A new method for the precise multiband microwave dielectric measurement using stepped impedance stub

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Abstract

This article presents a new method of wideband dielectric measurement at microwave frequencies. This method can be used to determine the complex dielectric properties of solid and semisolid materials from 0.9GHz to 4.5GHz, including the ISM bands of 915 MHz and 2450MHz. The new method is based on the scattering parameter measurement of a stepped impedance open circuited micro-strip stub, partly loaded with dielectric test material. Current microwave wideband spectroscopy techniques generally measure dielectric materials over a wide range of frequencies but their accuracy is limited. In contrast, narrowband techniques generally measure dielectric properties to a high accuracy but only at a single frequency. This new technique is capable of measuring dielectric properties over a wide range of frequencies to a high accuracy. The technique has been verified by the empirical characterisation of the dielectric properties of Teflon and Duroid 5880 materials. Empirical results were in good agreement with values in the manufacturer's data sheets. The complex permittivity data will be useful for further microwave processing of the materials.

Keywords:
Dielectric properties, loss factor, Microwave dielectric spectroscopy, wideband dielectric characterization

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1. Introduction

Microwave heating/ processing is extensively used in the food, chemical and pharmaceutical industries [1-5]. Whether a material is poor or good at absorbing microwave radiation obviously depends on its dielectric properties[6]. Microwave dielectric spectroscopy is therefore a useful tool to determine whether chemical and biological samples would be suitable for microwave processing.

There are two major classifications of the techniques used to measure the complex permittivity of materials using microwaves. These are (i) resonant (resonator and resonator perturbation methods) and (ii) non-resonant (reflection/transmission methods) [7]. Usually, resonant techniques are used to characterize materials with low dielectric loss factors over a narrow range of frequencies. Wideband frequency techniques typically use reflection or transmission methods to characterise materials with higher loss factors over a wide band of frequencies [8]. However their accuracy is limited [7]. A historic review of dielectric measurement techniques is presented in [9].

In this paper, an apparatus and a method to measure the dielectric properties of solid or powder materials over a wide band of frequencies is presented. The new technique has the merits of both high accuracy and wide bandwidth and, in particular, it allows the measurement of low loss factor materials with high accuracy over a wide bandwidth. The resonant technique is used to perturb the resonant frequency of a stepped impedance open circuit stub which is partially loaded with the powdered test material. A step change in the width of the open circuit stub is introduced to bring its' higher order mode frequency near to the 2450 MHz ISM band. Upon loading the sample, the relative shift in the bandstop resonance and dielectric absorption determine the complex permittivity of the material.

