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Optical Control of the Silicon–Vacancy Center in Diamond

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Abstract

The silicon–vacancy center in diamond has recently begun to receive significant attention as a candidate for quantum information processing (QIP). Historically, it has been hampered by short dephasing times and strong non-radiative decay from optically excited states. However, recent results indicate that these issues can be overcome for high-purity samples at low temperature. Here we investigate the potential of this center to achieve high-fidelity operations required for QIP.

1. Introduction

Physical platform selection is crucial to the design of a large-scale quantum information-processing machine. This is because the time and fidelity of operations, and also – given an operation group – the bases defining the generators, will differ from one physical platform to another. This means that the choice affects both resource costs in terms of the redundant physical qubits used in encoding, but also any cost associated with a decomposition of the abstract operations of an algorithm or protocol into concrete, physically realizable processes. As a result, the properties of potential physical platforms must be compared and contrasted with one another. As an initial step, comparisons between physical platforms may be performed at low-resolution using broad properties such as coherence times, the bounds on operation rates implied by coupling amplitudes and energy gaps, and transition branching ratios. Having first sorted candidate platforms roughly in this manner, however, a more detailed treatment is necessary.

The negatively charged silicon–vacancy center has recently begun to receive interest in the context of quantum information processing. Long considered a potential single-photon source due to its bright fluorescent emission, refinement of the model of the silicon–vacancy center's energy level structure and noise processes has revealed the potential at low temperatures for a stable pair of electronic ground states and coupling to a long-lived nuclear spin – as with the nitrogen–vacancy center. However, unlike the nitrogen–vacancy center, its primary point of comparison, the structure of the silicon–vacancy center protects its optical transitions at first order from electric field fluctuations, it has a high rate of radiative emission to the zero-phonon line, there is no metastable decay pathway, and optical driving does not appear to change the charge state. These discoveries raise the question: In a photonic module architecture for quantum information processing, should the silicon–vacancy center take the place of the nitrogen–vacancy center?

Here, we take a step toward addressing this question with theoretical estimates for the performance of a pair of operations on the silicon–vacancy center: Coherent population transfer via optical transitions and projective measurement of the spin component of the electronic state mediated by state-dependent cavity reflection statistics.

2. Method of Approach

We begin with some general approximations and assumptions about the center: No static Jahn-Teller or strain terms; no fluctuation, nor statistical uncertainty in the dynamical parameters; no non-radiative decay from the optically excited states; no native decay terms with decay times greater than O(10 microseconds); no nuclear (hyperfine) sublevels; and no conjectured additional energy levels around the optically excited states. These assumptions leave us with the canonical eight-state system of the silicon–vacancy center, with each subspace governed by the Hamiltonian,

$$\hat{H} = \hbar\lambda^{GS/ES}\hat{S}_Z^{(o)}\hat{S}_Z^{(e)} + \hbar f\gamma^{(o)}B_Z\hat{S}_Z^{(o)} + \hbar\gamma^{(e)}\left(B_x\hat{S}_X^{(e)} + B_y\hat{S}_Y^{(e)} + B_z\hat{S}_Z^{(e)}\right), \quad (1)$$

where the three terms respectively are the spin–orbit coupling, the suppressed (f=0.1) magnetic field dependence of the orbital component, and the magnetic field dependence of the spin component.

We simulate coherent population transfer via STIRAP by numerical integration of the master equation, where Linblad terms include O(1.8 nanoseconds) optical decay, O(66 nanoseconds) ground state orbital decay, and O(6.6 microseconds) ground state spin decay.

Following [1], Stokes' and pump pulses are Gaussian, have the same width and magnitude, and are separated by one standard deviation. Frequencies and polarizations are chosen resonant with the target transitions. The pulse standard deviation and magnitude are limited by the ground state decay times and the transition energy gaps, respectively. As a result of these considerations, we choose the total pulse time to be one hundredth of the spin decay time, and estimate an upper bound on the pulse magnitude of one third of the energy gap to the closest undesirable optical transition.

The differential equation solver was chosen for convenience to be the Scipy [2] implementation of the 'dop853' solver. The step time was set to half the period of the maximum energy gap to ensure at least two samples per oscillation, and the relative tolerance was set to 1e-6. The cumulative absolute error is estimated to be at order 1e-11, and therefore negligible.

We simulate measurement of the spin state of the center mediated by cavity reflection statistics by solving for the scattering matrix in the long-time limit. Necessary to this approach is the assumption that the order of optical decay terms (of both the center and cavity) is fast relative to the time between probe pulses and the time of ground state decay terms. Energy detunings between the probe field and the cavity mode, and between the cavity mode and the center transition, as well as the relative loss rates of the two cavity mirrors, are locally optimized via gradient descent. The cost function of this local optimization is the fidelity of the final state, while the initial condition is a balanced cavity with resonant modes. For convenience, we use the Scipy implementation of the Nelder-Mead algorithm with a tolerance of 1e-10. The time between probe pulses is set to 20 nanoseconds to suppress the expected remnant population between pulses, and the maximum number of such pulses is bounded by the spin relaxation time to order O(10). The problem of deriving the scattering matrix amounts to solving the matrix equation,

$$Mx + b = 0, \qquad (2)$$

where b are the driving fields, M is the set of Langevin equations, and x is the steady state solution. For this we use the solver in the Numpy linear algebra (linalg) library.

3. Key Results

We find, as depicted in Figure 1, that the fidelity of the STIRAP population transfer is limited to order 90% by undesirable population of the excited states and consequent rapid decay to ground states outside the qubit subspace.

Our model of cavity-mediated spin measurement achieves fidelities of order 99% for cavity cooperativities of order 100, as shown in Table I. Increasing the number of measurement probe pulses is found not to improve the fidelity in the ideal case, but can restore the order of the fidelity in the presence of photon loss in the source and detectors.

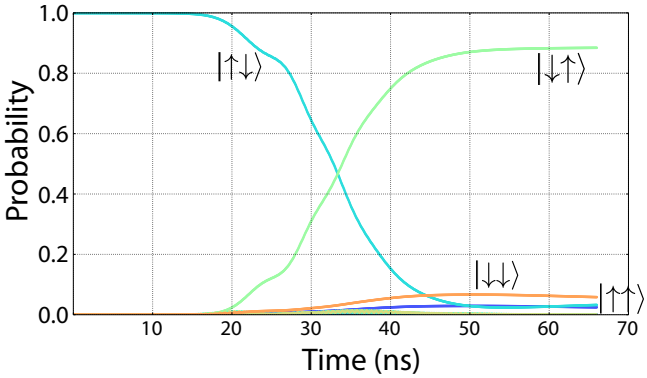

Fig. 1 Ground state population probabilities as a function of time for optical STIRAP population transfer.

Table I Performance of Cavity–Mediated Spin Measurement

Cavity Cooperativity	Pulse Number	Fidelity
1000	1	0.964469
100	1	0.989910
10	1	0.952721
100	10	0.954436
10	10	0.966740

4. Conclusions

We simulate estimates for the fidelity of coherent population transfer via optical STIRAP and of spin measurement mediated by cavity reflection statistics, for the silicon–vacancy center in diamond. These fidelities do not surpass those of the center's primary point of comparison, the nitrogen–vacancy center [3,4]. Nonetheless, the speed with which the projective measurements can be performed – roughly an order of magnitude faster than equivalent measurements with the nitrogen–vacancy center – suggests that the silicon–vacancy center could be usefully applied to efforts in quantum communication, where the strict error rate requirements of fault tolerant quantum computation need not necessarily apply.

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