waves [10] and this observed effect should also be taken into account in the application of soliton sources based on electro-absorption modulators in the dispersion shifted fibres.

## References


1. Karpman, V. I. and Maslov, E. M., 'Perturbation theory for solitons', Sov.Phys.JETP, 1977, **46,** (2), pp. 281-291

2. Gordon, J. P., and Haus, H. A.,'Random walk of coherently amplified solitons in optical fibre transmission', Opt.Lett., 1986, **11,** pp.665-667

3. Gordon, J. P.,'Interaction forces among solitons in optical fibres', Opt.Lett., 1983, **8**, pp.596-598

4. Dianov, E. M., Luchnikov, A. V., Pilipetskii, A. N and Starodumov, A. N., 'Long-range interaction of soliton pulse trains in a single-mode fibre', Sov.Lightwave.Commun., 1991, **1**, pp.37-43

5. Kelly, S. M. J.,'Characteristic sideband instability of periodically amplified average soliton', Electron.Lett., 1992, **28**, pp.806-807

6. Ong, J. T., Takahashi, R., Tsuchia, M., Wong, S.-H., Sahara, R. T., Ogawa, Y., and Kamiya, T.,'Subpicosecond soliton compression of gain-switched diode laser pulses using an erbium-doped fibre amplifier', IEEE Journal of Quantum El., 1993,**29**, pp.1701-1707

7. Suzuki, M., Noda, Y., Tanaka, H., Akiba, S., Kushiro, Y., and Isshiki, H., 'Monolitic integration of InGaAsP/InP distributed feedback laser and electroabsorption modulatorby vapor phase epitaxy', J.Lightwave Tech., 1987, **LT-5**, pp. 1277-1285

8. Grudinin, A. B., Richardson, D. J. and Payne, D. N., 'Passive harmonic mode-locking of a fibre soliton ring laser', Electron.Lett., 1993, **29**, pp.1860-1861

9. Mitschke, F. M. and Mollenauer, L. F.,'Experimental observation of interaction forces between solitons in optical fibres', Opt.Lett., 1986, **12**, pp.355-357

10.Wai, P. K. A., Menyuk, C. R., Chen, H. H., and Lee, Y. C.,'Soliton at the zero-group-dispersion wavelength of a single-mode fibre', Opt.Lett, 1987, **12**, pp.628-630

## Figure Captions

Fig.1 Experimental configuration

Fig.2 Pulse separation at the output versus same at the input of 2-km fibre. o - interacting solitons are in phase, • - interacting solitons are in opposite phase. Solid line, theoretical prediction by Eq.(1) in [9].

Fig.3 Deviation of the output pulse separation from that expected by the theory for the fraction of non-soliton component: (a) - $\leq 1\%$, (b)- 10%, c - 20%. o - interacting solitons are in phase, • - interacting solitons are in opposite phase.

