MICROWAVE DIELECTRIC MEASUREMENT OF SOLIDS AND LIQUIDS OVER 1 TO 4 GHZ USING TRANSMISSION LINE TECHNIQUE AND COAXIAL CAVITY

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Abstract

Accurate microwave dielectric measurement of materials is necessary data for the design engineer during the development stage of electronic and communication components. Several techniques have been published in recent years for measurement of dielectric properties of materials at microwave frequencies. Each of these techniques has some limitations in terms of accuracy and frequency coverage. This paper presents a novel method based on coaxial transmission line for the measurements of dielectric properties of a wide range of materials in the frequency range of 1 GHz to 4 GHz. A combined analytical-numerical method for conversion of smoothed transmission scattering (S_{21}) parameters to complex permittivity is also presented. The measurement method was validated using air, low-loss solid and a high-loss liquid. The technique was then used to investigate the microwave absorption of an iron complexed and ligated to polyarylonitrile yarn powder.

1. Introduction

Measurement of the dielectric properties of material at microwave frequencies has generated a lot of interest in recent years [1]. This has come about with increasing miniaturisation of communication devices, for example mobile phones, and the need for more exacting electromagnetic compatibility (EMC) specifications; both are placing further constraints on the design engineer [2]. The increasing use of microwaves in other applications, for example chemical processing and medicine are also requiring knowledge of microwave properties of a wider range of materials.

Researchers have investigated different techniques for measuring the dielectric properties of materials at microwave frequencies [3]; these include transmission line, coaxial probe, free space, and resonant techniques [3]. Resonant technique is considered to be the most accurate for dielectric measurements [4] however, it is limited to measuring dielectric properties at a single frequency or for a very narrow frequency range [4].

The microwave frequency band of 1 to 4 GHz covers a large range of applications including mobile phone, communications, blue-tooth, search radar, microwave oven, chemical synthesis, wastewater treatment and medical applications [5, 6]. For investigating the dielectric properties of materials over such a wide frequency range only the coaxial transmission line and coaxial probe technique can be utilised [1]. However, the transmission line method is considered to be more accurate when compared to coaxial probe as it is subject to increased stray reactance. Coaxial probe has an average percentage uncertainty level between 1-5% compared to 1% with using a coaxial transmission line method [4].

Improvement of accuracy of transmission line technique has been investigated by many researches [7]. Curve fitting of measured scattering parameters before conversion to dielectric properties is an efficient and cost-effective way for improving the accuracy of measurements and reducing measurement noise [8].

Promising results have been reported in the literature [4, 8] after applying curve fitting to the measured scattering parameters [8]. In 2011, Zhao was able to reduce uncertainties in measurements of dielectric properties of a liquid from 4% to less than 0.25% using curve fitting method in the frequency range of 0.1 to 4 GHz [8].

In this work, to enhance the accuracy of microwave dielectric measurements, a coaxial transmission line design was used; a pre-conversion curve fitting was applied to measurements and the fitted curves were converted to dielectric properties using an improved analytical numerical conversion method. The dielectric properties of materials have been investigated over the frequency range of 1 to 4 GHz.

2. Methodology

A three segment cavity was designed as a 50-ohm coaxial transmission line covering the frequency range of 1 to 4 GHz. The total length of the cavity was 72 mm to enhance the measurement accuracy for low-loss materials (e.g. solids). The cavity was made of brass as it has good corrosion resistance properties and high machinability rating. To enable realization of a short cavity length a plug to jack precision N-type connectors were used (Figure 1). This design also enabled the interconnection between the jack (of cavity) and plug (of adapter) to be screwed into the cavity forming a semi hermitic seal, which was found to be sufficiently good for laboratory measurements. The three segment design also reduced the electrical discontinuities by eliminating the bead sections found in five segment designs.

