Information transfer via cascaded collisions of vector solitons

Charalambos Anastassiou* and Jason W. Fleischer

Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, and Department of Physics, Technion—Israel Institute of Technology, Haifa 32000, Israel

Tal Carmon

Department of Physics, Technion—Israel Institute of Technology, Haifa 32000, Israel

Mordechai Segev

Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, and Department of Physics, Technion—Israel Institute of Technology, Haifa 32000, Israel

Ken Steiglitz

Department of Computer Science, Princeton University, Princeton, New Jersey 08544

Received April 30, 2001

We demonstrate experimentally the transport of information from one vector (Manakov-like) spatial soliton to another via collisions with a third, intermediate soliton.

OCIS codes: 190.5530, 020.2070.

Scalar solitons of an integrable system, such as those generated from the nonlinear Schrödinger equation (which describes propagation in Kerr media) remain unaffected during collisions with other solitons. In fact, collisions merely lead to a phase shift (a lateral displacement in the case of spatial solitons).[1] This result is intuitive if one views a soliton as a guided mode of its own induced waveguide (induced potential).[2] Thus, interactions between solitons can be viewed as interactions between guided modes of induced waveguides in close proximity.[3] For a Kerr soliton, the induced potential is reflectionless,[2] so scalar Kerr solitons (solitons that have only one field component) colliding at a nonzero angle cannot exchange energy. This is why solitons suffer only a phase shift (displacement) upon collisions. This phase shift depends only on the soliton power and velocity, which are both conserved quantities. Therefore, when two scalar soliton collisions occur sequentially, the outcome of the first collision does not affect the second collision (except for the uniform shift). On the one hand, this property is a manifestation of the robustness of solitons, which is important for communication applications in which temporal solitons are used as data bits carried along an optical fiber.[4] On the other hand, there are cases when it is desirable for solitons to interact more strongly, so that information may be transferred from one to another. For example, solitons have been suggested for information processing purposes, in which case they behave as particles in cellular automata.[5] For these purposes, scalar Kerr solitons offer very little.[5] One could, of course, employ collisions of solitons in nonintegrable systems, such as spatial solitons in saturable nonlinearities,[3] in which case the number of solitons is not always conserved. But it is very difficult to define a "state" in such systems, because even the main building block, the presence of a soliton, is not always guaranteed in a fusion process in which two solitons merge into one. For this reason, and for reasons of zero radiation loss, it would be highly desirable to find a method to transfer information between solitons in an integrable system. As it turns out, vector solitons (solitons that consist of more than one field component) in the integrable ideal Manakov system can do just that; the field components that make up the vector solitons exchange energy (symmetrically) upon collision, and at the same time they retain all other conserved quantities of integrable systems.[6,7] (For temporal Manakov solitons, this energy exchange is commonly referred to as polarization switching.) This energy-exchange effect has been proposed as a mechanism for performing computation through interaction of vector solitons.[8] Experimentally, however, thus far to our knowledge only a single collision (a single energy-exchange process) has been demonstrated,[9] and there is no experimental evidence of the ability to cascade information from one collision to the next. Here we experimentally demonstrate a sequence of two collisions of vector (Manakov-like) solitons and show how information can be passed from one collision to the next.

Vector solitons consist of two (or more) field components that mutually self-trap in a nonlinear medium. These solitons were first suggested by Manakov[6] for the Kerr nonlinearity, which leads to two coupled nonlinear Schrödinger equations, shown here in normalized units:

$$i\,\frac{\partial A}{\partial z} + \frac{1}{2}\,\frac{\partial^2 A}{\partial x^2} + (|A|^2 + |B|^2)A = 0\,, \tag{1}$$

$$i\,\frac{\partial A}{\partial z} + \frac{1}{2}\,\frac{\partial^2 B}{\partial x^2} + (|A|^2 + |B|^2)B = 0\,, \tag{2}$$

where x and z are the trapping and propagation directions. $A(x,z)$ and $B(x,z)$ are the two fields coupled through their total intensity only (no interference terms). Spatial Manakov-like solitons were demonstrated in planar waveguides[10] and in photorefractives (PRs).[11]

Extending earlier work,[6] Radhakrishnan *et al.*[7] derived a two-soliton solution, an example of which is shown in Fig. 1(a). When the peaks are well separated, one can think of the system as being composed of two vector solitons, i.e., (A_1, B_1) and (A_2, B_2). The result of the collision can be predicted,[6,7] and the collision process as a whole is tractable through a simple bilinear transformation.[8] In such a collision, the field constituents that make up the solitons exchange energy: A_1 exchanges energy with A_2, and B_1 with B_2. Such interaction does not occur with scalar solitons.

