Absorption and dispersion control in a five-level M-type atomic system*

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We investigate the steady optical response of a coherently driven five-level M-type atomic system in three different situations. When all three coupling fields have the same zero detuning, we just find one deep transparency window accompanied by a steep normal dispersion in the probe absorption and dispersion spectra. When two coupling fields are detuned from the relevant transitions to the same extent, however, a second deep transparency window may be observed in the presence of a narrow absorption line of linewidth ~ 50 kHz. In this case, two single-photon far-detuned transitions can be replaced by a two-photon resonant transition, so the five-level M system in fact reduces into a four-level quasi-Λ system. Finally, we note that no deep transparency windows and no narrow absorption lines can be found when all three coupling fields have unequal detunings.

Keywords: electromagnetically induced transparency, absorption and dispersion control, narrow spectral linewidth

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1. Introduction

Electromagnetically induced transparency (EIT) is an efficient technique for controlling atomic absorption and dispersion with laser induced quantum destructive interference.[1,2] The essence of EIT is to modify the resonant interaction of light and matter on demand by establishing quantum coherence and correlation between relevant atomic states. EIT has important applications in many aspects, such as light storage and retrieval,[3,4] lasing without population inversion,[5,6] all-optical fast switching,[7,8] electromagnetically induced focusing and defocusing,[9] spontaneous emission control,[10−12] and quantum computation and communication.[13−15] This is why EIT has been extensively studied in different circumstances, e.g., free space,[16,17] photonic crystals,[18,19] optical lattices,[20] and optical cavities.[21−24] In an EIT medium, all atoms may evolve into a simple or composite dark state[25−27] almost decoupled from the dissipative processes, which then allows weak light signals to freely travel or mutually interact with little loss. One prominent property of diverse EIT media is that extremely narrow spectral lines (either dark or bright) can be attained and applied in the precise measurement of atomic transition frequencies.[28−30] For instance, the EIT technique has been explored by Yang *et al.* to investigate the double-resonance optical pumping spectrum of sub-natural linewidth in a cesium vapor.[31,32] It is worth noting that double EIT as a direct extension of single EIT may provide us with additional freedoms, e.g., to realize ground-state laser cooling without blue-sideband heating,[33] to show the dynamic manipulation of a stand-still light having two frequency components,[34] to control the coupled harmonic oscillators and RLC (resistor, inductor, capacitor) circuits in the mechanical and electrical analogies.[35] Double EIT[36−40] is also important in quantum information processing, because it allows the simultaneous storage of two light fields, the temporarily bifurcation of a light field, the entanglement generation based on the cross-phase modulation, the quantum switching via enhanced four-wave-mixing, etc.[41−46] Note in particular that double EIT has been analyzed and discussed in the tripod system, the N system, the double-Λ system, and the inverted-Y system respectively.[35−40] Double or multiple EIT may also be attained in a three-level Λ system driven by multicolor coupling and probe

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fields,[47,48] which opens the multiple transition channels for a two-photon Raman process. The interference between these channels could result in rather rich spectral features depending on the relative phases of the multicolor coupling and probe fields. It is worth stressing that the sub-half-wavelength atom localization may be realized when one component of the multicolor coupling field is in a standing-wave configuration.[49,50]

In this paper, we study the absorption and dispersion properties of a five-level M-type atomic system, which may display double EIT features with narrow spectral lines. Our numerical calculations show that one deep EIT window accompanied by a steep dispersion of refractive index can be found in the probe absorption and dispersion spectra when all three coupling fields have vanishing detunings. Turning off one coupling field to reduce the five-level M system into a four-level N system, we find that a third absorption line arises at the probe resonance, which then conceals the EIT window. To recover the EIT window, we may further reduce the four-level N system into a three-level Λ system by turning off the second coupling field. A third absorption line can also be induced by setting equal nonzero detunings for the last two coupling fields without turning off any coupling fields in the five-level M system. In this case, the EIT window is well preserved on one side of the third absorption line, and a new absorption dip is found on the other side of the third absorption line. It is of particular interest that the third absorption line will become extremely narrow ($\sim$ 50 kHz) and the new absorption dip will turn into a second EIT window when the last two coupling fields have sufficiently large detunings. The underlying physics is that the five-level M system can be regarded as a four-level quasi-Λ system when two single-photon far-detuned transitions are replaced by a two-photon resonant transition. If all three coupling fields have unequal detunings, however, no deep EIT windows, no narrow absorption lines, and no steep dispersion of refractive index can be found in the probe absorption and dispersion spectra.

