Influences of control coherence and decay coherence on optical bistability in a semiconductor quantum well*

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We discuss the influences of two different types of mechanisms of quantum coherence on optical bistability in a semiconductor quantum well structure. In the first mechanism, only quantum coherence induced by the resonant coupling of a strong control laser is considered. In the second mechanism, the decay coherence is taken into account under the condition where the control field is weak. In two different cases, optical bistability can be obtained through choosing appropriate physical parameters. Our studies show quantum coherence makes the optical nonlinear effect of the system become stronger, which takes an important role in the process of generating optical bistability. A semiconductor quantum well with flexibility and easy integration in design could potentially be exploited in real solid-state devices.

Keywords: optical bistability, decay coherence, control coherence

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1. Introduction

Due to attractive nonlinear and coherent optical effects, semiconductor quantum well structures (SQWS) have attracted the attention of a lot of researchers.[1–10] An SQWS behaves as an "artificial atom" and has intersubband transition in the conduction band. Under the interaction with a strong control field, a quantum well structure exhibits many interesting and unexpected consequences which are similar to ones in atomic systems;[11–16] for example, electromagnetically induced transparency (EIT),[1,3] coherent oscillations,[4,5] and gain without population inversion.[6] Recently, the technology of quantum coherence and interference has been used to produce the optical bistability in SQWS.[17,18] Such a system with optically bistable behavior can be used for making efficient and fast all-optical switching devices.

Special quantum coherence, decay coherence, and spontaneously generated coherence (SGC) have been extensively investigated in atomic systems.[19–21] In SQWS, population scattering rate and dipole dephasing rate also exist. Recent studies show decay coherence and interference can significantly affect the EIT window and the propagation of the group velocity of a probe laser.[22] In SQWS, the existence of decay coherence makes the quantum well structure have more prominent nonlinear behavior, which motivates us to investigate the influences of decay coherence on the optical bistability.

In this paper, we report our study of the optical bistability behavior of a probe field in a unidirectional ring cavity containing a Λ-type SQWS resonantly coupled with a control field. We investigate the influences of quantum coherence (here we call it control coherence) generated by induction of the strong control field and decay interference on the optical bistability under the condition of steady state. In order to explain the optical bistability, the steady-state nonlinear behavior produced by two different types of mechanisms of quantum coherence is analyzed. Our physical system is based on an existing physical model[1] in which EIT and coherent population trapping are realized, and we attempt to obtain optical bistability in such a system by manipulating quantum coherence.

2. Model and approach

An asymmetric quantum well with three energy levels is considered and this system interacting with two light fields forms the well-known Λ-type (see Fig. 1): with the probe field

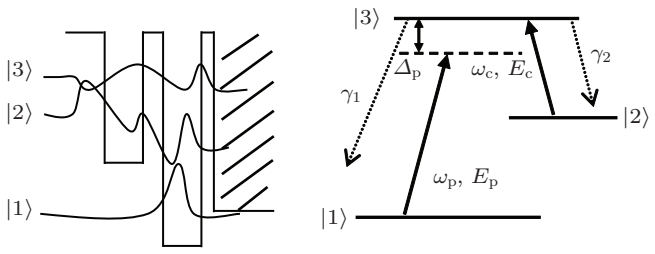


Fig. 1. Band diagram of a Λ-type semiconductor quantum well structure. A deep 7.1-nm-thick GaAs well is coupled, on one side, to a shallow 6.8-nm-thick $Al_{0.2}Ga_{0.8}As$ well by a 2.5-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier. Both of the quantum wells contact 36-nm $Al_{0.4}Ga_{0.6}As$, where the first excited state in the deep well and the ground state in the shallow well mix to form two new excited states of this system, and the ground state in the deep well and two newly created excited states are expressed as $|1\rangle$, $|2\rangle$, and $|3\rangle$, respectively, which refer to the electronic wave functions (subbands).

