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Two narrow bandwidth photons interfering in an electromagnetically induced transparency (EIT) system*

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In this paper, we have analysed in detail the quantum interference of the degenerate narrowband two-photon state by using a Mach–Zehnder interferometer, in which an electromagnetically induced transparency (EIT) medium is placed in one of two interfering beams. Our results clearly show that it is possible to coherently keep the quantum state at a single photon level in the EIT process, especially when the transparent window of the EIT medium is much larger than the bandwidth of the single photon. This shows that the EIT medium is possibly a kind of memory or repeater for the narrowband photons in the areas of quantum communication and quantum computer. This kind of experiment is feasible within the current technology.

Keywords: EIT, narrow bandwidth, photons, interference
PACC: 4250, 0367

1. Introduction

How to transform the quantum information from a photon to a matter system and from a matter system back to a photon is the base for realizing the distributed quantum computation and scalable quantum communication protocols.[1] A photon flies at a high speed and has a weak interaction with the environment, therefore the decoherence effect is quite small. The problem is that it is difficult to store photons, so photon can be a very good candidate as an information carrier. On the contrary, the matter has a relatively long decoherence time and is easy to store, therefore it can be a good candidate as a memory. Photons can be easily generated, for example, by using spontaneously parametric downconversion (SPDC) in a nonlinear optical crystal,[2,3] which is the most efficient way by far. A matter system such as an atomic vapour system or a trapped atomic ensemble has shown theoretically and experimentally that it can delay or even stop a photon by electromagnetically induced transparency (EIT), therefore it could be a good candidate for memory.[4−7] Then the following question arises: how can one efficiently realize the coupling between a photon and an atomic matter system in order to achieve the information transfer between them? The basic requirement for efficient coupling is that the bandwidth of the photon should be comparable with that of the atom. The natural linewidth of an atom is at the order of MHz. In the experiments of Refs.[5–7], the photon was generated from spontaneously Raman scattering in an atomic vapour or a cold atomic ensemble, so there is no problem about the bandwidth. As is known, the SPDC is the most accessible and controllable source of the entangled two-photon state and single photon state, therefore it is worth studying how to efficiently couple the photon generated by SPDC with an atomic system. It is well known that the photon prepared by SPDC has a very wide bandwidth, usually THz, which is much wider than that of the natural bandwidth of an atom, so there is no efficient coupling between them. Wen and Rubin[8] have analysed this problem theoretically by using a two-photon interference and shown that the nonclassical coherence can survive the storage due to the EIT effect, but it is difficult to realize this kind of experiment in practice because of the large bandwidth difference, as they stated in their paper. Recently, Ou and Lu [9] have shown a way to suppress the bandwidth of the photon, in which the bandwidth of the photon generated

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by SPDC is comparable with that of an atom, thereby making the efficient coupling possible. They produce a type-I narrow bandwidth two-photon state with an optical parametric oscillation (OPO) far below threshold. The bandwidth is limited by that of the OPO cavity which can be compared with the atomic natural linewidth. In the present paper, we carry out a two-photon interference experiment, in which an atomic ensemble is placed in one of two interfering beams, and the atomic ensemble operates under the condition of EIT. The motivation of this work comes from the fact that very recently, the EIT has been used to realize the quantum storage by turning off the coupling field adiabatically. After a controllable delay, the quantum information is retrieved by turning on the coupling field again.[5−7] Therefore, how to keep the fidelity of the quantum state is very important in this process. The decoherence effects during the storage have been considered in some papers, such as in Refs.[6, 7, 10]. In the present work, we mainly investigate the effect of EIT process on the fidelity of the quantum state by considering the collinear phase matching and using a Mach–Zehnder interferometer (MZI). The first MZI beamsplitter transforms the input two-photon state into two components. One is $|0\rangle_A|2\rangle_B + |2\rangle_A|0\rangle_B$, and the other is $|1\rangle_A|1\rangle_B$, where, A and B refer to the paths the photon goes through. $|0\rangle_A|2\rangle_B$ ($|2\rangle_A|0\rangle_B$) means that two-photon go through the path B (A). $|1\rangle_A|1\rangle_B$ means that there exists one photon in each path. The wavepackets along different paths will overlap and interfere at the second beamsplitter of the MZ interferometer. We will analyse these interferences in this work. We will consider states $|0\rangle_A|2\rangle_B+|2\rangle_A|0\rangle_B$ and $|1\rangle_A|1\rangle_B$ separately. These two cases correspond to the quantum lithography experiment and Hong–Ou Mandle (HOM) interference experiment respectively, which are widely used in quantum information field and quantum optical field. We find that the nonclassical coherence of the SPDC photons can survive after they pass through an EIT medium. It is shown that in the case of $|0\rangle_A|2\rangle_B + |2\rangle_A|0\rangle_B$ the EIT medium acts like a filter and in the case of $|1\rangle_A|1\rangle_B$ the EIT medium will not affect the correlation between two photons so much, therefore the EIT medium is suitable as a kind of memory or repeater for narrow bandwidth photons in the areas of quantum communication and quantum computer. In order to simplify the calculation, we use a constant coupling field instead of a variable coupling field. The rest of the present paper is organized as follows. In Section 2, we discuss the case of state $|0\rangle_A|2\rangle_B + |2\rangle_A|0\rangle_B$. In Section 3, we investigate the case of the state $|1\rangle_A|1\rangle_B$. Finally, we give a brief summary in Section 4.

