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# Determination of the Material Relative Permittivity in the UHF Band by Using T and Modified Ring Resonators

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***Abstract*—The complete methodology of designing T- and modified ring resonators in the UHF band are presented in the paper. On the basis of proposed algorithms, the dedicated software tool has been elaborated in order to determine material parameters of contemporary substrates. The program is implemented in the Mathcad environment and it includes the base of information on known materials used in electronic products. Also, test sample series for selected substrate materials (IS680, FR408, I-SPEED PCB ISOLA and A6-S LTCC FERRO) and operating frequencies from 1 GHz to 3 GHz are analyzed in details. The special test stand with a vector network analyzer has been applied in experiments. The obtained data of relative permittivity measurements and model calculations are described, discussed and concluded.**

***Keywords*—relative permittivity, UHF band, ring resonator, T-resonator**

## I. INTRODUCTION

WHILE developing and modelling radio frequency (RF) and microwave devices, designers have to rely on precise information on parameters of used materials [1], [2]. The relative permittivity ($\varepsilon_r$ also referred as the dielectric constant DK by material manufacturers) and the loss tangent (tan $\delta$ also referred as the dissipation factor DF) are the most essential quantities when considering dielectric products that are used for electronic device substrates [3]. They should be estimated at the target operating frequency but unfortunately this information is often inaccessible also for substrates frequently used in the electronic technology.

Low-loss materials (where the tan $\delta$ is approximately below 0.01 [4]) are usually used in the RF and microwave industry. Such hybrid devices are frequently manufactured on copper clad laminates or LTCC ceramic substrates. It should be noted that also modern low-loss composites [5], [6] (with high permittivity suitable for miniaturization of microwave circuits) or cheap flexible materials (e.g. paper [7], liquid crystal polymer LCP [8], textile [9], [10], polyethylene terephthalate PET [11], polydimethylsiloxane PDMS [12] and others) are used in such products.

The RF and microwave devices are usually designed on thin substrates with the tendency to develop multilayer structures. Additionally, since those materials are excellent insulators and their conductivity is very low [4], the relative permittivity influences significantly properties of designed products. In this scope, the values of product parameters vary depending on a frequency band and manufacturing process of substrate in different ways for each material type [3], [13]. For example, the relative permittivity of the copper clad laminate FR4 that is typically used in PCB technology, varies significantly with frequency [4] but also with fibre glass styles and resin contents [14]. These changes are very important e.g. for antenna constructions that are always designed for precisely selected frequency bands. Therefore, if the necessary information on parameters is inaccessible in knowledge bases, the material relative permittivity at the assumed frequency band should be always determined experimentally.

The authors focus on the UHF band (from 300 MHz to 3 GHz) in which many RF devices dedicated for different kinds of public radio communication systems work (e.g. UHF RFID [15], GSM/UMTS 900 [16], [17], GSM/LTE 1800 [16], [18], ISM 2,4 GHz [16], [19] and others [17]). Through many years of professional experience they have found that there is very often impossible to look up precise value of $\varepsilon_r$ especially for modern or untypical materials. The worst situation is when designer need to know how the value varies with the frequency. While modelling antenna circuits (by numerical procedures or dedicated software) and entering parameters of dielectric substrate layers, the authors have encountered the problem that consisted in not being able to find exact values of the material relative permittivity corresponding with the assumed operating frequency [20]. The problem could be solved by tests conducted on a prepared material sample in the UHF band using dedicated resonators. The experimental approach has been described by an appropriate numerical algorithm that includes designed constructions of resonators, their manufacturing technological parameters, measurements, as well as experimental verification and correction of developed theoretical models. On the basis of the algorithm, a software tool in Mathcad environment has been elaborated. It consists of material base of identified products and procedures for determining the parameters of unknown substrates.