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(with central frequency $\omega_{\rm p}$ and amplitude $E_{\rm p}$) coupling the first to the third intersubband transition and the strong field (with central frequency $\omega_{\rm c}$ and amplitude $E_{\rm c}$) coupling the second to the third intersubband transition. In order to achieve optical bistability, we enclose this quantum well with length L inside a unidirectional ring cavity containing four mirrors whose reflectivity is R and transmissivity is T (schematic diagram is shown in Refs. [17] and [18]).

In the interaction picture, the evolution of the density matrix element may be expressed

$$\begin{aligned}
\dot{\rho}_{11} &= \gamma_1\rho_{33} + {\rm i}\Omega_{\rm p}(\rho_{31}-\rho_{13}),\\
\dot{\rho}_{33} &= -(\gamma_1+\gamma_2)\rho_{33} + {\rm i}\Omega_{\rm p}(\rho_{13}-\rho_{31}) + {\rm i}\Omega_{\rm c}(\rho_{23}-\rho_{32}),\\
\dot{\rho}_{21} &= -{\rm i}\Delta_{\rm P}\rho_{21} + {\rm i}\Omega_{\rm c}\rho_{31} - {\rm i}\Omega_{\rm p}\rho_{23} + p\sqrt{\gamma_1\gamma_2}\rho_{33},\\
\dot{\rho}_{31} &= -(\gamma_1/2+\gamma_2/2+{\rm i}\Delta_{\rm p})\rho_{31} - {\rm i}\Omega_{\rm p}(\rho_{33}-\rho_{11}) + {\rm i}\Omega_{\rm c}\rho_{21},\\
\dot{\rho}_{32} &= -(\gamma_1+\gamma_2)\rho_{32}/2 - {\rm i}\Omega_{\rm c}(\rho_{33}-\rho_{22}) + {\rm i}\Omega_{\rm p}\rho_{12}. \qquad (1)
\end{aligned}$$

The physical parameters in the above equation are shown: $\Omega_{\rm p}$ and $\Omega_{\rm c}$ are the corresponding Rabi frequencies of the probe and the control field, respectively; $\Delta_{\rm p} = \omega_{31} - \omega_{\rm p}$ is the detuning of the probe field; decay rate γ_i $(i = 1,2)$ includes population decay $\gamma_i^{\rm p}$ and dipole dephasing rate $\gamma_i^{\rm d}$. For the population rate, it is due primarily to longitudinal optical phonon emission events at low temperature. For the dipole dephasing rate, it results from a combination of quasielastic interface roughness scattering or acoustic phonon scattering.[1,2] With low temperature, the dephasing rate is far less than the population rate. The parameter p stands for the alignment of two decay emission dipole matrix elements and is defined as $p = \boldsymbol{D}_{32}\cdot\boldsymbol{D}_{31}/|\boldsymbol{D}_{32}|\cdot|\boldsymbol{D}_{31}| = \cos\theta$ with θ being the angle between the two dipole elements. Observation of decay coherence requires two lower levels to be close and the corresponding dipole matrix elements to be nonorthogonal. If p is zero, there is no decay coherence, while if p is one, maximum decay interference occurs. These requirements are rarely met in atomic systems. In the SQWS however, energy spacing is easily adjusted by changing the structure of the well. In our paper, we assume the choice of parameter p's value is theoretically unrestricted ($p \in [0,1]$).

Now we consider properties of the transmission of the probe field in a unidirectional ring cavity. In the slowly varying envelope approximation, Maxwell's equation that describes the dynamic response of the probe field is expressed as

$$\frac{\partial E_{\rm p}}{\partial t} + c\frac{\partial E_{\rm p}}{\partial z} = {\rm i}\frac{\omega_{\rm p}}{2\varepsilon_0}P(\omega_{\rm p}), \qquad (2)$$

where $P(\omega) = ND_{31}\rho_{31}$ is the slow oscillation of the induced polarization in the intersubband transition $|3\rangle \leftrightarrow |1\rangle$, N is the number density of carriers.

In order to obtain optical bistability, we need to get the relation between the input $E_{\rm p}^{\rm I}$ and the output field $E_{\rm p}^{\rm T}$. For a perfectly tuned cavity, relations between fields $E_{\rm p}(0)$, $E_{\rm p}(L)$ at both ends of the SQWS sample and $E_{\rm p}^{\rm I}$, $E_{\rm p}^{\rm T}$ may be expressed as $E_{\rm p}^{\rm T} = \sqrt{T}E_{\rm p}(L)$, $E_{\rm p}^{\rm I} = (E_{\rm p}(0) - RE_{\rm p}(L))/\sqrt{T}$, which are also called the boundary conditions.

