A Novel Q-Choked Resonator for Microwave Material Measurements Alleviating Sample Thickness Limitations of Existing Techniques

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***Abstract*— A novel concept of choked resonators is presented and applied for microwave testing of thick samples of high-permittivity materials. A new 10-GHz Q-choked split cavity resonator (Q-SCR) is designed, manufactured, and validated for a stack of sapphire samples, up to 2 mm thick. The measured values of dielectric constant and loss factor are in excellent agreement with reference data. The work is supported with full-wave electromagnetic (EM) modeling, which is now further used for designing millimeter-wave (mmWave) Q-SCRs.**

***Index Terms*— Cavity resonators, chokes, electromagnetic (EM) measurements, materials testing, microwave sensors, nondestructive testing.**

I. Introduction

MATERIALS are recognized as the backbone of many contemporary industries [1]. This is well exemplified by the electronics industry, such as the next-generation (5G, 6G) communications or edge computing, which require ultralow-loss materials. Not only such materials need to be developed, but also their electromagnetic (EM) properties need to be precisely determined, as errors in materials data lead to design errors that need to be corrected by multiple trimming and tuning. Such iterative processes are costly and difficult to tolerate in today's competitive environment. For example, as noted in [2] and [3], errors in materials' characterization can cost many tens of millions of dollars for a single industrial program, or worse, and they may induce unexpected product failures. This gives rise to industrial initiatives, such as [2], aiming to identify materials testing techniques confirmed to be accurate, fast, reproducible, and applicable at use conditions. The selected results of [2] and recommendations for microwave and millimeter-wave (mmWave) material measurements were published in [4] and [5]. Our work reported herein aims to alleviate some of the limitations of the available measurement techniques, as identified in [2], [3], [4], and [5] and concerned with measuring material samples in form factors relevant to their actual use conditions.

The microwave testing of materials is a well-established field of research, reviewed, e.g., in [6]. Techniques based on cylindrical resonant cavities are prominent due to superior accuracy, especially in the case of ultralow-loss materials. Indeed, such techniques were identified in [2] as relevant to 5G applications and meeting the above listed industrial requirements. Two techniques in particular, split cylinder resonator (SCR) [7] and split-post dielectric resonator (SPDR) [8], are not only supported by over 25 years of research [7], [8], but easily available on the market [9], [10], [11] and standardized [12], [13]. Round-robin benchmarking of the SCR and SPDR techniques (and also the more recent FabryPerot Open Resonator, FPOR, [11], [14], [15]) was conducted in [2], for ten kits of material samples of low-thickness (H_s < 0.2 mm) and low relative permittivity (ε_s < 2.5), circulated between ten laboratories. Consistency and reproducibility (2% in measured ε_s) were found satisfactory, setting up industrial guidelines and best practices [2], [4], [5].

However, the same project [2] demonstrated an inherent deficiency of the available techniques in such practical applications, where the samples of bigger thickness and/or materials of higher permittivity are relevant. For example, real-life automotive plaques of 4 mm thickness posed a challenge and were not measurable in SCRs. For such samples of low permittivity (ε_s < 3.5), wideband FPOR measurements as well as SPDR measurements at 1.9 and 2.5 GHz were performed. However, for higher permittivity (ε_s > 3.5), only the low-frequency (1.1 and 2.5 GHz) SPDRs remained applicable, which gave general information about the sample properties but did not provide data at the actual use conditions at mmWaves. It should be noted that in cases like the considered

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multilayer varnished automotive plaques, requesting a thinner sample for testing purposes, it is neither feasible nor representative, as interactions of EM signals (e.g., radar) with the plaque as a whole are to be eventually evaluated.

The above observations have stimulated this work on new material testing techniques, applicable to thick samples of materials of arbitrary permittivities. This letter explains the problems inherent in the existing techniques (Section II) and proposes a remedy based on suppressing undesired modes with a dedicated choke, further called Q-choke (Sections III and IV), thereby extending the measurement range to thicker and / or higher permittivity samples. In Section V, a prototype of 10-GHz Q-choked SCR is successfully validated for a stack of sapphire disks, up to 2 mm thickness. Section IV summarizes the ongoing work toward mmWave measurements.

Since the Q-choke concept was partially inspired by door chokes in domestic microwave ovens [16], [17], a potential for knowledge transfer between the worlds of microwave processing and microwave characterization of materials is also hereby illustrated.

II. Sample Thickness Limitations in SCR and SPDR

Cylindrical cavity resonators supporting TE_{0np} modes are generic structures, from which SCR and SPDR test fixtures for microwave material measurements are derived. Fig. 1 illustrates the classical concepts, provides background for the new concept of Q-choked SCR, and defines models analyzed further in this work.

