Experimental Dielectric Sensing of materials using Epsilon-Near-Zero tunnel in SIW technology

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***Abstract* – A planar Epsilon-Near-Zero (ENZ) structure implemented on substrate integrated waveguide technology is used for the characterization of material dielectric permittivity. The proposed structure has very high sensitivity which yields more accurate results when compared to other techniques, such as perturbation of conventional cavities. This prototype presents a low profile, low cost, ease of fabrication and ease of integration, which add important characteristics for portable material analysis systems. Measurements are in good agreement with standard values.**

***Index terms* – permittivity measurements, substrate integrated waveguide, microwave measurements, plasmonic structure, Epsilon-Near-Zero.**

I. INTRODUCTION

Microwave sensors for material measurements are based on the interaction between microwaves and matter, and can be found in several applications such as research, industry and medicine [1] – [3]. They are based on the fact that the interaction between microwaves and the material under test is determined by its complex permittivity (1)

$$\varepsilon_s = \varepsilon'_s - j\varepsilon''_s , \qquad (1)$$

where ε'_s corresponds to the real part of the material permittivity and ε''_s is the imaginary part, which is related to the material dielectric loss tangent ($\tan\delta$) [4] by (2).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} . \qquad (2)$$

Microwave resonant cavities are often used for dielectric measurements due to their unique characteristics of high quality factor Q and good sensitivity [1] – [3]. However, compact devices are required for small measurement systems [5]. In [2], Saeed *et. al.* performed dielectric permittivity measurements of solvents using a microstrip closed loop resonator. Nevertheless, microstrip structures suffer of low Q factors in the range of 50 – 100 [1], [4].

With the development of Substrate Integrated Waveguide (SIW) technology, it is possible to design cavities in planar-form [3]. Moreover, this technique provides low profile, low cost and ease of fabrication of the structures. A Substrate Integrated Waveguide (SIW) cavity resonator is used in [3] to measure the dielectric properties of binary mixtures. Alu *et. al.* [6] proposed a theoretical study of Epsilon-Near-Zero (ENZ) tunnels for the evaluation of permittivity of the materials. However the proposed theory is not validated experimentally.

In this paper a novel ENZ tunneling circuit using SIW technology is proposed to evaluate the dielectric permittivity of materials. Moreover, this device offers higher sensitivity when compared with SIW cavities due to the high ***E***-field concentration through the narrow tunnel [6].

The paper is organized as follows: Section II describes the design and fabrication of the ENZ tunnel using SIW technology. And also sensitivity analysis is performed by choosing the various tunnel lengths. Section III presents the measurements on various dielectric samples using the proposed SIW ENZ tunnel.

II. DESIGN OF EPSILON-NEAR-ZERO STRUCTURE WITH SUBSTRATE INTEGRATED WAVEGUIDE TECHNOLOGY

A. Design of the ENZ structure

The phenomenon of Epsilon-Near-Zero (ENZ) consists of the energy squeezing and tunneling through a very narrow channel, and it has been recently led to several potential applications [6] – [8]. The tunneling effect can be obtained inside a rectangular waveguide channel of narrow height that operates near the cutoff frequency of its dominant TE_{10} mode. The cutoff frequency (f_{c10}) of a rectangular waveguide in its dominant mode TE_{10} is obtained by

$$f_{c10} = \frac{c}{2b\sqrt{\varepsilon_r}} , \qquad (3)$$

where c is the speed of light in a vacuum, b is the width of the waveguide and ε_r is the relative real permittivity of the material filling the waveguide.

As explained in [6], the tunneling effect is possible due to a dispersive behavior of the effective permittivity ε_{eff} in a waveguide operated at the TE_{10} mode [7]

$$\frac{\varepsilon_{eff}}{\varepsilon_0 \varepsilon_r} = n^2 - \frac{c^2}{4\varepsilon_r f^2 W_t^2} , \qquad (4)$$

where n is the refractive index of the substrate material, f is the frequency in operation and W_t is the waveguide width.

From Equation (4) it is clear that at cutoff frequency (f_{c10}), $\varepsilon_{eff} = 0$, therefore a phase constant $\beta = 0$ is obtained. This effect produces an infinite wavelength and infinite phase velocity of the mode [7], moreover, this results in a uniform and strong electric ***E***-field along the channel [6] – [8]. An abrupt height difference can exist between the feeding waveguides and the tunnel, and perfect transmission appears at tunnel cutoff, since $\beta = 0$.

