Phase control of group velocity in a dielectric slab doped with three-level ladder-type atoms

D. Jafari,[1,2] M. Sahrai,[2] H. Motavalli,[1] and M. Mahmoudi[3]
[1]*Department of Physics, University of Tabriz, Tabriz, Iran*
[2]*Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran*
[3]*Department of Physics, University of Zanjan, P.O. Box 45195-313, Zanjan, Iran*
(Received 14 August 2011; published 5 December 2011)

Propagation of an electromagnetic pulse through a dielectric slab doped with three-level ladder-type atomic systems is discussed. It is shown that the group velocity of the reflected and transmitted pulses can be switched from subluminal to superluminal light propagation by the thickness of the slab or the intensity of the coupling field. Furthermore, it is found that, in the presence of quantum interference, the reflected and transmitted pulses are completely phase dependent. So, the group velocity of the reflected and transmitted pulses can only be switched from subluminal to superluminal by adjusting the relative phase of the applied fields.

DOI: 10.1103/PhysRevA.84.063811 PACS number(s): 42.50.Gy, 42.25.Bs, 42.25.Gy, 42.70.Qs

I. INTRODUCTION

The study of light propagation in a dispersive medium has been triggered by a series of papers by Sommerfeld [1] and Brillouin [2] and continues to be of much interest [3–9]. It is shown that the group velocity of a light pulse can be slowed down [10,11], can become faster than its value *c*, speed of light in vacuum, or can even become negative [12–18]. The superluminal light propagation has been investigated for many potential uses, not only as a tool for studies of a very peculiar state of matter, but also for developing quantum computers, high-speed optical switches, and communication systems [19]. Both experimental and theoretical studies have been performed to realize superluminal and subluminal light propagation in a single system. It has been shown that switching from subluminal to superluminal pulse propagation can be achieved with the intensity of coupling fields [20–22] and the relative phase of applied fields [23,24]. The effect of controlling parameters, such as intensity of the incoherent pumping field and quantum interference on the group velocity of a light pulse has also been proposed [25–28]. In view of many experimental proposals for controlling the group velocity of a light pulse from subluminal to superluminal propagation, the proposal by Kim *et al.* [29] is notable. They have shown that, for a weak-coupling field, the superluminal Gaussian light pulse is accompanied by induced absorption. However, for a strong-coupling field, the subluminal probe light is accompanied by induced absorption that lies between two transparency windows. Experimental realization of an incoherent pump field on subluminal and superluminal light propagation has also been observed by Xiao *et al.* [30]. In addition, the transformation of electromagnetically induced transparency into enhanced absorption by a strong-coupling field in an Rb vapor has also been reported by Bae *et al.* [31]. The above experimental and theoretical studies on subluminal and superluminal light propagation are proposed in gaseous systems. However, light propagation in a solid-state material, such as a slab system or photonic crystals (PCs) also are important due to their potential applications. Propagation of an electromagnetic field in one-dimensional PCs (1DPCs) has attracted a lot of attention in recent years. In fact, periodic media called PCs are an important material for studying the subluminal and superluminal propagation of a light pulse [32,33]. A multilayered medium is considered as a simple example of the 1DPCs. The essential property of the PC is the band-gap structure. The electromagnetic field of frequency within the gap is evanescent. Since the evanescent field is analogous to the wave's function of an electron in a quantum barrier, the 1DPCs are used as an optical barrier to investigate the tunneling time [34–36]. In the present paper, the main attention was focused on the transmission of a pulse through the media. However, superluminality of the reflected pulse was theoretically discussed in an optical-phase conjugation mirror [37] and a symmetric 1DPC [38]. Nimtz *et al.* [39] demonstrated that the reflection delay was almost independent of the barrier's length. It is also predicted that the superluminal phenomena may occur simultaneously both in reflection and in transmission by using optical-phase conjugation in an unstable region [37].

On the other hand, the reflected and transmitted pulses of an electromagnetic field from a slab have widely been studied. In a conventional gas system, we can provide only subluminal or superluminal light propagation, whereas, in the slab system, we achieve the superluminal pulse reflection and the superluminal pulse transmission simultaneously. In addition, a slab system can be used for studying the light propagation in a photonic band-gap crystal. The superluminal pulse reflection and transmission in a slab system doped with two-level or three-level atoms has been studied [40].

In this paper, we extend the results of previous researchers and find that the reflected and transmitted pulses can simply be tuned from subluminal to superluminal by varying the controlling parameters. We consider a pulse incident on a slab system doped with three-level ladder-type atoms. The effect of quantum interference arising from spontaneous emission on the group velocity of the reflected and transmitted light then is discussed. It is found that, in the presence of quantum interference, the transmitted and reflected light can be switched from subluminal to superluminal just by the relative phase of the applied fields. An important key point is that the superluminal pulse reflection and the superluminal pulse transmission are simultaneously achieved. Furthermore, we find that both the reflected and the transmitted pulses are superluminal or subluminal for the doped slab depending on the intensity of the controlling field and the phase difference between the applied fields. Most of the related papers discuss gaseous systems. However, according to our knowledge, the important proposal on light transmission and light reflection from a slab system is discussed in Ref. [40]. In Ref. [40], the authors discussed the possibility of the light reflection and transmission in a slab system doped with two- or three-level atoms without introducing the explicit dependence of the group velocity on controlling parameters, such as intensity and the relative phase of the applied fields. However, we have discussed the effect of controlling parameters, such as intensity and the relative phase of the applied fields as well as quantum interference induced by spontaneous emission on the group velocity of the reflected and transmitted probe pulses.

The effect of spontaneously generated coherence (SGC) was employed by Javanainen [41] to show the disappearance of the dark state in a Λ-type three-level system. This coherence has also been employed by Menon and Agarwal [42] for phase control of the absorption and the dispersion. Here, we used this coherence for phase control of the reflected and transmitted light pulses from or through a slab doped with a three-level atomic system.

