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Polariton Peaks from the Coupled System of the Spin Triplet Transition and the Cavity, Classically Considered in the Linear Approximation

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Abstract

Investigation of the spin-cavity polaritons (SCP) is important since they play a decisive role in creating long-storage quantum memories and optical interfaces, polaritonic chemistry, and masers, especially those which operate at room temperature, being of great significance for a lot of different applications. In this report, we suggest an almost completely classical model for the description of the polaritonic peaks conditioned both by free and forced Rabi oscillations of the SCP system. Our investigation is based on the linearized coupled differential equations we derived semi-classically for the magnetization component of the transition of the spin triplet states and the varying field in a cavity when the empty cavity is exactly tuned to the transition. The normal frequencies of this system of equations were found, and the corresponding graphs were constructed for the appropriate values of the parameters. It is shown that the increase in the spin-photon coupling can cause both the pushing apart of normal frequencies at a mutual decay rate (which is the known effect) and the merging together of normal decay rates at a mutual frequency (which is the predicted effect here). Polariton peaks, observable by the cavity transmission function and by EPR in the form of absorption and dispersion signals, were also investigated, and corresponding graphs were constructed. At that, instead of a transition of spin triplet states, a variety of other two-level systems (atoms, molecules, excitons, and so on) can act as emitters. Since the value of the spin-photon coupling is of great interest for applied scientists, obtaining this value by comparing our results with experimental data is of great importance.

Keywords: Polariton peaks, Rabi oscillations, Transmission function, EPR signals, Spin-photon coupling

INTRODUCTION

The photon-matter hybrid states, considered as quasiparticles, called polaritons, typically materialize as a normal-mode splitting of the coupled radiation-matter system, where photons act on the radiation side and emitters act on the matter side. The paradigm of *N* quantum emitters coupled to a single cavity mode and performing Rabi oscillations appears in many situations ranging from quantum technologies to polaritonic chemistry (Haroche, 2006 and references therein), including maser generation from spin triplet states, especially those that operate at room temperature, being of great significance for a lot of different applications. Polariton peaks can be observed by the cavity transmission function and by EPR in the form of absorption and dispersion signals. From the above, it follows that the purpose of the study of this paper - investigation of the polariton peaks with the help of EPR and transmission function from the coupled system of spin triplet state transition and cavity - is of significant theoretical and practical interest. To achieve this goal, we almost throughout the paper use the classical approach in the linear approximation.

FORMULATION OF THE PROBLEM AND METHODS

The dynamics of the coupled system "STS transition + cavity" under the action of the steady-state weak probe MW field is described by us in the rotating-wave approximation with the help of the following system of differential equations for the field $B_{\mathbf{K}}^{i-j}$ and the magnetization $M_{\mathbf{K}}^{i-j}$ inside the sample, basing on Ref. by Fokina and Elizbarashvili (2021).

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$$d^2B_{\mathbf{K}}^{i-j}/dt^2+2\tau_c^{-1}dB_{\mathbf{K}}^{i-j}/dt+\omega_c^2B_{\mathbf{K}}^{i-j}=\eta_0\mu_0\omega_p dH_{\mathbf{K}}^{i-j}(probe)/dt-\eta_0\mu_0 d^2M_{\mathbf{K}}^{i-j}/dt^2$$
$$d^2M_{\mathbf{K}}^{i-j}/dt^2+2T_2^{-1}dM_{\mathbf{K}}^{i-j}/dt+\omega_0^2M_{\mathbf{K}}^{i-j}-4(\eta_0\mu_0)^{-1}T_R^{-1}\tau_c^{-1}B_{\mathbf{K}}^{i-j}=0 \tag{1}$$

where ω_0, ω_c are the frequencies of an STS *i-j* transition and of an empty cavity, respectively; T_2^{-1}, τ_c^{-1} are decay rates of the *i-j* transition and of a cavity, respectively; $H_{\mathbf{K}}^{i-j}(probe)$ is the probe field of the frequency ω_p in the cavity; $\left(T_R^{i-j}\right)^{-1}$ is the reciprocal radiation damping time (Abragam, 2006), written here for a cavity containing a sample possessing STSs, μ_0 is the magnetic constant; η_0 is the instrumental factor of the cavity with the sample. It should be mentioned that the coherent dynamics description with the help of Eqs. (1) is possible only for the case, when $\tau_c^{-1}>T_2^{-1}$(Fokina and Elizbarashvili, 2021).