Fig. 1 shows the layout of a narrow ENZ channel of height a_{ch} and length L, connected by two rectangular waveguides of height a and width b_{wg}. The three waveguide sections are filled with the same dielectric material with relative real permittivity ε_r. If $a >> a_{ch}$, a strong ***E***-field concentration is observed through the tunnel at the cutoff frequency due to energy squeezing. The frequency which tunnels through the channel is called tunneling frequency (f_0). This phenomenon can be used for sensing small dielectric variations produced by the insertion of small samples inside the narrow waveguide [6].

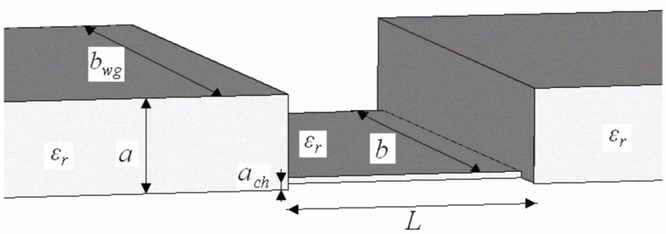

Fig. 1. Layout of an ENZ structure [6].

In this paper, an ENZ structure is designed using Substrate Integrated Waveguide (SIW) technology [9]. A Rogers RT/duroid 5880 substrate with thickness $h = 3.175$ mm is used for the implementation of the device. The proposed SIW ENZ structure operating at 5 GHz consists of *cavity-tunnel-cavity* configuration, with dimensions of the tunnel $b = 20$ mm, $a_{ch} = 0.5$ mm, and width and length of the cavities of 32 mm and 10 mm respectively. SIW cavities are coupled by microstrip transmission lines as shown in Fig. 2. They ensure a complete energy transmission along the whole structure by assigning their SIW TE_{10} dominant mode cutoff frequency below the tunneling frequency.

SIW ENZ tunnel is analyzed by using a full-wave EM simulator [10]. The simulated tunneling frequency is $f_0 = 5.36$ GHz.

Fig. 3 shows the simulated ***E***-field distribution [10] along the complete structure at the tunneling frequency. It is observed that a strong and constant ***E***-field enhancement is generated through the narrow tunnel along its y axis.

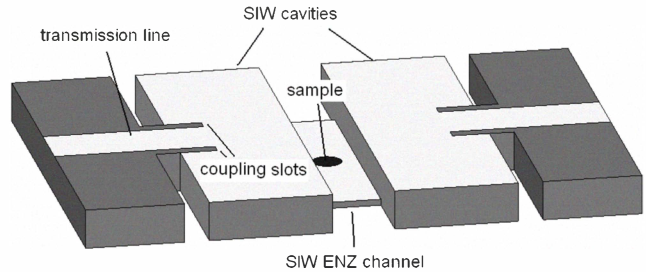

Fig. 2. Proposed SIW ENZ structure.

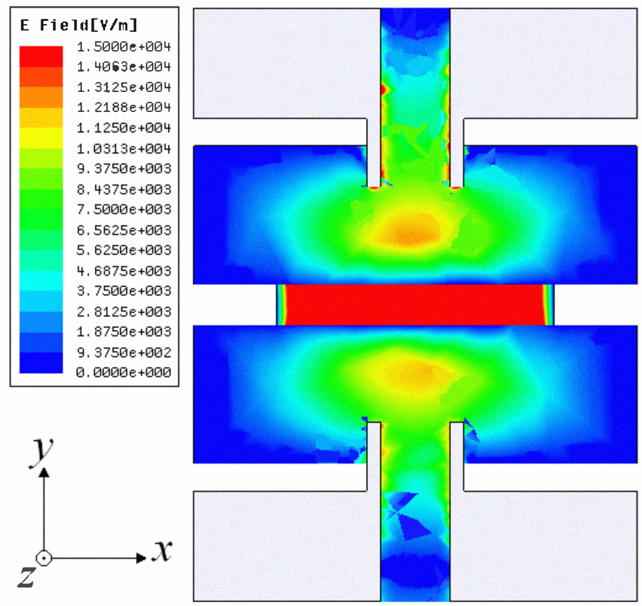

Fig. 3. Electric field distribution in the ENZ structure.

