Probe frequency- and field intensity-sensitive coherent control effects in an EIT-based periodic layered medium

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A periodic layered medium, with unit cells consisting of a dielectric and an electromagnetically-induced transparency (EIT)-based atomic vapor, is designed for light propagation manipulation. Considering that a destructive quantum interference relevant to a two-photon resonance emerges in EIT-based atoms interacting with both control and probe fields, an EIT-based periodic layered medium exhibits a flexible frequency-sensitive optical response, where a very small variation in the probe frequency can lead to a drastic variation in reflectance and transmittance. The present EIT-based periodic layered structure can result in controllable optical processes that depend sensitively on the external control field. The tunable and sensitive optical response induced by the quantum interference of a multi-level atomic system can be applied in the fabrication of new photonic and quantum optical devices. This material will also open a good perspective for the application of such designs in several new fields, including photonic microcircuits or integrated optical circuits.

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Significant attention has been paid to electromagnetically-induced transparency (EIT) in various fields in optics, such as in electromagnetism, photonics, and atomic physics. This physical mechanism can exhibit a large number of interesting quantum optical effects relevant to light wave manipulation[1]. Several remarkable physical effects associated with EIT include inversionless light amplification[2], spontaneous emission cancellation[3], multi-photon population trapping[4], coherent phase control[5,6], photonic resonant left-handed media[7,8], and light storage in atomic vapors[9−13]. Some effects are expected to be beneficial and powerful for developing new technologies in quantum optics and photonics. In this letter, several new effects for light propagation manipulation via EIT responses in an artificial periodic dielectric are proposed. These effects result from the combination of EIT and photonic crystals. This combination can be viewed as a new application of EIT for controllably manipulating light wave propagations, which can exhibit a tunable reflection and transmission (induced by an external control field) as well as extraordinary sensitivity to the frequency of the probe field. Hence, this method can be used for designing sensitive optical switches, photonic logic gates, and tunable photonic transistors[14−18].

In this letter, the stimulating optical behavior of an EIT-based atomic vapor is addressed. A lambda-configuration three-level atomic system with two lower levels $|1\rangle$ and $|2\rangle$ and one upper level $|3\rangle$ is considered (Fig. 1). This atomic system interacts with the electric fields of the probe and control light waves, which drive the $|1\rangle - |3\rangle$ and $|2\rangle - |3\rangle$ transitions, respectively. This three-level system can be found in metallic alkali atoms (e.g., Na, K, and Rb). Attention is focused on the influence of the external control field on the probe wave propagation inside an EIT-based periodic layered medium. The atomic microscopic electric polarizability of the $|1\rangle - |3\rangle$ transition can be expressed as

$$\beta = \frac{\mathrm{i}|\wp_{13}|^2}{\varepsilon_0\hbar}\frac{\frac{\gamma_2}{2}+\mathrm{i}\left(\varDelta_\mathrm{p}-\varDelta_\mathrm{c}\right)}{\left(\frac{\Gamma_3}{2}+\mathrm{i}\varDelta_\mathrm{p}\right)\left[\frac{\gamma_2}{2}+\mathrm{i}\left(\varDelta_\mathrm{p}-\varDelta_\mathrm{c}\right)\right]+\frac{1}{4}\varOmega_\mathrm{c}^*\varOmega_\mathrm{c}}, \tag{1}$$

where Γ_3 and γ_2 stand for the spontaneous emission decay rate and the collisional dephasing rate, respectively; $\varOmega_\mathrm{c}$ is the Rabi frequency of the control field defined by $\varOmega_\mathrm{c} = \wp_{32}E_c/\hbar$ with E_c as the slowly varying amplitude (envelope) of the control field; $\varDelta_\mathrm{p} = \omega_{31} - \omega_\mathrm{p}$ and $\varDelta_\mathrm{c} = \omega_{32} - \omega_\mathrm{c}$, are the two frequency detunings with ω_p and ω_c representing the mode frequencies of the probe and control fields, respectively. Using the Clausius-Mossotti relation, which governs the local field effect due to the dipole-dipole interaction between neighboring atoms, the relative electric permittivity of an EIT-based vapor at probe frequency $\omega_\mathrm{p} = \omega_{31} - \varDelta_\mathrm{p}$ is given by

$$\varepsilon_\mathrm{r} = 1 + \frac{N_a\beta}{1-\frac{N_a\beta}{3}}, \tag{2}$$

where N_a denotes the atomic concentration (atomic number per unit volume) of the atomic vapor.

