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Influence of Kerr Effect on Second-Order Nonlinearity Induced Transparency

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Abstract: We theoretically study the effect of Kerr effect on the second-order nonlinearity induced transparency in a double-resonant optical cavity system. We show that in the presence of the Kerr effect, as the strength of the Kerr effect increases, the absorption curve exhibits an asymmetric-symmetric-asymmetric transition, and the zero absorption point shifts with the increase of the Kerr effect. Furthermore, by changing the strength of the Kerr effect, we can control the width of the transparent window, and the position of the zero-absorption point and meanwhile change the left and right width of the absorption peak. The asymmetric absorption curve can be employed to improve the quality factor of the cavity when the frequency detuning is tuned to be around the right peak. The simple dependence of the zero-absorption point on the strength of Kerr effect suggests that the strength of Kerr effect can be measured by measuring the position of the zero-absorption point in a possible application.

Key words: Kerr effect; second-order nonlinearity induced transparency; nonlinear optics; quantum optics

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0 Introduction

Electromagnetically induced transparency (EIT)^[1] is a technique for turning an opaque medium into a transparent one as a result of quantum interference between two excited processes from independent states. Since it is proposed in the context of atomic systems, the first experimental realization of EIT is also in atomic systems^[2,3]. Recently, Weis *et al.*^[4] realized induced transparency in an optomechanical system for controlling the transport of light through the cavity by coupling a cavity

with a light pulse. This technology is called optomechanically induced transparency (OMIT)^[5-8]. Therefore, searching for possible induced transparent systems has become an active research topic in quantum optics^[9,10].

With recent technological advances, second-order nonlinearities have become a hot research area in modern quantum optics and quantum information processing. Second-order nonlinearity can be achieved with high- $\chi^{(2)}$ nonlinear materials such as III-V semiconductors (e.g., GaAs, GaN, GaP, etc.)^[11,12]. In 2017, Zhou *et al.*^[13] theoretically predicted another form of induced transparency caused by second-order nonlinearity, which

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is called second-order nonlinearity induced transparency (SONIT). They discussed the impact of second-order nonlinearity on SONIT and found that, unlike EIT and OMIT, the absorption spectrum of SOINT exhibits asymmetric features due to the presence of photon asymmetric switching induced by second-order nonlinearity, and a potential application is the measurement of second-order nonlinear coefficients.

In particular, it should be pointed out that introduction of Kerr medium in the optomechanical system can not only enhance the optomechanical coupling, but also prevent the suppression of nonlinearity^[14], which makes the system more excellent in multiple dimensions^[15-17]. Jiao *et al*^[18] found that the frequency shift induced by the Kerr effect leads to an asymmetric OMIT signal absorption window, which may enhance the performance of OMIT devices with various nonlinear optical cavities. Xiong *et al*^[15] introduced the cross-Kerr effect in the optomechanical system, and found that the cross-Kerr effect leads to the asymmetry of the absorption curve, which can be used to design a cavity with a higher quality factor.

Inspired by these studies, we introduce the Kerr medium in the double-resonant optical cavity system to study the influence of the Kerr effect on SONIT. Firstly, the Hamiltonian of the SOINT system including the Kerr effect is given. Secondly, the dispersion and absorption coefficients of the SOINT system are solved by analytical methods. Finally, the influence of the Kerr effect on SOINT is discussed. We find that the absorption curve exhibits an asymmetric-symmetric-asymmetric transition, and the zero absorption point shifts as the Kerr effect increases. The width of the transparent window and the position of the zero-absorption point can be controlled by changing the strength of the Kerr effect. Possible applications of these results are to improve the quality factor of the cavity and to measure the strength of the Kerr effect.

The structure of this paper is as follows. In Section 1, the theoretical model is introduced, the absorption coefficient and dispersion coefficient of the system is obtained by theoretical methods. In Section 2, the influence of the Kerr effect on the SOINT, the position of the zero-absorption point and the width of the transparent window are discussed. In Section 3, a short summary is given.