2. Theoretical models and equations

We consider here a five-level atomic system driven into the M configuration by four monochromatic laser fields, as shown in Fig. 1(a). A weak laser field of amplitude $E_{\rm p}$ and frequency $\omega_{\rm p}$ probes the transition $|1\rangle \leftrightarrow |2\rangle$. Three strong laser fields of amplitudes $E_{\rm c1}$, $E_{\rm c2}$, $E_{\rm c3}$ and frequencies $\omega_{\rm c1}$, $\omega_{\rm c2}$, $\omega_{\rm c3}$ are coupled to transitions $|2\rangle \leftrightarrow |3\rangle$, $|3\rangle \leftrightarrow |4\rangle$, $|4\rangle \leftrightarrow |5\rangle$, respectively. Single-photon detunings of the probe and the coupling fields are defined as $\Delta_{\rm p} = \omega_{21} - \omega_{\rm p}$, $\Delta_{\rm c1} = \omega_{23} - \omega_{\rm c1}$, $\Delta_{\rm c2} = \omega_{43} - \omega_{\rm c2}$, and $\Delta_{\rm c3} = \omega_{45} - \omega_{\rm c3}$, respectively, with ω_{ij} being the transition frequency between levels $|i\rangle$ and $|j\rangle$. The Rabi frequencies of the probe and the coupling fields are described by $\Omega_{\rm p} = E_{\rm p} \cdot d_{12}/2\hbar$, $\Omega_{\rm c1} = E_{\rm c1} \cdot d_{32}/2\hbar$, $\Omega_{\rm c2} = E_{\rm c2} \cdot d_{34}/2\hbar$, and $\Omega_{\rm c3} = E_{\rm c3} \cdot d_{54}/2\hbar$, respectively, with d_{ij} being the dipole moment of transition $|i\rangle \leftrightarrow |j\rangle$.

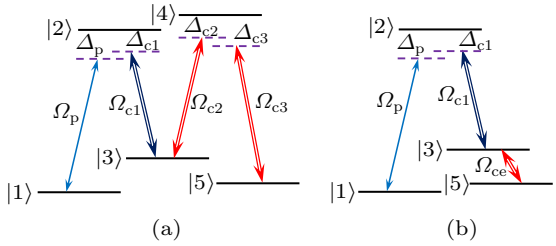


Fig. 1. (colour online) (a) Schematic diagram of a five-level M system interacting with one weak probe field $\Omega_{\rm p}$ ($\Delta_{\rm p}$) and three moderate coupling fields $\Omega_{\rm c1}$ ($\Delta_{\rm c1}$), $\Omega_{\rm c2}$ ($\Delta_{\rm c2}$), and $\Omega_{\rm c3}$ ($\Delta_{\rm c3}$). (b) Schematic diagram of a four-level quasi-Λ system attained by eliminating level $|4\rangle$ in the case of $|\Omega_{\rm c2} \approx \Omega_{\rm c3}| \ll |\Delta_{\rm c2} \approx \Delta_{\rm c3}|$. The $\Omega_{\rm ce} = \Omega_{\rm c2}^{*}\Omega_{\rm c3}/\Delta_{\rm c3}$ is the effective Rabi frequency on the two-photon resonant transition $|3\rangle \leftrightarrow |5\rangle$.