2. Case of state $|0\rangle_A|2\rangle_B + |2\rangle_A|0\rangle_B$

In our study, we will consider the two-photon state generated from the OPO cavity far below threshold, in which a single photon has a narrow bandwidth. The output operator of a degenerate OPO in resonance is related to the input as follows:[9]

$$\begin{aligned} a_{\rm out}(\omega_0+\nu) &= G_1(\omega)a_{\rm in}(\omega_0+\nu) \\ &\quad +g_1(\omega)a^{\dagger}_{\rm in}(\omega_0-\nu) \\ &\quad +G_2(\omega)b_{\rm in}(\omega_0+\nu) \\ &\quad +g_2(\omega)b^{\dagger}_{\rm in}(\omega_0-\nu), \end{aligned} \tag{1}$$

with

$$\begin{aligned} G_1(\nu) &= \frac{\gamma_1-\gamma_2+2{\rm i}\nu}{\gamma_1+\gamma_2-2{\rm i}\nu}, \\ g_1(\nu) &= \frac{4\epsilon\gamma_1}{(\gamma_1+\gamma_2-2{\rm i}\nu)^2}, \\ G_2(\nu) &= \frac{2\sqrt{\gamma_1\gamma_2}}{\gamma_1+\gamma_2-2{\rm i}\nu}, \end{aligned}$$

and

$$g_2(\nu) = \frac{4\epsilon\sqrt{\gamma_1\gamma_2}}{(\gamma_1+\gamma_2-2{\rm i}\nu)^2}. \tag{2}$$

Where ϵ is the single-pass parametric amplitude gain, and it is proportional to the pump amplitude and the nonlinear coefficient of the crystal used; ω_0 is the degenerate frequency of the OPO; $b_{\rm in}$ represents the vacuum mode; γ_1 and γ_2 are the coupling constants for $a_{\rm in}$ and $b_{\rm in}$, respectively; v is the detuning from the central frequency. Here, we consider only the degenerate type-I down-conversion.

The ensemble considered in our calculation is composed of many identical $\Lambda-$type atoms, their energy levels are shown in Fig.1(a). $\Omega_{\rm c}$ and $\Omega_{\rm p}$ are the Rabi frequencies of the coupling and the probe fields respectively. For simplicity, assume the frequency of coupling field to be resonate with $|b\rangle$ and $|c\rangle$, and the detuning of probe field associated with $|a\rangle$ and $|c\rangle$ is $\Delta = \omega_{\rm ca} - \omega_{\rm p}$, then the linear susceptibility of the probe field given by the following expression[10]

$$\chi = \frac{|\mu_{\rm ac}|^2 N}{\epsilon_0\hbar}\left[\frac{-4\Delta(|\Omega_{\rm c}|^2-4\Delta^2)+4\Delta\gamma_{\rm ba}^2}{\left||\Omega_{\rm c}|^2+(\gamma_{\rm ca}+{\rm i}2\Delta)(\gamma_{\rm ba}+{\rm i}2\Delta)\right|^2}\right.$$
$$\left.+{\rm i}\frac{8\Delta^2\gamma_{\rm ca}+2\gamma_{\rm ba}(|\Omega_c|^2+\gamma_{\rm ac}\gamma_{\rm ba})}{\left||\Omega_c|^2+(\gamma_{\rm ca}+{\rm i}2\Delta)(\gamma_{\rm ba}+{\rm i}2\Delta)\right|^2}\right], \tag{3}$$