In the mean field limit,[23,24] normalizing the input and output fields by letting $y = D_{31}E_{\rm P}^{\rm I}/(\hbar\sqrt{T})$ and $x = D_{31}E_{\rm P}^{\rm T}/(\hbar\sqrt{T})$ and using the boundary conditions, Maxwell's equation and steady state of Eq. (1), we derive the mean-field steady state equation that represents the relation between the input and the output lights

$$y = x - {\rm i}C\rho_{31}(x), \qquad (3)$$

where $C = LN\omega_{\rm p}D_{31}^2/(2\hbar c\varepsilon_0 T)$ is the co-operativity parameter.

3. Numerical results

Next, we numerically analyze the changes of output intensity $|x|$ versus the input intensity $|y|$ and theoretically investigate the influence of control coherence induced by the control field and decay interference on optical bistability. In all numerical calculations, we choose the parameters to be dimensionless units by scaling γ_1. In addition, we assume that all Rabi frequencies are real. First, we study how the control field affects optical bistability. In Fig. 2, the input–output field curves are shown by changing the intensity of the control field. Here the physical parameters are set as $\gamma_2 = 0.2\gamma_1$, the detuning $\Delta_{\rm p} = 4\gamma_1$, the decay coherence parameter $p = 0$, and the co-operativity parameter $C = 20$. This figure shows that when the intensity of the control field is very weak (here we let $\Omega_{\rm c}$ equal γ_1 or $2\gamma_1$), optical bistability cannot be realized in this quantum well structure. By increasing the intensity of the control field, the optical bistability occurs and the threshold value is significantly augmented. Furthermore, intensity of the output field becomes stronger with increasing intensity of the control field. The above phenomena result from quantum coherence induced by the control field. The properties of the absorption (solid line) and dispersion (dotted line) of the probe field are shown in Fig. 3 for different intensities of the control field, where $\Omega_{\rm c} = 4\gamma_1$ and the thin line is for $\Omega_{\rm c} = 2\gamma_1$. From this figure, we can see quantum coherence dramatically affects the nonlinearity of the quantum well structure when $\Omega_{\rm c} = 4\gamma_1$. For example, we obtain one transparent window for the probe field, that is, EIT occurs.[25] The effective nonlinearity, as well as a feedback mechanism due to the mirror, results in the occurrence of the optical bistability. In our work, the optical bistability does not require that the probe resonantly couple with the system, and through changing the intensity of

the control field and the technology of electromagnetically induced transparency, we can obtain optical bistability.

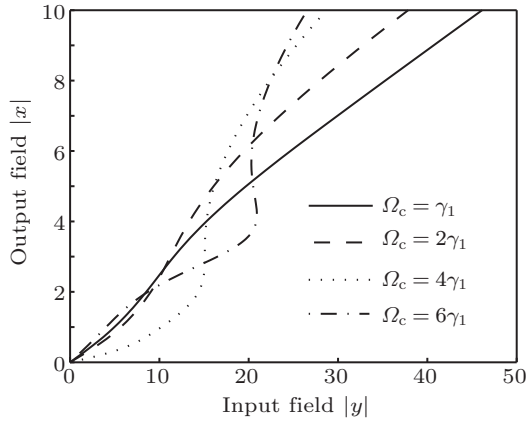


Fig. 2. Output field versus input field for different intensities of the control field Ω_c, and other parameters $C = 20$, $\gamma_2 = 0.2\gamma_1$, and $\Delta_p = 4\gamma_1$, $p = 0$.

