Storage by trapping and spatial staggering of multiple interacting solitons in Λ-type media

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In this paper we investigate the properties of self-induced transparency (SIT) solitons, propagating in a Λ-type medium. We find that the interaction between SIT solitons can lead to trapping with their phases preserved in the ground-state coherence of the medium. These phases can be altered in a systematic way by the application of appropriate light fields, such as additional SIT solitons. Furthermore, multiple independent SIT solitons can be made to propagate as bisolitons through their mutual interaction with a separate light field. Finally, we demonstrate that control of the SIT soliton phase can be used to implement an optical exclusive-or (XOR) gate.

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I. INTRODUCTION

Strong and coherent interactions between Λ-type three-level atomic media and resonant light pulses have been a topic of much interest recently. Driving this interest are various optical communications applications, such as optical buffers and phase shifters for optical routers [1,2]. Of particular interest is all-optical switching based on solitons to realize optical gates ([3] and references therein). Generally, the Kerr effect is chosen as the nonlinear interaction between solitons due to its presence in many different media. However, the low value of typical Kerr coefficients implies that intense optical pulses and/or long interaction lengths must be used. In contrast, self-induced transparency [4] (SIT) provides solitons that are based on a strong, resonant optical nonlinear effect, which could, in principle, reduce interaction lengths and pulse intensities required for all-optical switching.

The interaction of a single SIT soliton with a control pulse has been investigated by Vemuri *et al.* [5], who showed that a single SIT soliton can be cloned in a Λ-type medium by applying a weak control light field resonant with the $|2\rangle$–$|3\rangle$ transition (see Fig. 1). In doing so, the spatial region of the medium where the SIT soliton and control pulse overlap is left with a significant population in $|2\rangle$ and a ground-state coherence extending to either side of the region [6,7], which we refer to as the trapped soliton.

The trapped soliton presents an intriguing possibility: namely, that linear and nonlinear optical operations may be performed on the trapped soliton by using resonant light fields. Normally, operations between different solitons must be carefully timed so that the overlap in the linear (e.g., beam splitters) or nonlinear optical elements is maximized. However, in the case of a trapped soliton, the timing problem is much less critical because optical operations can be performed on the stationary coherence, rather than on the traveling soliton.

Unfortunately, very little is known about the quantum or classical interactions between trapped solitons, propagating SIT solitons, or other light fields. Recent work has shown that the presence of a captured soliton is sufficient to trap additional solitons [6,8]; however, the mechanism of such trapping, and the interaction of the trapped solitons with light fields resonant with the $|2\rangle$-$|3\rangle$ transition, remained unexplored. In what follows, we go beyond these results by examining the influence of additional control pulses and SIT solitons on the state of the medium and the phase of the emitted light.

The details of the trapping process are explained and we highlight this by examining three representative cases. The interaction of a control light field with both single captured solitons and multiple solitons is examined. We found that multiple trapped solitons can behave like bisolitons. Further, we show that the trapping process and interactions with control light fields manipulate the phases of the captured soliton. Finally, by choosing the soliton phase as an information carrier, we demonstrate a series of operations that implement an all-optical exclusive-or (XOR) gate.

II. THEORY

To study the propagation and interaction of light in a three-level medium, in which each atom has energy states as shown in Fig. 1, we employ a density-matrix approach in the rotating-wave approximation (RWA) [9]. The medium's constituent atoms have one excited state and two ground states. The $|1\rangle$–$|3\rangle$ and $|2\rangle$–$|3\rangle$ transitions are dipole-allowed radiative transitions, while the $|1\rangle$–$|2\rangle$ transition is dipole forbidden. The medium is discretized along the propagation axis, creating a one-dimensional (1D) grid. At each grid location along the propagation axis, the medium's state is represented by an independent density matrix. This leads to the following set of differential equations for each grid point, the solution of which provides the time- and space-dependent population densities and coherences between populations throughout the whole medium:

$$\dot{\rho}_{11} = -\frac{i}{2}(\chi_{13}\rho_{13} - \chi_{13}^*\rho_{13}^*) + \rho_{33}R_{31}, \tag{1}$$

$$\dot{\rho}_{22} = -\frac{i}{2}(\chi_{23}\rho_{23} - \chi_{23}^*\rho_{23}^*) + \rho_{33}R_{32}, \tag{2}$$

$$\dot{\rho}_{33} = \frac{i}{2}(\chi_{13}\rho_{13} + \chi_{23}\rho_{23} - \chi_{13}^*\rho_{13}^* - \chi_{23}^*\rho_{23}^*) - (R_{31} + R_{32})\rho_{33}, \tag{3}$$