Fig. 1(a) shows a vertical cross section of the cavity with magnetic field lines and currents in the cavity walls, for the TE_{011} mode. Since there are only angular currents in the vertical (cylindrical) wall, a slot for inserting a sample is made without causing radiation of the measurement mode. This leads to the SCR design, as shown on the left of Fig. 1(b). Fig. 1(c) defines a parameterized model, which reduces to the classical SCR by setting $h_a = h_c$ (so that the additional channels sketched in Fig. 1(c) for $\rho > R_c$ will not exist).

In SCR [7], [12], the sample is clamped between the two halves of the resonator. In SPDR [8], [13], the slot is fixed and the sample is always thinner than the slot, but the fields are additionally focused inside the cavity by a high-permittivity ceramic post (transforming the mode to $TE_{01\delta}$). Hence, in SPDRs, maximum sample thickness is even visually obvious from the test-fixture construction and for popular units [11] ranges from 6 mm in 1.1-GHz SPDR down to 0.6 mm in 15-GHz SPDR.

In SCR, such a mechanical constraint does not apply, as the slot is adjusted to the sample thickness. However, there are EM constraints, due to undesired modes (mostly, TE_{mnp} for $m > 0$). A typical spectrum of an empty SCR is shown by the gray line in Fig. 2. In the presence of a sample, different modes are differently shifted in frequency, making the readings of the measurement TE_{011} mode ambiguous and inaccurate.

Admittedly, such EM constraints also apply to SPDRs, but typically, they are more restrictive for an SCR than an SPDR at the same operating frequency, since the fields of the latter are stabilized by the ceramic posts. For example, by analyzing the available documentation [7], [8], [9], [10], [11], [12], [13], one finds that in 15-GHz SPDR, with a slot of 0.6 mm, a 0.6-mm-thick sapphire sample can be measured. In SCR, even at a lower frequency of 10 GHz, a sapphire sample would need to be thinner than 0.4 mm. In general, the higher the

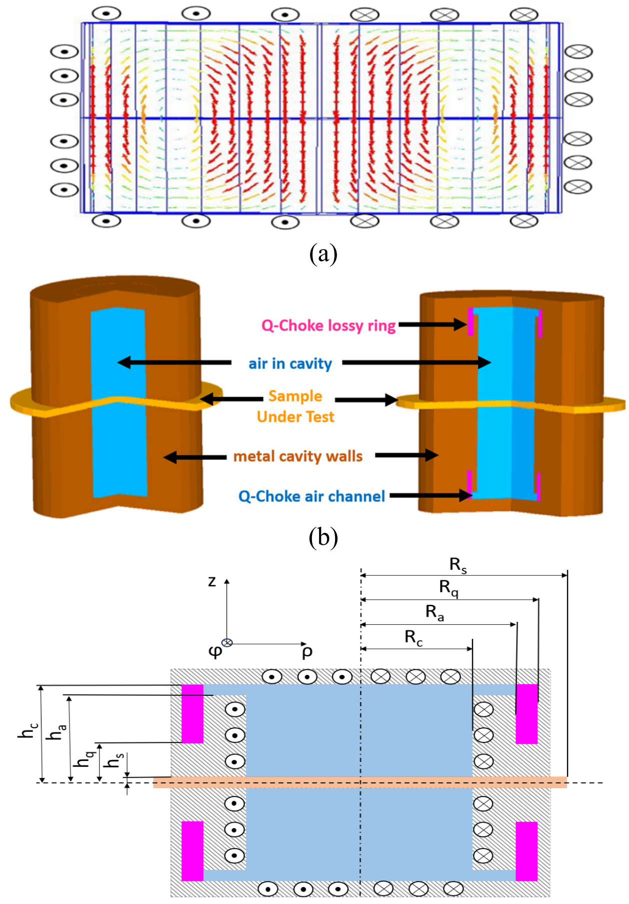

Fig. 1. Cylindrical resonators with TE_{011} mode. (a) Vertical cross section of a simple cavity indicating magnetic field lines and directions of currents in the cavity walls. (b) Three-dimensional views (with 90° cut to show the interior) of (left) classical SCR and (right) Q-SCR. (c) Vertical cross section of a parameterized model used to simulate Q-SCR and classical SCR (if $h_a = h_c$).