$$\left(T_R^{i-j}\right)^{-1}=\left[\mu_0h^{-1}\left(g_K^{i-j}\mu_B\right)^2NQP^{i-j}/V_m\right]\left\{\left(\tau_c^{-1}\right)^2/\left[\left(\tau_c^{-1}\right)^2+\left[\left(\omega_0^{i-j}\right)^2-\left(\omega_c\right)^2\right]\right]\right\}, \tag{2}$$

where P^{i-j} and g_K^{i-j} are the polarization and the g-factor of the *i-j* transition; V_m is the volume of the resonant magnetic mode inside the sample. The solution of (1) was sought in the form: $M_{\mathbf{K}}^{i-j}=m_{\mathbf{K}}^{i-j}e^{i\omega_pt}$; $B_{\mathbf{K}}^{i-j}=\eta_0\mu_0h_{\mathbf{K}}^{i-j}e^{i\omega_pt}$; $H_K^{i-j}(probe)=h_K^{i-j}(probe)e^{i\omega_pt}$. The system of equations (1) is a linear one and is valid when the slow $m_p^{i-j}=-g_{\mathbf{K}}^{i-j}\mu_BNP^{i-j}/V_m$ component of magnetization does not change under the action of the probe field ─ this means that hereafter we use the linear approximation. At that, the slow complex variables $m_{\mathbf{K}}^{i-j}$, $h_{\mathbf{K}}^{i-j}$ are the solutions of two algebraic equations, which we have written in the form for the oscillation amplitudes of two coupled oscillators (Migulin et al., 1978) under the action of a harmonic external force (further text goes without indexes *i-j*, although they are implied):

$$h_{\mathbf{K}}(probe)=im_{\mathbf{K}}+i\left[\Delta_{pc}-i\theta_c\right]h_{\mathbf{K}}$$
$$\left(\Delta_{p0}-i\theta_0\right)m_{\mathbf{K}}+\alpha_1\alpha_2h_{\mathbf{K}}=0 \tag{3}$$

$$\Delta_{pc}=\left(1-\frac{\omega_c^2}{\omega_p^2}\right);\ \theta_c=\frac{2\tau_c^{-1}}{\omega_p}\quad \Delta_{p0}=\left(1-\frac{\omega_0^2}{\omega_p^2}\right);\ \theta_0=\frac{2T_2^{-1}}{\omega_p};\ \alpha_1\alpha_2=4T_R^{-1}\tau_c^{-1}/\omega_p^2=4g_s^2N/\omega_p^2\equiv4\Omega_R^2/\omega_p^2. \tag{4}$$

$$g_s=\sqrt{\mu_0h^{-1}\left(g_{\mathbf{K}}\mu_B\right)^2P^{i-j}\omega_c/2V_m} \tag{5}$$

is the spin-photon coupling value of a single emitter (Breeze et al., 2017).

$$\Omega_R=\sqrt{T_R^{-1}\tau_c^{-1}}=g_s\sqrt{N}, \tag{6}$$

where T_R^{-1} corresponds to a resonant cavity **(** $\omega_c=\omega_0$**),** is the Rabi frequency of a cavity with *N* emitters in it, each having g_s spin-photon coupling, written in two forms ─ the classical one (Fokina and Elizbarashvili, 2022) and that of cQED (Breeze et al., 2017) with the difference that there is an additional factor $\sqrt{P^{i-j}}$ in our formula for g_s. Eq. (6) is the main one for the transition between the two forms of the description of the coupled system "emitters + cavity". The solution of (3) was sought in the form

$$h_K^{i-j}=h_K^{i-j}(probe)/\left(R_{eqv}+iX_{eqv}\right)\ \text{with}\ R_{eqv}^{-1}=\frac{\theta_0^2+\Delta_{p0}^2}{\theta_c\left(\theta_0^2+\Delta_{p0}^2\right)+\alpha_1\alpha_2\theta_0};\quad X_{eqv}=\Delta_{pc}-\frac{\alpha_1\alpha_2\Delta_{p0}}{\theta_0^2+\Delta_0^2}, \tag{7}$$

where the resonance condition is $X_{eqv}=0$, which is satisfied by the three values of detuning:

$$\Delta_{p0}(I)=0;\Delta_{p0}(II,III)=\pm\sqrt{\alpha_1\alpha_2-\theta_0^2}. \tag{8}$$

