CONTROL OF ABSORPTION AND DISPERSION PROPERTIES IN A VEE-TYPE DEGENERATED ATOMIC SYSTEM UNDER AN EXTERNAL MAGNETIC FIELD

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Received: 02/10/2019; Accepted for publication: 12/12/2019

ABSTRACT

In this work, we proposed a simple model for control of optical properties via an external magnetic field in a vee-type degenerated atomic medium. By numerically solving the density matrix equations in the steady-state, we show that the absorption and dispersion properties are influenced by the strength of coupling laser and external magnetic fields. Furthermore, it is found that in the presence of an external magnetic field, a medium can be switched from transparent to absorption, which corresponds with subluminal and superluminal lights. The suggestions scheme may be useful in the applications of magneto-optic switches and magneto-optic storage devices in processing telecommunication signals.

Keywords: Electromagnetically induced transparency, absorption, dispersion, subluminal and superluminal light, magnetic-optical switching.

1. INTRODUCTION

Over the last few years, there has stimulated tremendous interests in the study of quantum coherence and interference phenomena. One of the most significant phenomena is electromagnetically induced transparency (EIT) phenomenon [1, 2], which originates from to quantum interference between two different excitation pathways and an opaque optical medium can be rendered transparent to a probe field by applying an intense coupling laser field at a different frequency. EIT effect not only reduces the absorption but also enhances linear and nonlinear dispersions in the vicinity of atomic resonant frequency. Furthermore, along with absorption vanishment which on dispersion profile appears a normal dispersive curve with its height and slope can be controlled which leads to a significant reduction of the group velocity of light [3-5]. Based on the EIT effect, many interesting quantum optical phenomena have been studied in atomic systems, for example, control and slow down the group velocity of light and even to completely stop the light pulses propagating in a medium [4], enhances in Kerr nonlinearity [6-8], optical bistability (OB) and all-optical switching (AOS) [9-12], the formation and optical solitons propagation [13-18], and so on.

Beside absorptive and dispersive properties of EIT medium are controlled by the intensity and frequency of the laser fields, recent studies show that the optical properties of EIT medium are also controlled by external magnetic field and polarization of laser fields [19-21]. More recently, optical switching and bistability schemes have been also implemented in a degenerated two-level atomic medium under an external magnetic field effect [22]. Under the presence of an external magnetic field, the transparent window can be shifted or the system can switch from subluminal to superluminal light propagation which leads to the modification of transparency window and allows the possibility of electromagnetically induced absorption

(EIA), a phenomenon in which a transparent medium shows enhanced absorption at line center. EIA has been studied both theoretically as well as experimentally in multi-level systems [23-27]. However, most previous works on EIT and EIA have been studied in multi-level media, which has been considered to lack of the influence of the external magnetic field on the absorptive and dispersive properties in a vee-type degenerated atomic medium.

The organization of the paper is as follows. In Section 2, describe our theoretical model and present the density matrix equations of a vee-type degenerated model. In Section 3, we discuss the absorption-dispersion characteristics of the medium on the probe field under the applied magnetic field. Finally, a conclusion of the present work is given in the last section.

2. MODEL AND BASIC EQUATIONS

We consider a vee-type degenerated atomic system under interacting of an external magnetic field as shown in Figure 1. A weak probe laser field E_p with the right-circularly polarized component σ^+ (carrier frequency ω_p with Rabi frequency $2\Omega_p$) drives the transition $|1\rangle$ to $|3\rangle$. At the same time, a strong coupling laser field E_c with the left-circularly polarized component σ^- (carrier frequency ω_c with Rabi frequency $2\Omega_c$) is introduced to couple the transition $|1\rangle$ to $|2\rangle$. The medium is subject to an applied longitudinal magnetic field B that removes the degeneracy of the states $|2\rangle$ and $|3\rangle$, whose Zeeman shift is determined by $\Delta_B = \mu_B m_F g_F B/\hbar$, where μ_B is the Bohr magneton, g_F is the Lande factor, and $m_F = \pm 1$ is the magnetic quantum number of the corresponding state. The decay rates from the states $|3\rangle$ and $|2\rangle$ to $|1\rangle$ are given by γ_{31} and γ_{21}, respectively. Using the rotating-wave and the electric dipole approximations, the interaction Hamiltonian of system in the interaction picture can be written as (with the assumption of $\hbar$ =1):

