Effect of atomic coherence on temporal cloaking in atomic vapors

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We discuss a different scheme to achieve temporal cloaking in warm atomic vapors. Instead of creating a temporal-spatial window in a patched broadband short optical pulse using static differential dispersion of an optical fiber, we create a temporal-spatial window by directly controlling the propagation velocities of a pair of correlated narrow-band long optical pulses. This method eliminates the phase noise introduced by the broadband short-pulse swapping technique. When the event medium has a fast relaxation rate this leads to a temporal-cloaking scheme similar to that reported in fibers. When the event-medium relaxation cannot be neglected, we discuss a matched-mode scheme that can eliminate the phase change caused by the event field. The advantages of the dynamically and actively controlled atomic system over previously reported work are discussed.

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Temporal cloaking [1] loosely refers to a process in which a signal (probe) light field detects no effect of an event light field when it overlaps with the event light field in an interaction medium. This process has been recently demonstrated in optical fibers [2] using the combination of dispersion management and short-pulse nonlinear frequency conversion. Strictly speaking, such a process does not have real simultaneous temporal and spatial overlapping of the signal and event light fields in the interaction medium since technically it is still operated based on the principle of an avoided crossing. Here a section of a narrow-bandwidth continuous-wave (cw) light beam is first replaced with a frequency-gap broadband short-pulse light field (see Fig. 1). It is this gap in the continuous frequency spectrum of the short-pulse patch that serves as a temporal-spatial window that can be manipulated later. Upon entering a highly dispersive fiber the red portion and the blue portion of the frequency-gap broadband short-pulse light separate spatially because of the frequency-dependent propagation velocities of the different frequency segments. Consequently, the embedded frequency gap, which corresponds to a temporal-spatial window, opens and allows an event light field to transit through this temporal-spatial window. The signal field then subsequently enters a medium that has reversed dispersion properties so that the differential velocities of different frequency components are reversed. This effectively closes the temporal-spatial window by narrowing the widened embedded frequency gap. A subsequent nonlinear frequency conversion process is then carried out to replace the section of the light beam segment having broadband characteristics with a section of the original narrow-bandwidth cw light field. After the repatching operation all light fields exit the medium and are collected for analysis. The cloaking operation is verified by detecting any amplitude anomaly at the wavelength that corresponds to an interaction that requires simultaneous participation of both the event and the signal light fields in the interaction medium. It should be emphasized, however, that many temporal-cloaking schemes, including the reported work on fiber [2] and the different mode of operation to be discussed in the present work, rely on a temporal-spatial delay. This type of cloaking is not, in the true sense of cloaking (actually much less), as the spatial-cloaking effect, associated with novel properties of the medium permeability tensor in electrodynamics.

In this work we present a different mode of temporal-cloaking operation that is based on a quantum destructive interference that results in a matched-pulse propagation. We show that in a warm atomic vapor consisting of three-state Λ-scheme atoms the temporal cloaking as defined above can be achieved trivially if the temporal-spatial window is substantially larger than the inverse relaxation rate of the medium where the event was carried out. This is essentially equivalent to the temporal cloaking demonstrated in Ref. [2]. In contrast, when the inverse relaxation rate in the event operation medium is longer than the temporal-spatial window, we show mathematically that practical temporal cloaking is not achievable because of the noncompensable propagation amplitude and phase modifications due to the presence of the event light field in the interaction medium. We show there is, however, a unique propagation regime in which the phase modification due to the signal-wave propagation in the medium where the event occurs can be successfully eliminated even though the medium relaxation time is long. This process is based on the quantum destructive interference between different excitation pathways in the medium where the event occurs that leads to a matched-wave propagation [3]. Consequently, the only net effect to the signal wave is a static amplitude reduction determined by the initial population transfer and relative absorption coefficients. However, it travels with the speed of light in vacuum and has the same initial phase of the signal field. This phase-preserving propagation is a remarkable result and the reduction of the amplitude can be easily compensated for by using phase coherent amplification methods. It should be pointed out that the experiment reported in Ref. [2] did not analyze the phase change and the time-split

