Benchmarking of GHz resonator techniques for the characterisation of 5G / mmWave materials

M. Celuch[#1], M. J. Hill[*], T. Karpisz[%#], M. Olszewska-Placha[#3], S. Phommakesone[&], U. Ray[^4], B. Salski[%#]

[#]QWED Sp. z o.o., Poland

[*]Intel Corp., US

[%]Institute of Radioelectronics and Multimedia Technology, Warsaw University of Technology, Poland

[&]Keysight Technologies, US

^The International Electronics Manufacturing Initiative, US

[1] mceluch@qwed.eu , [2] molszewska@qwed.eu , [3] urmi.ray@inemi.org

***Abstract* — This paper presents the results of the first round of benchmarking measurements of material samples relevant to 5G/mmWave technologies. The benchmarking initiative has been set up by an international and intersectoral consortium of 25 partners who will perform round-robin testing of representative low Dk / Df materials with the use of a range of microwave and millimetre-wave techniques. In the first round, three GHz resonator techniques (SCR, SPDR, FPOR) have been applied to COP and Teflon samples at three laboratories. The results show a remarkable agreement both between the techniques and between the laboratories. Measurement repeatability is also evaluated, according to the industrial practice. The reported data provide a 'place holder' until SRMs are defined by standards organisations, for which this work provides background.**

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

I. Introduction

The fifth generation technology standard for broadband cellular networks (or simply 5G) responds to the increasing needs for high speed, low latency, low error-rate communications [1]. A quest for such characteristics poses many challenges for microwave and millimetre-wave (mmWave) design, where computer modelling and optimisation should ideally replace the traditional trimming and tuning. However, predictive value of the modelling is highly dependent on availability of electromagnetic parameters for the materials to be used. Errors in materials' characterisation limit the design accuracy and lead to time consuming iterations in the manufacturing process, which are estimated to cost many tens of millions of dollars in a single programme [2], or worse, may induce unexpected product failures. Also the development of new materials in a promising Materials-by-Design fashion [3] requires the ability to evaluate performance of those materials at use condition.

While solutions for 5G require ultra-low-loss laminate materials and substrates, no consistent methodology exists for measuring such material properties at mmWave frequencies. Few vendors provide mmWave permittivity equipment at above 20 GHz. At the lower 5G bands, many different approaches are in use, based on different fixtures and sample size requirements, such that consistency between those approaches has not been appropriately investigated and extrapolation to higher frequencies cannot be trusted.

To address the above problems in a coherent manner, a consortium of 25 members from industrial, academic, research, and standards institutions has been gathered within the International Electronics Manufacturing Initiative (iNEMI) [4]. By providing a linkage between equipment manufacturers and end users, the project aims to evaluate and benchmark methodologies for characterising ultra-low-loss laminate materials under the range of 10 – 110GHz. The first project report [5] has discussed industry best practices in the field and, with a view to severe limitations on sample thickness and requirement for measuring ultra small loss tangents, pointed to GHz-frequency resonators as appropriate test-fixtures. They are now being considered in a study to evaluate vendor-to-vendor and user-to-user differences, smoothing the way for traceability.

This paper reports the results of the first round of benchmarking measurements and is organised as follows. In Section II, the selection of GHz resonators and 5G-relevant material samples for this work is presented. Characterisation results are discussed in Section III, which includes repeatability study on 16 measurements for Cyclo Olefin Polymer (COP) sample in each test-fixture and at each frequency, followed by an independent measurement of Precision Teflon sample. Section IV concludes with an outline of forthcoming work.

II. Methods and Materials

A. Applied GHz resonators

Resonator techniques are recognised for high accuracy of non-destructive material measurements at microwave frequencies. Different resonator topologies have been proposed in response to different requirements in terms of measured material properties, relevant sample dimensions, and frequency range of use. A common feature of all resonant methods resides in extracting the material-under-test (MUT) parameters from resonant frequencies f_0 and Q-factors, measured twice: for a device without and with the MUT sample inserted.

