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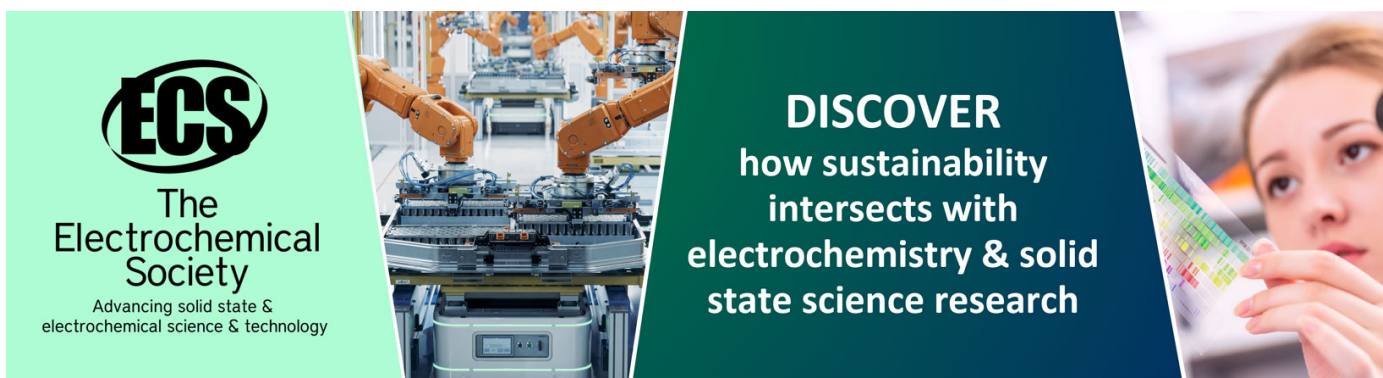
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Microwave Absorption Properties of PTFE Using T/R Rectangular Waveguide, Nicholson-Rose-Weir, and Finite Element Method

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Abstract. In this manuscript, the S-parameters, reflection and transmission coefficients, of PTFE at different thicknesses for microwave absorption applications were investigated in conjunction with WR90 T/R rectangular waveguide. Subsequently, the reflection and absorption shielding effectiveness SE_R and SE_A values were calculated using the measured S-parameters values, in which an inversely proportional relation was found. Furthermore, using Nicholson-Rose-Weir (NRW) and Finite Element Method (FEM) approaches, the measured S-parameters were validated. Herein, the mean relative errors were calculated; in particular, it was found that the FEM delivers an upright agreement with the measured data in comparison to the utilized NRW. This suggests the usefulness of the FEM approach as a low-cost alternative for the actual laboratory investigation.

Keywords: S-parameters, Shielding effectiveness, FEM, NRW

1. Introduction

Solid materials properties, such as reflection and transmission coefficients and/or microwave absorption, are of great importance due to their required knowledge in a number of applications such as telecommunication, microelectronics, aerospace...act [1-6]. Over the past decades, several approaches were well-developed and consequently applied to investigate both transmission and reflection coefficients and microwave absorption properties. As such, closed waveguide, free-space, and cavity perturbation are among the most popular techniques utilized for the evaluation of microwave absorption properties. However, the aforementioned approaches/techniques present a number of disadvantages. In particular, the stated closed waveguide approach has relatively low precision in comparison to the other two techniques; whereby the low precision is attained as a result of the cross-sectional area uniformity of the sample under test and any possibility of air-gaps [7-9]. In the meanwhile, free-space approach is utilized to characterize large dimensions' samples. However, diffractions from sample's edges, undesirable reflections, and complications of imposing a focused wave beam on a limited area result in low measurement accuracy [10-12]. Moreover, the so-called resonant cavity or cavity perturbation approach provides higher accuracy than the free-space approach,



yet limited frequency range applied and sensitivity of the design parameters in this technique are considered drawback [13-15]. Therefore, the search of an enhanced pathway to deliver a precise and accurate data is of great need.

In this attempt, the proposed manuscript aims to demonstrate the measurement and evaluation of microwave absorption properties for a series of PTFE samples with different thicknesses. The S-parameters were measured using T/R rectangular waveguide in conjunction with network analyzer, while the evaluation of the measurement accuracy was accomplished using NRW and FEM.

