

Hardware and Machine Learning Optimization of Diamond Quantum Sensors

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Abstract: Quantum sensing with nitrogen vacancy (NV) color center defects in diamond was optimized with hardware and machine learning approaches, which led to the development of small footprint quantum sensor devices. © 2024 The Author(s)

Quantum sensing represents a revolutionary shift in detection methodologies, harnessing the inherent sensitivities of quantum states to their environment for the precise identification of extremely small changes in physical quantities such as temperature, magnetic fields, and electric fields. Amid the array of emerging quantum science applications, including computing and communication, quantum sensing is gaining substantial recognition as a viable technology. Notably, commercially available products have already made significant strides in the market.

A particularly promising avenue in the realm of quantum sensing is the utilization of NV color center defects in diamond. This solid-state quantum sensing platform distinguishes itself by its ability to operate effectively under ambient conditions, setting it apart from many other systems. Recent attention has been captivated by the transformative potential of this approach, particularly in achieving picotesla-level sensitivity and high spatial resolution magnetometry. However, current sensitivities of solid-state defect-based quantum sensors are orders of magnitude less than the predicted theoretical limits [1]. A range of continuous wave (CW) and pulsed optically detected magnetic resonance (ODMR) protocols were developed for improving detection limits of quantum sensing experiments with defects. Machine learning (ML) algorithms also have the potential to enhance the sensitivities of these quantum sensors. In addition, there are numerous aspects of NV physics, including charge dynamics in ensembles, that are still not well understood and thus require further research and exploration. Furthermore, current experimental solid-state defect-based quantum sensor setups are bulky and small footprint versions are yet to be demonstrated.

We have implemented hardware optimization methods to increase sensitivities of diamond quantum sensing setups. Efficient delivery of microwave radiation to the samples is a critical aspect of solid-state defect-based quantum sensing experiments. Traditional approaches involve forming a wire loop at the tip of an RF cable and using gold wires as RF antennas. We designed, fabricated, and utilized high efficiency microstrip and coplanar RF antennas which removed the need for an RF amplifier and 0 dBm output of a standard RF signal generator was sufficient to observe ODMR and magnetic field sensing with NV defects in diamond [2]. Figure 1 shows the image, simulated and experimental S11 data of an example high efficiency coplanar RF antenna with a return loss of over 37 dB at 2.87 GHz zero field splitting (ZFS) frequency of NV diamond.

In ODMR experiments, photoluminescence (PL) data obtained from a spectrometer includes dark background counts originating

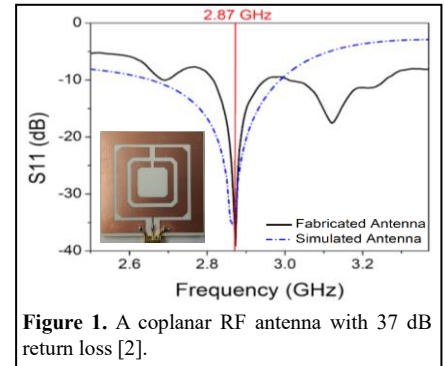


Figure 1. A coplanar RF antenna with 37 dB return loss [2].

in the detector chip, fluorescence background emission generated by the buffer media surrounding the sample, and the PL emission emanating from the diamond sample. It is crucial to accurately distinguish and separate these signals from various sources, with a specific focus on isolating the PL signal associated with NV defects. This precision is essential for ensuring the accurate quantification of ODMR spectra. We have developed machine learning (ML) algorithms based on the expectation-maximization (E-M) framework to effectively eliminate instrumental noise in CW ODMR experiments [2]. These ML algorithms ensure that automated experiments commence only when the laser power stabilizes, with fluctuations below 1%. In our standard experiments, pixel-level background counts are typically around 3%. Consequently, the ML algorithms enhance spectra by removing noise upfront, facilitating precise data collection through the spectrometer. For two types of background counts, namely dark counts and substrate/contamination-induced extra fluorescence, the ML algorithms leverage mixture models like Gaussian and/or Poisson distributions. These models learn from acquired signals to effectively distinguish between background and foreground signals, enabling accurate differentiation between background (including NV⁰ contribution) and sample signals using Gaussian and Poisson regression. Our analysis reveals that the estimated distribution parameters for background counts by mixture models stabilize after only 100 data samples and converge rapidly. This enables the use of ML models at the beginning of each experiment without significant delays, thereby enhancing the sensitivity of our measurements. Specifically, we can detect a less than 0.1% PL signal change in CW ODMR experiments, a feat not achievable before employing ML algorithms due to inherent experimental noise.

These optimization methods recently enabled the development of a battery-operated compact quantum sensor (CQS) device for magnetic field detection. The dimensions of the device are $\sim 10\text{cm} \times 10\text{cm} \times 4\text{cm}$ as shown in Figure 2. As built device has microtesla level magnetic field detection sensitivity. Further advancements in machine learning techniques have been devised to initially achieve nanotesla level sensitivity with the goal of attaining picotesla level magnetic field detection capabilities with the CQS device. Due to its small footprint, CQS device is expected to be utilized in a wide range of applications in different industries including space, biomedical, and automotive.

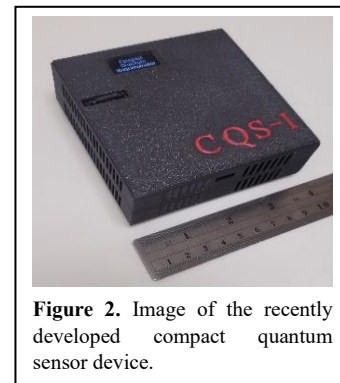


Figure 2. Image of the recently developed compact quantum sensor device.

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References

- 1- Barry, J. F., Schloss, J. M., Bauch, E., Turner, M. J., Hart, C. A., Pham, L. M., & Walsworth, R. L. (2020). Sensitivity optimization for NV-diamond magnetometry. *Reviews of Modern Physics*, 92(1), 015004.
- 2- Mahtab, S., P. Milas, D-T. Veal, M. G. Spencer, and B. Ozturk. "High efficiency radio frequency antennas for amplifier free quantum sensing applications." *Review of Scientific Instruments* 94, no. 4 (2023): 044701.