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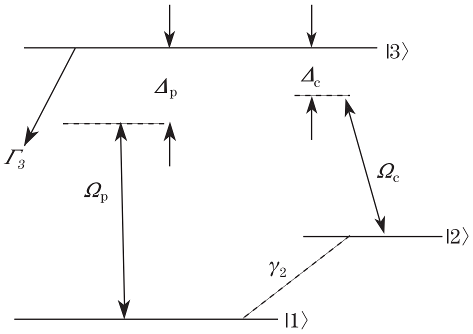

Fig. 1. Schematic diagram of a three-level EIT-based atomic system. Control and probe laser beams drive the $|2\rangle-|3\rangle$ and $|1\rangle-|3\rangle$ transitions, respectively.

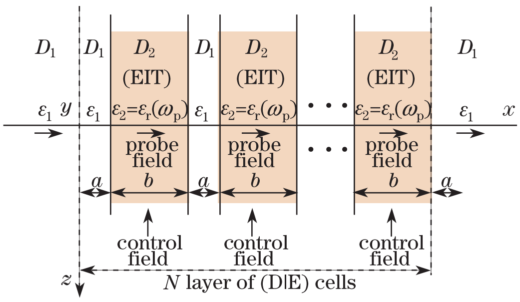

Fig. 2. 1D N-layers structure of (D|E) cells embedded in GaAs homogeneous dielectric. The dielectrics D_1 and D_2 stand for the GaAs and EIT-based atomic media, respectively. A (D|E) cell consists of GaAs dielectric (D) and EIT-based medium (E). The lattice constants of the (D|E) cells are chosen as $a = b = 0.1$ μm.

The one-dimensional (1D) periodic (D|E) cells shown in Fig. 2 are composed of two kinds of media, namely, a GaAs dielectric with the relative refractive index of $n_1 = 3.54$ and a typical lambda-configuration three-level EIT-based medium whose electric permittivity is determined by Eq. (2). The characters "D" and "E" in (D|E) denote the dielectric (GaAs) and the EIT-based medium, respectively. The two materials are assumed to be both homogeneous along the y direction (i.e., $\partial/\partial y = 0$), and the probe signal wave is also assumed to be always traveling in the (...D|E|D|E. . .) structure along the x direction. The reflection coefficient[19] on the left side interface ($x = 0$) of this EIT-based periodic medium, a 1D N-layer (D|E) layered structure bounded by the GaAs dielectric material, is addressed.

According to the theory of electromagnetism in photonic crystals, the electric field in the mth unit cell can be expressed by[19]

$$E(x)=\begin{cases} a_m e^{-jk_{1x}(x-m\Lambda)}+b_m e^{jk_{1x}(x-m\Lambda)} & m\Lambda-a<x<m\Lambda \\ c_m e^{-jk_{2x}(x-m\Lambda+a)}+d_m e^{jk_{2x}(x-m\Lambda+a)} & (m-1)\Lambda<x<m\Lambda-a \end{cases}, \quad (3)$$

where the wave vectors are $k_{1x} = n_1\omega/c$ and $k_{2x} = n_2\omega/c$. Using matrix formalism in treating the wave propagation in the layered media,

$$\begin{pmatrix} a_{m-1} \\ b_{m-1} \end{pmatrix}=\frac{1}{2}\begin{pmatrix} e^{jk_{2x}b}\left(1+\frac{k_{2x}}{k_{1x}}\right) & e^{-jk_{2x}b}\left(1-\frac{k_{2x}}{k_{1x}}\right) \\ e^{jk_{2x}b}\left(1-\frac{k_{2x}}{k_{1x}}\right) & e^{-jk_{2x}b}\left(1+\frac{k_{2x}}{k_{1x}}\right) \end{pmatrix} \cdot \begin{pmatrix} c_m \\ d_m \end{pmatrix}, \quad (4)$$

and the eigenvalue equation

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} a_m \\ b_m \end{pmatrix}=e^{iK\Lambda}\begin{pmatrix} a_m \\ b_m \end{pmatrix}, \quad (5)$$

for the column vector, characterizing the electromagnetic field strengths in the periodic layered structure, can be obtained. The matrix elements are given by[19]

$$\begin{aligned} A&=e^{jk_{1x}a}\left[\cos k_{2x}b+\frac{1}{2}j\left(\frac{k_{2x}}{k_{1x}}+\frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right], \\ B&=e^{-jk_{1x}a}\left[\frac{1}{2}j\left(\frac{k_{2x}}{k_{1x}}-\frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right], \\ C&=e^{jk_{1x}a}\left[-\frac{1}{2}j\left(\frac{k_{2x}}{k_{1x}}-\frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right], \\ D&=e^{-jk_{1x}a}\left[\cos k_{2x}b-\frac{1}{2}j\left(\frac{k_{2x}}{k_{1x}}+\frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right]. \end{aligned} \quad (6)$$

