Reversible storage of multiple light pulses in the EIT atomic medium

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In this paper, we first present a full numerical simulation for the trapping and retrieval procedure of eight continuing "1" Guassian pulses (i.e., "11111111") in the electromagnetically induced transparency (EIT) medium. This simulation shows that an EIT medium has the ability to store multiple light pulses in a shape-preserving way. And we also, for the first time, give the formula evaluating the maximum number of pulses that can be stored by an EIT medium at one time. This work reveals a new possible way to the reversible storage of the photonic information.

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The authors of Refs. [1] and [2] have recently identified the so-called dark-state polaritons (DSPs) associated with the propagation of quantum fields in the electromagnetically induced transparency (EIT) medium. The DSPs are actually the form-stable coupled excitations of light and matter. Based on the DSPs, the quantum state of photon can be reversibly transferred between light and metastable collective states of matter, which means the group velocity of photon propagating in coherently driven three-level atomic EIT medium may be reduced to zero. With this DSP theory, a famous "light-pulse-storage" experiment[3] is successfully explained.

Under the guidance of DSP theory, we first perform a full numerical simulation for the multiple-light-pulse storage EIT model, and then present the formula for evaluating the maximum number of pulses that can be stored by an EIT medium at one time.

We consider a collection of N three-level atoms with two metastable lower states as shown in Fig. 1. The transition between the ground state $|b\rangle$ and the excited state $|a\rangle$ is resonantly coupled by the quantum field $\hat{E}^{(+)}(z,t)$ described by a slowly varying operator

$$\hat{E}^{(+)}(z,t) = \sqrt{\frac{\hbar\nu}{2\varepsilon_0 V}}\hat{a}(z,t)\exp\left[i\frac{v}{c}(z-ct)\right], \tag{1}$$

where $\nu = \omega_{ab}$ is the carrier frequency of the optical field. The upper level $|a\rangle$ is, furthermore, coupled to the state $|c\rangle$ via a coherent control field with Rabi frequency Ω. The interaction between photon and atoms is controlled by the Hamitonian

$$\hat{V} = -\int\frac{\mathrm{d}z}{L}[\hbar g N\widetilde{\sigma}_{ab}(z,t)\hat{a}(z,t)$$
$$+\hbar\Omega(z,t)N(z)\widetilde{\sigma}_{ac}(z,t) + H.a.], \tag{2}$$

where $\hat{\sigma}_{ab}(z,t)$ and $\widetilde{\sigma}_{ac}(z,t)$ are slowly varying atomic operators[1].

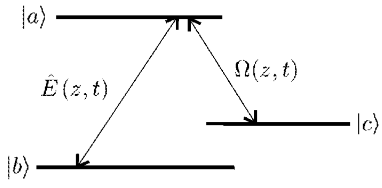

Fig. 1. A three-level medium resonantly coupled to a classical field with Rabi frequency $\Omega(z,t)$ and quantum field $\hat{E}(z,t)$.

The following propagation Eq. (3) and Heisenberg-Lagevin Eq. (4)[2] respectively control the evolution of the optical field and atoms

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right)\hat{a}(z,t) = igN\widetilde{\sigma}_{ba}(z,t), \tag{3}$$

$$\frac{\partial}{\partial t}\hat{\sigma}_{\mu\nu} = -\gamma_{\mu\nu}\sigma_{\mu\nu} + \frac{i}{\hbar}[\hat{V},\hat{\sigma}_{\mu\nu}] + F_{\mu\nu}. \tag{4}$$

A new quantum field $\hat{\psi}$ (i.e., the so-called DSP) defined in Ref. [1] is also introduced here

$$\hat{\psi} = \cos\theta(t)\hat{a}(z,t) - \sin\theta(t)\sqrt{N}\widetilde{\sigma}_{bc}(z,t)\mathrm{e}^{i\Delta kz}. \tag{5}$$

With the corresponding adiabatic limit, we solve Eqs. (3) and (4) through numerical simulation. In this simulation, the quantum field $\hat{E}^{(+)}(z,t)$ consists of eight continuing "1" Guassian pulses (i.e., "11111111"). The simulation details are shown in Fig. 2, where the "T" and "Z" are respectively the normalized versions of "t" and "z".

As shown in Fig. 2, the Guassian pulse series, "11111111", experiences a "shape-preserving" trapping and revival procedure. These simulation results clearly show that it is viable to realize the multiple-light-pulse storage in the EIT medium with high fidelity. However, it can be also noticed that there exists some distortion in the pulse's amplitude and time-domain width. The main reason is that the transparency window of an EIT medium is narrower than the pulse spectral width, and so the pulse's frequency component outside the