Three types of resonators have been chosen (Fig. 1), based on the theoretical considerations after [5] and practical factors of availability of the corresponding test-fixtures on the open market as well as published standards and / or research data:

1. Split Cylinder Resonator (SCR) [6], which is closest to a canonical cylindrical cavity supporting TE011 mode, with a slot for sample insertion (Fig 1a). SCR is standardised by IPC [7] and commercially available from Keysight Technologies [8] for nominal frequencies of 10, 20, 28, 40, 60, and 80 GHz.
2. Split-Post Dielectric Resonator (SPDR) [9] (Fig. 1b), where the sample is inserted into a slot between the ceramic posts and measured in $TE_{01\delta}$mode. SPDR is standardised by IEC [10]. Keysight [8] and QWED [11] offer units for several nominal frequencies between 1.1 and 15 GHz (a 20GHz unit no longer offered on the market is also used here).
3. Fabry-Perot Open Resonator (FPOR) which has been known for decades [12] but in this work is applied in a recently proposed fully automated version [13][11] (Fig. 1c) providing multiple measurements in the Gaussian beam at consecutive resonances in 20-110 GHz range.

In all the three resonators, the same (in-plane) component of sample permittivity is measured, which facilitates direct comparison of the SCR, SPDR, and FPOR results. For measuring the out-of-plane permittivity at multiple frequencies, a Balanced-Type- Circular Disk Resonator (BCDR) has been found promising in [5] and will be included at a further stage of our benchmarking process.

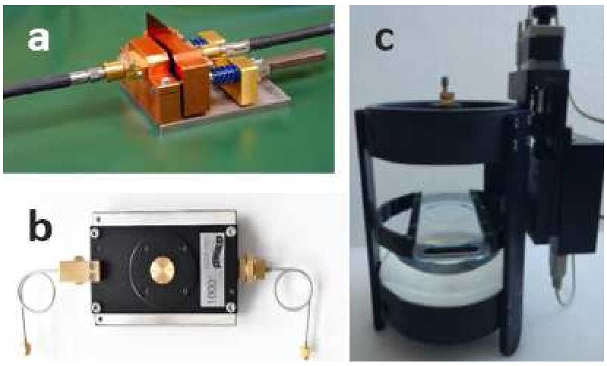

Fig. 1. Resonators applied in this work: (a) SCR, (b) SPDR, and (c) FPOR.

B. Considered material samples

The samples for this study have been selected in accordance with the stringent requirements of 5G technologies of low dielectric constant (Dk), ultra-low dissipation factor (Df), and small thickness (below 0.2 mm and as little as few mils). Furthermore, to be able to compare characterisation results for samples circulated between different testing sites, the requirements of stability, low moisture absorption, low temperature dependency, and good mechanical handling properties have been imposed. Last but not least, the availability of materials for purchase and preparation of several possibly identical kits has been a factor.

By the time of writing this paper, coupons of two types of materials: Cyclo Olefin Polymer (from Zeon) and Precision Teflon (from DuPont) have been acquired, in different thicknesses (COP in 186 µm, Teflon in 2 and 5 mils). Samples have been cut to sizes 35 mm x 45 mm and 90 mm x 90 mm, carefully selected to cover the requirements of all the resonant test fixtures identified for the benchmarking (SCRs, SPDRs, and FPOR as in this work and BCDR to be included further). Figure 2 shows the smaller COP and the bigger Teflon samples. The selection of materials and sample sizes can serve as a guideline for standards organisations developing standard reference materials (SRM) for 5G.

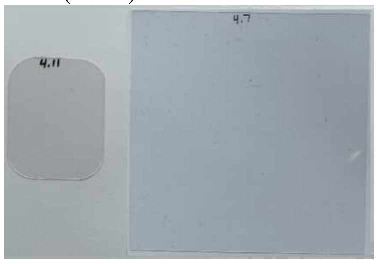

Fig. 2. Smaller COP and bigger Teflon samples considered in this work.

III. MEASUREMENT RESULTS AND DISCUSSION

Ten laboratories have volunteered to participate in the benchmarking, of which three have completed the results reported in this paper, using respectively:

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

In this way, SCRs and SPDRs have been used at two different sites, allowing one to differentiate user-to-user from vendor-to-vendor variabilities. The additional set of FPOR measurements is not available at this time but will be included at a later stage. It should also be noted that the three testing sites use different network analysers and different techniques for the extraction of resonant frequencies and Q-factors:

- Intel and Keysight use bench-top VNAs with Keysight Option N1500A [8] for extracting f_0 and Q from complex S-parameters,
- bench-top VNA with own software for post-postprocessing complex S-parameters is used with QWED FPOR,
- in SPDR measurements, QWED uses Keysight hand-held FieldFox VNA and extracts f_0 and Q from the magnitude of the transmission coefficient.