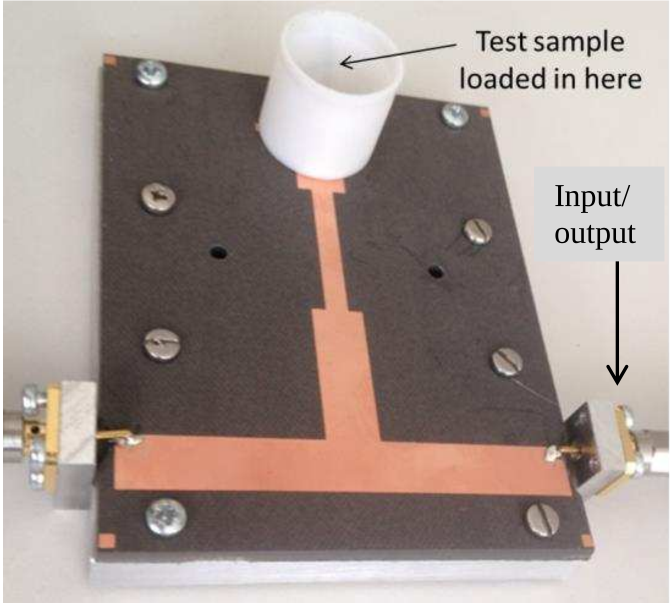

Fig.1 Microstrip dielectric measurement hardware

2. Stepped impedance resonator

A microwave microstrip bandstop filter can be designed using an open circuited transmission line coupled from a 50 Ω through line as shown in fig1. The stub introduces a bandstop resonance at a frequency where it's electrical length (θ) becomes a quarter of wavelength. This happens due to out of phase combination of signals coming from the input port and their delayed version travelled through open circuit stub. The open circuited stub re-resonates at the frequency where its total electrical length is three quarters of the wavelength. This higher order mode frequency can be changed by introducing the step in the width of the microstrip stub as shown in Fig2. This changes the impedance (Z) of the transmission line and hence the ratio of fundamental to higher order mode frequency as explained in section 3. Fig.2 shows the basic structure of a stepped impedance transmission line.

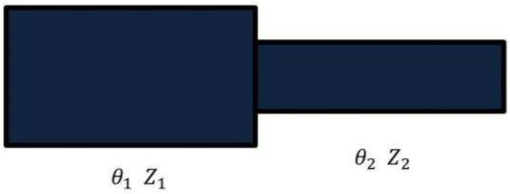

Fig.2 Stepped Impedance microstrip stub

3. Stepped impedance resonator theory

The Transfer matrix of a unit microstrip transmission line can be written as [10]

$$[T] = \begin{bmatrix} cos\theta & jZsin\theta \\ jYsin\theta & cos\theta \end{bmatrix} \quad (1)$$

Where θ is the electrical length (one quarter of wavelength) of the unit transmission line element and it can be related to its physical length (l) as

$$\theta = \beta l \quad (2)$$

Where β is the propagation constant of the line. For complex frequencies transfer matrix becomes[10]

$$[T] = \begin{bmatrix} \cosh(ap) & Z\sinh(ap) \\ Y\sinh(ap) & \cosh(ap) \end{bmatrix}$$

$$= \frac{1}{(1-t^2)^{\frac{1}{2}}} \begin{bmatrix} 1 & Zt \\ Yt & 1 \end{bmatrix} \quad (3)$$

Where

$$t = \tanh(ap) \quad (4)$$

Thus, the transfer matrix of a stepped impedance line with characteristic impedance of Z_1 and Z_2 would be

$$[T] = \frac{1}{1-t^2} \begin{bmatrix} 1 & Z_1 t \\ Y_1 t & 1 \end{bmatrix} \begin{bmatrix} 1 & Z_2 t \\ Y_2 t & 1 \end{bmatrix}$$

$$= \frac{1}{1-t^2} \begin{bmatrix} 1+t^2 Z_1 Y_2 & (Z_1+Z_2)t \\ (Y_1+Y_2)t & 1+t^2 Z_2 Y_1 \end{bmatrix}$$

$$= \frac{1}{1-t^2} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad (5)$$

The input impedance of the stepped impedance line can be written as

$$Z_{in} = \left[\frac{AZ_L + B}{CZ_L + D}\right] \quad (6)$$

Where

$$Z_L = \infty \quad (7)$$

$$Z_{in} = \frac{(1+t^2 Z_1 Y_2)}{(Y_1+Y_2)t} \quad (8)$$

By putting $Y = \frac{1}{Z}$, we get

$$Z_{in} = \frac{1+t^2 \frac{Z1}{Z_2}}{(\frac{1}{Z_1}+\frac{1}{Z_2})t} \quad (9)$$

