Preparing for 6G: Developing best practices and standards for industrial measurements of low-loss dielectrics

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***Abstract*— With growing interest in millimeter-wave (mmWave, 30 GHz – 300 GHz) technologies, researchers and manufacturers need standard reference materials and best practices for measurement validation, material acceptance, and quality assurance. Today, there is no standard reference material for dielectric permittivity and loss tangent in the mmWave regime. Here, we show the results of round robin experiments that evaluate the current state-of-the-art methods in dielectric measurements. Due to the wide spread in these results, we identify the need for a standard reference material at mmWave.**

***Keywords*— Dielectrics, measurements, mmWave, standard reference material**

I. INTRODUCTION

Commerce relies on traceable standards to ensure individual laboratories agree on the true value of measured quantities. From gauge blocks for mechanical dimensions [1] to ultra-pure chemical samples for biological applications [2], traceable standards and standard reference materials provide internationally-agreed-upon, known-value artifacts that are essential for calibrations, acceptance testing, and internal assessments. Today, no such standard reference material exists for complex permittivity.

A new standard reference material for complex permittivity would help the semiconductor manufacturing industry with acceptance testing and internal assessments. Without a standard, a material producer and consumer may disagree on the measured complex permittivity of a given sample and have no recourse to know the correct value. Errors in the complex permittivity can lead to disagreements between a device's measured and modeled performance. This problem has led the International Electronics Manufacturing Initiative (iNEMI) to coordinate 26 stakeholders in an effort to develop best practices and requirements for new standards for industrial measurements of low-loss dielectrics [3 - 5].

In the following, we show the results of round robin experiments on a cyclo-olefin polymer (COP) for complex permittivity from 10 GHz – 110 GHz. COP is commonly sold with many dielectric measurement instruments as an industrial benchmark, in lieu of a traceable standard reference material.

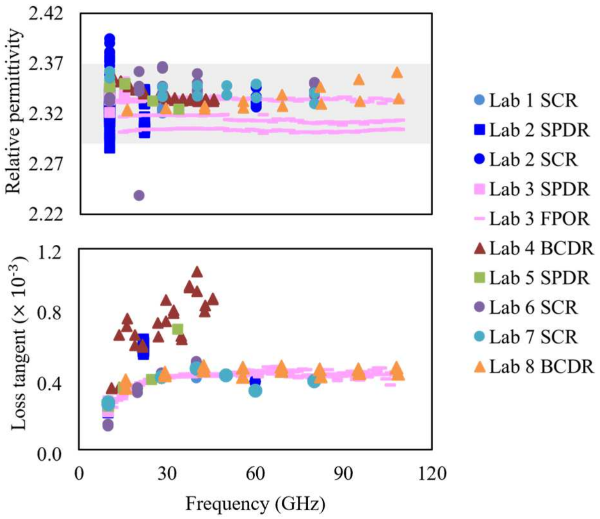

Fig. 1. Round robin measurement results for cyclo-olefin polymer from 10 GHz – 110 GHz. The shaded region indicates ± 2% spread.

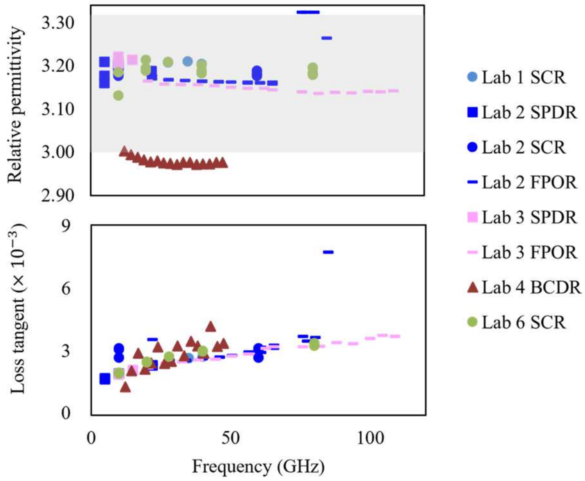

Fig. 2. Round robin measurement results for an anonymously submitted real industrial material from 10 GHz – 110 GHz. The shaded region indicates ± 5% spread.