## II. MEASUREMENT METHOD IN THE UHF BAND – REVIEW

Methods described by the IPC (the Association Connecting Electronics Industries) in the IPC-TM-650 – Test Method

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Manual, Section 2.5 – Electrical Test Methods [21] can be used for measuring material parameters of substrate that are utilized in RF electronic circuits. The method of no. 2.5.5.3 [22] can be applied to the lower part of the UHF band (several hundreds of MHz), no. 2.5.5.9 [23] – to the frequency of 1.5 GHz and no. 2.5.5.5 [24] – to the frequency of 3 GHz (the upper part of the UHF band). It should be noticed that all of them have some restrictions with respect to the target investigations. Although the method no. 2.5.5.3 is not the best for 300-1000 MHz, but it is suitable for determining the permittivity of thin films and laminates (sample of thickness up to 6.35 mm approximately). The method no. 2.5.5.9 is suitable for frequency band between 300 MHz and 1500 MHz but it is not intended for low-loss materials that are typically used in the RF industry. The method no. 2.5.5.5 is very useful for metal clad substrates but it is intended rather for measurements in the X-band (8-12.4 GHz). The frequency in the last method may be expanded towards the UHF band (1-3 GHz) [25] by using the Bereskin stripline [26].

The main disadvantage of the above mentioned methods is the necessity to use expensive fixture kits that are not always available in research laboratories. However, designers usually use suitable numerical software, have access to sophisticated equipment, e.g. 2-Port Vector Network Analyzer (VNA) and are familiar with electronic technology of RF circuits. It is the reason why experimental measurement methods of determining the permittivity by using a variety of microstrip resonator designs are widely discussed in the literature. E.g. ring resonator [27] and its modifications [28], T design [29], fork resonator [30] and other constructions can be quoted as an example. The T- and modified ring resonators are the most useful for designing RF devices created on the base of low-loss materials. These methods are adjusted to the applications in which the designed RF devices are going to be implemented and it is easy to accomplish them in most experimental laboratories by using the typical equipment. The choice of this kind of resonators follows that prepared samples have useful dimensions related to the wavelength ($\lambda$=1÷0.1 m). Moreover, the satisfactory convergence of calculation and measurement results are achievable during RF circuit synthesis in the UHF band.

## III. DETERMINATION OF RELATIVE PERMITTIVITY

### A. *Model*

The T- and modified ring resonator are made in the form of typical microstrip devices that can be fabricated using e.g. PCB or LTCC technology. A microstrip line (of width $w$ and thickness $t$) that forms the resonator shape is separated from a ground plane by a dielectric substrate of thickness $d$ and relative permittivity $\varepsilon_r$ (Fig. 1).

Estimated dependencies for empirical model of resonator can be obtained from a quasi-static analysis of the microstrip line [31]. For this assumption, the phase velocity can be expressed as:

$$\upsilon = \frac{c}{\sqrt{\varepsilon_e}} \tag{1}$$

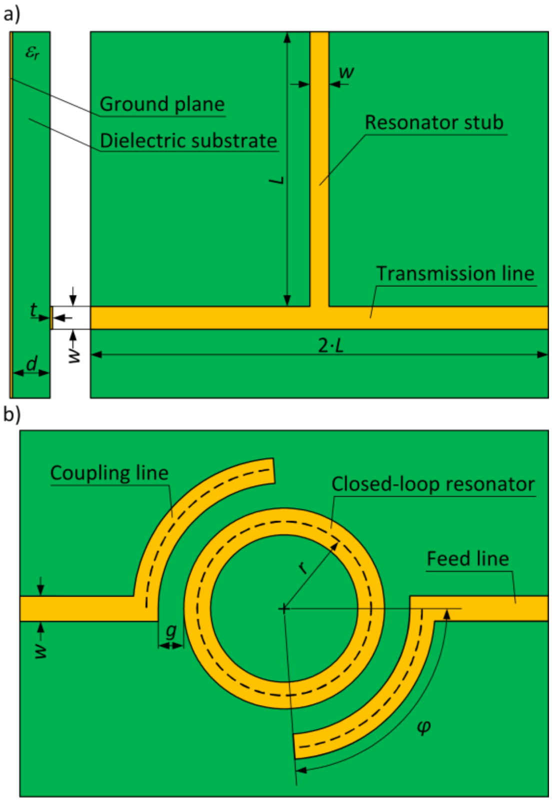


Fig. 1. Design model: a) T resonator, b) modified ring resonator

where $c$ is the speed of light, and $\varepsilon_e$ denotes the effective permittivity of microstrip line. The last parameter is correlated with the relative permittivity where $1<\varepsilon_e<\varepsilon_r$.

