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Active control of transmission and group velocity in one-dimensional photonic crystals

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ABSTRACT

Phase-dependent and switchable transmission and group velocity are achieved for a light beam traveling through a one-dimensional photonic crystal containing a dispersive layer. By proper selection of phase difference between probe and coupling fields, the quantum interference in dopant atoms to the defect layer leads to controlling of delay time of transmitted and reflected light. This way, simultaneous subluminal transmission and reflection are achievable. We also found that transmission of one-dimensional photonic crystals is actively controllable in a wide range only by controlling the characteristics of incident light with no need for altering the effective indices or thicknesses of layers.

1. Introduction

A multilayered medium is considered as a simple example of one-dimensional photonic crystals (1DPCs) [1]. The time delay of pulse propagation through dielectric media is defined as $t_d = t_0(c/v_g - 1)$, where t_0 is the time through the same vacuum distance and v_g is the group velocity. The group velocity, according to the definition $v_g = d\omega(k)/dk$, is dependent on the frequency–wave number dispersion relation. Dispersion behavior can be described by an effective refractive index that is defined by the complex transmission coefficient [2,3], and group velocity can be calculated from the effective refractive index. By introducing a defect layer in the system, some banned frequencies inside the gap would be propagated (defect modes). This defect layer also affects delay times of transmitted and reflected light [2]. The propagation of a light pulse passing through a dispersive medium has been extensively investigated [4,5]. Superluminal phenomenon (the group velocity is larger than c or even becomes negative) has been experimentally observed in absorptive media [6] and pulse tunneling through one-dimensional photonic band gaps (1DPBGs) [7–11]. In these investigations, the main focus was on the transmission of a pulse through the medium. In experiments, Longhi et al. [12,13] first observed superluminal reflection of an optical pulse by using a double-Lorentzian fiber Bragg grating. Later, Nimtz et al. [14] experimentally verified that the reflection delay was almost independent of the barrier's length (this effect is known as the Hartman effect [15]). In these discussions, the reflected pulse is superluminal, while the transmitted pulse is subluminal. Both experimental and theoretical studies have been performed to realize superluminal and subluminal light propagation in a single system, specifically in the gaseous phase. It has been shown that switching from subluminal to superluminal pulse propagation can be achieved with the intensity of coupling fields [16–18] and the relative phase of applied fields [19,20]. 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 [21–24]. Blaauboer et al. first predicted that superluminal phenomenon may occur simultaneously both in reflection and in transmission when using optical phase conjugation in the unstable regime [25]. Some literature has focused on the slab systems [26–30], for example a Fabry–Pérot cavity containing gaseous atoms [29] and semiconductor cavities with quantum wells [30], and a low-finesse Fabry–Pérot cavity (with silver mirrors) containing absorbing atoms [28]. According to the reciprocity theorem proposed by Agarwal et al. [27], in a lossless slab system, if there is a dip in transmissivity, according to the Kramers–Kronig relations, this dip corresponds to an anomalous dispersive region on the curve of the effective refractive index versus frequency [3], which leads to superluminal pulse transmission compared to that of the pulse through the same distance in vacuum. For reflection, if there is a peak in reflectivity, the phase time of the reflected pulse is positive (i.e., subluminal pulse reflection). Thus, reflected and transmitted pulses cannot be superluminal simultaneously. Wang et al. considered a pulse incident on a slab system doped with two-level or three-level atoms. The atoms can be passive (absorptive) or active (gain) [31]. They extended the results of previous researches

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[6,28,32,33] and found that the reflected pulse can be tuned from subluminal to superluminal by controlling the slab's thickness (or the slab's background dielectric constant). We and our collaborators [34] investigated the propagation of a pulse through a slab doped with three-level ladder-type atoms. We 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. In this paper, we have mainly focused on active control of group velocity and transmission of probe laser field incident on 1DPCs. We do not alter the thickness or the refractive index of layers for switching between sub-luminal and superluminal light propagation. We considered a pulse incident on a multilayered medium containing a defect layer doped with three-level ladder-type atoms. The effect of quantum interference arising from spontaneous emission on time delay of reflected and transmitted light is then discussed. The effect of spontaneously generated coherence (SGC) was used by Javanainen [35] to show the disappearance of the dark state in a Λ-type three-level system. This coherence has also been used by Menon and Agarwal [36] for phase control of the absorption and the dispersion. We found that, in the presence of quantum interference, time delay of reflected and transmitted light can be switched from positive to negative magnitudes just by switching the relative phase of the applied fields. Consequently, simultaneous superluminal and subluminal transmitted and reflected light are achievable in the proposed system. We also controlled the transmission of the whole system in a wide range by only controlling the atomic parameters. A huge transmission of about 2.5 is achieved for probe field detuned by zero relative to resonance frequency of an atomic system. That makes this system a good alternative for light amplification in layered systems. Another important key point is that subluminal pulse reflection and transmission are simultaneously achieved.

