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Phase control of group velocity in one-dimensional photonic crystal with a dispersive defect layer

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ABSTRACT

Propagation of an electromagnetic pulse through one-dimensional photonic crystal doped with three-level Λ-type atomic systems is discussed. It is found that in the presence of quantum interference and incoherent pump, the transmitted pulse becomes completely phase dependent. So, the group velocity of the transmitted pulse can be switched from subluminal to superluminal light propagation just by adjusting the relative phase of applied fields.

1. introduction

Propagation of an electromagnetic pulse in a dispersive medium has been triggered by Lord Rayleigh in 1899 [1]. However, controlling the group velocity of a light pulse in a dispersive medium has obtained a special attention in recent year. It is well known that the group velocity of a light can be slowed down [2,3], can become faster than speed of light in vacuum, or can even become negative [4–10]. The effect of superluminality is that the emerging pulse has essentially the same shape and width as that of the incident wave packet, but its peak travels with a velocity higher than *c* and even exits the medium before the incident pulse enters. This processes can be understood in terms of superposition and interference of traveling plane waves that have a distribution of frequencies and add up to form a narrow-band light pulse [11,12]. Both experimental and theoretical studies have been performed to realize superluminal and subluminal light propagation in a single gas system. It has been shown that switching from subluminal to superluminal pulse propagation can be achieved with the intensity of coupling fields [13–15] and the relative phase of applied fields [16,17]. The effect of other controlling parameters, such as intensity of incoherent pumping field and quantum interference on the group velocity of a light pulse, has also been proposed [18–22]. Controlling the group velocity of a light pulse from subluminal to superluminal via quantum interference induced by spontaneous emission, i.e. spontaneously generated coherence (SGC) [23] has widely been investigated [24–26]. It is also shown that the combined effect of incoherent pumping field and SGC makes the system phase dependent, where the propagation of a light pulse can be controlled by the relative phase of applied fields [18].

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) has attracted a lot of attraction in recent years. In fact, periodic media called PCs play an essential role in studying the subluminal and superluminal propagation of a light pulse [27]. Multilayered medium as a simple example of one-dimensional photonic crystals (1DPCs) is an important material for such studies [28,29]. The electromagnetic field of frequency within the gap is evanescent due to existence of band gap. 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 [27,30,31]. Although, superluminal propagation of the transmitted pulse through the multilayered medium has obtained spacial attention, superluminality of the reflected pulse has theoretically been discussed in optical phase conjugation mirror [32], and a symmetric 1DPCs [33]. It is also predicted that the superluminal phenomena may occur simultaneously in both reflected and transmitted pulses.

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For finite 1DPCs, the dispersion behavior can be described by an effective refractive index that is defined via the complex transmission coefficient; thus the group velocity can be calculated from the effective refractive index [34–36]. Centini et al. [35] showed that the group velocity of probe pulse in the stop band is superluminal due to the anomalous refractive index. Near the band edge, however, the effective refractive index has a positive steep slope such that group velocity can be slowed. Zhu et al. [36] predated that, if a periodic 1DPC is perturbed by a defect layer, the slope of the effective refractive index at the defect mode frequency will become very steep, which causes a great group delay. We emphasize that the group velocity of a probe field in 1DPCs can be changed by coherent control of effective refraction index.

Controlling the light propagation in 1DPCs doped by two-level atomic system is investigated by Liu et al. [37]. We (with collaborator) [38] also studied the dynamical evolution of the electric and magnetic components of a light field inside the 1DPCs contained in a dispersive defect layer. The defect layer containing three-level atoms leads to dispersion relation of Lorentzien type. In particular, the effect of controlling parameters such as frequency detuning and intensity of the coupling field on group velocity of the transmitted light through the 1DPCS was discussed. Finally, we studied the propagation of an electromagnetic pulse through a dielectric slab doped with three-level ladder-type atomic system. 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, in the presence of quantum interference, the group velocity of the reflected and transmitted pulses can only be switched from subluminal to superluminal by adjusting the relative phase of applied fields [39].

Now, an important question arises what is the effect of the relative phase of applied fields on group velocity of the transmitted probe pulse through the 1DPC? This is the main purpose of the present paper. Using a Λ-type three-level atomic system, in the presence of quantum interference, we show that the group velocity of the transmitted probe pulse inside the 1DPC is phase dependent. In fact, quantum interference induced by spontaneous emission, i.e. SGC, and incoherent pumping field, plays a critical role in phase control of group velocity of the transmitted probe pulse. Therefore, in the presence of SGC and incoherent pumping, the group velocity of the light pulse can be switched from superluminal to subluminal just by adjusting the relative phase of applied fields.

The paper is organized as follows: in Section 2, we propose a description of the light propagation in 1DPCs. The equation of motion for the atomic system is presented in Section 3. Results and discussions are given in Section 4, and conclusion can be found in Section 5.