2. Methodology and procedures

2.1. Measurement setup

The PTFE samples were cut into the required dimensions with rectangular shape ($22 \times 11 \times 15 \text{ mm}$; $22 \times 11 \times 30 \text{ mm}$; $22 \times 11 \times 50 \text{ mm}$) as width, height, and thickness, respectively. It is, therefore, the samples were denoted as 15 mm, 30 mm, and 50 mm. Subsequently, the fabricated samples were placed, in turn, inside an X-band waveguide (WR90, 8-12 GHz) to perform the microwave absorption measurements. Herein, Agilent vector network analyzer (Agilent 8720) was employed to measure the S-parameters on the utilized PTFE samples which correspond to the transmission and reflection coefficients, S_{11} and S_{21} , respectively. The measurement setup is illustrated in Figure 1. Prior to measurements and to perform accurate error-free measurements, full two-port calibration procedure was primarily executed.

The complex permittivity, which was applied as an initial input for the theoretical calculation, of the PTFE samples was measured using RF Impedance/Material analyzer on direct current-voltage measurement technique. The real part of the complex permittivity (ϵ') is exemplified by the electromagnetic waves storage in the material, while the imaginary part (ϵ'') is considered as the energy dissipation [16].

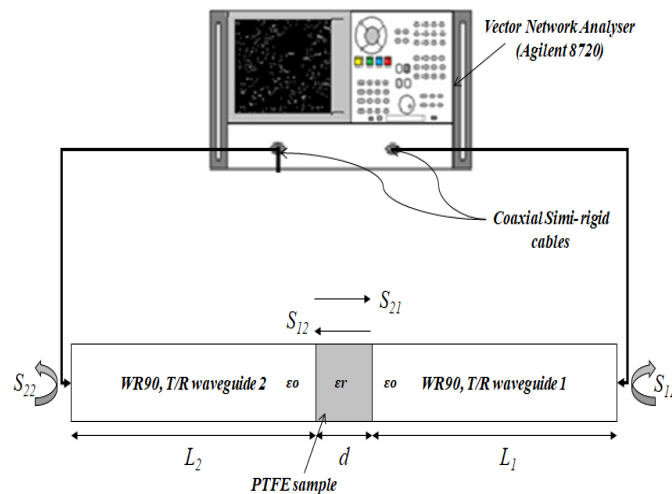


Figure 1: Schematic illustration of the measurements setup.

2.2. Theoretical concept

Continuously, as elaborated in Figure 1, both transmission and reflection coefficients can be calculated in accordance with NRW technique [17, 18]. Herein, the impedance of each presented medium is correlated to the complex permittivity as follow:

$$Z_{I,S,III} = \frac{Z_0}{\sqrt{\epsilon_{I,S,III}'^*}} \quad (1)$$

where the mentioned impedance in media *I*, *II*, and *III* are represented by $Z_{I,S,III}$, respectively, while $Z_0 = \sqrt{\mu_0/\epsilon_0}$ is the impedance of free space (medium *I* and *II*). Hence, both reflection and

transmission coefficients can be evaluated using Equations (2) and (3), taking into consideration the boundary conditions ($z = 0, z = d$).

$$S_{11} = \frac{E_{r0}}{E_{i0}} = \frac{(Z_{III} + Z_s)(Z_s - Z_I) \exp(-\gamma_s d) + (Z_{III} - Z_s)(Z_s + Z_I) \exp(\gamma_s d)}{(Z_{III} + Z_s)(Z_s - Z_I) \exp(-\gamma_s d) + (Z_{III} - Z_s)(Z_s + Z_I) \exp(\gamma_s d)} \quad (2)$$

$$S_{21} = \frac{E_3^+}{E_{i0}} = \frac{4(Z_s)Z_{III}}{(Z_{III} + Z_s)(Z_s + Z_I) \exp(-\gamma_s d) + (Z_{III} - Z_s)(Z_s - Z_I) \exp(-\gamma_s d)} \quad (3)$$

where γ_I, γ_s , and γ_{III} are known as the propagation constants in each mentioned media.