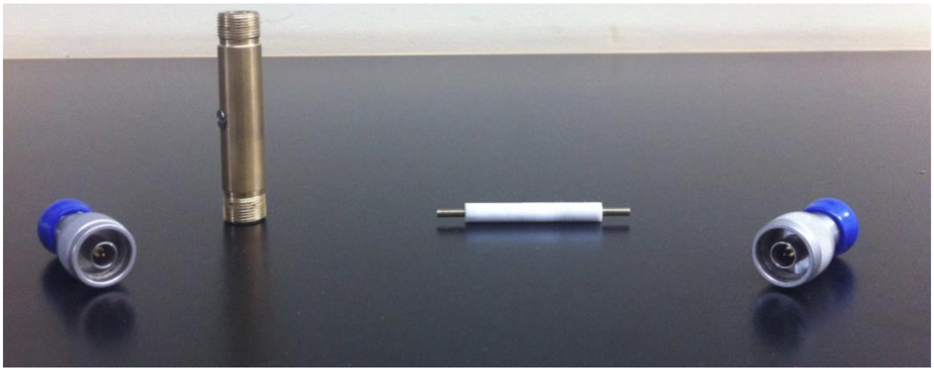

Figure 1 Coaxial Cavity design

The measurement methodology was based on implementation of transmission line technique using the self-hermetic designed coaxial cavity. This technique was chosen as it enabled direct conversion from scattering parameters (S-parameters) to complex permittivity, ease of applying s-parameter correction models [8,9] and could be used for measuring solids, liquids and powders.

To validate the coaxial cavity and measurement technique three materials air, water and PTFE were measured over the frequency range of 1 to 4 GHz. The s-parameters of the cavity/material were measured using an automatic vector network analyzer (Rhode & Schwarz ZVL6 (9 kHz to 6 GHz). The measured scattering parameters, before conversion to relative permittivity, were smoothed using MATLAB curve fitting routine to average out the measurement noise enabling the extraction of the complex permittivity of the material over the frequency range (Figure 2).

The extracted permittivity values were compared with known permittivity values for air, water and PTFE from the National Institute of Standards and Technology [10] over the measured frequency range (1 to 4 GHz). This ensured that the measurement technique could be used to extract the complex permittivity from a range of materials including gas, liquid and solid.

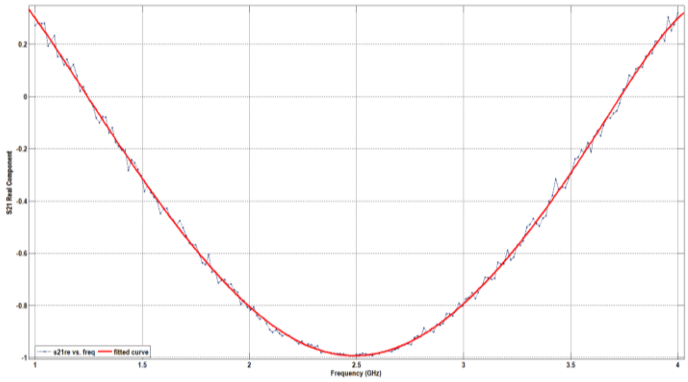

Figure 2 Curve fitting of real component of transmission scattering parameter (S_{21}); blue line represents the original measurement and red line represents the fitted curve

3. Combined Analytical-Numerical Conversion Method

The transmission scattering parameter (S_{21}) can be expressed in terms of transmission and reflections coefficients T and Γ respectively [10] and is given as equation (1), where R_1, R_2 are reference plane transformation of S-parameters to Port 1 and Port 2 of network analyzer; respectively.

$$S_{21} = R_1 R_2 \left[\frac{\Gamma(1-T^2)}{1-\Gamma^2 T^2} \right] \tag{1}$$

$$T = e^{-\gamma L} \tag{2}$$

$$\Gamma = \frac{(\mu/\gamma)-(\mu_0/\gamma_0)}{(\mu/\gamma)+(\mu_0/\gamma_0)} \tag{3}$$

The respective transmission T and reflection coefficient Γ are given by equations (2) and (3) where. L is the length of sample; γ_0, γ are propagation constant through air and the material under test and μ_0, μ are absolute permeability of air and the material under test.