SPECTRUM OF FREE OSCILLATIONS OF THE COUPLED SYSTEM "EMITTERS + CAVITY"

First of all, we were interested in the spectrum of the free oscillations of a coupled system "emitters + cavity", the latter being given by equating the determinant of (3) with $\omega_p = \omega$ to zero:

$$(\Delta_1 - i\theta_1)(\Delta_2 - i\theta_2) - \alpha_1\alpha_2 = 0, \tag{9}$$

where Δ_1, Δ_2 are the complex relative detunings. Supposing $\Delta_{1,2} \to \Delta'_{1,2} + i\Delta''_{1,2}$, the following results were obtained:

1. If $\Delta'_1, \Delta'_2 \neq 0$, the frequencies of the two coupled oscillators are pushed aside by the spin-photon coupling (Figure 1):

$$\omega'^2_{\pm} = \left[(\omega_0^2 + \omega_c^2) \pm \sqrt{(\omega_0^2 - \omega_c^2)^2 + 16\omega_0^2\Omega_R^2} \right] / 2; \qquad \Delta''_1 = \theta_1; \quad \Delta''_2 = \theta_2, \tag{10}$$

while the corresponding rates of decay remain non-modified by it**.** It should be mentioned that ω'^2_- corresponds to the case when emitters and the cavity field oscillate in phase, while ω'^2_+ corresponds to the case of their opposite phase oscillation. Using parameters of the Ref. of Breeze et al. (2017) experiments, the following plot of the repulsion of normal frequencies was obtained by us (Figure 1). The three possible resonance frequencies can be presented in another form — see Ref. of Diniz et al., (2011), and Figure 2:

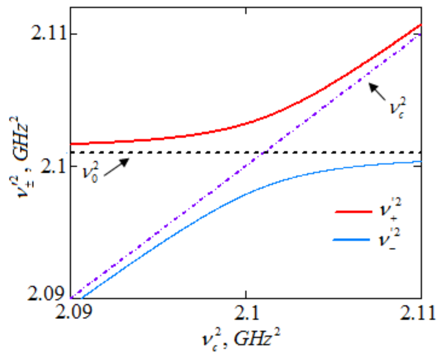

Figure 1. Repulsion of the normal frequencies ν'^2_+ and ν'^2_- of the coupled system "STS Z-X transition + cavity" of 0.053% mol/mol pentacene-doped p-terphenyl crystal, housed within a hollow cylinder of strontium titanate at the following values of the parameters: $\Omega_R = 2\pi \times 0.9 MHz$; $|\omega_0^{Z-X}| = 2\pi \times 1449.5 MHz$ (Breeze et al., 2017)

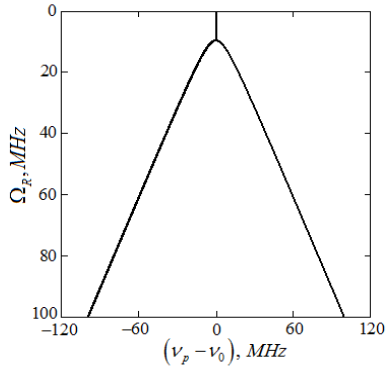

Figure 2. Dependence on Ω_R of the detuning $\nu_p(I, II, III) - \nu_0$ of the resonance probe field

($\nu_p = \nu_p(I,II,III)$) from the emitter frequency ν_0, for a cavity resonant at $\Omega_R = 0$ with the emitter, according to (8). For the emitter decay rate, the optional value $T_2^{-1} = 2\pi \times 9.5 MHz$ is taken.

2. If $\Delta_1^{'} \cdot \Delta_2^{'} = 0$, two coupled oscillators stay with their partial frequencies, but their decays are changed. If $4\alpha_1\alpha_2 < (\theta_1 - \theta_2)^2$:

$$\omega_+ = \omega_0; \quad \omega_- = \omega_c; \ \omega_\pm^{''} = \left(T_2^{-1} + \tau_c^{-1}\right) \pm \sqrt{\left(T_2^{-1} - \tau_c^{-1}\right)^2 - 4\Omega_R^2} \tag{11}$$