The above differences introduce a “user factor” (separate from the characteristics of the test methods themselves) and may become an additional source of discrepancies between the retrieved material parameters.

Fig. 3 shows the results of measurements of COP samples, all cut from the same material coupon, but with thickness measurements taken independently at each laboratory. Note that laboratory names in the legend denote testing sites, and not necessarily test-fixture vendors. The retrieved values of dielectric constant as a function of frequency (10-110 GHz) are in the range of 2.332-2.37, and after removing one outlier (SCR 28 GHz), are within 1% of 2.34. This is a remarkable result, better than expected when comparing three different techniques at three sites, over a decade frequency band. For reference, a stringent IEC norm [10] dictates accuracy of 0.3% for single-frequency SPDR measurement of a sample of ideally know thickness, which is relaxed to 1% in industrial practice [8].

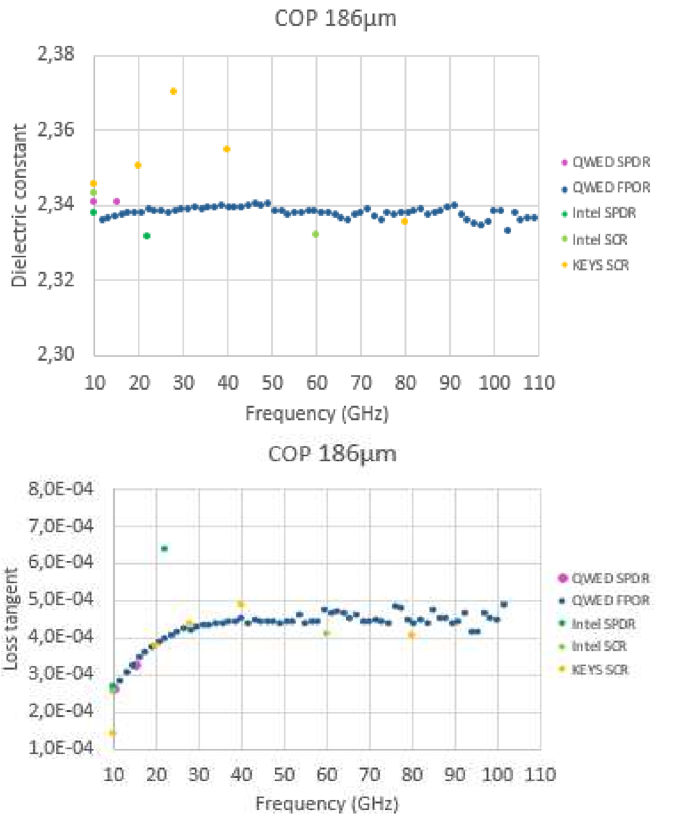

Fig. 3. Consistency of COP measurements in SCR, SPDR, and FPOR. Laboratory names in the legend denote testing sites.

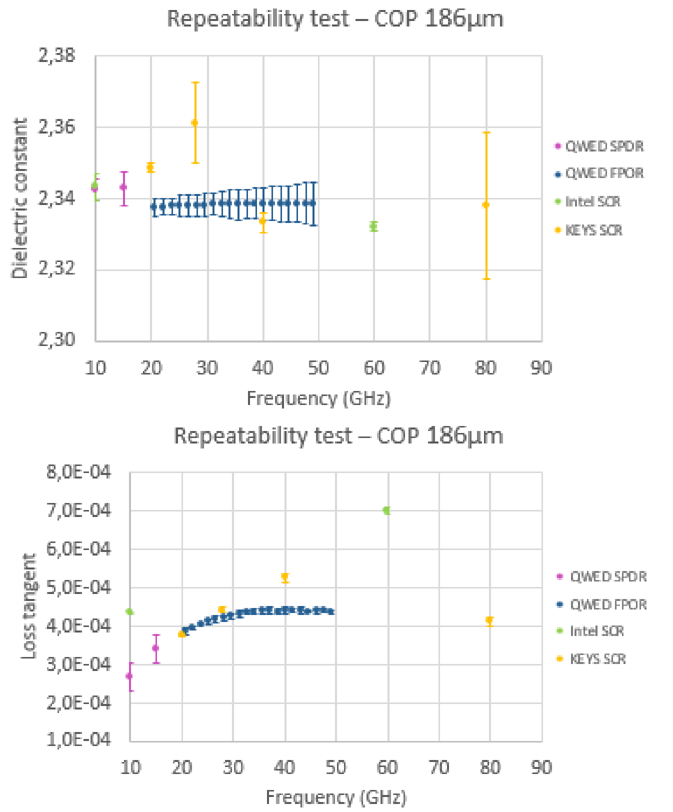

Fig. 4. Repeatability of COP measurements in SCR, SPDR, and FPOR: each symbol denotes an average of 16 measurements while error bar - triple of standard deviation. Laboratory names in the legend denote testing sites.