B. Sensitivity analysis

In order to characterize the permittivity of the samples, a high sensitive ENZ channel is used. An ***E***-field enhancement caused by energy squeezing and tunneling in the narrow channel ensures the high sensitivity to small permittivity variations in the samples. The dielectric properties of the sample materials are related to variations in the frequency response of the device.

In this paper, dielectric samples of 2.4 mm diameter and 0.5 mm height are placed at the center of the ENZ channel as shown in Fig. 2. Samples of different complex permittivity values are chosen for the analysis.

As the tunneling frequency is independent on the length L of the ENZ channel [6] – [8], it is possible to perform a sensitivity analysis by varying the length of the tunnel L, and keeping the sample dimensions constant. Fig. 4 shows the shift in the simulated tunneling frequency with the real permittivity of several samples for three different tunnel lengths. The reference value is the tunneling frequency of the structure. For comparison, the sensitivity of a conventional SIW cavity [3] operating at 5 GHz on the same RT/duroid substrate is also analyzed.

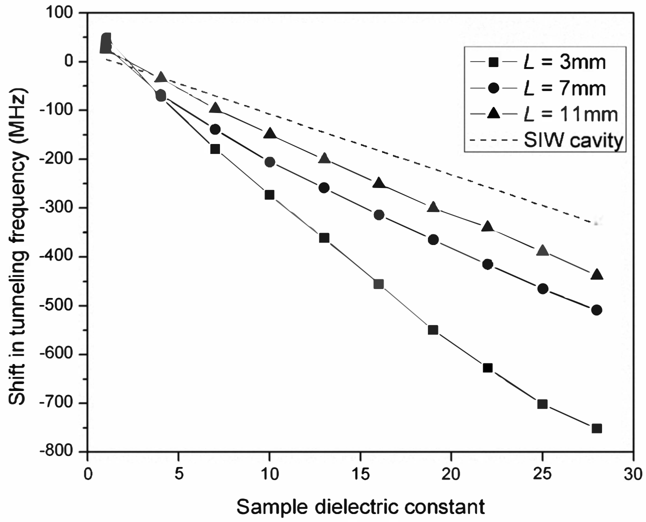

Fig. 4. Shift in tunneling frequency versus sample permittivity coefficient for three different tunnel lengths, and shift in resonant frequency for an SIW cavity resonator.

From Figure 4, it is observed that a shift of 800 MHz is obtained for a change in sample dielectric permittivity of $\Delta\varepsilon_r$ = 28 for the tunnel of length L = 3mm. A tunnel with L = 7 mm presents a variation of 500 MHz for a change in sample dielectric permittivity of $\Delta\varepsilon_r$ = 28, while a tunnel of L = 11 mm produces a shift of 400 MHz for the same sample permittivity variation. For an SIW cavity resonator [3] which operates at 5 GHz, a shift of only 340 MHz is obtained from a change in sample dielectric constant $\Delta\varepsilon_r$ = 28. It is evident that a larger tunnel length produces lower sensitivity. It is also observed that the sensitivity of the ENZ tunnel is higher than the conventional SIW cavity.

The tunneling frequency and the dielectric constant data obtained using the ENZ method shown in figure 4 are modeled using a second order polynomial expression (5) [2]

$$f_0 = a + b_1\varepsilon'_s + b_2\varepsilon'^2_s \tag{5}$$

where a, b_1 and b_2 correspond to the calibration parameters [11].

C. Fabrication of the SIW ENZ structure

To demonstrate the sample dielectric sensing, the ENZ SIW structure of Fig. 2 is fabricated on a Rogers RT/duroid 5880 substrate of thickness h = 3.175 mm. The height of the ENZ channel is a_{ch} = 0.5 mm. The length of the channel is chosen as L = 3 mm since it offers the highest sensitivity. A 2.4 mm diameter hole at the center of the ENZ channel is chosen for placing the sample. Fig. 5 depicts the simulated and measured frequency responses of the proposed ENZ tunnel.

