An alternative scheme for a soliton transmission system

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1. Introduction

As the length and bit rate of a soliton transmission line is increased, the behaviour of the pulses becomes increasingly analogous to those in a mode-locked fibre laser [1a]. It is in this limit that the relative amplifier spacing and the volume of information transmitted are maximised. However, a host of different effects come into play as one attempts to push transmission capacity to its limit. Two of the main constraints which limit the data rate are the interaction forces which exist between separate light pulses while they propagate and the Gordon-Haus timing jitter which can arise at the amplication stages [1b-d]. The incorporation of a series of frequency filters along the transmission line has been shown to combat the effects of timing jitter [1e]. However, such filtering introduces more loss into the system and its net effect on interaction forces, in a jitter-prone system, remains to be evaluated [2, 3].

The goal of this investigation group was, not only to combine expertise in transmission systems and laser modelocking but, also, to draw upon a background of work which dealt with the stabilisation and control of *spatial* solitons in optical ring cavities. Discussions centred around the exploration and refinement of analogies and the consideration of problems which would arise in their application. We report here on particular considerations concerning a novel scheme for the transmission of binary strings of solitons. This topic was motivated by an attempt to apply the principles underlying the storage of transverse arrays of optical information to the analogous problem of a soliton transmission system. During the latter stages of the Study Centre, existing numerical codes were modified and initial simulations were undertaken to investigate the feasibility of the proposed scheme.

2. Transverse optical memory devices

It has been known for some time that light circulating in a dispersively nonlinear ring cavity can self-organise into arrays of spatial solitons [4]. These solitons appear spontaneously across the transverse profile of the beam and uniformly fill the central region. One can interpret these soliton arrays as binary numbers and the nonlinear cavity as a rather primitive memory device. Strings such as "…0001000…", "…0011100…" and "…0111110…" may be stored in this device. In earlier work [5], it was shown that the incorporation of a small spatial amplitude modulation (AM) in the pump field could permit the storage of *arbitrary* binary strings. This AM scheme allowed the independent address, and subsequent "shepherding", of the soliton pixels. Each "1" could be located at one of the transverse locations defined by the maxima of the input modulation. The leap in the number of possible strings is associated with a corresponding increase in the amount of information that can be stored.

A detailed study of the nonlinear dynamics of the soliton switching process [6] allowed an understanding, and hence an optimisation, of the switching time of such pixels . It was found that address time could be less than the cavity transit time and that pixels could be quickly, and cleanly, annihilated using phased address beams. This work has recently been extended to consider, instead, the usefulness of a frequency modulation (FM) of the pump field. New results regarding the FM scheme were presented at the Study Centre. It was shown that, in this case, *two dimensional* binary optical patterns could be stored [1f]. In view of these developments, it appears that the FM scheme permits a more direct control of the optical bits and, generally, may allow the manipulation of information in systems with more degrees of freedom and in which other effects come into play.

3. Soliton transmission systems

In the related problem of a (temporal) soliton communication system, it has been shown that the incorporation of phase modulators can suppress the interactions of the soliton pulses and hence enhance the preservation of the information being transmitted [1a,7,8]. In contrast to systems which use filters, no net gain has to be introduced to maintain each soliton's amplitude. While these studies have a connection with the spatial work there is not an exact correspondence.

Closer to the case of spatial solitons in a ring cavity is the work that was presented by S. Wabnitz [1g,9]. He considered the effect of the presence a small cw background field on the interaction of 2 solitons. While, in this case, the phase of the background signal is uniform, the underlying principle behind these two configurations is, however, the same. As in the spatial case, an explanation can be given in terms of the solitons being shepherded, or locked, by the background phase. In fact, experimental results demonstrating the steering of spatial solitons using a background phase ramp were outlined in the presentation by J.S. Aitchison [1h]. Two weeks later, workers from British Telecom delivered a post-deadline paper at CLEO/Europe-EQEC'94 reporting the experimental realisation of soliton shepherding in a fibre laser [10].

4. Hybrid scheme

Each of the schemes discussed in Section 3 may allow the suppression of interaction forces. However, an exact equivalent of the work in the spatial domain has not been implemented. The above use of phase modulators is an

FM scheme without a cw background while, on the other hand, the investigations of S. Wabnitz considered a constant cw background without any phase modulation. The work on transverse optical memory devices, discussed in Section 2, resides between these two extremes. By continuity from each limit, a hybrid scheme appears feasible. Our initial studies on this topic have been numerical simulations to evaluate the performance of a transmission system which incorporates the injection of a small amplitude and phase-modulated cw signal. To the best of our knowledge, such a scheme has not previously been investigated even though, by analogy, continuity and hindsight, it appears to be a rather obvious candidate. Two distinct configurations can be identified; distinguished by whether the injected signal is launched with the soliton bit stream or whether it is injected at each, or some, of the amplifier stages.

It is proposed that we make further exploration and consolidation of ideas arising from the comparison of modelocked lasers, transmission systems and transverse effects in cavities. With regard to the above topic, provided that parameter regimes exist where the new scheme can outperform the existing ones, the following future developments may be envisaged:

- A mathematical description using soliton perturbation theory.
- Accounting for possible phase differences between the solitons, by defining "bit zones", instead of "bit positions", which contain a number a modulation cycles.
- A study of the nonlinear dynamics and instabilities of the proposed scheme. For example, can "sources" and "sinks", which were discovered in the work on optical memories when phase gradients were too large [1f], exist and find application in a transmission system?
- An examination of implementation aspects and experimental realisation.
- Investigations of all-optical encoding and manipulation of the information stream in analogy to the work on optical memories [6].
- More general modelling including higher order and other effects. (See Study Centre book of abstracts for examples.)

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References

[1] *Presentations by* (a) N.J. Smith, (b) N.J. Doran, (c) J.P. Gordon, (d) H.A. Haus, (e) L.F. Mollenauer, (f) W.J. Firth, (g) S. Wabnitz and (h) J.S. Atchison, E.S.F. Study Centre on “Nonlinear Optics and Guided Waves”, Edinburgh, UK, Aug. 1-20 1994.

[2] M. Nakazawa and H. Kubota, Electron. Lett. **28**, 958 (1992).

[3] Y. Kodama and S. Wabnitz, Opt. lett. **18**, 1311 (1993).

[4] H. Adachihara, D.W. McLaughlin, J.V. Moloney and A.C. Newell, J. Math. Phys. **29**, 63 (1988).

[5] G.S. McDonald and W.J. Firth, J. Opt. Soc. Am. B **7**, 1328 (1990).

[6] G.S. McDonald and W.J. Firth, J. Opt. Soc. Am. B **10**, 1081 (1993).

[7] N.J. Smith, K.J. Blow, W.J. Firth and K. Smith, Opt. Commun. **102**, 324 (1993).

[8] N.J. Smith, W.J. Firth, K.J. Blow and K. Smith, Opt. Lett. **19**, 16 (1994).

[9] S. Wabnitz, Opt. lett. **18**, 601 (1993).

[10] T. Widdowson, D.J. Malyon, A.D. Ellis, K. Smith and K.J. Blow, Post-deadline paper CPD2.7, CLEO/Europe-EQEC’94, Amsterdam, The Netherlands, Aug. 28 - Sept. 2 1994.