The S-parameters can then be calculated as follow:

$$S_{11} = \frac{\Gamma_a + \Gamma_b P_{theory}^2}{1 + \Gamma_a \Gamma_b P_{theory}^2} \quad (4)$$

$$S_{21} = \frac{(1 + \Gamma_b) P_{theory}}{1 + \Gamma_a \Gamma_b P_{theory}^2} \quad (5)$$

In Equations (4) and (5), Γ_b and Γ_a are the reflection coefficients at $Z = d$ and $Z = 0$, respectively, while the propagation factor of the PTFE sample is represented by the term P_{theory} . As such, it could be supposed that $Z_{III} = Z_I$ and/or $\Gamma_b = \Gamma_a = P_{theory}$, since media III and I are sample-free. Thus, both equation (4) and (5) can be further shortened/simplified as:

$$S_{11} = \frac{(1 + P_{theory}^2) \Gamma_{theory}}{1 + \Gamma_{theory}^2 P_{theory}^2} \quad (6)$$

$$S_{21} = \frac{(1 + \Gamma_{theory}^2) P_{theory}}{1 + \Gamma_{theory}^2 P_{theory}^2} \quad (7)$$

Within the FEM, the model is consisted of two T/R rectangular waveguide for electromagnetic propagation. The inner structure of the T/R waveguide is a typical decent conductor, silver for instance. The port is usually excited using transverse electric (TE) mode. In the meanwhile, the frequencies (X-band) are chosen so that the TE_{10} mode is the sole propagation arrangement. The cut-off frequency can be given systematically as follow:

$$f_c = \frac{c}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \quad (8)$$

where the mode number is represented by the symbols m and n and c is the speed of light. It should be mentioned that within TE_{10} mode, $m = 1$ and $n = 0$. Taking into consideration the rectangular cross-section, ($a = 2.285$ and $b = 1.143$ cm) the pronounced TE_{10} mode is the singular mode which propagates within frequency range 8-12 GHz.

The element matrices in the FEM geometry can be assembled over all the tetrahedron elements where the elements of element matrices are given by:

$$S_{el}(j, i) = \frac{1}{\mu_r} \iiint (\nabla \times \vec{W}_j \cdot \nabla \times \vec{W}_i - k_0^2 \epsilon_r \vec{W}_i \cdot \vec{W}_j) dv + \left(\frac{j\omega\mu}{\mu_r}\right) \sum_{p=0}^{\infty} Y_p^I \left(\iint \vec{W}_j \cdot \vec{e}_p(x, y) ds \cdot \iint \vec{W}_i \cdot \vec{e}_p(x, y) ds \right) \quad (9)$$

$$v(j) = 2 \left(\frac{j\omega\mu}{\mu_r}\right) \cdot Y_0^I \cdot \iint \vec{W}_j \cdot \vec{e}_0(x, y) ds \quad (10)$$

Herein, in order to obtain a global matrix equation over all the tetrahedron elements:

$$[S] \cdot \{N_i\} = \{v\} \quad (11)$$

The solution vector $[N_i]$ of the matrix is then used to determine reflection and transmission coefficients at the reference plane S_1 and S_2 [18, 19]:

$$a_0 = \iint \vec{E}|_{\text{over } S_1} \cdot \vec{e}_0 \, ds - 1 \quad (12)$$

$$a'_0 = \iint \vec{E}|_{\text{over } S_2} \cdot \vec{e}_0 \, ds \quad (13)$$

3. Results and discussion

The variation of the magnitude of reflection and transmission coefficients, $|S_{11}|$ and $|S_{21}|$, for PTFE samples at different thicknesses (15, 30, and 50 mm) are demonstrated in Figure 2 (a, b, and c). Magnitudes of $|S_{11}|$ and $|S_{21}|$ are demonstrated along y-axis, in the range from 0 to 1 with respect to the frequency range from 8 to 12 GHz along x-axis. There are two curves in these diagrams named $|S_{11}|$ and $|S_{21}|$ for magnitude of reflection coefficient (lower) and magnitude of transmission coefficient (upper), respectively. It was found from the presented results that the summation of the values of $|S_{11}|$ and $|S_{21}|$ should be constantly around unity, therefore, increasing in either one results a reduction in another where higher value of $|S_{11}|$ resulted in lower value of $|S_{21}|$. In particular, the magnitudes of $|S_{11}|$ were found to be 0.260, 0.304, and 0.351 for 15 mm, 30 mm, and 50 mm, respectively. Whereas the $|S_{21}|$ values for 15 mm, 30 mm, and 50 mm were found to be 0.875, 0.891, and 0.865, respectively. Additionally, it was found that increasing the thickness of the PTFE sample resulted in higher $|S_{11}|$ and subsequently lower $|S_{21}|$. The attained results are in a good agreement with the impedance mismatched theory in which a linear relation between the dielectric properties and the S-parameters are elaborated [20]. It is worth mentioning that the curve shaped ripples in the $|S_{21}|$ measurements were due to the internal surface roughness of the waveguide, possibility of air gap between the sample and the internal walls of the waveguide, surface irregularity of the absorber sample and certain voids in the sample... etc.

