Optics Communications 507 (2022) 127731

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

All-optical switching via spontaneously generated coherence, relative phase and incoherent pumping in a V-type three-level system

Hoang Minh Dong [a], Nguyen Huy Bang [b], Dinh Xuan Khoa [b], Le Van Doai [b,*]

[a] *Ho Chi Minh City University of Food Industry, Ho Chi Minh City, Viet Nam*
[b] *Vinh University, 182 Le Duan Street, Vinh City, Viet Nam*

ARTICLE INFO

Keywords:
All-optical switching
Electromagnetically induced transparency
Spontaneously generated coherence
Incoherent pumping

ABSTRACT

All-optical switching in a V-type three-level atomic medium is studied and controlled by spontaneously generated coherence (SGC), relative phase of applied fields and incoherent pumping rate. By simultaneously numerical solving the coupled Maxwell–Bloch equations for atom and field on a spatio-temporal grid, we have observed a continuous-wave probe field is switched ON or OFF by periodically modulating the coupling field intensity or the relative phase of applied fields. It also is shows that although the SGC can distort the switching probe pulse, however, under the SGC the response of the medium depends sensitively on the relative phase, and the probe field can be switched synchronous or anti-synchronous with the relative phase. On the other hand, in order to overcome the switching pulse distortion caused by SGC, we have included an incoherent pumping field. By choosing the appropriate phase and pumping rate, the fluctuations of switching probe pulse can be easily overcome. The proposed model can be useful for the design of optical switches and optical storage devices as well as possible experimental implementations.

1. Introduction

All-optical switching is an important component in optical networks and optical storage devices [1]. In modern optical-switching devices, tunable switching behaviors and high switching speed have always been the desire of researchers. However, these are often difficult to achieve in traditional nonlinear materials due to saturation effects.

In recent years, one can use quantum interference and coherence to modify the optical properties of the atomic medium through electromagnetically induced transparency (EIT) [2,3] or/and spontaneously generated coherence (SGC) [4,5]. The EIT and its applications have been extensively studied both theoretically and experimentally in various quantum systems [3]. It is showed that the EIT not only suppresses absorption but also enhances the nonlinear response of the atomic medium which can be observed optical nonlinear phenomena even with very low intensity light in the vicinity of atomic resonant frequency. For example, giant Kerr nonlinear coefficient [6–11], optical bistability [12–17], optical solitons [18–22]. In particular, all-optical switching based on EIT effect can achieve at low-threshold intensities with high responsibly speed and can control switching behaviors by external fields. Indeed, Schmidt et al. [23] presented a method for all-optical switching based on absorption modulation in a three-level system. Yavuz et al. [24] suggested a technique for all-optical femtosecond switching utilizing a two-photon absorption scheme of three-level ladder system. Antón et al. [25] obtained all-optical switching based on two-photon resonances in this five-level N-tripod-type atom. Yu et al. [26] studied the control of temporal propagation dynamics and optical switching a four-level atomic medium by the external RF-driving field. Paspalakis et al. [27] investigated the dependence of all-optical modulation on the atomic parameters and the applied laser fields in three-level Λ-type quantum systems. Qi et al. showed the switching operation via adjusting the relative phase or the intensity of the control fields in a four-level tripod system [28] and a four-level diamond configuration [29]. Li et al. [30] realized magneto-optic switching in a four-level inverted-Y atomic medium. Most recently, Dong et al. [31–33] represented optical switching based on the modulation of external light and magnetic fields.

Besides EIT, the SGC also significantly affects the optical properties of materials which have also been studied extensively, such as amplification without population inversion [34], absorption and dispersion [35–37], slow and fast light [38–40], Kerr nonlinearity [41–44], optical bistability [45–49], and pulse propagation [50]. In particular, in the presence of SGC, the optical properties of materials depend

* Corresponding author.
E-mail address: doailv@vinhuni.edu.vn (L.V. Doai).

https://doi.org/10.1016/j.optcom.2021.127731
Received 31 August 2021; Received in revised form 7 November 2021; Accepted 29 November 2021
Available online 2 December 2021

sensitively on the relative phase of the applied fields [49–52]. For example, Fan et al. [52] showed that in the presence of SGC, the steady-state property of a three-level cascade system can be changed from absorption to amplification and vice versa by adjusting the relative phase or/and the incoherent pumping rate. Dong et al. [50] investigated the influences of SGC, relative phase and incoherent pump field on the propagation dynamics in a three-level cascade atomic system and showed that the pulse modulations are increased with the growth of SGC but they can be depressed by choosing suitable relative phase and incoherent rate.

Although influences of SGC, relative phase of applied fields and incoherent pumping on optical bistability in steady-state regime are extensively studied up to date [45–49], however, there are no such studies for all-optical switching in pulsed regime, to our knowledge. In the direction of this interest, we study the realization of all-optical switching in a V-type three-level atomic system with incoherent pumping under spontaneously generated coherence and relative phase of applied fields. By simultaneously numerical solving the coupled Maxwell–Bloch equations for atom and field on a spatio-temporal grid, we demonstrate that the continuous-wave probe field can be switched to a nearly square pulse train with the same modulation period of the relative phase and the coupling field intensity. Moreover, the influences of SGC, relative phase and incoherent pumping rate on optical switching behaviors are also considered.

2. Model and basic equations

We consider a three-level V-type atomic system under coherent interaction of two laser fields as shown in Fig. 1(a). The transition $|1\rangle \leftrightarrow |3\rangle$ is excited by the probe laser field E_p with carrier frequency ω_p and one-half Rabi frequency $\Omega_p = \mu_{31}E_p/2\hbar$. The transition $|1\rangle \leftrightarrow |2\rangle$ is driven by the coupling laser field E_c with carrier frequency ω_c and one-half Rabi frequency $\Omega_c = \mu_{21}E_c/2\hbar$. We assume that the dipole moments are not orthogonal and choose an arrangement of dipole moment vectors as shown in Fig. 1(b), so that each laser field acts only on one transition. An incoherent pumping field with a pumping rate 2R is applied between levels $|1\rangle$ and $|3\rangle$. By defining φ_p and φ_c the phase of the probe and coupling fields, respectively, we can set $\Omega_1 = \Omega_p \exp\left(i\varphi_p\right)$ and $\Omega_2 = \Omega_c \exp\left(i\varphi_c\right)$ with Ω_p and Ω_c being real parameters.

