Split Ring Resonator for Complex Permittivity Measurement

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Abstract – **A microwave planar sensor based on a split ring resonator is proposed in order to measure the complex dielectric permittivity of material samples. The geometry of the sensor has been simulated and optimized by a commercial electromagnetic software. Simulations in the presence of the dielectric material sample show that the resonance frequency and quality factor are influenced by the material in contact with the sensor itself. A linear relation is obtained between sample loss tangent and the reciprocal of SRR quality factor. Measurements using high-purity grades liquids have been conducted through a vector network analyzer. A relationship between the resonance frequency and the sample permittivity has been found that is well approximated through a 2-parameter exponential. Finally, the model has been validated measuring the dielectric constant of a liquid by the Keysight High temperature probe kit.**

I. INTRODUCTION

Split ring resonators (SRRs) have important properties for the dielectric characterization of solid, liquid and granular materials, showing high measurement sensitivity, high quality factor and small dimensions, not requiring a particular sample preparation. The study of these structures is based on the analysis of the resonance frequency, which varies if the SRR is in contact with a material sample in relation to the dielectric and geometric characteristics of the material itself.

The SRR consists of metal tracks on a dielectric substrate. These tracks consist of concentric rings, circular crowns, with cuts along a diameter, hence the name of the resonator: "Split Ring". There are various types of SRR, which differ principally in their geometric characteristics [1]. The number of splits, the split width, the gap between the inner and outer ring, and the width of the metal strips forming the ring are significant in determining the resonant frequency and quality factor, therefore all these factors are considered in the SRR design.

The SRR behaves like an LC resonator, whose basic circuitry is shown in [2]. Among many SRRs used in the literature for various microwave applications, in this paper the focus is placed on SRRs used in the complex dielectric permittivity characterization of a material under test [3, 4].

II. METHODS AND MODELS

A. Geometry of the resonator

Fig. 1 shows the resonator, which consists of metal tracks on a dielectric substrate. To complete the geometry, there are two larger microstrips on the sides of the ring, which are used to access the resonator in a transmission configuration, while a smaller one is placed along the diameter of the innermost circular crown [5].

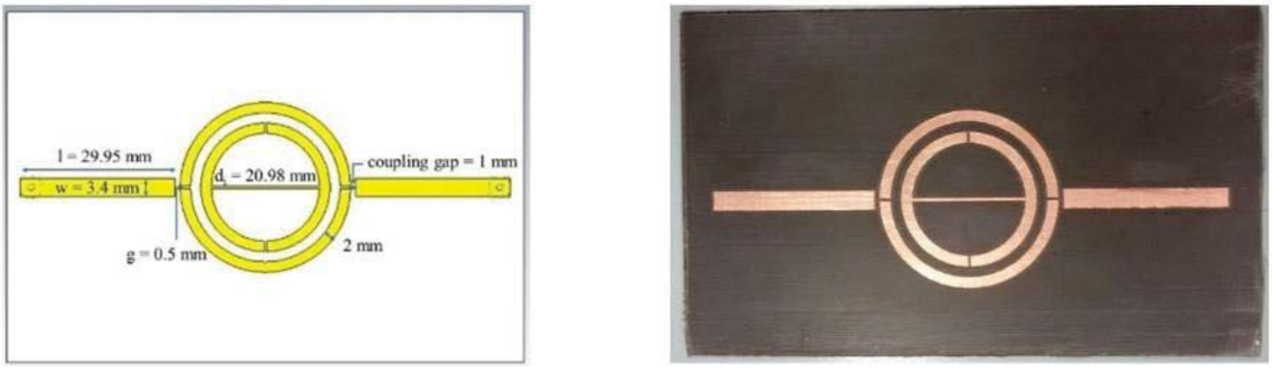
Starting from SRRs for microwave application present in literature [6, 7], attention has been focused mainly on geometry and characteristics of SRRs used for the dielectric characterization of solid, liquid and granular materials [8]-[11]. In particular, SRRs with high sensitivity, high quality factor, small size, and that do not require a particular sample preparation have been considered [6, 12]. The overall geometry has been simulated and optimized by the electromagnetic software CST Microwave Studio®.

The chosen substrate is the Duroid® RT-5870, with thickness t_s = 1.19 mm, relative permittivity ε_r = 2.5, loss tangent tanδ= 0.0012, copper thickness t_c = 0.035 mm, and a total substrate dimension of 68 mm x 100 mm. The SRR is accessible through two coaxial connectors, coupled to the feeding lines, which are located on the bottom part of the structure.