The stepped impedance resonator resonates when its input impedance becomes zero i.e. $Z_{in} = 0$, therefore,

$$1 + t^2 \frac{Z1}{Z_2} = 0 \quad (10)$$

By putting $t = jtan\theta$ for real frequencies

$$1 + (jtan\theta)^2 \frac{Z1}{Z_2} = 0 \quad (11)$$

$$=> \tan^2\theta = \frac{Z_2}{Z_1} \quad (12)$$

$$=> \theta = \tan^{-1}\sqrt{\frac{Z_2}{Z_1}} \quad (13)$$

The spurious or higher order mode resonant frequencies can be controlled by varying the impedance ratio of the transmission line resonator [11]. Thus, to keep the fundamental resonance frequency at the ISM band of 915MHz and to bring the first higher order mode near to ISM band of 2450 MHz, impedance step is introduced in the transmission line section. Stepped impedance resonators are commonly used in microwave filters to improve their performance by moving higher order mode frequencies up in frequency [12, 13]. The width of the microstrip stub is increased at the open end to increase the contact area with the loaded sample (see Fig.1). This will increase the capacitance at the end and its effect can be adjusted by changing the electrical length of the main section of the stub.

When dielectric sample is loaded in the sample holder the fringing capacitance at the open end of the stub is increased by a factor of ε_{sample} , therefore, the effective electrical length (l_{e0}) of the stub becomes [14]

$$l_{e0} = \frac{cZ_0 C_f}{\sqrt{\varepsilon_{sample}}\sqrt{\epsilon_{eff}}} \quad (14)$$

Where c, Z_0 and C_f represent speed of light, characteristic impedance of the stub and fringing capacitance at the open end of the stub, respectively. ε_{eff} is the effective dielectric constant of a homogenous medium which replaces the dielectric and air region of the microstrip. The open ended microstrip stub is coupled from a two port through transmission line and the scattering parameters of the two port networks are measured. The scattering parameters relate the voltage waves incident on the microwave network ports to those reflected from the ports [15].

4. Fabrication details

The stepped impedance microstrip stub is designed on Duriod 5870 substrate with $\varepsilon_r = 2.33$, $tan\delta = 0.0009$ and a thickness (d) of 3.18mm. A 10mm thick aluminium plate is used for proper grounding. The sample holder is made of Teflon material with dielectric properties of $\varepsilon_r = 2.1$ and $tan\delta = 0.0002$. The sample holder has a wall thickness of 1mm, internal diameter of 20mm and a height of 20mmm. For a 50Ω transmission line, the width (W) of the copper trace is calculated to be 9.1 mm using following relation[15].

$$W = \frac{2d}{\pi}[B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}] \quad for \quad \frac{W}{d} \geq 2 \qquad (15)$$

Where

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \qquad (16)$$

And

$$B = \frac{377\pi}{2z_0\sqrt{\varepsilon_r}} \qquad (17)$$

Where ε_r is the dielectric constant of the substrate material, W is the width of the conductor and d is the height of the substrate. The stepped width stub has widths of 9.1mm and 4mm with physical lengths of 27.35mm. The wide width end section has a physical length of 3 mm. SMA connectors are soldered at both ends of the main transmission line to connect it with the Network Analyzer using standard cables.

5. Measurement procedure

The process of determining dielectric properties of the material consists of two steps; (i) measure the scattering parameters of the transmission line with the test material loaded into the holder. (ii) Simulate the exact setup in HFSS and replicate the measured scattering parameters.

HFSS is commercially available software for finite element electromagnetic field simulations and is known to give very reliable results. The sample material is replaced in the software by a homogeneous material with an arbitrary dielectric constant and loss tangent. Iterative simulations are carried out until simulated and measured S-parameters come in a close agreement. Fig 3 represents the flow diagram of the process.