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

$$\frac{\partial\rho}{\partial t} = -i\left[H_{\mathrm{int}}, \rho\right] + \Lambda\rho, \tag{1}$$

In the rotating-wave and electric-dipole approximations, the relevant density matrix equations are given as follows:

$$\dot{\rho}_{11} = -2R\rho_{11} + 2\gamma_{21}\rho_{22} + 2\gamma_{31}\rho_{33} - i\Omega_p\left(\rho_{13} - \rho_{31}\right) - i\Omega_c\left(\rho_{12} - \rho_{21}\right), \\ + 2p\sqrt{\gamma_{21}\gamma_{31}}\left(e^{i\varphi}\rho_{32} + e^{-i\varphi}\rho_{23}\right) \tag{2a}$$

$$\dot{\rho}_{22} = -2\gamma_{21}\rho_{22} + i\Omega_c\left(\rho_{12} - \rho_{21}\right) - p\sqrt{\gamma_{21}\gamma_{31}}\left(e^{i\varphi}\rho_{32} + e^{-i\varphi}\rho_{23}\right), \tag{2b}$$

$$\dot{\rho}_{33} = 2R\rho_{11} - 2\gamma_{31}\rho_{33} + i\Omega_p\left(\rho_{13} - \rho_{31}\right) - p\sqrt{\gamma_{21}\gamma_{31}}\left(e^{i\varphi}\rho_{32} + e^{-i\varphi}\rho_{23}\right), \tag{2c}$$

$$\dot{\rho}_{21} = -(\mathrm{R} - i\Delta_c + \gamma_{21})\rho_{21} + i\Omega_c(\rho_{11} - \rho_{22}) - i\Omega_p\rho_{23} - p\sqrt{\gamma_{21}\gamma_{31}}e^{i\varphi}\rho_{31}\eta_\phi, \tag{2d}$$

$$\dot{\rho}_{32} = -\left(R - i\Delta_p + i\Delta_c + \gamma_{21} + \gamma_{31}\right)\rho_{32} - i\Omega_c\rho_{31} + i\Omega_p\rho_{12} \\ - p\sqrt{\gamma_{21}\gamma_{31}}e^{-i\varphi}\left(\rho_{22} + \rho_{33}\right), \tag{2e}$$

$$\dot{\rho}_{31} = -\left(2R - i\Delta_p + \gamma_{31}\right)\rho_{31} - i\Omega_c\rho_{32} + i\Omega_p(\rho_{11} - \rho_{33}) - p\sqrt{\gamma_{21}\gamma_{31}}e^{-i\varphi}\rho_{21}, \tag{2f}$$

where the matrix elements obey conjugated and normalized conditions: $\rho_{ij} = \rho^*_{ij}$ $(i \neq j)$, and $\rho_{11} + \rho_{22} + \rho_{33} = 1$. $\phi = \varphi_p - \varphi_c$ is the relative phase between the probe and the coupling fields. $\Delta_p = \omega_{31} - \omega_p$ and $\Delta_c = \omega_{21} - \omega_c$ are respectively the detunings of the probe and coupling fields. The decay rates from the states $|2\rangle$ and $|3\rangle$ to $|1\rangle$ are given by γ_{21} and γ_{31}, respectively. The term $p\sqrt{\gamma_{21}\gamma_{31}}$ represents SGC resulting from the cross coupling between the spontaneously emissions $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |3\rangle$, and $p = \vec{\mu}_{12}.\vec{\mu}_{13}/\left|\vec{\mu}_{12}\right|\left|\vec{\mu}_{13}\right| = \cos\theta$ with θ is the angle between the two dipole moments. Thus, for the parallel dipole moments the quantum interference due to spontaneous emissions is maximum and $p = 1$, while for the orthogonal dipole moments there is no quantum interference and $p = 0$.

In order to describe the propagation dynamics of the probe laser field inside the atomic medium, the following Maxwell's wave equations in the slowly-varying envelope approximation are required (along the z direction):

$$\frac{\partial\Omega_p(z,t)}{\partial z} + \frac{1}{c}\frac{\partial\Omega_p(z,t)}{\partial t} = i\alpha\gamma_{31}\rho_{31}(z,t), \tag{3}$$

here $\alpha = \frac{\omega_p N\left|d_{31}\right|^2}{4\varepsilon_0 c\hbar\gamma_{31}}$ is the propagation constant. It is convenient to transform equations (2a)–(2f) and (4) in a moving frame by replacing the space and time variables in the laboratory frame, z and t by those in the moving frame, ζ and τ through the relations of $\xi = \mathrm{z}$ and $\tau = t - z/c$, with c is the speed of light. In this frame, the Eq. (3) is rewritten as [50]:

$$\frac{\partial\Omega_p(\xi,\tau)}{\partial\xi} = i\alpha\gamma_{31}\rho_{31}(\xi,\tau), \tag{4}$$

To illustrate the proposed model, we apply to ^{87}Rb atom system on the 5S–5P transitions as a realistic candidate. The designated states and the decay rates can be chosen as follows [50]: $|1\rangle = |5\mathrm{S}_{1/2}, \mathrm{F} = 1\rangle$, $|2\rangle = |5\mathrm{P}_{3/2}, \mathrm{F} = 0\rangle$, $|3\rangle = |5\mathrm{P}_{3/2}, \mathrm{F} = 1\rangle$, and $\gamma = \gamma_{21} = \gamma_{31} = 6$ MHz.

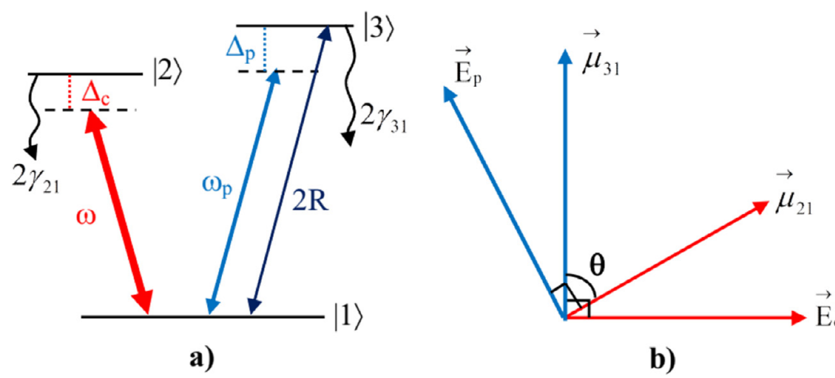

Fig. 1. (a) The three-level V-type system is excited by two coherent fields and an incoherent pumping field. (b) The polarizations are arranged so that one field drive only one transition.

