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Explicit construction of single input–single output logic gates from three soliton solution of Manakov system

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ABSTRACT

We construct single input logic gates using the energy sharing collisions of a minimal number of (three) bright optical solitons associated with the three soliton solution of the integrable Manakov system. As computation requires state changes to represent binary logic, here we make use of the state change of a particular soliton during its sequential collision with other two solitons for constructing single input gates. As a consequence, we clearly demonstrate the construction of various one-input logic gates such as COPY gate, NOT gate and ONE gate using energy sharing three soliton collision of Manakov system. This type of realization of logic gates just from a three soliton collision (pair-wise interaction) is clearly distinct from the earlier studies which require separate collisions of four solitons.

1. Introduction

The recent developments in optical computing, quantum computing, computing via chaos suggest that light can be used to execute logical operations instead of discrete electronic components used in the present day computer [1]. In this work, we focus on collision based computation involving energy sharing collisions of solitons in nonlinear media. Here, computation occurs by the pair-wise collisions of solitons, where each soliton bears a finite state value before collision, and state transformations occur at the time of collisions between solitons.

Collision based computation can be realized in several physical and chemical systems such as cellular automata [2], fiber couplers [3], Josephson junction [4], etc. This collision based computing originally introduced in conservative computation such as a billiard ball model [5] and its cellular automaton analogues [6], presents a novel approach of computation with mobile physical objects (e.g., billiard balls, chemical particles, self-localized patterns on cellular automata, and so on). The well-established problems of emergent computation and universality in cellular automata have been tackled by a number of researchers in the past 35 years [7–10] and still remains as an active area of theoretical computer science and nonlinear science. The best-known universal automaton is the Game of Life [11]. It was shown to be universal by Berlekamp et al. [12] who simulated logic gates by the Game of Life. An evolutionary algorithm searching for collision-based computing in cellular automata has been presented in Ref. [2]. Here, the AND gate has been simulated by the Game of Life. Also Adamatzky demonstrated exact implementation of basic logical operations with signals in Belousov–Zhabotinsky medium

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[13] and the experimental realization of logic gates has been presented in Ref. [14]. On the other hand, in fiber couplers a full set of logic functions including AND, NAND, XOR, NOT and OR gates are numerically demonstrated using two-core and three-core fiber coupler switches operating in the continuous wave regime [3]. Especially, it has been shown that the logic gates AND, OR and XOR can be constructed from an asymmetric two-core fiber coupler and in the symmetrical three core fiber coupler NAND, AND, OR, XOR and NOT logical gates can be realized. Likewise, using Josephson junction, collision based (fusion) computing has been performed in Ref. [4].

Using light field as carrier of information in modern day computers, which now employ electrons, has several advantages like faster speeds, smaller computers and less heat dissipation. To be specific, light creates virtually no heat when it travels while the electric current used in present day computers radiates a lot of heat. Additionally, light has the ability to pass through other beams of light. Two laser beams (pulses) can cross each other whereas electric currents cannot do this and the present computers are designed such that they never admit cross paths. Since the beam of light can cross each other, less space is required. This would result in smaller computers. Too many transistors used in modern day computers will also slow down the processor speed and metallic wires limit the speed of transmission whereas in a single light path, several data sets can be transmitted parallely at the same time using different wavelengths/polarizations. The higher parallelism and the faster velocity of light allow extreme processing speeds. These important characteristics of light suggest us to look for optical computing. In the pioneering work, Jakubowski, Steiglitz and Squier (JSS) [15] designed sequences of solitons operating on other sequences of solitons that effect logic operations, including controlled NOT gate. In this paper we have shown the explicit construction of one-input logic gates using three soliton collisions.

For this purpose, we consider the pico-second pulse propagation in a lossless strongly birefringent Kerr-type optical fiber [16–18] with local and instantaneous response in the anomalous dispersion regime which is governed by the following celebrated Manakov system [19]:

$$iq_{1,z} + q_{1,tt} + 2(|q_1|^2 + |q_2|^2)q_1 = 0, \tag{1a}$$

$$iq_{2,z} + q_{2,tt} + 2(|q_1|^2 + |q_2|^2)q_2 = 0, \tag{1b}$$

where q_1 and q_2 are the complex amplitudes of the first and second components, the subscripts z and t represent the partial derivatives of the normalized distance along the fiber and the retarded time, respectively. Here, solitons are used to carry the information inside the nonlinear medium and computation occurs when these solitons collide. Manakov solitons have been observed experimentally in Ref. [20]. These Manakov solitons undergo fascinating energy sharing collision as well as standard elastic collision. Radhakrishnan et al. [21] have obtained the two-soliton solution of the integrable Manakov system and revealed that solitons in this system exhibit intriguing shape changing or energy sharing collisions which subsequently have been well studied in Refs. [22–24] and various types of energy sharing collisions have been observed in different multicomponent systems in [23,25–28]. However, computation requires state changes to represent binary logic and the energy sharing collision properties of Manakov solitons suggest their feasibility for computation. A salient feature of this kind of computation is that it performs conservative logic operations as the collisions preserve total energy of the Manakov system irrespective of their state change. Collision dynamics of energy sharing solitons in Manakov system and its application in computing are studied in detail in Refs. [22–24]. Below, we first review this exciting energy sharing collision and then discuss the principle and our construction procedure of one-input logic gates.

2. Brief review of developments of soliton collision based optical logic gates construction

The Manakov system (1) describes the propagation of an intense electromagnetic wave in a two mode/birefringent fiber as mentioned in the introduction. Here, interaction between the field components results in intensity dependent nonlinear cross-coupling terms. In 1973, Manakov [29] solved the set of coupled nonlinear evolution Eq. (1) using the inverse scattering transform method and obtained multisoliton solutions. Later, in Ref. [21] fascinating collision properties of bright solitons in the Manakov system have been revealed. Also, here the polarization parameters bring an additional freedom so that there occurs an amplitude/intensity redistribution among the colliding solitons. As a consequence of this, a particular soliton in a given component can enhance its intensity along with suppression in the other component. There will also be commensurate changes in the other soliton. Thus in this interesting collision process, solitons in a given component exchange energy in order to conserve the energy in that component. Additionally, the solitons in different components also exchange energy so that the total intensity is also conserved. JSS [15] found that this energy sharing collision can be profitably used for performing nontrivial information transformation. In Ref. [15] the state change undergone by each colliding soliton was expressed as a linear fractional transformation (LFT). This transformation depends on the total energy and velocity of the solitons which are invariant under collision. JSS designed sequences of solitons operating on other sequences of solitons that effect logic operations, including controlled NOT gate. In this operation, both data and logic operators have the self-restoring and re-usability features of digital logic circuits. Also, numerical simulation of an energy switching NOT processor was implemented in the Manakov system. It was suggested that it might be possible to use these light–light interactions to do general computation in a bulk medium, without interconnecting discrete components.

In 2000, Steiglitz [30] extended the work to the Manakov (1+1) dimensional spatial solitons for performing arbitrary computation in a homogeneous medium with beams entering only at one boundary. Here both the dimensions are spatial. For computational purpose, separate collisions of *four solitons* (three down moving vertical solitons and one left moving