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REDUCTION OF SOLITON INSTABILITY IN TRANSMISSION SYSTEMS BY MEANS OF CHIRPED BANDWIDTH-LIMITED AMPLIFICATION

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ABSTRACT

We demonstrate both numerically and experimentally that soliton instability is substantially reduced in a system employing spectral filtering and chirped amplification. In such a system, 5 ps solitons remain stable over practically unlimited distance with the amplification period increased up to 3 dispersion lengths.

Repeaterless optical transmission links are the subject of active research and development. It is likely that soliton propagation will be chosen for future designs of long-haul transmission lines provided an inexpensive and practical solution to overcome the Gordon-Haus limit and the soliton resonance effect can be found. The Gordon-Haus effect is the result of the spontaneous emission from the amplifiers and sets an upper limit on the propagation distance.

Interaction between soliton pulses and the accompanying them nonsoliton component results in soliton instability and in order to minimize this effect one has to keep the amplifier spacing much shorter than the soliton period.

Several methods have been proposed to improve soliton stability: synchronous modulation [1], sliding filters [2] and systems with nonlinear gain [3].

In this paper we describe an alternative method for soliton transmission control which, being fully passive with instantaneous time response, is simple, practical and could be painlessly implemented in already installed fibre transmission systems.

It is well known that when a soliton propagates in a fibre with loss it becomes broader. It was shown [4] that for some distance the soliton remains essentially a nonlinear pulse which results in narrowing of its spectral bandwidth, but after that distance the soliton experiences only temporal broadening without any significant changes in spectral bandwidth which means that the original bandwidth-limited pulse becomes a chirped one. It is also known that chirped nonlinear pulses tend to split into fundamental soliton and nonsoliton components [5] and therefore after several amplification stages the fraction of nonsoliton component becomes unacceptably high and causes the soliton to break-up. (Note that the use of the multisoliton compression effect to compensate for the soliton broadening is inefficient due to a high level of the non-soliton component which again quickly destroys the soliton). However if one imposes a chirp over the soliton to compensate for the loss-induced chirp, then the soliton emits much less linear radiation and can propagate much longer distances without breaking up. Thus the use of chirped bandwidth-limited amplification (CBLA) results in stable soliton propagation.

To investigate this method of soliton control we have modelled a transmission system comprising a length of optical fibre, a bandpass optical filter with amplitude transmission function $H(\omega)= (1+2i\omega B)^{-1}$, where ω is the frequency relative to the pulse central frequency and B is the filter bandwidth, and a chirping device. Propagation in the fibre was modelled using the split-step Fourier method to solve the Nonlinear Shrodinger Equation. For the chirping device we use the model which transforms the incoming pulse according to $A(\omega)\rightarrow A(\omega)\exp(i\alpha\omega^2)$ where α is the chirp strength. The loss between amplifiers was chosen to be 10 dB, amplifier spacing is equal to three dispersion lengths and the filter spectral bandwidth was 8 times wider than the soliton bandwidth.

