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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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**Conference on
Ultrafast Transmission Systems in Optical Fibres**

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Pulse Interaction in Soliton Systems

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Multiple pulses in Soliton systems

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- Multiple Solitons
- Pulse pairs
- Phase modulation
- Noise

Assumptions

- Pure lossless NLS:

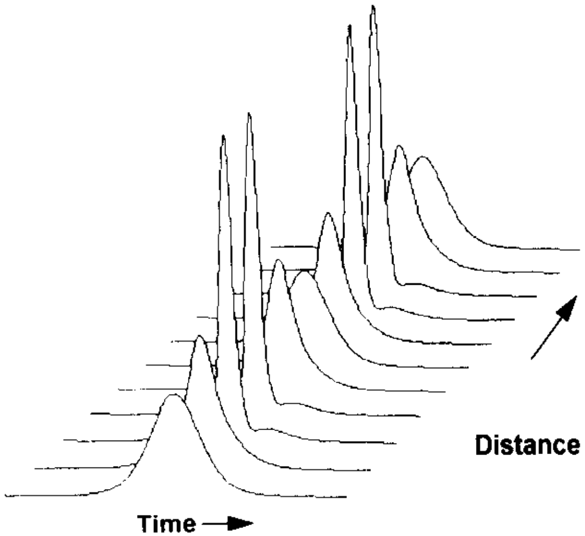
$$i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u = 0$$

- Also applies to amplified systems in correct limit
- Fibres are perfectly circular and have no higher order dispersion
- Nonlinearity is pure Kerr

Multiple solitons

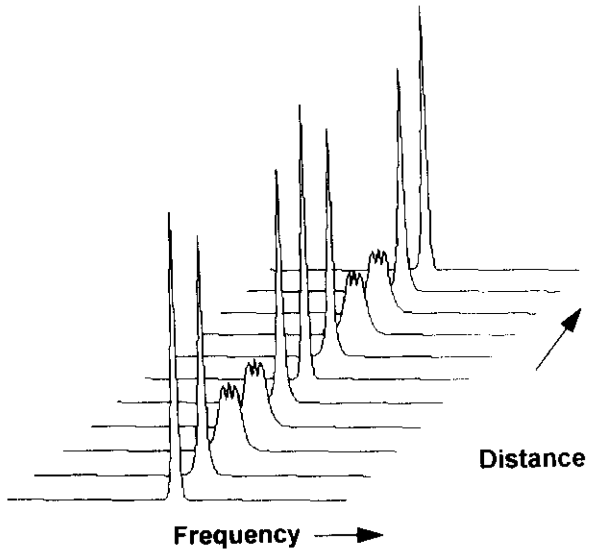
- Classic single soliton does not change with propagation
- Higher order solitons do,

both in time:



Multiple Solitons

- and frequency:

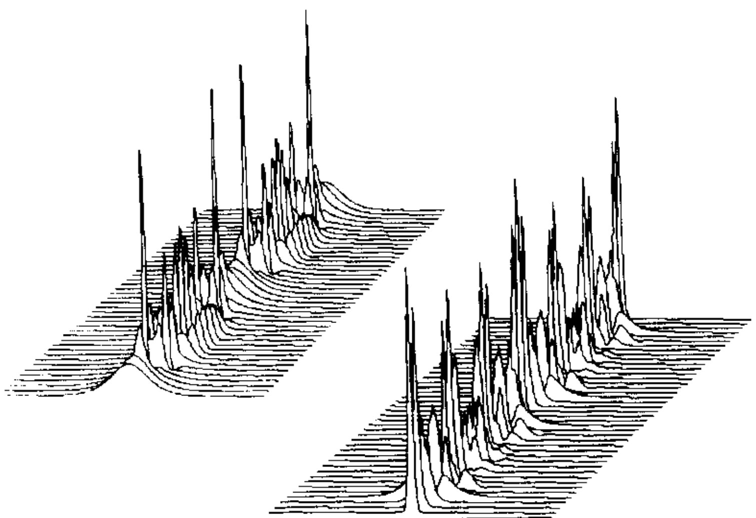


Multiple Solitons

- Simple initial form:

$$u(z=0,t)=N\text{sech}(t)$$

- For integer *N*, these are all pure solitons (e.g. *N*=4)



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Pulse Pairs

- In practice we want to send sequences of pulses
- Look at what happens when two are put together
- initial form:

$$u(z=0,t)=\text{sech}(t-\Delta)+e^{i\phi}\,\text{sech}(t+\Delta)$$

- ϕ defines the relative phase of the two pulses
- Important parameter is Δ=T/τ
- First look at ϕ=0 and Δ=1

