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# AN IMPROVED METHOD FOR MICROWAVE NONDESTRUCTIVE DIELECTRIC MEASUREMENT OF LAYERED MEDIA

**H. Zhang, S. Y. Tan, and H. S. Tan**

School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore
Singapore 639798

**Abstract**—This paper presents an improved method for microwave nondestructive dielectric measurement of layered media using a parallel-plate waveguide probe. The method bases on measuring the $S$ parameter $S_{11}$ or reflection coefficient from the $N$-layer media over the range of 1 to 10 GHz. Formulation for the aperture admittance is presented which allows the solving of the inverse problem of extracting the complex permittivity for two cases of the media, (1) one that terminates into an infinite half-space, (2) one that terminates into a sheet conductor. Our theoretical analysis allows the study of the effects of air gaps and slab thickness on the probe measurements. Through numerical simulations, the ability to use the proposed method for dielectric spectroscopy and thickness evaluation of layered media is demonstrated.

## 1. INTRODUCTION

Each and every material has its own set of electrical characteristics related to its dielectric properties. Knowing these properties precisely enables scientists and engineers to use the appropriate materials for intended applications, such as the design of ferroelectrics [1, 2], ceramics [3] and so forth. Understanding how dielectric material properties vary at frequencies above 1 GHz is especially important and challenging in the new areas of interest such as propagation modelling in wireless communications [4, 5], aerospace ice-detection [6], radar detection of buried objects which is influenced by soil characteristics [7–10], and biomedical systems such as in the detection of cancer [11–16], and diagnosis of the functional conditions of biological tissues [17, 18], where accurate data of dielectric properties is critically required.

Different measurement techniques have been developed to measure dielectric properties. Most commonly, the dielectric properties of the materials are derived from admittance measurement. Many factors have to be considered when choosing the appropriate technique to obtain the desired information on the dielectric properties. Some of these factors include the frequency range, required measurement accuracy, sample size, surface topology, state of the material (liquid, solid, powder, and so forth), destructive or nondestructive, and contacting or non-contacting. In applications such as biomedical microwave diagnostics where it is not permissible to destroy any part of the material under test (MUT), the solutions to nondestructive dielectric measurement restrict to a few. However the currently available techniques have their limitations in terms of bandwidth, accuracy, sample size, etc. Therefore there is a need for a new reliable device for dielectric measurements.

Intensive studies have been done in the area of high frequency measurement of the complex permittivity of dielectric materials. The basic principles of operation include transmission line and cavity resonance [19, 20]. Transmission techniques are attractive for measurements over a very wide swept of frequencies. On the other hand cavity resonant techniques are limited to only one or a few frequencies, defined by the cavity dimensions. Furthermore, these techniques are destructive. The solutions to nondestructive dielectric measurements of material at high frequency are thus limited to transmission techniques using open-ended coaxial (OEC) probe [21–24], open-ended rectangular waveguide [25–28] and free-space method [29]. The latter two present frequency limitations that affect the size of the MUT to be used. Hence the most widely used technique in dielectric spectroscopy is using the OEC probe due to its simplicity and accuracy in broadband nondestructive measurements. However the OEC probe is recommended for measuring liquids and semi-solids [23, 30–32].

In this paper, we propose an improved method for dielectric measurements of an $N$-layer dielectric material at microwave frequencies using a parallel-plate waveguide probe. This device has been used previously for microwave detection of breast cancer [33]. Similar to [33], the method derives information from $S_{11}$ measurements. $S_{11}$ or reflection coefficient from the MUT translated to the admittance at the aperture of the parallel-plate waveguide probe allows the inverse problem of obtaining the complex permittivity of the MUT to be solved.

The remainder of the paper is organized as follows. Section 2 presents the admittance models for the parallel-plate waveguide probe radiating into a layered dielectric terminated by an infinite half-space; and terminated by a conducting sheet, developed using a method employing mode matching technique with Fourier transform. Subsequently in Section 3, numerical results are presented to illustrate the effectiveness of this method. Also the effects of air gap and slab thickness on the probe measurement are analyzed in the same section. Finally, the conclusions are summarized in Section 4.

