Dielectric Permittivity Sensor Based on Quarter-Mode Resonant Cavities in Substrate Integrated Waveguide

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***Abstract*— This research activity is related to the design and realization of a dielectric permittivity sensor based on quarter-mode resonant cavities in Substrate Integrated Waveguide technology. The proposed solution allows obtaining performance comparable with non-planar structures, with the advantages of low cost and easy fabrication, typical of the planar ones. The configuration based on a quarter-mode SIW cavity permits to reduce the footprint by 75%, making the sensor attractive for Internet of Things and Wireless Sensor Networks applications. Preliminary results and the roadmap of the activity are presented.**

I. Introduction

In both academic and industrial research, there is a growing interest for topics related to Wireless Sensor Networks (WSN) and Internet of Things (IoT) technologies, with the aim to implement sensor networks for every-day life use. The main requirements for their development are low cost, easy manufacturing, highly compact size, low power consumption, and good performances.

In this scenario, the Substrate Integrated Waveguide (SIW) technology meets all these requirements. SIWs consist of structures composed of a substrate, usually with a dielectric permittivity from 2 to 10, whose superior and inferior faces are covered by a metallic layer. Lateral shielding is obtained by drilling cylindrical holes with an appropriate distance and by metalizing them. The final result is a planar object with almost the characteristics of a non-planar one [1], [2]. Components and antennas in SIW technology represent the best compromise between (cheap and compact) planar structures and (shielded and low-loss) planar metallic waveguides, especially for mm-wave frequencies. Another advantage of SIW technology is the possibility to integrate the entire wireless system in a single structure, with the System on Substrate approach [1], [2]. Moreover, because of the possibility of using a variety of substrate materials, SIW structures are adequate for eco-friendly applications and wearable devices [3]. Due to these advantages, SIW could play an important role in the next future, particularly in the development of WSN and IoT.

In the past years, numerous activities have been carried on, with the aim to miniaturize SIW components, and in particular cavity filters. As a result, several solutions based on half-mode, quarter-mode, and eight-mode SIW cavities have been proposed (Fig. 1) [4]. Since these solutions are partially open resonators, they present some issues in filter applications (due to undesired radiation), but on the other hand they are suitable for the implementation of compact sensors.

The development of dielectric permittivity sensors based on quarter-mode SIW cavities is presented here, along with preliminary results and the roadmap of the future activities.

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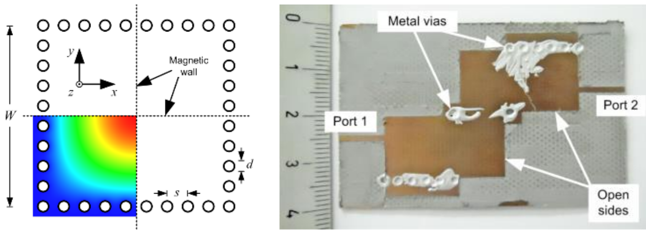

(*a*) (*b*)

Fig 1. Quarter-mode SIW structures: (*a*) Geometry of a quarter-mode SIW cavity, with drawing of the electric field amplitude; (*b*) Quarter-mode SIW filter (from [4]).

II. Description of the Project

The aim of the project is the design of permittivity sensors based on quarter-mode resonant cavities in SIW technology. The use of quarter-mode cavities allows reducing the footprint by 75%, cutting the structure along symmetry planes, corresponding to magnetic walls, where the electrical field is more intense. While quarter-mode cavities are more compact than traditional SIW cavities resonating at the same frequency, they are subject to radiation leakage, which limits their quality factor [5]. To mitigate this problem, modified quarter-mode cavities were proposed in [5], with a fence of vias in front of the open boundaries, which reduces radiation loss (Fig. 2).

The structure in Fig. 2 is anyway a partially open resonator, and the electromagnetic field is partially in the dielectric substrate and partially in the air. This operation principle can be exploited for sensing purposes. The field is particularly intense in the L-shaped slot, denoted as the sensing area in Fig. 2. In fact, positioning a dielectric material on top of this slot allows modifying the effective dielectric permittivity ε_{eff} of the cavity resonator, thus shifting its resonance frequency f_0.

A shielded quarter-mode resonator operating at approximately 3 GHz has been designed by using the commercial electromagnetic solver HFSS. The dielectric substrate Taconic CER-10, with dielectric permittivity ε_r=10.0 and thickness h=1.27 mm, was selected among several

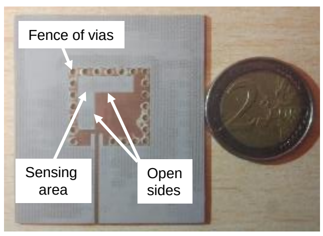

Fig 2. Shielded quarter-mode SIW structure, with the aim to mitigate radiation loss.