3. The case of level anticrossing (LAC) — the intersection point of the lines ν_0^2 and ν_c^2 in Figure 1:

$$\omega_0^2 = \omega_c^2 = \omega_{LAC}^2. \text{ If } 4\Omega_R^2 > \left(\tau_c^{-1} - T_2^{-1}\right)^2, \quad \Delta_{LAC}^{'} = \pm\sqrt{4\Omega_R^2 - \left(\tau_c^{-1} - T_2^{-1}\right)^2} / \omega_0, \ \Delta_{LAC}^{''} = \left(\tau_c^{-1} + T_2^{-1}\right) / \omega \tag{12}$$

— due to the spin-photon coupling, the frequencies of the normal modes repulse from each other, while the normal decay rate is the same for both modes, giving the complex frequency

$$\omega_\pm(LAC) = \omega_0 \pm \sqrt{\left(\Omega_R^{i-j}\right)^2 - \left(\frac{\tau_c^{-1} - T_2^{-1}}{2}\right)^2} + i\frac{\tau_c^{-1} + T_2^{-1}}{2}, \tag{13}$$

which coincides with the results of Refs. Thompson et al., (1992), Zhu et al., (1990), Diniz et al., (2011). If $4\Omega_R^2 < \left(\tau_c^{-1} - T_2^{-1}\right)^2$, then

$$\Delta_{LAC}^{'} = 0 \ (\omega_\pm^{'} = \omega_{LAC} = \omega_0): \ \Delta_{LAC}^{''} = \left[\left(\theta_1 + \theta_2\right) \pm \sqrt{\left(\theta_1 - \theta_2\right)^2 - 4\alpha_1\alpha_2}\right] / 2 \text{ or explicitly}$$

$$\omega_\pm^{''}(LAC) = \frac{\tau_c^{-1} + T_2^{-1}}{2} \pm \sqrt{\left(\frac{\tau_c^{-1} - T_2^{-1}}{2}\right)^2 - \Omega_R^2} \tag{14}$$

— the emitter and cavity frequencies stay unchanged, while the normal decay rates merge as a result of the spin-photon coupling, see Figure 3:

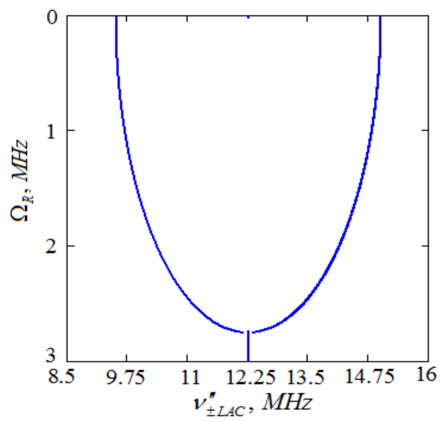

Figure 3. Predicted dependence of the normal decay rates $\nu_\pm^{''}(LAC)$ on Ω_R for a cavity, at $\Omega_R = 0$ resonant with the emitter, according to Eq. (14). For the emitter and cavity decay rates, the optional values $T_2^{-1} = 2\pi \times 9.5 MHz$; $\tau_c^{-1} = 2\pi \times 15 MHz$ are taken

SPIN-CAVITY POLARITON STUDY BY MEANS OF EPR SIGNALS AND CAVITY TRANSMISSION FUNCTION

Since EPR is one of the experimental methods of polariton investigation (see, for instance, Ref. of Salikhov et al (2023), where EPR of spin polaritons in a dilute solution of paramagnetic particles was observed), it is of interest to analytically obtain absorption and dispersion signals of spin-cavity polaritons to a weak (non-saturating) probe field. For this purpose, the classical approach in the linear approximation is valid (Thompson et al., 1992; Zhu et al., 1990). In this approximation, we have obtained the following general formulae in terms of Migulin et al., (1978) in the rotating field approximation for the case when an empty cavity is exactly tuned to the *i-j* transition of emitters ($\omega_c = \omega_0$, hereafter only this case is considered):

$$\chi' = \frac{\alpha_1\alpha_2\left(\theta_0 R_{eqv} - \Delta_{p0} X_{eqv}\right)}{\eta_0\left(\theta_0^2 + \Delta_{p0}^2\right)\left(R_{eqv}^2 + X_{eqv}^2\right)}; \qquad \chi'' = \frac{\alpha_1\alpha_2\left(\Delta_{p0} R_{eqv} + \theta_0 X_{eqv}\right)}{\eta_0\left(\theta_0^2 + \Delta_{p0}^2\right)\left(R_{eqv}^2 + X_{eqv}^2\right)}, \tag{15}$$

where R_{eqv}, X_{eqv} are defined by (7). The resonance condition of EPR signals reads as: $X_{eqv} = 0$ (Migulin et al, 1978), giving the three possible values (I,II,III) of the resonance frequency of the probe field

$$\omega_p\left(I\right) = \omega_0; \quad \omega_p^2\left(II, III\right) = \frac{\omega_0^2}{1m\sqrt{\alpha_1\alpha_2 - \theta_0^2}}. \tag{16}$$

