Detecting Low-Intensity Light at the Interface of Chromophores and Diamond

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Long spin coherence times of nitrogen vacancy (NV) center spins in diamond under ambient conditions have made these systems attractive candidates for quantum information processing [1]. Substantial progress has been accomplished in using NV centers as nanoscale magnetometers with a sensitivity to fields orders of magnitude smaller than the Earth's geomagnetic field [2]. Such small fields are measured from the small Zeeman shifts via optically-detected electron spin resonance spectra. The applications of NV centers is widespread — high spatial resolution of NV magnetometry has been achieved in imaging living cells [3]. Aside from zero-field splitting, the spin-orbit interaction in conjunction with an electric field also induces spin splitting of the $m_s = \pm 1$ states [4]. The dependence of the NV ground state on electric field suggests these centers are also useful as electric field sensors.

We develop a theory in which the optical output of an NV center is used to determine the presence of an electric field. Beyond this utility, we also present a nanoscale model of few photon detection accomplished when a chromophore lies at the interface of a NV center in diamond. Photons incident upon the chromophore induce a conformational change which includes a sizable charge polarization and electric dipole moment (>10 D). See Figure 1. Using the formalism of positive operator values measurements (POVMs), we predict the existence of the photo-excited electric dipole field and, by extension, the incident photon given a measured readout state (photoemission) from the NV center. We find that an applied magnetic field plays a non-trivial role that can reduce the error rate. We describe a scheme by which the time of the incident photon can be resolved. Finally we investigate the role of multiple, coupled NV centers interfaced with multiple chromophores in offering spatial resolution to the detection.

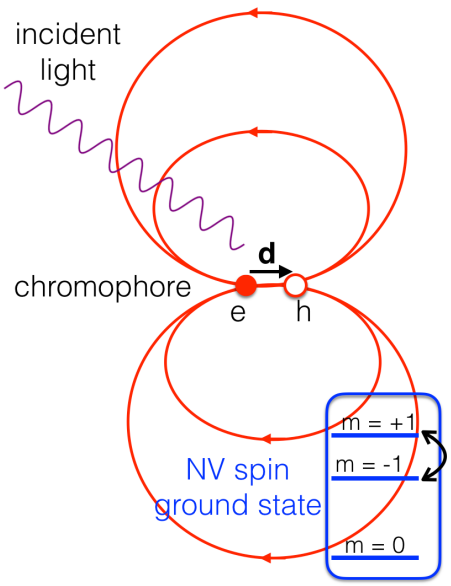

Figure 1: Model of photon detection. Dynamic charge polarization is detected by the NV center through spin transitions (black double arrow).

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[2] K. Jensen, *et al.*, Phys. Rev. Lett. **112**, 160802 (2014)
[3] D. Le Sage *et al.*, Nature **496**, 486 (2013)
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Supplementary Information

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The ground state and Zeeman Hamiltonians of the NV center are

$$\mathcal{H}_{gs}+\mathcal{H}_z=(2\pi\hbar D_{gs}+d_{gs,||}\Pi_z)S_z^2+d_{gs,\perp}\left[\Pi_x(S_x^2-S_y^2)+\Pi_y(S_xS_y+S_yS_x)\right]+g\mu_B B_z S_z,$$

where $\mathbf{\Pi}$ is the electric field vector, $\mathbf{d}_{gs}$ is the dipole moment vector of the triplet ground state, and D_{gs} is the zero-field spin splitting. S_i are spin-1 operators. The NV spin is initiated in a specified state and evolved according to the Liouville equation

$$\frac{\partial\rho}{\partial t}=-\frac{i}{\hbar}[\mathcal{H}_{gs}+\mathcal{H}_z]+\sum_{i=1,2,3}\left(L_i\rho L_i^T-\frac{1}{2}\{L_i^TL_i,\rho\}\right)$$

where the second term on the right hand side describes spin decoherence and relaxation. The theory of quantum state discrimination [4] allows us to choose a particular basis of measurement to optimally determine whether at some instant there is an electric field present or absent. Figure 2 plots the error probability of the measurement in time for different magnetic fields. The larger the electric field the smaller the error rate.

Our model of photon detection relies on chromophores near the surface of diamond with NV centers near that interface. Given a dipole of 10 D, the electric field 1 nm away at an NV center is over 10^8 V/m for which the error probability is < 0.005.

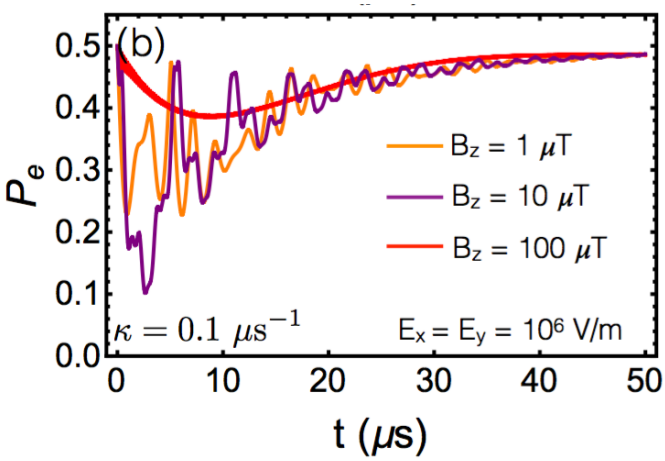

Figure 2: Error probability, P_e, as a function of time for three different applied magnetic fields. Measurements of the POVM should take place at times and magnetic fields where P_e, is minimum (around 3 microseconds and 10 microtesla). κ is the decoherence rate.

[4] J. A. Bergou, Journal of Modern Optics **57**, 160 (2015)