1 Model and Theoretically Analysis

We consider two single-mode cavities A and B , coupled through a second-order nonlinear medium $\chi^{(2)}$, where the second-order nonlinear medium $\chi^{(2)}$ mediates the conversion of two photons in cavity mode A into one photon in cavity mode B . The frequencies of the two cavity modes are ω_A and ω_B , respectively, and we have $\omega_B = 2\omega_A$. The scheme of a doubly resonant cavity is shown in Fig. 1.

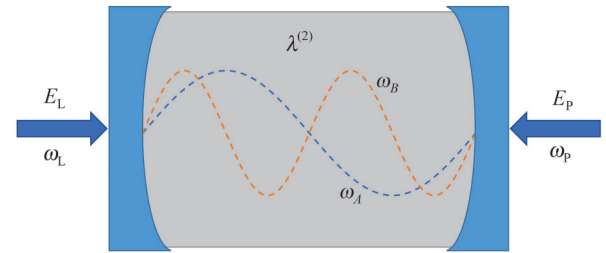


Fig. 1 Scheme of a doubly resonant cavity mode of $\chi^{(2)}$ nonlinearity material

E_L is the driving strength of strong control light, the frequency is ω_L , and E_p is the driving strength of weak probe light, and the frequency is ω_p

Considering the Kerr effect coefficient of the medium is μ , the Hamiltonian of the system can be written as

$$\hat{H} = \omega_A \hat{a}^\dagger \hat{a} + \omega_B \hat{b}^\dagger \hat{b} + g \left[(\hat{a}^\dagger)^2 \hat{b} + \hat{b}^\dagger \hat{a}^2 \right] + \mu \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} + i \left[E_L \hat{a}^\dagger e^{-i\omega_L t} + E_p \hat{b}^\dagger e^{-i\omega_p t} + \text{H.c.} \right] \quad (1)$$

where $\hat{a}^\dagger(\hat{a})$ denotes the creation (annihilation) operator of cavity mode A , $\hat{b}^\dagger(\hat{b})$ denotes the creation (annihilation) operator of cavity mode B , g denotes the coefficient of second-order nonlinear interactions, which can be calculated directly from $\chi^{(2)[13]}$, μ denotes the Kerr effect coefficient of the medium. The last term of Eq. (1) represents the two drives of the external light to the cavity, one is the strong control light, the intensity is E_L , the frequency is ω_L , and the other is the weak probe light, the intensity is E_p , and the frequency is ω_p .

To study the dynamics of the system, we want to turn to a rotating framework dominated by operators $\hat{U}(t) = \exp \left[i\omega_L t (\hat{a}^\dagger \hat{a} + 2\hat{b}^\dagger \hat{b}) \right]$, then we get an effective Hamiltonian $\hat{H}_{\text{eff}} = \hat{U} \hat{H} \hat{U}^\dagger - i\hat{U} \frac{d\hat{U}^\dagger}{dt}$. The effective Hamiltonian can be written as follows:

$$\begin{aligned} \hat{H}_{\text{eff}} = & \Delta \hat{a}^\dagger \hat{a} + 2\Delta \hat{b}^\dagger \hat{b} + g \left[(\hat{a}^\dagger)^2 \hat{b} + \hat{a}^2 \hat{b}^\dagger \right] + \mu (\hat{a}^\dagger)^2 (\hat{a})^2 \\ & + i \left(E_L \hat{a}^\dagger + E_p e^{-i\Omega t} \hat{b}^\dagger + \text{H.c.} \right) \end{aligned} \quad (2)$$

where $\Delta = \omega_A - \omega_L$, $\Omega = \omega_p - 2\omega_L$.

