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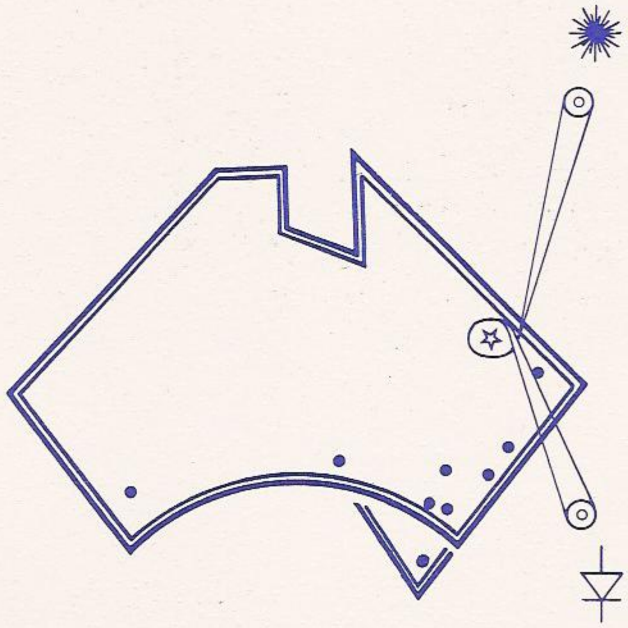

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Optical Conveyor Belts: A New Scheme for Fiber Communications

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A scheme is proposed for high-bandwidth, robust data transmission in silica fibers at wavelengths below 1.3 microns. The scheme is based on trains of gray solitons, but the solitons themselves do not carry any information. Rather, the signal is encoded in pulses of small but otherwise arbitrary amplitude in the orthogonal polarization and is carried along, without dispersion, by the soliton wavetrain. Data pulses carried by gray solitons of differing contrast do not interfere with each other when the solitons collide, so this allows many channels, each associated with a different contrast, to be multiplexed on the same fiber.

1 Introduction

Like bright solitons, dark solitons [1] can be observed in optical fibers [2, 3, 4] and used in telecommunications [5, 6]. The main difficulty in transmission of information using dark solitons lies in the modulation of the background field to encode a single bit of data. Because the phase of the background is shifted across each gray soliton by a finite angle, say $2\pi/m$, each bit must be introduced into or removed from the background as a group of m solitons. As $m = 2$ for "black" solitons, each bit must be carried by at least two solitons. The capacity of such a transmission line is correspondingly less than for a train of bright solitons with the same repetition rate. This fact would seem to spoil the whole idea of information transmission using dark solitons.

On the other hand, it is not difficult to produce uniform periodic trains of gray solitons in fibers [7], but then these trains themselves carry no information. However, such a train of solitons also induces a periodic modulation of the refractive index that moves rigidly along the fiber at a constant velocity v. The regions of higher index can trap weak signals at another frequency or in an orthogonal polarization and carry them along at the velocity v *without dispersion*. Thus, the dark soliton train acts as an "optical conveyor belt", moving packets of small but otherwise arbitrary energy along the fiber (see Figure 1).

We propose to use this fact as the basis for a new scheme for optical modulation. The train of small amplitude bright pulses that accompanies the uniform train of dark solitons can be easily modulated and can encode a data stream. The duration of each of these linear pulses is comparable with that of the dark soliton that confines it. Thus, the pulse rate of a transmission line based on this idea would equal the soliton transmission rate and so would avoid the "one bit — at least two solitons" problem described above. Moreover, since the amplitude of each data pulse is arbitrary, there is no theoretical restriction on the number of bits carried by each pulse; each may carry multi-level digital data or even an analog signal. Note again that the dispersion of these linear pulses is suppressed completely by the uniform nonlinear train of dark solitons, so that signals can be transmitted at a much higher rate than would be possible in a strictly linear system.