3. Results and discussions

In this section, we numerically solve the coupled Bloch–Maxwell equations (2a)–(4) and (2f) on a space–time grid by four-order Runge–Kutta and finite difference methods with initial condition that all atoms is in the ground state $|1\rangle$ and the boundary condition that the incident probe field is assumed as a continuous wave (cw) signal while the coupling field is modulated by a nearly-square pulse shape with smooth rising and falling edges [32]:

$$\begin{aligned}\Omega_c^{(i)}(\tau) = \Omega_{c0}\{1 - 0.5\,[\tanh(a_i\tau - 4) - \tanh(a_i\tau - 14)\\ + \tanh(a_i\tau - 24) - \tanh(a_i\tau - 34)]\}\end{aligned}, \tag{5}$$

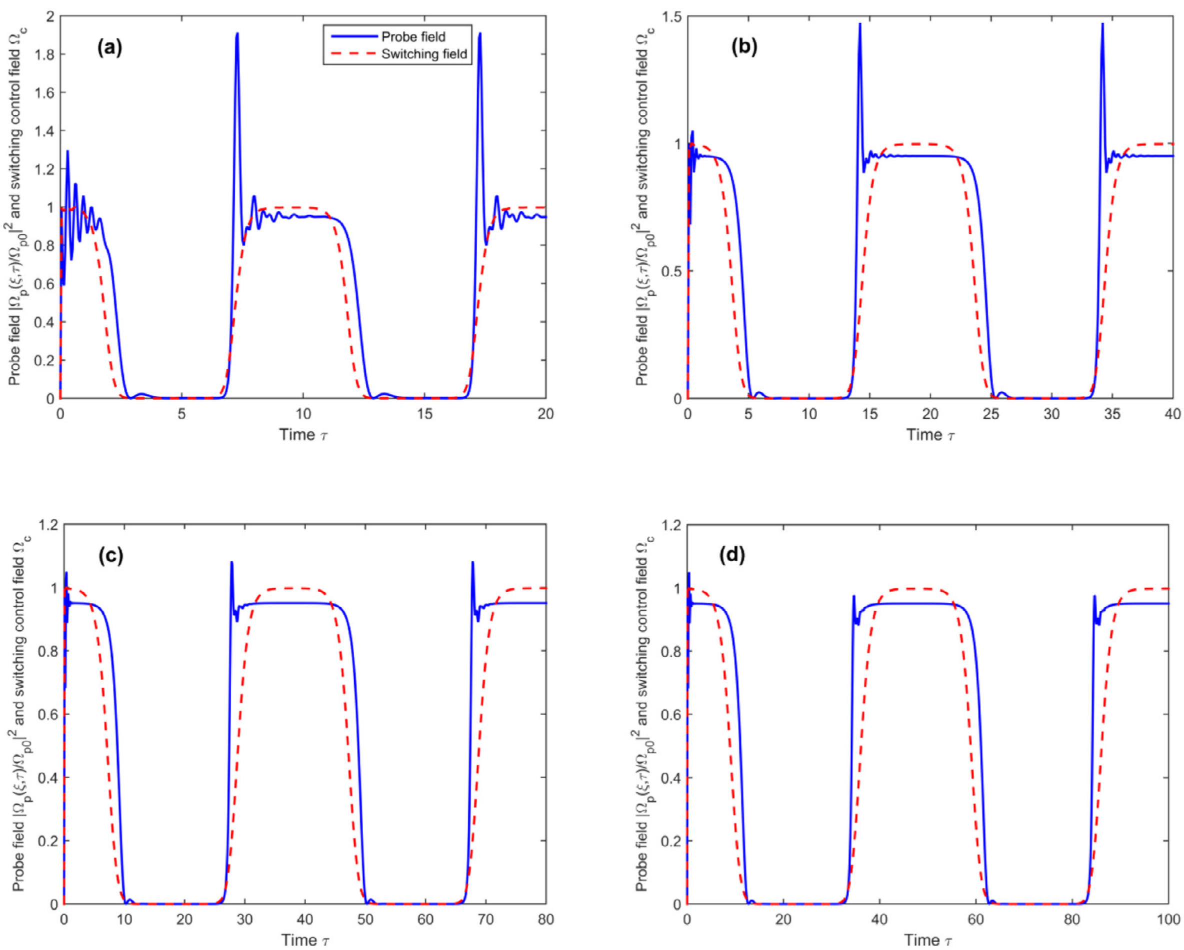

Fig. 2. Time evolution of a cw probe field (solid line) at $\xi = 50/\alpha$ versus time τ under variation of the coupling field $\Omega_c(\tau)$ (dashed lines) for different switching periods: (a) $10/\gamma_{31}$, (b) $20/\gamma_{31}$, (c) $40/\gamma_{31}$ and (d) $50/\gamma_{31}$. The other parameters are given by $\Omega_p = 0.2\gamma_{31}$, $\Omega_c = 10\gamma_{31}$, $p = 0$, $\phi = 0$ and $\Delta_p = \Delta_c = 0$, respectively.

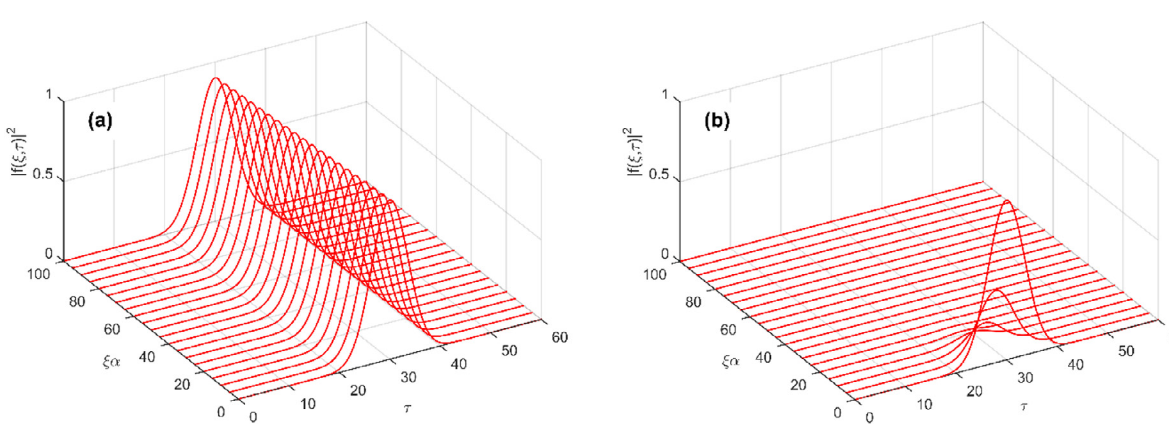

Fig. 3. Spatiotemporal evolution of the normalized probe envelope when the coupling field is ON (a) and OFF (b). Other parameters are the same as in Fig. 2(d).