## 2. APERTURE ADMITTANCE OF THE PARALLEL-PLATE WAVEGUIDE PROBE

The probe to be used as the dielectric measurement device is essentially a transverse electric and magnetic (TEM) mode-excited, parallel-plate waveguide opening onto a ground plane as depicted in Fig. 1. The aperture is in the $xy$ plane, positioned at $z = 0$. Evanescent $\mathrm{TM}_{0n}$ modes are assumed to co-exist near the probe end. Due to the symmetry of the problem, TE modes may be neglected. To simplify analysis, we consider the probe of width $2a$ is infinite in extent in the $y$-axis, with flanges infinite in extent in both the $x$- and $y$-axes.

The flanged probe acts as the microwave source radiating into the layered dielectric MUT. Each layer of the dielectric material is assumed to be homogeneous and isotropic, with a relative complex permittivity of $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$. The radiation fields into a stratified dielectric from this flanged guide have been suggested in [33, 34]. We extend and apply this theory to our method of nondestructive dielectric measurement of an $N$-layer stratified dielectric slab, backed and unbacked by a conducting sheet. The time harmonic variation of $e^{j\omega t}$ is assumed and suppressed throughout the paper.

### 2.1. Termination by an Infinite Half Space

Consider the parallel-plate waveguide probe radiating in the $N$-layer dielectric MUT (see Fig. 1). The $N$th layer is unbounded in the $z$-direction (Region $N$ is an infinite dielectric half space). The incident and reflected magnetic fields inside the parallel-plate waveguide are given respectively as

$$H_y^i(x,z) = H_0^I e^{-jk_c z} \tag{1}$$

$$H_y^r(x,z) = \sum_{m=0}^{\infty} c_m \cos a_m(x+a) e^{j\xi_m z} \tag{2}$$

where

$$\xi_m = \sqrt{k_c^2 - a_m^2} \tag{3}$$

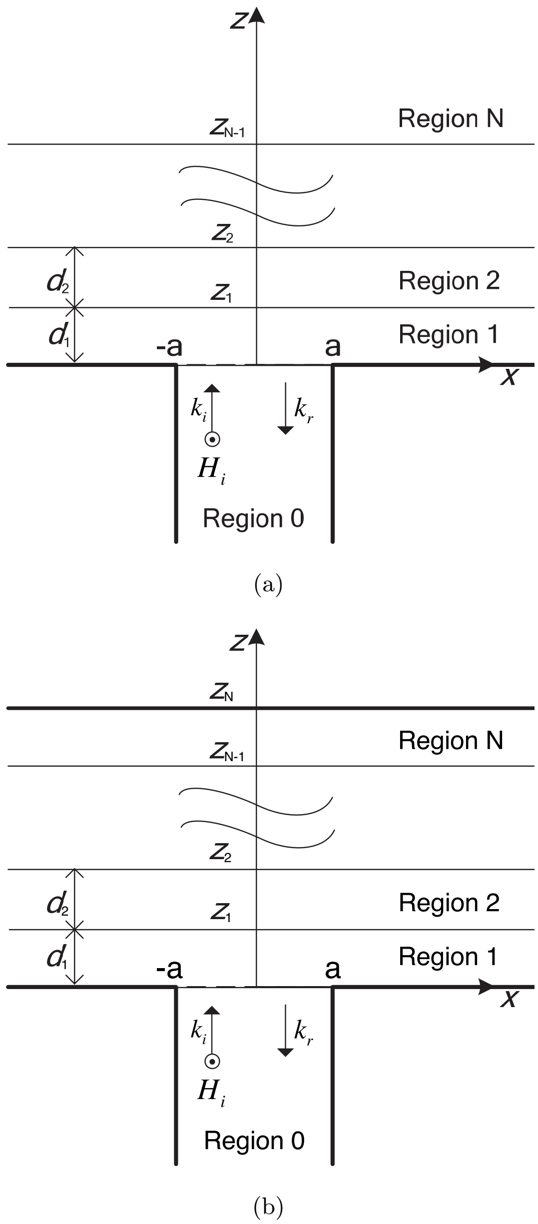



**Figure 1.** Geometry of the parallel-plate waveguide probe. (a) Radiation by a layered media terminated into an infinite half space. (b) Radiation by a layered media terminated into a PEC.

$$a_m = \frac{m\pi}{2a} \tag{4}$$

and $H_0^I$ is the amplitude of the incident magnetic field with wavenumber $k_c$ in the guide (Region 0).

