SUB-NATURAL SPECTRAL LINES VIA QUANTUM INTERFERENCES

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Abstract: The interaction of a single three-level ladder system with an external applied coherent field and damped via the surrounding electromagnetic field modes is investigated. It is demonstrated that the fluorescence spectral bands are narrowed depending on the mutual orientation of the transition dipole moments. Ultra-narrow spectral lines are obtained if the laser-atom interaction is mediated by an electromagnetic bath that possesses non-classical features.

Keywords: Controlling and Manipulation of Dissipative Systems.

INTRODUCTION

Controlling of spontaneous emission is in general an important and useful task. Much work has been devoted to the subject both for single atomic systems as well as for multi-atom samples [1-7]. The interest in these systems arises as many effects of quantum optics, such as entangled states which involve at least two two-state systems, play a vital role in quantum information theory. Another motivation for our investigations is to control the spontaneous emission of light which is the major sink for the threshold current in semiconductor lasers. In principle we can arrange to have all the spontaneous emission into a single optical mode and therefore to lower the current threshold of the semiconductor laser diode.

SYSTEM OF INTEREST
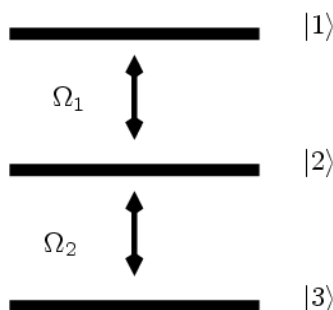
Fig.1

Our system is characterized by a single three-level atom that interacts, through a non-classical environmental EMF bath, with an external resonant coherent field (see **Fig. 1**). The atom may decay spontaneously on dipole-allowed transitions $|1\rangle \rightarrow |2\rangle \rightarrow |3\rangle$ (the transitions $|1\rangle \rightarrow |3\rangle$ are dipole-forbidden) via their interactions with the environmental vacuum fluctuations. In order to keep the calculations as simple as possible we limited ourselves to an atomic sample having equal transition frequencies ω_0 with parallel transitions dipole moments, $d_{12} \| d_{23} \equiv d$. We consider equal Rabi frequencies $|\Omega_\alpha| = |\Omega_\beta| \equiv \Omega_0$ and identical bare-state decay rates $\gamma_\alpha = \gamma_\beta = (\gamma_\alpha \gamma_\beta)^{1/2} \equiv \gamma = 4d^2\omega_0^3/(3\hbar c^3)$. In this case, the photons emitted on $|\alpha\rangle \rightarrow |\beta\rangle$ atomic transitions can not be

distinguished, i.e. they are indistinguishable (here $\{\alpha, \beta\} = 1,2,3$ according to **Fig. 1**). The carrier frequency ω_c of the squeezed bath is supposed to be in resonance with that of the laser one, i.e. $\omega_L = \omega_c$ and $\Delta \equiv (\omega_0 - \omega_L) << \omega_0$.

It should be emphasized here, that it is difficult to find an atomic gaseous system possessing parallel transition dipole moments. In principle, one may apply our scheme to a solid state system where a model with equally spaced energy levels and identical transitions dipole moments can be engineering. Adopting then the Born-Markov approximation, in the intense field limit $\Omega >> N\gamma$, we have obtained the following steady-state limit of the diagonal elements of the density operator $P_{nm} = \langle m, n, N = 1| \rho |N = 1, n, m \rangle$

$$P_{nm} = \eta^{n+m} / (1 + \eta + \eta^2), \tag{1}$$

where $\eta = \Gamma_-/\Gamma_+$ with $\Gamma_\pm = \gamma[(\overline{N} + 1)(1 \pm \Delta/\Omega)^2 + \overline{N}(1 \mp \Delta/\Omega)^2 + 4|\overline{M}|\Omega_0^2\cos\varphi/\Omega^2]/16$ and $\phi = \phi_s - 2\phi_L$, while the off-diagonal terms are equal to zero. The distribution of atoms on dressed-state energy levels can be modified by changing η which is a function of external control parameters.

NARROWING OF THE SPECTRAL LINES. DISCUSSIONS

The steady-state spectrum of the fluorescent light is proportional to the Fourier transform of the first - order correlation function $G^{(1)}(\tau)$ and reads

$$S(\omega) = \Phi(r)\,\mathrm{Re}\int_0^\infty d\tau e^{i(\omega-\omega_L)\tau}G^{(1)}(\tau), \tag{2}$$

where $\Phi(r) = 2d^2\omega_0^4/(3r^2c^4)$ is a geometrical factor which we set equal to unity in the following. The first-order correlation function $G^{(1)}(\tau)$ can be represented via the following atomic correlators ($\Delta=0$)

$$\left\langle R^+R^-(\tau)\right\rangle = \left\langle R^+R^-\right\rangle_s e^{-(i\Omega+\gamma_{sb})\tau}, \left\langle R_zR_z(\tau)\right\rangle = \left\langle R_z^2\right\rangle_s e^{-\gamma_{cb}\tau}, \left\langle R^-R^+(\tau)\right\rangle = \left\langle R^-R^+\right\rangle_s e^{(i\Omega-\gamma_{sb})\tau}$$