Solving equations (1)-(3) determines the complex permittivity and permeability of material from the measured transmission scattering parameter (S_{21}). In this work the materials under test were non-magnetic and therefore the permeability (μ) was assumed to be equal to one giving dependency only on the vacuum permeability (μ_0). The real part of relative permittivity ($\varepsilon_r^{'}$) was obtained directly from the phase delay of transmission scattering parameter (ϕ_{21}) and wavelength of free-space (λ_0) as follows [11]:

$$\varepsilon_r^{'} = \frac{(\phi_{21}\lambda_0)}{(2\pi L)} \tag{4}$$

From equations (1)-(3), the transmission scattering parameter (S_{21}) can be expressed in terms of propagation constant (γ) and sample length (L) and for nonmagnetic low conducting materials, $\gamma_0 = j(\omega/c)$ and $\gamma = \gamma_0\sqrt{\varepsilon_r}$ [12]; thus, transmission scattering parameter (S_{21}) can be expressed as a function of relative permittivity [12]:

$$S_{21} = |S_{21}| e^{j\phi_{21}} = \frac{-4\left(\omega^2/c^2\right)e^{-j(\omega/c)\sqrt{\varepsilon_r}L}}{\left(\left(j(\omega/c)\sqrt{\varepsilon_r}\right)+\left(j(\omega/c)\right)\right)^2 - \left(\left(j(\omega/c)\sqrt{\varepsilon_r}\right)-\left(j(\omega/c)\right)\right)^2 e^{-2j(\omega/c)\sqrt{\varepsilon_r}L}} \tag{5}$$

From equations (4) and (5), relation between magnitude of transmission scattering parameter ($|S_{21}|$) and imaginary part of relative permittivity ($\varepsilon_r^{''}$) was extracted as follows [12]:

$$|S_{21}| = \sqrt{16B(X^2+\rho^2)/\Psi} \tag{6}$$

$$X = \sqrt{\varepsilon_r^{'}} \tag{7}$$

$$\rho = \frac{0.5\varepsilon_r^{''}}{\sqrt{\varepsilon_r^{'}}} \tag{8}$$

Where $B(\rho)$ and $\Psi(\rho)$ are functions of the newly defined variable $\rho(\varepsilon_r^{'}, \varepsilon_r^{''}, f)$.

The Newton Raphson Iterative Method was used to iterate a solution to equation (6) to determine the variable ρ over the frequency range as follows:

$$F(\rho) = 16e^{-\frac{4\pi\rho L}{\lambda_0}}\left(X^2+\rho^2\right) - \left(|S_{21}|^2 * \left(P+Y-Z\right)\right) \tag{9}$$

$$P = \left(e^{-\frac{8\pi\rho L}{\lambda_0}} * \left((X-1)^2+\rho^2\right)^2\right) + \left(\left((X+1)^2+\rho^2\right)^2\right) \tag{10}$$

$$Y = \left(8\rho e^{-\frac{4\pi\rho L}{\lambda_0}} * \left(X^2+\rho^2-1\right)\sin\left(\frac{4\pi XL}{\lambda_0}\right)\right) \tag{11}$$

$$Z = \left(2e^{-\frac{4\pi\rho L}{\lambda_0}}\left(\left(X^2+\rho^2-1\right)^2-4\rho^2\right)\cos\left(\frac{4\pi XL}{\lambda_0}\right)\right) \tag{12}$$

By substituting in equation (8), the imaginary part of relative permittivity was determined at all frequency points.

4. Results and Discussion

The technique was validated by measuring the dielectric constant of known materials air, water (high-loss dielectric material) and PTFE (low-loss dielectric material) in the frequency range of 1 to 4 GHz. The real part of relative permittivity was obtained analytically using equation 4 while the imaginary of permittivity was obtained by iteration using equations 9-12.

Measurement of dielectric properties of air using the developed method gave comparable results to other publications [10]. The average uncertainty when compared to published data from National Institute of Standards and Technology [10] was 0.25% for the real part of relative permittivity and 0.5% for the imaginary part (Figure 3).

For the PTFE (i.e. low-loss solid material), the dielectric measurements indicated a nearly constant relative permittivity of PTFE over the frequency range of 1 to 4 GHz as expected for low-loss dielectric material [13]. The measurement uncertainty when compared to published data from National Institute of Standards and Technology [10] was of the order of 1.19% over the frequency range of 1 to 4GHz (Figure 3).

The method was also used to measure the dielectric properties of a high-loss liquid (i.e. water). The coaxial transmission line cavity was placed in a vertical position during RF measurements to ensure homogeneous distribution of water inside the cavity. To minimize measurement error the cavity was filled with water to depth of 70mm and the air space was taken into account during the measurement (equation 1).

