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DETERMINATION OF REFLECTION AND TRANSMISSION COEFFICIENT OF PTFE AT X-BAND FREQUENCY USING NRW AND FEM METHODS

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ABSTRACT

This paper presents a comparison of measurement results of polytetrafluoroethylene (PTFE) is loaded waveguide between Nicolson-Ross-Weir (NRW) method and Finite Element Method (FEM).The permittivity of PTFE values obtain from optimization technique and errors analysis have been conducted for scattering parameters in calculation and simulation results, variation mean relative errors with thickness of sample have been found and plotted.

INTRODUCTION

Application of materials in aerospace, microwave, microelectronics and communication industries requires the exact knowledge of material parameters such as reflection and transmission coefficient. Over the years many methods have been developed and used for measuring [1]. The most accurate measurement at high frequency can be done using the high Q resonant cavity technique [2].However; the main disadvantage of the cavity method is that the measured results are applicable only over a narrow frequency band. In transmission/reflection waveguide method (TR) an isotropic material sample with specific length is positioned in waveguide and scattering parameter have been defined by using an automatic network analyzer(VNA)in X-band frequency. Network analyzer was calibrated by implementing a standard full two-port calibration technique (SOLT). The material sample used in these measurements is usually of a cross section which is the same as that of the transmission line. The uniform cross section of the sample is selected so that a dominant mode analysis is sufficient and accurate for measuring the material constants.

The complex permittivity of the samples are measured using (TR) method based on the Nicolson and Ross [3], and Weir [4], and Baker-Jarvis *et al.* [5] algorithms for the characterization of isotropic solid materials. This experimental technique is based on the measurement of the scattering parameters (*S*- Parameters) of a sample of the test material.

In the present report, COMSOL software [6] based on the Finite Element Method (FEM) has been used to simulate rectangular waveguide with three dimension of the

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geometry. The model consists a pair of rectangular waveguides with microwave propagation transition between them. The propagating mode through the rectangular waveguide used in this study is the TE_{10} mode. The mode of incoming wave is specified and mode of the outgoing wave is given from an eigenmode analysis on the cross section of waveguide. This model applies the RF Module's Port boundary condition for the wave propagation problem. With this boundary condition the software computes the scattering parameters as a function of the dielectric constant automatically.

METHODOLOGY

Finite element method

The wave equation for the waveguide is:

$$\nabla \times (\mu_r^{-1} \nabla \times E) - k_0^2 (\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0}) E = 0 \qquad (1)$$

Where μ_r denotes the relative permeability, and k_0 the free space wave number. j the imaginary unit, σ the conductivity, ω the angular frequency, ε_r the relative permittivity, and ε_0 the permittivity of free space.

Because of the versatility to conform to many shapes, the element chosen to discretize the waveguide space is a tetrahedron, shown in Figure 2.

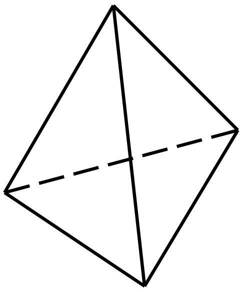

Figure 1: Tetrahedron element for waveguide meshes discretization

As a first step the Cross-section of the waveguides is drawn in two dimensions, with the material sample aligned. Then a mesh consisting of triangles is generated. The number of triangles increases with the electrical density of the material sample. The two-dimensional mesh is extruded into depth with a finite number of layers, producing triangular- prism elements which in turn axe partitioned into tetrahedral. In this way the three- dimensional waveguide is generated. Mesh of the waveguide with material sample inside has been shown in Figure 2.

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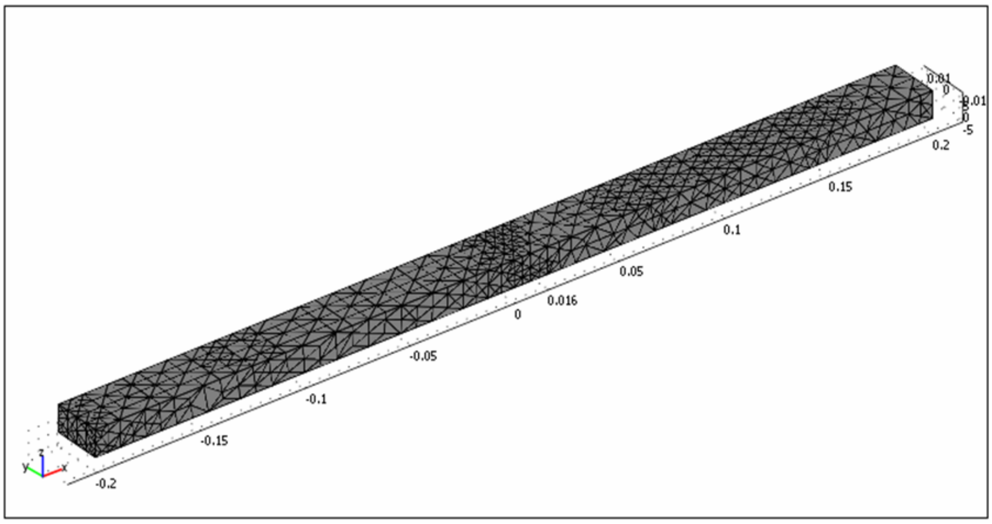

