Towards a Robust BCDR Design for Out-of-Plane Permittivity Measurements

Malgorzata Celuch
QWED Sp. z o.o.
Warsaw, Poland
mceluch@qwed.eu

Lukasz Nowicki
QWED Sp. z o.o.
Warsaw, Poland
lukasznowicki@qwed.eu

Marzena Olszewska-Placha
QWED Sp. z o.o.
Warsaw, Poland
molszewska@qwed.eu

Wojciech Gwarek
QWED Sp. z o.o.
Warsaw, Poland
wgwarek@qwed.eu

***Abstract*— The paper presents the electromagnetic modelling and mechanical considerations for the design of a Balanced-type Circular Disk Resonator (BCDR). The purpose of the work is to develop a robust in-house methodology for measuring the out-of-plane component of complex permittivity of materials at microwave and mmWave frequencies. In this summary, a novel concept of a thick central electrode manufactured as a pair of discs on a double-sided PCB substrate is proposed, evaluated by modelling, implemented, and validated in a BCDR prototype.**

***Keywords*— BCDR, complex permittivity, material measurements, modelling-based material characterisation, out-of-plane permittivity.**

I. Introduction

Precise knowledge of the electromagnetic parameters of materials is essential for reliable design of microwave- and millimetre-wave (mmWave) circuits. This stimulates research efforts on the development of material measurement methods, as well as industrial efforts on benchmarking such existing and emerging methods, in terms of accuracy, reproducibility, and ease-of-use. In recent years, inntersectoral benchmarking activities have been coordinated by The International Electronics Manufacturing Initiative; full reports concerning methods for substrate characterisation for 5G applications are available at [1], with publicly available summaries e.g. in [2], [3]. In brief, these reports indicate that:

- resonant methods need to be used for the characterisation of 5G-relevant materials, since such materials need to be ultra-low-loss and are often available in the form of ultra-thin sheets;
- very good agreement (within 1-2%) is observed between the three commercially available methods (SCR, SPDR, FPOR) for the characterisation of in-plane permittivity;
- the only commercially available and standardised resonant method for the out-of-plane permittivity characterisation, a Balanced-type Circular Disk Resonator (BCDR) [4], is less reproducible, more difficult to use, and tends to visibly diverge (even at the level of 10%) from the in-plane methods (for substrates known to be isotropic), for reasons which have not yet been adequately understood.

While the practice of 5G industries is based on using isotropic materials [1][3], there is a need to verify the material's isotropy. Moreover, many of the classically used materials, especially laminates, are anisotrpic by nature. This has motivated our development of an in-house BCDR test-fixture. **The goals are**: to complement our existing in-plane measurement capabilities [5]; to obtain insider knowledge needed for explaining the observed divergences between the pre-existing BCDRs and in-plane methods [1]; and to provide guidelines for future industrial applications of the out-of-plane materials' characterisation techniques. **The unique asset** in our work are our in-house electromagnetic (EM) modelling and simulation tools [6], allowing us to capture and interpret the physical effects involved in the BCDR measurement.

II. BCDR Concept and Modelling

The concept of a BCDR after [4] is illustrated in Fig. 1. The resonator is formed by the inner disk electrode sandwiched between two identical concentric dielectric samples, which in turn are sandwiched between the two outer electrodes. The resonator is fed by a coaxial line, which excites the electric field component perpedicular to the electrodes at their centre. The excited modes of the TM0m0 type travel outwards in the radial direction. Transmission through the BCDR peaks at the resonant frequencies (Fig. 2), when the direction of wave propagation bends around the central electrode, forming a resonant pattern in the dielectric samples (Fig. 3). Specifically, the electric field envelopes shown in Fig. 1 a, b correspond to the 2nd and 5th resonant mode, respectively, depicted by the red curve in Fig. 2, which illustrates the case of the resonator fileld with air. When a pair of dielectric samples under tests (SUT) is placed between the electrodes, the resonant frequencies decrease approximately proprotionally to the square root of the SUT's relative permittivity and the resonant peaks broaden due to losses, as illustrated by the green curve in Fig. 2.