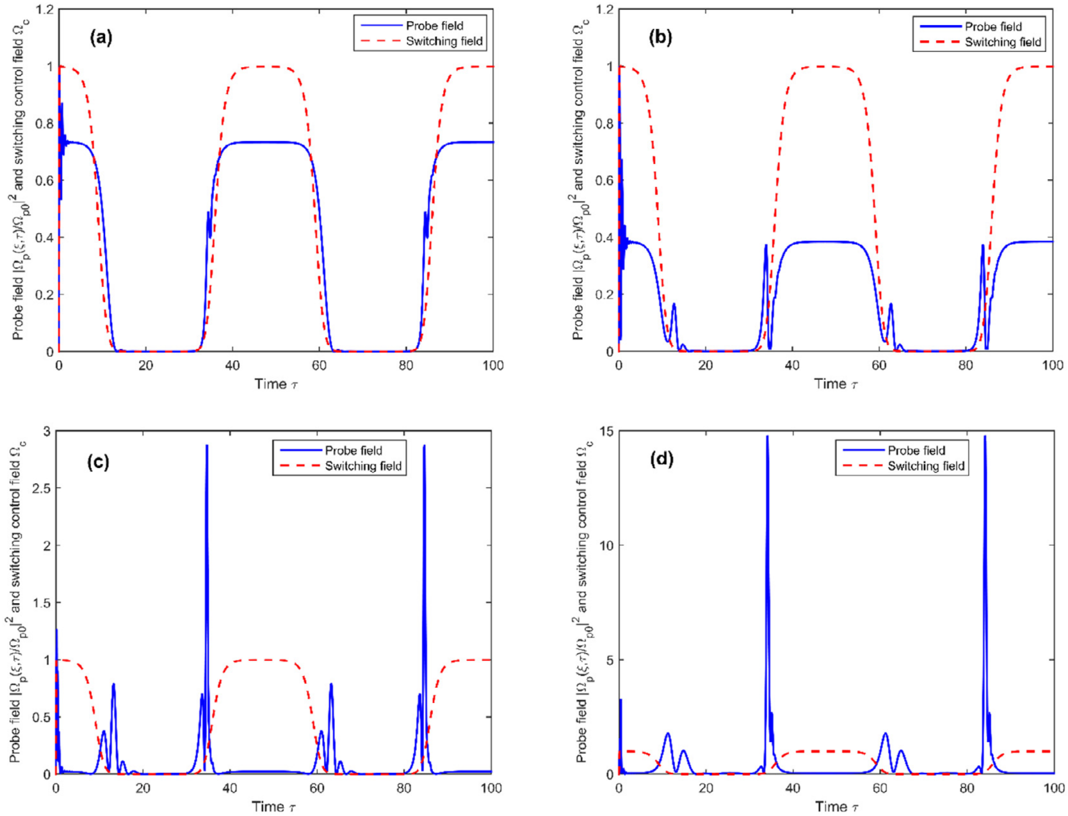

Fig. 4. Time evolution of a cw probe field (solid line) at $\xi = 50/\alpha$ versus time τ under variation of the coupling field $\Omega_c(\tau)$ (dashed lines) for different values of the parameter SGC: (a) $p = 0.1$, (b) $p = 0.3$, (c) $p = 0.7$ and (d) $p = 0.99$. Other parameters are the same as those in Fig. 2(d).

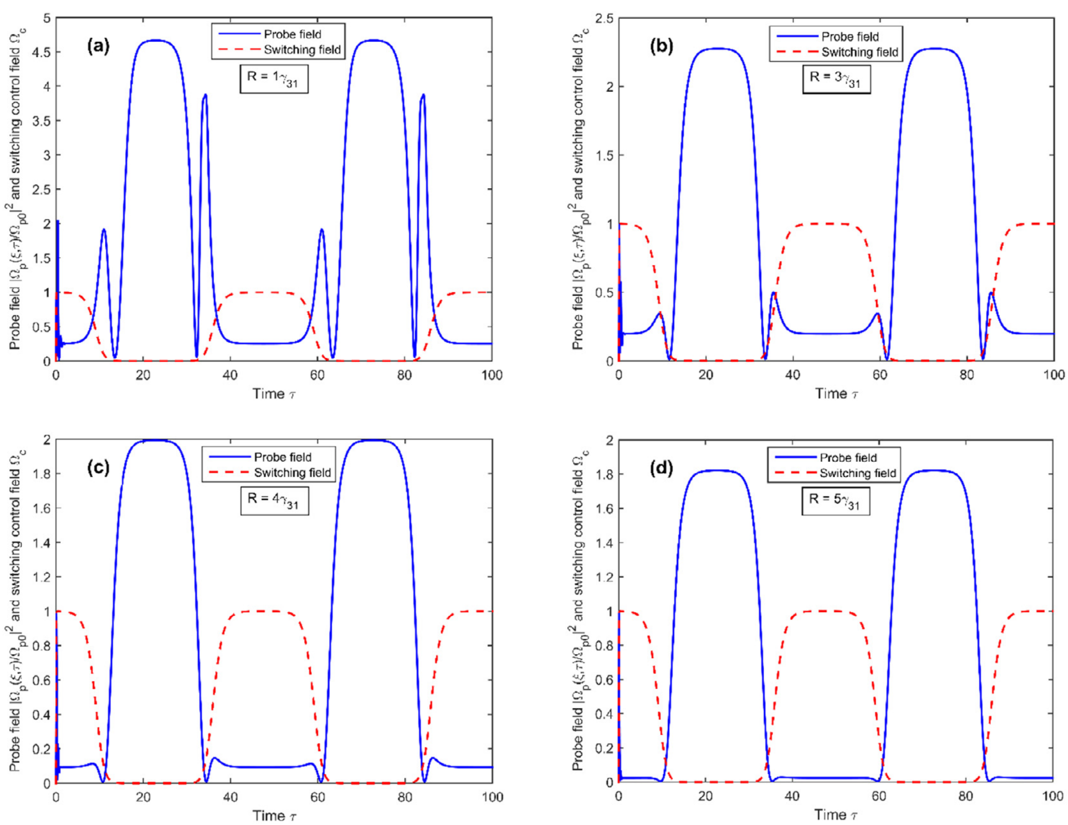

Fig. 5. Time evolution of a cw probe field (solid line) at $\xi = 50/\alpha$ versus time τ under variation of the coupling field $\Omega_c(\tau)$ (dashed lines) for different values of the incoherent pump rate: (a) $R = 1\gamma_{31}$, (b) $R = 3\gamma_{31}$, (c) $R = 4\gamma_{31}$ and (d) $R = 5\gamma_{31}$. Other parameters are the same as those in Fig. 4(d).