The transmitted field outside the probe unbounded in Region $N$ in the spectral domain $\zeta$ can be represented as

$$H_y^N(x,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{H}_N^+(\zeta) e^{j\zeta x - jk_{z_N} z} d\zeta \tag{5}$$

where

$$k_{z_N} = \sqrt{k_N^2 - \zeta^2} \tag{6}$$

$\tilde{H}_N^+(\zeta)e^{-jk_{z_N}z_N}$ and $H_y^N(x, z_N)$ are Fourier transform pair. In the bounded Region $n$, $1 \leq n \leq N-1$, the field is

$$H_y^n(x,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left[\tilde{H}_n^+(\zeta)e^{-jk_{z_n}z} + \tilde{H}_n^-(\zeta)e^{jk_{z_n}z}\right] e^{j\zeta x} d\zeta \tag{7}$$

where

$$k_{z_n} = \sqrt{k_n^2 - \zeta^2} \tag{8}$$

$k_N$ and $k_n$ are the wavenumbers in the Regions $N$ and $n$ respectively.

The boundary conditions require tangential $E$ field continuity in the $x$-direction and tangential $H$ field continuity at $z_n = \sum_{i=1}^{n} d_i$, $1 \leq n \leq N-1$, that is

$$\begin{aligned} \tilde{E}_x^n(\zeta, z = z_n) &= \tilde{E}_x^{n+1}(\zeta, z = z_n) \\ \tilde{H}_y^n(\zeta, z = z_n) &= \tilde{H}_y^{n+1}(\zeta, z = z_n) \\ \tilde{E}_x^N(\zeta, z = z_N) &= 0 \end{aligned} \tag{9}$$

Conforming tangential $E$ field boundary condition at the aperture $(-a < x < a,\ z = 0)$ yields

$$\tilde{H}_1^+(\zeta) = \left(\frac{1}{1-\alpha_1(\zeta)}\right)\frac{\varepsilon_1}{\varepsilon_c}\left[H_0^I\xi_0 K_0(\zeta) - \sum_{m=0}^{\infty} c_m \xi_m K_m(\zeta)\right] \tag{10}$$

where

$$\alpha_1(\zeta) = \frac{\tilde{H}_1^-(\zeta)}{\tilde{H}_1^+(\zeta)} \tag{11}$$

$$K_m(\zeta) = \frac{j\zeta}{k_{z_1}(\zeta^2 - a_m^2)}[e^{-j\zeta a}(-1)^m - e^{j\zeta a}]. \tag{12}$$

Subsequently enforcing boundary conditions for each layer leads to recurrence relations as given below

$$\alpha_n = \frac{\tilde{H}_n^-(\zeta)}{\tilde{H}_n^+(\zeta)} = \left(\frac{1-\beta_n\gamma_{n+1}}{1+\beta_n\gamma_{n+1}}\right) e^{-j2k_{z_n}z_n} \tag{13}$$

where

$$\beta_n = \frac{\varepsilon_{rn}k_{z_{n+1}}}{\varepsilon_{rn+1}k_{z_n}} \tag{14}$$

and

$$\gamma_{n+1} = \frac{1-\alpha_{n+1}e^{j2k_{z_{n+1}}z_n}}{1+\alpha_{n+1}e^{j2k_{z_{n+1}}z_n}}. \tag{15}$$