Using the Heisenberg equations $\frac{\partial \hat{a}}{\partial t} = \frac{1}{i\hbar} [a, H_{\text{eff}}]$

for the cavity variables, here $a = U\hat{a}U^\dagger$. For convenience, we set $\hbar = 1$, then we get

$$\begin{cases} \frac{\partial \hat{a}}{\partial t} = -i \left[\Delta \hat{a} + 2g \hat{a}^\dagger \hat{b} + 2\mu \hat{a}^\dagger (\hat{a})^2 + iE_L \right] - \frac{\gamma_a}{2} \hat{a} + \hat{a}_{\text{in}} \\ \frac{\partial \hat{b}}{\partial t} = -i \left(2\Delta \hat{b} + g \hat{a}^2 + iE_p e^{-i\Omega t} \right) - \frac{\gamma_b}{2} \hat{b} + \hat{b}_{\text{in}} \end{cases} \quad (3)$$

where γ_a and γ_b are decay rates of cavity mode A and cavity mode B , respectively, $\hat{a}_{\text{in}}$ and $\hat{b}_{\text{in}}$ are the corresponding input fields. It is important to point out that the input field has a mean value of zero, that is $\langle \hat{a}_{\text{in}} \rangle = 0$, and $\langle \hat{b}_{\text{in}} \rangle = 0$.

We take the mean values of Eq. (3), and take the notation $\langle \hat{a} \rangle = a$, $\langle \hat{a}^\dagger \rangle = a^*$, and $\langle \hat{b} \rangle = b$, here the asterisk "*" represents complex conjugation. Then Eq. (3) can be rewritten as

$$\begin{cases} \frac{\partial a}{\partial t} = -i \left[\Delta a + 2ga^*b + 2\mu a^2 a^* + iE_L \right] - \frac{\gamma_a}{2} a \\ \frac{\partial b}{\partial t} = -i \left(2\Delta b + ga^2 + iE_p e^{-i\Omega t} \right) - \frac{\gamma_b}{2} b \end{cases} \quad (4)$$

Then we apply the linearization approach by assuming that each operator mean value in the system can be written as a sum of its steady-state mean value and deviations from the stationary state, i.e., $a = \alpha + \delta a$ and $b = \beta + \delta b$. We should note that both δa and δb are small quantity. Considering the control field is much stronger than the probe field, which is $E_L \gg E_p$, E_p is regarded as a small quantity, too.

The steady-state mean values of the system can be obtained from Eq. (4) as

$$\begin{cases} i\Delta \alpha + i2ga^* \beta + i2\mu \alpha^2 \alpha^* - E_L + \frac{\gamma_a}{2} \alpha = 0 \\ i2\Delta \beta + i g \alpha^2 + \frac{\gamma_b}{2} \beta = 0 \end{cases} \quad (5)$$

when the high-order small quantity is ignored, the deviations from the stationary state can be obtained as

$$\begin{cases} \frac{\partial(\delta a)}{\partial t} = -i\Delta \delta a - i2g(\alpha^* \delta b + \beta \delta a^*) \\ \quad - i\mu 2\alpha(2\alpha^* \delta a - \alpha \delta a^*) - \frac{\gamma_a}{2} \delta a \\ \frac{\partial(\delta b)}{\partial t} = -i2\Delta \delta b - i2g\alpha \delta a + E_p e^{-i\Omega t} - \frac{\gamma_b}{2} \delta b \end{cases} \quad (6)$$

For Eq. (5), it is assumed that the solution can be expressed as $\alpha = A_1 + iA_2$ and $\beta = B_1 + iB_2$, where A_1 , A_2 , B_1 , and B_2 are real numbers, and substitute them into Eq. (5), then separate the real and imaginary part, we can get

$$\begin{cases} \Delta A_1 + 2gA_1B_1 + 2gA_2B_2 + 2\mu A_1^3 + 2\mu A_1A_2^2 + \frac{\gamma_a}{2} A_2 = 0 \\ \Delta A_2 + 2gA_1B_2 - 2gA_2B_1 + 2\mu A_1^2A_2 + 2\mu A_2^3 + E_L - \frac{\gamma_a}{2} A_1 = 0 \\ 2\Delta B_1 + gA_1^2 - gA_2^2 + \frac{\gamma_b}{2} B_2 = 0 \\ 2\Delta B_2 + g2A_1A_2 - \frac{\gamma_b}{2} B_1 = 0 \end{cases} \quad (7)$$

To our knowledge, the analytical solution of Eq. (7) is difficult to obtain, we can solve it numerically.