Under the rotating-wave and the electric-dipole approximations, we first write down the interaction Hamiltonian

$$\begin{aligned} H_5 =& \hbar(\Delta_{\rm p}|2\rangle\langle 2| + \delta_2|3\rangle\langle 3| + \delta_3|4\rangle\langle 4| + \delta_4|5\rangle\langle 5|) \\ & -\hbar(\Omega_{\rm p}|2\rangle\langle 1| + \Omega_{\rm c1}|2\rangle\langle 3| + \Omega_{\rm c2}|4\rangle\langle 3| \\ & +\Omega_{\rm c3}|4\rangle\langle 5| + {\rm h.c.}), \end{aligned} \tag{1}$$

where $\delta_2 = \Delta_{\rm p} - \Delta_{\rm c1}$, $\delta_3 = \Delta_{\rm p} - \Delta_{\rm c1} + \Delta_{\rm c2}$, and $\delta_4 = \Delta_{\rm p} - \Delta_{\rm c1} + \Delta_{\rm c2} - \Delta_{\rm c3}$ denote two-photon, three-photon, and four-photon detunings of the probe and the coupling fields from level $|1\rangle$ to levels $|3\rangle$, $|4\rangle$, and $|5\rangle$, respectively. After substituting H_5 into the master equation of motion for the density operator, we attain the following dynamic equations for 5×5 density matrix elements:

$$\partial_t\rho_{11} = -{\rm i}\Omega_{\rm p}\rho_{12} + {\rm i}\Omega_{\rm p}^{*}\rho_{21} + \Gamma_{21}\rho_{22}, \tag{2}$$

$$\begin{aligned} \partial_t\rho_{12} =& -(\gamma_{12} - {\rm i}\Delta_{\rm p})\rho_{12} + {\rm i}\Omega_{\rm p}^{*}(\rho_{22} - \rho_{11}) \\ & -{\rm i}\Omega_{\rm c1}^{*}\rho_{13}, \end{aligned} \tag{3}$$

$$\begin{aligned} \partial_t\rho_{13} =& -(\gamma_{13} - {\rm i}\delta_2)\rho_{13} + {\rm i}\Omega_{\rm p}^{*}\rho_{23} - {\rm i}\Omega_{\rm c1}\rho_{12} \\ & -{\rm i}\Omega_{\rm c2}\rho_{14}, \end{aligned} \tag{4}$$

$$\begin{aligned} \partial_t\rho_{14} =& -(\gamma_{14} - {\rm i}\delta_3)\rho_{14} + {\rm i}\Omega_{\rm p}^{*}\rho_{24} - {\rm i}\Omega_{\rm c2}^{*}\rho_{13} \\ & -{\rm i}\Omega_{\rm c3}^{*}\rho_{15}, \end{aligned} \tag{5}$$

$$\partial_t\rho_{15} = -(\gamma_{15}-\mathrm{i}\delta_4)\rho_{15}+\mathrm{i}\Omega_{\mathrm{p}}^*\rho_{25}-\mathrm{i}\Omega_{\mathrm{c3}}\rho_{14}, \quad (6)$$

$$\partial_t\rho_{22} = -\mathrm{i}\Omega_{\mathrm{p}}^*\rho_{21}+\mathrm{i}\Omega_{\mathrm{p}}\rho_{12}-\mathrm{i}\Omega_{\mathrm{c1}}^*\rho_{23}+\mathrm{i}\Omega_{\mathrm{c1}}\rho_{32} -(\Gamma_{21}+\Gamma_{23})\rho_{22}, \quad (7)$$

$$\partial_t\rho_{23} = -(\gamma_{23}+\mathrm{i}\Delta_{\mathrm{c1}})\rho_{23}+\mathrm{i}\Omega_{\mathrm{p}}\rho_{13}-\mathrm{i}\Omega_{\mathrm{c2}}\rho_{24} +\mathrm{i}\Omega_{\mathrm{c1}}(\rho_{33}-\rho_{22}), \quad (8)$$

$$\partial_t\rho_{24} = -(\gamma_{24}+\mathrm{i}\Delta_{\mathrm{c1}}-\mathrm{i}\Delta_{\mathrm{c2}})\rho_{24}+\mathrm{i}\Omega_{\mathrm{p}}\rho_{14}+\mathrm{i}\Omega_{\mathrm{c1}}\rho_{34} -\mathrm{i}\Omega_{\mathrm{c2}}^*\rho_{23}-\mathrm{i}\Omega_{\mathrm{c3}}^*\rho_{25}, \quad (9)$$