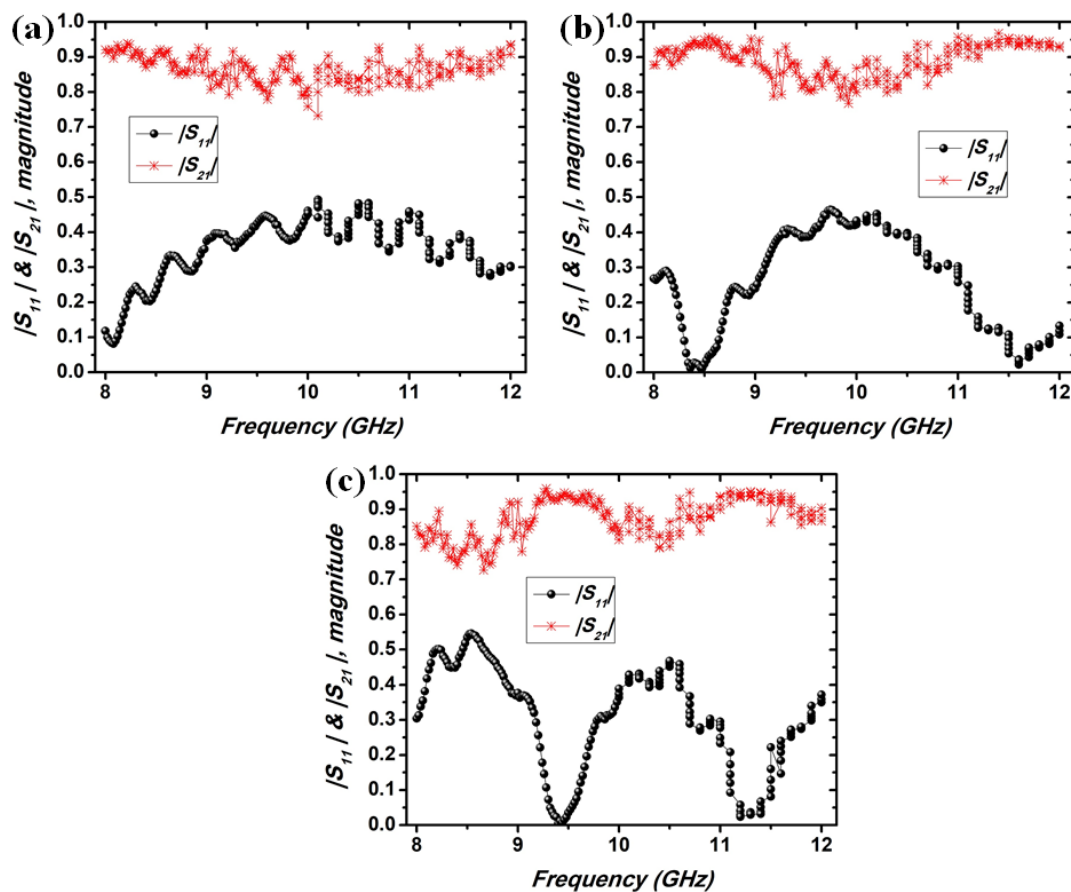


Figure 2. Measured S-parameters of (a) 15 mm, (b) 30 mm, and (c) 50 mm.

The shielding effectiveness attained due to reflection and absorption, SE_R and SE_A , are calculated in accordance with Equations (14) and (15) by which the attained results are presented in Figure 3 as a function of the used thickness (15, 30, and 50 mm) [1, 21]. It is clear to be noticed from the Figure that increasing the material thickness resulted in higher values of SE_R and SE_A . Specifically, increasing the PTFE thickness from 15 to 50 mm exhibited SE_R values of 1.308 and 1.878 dB, respectively. While SE_A values were increased from 0.728 to 1.248 dB. It can be concluded that the utilized PTFE possesses a higher tendency to reflect/absorb electromagnetic waves in the X-band frequency range (8 – 12 GHz) at higher thickness. This phenomenon could be attributed to the multiple reflection within the PTFE at higher thickness.