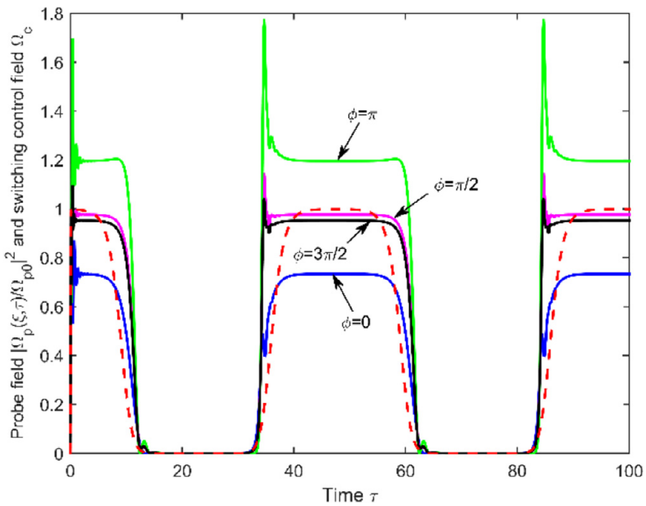

Fig. 6. Time evolution of a cw probe field (solid lines) at $\xi = 50/\alpha$ versus time τ under variation of the coupling field $\Omega_c(\tau)$ (dashed line) for different values of the relative phase ϕ. Other parameters are the same as those in Fig. 4(a).

where, $a_i = 2.0$, 1.0, 0.5, and 0.4 ($i = 1, 2, 3, 4$) represents the switching periods as $10/\gamma_{31}$, $20/\gamma_{31}$, $40/\gamma_{31}$, and $50/\gamma_{31}$, respectively.

To start with, we consider the case without SGC and incoherent pumping by plotting time evolution of the probe light via periodic modulating of the coupling field intensity with $p = 0$ and $R = 0$ for different periods (a) $10/\gamma_{31}$, (b) $20/\gamma_{31}$, (c) $40/\gamma_{31}$ and (d) $50/\gamma_{31}$ as shown in Fig. 2. We observe that the probe transmission is switched to the ON or OFF mode when the coupling field is ON or OFF, respectively. However, we also see that when the switching period is small (Fig. 2a), the switched probe pulse oscillates strongly at the peaks of the rising edges. As the switching period increases, these oscillations also decrease significantly, and with the switching period is $50/\gamma_{31}$ (Fig. 2d), the probe pulse achieves a nearly square pulse.

To explain the probe switching behaviors via modulating the intensity of the coupling field, in Fig. 3 we have plotted the spatiotemporal evolution of the magnitude squared of the normalized probe pulse envelope $|f(\xi,\tau)|^2$ when the coupling field is on (a) and off (b) for the case of Fig. 2(d). From Fig. 3(a) one can see that when the coupling field is on, the switched probe pulse is transmitted through the medium almost without loss (the EIT effect is established) and still can preserve its shape for quite a long propagation distance. However, when the coupling field is off, the probe pulse can be completely absorbed by the medium in a very short propagation distance, as shown in Fig. 3(b).

Next, we investigate the influence of SGC on the switching behaviors of the probe field without the relative phase and incoherent pumping field by plotting the evolution of the probe field at different values of the parameter p as shown in Fig. 4. The parameters used in Fig. 4 are the same as those in Fig. 2(d). It shows that when increasing the interference parameter p, the pulse oscillations at the peaks of the rising edges increase strongly while the switching efficiency is also significantly reduced. In particular, when $p = 0.99$, the probe switching behavior can be vanished, as we can be seen from Fig. 4(d). This is because when increasing the parameter p, the oscillations at the leading edge of the pulse increases strongly [50].

In order to overcome the pulse distortion caused by SGC, we have added an incoherent pumping field between levels $|1\rangle$ and $|3\rangle$. Indeed, as in Fig. 5 we simulate the spatiotemporal evolution of probe pulse in the case of Fig. 4(d) at different pumping rates (a) $R = 1\gamma_{31}$, (b) R

