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Reconstruction of Relative Permittivity and Thickness Profiles of Different Dielectric Samples Using Time Domain Multiple Reflection Method

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Abstract

In this paper, a novel method involving multiple reflections has been proposed for the reconstruction of the relative permittivity and thickness pertaining to different dielectric samples from the measurement of the reflection coefficients only. The unique advantage of this method is no requirement of measurement of any additional parameter to determine relative permittivity and thickness profile of the sample. Thus, it provides a cost-effective solution. The accuracy of this method for reconstructing the permittivity and thickness of the dielectric wall is very high and the measured error is less than 0.26% for permittivity values and 1.4% for thickness values for the most optimized reconst1ructed values. This method has been verified for different samples having different thickness and hence the optimum thickness for each sample has been determined.

1. Introduction

In microwave imaging especially through-wall imaging, there is a need for the accurate determination of the relative permittivity and thickness of the wall for accurate localization and imaging of the target behind the wall [1]. In the recent past, several methods have been proposed for determining the relative permittivity and thickness of the wall [2]-[7]. However, most of these methods are based on the involvement of insertion transfer function, which is defined as the ratio of two frequency-domain signals measured in presence and absence of the concerned material under test, as well as the knowledge of reflection and transmission coefficients simultaneously [5, 6]. In practice, the measurement of transmission coefficient requires the access to the environment from both sides of the object. Although in defense applications, this is hard to realize. Till date, several methods have been incorporated to calculate relative permittivity from the data of reflection coefficients only but some additional materials like a large metal plate are involved to calibrate the reference measurement [2]-[4]. The additional materials not only increase the cost of the final product but also increase the overall data collection time.

In this paper, a novel method has been proposed for determining the relative permittivity and thickness of a wall by reflection coefficient measurement without the introduction of any additional material and thus reduces the data collection time. This method is based on the concept of multiple reflections within the wall. The time domain measurement has been used because it is very easy to analyze the output response in the time domain. The scope of this concept is not limited to the conventional wall only, but this principle can be used to find the permittivity and thickness profile of any dielectric sample which is available in slab form. It can also be used in monitoring the health of the building, ground-penetrating radar (GPR) and defense applications.

2. Principle

In the proposed method, an ultra-wideband horn antenna with 14 GHz bandwidth is used, which is placed in the far field with respect to the wall as shown in Figure 1. An ultra-wideband horn antenna is connected to a single port of a vector network analyzer (VNA) while the other port of VNA is matched terminated. When the plane wave 1 emitted from the antenna is incident on the wall as shown in Figure 1, then some part of the wave gets reflected and the rest part of the wave gets transmitted through the thickness of the wall. The reflected wave 2 from the front interface AD will provide the first peak P_{r1} as shown in Figure 1. The transmitted wave 3 travels through the dielectric and some portion of the wave gets reflected from the back-interface BC while the rest portion gets transmitted through the interface BC. The reflected wave 4 again strikes at interface AD where some portion of the wave gets transmitted in the form of wave 5 to provide the second peak P_{r2} as shown in Figure 1 and the remaining portion 6 gets reflected from the interface AD and travel within the wall and again get reflected from the interface BC. In this way, the wave undergoes multiple reflections within the wall.

The received power P_{r1} from the first peak i.e. the reflected power from the first interface AD, can be expressed in terms of cable loss, path loss and reflection coefficient according to equation (1) where C_1 is the two-way (transmitting and receiving) cable losses from VNA to antenna and the antenna feeding losses. L_1 is the two-way path loss from the antenna to the wall, R_1 is the reflection coefficient from the interface AD, *u(t)* is the unit step function and t_1 is the time corresponding to the first reflection peak for transmitted power P_t from the antenna [6].

