MEASUREMENTS OF PERMITTIVITY BASED IN MICROSTRIP TECHNOLOGY

MEDIDAS DE PERMITIVIDAD BASADAS EN TECNOLOGÍA DE MICROCINTA

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Abstract

The Complementary Split Ring Resonator (CSRR) geometry is used in conjunction with a microstrip line to create a device able to measure the electric permittivity of liquids. Simulations and measurements of the S-parameters are performed to correlate the resonance frequency and the permittivity of five common samples in order to calibrate the device. Once calibrated, we also provide an estimate of the permittivity of a solution of silver nanoparticles. These measurements are attractive given the limited the noninvasive techniques available for nanomaterial characterization and the lack of results at the microwave range. The results estimate the relative permittivity of the silver nanoparticles ϵ_r^{Ag-NPS} =101.46 ± 19.53.

Keywords: Microstrip Line, SRR, Nanocomposite

Resumen

El anillo resonador cortado complementario (CSRR) se utilizó en conjunto con una línea de microcinta para crear un dispositivo capaz de medir la permitividad de líquidos. La simulación y medida de los parámetros de dispersión fueron

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obtenidos para correlacionar la frecuencia de resonancia con la permitividad conocida de cinco muestras y así calibrar el dispositivo. Una vez calibrado, fue posible obtener un valor estimado de la permitividad de una solución con nanopartículas de plata. Estas medidas son interesantes dadas las limitadas técnicas no invasivas disponibles para la caracterización de nanomateriales y la falta de medidas en el rango de microondas. Los resultados estiman la permitividad de la solución de nanopartículas ϵ_r^{Ag-NPS} =101.46 ± 19.53.

Palabras clave: Línea de Microcinta, SRR, Nanocompuestos

Introduction

Measurements of the complex permittivity of gases, liquids, and solids at the microwave range, have been developed by using devices in which the electromagnetic fields are known,[1]. These microwave techniques employ a cavity resonator or waveguides which are completely filled in the dielectric region with the solution under test. In the case of 2D materials, many advances in microstrip based sensors and coplanar waveguides have been developed in order to have compact, lightweight and low-cost devices [2].

For instance, by using a microstrip line, its work frequency can be calculated by means of the phase shift $\phi = \sqrt{\epsilon_e}k_0 L$, where $k_0 = \frac{2\pi f}{c}$, c is the speed of light and ϵ_e is the effective dielectric constant of a homogeneous medium that replaces the air and the substrate of the microstrip. When the phase shift is half wavelength, the frequency is [3]

$$f = \frac{c}{2\sqrt{\epsilon_e}L}, \quad \epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12d/w}}. \qquad (1)$$

Thus, once the work frequency is measured, the effective permittivity can be computed and therefore we get the permittivity of the solution. However, the volume needed must be big enough

because the approximation of 1 requires all the space to be replaced by the solution. A different approach uses resonator techniques [4] in which the ground plane of the microstrip line is drilled with holes and the solution is placed on them, see Fig 1 (up). In this case, the measurement is calculated by means of an effective permittivity. In order to avoid this calculation, the use of resonators can be developed to estimate the permittivity of the solution under test only.

Baena et al.[5] analyzed the resonant response of the Complementary Split Ring Resonator, highlighting its small electrical size and good quality factor. A microstrip line with holes having this shape could perform a good response for permittivity measurements with less volume of solution under test and higher precision. Moreover, until now, no truly measurement of the permittivity of a solution of silver nanoparticles has been introduced. Due to the advantages of the CSRR geometry, it would be possible to measure the electrical response of nanocomposites in terms of it concentration and particle size. It will be shown that this characterization is useful to determine its use for electrical energy storage at the microwave range.