In this empirical study, the effective width of microstrip line can be expressed as:

$$w_e = \begin{cases} w + \dfrac{t}{\pi}\left(1+\ln\left(\dfrac{2\cdot d}{t}\right)\right) & \text{for} \quad \dfrac{w}{d} \geq \dfrac{1}{2\pi} \\ w + \dfrac{t}{\pi}\left(1+\ln\left(\dfrac{4\pi\cdot w}{t}\right)\right) & \text{for} \quad \dfrac{w}{d} < \dfrac{1}{2\pi} \end{cases} \tag{2}$$

Based on the width $w_e$, the effective permittivity of microstrip line can be expressed by the formula:

$$\varepsilon_e = \begin{cases} \dfrac{\varepsilon_r+1}{2} + \dfrac{\varepsilon_r-1}{2}\cdot\left(1+12\cdot\dfrac{d}{w_e}\right)^{-0.5} & \text{for} \quad \dfrac{w_e}{d} \geq 1 \\ \dfrac{\varepsilon_r+1}{2} + \dfrac{\varepsilon_r-1}{2}\cdot \\ \cdot\left[\left(1+12\cdot\dfrac{d}{w_e}\right)^{-0.5} + 0.04\left(1-\dfrac{w_e}{d}\right)^2\right] & \text{for} \quad \dfrac{w_e}{d} < 1 \end{cases} \tag{3}$$

On the basis of (2)–(3), the characteristic impedance of microstrip line can be calculated from the dependence:

$$Z_f = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}}\ln\left(\dfrac{8d}{w_e}+\dfrac{w_e}{4d}\right) & \text{for} \quad \dfrac{w_e}{d} < 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_e}\cdot\left(1.393+\dfrac{w_e}{d}+\dfrac{2}{3}\ln\left(\dfrac{w_e}{d}+1.444\right)\right)} & \text{for} \quad \dfrac{w_e}{d} \geq 1 \end{cases} \tag{4}$$

The dimensions of microstrip line for T- and modified ring resonator should be calculated in such a way as to obtain the characteristic impedance of VNA ports ($Z_f$=$Z_0$=50 Ω).

The T-resonator consists of a transmission line and an open-ended stub (Fig. 1-a). On the basis of (3), the length of this stub can be calculated from equation:

$$L = \frac{nc}{4 f_0 \sqrt{\varepsilon_e}} \tag{5}$$

where $n$ is the order of resonance and $f_0$ is the resonance frequency. The resonance occurs for $n$=1,3,5,… (for the wave $\lambda$/4 that is transmitted in the microstrip line). In many publications, the relative permeability is determined for a broad frequency band from one sample [28]-[30]. Nevertheless, it should be emphasized that the maximum accuracy of material parameters determination can be achieved only for the test sample that is designed for $n$=1 (attenuation at the first resonance is higher) [29]. It is especially important for example when antennas are intended for narrow frequency band (e.g. in the UHF band).

The closed-loop resonator is the main element of the second design – ring resonator (Fig. 1-b). On the basis of (3), the mean radius of this ring can be calculated from:

$$r = \frac{nc}{2\pi f_0 \sqrt{\varepsilon_e}} \tag{6}$$

The equivalent circuit of ring resonator can be represented as a connection between two feed lines of the impedance $Z_f$, two coupling gaps of the capacitance $C_g$ and the main ring of the impedance $Z_r$ (Fig. 2).