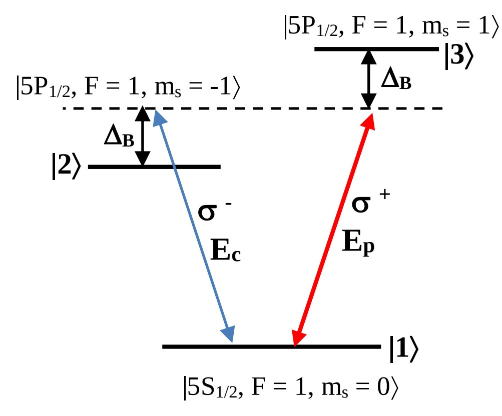

Figure 1. Schematic diagram of vee-type degenerate atoms in the media interacting with a weak probe field with Rabi frequency $2\Omega_p$, and a strong control field with Rabi frequency $2\Omega_c$.

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

where $\Delta_p = \omega_{31} - \omega_p$, and $\Delta_c = \omega_{21} - \omega_c$ are detunings of the probe field and coupling field from the atomic transition frequencies, respectively. Δ_B is the Zeeman shift of the levels $|2\rangle$ and $|3\rangle$ in the presence of the magnetic field (see Fig. 1) and Δ_B is taken to zero for zero magnetic field. The dynamical evolution of the system can be described by the Liouville equation [2]:

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

and the relevant density matrix equations obtained for the three-level vee-type degenerate system are given as follow:

$$\frac{\partial \rho_{11}}{\partial t} = \gamma_{21}\rho_{22} + \gamma_{31}\rho_{33} + i\Omega_c^*\rho_{21} - i\Omega_c\rho_{12} + i\Omega_p^*\rho_{31} - i\Omega_p\rho_{13} \,, \tag{3a}$$

$$\frac{\partial \rho_{22}}{\partial t} = -\gamma_{21}\rho_{22} + i\Omega_c\rho_{12} - i\Omega_c^*\rho_{21} \,, \tag{3b}$$

$$\frac{\partial \rho_{33}}{\partial t} = -\gamma_{31}\rho_{33} + i\Omega_p\rho_{13} - i\Omega_p^*\rho_{31} \,, \tag{3c}$$

$$\frac{\partial \rho_{21}}{\partial t} = -\left(i\left(\Delta_c + \Delta_B\right) + \frac{\gamma_{21}}{2}\right)\rho_{21} + i\Omega_c\left(\rho_{11} - \rho_{22}\right) - i\Omega_p^*\rho_{23} \,, \tag{3d}$$

$$\frac{\partial \rho_{31}}{\partial t} = -(i\left(\Delta_B - \Delta_p\right) + \frac{\gamma_{31}}{2})\rho_{31} + i\Omega_p(\rho_{11} - \rho_{33}) - i\Omega_c\rho_{32} \,, \tag{3e}$$

$$\frac{\partial \rho_{32}}{\partial t} = -i\left(\Delta_c - \Delta_p + 2\Delta_B\right)\rho_{32} + i\Omega_p^*\rho_{12} - i\Omega_c\rho_{31} \,, \tag{3f}$$

where, the matrix elements obey conjugated and normalized conditions, namely $\rho_{ij} = \rho_{ij}^*$ ($i \neq j$), and $\rho_{11} + \rho_{22} + \rho_{33} = 1$, respectively.

In order to illustrate applications of the model, we apply to 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, as well as the coupling, $\lambda_p = \lambda_c = 795$ nm, [28]. Landé factor $g_F = -1/2$ and the Bohr magneton $\mu_B = 9.27401 \times 10^{-24}$ JT^{-1}, [28], respectively. Note that the system parameters used in this paper are scaled by γ_{31}, thus when the Zeeman shift Δ_B is scaled by γ_{31}, then the magnetic field strength B should be in units of the combined constant $\gamma_c = \hbar\mu_B^{-1}g_F^{-1}\gamma_{31}$.