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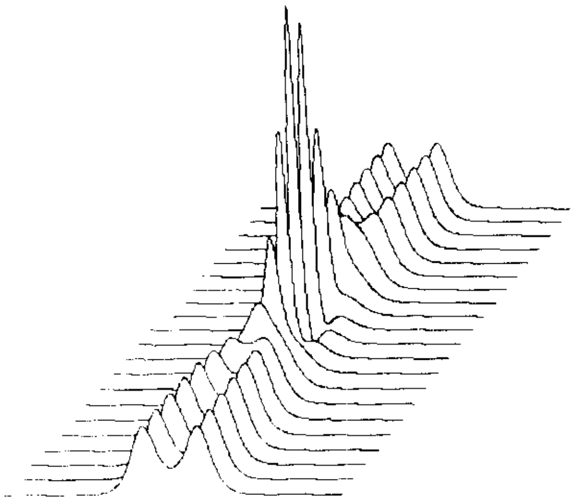
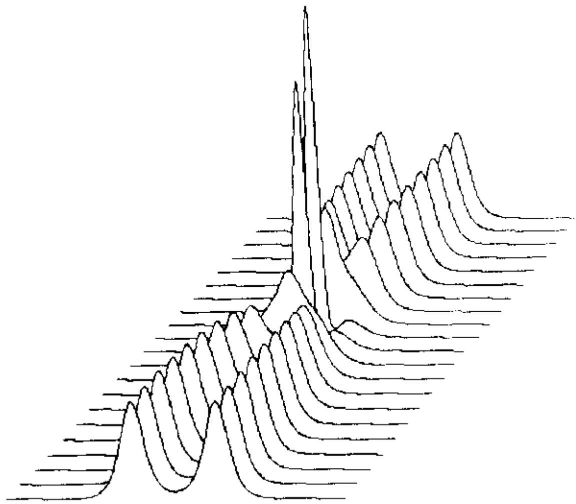
Pulse Pairs



- This interaction is periodic and will continue forever
- Perhaps they were too close together?
- Look at Δ=1.5

Pulse Pairs



- The interaction still occurs but on a longer length scale

Simple Model

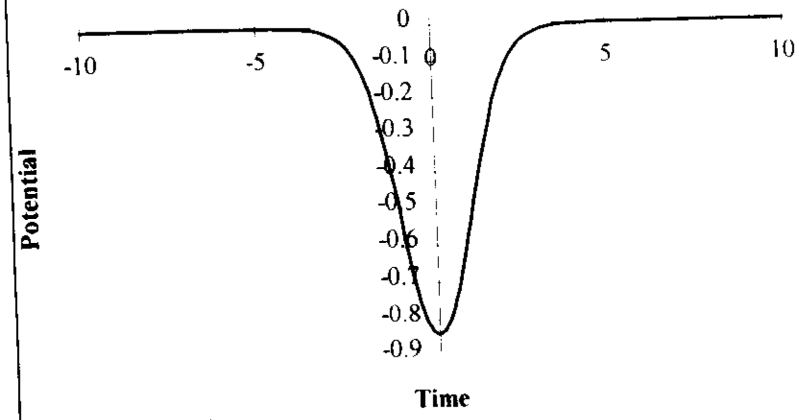
- Look at NLS $-\frac{\partial^2 u}{\partial t^2} - |u|^2 u = -i\frac{\partial u}{\partial z}$
- 1D Schrodinger equation with $V(t)=-|u|^2$
- Initially the individual solitons are disturbed by the interaction potential

$$V(t) = -\left|\operatorname{sech}(t-\Delta) + \operatorname{sech}(t+\Delta)\right|^2 + \operatorname{sech}(t-\Delta)^2 + \operatorname{sech}(t+\Delta)^2$$

or

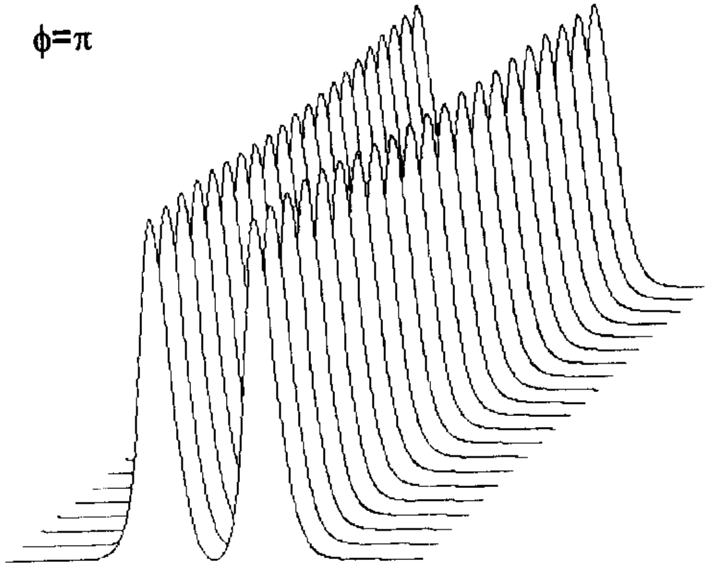
$$V(t) = -2\operatorname{sech}(t-\Delta)\operatorname{sech}(t+\Delta)$$

