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Research Article

Feedback Control over Response in the Cavity Quantum Electromagnetic Sensor

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Abstract – Here we discuss as an important particular case the hybrid quantum electromagnetic sensor represented by a nitrogen-vacancy (NV) ensemble of $N >> 1$ centers in the doped diamond coupled to a high-quality factor dielectric resonator. The existing NV ensemble-based devices exhibit sensitivities that are several orders of magnitude away from theoretical limits. On the one hand, improvements in spin dephasing time, readout accuracy, and properties of the base diamond material can significantly improve the quality of operation of a quantum sensor. On the other hand, sensing optimization schemes also significantly affect its performance. We focus on the application of feedback to control the response in the cavity quantum electromagnetic sensor. We use the standard Tavis-Cummings model for the system and then introduce control over the target attractor method. In this model they are considered to be non-interacting two-level systems with transition frequencies ω_j, distributed inhomogeneously due to heterogeneous local magnetic and strain environments as well as hyperfine coupling with ^{14}N nuclear spins. We adopted an operator form of closed-loop algorithm to the semi-classical Tavis-Cummings model in its 'weak microwave drive' limit. We used here target attractor Kolesnikov's formulation of feedback to track the sensor response r or, alternatively, the reflected signal to the input drive field. In both cases, we achieve the tracking goal in the exponentially fast convergence.

Keywords – Nitrogen-vacancy-cavity system, quantum electrodynamics, Tavis-Cummings model, weak microwabe drive, target attractor feedback.

I. Introduction

Ultrasensitive quantum sensing can be implemented in a wide variety of forms, allowing the detection of weak signals at the nanolevel. An important feature of the technical implementation is the preservation of quantum coherence. A good example of such stable behavior are the nitrogen vacancy (NV) centers in diamond [1-3].

One of the basic characteristics for the efficiency of the implementation of quantum sensing process is the opportunity to control over the sensor ***response*** r to the environmental change, which is defined as the ration of the output (reflected) signal β_{out} to the input drive field β_{in}:

$$r = \frac{\beta_{\text{out}}}{\beta_{\text{in}}} \ . \tag{1}$$

In this paper, we discuss as an important particular case the hybrid quantum electromagnetic sensor represented by a nitrogen-vacancy ensemble of *N* centers in the doped diamond coupled to a high-quality factor dielectric resonator, see the experimental setup [4] on Fig. 1.

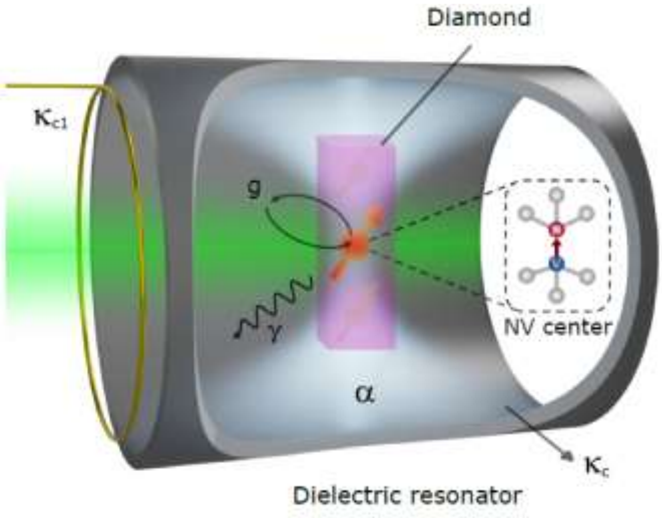

Fig. 1 Hybrid quantum sensor based on NV-cavity coupled to dielectric resonator [4].

A green laser field (green color) performs a continuous polarization of the NV spin ensemble. The detection loop (left) is incorporated to electrically probe the system, for details see [4].

One of the first successful protocols for such type of hybrid quantum sensors has been developed in [5]. Since then, the popularity of solid-state spin systems using the properties of nitrogen-vacancy centers in diamond has been continuously growing [5,6]. Essentially, the centers of color defects in the diamond behave like miniature compasses. They are extremely sensitive to the external magnetic fields [7]. However, existing NV ensemble-based devices exhibit sensitivities that are several orders of magnitude away from theoretical limits [5]. On the one hand, improvements in spin dephasing time, readout accuracy, and properties of the base diamond material can significantly improve the quality of operation of a quantum sensor. On the other hand, sensing optimization schemes also significantly affect its performance.

