Scanning Microwave Microscopy of Quantum Materials with a Nano-Coaxial Probe

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***Abstract*— We present a hybrid measurement platform that integrates super-resolution fluorescence microscopy with an open-ended nano-coaxial scanning microwave microscope (SMM). We demonstrate this system on diamond particles, which simultaneously emit bright fluorescence from nitrogen-vacancy (NV) centers. The nano-coaxial apex structure consists of a fused silica dielectric (outer diameter: 5 µm), a Pt inner conductor (~1.2 µm diameter), coated with a Cr/Au bilayer (10 nm/200 nm). This proof-of-concept study demonstrates simultaneous microwave and optical imaging of a new class of quantum materials, and may have applications ultimately in quantum state manipulation of qubits using nanoscale confinement of microwave pulses.**

Keywords*— Scanning microwave microscopy (SMM), coaxial probe, nitrogen-vacancy (NV) center, super-resolution microscopy.

I. INTRODUCTION

The emergence of quantum information science [1] has motivated the demand for new classes of materials and technologies with the ability to control qubits in solid state materials at room temperature. Broadly speaking, these are based on charge and spin degrees of freedom, for example nitrogen vacancy (NV) color centers in diamond [2]. The characterization of these materials is important for their ultimate use in quantum information processing systems. This requires "Metrology for the second quantum revolution" [3]. Consequently, advanced techniques are required to enable precise characterization of emerging quantum materials.

Scanning microwave microscopy (SMM) has recently been developed, optimized, and demonstrated for a broad variety of characterizations, including materials science, semiconductor device characterization, and even living biological systems [4], [5]. To improve the spatial confinement of fields, we have recently extended the original coaxial work of Univ. of Maryland [6], [7] from the 90's to include room temperature biological systems [8] as well as extended the tip geometry from millimeter scale to the micron and nanoscale [9]. These technological innovations, together with simultaneous super-resolution optical access to quantum bits in solid state systems [10] are ideal ingredients to ultimately provide the ability to provide locally addressable radio frequency (RF) signals to individual qubits.

In this work, we take a step in that direction. We use a nano-coaxial structure as an SMM probe tip to characterize 15 µm diamond particles with optically accessible NV centers. The SMM is integrated into a super resolution microscope in which we previously demonstrated quantum state manipulation of these particles [10]. This integrated system can perform SMM and quantum state manipulation in a single platform, providing proof of concept demonstration of microwave characterization of quantum materials.

II. EXPERIMENTAL SET-UP

The experimental set-up integrates an open-ended coaxial SMM setup with a super-resolution fluorescence microscope. The complete system configuration is illustrated in Fig. 1. A miniaturized open-ended nano-coaxial probe is connected to a 1-port USB vector network analyzer (VNA - Anritsu^{TM} MS46121B) to measure the microwave complex reflection coefficient S_{11}. The nano-coaxial probe is fabricated using a modified nano-pipette pulling technique. A fused silica capillary (outer diameter: 1.2 mm, inner diameter: 0.4 mm) serves as the structural base. A platinum (Pt) wire (0.15 mm diameter) is inserted prior to pulling to act as the inner conductor. The pulled tip tapers to nanoscale dimensions, with typical apex diameters of 5 µm for the outer conductor and approximately 1.2 µm for the inner conductor. The outer surface is coated via sputtering with a Cr/Au bilayer (10 nm/200 nm), forming the outer conductor of the coaxial transmission line. This results in a shielded coaxial geometry. The detailed fabrication process is available in reference [9]. The probe is mounted on a piezoelectric nano-positioning stage (SmarAct^{TM} SLC-17 series) with 1.2 cm-range travel and closed-loop displacement resolution of 1 nm in XYZ. Both the stage and the VNA are synchronized and automated using custom LabVIEW^{TM}-based control software.

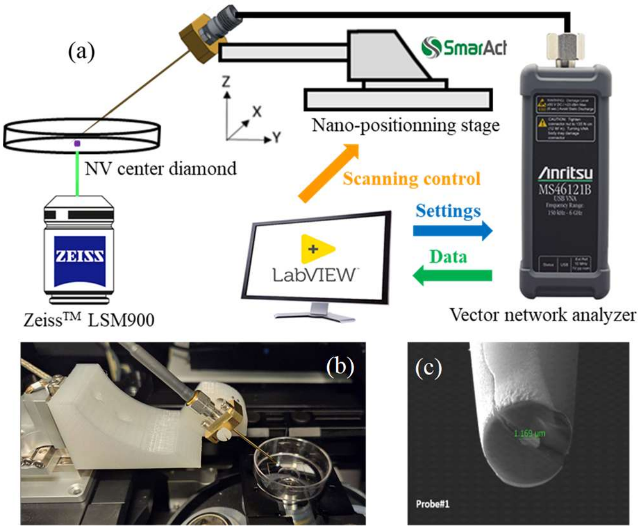

Fig. 1. (a) Schematic illustration of the integrated system combining high-resolution fluorescence and SMM. (b) Photograph of the open-ended nano-coaxial probe integrated into a super resolution confocal microscope (Zeiss^{TM} LSM900 with Airyscan 2 detector). (c) Scanning electron microscopy (SEM) image of the apex of the nano-coaxial probe. The center conductor diameter is ~ 1.2 µm.