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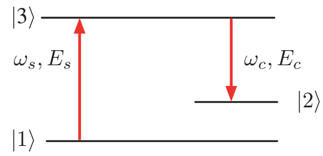

FIG. 1. (Color online) Λ-three-level system with two ground states and one excited state. A transition from state $|1\rangle$ to state $|3\rangle$ can be performed with an SIT soliton. The transition from $|2\rangle$ to $|3\rangle$ can be performed with a control light field. A radiative transition between $|1\rangle$ and $|2\rangle$ is dipole forbidden.

$$\dot{\rho}_{12} = \frac{i}{2}(\chi_{13}^*\rho_{23}^* - \chi_{23}\rho_{13}), \tag{4}$$

$$\dot{\rho}_{13} = \frac{i}{2}[\chi_{13}^*(\rho_{33} - \rho_{11}) - \chi_{23}^*\rho_{12}] - \beta_{13}\rho_{13}, \tag{5}$$

$$\dot{\rho}_{23} = \frac{i}{2}[\chi_{23}^*(\rho_{33} - \rho_{22}) - \chi_{13}^*\rho_{12}^*] - \beta_{23}\rho_{23}. \tag{6}$$

The diagonal elements of the density matrix ρ_{ii} are the population densities, normalized such that $\mathrm{Tr}(\rho) = 1$, of the energetic states of the medium. The off-diagonal elements ρ_{ij} are the coherence terms that are proportional to the polarization of the medium. The decay constants R_{31} and R_{32} account for spontaneous emission from $|3\rangle$ to $|1\rangle$ and $|2\rangle$, respectively. Decay of the coherence between states i and j is given by the rate β_{ij} representing nonradiative processes, such as collisional dephasing. The relationship between the Rabi frequencies χ_{ij} and the applied light pulses field envelopes E_s and E_c is given by

$$\chi_{13} = \frac{E_s\mu_{13}}{\hbar}, \tag{7}$$

$$\chi_{23} = \frac{E_c\mu_{13}}{\hbar}, \tag{8}$$

where μ_{13} and μ_{23} are the transition dipole moments of the two radiative transitions.

The light fields are assumed to be resonant with their respective transitions. The durations of the light pulses are assumed to be much shorter than the spontaneous emission rates, but long enough for the slowly varying envelope approximation (SVEA) to hold. We also require that the lifetime of $|3\rangle$ is sufficient to allow stimulated emission processes to dominate spontaneous emission. The temporal profiles of the light field envelopes are given by sech^2 functions, as SIT solitons assume this form naturally [4].

By applying the SVEA and limiting ourselves to one spatial dimension (plane-wave propagation into the positive z-direction), the Maxwell equations are given by

$$\frac{dE_s}{dz} = i\frac{k_s}{\epsilon_0}N\mu_{13}\rho_{13}^*, \tag{9}$$

$$\frac{dE_c}{dz} = i\frac{k_c}{\epsilon_0}N\mu_{23}\rho_{23}^*, \tag{10}$$

where k_s and k_c are the wave numbers of the SIT and coupling fields, N is the density of the active medium, and ϵ_0 is the electric permittivity of the vacuum.

The coupled set of density and Maxwell equations (1)–(6), (9), and (10) were solved numerically by using a fourth-order Runge-Kutta algorithm. All calculations begin with the $|1\rangle$ state fully occupied ($\rho_{11} = 1$) and with no coherence between any of the levels. In our calculations we use a value for the product of $N\mu = 1.7 \times 10^{-10}$ cm^{-2} [10], which corresponds, for example, to probing the transition from state 4^1P to state 3^1D of calcium in a gas cell with a 30-mbar partial pressure of calcium.