Interaction potential



- The overlap of the pulses looks like an attractive potential mid way between them
- This was for $\phi=0$, when $\phi=\pi$ the potential changes sign
- So the pulses repel?

Pulse Pairs



- Now the pulses repel and continue to separate forever
- Eventually the energy will leave the time slot causing an error

Perturbation Theory

- Take pulses of the form

$$u = \operatorname{sech}(t - T_i)e^{i\omega_i t} \quad with \quad i = 1,2$$

- then we can obtain equations of motion for ω and T

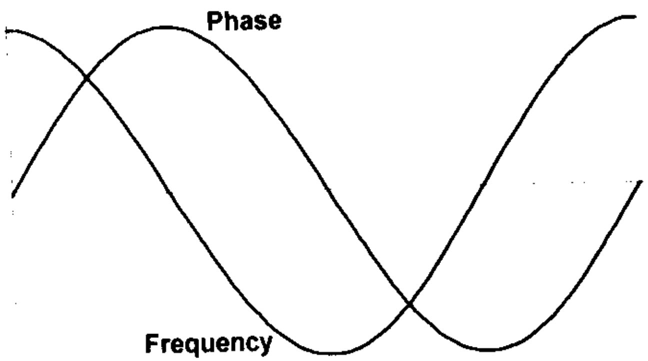
$$\frac{d\omega_i}{dz} = (-1)^i 4e^{-(T_1 - T_2)}$$

$$\frac{dT_i}{dz} = \omega_i$$

- so frequency and time become coupled

Phase Modulation

- Want to control soliton motion
  - these interactions
  - Gordon Haus jitter
  - long range acousto-optic effects
- Since time and frequency are coupled, use phase modulation



Perturbation Theory

- While the solitons remain near the peaks we can modify the perturbation theory in a simple way
- Also assume symmetry

$$\frac{d\omega}{dz} = -4e^{-2T} - \alpha\left(T - T_0\right)$$

$$\frac{dT}{dz} = \omega$$

- Now have a competition between internal and pinning forces

Perturbation Theory

- The simple model system can have zero or two fixed points

$$0 = -4e^{-2T} - \alpha\left(T - T_0\right)$$

- or, putting $T = T_0 - \Delta T$

$$\Delta T = \frac{4e^{-2T_0}}{\alpha} e^{2\Delta T}$$

- Now ask for threshold condition

$$1 = \frac{8e^{-2T_0}}{\alpha} e^{2\Delta T}$$

Pertrubation Theory

- Solving these equations simultaneously gives

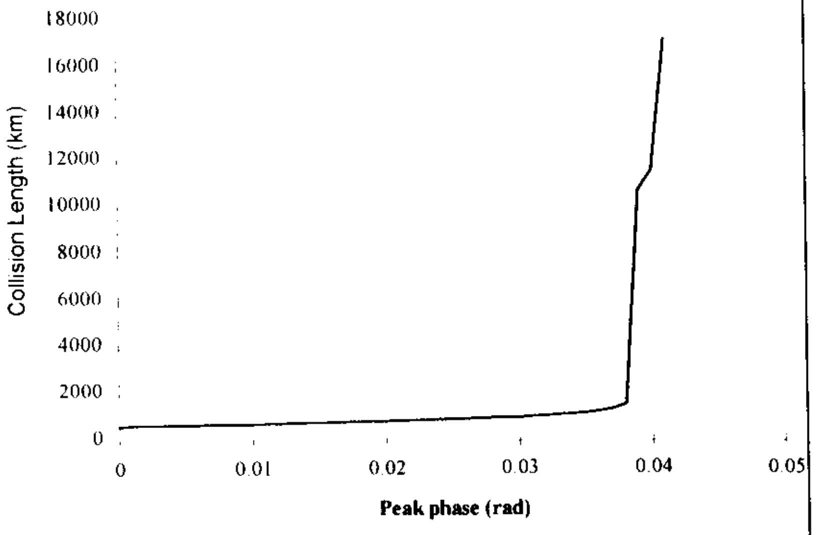
$$\Delta T = \frac{1}{2}$$

$$\alpha = 8e^{1-2T_0}$$

- How does the system do in practice?

