Controllable light group velocity in a degenerate two-level medium under the assistance of an external magnetic field

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Received 7 Oct. 2023; Revised 1 Nov. 2023; Accepted 10 Feb. 2024; Published 25 Feb. 2024.
DOI: https://doi.org/10.54939/1859-1043.j.mst.93.2024.106-113

ABSTRACT

In this work, we proposed a simple model for control of subluminal and superluminal light propagation via an external magnetic field in a lambda configuration degenerate two-level atomic medium. We show that the absorption-dispersion properties and group index under the influence of the strength of coupling laser and external magnetic fields are controlled. By changing the direction and magnitude of the magnetic field, the medium switches from transparency with normal dispersion to enhanced absorption with anomalous dispersion at the line center, corresponding with the transfer from slow light to fast light. This work may provide for the application realization of magneto-optic switches and storage devices in quantum information processing.

Keywords: Electromagnetically induced transparency; Electromagnetically induced absorption; Degenerate two-level atomic; Group index; Group velocity; Subluminal and superluminal light propagation.

1. INTRODUCTION

In recent years, there has been a surge of interest in the exploration of slow and fast light propagation within dispersion materials due to their possible applications in quantum memory, high-speed optical switches, optical delay lines and optical communication, and quantum information processing [1-3]. The key to successful investigations hinges on the capacity to manipulate the optical characteristics of the medium using laser fields. A significant milestone was achieved when Hau et al. observed light slowing down to 17 m/s in a Bose-Einstein condensate of three-level sodium (Na) atoms at a temperature of approximately 50 nK through the application of electromagnetically induced transparency (EIT) [3]. Subsequently, Kash et al. [4] slowed light down to 90 m/s in rubidium vapor. This experiment was further refined by Budker and others, resulting in light slowing down to 8 m/s [5]. Apart from atomic vapor media, numerous research groups have explored the phenomenon of slow light in diverse materials such as optical fibers, waveguides, crystals, semiconductors, and quantum wells [6-9], among others. Notably, based on the EIT effect, some research groups completely stopped a light pulse [10, 11]. In these experiments, information carried by light pulses could be temporarily stored within the dispersion medium, permitting researchers to subsequently recreate light pulses carrying the same information with relatively minimal losses.

In other studies, the subluminal and superluminal light pulse propagation can also be obtained by combining electromagnetically induced transparency and electromagnetically induced absorption (EIA) [12, 13]. EIA is a phenomenon where a transparent medium exhibits heightened absorption at the center of a spectral line. Under conditions of EIT and EIA, numerous theoretical and experimental studies have explored the subluminal and superluminal propagation of light [14, 15]. Besides that, some studies have focused on the dynamic switching between subluminal and superluminal light propagation within an atomic medium, achieved by manipulating factors like frequency, intensity, phase, and polarization of applied fields [16-18]. More recently, research endeavors have honed in on the utilization of an external magnetic field to exert control over EIT [19, 20] and pulse propagation and all-optical switching [21, 25].

Despite many proposals in multi-level atom systems for subluminal and superluminal light propagation, in which all interacting fields must be controlled synchronously, there is a need for a simpler excitation scheme, e.g., two-level, for comfortable realization. Furthermore, the studies often neglect the degeneration of Zeeman levels, although it should be considered when the atoms are immersed in external magnetic fields or polarized optical fields. Growing on this interest, in this work, we propose a simple scheme based on a degenerate two-level medium under the external magnetic field that can change the magnitude/sign of the group index. This outcome can be archived by changing the strength/direction of the magnetical field, which corresponds with switching the propagation of light from subluminal to superluminal.