As a consequence, the tangential $H$ field continuity in the aperture plane yields

$$H_0^I + \sum_{m=0}^{\infty} c_m \cos a_m(x+a) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{H}_1^+(\zeta)(1+\alpha_1)e^{j\zeta x}d\zeta$$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty}\left(\frac{1+\alpha_1}{1-\alpha_1}\right)\frac{\varepsilon_1}{\varepsilon_c}\left[H_0^I\xi_0K_0(\zeta) - \sum_{m=0}^{\infty} c_m\xi_mK_m(\zeta)\right]e^{j\zeta x}d\zeta. \tag{16}$$

Multiplying (16) by $\cos a_n(x+a)$ and integrating both sides with respect to $x$ from $-a$ to $a$, one obtains

$$\frac{\varepsilon_1}{\varepsilon_c}\left[H_0^I\xi_0J_{0n} - \sum_{m=0}^{\infty} c_m\xi_mJ_{mn}\right] = 2\pi a\left(H_0^I\delta_{n0} + c_n\right)\psi_n \tag{17}$$

where $\delta_{mn}$ represents the Kronecker delta, $\psi_0 = 2,\ \psi_1 = \psi_2 = \cdots = 1$, and

$$J_{mn} = \int_{-\infty}^{\infty} G(\zeta)\frac{\zeta^2\left[(-1)^m e^{-j\zeta a} - e^{j\zeta a}\right]\left[(-1)^n e^{j\zeta a} - e^{-j\zeta a}\right]}{k_{z_1}\left(\zeta^2 - a_m^2\right)\left(\zeta^2 - a_n^2\right)}d\zeta \tag{18}$$

where

$$G(\zeta) = \frac{1+\alpha_1}{1-\alpha_1}. \tag{19}$$

The value of $\alpha_1$ is found by using the recurrence relations in (13) to (15), starting calculations from $n = N-1$ with $\alpha_N = 0$.

After solving for the unknown coefficients $c_m$ in (17), the reflection coefficient at the aperture of the probe $\Gamma_0$ (which is of primary interest as other modes are evanescent) is given by

$$\Gamma_0(\omega) = -\frac{c_0}{H_0^I} \tag{20}$$

where $c_0$ is the amplitude of the dominant mode reflected magnetic field in Region 0.

Many practical applications involve a 2-layer case. Hence the explicit form of $G(\zeta)$ for $N = 2$ is presented. Applying the recurrence relations given in (13) to (15), $G(\zeta)$ is found to be

$$G(\zeta) = \frac{1 + j\beta_1 \tan(k_{z_1} d_1)}{\beta_1 + j \tan(k_{z_1} d_1)} \tag{21}$$

where $d_1$ is the thickness of the first layer of the dielectric MUT with wavenumber $k_1$.

The aperture admittance of the parallel-plate waveguide probe can thus be obtained by

$$y = \frac{1 - \Gamma_0}{1 + \Gamma_0}. \tag{22}$$

### 2.2. Termination by a PEC

The admittance at the aperture of the parallel-plate waveguide radiating into a layered dielectric media backed by a perfect electrical conductor (PEC) can be obtained in a similar manner as presented in Section 2.1 with the boundary conditions in (9) to be applied with

$$z_n = \sum_{i=1}^{n} d_i, \qquad 1 \le n \le N. \tag{23}$$

The recurrence relations in (13) to (15) apply with $\alpha_N$ defined as

$$\alpha_N = e^{-j2k_{z_N} z_N}. \tag{24}$$

Consequently, (17) to (19) are still applicable to obtain the reflection coefficient at the aperture of the probe. Hence the explicit formulation for $G(\zeta)$ for a 2-layer dielectric material backed by a PEC is given as

$$G(\zeta) = j\left[\frac{\beta_1 \tan(k_{z_1} d_1) \tan(k_{z_2} d_2) - 1}{\tan(k_{z_1} d_1) + \beta_1 \tan(k_{z_2} d_2)}\right] \tag{25}$$