For Eq. (6), we suppose the solutions take the form of

$$\begin{cases} \delta a = A^+ E_p e^{-i\Omega t} + A^- E_p^* e^{i\Omega t} \\ \delta a^* = A^{+*} E_p^* e^{i\Omega t} + A^{*-} E_p e^{-i\Omega t} \\ \delta b = B^+ E_p e^{-i\Omega t} + B^- E_p^* e^{i\Omega t} \\ \delta b^* = B^{+*} E_p^* e^{i\Omega t} + B^{*-} E_p e^{-i\Omega t} \end{cases} \quad (8)$$

By substituting Eq. (8) into Eq. (6), we obtain

$$\begin{cases} \left(\frac{\gamma_a}{2} - i\Omega + i\Delta + i4\mu \alpha \alpha^* \right) A^+ + i2g\alpha^* B^+ \\ \quad + (i2g\beta + i2\mu \alpha^2) A^{*-} = 0 \\ \left(\frac{\gamma_a}{2} + i\Omega + i\Delta + i4\mu \alpha \alpha^* \right) A^- + i2g\alpha^* B^- \\ \quad + (i2g\beta + i2\mu \alpha^2) A^{+*} = 0 \\ \left(\frac{\gamma_b}{2} - i\Omega + i2\Delta \right) B^+ + i2g\alpha A^+ - 1 = 0 \\ \left(\frac{\gamma_b}{2} + i\Omega + i2\Delta \right) B^- + i2g\alpha A^- = 0 \end{cases} \quad (9)$$

The transmission rate of the probe field depends only on B^+ . By solving Eq. (9), we get

$$B^+ = \frac{1}{f_3} - \frac{f_5 f_7 (f_7 f_5 - f_2 f_4)^*}{f_3 \left[(f_5 f_7 - f_1 f_3) (f_5 f_7 - f_2 f_4)^* - f_3 f_6 (f_4 f_6)^* \right]} \quad (10)$$

where $f_1 = \frac{\gamma_a}{2} - i\Omega + i\Delta + i4\mu \alpha \alpha^*$, $f_2 = \frac{\gamma_a}{2} + i\Omega + i\Delta + i4\mu \alpha \alpha^*$, $f_3 = \frac{\gamma_b}{2} - i\Omega + i2\Delta$, $f_4 = \frac{\gamma_b}{2} + i\Omega + i2\Delta$, $f_5 = i2g\alpha^*$, $f_6 = i2g\beta + i2\mu \alpha^2$, and $f_7 = i2g\alpha$.

To simplify the discussion, we can consider that the output of probe light in the cavity is equal to the input probe light minus the light dissipated in the cavity. Applying the input-output relationship of the cavity^[4, 19], we can get the output field

$$b_{\text{out}} = b_{\text{in}} - \sqrt{\gamma_b} b = E_p e^{-i\Omega t} - \sqrt{\gamma_b} (\beta + B^+ E_p e^{-i\Omega t} + B^- E_p^* e^{i\Omega t}) \quad (11)$$

Here, we refer to the probe transmission in the general sense of the ratio of the probe field returned from the system divided by the sent probe field. The transmission rate of the probe field is given by^[4, 19]

$$t_p = \frac{E_p - \sqrt{\gamma_b} E_p B^+}{E_p} = 1 - \sqrt{\gamma_b} B^+ \quad (12)$$

which could be measured by the homodyne technique^[20]. The corresponding quadrature field can be defined as^[21]

$$\varepsilon_T = \sqrt{\gamma_b} B^+ \quad (13)$$

Its real part $\text{Re}[\varepsilon_T]$ is the absorption coefficient, and the imaginary part $\text{Im}[\varepsilon_T]$ is the dispersion coefficient.