We also studied an anonymous industrial material commonly used in the communications industry. These results show that for an anonymous industrial material, even the best industrial and government labs may differ by ± 5%.

II. EVALUATING THE STATE-OF-THE-ART

Our objective was to provide a best-case expectation for cross-laboratory comparisons. To facilitate this objective, we developed best practices to minimize the impact of sample handling on lab-to-lab results. After agreeing on measurement best practices, we performed round robin measurements of cyclo-olefin polymer ($\tan\delta < 0.001$) (Fig. 1) and a more lossy anonymous industrial material (Fig. 2). The round robin included 8 industry participants.

These industry participants are a cross-section of national metrology institutes, instrument manufacturers, materials vendors, microelectronics manufacturers, and system integrators. Participants used split-post dielectric resonators (SPDR), split-cylinder resonators (SCR), Fabry-Perot open resonators (FPOR), and balanced-type circular disk resonators (BCDR) [6]. Specific measurement procedures vary by instrument, but general best practices include wearing gloves to minimize the impact of finger oils, thickness measurements at multiple points to minimize the impact of thickness variation, and temperature/humidity control.

Fig. 1 and Fig. 2 show the results from the round robin. For the COP sample (Fig 1, top), the range of the data is 2.24 to 2.40 with most of the results falling within $\pm$ 2% for the real part of the permittivity. The range of the loss tangent (Fig. 1, bottom) for COP is 0.14×10^{-3} to 1.06×10^{-3}. This range is nearly an order of magnitude for the loss tangent, which is unsurprising given that the material has low loss. For the anonymous industrial material (Fig. 2), the range on both the real part of the permittivity and the loss tangent are much larger. The range for the real part of the permittivity is 2.97 to 3.32 with most of the results falling within $\pm$ 5% (Fig. 2, top). The range of the loss tangent (Fig. 2, bottom) for anonymous industrial material is 1.35×10^{-3} to 7.71×10^{-3}.

These measurements helped identify the dominant sources of uncertainty, including thickness characterization of samples. Even when we accounted these sources of uncertainty, method-to-method discrepancies persist that lie beyond the measurement repeatability, which we cannot explain without a standard reference material [6].

III. DEVELOPING A STANDARD REFERENCE MATERIAL

A standard reference material that has an SI-traceable complex permittivity would help identify underlying issues with operator error, measurement setup, and analysis by providing a common point of comparison. Traceability implies an unbroken chain of measurements with uncertainties that connect to fundamental constants of nature through the international system of units. For complex permittivity, traceability connects to the SI through definitions for the meter and second. In the industrial use-case, one could use a standard reference material as a first step to calibrate measurement instrumentation or to help identify manufacturing issues with a given instrument. This use-case led to a new program for developing a standard reference material for mmWave dielectric properties to improve industrial measurement capabilities [4] because 5% best case agreement on the real part of the permittivity and an order of magnitude variation in the loss tangent is not adequate for 6G electronic manufacturers.

IV. CONCLUSIONS

Industrial labs use measurements of dielectrics to evaluate trade-offs between improving performance and controlling costs. Without a standard reference material, this round robin demonstrated that this representative set of test labs could only agree to $\pm$ 2% of the dielectric permittivity in a controlled experiment designed to have a best-case result on the COP sample. This 2% agreement sets an estimate for the limit on cross-laboratory agreement, vendor specification, and acceptance testing. Given the results on the anonymous industrial material, this 2% agreement is likely an underestimate. 6G circuit designers should expect to design for a 5% uncertainty on the real part and an order of magnitude uncertainty in the loss tangent. Without anticipating the potential disagreements, devices will likely not perform as intended and require additional design cycles.

Despite our efforts to design a best-case round robin experiment, our results demonstrate substantial measurement disagreement among labs. Unfortunately, we cannot make any claims about measurement accuracy and why some measurement methods agreed while others did not. Improving the state-of-the-art requires a standard reference material for complex permittivity. With a standard, it may be possible to improve agreement across labs and methods to well below 1%, which is on the order of the measurement repeatability.

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