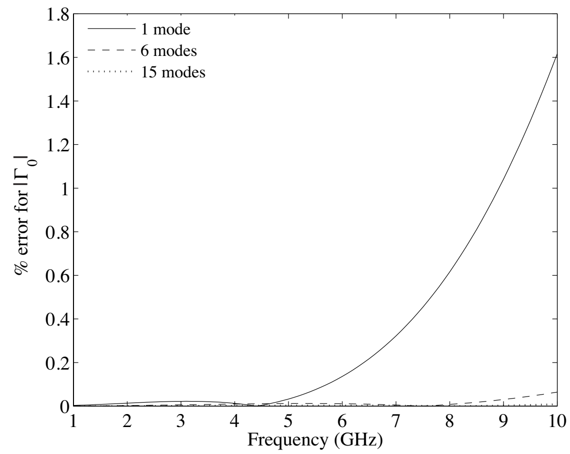
where $d_1$ and $d_2$ are the thicknesses of the first and second layer of the dielectric MUT with wavenumbers $k_1, k_2$ respectively.

## 3. NUMERICAL RESULTS AND DISCUSSIONS

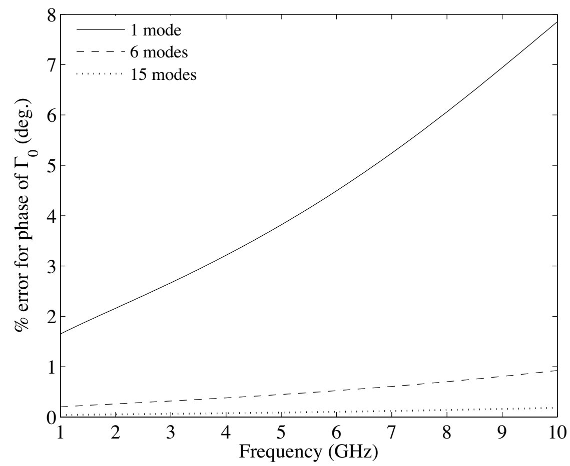
Numerical simulations have been conducted to verify the performance of the proposed technique for nondestructive measurement of the dielectric properties of layered media. Consider the parallel-plate waveguide probe is designed to have a next higher order mode cut-off frequency of more than 10 GHz, e.g., a probe with width $2a = 10\,\text{mm}$, with the dielectric filling between the plates $\varepsilon_{rc} = 2.54$.

As the solution of the reflection coefficient $\Gamma_n$ of the TEM and $\text{TM}_{0n}$ is dependent on the number of modes considered, the measurable reflection coefficient $\Gamma_0$ is computed for by considering different number of modes. It is assumed that the final convergence of the solution of $\Gamma_0$ is obtained by considering twenty modes. Figs. 2(a) and (b) show the plots of the percentage error of the magnitude and phase of $\Gamma_0$ for the parallel-plate waveguide radiating into an infinite free space for the case of considering one, six, and fifteen modes, with reference to that of twenty modes respectively. As observed in Figs. 2(a) and (b), to achieve a percentage error of less than 1% for both the magnitude and phase of $\Gamma_0$ it required to consider six modes or more. Hence due to practicality and ease of computations, henceforth for the computations of $\Gamma_0$, only six modes will be considered. It is noted that in the analyses of the reflection properties of the OEC [23] and open-ended rectangular waveguide [25], the number of modes considered sufficient for computations corresponds to six modes.

The effect of air gap on the reflection coefficient is of interest in many applications, especially in the measurement of dielectric properties of solids. In the case of the OEC, as the air gap presents a discontinuity between the MUT and the coaxial probe, there may exists a large error in the predicted complex permittivity. This accounts for the reason the probe is recommended for liquid and semi-solid measurements as good contact can be achieved. Therefore using air gap variation between the aperture and the MUT has been proposed as a means of calibration [22, 24]. In this paper, we simulated the dominant mode reflection coefficient $\Gamma_0$ as a function of air gap spacing $d_1$ between the measuring device and a lossy dielectric of infinite thickness, i.e., $N = 2$, $\varepsilon_{r1} = 1$, with $\varepsilon_{r2}$ arbitrarily selected to be $10 - j1$; for the case of using the OEC and parallel-plate waveguide probe for measurements. The OEC of inner radius $r_a$ and outer radius $r_b$ is assumed to have the dielectric filling of $\varepsilon_{rc} = 2.54$, with $r_b/r_a = 2.3$ [23]. It is simulated that $r_b = 5\,\text{mm}$. The reflection coefficient for using the OEC is calculated using the formulations in [23], with six $\text{TM}_{0n}$ modes used. These conditions for the OEC having used throughout every simulation.