In this work, we focus on the application of feedback to control the response in the cavity quantum electromagnetic sensor. We use the standard Tavis-Cummings model for the system and then introduce control over the target attractor method.

II. Model and Method

The energetic structure of the quantum sensor covers $N \gg 1$ NV centers. In the Tavis-Cummings model they are considered to be non-interacting two-level systems with transition frequencies ω_j, distributed inhomogeneously due to heterogeneous local magnetic and strain environments as well as hyperfine coupling with ^{14}N nuclear spins, see Fig. 2.

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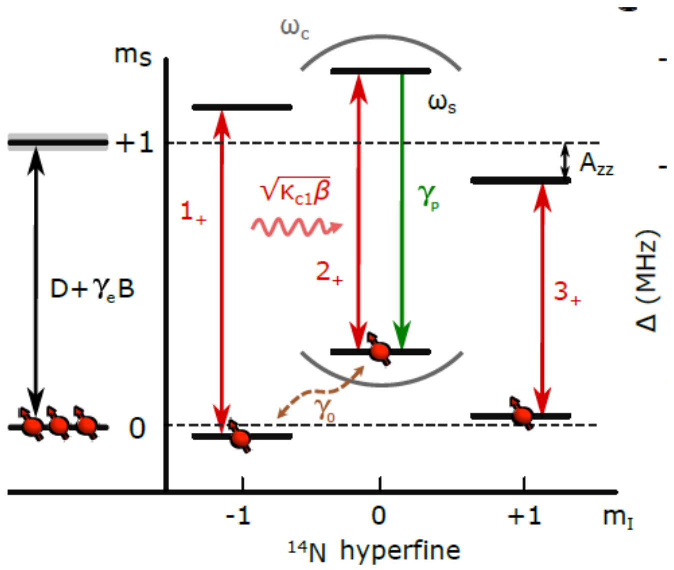

Fig. 2. The energetic structure of the quantum sensor [4].

The total spin relaxation rate in Fig. 2 consists of two parts: $\gamma = \gamma_0 + \gamma_p$, where γ_0 is the thermalization rate, γ_p is the uniform optical polarization rate, and $\gamma_0 \ll \gamma_p$.

The relaxation rate for the cavity mode is given by $\kappa = \kappa_c + \kappa_{c1}$, where κ_c is the intrinsic relaxation rate, and κ_{c1} is the coupling strength to a microwave probe line.

The uniform coupling strength between each individual j-th spin and the cavity mode is denoted by g_s.

A. *The Tavis-Cummings Model*

The standard semi-classical Tavis-Cummings model [8,9] includes the set of differential equations for the following dynamical variables: the cavity field α, spin coherence s_j, and excited-state population p_j:

$$\begin{aligned} \frac{d\alpha}{dt} &= -\left(i\Delta + \frac{\kappa}{2}\right)\alpha - ig_s\sum_j s_j + \sqrt{\kappa_{c1}}\beta_{\text{in}}\ ; \\ \frac{ds_j}{dt} &= -\left(i\Delta_j + \frac{\gamma}{2}\right)s_j - ig_s(1-2p_j)\alpha\ ; \\ \frac{dp_j}{dt} &= -\gamma_p p_j + ig_s\left(s_j\alpha^* - s_j^*\alpha\right). \end{aligned} \quad (2)$$

RHS (2) includes two detuning parameters: $\Delta = \omega_d - \omega_c$ between the drive frequency ω_d and the cavity frequency ω_c, and $\Delta_j = \omega_d - \omega_j$ between drive frequency ω_d and NV transition frequency ω_j.

The evolution of the dynamical variables α and β_{in} defines the reflecting signal β_{out} [4]:

$$\beta_{\text{out}} = \sqrt{\kappa_{c1}}\alpha - \beta_{\text{in}}\ . \quad (3)$$

The case of $p_j \ll 1$ for all j is called 'the limit of weak microwave drive', in this case the reflection coefficient (1) does not depend on the drive amplitude and can be expressed as a linear response:

$$r = -1 + \frac{\kappa_{c1}}{\dfrac{\kappa}{2} + i\Delta + g^2\displaystyle\int \frac{P(\omega')}{\gamma/2 + i(\omega-\omega')}d\omega'}\ . \quad (4)$$

where the parameter of the collective coupling between the spin ensemble and the cavity is given by $g = g_s\sqrt{N}$, and $P(\omega)$ is the normalized nitrogen-vacancy density per unit frequency with a center frequency of ω_s.