The results in Fig. 1 and Fig. 2 have been obtained by full-wave electromagnetic modelling and Vector-2D (Bodies-of-Revolution) FDTD solver as described in [7] and implemented in [6]. The absorbing material (green in Fig. 1) is inserted in the model solely for the purpose of reducing the computational domain. In further studies concerning effects of eccentricity (between the three electrodes and/or the SUTs), a full 3D solver of [6] will be used. In all cases, the FDTD approach provides more flexibility than the earlier semi-analytical or mode-matching approaches to the BCDR design [8] [9], which we shall explore in order to arrive at a new more robust construction of the BCDR test-fixture.

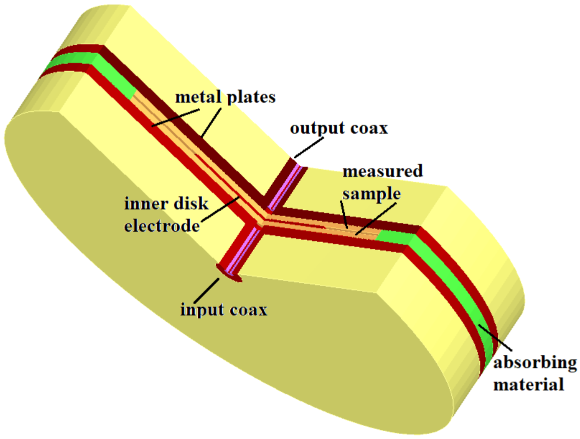

Fig. 1. Conceptual design of BCDR (three-quarters view).

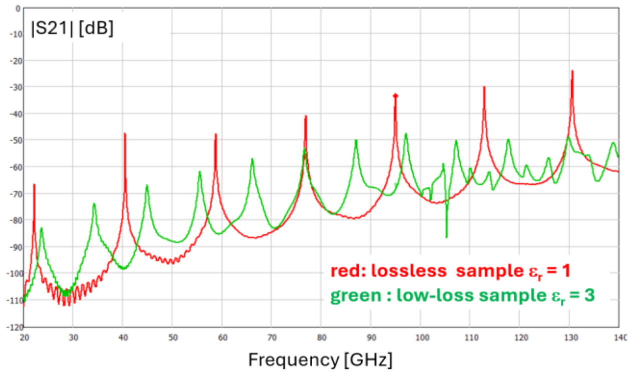

Fig. 2. Simulated transmission through an example BCDR (inner electrode diametre 16 mm, thickness 0.2 mm) when a pair of samples (each 0.4 mm thick) is made of air (green) and low-loss dielectric (red).

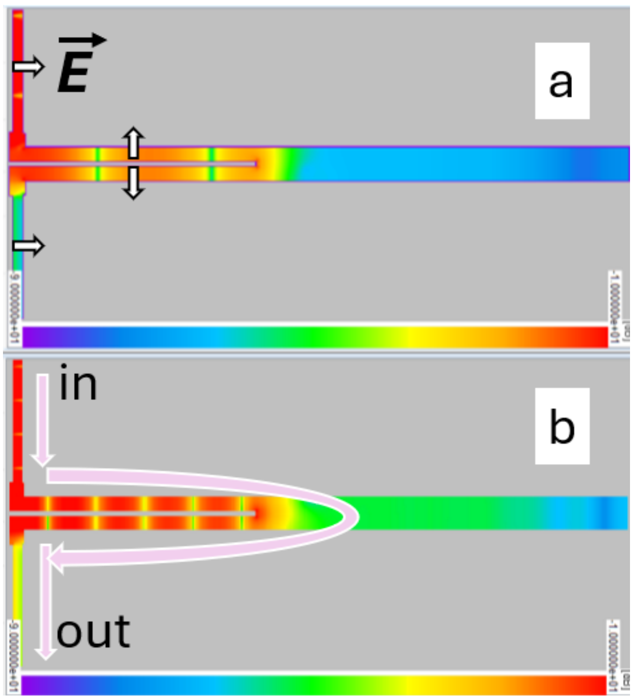

Fig. 3. Envelope of the electric field intensity in one-half of the vertical cross-section of the dielectric-loaded BCDR of Fig. 2 at (a) 40.49 GHz and (b) 95.06 GHz; white arrows in (a) indicate the field direction, pink arrows in (b) - direction of energy flow.