3. NUMERICAL RESULTS AND DISCUSSIONS

First of all, we will discuss the effect of the coupling field on absorption-dispersion coefficients of the probe field by numerically solving the above density matrix equations (3a)-(3f) in the steady state, that initial the atoms are assumed in the ground-state $|1\rangle$, i.e. $\rho_{11} = 1$. In Figure 2, we display the properties of absorption and dispersion of the probe field versus the probe detuning Δ_p/γ_{31} for different values of the coupling field Ω_c, when the magnetic field B is turn off (i.e., B = 0), the levels $|2\rangle$ and $|3\rangle$ are the same. Figure 2(a) shows that for $\Omega_c = 0.5\gamma_{31}$, the probe absorption presents a sharp peak around $\Delta_p = 0$, the EIT window is yet to appear. As the value of the coupling field increases (i.e., $\Omega_c = 0.5\gamma_{31}$), the probe absorption exhibits two absorption peaks and a dip around $\Delta_p = 0$, the transparency window arises, this is due to the quantum interference between the two quantum paths $|1\rangle \rightarrow |3\rangle$ and $|1\rangle \rightarrow |2\rangle$ enhanced. It is clear that the depth and width of the EIT window increase when the strength of the coupling field Ω_c increasing and as the coupling field up to $\Omega_c = 3\gamma_{31}$ as shown in Figure 2(d), we obtain a transparency window with vanishing probe absorption at the line center and the positive steep dispersion curve, which corresponds to the subluminal propagation of the probe field.

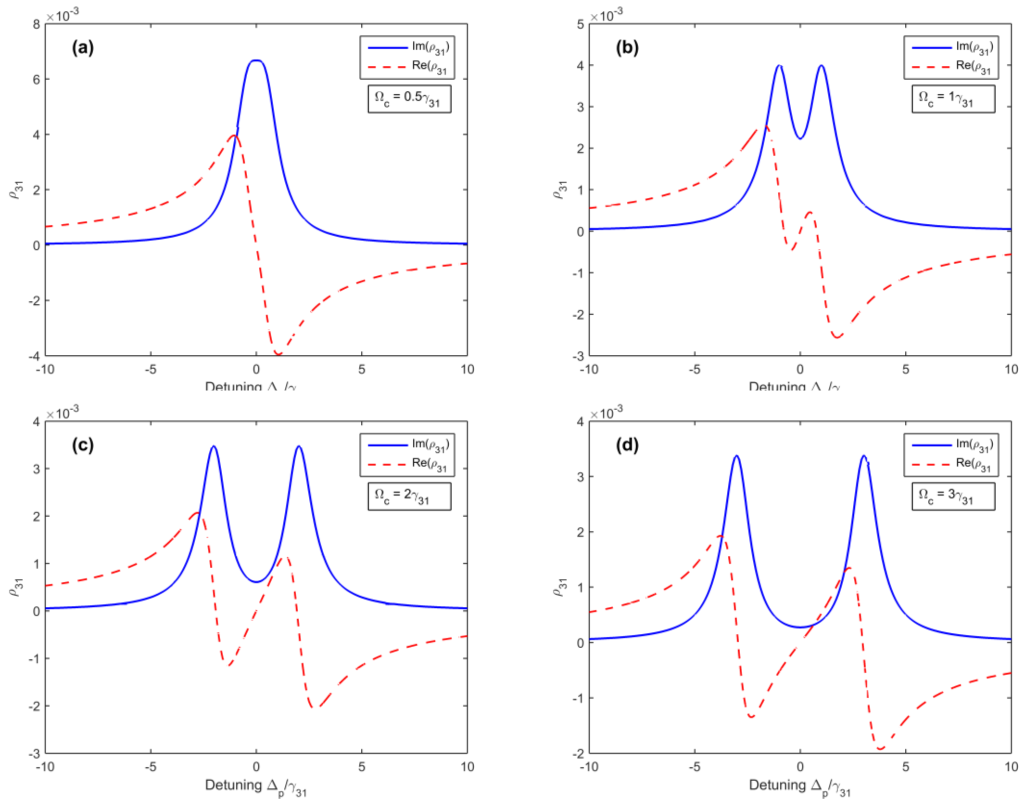

Figure 2. Plot of the absorption- dispersion curves versus the probe detuning Δp at different values of the coupling field Ω_c: $\Omega_c = 0.5\gamma_{31}$ for (a), $\Omega_c = 1\gamma_{31}$ for (b), $\Omega_c = 2\gamma_{31}$ for (c), $\Omega_c = 3\gamma_{31}$ for (d). Other system parameters are chosen as $\Omega_p = 0.01\gamma_{31}$, $\Delta_B = \Delta_c = 0$, and $\gamma_{21} = \gamma_{31}$, respectively.