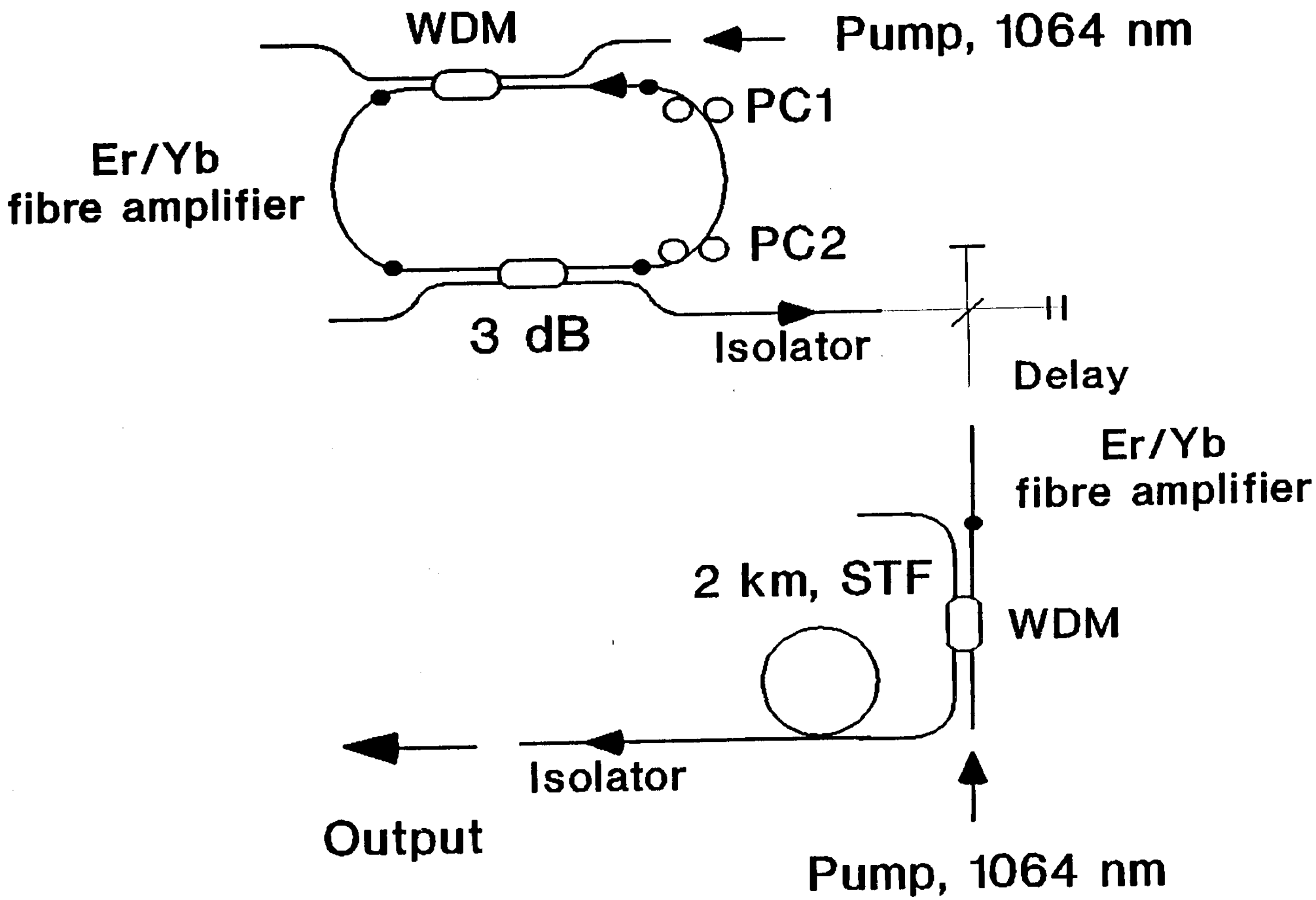
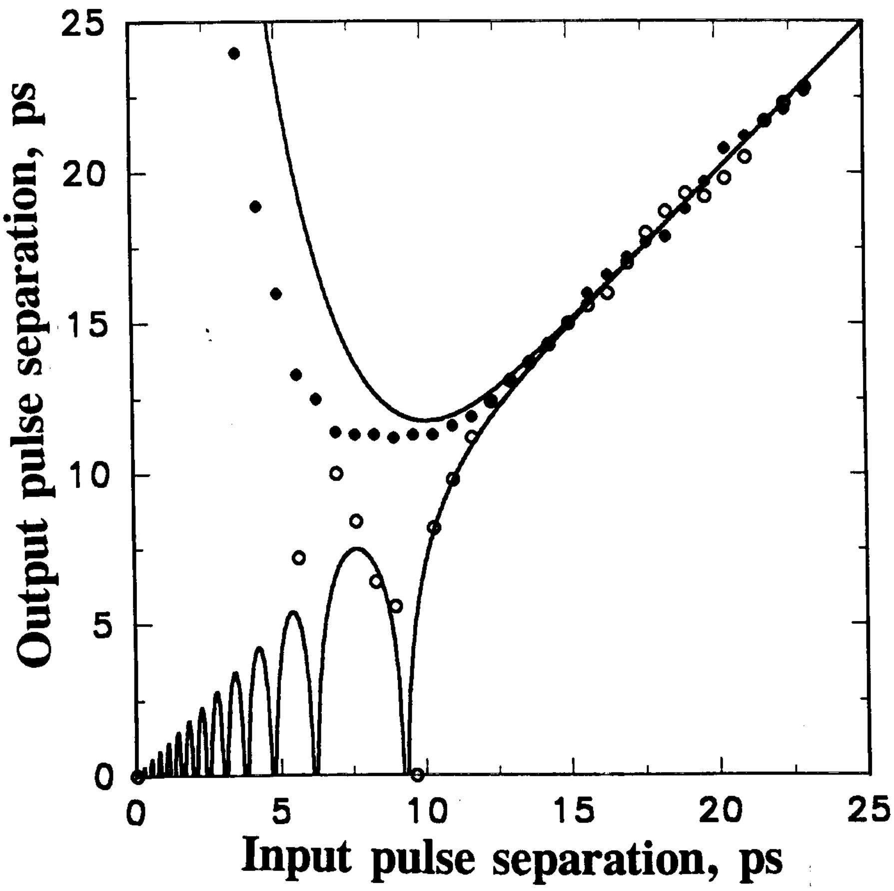