$$P_{r1} = C_1.L_1.R_1.P_t.u\left(t - t_1\right) \qquad (1).$$

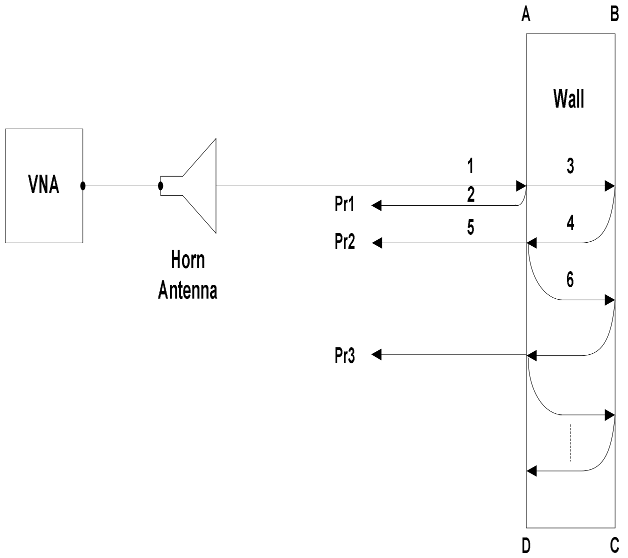

Figure 1. Block diagram of multiple reflections inside the wall.

The received power P_{rn} from the nth peak (n > 1) i.e. the reflected power due to multiple reflections within the wall, can be expressed according to equation (2) where C_n is the two-way (transmitting and receiving) cable losses from VNA to antenna and the antenna feeding losses. L_n is the two-way path loss from the antenna to the wall. R_n corresponds to the (n-1) times reflection coefficient from the interface BC and (n-2) times reflection coefficient from the interface AD. T_n is the two times transmission coefficient (forward and reverse) at the interface AD and t_n is the time corresponding to the nth reflection peak.

$$P_{rn} = C_n.L_n.R_n.T_n.P_t.u\left(t - t_n\right) \qquad (2).$$

Assuming identical cable and path losses in all the reflections involved, equation (3) can be obtained to derive the reflection coefficient and hence to reconstruct relative permittivity and thickness of the wall from equations (4) and (5) respectively where d is the thickness of the wall. Γ corresponds to the reflection coefficient and $\Delta\tau = t_2 - t_1$ is the time difference between the first and second peak.

$$\frac{P_{r1}.P_{r3}}{\left(P_{r2}\right)^2} = \left[\frac{|\Gamma|^2}{1-|\Gamma|^2}\right]^2 \qquad (3).$$

$$\varepsilon_r = \left[\frac{1+|\Gamma|}{1-|\Gamma|}\right]^2 \qquad (4).$$

$$d = \frac{c.\Delta\tau}{2.\sqrt{\varepsilon_r}} \qquad (5).$$

3. Simulation and Measurement Setup

The simulation has been performed in CST microwave studio. A dielectric rectangular slab made with three different samples ($\varepsilon_r = 9.9, 6, 3.5$) are exposed to transverse electromagnetic (TEM) plane wave which is incident normally on the front surface. The ultrawideband frequency range of 1-15 GHz has been taken for the simulation.

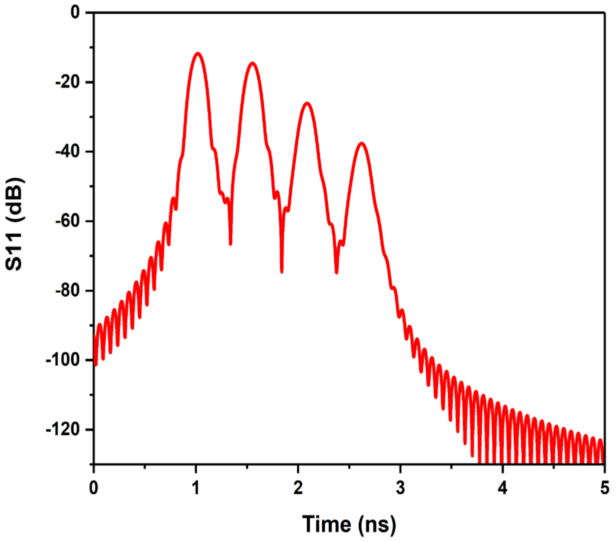

Figure 2. Time domain reflections graph of Alumina with 25 mm thickness.