1) In the case $\alpha_1\alpha_2 < \theta_0^2$ there is only one resonance frequency I. The corresponding steady-state EPR signals nearby this I resonance appeared to have the form:

$$\chi''\left(\Delta_{p0} \approx 0, noncritical\right) \approx \frac{\alpha_1\alpha_2\Delta_{p0}\left(\theta_c + \theta_0\right)}{\eta_0\left(\theta_0^2 + \Delta_{p0}^2\right)\left(\theta_c^2 + \Delta_{p0}^2\right)}; \chi'\left(\Delta_{p0} \approx 0, noncritical\right) \approx \frac{\alpha_1\alpha_2\left(\theta_c\theta_0\right)}{\eta_0\left(\theta_0^2 + \Delta_{p0}^2\right)\left(\theta_c^2 + \Delta_{p0}^2\right)} \tag{17}$$

where the absorption signal has the dispersion form, while the dispersion signal has the absorption form.

2) In the case $\alpha_1\alpha_2 \geq \theta_0^2$ two side peaks II, III (see Figure 4) appear in the EPR spectrum in addition to the I resonance, the latter now being a minimum of EPR signals at halfway between side peaks (Migulin et al., 1978). At $\alpha_1\alpha_2 >> \theta_0^2, \theta_c\theta_0$ these peaks have the Lorenzian form with the FWHM$\left(\theta_c + \theta_0\right)$:

$$\chi''\left(\Delta_{p0} \approx m\sqrt{\alpha_1\alpha_2}\right) \approx m\frac{\sqrt{\alpha_1\alpha_2}\left(\theta_c + \theta_0\right)/4}{\eta_0\left[\left(\theta_c + \theta_0\right)^2/4 + \left(\Delta_{p0} \pm \sqrt{\alpha_1\alpha_2}\right)^2\right]}; \tag{18}$$

$$\chi'\left(\Delta_{p0} \approx m\sqrt{\alpha_1\alpha_2}\right) \approx \frac{\theta_0\left(\theta_c + \theta_0\right)/4}{\eta_0\left[\left(\theta_c + \theta_0\right)^2/4 + \left(\Delta_{p0} \pm \sqrt{\alpha_1\alpha_2}\right)^2\right]}. \tag{19}$$

3) The point $\alpha_1\alpha_2 = \theta_0^2$ is critical — there all three resonances coincide with each other and have the features of the 1) resonance:

$$\chi'\left(\Delta_{p0} \approx 0, critical\right) \approx \frac{\theta_0^3}{\eta_0\left(\theta_0^2 + \Delta_{p0}^2\right)\left(\theta_c + \theta_0\right)}; \quad \chi''\left(\Delta_{p0} \approx 0, critical\right) \approx \frac{\Delta_{p0}\theta_0^2}{\eta_0\left(\theta_0^2 + \Delta_{p0}^2\right)\left(\theta_c + \theta_0\right)} \tag{20}$$

It is interesting to note that though Eqs. (17) and (20) describe EPR signals at the same detunings of the probe field, the predicted values of signals are different, since signals (17) correspond to the low-coupling end of the fork's handle of Figure 2, while signals (20) correspond to the stronger-coupling end of the fork's handle.

The general formulae of EPR absorption and dispersion signals, obtained by us for case 2), have the following form:

$$\chi''(peaks) \approx \frac{1}{\eta_0}\left\{ \frac{\Omega_R^4\sqrt{\Omega_R^2-\left(T_2^{-1}\right)^2}\left(T_2^{-1}+\tau_c^{-1}\right)}{\Omega_R^4\left(T_2^{-1}+\tau_c^{-1}\right)^2+4\left[\Omega_R^2-\left(T_2^{-1}\right)^2\right]^2\left(\omega_p-\omega_0-\sqrt{\Omega_R^2-\left(T_2^{-1}\right)^2}\right)^2} - \frac{\Omega_R^4\sqrt{\Omega_R^2-\left(T_2^{-1}\right)^2}\left(T_2^{-1}+\tau_c^{-1}\right)}{\Omega_R^4\left(T_2^{-1}+\tau_c^{-1}\right)^2+4\left[\Omega_R^2-\left(T_2^{-1}\right)^2\right]^2\left(\omega_p-\omega_0+\sqrt{\Omega_R^2-\left(T_2^{-1}\right)^2}\right)^2}\right\}; \quad (21)$$