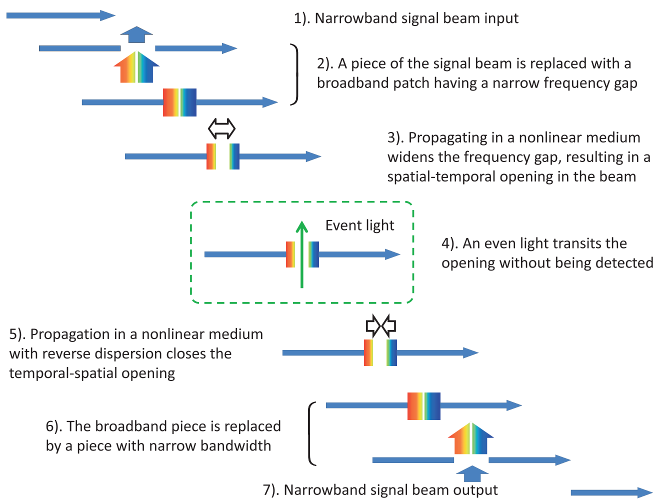

FIG. 1. (Color online) Schematic drawing of the reported temporal cloaking based on optical beam replacement via nonlinear frequency conversion and the passive dispersion effect in a solid medium.

lensing is accomplished by introducing two short pulses via nonlinear wave mixing. Clearly, the insertion of a broad-bandwidth short pulse using nonlinear frequency conversion technique introduces significant phase noise and spectrum fluctuations that cannot be easily eliminated.

For simplicity we consider two correlated long optical pulses having a fixed phase relation. Such a pulse pair could correspond to a pair of sidebands generated, for instance, from a single-frequency optical field by a modulation method. One of the advantages of an atomic medium is that the sharp energy levels permit a substantial group-velocity dispersion on the scale of a few hundred MHz frequency separation in a short propagation distance. This is particularly true when the group dispersion properties are actively controlled via a separate external pump using an electromagnetically induced transparency (EIT) [4] technique or a Raman gain [5] medium.

We assume that the center frequencies of both sideband fields, labeled $\omega_\pm$, are well below the upper electronic P state of the three-state atoms. We take $\omega_\pm = \omega_L \pm \Delta$ and $\omega_L - \omega_0 = \delta$, where ω_0 and δ are the atomic resonance frequency and the large one-photon detuning, respectively, and Δ is the modulation frequency used to generate the two-frequency modes.

In the first cell (Fig. 2, left), we set up a Raman gain [5] medium with a single-frequency pump laser $E_{P1}(\omega_{P1})$ that achieves a two-photon resonance with the ω_+ mode only. Consequently, the ω_+ mode travels slowly, whereas the ω_- mode travels as if it were in free space. In the second cell an EIT or active Raman gain scheme is used as the event (Fig. 2, middle) that transfers an appreciable coherent population to the lower excited state of the Λ medium, which has a very long relaxation time, leading to a coherently prepared medium. In the third cell a single-frequency pump field $E_{P3}(\omega_{P3})$ completes the two-photon resonance only with the ω_- mode (Fig. 2, right). Now it is the ω_- mode that travels slowly and the ω_+ mode propagates as if it were in free space. After a certain distance of propagation the two modes simultaneously arrive at a detector where they are demodulated and phase analysis of the resulting signal is carried out [6]. Mathematically, the amplitude change of the two modes $\omega_\pm$ after they have traversed all three cells can be expressed as

$$\omega_+ \text{ mode} \rightarrow \exp[iF_1^{(+)}L_1]\exp[iF_2^{(+)}L_2], \tag{1a}$$

$$\omega_- \text{ mode} \rightarrow \exp[iF_3^{(-)}L_3]. \tag{1b}$$

Here the superscripts $\pm$ represent the frequency mode and the subscripts denote which cell that quantity is referring to. Also, $F_2^{(+)}$ represents both phase variations and amplification or attenuation of the ω_+ mode in the event occurring in the medium during the propagation process. We have neglected loss by linear absorption in each cell.

