Manipulating Synchronous Optical Signals with a Double Λ Atomic Ensemble

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Abstract

We analyze a double Λ atomic configuration interacting with two signal beams and two control beams. Because of the quantum interference between the two Λ channels, the four fields are phase-matched in electromagnetically induced transparency. Our numerical simulation shows that this system is able to manipulate synchronous optical signals, such as generation of optical twin signals, data correction, signal transfer and amplification in the atomic storage.

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In modern communication, the transmission of information is usually carried out among multi-users which are organized in a network. The network consists of spatially separated nodes in which information can be stored and locally manipulated. Recently, experiments have demonstrated that optical signal can be stored in and then retrieved from an atomic ensemble¹². Light storage is implemented in a scheme of electromagnetically induced transparency (EIT) in which the atoms with a Λ configuration interact resonantly with both a signal beam and a control beam³. Theoretically, it has been proved that the scheme can also be used as a quantum memory⁴-⁹. Then, EIT is extended to a double Λ configuration in which two couples of probe and control beams interact resonantly with a four-level atom¹⁰-¹³. In this model the two Λ subsystems share a common dark state and the quantum interference exists not only between the two lower states, but also between the two Λ channels. Therefore, the EIT effect occurs only when the ratio of Rabi frequencies in each Λ channel is equal. Ref.¹⁰ pointed out the lossless propagation of shape matched probe pulses interacting with one Λ channel when the strong identical pulses drive another Λ channel. However, the storage mechanism of optical pulse in the standard EIT interaction can be applied to double Λ configuration where two probe pulses can

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be simultaneously stored and released\textsuperscript{10}. Considering the special features of double Λ configuration, in this paper, we show that this atomic system is capable of manipulating synchronous optical signals, such as generation of optical twin signals, data correction, signal transfer and amplification.

We consider a double-Λ configuration with two lower levels $|b\rangle$ and $|c\rangle$, and two upper levels $|a\rangle$ and $|d\rangle$, as shown in Fig. 1. The two weak signal fields $\Omega_{1s}$ and $\Omega_{2s}$ couple the atomic transitions $|b\rangle - |a\rangle$ and $|b\rangle - |d\rangle$, respectively, while the two control fields $\Omega_{1c}$ and $\Omega_{2c}$ couple the transitions $|c\rangle - |a\rangle$ and $|c\rangle - |d\rangle$, respectively. We assume full resonance between fields and atomic transitions, and the four levels of atom form a closed loop. The collective atomic operators obey the Heisenberg-Langevin equation\textsuperscript{17}. However, the propagation equations of the two signal beams are written as

\begin{align}
\frac{c}{\partial z} \frac{\partial \Omega_{1s}}{\partial t} + \frac{\partial \Omega_{1s}}{\partial t} &= i \frac{g_1^2}{2} N \rho_{ba}, \quad (1a) \\
\frac{c}{\partial z} \frac{\partial \Omega_{2s}}{\partial t} + \frac{\partial \Omega_{2s}}{\partial t} &= i \frac{g_2^2}{2} N \rho_{bd}, \quad (1b)
\end{align}

where $g_i$ is the coupling coefficient between the signal beam and the atomic transition, and $N$ is the number of atoms. In order to minimize the parameters of the model, we assume a uniform atomic decay $\gamma$ and $g_1 = g_2 = g$.

Assuming that the atomic relaxation is much faster than the variation of the signals, we may obtain approximately the autonomous equations for the two plane-wave signals

\begin{align}
\frac{\partial \Omega_{1s}}{\partial \tau} &= -\eta \frac{|\Omega_{2c}|^2}{|\Omega_{1c}|^2 + |\Omega_{2c}|^2} \Omega_{1s} - \frac{\Omega_{1c} \Omega_{2c}^*}{|\Omega_{1c}|^2 + |\Omega_{2c}|^2} \Omega_{2s}, \quad (2a) \\
\frac{\partial \Omega_{2s}}{\partial \tau} &= -\eta \frac{|\Omega_{1c}|^2}{|\Omega_{1c}|^2 + |\Omega_{2c}|^2} \Omega_{2s} - \frac{\Omega_{1c}^* \Omega_{2c}}{|\Omega_{1c}|^2 + |\Omega_{2c}|^2} \Omega_{1s}, \quad (2b)
\end{align}