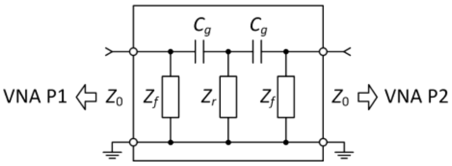


Fig. 2. Equivalent circuit of ring resonator

In practice, the gap width $g$ (Fig. 1-b) is in the range of (0.1÷1)·$w$. Accurate determination of this parameter is a result of many theoretical and experimental research [32]. It should be noted that the gap capacitance may change the resonance frequency, because the ring resonator works as a filter. Additionally, the low-level coupling between the feed lines and the ring in the classical construction results in the need for designing a solution that could reduce the signal attenuation between ports P1 and P2. The coupling level can be enhanced by expanding the feed lines around the ring. Such a modification directly affects the gap capacitance and the resonance frequency. The adverse effect of the resonance frequency filtering can be minimized by setting the length of coupling line equal $\lambda$/4. Therefore the angle that describes this length can be expressed by formula:

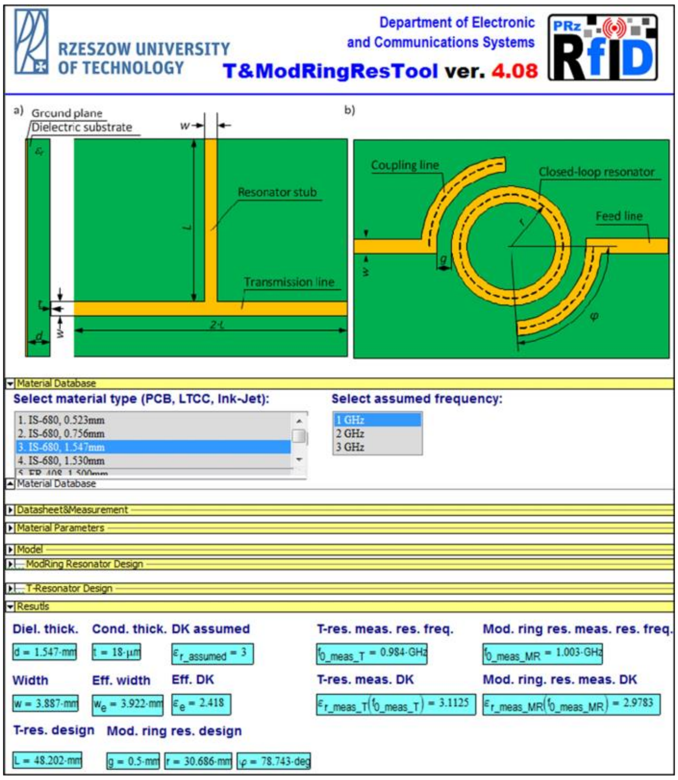
$$\varphi = \frac{\lambda}{4r}, \text{ rad} \tag{7}$$

The above described parameters and dependencies are fundamental for designing resonators operating at a given frequency. The elaborated resonators can be utilized for obtaining the relative permittivity of substrate material. Available but suitable numerical software has to be involved in the calculation, modelling and data processing.

### B. Results

Determination of the relative permittivity in the UHF band is discussed on the basis of practical implementations of T- and modified ring resonator constructions that are made in PCB and LTCC technology. The measurement data are compared with numerical results obtained for models created in the Mentor Graphics HyperLynx 3D EM (HL3DEM).

On the basis of (1)–(7), the special program *T&ModRingResTool* (prepared in the Mathcad environment) has been elaborated to support the described task (Fig. 3). Its output data can be easily implemented for preparing a base geometrical model of selected resonators. This model can be used in an available numerical software (such as HL3DEM) in which a final layout for technological process can be prepared.


