

Revealing and Modeling Frequency-Dependent Field Redistribution for Calibration-Free Wideband Four-Electrode Impedance Spectroscopy

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Summary:

Wideband impedance spectroscopy of conductive liquids is fundamentally limited by frequency-dependent distortion that cannot be removed by conventional calibration. This work shows, for the first time, that such distortion originates from redistribution of internal electric fields and current paths induced by loading of the measurement system, rather than a simple additive error. A system-aware field-circuit coupled framework is proposed that enables calibration-free extraction of intrinsic electrical properties and accurate fitting of impedance spectra from 10 kHz to 10 MHz, outperforming conventional models.

Keywords: Wideband impedance spectroscopy, Four-electrode configuration, Field-circuit coupling, Field redistribution, Calibration-free measurement

Background

Wideband impedance spectroscopy is widely used for electrical characterization of conductive liquids [1]. Although four-electrode configurations suppress electrode polarization at low frequencies, significant distortion appears at higher frequencies and cannot be removed by conventional calibration methods [2]. This indicates that the error is not purely additive. In fact, frequency-dependent loading of the measurement system, alters boundary conditions and redistributes internal electric fields and current paths within the liquid. As a result, the effective impedance becomes strongly frequency-dependent, making accurate extraction of intrinsic properties challenging.

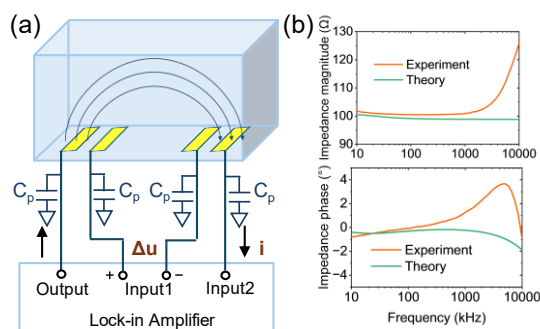


Fig. 1. (a) Schematic of Four-electrode impedance measurement setup. A lock-in amplifier (HF2LI, Zurich, CH) excites and measures the voltage and current

through coaxial cables with parasitic capacitance. (b) Representative experimental impedance spectra showing frequency-dependent distortion under wide-band conditions.

Description of the System

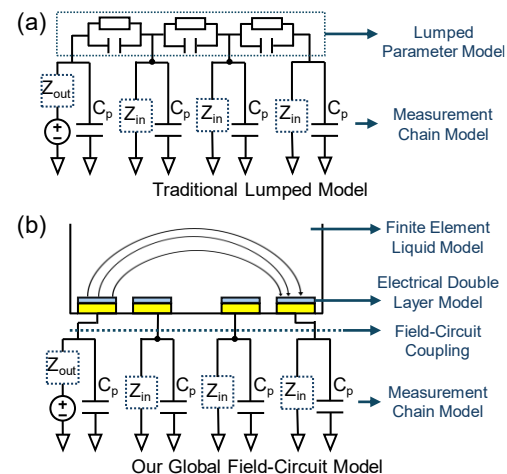


Fig. 2. (a) Conventional lumped-parameter model, neglecting the interaction between the measurement system and the internal field distribution. (b) Proposed system-aware field-circuit coupled model integrating the liquid domain with the measurement chain.

Conventional lumped or liquid-only models fail to capture the interaction between the measurement system and the internal field distribution. A system-aware field-circuit coupled framework is developed, where the liquid is modeled by finite

elements and the measurement chain is described by its equivalent circuit including instrument impedance and parasitic. These components are coupled through electrical ports to jointly solve the frequency-dependent response. By fitting measured spectra with forward simulations, intrinsic electrical properties can be extracted without reference-based calibration.

Results

The proposed method achieves accurate fitting of impedance spectra from 10 kHz to 10 MHz and significantly outperforms conventional models (Fig. 3). The results show that internal electric field distribution and current paths vary with frequency, even under fixed electrode and fixture conditions, confirming that high-frequency distortion arises from frequency-dependent field redistribution rather than a fixed additive error. The liquid-only finite-element model cannot explain the distortion, whereas the field–circuit coupled method can capture this process and explains several seemingly unintuitive results in wideband four-electrode liquid impedance measurement (Fig. 4). Consistent fitting across solutions with different conductivities further demonstrates the capability of calibration-free wideband characterization (Fig. 5).

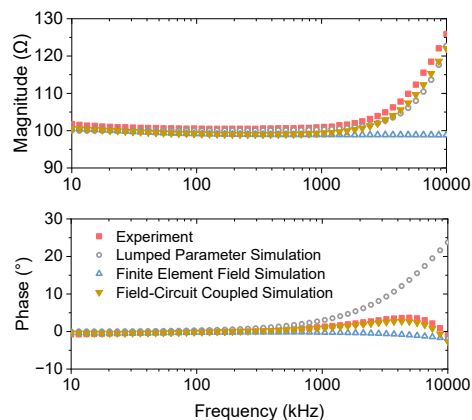


Fig. 3. Comparison of measured and fitted impedance magnitude and phase for PBS solution using different models.

This work reveals the physical origin of high-frequency distortion in wideband four-electrode impedance measurement and establishes a unified modeling framework that explicitly accounts for the measurement system. By transforming the problem from empirical calibration to physics-based forward modeling, the proposed approach enables accurate and calibration-free extraction of intrinsic electrical properties over a wide frequency range, providing a new foundation for high-frequency impedance sensing in biological and microfluidic applications.

Surface: Electric potential (V) Streamlines: Conduction current density

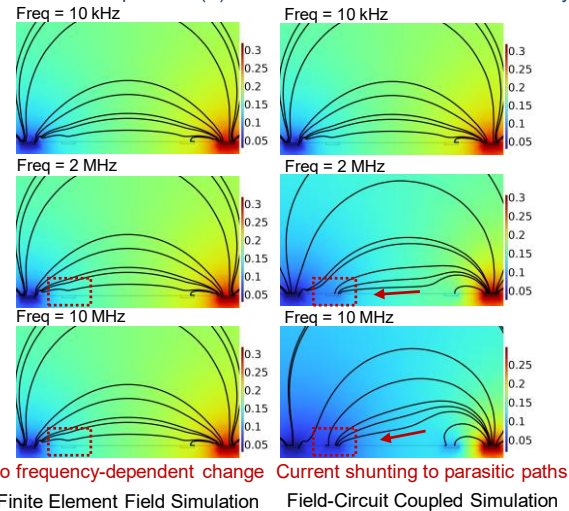


Fig. 4. Simulated evolution of the internal field distribution in the liquid under wideband conditions, illustrating frequency-dependent redistribution of current paths under realistic measurement conditions.

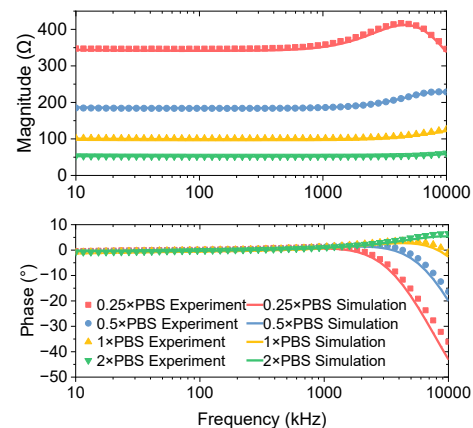


Fig. 5. Comparison between measured and field-circuit coupled simulated impedance magnitude and phase for solutions with different conductivities, showing consistent wideband fitting without calibration.

References

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