Surface Resistance Mapping of Graphite Battery Cathodes with a 10 GHz Inverted Single Post Dielectric Resonator Scanner

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ABSTRACT

We present an integrated microwave method for characterising graphene-based films that combines classical single-post and split-post dielectric resonators with a two-dimensional imaging single-post resonator. Free-standing graphene oxide and chemically reduced graphene oxide produced by a modified Hummers process were first benchmarked in stand-alone fixtures at five and ten gigahertz. The study is then extended to two-dimensional imaging, which uses numerical electromagnetic calibration and automated horizontal scanning to generate millimetre-resolution maps of sheet resistance across twenty-by-twenty-millimetre samples. The split-post resonator recorded a density-dependent real permittivity between six point eight and seven point four and a loss tangent up to zero point zero three five for graphene oxide, while the single-post resonator showed that chemical reduction increases conductivity by about three orders of magnitude. Imaging revealed clear in-plane gradients; the reduced material displayed a sheet resistance that differed by only three percent between the two approaches yet showed noticeably lower spatial uniformity. The combined workflow links bulk and local microwave responses and offers a practical route for optimising graphene-based coatings for shielding applications.

B. Dual-Mode ruby resonator for validation

A cylindrical ruby dielectric resonator (RuDR) operates at TE011 mode near 13.8 GHz and TE021 at 20.1 GHz. Two metallic (conductive) samples of ca. 20 mm × 20 mm are placed to form the bottom and cover boundary conditions for the resonator. Loading the resonator with those samples perturbs its Q-factor, due to changes of loss in the resonator walls. The change of Q-factro is converted to Rs via retro-modelling, based on BoR FDTD, as in the iSiPDR case. Samples are measured with the coated side and the bare-Cu side facing the cavity, furnishing traceable spot values for scanner cross-checks [10]. Repeatability is ±0.5 %.

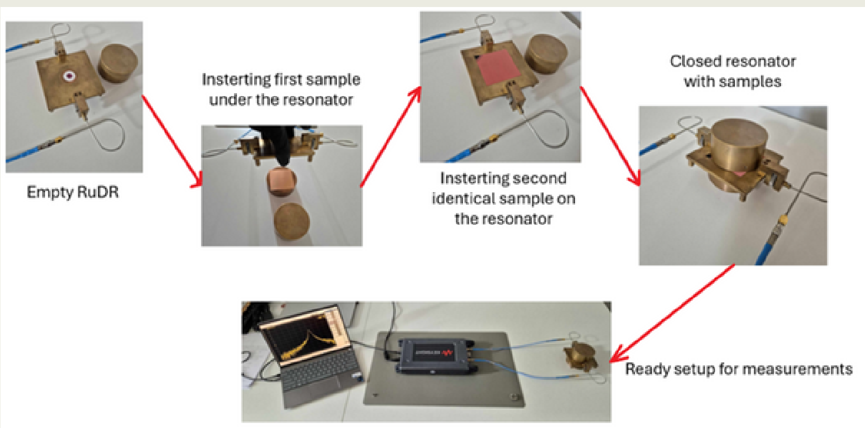
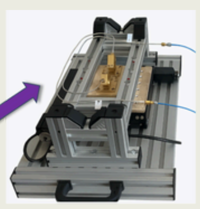


Fig. 3 Material Measurement Procedure on Dual-Mode Ruby Dielectric Resonator.

Fig. 2 Electrodes under test - Graphite on Copper foil



PARAMETERS

- Operational frequency: **10 GHz**
- Resistivity (bulk): **$10^{-4} - 10^{3}$ Ω·cm**
- Surface resistance (thin films): **$10^{-1} - 2 \times 10^{4}$ Ω/sq**
- Sample thickness: **few µm up to 1 mm**
- Sample size (diameter or square): **up to 100 × 100 mm**
- Suitable for lossy thin films, resistive layers & doped semiconductor wafers
- Fully automated, software-controlled measurement

PARAMETERS

- Resonant modes & frequencies: **14 & 20 GHz or 28 & 44 GHz**
- Conductivity range: **$\sigma = 10^{5} - 6 \times 10^{7}$ S/m**
- Sample size: **23 × 23 mm – 60 × 60 mm**
- Sample thickness: **≥ 3 skin depths** (e.g., a few µm for Cu)
- Software-controlled measurement

ACKNOWLEDGMENTS

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INTRODUCTION

Microwave dielectric-resonator techniques have matured into powerful, non-destructive probes of sheet resistance Rs and conductivity σ in thin conductive layers. The inverted Single-Post Dielectric Resonator (iSiPDR) extends the classical single-post design to a two-dimensional scanner that maps Rs with sub-millimetre resolution over panels as large as 10×10 cm² .

