

Development of a low cost dielectric permittivity sensor for organic and inorganic materials in the microwave frequency range

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Abstract—This work shows a low cost system for dielectric permittivity sensor in the microwave frequency range. All components of system are described. With this system, the real part of permittivity of low loss dielectrics can be obtained. It provides the same results that a Vector Network Analyzer (VNA). The permittivities of Teflon, wood, paper, white and yellow corn and sorghum are obtained.

Keywords—Cavity perturbation technique; Permittivity; VNA; Low cost system; Organic and inorganic materials

I. INTRODUCTION

Permittivity measurement of materials plays a very important role in several industrial, scientific, and medical applications [1-3]. Diverse techniques exist for the measurement of permittivity of low loss dielectrics in the microwave range. These can be divided in two groups: resonant methods and transmission and/or reflection methods. The permittivity of materials can be determined from the measured changes of the resonance frequency and quality factor of a resonant cavity. Cylindrical and rectangular cavities are commonly adapted for this purpose, due to their precision and that the equations of electric and magnetic fields are easier to derive in simple geometries [1]. Regarding costs, measurements in microwave range are very expensive. The VNA is a measuring device very expensive employed to characterize materials in this range. The objective of this study is to develop a low cost system permittivity sensor in the microwave frequency range.

II. PROPOSED SYSTEM

Fig. 1 shows the schematic of proposed system. It consists of a cylindrical cavity resonator at 2.45 GHz, where a sample under test (SUT) is inserted, a microwave synthesizer, an isolator for shielding, one directional coupler, and a microwave detector.

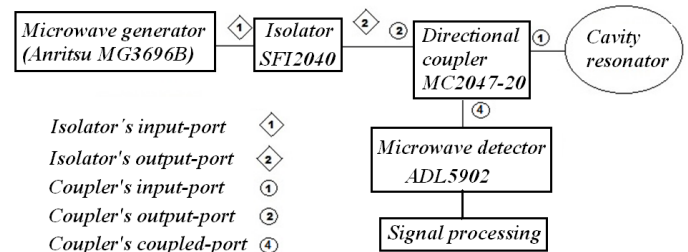


Fig. 1. Proposed system of low cost for dielectric properties measurement.

A. Cylindrical cavity resonator

A cylindrical cavity resonator can be constructed from a section of circular waveguide shorted at both ends [4]. The geometry of a cylindrical cavity is shown in Fig. 2, which was built with aluminum and dimensions a and d (a =internal radius, d =height).

The resonant frequency, for TE_{nml} mode, is calculated from (1) [4]:

$$f_{nml} = \{ c / [2\pi (\mu_r \epsilon_r)^{1/2}] \} [(p'_{nm}/a)^2 + (1\pi/d)^2]^{1/2} \quad (1)$$

The term f indicates the resonant frequency; and the subscripts nml , the propagation mode. The terms μ_r and ϵ_r are the real part of permeability and the real part of permittivity, respectively. p'_{nm} is the Bessel constant. For the implemented cavity, the value of μ_r and ϵ_r are equal to 1, because the cylinder contains only air. p'_{nm} has a value of 1.841 [5]. For the fundamental mode (TE_{111}) at a resonant frequency of 2.45 GHz and the height (d) of 111 mm, a radius (a) of 41 mm is obtained. On the top of cavity, there

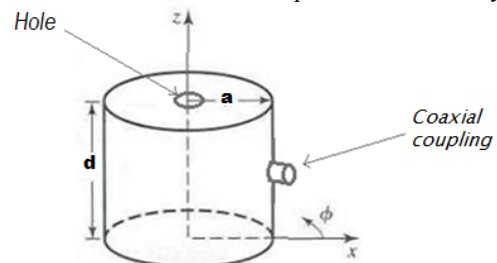


Fig. 2. Cylindrical cavity resonator.