2. MODEL AND BASIC EQUATIONS

We consider a lambda configuration degenerate two-level atomic system under the interaction of an external magnetic field as shown in Fig.1. A weak probe laser field E_p with the left-circularly polarized component σ^- (carrier frequency ω_p with Rabi frequency $2\Omega_p$) drives the transition $|2\rangle$ to $|1\rangle$. At the same time, a strong coupling laser field E_c with the right-circularly polarized component σ^+ (carrier frequency ω_c with Rabi frequency $2\Omega_c$) is introduced to couple the transition $|2\rangle$ to $|3\rangle$. In this configuration, the probe field is traveling in the direction parallel to both the polarization of the control light E_c and the direction of the applied longitudinal magnetic field B, which is used to remove the degeneracy among the ground-state sublevels $|1\rangle$ and $|3\rangle$ ($m_F = \pm 1$). The Zeeman shift of the levels $|1\rangle$ and $|3\rangle$ is given by $\hbar\Delta_B = \mu_B m_s g_s B$, where μ_B is the Bohr magneton, g_s is the Lande factor and $m_s = \pm 1$ is the magnetic quantum number of the corresponding state. All the atoms are assumed to be optically pumped to the states $|1\rangle$ and $|3\rangle$, which therefore have the same incoherent populations equal to 1/2, i.e., $\rho_{11} = \rho_{33} = 1/2$ [22]. The decay rates from the state $|2\rangle$ to the states $|1\rangle$ and $|3\rangle$ are given by γ_{21} and γ_{23}, respectively. Using the rotating-wave and the electric dipole approximations, the interaction Hamiltonian of a system in the interaction picture can be written as (with the assumption of $\hbar$ =1):

$$H_{\text{int}} = \left(\Delta_p + \Delta_B\right)|2\rangle\langle 2| + \left(\Delta_p - \Delta_c + 2\Delta_B\right)|3\rangle\langle 3| - \left(\Omega_p |2\rangle\langle 1| + \Omega_c |3\rangle\langle 2| + H.c\right) \tag{1}$$

where $\Delta_p = \omega_{21} - \omega_p$, and $\Delta_c = \omega_{23} - \omega_c$ are detunings of the probe field and two coupling fields from the atomic transition frequencies, respectively. Δ_B is the Zeeman shift of the levels $|1\rangle$ and $|3\rangle$ in the presence of the magnetic field and Δ_B is taken to zero for zero magnetic field.

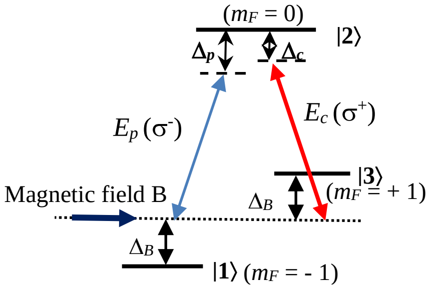

***Figure 1.** Schematic model of a lambda degenerate two-level atom system interacting with a static magnetic field, and two coupling and probe laser fields.*

The dynamical evolution of the system can be described by the Liouville equation:

$$\frac{\partial\rho}{\partial t} = -i\left[H_{\text{int}}, \rho\right] + \Lambda\rho \tag{2}$$

and the relevant density matrix equations obtained for this system are given as follows:

$$\frac{\partial \rho_{11}}{\partial t} = 2\gamma_{21}\rho_{22} + 2\gamma_{31}\rho_{33} + i\Omega_p^*\rho_{21} - i\Omega_p\rho_{12} \tag{3a}$$

$$\frac{\partial \rho_{22}}{\partial t} = -\left(2\gamma_{21} + 2\gamma_{23}\right)\rho_{22} + i\Omega_p\rho_{12} - i\Omega_p^*\rho_{21} + i\Omega_c\rho_{32} - i\Omega_c^*\rho_{23} \tag{3b}$$

$$\frac{\partial \rho_{33}}{\partial t} = \gamma_{23}\rho_{22} - \gamma_{31}\rho_{33} + i\Omega_c^*\rho_{23} - i\Omega_c\rho_{32} \tag{3c}$$

$$\frac{\partial \rho_{21}}{\partial t} = -\left(\gamma_{21} + \gamma_{23} + i\left(\Delta_p + \Delta_B\right)\right)\rho_{21} - i\Omega_p(\rho_{22} - \rho_{11}) + i\Omega_c\rho_{31} \tag{3d}$$