Accurate electrode parameters are indispensable for electro-thermal design of lithium-ion cells and for emerging quality-assurance. In this work we focus on a 10 GHz iSiPDR scanner and benchmark its performance on a commercially available single-side-coated graphite anode sheet (41 µm graphite on 9 µm Cu foil). Local (quasi-point-wise) measurements are compared to those with a high-Q ruby dielectric resonator (RuDR)

METHODOLOGY

I. Measurement Method

A. 10 GHz iSiPDR Scanner

The iSiPDR as used in the setup of Fig. 1 employs a single low-loss dielectric pill inverted into a copper cavity and supports the TE01d-like mode. A sample-under-test is inserted through a fixed slot and placed in the region between the dielectric pill and the ground plane. The electric field in this rgeion is well-controleld but relatively weak, which allows testing relatively high-loss (high-conductivity) materials. After inserting the material sample, the resonant frequency is slightly shifted while the Q-factor is substantially lowered, maintaing however the resonance at a detectable level.

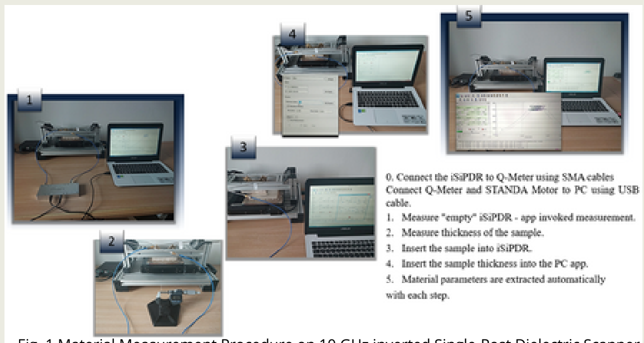
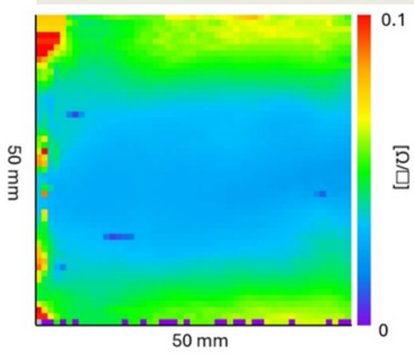


Fig. 1 Material Measurement Procedure on 10 GHz inverted Single-Post Dielectric Scanner

RESULTS & DISCUSSION



Two-dimensional maps of surface resistance extracted by 10 GHz iSiPDR of Graphite on Copper foil

TABLE I. Surface resistance and derived conductivity for Graphite and Copper surfaces; values are means of sixteen repeats

f [GHz]	Electrode side	Rs [mΩ sq⁻¹]	σ [S m⁻¹]	δ [µm]
10,21 (iSiPDR)	Graphite	825± 54.5	1.85×10^{5}	11,6
10,21 (iSiPDR)	Graphite	799 ± 22	1.91×10^{5}	11,4
13,76 (RuDR)	Graphite	661 ± 35	1.25×10^{5}	12,1
13,76 (RuDR)	Cu	31.5 ± 0.3	5.51×10^{7}	0,58

The investigated material (Fig. 2) features a 9 µm rolled-copper foil carrying a 41 µm graphite coating deposited by screen printing. Twenty-millimetre squares were laser-cut, rinsed in isopropanol, and vacuum-dried at 60 °C. Stylus profilometry confirmed thicknesses within the quoted ±1–2 µm tolerances, and these values propagate directly into the conductivity uncertainty. For iSiPDR mapping, a 90 mm × 90 mm region centred on the sheet was scanned. For RuDR validation, 20 mm × 20 mm samples were extracted from that region. During scanning, the sample was attached to the scanner via thin tape placed at the corners to prevent out-of-plane deformation; the tape appears as low-contrast artefacts in the maps. Tape can be seen on Fig. 4 on corners of the map. In the retro-modelling formula, the dominant term is the assumed coating thickness: ±2 µm error on 41 µm produces ±5 % error on conductivity. Scanner and RuDR repeatabilities contribute ±2 % and ±0.5 %, respectively; other terms such as temperature drift and fitting error are below 1 %.

CONCLUSION

•10 GHz inverted SPDR scanner + retro-modelling gives 2%-repeatable Rs maps over 90 mm in ~15 min.
•Combined scanner + model achieves ±5% uncertainty for graphite coatings on copper.
•Retro-modelling removes empirical scaling, linking fast imaging with rigorous EM simulation.
•Dual-mode RuDR validation captures both DC-like and skin-depth-limited regimes in one dataset.
•Method scales to a wide range of cathodes (incl. Ni-rich oxides, solid-state sulfides) spanning ~6 orders of resistivity.
•Current limitations: need accurate layer thickness and care near edges/tabs to avoid mapping artifacts.