In particular, it is known from practice [1], and confirmed by our present simulations, that the accuracy of BCDR material measurements tends to be deteriorated by two factors:

- air slots between the SUT and the electrodes,
- eccentricity of the structure.

Herein, we focus on the latter factor. By 3D FDTD simulations we have found that a displacement of the central disk by 0.5 mm (5% of the disk diametre in Fig. 1) causes shifts in the resonant frequencies by about 3.15%, which leads to 6.4% errors in SUT permittivity extraction. It also gives rise to spuroius non-TE0m0 modes (and splitting of the resonant peaks), which poses challenges in identifying the desired mode. To keep the BCDR operation robust, and to limit the measurement error to 0.5%, we need to centre the disk with possible displacement below 0.8% of its diametre. This is difficult to achieve with an ultra-thin central electrode, such as was assumed in earlier BCDR modelling approaches [8][9]. By FDTD simulations of different thicknesses and different designs of the central electrode, we have found that:

- larger thickness of the central electrode limits the measurement frequency range, but is not critical in terms of the measurement accuracy,
- central positioning of the central electrode is critical, in terms of both the accuracy and the frequency range,
- losses in the central electrode have negligible influence on the overall losses of the structure.

These observations have first inspired us to design the central electrode as two metallic patches on a double-sided PCB. However, further modelling has revealed spurious resonances in the PCB substrate between such two metallic sheets, which perturb the measurements. Hence in the next step, we have proposed to connect the two sides of the PCB by a ring of vias., as shown in Fig. 4b and explained in the following section.

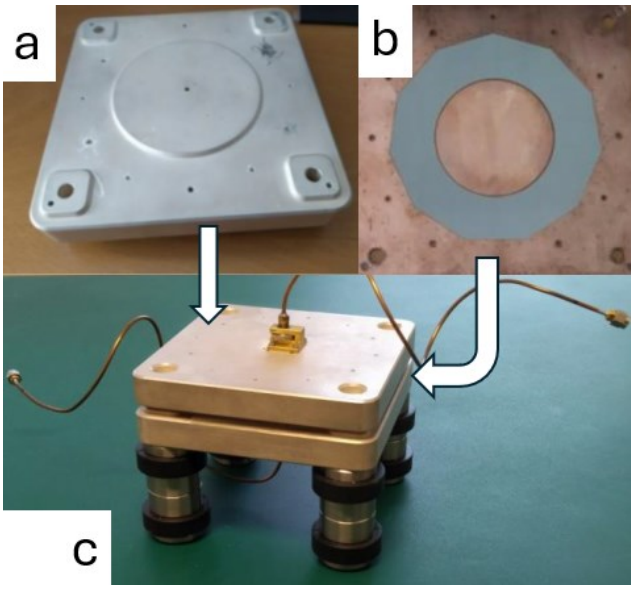

Fig. 4. Photos of the BCDR prototype: (a) bottom surface of the upper electrode, (b) central electrode, (c) complete device with I/O cables.

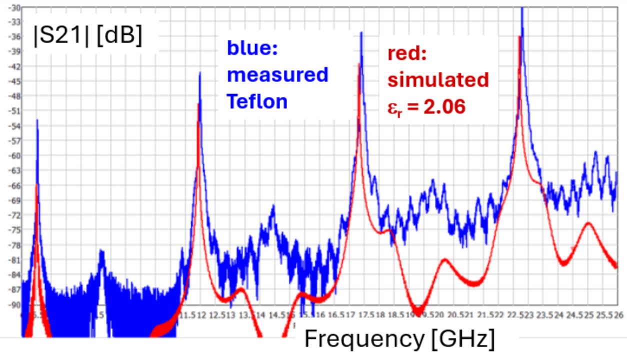

Fig. 5. Transmission through BCDR loaded with a pair of 0.5 mm-thick Teflon samples: measured (blue) and simulated assuming ε_r=2.06 (red).