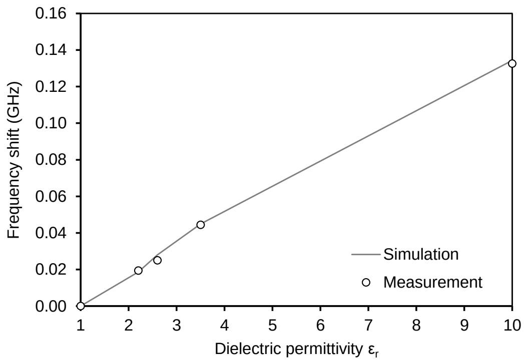

Fig 3. Frequency shift of the resonance frequency of the fundamental cavity mode versus dielectric permittivity: simulated and measured results.

candidates because it allows compact size and maximum sensitivity. The picture of the prototype is shown in Fig. 2. The size of the cavity is approximately 20 mm, making it a suitable candidate for most IoT applications.

The cavity was measured under nominal operation conditions, with no dielectric material covering the sensing area, and subsequently with several dielectric samples positioned on top of the sensing area. The presence of the dielectric sample determines a frequency shift of the resonance frequency of the fundamental cavity mode, which is larger for higher-permittivity dielectric samples. Due to the confinement of the field in the proximity of the dielectric-air interface in the sensing area, the thickness of the sample plays a minor role, provided it exceeds 1 mm. Fig. 3 shows the simulated and measured frequency shift versus the value of the dielectric permittivity of the samples.

To better appreciate the agreement between simulated and measured data, Table I reports the measured resonance frequency f_{meas} and the simulated one $f_{sim,1}$, for all considered materials. The percentage relative error is in the order of 3% to 4% in all cases. This error is partially attributed to the air gap between the dielectric substrate of the cavity resonator and the dielectric sample under test. Subsequently, this effect was included in the simulation, by considering an air gap of 140 μm, and obtaining the simulated resonance frequency $f_{sim,2}$. As shown in Table I, the relative error is much smaller in this case (better than 0.38%).

The last step done has been the derivation of a curve that relates the frequency shift to the dielectric permittivity of the sample under test. In the simulations, the permittivity of the samples is set, and the corresponding frequency shifts are calculated. Conversely, in the measurement phase, the measured frequency shift is used to retrieve the dielectric permittivity that, in theory, shouldn't be known a-priori. Moreover, a study on the loss tangent of the dielectric material put under test has been carried on.

TABLE I. Simulated and Measured Shift of the Resonance Frequency due to the Dielectric Sample

Sample	f_{meas}	$f_{sim,1}$	% error	$f_{sim,2}$	% error
Air (ε_r=1)	2.989	2.915	2.53%	2.993	0.14%
TLY-5 (ε_r=2.2)	2.969	2.896	2.51%	2.980	0.38%
Duroid 5880 (ε_r=2.2)	2.963	2.882	2.81%	2.965	0.06%
RF-35 (ε_r=3,5)	2.944	2.856	3.09%	2.940	0.15%
CER10 (ε_r=10.0)	2.856	2.743	4.11%	2.856	0.01%

III. Conclusion

The research activity described in this document aims to develop a compact yet accurate sensor to measure the dielectric permittivity of solids, which exploits the potential of quarter-mode SIW structures.

This project falls in the framework of a more general activity, aiming at the complete system integration of novel wireless devices, according to the paradigm of the lab-on-chip. These devices will open new perspectives in the field of the Wireless Sensor Networks and of the Internet of Things, thanks to their compact size, low cost, and easy manufacturing.

IV. Acknowledgment and Next Plans

The IEEE MTT-S Undergraduate/Pregraduate Scholarship motivated and supported me to pursue research in the microwave. Unfortunately, due to the current pandemic situation, no one had been able to participate to IMS2020, then I hope to participate at some other conference soon. I'm really interested in the development of microwave technologies in both academic and industry background. Currently I'm terminating my master's degree studies in the microwave field, studying monopulse tracking couplers and the effects of the high order modes excitation in such systems, in collaboration with the University of Cantabria (Spain).

Finally, I also want to thank my supervisor, Professor Bozzi, and the PhD student Nicolò Delmonte, for dedicating a lot of time helping me in the bachelor's degree project and in the achievement of this scholarship.

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