By an extension of this idea, it is also possible to multiplex several channels on the same fiber. Instead of just a single uniform train of gray solitons, one may consider solitons of several levels of contrast propagating together in the fiber. Gray solitons with different levels of contrast have different characteristic widths, and thus the linear signals trapped by the solitons can be separated according to width at the output. Although gray solitons with different levels of contrast propagate at different velocities in the fiber and hence must eventually collide, *there is no loss of data* since not only the dark solitons, but also the bright pulses that are guided by them, survive intact after collisions [8]. By comparison, this remarkable feature is not shared by linear pulses guided by trains of bright solitons.

Below, we create a theoretical basis for these "optical conveyor belts". Beginning with a reasonable model, we show how all the features of the data transmission scheme outlined above can be concretely described. The concluding discussion summarizes the advantages of the scheme and addresses its robustness to noise and loss.

2 Single-Channel Optical Conveyor Belts

Imagine an intense pump field and an orthogonally-polarized weak signal field, both at the same wavelength, λ ($< 1.3\mu$m). Let $p(z,t)$ and $s(z,t)$ be the complex envelopes of the pump and signal respectively, where z is the distance along the fiber and t is the time. We take the coupled system

$$ip_z + \frac{1}{2}p_{tt} - |p|^2 p = 0, \tag{1}$$

$$is_z + \frac{1}{2}s_{tt} - |p|^2 s = 0, \tag{2}$$

as a model. Subscripts denote partial derivatives. The signal field is sufficiently weak that its effect on the evolution of the pump has been neglected. Since we are operating in the normal dispersion regime, the nonlinear Schrödinger equation (1) for the pump is of defocusing type. The equations describing a real physical system may involve small additional terms, but at this stage we ignore such a complication.

The pump equation (1) has gray soliton solutions of the form

$$p(z,t) = \left\{ v - k + i\rho \tanh\left(\rho(z - vt)\right) \right\} \exp(i(kz - \omega t - \theta)) \tag{3}$$

where $\rho = \sqrt{A^2 - (v-k)^2}$, and A, k, and $\omega = A^2 + k^2/2$ are the amplitude, wavenumber, and frequency respectively of the background field. The soliton contrast is ρ/A. There is a corresponding bound state solution of the linear problem (2)

$$s(z,t) = B\,\mathrm{sech}(\rho(z - vt)) \exp(i(vz - v^2t/2 - \phi)), \tag{4}$$

that moves with the soliton velocity v but has an arbitrary amplitude B (and an arbitrary phase ϕ). The dispersion of this bright pulse is completely suppressed by the presence of the dark soliton.

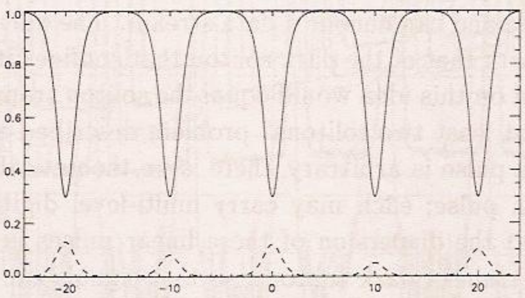

Figure 1: *The temporal pump and signal wavetrains for a single channel. The intensity of the pump, $|p|^2$, is shown with a solid curve, and that of the signal, $|s|^2$, is shown with a dashed curve. Note that, while the dispersion inhibited pulses carried by the train of dark solitons all have the same width, their amplitudes are arbitrary.*

Suppose now that the pump field is taken to be a uniform train of well-separated gray solitons of the form (3), rigidly propagating at a speed close to v in the fiber. Along with each soliton in the train, the orthogonal polarization may now contain a dispersion-inhibited pulse of the form (4), with B arbitrary. Because the amplitude of the signal pulses is arbitrary, each soliton of the pump carries along the fiber one continuous degree of freedom, namely the intensity of the dispersion-inhibited pulse in the orthogonal polarization (see Figure 1). Thus, although the uniform pump wavetrain itself carries no information, it acts as a conveyor belt, moving arbitrary amplitude pulses along the fiber in the orthogonal polarization. Each of these pulses can encode many bits of information, and their repetition rate matches that of the carrier train.