2 Results and Discussions

We have learned that, as the Kerr coefficient for third-order nonlinear effects in nonlinear materials^[22-28], it is usually a small quantity. In order to discuss its effect on second-order nonlinearity induced transparency, we use available experimental data to estimate the magnitude of the Kerr nonlinearity coefficient. The Kerr coefficient can be expressed as $\mu = \frac{3(\hbar\omega_0)^2 \chi^{(3)}}{4\varepsilon_0 V_{\text{eff}} \varepsilon_r^2}$ ^[29], where V_{eff}

is the effective cavity mode volume, ω_0 is the frequency of the optical mode, and ε_r is the relative dielectric permittivity.

The highly nonlinear materials currently used in experiments mainly include silicon (Si), germanium (Ge), silicon dioxide (SiO₂) or gallium arsenide (GaAs)^[30]. Typical orders of magnitude for $\chi^{(3)}$ of these materials are in the range of $4 \times 10^{-19} - 4 \times 10^{-18} \text{ m}^2/\text{V}^2$. In addition, larger $\chi^{(3)}$ values can be found in certain nanoparticles-doped glasses, chalcogenide glasses, or other polymeric materials^[31, 32]. For a typical parameter setting, such as the data used in Ref. [29], $\hbar\omega_0 = 1 \text{ eV}$, $V_{\text{eff}} \approx 0.01 \mu\text{m}^3$, $\varepsilon_r = 2.0$, $\chi^{(3)} = 4 \times 10^{-18} \text{ m}^2/\text{V}^2$, then the Kerr coefficient is about $\mu = 3.4 \times 10^{-7} \text{ eV}$. As a typical value for the decay rate of cavity mode A , taking $\gamma_a = 10^9 \text{ s}^{-1}$, we get $\frac{\mu}{\hbar\gamma_a} =$

1.04. Considering that the smaller the value of μ is, the better it can be realized experimentally, we set the value of μ in the range of $0-0.25\gamma_a$ in the follow-up discussion of this article.

Now, we can discuss the influence of Kerr effect on the second-order nonlinearity induced transparency. We plot absorption coefficient $\text{Re}[\varepsilon_T]$ and dispersion coefficient $\text{Im}[\varepsilon_T]$ as a function of frequency detuning Ω/γ_b with different values of Kerr effect coefficient μ , as shown in Fig. 2.

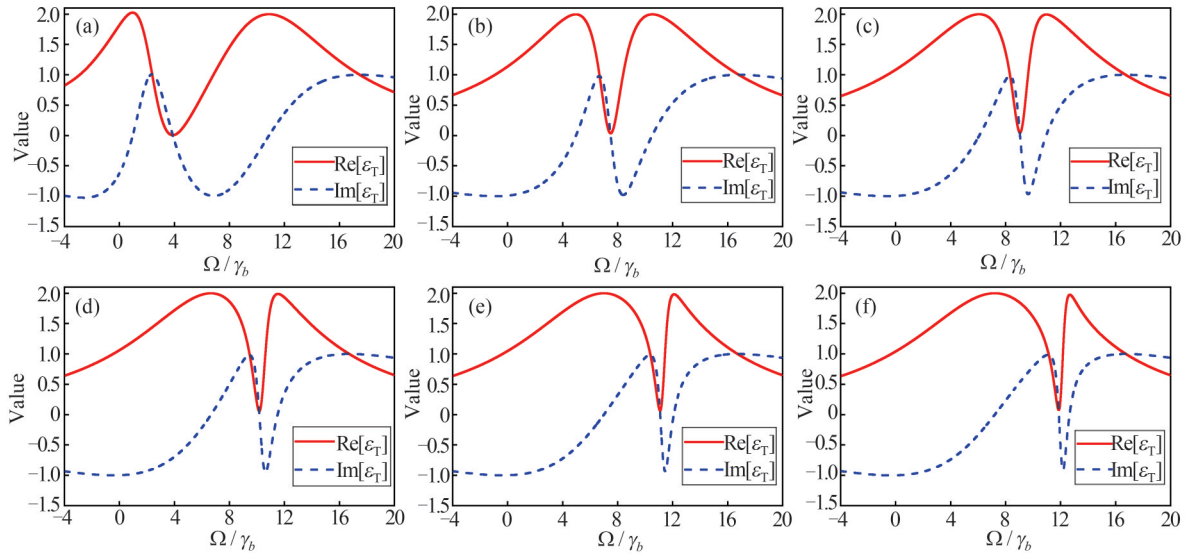


Fig. 2 The absorption coefficient $\text{Re}[\varepsilon_T]$ and dispersion coefficient $\text{Im}[\varepsilon_T]$ as a function of Ω/γ_b with different Kerr effect coefficient μ