Figure 2: Mesh for the waveguide with material sample inside

Within each tetrahedron the unknown field can be interpolated from each node value by using the first order polynomial. With this definition of the basis (interpolation), the electric field inside a single Tetrahedron can be expressed as

$$E^e = \sum_{i=1}^{6} N_i^e \, E_i^e(x,y,z) \tag{2}$$

Where N_i^e, i=1, 2, 3...6 are the six complex amplitudes of electric field associated with the six edges of the tetrahedron, and $E_i^e\ (x,y,z)$ is the vector basis function associated with the ith edge of the tetrahedron. Detail derivation for the expression forE^e is given in reference [7]. Using equation (2) in boundary condition and integration over the volume of one tetrahedron then matrix form can be written for tetrahedron [8].

$$[S_e].[N^e] = [v] \tag{3}$$

That v can be founded from boundary condition. These element matrices can be assembled over all the tetrahedron elements in region consist of sample to obtain a global matrix equation

$$[S].[N^e] = [v] \tag{4}$$

The solution vector $[N^e]$ of the matrix equation (4) is then used to determine reflection and transmission coefficient. This study is based on both FEM simulation and experimental measurements, as well, as compare to NRW method.

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EXPERIMENTAL METHOD

An Agilent N5230A PNA-L network analyzer setup is used to measure the S parameters of the cell containing the material under test over a wide range of frequencies (8GHz-12GHz). In this (TR) method the fundamental transverse electromagnetic TEM mode is the only mode that propagates in transmission line. The short-open load (SOLT) two-port procedure calibration to the measurement has been applied, since this method permits error correction over a wide frequency band. The electromagnetic analysis of the propagation line permits us to use NRW Equations to finding complex permittivity and permeability from reflection coefficient (Γ) and the transmission coefficient (T) at the interface between the air-filled and dielectric-filled based on the measurement of the scattering parameters (S-parameter) of rectangular sample of the test material which to avoid the presence of air gaps between the sample and the waveguide walls it has been fixed in order that the geometrical dimension fit well.

All the data reported in this article were carried out at room temperature. Two kinds PTFE sample have been prepared, PTFE A (22.86mm x11.43mm x 15mm) and PTFE B (22.86 mm x 11.43 mm x 50 mm).

RESULTS AND DISCUSSION

Dependence of magnitude S11 and S21 as function frequency for both PTFE samples have been shown in figures 3, 4, 5 and 6, the agreement between measured, NRW calculated and FEM simulated of magnitude S11 and S21 for two kinds of sample thickness can be observed.