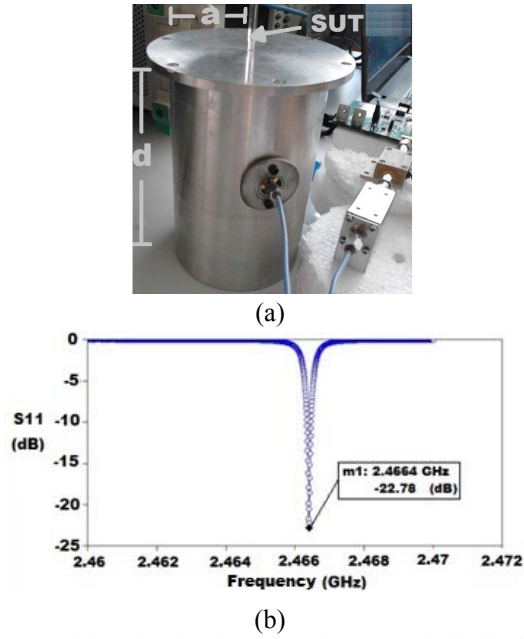


Fig. 3. (a) Fabricated cavity. (b) Measured response of cylindrical cavity resonator.

is a thin hole of 4 mm where samples are introduced into the cavity. The microwave signals are delivered to the cavity by coaxial coupling. In Fig. 3, fabricated cavity and its return loss (S11) are shown. It can be seen that excellent coupling was achieved. The return loss is related with reflection coefficient of the cavity. When all power is reflected, return loss is zero. When a considerable amount of power is absorbed by the cavity, return loss is much lower than zero. S11 parameter was measured using a VNA (E8361A, Agilent Technologies, USA).

B. Microwave components

- *Microwave synthesizer:* A synthesizer produces several output frequencies adding, subtracting, multiplying or dividing a lower quantity of fixed frequencies. In this work, a high performance microwave synthesizer (MG3696B, Anritsu, Japan) is employed to generate microwaves from 2.461 GHz to 2.4675 GHz, however, in a future work, it will be replaced with a low-cost synthesizer such as ADF4360-0, Analog devices, USA. Fig. 4 shows measured response of synthesizer by a spectrum analyser (8592B, HP, USA).

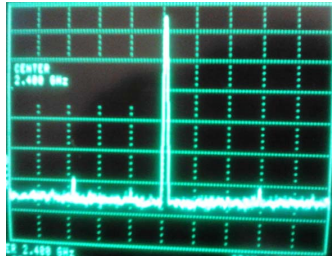


Fig. 4. Measured response of synthesizer MG3696B. In this case, the signal has a frequency of 2.4 GHz and a power of 8 dBm.

- *Isolator:* It is well known that an isolator is a two-port device that transmits microwave or radio frequency power in one direction only. In this system, the isolator (SFI4020, Fairview Microwave Inc, USA) is used to shield the synthesizer at its input side. The isolator was measured with a VNA (SPARQ-3002E, LeCroy, USA) and its measured response is shown in Fig 5. The parameter S11 indicates how much power is reflected at port 1. The parameter S21 shows how much power is sent from port 1 to port 2. The parameter S12 shows how much power is sent from port 2 to port 1. The parameter S22 indicates how much power is reflected at port 2. In Fig. 5, S11 indicates that low power is reflected at port 1. S21 shows that almost all power in port 1 is sent to port 2. S12 indicates that low power is transmitted from port 2 to port 1. S22 shows that low power is reflected at port 2. At center frequency (2.45

