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Instantaneous processing of "slow light": Amplitude-duration control, storage, and splitting

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A nonadiabatic change of the control field or the low-frequency coherence allows for an almost instantaneous change of the signal field propagating in a thick resonant absorber where electromagnetically induced transparency is realized. This finding is applied for the storage, retrieval, and splitting of the signal into two parts separated by a time interval that is as long as the lifetime of the low-frequency coherence. Pulse shaping is also possible.

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A seminal idea of storage and retrieval of light pulses (SRLP) using a medium with electromagnetically induced transparency (EIT) was proposed in Ref. [1] by Fleischhauer and Lukin. Shortly after the proposal, SRLP was experimentally demonstrated in ultracold Na, in hot Rb vapor, and in a solid (Pr:YSO) [2]. Later, SRLP received much attention in the framework of quantum computing and quantum memory (see, for example, Ref. [3]). The core idea of such a storage is the dark-state polariton (DSP), which is a particular superposition of the signal pulse amplitude and the low-frequency atomic coherence [1]. The latter is created in a two-quantum process by the signal pulse, driving the transition from the ground state $|g\rangle$ to an excited state $|e\rangle$, together with the cw control field, driving the transition between $|e\rangle$ and a metastable state $|m\rangle$ (see inset in Fig. 1). Reducing adiabatically the amplitude of the control field to zero, one can stop this polariton in a state that has zero amplitude for the signal pulse component and a nonzero amplitude for the component containing the coherence $g-m$. This coherence resembles a standstill "spin wave" whose spatial shape coincides with the spatial shape of the signal pulse if it were to have zero group velocity $V=0$. An adiabatic increase of the control field amplitude from zero back to its initial value retrieves the signal pulse from the spin wave, both propagating with group velocity $V\neq 0$. This simple picture is applicable since the DSP is an eigenstate of the atom-field system and, hence, any adiabatic change of its parameters keeps the system in the changing DSP state. Later, it was shown [4] that an abrupt change of the control field gives almost the same result.

In this paper we show that the coincidence of the adiabatic and nonadiabatic regimes of switch off and on is not accidental. We show that any instantaneous change of the control field amplitude to an arbitrary value does not affect the spin wave amplitude but changes proportionally the signal field amplitude. This is because for the slow DSP an atom-field coupling constant g_c, multiplied by the square root of a macroscopic number of atoms, N, is much greater than the Rabi frequency of the control field Ω. Therefore, $g_c\sqrt{N}$ is always much greater than any reasonable variation of Ω. This secures the adiabatic change of the DSP state for an arbitrary change of the control field. On the contrary, any change of the spin wave amplitude—for example, by rf pulses—causes a proportional change of the signal field amplitude. This is because the spin wave component is the backbone of the DSP, specifying all its properties. Our findings give opportunities to coherently control the radiation field and to pulse shaping.

First, we give qualitative arguments based on the DSP properties. Then, we prove our speculations by an analytical solution of the atom-field equations for two examples of the