Theory

A metallic layer with shape of the CSRR etched on it can be used as a frequency filter. Its resonance frequency depends on the geometrical parameters and the permittivity of the substrate placed behind the metallic layer. Basically, when a electromagnetic signal excites the CSRR, the induced currents in the metallic layer can be modelled by means of an equivalent inductance and a capacitance. The inductance is calculated as $L_0 = 2\pi r_0 L_{\mathrm{pul}}$ with L_{pul} the inductance formed in the circular metallic strip between the rings. The capacitance is calculated as the one formed in a planar ring of average radius r_0, width c and relative permittivity of the solution [6], [5]. In comparison with a similar device developed by [4] made of circles instead of the CSRR, as shown in Fig. 1, the main difference is the form of introduce the resonance: The
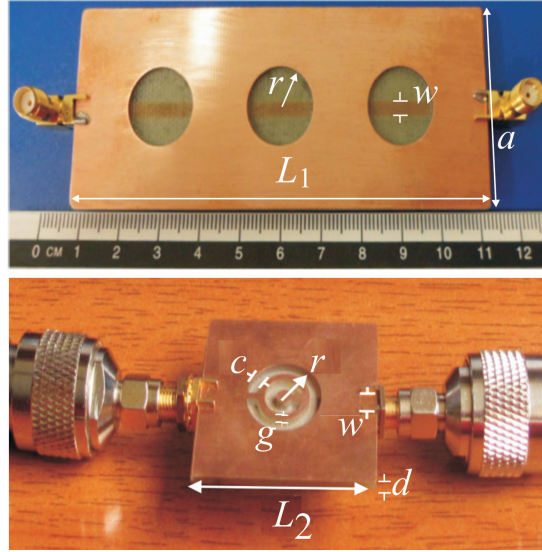
FIGURE 1. *a.) Proposal of [4] for permittivity measurements based in circular cavities. b.) Proposal based in CSRR geometry. The geometric parameters are $L_1 = 10cm$, $a = 36$ mm, $L_2 = 33$ mm , $w = 3$ mm, $r = 8$ mm, $c = 2$ mm, $g = 2mm$, $d = 1.57$ mm. The depth of the circular cavities and the slots is $h = 1$ mm.*

microstrip line with circles behave as a Fabry-Perot resonator such that the resonance appears when the length of the microstrip is half wavelength. On the other hand, the resonance of the CSRR appears because of its own excitation, caused by the magnetic field perpendicular to the metallic surface [6].

Numerical Simulation

In order to test the response of the device before the experiment, the $S-$parameters within the frequency range [0.5-2.5] GHz were calculated by full-wave simulation, by using *CST-Microwave Studio* Software. We got a relation between the resonance frequency and ϵ_r shown in Fig. 2, varying the relative permittivity of the filler and calculating the minimum in the $|S_{21}|$ parameter.

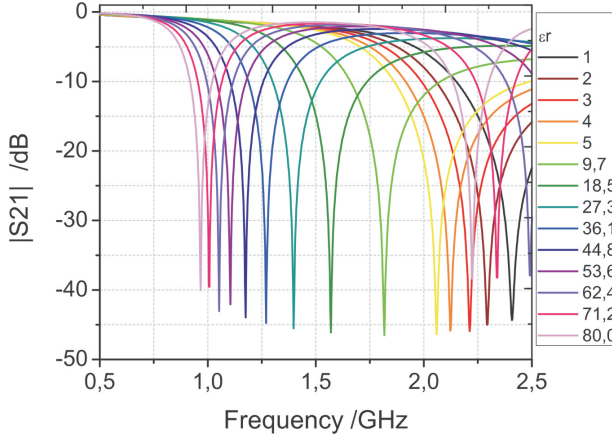The simulation shows that the minimum frequency shifts from 2.4

FIGURE 2.   *$|S_{21}|$ coefficient varying ϵ_r of the fill solution. The geometrical parameters of the device are described in Fig. 1.*

GHz to 0.8 GHz when the relative permittivity changes from 1-80. We are interested into simplify the simulation process considering that the CSRR resonates by its geometry only and that the electric field lines are more intense in the slits rather than the rest of the structure. To validate this approximation, we used a program that calculates the resonance of the CSRR by means of the equivalent circuit model and we compared it with the *CST-Microwave Studio* simulations, in which the substrate was replaced by the solvent under test.   The results shown in Table 1, shows that when $\epsilon_{solution} \approx \epsilon_{substrate}$, the resonance is higher than the resonance achieved when the microstrip line is introduced, because the electric field distribution changes.   Therefore, our approximation is no longer valid.

Experimental Development

The device for permittivity measurements was fabricated and analyzed with five commercial solvents.   For the fabrication process, we designed the geometrical parameters by using Eagle software.   The device was manufactured using basic processes of photolithography and etching on a substrate FR4 covered with a thin layer of copper. The slits were manufactured with a Bungard CCD/2 (Germany) computer-controlled milling machine using a 1

Material	ϵ_r	CSRR Model (GHz)	CST Simulation (GHz)
Air	1	3.84	3.26
Immersion Oil	3.2	3.05	2.54
FR4	4.3	2.84	2.34
Acetone	20.7	1.62	1.29
Ethyl Alcohol	24.3	1.51	1.20
Water	80.4	0.87	0.68

TABLE 1. Permittivity of solvents to be tested experimentally and its resonance frequency calculated by means of LC-circuit model of the CSRR geometry and *CST-Studio* numerical simulation. The relative permittivity of the commercial solvents is known. [7]

mm drill bit, drilling up to 1mm of depth.