$$\chi' = \frac{1}{\eta_0}\left\{ \frac{\Omega_R^4\left(-2\left[\omega_p-\omega_0-\sqrt{\Omega_R^2-T_2^{-2}}\right]\sqrt{\Omega_R^2-T_2^{-2}}+T_2^{-1}\left(T_2^{-1}+\tau_c^{-1}\right)\right)}{\Omega_R^4\left(T_2^{-1}+\tau_c^{-1}\right)^2+4\left(\Omega_R^2-T_2^{-2}\right)^2\left[\omega_p-\omega_0-\sqrt{\Omega_R^2-T_2^{-2}}\right]^2} + \frac{\Omega_R^4\left(2\left[\omega_p-\omega_0+\sqrt{\Omega_R^2-T_2^{-2}}\right]\sqrt{\Omega_R^2-T_2^{-2}}+T_2^{-1}\left(T_2^{-1}+\tau_c^{-1}\right)\right)}{\Omega_R^4\left(T_2^{-1}+\tau_c^{-1}\right)^2+4\left(\Omega_R^2-T_2^{-2}\right)^2\left[\omega_p-\omega_0+\sqrt{\Omega_R^2-T_2^{-2}}\right]^2}\right\}. \quad (22)$$

The plots, constructed according to Eqs. (21) and (22) of the given paper and scaled in the units of the instrumental factor η_0, are shown in the following Figure 4:

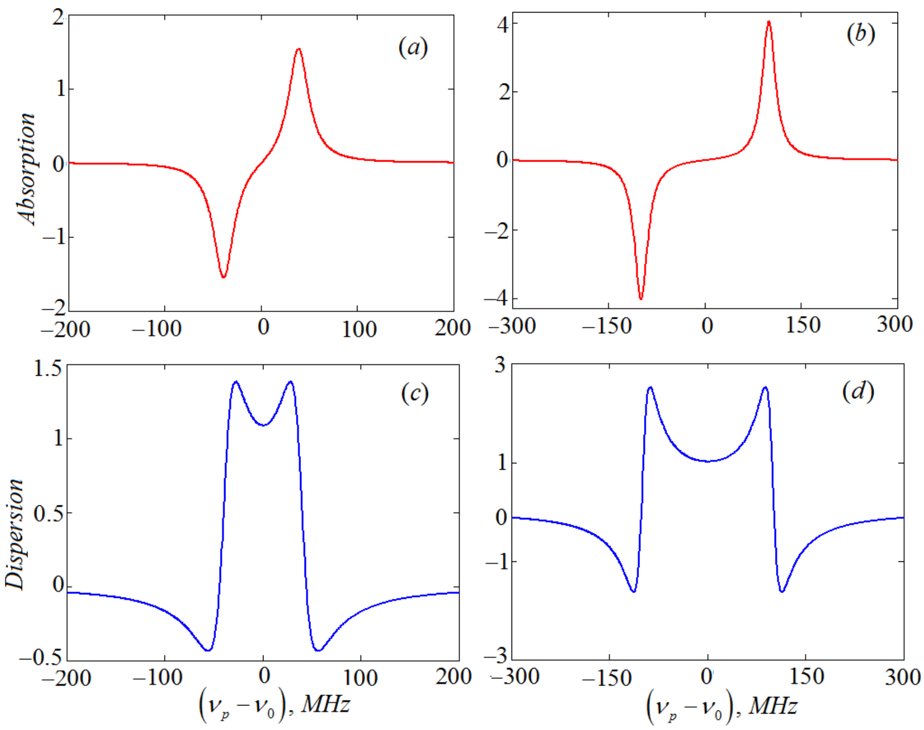

Figure 4. EPR signals plotted according to Eqs. (21) and (22) of the given paper and scaled in the units of the instrumental factor η_0: (a), (b) – absorption signals; (c), (d) – dispersion signals, both for the optional values of the parameters: decay rates $\tau_c^{-1} = 2\pi\times 15MHz$ (for cavity) and $T_2^{-1} = 2\pi\times 9.5MHz$ (for emitters); Rabi frequency for (a) and (c) is $\Omega_R = 2\pi\times 40MHz$; for (b) and (d), it is $\Omega_R = 2\pi\times 100MHz$