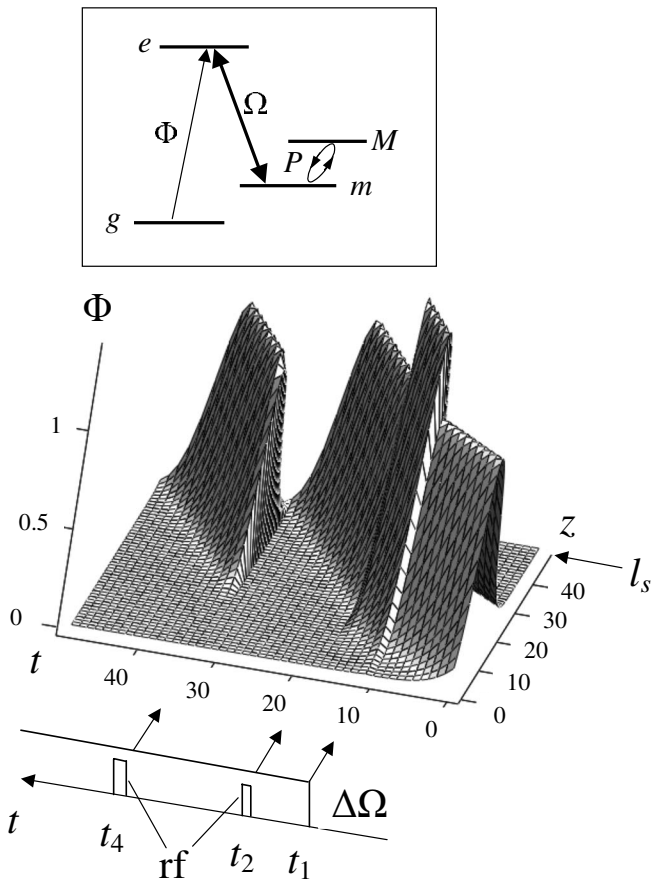

FIG. 1. Three-dimensional plot showing the spatial-temporal evolution of the signal field. Coordinates z, t, and amplitude Φ of the signal field are in arbitrary units. The instances of the control, t_1, t_2, and t_4, are indicated by arrows, as well as the end of the sample $z=l_s$. By step $\Delta\Omega$ we show the abrupt change of the coupling field, and by two bars we show rf pulses. The excitation scheme of the four-level atom is shown in the inset (see the text for details).

abrupt changes of the coupling field and the spin wave. The DSP has the form [1]

$$\Psi(z,t) = \cos\,\vartheta(t)\hat{E}(z,t) - \sin\,\vartheta(t)\sqrt{N}\hat{\sigma}_{gm}(z,t), \qquad (1)$$

where $\hat{E}(z,t)$ is the signal field operator, $\hat{\sigma}_{gm}$ is the $g-m$ coherence operator for the atomic ensemble, and $\tan\vartheta(t) = g_c\sqrt{N}/\Omega$. The DSP propagates with group velocity $V = c\cos\vartheta(t)$. If the control field creates a transparency window for the signal field and $V \ll c$, then we have $\vartheta \approx \pi/2$ and, hence, $\sqrt{N}g_c \gg \Omega$. Therefore, an arbitrary change of Ω almost does not change $\sin\vartheta(t) \approx 1$ and the spin wave keeps its spatial shape, while $\cos\vartheta(t)$ changes proportionally to $\Omega(t)$ and, hence, the group velocity of the DSP changes. It is well known that EIT appears due to population trapping in the dark state [5]: $|d\rangle = \cos\theta_1|g\rangle - \sin\theta_1|m\rangle$, where $\tan\theta_1 = \Phi/\Omega$ and Φ is the Rabi frequency of the signal field ($\Phi \ll \Omega$). We remind the reader that the $g-m$ coherence $\langle g|\hat{\sigma}_{gm}|m\rangle \approx -\Phi/\Omega$ specifies the spin wave amplitude. If the population trapping is not destroyed by the change of the control field, the amplitude of the signal field should change proportionally to conserve the ratio Φ/Ω. Thus, an arbitrary change of Ω is immediately followed by a change of Φ, conserving the spin wave amplitude, and an arbitrary change of the spin wave (for example, by an rf field) produces a change of Φ for the same reason. A nonadiabatic change of the spin wave by short rf pulses is of interest since it allows storage and splitting of quantum information [6,7].

We consider a simplified excitation protocol to prove the arguments given above. First, we double the intensity of the signal pulse by an instantaneous doubling of the intensity of the control field. This operation doubles the group velocity of the signal pulse. Then by a short rf pulse we transfer half of the population of the metastable state $|m\rangle$ to another hyperfine level $|M\rangle$ of the ground-state atom, also metastable. This imprints a snapshot of the spatial shape of the spin wave to state $|M\rangle$ [7]. Since state $|M\rangle$ is supposed to be not coupled to the other atomic states by the driving fields, this part of the spin wave comes to a standstill. But what is left in state $|m\rangle$ continues propagating with group velocity $2V$. Its probability amplitude reduces by a factor of $1/\sqrt{2}$ and, therefore, the intensity of the signal pulse drops back to its initial value. After some delay time, which is long enough to ensure that the signal pulse has left the medium, we apply an rf pulse to bring back the atomic population from state $|M\rangle$ to state $|m\rangle$, which has been emptied by this time. The control field acts on the appearing standstill spin wave in state $|m\rangle$ such that the signal pulse is produced again and both the spin wave and the signal pulse travel with group velocity $2V$.