RZESZOW UNIVERSITY OF TECHNOLOGY
Department of Electronic and Communications Systems
T&ModRingResTool ver. 4.08

Select material type (PCB, LTCC, Ink-Jet):
1. IS-680, 0.523mm
2. IS-680, 0.756mm
3. IS-680, 1.547mm
4. IS-680, 1.530mm

Select assumed frequency:
1 GHz
2 GHz
3 GHz

Diel. thick. $d$ = 1.547·mm
Cond. thick. $t$ = 18·µm
DK assumed $\varepsilon_{r\_assumed}$ = 3
T-res. meas. res. freq. $f_{0\_meas\_T}$ = 0.984·GHz
Mod. ring res. meas. res. freq. $f_{0\_meas\_MR}$ = 1.003·GHz
Width $w$ = 3.887·mm
Eff. width $w_e$ = 3.922·mm
Eff. DK $\varepsilon_e$ = 2.418
T-res. meas. DK $\varepsilon_{r\_meas\_T}(f_{0\_meas\_T})$ = 3.1125
Mod. ring. res. meas. DK $\varepsilon_{r\_meas\_MR}(f_{0\_meas\_MR})$ = 2.9783
T-res. design $L$ = 48.202·mm
Mod. ring res. design $g$ = 0.5·mm $r$ = 30.686·mm $\varphi$ = 78.743·deg

Fig. 3. Screenshot of *T&ModRingResTool* program

The test sample series for selected substrate materials (IS680, FR408, I-SPEED PCB ISOLA and A6-S LTCC FERRO) and operating frequencies from 1 GHz to 3 GHz are analyzed in details (Table I). The substrates are part of the material base that is used at the Department of Electronic and Communications Systems, Rzeszow University of Technology (especially under Grant No. PBS1/A3/3/2012).

A preliminary assumption of the $\varepsilon_r$ is necessary for the proper sample design. The estimated $\varepsilon_r$ value for demanded frequency can be predicted on the basis of producer's datasheets. The data can be only rough approximated because manufacturing tests are carried out for just several points in the nominal frequency band. The $\varepsilon_r$ has to be measured by using classical capacitance method [33] when the information is completely not accessible.