(a)




(b)

**Figure 2.** Percentage error in the reflection coefficient $\Gamma_0$, considering different number of modes. (a) Magnitude. (b) Phase.

Figs. 3(a) and (b) show the influence of the air gap on the magnitude and phase of the reflection coefficients $\Gamma_0$ measured by the two different probes at 1 GHz. It is observed $\Gamma_0$ for the OEC approaches $1\angle 0°$ as the air gap increases beyond 1 mm. However in the case of using parallel-plate waveguide probe $\Gamma_0$ is distinguishable for different air gaps. With the same outer dimensions of the measuring device, the field penetration from the end of the parallel-plate waveguide probe is further than that of the OEC, hence multiple

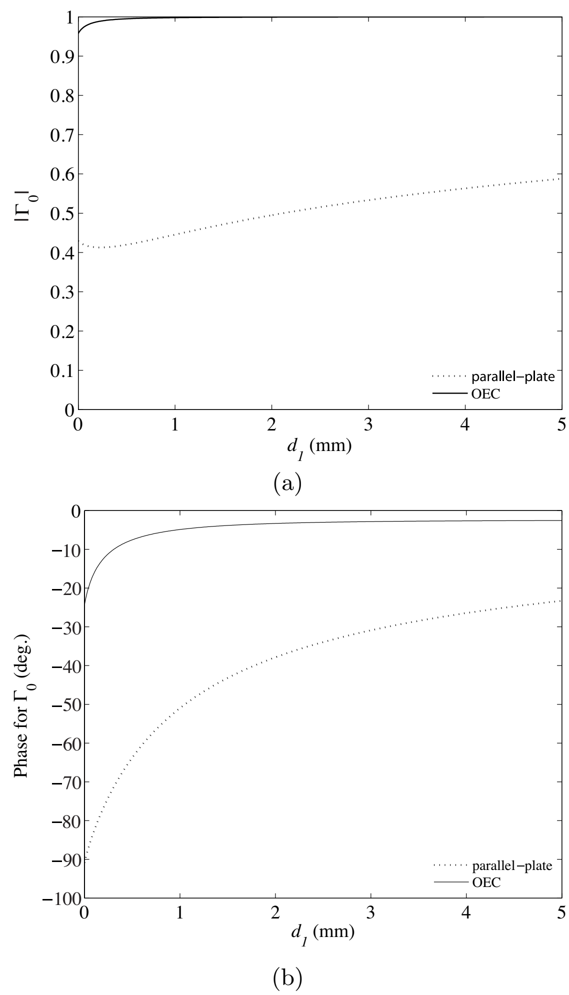


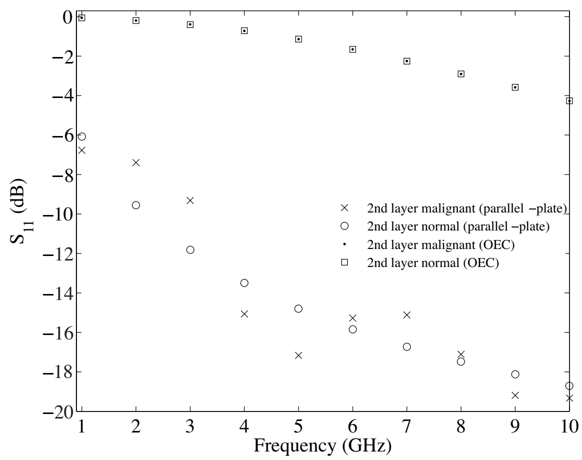

**Figure 3.** Reflection coefficient $\Gamma_0$ for dielectric of infinite thickness with varying air gap spacing $d_1$ between the measuring probe and the dielectric at 1 GHz. (a) Magnitude. (b) Phase.

calibration points (different air gaps in the calibration technique) can be used to render more accurate readings for solid measurements using the parallel-plate waveguide probe by taking into consideration $d_1$ in the solution of $\Gamma_0$.