The paper is organized as follows: In Sec. II, we present the slab model and a brief representation on light propagation in a slab system. The reflected and the transmitted pulses are also discussed via the transfer-matrix method. The equation of motion for the atomic system is presented in Sec. III. Results and discussions are given in Sec. IV, and a conclusion can be found in Sec. V.

II. PULSE PROPAGATION IN A SLAB

A light pulse is normally incident on the weakly absorbing and nonmagnetic slab (extended from $z = 0$ to $z = d$ in the z direction) with the complex relative permittivity $\varepsilon(\omega_p) = \varepsilon_r + i\varepsilon_i$ where ε_r and ε_i represent the dispersion and the absorption parts, respectively (Fig. 1). Both sides of the slab are vacuums. The incident pulse is a Gaussian form at the surface of the slab in plane $z = 0$, and its electric field is expressed as $E_p(0,t) = A_0\exp[-\frac{t^2}{2\tau_0^2}]\exp[-i\omega_0 t]$ at the incident surface with the Fourier component given by $E_p(0,\omega_p) = (\frac{\tau_0 A_0}{2\sqrt{\pi}})\exp[-\tau_0^2\frac{(\omega_p-\omega_0)^2}{2}]$. Here, τ_0 is the temporal width of the Gaussian pulse, ω_0 is the center frequency, and A_0 denotes the amplitude of the incident pulse. For a TE plane wave, the transfer matrix for the electric and magnetic components of a monochromatic wave of frequency ω through the slab is given by [40,43]

$$\begin{pmatrix} \cos[kd] & i\frac{1}{n(\omega_p)}\sin[kd] \\ in(\omega_p)\sin[kd] & \cos[kd] \end{pmatrix}, \tag{1}$$

where $n(\omega_p) = \sqrt{\varepsilon(\omega_p)}$ is the refractive index of the slab. We assume that the slab is doped by three-level atoms, so the dielectric function, i.e., (ω_p), can be divided into two parts,

$$\varepsilon(\omega_p) = \varepsilon_b + \chi(\omega_p), \tag{2}$$

where $\varepsilon_b = n_b^2$ is the background dielectric function and $\chi(\omega_p)$ represents the susceptibility of the atoms doped in the dielectric slab. The linear susceptibility of a weak probe field, i.e., $\chi(\omega_p)$, is calculated in following section. Using

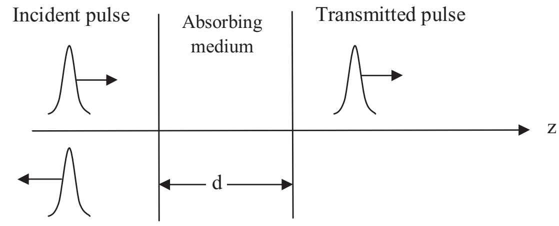

FIG. 1. Schematic of the weakly absorbing dielectric slab.

the transfer-matrix method, one can obtain the reflection and transmission coefficients of the monochromatic wave as [40]

$$r(\omega_p) = \frac{-\left(\frac{i}{2}\right)\left(\frac{1}{\sqrt{\varepsilon}} - \sqrt{\varepsilon}\right)\sin(kd)}{\cos(kd) - \left(\frac{i}{2}\right)\left(\frac{1}{\sqrt{\varepsilon}} + \sqrt{\varepsilon}\right)\sin(kd)}, \tag{3}$$

$$t(\omega_p) = \frac{1}{\cos(kd) - \left(\frac{i}{2}\right)\left(\frac{1}{\sqrt{\varepsilon}} + \sqrt{\varepsilon}\right)\sin(kd)}, \tag{4}$$

where we have assumed $\varepsilon_b = 4.0$. For a narrow spectral pulse, the group delay time can be defined from the peak times $T_{r,t}^{\text{peak}}$ of the transmitted and reflected pulses (the subscripts r and t denote the reflected and transmitted pulses, respectively) [40,44]. From the shapes of the reflected and transmitted pulses, we can obtain the peak times $T_{r,t}^{\text{peak}}$ of the resulting pulses. For the reflected pulse, $T_r^{\text{peak}} < 0$ means the superluminal pulse reflection, while for the transmitted pulse, $T_t^{\text{peak}} < d/c$ means the superluminal pulse transmission. The peak time $T_{r,t}^{\text{peak}}$ is equivalent to the phase time delay defined as $\tau_{r,t} = [\frac{\partial\varphi_{r,t}}{\partial\omega}]_{\omega=\omega_0}$ [where $\varphi_{r,t}$ are the phases of the reflection and transmission coefficients $r(\omega)$ and $t(\omega)$, respectively] [2,45,46].

Equations (3) and (4) imply that the reflection and transmission coefficients depend on the thickness of the slab and the refractive index of the slab. For the resonance condition, the thickness of the slab is employed as $d = 2m(\frac{\lambda_0}{4\sqrt{\varepsilon_b}})$, whereas, for the off-resonance condition, it is considered as $d = (2m+1)(\frac{\lambda_0}{4\sqrt{\varepsilon_b}})$. Note that the other values also are available.

III. ATOMIC SYSTEM

The doped atomic system inside the slab is an equispaced ladder-type three-level atomic system with lower level $|1\rangle$, upper level $|3\rangle$, and intermediate level $|2\rangle$ as depicted in Fig. 2(a). Two lower levels $|1\rangle$ and $|2\rangle$ are coupled by a weak tunable probe field of frequency ω_p and Rabi frequency

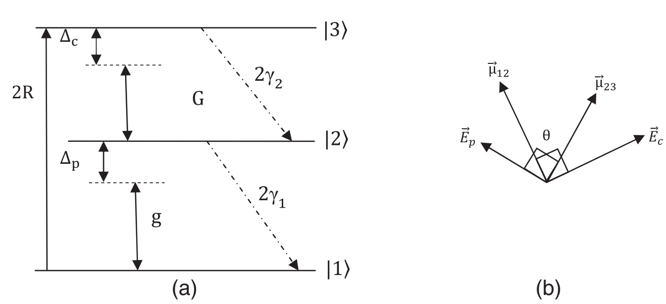

FIG. 2. A three-level ladder-type system with nearly equispaced levels.