The eigenvalue equation yields

$$\det\begin{pmatrix} A-e^{jK\Lambda} & B \\ C & D-e^{jK\Lambda} \end{pmatrix}=0, \quad (7)$$

which can be rewritten as

$$\cos K\Lambda=\cos k_{1x}a\cos k_{2x}b-\frac{1}{2}\left(\frac{n_2}{n_1}+\frac{n_1}{n_2}\right)\sin k_{1x}a\sin k_{2x}b. \quad (8)$$

From this relation, the Bloch wave number K can be obtained. The reflection coefficient, defined as $r_N = b_0/a_0$, can be derived. Therefore, the relation of the column vectors between the left side interface (at $x = 0$) and in the Nth unit cell is given by

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix}=\begin{pmatrix} A & B \\ C & D \end{pmatrix}^N\begin{pmatrix} a_N \\ b_N \end{pmatrix}, \quad (9)$$

with

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^N=\begin{pmatrix} AU_{N-1}-U_{N-2} & BU_{N-1} \\ CU_{N-1} & DU_{N-1}-U_{N-2} \end{pmatrix}. \quad (10)$$

The explicit expression for U_N is $U_N=\frac{\sin[(N+1)K\Lambda]}{\sin K\Lambda}$. Using the following relations:

$$\begin{aligned} a_0&=(AU_{N-1}-U_{N-2})\,a_N+BU_{N-1}b_N, \\ b_0&=CU_{N-1}a_N+(DU_{N-1}-U_{N-2})\,b_N, \end{aligned} \quad (11)$$

the reflection coefficient of an N-layer periodic medium is given by[19]

$$r_N=\frac{CU_{N-1}}{AU_{N-1}-U_{N-2}}, \quad (12)$$

where $b_N = 0$ has been substituted (Considering that the present periodic layered medium is composed of N

unit cells and is bounded by the medium of the refractive index n_1, the reflected amplitude of the electric field in the last unit cell vanishes.). The phasor time dependence $e^{-i\omega t}$ is adopted for the time harmonic wave in deriving the atomic microscopic electric polarizability (1) of the EIT, which is often used by physicists. In the convention of engineers, however, the time dependence is $e^{+j\omega t}$[19]. Given that the formalism in Ref. [19] is employed to treat the wave propagation in the periodic layered medium, the convention of physicists should be converted to that of engineers. This conversion can be accomplished using the imaginary variable substitution $i \rightarrow -j$.

The reflection coefficient should be sensitive to the probe frequency when it is tuned onto the two-photon resonance ($\varDelta_p \rightarrow \varDelta_c$). The typical atomic and optical parameters chosen for the numerical results are as follows: atomic number density $N_a = 5.0 \times 10^{20}$ m^{-3}, electrical dipole moment$|\wp_{31}| = 1.0\times10^{-29}$ C·m, spontaneous emission decay rate $\varGamma_3 = 2.0 \times 10^7$ s^{-1}, frequency detuning of the control field $\varDelta_c = 0.5\varGamma_3 = 1.0 \times 10^7$ s^{-1}, and dephasing rate $\gamma_2 = 1.0\times10^5$ s^{-1}. In Fig. 3, the real and imaginary parts of the reflection coefficient r corresponding to N-layer (D|E) cells are illustrated, where the layer number $N = 1, 5, 20, 100$. The reflection coefficient is noted to change drastically in the frequency detuning range of concern. Figure 3 illustrates the dispersive behavior of r in the range of $\varDelta_p/\varGamma_3 \in [0.3, 0.7]$, i.e., the probe frequency detuning changes at the level of one part in 10^8 in the probe frequency ω_p (the typical value of the probe frequency $\omega_p \approx 10^{15}$ s^{-1}). The real and imaginary parts of r vary from approximately 0.25 and –0.25 to 0.95 and 0.40, respectively (Fig. 3). As expected, such dramatic change in the reflection coefficient results from the two-photon resonance due to the destructive quantum interference between the $|1\rangle - |3\rangle$ and $|2\rangle - |3\rangle$ transitions. In general, the more layers there are in a dielectric-EIT–based cell structure, the more drastic changes would appear in the reflection coefficient on the left-side interface of an EIT-based periodic layered medium. Thus, the total number of valleys and peaks in the curve of the reflection coefficient r in a narrow band close to $\varDelta_p = 0.5\varGamma_3$ increases as the total layer number N increases. However, valleys and peaks in the reflection coefficient are no longer conspicuous for cases of large N, considering that the amplitudes of fluctuation become smaller when the layer number N is adequately large. For example, if the layer number $N = 100$, the small fluctuations tend to efface themselves (Fig. 3).