III. BCDR Prototype and Validation

Figure 4 shows photos of the manufactured BCDR prototype: its upper (a) and central (b) electrode after dismantling, and the assembled (c) device. Several variants of the central electrode have been manufactured, on several substrates. Here, we shall consider the electrode of 19.05 mm radius on Taconic TLC-32-0310-C1/C1 substrate of 0.78 mm thickness (0.92 mm including metal layers). The metal around the electrodes has been removed over an area limited by a polygon, in order to break the axial symmetry of the structure and limit the risk of cylindrical modes reflecting from the edge. Along that outer edge, a row of closely spaced 0.5 mm vias has been processed. Additionally, the substrate has been equipped with holes for correct positioning with respect to the BCDR centre.

Figure 5 presents intial validation results of the prototype. A pair of Teflon samples, each 0.5 mm thick, has been placed in the BCDR and the measured transmission is shown by the blue curve in Fig. 5. The detected resonant frequencies agree very well with those obtained by FDTD simulations (red curve) of the model, with samples assumed to have permittivity of 2.06, as known for the considered Teflon material from the benchmarking of [1].

IV. Conclusion and Outlook

Parameterised BCDR models implemented in the 2D Bor and 3D FDTD EM software allow for exploration of unconventional resonator designs. The goal of the work is to develop a setup for measuring the out-of-plane component of complex permittivity in the GHz frequency range, improving robustness and accuracy with respect to pre-existing BCDR instruments benchmarked in [1]. In particular, in this summary, a novel design of a thick central electrode processed on a double-sided PCB substrate has been presented. The electrode is easy to centre in the BCDR prototype. The initial validation shows good agreement between the modelling and experimental results for a reference Teflon material. In our present M-ERA.NET I4Bags project [10], the work is ongoing on developing a computer application for automatic mapping of measured resonant frequencies and Q-factors of BCDR loaded samples-under-test, into the sample's complex permittivity.

Acknowledgment

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References

[1] International Electronics Manufacturing Initiative. (2023). The iNEMI "5G/mmWave Materials Assessment and Characterization" project. [Online]. Available: https://www.inemi.org/article_content.asp?adminkey=5cc4f4100ebf2ba1f3e6fd6294749139&article=161

[2] M. Celuch, M. J. Hill, T. Karpisz, M. Olszewska–Placha, S. Phommakesone, U. Ray, and B. Salski, "Benchmarking of GHz resonator techniques for the characterisation of 5G / mmWave materials," *2021 51st Eur. Microwave Conf. (EuMC)*, London, UK, 2022, pp. 568-571.

[3] M. J. Hill and M. Celuch, "Benchmarking Resonator Based Low dK/dF Material Measurements", *IPC-APEX,* Session "5G/ High Frequency Materials Characterization Challenges and Opportunities", 8-12 March 2021. {Online]. Available: https://www.qwed.eu/nanobat/IPC_APEX_2021_5GMaterialsCharacterisation.pdf

[4] *Measurement of the complex permittivity for low-loss dielectric substrates balanced-type circular disk resonator method*, Std. IEC 63185:2020.

[5] QWED (2023). *Test Fixtures and Setups for Precise Measurements of Electric and Dielectric Properties of Materials at Microwave Frequencies*. [Online]. Available: https://www.qwed.eu/test_fixtures_brochure.pdf

[6] QWED (2023). QuickWaveTM EM Software. [Online]. Available: https://qwed.eu/quickwave.html .

[7] M. Celuch and, W. K. Gwarek, "Industrial design of axisymmetrical devices using a customized FDTD solver from RF to optical frequency bands", *IEEE Microw. Mag.*, Dec. 2008, Vol. 9, No. 6, pp. 150-159, doi: 10.1109/MMM.2008.929686

[8] H. Kawabata, K. I. Hasuke, 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," *Eur. Microwave Conf.*, Manchester, 2006, pp. 388-391.

[9] K. Tanabe, Y. Kobayashi, and S. Tanaka, "Numerical Analysis of Eigenvalue Solution of Disk Resonator (Short Papers)," *IEEE Trans. Microw. Theory Tech.*, vol. 23, no. 6, pp. 508-511, Jun.1975.

[10] M-ERA.NET I4Bags Project: Ion Implantation for Innovative Interface modifications in BAttery and Graphene-enabled Systems. [Online]. Available: https://qwed.eu/i4bags.html