Bridging the materials' permittivity traceability gap for 5G applications

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***Abstract*—This paper reports recent efforts of the intersectoral iNEMI consortium towards bridging the traceability gap in the characterisation of dielectric materials used in 5G applications. Several GHz resonators, in SCR, SPDR, and FPOR topologies are applied to four samples fabricated from the same COP coupon. Characterisation is performed at three laboratories, using VNAs of different form-factors, and covering the frequency range of 10-110GHz. Excellent agreement is demonstrated between the methods and the samples. Consistent measurements at 10 GHz provide a trace to more conventional material measurements in the microwave range.**

***Keywords*—5G, millimetre waves, material measurement, non-destructive testing, GHz resonator, SCR, SPDR, FPOR, complex permittivity, repeatability.**

I. INTRODUCTION

Development of telecommunication technologies for 5G and beyond is currently hindered by insufficient knowledge about the properties of materials that need to be used [1][2]. While at lower frequency bands a traceable path links national metrology institutes, factory calibrations, and in house standards - at millimetre-waves (mmWaves) standard reference materials are not available and many in-house material characterisation techniques are no longer applicable. This causes a gap between standardisation status and the needs of 5G antenna and circuit designers, relevant industries, and end-users.

To help bridging this gap, an intersectoral consortium bringing together industry and academia with research and standards institutes has been set up by the The International Electronics Manufacturing Initiative (iNEMI). Its first report [3] reviews the loss- and form-factor requirements for 5G materials and points to material measurement methods based on GHz resonators as appropriate candidates for standardisation and industrial implementation in the 5G sector [4]. In summary, this choice is due to high sensitivity of the resonant methods to ultra-low-loss and their handling of samples in the form of thin film sheets, such as those used for fabricating HDI (high density interconnect) boards, on which many 5G antennas and circuits are manufactured.

The iNEMI project proceeds with a round-robin sample testing, of which recent progress is reported herein. The testing is performed at 10 laboratories in the US, Asia, and Europe. It currently involves three types of GHz resonators:

- Split Cylinder (SCR) based on e.g. [5][6], commercially available as [7],
- Split-Post Dielectric Resonator (SPDR) based on e.g. [8][9], commercially available as [10],
- Fabry-Perot Open Resonator (FPOR) based on e.g. [11][12], commercially available as [10].

The first round of testing focused on verifying the consistency between SCR, SPDR, and FPOR measurements and the initial results have been submitted in [13].

In this paper, we take a material perspective and test to what extent different samples cut from the same coupon but handled by different operators lead to consistent information about the original material itself. The coupon of Cyclo Olefin Polymer (COP; from Zeon) of nominal thickness 186 μm has been cut into 40 samples and circulated between 10 laboratories. So far, over 1500 measurements have been performed of which 112 representative results are summarised in this paper.

II. BENCHMARKED METHODS AND REFERENCE MATERIAL

The following implementations of resonators, for different nominal frequencies, have been used in the study reported herein at three testing sites (testing sites are given in brackets and frequencies are separated by /):

- SCR 10 / 60 GHz (Intel) and 10 / 20 / 28 / 40 / 80 GHz (Keysight)
- SPDR 10 / 15 GHz (QWED) and 10 / 22 GHz (Intel)
- FPOR over 10-110 GHz (QWED).

Note that 10 GHz SPDRs and SCRs have been used each at two sites independently, which provides an additional reproducibility information, allowing one to differentiate user-to-user from vendor-to-vendor variabilities. It also serves as a traceability link to material testing at lower frequency bands, for which industrial experience and standards [6][9] exist.

The following four samples fabricated from the aforementioned COP coupon have been characterised in the overlapping frequency ranges (colours on the list are further used in Fig. 1):

- **Sample #1** - 90 mm x 90 mm - in 10-110 GHz range,
- **Sample #2** - 90 mm x 90 mm - in 10-50 GHz range,
- **Sample #3** - 35 mm x 45 mm - in 10-110 GHz range,
- **Sample #4** - 35 mm x 45 mm - in 10-50 GHz range.

Either laboratory or hand-held Vector Network Analysers (VNA) have been used to measure transmission through the resonator, from which resonant frequencies and Q-factors have been extracted. These are needed for an empty resonator and the resonator loaded with the sample. Material parameters are then obtained by proprietary software of each resonator, based on the SCR, SPDR or FPOR method, as applicable.