In this section, we consider the influence of the magnetic field on the absorption-dispersion behaviors of the probe field in the presence of coupling field $\Omega_c = 3\gamma_{31}$. As shown in Figure 3, when the magnetic field B is turn on (i.e., $B \neq 0$), the level splitting between $|2\rangle$ and $|3\rangle$ is enhanced, the quantum interference between the two quantum paths $|1\rangle \rightarrow |3\rangle$ and $|1\rangle \rightarrow |2\rangle$ is reduced, which increases the absorption of probe field. When the external magnetic field B increases to a certain value $B = 2\gamma_c$, the absorption of the probe field reaches a maximal value as shown in Figure 2(d), i.e. the medium switched from the electromagnetically induced transparency (EIT) to the electromagnetically induced absorption (EIA), which corresponds to the superluminal propagation of the probe field. When B further increases, the magnitude of the probe absorption decreases dramatically and finally trends to a small steady-state value. Such, the absorption of the probe field can be controlled by properly adjusting the magnetic field.

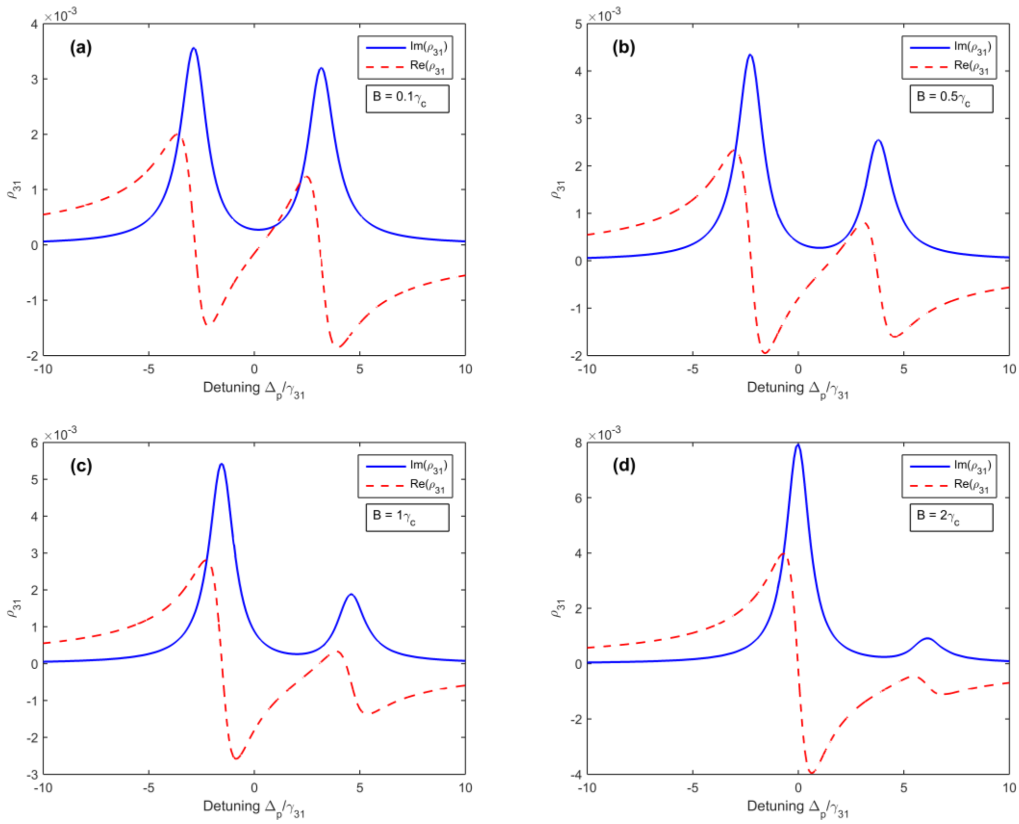

Figure. 3. Plot of the absorption- dispersion curves versus the probe detuning Δp at different values of the magnetic field B: B = $0.1\gamma_c$ for (a), B = $0.5\gamma_c$ for (b), B = $1\gamma_c$ for (c), B = $2\gamma_c$ for (d). Other system parameters are chosen as $\Omega_p = 0.01\gamma_{31}$, $\Omega_c = 3\gamma_{31}$, $\Delta_c = 0$, and $\gamma_{21} = \gamma_{31}$, respectively.

In order to further illustrate explicitly the dependence of the absorption spectra of the weak optical field on the magnetic field strength B, the probe absorption coefficient Im(ρ_{31}) as a function of B (in units of γ_c) are plotted in Figure 4. From this figure, we find that the magnitude of the probe absorption first increases rapidly from nearly zero to a maximal value, then decreases dramatically and finally trends to a nearly zero small steady-state value with increasing magnetic field strength B.