After a number of solitons and control pulses have interacted with the medium, we examine the spatial structure of the ground-state coherence (ρ_{12}), the phase of the ground-state coherence, and the phase of light emitted by the medium. In general, the phase of the light envelope is given by the argument of $E_i = A_i\exp(i\phi_i)$. Likewise, the phase of the ground-state coherence is given by the argument of $\rho_{12} = A_\rho\exp(i\theta)$. The phases are defined with respect to an initial control pulse, which we consider to have a phase of zero. In other words, the control pulse has a purely real field envelope.

III. RESULTS

We begin by partially repeating the work of Vemuri *et al.* [5], in which a single SIT soliton is trapped by the application of a single control pulse. This occurs because, as the SIT soliton excites population into $|3\rangle$, the control pulse stimulates emission into $|2\rangle$. The result is that the control pulse is amplified at the expense of the SIT soliton, which is absorbed by the medium. As shown by Loiko *et al.* [7], in this process, the medium has stored the sech^2 shape of the SIT soliton in the medium as a sech^2-shaped distribution of population in the second ground state. As a first phenomenon we observe that, in addition to the shape preservation, the phase of the stored soliton is also stored in the ground-state coherence of the medium (see the red solid trace in Fig. 2). More precisely,

$$\theta = \phi_{23} - \phi_{13}, \tag{11}$$

where ϕ_{23} is the phase of the control pulse and ϕ_{13} is the phase of the SIT soliton. This relationship comes from the fact that the coherence of the medium is proportional to the polarization of the medium, which opposes the light fields. Our calculations show another phenomenon: The blue dashed trace in Fig. 2 shows the resulting ground-state coherence after a sufficiently intense control pulse has interacted with the captured SIT soliton. Note that this control pulse shifts the SIT soliton's phase by π, while also shifting the location of the captured SIT soliton. However, control pulses with a relatively low intensity shift the location of the ground-state coherence without altering its phase [11].

A. Interactions between SIT solitons

We now turn to the case in which a second SIT soliton is injected into the medium after the capture of a first SIT soliton. In this case, the second SIT soliton encounters a medium with populations and coherences as described earlier and illustrated in Fig. 2. As will be described in more detail, we observed that, in general, these additional SIT solitons are trapped as well upon "collision" with the excited region, and that this leads to the creation of additional excited regions. An important feature of this process is that the second and subsequent SIT solitons are trapped without a control pulse being injected.

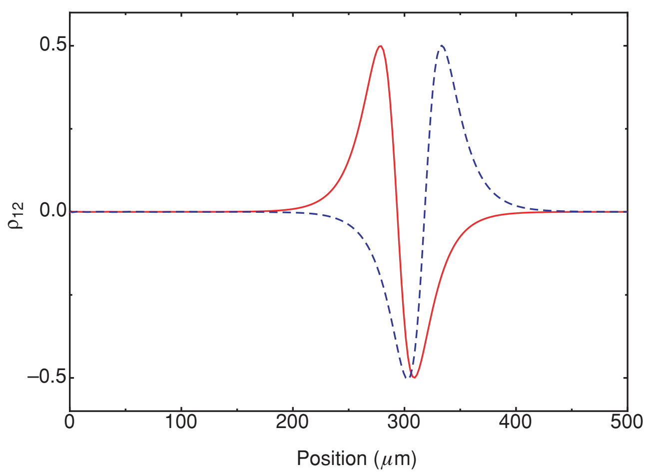

FIG. 2. (Color online) State of the ground-state coherence after the storage of a single SIT soliton by a small coupling pulse (red solid trace). Ground-state coherence after the application of a sufficiently intense control pulse to a medium containing a captured SIT soliton (blue dashed trace). The excited region is shifted deeper into the medium and the ground-state coherence undergoes a π phase shift.