2. Pulse propagation in photonic crystal

Photonic crystals (PCs) are formed by wavelength-scale periodic patterning of dielectric materials in one, two and three dimensions. The unique properties displayed by such crystals depend crucially on their dimensionality [34]. A 1DPC is the well-known dielectric Bragg mirror consisting of alternating layers with low and high indices of refraction. The term “one dimensional” refers to the fact that the arrangement is periodic only in one direction (chosen here as the z-direction) and homogeneous in the xy-plane. Photonic bond gaps (PBGs) appear in the direction of periodicity, the z-direction. A mode with frequency in the gap region and propagating in the z-direction (on-axis propagation) will be totally reflected from the PC. For off-axis propagation, however, there are no band gaps, since the off-axis direction contains no periodic dielectric regions to coherently scatter light and split open a gap. Thus, off-axis propagating modes are expected to be oscillatory, with real wave vectors.

In a 1DPC, the propagation of an optical pulse is governed by the wave equation [40]

$$\frac{\partial^2}{\partial z^2}E(z,t)-\frac{1}{c^2}E(z,t)=\frac{1}{\epsilon_0 c^2}\frac{\partial^2}{\partial t^2}P(z,t), \tag{1}$$

where $E(z, t)$ and $P(z, t)$ are the electric field and the electric polarization, respectively. Suppose the pulse can be expressed as an integral of its Fourier components

$$E(z,t)=\int E(z,\omega)e^{i\omega t}\,d\omega, \tag{2}$$

and in linear response approximation the Fourier component of the polarization is given by $P(z, \omega) = \chi(z, \omega)E(z, \omega)$. The equation for the Fourier component of electric field can be written as

$$\frac{\partial^2}{\partial z^2}E(z,\omega)-\frac{\omega^2}{c^2}\epsilon(z,\omega)E(z,\omega)=0, \tag{3}$$

where $\epsilon(z, \omega) = 1 + \chi(z, \omega)$ is the dielectric function. By using the transfer matrix method and matching the boundary condition, the reflection and transmission coefficient of a monochromatic pulse wave of frequency ω can be obtained as [37,38]

$$r(\omega)=\frac{[X_{22}(\omega)-n_sX_{11}(\omega)]-i[n_sX_{12}(\omega)+X_{21}(\omega)]}{[X_{22}(\omega)+n_sX_{11}(\omega)]-i[n_sX_{12}(\omega)-X_{21}(\omega)]}, \tag{4}$$

and

$$t(\omega)=\frac{2}{[X_{22}(\omega)+n_sX_{11}(\omega)]-i[n_sX_{12}(\omega)-X_{21}(\omega)]}. \tag{5}$$

Here, n_s is the refractive index of the substrate, and X_{ij} are the elements of the matrix connecting the incident end and the exit end defined as

$$\chi_N(\omega)=\prod_{j=1}^{N}M_j(d_j,\omega)=\begin{pmatrix} x_{11}(\omega) & x_{12}(\omega)\\ x_{21}(\omega) & x_{22}(\omega)\end{pmatrix}. \tag{6}$$

In addition, $M_j(d_j, \omega)$ is the transfer matrix defined as

$$M_j(d_j,\omega)=\begin{pmatrix} \cos\left[\frac{\omega}{c}n_j(\omega)d\right] & \frac{1}{n_j(\omega)}\sin\left[\frac{\omega}{c}(\omega)d\right]\\ -n_j(\omega)\sin\left[\frac{\omega}{c}n_j(\omega)d\right] & \cos\left[\frac{\omega}{c}n_j(\omega)d\right]\end{pmatrix}, \tag{7}$$

where $n_j(\omega)$ is the refractive index of the jth layer. We assume that the dielectric function of the doped layer $\epsilon(\omega)$ can be divided into two parts

$$\epsilon(\omega)=\epsilon_B+\chi(\omega), \tag{8}$$

where $\epsilon_B=n_B^2$ is the background dielectric function, and represents the susceptibility of the atoms doped in the defect layer. The susceptibility of a probe field, i.e. $\chi(\omega)$, is calculated in the following section. In finite 1DPCs, the grope delay through the whole structure can be written as $t_d = t_0(n_g - 1)$, where t_0 is the time through the same vacuum distance, and $n_g \equiv c/v_g$ is the group index. The group index can be determined by

$$n_g(\omega)=n(\omega)+\omega\frac{dn(\omega)}{d\omega}, \tag{9}$$

where $n(\omega)$ is the real part of an effective refractive index $n_{eff}(\omega) = n(\omega) + ik(\omega)$ which is defined by the transmission coefficient $t=\sqrt{T}\exp(i\phi)$, where $T = |t|^2$. The real part of $n_{eff}(\omega)$ is [36,35]

$$n(\omega)=\frac{c\phi(\omega)}{L\omega}, \tag{10}$$