Initially, two ground-state levels m and M are depopulated by optical pumping and only state g is populated. The control field (cw) and the signal pulse, which enters the sample at $t_0 = 0$, propagate along coordinate z. The spectral width of the pulse Δ_Φ is smaller than the width of the transparency window, $\Delta_T = 2\Omega^2/\gamma$, where γ is the decay rate of the coherence $g-e$, which is fast, $\gamma > 2\sqrt{2}\Omega$. Since the signal pulse is weak, we can apply the linear response approximation for a solution of the Schrödinger equation for the atomic state:

$$|\phi\rangle = C_g|g\rangle + C_m|m\rangle + C_M|M\rangle + C_e|e\rangle, \qquad (2)$$

where $C_M = 0$. State $|M\rangle$ need only be considered when the rf pulse is applied. In this approach it is sufficient to consider only the evolution of the amplitudes C_m and C_e, which are described by the equations

$$\partial X(z,t)/\partial t = \Omega(z,t)Y(z,t), \qquad (3)$$

$$\partial Y(z,t)/\partial t = -\gamma Y(z,t) - \Omega(z,t)X(z,t) - \Phi(z,t), \qquad (4)$$

where $X = C_m$ and $Y = iC_e$. Here it is assumed that $C_g \approx 1$ holds with a small deviation of the order of $(\Phi/\Omega)^2 \ll 1$. If the condition of the adiabatic following of the dark state, $\Delta_\Phi \ll \Delta_T$, is satisfied, an approximate solution of Eqs. (3) and (4) can be easily found [8]:

$$X(z,t) = -\Phi(z,t)/\Omega + \cdots, \qquad (5)$$

$$Y(z,t) = -\Phi_t(z,t)/\Omega^2 + \cdots, \qquad (6)$$

where $\Phi_t(z,t) = \partial\Phi(z,t)/\partial t$ and the ellipses stand for terms that are at least Δ_Φ/Δ_T times smaller. The wave equation for Φ is

$$\hat{L}_c\Phi(z,t) = i\alpha C_g^* C_e \approx \alpha Y(z,t), \qquad (7)$$

where α is the coupling constant [8] and $\hat{L}_c$ is the differential operator $\hat{L}_c = \partial_z + c^{-1}\partial_t$, where the subscript c stands for the group velocity of the wave. Substitution of the solution (6) into Eq. (7) gives $\hat{L}_c\Phi(z,t) = -(\alpha/\Omega^2)\Phi_t(z,t)$, which can be transformed to $\hat{L}_{V_1}\Phi(z,t) = 0$, where $V_1 = (c^{-1} + \alpha/2\Omega^2)^{-1}$ is the new group velocity. The solution of this equation is $\Phi(z,t) = \Phi^0(t - z/V_1)$, where $\Phi^0(t)$ is the amplitude of the signal field at the input.

At time $t_1 > 0$, when the pulse is in the sample, we abruptly change the amplitude of the control field, $\Omega(z,t) = \Omega[1 + h\Theta(t - t_1 - z/c)]$, where $\Theta(t)$ is the Heaviside step function, and we choose $h = \sqrt{2} - 1$ to double its intensity. This stepwise change of the control field amplitude propagates in the sample with velocity c. Before it arrives at the atoms with coordinate z—i.e., for $t < t_z = t_1 + z/c$—their amplitudes $X(z,t)$ and $Y(z,t)$ are described by Eqs. (5) and (6). After t_z, the solution of Eqs. (3) and (4) gives the amplitudes

$$X(z,t) \approx -\frac{\Phi(z,t)}{\sqrt{2}\Omega} - \frac{K_x(t - t_z)}{\sqrt{2}\Omega}\Phi^0(t_z - z/V_1), \qquad (8)$$

$$Y(z,t) \approx -\frac{\Phi_t(z,t)}{2\Omega^2} + K_y(t - t_z)\Phi^0(t_z - z/V_1), \qquad (9)$$

where

$$K_x(\tau) = h\frac{\gamma_+ e^{-\gamma_-\tau} - \gamma_- e^{-\gamma_+\tau}}{\gamma_+ - \gamma_-}\Theta(\tau), \qquad (10)$$

$$K_y(\tau) = h\frac{e^{-\gamma_-\tau} - e^{-\gamma_+\tau}}{\gamma_+ - \gamma_-}\Theta(\tau), \qquad (11)$$

$$\gamma_{\pm} = \frac{\gamma}{2} \pm \sqrt{\frac{\gamma^2}{4} - 2\Omega^2}. \tag{12}$$

Here, the first and second terms in the solution (8) and (9) represent the main contributions originating from the nonhomogeneous term $-\Phi(z,t)$ in Eq. (4) and from the initial condition at t_z. The omitted terms are at least Δ_Ψ/Δ_T times smaller.