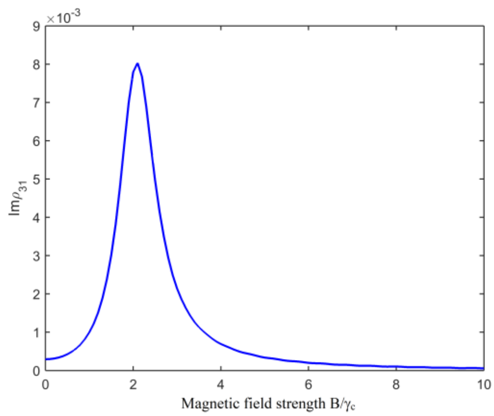

Figure 4. The probe absorption Im(ρ_{31}) responses versus the magnetic field strength B. Other system parameters are chosen as $\Omega_p = 0.01\gamma_{31}$, $\Omega_c = 3\gamma_{31}$, $\Delta_p = \Delta_c = 0$, and $\gamma_{21} = \gamma_{31}$, respectively.

4. CONCLUSIONS

We have studied the control of optical properties via an external magnetic field in a vee-type degenerated atomic medium based on the EIT. We showed that in the absence of a magnetic field, the system exhibits transparent for the probe field, therefore the subluminal light propagation can be formed in a medium. When the magnetic field is turned on, the medium can be switched from EIT to EIA, which performs as the magneto-optic switches. Hence, the result indicates potential applications in magneto-optical switching and optical storage devices in processing telecommunication signals.

REFERENCES

1. Boller K. J, Imamoglu A, Harris S. E - Observation of electromagnetically induced transparency, Physics Review Letters **66 (20)** (1991) 2593-2596.
2. Fleischhauer M., Imamoglu A., Marangos J.P. - Electromagnetically induced transparency: optics in coherent media, Reviews of Modern Physics **77 (2)** (2005) 633-673.
3. Hau L.V, Harris S. E, Dutton Z, Bejroozi C.H. - Light speed reduction to 17 metres per second in an ultracold atomic gas, Nature, **397** (1999) 594.
4. Dutton. Z, Slowe. N.G.C, Hau. L.V. - The art of taming light: ultra-slow and stopped light, Europhysics News, **35 (2)** (2004) 33–39.
5. Kash M.M, Sautenkov V.A, A.S. Zibrov, L. Hollberg, G.R. Welch, M.D. Lukin, Y. Rostovtsev, E.S. Fry, M.O. Scully - Ultraslow Group Velocity and Enhanced Nonlinear Optical Effects in a Coherently Driven Hot Atomic Gas, Physics Review Letters **82** (26) (1999) 5229-2532.
6. Khoa D X, Doai L V, Son D H and Bang N H - Enhancement of self-Kerr nonlinearity via electromagnetically induced transparency in a five-level cascade system: an analytical approach, Journal of the Optical Society of America B **31 (6)** (2014) 1330-1334.
7. Doai L V, Khoa D X, Bang N H - EIT enhanced self-Kerr nonlinearity in the three-level lambda system under Doppler broadening, Physica Scripta **90 (4)** (2015) 045502-045506.
8. Hamedi H.R., Gharamaleki A.H., and Sahrai M. - Colossal Kerr nonlinearity based on electromagnetically induced transparency in a five-level double-ladder atomic system, Applied Optics 55 (**22)** (2016) 5892-5899.
9. Schmidt H, Ram R.J. - All-optical wavelength converter and switch based on electromagnetically induced transparency, Applied Physics Letters **76** (22) (2000) 3173-3175.
10. Fountoulakis A., Terzis A.F, Paspalakis E. - All-optical modulation based on electromagnetically induced transparency, Physics Letters A **374**, (2010) 3354-3364.
11. Khoa D X, Doai L V, Mai Anh L. N, Trung L. C, Thuan P. V, Dung N. T, and Bang N. H. - Optical bistability in a five-level cascade EIT medium: An analytical approach, Journal of the Optical Society of America B **33** (44) (2016) 735-739.
12. Dong H. M., and Bang N. H. - Controllable optical switching in a closed-loop three-level lambda system, Physica Scripta **94** (2019) 115510-115515.
13. Huang G, Jiang K, Payne M G and Deng L. - Formation and propagation of coupled ultraslow optical soliton pairs in a cold three-state double-Λ-system, Physics Review E **73** (2006) 0566061-0566068.

