

Development of a new prototype system for measuring the permittivity of dielectric materials

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Abstract: A simple prototype for measuring the properties of dielectric materials is introduced in this Letter. A homogeneous dielectric sample placed in a field produced by a nearby antenna will affect the input impedance of the antenna. The permittivity and the loss of the dielectric sample can then be determined from the change of the input impedance of the antenna. The prototype has been validated by experiments.

1 Introduction

There are many ways to measure the dielectric properties. Generally speaking, the methods for measuring the dielectric constants can be classified into two categories: non-resonant methods [1] and resonant methods [2]. Reflection method and transmission/reflection method are two main non-resonant methods, in terms of which the permittivity of dielectric material are deduced from the reflection from the sample and the transmission through the sample. Resonant methods usually include the resonator method and the resonant-perturbation method. Based on the resonant frequency and quality factor Q , the permittivity of the dielectric sample can be determined by some calculations. Resonant methods generally have higher accuracies than non-resonant methods and are good for low-loss materials.

This Letter studies the design and implementation of a new prototype system for measuring the dielectric properties. Through measuring the input impedances of the antenna without and with the sample, the permittivity and the loss of the dielectric sample can be determined by the proposed system.

2 Theory and design of the system

When the medium parameters ϵ and σ in a homogeneous region V_p (the region occupied by the dielectric sample) illuminated by an antenna are changed to ϵ' and σ' , the electric field inside the sample will be changed from E to E' . The input impedance of the antenna then changes from Z to Z' . Using the frequency domain reciprocity theorem and compensation theorem, we obtain [3, 4]

$$Z' - Z = \frac{1}{I^2} \int_{V_p} \{ -[\sigma' - \sigma + j\omega(\epsilon' - \epsilon)]E'E \} dV \quad (1)$$

where I denotes the terminal current at the reference plane of the antenna. The field E is assumed to be known. For small samples, the field E' can be determined from E by quasi-static methods [3, 5]. If the change in permittivity has negligible effect on the field, the field E' can be replaced by E through an algorithm based on perturbation [3]. The relative permittivity and the loss tangent can be found from (2) and (3) listed below

$$\epsilon_r = \frac{1}{\omega\epsilon_0} \text{Im} \frac{I^2(Z - Z')}{\int_{V_p} E E' dV} + 1 \quad (2)$$

$$\tan \delta = \frac{1}{\omega\epsilon_0\epsilon_r} \text{Re} \frac{I^2(Z - Z')}{\int_{V_p} E E' dV} \quad (3)$$

The block diagram of the proposed prototype system is sketched in Fig. 1 and the photograph of the prototype is shown in Fig. 2. The whole system can be divided into three main parts: the antenna part, the radio frequency (RF) module and data processing module. The antenna produces an incident field on the dielectric sample and the existence of the dielectric sample will change the input impedance of the antenna. The RF module is used to separate the incident wave and the reflected wave from the antenna. The magnitude and phase of the reflected wave are converted to direct-current (DC) voltage as the output signals of the RF module, and they can be readily measured by the data processing module. The directional coupler is used to separate the incident wave and the reflected wave in antenna port. One frequency mixer detects the phase difference of the incident wave and the reflected wave and the other deliver the magnitude of the reflected wave. The low-pass filter is used to filter the high-frequency component from the mixer. The outputs of magnitude and phase are all DC voltage. In the data processing module, an arm board is used to do data processing. The input DC voltages of magnitude and phase from the preceding circuit are amplified for the analog-to-digital converters (ADCs). The fields