System Simulation

- Numerical results from simulations of pulses pairs propagating in a phase modulated system



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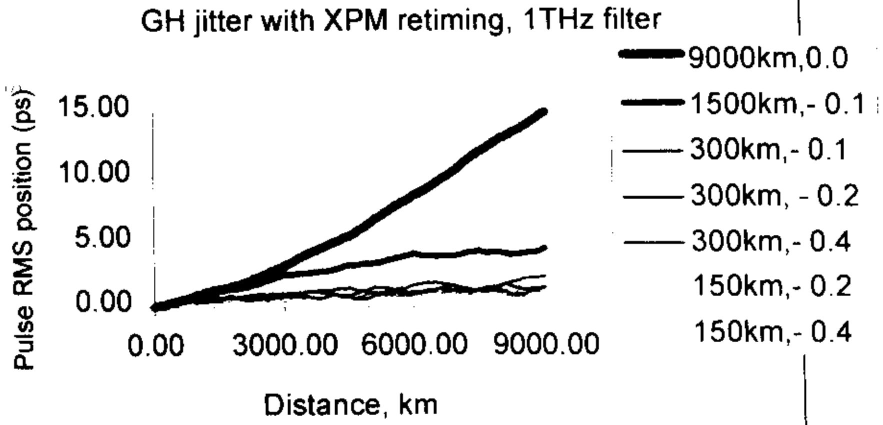
Noise

- What about noise and Gordon-Haus jitter?



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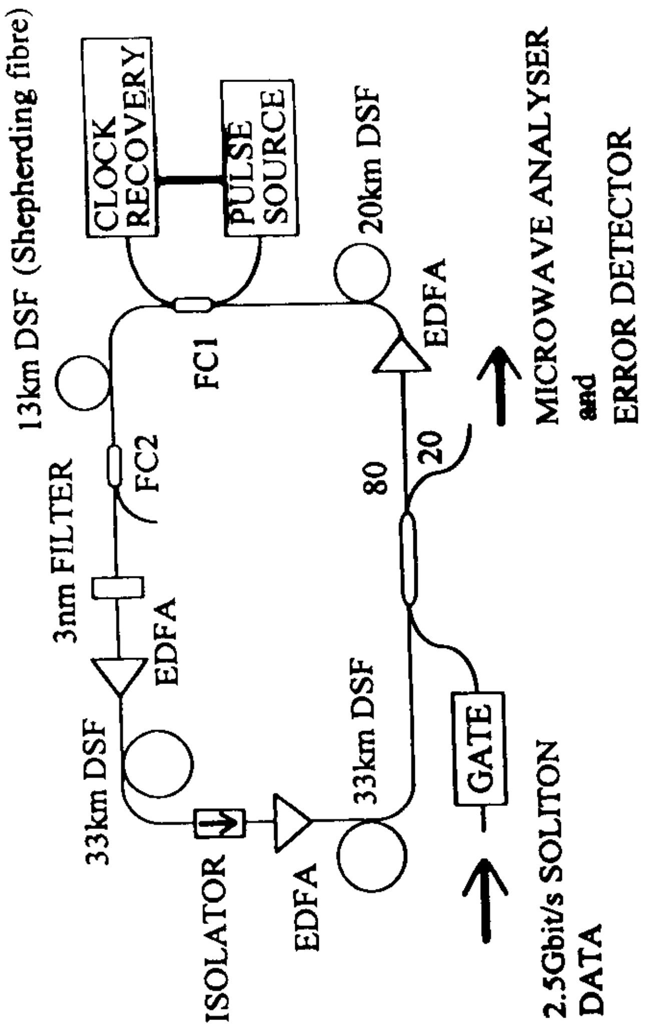
The Experimental Configuration



Experimental Details

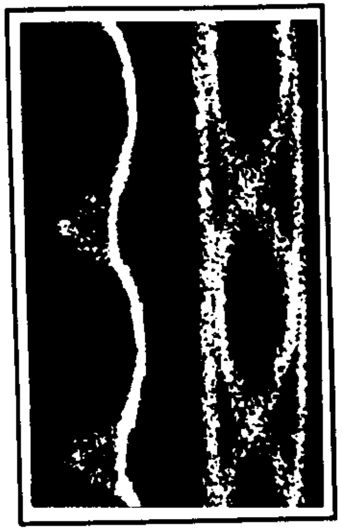
Soliton source: mode-locked erbium fibre ring laser
- 2.5GHz stream of ~20ps pulses at 1.562μm.