14. Si L.G, Lu X.Y., Hao X. and Li J.H. - Dynamical control of soliton formation and propagation in a Y-type atomic system with dual ladder-type electromagnetically induced transparency, Journal of Physics B: Atomic, Molecular and Optical **43** (2010) 065403 8pp.
15. Chen Y, Bai Z, and Huang G. - Ultraslow optical solitons and their storage and retrieval in an ultracold ladder-type atomic system, Physics Review A **89** (2014) 023835-7pp.
16. Dong H M, Doai L V, Sau V N, Khoa D X and Bang N.H. - Propagation of laser pulse in a three-level cascade atomic medium under conditions of electromagnetically induced transparency, Photonics Letter Poland **3** (2016) 73-75.
17. Khoa D X, Dong H M, Doai L V and Bang N.H. - Propagation of laser pulse in a three-level cascade inhomogeneously broadened medium under electromagnetically induced transparency conditions, Optik **131** (2017) 497-452.
18. Dong H. M., Doai L.V., and Bang N.H. - Pulse propagation in an atomic medium under spontaneously generated coherence, incoherent pumping, and relative laser phase, Optics Communications **426** (2018) 553-557.
19. Li J. H, Yu R, Si L. g, and Yang X. - Propagation of twin light pulses under magneto-optical switching operations in a four-level inverted-Y atomic medium, Journal of Physics B: Atomic, Molecular and Optical **43** (2010) 065502 10pp.
20. Yu R, Li J, Ding C, Yang X. - Dual-channel all-optical switching with tunable frequency in a five-level double-ladder atomic system, Optics Communications **284** (2011) 2930-2936.
21. Asadpour S. H., Soleimani H. R. - Polarization dependence of optical bistability in the presence of external magnetic field, Optics Communications **310** (2014) 120-124.
22. Dong H.M., Nga L.T.Y., and Bang N.H. - Optical switching and bistability in a degenerated two-level atomic medium under an external magnetic field, Applied Optics **58** (2019) 4192-4199.
23. Goren C., Wilson-Gordon A.D., Rosenbluh M., Friedmann H. - Atomic four-level N systems, Physics Review A **69** (2004) 053818 9pp.
24. Bason M.G., Mohapatra A.K., Weatherill K.J., Adams C.S. - Narrow absorptive resonances in a four-level atomic system, Journal of Physics B **42 (7)** (2009) 075503.
25. Chanu S.R., Pandey K., Natarajan V. - Conversion between electromagnetically induced transparency and absorption in a three-level lambda system, Europhysics Letters Association **98** (4) (2012) 44009-14.
26. Bharti V., Natarajan V. - Study of a four-level system in vee + ladder configuration, Optics Communications **356** (2015) 510–514.
27. Dong H M, Khoa D X, Doai L V and Bang N H - Dynamic Control of Pulse Propagation and All-Optical Switching in a Four-Level Atomic Medium, Optik (submited 2019).
28. Steck D. A, “Rubidium 87D Line Data,” http://steck.us/alkalidata.

TÓM TẮT

ĐIỀU KHIỂN CÁC ĐẶC TRƯNG TÁN SẮC VÀ HẤP THỤ CỦA MÔI TRƯỜNG NGUYÊN TỬ SUY BIẾN CẤU HÌNH CHỮ V DƯỚI TỪ TRƯỜNG NGOÀI

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Trong bài báo này, nhóm tác giả đề xuất một mô hình đơn giản để điều khiển các đặc trưng quang học của môi trường nguyên tử suy biến cấu hình chữ V dưới tác dụng của từ trường ngoài. Bằng cách giải số bằng các phương trình ma trận mật độ trong trạng thái dừng, kết quả cho thấy tính chất hấp thụ và tán sắc của môi trường là bị ảnh hưởng bởi cường độ của laser điều khiển và từ trường ngoài. Hơn nữa, kết quả nghiên cứu cũng chỉ ra rằng khi có mặt của từ trường ngoài, môi trường có thể được chuyển từ trong suốt sang hấp thụ mà tương ứng với lan truyền ánh sáng siêu chậm và siêu nhanh. Mô hình là hữu ích trong các ứng dụng của thiết bị chuyển mạch và lưu trữ quang-từ trong xử lý tín hiệu truyền thông.

Từ khóa: Trong suốt cảm ứng điện từ, hấp thụ, tán sắc, ánh sáng siêu chậm và siêu nhanh, chuyển mạch quang-từ.