Multiple Transparency Windows and Fano interferences Induced by Dipole-Dipole Couplings

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The understanding of the light-matter interaction has been the focus of intense research during the last decades, mainly due to the advances in its manipulation allowed by the introduction of laser fields. In this sense, electromagnetically induced transparency (EIT) [1] has been shown to be a phenomenon very useful for manipulating light with light, allowing huge number of different applications. Here we investigate the optical response of a two-level system (TLS) coupled to a linear series of N other TLS with dipole-dipole coupling between the first neighbours [2].

In Figs. 1(a) and (b) we plot the absorption and dispersion (imaginary and real parts of the stationary average value of the electrical dipole moment $\langle\sigma_+^0\rangle_{ss}$, respectively) of the first TLS coupled to $N = 4$ other TLS's as a function of the normalized detuning Δ_P/γ_0 between the transition frequency of main TLS and the oscillation frequency of a probe field (here γ_0 is the decay rate of the main TLS). We have shown that the number of transparency windows is exactly equals to the number of TLS's (N) coupled to the main one [2]. The positions of the outer peaks depend on d_0 (coupling between the first and the second TLS), while the positions and widths of the inner peaks depend on the coupling d between the other TLS's. For $d_0 < \gamma_0$, Figs. 1(a), we have multiple transparency windows, while for $d_0, d \gg \gamma_0$ we have a Autler-Townes (AT) splitting. By increasing the coupling d the inner peaks become broader and then, depending on the coupling d_0, they can approach the other peaks, producing interference in the absorption paths, i.e., Fano interferences [3], as we see in Fig. 1(b). To see multiple transparency windows we must set γ_i (the decay rate of the i-esim TLS) much weaker than γ_0 [2].

The multiple dipole-dipole induced transparency and multi-Fano interferences also appear when we couple the series of $1+N$ TLS's to a dissipative cavity mode (with decay rate κ). Considering N TLS's coupled to the main one (all the couplings given by d), which in turn is coupled to the cavity mode (coupling g), we will have N transparency windows, as we see in Fig. 1(c) ($N = 4$), which present 4 inner and two additional outer peaks. Here we plot the normalized absorption and dispersion of the cavity mode (imaginary and real parts, respectively, of the stationary average value of the annihilation cavity field operator a) as a function of the normalized detuning between the probe field and cavity mode frequencies (Δ_P/κ). The positions of the resonance peaks are determined by all the couplings. However, the two outer peaks are mainly due to the atom-field coupling g and the inner peaks (and their widths) are mainly influenced by the dipole-dipole couplings d. For stronger values of g and d we can have a large separation between the resonance peaks (AT splitting) or even Fano interference when $d > g$, as we see in Fig. 1(d). So, here we have a tunable system which allows us to arbitrarily choose the number of transparency windows, and their width, by simply adjusting the number of TLS's and the dipole-dipole coupling in our model.

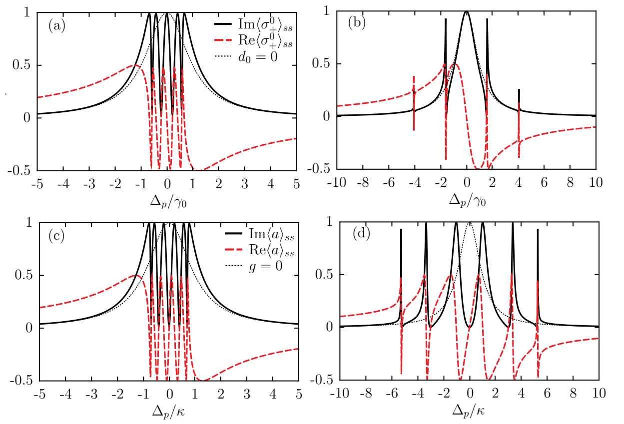

Figure 1: (a) and (b) normalized absorption (black solid line) and dispersion (red dashed line) of the main TLS for $N = 4$ as function of Δ_p/γ_0. The parameters used here were Rabi frequency of the probe field $\Omega_p = 0.03\gamma_0$, $\gamma_i = \gamma = 10^{-3}\gamma_0$ and $d_0 = 0.5\gamma_0$. The d couplings chosen here are: (a) $d = d_0/\sqrt{2}$; (b) $d = 2.5\gamma_0$. The black dotted lines represent the absorption for $d_0 = 0$. (c) and (d) normalized absorption (black solid line) and dispersion (red dashed line) of the cavity mode when coupled to 5 TLS's (i.e., $N = 4$) as a function of Δ_p/κ. The parameters used here were $|\epsilon| = 0.03\kappa$ (being ϵ the strength of the probe field on the cavity mode), $\gamma_i = \gamma = 10^{-3}\kappa$. The other parameters chosen were: (c) $d = 0.4\kappa$ and $g = \sqrt{2}d$; and (d) $d = 3.0\kappa$ and $g = 2.0\kappa$. The black dotted lines represent the absorption at $g = 0$.

In summary, we have shown that the dipole-dipole coupling plays exactly the same role as the control field in the EIT phenomenon, either in free space [1] or in cavity QED experiments [4, 5]. We also investigate the scalability of this system, i.e., how it is possible to control the number of transparency windows by adding more TLS [2].

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