Cascading Collisions Between Vector Solitons

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Abstract: We present the first experimental observation of cascading two collisions between vector (Manakov-like) solitons. This experiment shows that it is possible to use collisions between vector solitons as a means of transferring information.

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It is well known that when two scalar solitons (of a fully integrable system) collide, they experience only a phase shift while conserving their energies, linear momenta, and shapes [1]. Vector (Manakov-type) solitons, on the other hand, consisting of two [2] or more components, display a spectrum of interactions that is much richer than that of scalar solitons [3,4,5]. Each vector soliton as a whole preserves its shape and total intensity upon collisions with other vector (or scalar) solitons, yet the components that make up the vector soliton are free to exchange energy. (In the terminology used in the seventies, this is referred to as “polarization flipping”. For example, if a signal is represented by a particular field-component of a vector soliton, then subsequent collisions can be used to manipulate and split the signal in a very controlled and predictable fashion, depending on soliton parameters, e.g., collision angle, intensity, and width.

Here we investigate collisions of the form shown in Fig. 1, where a scalar soliton A2 collides first with a vector soliton, (A1, B1), and then with a second scalar soliton, A3. The A and the B fields can be thought of as orthogonally polarized just as in an ideal Manakov system [2].

Fig1. The dotted line represents the B-field. Initially, at z=0, B only exists as B1, which forms soliton 1 together with A1. After the first collision, B1 splits and gives part of its energy to soliton 2 in the form of a new field component B2 (A2 and B2 emerge as soliton 2 after the collision). At the second collision, B2 splits to give energy to B3.

To understand how the cascaded collisions work, let us first concentrate on the first collision between A2 and vector soliton, (A1, B1). This collision is identical to the one studied in [5], for which exact analytical results exist for the Manakov system. Intuitively A1 and A2, which belong to the same field, write a grating inside the nonlinear medium. B1, which travels in the A1 direction, gets partially diffracted
towards the A2 direction. Following the first collision, A2 and B2 emerge as soliton 2, which has now two field components. Subsequently, this soliton 2 collides with another (initially scalar) soliton A3. In the second collision, through a mechanism that is the same as the first collision, B2 transfers some of its energy to B1, and A1 and B1 emerge as soliton 3 (which at the end is a vector soliton as well). In this way, some of the energy contained in the B component of soliton 1 was transferred, in a sequential fashion, to both solitons 2 and 3 (shown schematically in Fig. 1). It is important to say that, to maintain the symmetry, wherever energy was transferred from the B field of soliton "i" to the B field of soliton "j", the exact amount of energy was transferred back between the A fields (from A1 to A3).

We performed our experiment in a photorefractive SBN crystal using 1 dimensional solitons. The two fields are coupled through a saturable nonlinearity of the form 1/(|A|^2 + |B|^2) which differs from the one in the Manakov system, (|A|^2 + |B|^2). Soliton interactions, however, are almost identical in both systems for collision angles greater than the (complementary) critical angle (for total internal reflection in the waveguide induced by each soliton; in our experiments, this angle is roughly 0.2 degrees) [5]. As for ideal Manakov solitons, our system dictates that the interference between A and B does not contribute to the nonlinearity, yet the self- and cross-phase modulation are identical, and there are no additional nonlinear (four wave mixing) terms. This is accomplished experimentally through the mutual incoherence method [6]: the beams have the same polarization and wavelength but B is reflected from a fast vibrating mirror (driven by a piezoelectric transducer). This causes the interference pattern of A and B to move much faster than the response time (∼3 sec) of the photorefractive crystal. 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 beam individually by blocking the remaining ones (with a mechanical shutter) and sampling the other within a time interval (∼10 msec) shorter than 10s.

![Image](image-url)
In Fig. 2 we show the results of the first collision, where we turn $A_3$ off. The solitons are 14 $\mu$m wide (FWHM) and they are 58 $\mu$m apart at the input and 48 $\mu$m at the output after 13 mm of propagation. The angle of collision is 0.46° and the maximum nonlinearity (change in the index of refraction) is $1.3 \times 10^{-4}$.

Notice that the total intensity of each soliton is constant; the field components exchange energy in a symmetric (and opposite) way as to ensure that.

In the second experiment, shown in Fig.3, 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 shown schematically in Fig. 1. As clearly shown in Fig. 3, the $B$ field is part of both solitons 2 and 3 emerging from the collision.

In summary, we have demonstrated the cascaded collision between vector (Manakov-like) solitons. This experiment shows that information can be transferred from a soliton (an "input state") to a second soliton ("intermediate state") and eventually relayed to a third soliton ("final state"). The importance to the new concept of soliton computation is obvious: soliton collisions can serve as a means to transfer complex state information. Yet this experiment has importance even in modest integrated optics applications: if $B_1$ is thought of as a signal beam, this setup can be used for a very directional and tunable all optical beam splitter.

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References