(a) $\mu=0$, (b) $\mu=0.05\gamma_a$, (c) $\mu=0.1\gamma_a$, (d) $\mu=0.15\gamma_a$, (e) $\mu=0.2\gamma_a$, and (f) $\mu=0.25\gamma_a$. Values of other parameters are $\gamma_a/\gamma_b = 0.0025$, $g/\gamma_b = 0.004$, $\Delta/\gamma_b = 0.25$, and $E_L/\gamma_b = 7.5$. For convenience, we rescale all the parameters with respect to the decay rate γ_b

First of all, we set $\mu=0$, that is to say, there is no Kerr effect, the corresponding graph of absorption and dispersion coefficients as a function of Ω/γ_b is shown in Fig. 2(a). From Fig. 2(a), it can be concluded that the second-order nonlinearity induced transparency can be observed at point $\Omega/\gamma_b=4$ in the system without Kerr effect. At that point, both absorption coefficient $\text{Re}[\varepsilon_T]$ and dispersion coefficient $\text{Im}[\varepsilon_T]$ are equal to zero, which means that the absorption of the medium is almost zero, and the refractive index of the medium is close to 1, so the medium becomes transparent under the action of a strong coherent field. We have also found that, unlike electromagnetically induced transparency and optomechanically induced transparency, the absorption curve of second-order nonlinearity induced transparency is asymmetric. This is due to the presence of asymmetric switching of photons caused by the second-order nonlinearity.

When Kerr effect is introduced, we set $\mu=0.05\gamma_a$, the position of the zero-absorption point is shifted to $\Omega/\gamma_b=7.48$ and the absorption curve becomes almost symmetric about the zero-absorption point, as shown in Fig. 2(b). This suggests that the Kerr effect can balance the second-order nonlinearity, resulting in a left-right symmetric absorption curve. When the strength of Kerr effect increases, we set $\mu=0.1\gamma_a$, the position of the zero-absorption point moves to $\Omega/\gamma_b=9.04$, as shown in Fig. 2(c), and the absorption peak on the left becomes wider and the absorption peak on the right becomes narrower, the absorption curve becomes asymmetric again. When we further increase the strength of Kerr effect to $\mu=0.15\gamma_a$, the corresponding absorption and dispersion curves are shown in Fig. 2(d). At this time, the position of the zero-absorption point moves to $\Omega/\gamma_b=10.16$, and the absorption peak on the left side continues to widen and the one on the right side further narrows.

We continue to increase the strength of Kerr effect to $\mu=0.2\gamma_a$, in which case the position of the zero-absorption point is moved to $\Omega/\gamma_b=11.08$. When we set Kerr effect $\mu=0.25\gamma_a$, the zero-absorption point is at $\Omega/\gamma_b=11.88$. The corresponding images are shown in Fig. 2(e) and 1(f), respectively. At the same time, we can also see from the Fig. 2(e) and 1(f) that the left absorption peak is getting wider and wider, while the right absorption peak is getting narrower and narrower. Many interesting applications of EIT arise from the spectral properties of dark resonances^[33], i. e., narrow transmission

windows in opaque media. This result suggests that the Kerr effect may be employed to improve the quality factor of the cavity when the frequency detuning Ω/γ_b is tuned to be around the right peak.