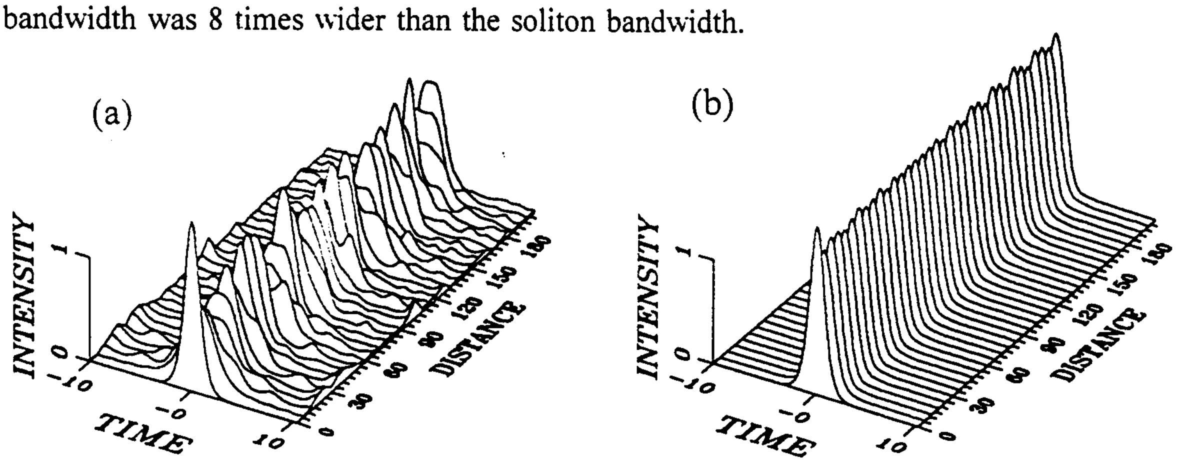

Fig.1 Soliton dynamics without (a) and with (b) CBLA

Fig.1a shows soliton propagation in the absense of both spectral filtering and chirping. The soliton is unstable and breaks up after several amplifications. The situation is getting marginally better with spectral filtering.

In a system with CBLA (Fig.1b) the soliton is much more stable and capable of propagation over 200 dispersion lengths without any significant degradation. The additional gain due to the filter is 0.2 dB, chirp strength parameter is 0.6 or 4 ps^2 for 5 ps pulses. After several dispersion lengths the pulse comes to a steady-state regime which is characterised by almost periodic intensity variations of ~10% (Fig.2a). The effect of chirping results in pulsewidth variations between amplifiers of less than 20 percent which is rather small for amplifier spacing equal to $3z_d$.

Fig.2b shows the pulse phase before and after a chirping element which indicates almost complete compensation of the loss-induced chirp.

There are several methods for practical implementation of CBLA. The obvious and straightforward way is the use of chirped fibre gratings. The required chirp parameter for 5 ps pulses - 4 ps^2 - is well within reach of modern technology. Another possible scheme of

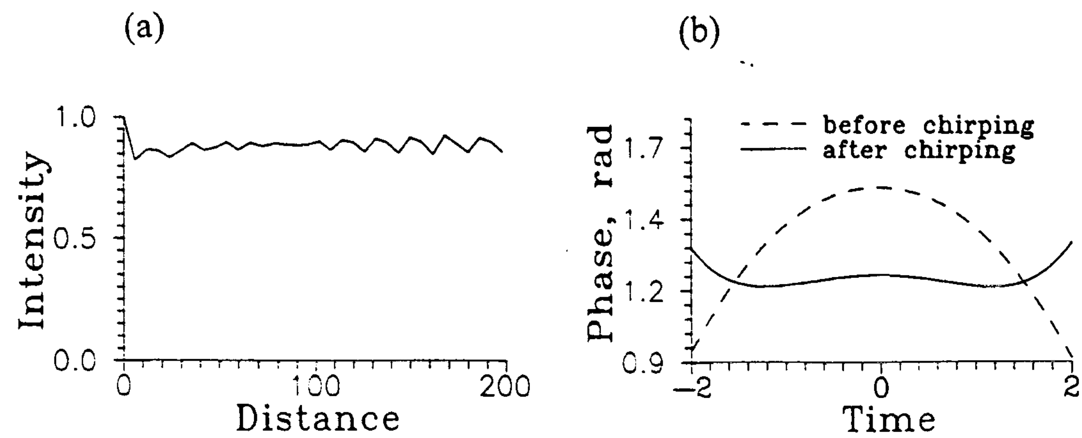

Fig.2 (a) Soliton intensity along the system with CBLA;
(b) Solion phase before and after chirping

CBLA is an optical amplifier followed by a NOLM. The pulse dynamics along the system with a NOLM (NOLM length is $0.3z_d$ and splitting ratio is 4:1) are alomost similar to that presented in Fig.1b.