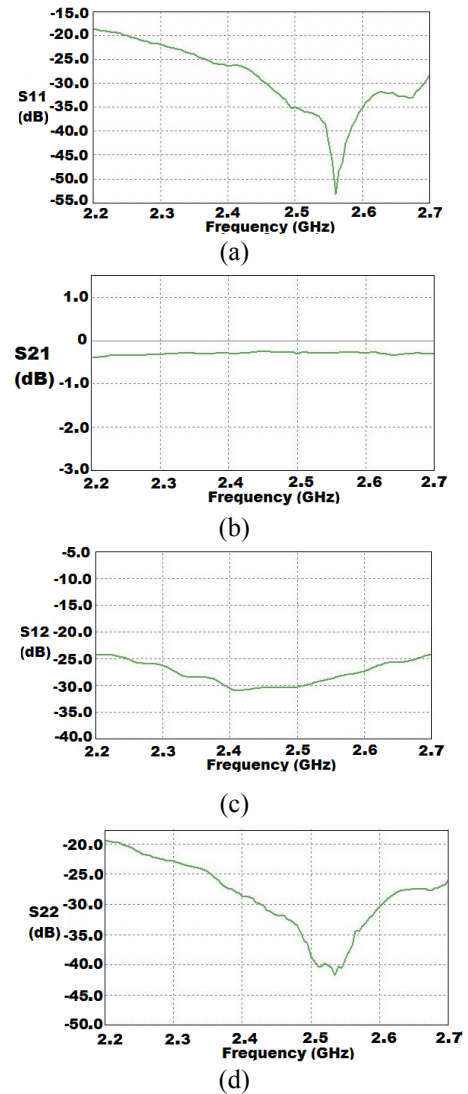


Fig. 5. Measured response of the SFI4020 isolator . (a) S11 parameter. (b) S21 parameter. (c) S12 parameter. (d) S22 parameter.

GHz), S_{11} is -30 dB; S_{21} , -0.25 dB; S_{12} , -30 dB; and S_{22} , -32 dB.

- Directional coupler:** A directional coupler is a component which allows two microwave circuits to be combined into one integrated system in one direction, while being completely isolated from each other in opposite direction [6]. For obtaining samples of the signals from cylindrical cavity resonator, a directional coupler is used. The scheme is exhibited in Fig. 6. The response of the employed coupler (MC2047-20, Fairview Microwave, Inc., USA) was measured with a Vectorial Network Analyzer (SPARQ-3002E, LeCroy, USA), shown in Fig. 7. This directional coupler is characterized by the return loss (S_{11}), insertion loss (S_{21}), coupling (S_{41}) and isolation (S_{31}). For this case, the return loss is the ratio of the reflected power to the incident power at the input port. The insertion loss is the ratio of the power at output port to the power at the input port. Usually, the power at the output port is approximately equal to the power at input port. The coupling is the ratio of the power available at the coupled port to the power at the input port. The isolation is the ratio of the power available at the isolated port to the power at the input port. In the ideal case, the isolation is much lower than zero. In Fig. 7, the return loss (S_{11}) is better than -30 dB, insertion loss (S_{21}) is better that -0.3 dB, the coupling (S_{41}) is -20 dB and the isolation (S_{31}) is lower than -48 dB. Because a directional coupler is reciprocal, $S_{11}=S_{22}=S_{33}=S_{44}$, $S_{12}=S_{21}$, $S_{13}=S_{31}$, $S_{14}=S_{41}$, $S_{23}=S_{32}$, $S_{24}=S_{42}$ and $S_{34}=S_{43}$. Further, $S_{23}=S_{14}$, $S_{24}=S_{13}$ and $S_{34}=S_{12}$.

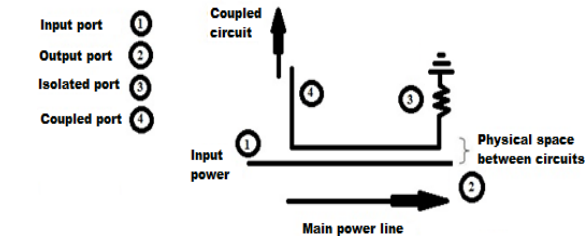


Fig. 6. Directional coupler.