$g = \frac{\vec{\mu}_{12}\cdot\vec{E}_p}{\hbar}$, while the upper level $|3\rangle$ and the intermediate level $|2\rangle$ are coupled by a strong-coupling field of frequency ω_p and Rabi frequency $G = \frac{\vec{\mu}_{23}\cdot\vec{E}_c}{\hbar}$. Here, $\vec{\mu}_{ij}$ are the atomic dipole moments, and $\vec{E}_c(\vec{E}_p)$ is the amplitude of the coupling (probe) field. The spontaneous emission from upper level $|3\rangle$ to intermediate level $|2\rangle$ is denoted by $2\gamma_2$, while the corresponding decay from level $|2\rangle$ to lower level $|1\rangle$ is denoted by $2\gamma_1$. An incoherent pump with a pumping rate $2R$ is applied between levels $|1\rangle$ and $|3\rangle$. We further assume that the incoherent pump process from level $|1\rangle$ to level $|3\rangle$ takes place via some unspecified auxiliary states. Thus, some terms corresponding to the inverse pumping from level $|3\rangle$ to level $|1\rangle$ and the terms corresponding to the interference effect due to the pumping processes are all ignored. The density-matrix equations of motion in the rotating frame and in the rotating wave approximation are given by [47,48]

$$\begin{aligned}
\rho_{11} &= -2R\rho_{11} + 2\gamma_1\rho_{22} + ig^*\rho_{21} - ig\rho_{12},\\
\rho_{22} &= 2\gamma_2\rho_{33} - 2\gamma_1\rho_{22} - ig^*\rho_{21} + ig\rho_{12} - iG\rho_{23} + iG^*\rho_{32},\\
\rho_{33} &= 2R\rho_{11} - 2\gamma_2\rho_{33} + iG\rho_{23} - iG^*\rho_{32},\\
\rho_{23} &= -(\gamma_1 + \gamma_2 + i\Delta_c)\rho_{23} + iG^*(\rho_{33} - \rho_{22}) + ig\rho_{13},\\
\rho_{12} &= -\left(R + \gamma_1 + i\Delta_p\right)\rho_{12} + ig^*(\rho_{22} - \rho_{11})\\
&\quad - iG\rho_{13} + 2P\sqrt{\gamma_1\gamma_2}\rho_{23},\\
\rho_{13} &= -[\gamma_2 + R + i(\Delta_p + \Delta_c)]\rho_{13} - iG^*\rho_{12} + ig^*\rho_{23},
\end{aligned} \tag{5}$$

Here, Δ_p and Δ_c are the detuning of the probe and coupling fields with respect to the corresponding atomic transition that defines as $\Delta_p = \omega_{21} - \omega_p$ and $\Delta_c = \omega_{32} - \omega_c$, where ω_{ij} is the frequency difference between corresponding levels. Note that, in the case of nearly equispaced levels, the inclusion of two coupling fields of different frequencies would lead to the optical Bloch equations with the additional term $2P\sqrt{\gamma_1\gamma_2}\rho_{23}$, which represents the effect of the SGC. The parameter $P(= \frac{\vec{\mu}_{12}\cdot\vec{\mu}_{23}}{|\vec{\mu}_{12}||\vec{\mu}_{23}|} = \cos\theta)$ denotes the alignment of the two dipole moments $\vec{\mu}_{12}$ and $\vec{\mu}_{23}$, where θ is the angle between the two induced dipole moments $\vec{\mu}_{12}$ and $\vec{\mu}_{23}$. In fact, they present the strength of the interference in spontaneous emission. According to its definition, the alignment factor takes the value 1 for parallel dipole moments, -1 for antiparallel, and 0 for orthogonal. Maximal coherence corresponds to parallel and antiparallel dipole moments. These two extremes of maximal and minimal coherence deserve special attention. However, intermediate values on the $[-1, 1]$ interval are also possible.

Since the existence of SGC depends on nonorthogonality of the dipole moments $\vec{\mu}_{12}$ and $\vec{\mu}_{23}$, linearly polarized fields $\vec{E}_c$ and $\vec{E}_p$ are arranged as in Fig. 2(b) so that one field acts only on one transition. The Rabi frequencies are connected to parameter P by the relations $G = |G_0|\sqrt{1-P^2}$ and $= |g_0|\sqrt{1-P^2}$. In the nonequispaced level situation, Rabi frequencies may be treated as real parameters. However, for the case with nearly equispaced levels, the SGC effect must be taken into account. In this case, the system becomes quite sensitive to the relative phase between the probe and the coupling fields. Therefore, if we use $g = |g|\,e^{i\varphi_p}, G = |G|\,e^{i\varphi_c}$ and redefining the atomic variables in Eqs. (5) as $\tilde{\rho}_{12} = \rho_{12}e^{i\varphi_p}, \tilde{\rho}_{23} = \rho_{23}e^{i\varphi_c}$, and $\tilde{\rho}_{23} = \rho_{23}e^{i(\varphi_p - \varphi_c)}$, we obtain equations for the redefined density-matrix elements to be identical by Eqs. (5) except that P is replaced by

$$P \rightarrow Pe^{i\varphi}, \tag{6}$$

where $\varphi = \varphi_c - \varphi_p$. Solving Eqs. (5) at the steady state, by the matrix form, and in the weak-field approximation, we obtain the real and imaginary parts of coherence term $\tilde{\rho}_{12}$ as

$$\mathrm{Re}\,(\tilde{\rho}_{21}) = \frac{z_1(\Delta_p + \Delta_c) + RGL\Delta_2(\gamma_2 + R)}{Z}, \tag{7}$$