$$\partial_t\rho_{25} = -(\gamma_{25}+\mathrm{i}\Delta_{\mathrm{c1}}-\mathrm{i}\Delta_{\mathrm{c2}}+\mathrm{i}\Delta_{\mathrm{c3}})\rho_{25}+\mathrm{i}\Omega_{\mathrm{p}}\rho_{15} +\mathrm{i}\Omega_{\mathrm{c1}}\rho_{35}-\mathrm{i}\Omega_{\mathrm{c3}}\rho_{24}, \quad (10)$$

$$\partial_t\rho_{33} = -\mathrm{i}\Omega_{\mathrm{c1}}\rho_{32}+\mathrm{i}\Omega_{\mathrm{c1}}^*\rho_{23}-\mathrm{i}\Omega_{\mathrm{c2}}\rho_{34}+\mathrm{i}\Omega_{\mathrm{c2}}^*\rho_{43} +\Gamma_{23}\rho_{22}+\Gamma_{43}\rho_{44}, \quad (11)$$

$$\partial_t\rho_{34} = -(\gamma_{34}-\mathrm{i}\Delta_{\mathrm{c2}})\rho_{34}+\mathrm{i}\Omega_{\mathrm{c1}}^*\rho_{24}-\mathrm{i}\Omega_{\mathrm{c3}}^*\rho_{35} +\mathrm{i}\Omega_{\mathrm{c2}}^*(\rho_{44}-\rho_{33}), \quad (12)$$

$$\partial_t\rho_{35} = -(\gamma_{35}-\mathrm{i}\Delta_{\mathrm{c2}}+\mathrm{i}\Delta_{\mathrm{c3}})\rho_{35}+\mathrm{i}\Omega_{\mathrm{c1}}^*\rho_{25} +\mathrm{i}\Omega_{\mathrm{c2}}^*\rho_{45}-\mathrm{i}\Omega_{\mathrm{c3}}\rho_{34}, \quad (13)$$

$$\partial_t\rho_{44} = -\mathrm{i}\Omega_{\mathrm{c2}}^*\rho_{43}+\mathrm{i}\Omega_{\mathrm{c2}}\rho_{34}-\mathrm{i}\Omega_{\mathrm{c3}}^*\rho_{45}+\mathrm{i}\Omega_{\mathrm{c3}}\rho_{54} -(\Gamma_{43}+\Gamma_{45})\rho_{44}, \quad (14)$$

$$\partial_t\rho_{45} = -(\gamma_{45}+\mathrm{i}\Delta_{\mathrm{c3}})\rho_{45}+\mathrm{i}\Omega_{\mathrm{c2}}\rho_{35} +\mathrm{i}\Omega_{\mathrm{c3}}(\rho_{55}-\rho_{44}). \quad (15)$$

The trace condition $\sum_i \rho_{ii} = 1$ and the conjugation condition $\rho_{ij} = \rho_{ji}^*$ are satisfied. Note that we have phenomenologically added the population decay rates Γ_{ij} and the coherence dephasing rates γ_{ij} into Eq. (2). To be more specific, we have $\gamma_{ij} = (\Gamma_i+\Gamma_j)/2+\gamma_{ij}^{\mathrm{d}}$, with $\Gamma_i = \sum_m \Gamma_{im}$, $\Gamma_j = \sum_n \Gamma_{jn}$, and γ_{ij}^{d} being the pure dephasing rate involving no population decay.

With Eqs. (2)–(15), we can numerically examine the steady optical responses, i.e., absorption and dispersion properties. In particular, the five-level M system may be reduced into a four-level quasi-Λ system (see Fig. 1(b)) if we have $|\Omega_{\mathrm{c2}} = \Omega_{\mathrm{c3}}| \ll |\Delta_{\mathrm{c2}} = \Delta_{\mathrm{c3}}|$. In this case, the two-photon resonant transition $|3\rangle \leftrightarrow |5\rangle$ is dominant over single-photon far-detuned transitions $|3\rangle \leftrightarrow |4\rangle$ and $|4\rangle \leftrightarrow |5\rangle$, we can attain by adiabatically eliminating level $|4\rangle$ the effective interaction Hamiltonian[51,52]