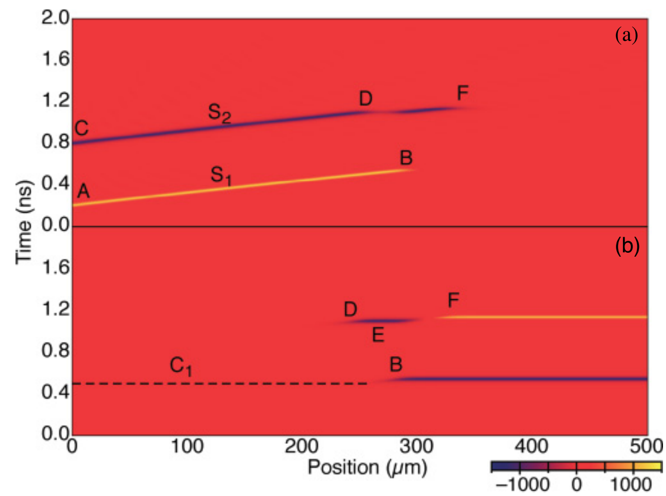

FIG. 3. (Color online) Electric field amplitude of light resonant with the $|1\rangle$–$|3\rangle$ transition, as either an injected SIT soliton or an emission from the medium. (a) Electric field amplitude (V m^{-1}) of light resonant with the $|1\rangle$–$|3\rangle$ transition and (b) electric field amplitude (V m^{-1}) of light resonant with the $|2\rangle$–$|3\rangle$ transition, as either an injected control pulse or an emission from the medium. Event A: The first SIT soliton is introduced to the medium. Event B: The SIT soliton and control pulse overlap, resulting in the SIT soliton's capture and the coupling pulse's amplification. Event C: The second SIT soliton is introduced to the medium. Event D: The SIT soliton collides with the first half of the excited region, emitting a negative control pulse. Event E: The negative control pulse captures the SIT soliton and is amplified. It then destructively interferes with the ground-state coherence of the second half of the excited region, resulting in the emission of a transitory SIT soliton. Event F: The remaining control light field is amplified by the transitory SIT soliton, capturing it in the process and extending the original excitation region.

This can be understood by examining the behavior of the SIT soliton and the Λ system, illustrated in Fig. 3. Figure 3(a) shows the intensity of the SIT solitons as a function of time and space, while Fig. 3(b) shows the intensity of control light fields. An initial SIT soliton is injected into the medium at time A, and travels slowly through the medium. A short time later, a control pulse is injected; it is, however, too weak to be visible on the scale of Fig. 3(b). The control pulse overtakes the SIT soliton at time and position B, where it is amplified at the expense of the SIT soliton, producing the excited region illustrated in Fig. 2. Note that the amplified control pulse exits the medium without further perturbation.

A second SIT soliton, with equal intensity to the first, is injected into the medium at time C; however, no control light fields are injected. Nevertheless, the SIT soliton is trapped in the medium by the collision with the excited region at time and position D. When the SIT pulse enters the first half of the excited region, the ground-state coherence ensures that there is simultaneous stimulated emission on both the $|1\rangle$–$|3\rangle$ and $|2\rangle$–$|3\rangle$ transitions. However, for this case, the light on the control transition is out of phase with the original control pulse, indicated by a negative value in Fig. 3(b) at location D. This control pulse is amplified at the expense of the SIT soliton, creating a new excited region in the medium.

At location E, the control light field enters the second half of the excited region, where the sign of the coherence is the reverse of the first half. The population transfer due to the control pulse removes this coherence, generating a new SIT soliton, which we refer to as a transitory SIT soliton. In doing so, the control pulse is completely absorbed and a new control light field with the phase of the original control pulse is emitted by the residual population and ground-state coherence. This control pulse captures the newly generated SIT pulse and is amplified in the process, and exits the medium (location F). The second capture process generates another excitation region. As a result, the medium now has a differently shaped excitation region, which is wider than before.

It is also important to note that the soliton collision results in a control pulse exiting the medium. This is a general result, and also occurs if collisions occur by inserting subsequent SIT pulses.