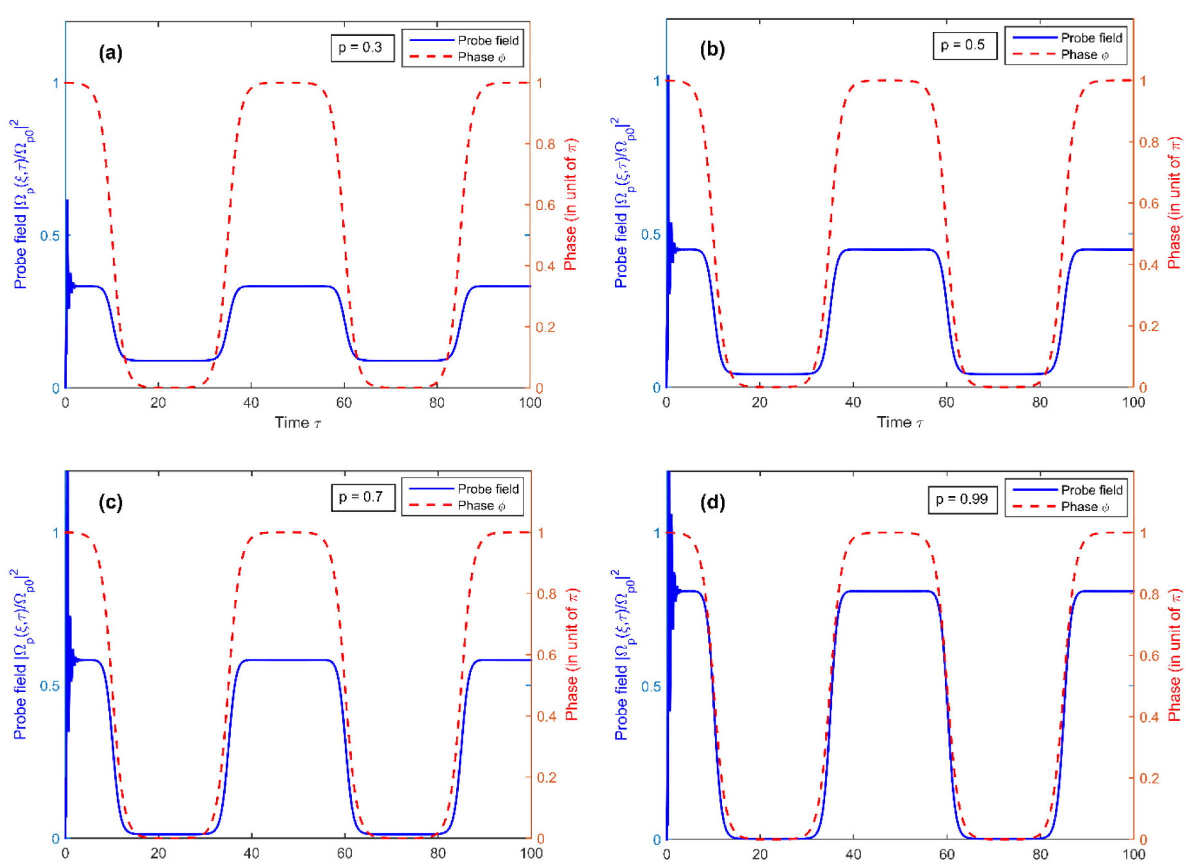

Fig. 7. Time evolution of a cw probe field (solid lines) at $\xi = 45/\alpha$ versus the variation of the relative phase $\phi(\tau)$ (dashed lines) in the range 0-π for the different values of the parameter SGC: $p = 0.3$ (a), $p = 0.5$ (b), $p = 0.7$ (c) and $p = 0.99$ (d). The other parameters are given by $\Omega_p = 0.2\gamma_{31}$, $\Omega_c = 10\gamma_{31}$, $R = 0$, $\Delta_p = \Delta_c = 0$, and $\gamma_{21} = \gamma_{31}$, respectively.

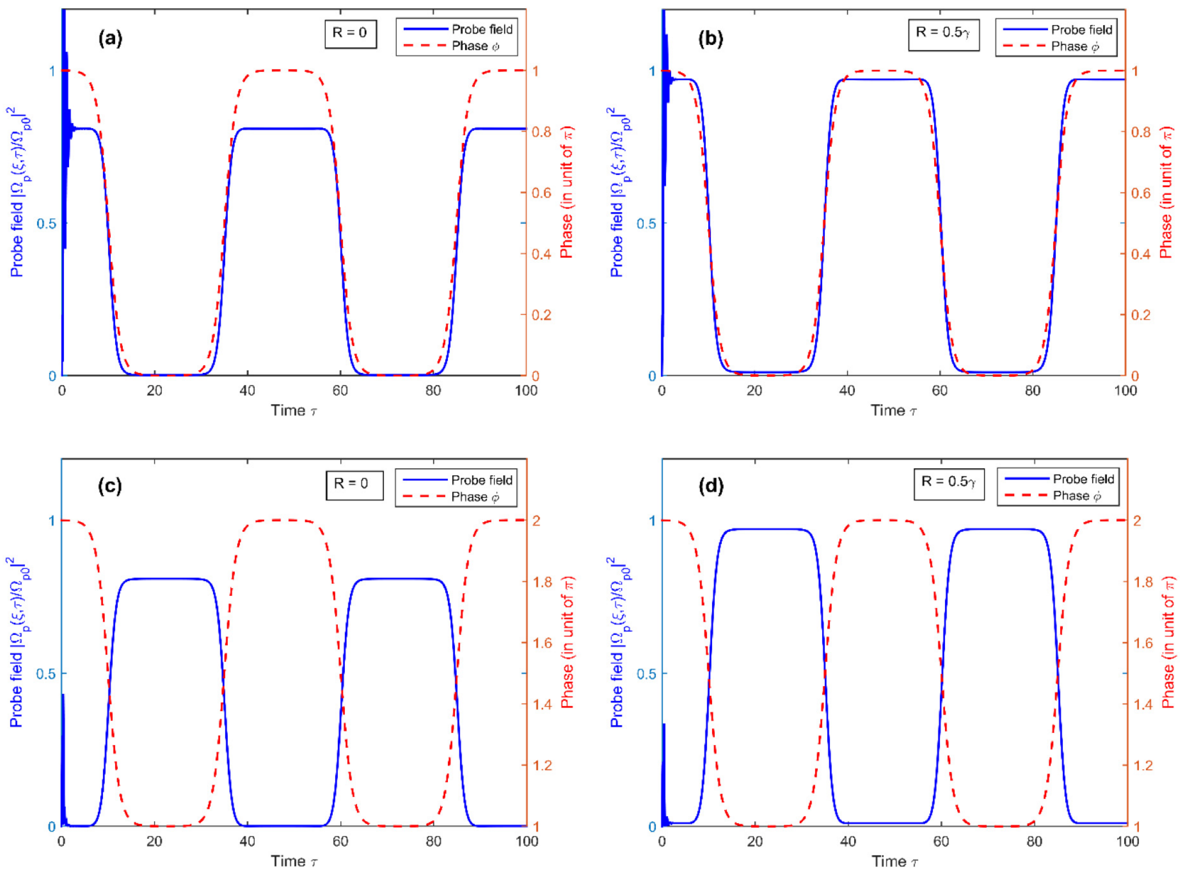

Fig. 8. Time evolution of a cw probe field (solid lines) at $\xi = 45/\alpha$ versus the variation of the relative phase $\phi(\tau)$ (dashed lines) in the two ranges of the relative phase ϕ: from 0 to π for (a) and (b); from π to 2π for (c) and (d). The other parameters are given by $\Omega_p = 0.2\gamma_{31}$, $\Omega_c = 10\gamma_{31}$, $p = 0.99$, $\Delta_p = \Delta_c = 0$, and $\gamma_{21} = \gamma_{31}$, respectively.

$= 3\gamma_{31}$, (c) $R = 4\gamma_{31}$ and (d) $R = 5\gamma_{31}$. From Fig. 5 we can see that by increasing the incoherent pumping rate, the pulse oscillations are also significantly reduced and the switching probe pulse is gradually attained a nearly-square shape with amplified amplitude. At the same time, the switching efficiency increases when the incoherent pumping rate is increased. This phenomenon can be explained that as the incoherent pumping rate increases, the medium can be changed from absorption to amplification [52] and thus the pulse can be stabilized and amplified (see Fig. 5d).

The influence of the relative phase on the switching behavior in the presence of SGC ($p = 0.1$) and without incoherent pumping is shown in Fig. 6. It shows that the switching process of the probe field is greatly affected by the relative phase ϕ. At different phases, the peak intensity of the switching probe pulse can be enhanced or decreased depending on the absorption or amplification of the medium. For example, the switching probe amplitude is dramatically decreased when $\phi = 0$, and is enhanced when $\phi = \pi$.