where $\eta = g^2 N/(4\gamma^2)$ and $\tau = \gamma t$. Given the initial values, Equation (2) can be analytically solved. Then we set $\tau \to \infty$ and obtain

\begin{align}
\frac{\Omega_{1s}(\infty)}{\Omega_{1s}(0)} &= \frac{1 + \sqrt{\xi \mu \exp(i\delta_0)}}{1 + \xi}, \quad (3a) \\
\frac{\Omega_{2s}(\infty)}{\Omega_{2s}(0)} &= \frac{\xi + \sqrt{\xi \mu \exp(-i\delta_0)}}{1 + \xi}. \quad (3b)
\end{align}

where $\xi = |\Omega_{2c}|^2 / |\Omega_{1c}|^2$, $\mu = |\Omega_{2s}(0)|^2 / |\Omega_{1s}(0)|^2$, and $\delta_0 = \arg[\Omega_{1c}] - \arg[\Omega_{2c}] + \arg[\Omega_{2s}(0)] - \arg[\Omega_{1s}(0)]$. By eliminating the initial values $\Omega_{1s}(0)$ and $\Omega_{2s}(0)$, the four fields satisfy the relation

\begin{equation}
\frac{\Omega_{2s}(\infty)}{\Omega_{1s}(\infty)} = \frac{\Omega_{2c}}{\Omega_{1c}}, \quad (4)
\end{equation}
under which the double-Λ atom is in a dark state and hence the dual EIT effect occurs. Equation (4) indicates the phase matching relation \( \delta \equiv \arg[\Omega_{1c}] - \arg[\Omega_{2c}] + \arg[\Omega_{1s}(\infty)] - \arg[\Omega_{2s}(\infty)] = 0 \), and implies shape-matched propagation of the two signal fields. Furthermore, according to Eqs. (3), the magnitudes of the transmitted signal fields depend on their initial values, the intensity ratio of the control fields, and the phase \( \delta_0 \). Figure 2 shows the amplification/attenuation ratio of the signal intensity \( |\Omega_i(\infty)|^2 / |\Omega_i(0)|^2 \) as a function of the intensity ratio \( \xi \) of the control fields for the three phases \( \delta_0 = 0, \pi/2 \) and \( \pi \), where the two signal beams at the initial time have the same intensity (\( \mu = 1 \)). It can be seen from Fig. 2 that the initial phase matching parameter \( \delta_0 \) dominates the amplification of signals. For \( \delta_0 = 0 \), one of two signal beams can be amplified (with the maximum amplification 1.457), while the phase matching maintains, i.e. \( \delta = \delta_0 = 0 \). At \( \xi = 1 \), the two signal beams, which are equal initially, propagate transparently in the medium and the EIT effect occurs. However, if \( \delta_0 = \pi \) is set, the two signal beams quench simultaneously at \( \xi = 1 \). This is so called electromagnetically induced absorption (EIA).

In the following, we discuss the schemes using the double Λ model to manipulate synchronous signals.

(i) **Generation of optical twin signals.** If only one signal enters into the atomic medium, the modulation of the signal can be duplicated to a new beam which may have different frequency and polarization. This effect refers to a four-wave mixing (FWM) mechanics but it contains strongly quantum interference resulting in beam matching. In the analytical solution, by setting \( \Omega_{1s}(0) = 0 \) we obtain \( \Omega_{1s}(\infty) = \sqrt{\frac{\xi}{1+\xi}} \Omega_{2s}(0) \exp[i \arg(\Omega_{1c}) - i \arg(\Omega_{2c})] \) and \( \Omega_{2s}(\infty) = \frac{\xi}{1+\xi} \Omega_{2s}(0) \). For example, if \( \Omega_{2c} = \Omega_{1c} \), the two signal beams are identical, \( \Omega_{1s}(\infty) = \Omega_{2s}(\infty) = (1/2) \Omega_{2s}(0) \).

The numerical simulation of this scheme is shown in Fig. 3, in which all the atoms are initially at the ground level \(|b\rangle \) (the same for Figs. 4-7 as well). When the two control beams are set to be equal, we obtain the twin signals after a few times of atomic relaxation by inputting only one signal beam.