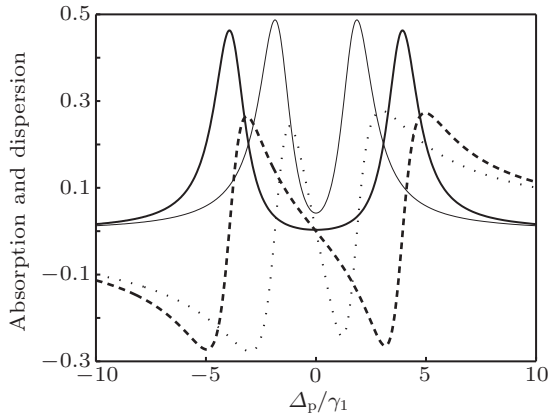


Fig. 3. Curves of absorption (solid line) and dispersion (dotted line) of the weak probe light under the coupling of the control field. Physical parameters: $\gamma_2 = 0.2\gamma_1$, and $\Omega_p = \gamma_1$, but the thick line is for $\Omega_c = 4\gamma_1$, and the thin line is for $\Omega_c = 2\gamma_1$.

Finally, we investigate the influences of the decay coherence on optical bistability. In the system of SQWS, we choose the co-operativity parameter $C = 20$, $\gamma_2 = 0.2\gamma_1$, $\Omega_c = 2\gamma_1$, and $\Delta_p = 1.8\gamma_1$, and gradually increase the decay coherence from $p = 0$ to $p = 0.7$, and then we get the changes of output intensity versus the input intensity. (See Fig. 4, where the dotted line is for $p = 0$, the dashed line is for $p = 0.3$, and the solid line is for $p = 0.7$.) Through this figure, we find that, for given physical parameters, if the system has no decay coherence ($p = 0$), the optical bistability cannot be realized, and the relation between the output and the input intensity approaches linear change (see dotted line). With the increase of the decay coherence, the relation has nonlinear change. When the decay coherence $p = 0.7$, optical bistability is achieved, which means nonlinear behavior of the system becomes significantly stronger. Enhancement of the nonlinearity depends on the decay coherence. The influences of decay coherence on the absorption of the probe field are shown in Fig. 5. From Fig. 5, under a weak control field, if the decay coherence is zero or very weak in this SQWS, the coherence of the system results from induction of the weak control field. Due to the coupling of the weak field, the system has no wide transparent windows (see dotted and dashed lines) near the resonant place. If the decay coherence is strong enough, we can get wide transparent windows (see solid line), which is similar to EIT. Through analyzing the effects of the decay coherence on the absorption, we find strong decay coherence changes the nonlinear behavior of SQWS. By using enhanced nonlinearity, we can get optical bistability at the nonresonant place.

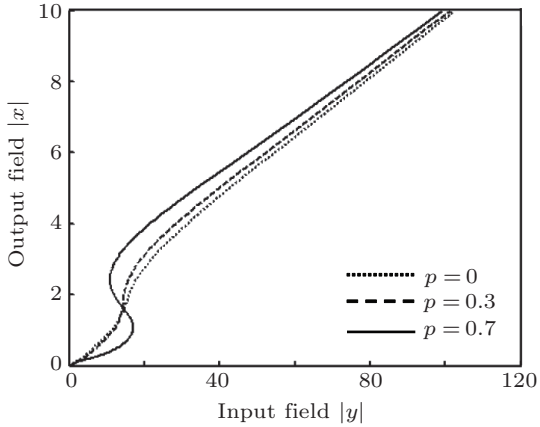


Fig. 4. Output field versus input field for different decay coherence p, and other parameters $C = 20$, $\gamma_2 = 0.2\gamma_1$, and $\Delta_p = 1.8\gamma_1$, and $\Omega_c = 2\gamma_1$.

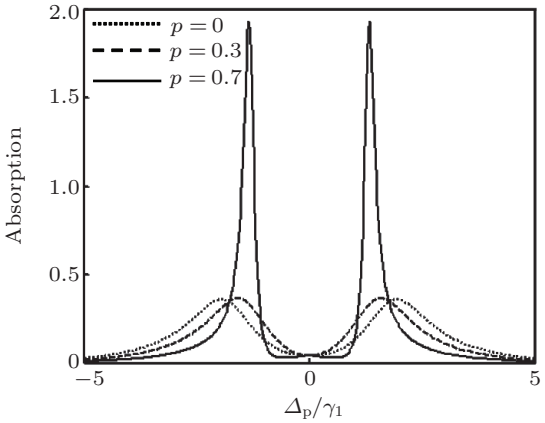


Fig. 5. Curves of absorption of the weak probe light for different decay coherence under the condition of the coupling of the weak control field. Physical parameters: $\gamma_2 = 0.2\gamma_1$, $\Omega_p = \gamma_1$, and $\Omega_c = 2\gamma_1$.