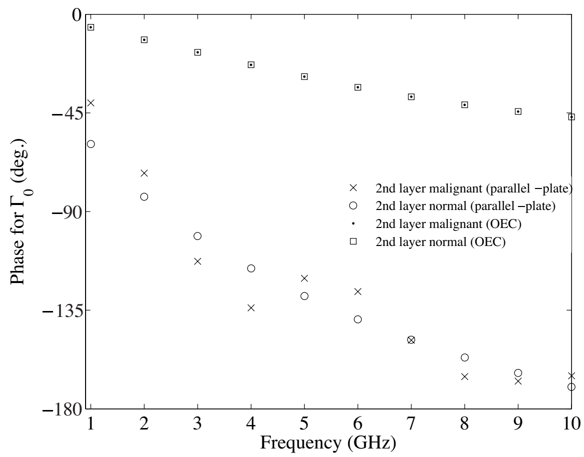
As the field penetration from the end of the OEC is minimal compared to that of the parallel-plate waveguide probe, thus the OEC may not be efficient for dielectric spectroscopy of biological tissues, for example, in determining malignant growth embedded in benign tissue. In the following, we present a comparative study of the efficiency in identifying a layer of malignant tissue beneath the benign tissue using the different probes. Assuming a 2-layer dielectric media, numerical calculations are done for two cases. Firstly consider the first layer of thickness $d_1 = 2\,\mathrm{cm}$ represents normal breast tissue with the second layer infinite in extent represents abnormal growth. The dielectric properties for the different tissues are as reported in [33]. Subsequently, it is simulated the second layer is having same $\varepsilon_r$ as the first layer, i.e., the dielectric is a homogeneous normal breast tissue.

It is evident in Fig. 4(a) that the fields radiated from the OEC which is capacitive in nature does not penetrate deep to interact with the second layer of the dielectric. The magnitude of $\Gamma_0$ for the OEC does not vary whether the complex permittivity of the second layer changes. On the contrary, in the same figure, $\Gamma_0$ for the parallel-plate waveguide probe is dependent on the complex permittivity of the second layer. The parallel-plate waveguide probe can distinguish if there is another layer of different medium embedded at some depth. Therefore this demonstrates the parallel-plate waveguide probe may be more suitable than the OEC to be used in microwave cancer diagnostics where it is important to identify any abnormal growth embedded within a normal tissue. Similar conclusion can be derived from Fig. 4(b) that shows the phase of $\Gamma_0$ for the two measuring probes.

Evaluation of the thickness of dielectric slabs is of great interest in many aspects of the industry, such as the monitoring of thickness variation of composite materials coatings on other substrates [26, 27]. Following, investigation on the effectiveness for nondestructive measurement of the thickness of a lossy dielectric slab using the parallel-plate waveguide probe and the OEC is presented. Consider a 2-layer dielectric slab backed by an infinite half-space, arbitrarily chosen to be $\varepsilon_{r1} = 5 - j0.05$ and $\varepsilon_{r2} = 50 - j0.5$ with a varying thickness $d_1$. The plots of the phase of $\Gamma_0$ measured by the parallel-plate waveguide probe and the OEC at 1 GHz for varying $d_1$ are given in Fig. 5 where it is observed that variations of less than 0.1 mm, in the thickness of the first layer dielectric $d_1$, may be detected by the parallel-plate waveguide probe if the measurement apparatus such as the vector network analyzer (VNA) can resolve a change of one degree in phase. This illustrates the sensitivity of the parallel-plate waveguide probe to different thickness $d_1$. However, it is identified in the same figure the OEC may detect the same variation of 0.1 mm only for $d_1$ less than 1mm where thereafter the sensitivity of the OEC decreases rapidly. The OEC may not distinguish the variations in $d_1$ for $d_1$ beyond 3 mm as the phase of $\Gamma_0$ converges after this thickness.