B. Sample characteristics

In order to simulate the material in contact with the SRR, a straight parallelepiped of dimensions 40 mm × 40 mm × 30 mm was created, with parametric relative dielectric cost ε_r and loss tangent tgδ. The parallelepiped was positioned in the center of the SRR as shown in Fig. 2.

The relative dielectric constant was simulated with values ε_r = 1-2-3-4-5-6-8. The loss tangent tgδ between 0.001 and 0.1 with the following values: 0.001-0.003-0.006-0.009-0.012-0.023-0.033-0.044-0.055-0.066-0.077-0.088-0.1.



(a) (b)

Fig. 1. Geometry of the SRR designed with CST (a); realization of the resonator (b).

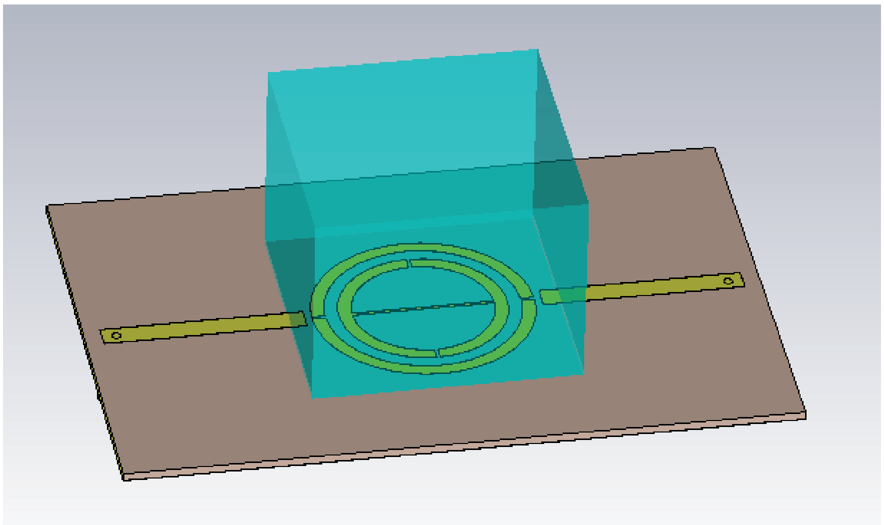


Fig. 2. Geometry of the system composed by the SRR and the sample material in contact with the sensor.

C. Measurement set-up

The transmission coefficient values are measured through the VNA (model Agilent E8363C) using liquids, which are largely employed in calibration measurements since they are commercially available for a range of static permittivities ε_s and in high-purity grades [13].

In particular, distilled water and acetone were used with a constant dielectric permittivity equal to 78.55 and 20.59 @ T = 25 °C [13], respectively. Furthermore, they have the significant advantage of completely covering the sensor surface avoiding gaps or undesired interfaces. The measurement set-up for liquids was setted using a silicone support.

III. RESULTS

The final SRR has a simulated resonance frequency in air of approximately 2.22 GHz (see Fig. 3) with a quality factor of about 160.

If the SRR is working in the presence of a dielectric material sample in contact with the resonator, its resonance frequency and quality factor are influenced by the material in contact with the sensor itself. Performing a series of full-wave electromagnetic simulations keeping the material ε_r constant and varying its loss tangent tanδ, in order to relate the variation of the quality factor Q to the loss tangent of the sample.

The resonance frequency f_r of the SRR and the -3dB bandwidth Δf_{-3dB} have been found in the presence of the material thus obtaining the quality factor Q from the following relationship:

$$Q = \frac{f_r}{(\Delta f)_{-3dB}}$$

The relationship between the simulated tgδ (varying between 0.001 and 0.1) and the inverse of the quality factor Q was found, obtaining a linear correlation for the different values of ε_r. Fig. 4 shows the graph relating to $\varepsilon_r = 6$.

Hence, by performing Q measurements in the presence of a material sample it is possible to evaluate its *tanδ*, once its ε_r has been estimated.