and

$$\mathrm{Im}\,(\tilde{\rho}_{21}) = -\frac{z_1(\gamma_2 + R) + RGL\Delta_c(\Delta_p + \Delta_c)}{Z}, \tag{8}$$

where $= 2P\sqrt{\gamma_1\gamma_2}$, and

$$\begin{aligned}
z_1 &= g\big[-\gamma_2(\gamma_1+\gamma_2)^2 - 2G^2(\gamma_1+\gamma_2)\\
&\quad + \Delta_c^2\gamma_2\big] + RGL(\gamma_2 + 2\gamma_1),
\end{aligned} \tag{9}$$

with

$$Z = (A^2 + B^2)C, \tag{10}$$

$$A = R(R+\gamma_1) - \Delta_p(\Delta_p + \Delta_c) + \gamma_1\gamma_2 + G^2, \tag{11}$$

$$B = R(\Delta_p + \Delta_c) + \Delta_p(\gamma_1 + \gamma_2) + \gamma_1(\gamma_1 + \Delta_c), \tag{12}$$

and

$$C = \left\{\gamma_2\big[(\gamma_1+\gamma_2)^2 + \Delta_c^2 + 2G^2\big] + 2\gamma_1G^2\right\}. \tag{13}$$

The linear susceptibility of the weak probe field can be written as

$$\chi(\omega_p) = \frac{2N\mu_{12}}{\varepsilon_0 E_p}\tilde{\rho}_{21}, \tag{14}$$

where N is the atomic number density in the medium [49]. The susceptibility $\chi(\omega_p)$ is related to the index of reflection $n = n' + in''$ via $n^2(\omega_p) = 1 + \chi(\omega_p)$. The real and imaginary parts of $\chi(\omega_p)$ are corresponding to the dispersion and absorption, respectively. So, the gain or absorption coefficient for the probe laser coupled to transition $|2\rangle \rightarrow |1\rangle$ is proportional to the imaginary part of susceptibility χ, i.e.,χ'', while the dispersion is characterized by the real part of χ, i.e., χ'. If $\chi'' > 0(\chi'' < 0)$, the probe laser will be absorbed (amplified) [50]. The slope of the dispersion with respect to the probe-field detuning plays a major role in the determination of the group velocity.

Note that the relative phase appears in the equations through P, that is, appears in L. For $P = 0$, the phase dependence of the medium will be canceled. The phase dependence of the susceptibility χ is also related to the incoherent pumping field. For $R = 0$, the second term in χ' and χ'' will be omitted leading to the cancellation of the phase dependence.

IV. RESULT AND DISCUSSION

Now, we consider a dielectric layer doped with the three-level ladder-type atoms. We investigate the propagation of the reflected and transmitted pulses from this layer. The effect of the Rabi frequency of the coupling field and the relative phase of the applied fields on the group velocity of the reflected and transmitted pulses then is discussed. A probe