where N is the atomic density; $\mu_{\rm ac}$ is the dipole moment; $\gamma_{\rm ca}$ and $\gamma_{\rm ba}$ are the coherence decay rates. One can obtain the spectrum of transmission and the refractive index of the probe field corresponding to the EIT from the susceptibility.[10] After quantizing the probe field, one can obtain the effective Hamiltonian operator:[8]

$$H_{\rm eff} = -\frac{\hbar\omega_{\rm p}}{2}\chi a_{\rm p}^{\dagger}(t)a_{\rm p}(t). \tag{4}$$

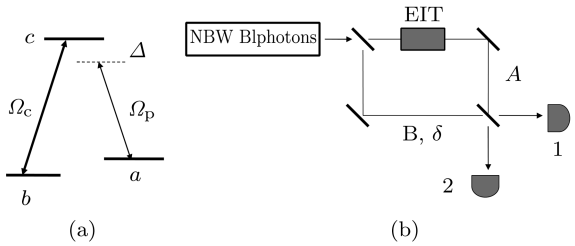


Fig.1. The Λ-type atomic energy levels (a), and the experimental setup we consider in this work (b). The collinear narrow bandwidth of bi-photon is divided into two parts by the first beamsplitter. There exists an EIT medium in one of two paths. The two beams overlap at the second beamsplitter. The outputs will be detected by the two single photon detectors, D1 and D2.

And by solving the Heisenberg equation of $a_{\rm p}$: $\frac{\partial a_{\rm p}}{\partial t} = \frac{1}{{\rm i}\hbar}[a_{\rm p}, H_{\rm eff}]$, the output operator of $a_{\rm p}$ is obtained as

$$a_{\rm p}^{\rm out}(t) = Ta_{\rm p}^{\rm in}(0),$$

where $T = {\rm e}^{-\frac{\chi''\omega_{\rm p}t_0}{2}}{\rm e}^{{\rm i}\frac{\chi'\omega_{\rm p}t_0}{2}}$, $\chi = \chi' + {\rm i}\chi''$, $t_0 = l/c$, and l is the length of atomic ensemble.

Now, we consider the two-photon MZI interference experiment illustrated in Fig.1(b). The output operators at the output ports of the MZI are expressed as

$$E_1^{(+)}(t_1) = \frac{1}{\sqrt{2}}\left(E_{\rm A}^{(+)}(t_1) + {\rm i}E_{\rm B}^{(+)}(t_1+\delta)\right),$$

and

$$E_2^{(+)}(t_2) = \frac{1}{\sqrt{2}}\left(E_{\rm B}^{(+)}(t_2+\delta) + {\rm i}E_{\rm A}^{(+)}(t_2)\right), \tag{5}$$

where $E_{\rm A}^{(+)}(t) = \frac{1}{\sqrt{2\pi}}\int {\rm d}\omega T a_A(\omega){\rm e}^{-{\rm i}\omega t}$, $E_B^{(+)}(t) = \frac{1}{\sqrt{2\pi}}\int {\rm d}\omega a_B(\omega){\rm e}^{-{\rm i}\omega t}$, $E^{(+)}(t+\delta) = {\rm e}^{-{\rm i}\omega_0\delta}E^{(+)}(t)$, and δ is the time delay relative to the EIT medium. To find the correlation between two outputs of MZI, we calculate the intensity correlation function defined as[11]

$$\begin{aligned}
&\Gamma \\
&= \left\langle E_1(t_1)E_2(t_2)E_2^{\dagger}(t_2)E_1^{\dagger}(t_1)\right\rangle \\
&= \left\| \frac{1}{2}\left[E_B^{\dagger}(t_1+\delta)E_B^{\dagger}(t_2+\delta) + E_A^{\dagger}(t_1)E_A^{\dagger}(t_1)\right]|\Psi\rangle \right\|^2 \\
&\quad + \left\| \frac{1}{2}\left[E_B^{\dagger}(t_1+\delta)E_A^{\dagger}(t_2)\right.\right. \\
&\quad \left.\left. -E_A^{\dagger}(t_1)E_B^{\dagger}(t_2+\delta)\right]|\Psi\rangle \right\|^2 \\
&= \Gamma_1 + \Gamma_2,
\end{aligned} \tag{6}$$