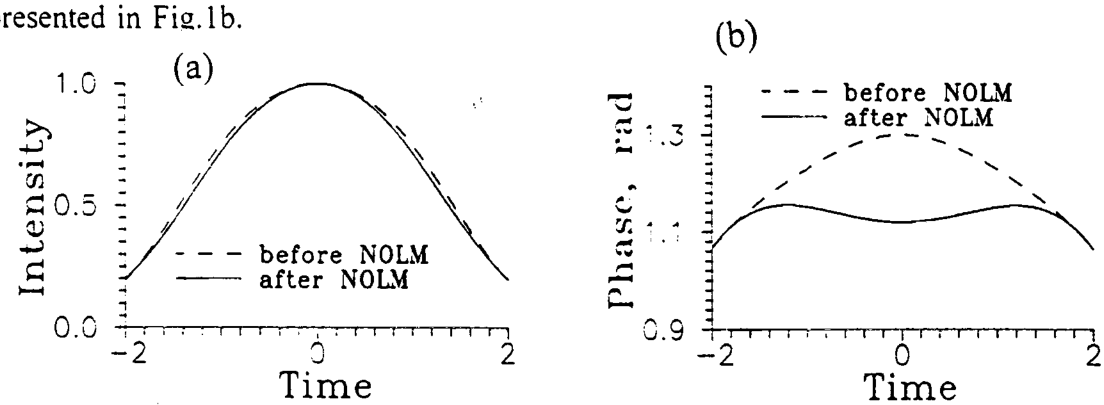

Fig.3 Soliton shape (a) and phase (b) before and after NOLM

Fig.3 shows the pulse profile and phase before and after the NOLM and suggests negligible pulse-shaping action and strong phase change. This scheme has an additional advantage of suppression of low-level non-soliton component [6].

Owing to simplicity and availability of components we have chosen the last scheme to prove the viability of the proposed method. Fig.4 shows the experimental configuration. 2.5 ps pulses from a harmonically mode-locked fibre soliton laser [7] are switched into the loop comprising 24 km of dispersion shifted fibre with average dispersion 0.3 ps/nm·km, an erbium-doped fibre amlifier, a 10 nm bandwidth optical filter and NOLM. The last was made from a 80/20 coupler and 2 km of dispersion shifted fibre with dispersion 0.1 ps/nm·km. Fig.5 shows the intensity dynamics for a 10 μsec pulse train switched into the loop. Each pulse in Fig.5 corresponds to the pulse train intensity after successive round trips while the baseline reflects the accumulated noise level. It is clearly seen that after approximately 400 km the noise level saturates and the system comes to a to a steady state. The full length of the pulse propagation in this particular case corresponds to 4500 km, but the system remains stable for much longer distances

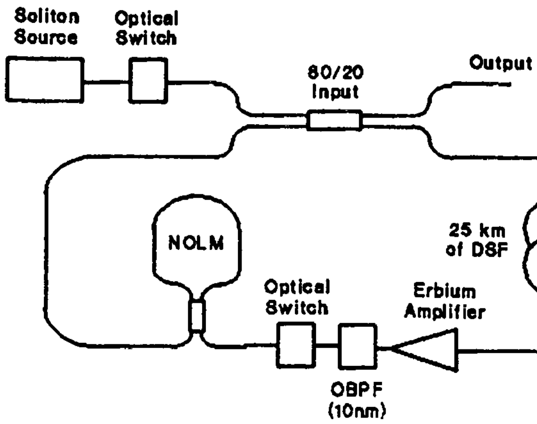

Fig.4 Experimental set-up

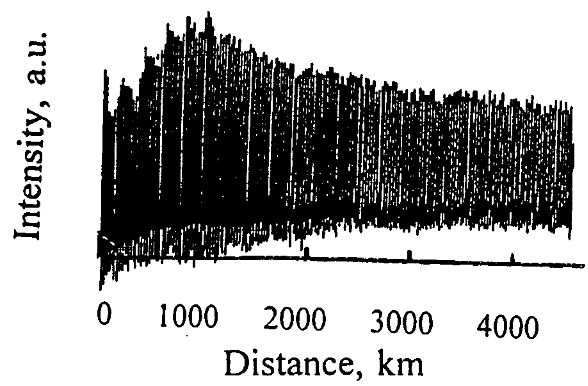

Fig.5 Train intensity at successive round trips

Spectra taken after 100 km and 4000 km are absolutely identical and around 40% narrower than the input one, that indicates that steady-state pulsewidth is around 5 ps. At the moment it is not entirely clear what mechanism - intensity-dependent loss (which is quite weak in this case) or chirping - is responsible for such remarkable pulse stabilization. Our computer simulations suggest the last effect and further experiments are now in progress. The measurement of steady-state pulsewidth and time jitter data for various configurations including chirped gratings will be presented at the conference.

Note that very recently a quite similar method has been proposed [8] where a length of dipersion compensated fibre was employed to reduce timing jitter.

In conclusion, we have presented a method for soliton transmission control based on bandwidth-limited chirped amplification. Computer simulations and preliminary experiments with a recirculating loop show that in such a system the amplifier spacing can be increased up to at least 25 km for 5 ps pulses which in combination with the instantaneous time response of the chirping device gives very good prospects of reaching a transmission rate of 40 Gbit/sec over transoceanic distances in a very simple and practical configuration.

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