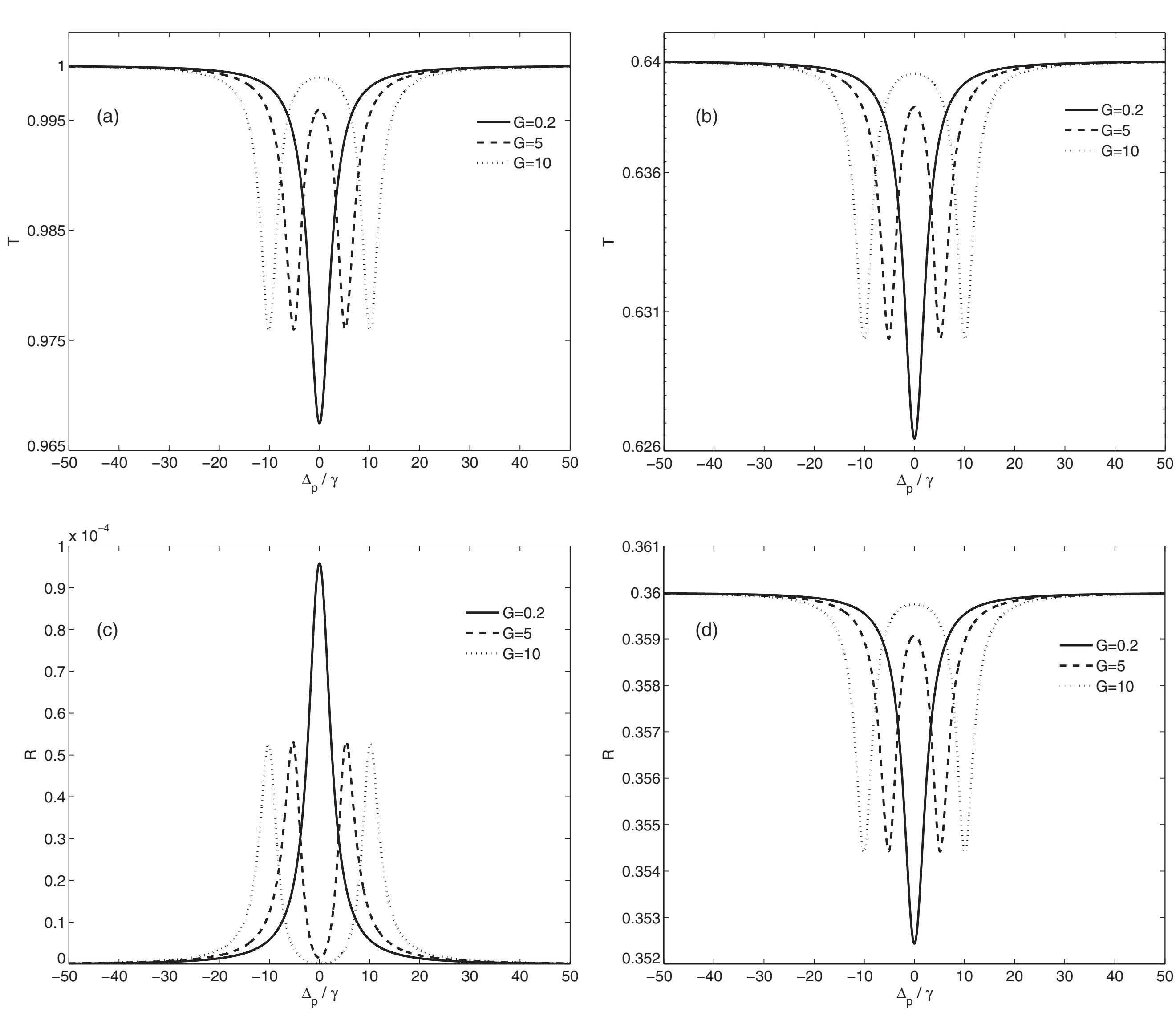

FIG. 3. (a) and (b) Transmittivity and (c) and (d) reflectivity versus probe-field detuning. Selected parameters are $P = 0, R = 0.5\gamma, g_0 = 0.1\gamma, \gamma_1 = 2\gamma$, and $d = (2m)\,(\frac{\lambda_0}{4\sqrt{\varepsilon_b}})$ for (a) and (c) and $d = (2m + 1)\,(\frac{\lambda_0}{4\sqrt{\varepsilon_b}})$ for (b) and (d).

pulse with a center frequency ω_0 normally is incident on the slab. The nature of ω_0 depends on the level structure, but for a realistic example of sodium D_1 transition, $3\ ^2S_{1/2} \rightarrow 3\ ^2P_{1/2}$, the center frequency of the probe field is $\omega_{12} = \omega_0 = 2\pi \times 508.332$ THz. We typically assume a decay rate of sodium D_1 transmission $= 2\pi \times 9.75 \times 10^6$ Hz . All the other parameters are reduced to dimensionless units through scaling by $\gamma_2 = \gamma$. So, the electric dipole moment, the Rabi frequency of the probe field, and the density of the atomic number are chosen as $\mu_{12} = 2.1 \times 10^{-29}$cm, $g_0 = 0.1\gamma$, and $N = 1 \times 10^{11}$atom cm^{-3}, respectively. This may lead to $\frac{2N\mu_{12}}{\varepsilon_0 E_p} \approx 0.02$.

The transmitted and reflected pulses from a slab are discussed for two different thicknesses. In a resonance condition, we choose $d = 2m(\frac{\lambda_0}{4\sqrt{\varepsilon_b}})$, while for the off-resonance condition, the thickness is chosen as $d = (2m + 1)(\frac{\lambda_0}{4\sqrt{\varepsilon_b}})$. Here, m is an integer number, and in the following numerical calculation, we choose $m = 100$. Note that a peak in the curve of the reflectivity or transmittivity corresponds to subluminal pulse reflection or transmission. However, a dip corresponds to superluminal pulse reflection or transmission. Figure 3 shows a typical transmittivity $T = |t|^2$ and reflectivity $R = |r|^2$ curves versus probe-field detuning. We observe that, for $P = 0$ and for a weak-coupling field, i.e., $G = 0.2\gamma$, each transmitted pulse has a dip, so superluminal light propagates through the medium in both selected thicknesses. For a strong-coupling field, i.e., $G = 5\gamma$ (or 10γ), the dip changes to the peak corresponding to subluminal light propagation through the medium [Figs. 3(a) and 3(b)]. From Figs. 3(c) and 3(d), we observe that the behavior of the reflected pulse is quite different for the two cases. In fact, for $G = 0.2\gamma$ and for a resonance case [Fig. 3(c)], there is a peak in the curve of reflectivity, while for an off-resonance case [Fig. 3(d)], there is a dip in the curve of reflectivity. Therefore, for a weak-coupling field, in the resonance condition, the subluminal light is reflected from the slab, while for the off-resonance condition, the superluminal light is reflected from the slab. This is to say