where $\Gamma_1 = \left\| \frac{1}{2}\left[E_B^{\dagger}(t_1+\delta)E_B^{\dagger}(t_2+\delta) + E_A^{\dagger}(t_1)E_A^{\dagger}(t_1)\right]|\Psi\rangle \right\|^2$, and $\Gamma_2 = \left\| \frac{1}{2}\left[E_B^{\dagger}(t_1+\delta)E_A^{\dagger}(t_2) - E_A^{\dagger}(t_1)\,E_B^{\dagger}(t_2+\delta)\right]|\Psi\rangle \right\|^2$ with Γ_1 corresponding to the correlation function of the state $|0\rangle_A|2\rangle_B + |2\rangle_A|0\rangle_B$ which will be analysed in this section, and Γ_2 corresponding to the state $|1\rangle_A|1\rangle_B$ which gives the HOM interference and will be analysed in next section.

In the following, we will calculate three different values of Γ_1 corresponding to three different cases: without an EIT medium (the first case); with a narrow transparency EIT window (the second case); and with a wide transparency EIT window (the third case).

In the first case, the coincidence count can be calculated from the following expression:

$$\begin{aligned}
R_{\rm cc}^{\rm vac} &= \frac{1}{T}\int_0^T {\rm d}t_1 \int_0^T {\rm d}t_2 \Gamma_1^{\rm vac} \\
&\cong \int [G_1(\nu)g_1(-\nu) + G_2(\nu)g_2(-\nu)] \\
&\quad \times {\rm d}\nu^2(1+\cos(2\omega_0\delta).
\end{aligned} \tag{7}$$

In the second and third cases,

$$\begin{aligned}
R_{\rm cc}^{\rm EIT} &= \frac{1}{T}\int_0^T {\rm d}t_1 \int_0^T {\rm d}t_2 \Gamma_1^{\rm EIT} \\
&\cong \int {\rm d}\nu\,|G_1(\nu)g_1(-\nu) + G_2(\nu)g_2(-\nu)|^2 \\
&\quad + \int {\rm d}\nu\,|G_1(\nu)g_1(-\nu) + G_2(\nu)g_2(-\nu)|^2 \\
&\quad \times {\rm e}^{-2\omega_0 t_0\chi''(\nu)} \\
&\quad + 2{\rm Re}\left({\rm e}^{2{\rm i}\omega_0\delta}\int {\rm d}\nu |G_1(\nu)g_1(-\nu) \right. \\
&\quad \left. + G_2(\nu)g_2(-\nu)|^2 {\rm e}^{-\omega_0 t_0\chi''(\nu)} \right),
\end{aligned} \tag{8}$$

where the terms of the higher order of $|\epsilon|^2$ in expressions (7) and (8) have been dropped, since $|\epsilon| \ll$

$\gamma_1 + \gamma_2$. For simplicity, we assume $\gamma_{ca} = 15 \times 10^6$ rad/s, $\gamma_1 = 50 \times 10^6$ rad/s, $\gamma_2 = 0$, and $\gamma_{ba} = 0$ (we have also investigated the case of $\gamma_{ba} \neq 0$, and we find the results to be almost the same as those in the case of $\gamma_{ba} = 0$). We have calculated the coincidence rates in three cases and made a comparison between the coincidence counting rate in the first case respectively with that in the second case and with that in the third case, which are shown in Fig.2. From Fig.2, one can see that the joint detection probability exhibits a cosine modulation. The visibilities of the three different cases are different. In Figs.2(a) and 2(b), the parameters used for calculation are as follows: the values of EIT width of transparency window $\Delta\omega_{tr}$ are about 16 and 145 MHz, the values of Rabi frequency of coupling field Ω_c are 40 and 120 MHz, respectively, and the full width at half-maximum (FWHM) of the single photon band, $\Delta\omega_p$, is about 35 MHz. We can see clearly that when $\Delta\omega_{tr} \ll \Delta\omega_p$, the visibility V is small (for example in Fig.2(a) $V = 69\%$). This is because the EIT medium here acts like a filter which modifies the spectrum of the photon through the EIT medium, which make the two-photon wavepackets along the two interfering beams distinguishable, therefore the visibility is lower. When $\Delta\omega_{tr} \gg \Delta\omega_p$, all photons are in the transparency window, so the EIT medium has no effect on the photons, i.e. it does not affect the visibility of interference as shown in Fig.2(b). One can see that the visibility in Fig.2(b) is almost equal to that in Fig.2(c) which represents the case without the EIT medium in the MZI.