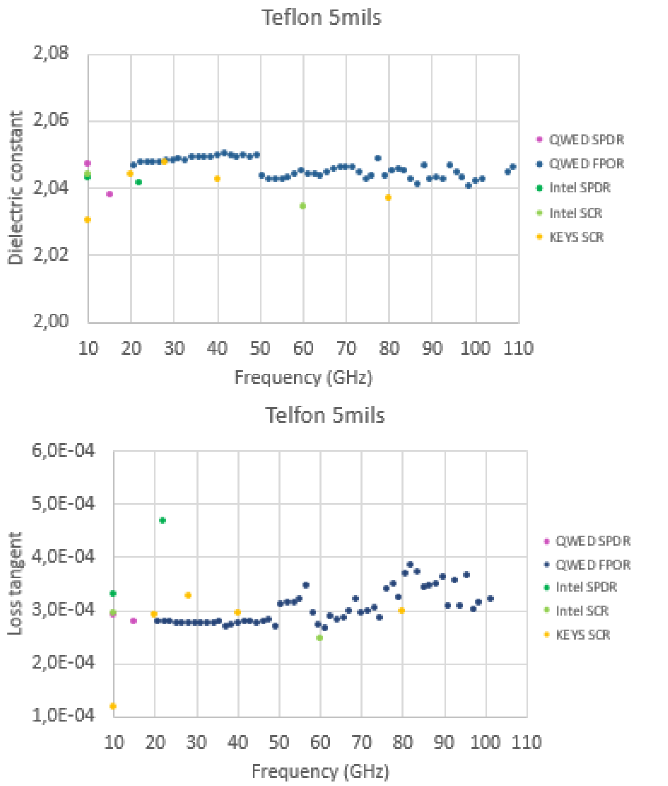

Fig. 5. Consistency of Teflon measurements in SCR, SPDR, and FPOR. Laboratory names in the legend denote testing sites.

As concerns the loss tangent (Fig. 3, lower), most interesting appears its frequency dependence below 30 GHz, while above 30 GHz it remains constant between 4..5x10^{-4} in all measurements. This is confirmed in all the applied test-fixtures except for one outlier - SPDR 20 GHz - which is no longer manufactured (due to difficulties in ensuring ultra-low internal losses for high-frequency SPDRs), and therefore removed from further repeatability study.

The repeatability study has been conducted following standard industrial recommendations [5]. Each measurement has been repeated 16 times. The extracted average values and repeatability, defined as three time standard variation, are shown in Fig. 4 by symbols and error bars, respectively. Due to time constraints, the study has been limited to 10-80 GHz band.

In a final experiment, an ultra-thin (5 mils) Precision Teflon sample has been characterised. As presented in Fig. 5, all the techniques are consistent in measuring the dielectric constant of 2.03..2.05 (spread below 1%) and loss tangent of 2.5..3.9x10^{-4} (except for the same outlier as in Fig. 3). FPOR measurements provide a nearly continuous plot of material parameters as a function of frequency. A minor discontinuity in Dk close to 50 GHz is due to switching of the measurement equipment by adding frequency extenders, which imposes a removal and insertion of the sample again into the FPOR.

IV. Conclusion

The paper has introduced the international and intersectoral iNEMI initiative [4][5] for the assessment of 5G/mmWave materials and reported on the first round of its benchmarking project. The measurements of representative COP and Teflon samples have been performed in SCR, SPDR, and FPOR test-fixtures available on the market and earlier validated in microwave research and industry, in the frequency range from 10 to 110 GHz. Sample dimensions have been optimised to overcome the incompatible requirements of the different techniques. A total of 745 measurements have been made in the project so far, of which 536 are presented in this paper.