$$SE_R(dB) = -10 \log(1 - R) \quad (14)$$

$$SE_A(dB) = -10 \log(1 - A_{eff}) = -10 \log T / (1 - R) \quad (15)$$

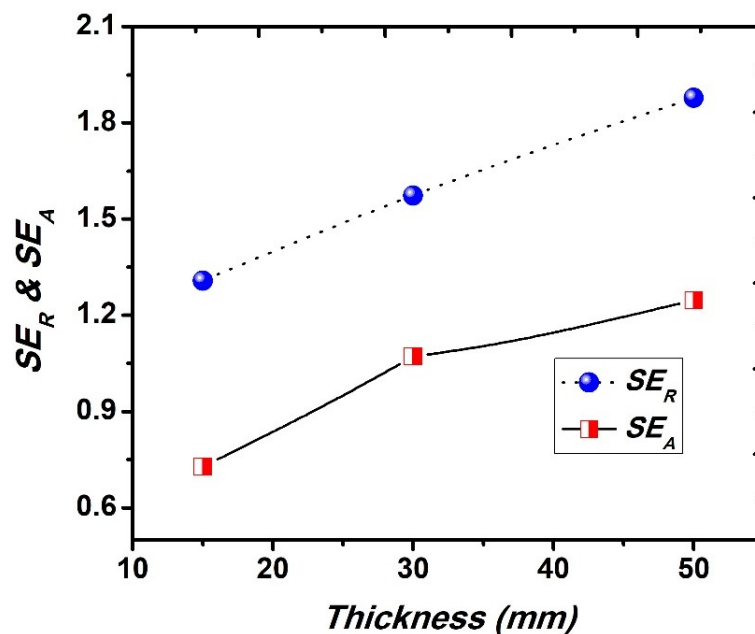


Figure 3. Shielding effectiveness due to reflection (SE_R) and absorption (SE_A) at different sample thickness.

Figure 4 illustrates a logarithmic scale of the measured $|S_{11}|$ and $|S_{21}|$ via R/T rectangular waveguide alongside the estimated values using NRW and FEM approaches. Higher PTFE thickness resulted in higher $|S_{11}|$ and continuously lower $|S_{21}|$ values. The cut-off frequency attained within the $|S_{21}|$ outcomes using FEM is observed as two-modes in m and one-mode in n . This could be due to the fact, in accordance with Equation (8), that the cut-off frequency depends basically on the number of modes; whereby increasing the number of modes results in higher cut-off frequency [22]. In the meanwhile, Table 1 tabulates the mean relative error between the measured values and the estimated ones, in which the outcomes presented in Table 1 were acquired based on Equation (16) as follow:

$$relative\ error\ S_{11} = \frac{1}{201} \sum_{i=1}^{i=201} \left(\frac{|S_{11}(meas.) - S_{11}(NRW, FEM)|}{S_{11}(meas.)} \right) \quad (16)$$

The mean relative error in term of $|S_{21}|$ was also calculated using the same aforementioned equation with respect to the symbol utilized.