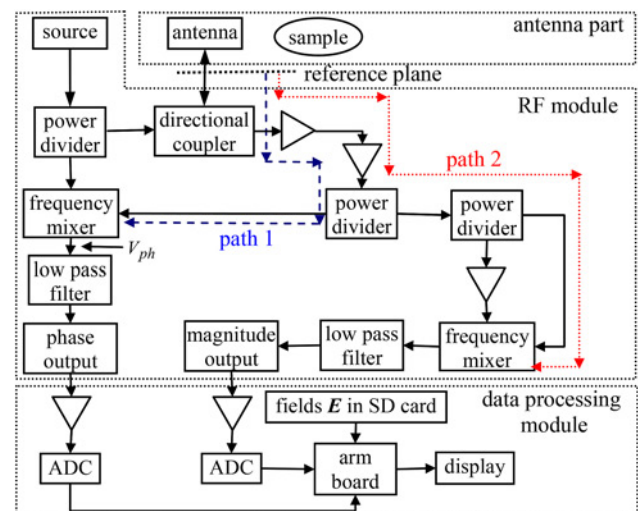


Fig. 1 Block diagram of the measurement system

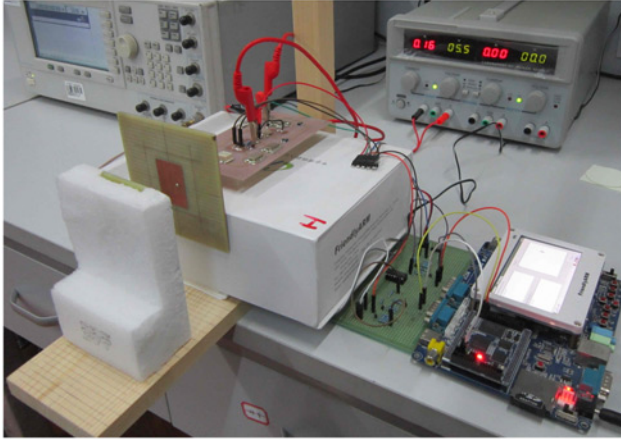


Fig. 2 Photograph of the measurement system

E are saved into the secure digital card in the arm board. After processing, the permittivity and the loss tangent of the dielectric sample are displayed on the liquid crystal display screen.

The system must be calibrated before it can be used to measure the dielectric properties. This process essentially is the determination of the path losses and phase delays in the two paths shown in Fig. 1. We use path 1 as an example to illustrate the calibration process. In the antenna input reference plane (the dotted line in Fig. 1), the magnitudes and the phases of the input voltage V_{in} and reflected voltage V_{ref} may be expressed as $V_{in} = ae^{j\alpha}$ and $V_{ref} = be^{j\beta}$, where a and b denote the magnitudes; α and β are the phases. The reflection coefficient at the antenna input S_{11} can be written as

$$S_{11} = \frac{V_{ref}}{V_{in}} = \frac{be^{j\beta}}{ae^{j\alpha}} = \frac{be^{j(\beta-\alpha)}}{a} \quad (4)$$

when the dielectric sample is not present, all the parameters in (4) are known quantities.

If the frequencies of the two inputs of the frequency mixer are the same, the down-conversion output becomes the DC voltage. The output will change along with the phase difference $\Delta\theta$ of the two inputs as shown below

$$V_{ph} = A \cos(\Delta\theta) \quad (5)$$

where A is the magnitude of reflected wave at the output of the mixer and $\Delta\theta$ is the phase difference of the two inputs. As the output of the frequency mixer, V_{ph} is a known quantity in the process of calibration. Let the loss of path 1 in Fig. 2 be denoted by L_1 . Then we have

$$|S_{11}|(\text{dB}) + L_1(\text{dB}) = A(\text{dB}) \quad (6)$$

Fig. 3 shows the phase diagram of two paths in the layout of the RF module. The phase change from the antenna input to the RF input of the frequency mixer along path 1 is $\theta_0 + 90^\circ$, where $\theta_0 = \alpha_2 - \alpha_1$. Here α_1 stands for the phase difference between antenna input and the source output (see Fig. 3), α_2 is the phase difference between the local oscillator input of the mixer and the output of the source. Thus the phase difference $\Delta\theta$ may be determined as follows

$$\Delta\theta = \beta + \theta_0 + 90^\circ - (\alpha - \alpha_1 + \alpha_2) = \beta - \alpha + 90^\circ \quad (7)$$

Finally, the loss L_1 in path 1 can be derived from (4) to (7).