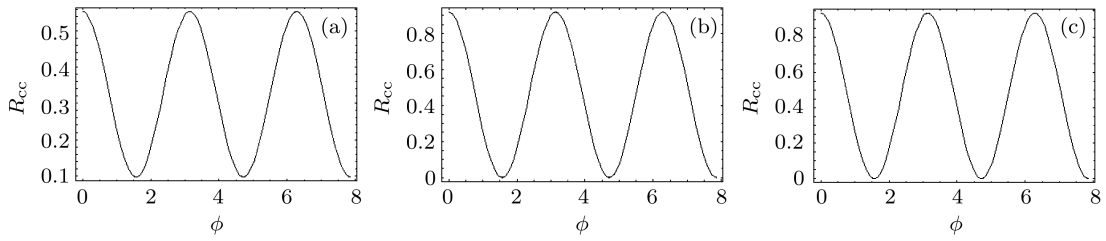


Fig.2. Two-photon coincidence counting (R_{cc}, in arbitrary units) for state $|0\rangle_A |2\rangle_B + |2\rangle_A |0\rangle_B$. $\phi = 2\omega_0\delta$ where δ is the time delay relative to the EIT medium. The atoms we used here are rubidium atoms. In the calculation, we assume $N = 2 \times 10^{16}/\mathrm{m}^3$, $\gamma_{ca} = 15 \times 10^6$ rad/s, $\gamma_1 = 50 \times 10^6$ rad/s, $\gamma_2 = \gamma_{ba} = 0$. (a) $\Delta\omega_{tr} \ll \Delta\omega_p$($\Delta\omega_{tr} = 40$ MHz, $\Delta\omega_p = 35$ MHz). The visibility V is about 69%. (b) $\Delta\omega_{tr} \gg \Delta\omega_p$ ($\Delta\omega_{tr} = 145$ MHz, $\Delta\omega_p = 35$ MHz). V is nearly 100%. (c) Without EIT medium in the MZI.

3. Case of state $|1\rangle_A |1\rangle_B$

In this section, we will show the effect of the EIT medium in HOM interference, which is more complex than in the case of $|0\rangle_A |2\rangle_B + |2\rangle_A |0\rangle_B$. The large bandwidth case has been discussed by Wen and Rubin.[8] In this section, we calculate two interesting parameters. One is the coincidence counting rate R_{cc}^{HOM}, and the other is the intensity correlation function $\Gamma(\tau)$. Time resolution of the detector, Δt, can be much small than τ, because of the long wavepacket of the narrow bandwidth photon. The R_{cc}^{HOM} can be expressed as

$$\begin{aligned} R_{cc}^{HOM} &= \frac{1}{T}\int_0^T \mathrm{d}t_1 \int_0^T \mathrm{d}t_2 \Gamma_2^{EIT} \\ &\cong \int \mathrm{d}\nu \left|G_1(\nu)g_1(-\nu) + G_2(\nu)g_2(-\nu)\right|^2 \\ &\quad \times \mathrm{e}^{-\omega_0 t_0 \chi"(\nu)} \\ &\quad \times [1 - \cos(-\chi'(\nu)\omega_0 t_0 + 2\nu\delta)]. \end{aligned} \tag{9}$$

The parameters used here are $\gamma_{ca} = 15 \times 10^6$ rad/s, $\gamma_1 = 50 \times 10^6$ rad/s, $\gamma_2 = 0$, $\gamma_{ba} = 0$, and $\Omega_c = 40$ MHz. One can see that in Fig.3(a), there are only a few oscillations on the left side of the HOM dip. A slight modulation to the shape of the dip means that the correlation between two photons is preserved well. Another interesting thing is that when γ_{ca} increases to 60×10^6 rad/s and Ω_c is still 40 MHz, the oscillation on the left side of the dip disappears as shown in Fig.3(b). This is a complete HOM dip without any oscillation on both sides. It is known that the γ_{ca} of cold Rubidium atoms is about 60×10^6 rad/s, so in an actual system the EIT medium will not affect the correlation between the two photons. In our calculation, we also make Ω_c large, for example, we let $\Omega_c = 120$ MHz, then we find that the dip becomes standard HOM dip as shown in Fig.3(c). This shows that if the transparency width is large enough, the EIT effect can be neglected. When the Rabi frequency Ω_c decreases to