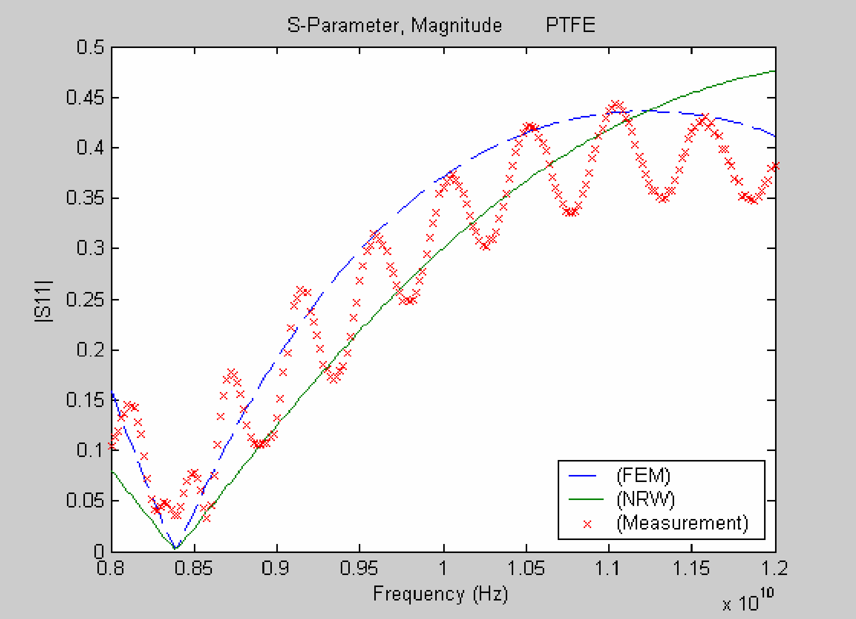

Figure 3: Measured, calculated and simulated magnitude of S11 for PTFE A

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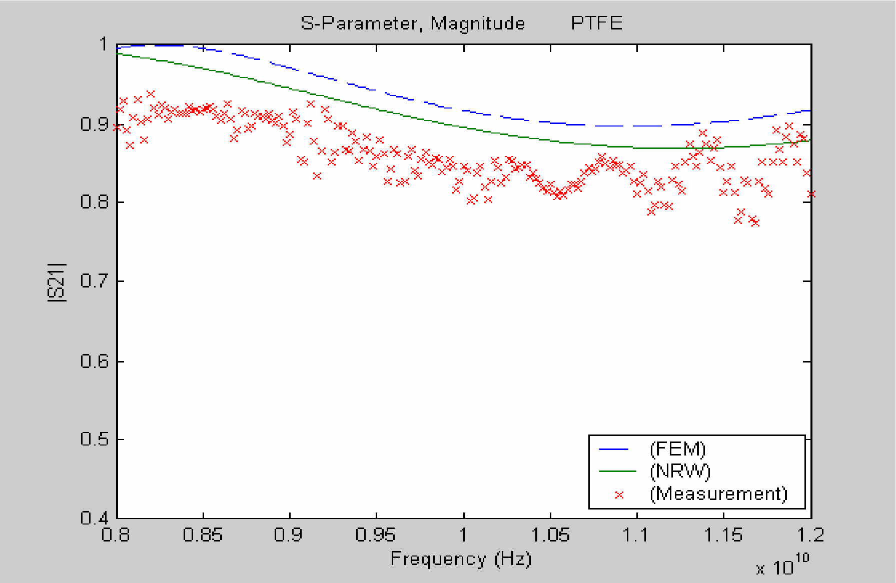

Figure 4: Measured, calculated and simulated magnitude of S21 for PTFE A

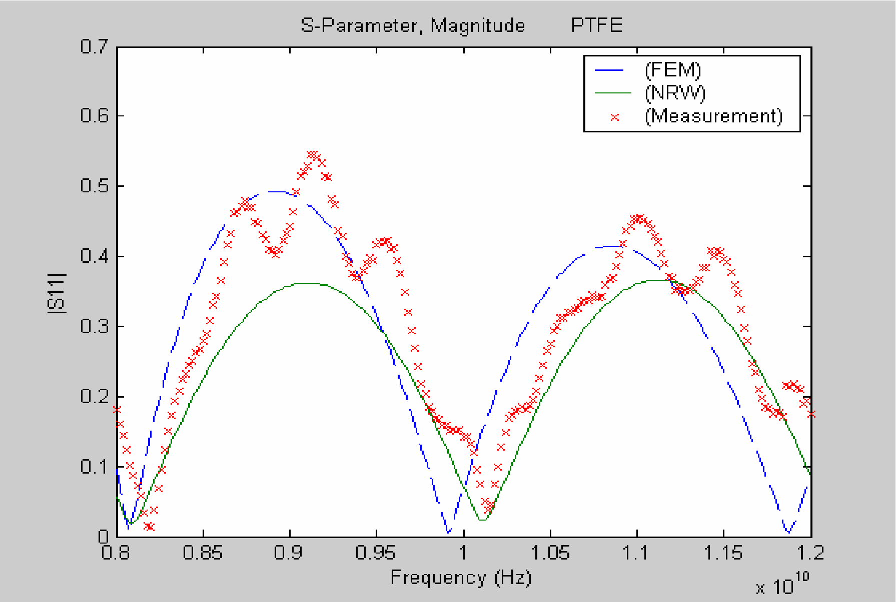

Figure 5: Measured, calculated and simulated magnitude of S11 for PTFE B

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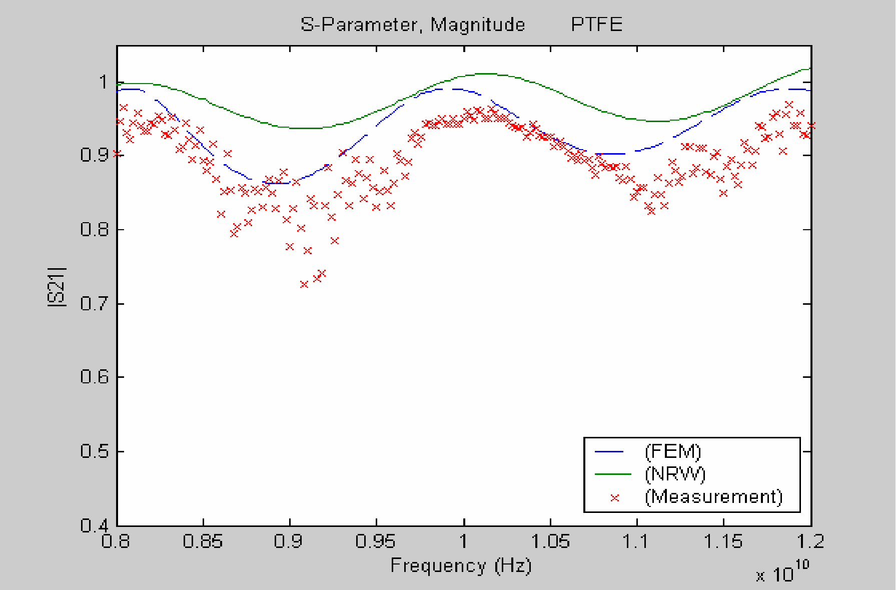