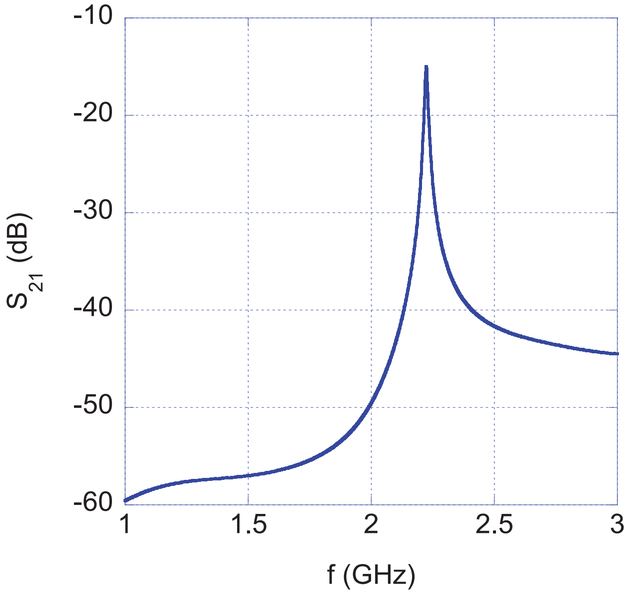


Fig. 3. Simulated transmission coefficient of the SRR in air.

Furthermore, the relationship between the relative dielectric constant as a function of the resonance frequency was obtained. In particular, besides the simulated material introduced in Section II.b, measurements on known liquids ($\varepsilon_{r,distwater}$ = 78.55 and $\varepsilon_{r,acetone}$ = 20.59) were added. The data have been fitted using a 2- parameter exponential (model in Table I) as shown in Fig. 5.

Thus, by performing f_r measurements in the presence of a material sample it is possible to evaluate its dielectric constant.

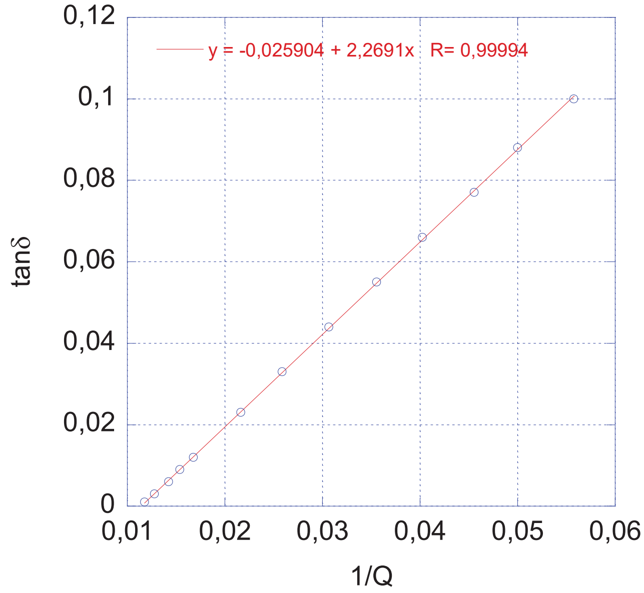


Fig. 4. Relation between sample loss tangent and quality factor of the SRR for a sample permittivity ε_r = 6, obtained through full-wave electromagnetic simulations: numerical results (blue circles) and linear regression line (red line).

IV. MODEL EXPERIMENTAL VALIDATION

In order to verify the ε_r-f_r model, the dielectric constant of the Propan-2-ol is measured with the SRR sensor. Ten repeated measurements of SRR resonance frequency in presence of the liquid are conducted finding a mean value of $f_{r,M}$ = 1.719 GHz. This value, using the exponential model of Table I, corresponds to a dielectric constant equal to 6.1.

Table I. Model fitting parameters.

Exponential model
f(x) = a*exp(b*x) Coefficients (with 95% confidence bounds): a = 599 (575.5, 622.5) b = -2.667 (-2.713, -2.621)
SSE: 0.9163 R-square: 0.9998 Adjusted R-square: 0.9998 RMSE: 0.3384