As described above, a transitory SIT soliton is emitted during the collision and subsequently recaptured by control light fields that are also emitted during the collision process. Thus, one would expect that the coherence generated during the capture of the transitory SIT soliton replicates that of the second SIT soliton capture. However, the original coherence, which is the source for all the control light fields after the first SIT soliton is captured, is an odd function with respect to the center location of the captured SIT soliton. Thus, the control light fields, emitted from each side of this location during the collision, are out of phase with each other. Consequently, these two light fields destructively interfere with each other. In this case, the two SIT solitons are identical, leading to a nearly complete destructive interference of the control light field. The control light that subsequently captures the transitory SIT soliton is generated from the residual excited population and coherence, which has a phase identical to the original control pulse. Thus, the coherence associated with the transitory SIT soliton is identical to that of the first SIT soliton.

This is highlighted by examining three cases: $P_{\rm pr} < P_{\rm tr}$, $P_{\rm pr} \geqslant P_{\rm tr}$, and $P_{\rm pr} \gg P_{\rm tr}$, where $P_{\rm tr}$ is the peak intensity of the SIT soliton that is captured by a control light field and P_{pr} is the peak intensity of the SIT soliton that collides with the ground-state coherence, which was written into the medium due to the capture of the first SIT pulse.

1. *Case 1: $P_{pr} < P_{tr}$*

As shown in Fig. 4(a), the second SIT soliton is trapped. For $P_{pr} < P_{tr}$, the lower-amplitude and slower-traveling second SIT soliton emits a lower-amplitude and slower-traveling transitory SIT soliton during the collision. Consequently, the second ρ_{22} peak is not shifted as deeply into the medium [60% of its full width at half maximum (FWHM) width] compared to the latter two cases. The distance between both peaks is about 5.5 times the FWHM of the original excited region, which is greater than for the latter cases. The greater separation is due to the fact that the second injected SIT soliton travels slower and is thus trapped within a shorter propagation distance by the control light fields emitted by the residual coherence, which extends throughout the medium.

Note also that the phase of the coherence appears to be inverted with respect to the original shape. The inversion occurs because the control light field that captures the second SIT soliton is generated by the coherence on the left-hand side of the excited region in Fig. 2. This light is out of phase with respect to the original control pulse (we also refer to this as a negative control pulse); thus, from Eq. (11), a shift of π is expected.

The excited population is surrounded by ground-state coherence that possesses a π phase step when ρ_{22} returns to zero between the two peaks. This indicates that the transitory SIT soliton is captured by a positive coupling pulse, which is expected because the relatively less intense control fields, emitted during the trapping of the second SIT soliton on the left-hand side of the original capture location, destructively interfere with the more intense control light fields emitted from the right-hand side of the capture location. The end result is a control light field with the same phase as the original control pulse.

2. *Case 2: $P_{pr} \geqslant P_{tr}$*

For the case of equal intensity SIT solitons, the second SIT soliton collides with the excited region and, as a result, does not penetrate as far into the medium as the first SIT soliton [see Fig. 4(b)] in comparison to Fig. 2. The act of colliding emits a transitory SIT soliton, which expands the excited region deeper into the medium by approximately twice its original FWHM width. The two peaks in ρ_{22} are separated by 1.5 times the FWHM width of the original excited-state regions. Note that ρ_{22} falls close to zero between the two peaks; however, as we will show later, these two regions remain coupled.

The trend between population peak locations and SIT soliton peak intensity is further illustrated for $P_{pr} > P_{tr}$[Fig. 4(c)], in which the second SIT soliton travels faster and emits a transitory SIT soliton that has a faster velocity during the collision. As a result, both population peaks are deeper in the medium.