Thus, the probe frequency-sensitive behavior of an EIT-based periodic layered material has been demonstrated. This material can exhibit another effect, i.e., field-controlled tunable optical response, where the control field can be used to manipulate the photonic band structure. Thus, the reflection coefficient would vary as the control Rabi frequency $\varOmega_c$ is being tuned. As shown in Fig. 4, the tunable reflection coefficient of an EIT-based periodic layered medium is also sensitive to the Rabi frequency of the control field when the total layer number N increases. This condition indicates that the incident probe signal is either reflected or transmitted depending quite sensitively on the intensity of the external control field (characterized by $\varOmega_c^* \varOmega_c$). Therefore, this material can be used for designing several sensitive photonic devices (e.g., optical switches, photonic logic gates, and tunable photonic transistors). Full controllability of reflection and transmission of the present EIT-based layered structure is also demonstrated in Fig. 4. Both real and imaginary parts of the reflection coefficient r are less than 0.1. Hence, the reflectance ($R = r^*r$) approaches zero (or almost zero) when certain values of the normalized control Rabi frequency $\varOmega_c/\varGamma_3$ are considered, such as $\varOmega_c/\varGamma_3 = 6.0$ (for $N = 5$), $\varOmega_c/\varGamma_3 = 8.5$ (for $N = 20$), and $\varOmega_c/\varGamma_3 = 10, 20$ (for $N = 100$). Thus, a field intensity-sensitive switchable mirror can be fabricated with an EIT-based layered structure having a large total layer number N (e.g., $N > 100$). The three-dimensional (3D) behavior of the reflectance of an EIT-based periodic layered medium as both the control Rabi frequency $\varOmega_c$ and the probe frequency detuning $\varDelta_p$ is demonstrated in Fig. 5. The reflectance and transmittance of 1-, 5-, 20-, and 100-layer periodic structures at the other probe frequency detuning, e.g., $\varDelta_p = -10^8$ s^{-1},

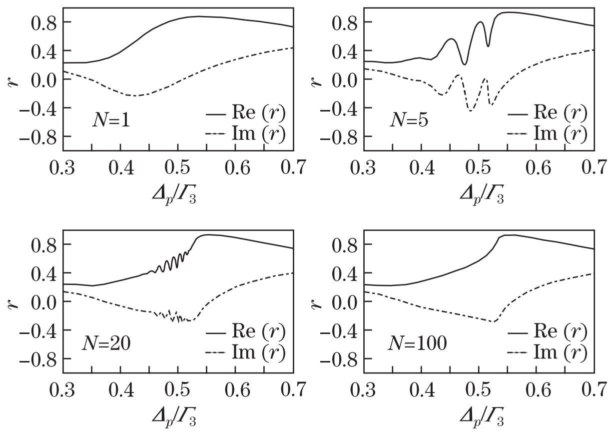

Fig. 3. Real and imaginary parts of the reflection coefficient r versus the normalized probe frequency detuning $\varDelta_p/\varGamma_3$ in the frequency range of two-photon resonance caused by the destructive quantum interference between the $|1\rangle - |3\rangle$ and $|2\rangle - |3\rangle$ transitions (close to $\varDelta_p = 0.5\varGamma_3$). The layer number of the EIT-based periodic medium $N = 1, 5, 20, 100$. The control Rabi frequency is chosen as $\varOmega_c = 2.0 \times 10^7$s^{-1}.

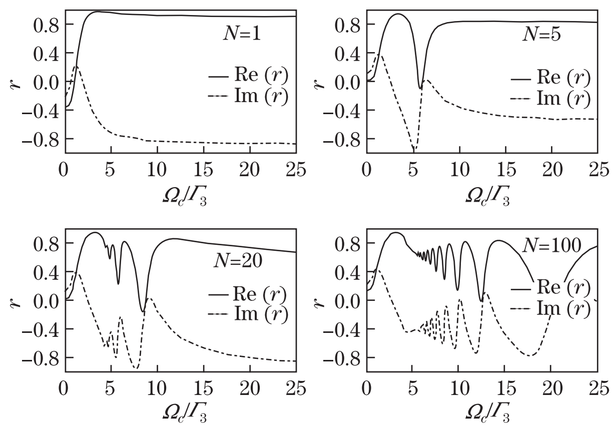

Fig. 4. Real and imaginary parts of the reflection coefficient r versus the normalized Rabi frequency $\varOmega_c/\varGamma_3$ of the control field. The probe frequency detuning is $\varDelta_p = 2.0 \times 10^7$ s^{-1}. All the atomic and optical parameters such as $\wp_{31}$, $\varGamma_3$, γ_2, $\varDelta_c$, and N_a are chosen exactly the same as those in Fig. 3. For $N = 100$ the reflection coefficient depends quite sensitively on the Rabi frequency of the control field.

