Measurement of Electric Permittivity based on Substrate Integrated Waveguide (SIW) Cavity

Giuseppe Siciliano, *Student Member, IEEE*, and Maurizio Bozzi, *Senior Member, IEEE*

***Abstract*—The design of a microwave sensor for material characterization is presented, based on a cavity resonator realized in Substrate Integrated Waveguide (SIW) technology. The measurement of electric permittivity opens great opportunities for sensing applications.**

Different topologies are considered, and preliminary experimental results are reported and compared with simulation data. Finally, the strength-points and drawbacks of such solutions are pointed out, and the possible implementation of such sensors on paper substrates is briefly discussed.

***Index Terms*—Electric Permittivity, Material Characterization, Microwave Sensors, Resonant Cavities, Sensors on Paper, Substrate Integrated Waveguide (SIW).**

I. Introduction

MATERIAL characterization in the microwave regime is a fundamental step prior to the use of any material, and requires the determination of two quantities: electric permittivity ε_r and dielectric loss tangent $tan\,\delta$, the first affecting the speed of the wave and the second related to the electromagnetic energy absorbed by the material. In addition, the measurement of such quantities finds interesting applications for sensing purposes. Almost all materials, in fact, change their electromagnetic parameters depending on environmental conditions. For instance, on board of an airplane, the temperature variation in coatings used for isolating metal wires in electronic circuits need to be detected and evaluated. Similarly, humidity, atmospheric pressure, solar irradiance, and other external agents could be sensed, and they represent valuable information for agricultural applications.

There are many techniques for measuring the electromagnetic parameters of materials; in this paper, we will concentrate on the use of resonant cavities, which feature excellent performance in terms of sensitivity at the microwave frequencies. In particular, for sake of simplicity, we will focus on cylindrical resonant cavities, implemented in substrate integrated waveguide (SIW) technology.

The paper is organized as follows: Section II describes the operation principle of a properly modified cylindrical SIW cavity. SIW technology is also discussed, showing its advantages over classical shielded structures. Section III reports the design steps of a cylindrical cavity, with the initial analytical considerations and subsequent full-wave modeling. Results of simulations and measurements are given in Section IV, with a performance comparison between the various topologies.

The authors are with the Department of Electrical, Computer and Biomedical Engineering, University of Pavia, 27100 Pavia, Italy (giuseppe.siciliano01@universitadipavia.it, maurizio.bozzi@unipv.it).

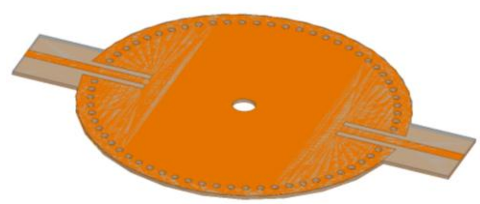


Fig. 1. Cavity-sensor topology on SIW technology.

II. Microwave Cavity-Sensor

A sensor for electric permittivity can be realized by using a circular-sectioned cylindrical resonant cavity operating on its fundamental mode. A hole is subsequently drilled in the center of the cavity, where the sample material is located. When the sample is inserted, the resonance frequency of the mode drifts off. The extent of the frequency shift is related to the electric permittivity of the sample material.

In this work, the resonant cavity has been realized in SIW technology, an emerging approach for easy fabrication of waveguide-like components, with the waveguide's side walls being replaced by rows of metalized vias. SIW technology offers notable advantages, like complete shielding, low manufacturing costs, simple fabrication, and easy integration with active and non-linear components.

Fig. 1 depicts the topology of an SIW cavity-sensor. The input and output microstrip lines are used to excite the cavity mode and to connect the device to a Vector Network Analyzer (VNA) for the measurement of the scattering parameters.

III. Design of the Resonant Cavity

The cavity was designed to operate with the fundamental TM_{010} mode around the frequency of 2.45 GHz. The dielectric substrate has a thickness of 0.76 mm, permittivity $\varepsilon_r = 2.33$ and loss tangent $tan\,\delta = 0.0035$. The radius of the cylindrical cavity is $D = 30.6$ mm, and the radius of the hole is $d = 2.375$ mm.

When the hole is filled with a given dielectric material, the resonance frequency of the cavity changes. In particular, the cavity resonates at $f = 2.485$ GHz when the hole is filled with air, and $f = 2.467$ GHz when the hole is filled with a puck of dielectric material with $\varepsilon_r = 9.8$.

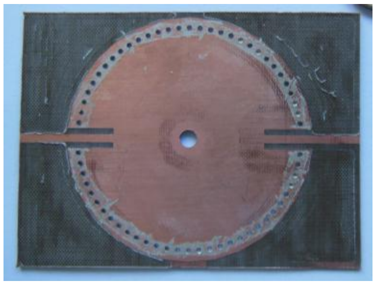


Fig. 2. Photograph of the prototype.