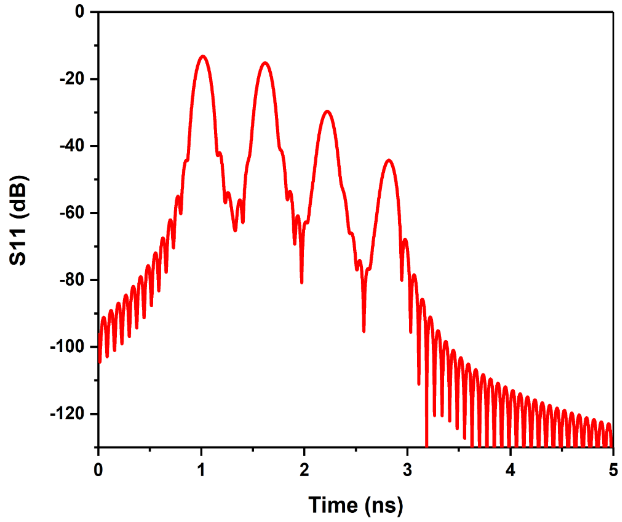

Figure 3. Time domain reflections graph of Beryllia with 35 mm thickness.

Table 1. Reconstructed relative permittivity and thickness profiles for three samples with different thickness.

1-15 GHz		**Different dielectric samples used for reconstruction**					
		Alumina (ε_r = 9.9)		**Beryllia (ε_r = 6.5)**		**Rogers RO 3035 (ε_r = 3.5)**	
S.No.	**Thickness (in mm)**	**Relative Permittivity**	**Thickness (in mm)**	**Relative Permittivity**	**Thickness (in mm)**	**Relative Permittivity**	**Thickness (in mm)**
1	**10**	9.6519	10.3069	7.0664	10.2196	2.2936	12.2272
2	**15**	10.1751	15.2524	6.9065	15.2971	4.4012	15.8352
3	**20**	9.8524	20.3803	6.5396	20.298	3.7548	20.3413
4	**25**	**9.9248**	25.4431	6.4728	25.3755	3.6127	25.3524
5	**30**	9.8469	30.568	6.5225	30.447	3.5516	30.3635
6	**35**	9.84	35.6357	**6.498**	35.5245	3.5122	35.4789
7	**40**	9.8199	40.7605	6.4764	40.596	**3.4952**	40.5863

Table 2. Error (in %) analysis of the relative permittivity and thickness profiles for three samples with different thickness.

1-15 GHz		**Different dielectric samples used for reconstruction**					
		Alumina (ε_r = 9.9)		**Beryllia (ε_r = 6.5)**		**Rogers RO 3035 (ε_r = 3.5)**	
S.No.	**Thickness (in mm)**	**Relative Permittivity**	**Thickness (in mm)**	**Relative Permittivity**	**Thickness (in mm)**	**Relative Permittivity**	**Thickness (in mm)**
1	10	2.506061	3.069	8.713846	2.196	34.46857	22.272
2	15	2.778788	1.682667	6.253846	1.980667	25.74857	5.568
3	20	0.480808	1.9015	0.609231	1.49	7.28	1.7065
4	25	**0.250505**	1.7724	0.418462	1.502	3.22	1.4096
5	30	0.536364	1.893333	0.346154	1.49	1.474286	1.211667
6	35	0.606061	1.816286	**0.030769**	1.498571	0.348571	1.368286
7	40	0.809091	0.363077	0.363077	1.49	**0.137143**	1.46575

The reflection coefficient has been computed and converted into the time domain. The same procedure has been repeatedly carried out for different thickness values of the samples. The time domain reflections graphs of Alumina corresponding to 25 mm thickness and Beryllia with 35 mm thickness are shown in Figure 2 and 3 respectively. The first peak represents P_{r1}, while the second and third peaks represent P_{r2} and P_{r3} respectively.