Clock pulses: electrical PLL followed by external modulation of a CW DFB laser
- 50ps pulses tuned to 1.538μm

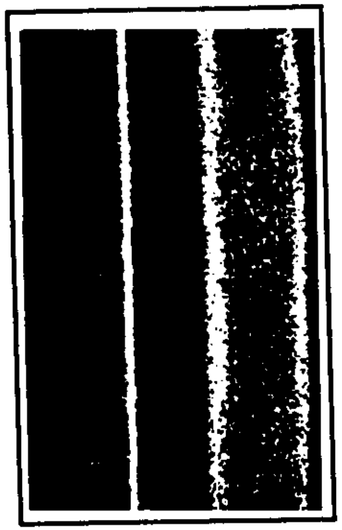
Shepherding fibre: 13km length of dispersion-shifted fibre
- $\lambda_0 \sim 1.55\mu m$

Path average dispersion of the loop was ~1ps/nm.km at the signal wavelength
- calculated accumulated timing jitter of ~22ps (rms) at 9000km giving a BER of $\sim 10^{-9}$

System temporal jitter



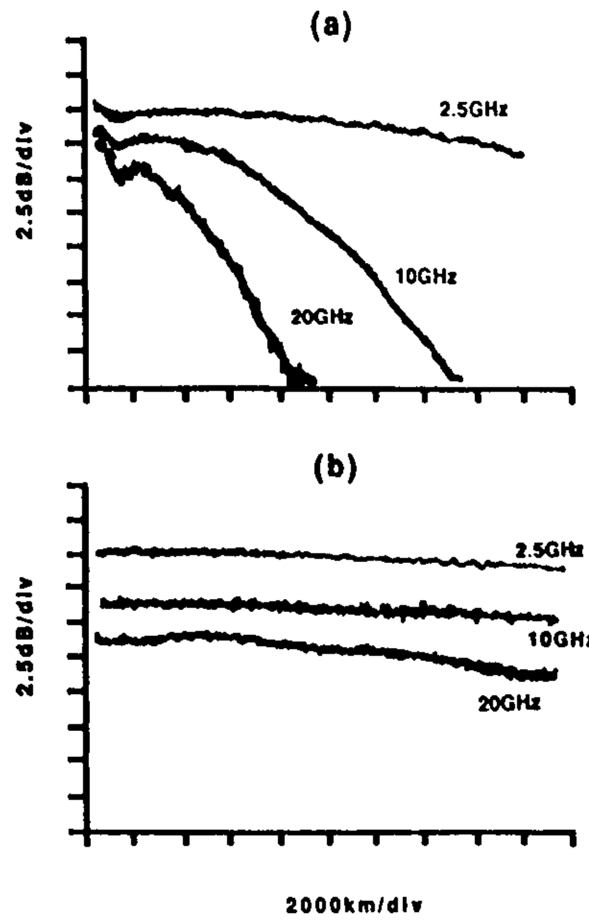
With shepherding



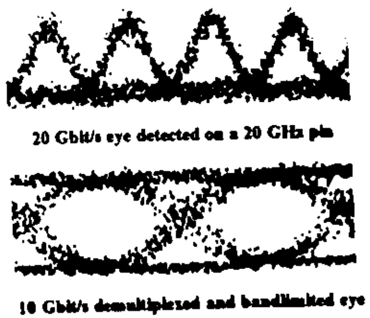
Without shepherding

Soliton data stream detected on 32 GHz *pin* and resultant bandlimited eye diagram

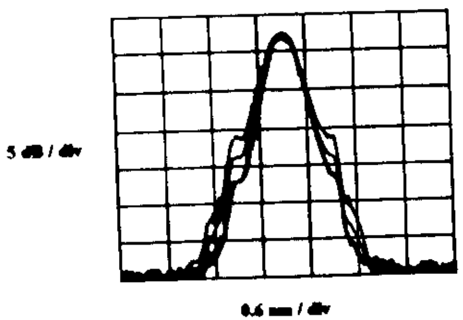
Experimental Results



Microwave components (2.5, 10, 20GHz) of the 2.5Gbit/s soliton data as a function of distance for (a) no shepherding beam and (b) a weak shepherding beam (-13dBm mean power).



125,000 km eye diagrams, error free operation.



Optical spectra of propagating solitons
for pulse widths of 5, 6.5 & 8 ps