Here we investigate collisions in the configuration illustrated in Fig. 1(b), in which a scalar soliton A_2 collides first with a vector soliton, (A_1, B_1), and then with a second scalar soliton, A_3. For the Manakov system, the collision results can be calculated analytically.[6–8] However, it is insightful to explain the energy-exchange interaction through induced gratings.[9] To understand how the cascaded collisions work, let us first concentrate on the first collision between A_2 and the vector soliton (A_1, B_1). Intuitively, A_1 and A_2, which belong to the same field, write a grating inside the nonlinear medium. B_1, which travels in the A_1 direction, gets partially diffracted toward the A_2 direction. This diffracted B field propagates with A_2 after the collision, resulting in a vector soliton (A_2, B_2). [Soliton momentum is conserved by transfer of energy from A_2 (equal to the energy split from B_1) to A_1]. In the second collision, the resultant soliton 2 collides with another (initially scalar) soliton, A_3. In this second collision, through a mechanism that is identical to that of the first collision, B_2 transfers some of its energy to B_3, resulting in the vector soliton (A_3, B_3). In this way, some of the energy contained in the B component of soliton 1 is transferred, in a sequential fashion, to both solitons 2 and 3 [shown schematically in Fig. 1(b)]. It is important to say that, to satisfy conservation of energy and linear momentum, wherever energy is transferred from the B field of soliton i to the B field of soliton j, the exact amount of energy is transferred back between the A fields (from A_j to A_i).

In our experiment, we employ the PR screening nonlinearity.[12,13] Collisions of PR screening solitons may add contributions from diffusion fields that result in a unidirectional transfer of energy from one soliton to another, with energy flowing toward a preferential axis. However, the collision angle in our experiment (~0.5°) between A_1 and A_2 induces an interference grating with an ~20-μm period, giving a negligible diffusion field, ~20 V/cm, compared with the screening field supporting the soliton (~1 kV/cm). Thus the contribution of the PR diffusion field to energy exchanges between colliding solitons is negligible at such shallow angles, as demonstrated experimentally in Ref. 9. The PR screening nonlinearity is saturable, i.e., not Kerr, but when two such scalar solitons collide at angles larger than the complementary critical angle, θ_c, they behave almost as Kerr solitons.[3,9] When a soliton is viewed as a mode of its own induced waveguide, θ_c determines the maximum incidence angle at which light can couple into the waveguide. Thus, when two scalar solitons of a saturable nonlinearity collide at angles larger than θ_c, they cannot couple light into each other, and they behave just as Kerr solitons.[3] Here, all our experiments are with collision angles above θ_c, so the solitons behave as Kerr solitons. We generate vector (Manakov-like) solitons in PRs by preventing interference terms from contributing to Δn.[14] We bounce one of the fields (B) off a piezoelectric mirror moving much faster than the response time of the nonlinearity. As a result, all (time-dependent) interference terms average out and do not contribute to Δn.

Our setup is similar to that of Ref. 9. We expand and collimate an Ar^+ laser beam, polarized parallel to

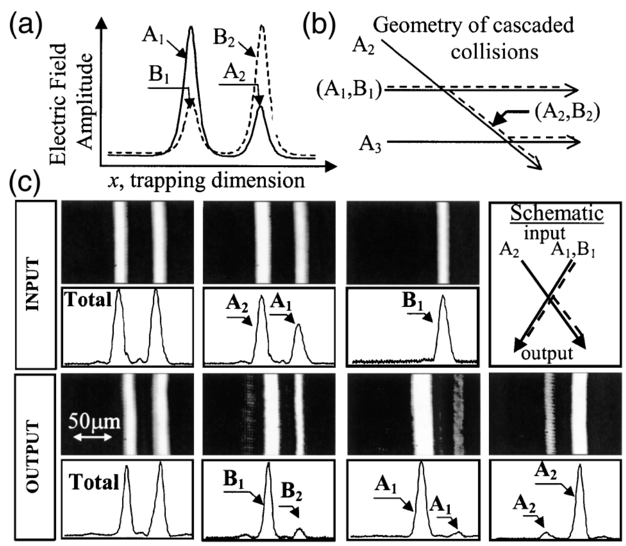

Fig. 1. (a) Two Manakov solitons, showing the A-field (solid curve) and the B-field (dotted curve) constituents. (A_1, B_1) are one vector soliton, and (A_2, B_2) are the other vector soliton. (b) Schematic representation of the cascaded collisions. A scalar soliton, A_2, collides with a vector (A_1, B_1) and the another scalar soliton, A_3. For illustration purposes A_1 and B_1 are slightly separated, but in reality they overlap. (c) Experiment for the first collision with A_3 is off. The top row shows the input conditions for the total input (left), the A field (middle), and the B field (right). The bottom row shows the output, from left to right: the total, B_1, A_1, and A_2 intensities after the collision. The total energy in each vector soliton is conserved, but the components exchange energy. The arrows in the geometry and the schematic point out the energy exchange.