$$H_4 = \hbar(\Delta_{\mathrm{p}}|2\rangle\langle 2|+(\delta_2-\Delta_{s2})|3\rangle\langle 3| +(\delta_4-\Delta_{\mathrm{s3}})|5\rangle\langle 5|)-\hbar(\Omega_{\mathrm{p}}|2\rangle\langle 1| +\Omega_{\mathrm{c1}}|2\rangle\langle 3|+\Omega_{\mathrm{ce}}|3\rangle\langle 5|+\mathrm{h.c.}), \quad (16)$$

where $\Omega_{\mathrm{ce}} = \Omega_{\mathrm{c3}}\Omega_{\mathrm{c2}}^*/\Delta_{\mathrm{c3}}$ is the effective Rabi frequency on the two-photon resonant transition $|3\rangle \leftrightarrow |5\rangle$, and $\Delta_{\mathrm{s2}} = |\Omega_{\mathrm{c2}}|^2/\Delta_{\mathrm{c2}}$ ($\Delta_{\mathrm{s3}} = |\Omega_{\mathrm{c3}}|^2/\Delta_{\mathrm{c3}}$) is the dynamic Stark shift due to the virtual absorption and emission of photons ω_{c2} (ω_{c3}). Substituting H_4 into the master equation of motion for the density operator, we can write down a set of reduced dynamic equations for 4×4 density matrix elements (not shown here). The reduced 4×4 equations and the original 5×5 equations will result in consistent numerical results in the case of $|\Omega_{\mathrm{c2}} = \Omega_{\mathrm{c3}}| \ll |\Delta_{\mathrm{c2}} = \Delta_{\mathrm{c3}}|$.

3. Numerical results and discussion

In Fig. 2, we examine the steady absorption and dispersion spectra on the probe transition by plotting both $\mathrm{Im}(\rho_{12})$ and $\mathrm{Re}(\rho_{12})$ as a function of Δ_{p} with $\Delta_{\mathrm{c1}} = \Delta_{\mathrm{c2}} = \Delta_{\mathrm{c3}} = 0$. As we can see from the black-solid curves, the probe absorption is well eliminated around $\Delta_{\mathrm{p}} = 0$ to result in a narrow and deep EIT window accompanied by a steep normal dispersion of refractive index. The result of $\mathrm{Im}(\rho_{12}) = 0$ at $\Delta_{\mathrm{p}} = 0$ indicates the existence of a composite dark state $|D_1\rangle = [\Omega_{\mathrm{c1}}\Omega_{\mathrm{c3}}|1\rangle - \Omega_{\mathrm{p}}\Omega_{\mathrm{c3}}|3\rangle + \Omega_{\mathrm{p}}\Omega_{\mathrm{c2}}|5\rangle]/\Omega$ with $\Omega = \sqrt{\Omega_{\mathrm{p}}^2\Omega_{\mathrm{c2}}^2+\Omega_{\mathrm{p}}^2\Omega_{\mathrm{c3}}^2+\Omega_{\mathrm{c1}}^2\Omega_{\mathrm{c3}}^2}$ decoupled from the probe field. Purposely setting $\Omega_{\mathrm{c3}} = \Delta_{\mathrm{c3}} = \Gamma_{45} = 0$, we can reduce the five-level M system into a four-level N system, in which a third absorption line is seen to arise at $\Delta_{\mathrm{p}} = 0$ with the dispersion of refractive index modified accordingly (see the red-dashed curves).