The frequency variation of this cavity topology is rather limited. The physical reason is the truncation of the top and bottom metal walls of the cavity at the edges of the dielectric puck under test: in this way, the field hardly penetrates into the dielectric puck, thus resulting in a low sensitivity of the sensor.

This problem can be mitigated by metalizing the top and bottom sides of the dielectric puck. In this new configuration, the cavity resonates at $f=2.479$ GHz when the hole is filled with air, and $f=2.362$ GHz when the hole is filled with a puck of dielectric material with $\varepsilon_r=9.8$. The frequency variation in this case is 117 MHz, compared to only 18 MHz of the previous case. In addition, in this latter case the resonance frequencies and the quality factors of the modes can be directly related to the electric permittivity and the loss tangent of the puck by analytical formulas.

IV. Simulation and Experimental Results

The cylindrical cavity described in the previous section has been fabricated by milling machining (Fig. 2) and measured under different operation conditions.

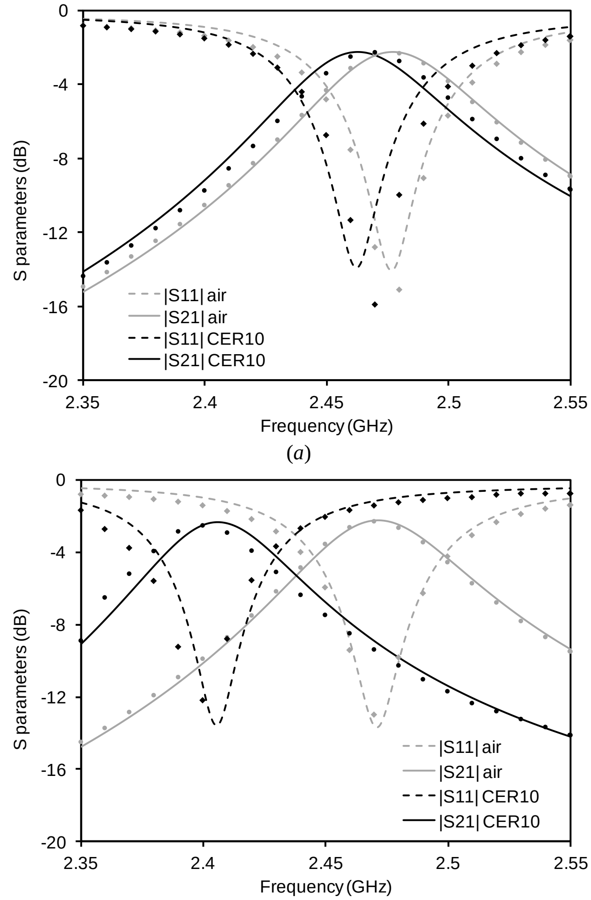
In the first set of measurements, the cavity without metal caps at the top and bottom of the dielectric sample was considered. The hole was filled with air and with a dielectric puck made in CER10 ($\varepsilon_r=9.8$). Measurement results are reported in Fig. 3*a* and compared with simulations made by using Ansys HFSS.

In the second set of measurements, the same materials were considered, but in this case the top and bottom sides of the dielectric puck were covered with conductive tape. Measured and simulation results are reported in Fig. 3*b*.

V. Conclusion

A sensor for electric permittivity was designed, based on a resonant cavity operating on its fundamental mode. The electric permittivity of a sample material can be retrieved from the resonance-frequency offset between the cavity with and without the sample. The cavities were designed on SIW technology, thus being very easy-to-fabricate, cheap, and light. Two different topologies were considered, showing through experimental results their validity and limitations.

Future implementations of SIW cavities on paper substrate, aiming at the development of eco-friendly systems, are currently under development.



(*b*)

Fig. 3. Measured and simulated scattering parameters of the resonant cavity, filled with different materials (markers: measurements; lines: simulations): (*a*) without metal caps at the top and bottom of the dielectric sample; (*b*) with metal caps at the top and bottom of the dielectric sample.

VI. My MTT-S Experience

I am currently completing my Master Degree in Electronics, with curriculum in Space Communications and Sensing. I expect to graduate in October 2015. I am particularly interested in the design of antenna systems for satellite communications. Starting in March 2015, I will be spending a 6-month traineeship at the European Space Operations Center of the European Space Agency (ESA-ESOC), in Darmstadt, Germany. I will be involved in the design and simulation of radar systems for space debris detection, within the ESA's SSA (Space Situational Awareness) program. After my graduation, I would like to continue to work in the field of space systems, either at a space agency or at my university in the framework of a PhD program.

The MTT-S Scholarship has impacted very positively on the choices for my future career, promoting my interest in the microwave applications. The scholarship has given me the great opportunity to attend the IMS 2014, that was illuminating and inspiring, unrevealing to me the huge world of microwave research and industry. I have met lots of teachers, managers, and students from all over world, in an explosion of ideas, ambition, and passion. I look to all that as the true award from MTT-S.