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 in the normal-dispersion regime. The scheme uses a uniform periodic train of dark solitons to eliminate completely the dispersion of a data stream encoded in linear pulses of small but otherwise arbitrary amplitude in the orthogonal polarization. Data pulses carried by dark solitons of differing contrast do not interfere with one another when the solitons collide. Thus many channels, each associated with a different contrast, can be multiplexed on the same fiber. © 1996 Optical Society of America

Like bright solitons, dark solitons[1,2] can be observed in optical fibers[3–5] and used in telecommunications applications.[6–8] In such applications dark solitons are potentially useful because they are more robust than bright solitons. First, at a fixed loss coefficient γ, dark solitons dilate less than bright ones over the same distance.[9] Although in ordinary glass γ is larger in the normal-dispersion regime than in the anomalous-dispersion regime, one can use dispersion-shifted fibers in which dark solitons can propagate at the erbium amplifier wavelength of 1530 nm, where γ is minimized.[8] Second, dark solitons feel the effects of noise less than do bright solitons.[7] In particular, Gordon–Haus-like jitter of dark solitons is less pronounced than the classical Gordon–Haus effect for bright solitons.[10] These features favor dark solitons as candidates for data bits in fiber communications.

So why has work on sending data with dark solitons progressed so slowly, the first successful scheme[8] being demonstrated only recently? The problem is that the phase of the background field differs from one side of the soliton to the other by a finite angle, say $2\pi/m$. If solitons are to be created arbitrarily in time, then one requires a coding scheme able to count to m to ensure that after m 1's are sent the background phase is restored to its original value. Thus, to encode a pseudorandom bit sequence using black solitons ($m = 2$), Nakazawa and Suzuki[8] used an electronic flip-flop in conjunction with an electro-optic phase modulator to restore the phase after sending two 1's. Unfortunately, electronics can be used only at relatively low bit rates (<50 Gbits/s), so making the leap to Tbit/s frequencies with such a scheme will require all-optical logic gates to count the solitons. This difficulty arising from the soliton phase shift would seem to frustrate the program of data transmission using dark solitons, unless an alternative scheme can be found.

In this Letter we propose such an alternative. Uniform periodic trains of dark solitons can be created all-optically in fibers without logic gates to monitor the phase,[11] but then these trains themselves carry no information. However, such a soliton train also induces a periodic modulation of the refractive index that moves rigidly at a constant velocity. The regions where the ratio of refractive index to group-velocity dispersion is high can trap weak signals in the orthogonal polarization and carry them along without dispersion. Thus the soliton train acts as an optical conveyor belt, moving packets of small, but otherwise arbitrary, energy along the fiber, as shown in Fig. 1.

This fact can serve as the basis for a new scheme for optical fiber communications. Because they are based on dark solitons, optical conveyor belts are robust with respect to perturbations. Moreover, because the solitons occur only in an unmodulated train, generating them requires no counting logic, and the bit rate of the train of copropagating dispersionless bright pulses is at least as high as the soliton repetition rate. Thus all-optical generation of the pulse train can lead to transmission rates as high as 1 Tbit/s. There is even the possibility of several optical conveyor belts simultaneously sharing the same fiber.

Let us describe the theory of these optical conveyor belts. Imagine an intense pump field and an orthogonally polarized weak signal field, both at the same wavelength in the normal-dispersion regime. Let $p(z,t)$ and $s(z,t)$ be the envelopes of the pump and

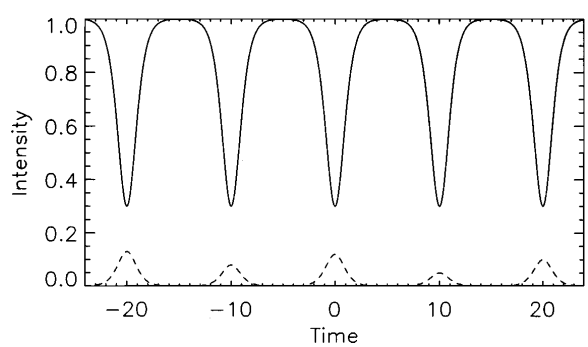

Fig. 1. Schematic diagram of the temporal pump and signal wave trains for a single channel. The intensity of the pump (signal) is shown with a solid (dashed) curve. Note that, whereas the dispersionless pulses carried by the train of dark solitons all have the same width, their amplitudes are arbitrary.