(ii) **Data correction.** If there are two identical digital signals generated, for example, by the above scheme, and a few pulses are lost in transmission, they can be corrected by parallel comparison of these two series of pulses. In Figs. 4a and 4b, we consider such two imperfect digital signals as input and set two equal control beams in the double Λ atoms. The numerical simulation shows that two identical series of pulses are resumed, as shown in Figs. 4c and 4d, in which the blank pulses are recovered. This correction method is simple and effective. Only when two corresponding pulses of the two beams are lost simultaneously, they are non-recoverable. But this happens with a negligible probability.

(iii) **Signal amplification in transmission.** If there are two synchronous signals available, one of the signals can be amplified in this system. The analytical solution provides the indication how to choose the parameters for amplification. When two signals are identical (\( \mu = 1 \)), for instance, the maximum amplification ratio 1.457 occurs for \( \delta_0 = 0 \) and \( \xi = 3 \pm 2\sqrt{2} \) (see Fig. 2). In Fig. 5, we prepare two identical pulses at time \( \tau_0 \). By setting the parameter
ξ = 0.1716, the signal Ω₁s is amplified with the maximum amplification.

(iv) Signal transfer from one beam to another. The dual EIT system is able to transfer a signal from one beam to another which may have different frequency and polarization. The transfer process is implemented through the atomic storage. In Fig. 6, a pulse is initially carried by the signal beam 1 while the control beams 1 and 2 are set to a high and a low levels, respectively. When the levels of the two control beams are gradually exchanged, the pulse has been transferred from one signal beam to another.

(v) Signal amplification in atomic storage. In the signal storage scheme carried out by a three-level EIT model, loss occurs in the atomic storing process because of the atomic decay. However, in the dual EIT model, it is possible to amplify optical signal in the atomic storing process. Similar to scheme (iii), we should prepare two synchronous signals as input. Figure 7 shows the signal amplification through the atomic storage. In the first stage when the two control beams have the same high strength, the dual EIT condition is satisfied and the two signals propagate transparently in the medium. When the two control beams are decreased to a low level in the second stage, the two signals are simultaneously stored in the atomic ensemble. In the final stage in which only one control beam is recovered to the previous high level, one of the signal beams has been retrieved with the amplification ratio 1.452 while the other one vanishes.

In summary, we show that the double Λ configuration atomic system possesses additional quantum interference between the two EIT channels and can provide powerful application to manipulate optical synchronous signals.

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Captions of Figures:
Fig. 1 Atomic levels of a double Λ configuration.

Fig. 2 Intensity amplification/attenuation ratios of the two signal beams as functions of the control field parameter ξ for the three phases δ0 = 0, π/2 and π. The two input signals at the initial time have the same intensity (μ = 1).

Fig. 3 Generation of twin signals. The two control beams are equal Ωc/(g√N) = Ωc/(g√N) = 12. In the pulse propagation, the normalized times (τ = γt) are set as τ0 = 0, τ1 = 1.5, τ2 = 3, τ3 = 4.5, τ4 = 9.5, τ5 = 14.5, τ6 = 19.5, τ7 = 24.5, τ8 = 29.5. In Figs. 3-7, the coupling strength is taken as g√N/γ = 2.

Fig. 4 An example of data correction in which (a) and (d) are the two imperfect pulse signals as input. In the propagation, the lost pulses are recovered. The control beams are the same as in Fig. 3.

Fig. 5 Signal amplification in transmission. In the pulse propagation, the normalized times are set as τ0 = 0, τ1 = 1.5, τ2 = 3, τ3 = 10.5, τ4 = 18, τ5 = 25.5, τ6 = 33.

Fig. 6 Signal transfer process. (a) Evolution of the signal beam 1 and (b) Evolution of the signal beam 2. The insets show variations of the corresponding control beams.

Fig. 7 Signal amplification in atomic storage. The descriptions are the same as in Fig. 6. Note that the two control beams are equal until the time γt = 150.
\[ |\Omega_{1s}(\infty)|^2/|\Omega_{1s}(0)|^2 \]

\[ |\Omega_{2s}(\infty)|^2/|\Omega_{2s}(0)|^2 \]

(a) 

(b)
\[
|\Omega_{1s}^2|/(gN) | \Omega_{2s}^2|/(gN)
\]

\(\gamma z/c\)

(a)

(b)
\[ |\Omega_{1s}|^2/(g^2N) \]

\[ |\Omega_{2s}|^2/(g^2N) \]

\(\gamma t = 0\)

\(\gamma t = 20\)