Before t_z, the atomic state $|\phi\rangle$ was close to the dark state $|d\rangle$ with $\tan\theta_1=\Phi^0/\Omega$, the state that is uncoupled from the signal and control fields. The abrupt change of the control field amplitude from Ω to $\sqrt{2}\Omega$ makes this state coupled since it acquires a particular component, which is the bright state $|b\rangle=\sin\theta_2|g\rangle+\cos\theta_2|m\rangle$, coupled to the signal and control fields [5], where $\tan\theta_2=\Phi^0/\sqrt{2}\Omega$. The probability amplitude of $|b\rangle$ is proportional to the signal field amplitude Φ^0. Therefore, the amplitudes of the transient part of the solution—i.e., the second terms in Eqs. (8) and (9)—are proportional to the signal field amplitude Φ^0. Because of the fast decay of the excited state, the atom terminates its evolution in a new dark state with the mixing angle θ_2 [see Eq. (8)].

With the solution (9), the propagation equation (7) can be transformed to

$$\hat{L}_c\Phi(z,t) = -A(z,t)\Phi_t(z,t) + \alpha K_y(t-t_z)\Phi^0(t_z - z/V_1), \tag{13}$$

where $A(z,t)=\beta_1+(\beta_2-\beta_1)\Theta(t-t_z)$, $\beta_{1,2}=V_{1,2}^{-1}-c^{-1}$, and $V_2=(c^{-1}+\alpha/4\Omega^2)^{-1}$ is the new group velocity of the signal field after the jump of the amplitude $\Omega(z,t)$. The solution of Eq. (13) for $t<t_z$ is $\Phi(z,t)=\Phi^0(t-z/V_1)$. For $t>t_z$ this solution changes to

$$\Phi(z,t) = \Phi^0(T) + F(z,t), \tag{14}$$

$$F(z,t) = \alpha\int_0^z K_y\left(t - t_{z'} - \frac{z-z'}{V_2}\right)\Phi^0(t_{z'} - z'/V_1)dz', \tag{15}$$

where $T=\kappa(V_2/V_1)[t-t_c-(z-z_c)/V_2]$, $\kappa=(c-V_1)/(c-V_2)$, and $t_{z'}=t_1+z'/c$. $z_c=V_1t_c$ is a coordinate where at time $t_c=t_1c/(c-V_1)$ the central part of the signal pulse changes its velocity from V_1 to V_2. Taking the integral (15) by parts and retaining only the two main terms, we obtain

$$F(z,t) = \eta h\Phi^0(T) - \eta K_x(t-t_z)\Phi^0(t_z - z/V_1), \tag{16}$$

where $\eta=(c-V_2)/c$. After a short time $t-t_z=\tau_\gamma\sim 1/\gamma$, the function $K_x(t-t_z)$ decays to zero. If $c\gg V_1,V_2$, then $V_2=2V_1$, $\eta\approx\kappa\approx 1$, and $z_c\approx V_1t_1$, and hence, for $t>t_z+\tau_\gamma$ we have $\Phi(z,t)=(1+h)\Phi^0(T)$ where $T=2[t-t_1-(z-z_c)/V_2]$. This means that after an abrupt change of the amplitude of the control field the amplitude of the signal field also changes by the same factor $(1+h)$. In such a way the ratio $\Phi(z,t)/\Omega(z,t)$ is conserved. Since $C_m(z,t)\approx-\Phi(z,t)/\Omega(z,t)$, the spin wave also conserves its amplitude and length. The latter coincides with the spatial length of the signal pulse in the sample before the change of the control field. This length is $l_p=V_1t_{p_1}$, where $t_{p_1}=1/\Delta_\Phi$ is the duration of the signal pulse at the input. Meanwhile, the spin wave and the signal field alter their group velocity from V_1 to V_2. Therefore, the duration of the signal pulse shortens to $t_{p_2}=t_{p_1}V_1/V_2=t_{p_1}/2$ such that the spatial length l_p of the pulse and the spin wave is conserved.