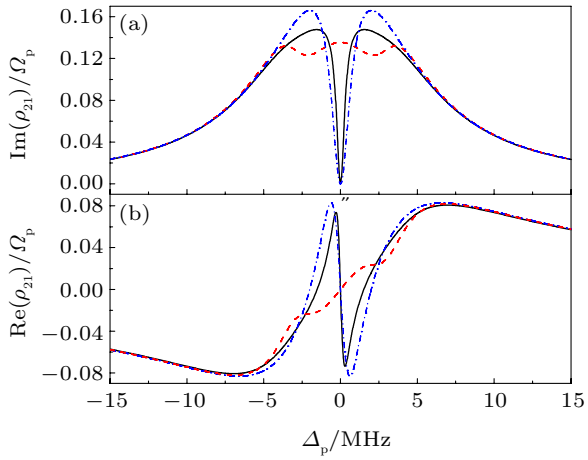


Fig. 2. (colour online) (a) Probe absorption $\mathrm{Im}(\rho_{12})$ and (b) probe dispersion $\mathrm{Re}(\rho_{12})$ each as a function of probe detuning Δ_{p} with $\Omega_{\mathrm{p}} = 1.0$ kHz, $\Omega_{\mathrm{c1}} = 2.0$ MHz, $\Omega_{\mathrm{c2}} = \Omega_{\mathrm{c3}} = 3.0$ MHz, $\Delta_{\mathrm{c1}} = \Delta_{\mathrm{c2}} = \Delta_{\mathrm{c3}} = 0.0$ MHz, $\Gamma_{21} = \Gamma_{23} = \Gamma_{43} = \Gamma_{45} = 6.0$ MHz, and $\gamma_{13}^{\mathrm{d}} = \gamma_{15}^{\mathrm{d}} = \gamma_{35}^{\mathrm{d}} = 1.0$ kHz. The black-solid, red-dashed, and blue-dotted curves correspond to the five-level M system, the four-level N system, and the three-level Λ system, respectively.

The absence of narrow and deep EIT windows between any two absorption lines means that the four-level N system is always in bright states interacting (i.e., communicating energy) with the probe field. Further setting $\Omega_{c2} = \Delta_{c2} = \Gamma_{43} = 0$ to attain a three-level Λ system, we are allowed to recover the narrow and deep EIT window at $\Delta_p = 0$ accompanied by a steep normal dispersion of refractive index (see the blue-dotted curves), which corresponds to a simple dark state $|D_2\rangle = [\Omega_{c1}|1\rangle - \Omega_p|3\rangle]/\Omega$ with $\Omega = \sqrt{\Omega_p^2 + \Omega_{c1}^2}$ instead. With these numerical results, we may conclude that a dark state always exists in the chain-like multiple Λ system but suddenly disappears when the last coupling field is turned off to decouple the last level from the others.

In Fig. 3, we examine the steady spectra of probe absorption and dispersion in another case, where $\Delta_{c1} = 0.0$ MHz but $\Delta_{c2} = \Delta_{c3} = 10$ MHz (black-solid curves), 20 MHz (red-dashed curves), or 100 MHz (blue-dotted curves). As can be seen, a third absorption line arises near $\Delta_p = 0$ yet without destroying the EIT window, i.e., without leading to more absorption at $\Delta_p = 0$. Note in particular that the new absorption line becomes narrower and narrower when $\Delta_{c2} = \Delta_{c3}$ is gradually increased to exceed $\Omega_{c2} = \Omega_{c3}$. In addition, we can find a clear absorption dip at the right hand of this new absorption line, which tends to be as deep as the EIT window for $\Delta_{c2} = \Delta_{c3} \gg \Omega_{c2} = \Omega_{c3}$. To be more specific, we plot in Fig. 4 the full width of this new absorption line and the relative depth of this new absorption dip each as a function of the second coupling detuning Δ_{c2} restricted by $\Delta_{c2} = \Delta_{c3}$. The relative depth is defined as $1 - A_p/A_d$ with A_d being the maximum value of the absorption dip under consideration and A_p being the minimum value of the absorption line nearest to the dip. It is clear that for $\Delta_{c2} = \Delta_{c3} = 100$ MHz, the full width is 46 kHz in Fig. 4(a), and the relative depth is 94% in Fig. 4(b). Then we may conclude that the five-level M system behaves like a four-level quasi-Λ system in the limit of $\Delta_{c2} = \Delta_{c3} \gg \Omega_{c2} = \Omega_{c3}$. This is why we can find two EIT windows, corresponding to two dark states $|D_2\rangle = [\Omega_{c1}|1\rangle - \Omega_p|3\rangle]/\Omega$ with $\Omega = \sqrt{\Omega_p^2 + \Omega_{c1}^2}$ and $|D_3\rangle = [\Omega_{c1}|1\rangle - \Omega_p|3\rangle + \Omega_p|5\rangle]/\Omega$ with $\Omega = \sqrt{2\Omega_p^2 + \Omega_{c1}^2}$, separated by an extremely narrow absorption line (see the blue-dotted curve in Fig. 3(a)).[26]