4. Summary

The influences of quantum coherence and interference on the optical bistability were investigated. Our mechanisms of quantum coherence include the control coherence induced by the strong control laser and decay coherence. The two different types of quantum coherence can enhance the nonlinear behavior of the semiconductor quantum well structure. By using strong nonlinearity as well as design of the ring cavity,

the bistable behavior for the weak probe field can be obtained. The technology of quantum coherence and interference in the SQWS is expected to have potentially important application in various fields such as ultrafast optical switches and quantum switches. In addition, compared with atomic systems,[26,27] the semiconductor quantum well structure has the advantages of flexibility and easy integration, so the manipulation of optical bistability in this system has more practical value.

References

[1] Dynes J F, Frogley M D, Rodger J and Phillips C C 2005 *Phys. Rev.* B **72** 085323
[2] Dynes J F, Frogley M D, Beck M, Faist J and Phillips C C 2005 *Phys. Rev. Lett.* **94** 157403
[3] Phillips M and Wang H 2003 *Opt. Lett.* **28** 831
[4] Vasko F T and Raichev O E 1995 *Phys. Rev.* B **51** 16965
[5] Luo M S C, Chuang S L, Planken P C M, Brener I and Nuss M C 1993 *Phys. Rev.* B **48** 11043
[6] Frogley M D, Dynes J F, Beck M, Faist J and Phillips C C 2006 *Nature Mater.* **5** 175
[7] Cao X L, Li Z Y, Yao J Q, Wang Y Y, Zhu N N, Zhong K and Xu D G 2012 *Chin. Phys.* B **21** 084207
[8] Huang Z H, Chen A X, Chen Z C and Deng L 2010 *Chin. Phys.* B **19** 124208
[9] Lee C R, Li Y, Men F K, Pao C, Tsai Y and Wang J 2005 *Appl. Phys. Lett.* **86** 201112
[10] Lü X and Wu J 2010 *Phys. Rev.* A **82** 012323
[11] Wu Y and Yang X X 2005 *Phys. Rev.* A **71** 053806
[12] Hang C and Huang G 2008 *Phys. Rev.* A **77** 033830
[13] Barberis-Blostein P 2008 *Phys. Rev.* A **77** 013821
[14] Zhang Y, Brown A W and Xiao M 2007 *Phys. Rev. Lett.* **99** 123603
[15] Wu Y and Yang X X 2007 *Phys. Rev.* A **76** 013832
[16] Wu Y 2005 *Phys. Rev.* A **71** 053820
[17] Joshi A and Xiao M 2007 *Appl. Phys.* B: *Lasers Opt.* **79** 65
[18] Li J H 2007 *Phys. Rev.* B **75** 155329
[19] Li A J, Song X L, Wei X G, Wang L and Gao J Y 2008 *Phys. Rev.* A **77** 053806
[20] Lü X, Li J H, Liu J B and Luo J M 2006 *J. Phys.* B: *At. Mol. Opt. Phys.* **39** 5161
[21] Yang X and Zhu S 2008 *Phys. Rev.* A **77** 063822
[22] Chen A X 2011 *Opt. Express* **19** 11944
[23] Bonifacio R and Lugiato L A 1978 *Phys. Rev.* A **18** 1129
[24] Antón M A, Calderón O G and Carreño F 2003 *Phys. Lett.* A **311** 297
[25] Harris S E 1997 *Phys. Today* **50** 36
[26] Chen J, Liu Z D, Zheng J, Pang W and You S P 2010 *Chin. Phys.* B **19** 044201
[27] Chen A X, Wang Z P, Chen D H and Xu Y Q 2009 *Chin. Phys.* B **18** 1072