3 Channel Contrast Multiplexing

For the purposes of dragging along linear pulses in the orthogonal polarization, we may as well have chosen to use frequencies in the anomalous dispersion regime and made use of a periodic train of bright solitons in the pump to guide the weaker pulses. However, one of the most striking properties of linear pulses carried by dark solitons, as opposed to bright ones, is that two such pulses carried by solitons with different velocities *do not interact with each other during the collision* (see Figure 2). This remarkable fact has been observed

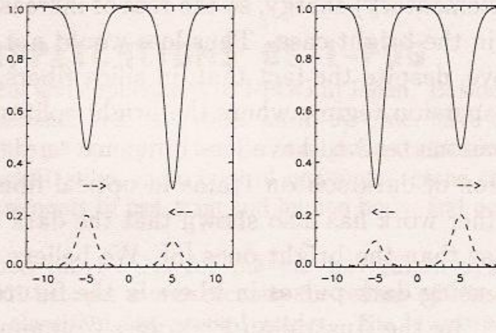

Figure 2: *Linear pulses carried by colliding dark solitons survive collisions just like the dark solitons do.*

experimentally in the analogous spatial system [9, 10], has been computed numerically [11], and has recently been proved analytically [8] using the of coupled equations (1) and (2) as the model. The robustness of the linear pulses during collisions gives us the possibility of multiplexing signal packets from several different sources onto the same fiber. If we use a pump field made up many periodic trains of dark solitons of different levels of contrast (and hence different velocities) propagating on the same background, then when one train of grey solitons carrying linear signals overtakes another train, both the solitons and the signals carried maintain their identity exactly after the collisions. As the width of the linear pulse carried is determined by the contrast of its guiding gray soliton, the pulses in each channel can be separated at the output of the fiber. It would be necessary to have a coincidence detector at the receiver end with a fiber memory loop to avoid the possibility of channel collisions occurring at the point of reception.

4 Discussion

We have shown that small-amplitude pulses of orthogonal polarization (or perhaps even of a different wavelength) propagating in the field of moving potential wells created by a train of gray solitons in an optical fiber can potentially be used for extremely high bandwidth data transmission.

The main advantages of the proposed scheme are:

- Each dispersion-inhibited linear pulse carries an analog signal — its amplitude. With the quantization of this amplitude, each pulse can, in practice, encode several bits of data.
- Many channels can be multiplexed on the same fiber. The dark pulse trains guiding the linear pulses of each channel travel with different velocities along the fiber, but both the dark solitons and the linear pulses survive periodic collisions with the other channels.
- The dark solitons making up the (quasiperiodic) pump field can be created more easily than those in traditional approaches in which dark solitons must be produced or removed from a uniform pulse train on demand to encode the presence or absence of a bit.
- The system enjoys the stability and robustness of dark solitons (see below).

Losses in the pump field may be considered by introducing the term $-i\gamma p$ on the right hand side of (1). Using a series solution, Giannini and Joseph [12] showed that losses cause the energy of a bright soliton to decay as $\exp(-2\gamma z)$, while for a dark soliton, the "complementary" energy decays only as $\exp(-\gamma z)$. The soliton pulse width is inversely proportional to the (complementary) energy, so the rate of increase of width in the dark case is considerably less than in the bright case. Thus loss would not have any drastic effect on the scheme proposed above, despite the fact that, in silica fibers, γ is greater below $1.3\mu m$ than in the anomalous dispersion regime where the bright solitons live.

Furthermore, perturbations tend to have less influence on dark solitons than on bright solitons. Indeed, generation of dark soliton trains in optical fibers has been demonstrated experimentally [7], and other work has also shown that the dark pulses suffer less from the effects of background noise than the bright ones [6]. We believe that there are benefits for information transmission using dark pulses in fibers in the future.

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