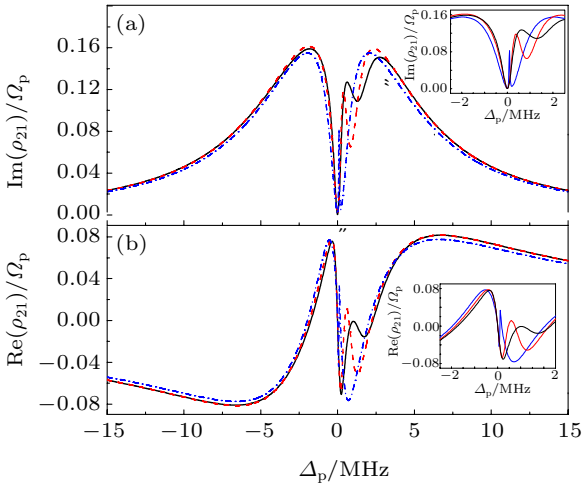


Fig. 3. (colour online) (a) Probe absorption $\mathrm{Im}(\rho_{12})$ and (b) probe dispersion $\mathrm{Re}(\rho_{12})$ each as a function of probe detuning Δ_p with $\Delta_{c1} = 0.0$ MHz and $\Delta_{c2} = \Delta_{c3} = 10$ MHz (black-solid), 20 MHz (red-dashed), 100 MHz (blue-dotted). The other parameters are the same as those in Fig. 2 if not specified. The insets show more details around the probe resonance.

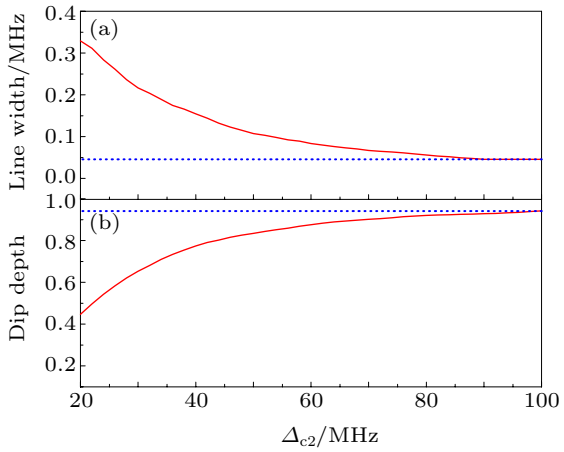


Fig. 4. (colour online) (a) Full width of the new absorption line and (b) the relative depth of the new absorption each dip as a function of coupling detuning Δ_{c2} restricted by $\Delta_{c2} = \Delta_{c3}$. The other parameters are the same as those in Fig. 2 if not specified.

In Fig. 5, we examine the steady spectra of probe absorption and dispersion in a more general case, where $\Delta_{c1} \neq \Delta_{c2} \neq \Delta_{c3}$. As we can see, there exists only one very shallow dip in the probe absorption spectrum, which means that no deep EIT windows corresponding to the dark states of zero eigenvalues can be found in the case of $\Delta_{c1} \neq \Delta_{c2} \neq \Delta_{c3}$. The relative depth of the absorption dip is 57%, 72%, and 82% for the black-solid, red-dashed, and blue-dotted curves, respectively. These values are surely much smaller than the relative depth $\sim 100\%$ of a typical EIT window attained in the presence of perfect quantum destructive interference.