20 MHz, there are some strong oscillations appearing on the right side of HOM dip as shown in Fig.3(d). In our calculation, when we decrease the integral area of ν, the oscillation disappears. These results show that this phenomenon is strongly related to the competition between the bandwidth of the single photon $\Delta\omega_{\rm p}$ and transparent window of EIT $\Delta\omega_{\rm tr}$. In the photon storage experiments, one controls the $\Omega_{\rm c}$ adiabatically to transfer quantum information of photons to an atomic ensemble.[12,13] From our calculation, we see that $\Omega_{\rm c}$ should be large enough initially. If the transparency width is much smaller than the bandwidth of photons, the EIT medium will change the correlation between photons. Because the spectrum of probe pulse narrows in proportion to the group speed, and the spectrum of the probe pulse stays within the transparency window at all times, provided that $\Omega_{\rm c}$ reduces adiabatically. To ensure that the photons lie in the transparency window initially, the correlation between the two photons can be preserved. In addition, the different widths of the dip come from the different transparency widths.

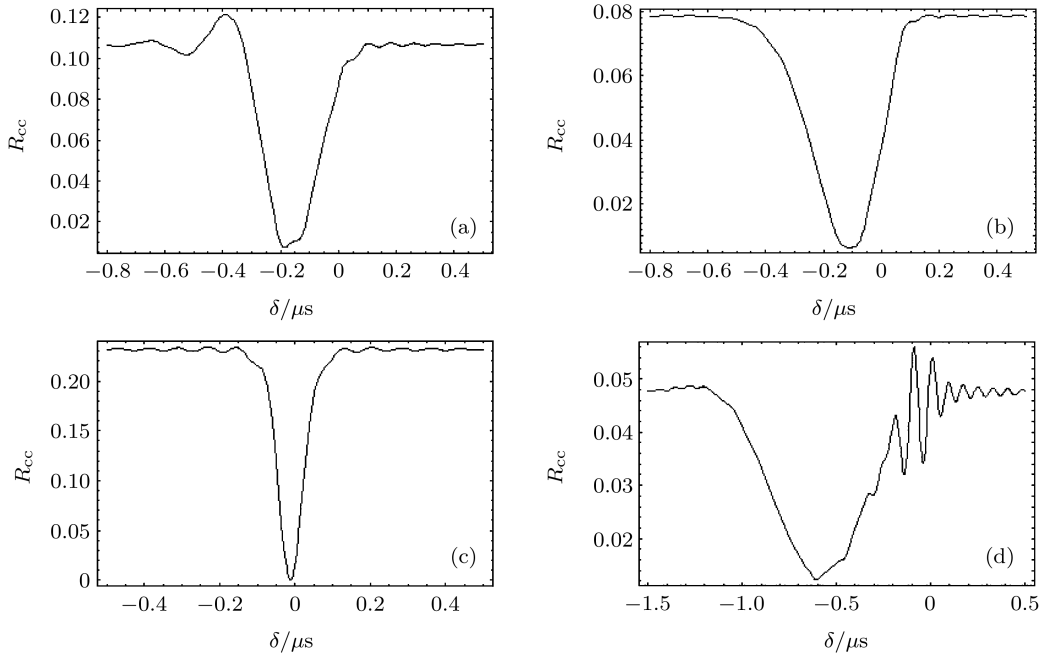


Fig.3. Two-photon coincidence counting rate ($R_{\rm cc}$, in arbitrary units) for state $|1\rangle_A|1\rangle_B$. δ is the time delay relative to the EIT medium. We assume $N = 2\times10^{16}/{\rm m}^3$, $\gamma_{\rm ca} = 15\times10^6$ rad/s, $\gamma_1 = 50\times10^6$ rad/s, $\gamma_2 = \gamma_{\rm ba} = 0$. (a) When $\Omega_{\rm c}$ is 40 MHz, there are some oscillations on the left side of the HOM dip. The group speed $V_{\rm g} = 0.89\times10^5$ m/s (b) When $\gamma_{\rm ca}$ increases to 60×10^6 rad/s, the oscillations on both sides of the dip disappear. It is a complete HOM dip. $V_{\rm g} = 0.8\times10^4$ m/s (c) When $\Omega_{\rm c}$ is 120 MHz, the dip becomes a standard HOM dip. $V_{\rm g} = 8.0\times10^5$ m/s (d) When $\Omega_{\rm c}$ decreases to 20 MHz, there are some oscillations appearing on the right side of the dip. $V_{\rm g} = 0.22\times10^5$ m/s.