However, the observation of the transmission function (TF) of a cavity with *N* emitters in it is seemingly the best method to investigate polaritonic peaks (Thompson et al., 1992; Zhu et al., 1990). TF

$T(\omega_p) = |t(\omega_p)|^2$ for a weak probe field is the ratio of the energy transmitted through the cavity to that of the energy incident on it. It appeared that the quantum-mechanical method of $t(\omega_p)$ calculation is more suitable now. So, using expressions (5, 6) from the Ref. of Diniz et al. (2011), the following general expression for $t(\omega_p)$ can be written:

$$t(\omega_p) = \frac{\tau_c^{-1}}{i} \frac{\omega_p - \omega_0 + iT_2^{-1}}{(\omega_p - \omega_0 + iT_2^{-1})(\omega_p - \omega_c + i\tau_c^{-1}) - \Omega_R^2} \tag{23}$$

From (23), TF behavior in particular areas of the parameters can be described:

At $\Omega_R^2 < T_2^{-1}\tau_c^{-1}, T_2^{-2}$,

$$|t(\omega)|^2 = \left[\frac{\tau_c^{-1}T_2^{-1}(\Omega_R^2 + T_2^{-1}\tau_c^{-1})}{\left[(\omega-\omega_0)^2 - \Omega_R^2 - T_2^{-1}\tau_c^{-1}\right]^2 + (\omega-\omega_0)^2 (T_2^{-1} + \tau_c^{-1})^2} \right]^2, \tag{24}$$

i.e. TF is a Lorenzian squared with the FWHM $2(T_2^{-1}\tau_c^{-1})/(T_2^{-1} + \tau_c^{-1})$ and at $\Omega_R^2 > T_2^{-1}\tau_c^{-1}, T_2^{-2}$

$$|t(\omega \approx \omega_+)|^2 + |t(\omega \approx \omega_-)|^2 = \frac{\Omega_R^2 + T_2^{-1}\tau_c^{-1} + T_2^{-2}}{4(\Omega_R^2 + T_2^{-1}\tau_c^{-1})} \times$$

$$\times \left\{ \left[\frac{\tau_c^{-1}(T_2^{-1} + \tau_c^{-1})/2}{\left[(\omega-\omega_0) - \sqrt{\Omega_R^2 + T_2^{-1}\tau_c^{-1}}\right]^2 + \left[(T_2^{-1} + \tau_c^{-1})/2\right]^2} \right]^2 + \left[\frac{\tau_c^{-1}(T_2^{-1} + \tau_c^{-1})/2}{\left[(\omega-\omega_0) + \sqrt{\Omega_R^2 + T_2^{-1}\tau_c^{-1}}\right]^2 + \left[(T_2^{-1} + \tau_c^{-1})/2\right]^2} \right]^2 \right\} \tag{25}$$

— TF is two squared Lorenzians with equal heights and equal FWHMs $(T_2^{-1} + \tau_c^{-1})$. These features of TF, which are in accord with the Ref. of Zhu et al. (1990), are illustrated by Figure 5.

RESULTS AND DISCUSSION

The significance of the results of this paper lies in the fact that it presents the values directly measured in various types of experiments in a simple and clear form via experimental parameters for spin-cavity polaritons. At that, a variety of two-level systems (atoms, molecules, excitons, and so on) can act as emitters. The "fork" effect is predicted for normal decays with the decreasing value of the spin-photon coupling, in contrast to the known "fork" effect of normal frequencies with increasing spin-photon coupling. Our research shows that the classical approach in the linear approximation is well suited for solving the stated problems. However, it should be mentioned that the so-called "cavity protection" effect, associated with non-Markovian memory effects and inhomogeneous broadening of spin transitions with non-Lorentzian lineshapes, could not be described in our linear approximation — this is the expected limitation of our method.