B. *The Target Attractor Feedback Method*

The method of target attractor feedback proposed by Kolesnikov [10,11] deals with the design in the dynamical system an artificial target attractor forcing the dynamical variables be driven towards the desired fixed constants or time-dependent To adopt the target attractor feedback to our quantum model (2), we need to apply its operator formulation similar to proposed in [12,13].

The target attractor control is defined as an exponential convergence to the target function $\beta_{\text{out,t}}$ in case if we track the output:

$$\frac{d}{dt}(\beta_{\text{out}} - \beta_{\text{out,t}}) = -\frac{1}{T_\beta}(\beta_{\text{out}} - \beta_{\text{out,t}}) \ , \tag{5}$$

or, alternatively, if we control the response with its target function r_{t}:

$$\frac{d}{dt}(r - r_{\text{t}}) = -\frac{1}{T}(r - r_{\text{t}}) \ . \tag{6}$$

Here T_β, T are positive constants which define the time scales of Kolesnikov's feedback.

In the limit of weak microwave drive, by chosing the control signal as:

$$u = \sqrt{\kappa_{c1}} \ , \tag{7}$$

and demanding the control process to be much faster than decay in (2), by the fist equation in (2) and by (3) we obtain:

$$\begin{aligned} \frac{d\alpha}{dt} &= u\beta_{\text{in}} \ ; \\ \beta_{\text{out}} &= u\alpha - \beta_{\text{in}} \ , \end{aligned} \tag{8}$$

which implies:

$$u = \sqrt{\frac{1}{\beta_{\text{in}}}\left(\frac{d\beta_{\text{in}}}{dt} + \frac{d\beta_{\text{out}}}{dt}\right)} \ . \tag{9}$$

For the case of driving the output (5), it can be expressed in the form:

$$\frac{d\beta_{\text{out}}}{dt} = \frac{d\beta_{\text{out,t}}}{dt} - \frac{1}{T_\beta}(\beta_{\text{out}} - \beta_{\text{out,t}}) \ . \tag{10}$$

Due to the exponential convergence to the target attractor (5), the output can be evaluated by the substitution of the tracking function $\beta_{\text{out,t}}$ to (9), such that:

$$u = \sqrt{\frac{1}{\beta_{\text{in}}}\left(\frac{d\beta_{\text{in}}}{dt} + \frac{d\beta_{\text{out,t}}}{dt}\right)} \ . \tag{11}$$

Similarly, in case of (6), using (1) and making the same steps we get by (8):

$$u = \sqrt{\frac{1}{\beta_{\text{in}}}\left((1 + r_{\text{t}})\frac{d\beta_{\text{in}}}{dt} + \beta_{\text{in}}\frac{dr_{\text{t}}}{dt}\right)} \ . \tag{12}$$

Thus, the control signal in our algorithm is expressed via the input field β_{in} and the target output $\beta_{\text{out,t}}$ or, alternatively, the target response r_{t}.

III. RESULTS

We adopted an operator form of closed-loop algorithm to the semi-classical Tavis-Cummings model in its 'weak microwave drive' limit. We used here target attractor Kolesnikov's formulation of feedback to track the sensor response *r* or, alternatively, the reflected signal β_{out} to the input drive field β_{in}. In both cases we achieve the tracking goal in the exponentially fast convergence.

IV. DISCUSSION

Different stages of the working cycles of quantum sensors may demand different parameters of the optimization in the model systems. That's why it is so important to investigate tracking (dynamical goal) rather than stabilization It makes possible a kind of 'soft switching' among the different time stages of the sensor operation.

Our further research will focus on the problem of computational cost and complexities of the practical implementation of alternative feedback algorithms, especially in their alternative gradient and attractor formulations.

V. CONCLUSION

A response to the environmental change in the form of tracking, i.e. an arbitrary time-dependent function in the cavity quantum electromagnetic sensor based on the nitrogen vacancy (NV) centers in diamond can be efficiently controlled by the application of the operator form of target attractor feedback algorithm.

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