The most important factor is $F_2^{(+)}$ in Eq. (1a). It is this additional phase that stems from the event that determines if the original phase relation can be fully recovered upon demodulation. An event may consist of two additional lasers α_{P1} and α_{P2} used in an EIT or a Raman configuration to achieve a coherent population transfer *after* the ω_- mode has passed the medium yet *before* the ω_+ mode enters the medium. Equation (1a) indicates that the key step to ensure temporal cloaking is the proper shielding of this population transfer from the slow mode ω_+. Aside from the usual Gaussian pulse profile, the effect [7,8] of the event on the slow mode ω_+ in the Fourier space can be expressed as

$$\exp[iF_2^{(+)}L_2] = \frac{\kappa_{12}\rho_{11} + \kappa_{23}\rho_{33}\,e^{-AL_2}}{\kappa_{12}\rho_{11} + \kappa_{23}\rho_{33}}, \tag{2}$$

where $A = i(\kappa_{12}\rho_{11} + \kappa_{23}\rho_{33})/(\omega + \delta + i\gamma_{23})$, ω is the Fourier transform variable, and γ_{23} and γ_{31} are the transition linewidths of the one- and two-photon states, respectively. Further, $\kappa_{23(12)} = 2\pi|D_{23(12)}|^2\omega_{+(TWM)}N/c\hbar$, where N is the concentration, with D_{jk} and ρ_{jk} the dipole transition matrix elements and density matrix elements between states j and k.

If $\Delta/\delta < 0.1$ and $\Gamma_{21}/\delta < 0.1$ then to first order [8] we have

$$F_1^{(+)} = -i\kappa_{32}^{(1)}\frac{|\Omega_{P1}|^2}{\gamma_{31}\delta^2}, \quad F_3^{(-)} = -i\kappa_{32}^{(3)}\frac{|\Omega_{P3}|^2}{i\gamma_{31}\delta^2} \tag{3}$$

and the propagation velocities are given by [8]

$$V_1^{(+)} = \frac{\delta^2\gamma_{31}^2}{\kappa_{32}^{(1)}|\Omega_{P1}|^2}, \quad V_3^{(-)} = \frac{\delta^2\gamma_{31}^2}{\kappa_{32}^{(3)}|\Omega_{P3}|^2}. \tag{4}$$

To achieve a temporal cloaking we require that

$$\exp[iF_1^{(+)}L_1]\exp[iF_2^{(+)}L_2] = \exp[iF_3^{(-)}L_3], \tag{5a}$$

$$\frac{L_1}{V_1^{(+)}} + \frac{L_2}{V_2^{(+)}} = \frac{L_3}{V_3^{(-)}} \tag{5b}$$

be satisfied simultaneously. Here Eq. (5a) describes the complete compensation of both phase and amplitude changes, whereas Eq. (5b) ensures the simultaneous arrival to the detector for phase analysis using a demodulation technique. In writing Eqs. (5a) and (5b) we have neglected the fast component of the new field by assuming a proper time-gated detection at the end of the third cell. In the following we first briefly comment on a trivial temporal-cloaking resulting from the fast decoherence rate of the medium in which the event occurred. We then discuss in detail a scheme