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the signal, respectively, where z is the distance along the fiber and t is the retarded time. We take the coupled system

$$i\,\frac{\partial p}{\partial z} - \frac{1}{2}\,\frac{\partial^2 p}{\partial t^2} + |p|^2 p = 0\,, \tag{1}$$

$$i\,\frac{\partial s}{\partial z} - \frac{1}{2}\,\frac{\partial^2 s}{\partial t^2} + |p|^2 s = 0 \tag{2}$$

as a model. Equations (1) and (2) are a linearized version, obtained by assuming that $|s| \ll |p|$, of the Manakov model, which directly describes the propagation of pulses in a special case of uniform elliptical birefringence.[12] The equations that describe general pulse propagation in a homogenous fiber have additional terms describing enhanced cross-phase modulation and energy exchange between the components. However, if the fiber is randomly birefringent, the Manakov model again describes pulse propagation in the sense of an average of the nonlinear terms over the Poincaré sphere.[13] In fact, it has been shown experimentally[14] that solitons in two orthogonal polarizations remain orthogonally polarized along the whole fiber, in agreement with the theoretical predictions of the Manakov model.

Because of normal dispersion, the nonlinear Schrödinger equation (1) for the pump has dark soliton solutions of contrast $0 \le C \le 1$ of the form

$$p(z,t) = A_p\left\{\sqrt{1 - C^2} + iC\,\tanh[\mu(z - vt)]\right\} \times \exp[i(k_p z - \omega_p t + \theta_p)], \tag{3}$$

with velocity $v = 1/(\omega_p + A_p\sqrt{1 - C^2})$ and inverse width proportional to $\mu = A_p C(\omega_p + A_p\sqrt{1 - C^2})$, where A_p, θ_p, ω_p, and $k_p = A_p{}^2 + \omega_p{}^2/2$ are the amplitude, phase, frequency, and wave number, respectively, of the fixed background field. We allow contrast C to be arbitrary rather than restricting it to the black case, $C = 1$, to reserve a parameter for channel multiplexing. Linear equation (2) has the corresponding solution:

$$s(z,t) = A_s\,\mathrm{sech}[\mu(z - vt)]\exp[i(k_s z - \omega_s t + \theta_s)], \tag{4}$$

which moves with the soliton velocity v but has arbitrary amplitude A_s and phase θ_s. The wave number is $k_s = 1/(2v^2)$, and the signal frequency, $\omega_s = \omega_p + A_p\sqrt{1 - C^2}$, is detuned from the pump frequency ω_p by an amount that depends on the soliton contrast C. The pulse [Eq. (4)] is simply a linear pulse whose group velocity matches the soliton velocity and whose dispersion is completely suppressed by the presence of the dark soliton in the orthogonal polarization.

Suppose now that the pump field is taken to be a uniform train of well-separated dark solitons, each of the form of Eq. (3) for fixed contrast C, moving at a speed close to v in the fiber. Such a periodic train can be created all-optically, and we assume that the contrast of the train is accurately maintained in the fiber. Along with each soliton in the train the orthogonal polarization may now contain a dispersionless pulse of the form of Eq. (4), with A_s arbitrary. These pulses will remain trapped as they propagate over distances that are exponentially long in the pulse separation. Thus each soliton of the pump carries along the fiber one analog value, namely, the intensity of the dispersionless pulse in the orthogonal polarization, as shown in Fig. 1. Although the pump itself carries no data, it serves to move arbitrary-amplitude pulses along the fiber without dispersion. By quantized amplitude modulation, each of these pulses can encode as many bits of information as the available signal-to-noise ratio will allow, and their repetition rate matches that of the carrier train.

Now let us consider how several optical conveyor belts might simultaneously share a single fiber. For the purpose of merely dragging along signal pulses in the orthogonal polarization, one can just as well choose a wavelength in the anomalous-dispersion regime and use a periodic train of bright solitons in the pump to guide the weaker pulses. However, a striking feature of dark solitons not shared by bright ones is that pulses carried by solitons with different velocities do not interact with one another during collisions, as depicted schematically in Fig. 2. (Note that the relevant numerical experiments are described in detail elsewhere[15].)