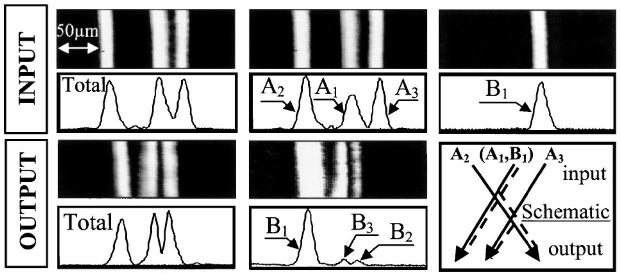

Fig. 2. Same conditions as in Fig. 1(c) but with A_3 on, so two collisions occur. The input and output conditions are shown at the top and bottom row, respectively. From the bottom row, we see that the B field has split twice as a result of the collision, but the total energy in each vector soliton is still conserved as expected.

the c axis of the PR crystal. The beam is split into A_1, A_2, A_3 (all belong to the same field, A), and B_1. B_1 is reflected off a fast-vibrating piezoelectric mirror and then recombined with A_1 (with a beam splitter) to form the beam that will be soliton 1: The combined beam is focused with a cylindrical lens on the input face of a 1.3-cm-long $SrBa_{0.6}Nb_{0.4}O_3$ crystal. A_2 and A_3 (forming solitons 2 and 3, respectively) are also focused at the crystal input. The uniform background illumination that is necessary for screening solitons[9] is from a white-light source illuminating the crystal perpendicular to the propagation direction. An electric field is applied along the c axis.[9] The input and output faces of the crystal are imaged on a CCD camera. The slow response of the crystal enables us to view each component (that makes up each soliton) individually[9] by blocking one beam and sampling the other within a time interval ($\sim$1 ms) much shorter than the response time of the crystal ($\sim$3 s).

In Fig. 1(c) we show results of the first collision (A_3 is off). The input conditions are shown in the top row. The total input (left) is symmetric in intensity and is composed of the A field (middle) and the B field (right). The soliton outputs after 13 mm of propagation are shown in the bottom row. The total output (left) resembles the total input, as expected, since the total intensity of each vector soliton must be conserved. When we sample each field and each beam at the output (with the technique described above), we see that energy is exchanged. B_1, which starts at the input as one beam, splits into two as a result of collision. Since the total intensity in each vector soliton is conserved, A_1 and A_2 also exchange energy with each other. The solitons are 14 μm FWHM, 58 μm apart at the input, and 48 μm apart at the output. We tune the intensity ratio (maximum intensity of the soliton normalized to the background[12]) to $\approx$2, which corresponds to the minimum applied field required for trapping. The collision angle is 0.46°, and the maximum Δn (estimated from the existence curve) is $\approx 1.3 \times 10^{-4}$. Under these conditions, the critical angle is $<0.3°$, so all our collisions are above critical, ensuring that the solitons behave as Kerr solitons. The efficiency of this energy-exchange interaction is $\sim$15%, and it increases with smaller angles and smaller intensity ratios (closer to the Kerr limit).[9]

In the second experiment (Fig. 2), all the experimental conditions are the same as before, but we now turn on A_3 and launch it parallel to (A_1, B_1), as illustrated in Fig. 1(b). The total input and output are symmetric, showing that each vector soliton conserves its energy. When we observe the output of the B field (bottom row, right), we notice that B_1 is split twice, becoming part of both solitons 2 and 3 after the collision. Thus we have shown experimentally that the energy-exchange interaction can transfer information from one soliton (soliton 1) to another (soliton 2), which then relays it to a third (soliton 3).

In conclusion, we have studied experimentally the energy-exchange interactions between vector solitons. Such interactions are not possible with scalar solitons. We have shown how, in a sequence of two collisions, the outcome of the first collision directly affects the outcome of the second. One potential application of this arrangement is as a tunable, directional beam splitter, in which B_1 is the signal that is successively split off after each collision. Another application is coding of information bits that are carried by solitons and then transferred through collisions to numerous layers of interacting solitons. This cascaded interaction of vector solitons lays the experimental foundations for computation with solitons.[8]

This work was funded by a Multidisciplinary University Research Initiative on optical solitons, by the U.S. Army Research Office and by the Ministry of Science of Israel.

*Present address, Omniguide Communications, Cambridge, Massachusetts 02139.

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