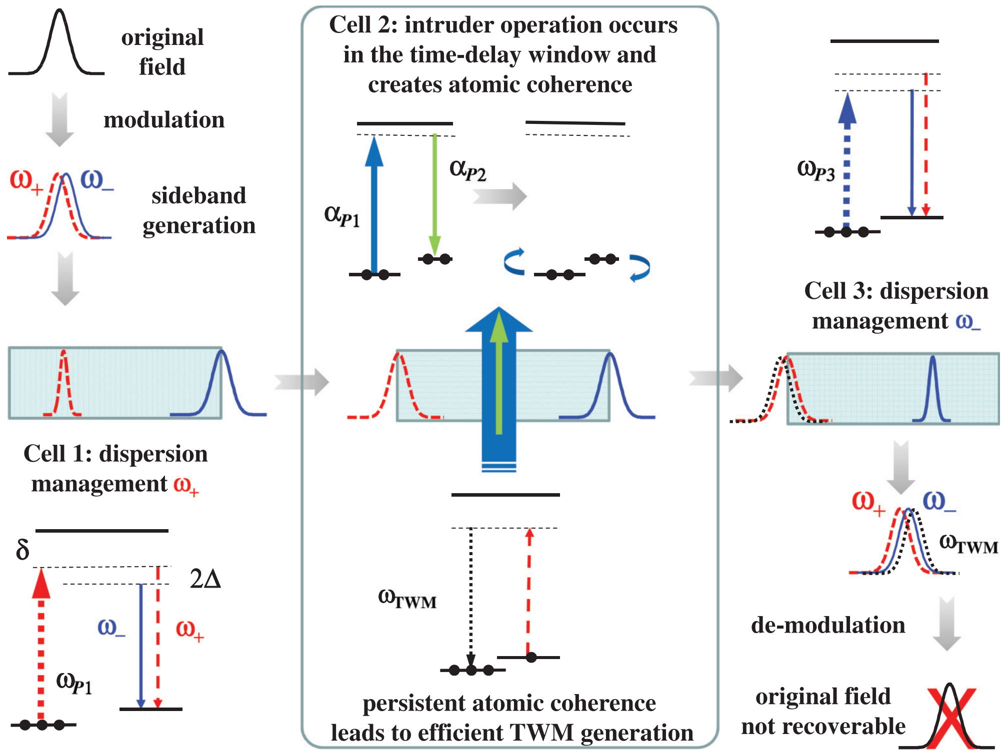

FIG. 2. (Color online) Schematic drawing of a temporal-cloaking scheme using atomic vapor. A pair of long and correlated optical pulses (sidebands) are generated by modulating a single-frequency light field ω_L so that $\omega_\pm = \omega_L \pm \Delta$. In the first cell a pump field preferentially reduces the group velocity of the ω_+ mode, resulting in a sufficient delay in time and space. In the second cell, an event (light field represented by the green arrow) is carried out in the temporal-spatial window between the fast ω_- mode and the slow ω_+ mode. If the atomic coherence and coherent population in the lower excited state persist, the later arrival of the ω_+ mode can trigger an efficient two-wave mixing process that modifies both the phase and amplitude of the ω_+ mode and generates a new field. In the third cell, a pump laser creates a reverse dispersion so that the velocity of the ω_- mode is reduced so that both $\omega_\pm$ modes arrive simultaneously at a detector where the relative phase information can be extracted after demodulation.

where the temporal cloaking is achieved using matched-pulse propagation and destructive quantum interference.

Case 1. Fast event-medium decoherence: $\gamma_{31} t_D \ll 1$. The temporal-cloaking experiment reported has two important aspects: (i) the realization of a split-time lens that is based on well-known dispersion management techniques widely used in regenerative amplifiers for ultrashort-pulse generation and (ii) the assumption or reality that the decoherence time of the fiber (medium) $t_{\rm coh} = 1/\gamma_{\rm coh} = 1/\gamma_{31}$ and consequently the lifetime of the event disturbance are much shorter than the temporal opening t_D in the probe laser beam by the statically dispersion-managed short pulse. In fact, if $t_D \leqslant t_{\rm coh}$ the event will inevitably leave detectable effects regardless of how elaborate the dispersion management scheme. In the case of the optical fiber used in the experiment reported, the solid core relaxation time is typically on the order of 1 ps, which is significantly less than the temporal delay window of 50 ps, thus the event does not leave any detectable effects and the foundation of the experiment is simply dispersion and time-managed pulse propagation.