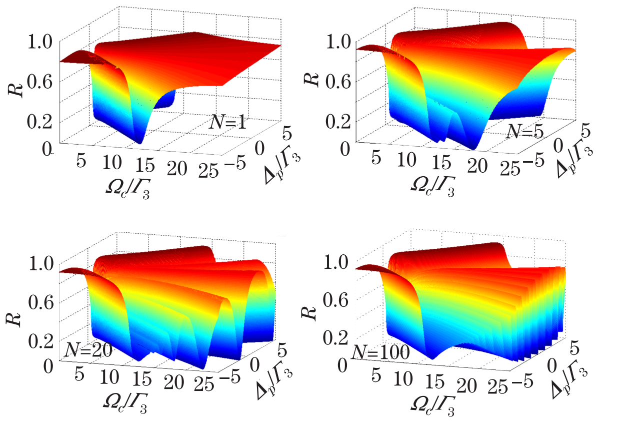

Fig. 5. 3D behavior of the reflectance of the EIT-based layered medium versus the normalized control Rabi frequency Ω_c/Γ_3 and the normalized probe frequency detuning Δ_p/Γ_3. All the atomic and optical parameters such as $\wp_{31}$, Γ_3, γ_2, Δ_c, and N_a are chosen exactly the same as those in Figs. 3 and 4.

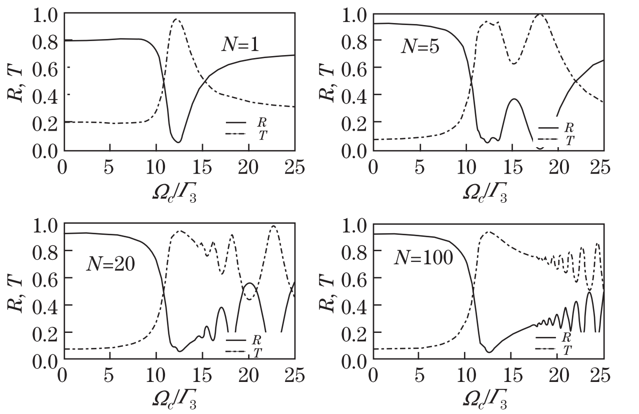

Fig. 6. Reflectance and transmittance versus the normalized Rabi frequency Ω_c/Γ_3 of the control field. The probe frequency detuning is chosen as $\Delta_p = -10^8$ s^{-1}. All the atomic and optical parameters such as $\wp_{31}$, Γ_3, γ_2, Δ_c, and N_a are chosen exactly the same as those in Fig. 3.

are considered and shown in Fig. 6 as illustrative examples of the effects of a tunable field intensity-sensitive coherent control.

The probe frequency detuning Δ_p is not equal to the control frequency detuning Δ_c in Figs. 4–6, which are typical cases exhibiting the general optical behavior of EIT-based photonic crystals. The quantum interference between atomic transitions (particularly when the condition of two-photon resonance, $\Delta_c = \Delta_p$, is fulfilled) can result in a strong dispersion that is tunable by the external control field. Thus, the structure of an EIT-based photonic crystal can be designed by taking advantage of the aforementioned effect of quantum coherence. The demonstrated effects of probe frequency- and field intensity-sensitive coherent control of an EIT-based periodic layered structure is expected to be used as a fundamental mechanism for the design and fabrication of new quantum optical and photonic devices.

In conclusion, a layered structure of 1D photonic crystal, consisting of EIT-based vapor and host dielectric layers, can show extraordinary sensitivity to the frequency of the probe field because of the two-photon resonance relevant to the destructive quantum interference between the $|1\rangle - |3\rangle$ and $|2\rangle - |3\rangle$ transitions. An EIT-based periodic layered material can also exhibit an effect of field intensity-sensitive switching control (depending quite sensitively on the Rabi frequency of the control field) in cases of large layer number N. Thus, several new photonic devices (e.g., photonic transistors, logic, and functional gates) and sensitive switchable devices (fundamental building blocks, e.g., photonic microcircuits on silicon, in which light replaces electrons) could be realized by taking advantage of the coherent switching control. These devices may be used in new applications in photonic quantum information processing.

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