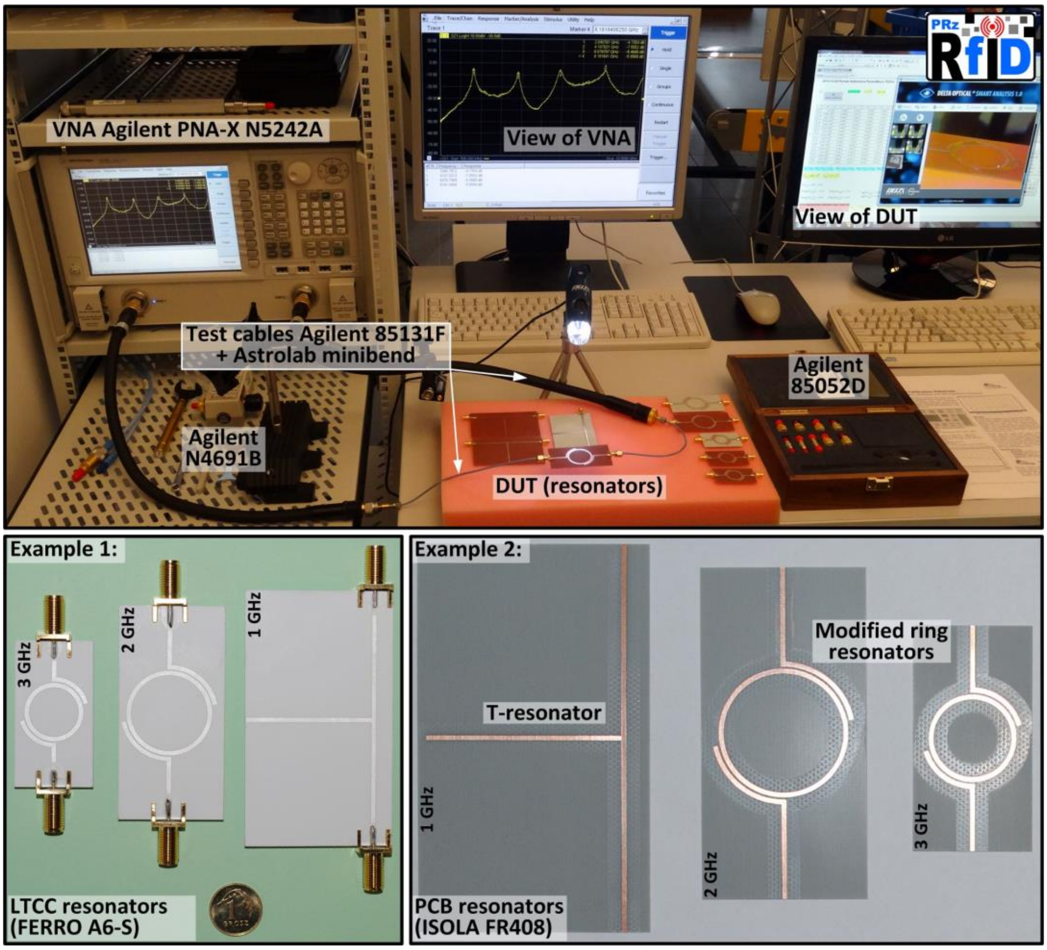


Fig. 4. Test stand in the RFID laboratory.

TABLE I
ASSUMED RELATIVE PERMITTIVITY OF SELECTED MATERIALS

| No. | Material type | $d$ | $t$ | $\varepsilon_r$ (assumed) | | |
|---|---|---|---|---|---|---|
| | | | | 1 GHz | 2 GHz | 3 GHz |
| | | mm | μm | - | - | - |
| 1 | IS 680 | 1.547 | 18 | 3.00 | 3.00 | 3.00 |
| 2 | FR408 | 0.510 | 18 | 3.66 | 3.66 | 3.66 |
| 3 | FR408 | 0.510 | 18 | 4.07 | 4.06 | 4.05 |
| 4 | FR408 | 1.080 | 18 | 4.07 | 4.06 | 4.05 |
| 5 | I-SPEED | 0.529 | 18 | 3.73 | 3.72 | 3.70 |
| 6 | I-SPEED | 0.706 | 18 | 3.83 | 3.82 | 3.80 |
| 7 | A6-S | 0.770 | 10 | 5.90 | 5.90 | 5.90 |

TABLE II
MEASURED RESONANCE FREQUENCY ($n$=1)

| No. | Material type | $f_0$ (T-resonator) | $f_0$ (modified ring resonator) | |
|---|---|---|---|---|
| | | 1 GHz | 2 GHz | 3 GHz |
| | | GHz | GHz | GHz |
| 1 | IS 680 | 0.984 | 2.013 | 3.020 |
| 2 | FR408 | 0.933 | 1.898 | 2.857 |
| 3 | FR408 | 0.984 | 1.980 | 3.000 |
| 4 | FR408 | 1.021 | 2.030 | 3.041 |
| 5 | I-SPEED | 1.003 | 2.013 | 3.028 |
| 6 | I-SPEED | 1.018 | 2.041 | 3.058 |
| 7 | A6-S | 0.982 | 1.964 | 2.945 |

The investigations were performed on the special test stand in the RFID laboratory at the Department of Electronic and Communications Systems, Rzeszow University of Technology (Fig. 4). The $S_{21}$-parameter of the prepared resonators was measured by using the VNA (Agilent PNA-X N5242A). The samples were connected by the flexible test cables: Agilent 85131F and Huber+Suhner (Astrolab) minibend. The measuring circuit was calibrated at the end of test cables by the electronic calibration module (Agilent N4691B) or the economy mechanical calibration kit (Agilent 85052D).

The values of relative permittivity for tested materials (Table III) were obtained on the basis of the first resonance that was measured for every prepared sample (Table II).