From Eq. (1a) it is clearly that if the second exponential, which represents the effect of the event, is neglected, then both $\omega_\pm$ modes experience identical phase and amplitude changes so that upon recombination and demodulation the exactly same initial single-frequency input field is recovered and the temporally cloaked process as defined here can be claimed. Mathematically, if $\gamma_{31} \gg 1/t_D$ then Eqs. (5a) and (5b) are reduced to (note that $\rho_{31} \to 0$ and $\rho_{33} \to 0$)

$$\exp[iF_1^{(+)}L_1] = \exp[iF_3^{(-)}L_3], \tag{6a}$$

$$\frac{L_1}{V_1^{(+)}} = \frac{L_3}{V_3^{(-)}}, \tag{6b}$$

where $L_1 = L_3$ and $\kappa_{32}^{(1)}|\Omega_{P1}|^2 = \kappa_{32}^{(3)}|\Omega_{P3}|^2$ are satisfied; this is in principle the same as what Ref. [2] reported.

Case 2. Slow event-medium decoherence: $\gamma_{31} t_D \geqslant 1$. The consequence of $\gamma_{31} t_D \geqslant 1$ is that an appreciable population is transferred coherently to the lower excited state that has very long lifetime (typically $1/\gamma_{31}$ is several hundreds of microseconds in atomic vapors). The long coherence time plays the key role in changing the phase and amplitude of the incoming ω_+ mode. From the theory of inelastic two-wave mixing with prepared states [7] it is known that the persistent atomic coherence ρ_{31} leads to an efficient generation of a new frequency field that copropagates with the ω_+ mode. Equation (2) indicates that the ω_+ component now contains two velocity components and this is detrimental to achieving the perfect compensation required for temporal cloaking. It must be emphasized that the persistent atomic coherence can lead to efficient generation of a new field $E_{TWM}(\omega_{TWM})$ [7] with a different frequency $\omega_{TWM} = \omega_+ + \omega_{31}$ (which actually is the frequency ω_{P1} of the pump field E_{P1}). This new field copropagates with the slow mode ω_+ and has a normalized amplitude (with respect to the initial ω_+ mode at the entrance of the second cell) given by

$$\exp\left[iF_2^{(TWM)}L_2\right] = -\frac{\kappa_{12}\rho_{31}[1-e^{-AL_2}]}{\kappa_{12}\rho_{11}+\kappa_{23}\rho_{33}}, \quad (7)$$

which also has two velocity components just like the ω_+ mode, unless $\rho_{31} \to 0$ prior to the entry of the ω_+ mode in the medium. It can be seen from Eq. (2) that in addition to the amplitude reduction the signal wave (ω_+ mode) also acquires an additional propagation phase because of the persistent atomic coherence. It is practically impossible to achieve temporal cloaking because the additional propagation loss and phase cannot be completely compensated for or canceled.

Case 3. Temporal cloaking by quantum interference. There is, however, a special propagation mode that is worth discussing for the purpose of compensating for the propagation phase introduced by the residual atomic coherence left by the event field. From the expression of A in Eq. (2) it can be seen that for a sufficient optical depth NL_2 the quantity Re$[AL_2]$ can be large and positive [9]. This is the condition for a quantum destructive interference between different excitation pathways [7] that involves the signal mode ω_+ and the new frequency mode ω_{TWM}. It is straightforward to show that when Re$[AL_2] \gg 1$ we have

$$\rho_{11}\Omega_{TWM}(z,t) + \rho_{31}\Omega_+(z,t) = 0, \quad (8)$$

where Ω_{TWM} and Ω_+ are the Rabi frequencies of the ω_{TWM} mode and the signal mode ω_+. Under this matched-pulse condition, the destructive interference dampens the slow group velocity components in both the ω_{TWM} and ω_+ modes and therefore $\exp[iF_2^{(+)}L_2] \to \kappa_{12}\rho_{11}/[\kappa_{12}\rho_{11}+\kappa_{23}\rho_{33}]$ is real. Now the signal mode ω_+ travels at c in the event medium and we have satisfied one of the conditions for the temporal-cloaking operation [Eq. (6b)]. The resulting amplitude reduction can be significantly reduced by carefully choosing two lower electronic states with a large total angular momentum difference (for instance, $\kappa_{32}/\kappa_{12} = 0.1$ so that the amplitude reduction for the signal mode ω_+ is only about 5%).