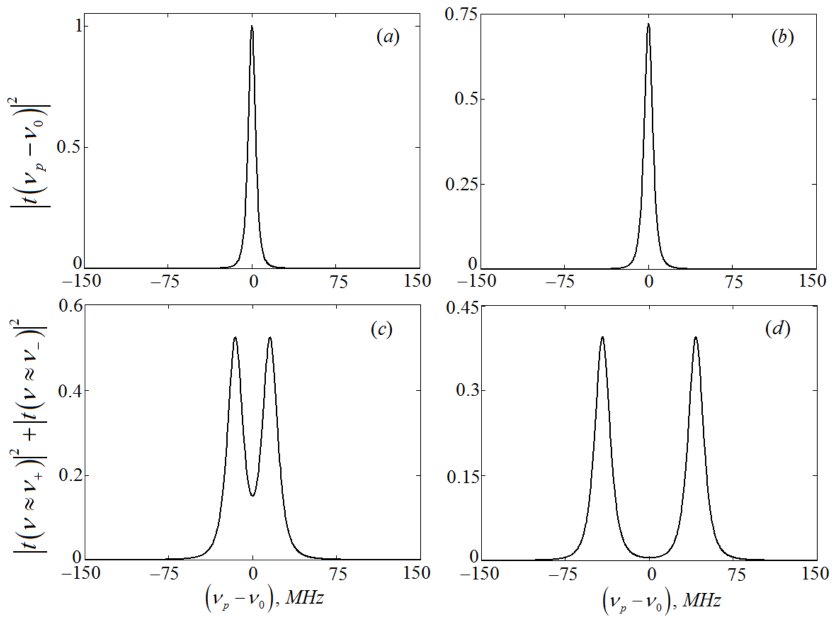

Figure 5. Intensity transmission function of the coupled atom-cavity system, plotted according to Eqs. (24) and (25) of the given paper. For the cavity decay rate, the value $\tau_c^{-1} = 2\pi \times 15MHz$ is taken, and for the EPR linewidth, the value $T_2^{-1} = 2\pi \times 9.5MHz$ is taken of $Ba6S^2\ {}^1S_0 - 6S6p^1P_1$ transition of an ensemble of barium atoms from the Ref. of Zhu et al. (1990). Plots are constructed for different Rabi frequencies: (a) $\Omega_R = 0MHz$; (b) $\Omega_R = 2\pi \times 5MHz$; (c) $\Omega_R = 2\pi \times 10MHz$; (d) $\Omega_R = 2\pi \times 40MHz$

CONCLUSION

Using the analytics of this article can help experimentalists successfully study spin-cavity polaritons.

REFERENCES

Abragam A 2006. Principles of Nuclear Magnetism. Oxford: Oxford University Press, 599pp.

Breeze J, Salvadori E, Sathian J, Alford N, Kay Ch 2017. Room-temperature cavity quantum electrodynamics with strongly coupled Dicke states. npj Quantum Information, 3:40.

Diniz I, Portolan S, Ferreira R, Gerard JM, Bertet P, Auffeves A 2011. Strongly coupling a cavity to inhomogeneous ensembles of emitters: potential for long lived solid-state quantum memories. Phys. Rev. A, 84: 063810.

Fokina N and Elizbarashvili M 2022. Pure Superradiance at the Inhomogeneous Broadening of Inverted Transitions of Spin-Triplet States. International Conference on Global Practice of Multidisciplinary Scientific Studies, Proceeding book, 437-447.

Fokina N and Elizbarashvili M 2021. Pure Superradiance from the Inverted Levels of Spin Triplet States Coupled to Resonator. Appl. Mag. Reson., 52:769-780.

Haroche S and Raimond JM 2006. Exploring the Quantum Atoms, Cavities and Photons. Oxford: Oxford University Press, 605 pp.

Migulin VV, Medvedev VI, Mustel ER, Parygin VN 1978. Basic Theory of Oscillations (in Russian). Moscow: Nauka, 392 pp.

Salikhov KM, Bakirov MM, Zaripov RB, Khairutdinov IT 2023. Experimental confirmation of the formation of a spin polariton in dilute solutions of paramagnetic particles. Phys. Chem. Chem. Phys., 25: 17966–17977.

Thompson R J, Rempe G, Kimble HJ 1992. Observation of normal-mode splitting for an atom in an optical cavity. Phys. Rev. Lett. 68: 1132-1135.

Zhu Y, Gauthier DJ, Morin SE., Wu Q, Carmichael H J, Mossberg TW 1990.Vacuum Rabi splitting as a feature of linear-dispersion theory: Analysis and experimental observations. Phys. Rev. Lett. 64: 2499-2502.