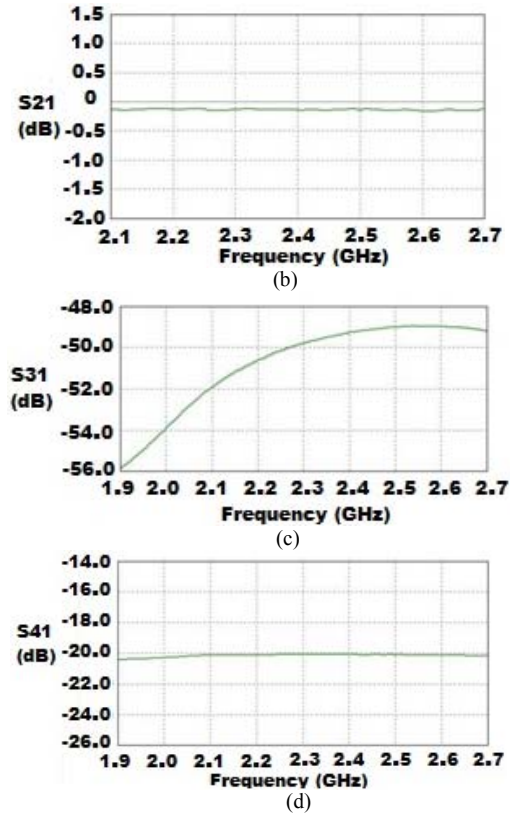
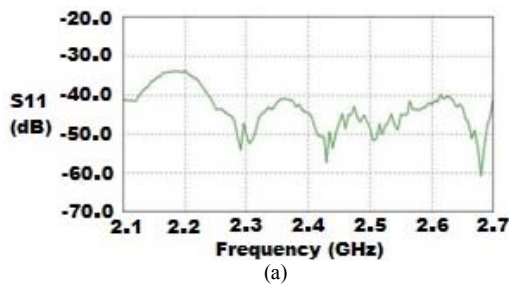


Fig. 7. Measured response of directional coupler MC2047-20. (a) Return loss. (b) Insertion loss. (c) Isolation. (d) Coupling.

- C. Microwave detector (Conversion of RF power to a measurable DC or low frequency signal):** The microwave detector (ADL5902, Analog Devices, Inc., USA) is basically a converter microwave signals to dc voltage. The detector converts the microwave reflected signals, from cavity, to DC voltage. For its correct use, it is necessary to characterize the detector for obtaining the relation between input power and output voltage, which was measured with a multimeter. The detector was characterized to the frequencies of 2.4, 2.45, 2.5, 2.6 y 2.7 GHz, obtaining the same results. The measured response of detector to the frequency of 2.4 GHz is exhibited in Fig. 8.

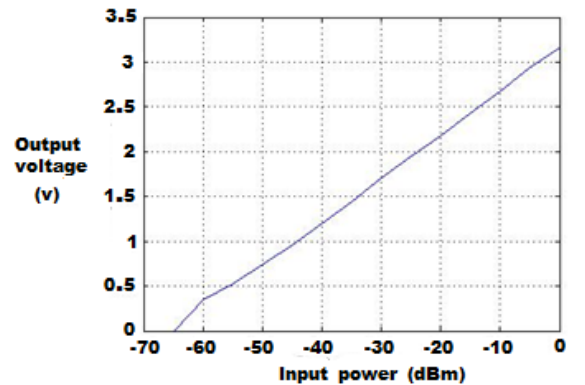


Fig. 8. Measured response of microwave detector ADL5902.

Fig. 9 illustrates the equivalent circuit of detector.

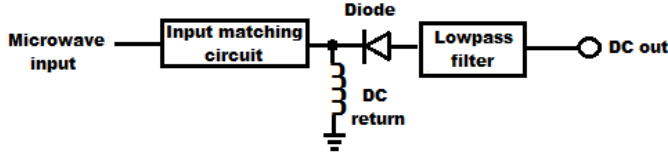


Fig. 9. Basic microwave detector.

III. METHODOLOGY FOR EXTRACTING THE DIELECTRIC CONSTANT

The permittivity may be calculated from (2) [1]:

$$(f_{rc} - f_{rs})/f_{rs} = A (\epsilon' - 1)(V_s/V_c) \quad (2)$$

where f_{rc} is the resonant frequency of cavity without sample (Hz), f_{rs} is the resonant frequency of cavity with sample (Hz), V_s is the sample volume (m^3), V_c is the internal volume of the cavity (m^3) and ϵ' is the real part of permittivity of the sample. The parameter A is a constant obtained from a dielectric with known permittivity (Teflon was used as reference). f_{rc} and f_{rs} are obtained from return losses.