$$\frac{\partial \rho_{31}}{\partial t} = -\left(\gamma_{31} + i\left(\Delta_p - \Delta_c + 2\Delta_B\right)\right)\rho_{31} - i\Omega_p\rho_{32} + i\Omega_c^*\rho_{21} \tag{3e}$$

$$\frac{\partial \rho_{23}}{\partial t} = -\left(\gamma_{21} + \gamma_{23} + i\left(\Delta_c - \Delta_B\right)\right)\rho_{23} - i\Omega_c\left(\rho_{22} - \rho_{33}\right) + i\Omega_p\rho_{13} \tag{3f}$$

where, $\rho_{ij} = \rho_{ji}^*$ (i, j = 1, 2, 3; $i \neq j$), $\rho_{11} + \rho_{22} + \rho_{33} = 1; \gamma = \left(\gamma_{21} + \gamma_{23}\right)/2$, and γ_{ij} is the decay rate between levels $|i\rangle$ and $|j\rangle$, respectively.

The relationship of the refraction index of medium n_g and the susceptibility χ_{21} is expressed as [16].

$$n_g = 1 + \frac{1}{2}\mathrm{Re}\left[\chi_{21}\right] + \frac{1}{2}\omega_p\frac{\partial \mathrm{Re}\left[\chi_{21}\right]}{\partial \omega_p} \tag{4}$$

where $\chi_{21} = 2N\left|d_{21}\right|^2 \rho_{21} / \hbar\varepsilon_0\Omega_p$. According to the definition of the group velocity $v_g = c/n_g$ with c being the light speed in a vacuum, we can find that the group velocity is related to the coherence term ρ_{21} from Eq. (4).

To obtain linear susceptibility, we need to give the steady-state solution of the density matrix Eqs. (3). To attain this aim, the perturbation approach is used to the density matrix elements, which are expressed as: $\rho_{mn} = \rho_{mn}^{(0)} + \rho_{mn}^{(1)} + \rho_{mn}^{(2)} + \rho_{mn}^{(3)} +,...\rho_{mn}^{(n)}$. We assume that the coupling field is much stronger than the probe field and the zeroth-order solution of the population $\rho_{11}^{(0)} = \rho_{33}^{(0)} = 1/2$, while the other elements are equal to zero. In the weak-probe field approximation, we obtain the first-order solution of the matrix element ρ_{21} from Eq. (3d) and Eq. (3e):

$$\rho_{21}^{(1)} = \frac{i\Omega_p\left(\rho_{11}^{(0)} - \rho_{22}^{(0)}\right)}{\gamma \ + i\left(\Delta_p + \Delta_B\right) + \dfrac{\Omega_c^2}{\gamma_{31} + i\left(\Delta_p - \Delta_c + 2\Delta_B\right)}} \simeq \frac{i\Omega_p}{2F} \tag{5}$$

where:

$$F = \gamma \ + i\left(\Delta_p + \Delta_B\right) + \frac{\Omega_c^2}{\gamma_{31} + i\left(\Delta_p - \Delta_c + 2\Delta_B\right)} \tag{6}$$

Therefore, the first-order susceptibility is determined as follows:

$$\chi^{(1)} = -\frac{N\left|\mu_{21}\right|^2}{\varepsilon_0\hbar\Omega_p}\rho_{21}^{(1)} = -\frac{iN\left|\mu_{21}\right|^2}{\varepsilon_0\hbar}\frac{1}{2F} = -\frac{iN\left|\mu_{21}\right|^2}{2\varepsilon_0\hbar}\left(\frac{N}{M^2 + N^2} - i\frac{M}{M^2 + N^2}\right) \tag{7}$$

where the μ_{21} is the dipole moment for the $|2\rangle \leftrightarrow |1\rangle$ transition, the expressions M and N are determined by:

$$M = \left(\Delta_p + \Delta_B\right) - \frac{\Omega_c^2\left(\Delta_p - \Delta_c + 2\Delta_B\right)}{\gamma_{31}^2 + \left(\Delta_p - \Delta_c + 2\Delta_B\right)^2} \tag{8}$$

$$N = \gamma + \frac{\Omega_c^2\gamma_{31}}{\gamma_{31}^2 + \left(\Delta_p - \Delta_c + 2\Delta_B\right)^2} \tag{9}$$