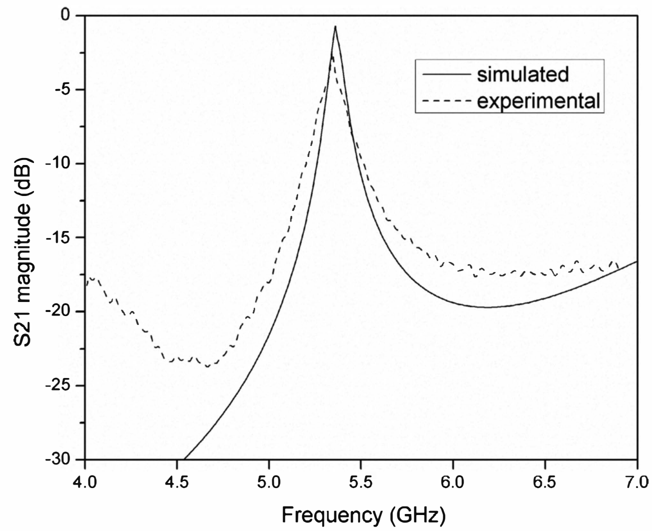

Fig. 5. Simulated and experimental frequency responses of the proposed tunnel structure.

III. *Material Characterization*

The dielectric materials chosen for characterization are Teflon, acrylic, polyamide, nylon, Rogers RO4003 [11], wood, quartz, Rogers RT/duroid 6010.2LM [11] and RT/duroid 6010.8LM [11]. Measurements are performed by using an *Agilent –PNA* series Vector Network Analyzer (E8361A) at room temperature. For material characterization, the calibration parameters a, b_1 and b_2 of the second order polynomial are obtained by using the standard samples (air, RO4003C, RT/duroid 6010.2LM and RT/duroid 6010.8LM) [11]. The evaluated values are: a = 5.5081, b_1 = -0.0137 and b_2 = 0.0002.

Fig. 6 shows the simulated and the measured tunneling frequency with the sample real permittivity. Table I tabulates theoretical and measured values of ε'_s obtained from the measurements using the proposed second order polynomial. It is clearly observed that a good agreement between theoretical and measured data is obtained. The error in measured values in comparison with the standard materials using the ENZ structure is within ±0.6 %.

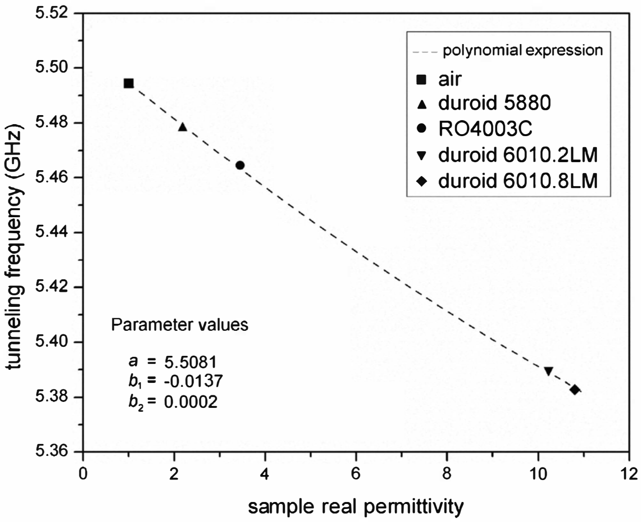

Fig. 6. Measured tunneling frequency versus real permittivity of standard materials.

TABLE I

CHARACTERIZED PERMITTIVITY VALUES OF SAMPLES

Material	f_0 (GHz)	Theoretical $'_s$	Measured $'_s$
Air	5.4945	1	1.0113
Teflon	5.4803	2.1	2.0932
RT/duroid 5880	5.4792	2.2	2.1788
Acrylic	5.4754	2.7	2.4773
RO4003C	5.4639	3.38	3.3945
Quartz	5.4565	4.2	4.0033
Wood	5.4553	2 – 6	4.0993
Nylon	5.4536	4 – 5	4.2368
Duroid 6010.2	5.3887	10.2	10.2487
Duroid 6010.8	5.3837	10.8	10.7753

IV. CONCLUSIONS

A compact experimental Substrate Integrated Waveguide (SIW) Epsilon-Near-Zero (ENZ) structure has been presented for dielectric permittivity characterization. The proposed structure presents higher sensitivity when compared to conventional SIW cavities. Sensitivity analysis is performed on the SIW ENZ structure by choosing the various tunnel lengths. The second order polynomial model is used to analyze the data. The error of the characterized dielectric values is within 6 %.

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