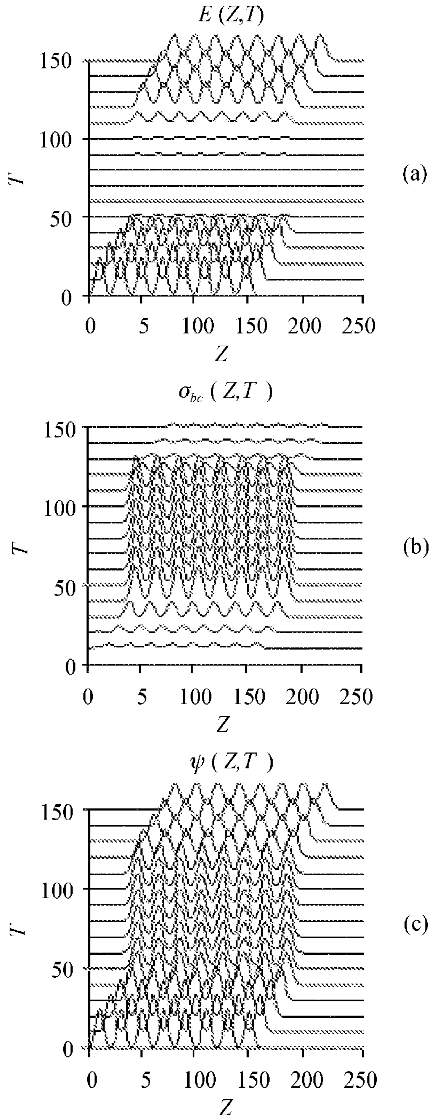

Fig. 2. Propagation of eight continuing “1” pulses in the EIT medium. (a) The signal electrical field, (b) the atomic transition, and (c) new quantum field, DSP.

transparency window will be filtered. In the realistic environment, there are still some other factors[1], such as the nonadiabatic correction, weak-field approximation, decay of Raman coherence, and atomic motion, which will affect the pulse's storage fidelity.

In an EIT medium, due to the phenomenon of ultraslow light group velocity, a light pulse, which is several kilometers in free space, is easily compressed to a length of several centimeters. Therefore, an EIT medium with small size can store many pulses at the same time. Figure 3 gives an illustration for the theoretical storage volume of an EIT medium. The theoretical maximum number of pulses stored by an EIT medium mostly depends on the following five factors: the length of the EIT medium in the pulse propagation direction (i.e., L, see Fig. 3(a)), the pulse's group velocity in the EIT medium (i.e., v_g), the pulse's time-domain width (i.e., τ), the distance that pulse travels in the medium from the time at which the coupling laser begins to be attenuated adiabatically to the time that the coupling laser is completely turned off (i.e., s', see Fig. 3(c)), and the distance that pulse travels in the medium from the time at which the coupling laser begins to be restored adiabatically to the time that the coupling laser is completely turned on (i.e., s'', see Fig. 3(d)). With these parameters, we give the equation to calculate the maximum number n of pulses that can be stored by an EIT medium

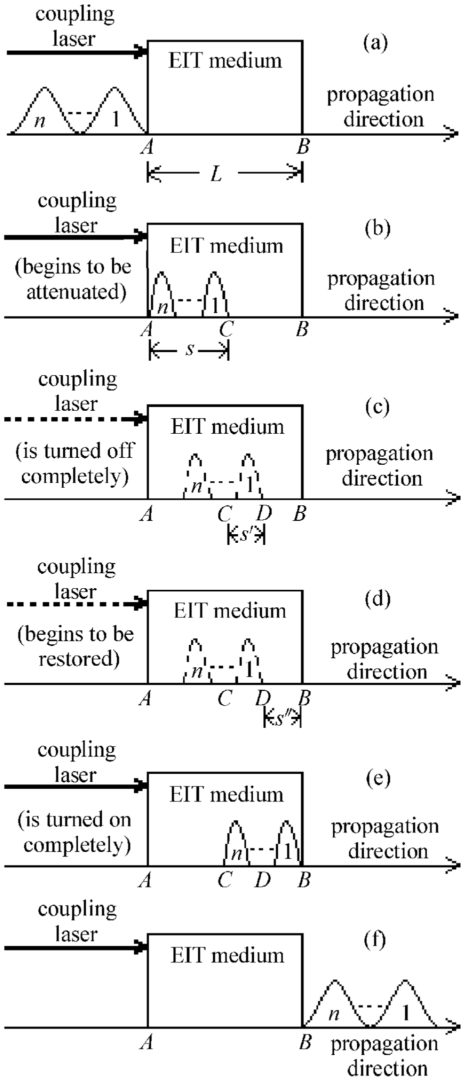

Fig. 3. Illustration for the theoretical storage volume (i.e., the possible stored number of pulses) of an EIT medium.

$$n = \frac{L - (s' + s'')}{v_g \tau}, \tag{6}$$

where L must also satisfy the following equation (see Fig. 3)

$$L = s + s' + s''. \tag{7}$$

In the Eq. (6), $s' + s''$ denotes the necessary medium length for a pulse to fulfill its “storage and retrieval” procedure. Within this length, the adiabatically changed control field can have a pulse's quantum information mapped into and retrieved from the EIT medium coherently (see Figs. 3(b), (c), (d) and (e)). So, when the first one of a series of pulses reaches the point C (see

Fig. 3(b)), the number of pulses that are already in the EIT medium at this time will be taken as the maximum number of pulses that can be stored in this EIT medium at one time.

For example, with $L = 10$ cm, $s' = 1.65$ cm, $s'' = 1.65$ cm, $\tau = 10^{-6}$ s, $v_g = 10^3$ m/s, we can get the maximum stored-pulse number of this EIT medium $n = 67$.

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