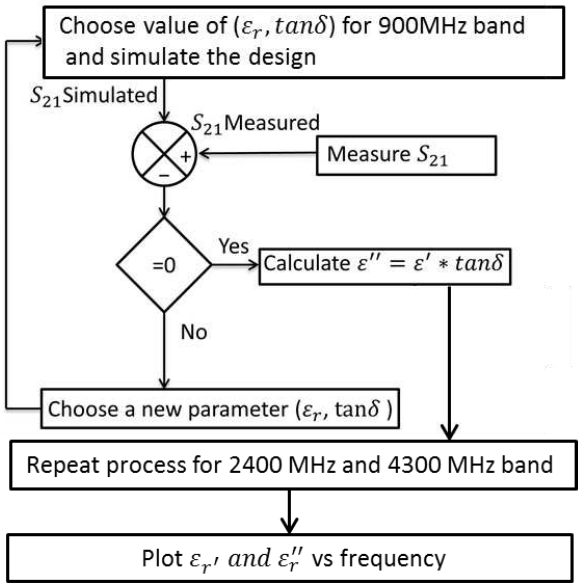

Fig. 3 Dielectric characterization flow diagram

An E5071 Network Analyzer from Keysight Technologies is used to measure the scattering parameters of the circuit. The scattering parameters of the open ended microstrip stub without the sample holder are measured and replicated by HFSS simulation over a broad bandwidth. Then, the Teflon sample holder is fixed at the open end of the stub and the setup is again measured and simulated for scattering parameters over a broad bandwidth. The bandstop resonance shifts down in frequency when the Teflon holder is fixed at the end of the open stub due to dielectric loading.

Finally, the sample is loaded in the sample holder and the S-parameters are measured over a broad bandwidth. The sample will introduce a further downshift in frequency in each of three bandstop frequency dips of the measured S-parameter response. Next, narrowband simulations of the setup are carried out to match the frequency shift introduced in the measured S-parameters due to the sample loading at each of the three frequency bands. The dielectric sample is replaced with homogeneous materials with three different arbitrary dielectric constants and loss tangents to match the frequency shift of each of the bandstop resonance at 900 MHz, 2450 MHz and 4300 MHz band. Finally, the complex part of the dielectric permittivity is calculated from the real part and loss factor information.

6. Results

The complex permittivity of the Teflon and Duriod 5880 samples has been determined using this apparatus. Fig.4 shows the measurement setup where the circuit is connected to the Network Analyzer using SMA connectors. The loading of samples down shifts the resonance as shown in Fig.5. The higher the dielectric constant of the material, the bigger is the corresponding frequency downshift. The measured scattering parameters are reproduced using the HFSS simulation tool. Both dielectric constant and loss tangent variables are optimized in an iterative manner until the simulated and measured S-parameters come in close agreement.

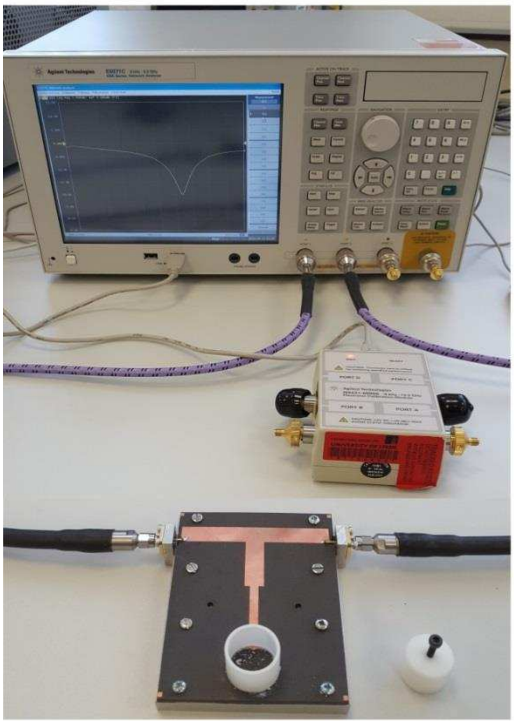

Fig.4 Measurement setup (circuit connected to Network Analyzer to measure S-parameters

Table 1 presents the comparison of the measured dielectric permittivity of the samples vs manufacturer's data sheet values. It is evident that the measured results are in close agreement with the manufacturer data sheets. These measurements were carried out at an ambient room temperature of 25c.