The probe was operated in non-contact mode at a fixed height above the sample under test and scanned across the sample in both one-dimensional (line scan) or two-dimensional (area scan) modes. At each spatial point, S_{11} was recorded. The probe is connected via a flexible coaxial cable (MegaPhase^{TM} Ultraphase 1.85 mm 12 inch) to the VNA, operating over a frequency range of 150 kHz to 6 GHz. The input RF power is fixed at 3 dBm for frequencies up to 4 GHz and −5 dBm in the 4–6 GHz range.

Prior to measurements, the probe was characterized at the input of its 1.85 mm coaxial connector (Fig. 2). For an ideal system, the expected response is 0 dB and frequency-independent. In practice, we observe an insertion loss of approximately 5 dB, primarily attributed to resistive losses in the nano-coaxial probe. The frequency response remains relatively flat up to approximately 3 GHz. Accordingly, all measurements presented in this work were performed at a continuous-wave (CW) frequency of 2 GHz.

The scan covers a 40 × 40 µm area with a step size of 2 µm, resulting in a total of 400 measurement points (20 × 20). Each point is measured in CW mode with two data points acquired per location, and the final value is computed as their mean. With an intermediate frequency bandwidth (IFBW) set to 10 Hz and corresponding to 100 ms per point, the total acquisition time per pixel is approximately 200 ms, yielding a total scan time of 80 s per image.

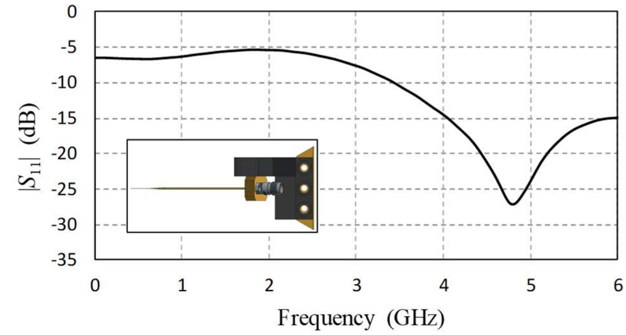

Fig. 2. Measured and calibrated amplitude of the reflection coefficient S_{11} at the input of its 1.85 mm coaxial connector.

For the optical measurements, fluorescence was recorded using a super-resolution confocal microscope (Zeiss™ LSM900 with Airyscan 2 detector). Excitation was performed at 561 nm, and fluorescence was detected in the 600–700 nm spectral range.

III. EXPERIMENTAL RESULTS

The sample under investigation was a 15 µm diamond particle containing NV centers (Adamas Nanotechnologies™, MDNV15umHi30mg) with an NV concentration of approximately 3.5 ppm. The diamond was mounted on a glass coverslip to ensure compatibility with the confocal microscope. The NV centers are bright fluorophores, and quantum state manipulation using optically detected magnetic resonance (ODMR) has previously been demonstrated in this system [10].

Fig. 3(a) presents a bright-field image of the array of particles, and a fluorescence image of an NV center within a single diamond particle. The scanning probe tip was also visible in the optical image (data not shown), enabling precise identification of the particle being scanned. Fig. 3(b) and Fig. 3(c) show two-dimensional SMM maps of the uncalibrated amplitude and phase shift of the complex reflection coefficient S_{11}, acquired over the same region. A strong microwave contrast is observed at the location of the diamond particle. The scan was performed at an approximate tip height of 1 µm above the sample surface. These results confirm the spatial correlation between the fluorescence and microwave signals and demonstrate the ability of the coaxial probe to characterize the localized electromagnetic response at the nanoscale.

In order to enable a more quantitative comparison between fluorescence and microwave characterization, Fig. 4 presents a line scan of the optical fluorescence intensity alongside the corresponding variation of $|S_{11}|$ response from a single diamond particle. Within the region from approximately 40 µm to 65 µm, corresponding to the spatial extent of the diamond, both signals exhibit correlated behavior. The fluorescence signal displays multiple localized dips, which align with corresponding variations in the SMM signal $\Delta S11$. This correlation is consistent with local variations in the complex permittivity, likely induced by substructures or internal domains within the particle. These results confirm the system's capability to resolve spatially varying electromagnetic properties that are directly associated with optically active quantum features.