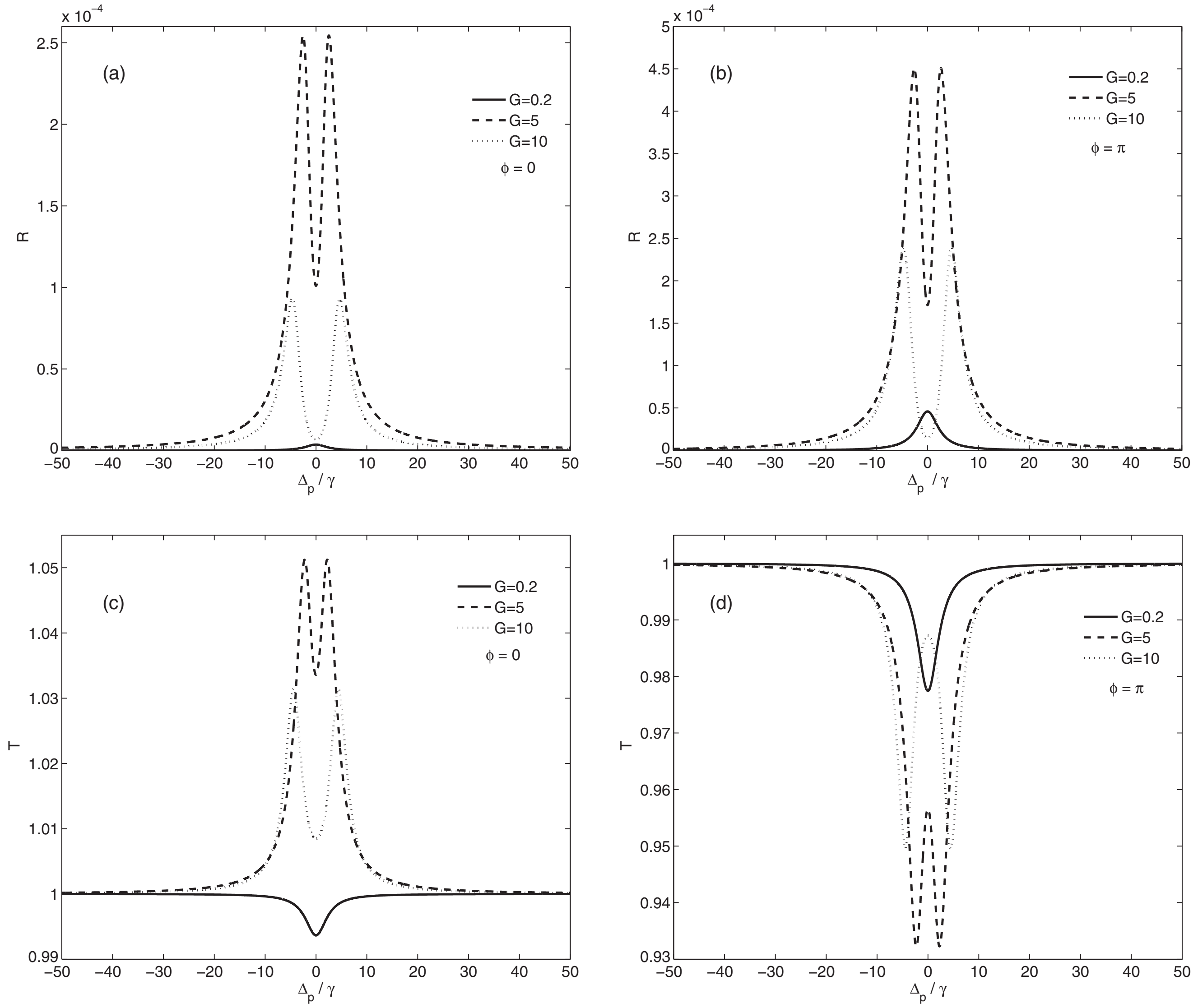

FIG. 4. Transmittivity and reflectivity versus probe-field detuning for a resonance condition $d = 2m\frac{\lambda_0}{4\sqrt{\varepsilon_b}}$. Selected parameters are $P = 0.9, R = 0.5\gamma, g_0 = 0.1\gamma$, and $\gamma_1 = 2\gamma$, (a) and (c) $\varphi = 0$, and (b) and (d) $\varphi = \pi$.

that there is a switching from subluminal to superluminal for the reflected pulse by changing the slab's thickness. By increasing the Rabi frequency of the coupling field, the peak (dip) converts to the dip (peak), and the subluminal (superluminal) light reflection converts to superluminal (subluminal) light reflection. Therefore, we find that, for the off-resonance condition by adjusting the intensity of the coupling field, both the transmitted and the reflected pulse can become subluminal or superluminal simultaneously [Figs. 3(b), and 3(d)]. However, for a resonance condition, the group velocity of the reflected and transmitted pulses is completely different. So, the transmitted pulse becomes superluminal, while the reflected pulse becomes subluminal and vice versa [Figs. 3(a) and 3(c)]. This is an important case in which the group velocity of the reflected and transmitted pulses can be controlled only by adjusting the intensity of the coupling field.

It is well known that, in a ladder-type equispaced three-level atomic system, the quantum interference due to the spontaneous emission, i.e., SGC, makes the system completely phase dependent [47,48]. Here, we discuss the effect of the relative phase of the applied fields on the group velocity of the reflected and transmitted light. The effect of the relative phase on the group velocity of the reflected and transmitted pulses for a resonance condition is displayed in Fig. 4. We observe that, in the presence of quantum interference, i.e., $P = 0.9$, for two different relative phases $\varphi = 0$ (or π) and for $G = 0.2\gamma$, the reflectivity curves have peaks corresponding to subluminal light propagation. They change to the dip for a strong-coupling field, i.e., $G = 5\gamma$ (or 10γ). However, the behavior of the transmittivity curves is different; for a weak-coupling field, the transmittivity curves have a dip for $\varphi = 0$ (or π), while for $G = 5\gamma$ (or 10γ), the dip changes to a peak by the change in the relative phase from $\varphi = 0$ to $\varphi = \pi$. We find that, for a strong-coupling field and in the presence of SGS, the transmitted pulse can be controlled just by the relative phase of the applied fields.

The effect of the relative phase on the group velocity of the reflected and transmitted pulses for an off-resonance condition