Based on the above discussion, we find that the zero-absorption point moves to the right side with the increase of the strength of Kerr effect μ . Therefore, we plot the zero-absorption point Ω_p as a function of μ/γ_a in Fig. 3. Here, we define the point where the absorption coefficient $\text{Re}[\varepsilon_T]$ and the dispersion coefficient $\text{Im}[\varepsilon_T]$ are both equal to zero as zero-absorption point Ω_p . It can be seen from Fig. 3 that the zero absorption point Ω_p first increases rapidly with the enhancement of the Kerr effect strength μ , and then slowly increases with the increase of μ . These results show that by adjusting the strength of Kerr effect, the position of the zero-absorption point can be controlled. The simple dependence shown in Fig. 3 indicates that the strength of Kerr effect can be measured by measuring the position of the zero-absorption point in a possible application.

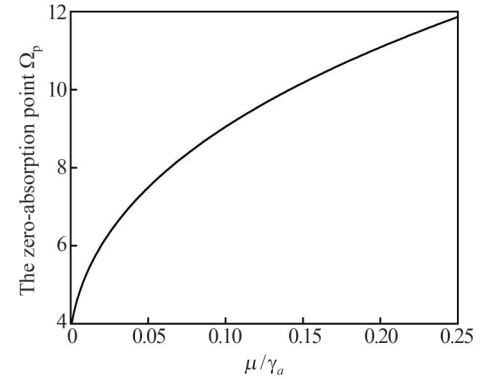


Fig. 3 The zero-absorption point Ω_p as a function of μ/γ_a

The other parameters used are the same as those in Fig. 2

Observing Fig. 2, we can see that the left and right absorption peaks have a maximum value respectively, and the positions of these two maximum values which can be evaluated by

$$\left. \frac{d\text{Re}[\varepsilon_T]}{d\Omega} \right|_{\Omega=\Omega_L} = 0, \quad \left. \frac{d\text{Re}[\varepsilon_T]}{d\Omega} \right|_{\Omega=\Omega_R} = 0 \quad (14)$$

where Ω_L and Ω_R are the two points corresponding to the maximums of the left and right absorption peaks. Here, we define the width of transparent window $d = (\Omega_R - \Omega_L)/\gamma_b$. In order to discuss the variation of the width of transparent window with the Kerr effect strength, we plot the width of transparent window d as a function of μ/γ_a in Fig. 4. We can see from Fig. 4 that, at

the beginning, the width of transparent window d decreases rapidly with the increase of μ . The minimum value of the width of transparent window is $d=4.8368$, and the corresponding Kerr effect strength is $\mu/\gamma_a=0.125$. After that, the width of transparent window increases almost linearly with Kerr effect strength μ . This result also reminds us of the possibility of detecting the Kerr effect strength μ by measuring the width of transparent window d in the absorption spectrum of the output field, which may have important applications in the future.

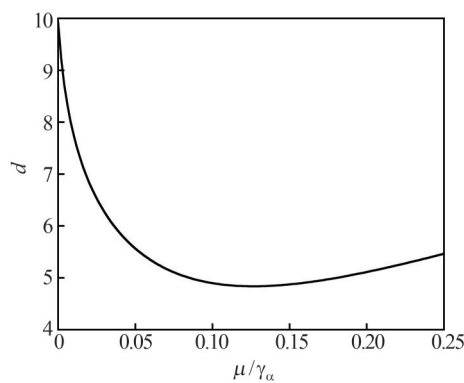


Fig. 4 The width of transparent window d as a function of μ/γ_a

The other parameters used are the same as those in Fig. 2

3 Conclusion

In conclusion, we theoretically investigate the impacts of the Kerr effect on the second-order nonlinearity induced transparency in a double-resonant optical cavity coupled by a second-order nonlinearity material. Concerning the second-order nonlinearity induced transparency phenomenon, we have predicted an asymmetric-symmetric absorption curve transition and a shift of the zero-absorption point with the increasing of Kerr effect strength. This asymmetric absorption curve can be employed to improve the quality factor of the cavity when the frequency detuning is tuned to be around the right peak. The strength of Kerr effect can be measured by measuring the position of the zero-absorption point. Therefore, by changing the strength of the Kerr effect, we can control the width of the transparent window, the position of the zero-absorption point and change the left and right width of the absorption peak, which may have potential practical applications in the future.

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