IV. RESULTS

The studied samples were Teflon, wood, paper, white and yellow corn and sorghum. For these measurements, one port of the VNA (E8361A, Agilent Technologies, USA) was connected directly to the cavity and return losses were measured from 2.461 GHz to 2.4675 GHz. These results were taken as reference to evaluate the performance of the proposed system.

Then, the same samples within the cavity were measured with the proposed system. Results were compared for the two methods.

Fig. 10 shows the measured response of cavity without perturbation and the response of cavity when it is perturbed with samples using a VNA.

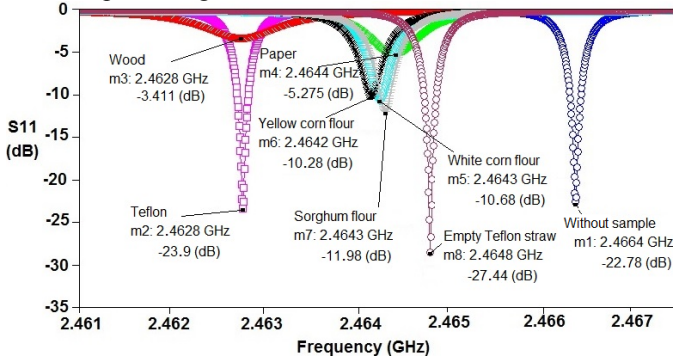


Fig. 10. Measured Return losses with VNA Agilent Technologies E8361A.

On the other hand, Fig. 11 shows the return losses, for the same samples, measured with the proposed system. In the cavity perturbation technique, the real part of the permittivity is a function of the resonant frequencies as can be seen in (2). Due the obtained results, we establish that the proposed

system is able to measure the real part of permittivity ϵ' with the same accuracy that a high cost VNA.

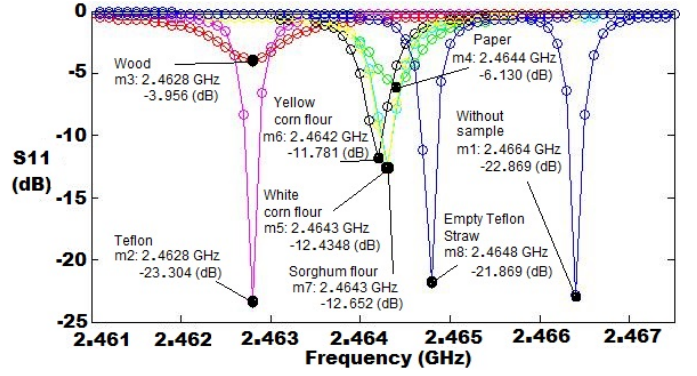


Fig. 11. Measured Return losses with the proposed system.

TABLE 1. Real part of the permittivity

Material	Obtained ϵ' with the proposed system ($V_c = 6.224 \times 10^{-4}$)	Obtained ϵ' with a VNA ($V_c = 6.224 \times 10^{-4}$)
Teflon ($V_s = 1.326 \times 10^{-6} m^3$)	2.1	2.1
Wood ($V_s = 1.252 \times 10^{-6} m^3$)	2.165	2.165
Paper ($V_s = 4.107 \times 10^{-7} m^3$)	2.972	2.972
White corn ($V_s = 1.7087 \times 10^{-7} m^3$)	2.86	2.86
Yellow corn ($V_s = 1.7087 \times 10^{-7} m^3$)	3.232	3.232
Sorghum ($V_s = 1.7087 \times 10^{-7} m^3$)	2.86	2.86

V. CONCLUSION

In this work, a low cost system for dielectric permittivity sensor in the microwave frequency range is presented. Results shows that obtained ϵ' with the proposed system and obtained ϵ' with the VNA are in good agreement. From these results we can conclude that the proposed system may be an unexpensive substitute to measure the real part of permittivity ϵ' with the same accuracy that a high cost VNA. Results show that.

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