At time $t_2=t_1+\tau_\gamma+l_p/c$, all spatial components of the spin wave and the signal pulse complete such a transformation. Following our scheme of the signal field processing, at time t_2 we apply a short, rectangular-shaped rf pulse, which drives resonantly the transition $m-M$ (see inset in Fig. 1). The wavelength of the rf pulse is much greater than the spatial length l_p of the signal pulse. Therefore, we disregard its spatial dependence. The evolution of the probability amplitudes C_m and C_M of the atomic state $|\phi\rangle$, Eq. (2), is described by the equations

$$\partial C_m/\partial t = iPC_M + i\Omega C_e, \tag{17}$$

$$\partial C_M/\partial t = iPC_m. \tag{18}$$

where P is the amplitude of the coupling $m-M$ with the resonant rf pulse. We take $P\gg\Omega$ and choose the duration of this pulse, τ_{rf}, such that it forms a so-called $\pi/2$ pulse: $P\tau_{rf}=\pi/4$. Before the rf pulse, we have $C_M=0$ and $C_m=-\Phi^0/\Omega$. Since $\tau_{rf}\Omega\ll 1$, we can disregard the interaction with the control field during the rf pulse. Then, at the end of the pulse, $t_3=t_2+\tau_{rf}$, we have $C_m=-\Phi^0\cos(P\tau_{rf})/\Omega=-\Phi^0/\sqrt{2}\Omega$ and $C_M=-i\Phi^0\sin(P\tau_{rf})/\Omega=-i\Phi^0/\sqrt{2}\Omega$. To simplify our consideration, we assume that the transition $M-e$ is not allowed or far from resonance. Therefore the presence of the coherence $m-M$ does not influence the signal and the control fields. Only the change of the probability amplitude C_m introduces transients. They are described by Eqs. (3) and (4), where $\Phi(z,t)$ and $\Omega(z,t)$ are replaced by $\sqrt{2}\Phi^0$ and $\sqrt{2}\Omega$ (these amplitudes were present before the rf at $t_2\approx t_3$). At the end of the rf pulse, t_3, the initial condition for an atom with coordinate z is $X(z,t_3)=-\Phi^0(T_3)/\sqrt{2}\Omega$ and $Y(z,t_3)=-\Phi_t^0(T)|_{t=t_3}/\sqrt{2}\Omega^2$, where $T_3=(V_2/V_1)[t_3-t_1-(z-z_c)/V_2]$. After these modifications the solution of Eqs. (3) and (4) is

$$Y(z,t) \approx -\frac{\Phi_t(z,t)}{2\Omega^2} - K_y(t-t_3)\Phi^0(T_3), \tag{19}$$

with the initial condition $\Phi_t(z,t_3)=\sqrt{2}\Phi_t^0(T)|_{t=t_3}$.

The solution of the wave equation (7) for $t<t_3$ is $\Phi(z,t)=\sqrt{2}\Phi^0(T)$. For $t>t_3$, the right-hand side of this equation changes to Eq. (19). Then its solution transforms to $\Phi(z,t)=\sqrt{2}\Phi^0(T)-F_1(z,t)$, where $F_1(z,t)$ coincides with the function $F(z,t)$ in Eq. (15), if $t_{z'}$ and V_1 are replaced by t_3 and V_2, respectively. Within the same approximation adopted for $F(z,t)$, we obtain $F_1(z,t)=h\eta\Phi^0(T)-\eta K_x(t-t_3)\Phi^0(T_3)$. Thus, after a short time τ_γ—i.e., for $t>t_3+\tau_\gamma$—and if $\eta\approx 1$, we have $\Phi(z,t)=\Phi^0(T)$. This means that after the switch off of the rf pulse the signal field changes its amplitude to its original value, which was at the input of the sample.

We allow the signal field, having resumed its original amplitude, to leave the sample. The spin wave $C_m(z,t)$ accompanying the signal field and propagating with group velocity