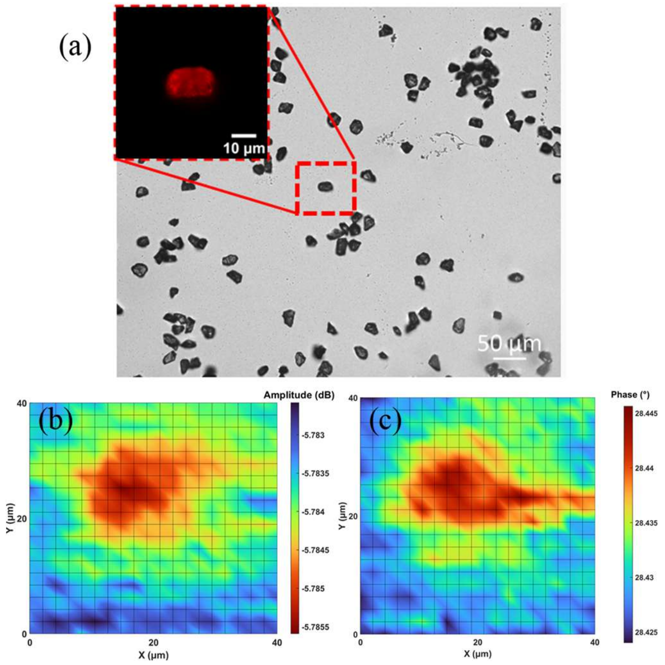

Fig. 3. (a) Bright-field image of multiple NV-center diamond particles, with an inset showing the fluorescence image of the target particle. Amplitude (b) and phase-shift (c) SMM images of the uncalibrated reflection coefficient S_{11}, acquired over the central particle in (a), shown in color scale. The measurements were performed in CW mode of 2 GHz with an IFBW set to 10 Hz.

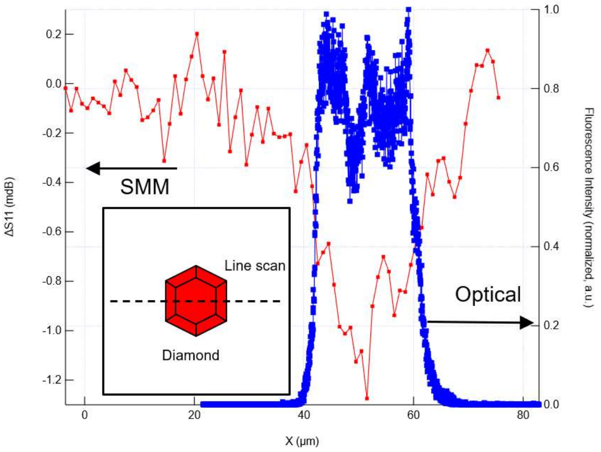

Fig. 4. 1 dimensional line scan of fluorescence intensity (blue) and relative SMM amplitude signal (ΔS11) (red) across a single NV-center diamond particle. The two signals exhibit strong spatial correlation, confirming accurate optical–microwave alignment.

IV. DISCUSSION

The measured change in $|S_{11}|$, approximately 1 mdB, is consistent for an insulating sample. This response results from the tip–sample interaction, which differs from free space primarily through the local permittivity. The interaction with the NV centers is likely much weaker and not observable in this experiment. Although the long-term goal of this system is to enable microwave coupling to the two-level qubit states of NV centers, such interactions are beyond the scope of this work. In previous studies, we have demonstrated sensitivity in SMM down to 1e-6 dB [11]–[14]. The calibration was not considered in this proof-of-concept demonstration.

The spatial resolution of the SMM image (Fig. 4) was ~10 μm, lower than expected from the tip diameter. This may be attributed to fringe fields or tip–sample separation, though the exact cause remains unclear. Quantitative simulation is planned for future work.

V. CONCLUSION

In this study, we developed an integrated measurement platform combining super-resolution fluorescence imaging with SMM using a miniaturized coaxial probe. The system was demonstrated on diamond particles containing NV centers, showing that the coaxial SMM setup can detect localized dielectric responses that closely align with optically defined structures. This proof-of-concept establishes the feasibility of SMM characterization for emerging quantum materials. Future work will focus on enabling quantitative, calibrated measurements of qubits and the potential to individually address qubits with highly localized delivery of microwave pulse sequences for quantum state manipulation.

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