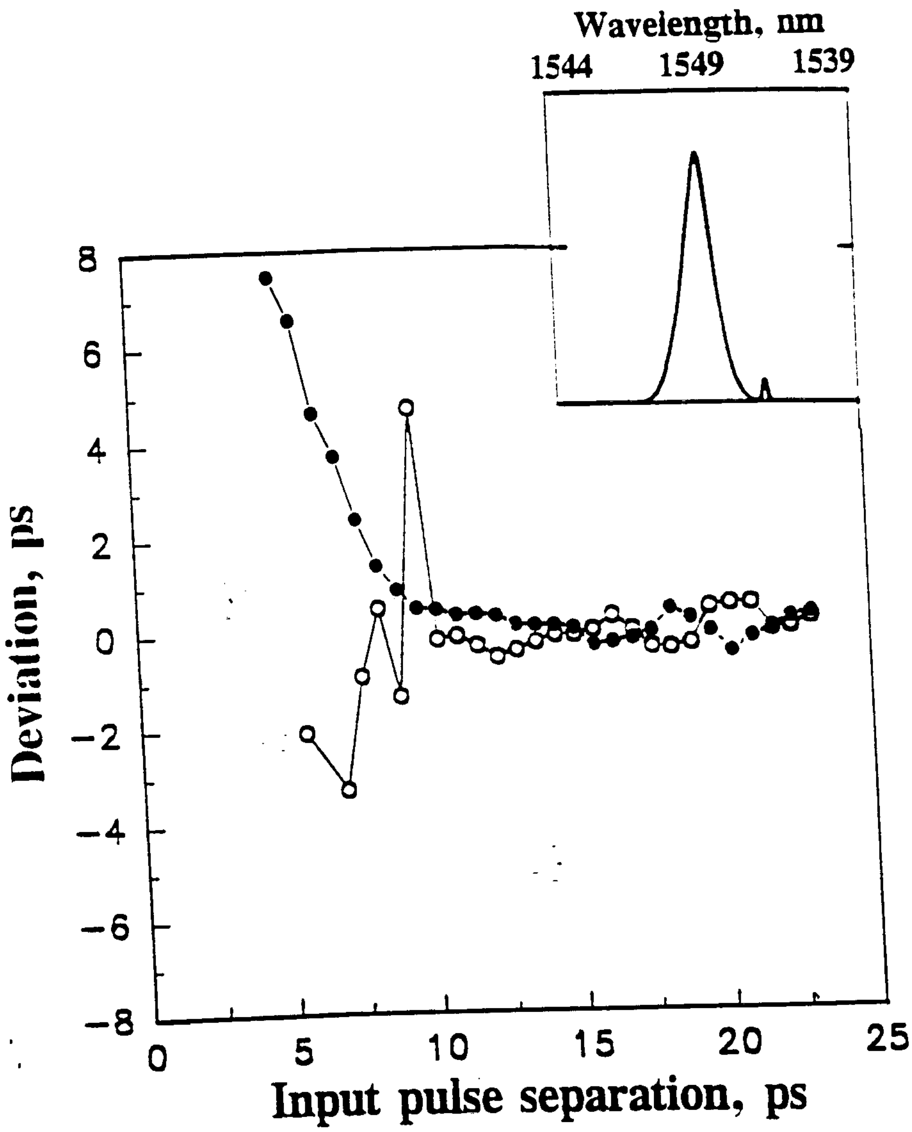