As is well known, the imaginary part and the real part of susceptibility determine the absorption and dispersion of the system, respectively. Therefore, from Eq. 4, the group index can be defined:

$$\begin{aligned} n_g &= \frac{c}{v_g} = 1 + \frac{1}{2}\mathrm{Re}\left[\chi^{(1)}\right] + \frac{1}{2}\omega_p \frac{\partial \mathrm{Re}\left[\chi^{(1)}\right]}{\partial \omega_p} \\ &= -\omega_p \frac{iN\left|\mu_{21}\right|^2}{2\varepsilon_0\hbar}\left(\frac{M'\left(M^2+N^2\right) - 2M\left(MM'+NN'\right)}{\left(M^2+N^2\right)^2}\right) \end{aligned} \tag{10}$$

where M′ and N′ are respectively the derivatives of M and N over ω_p, that given by:

$$M' = 1 - \frac{\Omega_c^2\left(\Delta_p - \Delta_c + 2\Delta_B\right)}{\gamma_{31}^2 + \left(\Delta_p - \Delta_c + 2\Delta_B\right)^2} + \frac{\Omega_c^2\left(\Delta_p - \Delta_c + 2\Delta_B\right)\left(2\Delta_p - 2\Delta_c + 4\Delta_B\right)}{\left(\gamma_{31}^2 + \left(\Delta_p - \Delta_c + 2\Delta_B\right)^2\right)^2} \tag{11}$$

$$N' = -\frac{\Omega_c^2\gamma_{31}\left(2\Delta_p - 2\Delta_c + 4\Delta_B\right)}{\left(\gamma_{31}^2 + \left(\Delta_p - \Delta_c + 2\Delta_B\right)^2\right)^2} \tag{12}$$

3. RESULTS AND DISCUSSION

To illustrate applications of the model, we apply a cold atomic medium of ^{87}Rb on the 5S-5P transitions as a realistic candidate. The designated states and the decay rates can be chosen as follows: $|1\rangle = |5S_{1/2}, F = 1, m_F = 0\rangle$, $|2\rangle = |5P_{1/2}, F = 1, m_F = -1\rangle$, $|3\rangle = |5P_{1/2}, F = 1, m_F = 1\rangle$, and $\gamma_{21} = \gamma_{31} = 2\pi$ x 5.3 MHz, and wavelength of the probe, coupling, $\lambda_p = \lambda_c = 795$ nm. Landé factor $g_F = -1/2$ and the Bohr magneton $\mu_B = 9.27401 \times 10^{-24}$ JT^{-1}, [22, 26], respectively. Note that the system parameters used in this paper are scaled by γ_{21}. Thus, when the Zeeman shift Δ_B is scaled by γ_{21}, then the magnetic field strength B should be in units of the combined constant $\gamma_c = \hbar\mu_B^{-1}g_F^{-1}\gamma_{21}$.