As with case 1, the coherence appears to be inverted with respect to the original shape. The inversion occurs because the control light field that captures the second SIT soliton

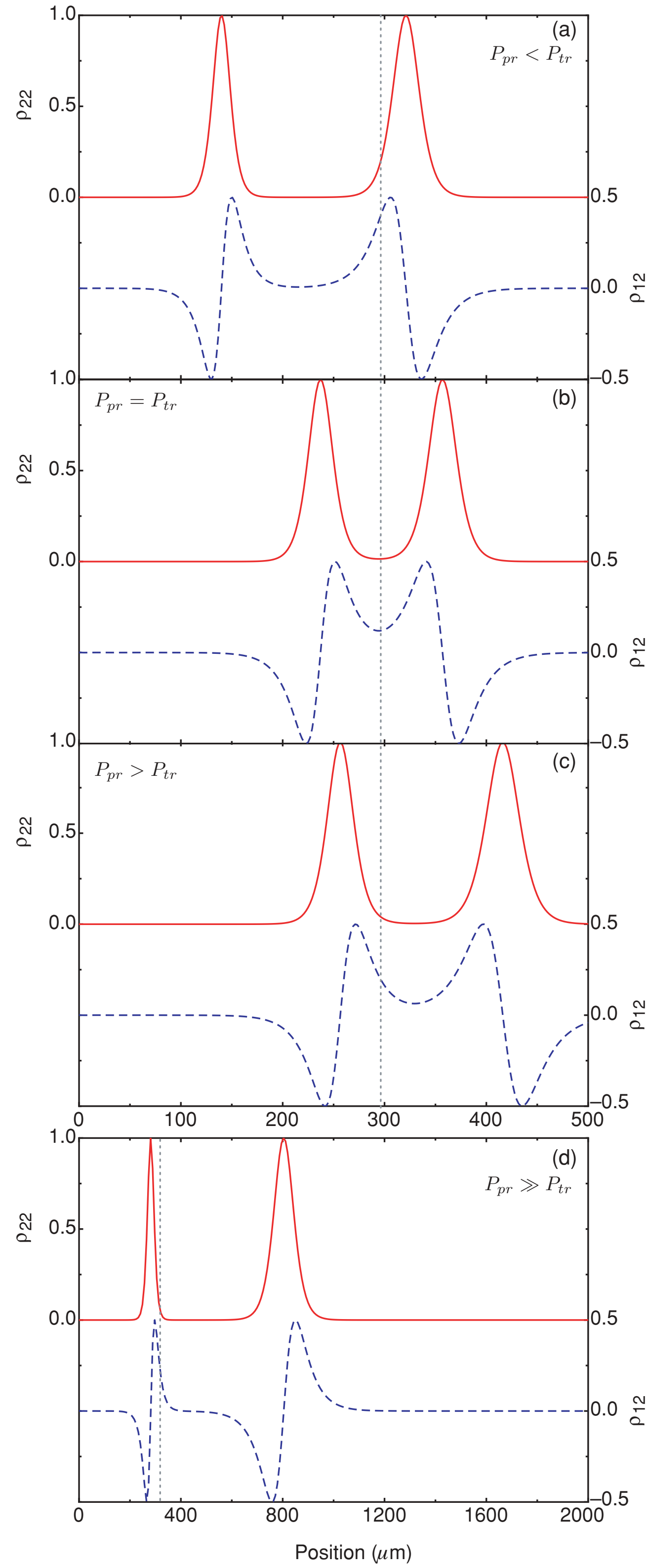

FIG. 4. (Color online) ρ_{22} (red solid trace) and ground-state coherence (blue dashed trace) throughout the medium after two SIT solitons are captured. Here, we show four examples labeled by the relative peak intensities of the SIT solitons: (a) $P_{pr} < P_{tr}$, (b) $P_{pr} = P_{tr}$, (c) $P_{pr} > P_{tr}$, and (d) $P_{pr} \gg P_{tr}$. The gray dotted vertical line indicates the original capture location of P_{tr}.

is generated by the coherence on the left-hand side of the excited region in Fig. 2. This light is out of phase with respect to the original control pulse (we also refer to this as a negative control pulse); thus, from Eq. (11), a shift of π is expected.