Table1: Measured dielectric properties vs data sheet

Material	Frequency (MHz)	Dielectric constant		Dissipation (Loss) factor	
		Measured	Data sheet	Measured	Data sheet
Teflon	900	2.1	2.1±0.02	0.0002	0.0002
	2450	2.1		0.0003	
	4300	2.1		0.0004	
Duriod 5880	900	2.2	2.2±0.02	0.0009	0.0009
	2450	2.2		0.0009	
	4300	2.2		0.0010	

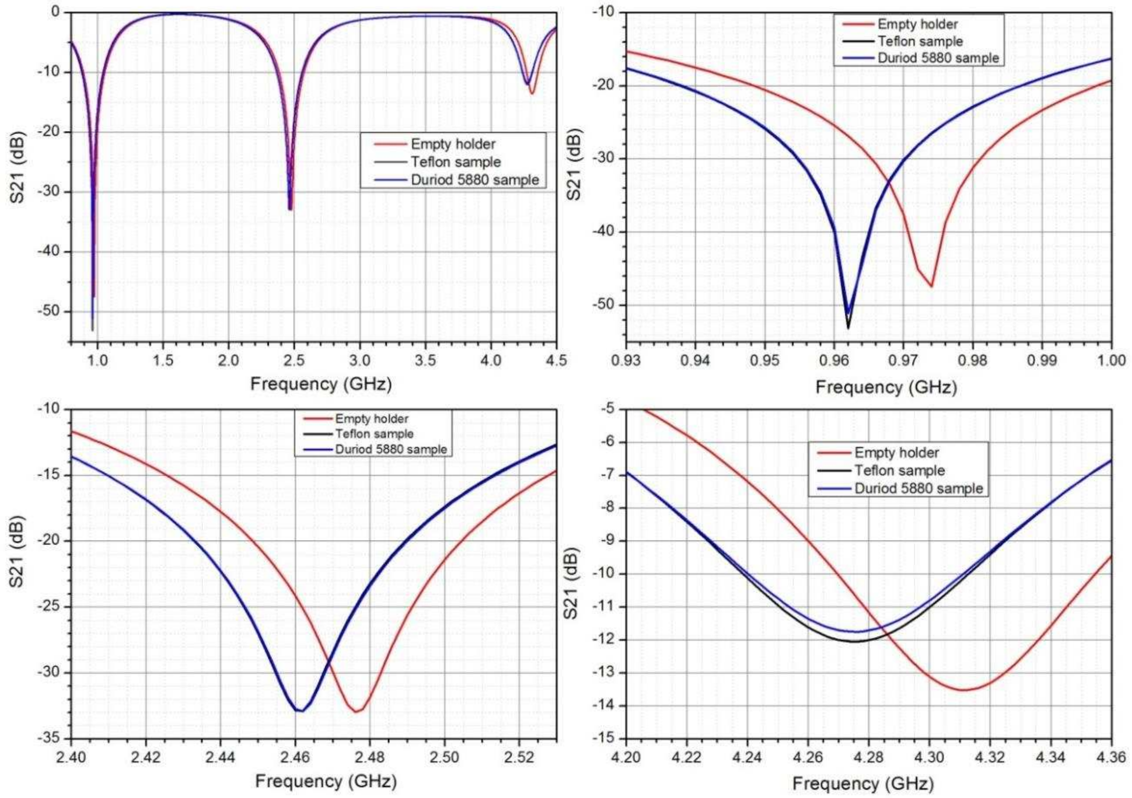

Fig. 5 Wideband and narrowband measured S-parameters of circuit with empty holder, Teflon and duriod samples

7. Conclusion

In this paper, a new apparatus and technique to accurately characterize the complex permittivity of solid or semi-solid materials over multiple frequency bands is introduced. The new technique has merits of both high accuracy to measure low loss materials and broadband frequency sweep. The validity of method is proven by measuring well known Teflon and Duriod low loss dielectric material samples.

8. Acknowledgement

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9. References

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