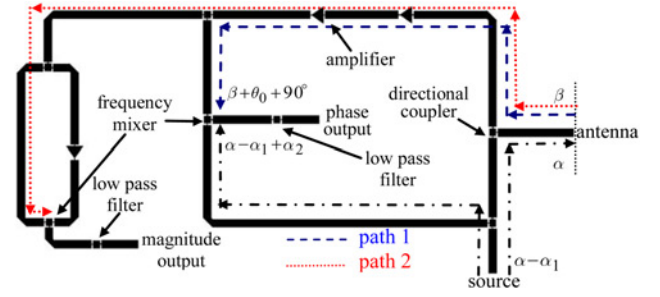


Fig. 3 Phase diagram of two paths in the layout of the RF module

The path loss L_2 in path 2 can be determined in a similar way. In this case, we have $\Delta\theta = 0$ by design. After calibration, the measurement system should yield $\epsilon_r \simeq 1$ and $\tan \delta \simeq 0$ when the dielectric sample is not present.

3 Experiment results

To demonstrate the validity of the prototype system, we use a rectangular microstrip patch antenna as the transmitting antenna. The RF source operates at 2.45 GHz. As illustrated in Fig. 4a, the dimensions of the patch and the substrate are 27.5 mm \times 38 mm and 100 mm \times 100 mm, respectively. A dielectric disc with known relative permittivity $\epsilon_r = 4.4$ and loss tangent $\tan \delta = 0.02$ is placed in front of the antenna. The separation between the antenna and the disc is denoted by r . The centre of the antenna is selected as the origin of the rectangular system (x, y, z) and the

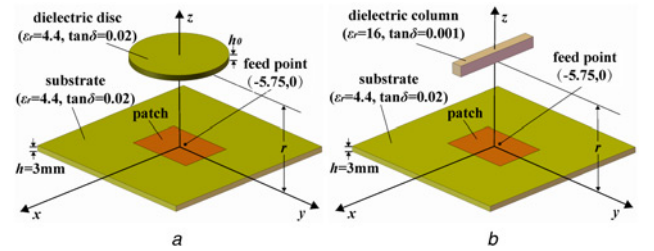


Fig. 4 Dielectric samples illuminated by microstrip antenna

a Dielectric disc illuminated by microstrip antenna
b Dielectric column illuminated by microstrip antenna

Table 1 Measurement results for dielectric disc ($\epsilon_r = 4.4$, $\tan \delta = 0.02$)

r , mm	$h_0 = 3$ mm		$h_0 = 1.6$ mm	
	ϵ_r	$\tan \delta$	ϵ_r	$\tan \delta$
25	4.162	0.0175	4.201	0.0215
30	4.159	0.0162	4.374	0.0193
35	4.038	0.0131	4.300	0.0207

Table 2 Measurement results for dielectric square column ($\epsilon_r = 16$, $\tan \delta = 0.001$)

r mm	Perturbation		Quasi-static	
	ϵ_r	$\tan \delta$	ϵ_r	$\tan \delta$
25	15.975	0.00125	16.679	0.000944
30	16.644	0.00134	16.469	0.00110
35	17.239	0.00123	16.821	0.00103

centre of the dielectric disc is on the z -axis. The diameter and the thickness of the disc are 50 mm and h_0 , respectively.

The measurement results for various separation distance r obtained from the prototype system are listed in Table 1, which agree well with the known results. The measurement is based on the method of perturbation and it can be seen that the thinner sample gives better results than the thick one.

Next, we use a square column with $\epsilon_r = 16$ and $\tan \delta = 0.001$ as the dielectric sample. The dimensions of the column are 55 mm \times 5 mm \times 5 mm. The arrangement of the measurement system is shown in Fig. 4b.

The measurement results based on the quasi-static approximation and perturbation are shown in Table 2. Note that the quasi-static approximation yields more accurate results than the perturbation algorithm.

4 Conclusion

A prototype system for measuring dielectric properties has been proposed, which consists of a transmitting antenna, an RF module and a data processing module. The dielectric samples under test are placed in close proximity of the transmitting antenna and will change the antenna input impedance. The change in the antenna input impedance can then be used to

determine the properties of the dielectric sample. It is noted that the measurement accuracy of the proposed system depends on a number of factors, such as the shape of the dielectric sample, the separation between the sample and the antenna, the quantisation error in ADC and the algorithms deployed. For high dielectric constant, the quasi-static algorithm is more accurate than that based on perturbation.

5 References

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