(a)




(b)

**Figure 4.** Reflection coefficient $\Gamma_0$ for 2-layer dielectric with $\varepsilon_{r2}$ having varying values. (a) Magnitude. (b) Phase.

From the plot of the magnitude of $\Gamma_0$ for the parallel-plate waveguide probe in Fig. 6, it is shown that $\Gamma_0$ is able to tolerate calibration noise (due to calibration of the probe with known loads). The parallel-plate probe is capable of measuring the thickness variations in $d_1$ as small as 0.25 mm for the first 1mm even if it is subjected to a calibration noise of 30 dB as indicated by the error bars in the figure. For $d_1$ greater than 1 mm, the parallel-plate probe is able to measure variations as small as 0.5 mm if it is subjected

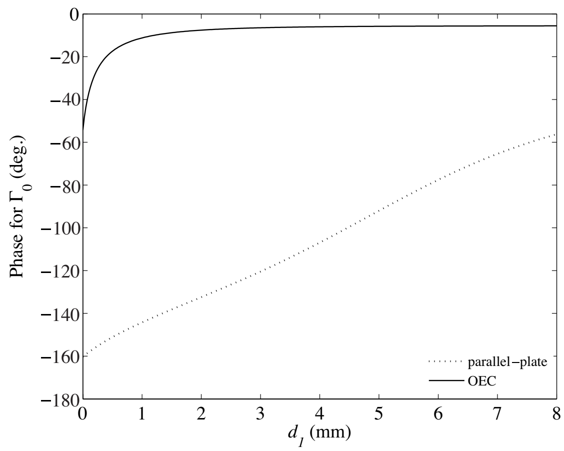



**Figure 5.** Phase of reflection coefficient $\Gamma_0$ for varying $d_1$ for the two different probes at 1 GHz.

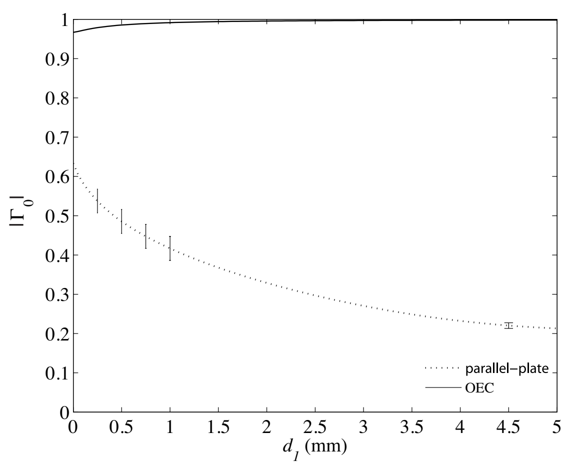



**Figure 6.** Magnitude of reflection coefficient $\Gamma_0$ for varying $d_1$ for the parallel-plate probe at 1 GHz.

to a calibration noise of 40 dB. As a consequence, the parallel-plate waveguide probe may be more suitable than the OEC for the evaluation of the thickness of a layered dielectric.

## 4. CONCLUSIONS AND FUTURE WORK

An improved method using a parallel-plate waveguide probe is proposed for nondestructive dielectric measurements. In the paper, we developed a simple solution for the aperture admittance of the parallel-plate probe radiating into a layered dielectric backed and unbacked by a PEC, derived from the reflection coefficient. Additionally, we have shown that only six modes are necessary to obtain the solution for the reflection coefficient for good accuracy. This is significant in the practical implementation of this technique when solving the inverse problem of extracting the complex permittivity of the material under test as computations will be easily facilitated. Numerical results have also shown that by using a calibration technique taking into consideration air gap variation, the parallel-plate probe may be effective in measuring the dielectric properties of solids. Furthermore, on the assumption that the dielectric properties of the layered media are known, the probe may be used for evaluation of the thickness of layers. Solving the inverse problem [35] will be addressed in the future work.

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