TABLE III
DETERMINED RELATIVE PERMITTIVITY

| No. | Material type | $\varepsilon_r$ (T-resonator) | $\varepsilon_r$ (modified ring resonator) | |
|---|---|---|---|---|
| | | 1 GHz | 2 GHz | 3 GHz |
| 1 | IS 680 | 3.08 | 2.96 | 2.95 |
| 2 | FR408 | 4.26 | 4.11 | 4.08 |
| 3 | FR408 | 4.22 | 4.15 | 4.05 |
| 4 | FR408 | 3.89 | 3.93 | 3.93 |
| 5 | I-SPEED | 3.70 | 3.67 | 3.62 |
| 6 | I-SPEED | 3.68 | 3.65 | 3.64 |
| 7 | A6-S | 6.13 | 6.14 | 6.14 |

The items 2 and 3 concern the test samples made from the same material but the designs were prepared for two different $\varepsilon_r$ values that had been predicted previously (Table I).

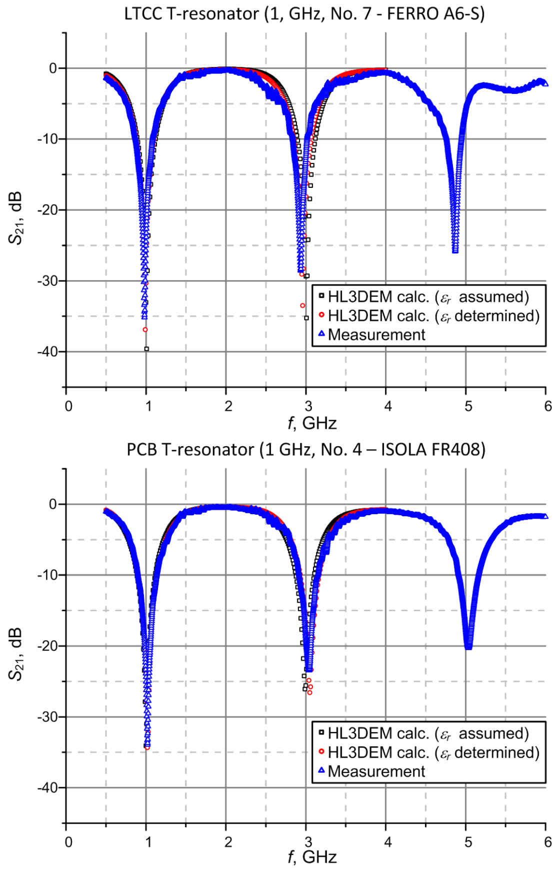


Fig. 5. Examples of results for T-resonator and 1 GHz.

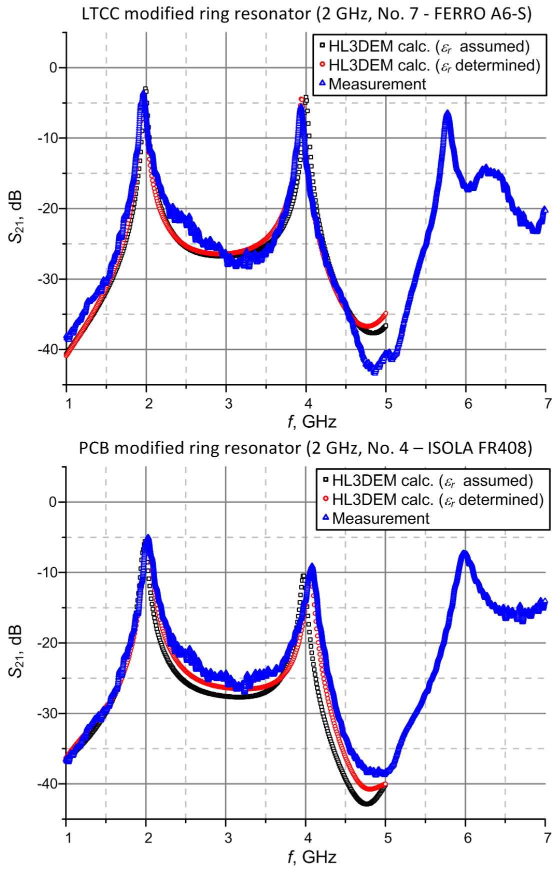


Fig. 6. Examples of results for modified ring resonator and 2 GHz.