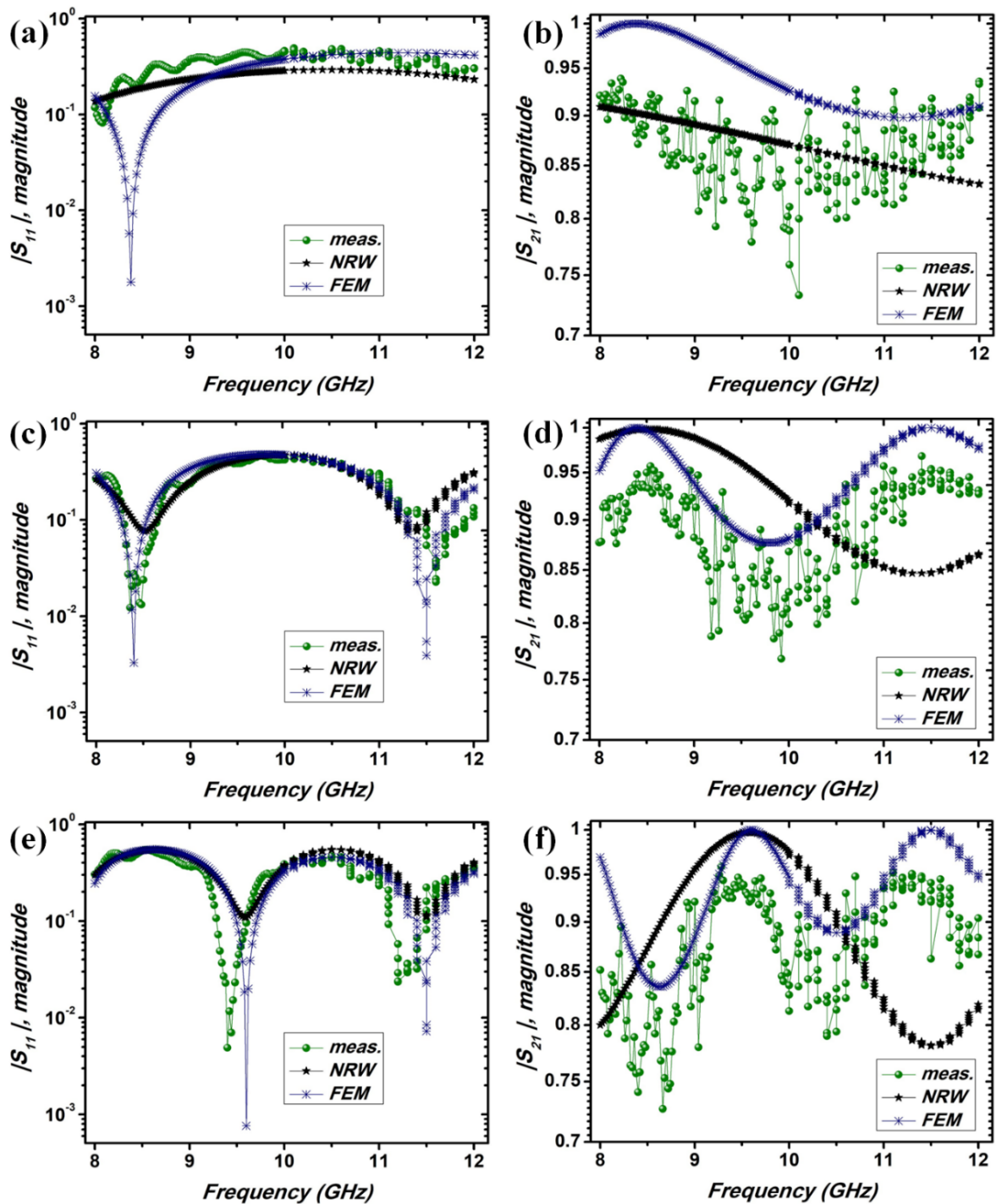


Figure 4. Measured and estimated S-parameters using R/T rectangular waveguide, NRW, and FEM, respectively; (a) 15 mm $|S_{11}|$, (b) 15 mm $|S_{21}|$, (c) 30 mm $|S_{11}|$, (d) 30 mm $|S_{21}|$, (e) 50 mm $|S_{11}|$, and (f) 50 mm $|S_{21}|$.

Herein, the results demonstrated in Table 1 suggest that the applied FEM showed higher accuracy than the NRW. This particular observation was noticed in the $|S_{11}|$ profile along the thickness range (15, 30 and 50 mm). However, in the $|S_{21}|$ profile, NRW exhibited almost higher, if not similar, accuracy in comparison with FEM. This is because of the calculation of the S-parameters using NRW involves several approximations that are mostly eliminated with the FEM approach. This in turn

suggests that the NRW requires further improvement through a mathematical optimization. Additionally, the mean relative error is believed to be due to the fact that the input dielectric constant and loss factor are fitted approximately to a normal distribution with center frequency at 10 GHz.

Table 1. Mean relative error of $|S_{11}|$ and $|S_{21}|$ using FEM and NRW.

Sample	Mean measured S-parameters		S_{11}		S_{21}	
	S_{11}	S_{21}	NRW	FEM	NRW	FEM
15 mm	0.351	0.865	0.1912	0.1326	0.0733	0.0791
30 mm	0.260	0.891	0.4480	0.0703	0.0341	0.0621
50 mm	0.304	0.875	0.2050	0.0710	0.016	0.0650

4. Conclusion

The reflection and transmission coefficients measurements using R/T rectangular waveguide were successfully demonstrated for PTFE with different thicknesses. In addition, the shielding effectiveness due to reflection and absorption of the utilized material was also presented. In particular, the highest SE_R and SE_A values were noticed at higher thickness of PTFE; there were 1.878 and 1.248 dB, respectively. Furthermore, a detailed comparison between the measured $|S_{11}|$ and $|S_{21}|$ as well as the estimated ones were elucidated using two different approaches; namely, NRW and FEM. Within this investigation, it was found that, generally, FEM deliver higher accuracy than NRW, particularly in the $|S_{11}|$ profile.

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