This remarkable fact has been observed numerically[15] and proved analytically.[16] This exact result holds regardless of the number of dark solitons colliding at the same place. Although the refractive-index pattern induced during the collision can be quite complicated, there is no need to calculate it to show that the pulses are always restored after the impact. The elasticity of the linear pulses during collisions permits the multiplexing of several channels (indexed by $i = 1, 2, \ldots$) onto the same fiber. The idea is to replace the periodic pump field with a pump field composed of several periodic trains of dark solitons at different levels of contrast C_i (and hence different velocities v_i) propagating on the same background: a so-called multiphase solution[17] of Eq. (1). Then, when one soliton overtakes another, the solitons and the signals carried by them maintain their identities exactly after collision. As the frequency of pulses in the ith signal channel is detuned from ω_p by an amount that depends on the contrast C_i of the guiding solitons, the

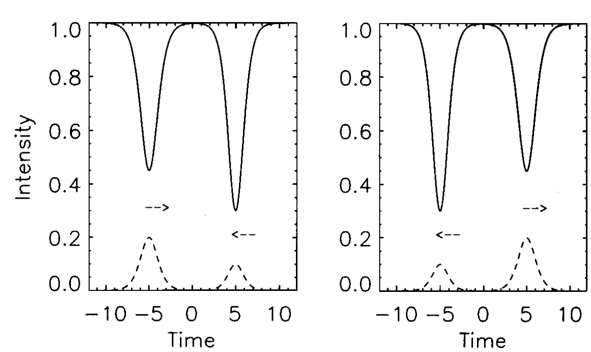

Fig. 2. Linear pulses carried by dark solitons survive collisions just as dark solitons themselves do. The curves are marked as in Fig. 1.

channels can be separated at the output of the fiber by simple spectral filtering of the signal polarization, as with wavelength-division multiplexing of bright solitons. As in the bright case, a coincidence detector with a fiber memory loop is needed at the point of reception to prevent channel collisions from occurring there. Although multiplexing requires the use of gray soliton trains that can experience jitter, this effect is smaller than the Gordon–Haus effect for bright soliton wave trains by a factor of at least $1/\sqrt{2}$.[10] Jitter decreases as contrast decreases.

What physical parameter values would be required for implementing an optical conveyor belt? For rough estimates, suppose that we use the same dispersion-shifted fiber as did Nakazawa and Suzuki[8]; this has zero dispersion at 1550 nm, and the group-velocity dispersion at the operating wavelength of 1530 nm is ~1 ps/(km/nm). The loss coefficient at this wavelength is minimal: $\gamma \approx 0.2$ dB/km. We may have dark pulses of duration close to 1 ps with soliton period ~1 km by using a background power level of ~0.1 W. The bit rate in such a system can thus be as high as 1 Tbit/s, especially if we assume that several bits are coded into each bright pulse by quantized amplitude modulation. It would be prudent first to implement the scheme by using black solitons alone, because both pump and signal then share the same frequency ω_p. Multiplexing with gray solitons would then permit even higher bit rates.

We have thus suggested in this Letter that small-amplitude pulses trapped in the field of moving potential wells created in an optical fiber by a train of orthogonally polarized dark solitons can be used for extremely high-bandwidth data transmission. The advantages of the proposed scheme are the following:

1. Each dispersionless data pulse carries an analog value: its amplitude. Amplitude quantization can permit several bits per pulse.
2. Several channels can share the same fiber without interference. The channels are separated by spectral filtering of the signal polarization.
3. Because it is not modulated, the multiphase pump field can be created all-optically without any logic gates to keep track of the dark soliton phase shifts.
4. The scheme enjoys the stability and robustness of dark solitons. Furthermore, it is not particularly sensitive to the restriction $|s| \ll |p|$, because for finite signal amplitude the soliton-pulse combination becomes a bright-plus-dark soliton of the Manakov model, which is stable.[18]

In particular, features (1) and (4) are clear advantages over coding schemes that use bright solitons, feature (2) is not shared by coding schemes based on nonintegrable models (e.g., the dual-wavelength scheme of Haelterman and Badolo[19]), and feature (3) is an advantage over any scheme that used dark solitons alone. We are confident that data transmission methods such as the optical conveyor belts proposed here will be useful in future applications.

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