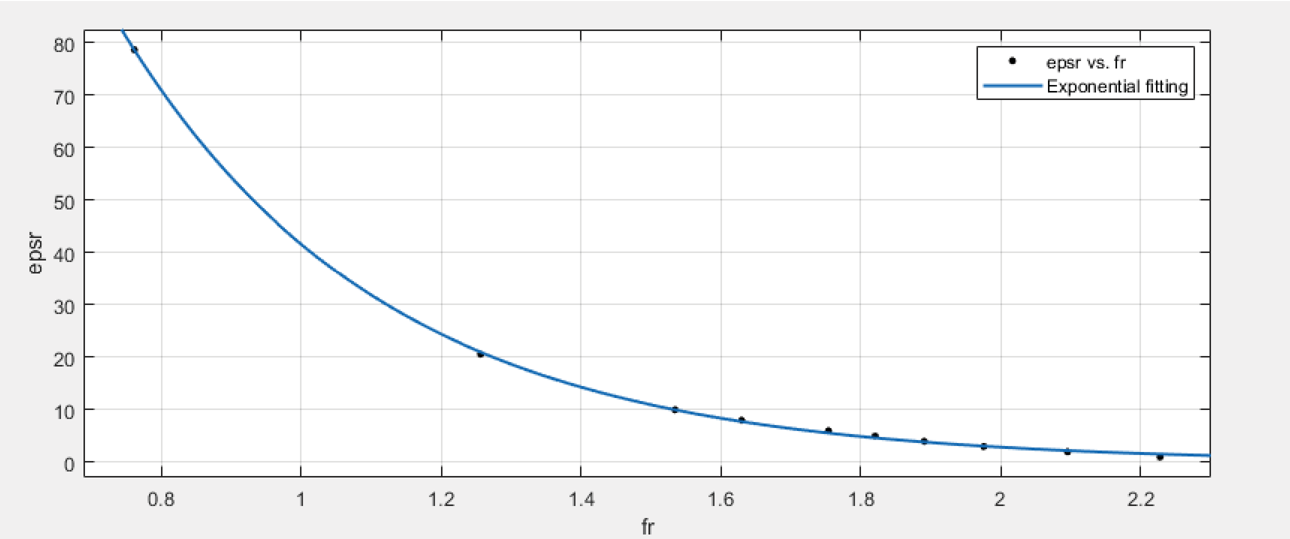


Fig. 5. Relation between the resonance frequency of the SRR and the sample permittivity, obtained through full-wave electromagnetic simulations and measurements: numerical results and measurements (black disks) and second order polynomial fitting (blue curve).

The same liquid has been measured with the Keysight High temperature probe [11] finding a value of $\varepsilon_{r,HTP}$ = 5.6 at the same frequency (see Fig. 6). Hence, results show an absolute error of 0.5 and a relative error of 9%. These obtained values are quite promising although a wider measurement campaign needs to be carried out to further validate the achieved results.

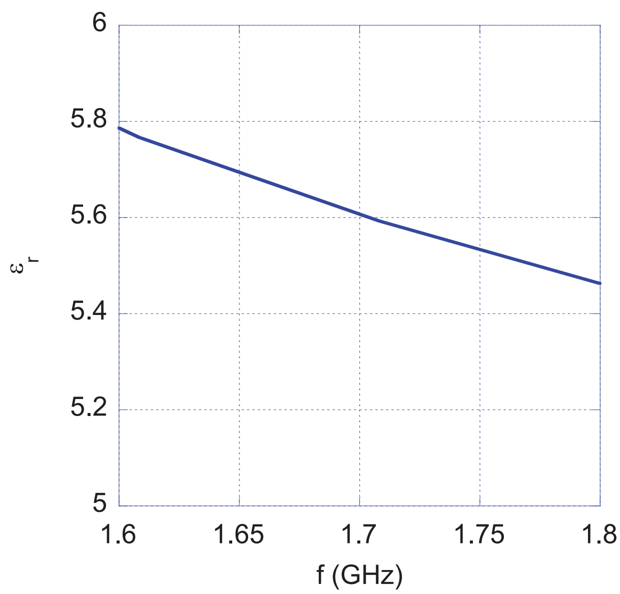


Fig. 6. Relative dielectric constant measured with the high temperature probe.

V. CONCLUSIONS

In this paper, a SRR has been presented, used for complex dielectric permittivity characterization of a material. Through full-wave electromagnetic simulations varying ε_r of the material under test and also by measurements on high pure grade liquids, it is possible to evaluate the relation between resonance frequency and the permittivity. By fitting the numerically obtained data, a 2-parameter exponential is obtained. Therefore, by performing f_r measurements in the presence of a material sample it is possible to evaluate its dielectric constant. Similar simulations have been performed, keeping the material ε_r constant and varying its loss tangent $tan\delta$, in order to relate the variation of the quality factor Q to the loss tangent of the sample. Results show that, by performing Q measurements in the presence of a material sample it is possible to evaluate its $tan\delta$, once its ε_r has been estimated.

For future developments, a measurement campaign will be conducted using a wide range of different materials. Moreover, materials with a dielectric constant between 20 and 80, obtained for example by water with a certain amount of sugar, will be measured in order to further verify the exponential model.

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