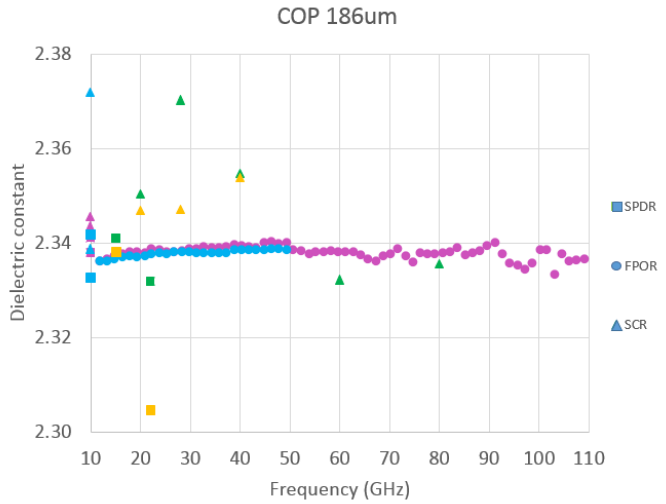
III. RESULTS AND DISCUSSION

Figure 1 presents the results of the characterisation of the COP material in the frequency range 1-100 GHz, which bridges higher microwave to millimetre-wave frequencies including e.g. automotive radar antennas. The four samples are identified by the colours defined in Section II. Symbols (square, circle, triangle) denote the three types of resonator test-fixtures (SPDR, FPOR, SCR) but different resonator units of the same type are assigned the same symbol. Each symbol in Fig. 1 represents a single measurement, falling within evaluated repeatability margins (repeatability tests have been conducted for Sample 1 and 3; each measurement has been repeated 16 times and repeatability, defined as three time standard deviation to average ratio, did not exceed 0.5%).

The results of FPOR characterisation are especially illustrative. We have obtained quasi-continuous (in 1.5 GHz steps) functions of dielectric constant and loss tangent in the frequency range 10-110 GHz for Sample 1 and 10-50 GHz for Sample 2. Above 40 GHz both parameters are constant (with measured dielectric constant fluctuations below 0.1%) but loss tangent is higher by nearly a factor of 2 than that at 10 GHz. This behaviour is confirmed by SPDR and SCR measurements at discrete frequencies. This invokes the caution for increased substrate heating at 5G, as compared to lower bands.

Overall, all four COP samples are measured by all the three methods with excellent consitency. For dielectric constant, the spread, after removing three outliers, is below 1% (below 3% including outliers). The relatively outlying values of SPDR loss measurements at ca. 20 GHz have been traced back to the respective 22 GHz SPDR being a non-standard unit.

A majority of measurements have been performed by connecting the resonators to laboratory VNAs. Additionally, SPDR measurements at 10 GHz and 15 GHz have been repeated in a portable setup, involving a hand-held VNA (Fig. 2), with no visible difference in the measured dielectric constant and loss tangent. This implies that reference testing at



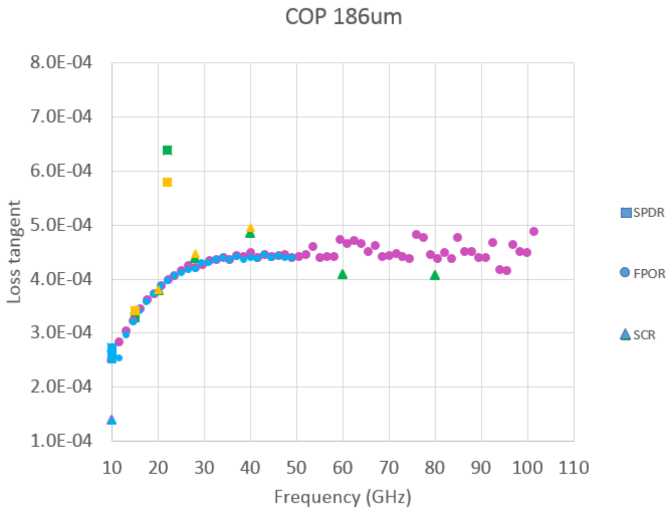


Fig. 1. Characterisation results for four COP samples (denoted by four different colours, as explained in text) in three types of GHz resonators (denoted by different markers, as shown in the legend).

Fig. 2. Example of a portable setup applicable in the industrial environment (10 GHz SPDR, hand-held VNA, and laptop running a control application).

microwave frequencies can be performed in the industrial environment easily and at low cost. Methodologies for correlating microwave and millimetre-wave characteristics of materials used in antenna technology, with a focus on 5G, are a further goal of this work.

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