Filling the slits with 200 μL of the solvents in Table 1, we verified the matching between the experimental and simulated curves, see Fig.4. The experimental curves present a ripple that prevent us from information about the dielectric losses. It is associated to a calibration process because the cables of the VNA mismatch the impedance of the microstrip. In order to avoid this ripple for further analysis of the quality factor, we propose the TRL Calibration Method, presented in [3].

The decreasing shape of the curve in Fig. 4 stablish two regions of interest, the response of the technique for solvents with low and high permittivity. Below ϵ_r =20 approximately, small variations in ϵ_r yields high variation of the frequency, so different oils could be accurately measured. On the other hand, at high ϵ_r like the solution of silver nanoparticles, even the smaller variation of frequency represent an important change in the permittivity. Therefore, the possibility of measuring this small differences allows us to characterize the nanocomposites in terms of any intrinsic characteristic, like the concentration or the particle size.

Equation 2 yields an estimation of the permittivity of a solution of silver nanoparticles ϵ_r^{Ag-NPS} =101.46 $\pm$ 19.53. Higher than the permittivity of water, this result is interesting because it means that these nanocomposites possesses strong response to electric field in
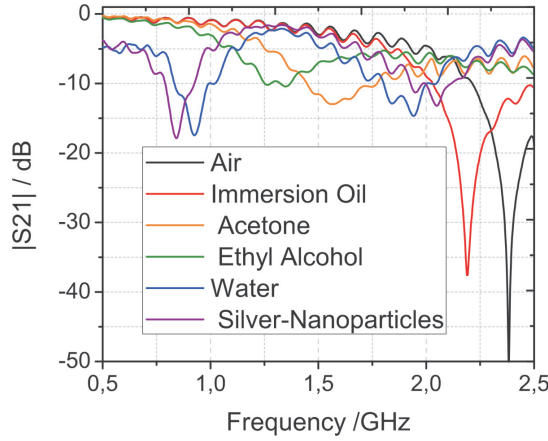
FIGURE 3. *Experimental measurements. (Up)The structure manufactured has the same geometrical parameters described in Fig. 2 (Down) S_{21} parameter when different solutions are placed in the sensor. The ripple is associated to the calibration process.*
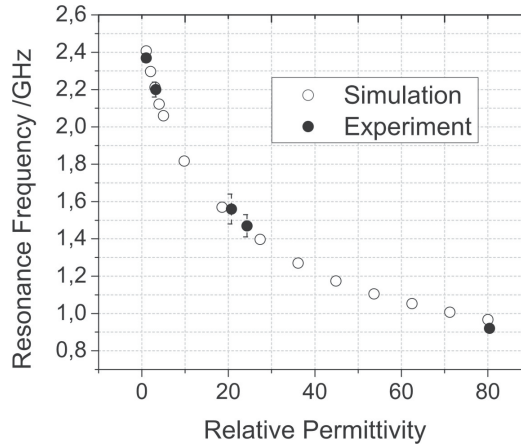

FIGURE 4. *Resonance Frequency vs. Relative Permittivity for the sensor in the experimental and computational form.*

the microwave range. Improvements of resonator techniques could be performed the analyze the response of the electromagnetic fields for solvents with a response that depends on the concentration of its components. Both improvements in design and fabrication could be performed by cutting the ground plane with other CSRR's related geometries, like spirals (CSR2) whose resonance has been previously

described in [6].

$$\epsilon_r = A \exp^{-f/B} + C$$
$$A = 916.37 \pm 78.54, \ B = 0.393 \pm 0.013, \ C = -0.121 \pm 0.74 \quad (2)$$
$$r^2 = 0.998$$

Conclusions

The resonant device based on the CSRR has been developed for measuring the permittivity of different solutions within the microwave range (0.5-2.5 GHz). In addition to the frequency selectivity, the ability of this device to provide an accurate measure and the advantage of size reduction in comparison with other devices has been presented. An analytical model has been used to simplify the computational simulation and it is demonstrated that these models are valid at high permittivity. The computational results compared with experimental results provide a good qualitative agreement, as well as a very good quantitative prediction of the permittivity of the solvent under test (i.e. for a solution of silver nanoparticles diluted in water with an estimated permittivity $\epsilon_r^{Ag-NPS} = 101.46 \pm 19.53$). The experimental results for the bandwidth are inaccurate due to a mismatch between the ports and the microstrip line, although they can be improved by performing a calibration process. Two regions in the curve of frequency and permittivity have been discussed, and the most relevant qualitative predictions rely at high permittivity, in which the nanocomposites respond. Improvements in design and fabrication, have been proposed.

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