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Electro-optic sensing technique for electric field diagnostics of plasma electrodes

D. J. Lee[1], H. G. Kang[2] and G.S. Yun[2,3]
[1] Electromagnetic Measurement Group, Korea Research Institute of Standards and Science
[2] Division of Advanced Nuclear Engineering, [3] Department of physics, Postech
e-mail (speaker): dongjoonlee@kriss.re.kr

Diagnosing atmospheric-pressure plasma generated by intense RF electromagnetic waves requires probes capable of measuring the surrounding electric (E-) field that interacts with the plasma. E-field diagnostics are essential for understanding plasma behavior, as the field governs charged particle motion and affects plasma generation, transport, and stability. Measuring the spatial distribution of the E-field enables deeper insights and is critical for feedback control in precise applications such as semiconductor processing. Additionally, E-field measurements help quantify energy transfer mechanisms, including energy coupling and electron heating, and reveal the influence of electrode geometry and RF excitation on plasma structure.

However, due to high temperatures and strong localized fields, metal-based E-field probes are unsuitable for these environments. To address this, electro-optic (EO) sensing technologies using non-metallic materials have been introduced [1]. EO probes employ optical crystals that exhibit the Pockels effect, changing refractive index in response to E-fields and light. These crystals are miniaturized and mounted on optical fiber tips, enabling flexible, spatially resolved measurements with minimal disturbance to resonant plasma systems.

The coaxial transmission line resonator (CTLR) shown in Fig.1(a) generates dielectric barrier plasma at 2.515 GHz. It consists of inner and outer conductors with a dielectric gas-flow tube at the open end, where the E-field is concentrated. The dielectric tube isolates the conductors from the plasma, and adjustable metal or dielectric pins between conductors enable impedance matching and frequency tuning.

The EO probe, composed entirely of dielectric materials ($LiTaO_3$: lithium tantalate), is installed above the aperture to diagnose the strong, localized E-fields generated between the conductors [2]. The probe provides ultra-fine spatial resolution on the order of several micrometers and measures E-fields linearly up to 100 kV/m with minimal distortion. Its extremely low dielectric capacitance helps maintain the highly resonant characteristics of the plasma electrode. This allows intense and confined E-fields from the CTLR to be measured with minimal invasiveness.

The EO probe also offers excellent cross-polarization performance, meaning it can selectively measure a specific directional component of the E-field. For example, it can be configured to detect the y-directional field component over the CTLR aperture, as shown in Fig. 1(a). The corresponding magnitude and phase distributions, shown in Fig. 1(b) and (c), demonstrate over 60 dB of signal-to-noise and cross-polarization isolation, with opposite phases across the symmetrical midline. Other orthogonal components—such as the x- or z-direction—can be measured by simply rotating the probe 90 degrees in the x–y or x–z plane, allowing for full vector field characterization.

To express the measured fields in absolute units (V/m), the EO probe is calibrated by inserting it into a standard WR-284 rectangular waveguide. This waveguide generates a well-defined E-field distribution in the 2.6–3.95 GHz frequency range. This waveguide-based, endoscopic calibration technique ensures accurate field measurements even in harsh plasma environments. The detailed EO probing methodology and its application under turbulent plasma plume conditions will be presented at the conference.

References
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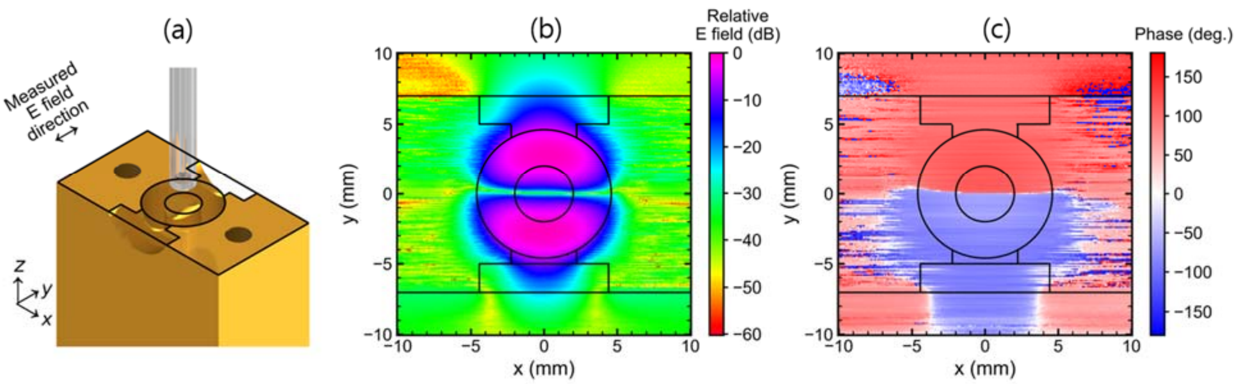

Figure1. (a) coaxial transmission line resonator with EO probe, (b) normalized E-field magnitude distribution in y-direction, (c) phase distribution of (b).