Optimal control of diamond spin qubits for quantum sensing in noisy environments

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Abstract: We devise a robust quantum sensing scheme based on optimal control. We experimentally demonstrate sensitivity enhancement of diamond spin-qubits sensors to measure ultraweak time-varying magnetic fields in noisy environments.

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1. Introduction

Optimal control theory [1] provides valuable tools for steering the dynamics of a quantum system and performing desired operations, with high fidelity and speed. However, quantum sensing poses peculiar challenges to control. The information on the unitary dynamics of the system is not a priori accessible, due to the presence of unknown external field to be measured. Thus, fidelity cannot be a suitable figure of merit to optimize control. Moreover, the goal of sensing requires both maximizing the effect of the field to be measured, and protecting the sensor from unwanted external noise, two tasks that are inherently contrasting each other.

We devise an optimal control scheme that exploits sensitivity as a novel optimization metric [2]. We experimentally implement this control paradigm using a Nitrogen-Vacancy (NV) center in diamond as a magnetic field sensor. Advantageously, sensitivity includes both the unknown external field to be measured, and decoherence induced by environmental noise, which we spectroscopically characterize [3]. Our optimal control scheme demonstrates superior performances in complex sensing tasks, such as measuring multi-chromatic ac fields and arbitrary waveforms.

2. Discussion

The electronic spin of the Nitrogen-Vacancy center has emerged as a prominent quantum sensor thanks to combination of sensitivity, spatial resolution, and ultralong coherence. In the presence of a static bias magnetic field, we exploit the $S_z = 0, -1$ ground-state spin projections as an effective two-level system. The spin qubit is coupled both to the external field $b(t)$ to be measured (inducing unitary but unknown dynamics), and to noise $\beta(t)$, inducing decoherence. We assume $\beta(t)$ to be described by a stochastic variable with power spectral density $S(\omega)$ in frequency domain. Control is applied to the spin qubit via pulsed dynamical decoupling (DD) [4], consisting in series of π pulses that repeatedly flip the spin, thus reversing its evolution. A Ramsey interferometer embedding the control sequences measures $b(t)$.

The considered sensing task consists in measuring the amplitude of an ultraweak spectrally characterized magnetic field with multiple frequency components. Common equispaced DD pulse sequences show high frequency selectivity that can be exploited to measure monochromatic ac magnetic fields [6], but for this reason they may exhibit suboptimal performances when probing a multitone target field due to attenuation of some frequency components. We have thus designed a direct and fast search method that looks for the optimal pulse sequence minimizing the cost function η, that is, sensitivity. Note that sensitivity $\eta = e^{\chi_n(t)}\sqrt{t}/|\phi_n(t)|$, depends on the applied control both via the decoherence functional $\chi_n(t)$, and via the spin phase $\phi_n(t)$ accumulated during the evolution time t under the unknown field. The search is performed in a multidimensional parameter space. We analyze which optimization parameters (e.g., total sensing time, π-pulse positions, signal phase, signal trigger time) provide the largest improvement without requiring excessive computational resources. An example of optimization for a multitone magnetic field is given in Fig. 1 a, showing a remarkable enhancement of sensitivity compared to standard control when measuring multitone ac fields at fixed interrogation time.

To effectively suppress the effect of unwanted noise, superimposed to the field to be measured, the knowledge of its sources is critical. We thus demonstrate a noise spectroscopy protocol [3] that complements our optimal control

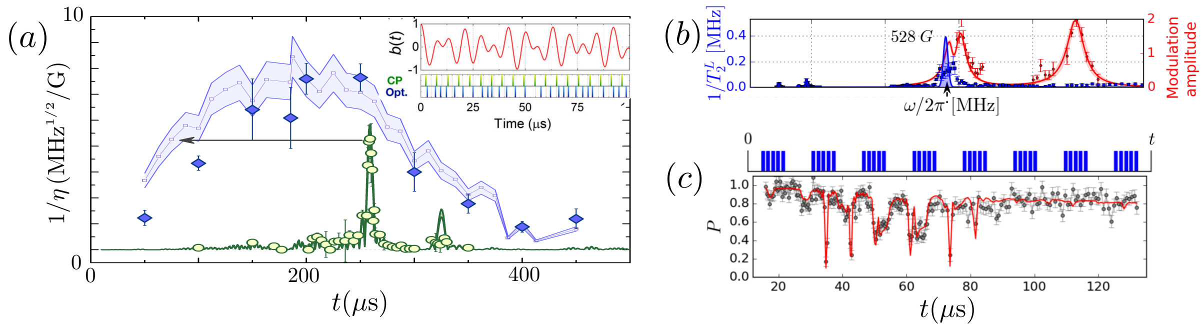

Fig. 1. (a) Inverse of sensitivity, measured in the presence of a sample multitone target field $b(t)$ under equispaced DD sequences (dots), and under optimized control (diamonds). The curves represent the theoretical predictions for the equispaced sequence (green) and the optimized one (blue). The inset shows the time dependece of $b(t)$ and subsets of the two pulse distributions (comprising 50 pulses in both the cases). (b) Noise spectrum (in blue) and coupling with nearby nuclei (in red), due to Carbon nuclear spins inside diamond. (c) Time evolution of spin coherence under different non-equispaced AXY8 pulse sequences. Dots are experimental data with statistical error. Red lines are the predicted coherence simulated using the measured environment, with no free parameters.

strategy. In the absence of any target field, we characterize the nuclear spin environment of the NV qubit inside diamond, comprising both coherently coupled quantum systems, and a larger quantum bath that can be modeled as a classical stochastic field $\beta(t)$ (Fig. 1 b). We overcome the limitation due to the relatively short coherence times by using the higher-order harmonics of DD sequence to provide noise attenuation, and avoid signal saturation from the strong noise peak. Remarkably, in the weak coupling regime of the qubit to the spin environment (high bias field), the obtained environment model shows predictive behavior (Fig. 1 c) under different different kinds of time-dependent control, beyond monochromatic filters.

3. Conclusions

We demonstrated a robust and efficient control method adapted for quantum sensing applications. A precise modeling of the NV spin environment can be used to further improve environment noise suppression, specifically tailored to the measured noise spectrum.

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