WDM
Pump, 1064 nm
PC1
Er/Yb
fibre amplifier
PC2
3 dB
Isolator
Delay
Er/Yb
fibre amplifier
2 km, STF
WDM
Isolator
Output
Pump, 1064 nm

Fig 1



25
20
15
10
5
0
Output pulse separation, ps
0
5
10
15
20
25
Input pulse separation, ps


Fig2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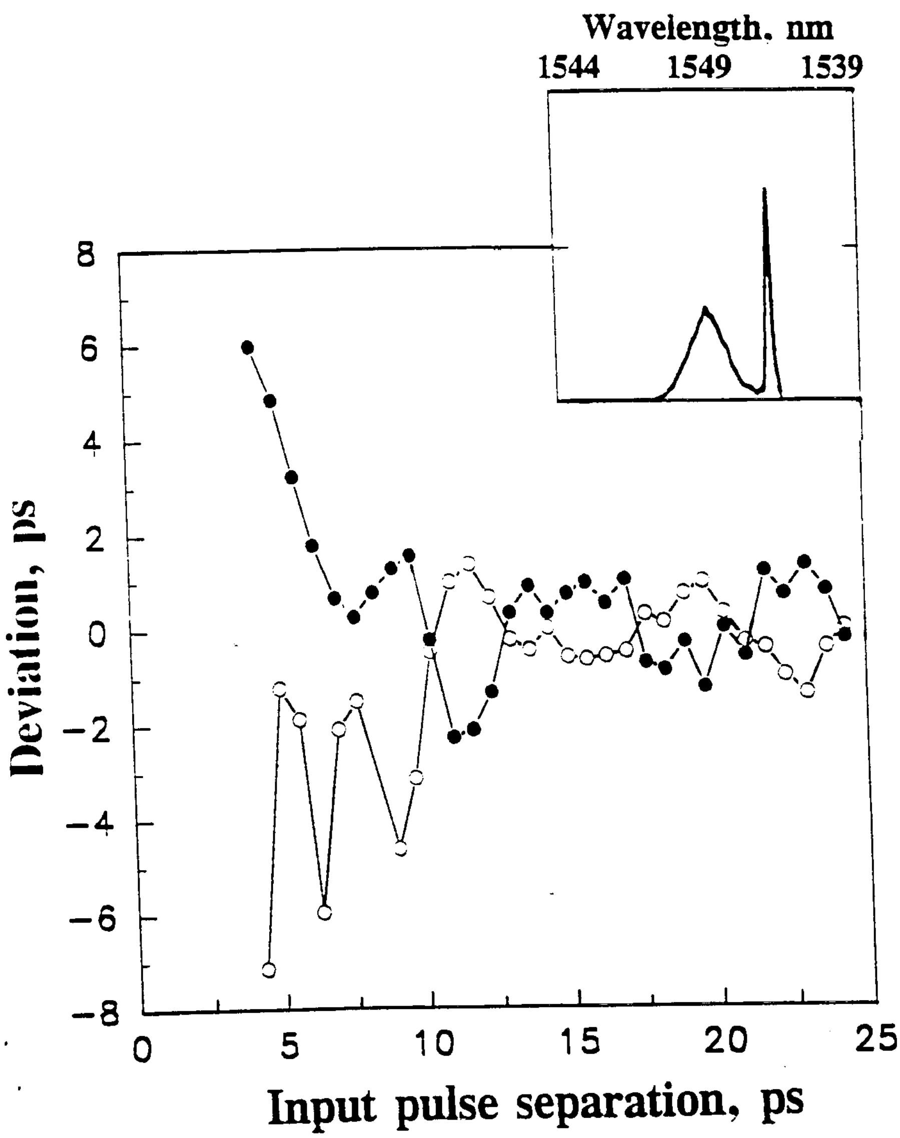
1544
1549
1539
8
6
4
2
0
−2
−4
−6
−8
Deviation, ps
0
5
10
15
20
25
Input pulse separation, ps

