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Laser polarization dependent and magnetically control of group velocity in a dielectric medium doped with nanodiamond nitrogen vacancy centers

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ABSTRACT

In this paper, group velocity control of Gaussian beam in a dielectric medium doped with nanodiamond nitrogen vacancy (NV) centers under optical excitation is discussed. The shape of transmitted and reflected pulses from dielectric can be tuned by changing the intensity of magnetic field and polarization of the control beam. The effect of intensity of control beam on group velocity is also investigated.

1. Introduction

Propagation of light in a dispersive medium due to wide applications in all-optical communication systems and quantum information processing has been a well-developed field for many years [1]. Coherent control of optical properties of a dispersive medium leads to observation of many interesting phenomena such as electromagnetically induced transparency (EIT) [2], lasing without population inversion (LWI) [3], four wave mixing (FWM) [4], dark and bright optical solitons [5], optical bistability [6], giant Kerr nonlinearity [7] and so on [8,9]. In recent years, superluminal (the group velocity is larger than c or even becomes negative) and subluminal light propagation in quantum systems both studied theoretically and experimentally. Subluminal and superluminal light propagation have potential applications in optical buffering, data synchronization, optical memories, optical signal processing and developing quantum computers, high-speed optical switches and communication systems [1]. According to the definition $v_g = d\omega(k)/dk$, the group velocity is dependent on the frequency wave number dispersion relation. Dispersion behavior is illustrated by an effective refractive index that can be specified by the complex transmission coefficient [10], and group velocity can be calculated from the effective refractive index. Some defect modes (banned frequencies) inside the gap can be distributed by introducing a defect layer in the system. These phenomena has been experimentally observed in absorptive media [11] and one-dimensional photonic band gaps (1DPBGs) [12]. Moreover, various studies have been done to investigating superluminal and subluminal light propagation in single atomic systems [13]. It has also been shown theoretically that switching between subluminal and superluminal pulse propagation can be obtained by the intensity of coupling field [14], relative phase between applied fields [15], intensity of the incoherent pump [16] and quantum interference from spontaneous emission [17]. There are also some proposals for superluminal and subluminal light propagation on the slab systems [18–20]. In proposed model by Agarwal [20], it was shown that in a lossless slab system, a dip in a transmissivity corresponds to an anomalous dispersive region on the effective refractive index curve which leads to superluminal light transmission. However, a peak in reflectivity corresponds to subluminal pulse reflection. In contrast with gas systems, in the slab system the superluminal pulse reflection and the superluminal pulse transmission can be obtained simultaneously. The superluminal pulse reflection and transmission in a slab system doped with two-level or three-level atoms has been investigated [21]. They confirmed the previous research results [18–20] and displayed that by slab's thickness, the switching between subluminal pulse reflection and superluminal pulse reflection can be obtained. In our recent study [22], we investigated the propagation of a pulse through a slab doped with four-level quantum dots. We found that by using the electron tunneling in a quantum dot, the transmission and reflection coefficients can be controlled at different wavelengths. In this paper, controlling of group velocity and transmission and reflection of probe laser field incident on slab which doped with diamond nitrogen vacancy (NV) centers is investigated. The NV centers in diamond nanocrystal have transpired as suitable candidates for solid-state quantum physics and

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quantum information experiments. At the room temperature, they have a long electronic spin decoherence time, subnanosecond spin control, single-shot spin detection and efficient quantum state transfer between electron and nearby nuclear spins [23–48]. For example, recently Li et al. [49], realized optical bistability in an optical ring cavity filled with diamond NV defect centers under optical excitation. In another study by Li et al. [50], they studied phase controlled absorption-gain and dynamic switching behaviors in a nanodiamond NV center. However, to the best of our knowledge, no related theoretical or experimental work has been carried out to study group velocity in diamond NV centers which doped to the dielectric slab. Based on recent study, the control of group velocity in dielectric slab which doped with nanodiamond NV centers driven by an elliptically polarized coherent field and an external magnetic field are investigated.

2. Model and equations

2.1. Pulse propagation

Consider a weakly absorbing and nonmagnetic slab with the complex relative permittivity $\varepsilon(\omega_p)=\varepsilon_r+i\varepsilon_i$ where ε_r and ε_i correspond to the dispersion and absorption part, respectively (Fig. 1(a)). Both sides of slab are vacuums and a light pulse with Gaussian form at the surface of slab in plane $z=0$, incident on it. Its electric field is expressed as $E_p(0,t)=A_0\exp[-t^2/2\tau^{2/0}]\exp[-i\omega_0 t]$ at the incident surface and its Fourier form given by $E_p(0,\omega_p)=(\tau_0 A_0/2\sqrt{\pi})\exp[-\tau^{2/0}(\omega_p-\omega_0)^2/2]$. Here, τ_0 is the temporal width of Gaussian Pulse, ω_0 is the center frequency, and A_0 denotes the amplitude of 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 Ref. [21].

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

where $n(\omega_p)=\sqrt{\varepsilon_p}$ represent the refractive index of the slab. It is assumed that the slab is doped with GaAs quantum well waveguide. Thus, the dielectric function can be separated into two parts.

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

here, ε_b is the surroundings dielectric functions and $\chi(\omega_p)$ is the susceptibility of nanodiamond NV centers doped in the slab. Using the transfer-matrix method, the reflection and transmission coefficients of the monochromatic wave can be obtained as Ref. [21]

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

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

here, it is assumed that $\varepsilon_b=4$.