We now consider the switching behaviors of the probe field via the modulation of the relative phase between the probe and coupling fields by choosing the relative phase $\phi(\tau)$ of the form [32]:

$$\phi(\tau) = \pi \left\{ a_n - 0.5\left[\tan h0.4(\tau - 10) - \tan h0.4(\tau - 35) + \tan h0.4(\tau - 60) - \tan h0.4(\tau - 85)\right]\right\}, \quad (6)$$

where $a_n = 1$, and 2, corresponding to the ranges 0-π, and π-2π, respectively.

Fig. 7 shows the switching of the probe field via the modulation of relative phase with an approximate period of $50/\gamma_{31}$ in the presence of SGC and without incoherent pumping. We can see that the *cw* probe field is switched a nearly-square pulse shape when the relative phase is periodically modulated, and the switching of probe field is synchronously with the relative phase. At the same time, the switching efficiency increases gradually when the parameter p is increased from 0 to 1. The physical reason for these phenomena is that, in the presence of SGC the absorption also varies periodically with relative phase from zero to maximum and vice versa with a period of 2π [50], so the probe field can be quenched or transmitted completely with maximum or zero absorption, respectively. In addition, increasing the parameter p can amplify the probe light, so the switching efficiency is also increased.

Finally, we represent the influence of incoherent pumping rate on the probe switching with relative phase when the parameter $p = 0.99$, as in Fig. 8. It shows that in range $[0, \pi]$, the switching of probe field is synchronously (see Fig. 8(a and (b) while in range $[\pi, 2\pi]$, the switching is anti-synchronously (see Figs. 8c and d) with the relative phase. In two cases the switching efficiency is greatly increased (approximately 100%) in the presence of incoherent pumping even with $R = 0.5\gamma$. From the above investigations we can see that, although the SGC can distort the switching probe pulse, however, by choosing the appropriate phase and pumping rate, such pulse fluctuations can be easily overcome (can see Fig. 8d).

4. Conclusion

We realized all-optical switching in a V-type three-level atomic system with the presence of spontaneously generated coherence (SGC), relative phase of applied fields and incoherent pumping. It is shown that the continuous-wave probe field can be switched to a nearly square pulse train by periodically modulating the coupling field intensity or the relative phase of applied fields. Under SGC, the response of the medium depends sensitively on the relative phase and the probe field can be switched synchronous or anti-synchronous with relative phase, depending on the relative phase being modulated in the range 0-π or π-2π. Although the SGC can distort the switching probe pulse, however, by choosing the appropriate phase and pumping rate, such pulse fluctuations can be easily overcome.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work has been funded by Vietnam Ministry of Education and Training under Grant No. B2020-TDV-03.