3. Case 3: $P_{pr} \gg P_{tr}$

In this case, the second SIT soliton is more intense and has a shorter temporal duration than the preparatory pulse, resulting in quite different behavior compared to the previous two cases. The second SIT soliton is still captured; however, it generates a fast-moving, high-amplitude, transitory SIT soliton that is captured much deeper in the medium than the location of the original excited region [see Fig. 4(d)]. Furthermore, the intensity of the negative control pulse, generated during the capture of the second SIT soliton from the left-hand side of the original coherence, is large enough to overwhelm the positive control light field, emitted from the right-hand side of the original excited region. As a result, the transitory SIT soliton is captured by a negative control pulse and the phase of the ground-state coherence remains constant between the two ρ_{22} peaks.

Because the transitory SIT soliton has a higher intensity than the first SIT soliton, it appears as though the second SIT soliton travels through the excitation region associated with the first SIT soliton without any interaction, but this is not the case. The second SIT soliton is trapped deeper in the medium than both the preceding cases, due to the strong control field amplification associated with the high peak intensity of the SIT soliton. However, the emitted control light field and transitory SIT soliton removes much of the excited population associated with the trapping, leaving the first ρ_{22} region smaller than expected. As a result of these interactions, the second SIT soliton is trapped earlier, while the distance between the two excited regions is six times the FWHM of the original excitation region.

B. Interaction between multiple trapped solitons and a control light field

As shown in Fig. 2, injecting a control light field alters the location of the captured soliton. In this section, we investigate this behavior after one SIT soliton has been captured by a control pulse and up to four subsequent SIT solitons have been trapped by the preexisting ground-state coherence. A control light field is then applied and the behavior of the trapped solitons is observed. In Fig. 5, the electric field E_S throughout the medium is shown for several different situations.

Figure 5(a) shows two SIT solitons propagating in response to the application of a cw control field after $\tau_0 = 0.8$ ns. The first SIT soliton is launched into the medium at $\tau_0 = 0.1$ ns and is captured by a small control pulse. At $\tau_0 = 0.4$ ns, a second SIT soliton is launched into the medium, colliding with the ground-state coherence ρ_{12} structure (lower) as left over from the first SIT soliton and trapping it. From $t = 0.8$ ns on, a cw control light field $E_c = 0.5E_S$ is launched into the medium. This light field interacts with the ground-state coherence structure as left by the two SIT solitons in the medium, and generates a light field E_S that propagates as a pair

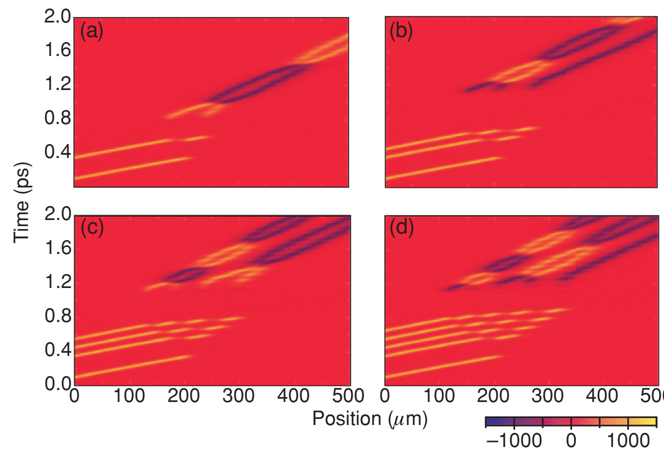

FIG. 5. (Color online) Electric field E_S (V m^{-1}) throughout the medium in a set of calculations where (a) two, (b) three, (c) four, and (d) five SIT solitons are trapped in the medium. Subsequently, from $t = 0.8$ ns, a cw control field is launched into the medium that interacts with the ground-state coherence structure to form sets of bisolitons and single solitons that propagate in the $+z$ direction.

of coupled solitons in the positive z direction. The ground-state coherence (not shown in the figure) moves together with the pair as well.

More than two SIT solitons can be stopped and staggered in the medium, which is shown in Fig. 5, where (b) shows the case of three SIT solitons, (c) four, and (d) five solitons stored. As can be seen, when the cw control field is injected from $t = 0.8$ ns, only pairs of solitons are formed and those pairs do not cross to form larger structures. Furthermore, for an odd number of SIT pulses, one of the pulses (the last as seen from the entrance of the medium) does not pair up.