We emphasize that the key to the matched-pulse propagation using a destructive interference is the diminishing exponential terms in Eqs. (2) and (7). This removes the concentration- and propagation-dependent phase from both the ω_+ and the ω_{TWM} modes.

The advantage of the atomic vapor scheme is that it does not rely on patching and removing broadband short-pulse segments in the probe beam. Clearly, segment patching and removing processes introduce external fluctuations that cannot be easily controlled or eliminated, and therefore in principle can be detected, with or without an actual event. Indeed, the fluctuations introduced by nonlinear frequency conversion processes with short-pulse broadband patches may give a false indication or even completely undermine the truthfulness of the presence of the event in a phase-sensitive analysis. It should be pointed out that Ref. [2] does not interferometrically analyze the phase relation between the final output field and the input signal field. A more fundamental advantage of the atomic vapor scheme, however, is that the scheme can be scaled down directly to the single-photon level (single-photon wave packets). There has been ample evidence where dynamic dispersion management using an EIT or a Raman gain scheme results in ultraslow propagation of correlated and entangled photon pairs and the correlation and entanglement properties of the photon pairs are fully preserved during a quantum memory-based operation [10]. The technique for patching and the subsequent removal of the broadband short-pulse segments requires nonlinear processes that must completely remove and then refill all narrow bandwidth photons in the corresponding segments of the probe beam and this technique cannot be easily extended to operations involving correlated and entangled photon pairs.

We now comment on the residual coherence left by an event, which will be the main issue with warm-vapor-based time cloaking. One may attempt to clean this residual coherence by introducing a repump laser. In a warm vapor, however, introducing this second event may not achieve that goal. Because of the Doppler broadened lines a repump inevitably has cross-talk effect. For instance, when the two lower levels belong to the same ground-state manifold a repump laser will connect both the ground state and the low excited state with residual coherence the same upper P state manifold. Consequently, residual coherence cleaning will not be 100% efficient. In addition, the repump laser will generates photons in other directions (so does the first event light). This is because spontaneous processes could not be completely avoided in a medium with large and mixed Doppler broadened lines and fast collisional dephasing. Even with a repump that propagates orthogonally to the ω_+ mode, some spontaneously emitted photons in the repump process will inevitably enter the path of the ω_+ mode in the third cell. These unwanted photons cannot be waited out by increasing the delay time t_D. In general, the usable t_D is limited by the phase change of the slowed component. A large slowdown (therefore large t_D) will result in a more significant loss in the EIT scheme and a more distorted phase that cannot be corrected later. We also note that in a warm vapor, the collisional process is relatively fast, which will also affect the phase of the stored light. In addition, waiting also introduce problems such as the drift of atoms that have been put into the coherent mixture by the first event laser. For a 10-μs waiting time an atom moving at 500 m/s will drift by 5 mm, which is already substantially large than the typical laser beam diameter used; it has been shown experimentally that these atoms drifted out of the laser beam can give a strong signal in other locations.

In conclusion, we have described a different method of temporal cloaking based on dynamic wave propagation and dispersion control in an atomic system. We have shown an interference-based matched-pulse propagation scheme that can completely remove phase changes caused by the event field even when the event field and the signal field simultaneously coexist (i.e., no temporal-spatial window) in the interaction medium. By carefully choosing the transition pathways, such a matched-pulse operation is a more realistic scheme for temporal cloaking because it does not rely on temporal-spatial delay and both the amplitude and the phase changes of the signal mode can be minimized. We note that the reported work on fiber using beam-segment patching and replacement between narrow-band and broadband short pulses introduces detectable phase changes and glitches, which may be considered as precursors or even warnings of the event. That is, the event is not fully cloaked.

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