The reflected powers P_{r1}, P_{r2} and P_{r3} for Alumina are -11.78 dB, -14.58 dB and -26.08 dB respectively while for Beryllia they correspond to -13.25 dB, -15.18 dB and -29.68 dB.

4. Results and Discussion

Table 1 represents reconstructed relative permittivity and thickness values for the three samples. The original thickness of the sample taken during the simulation has been mentioned in Table 1 along with the reconstructed thickness values. It is observed that the permittivity and thickness profiles have been accurately reconstructed for different thickness values of the wall. For Alumina, the best result is obtained at the 25 mm thickness. For Beryllia and Rogers RO 3035, the best results are obtained at 35 mm and 40 mm thickness respectively. Since the range resolution for 1-15 GHz bandwidth is 10.714 mm, the reconstructed results are not in good matching with the original values for the 10 mm thickness of the dielectric sample under consideration.

In Table 2, the error (in percentage) analysis of different thickness values of the sample (Alumina, Beryllia and Rogers RO 3035) is shown. It can be observed that 0.25% error can be achieved in relative permittivity value for Alumina at 25 mm thickness, 0.03% error in relative permittivity value for Beryllia at 35 mm thickness and 0.14% error in relative permittivity value for Rogers RO 3035 at 40 mm thickness where the best-reconstructed values have been achieved.

One interesting thing to observe in error analysis of relative permittivity value is that the error decreases as thickness increases to the optimum thickness and then it starts increases as the thickness increases from that optimum thickness. As an example, in case of Alumina slab, the error decreases with the thickness till 25 mm and then it starts increasing with thickness after 25 mm as shown in Figure 4. The same case with Beryllia, the error decreases with the thickness till 35 mm and then it starts increases with the increase in thickness.

Error in thickness profile is almost constant (varying around 1% - 2%) for all the cases. For Alumina at 25 mm thickness, an error of 1.77% is observed while approximately 1.4% for Beryllia and Rogers RO 3035 at optimum thickness have been computed.

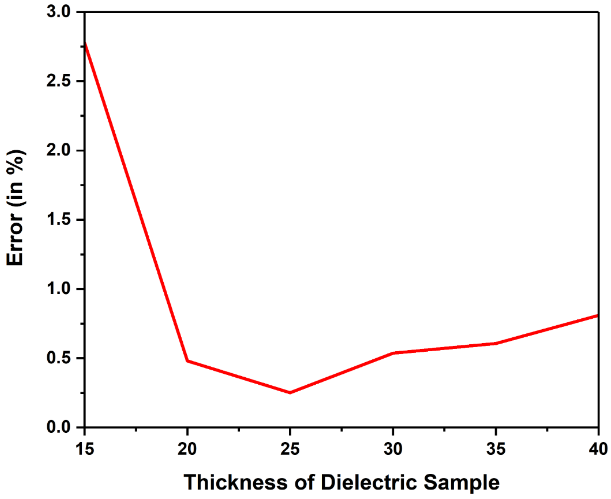

Figure 4. Variations of error (in %) in relative permittivity profile referred to the thickness of the Alumina ($\varepsilon_r = 9.9$).

5. Conclusion

In this paper, a novel time-domain method has been proposed for reconstructing the relative permittivity and thickness of the wall by using only the reflection coefficient. This method also holds good if the wall may be replaced by the slab and the deviation from the original value is very small. The relative permittivity and thickness values have been successfully reconstructed for different samples and the optimum thickness is also found for all the samples. It has been observed that the error (in %) in thickness values remain almost constant while error (in %) in relative permittivity values first decreases with increase in thickness till some optimum thickness and then it increases with the increase in thickness of the sample.

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7. References

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