This behavior can be understood as follows. The control field, which is absorbed by the first region of excited ground-state coherence, is amplified by the second region and, as a result, has approximately the same amplitude after passing the excited regions (consisting of two trapped pulses) as before entering them. Furthermore, where multiple SIT pulses were trapped in the medium, each new pulse creates an excited region of ground-state coherence that is shorter than the previous one. The control pulse interacts with these excited regions and creates a field E_S, where the power in the pulse is proportional to the total amount of ground-state coherence with which the control pulse has interacted. The propagation speed of these created pulses is proportional to the power in the pulse. Therefore, the second soliton pair (as counted from the entrance of the medium) propagates faster than the first pair of solitons because it has a larger excited region and, as a result, generates more optical power. When an odd number of SIT pulses is inserted, the control field creates a single pulse in the E_S field that propagates faster than the closest soliton pair.

Other systems (with different physical processes at work) in which such similar soliton structures propagate have been reported by Maruta and Hause [12,13], in which these soliton structures were named bisolitons. However, such bisolitons in a Λ-type system have, to our knowledge, not been reported.

C. Optical logic gates

Here, we show that an all-optical XOR gate can be implemented by using combinations of SIT solitons and control pulses. By using the SIT soliton phase as the information carrier, an XOR operation is given by $|\phi_1,\phi_2\rangle \rightarrow |\phi_1,\phi_1+\phi_2\rangle$. The logic operation begins with the cloning and capturing of the first SIT soliton (ϕ_{13}), by the application of a control pulse (ϕ_{23}). The phase difference between the control pulse and this SIT soliton is transferred to the ground-state coherence of the medium at the cloning location [recall Eq. (11)], storing it. Thereafter, the SIT soliton with the phase to be operated on (ϕ_2) is inserted into the medium. This SIT soliton collides with the stored coherence, generating a control pulse possessing a phase as described by Eq. (12). For the case in which the first SIT pulse has a phase with the value zero, the resulting second control pulse that exits the medium has a phase that is the sum of the first small control pulse and the second SIT pulse, as needed to perform the XOR operation:

$$\theta = \phi_2 + \phi_{23} - \phi_{13}. \tag{12}$$

Note that, in addition to encoding the result of the XOR operation in the phase of the emitted control pulse, the ground-state coherence of the medium also stores the result of the operation. The stationary nature of the ground-state coherence then allows multiple operations to be performed. Furthermore, because each operation results in the medium emitting a pulse of light that encodes the result of that operation, conditional operations become feasible.

It is interesting to estimate the number of optical logic operations that might be performed on a trapped SIT soliton. The limit to the number of operations that can be performed on a stored soliton can be estimated by comparing laser pulse repetition frequencies and ground-state coherence times. An ultracold atomic ensemble quantum memory gate with a 1-ms decoherence time was recently demonstrated [14], while laser repetition rates exceeding 300 GHz have also been demonstrated [15]. This provides an upper bound of 3×10^8 operations on a stored SIT pulse.

IV. CONCLUSIONS

We have analyzed the behavior of SIT solitons in a three-level medium by solving the density-matrix and Maxwell equations. We have found that multiple SIT solitons can be stored as a ground-state coherence in the three-level medium either by the application of a control light field or by colliding the SIT soliton with a preexisting ground-state coherence generated by a capture event. We have analyzed how the phase of the ground-state coherence is related to the phase of the SIT soliton and the control pulse. The process of trapping SIT solitons has been investigated and has been shown to be the result of a complex process of repeated SIT soliton absorption and emission events.

The propagation of trapped SIT solitons, driven by a control light field, has been investigated. As a result, bisoliton behavior was observed with SIT solitons. Finally, we have shown that the phase of the SIT soliton can be used to encode information and to demonstrate the operations required to provide an all-optical XOR gate. We note that the results from every operation on the ground-state coherence are stored in the ground-state coherence *and* emitted as a control light field pulse.

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