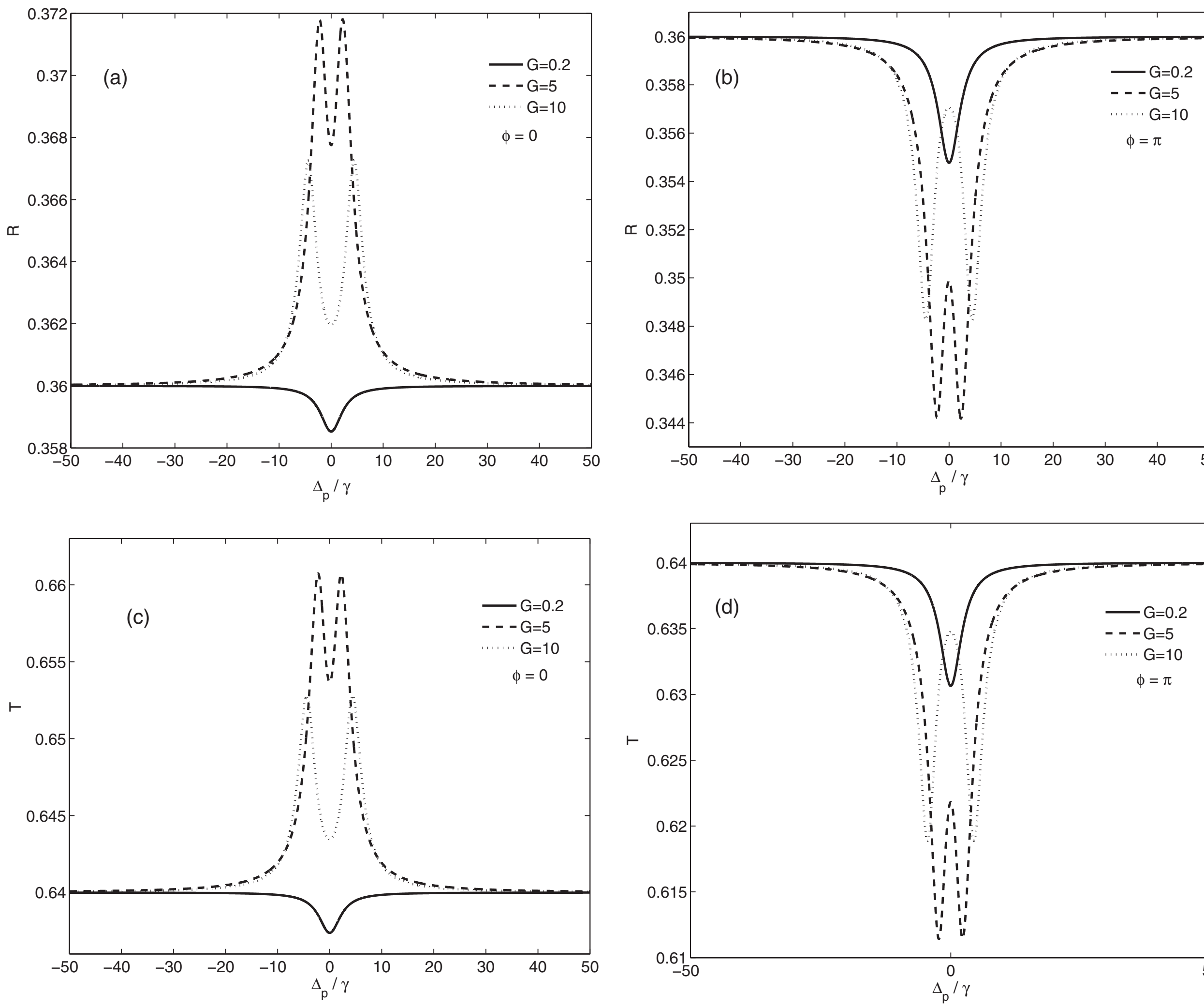

FIG. 5. Transmittivity and reflectivity versus probe-field detuning for the off-resonance condition $d = (2m+1)\frac{\lambda_0}{4\sqrt{\varepsilon_b}}$. Selected parameters are $P = 0, R = 0.5\gamma, g_0 = 0.1\gamma$, and $\gamma_1 = 2\gamma$, (a) and (c) $\varphi = 0$, and (b) and (d) $\varphi = \pi$.

is displayed in Fig. 5. We observe that, in the presence of quantum interference, i.e., $P = 0.9$, and for $G = 0.2\gamma$, there is a dip in the reflectivity curve for $\varphi = 0\,(\text{or}\ \pi)$. So, the group velocity of the reflected pulse is superluminal. However, for $G = 5\gamma$ (or 10γ) , the medium completely becomes phase dependent. For $\varphi = 0$, there is still a dip in the reflectivity curve, while for $\varphi = \pi$, the dip changes to a peak. This is to say that the superluminal light reflection changes to subluminal light reflection. In Figs. 5(c) and 5(d), it is worth noting that, for $\varphi = 0$, we observe only a dip in the transmittivity curve, but for $\varphi = \pi$, the dip changes to a peak by increasing the Rabi frequency of the coupling field. From Fig. 5, we conclude that, for the off-resonance condition, the group velocity of the transmitted light and the reflected light is completely phase dependent. In fact, for the strong-coupling field and in the presence of SGC, the superluminal light reflection (transmission) changes to subluminal light reflection (transmission) just by changing the relative phase from $\varphi = 0$ to $\varphi = \pi$. This is an important case in which the reflected and transmitted pulses can be controlled from superluminal to subluminal (or vice versa) just by the relative phase of the applied fields. Note that, from an experimental point of view, the relative phase between laser fields can be changed by setting a moving prism perpendicular to the propagation direction of one laser field.

V. CONCLUSION

We investigated the effect of the intensity of a coupling field and the relative phase of the applied fields on the group velocity of the reflected and transmitted pulses in a slab system doped with three-level ladder-type atoms. We found that the group velocity of the reflected pulse can be controlled from subluminal to superluminal just by changing the slab's thickness. We also demonstrated that, in the absence of quantum interference, both the reflected and the transmitted pulses can be switched from subluminal to superluminal (or vice versa) by the Rabi frequency of the coupling field. In addition, in the presence of quantum interference, the medium completely becomes phase dependent. So, the group velocity of the reflected and transmitted pulses can be controlled from subluminal to superluminal (or vice versa) just by the relative phase of the applied fields. The behavior of the gas system and slab medium is defiantly deferent. Spatially, the existence of a doped atom through the slab may change the dispersive properties of the medium. For many potential applications of slow light, a solid-state medium is preferred. However, most solid material has relatively broad optical linewidths, which limits the achievable light-speed reduction. A notable exception to this general rule is a class of materials consisting of multilayer systems, such as PCs and the slab system. These materials generally are used for ultrahigh density optical memories and processors.