From Eqs. (3) and (4), it is found that the reflection and transmission coefficients depend on the thickness and the refractive index of the slab. For the resonance condition, the thickness of the slab is employed as $d=2m(\lambda_0/4\sqrt{\varepsilon_b})$, whereas, for the off-resonance condition, it is considered as $d=(2m+1)(\lambda_0/4\sqrt{\varepsilon_b})$. A subluminal pulse reflection or transmission corresponds to peak in the curve of the reflectivity and transmittivity, while a dip corresponds to superluminal pulse reflection or transmission.

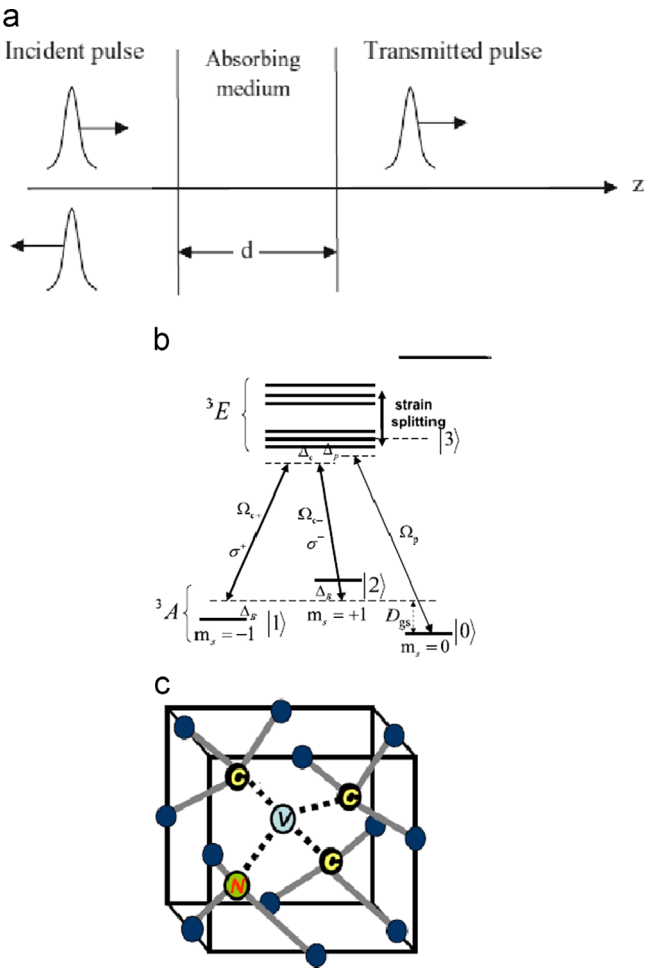

Fig. 1. (a) Schematic of the weakly absorbing dielectric slab (b) structure of the nanodiamond NV centers (c) a schematic diagram of an NV center interacting with an elliptically polarized control field and an external magnetic field. More physical interpretation about this system can be found in Ref. [52].

2.2. Nanodiamond NV centers

The medium doped to the slab is a nanodiamond NV centers. Nanodiamond NV color centers is consisted of a substitutional nitrogen atoms (N) plus a vacancy (V) in an adjacent lattice site as shown in Fig. 1(c). The NV center is negatively charged with two unpaired electrons located at the vacancy, usually treated as electron spin-1. The spin–spin interaction leads to the energy splitting $D_{gs}=2.88$ GHz between the ground levels $|^3A, m_s=0\rangle$ and $|^3A, m_s=\pm 1\rangle$ as depicted in Fig. 1(c). By employing an external static magnetic field B along the quantized axis of diamond NV centers, the degeneracy of the ground sublevels $|^3A, m_s=\pm 1\rangle$ can be lifted. We label $|^3A, m_s=0\rangle$, $|^3A, m_s=-1\rangle$ and $|^3A, m_s=+1\rangle$ as $|0\rangle$, $|1\rangle$ and $|2\rangle$, respectively. The state $|3\rangle$ can be coupled to the ground state $|0\rangle$ with linear polarization [34] and decays to the ground-states sublevels $|1\rangle$ and $|2\rangle$ with radiation of σ^+ and σ^- circular polarization, respectively. Thus, the transition $|3\rangle\leftrightarrow|0\rangle$ is coupled with a linearly polarized probe field with a carrier frequency ω_p and one-half Rabi frequency $\Omega_p=\mu_{30}E_p/2\hbar$, where E_p is the amplitude of the probe field and μ_{30} is the electric dipole moment for the transition $|3\rangle\leftrightarrow|0\rangle$. An elliptically polarized control field with frequency ω_c and wave vector k_c is used to create electric dipole transitions from the exited state $|3\rangle$ to the ground states $|1\rangle$ and $|2\rangle$ simultaneously. A control beam with electric field amplitude E_0 after passing through the QWP that has been rotated by angle θ becomes elliptically polarized. Thus the polarized control beam can be decomposed into $E_c=E^+\sigma^++E^-\sigma^-$, where $E^+=E_0/\sqrt{2}(\cos\theta+\sin\theta)\,e^{i\theta}$ and $E^-=E_0/\sqrt{2}(\cos\theta-\sin\theta)\,e^{-i\theta}$. Here, σ^+ and σ^- are the unit vectors of