This paper is organized as follows: in Section 2, we present the 1DPCs model and a brief representation on light propagation in a multilayered system governed via a transfer-matrix method. The equation of motion for the dopant atomic system for the defect layer is presented in Section 3. Results and discussions are given in Section 4 and the conclusion in Section 5.

2. 1DPCs model

We consider a layered medium with $(AB)^5A$ structure that is replaced at the center with a layer doped with three-level ladder-type atoms. So the structure of 1DPCs is characterized by *ABABABADABABA*. The *AB* layer has two high and low refractive indices. According to expected applications and fabrication issues one can choose proper refractive indices. Here, we have considered $n_A = 2.22$ and $n_B = 1.41$ representing titanium oxide and fused silica, respectively, consistent with Ref. [7]. The optical thickness of each layer is $n_A d_A = n_B d_B = m\lambda_0/4$, where $\lambda_0 = 590.17$ nm is the central wavelength of a wave packet launched into the system and m is an integer. The thickness of the defect layer is $n_D d_D = m\lambda_0/2$, where $n_D = n_B$. For the proposed system, we consider $m = 100$. For normal incident wave to 1DPCs and considering the z-axis to be the propagation direction, for a given z, the complete transfer matrix T for wave propagation relates the complex amplitudes of fields just before and just behind the first and last interface of the multilayer stack [15]:

$$T(\omega) = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}. \tag{1}$$

This matrix is formed by successive multiplication of propagation and scattering matrices of layers of the stack.

The complex reflection and transmission coefficients of a monochromatic pulse wave of frequency ω can be obtained by the transfer matrix method by [15]

$$r(\omega) = \frac{T_{21}}{T_{11}}, \tag{2}$$

and

$$t(\omega) = \frac{1}{T_{11}}, \tag{3}$$

By setting $t(\omega) = |t(\omega)| \exp[i\phi_t(\omega)]$ and $r(\omega) = |r(\omega)| \exp[i\phi_r(\omega)]$ (where the real functions $\phi_{r,t}(\omega)$ are the phases of transmission and reflection coefficients, respectively), the phase times for transmitted and reflected pulses are calculated as $\tau_{r,t}(\omega) = \partial\phi_{r,t}/\partial\omega$ [28]. These phase times also define the delay time of transmitted and reflected pulses and relate the behavior of group velocity of pulses inside the system.

We assume that the dielectric function of the doped layer $\varepsilon_r(\omega)$ can be divided into two parts [37]:

$$\varepsilon_r(\omega) = \varepsilon_B + \chi(\omega), \tag{4}$$

where $\varepsilon_B = n_B^2$ is the background dielectric function and χ represents the susceptibility of the three-level ladder-type atoms doped in the defect layer. The response of dopant atoms to applied fields is accessible by solving the density matrix equations that are presented in Section 3.

3. Atomic system

The atomic system inside the slab is a ladder-type three-level system with a lower level $|1\rangle$, an upper level $|3\rangle$, and an

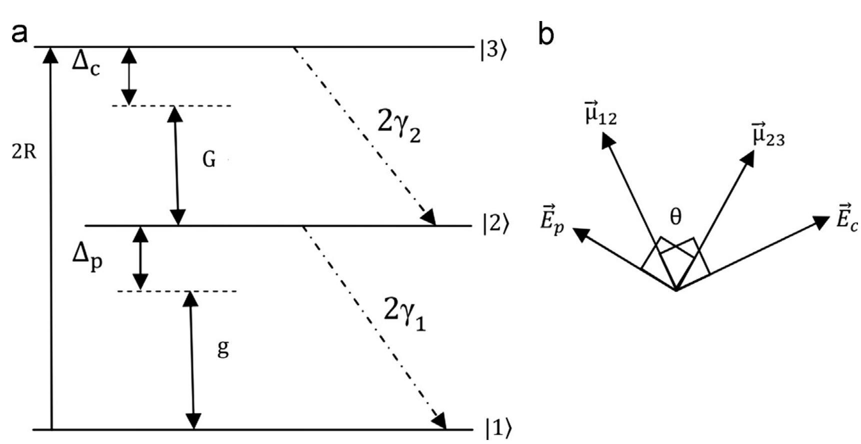

Fig. 1. A three-level ladder-type system with nearly equispaced levels.