References

[1] H. Ishikawa, Ultrafast All-Optical Signal Processing Devices, John Wile & Sons, Singapore, 2008.
[2] K.J. Boller, A. Imamoglu, S.E. Harris, Observation of electromagnetically induced transparency, Phys. Rev. Lett. 66 (1991) 2593.
[3] N.H. Bang, L.V. Doai, D.X. Khoa, Controllable optical properties of multiple electromagnetically induced transparency in gaseous atomic media, Comm. Phys. 28 (2019) 1–33.
[4] J. Javanainen, Effect of state superpositions created by spontaneous emission on laser-driven transitions, Europhys. Lett. 17 (1992) 407.
[5] H.R. Xia, C.Y. Ye, S.Y. Zhu, Experimental observation of spontaneous emission cancellation, Phys. Rev. Lett. 77 (1996) 1032.
[6] H. Wang, D. Goorskey, M. Xiao, Enhanced Kerr nonlinearity via atomic coherence in a three-level atomic system phys, Rev. Lett. 87 (2001) 073601.
[7] D.X. Khoa, L.V. Doai, D.H. Son, N.H. Bang, Enhancement of self-Kerr nonlinearity via electromagnetically induced transparency in a five-level cascade system: an analytical approach, Opt. Soc. Am. B 31 (N6) (2014) 1330.
[8] Z. Bai, G. Huang, Enhanced third-order and fifth-order Kerr nonlinearities in a cold atomic system via Rydberg-Rydberg interaction, Opt. Express 24 (2016) 4442–4461.
[9] L.V. Doai, Giant cross-Kerr nonlinearity in a six-level inhomogeneously broadened atomic medium, J. Phys. B: At. Mol. Opt. Phys. 52 (2019) 225501.
[10] N.H. Bang, D.X. Khoa, L.V. Doai, Controlling self-Kerr nonlinearity with an external magnetic field in a degenerate two-level inhomogeneously broadened medium, Phys. Lett. A 384 (2020) 126234.
[11] Y. Mu, L. Qin, Z. Shi, G. Huang, Giant Kerr nonlinearities and magneto-optical rotations in a Rydberg-atom gas via double electromagnetically induced transparency, Phys. Rev. A 103 (2021) 043709.
[12] A. Joshi, A. Brown, H. Wang, M. Xiao, Controlling optical bistability in a three-level atomic system, Phys. Rev. A 67 (2003) 041801, (R).
[13] Z. Wang, B. Yu, Optical bistability and multistability via dual electromagnetically induced transparency windows, J. Lumin. 132 (2012) 2452–2455.
[14] H.R. Hamedi, S.H. Asadpour, M. Sahrai, B. Arzhang, D. Taherkhani, Optical bistability and multi-stability in a four-level atomic scheme, Opt. Quantum Electron. 45 (3) (2013) 295–306.
[15] D.X. Khoa, L.V. Doai, L.N.M. Anh, L.C. Trung, P.V. Thuan, N.T. Dung, N.H. Bang, Bang: Optical bistability in a five-level cascade EIT medium: An analytical approach, J. Opt. Soc. Amer. B 33 (4) (2016) 735–740.
[16] Abdelsalam H.M. Abdelaziz, Amarendra K. Sarma, Effective control and switching of optical multistability in a three-level V-type atomic system, Phys. Rev. A 102 (2020) 043719.
[17] W. Shi, H. Zhang, H. Sun, P. Wang, Nonreciprocal optical bistability based on Doppler effect in a three-level atomic system, Opt. Commun. 488 (2021) 126862.
[18] G. Huang, K. Jiang, M.G. Payne, L. Deng, Formation and propagation of coupled ultraslow optical soliton pairs in a cold three-state double-Λ-system, Phys. Rev. E 73 (2006) 056606.
[19] L.G. Si, X.Y. Lu, X. Hao, J.H. Li, Dynamical control of soliton formation and propagation in a Y-type atomic system with dual ladder-type electromagnetically induced transparency, J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 065403.
[20] B. Buica, T. Nakajima, Propagation of two short laser pulse trains in a Λ-type threelevel medium under conditions of electromagnetically induced transparency, Opt. Commun. 332 (2014) 59.
[21] Y. Chen, Z. Bai, G. Huang, Ultraslow optical solitons and their storage and retrieval in an ultracold ladder-type atomic system, Phys. Rev. A 89 (2014) 023835.
[22] D.X. Khoa, H.M. Dong, L.V. Doai, N.H. Bang, Propagation of laser pulse in a three-level cascade inhomogeneously broadened medium under electromagnetically induced transparency conditions, Optik 131 (2017) 497.
[23] H. Schmidt, R.J. Ram, All-optical wavelength converter and switch based on electromagnetically induced transparency, Appl. Phys. Lett. 76 (2000) 3173.
[24] D.D. Yavuz, All-optical femtosecond switch using two-photon absorption, Phys. Rev. A 74 (2006) 053804.
[25] M.A. Antón, F. Carreño, O.G. Calderón, S. Melle, I. Gonzalo, Optical switching by controlling the double-dark resonances in a N-tripod five-level atom, Opt. Commun. 281 (2008) 6040–6048.
[26] R. Yu, J. Li, P. Huang, A. Zheng, X. Yang, Dynamic control of light propagation and optical switching through an RF-driven cascade-type atomic medium, Phys. Lett. A 373 (2009) 2992.
[27] A. Fountoulakis, A.F. Terzis, E. Paspalakis, All-optical modulation based on electromagnetically induced transparency, Phys. Lett. A 374 (2010) 3354–3364.
[28] Y. Qi, Y. Niu, F. Zhou, Y. Peng, S. Gong, Phase control of coherent pulse propagation and switching based on electromagnetically induced transparency in a four-level atomic system, J. Phys. B: At. Mol. Opt. Phys. 44 (2011) 085502.
[29] Y. Qi, F. Zhou, J. Yang, Y. Niu, S. Gong, Controllable twin laser pulse propagation and dual-optical switching in a four-level quantum dot nanostructure, J. Opt. Soc. Amer. B 30 (2013) 1928.
[30] J.H. Li, R. Yu, Y. Wu, Propagation of magnetically controllable lasers and magneto-optic dual switching using nitrogen-vacancy centers in diamond, J. Appl. Phys. 113 (2013) 103104.
[31] H.M. Dong, L.T.Y. Nga, N.H. Bang, Optical switching and bistability in a degenerated two-level atomic medium under an external magnetic field, Appl. Opt. 58 (2019) 4192.
[32] H.M. Dong, N.H. Bang, Controllable optical switching in a closed-loop three-level lambda system, Phy. Scr. 94 (2019) 115510.
[33] N.T. Anh, T.D. Thanh, N.H. Bang, H.M. Dong, Microwave-assisted all-optical switching in a four-level atomic system, Pramana - J. Phys. 95 (2021) 37.
[34] H.M. Ma, S.Q. Gong, C.P. Liu, Z.R. Sun, Z.Z. Xu, Effects of spontaneous emission-induced coherence on population inversion in a ladder-type atomic system, Opt. Commun. 223 (2003) 97.
[35] S.Q. Gong, Z.Z. Xu, The effect of phase fluctuation on absorption and dispersion in a V medium, Opt. Commun. 115 (1995) 65.
[36] M. Sahrai, The effect of the spontaneously generated coherence on the dynamical behaviors of the dispersion and the absorption, Eur. Phys. J. Spec. Top. 160 (2008) 383.
[37] H.M. Ma, S.Q. Gong, Z.R. Sun, R.X. Li, Z.Z. Xu, Effects of spontaneously induced coherence on absorption of a ladder-type atom, Chin. J. Phys 11 (2006) 2588.
[38] Y. Bai, H. Guo, D. Han, H. Sun, Effects of spontaneously generated coherence on the group velocity in a v system, Phys. Lett. A 340 (2005) 342.
[39] M. Mahmoudi, M. Sahrai, H. Tajalli, The effects of the incoherent pumping field on the phase control of group velocity, At. Mol. Opt. Phys. 39 (2006) 1825.
[40] N.H. Bang, L.N.M. Anh, N.T. Dung, L.V. Doai, Comparative study of light manipulation in three-level systems via spontaneously generated coherence and relative phase of laser fields, Commun. Theor. Phys. 71 (2019) 947–954.
[41] Y.P. Niu, S.Q. Gong, Enhancing Kerr nonlinearity via spontaneously generated coherence, Phys. Rev. A 73 (2006) 053811.
[42] W. Jiang, X. Yan, J. Song, H. Zheng, Ch. Wu, B. Yin, Y. Zhang, Enhancement of Kerr nonlinearity via spontaneously generated coherence in a four-level N-type atomic system, Opt. Commun. 282 (2009) 101–105.
[43] Y. Bai, T. Liu, X. Yu, Giant Kerr nonlinearity in an open V-type system with spontaneously generated coherence, Optik 124 (2012) 613.
[44] H. Ali, M. Khan, M. Zubair, P. Ahmad, M.U. Khandaker, T. Ali, F. Khan, Control over spectral hole burning via spontaneously generated coherence and Kerr non-linearity, Optik 224 (2020) 165558.
[45] D.C. Cheng, C.P. Liu, S.Q. Gong, Optical bistability and multistability via the effect of spontaneously generated coherence in a three-level ladder-type atomic system, Phys. Lett. A 332 (2004) 244.
[46] K.I. Osman, A. Joshi, Controlling double-cavity optical switching in a K-type multilevel system including spontaneously generated coherence, Phys. Lett. A 376 (2012) 2565–2573.
[47] Z. Zhu, A.-X. Chen, W.-X. Yang, R.-K. Lee, Phase knob for switching steady-state behaviors from bistability to multistability via spontaneously generated coherence, J. Opt. Soc. Amer. B 31 (2014) 2061.
[48] H. Jafarzadeh, All-optical switching in an open V-type atomic system, Laser Phys. 27 (2017) 025204.
[49] L.V. Doai, Role of incoherent pumping field on control of optical bistability in a closed three-level ladder atomic system, Eur. Phys. J. D 74 (2020) 171.
[50] H.M. Dong, L.V. Doai, N.H. Bang, Pulse propagation in an atomic medium under spontaneously generated coherence, incoherent pumping, and relative laser phase, Opt. Commun. 426 (2018) 553–557.
[51] A. Li, H. Ma, X. Tan, Y. Yang, D. Tong, X. Fan, Phase control of probe response in an open ladder type system with spontaneously generated coherence, Opt. Commun. 280 (2007) 397.
[52] X.J. Fan, A.Y. Li, F.G. Bu, H.X. Qiao, J. Du, Z.Z. Xu, Phase-dependent properties for absorption and dispersion in a closed equispaced three-level ladder system, Optik 119 (2008) 540.