[1] A. Sommerfeld, Z. Physik. **8**, 841 (1907).
[2] L. Brillouin, *Wave Propagation and Group Velocity* (Academic, New York, 1960).
[3] S. E. Harris, J. E. Field, and A. Kasapi, Phys. Rev. A **46**, R29 (1992).
[4] O. Schmidt, R. Wynands, Z. Hussein, and D. Meschede, Phys. Rev. A **53**, R27 (1996).
[5] J. E. Field, K. H. Hahn, and S. E. Harris, Phys. Rev. Lett. **67**, 3062 (1991).
[6] S. E. Harris, J. E. Field, and A. Imamoglu, Phys. Rev. Lett. **64**, 1107 (1990).
[7] M. Xiao, Y.-q. Li, S.-z. Jin, and J. Gea-Banacloche, Phys. Rev. Lett. **74**, 666 (1995).
[8] G. S. Agarwal and T. N. Dey, Phys. Rev. Lett. **92**, 203901 (2004).
[9] A. K. Patnaik, F. L. Kien, and K. Hakuta, Phys. Rev. A **69**, 035803 (2004).
[10] L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, Nature (London) **397**, 594 (1999).
[11] M. M. Kash, V. A. Sautenkov, A. S. Zibrov, L. Hollberg, G. R. Welch, M. D. Lukin, Y. Rostovtsev, E. S. Fry, and M. O. Scully, Phys. Rev. Lett. **82**, 5229 (1999).
[12] A. M. Steinberg and R. Y. Chiao, Phys. Rev. A **49**, 2071 (1994).
[13] E. L. Bolda, J. C. Garrison, and R. Y. Chiao, Phys. Rev. A **49**, 2938 (1994).
[14] A. M. Akulshin, A. Cimmino, A. I. Sidorov, P. Hannaford, and G. I. Opat, Phys. Rev. A **67**, 011801 (2003).
[15] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, Science **301**, 200 (2003).
[16] C. Goren, A. D. Wilson-Gordon, M. Rosenbluh, and H. Friedmann, Phys. Rev. A **68**, 043818 (2003).
[17] L. J. Wang, A. Kuzmich, and A. Dogario, Nature (London) **406**, 277 (2000).
[18] A. Kuzmich, A. Dogariu, L. J. Wang, P. W. Milonni, and R. Y. Chiao, Phys. Rev. Lett. **86**, 3925 (2001).
[19] M. Bajcsy, S. Hofferberth, V. Balic, T. Peyronel, M. Hafezi, A. S. Zibrov, V. Vuletic, and M. D. Lukin, Phys. Rev. Lett. **102**, 203902 (2009).
[20] G. S. Agarwal, T. N. Dey, and S. Menon, Phys. Rev. A **64**, 053809 (2001).
[21] D. Han, H. Guo, Y. Bai, and H. Sun, Phys. Lett. A **334**, 243 (2005).
[22] H. Tajalli and M. Sahrai, J. Opt. B: Quantum Semiclassical Opt. **7**, 168 (2005).
[23] D. Bortman-Arbiv, A. D. Wilson-Gordon, and H. Friedmann, Phys. Rev. A **63**, 043818 (2001).
[24] M. Sahrai, H. Tajalli, K. T. Kapale, and M. Suhail Zubairy, Phys. Rev. A **70**, 023813 (2004).
[25] M. Mahmoudi, M. Sahrai, and H. Tajalli, J. Phys. B **39**, 1825 (2006).
[26] M. Mahmoudi, S. Worya Rabiei, L. Ebrahimi Zohravi, and M. Sahrai, Opt. Commun. **281**, 4681 (2008).
[27] M. Sahrai, M. Sharifi, and M. Mahmoudi, J. Phys. B **42**, 185501 (2009).
[28] M. Mahmoudi, M. Sahrai, and H. Tajalli, Phys. Lett. A **357**, 66 (2006).
[29] K. Kim, H. S. Moon, C. Lee, S. K. Kim, and J. B. Kim, Phys. Rev. A **68**, 013810 (2003).
[30] F. Xiao, H. Guo, L. Li, C. Liu, and X. Chen, Phys. Lett. A **327**, 15 (2004).
[31] I.-H. Bae, H. S. Moon, M. K. Kim, L. Lee, and J. B. Kim, Opt. Express **18**, 1389 (2010).
[32] *Photonic Band Gap and Localization*, edited by C. M. Souk-Oulis (Plenum, New York, 1993).
[33] E. Yablonovitch, T. J. Gmitter, and K. M. Leung, Phys. Rev. Lett. **67**, 2295 (1991).
[34] A. M. Steinberg, P. G. Kwiat, and R. Y. Chiao, Phys. Rev. Lett. **71**, 708 (1993).
[35] A. M. Steinberg and R. Y. Chiao, Phys. Rev. A **51**, 3525 (1995).
[36] I. V. Konoplev, P. MacInnes, A. W. Cross, A. D. R. Phelps, L. Fisher, and K. Ronald, Appl. Phys. Lett. **93**, 231110 (2008).
[37] M. Blaauboer, A. G. Kofman, A. E. Kozhekin, G. Kurizki, D. Lenstra, and A. Lodder, Phys. Rev. A **57**, 4905 (1998).
[38] S. Longhi, Phys. Rev. E **64**, 037601 (2001).
[39] G. Nimtz, A. Haibel, and R. M. Vetter, Phys. Rev. E **66**, 037602 (2002).
[40] L. G. Wang, H. Chen, and S. Y. Zhu, Phys. Rev. E **70**, 066602 (2004).
[41] J. Javanainen, Europhys. Lett. **17**, 407 (1992).
[42] S. Menon and G. S. Agarwal, Phys. Rev. A **57**, 4014 (1998).
[43] L. G. Wang and S. Y. Zhu, Opt. Lett. **31**, 2223 (2006).
[44] L. G. Wang, N. H. Liu, Q. Lin, and S. Y. Zhu, Phys. Rev. E **68**, 066606 (2003).
[45] C. G. B. Garrett and D. E. McCumber, Phys. Rev. A **1**, 305 (1970).
[46] A. Dogariu, A. Kuzmich, and L. J. Wang, Phys. Rev. A **63**, 053806 (2001).
[47] X. J. Fan, A. Y. Li, F. G. Bu, H. X. Qiao, J. Du, and Z. Z. Xu, Optik **119**, 540 (2008).
[48] M. Sahrai and M. Mahmoudi, J. Phys. B **42**, 235503 (2009).
[49] M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge University Press, Cambridge, UK, 1997).
[50] Y. Zhu, Phys. Rev. A **53**, 2742 (1996).