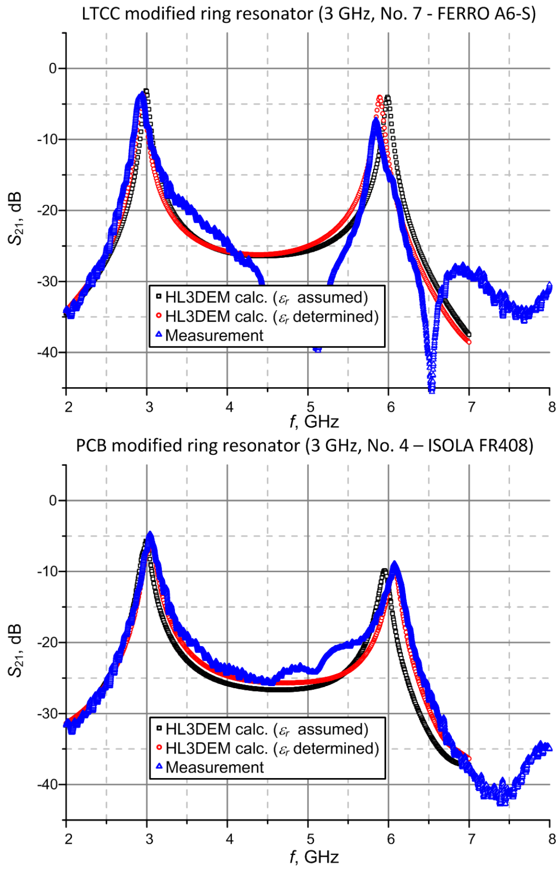


Fig. 7. Examples of results for modified ring resonator and 3 GHz.

The numerical recalculations of the models HL3DEM was accomplished in the last step of the investigation procedure. Instead of $\varepsilon_r$ prediction the values obtained on the basis of measurements were put into the model. The most representative results for selected materials are compared in the Fig. 5 – Fig. 7.

After the HL3DEM models correction, the full convergence of the calculation and measurement results has been achieved for a given resonant frequency. Thus it confirms the accuracy of the proposed process dedicated to determining the material relative permittivity in the UHF band by using T- and modified ring resonators.

## IV. CONCLUSION

Since the materials that are used for electronic substrates are usually excellent insulators and their conductivity is very low, the relative permittivity influences significantly properties of designed products. Unfortunately, this parameter varies a lot depending on a frequency band, chemical constitution of used material, its physical composition and even technological parameters of manufacturing processes. Therefore, it is important to have access to trustworthy information about its real value at a demanded frequency or to have ability of determining it in a reliable experiment. The authors encountered this problem while designing antenna circuits of RF devices dedicated to public radio communication systems working in the UHF band. They solved the problem by preparing adequate numerical algorithm and corresponding software tool that allows user to take into consideration available knowledge base of material properties, constructions of resonators, their manufacturing technological parameters, measurements realized by using VNA, as well as experimental verification and correction feedback for developing theoretical models.

A preliminary assumption of the $\varepsilon_r$ is necessary for realizing the proper sample design. The estimated $\varepsilon_r$ value for demanded frequency can be predicted on the basis of producer's datasheets. Unfortunately, the data can be only rough approximated because manufacturing tests are carried out for just several values of nominal frequency band and on the basis of only one basic sample, despite the fact that the maximum accuracy of material parameters determination can be achieved only for the test sample that is designed especially for the first resonance. When the proper algorithm – proposed by the authors – is executed, the full convergence of the calculation and measurement results can be achieved. Thus it confirms the accuracy of the proposed process dedicated to determining the material relative permittivity in the UHF band by using T- and modified ring resonators.

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