Absorption-Based Diamond Spin Microscopy on a Plasmonic Quantum Metasurface

Laura Kim1, Hyeongrak Choi1,2, Matthew E. Trusheim1,3, and Dirk R. Englund1,2

1. Research Laboratory of Electronics, MIT, Cambridge, MA 02139, USA
2. Department of Electrical Engineering and Computer Science, MIT, Cambridge, MA 02139, USA
3. U.S. Army Research Laboratory, Sensors and Electron Devices Directorate, Adelphi, Maryland 20783, USA

lbkim@mit.edu

Abstract: We propose a resonant diamond plasmonic metasurface coupled with nitrogen-vacancy ensembles as a quantum imaging surface and report a sensitivity below 1 nT/Hz1/2 per µm2 of sensing area.

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Nitrogen vacancy (NV) centers in diamond have emerged as a leading quantum sensor platform, combining exceptional sensitivity with nanoscale spatial resolution by optically detected magnetic resonance (ODMR). Because fluorescence-based ODMR techniques are limited by low photon collection efficiency and modulation contrast, there has been growing interest in infrared (IR)-absorption-based readout of the NV singlet state transition. IR readout can improve contrast and collection efficiency [1-3], but it has thus far been limited to long-pathlength geometries in bulk samples due to the small absorption cross section of the NV singlet state. This long pathlength requirement presents the central challenge in IR readout to imaging microscopy, where the sensing depth should commonly be below the micron-scale. We solve this problem by introducing a diamond resonant metallodielectric metasurface that couples localized surface plasmon polaron resonance (SPP) resonance with long-range Rayleigh-Wood anomaly (RWA) mode [4,5]. This plasmonic quantum sensing metasurface (PQSM) amplifies the IR absorption by confining vertically incident IR probe light in a few-micron-thick diamond layer with a quality factor near 1,000. The structure dimensions can be chosen to find the desired balance between SPP modes and RWA modes: stronger SPP localization resulting in more localized sensing can be traded against better sensitivity, and vice versa, depending on the use case. The PQSM combines a large field enhancement of the SPP mode and delocalization of the RWA mode, making the SPP-RWA hybrid mode well suited for ensemble-based sensing (Fig. 1b).

Fig. 1 (a) Plasmonic quantum sensing metasurface (PQSM) consisting of a metallodielectric grating and proposed homodyne-detection-based sensing scheme. TM-polarized incoming light induces a SPP-RWA hybrid mode, creating a vertically extended field profile as shown in the the overlapping Re(\(E_y\)). The interfered output beam is detected by a CCD camera. (b) Total electric field intensity of RWA-SPP resonances upon normal incidence at \(\lambda_0 = 1042\) nm with a period of \(\lambda_0 / n\), where \(\lambda_0\) is 1042 nm and \(n\) is the refractive index of diamond. The arrow plot shows the magnetic field generated by a uniform driving current in an infinite array of plasmonic Ag wires.

Fig. 1 (a) shows the proposed PQSM for the IR-absorption-based detection scheme. The sensing surface is pumped with a green laser at 532 nm for NV spin initialization and illuminated with transverse magnetic (TM) polarized probe light at 1042 nm for IR readout. The PQSM-NV layer causes a spin-dependent phase and amplitude
of the IR reflection. The spatially well-defined signal beam is separated from the incident probe field in a dark-field excitation geometry (i.e., k-vector filtering). Unlike fluorescence, the directional reflection (or transmission) can be captured with near-unity efficiency. By interfering with a local oscillator, phase-sensitive homodyne detection at the camera enables measurement at the photon shot noise limit, eliminating the need of single photon detectors. The PQSM doubles as a wire array for NV microwave control: with a subwavelength spacing, an array of the silver wires produces a homogeneous transverse magnetic field as shown in Fig. 1 (b). Local excitation and probing of NVs within a pixel are possible by running a current through an individual wire.

We estimate the shot-noise-limited sensitivity below 1 nT/Hz\(^{1/2}\) per µm\(^2\) of sensing area using numbers for present-day NV diamond samples and fabrication techniques and assuming no power broadening from pump or microwaves. As expected, sensitivity improves with increasing green laser intensity until two-photon-mediated photo-ionization processes start to become considerable. Furthermore, as shown in Fig. 2 (b), increasing the sensing depth from 500 nm to 10 µm improves the sensitivity by a factor of up to ~ 9. There exists a tradeoff between achievable sensitivity and spatial resolution. Under the conditions considered in this work, the photon shot noise dominates, and a better SNR is achieved by biasing the interferometric readout with a controlled phase difference. Homodyne detection is particularly advantageous for fast imaging on focal plane arrays.

In summary, the exceptional performance of the PQSM is achieved by the SPP-RWA resonance that optimizes an electric field enhancement within a micron-scale NV layer, and it already approaches the requirement for the most demanding applications such as imaging through scattering tissue and spatially-resolved chemical NMR detection. The plasmonic structures of the PQSM also provide an optimal microwave control by generating a homogeneous magnetic field across a large sensing area. Combined with a homodyne detection, the PQSM makes a new type of quantum microscope that enables high-speed imaging measurements at the photon shot noise limit.

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