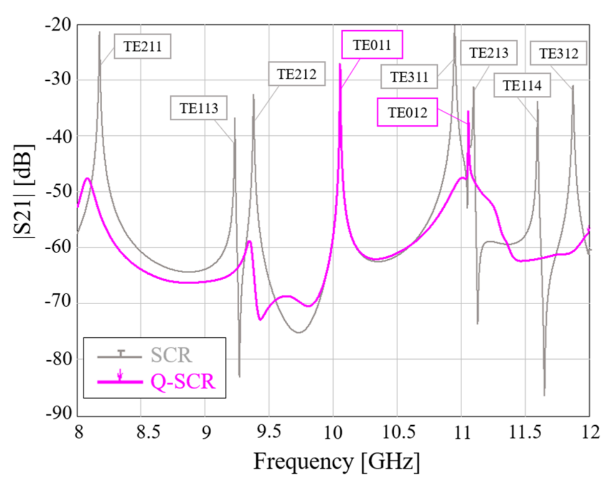

Fig. 2. Simulated transmission spectrum of classical SCR and new Q-SCR, depicting the excited modes and confirming the suppression of undesired modes by the Q-choke.

frequency and the sample permittivity, the thinner the sample needs to be.

III. Concept of Q-Choke

The Q-choke concept stems from similar observations as the basic concept of making a slot in the cylindrical cavity wall for sample insertion [$H_s = 2h_s$ in Fig. 1(c)]. Namely, the measurement TE_{011} mode (or more generally, TE_{0np} modes) will remain essentially unperturbed, if two additional slots are made close to the cavity top ($h_a < z < h_c$) and symmetrically—the cavity bottom. Yet such slots will break the paths of currents flowing vertically in cavity walls for other modes, including TE_{mnp} for $m > 0$ and all TM modes, directing such currents into the channels for $\rho > R_c$. By terminating the channels with lossy pockets (magenta rings for $R_a < \rho < R_q$), the energy of undesired modes will be dissipated. The channels with the pockets form a choke, which will be referred to as Q-choke.

Fig. 2 demonstrates the effectiveness of the Q-choke designed for a 10-GHz SCR, for which simulation parameters will be discussed in Section IV-A. More details of the Q-choke design and its potential applications are given in the patent application [18].

IV. Modeling-Based Design of Q-SCR

A. Three-Dimensional Model of Q-SCR

A series of Q-choked SCRs are being designed for frequencies from 10 to 50 GHz. Here, the first Q-choked split cavity resonator (Q-SCR) for 10 GHz is reported. This lowest frequency is chosen due to the associated lowest cost of manufacturing a prototype, for the purpose of concept validation. Moreover, it overlaps with the reference frequency of the round-robin testing in [2], [3], [4], and [5] and allows direct comparisons with measurements in the available 10-GHz SPDR.

The 10-GHz Q-SCR design follows the schematics of Fig. 1(c) with the following dimensions. $R_c = 18.85$ mm, $h_c = 28.2$ mm, $R_a = 25$ mm, $h_a = 26.2$ mm, $R_q = 28$ mm, and $h_q = 10$ mm. The cavity walls in contact with the EM fields will be made of copper, for which $\sigma = 5 \times 10^7$ S/m is set in the simulation model. Lossy rings for the choke pockets will be 3-D printed with PLA conductive 750-g Capifil. Excitation is applied via coupling loops, analogous to [6], and transmission through the test fixture is considered.

For simulation, the conformal finite-difference time-domain (FDTD) method implemented in QuickWave software [19] is used. For faster convergence of high-Q calculations, input and output signals are postprocessed with the Prony method, based on [20] and available in [19]. A full 3-D model of an empty Q-SCR (without any sample) is defined first, in order to numerically verify the Q-choke concept. With a basic meshing of 0.4 mm and mesh refinement to 0.1 mm at the center height (where samples will be later placed), the total mesh amounts to 921 188 FDTD cells. Simulation times leading to the transmission curves of Fig. 2 are of the order of 547 s on NVIDIA GeForce RTX 2080 Ti GPU card or 1172 s using multicore/multithread software version on AMD Ryzen Threadripper 2950X 16-core processor 3750 MHz.

Fig. 2 shows the simulated transmission characteristics through a classical SCR (without any choke) and the Q-SCR proposed herein (with the Q-choke). The resonant modes corresponding to the transmission peaks are identified and annotated. The Q-choke damps all TE_{mnp} modes, with $m > 0$, to at least 20 dB below the measurement mode. In the considered frequency range (±20% of the center frequency), the only mode within 10 dB of the measurement mode is TE_{012}. It will not perturb or confuse measurements, as it will remain above the TE_{011} resonance. The effectiveness of the Q-choke in suppressing undesired modes is thereby computationally demonstrated, which makes Q-SCR a promising candidate for measuring thick and also high-permittivity material samples.