First, we analyze the absorption and dispersion properties of the medium for the probe beam in the absence of B = 0 (solid line) and the presence of B = ±2γ_c (dashed line) of the external magnetic field, as illustrated in Fig. 2. The coupling parameters are specified as $\Omega_c = 3\gamma_{21}$, $\Omega_p = 0.01\gamma_{21}$, and $\Delta_c = 0$. As shown in Fig. 2, the absorption-dispersion behavior of the probe field depends so sensitively on the turn-on and off of the magnetic field. Specifically, in the case the magnetic field is turned off, i.e., B = 0, the probe absorption can be completely suppressed, and the opaque medium becomes transparent to the probe field at the center line [see solid line in Fig. 2 (a-b)]. At the same time, the dispersion profile with the positive slope in the transparent regime appears [see solid line in Fig. 2 (c-d)], which corresponds to subluminal light propagation. Contrarily, when the magnetic field B is presented (i.e., B ≠ 0), the level splitting between $|1\rangle$ and $|3\rangle$ is enhanced, the quantum interference between the two quantum paths $|1\rangle \rightarrow |2\rangle$ and $|3\rangle \rightarrow |2\rangle$ is reduced, which increases the absorption of probe field. When the external magnetic field B increases to a certain value B = ±2γ_c (i.e., $\Delta_B = \pm 2\gamma_{21}$), the absorption of the probe field reaches a maximal value at the resonant frequency [see dashed line in Fig. 2 (a-b)], i.e., the medium switched from electromagnetically induced transparency (EIT) at the resonant frequency is converted to electromagnetically induced absorption (EIA). Simultaneously, strong absorption peaks at the positions of $\Delta_p = -3\gamma_{21}$ or $\Delta_p = 3\gamma_{21}$ are transformed into the transparency windows. As a consequence, the normal dispersion properties found in transparency regions change into anomalous dispersion in regions [see dashed line in Fig. 2 (c-d)], with strong absorption, which leads to superluminal light propagation. These results show that the slope of the dispersion profile changes from positive to negative by turning the magnetic field on or off. This leads to the switching of the group velocity of the probe field from the sub- to the superluminal domain.

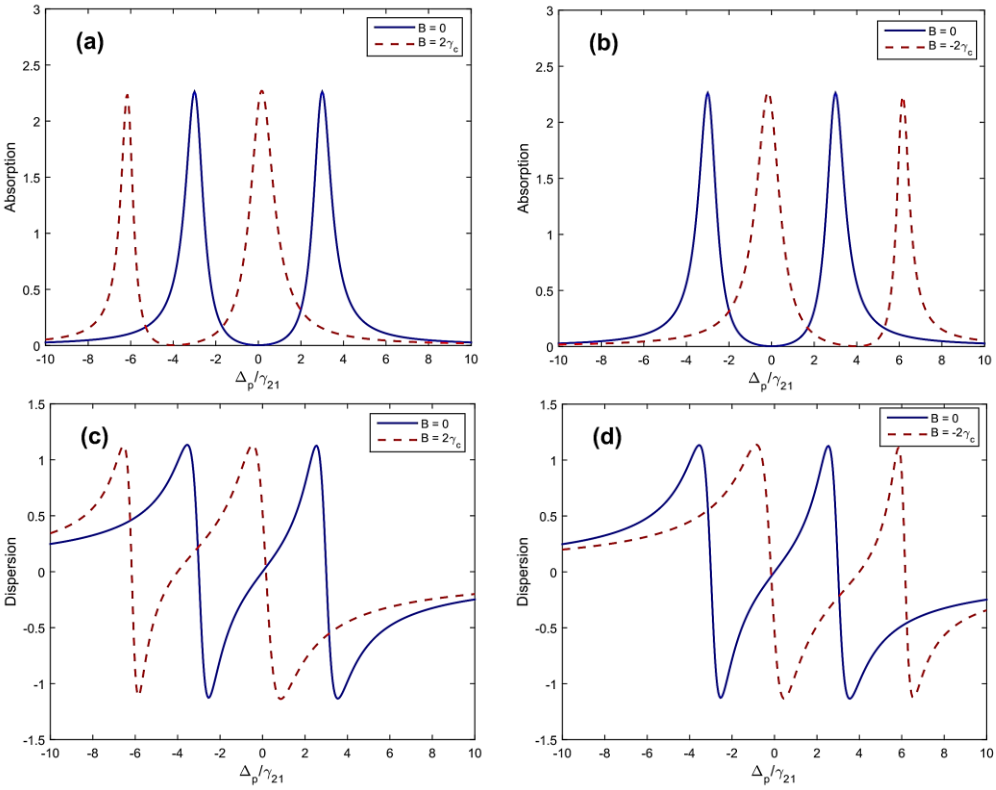

Figure 2. *Graph of the absorption - dispersion behavior versus the probe detuning Δ_p for the absence ($B = 0$) and presence ($B = \pm 2\gamma_c$) of the magnetic field. Other system parameters are chosen as $\Omega_c = 5\gamma_{21}$, $\Omega_p = 0.01\gamma_{21}$, $\Delta_c = 0$, and $\gamma_{21} = \gamma_{23}$, respectively.*