Fig 3a



Wavelength, nm
1544
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Deviation, ps
0
5
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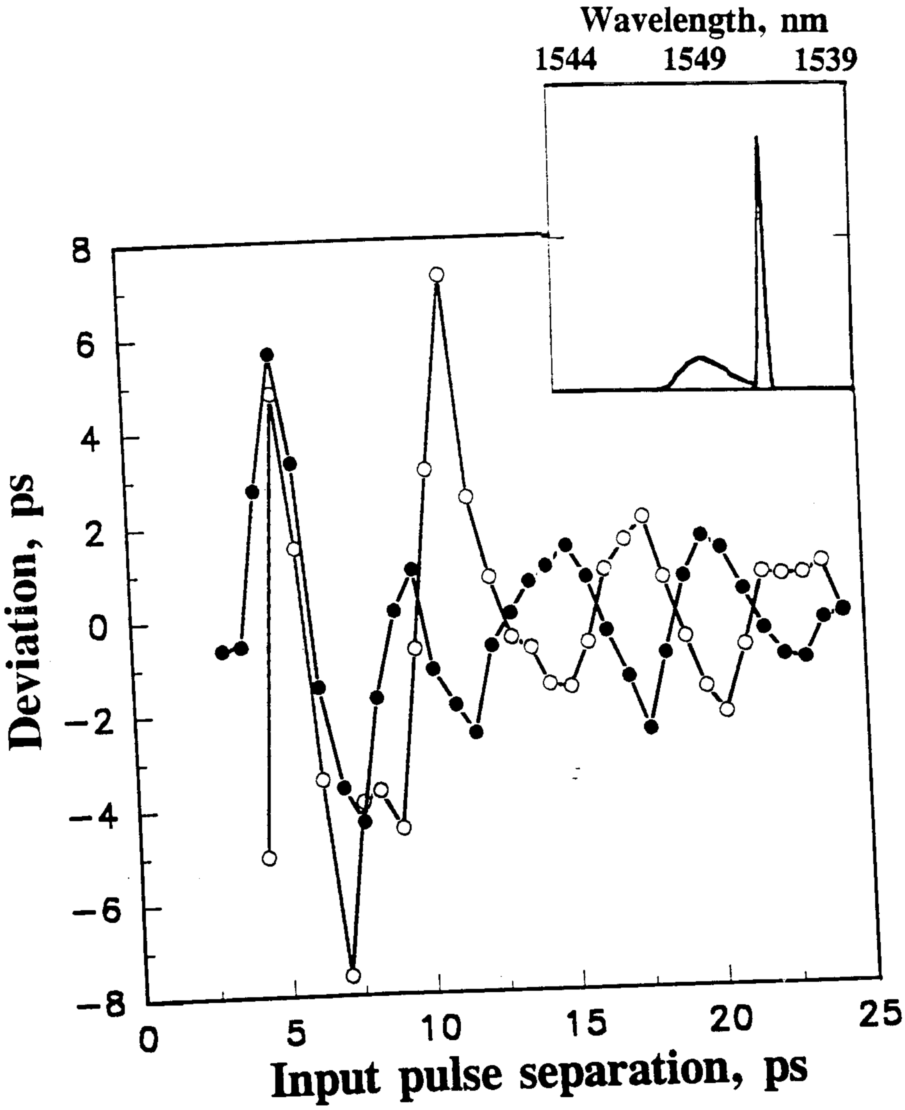
15
20
25
Input pulse separation, ps


Fig 3b


Wavelength, nm
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−6
−8
Deviation, ps
0
5
10
15
20
25
Input pulse separation, ps

Fig 3c