Figure 3c shows that multiple resonances occur inside the cavity, which are due to the high loss material. At frequencies above 2.5 GHz, the resonances are smaller in magnitude thereby decreasing average uncertainty level when compared to published measurements made by National Institute of Standards and Technology [10] (Figure 3).

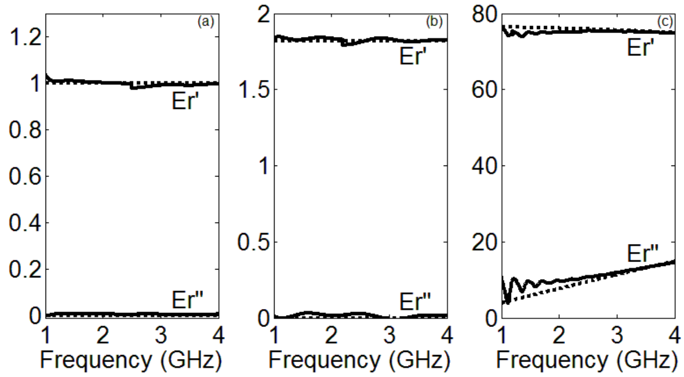

Figure 3 Complex relative permittivity of (a) Air (b) Teflon and (c) Water; solid line represents measurements and dotted line represents figures from National Institute of Standards and Technology [10]

The above technique has been used to characterise a complex litigated to polyarylonitrile yarn powder in the microwave frequency band of 1 to 4 GHz. This material can be used as a chemical catalyst in an application using microwave heating. Therefore, it was necessary to know if the material absorbed microwave radiation particularly at 2.45 GHz but also outside of the allocated commercial band of 2.45 GHz.

The average relative permittivity of the iron complex litigated polyarylonitrile yarn was found to be 2.5-j0.14 over the frequency range of 1 to 4 GHz. The small imaginary part indicates little microwave absorption of the iron complex yarn. The performance of this yarn compared with other iron compounds is shown in Table 1.

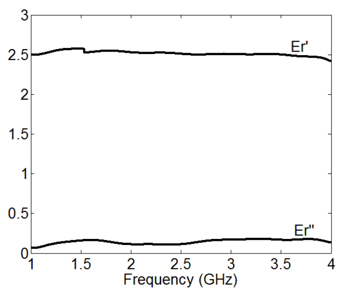

Figure 4 Complex relative permittivity of the iron complex litigated polyarylonitrile yarn powder

Iron powder compound	Average Relative Permittivity	Frequency Range	Measurement Method
Iron complex litigated polyarylonitrile yarn powder	2.5-j0.14	1-4 GHz	Coaxial transmission line
Sr-Hexaferrite powder ($SrFe_{12}O_{19}$)[14]	2.65-j0.05 [14]	8-40 GHz	Waveguide
Sr-Hexaferrite powder ($SrFe_{12}O_{19}$)[15]	2.580-j0.06 [15]	8-26.5 GHz	Waveguide
Sr-Hexaferrite powder ($SrFe_{12}O_{19}$)[15]	2.557-j0.06 [15]	8-26.5 GHz	Resonant
Ba-Hexaferrite powder ($BaFe_{12}O_{19}$)[14]	2.6-j0.05 [14]	8-40 GHz	Waveguide
Ba-Hexaferrite powder ($BaFe_{12}O_{19}$)[15]	2.583-j0.07 [15]	8-26.5 GHz	Waveguide
Ba-Hexaferrite powder ($BaFe_{12}O_{19}$)[15]	2.559-j0.07 [15]	8-26.5 GHz	Resonant

Table 1 Values of complex relative permittivity of iron powder compounds

5. Conclusion

The coaxial transmission line method was used to make dielectric measurements in the frequency range of 1 to 4 GHz on different types of material (i.e. air, liquid, solid and powder). The measured transmission s-parameters were smoothed to minimize measurement uncertainties and a novel method used to extract the real and imaginary part of the permittivity of the material. The method enabled measurement of air, water, and PTFE which were compared to measurements by National Institute of Standards and Technology and found to be within 1% of those measurements [10].

The developed method was used to measure the dielectric properties for the first time of a complex iron litigated to a polyarylonitrile yarn, which will be used in a chemical process using microwave energy. The measurements indicated almost constant dielectric properties over the 1 to 4GHz range, and an average complex dielectric of 2.5-j0.14 was allocated to the material.

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