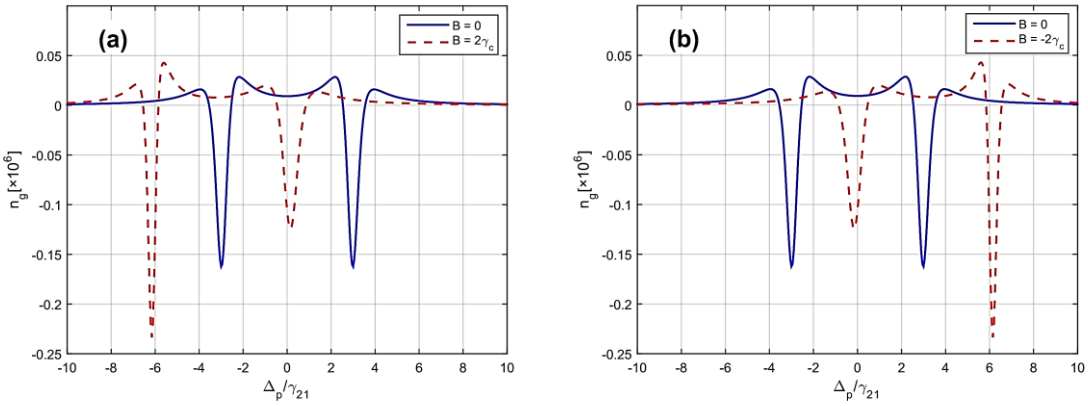

Figure 3. *Graph of the group index versus the probe frequency detuning Δ_p when the absence $B = 0$ (solid line), and present $B = \pm 2\gamma_c$ (dashed line) of the magnetic field. Other parameters are chosen in the same as in figure 2.*

Next, we demonstrate that the magnetic field can be used as a knob for changing the group velocity of the probe light propagation. We illustrate a variation of group index n_g versus probe frequency detuning in two cases: as the magnetic field is absent B = 0 [see solid line in Fig. 3], and as the magnetic field is present $B = \pm 2\gamma_c$ [see dashed line in Fig. 3]. Specifically, the subluminal light behavior observed in the resonant region ($\Delta_p = 0$) when B = 0 transforms into superluminal light behavior when $B = 2\gamma_c$ or $B = -2\gamma_c$. Otherwise, the superluminal regime at positions $\Delta_p = \pm 3\gamma_{21}$ when B = 0 is converted into the subluminal light regime when $B = 2\gamma_c$ or $B = -2\gamma_c$.

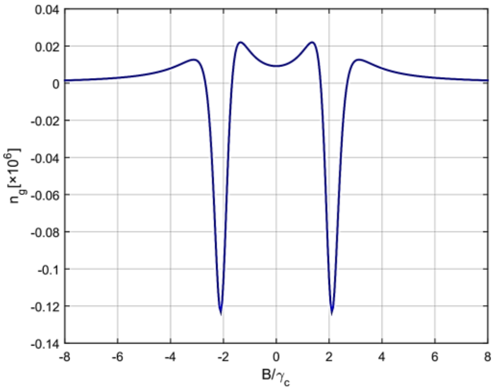

Figure 4. *Graph of the group index versus the external magnetic field strength B. Other system parameters are chosen as* $\Omega_p = 0.01\gamma_{21}$, $\Omega_c = 3\gamma_{21}$, $\Delta_p = \Delta_c = 0$, *and* $\gamma_{21} = \gamma_{23}$, *respectively.*