Here $\widetilde{\Omega} = \sqrt{2}\Omega_0$, and the spectral bandwidths of the central line (γ_{cb}) as well as of the sidebands (γ_{sb}) are given, respectively, by

$$\gamma_{cb} = \frac{\gamma}{4}\left[1 + 2\overline{N} + 2|\overline{M}|\cos\phi\right], \quad \gamma_{sb} = \frac{\gamma}{4}\left[\frac{3}{2} + 3\overline{N} - |\overline{M}|\cos\phi\right]. \tag{3}$$

With the help of Eq. (1) one can show that at resonance $2\left\langle R_z^2\right\rangle_s = \left\langle R^+R^-\right\rangle_s = \left\langle R^-R^+\right\rangle_s = \frac{4}{3}$. Then after integration in Eq. (2) taking into account $G^{(1)}(\tau)$ one obtains:

$$S(\omega) = \frac{1}{6}\left[\frac{\gamma_{sb}}{\gamma_{sb}^2 + \left(\overline{\Delta} + \tilde{\Omega}\right)^2} + 2\frac{\gamma_{cb}}{\gamma_{cb}^2 + \overline{\Delta}^2} + \frac{\gamma_{sb}}{\gamma_{sb}^2 + \left(\overline{\Delta} - \tilde{\Omega}\right)^2}\right], \tag{4}$$

where $\overline{\Delta} = \omega - \omega_L$. One can observe here that at the exact resonance the resonance fluorescence spectrum is composed from three bands located at $\{\omega_L \pm \tilde{\Omega}, \omega_L\}$ (see **Fig. 2**). The spectral line-widths are two times narrowed in comparison to the analogous problem but for two - level atoms [7]. Eqs (3,4) give, in addition, the corresponding exact results in the case when the atoms are surrounded by the EMF vacuum modes $\left(\{\overline{N}, |\overline{M}|\} = 0\right)$ or a thermal heat bath at temperature $T\left(|\overline{M}| = 0, \overline{N} \to \overline{n} = \left[\exp(\hbar\omega_0 / k_b T) - 1\right]^{-1}\right)$ Note that when the atomic sample emits distinguishable photons, i.e. $\vec{d}_{12} \perp \vec{d}_{23}$, through its interaction with vacuum modes of the EMF the fluorescent spectrum generated at $|1\rangle \to |2\rangle$ atomic transitions consists of five lines located at
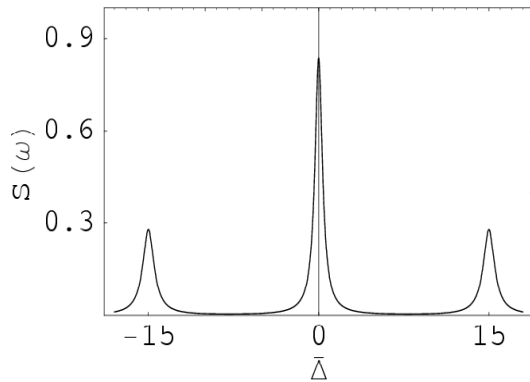
$\{\omega_{12} \pm 2\tilde{\Omega}, \omega_{12} \pm \tilde{\Omega}, \omega_{12}\}$. Their fluorescent spectral widths are γ, 5γ/8 and 3γ/4, respectively. Inspecting of Eq. (3) one can see that in our case the bandwidths of the spectral lines at $\{\omega_0 \pm \tilde{\Omega}, \omega_0\}$, due to the interaction of the atomic sample with the vacuum modes of the EMF $\left(i.e. \overline{N} = |\overline{M}| = 0\right)$, are respectively, 3γ /8

Fig.2

and γ/4 which are narrowed with respect to the case of orthogonal dipole moments. Thus, we get sub-natural line-widths even for a weak thermal heat bath, i.e. $\overline{n} \ll 1$, and without the squeezed reservoir, an effect which is absent in the collective resonance fluorescence of driven two-level ensembles [7] (the well-known line-widths of the Mollow triplet in the case of ordinary fluorescence are, respectively, 3γ/4 and γ/2). To estimate, further, the spectral line-widths (3) we consider minimum uncertainty squeezing for which $|\overline{M}| = \sqrt{\overline{N}(\overline{N} + 1)}$ In the case of very weak squeezed bath, i.e. $\overline{N} \ll 1$, we have for the spectral bands widths the following expressions

$$\gamma_{cb} \approx \frac{\gamma}{2}\left[\frac{1}{2} + \sqrt{\overline{N}}\cos\phi\right], \gamma_{sb} \approx \frac{\gamma}{4}\left[\frac{3}{2} - \sqrt{\overline{N}}\cos\phi\right], \tag{5}$$

while for a strong squeezed bath, i.e. $\overline{N} \gg 1$, we get

$$\gamma_{cb} \approx \frac{\gamma}{2}\left[\left(\overline{N} + \frac{1}{2}\right)(1 + \cos\phi) - \frac{1}{8\overline{N}}\cos\phi\right], \gamma_{sb} \approx \frac{\gamma}{4}\left[\left(\overline{N} + \frac{1}{2}\right)(3 - \cos\phi) + \frac{1}{8\overline{N}}\cos\phi\right]. \tag{6}$$

Eq. (5) gives the results for the widths of the spectral lines for accessible experimental parameters of the squeezed bath. Sub-natural line-widths are obtained by varying ϕ between 0 and π. Concluding, we have shown that intense fluorescence spectral bands possessing sub-natural line-widths can be obtained when driving the three-level ladder atoms with a strong laser field. The environmental non-classical bath may lead to a significant narrowing of the spectral lines or to a complete inhibition of the fluorescence on a particular frequency.

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