The results confirm the relevance of the selected test-fixtures for the characterisation of materials used in 5G technologies. The higher-frequency SCRs and FPOR are directly relevant to millimetre-waves (i.e., above 30 GHz). The SCR and SPDR measurements at 10 GHz and 15 GHz can be used by extrapolation and for cross-validation purposes for new materials, which is advantageous due to their lower cost, ease-of-use, and robustness (good repeatability and reproducibility, also at different laboratories). After removing one obvious outlier in each of the reported experiments, repeatability for all the considered techniques has been very good and estimated as 0.5% in dielectric constant for a sequence of 16 measurements.

At the next stage of the project, benchmarking effort of the three laboratories contributing to this paper will be extended to ten laboratories and performed in a round-robin style, circulating sample kits between the testing sites. Also, the fourth resonant test fixture (BCDR) and additional samples of Rexolite and fused silica will be included. Emerging wafer-level and time-domain techniques for dielectric measurements as well as materials from industry will be evaluated at the final stage [15]. The long-term goal is to develop and publish guidelines of best practices to the industry on the material testing methodologies for 5G/mmWave technologies. The results reported herein provide a 'place holder' until SRMs are defined by standards organisations, for which this work provides the background in terms of studied material types and sample sizes.

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References

[1] T. M. Wallis and N. Orloff, "Microwave Materials: Enabling the Future of Wireless Communication", workshop materials, at *IEEE Intl. Microwave Symp.*Boston, MA, US, June 2021.

[2] M. J. Hill and M. Celuch, "Benchmarking resonator based low Dk/Df material measurements", at *IPC-APEX EXPO*, 12 March 2021. Available: https://www.qwed.eu/nanobat/IPC_APEX_2021_5GMaterialsCharacterisation.pdf

[3] T. M. Wallis and N. Orloff, "Materials by Design for Microwave and mm-Wave Communications", workshop accepted for *IEEE Intl. Microwave Symp.*, Atlanta, June 2021.

[4] R. Stephenson, S. Phommakesone, C.-S. Chen, and U. Ray, *iNEMI Statement of Work*, 22 May 2020. Available: http://thor.inemi.org/webdownload/2020/5G_Materials_Characterization_SOW.pdf

[5] iNEMI 5G Project Report 1: *Benchmark Current Industry Best Practices for Low Loss Measurements*, Nov. 2020. Available: https://community.inemi.org/content.asp?admin=Y&contentid=676

[6] M. D. Janezic and J. Baker-Jarvis, "Full-wave analysis of a split-cylinder resonator", *IEEE Trans. Microwave. Theory Tech.*, vol. 47, no. 10, pp. 2014-2020, Oct. 1999..

[7] IPC Standard: IPC-TM-650 2.5.5.13

[8] N1500A Materials Measurement Suite. Available: https://www.keysight.com/zz/en/product/N1500A/materials-measurement-suite.html

[9] J. Krupka, A. P. Gregory, O. C. Rochard, R. N. Clarke, B. Riddle, and J. Baker-Jarvis, "Uncertainty of complex permittivity measurements by split-post dielectric resonator technique", *J. Eur. Ceramic Soc.*, vol. 21, pp. 2673-2676, 2001.

[10] European Standard: IEC 61189-2-721:2015

[11] QWED Measurement Setups. Available: https://www.qwed.eu/resonators.html

[12] A. L. Cullen, P. K. Yu, and H. E. M. Barlow, "The accurate measurement of permittivity by means of an open resonator," *Proc. R. Soc. Lond. Math. Phys. Sci.*, vol. 325, no. 1563, pp. 493–509, Dec. 1971.

[13] T. Karpisz, B. Salski, P. Kopyt, and J. Krupka, "Measurement of Dielectrics From 20 to 50 GHz With a Fabry–Pérot Open Resonator," *IEEE Trans. Microwave Theory Tech*., vol. 67, no. 5, pp. 1901–1908, May 2019.

[14] H. Kawabata, K. Hasuike, Y. Kobayashi, and Z. Ma, "Multi-frequency measurements of complex permittivity of dielectric plates using higher-order modes of a Balanced-Type Circular Disk Resonator," *Proc. 2006 European Microwave Conf.*, pp. 388–391, Sep. 2006.

[15] iNEMI 5G Project Report 2*: Benchmark Emerging Industry Best Practices for Low Loss Measurements*, Nov. 2020. Available: https://community.inemi.org/content.asp?admin=Y&contentid=676