B. BoR Model of Q-SCR

Similarly as in classical SCRs and SPDRs, material properties will be calculated from downward shifts of the TE_{011} resonant frequency and broadening of the resonant peak, when a sample is inserted. The formulas for complex permittivity (or ε_s and $\tan\delta_s$) are analogous to the classical SCR [7], [12] and therefore will not be repeated here. Instead of approximate analytical [12] or semi-analytical [7] calculations, a numerical fast bodies-of-revolution (BoR) FDTD method is further used. The 3-D model of Section IV-A is reduced to 2-D BoR [19], [21], which limits the number of FDTD cells to 4480 and simulation time for one model to 52 s on AMD Ryzen Threadripper 2950X 16-core processor 3750 MHz. The maps of resonant frequency and *Q*-factor changes over a grid of values of sample thickness and material parameters are created are stored as a database for Q-SCR measurements.

V. Measurements and Validation of Q-SCR

Fig. 3 shows a photograph of the measurement system, including the prototyped 10-GHz Q-SCR, VNA (Keysight Streamline P5008B), and a laptop running a dedicated application. The capability of making unambiguous measurements of samples thicker than allowed in the pre-existing techniques is first validated. A batch of five sapphire samples is considered, each of ca. 0.4 mm thickness. The expected value of relative in-plane permittivity is 9.3954, based on the reference measurements with whispering gallery modes for ultralow-loss dielectric materials [22]. According to the brochures [10], [15], even a single such sample exceeds the maximum thickness limitations of commercially available SCR [10] and FPOR [15] instruments. In a 10-GHz SPDR of [11], a single sample can be measured, giving $\varepsilon_s = 9.390$ and $\tan\delta_s = 1.21\cdot 10^{-5}$. In the new 10-GHz Q-SCR, all five samples are stacked and successfully measured.

Table I reports the Q-SCR results for stacks of 1÷5 disks. For each such a stack, the total thickness (H_s in column 2 of Table I) is confirmed with a micrometer, indicating minor total thickness variations (TTW), which lead to averaged single-disk thickness variations within ±0.3%. While TTW

Fig. 3. Measurement setup featuring the 10-GHz Q-SCR prototype (on the right).

TABLE I
MEASURED IN-PLANE PERMITTIVITY (ε_s) OF A STACK OF SAPPHIRE DISKS OF TOTAL THICKNESS H_s AND RELATIVE ERRORS WITH RESPECT TO THE AVERAGE OF THE MEASURED VALUES ($\varepsilon_{s,av} = 9.403$) AND TO THE MEASUREMENT OF [22] (9.3954 AT 296.5 K)

Nb. of discs	H_s [mm]	ε_s	$\delta\varepsilon_s$ [%] wrt $\varepsilon_{s,av}$	$\delta\varepsilon_s$ [%] wrt [21]
1	0.404	9.407	0.043	0.123
2	0.812	9.398	-0.053	0.028
3	1.219	9.415	0.128	0.211
4	1.625	9.401	-0.021	0.060
5	2.030	9.395	-0.085	-0.004

contributes to measurement uncertainties, all the resulting ε_s values (column 3) measured for 1÷5 disks are within 0.13% of one another (column 4). All the measured values are within 0.2% of [22] (column 5).

Very good accuracy of the proposed Q-SCR is also demonstrated for dielectric loss extraction. Measured loss tangent values are $\tan\delta_s = 1.37\cdot10^{-5}$, $1.89\cdot10^{-5}$, $1.83\cdot10^{-5}$, $1.93\cdot10^{-5}$, and $1.9\cdot10^{-5}$ for stacks of 1÷5 disks, respectively, showing a spread of 0.16–$0.72\cdot10^{-5}$ compared to the value measured in 10-GHz SPDR, which is noticeably below the declared SPDR accuracy [11], [13].

VI. CONCLUSION

A novel concept of Q-choked resonators for microwave measurements of thick material samples of arbitrary permittivity has been presented, explained, and verified via computational modeling. A prototype of 10-GHz Q-SCR has been designed, manufactured, and validated by measuring the stacks of sapphire samples up to 2.03 mm (0.2 wavelength) thick, which exceeds by over a factor of 8 the declared thickness limitations of commercially available SCRs [10]. The measured permittivity and loss tangent are in excellent agreement with reference data [22] and own SPDR measurements of a single (0.4 mm) sample. A series of Q-SCRs for mmWave frequencies are now being designed. Q-SCRs open new horizons for accurate, reproducible, and easy testing of real-life materials, such as automotive plaques, semiconductor wafers, glass panes, or multilayer boards, for the electronics industry and microwave material processing applications.

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