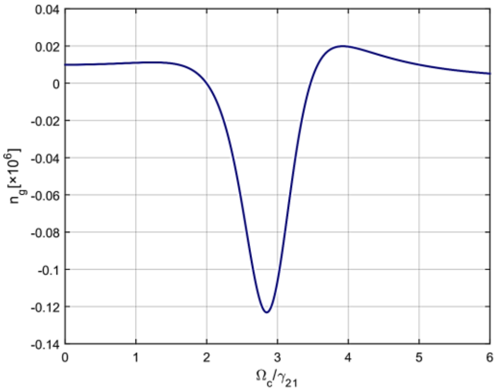

Figure 5. *Graph of the group index versus the controlling field strength* Ω_c. *Other system parameters are chosen as* $\Omega_p = 0.01\gamma_{21}$, $B = 2\gamma_c$, $\Delta_p = \Delta_c = 0$, *and* $\gamma_{21} = \gamma_{23}$, *respectively.*

In Fig. 4, we illustrate the variation of group index versus the external magnetic field when $\Delta_p = \Delta_c = 0$ and $\Omega_c = 3\gamma_{21}$. The variation in Fig. 4 shows that both the magnitude and the sign of the group index are changed concerning the magnetic field. Notably, in the vicinity of the external magnetic field B = 0, the group index is positive, whereas $B = \pm 2\gamma_c$, the group index is negative. Therefore, for the given values of parameters Δ_c, Δ_p, and Ω_c we can choose an optimized magnetic field to attain the maximum value of the group index.

Finally, we consider the dependence of sub- and superluminal behavior on the strengths of the control field under the presence of the magnetic field. Fig. 5 shows that appear a valley of negative n_g in the group index profile of the enhanced absorption region is obtained. In the region with the strength of control field intensity from $2\gamma_{21}$ to $3.5\gamma_{21}$, superluminal will be produced, the rest will be subluminal. Therefore, by using a lambda configuration degenerate two-level atomic system via the external magnetic field, we can control the group index and so convert from sub- to superluminal propagation and vice versa.

4. CONCLUSIONS

We have studied the dispersion and absorption properties of a lambda configuration degenerate two-level atomic medium via an external magnetic field. It is shown that the medium can be switched from EIT to EIA, corresponding with the shift from normal dispersion without absorption to fully absorption anomalous dispersion regime by modulating the direction and magnitude of the magnetic field. The magnetic field has been used as a "knob" to tune from subluminal to superluminal light propagation in the degenerate two-level atomic medium. The proposed scheme may be helpful for the storage and information processing devices in quantum communication.

Acknowledgment: *This research was funded by Vingroup Innovation Foundation (VINIF) under project code VINIF.2022.DA00076.*

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TÓM TẮT

Vận tốc nhóm ánh sáng có thể điều khiển được trong môi trường hai mức suy biến dưới sự hỗ trợ của từ trường bên ngoài

Trong nghiên cứu này, chúng tôi đã đề xuất một mô hình đơn giản để điều khiển sự truyền ánh sáng siêu chậm và siêu nhanh thông qua từ trường bên ngoài trong môi trường nguyên tử hai mức suy biến có cấu hình dạng lambda. Kết quả cho thấy rằng các đặc tính hấp thụ-tán sắc và chiết suất nhóm dưới ảnh hưởng của cường độ laser điều khiển và từ trường bên ngoài là được điều khiển. Bằng cách thay đổi hướng và cường độ của từ trường, môi trường có thể chuyển từ trong suốt với tán sắc thường sang hấp thụ mạnh với tán sắc dị thường tại tần số cộng hưởng nguyên tử, tương ứng với sự chuyển từ ánh sáng chậm sang ánh sáng nhanh. Nghiên cứu này có thể cung cấp cho việc hiện thực hóa ứng dụng các thiết bị lưu trữ và chuyển mạch quang từ trong xử lý thông tin lượng tử.

Từ khoá: Trong suốt cảm ứng điện từ; Hấp thụ cảm ứng điện từ; Nguyên tử hai mức suy biến; Chiết suất nhóm; Vận tốc nhóm; Lan truyền ánh sáng siêu chậm và siêu nhanh.