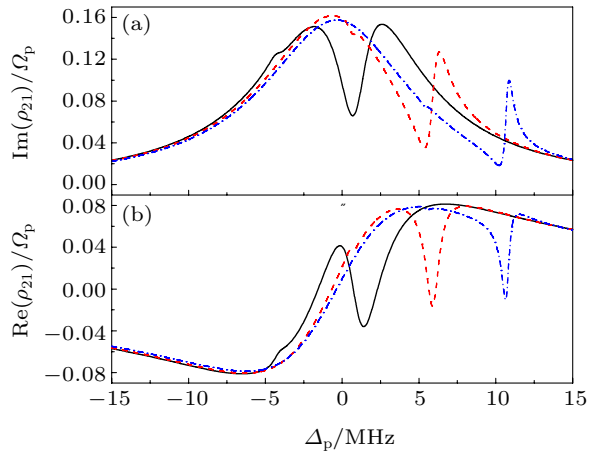


Fig. 5. (colour online) (a) Probe absorption $\mathrm{Im}(\rho_{12})$ and (b) probe dispersion $\mathrm{Re}(\rho_{12})$ each as a function of probe detuning Δ_p with $\Delta_{c1} = 0$ MHz, $\Delta_{c2} = 5$ MHz, $\Delta_{c3} = 10$ MHz (black-solid); $\Delta_{c1} = 5$ MHz, $\Delta_{c2} = 10$ MHz, $\Delta_{c3} = 15$ MHz (red-dashed); $\Delta_{c1} = 10$ MHz, $\Delta_{c2} = 15$ MHz, $\Delta_{c3} = 20$ MHz (blue-dotted). The other parameters are the same as those in Fig. 2 if not specified.

Finally, we stress that our main result shown in Fig. 3 corresponds to the case where a five-level M system is reduced into a four-level quasi-Λ system. The most important advantage of the M system is relevant to a possible experiment, in which we may choose cold ^{87}Rb atoms as the medium so that levels $|1\rangle$, $|2\rangle$, $|3\rangle$, $|4\rangle$, $|5\rangle$ correspond to states $5\mathrm{S}_{1/2}|F = 2, m = +2\rangle$, $5\mathrm{P}_{3/2}|F = 2, m = +1\rangle$, $5\mathrm{S}_{1/2}|F = 1, m = 0\rangle$, $5\mathrm{P}_{3/2}|F = 2, m = -1\rangle$, $5\mathrm{S}_{1/2}|F = 2, m = -2\rangle$, respectively. Then it is clear that in the simple quasi-Λ system, we have to use a micro-wave field with frequency 6.8 GHz to couple levels $|3\rangle$ and $|5\rangle$. As we know, however, it is not so easy to precisely generate and control a micro-wave field with frequency 6.8 GHz in the experiment. In addition, such a micro-wave field has the wavelength of about 4.4 cm, which is just one order larger than the sample length. Thus cold atoms at different positions will experience different Rabi frequencies of the micro-wave field. This may become a large obstacle to observe the desired result. In the complex M system, levels $|3\rangle$ and $|5\rangle$ are coupled by two laser fields via a two-photon transition, so the relevant experiment is much easier to be implemented. In addition, we can examine a situation where the detunings of the two laser fields are not so large that a M system cannot be reduced into a quasi-Λ system. In this situation, the absorption dip should not be identified as an EIT window, because it is not deep enough to verify the perfect quantum destructive interference. That is, in the M system, we can examine how a shallow absorption dip gradually turns into a deep EIT window just by controlling the detunings of the two laser fields. Note also that the double EIT windows and the in-between narrow absorption line are attained with a new mechanism, i.e., in the presence of a resonant single-photon transition between levels $|2\rangle$ and $|3\rangle$ and a far-detuned two-photon transition between levels $|3\rangle$ and $|5\rangle$.

4. Conclusion

In summary, we have studied the steady optical response of a five-level atomic system driven into the M configuration by examining its absorption and dispersion spectra in different situations. In the case where all three coupling fields have zero detuning, we find only one narrow and deep EIT window at the probe resonance accompanied by a very steep normal dispersion. Turning off the last coupling field, we can reduce the five-level M system into a four-level N system and then observe a third absorption line completely destroying the EIT window. To recover the EIT window, we just need to reduce the four-level N system into a three-level Λ system by turning off the second coupling field. In the case where the last two coupling fields have nonzero detunings, a third absorption line arises beside the EIT window yet without introducing more absorption therein. Simultaneously, a new absorption dip is found on the other side of the third absorption line. It is worth stressing that the new absorption line will become extremely narrow and the new absorption dip will be as deep as the EIT window when the last two coupling fields are far detuned from the relevant transitions. In the case where all three coupling fields are detuned to different extents, we cannot find deep EIT windows, narrow absorption lines, and steep dispersion curves in the probe absorption and dispersion spectra.

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