V_2 vanishes at the sample end, $z=l_s$. Meanwhile, the snapshot of the signal field at time t_2 was imprinted by the rf pulse to the probability amplitude $C_M(z,t_3)=-i\Phi^0(T_3)/\sqrt{2}\Omega$ of state $|M\rangle$. This amplitude can be considered as another spin wave with zero group velocity (standstill wave). Following the procedure described in the beginning of the paper, we apply a second rf pulse at time t_4 when the signal field has already left the sample. The second rf pulse lasts 6 times longer than the first rf pulse—i.e., $6\tau_{rf}$—such that it forms a 3π pulse: $P6\tau_{rf}=3\pi/2$. The initial condition for this pulse is $C_m(z,t_4)=0$ and $C_M(z,t_4)=-i\Phi^0(T_3)/\sqrt{2}\Omega$. According to Eqs. (17) and (18), at the end of this rf pulse, $t_5=t_4+6\tau_{rf}$, we have $C_m=\Phi^0(T_3)\sin(P6\tau_{rf})/\sqrt{2}\Omega=-\Phi^0(T_3)/\sqrt{2}\Omega$ and $C_M=-i\Phi^0(T_3)\cos(P6\tau_{rf})/\sqrt{2}\Omega=0$. The extra 2π rotation of the pseudospin 1/2, corresponding to the transition m-M, is necessary to obtain the proper sign for the final value of C_m. Otherwise, if an rf pulse with π area were to be applied, the $C_mC_g^*$ coherence would generate a signal field with a phase that is opposite to the initial one. In our case this coherence generates a field Φ with the same phase as before. To show this we solve Eqs. (3) and (4) with an arbitrary function $\Phi(z,t)$ and $\Omega(z,t)=\sqrt{2}\Omega$ for the initial condition $Y(z,t_5)=0$, $X(z,t_5)=-\Phi^0(T_3)/\sqrt{2}\Omega$, and $\Phi(z,t_5)=0$. The solution for $Y(z,t)$ is

$$Y(z,t)\approx-\frac{\Phi_t(z,t)}{2\Omega^2}+\frac{K_y(t-t_5)}{h}\Phi^0(T_3). \tag{20}$$

Substituting $Y(z,t)$ into the wave equation (7), we obtain the solution

$$\Phi(z,t)=\frac{\alpha}{h}\int_0^z K_y\left(t-t_5-\frac{z-z'}{V_2}\right)\Phi^0(T_3')dz', \tag{21}$$

where $T_3'=(V_2/V_1)[t_3-t_1-(z'-z_c)/V_2]$. Approximately this integral is $\Phi(z,t)=\eta[\Phi^0(T_{3-5})\Theta(t-t_5)-\Phi^0(T_3)K_x(t-t_5)/h]$, where $T_{3-5}=(V_2/V_1)[t-t_1+t_3-t_5-(z-z_c)/V_2]$. If $\eta\approx1$, then for $t>t_5+\tau_\gamma$ we have $\Phi(z,t)=\Phi^0(T_{3-5})$ and the signal field is retrieved from the spin coherence. Now we have a copy of the signal field in the sample and the signal field outside the sample, both with the same amplitude and duration. Figure 1 shows a three-dimensional plot of the signal field evolution controlled by the amplitude change of the control field and rf pulses. By numerical simulations we verified our approximate solution and obtained a fair agreement. It becomes almost perfect if our idealized solution is convoluted with a Gaussian function, described in [8], which takes into account a pulse broadening due to the narrowing of the EIT window with distance.

Since the DSP changes adiabatically for an arbitrary change of the coupling field we can assume that the general solution for the signal field is $\Phi(t,z)=[\Omega(t)/\Omega(t_0)]\Phi^0\{[c\int_{t_0}^t d\tau\cos^2\vartheta(\tau)-z]/V_1\}$. We showed also that an arbitrary change of the spin wave amplitude by short rf pulses causes an instantaneous, proportional change of the signal field amplitude. While the first finding follows directly from the DSP concept, the second does not. One can assume that the fast decay γ of the excited state gives a natural explanation of the second finding. We verified numerically the case of $\gamma=0$ and found that an instantaneous change of the spin wave also causes an instantaneous, proportional change of the signal without visible transients. This result is not obvious and does not follow directly from the simple picture of the dark and bright states.

Summarizing, we found that an instantaneous change of the amplitude of the control field produces an almost instantaneous change of the amplitude of the signal field and it does not affect the amplitude of the spin wave. This change also results in the variation of the group velocity and of the duration of the signal pulse. However, their product, which is the spatial length of the pulse and the spin wave, does not change if both are in the EIT sample when the change happens. The instantaneous change of the spin-wave amplitude by a short rf pulse produces an instantaneous change of the amplitude of the signal field without changing its group velocity and duration. By a train of rf pulses the signal field can be split into two parts, one of which can be temporarily stored in the sample. These findings can be applied to information processing and storage, the creation of a new type of entangled states, if the signal field contains only one photon.

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