We also calculate the intensity correlation function $\Gamma_2(\tau)$ that is given as

$$\Gamma_2(\tau) \cong \left| \int {\rm e}^{\frac{-\omega_0 t_0 \chi''(\nu)}{2}} [G_1(\nu)g_1(-\nu) + G_2(\nu)g_2(-\nu)] \times \left({\rm e}^{-{\rm i}[\nu(\tau-\delta) - \frac{\chi'(\nu)\omega_0 t_0}{2}]} - {\rm e}^{-{\rm i}\left[\nu(\tau+\delta) + \frac{\chi'(\nu)\omega_0 t_0}{2}\right]} \right) \right|^2, \quad (10)$$

where $\tau = t_2 - t_1$.

The parameters used here are $\gamma_{\rm ca} = 15\times10^6$ rad/s, $\gamma_1 = 50\times10^6$ rad/s, $\gamma_2 = 0$, $\gamma_{\rm ba} = 0$ and $\Omega_{\rm c} = 45$ MHz in Fig.4(a), $\Omega_{\rm c} = 200$ MHz in Fig.4(b). The results also show clearly the difference between the case of narrow transparency window ($\Omega_{\rm c}$ is small) and the case of wide one ($\Omega_{\rm c}$ is large), and they are the same as those for $R_{\rm cc}$ calculated before. When $\Omega_{\rm c}$ is small, there appear slight oscillations, and when $\Omega_{\rm c}$ is large the dip evolves into a complete HOM dip.

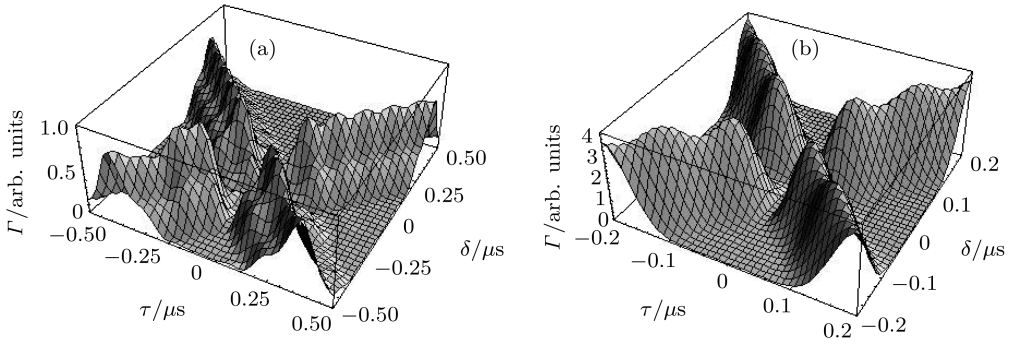


Fig.4. Two-photon intensity function Γ of state $|1\rangle_A |1\rangle_B$. The parameters used here are $\tau = t_2 - t_1$, $N = 2 \times 10^{16}/\mathrm{m}^3$, $\gamma_{\mathrm{ca}} = 15 \times 10^6$ rad/s, $\gamma_1 = 50 \times 10^6$ rad/s, $\gamma_2 = \gamma_{\mathrm{ba}} = 0$. (a) When Ω_{c} is 45 MHz, there are some oscillations on the side of the hole. (b) When Ω_{c} is 200 MHz, the hole becomes a complete HOM hole, which looks like the one without EIT medium.

4. Conclusion

In this paper, we have analysed in detail the quantum interference of the degenerate narrowband two-photon state by using a Mach–Zehnder interferometer, and an EIT medium is placed in one of two interfering beams. Our results clearly show that it is possible to coherently store and retrieve the light at a single photon level, especially when the transparent window of the EIT medium is much larger than the bandwidth of the single photon. So the EIT medium is suitable as a kind of memory or repeater for narrowband photons in quantum communication and quantum computer areas. This kind of experiment is feasible within the current technology.

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