Figure 6: Measured, calculated and simulated magnitude of S21 for PTFE B

The results of magnitude S-parameters NRW equations and FEM simulation have been shown and comparisons of them with measurement have been done. But, the relative error between them is still high. To reduce the relative error, the optimization technique can be used [9].

The least squares curves fitting were used to produced the best fitting line through the measurement data with (NWR) equation. The model is formed by inserting unknown coefficient t (1), t (2), t (3) as real part of permittivity, imaginary part of permittivity and thickness respectively. Then objective functions was used to finding these unknown coefficients in the equations by minimizing the difference between measured and calculated (theory) of S-parameters.

$$F(\varepsilon',\varepsilon'',d)=\sum_{i}^{201}((|S_{11}|_{Theory}-(|S_{11}|_{Meas})^{2} \qquad (5)$$

In fact, an optimization based on least square Fitting is employed to obtain best fit values for permittivity, permeability and thickness. The measured thickness (15mm) of PTFE A was chosen as initial thickness estimate value, the initial estimate for ε' was 1.96, increased by 0.01 in the following to 2.06, the optimization program was run with ε''=0.005. It was found that the optimum values of $\varepsilon'$and ε''can be obtained when the calculated thickness is 15.4mm with F=0.6387, ε'=2.0456, ε''=0.1972. the optimization results for PTFE with measured thickness 15 mm in estimate ε' range between 1.95and 2.06 obtained using the objective function are list in table I. According this table, the best minimum of objective function (F) is located in ε' =2.03, ε'' =0.005 (shaded row at table 1).

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The results using objective function are provided in table 2 for trial value thickness. The ε' and ε'' were chosen 2.04 and 0.19 respectively. Initial estimate for d was 13 mm, increased by 0.5 in the following to 17 mm. Optimization program was run with ε'=2.04, ε''=0.19. The selection optimum value of thickness will be based on the calculated value of the sample thickness which is nearest to the measured values with minimum in error function (F). In this case the best minimum of objective function is F=0.3265 that it is located in d= 15.4 mm (shaded row at table 2).

Table 1: Optimization Results for PTFE measured thickness equal to 15 mm in estimate ε' range between 1.95 and 2.06

INITIAL ESTIMATE ε'	FINAL OBJECTIVE VALUE, F	OPTIMIZATION		
		ε'	ε''	THICKNESS, d_{opt} (mm)
1.95	0.8323	2.05	0.20	15.4
1.96	0.7899	2.04	0.19	15.4
1.97	0.7527	2.03	0.18	15.5
1.98	0.7274	1.96	0.12	15.1
1.99	0.6963	2.11	0.29	14.2
2.00	0.6718	2.07	0.20	15.3
2.01	0.6538	2.05	0.20	15.4
2.02	0.6428	2.05	0.19	15.4
2.03	0.6387	2.04	0.19	15.4
2.04	0.6416	2.04	0.19	15.4
2.05	0.6513	2.04	0.19	15.4
2.06	0.6677	2.04	0.19	15.4

Optimization for magnitude of S11 and S21on FEM has been done, the initial estimate for ε' was 1.96, increased by 0.01 in the following to 2.06 with different thickness (d=13.2mm, 14.8mm, 15.4 mm, 16mm and 17.3mm) and ε''=0.1972 that the best minimum of objective functions are 0.3009 and 0.9230 for S11and S21 respectively that they are located in d= 15.4 mm with ε'=2.04.

Comparison between the NRW method ($\varepsilon = 2.03 - j0.005, d = 15mm,$) and FEM method $\varepsilon = 2.03 - j0.005, d = 15mm,$) and optimization method ($\varepsilon = 2.04 - j0.19 , d = 15.4mm,$)in NRW and FEM for magnitude both of S11 and S21 are shown in Figures 7 and 8, the figures indicate good fitting between results.

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Table 2: Optimization results for PTFE (ε'=2.04, ε''=0.19) in estimate thickness range between 13.0 mm and 17.0 mm

INITIAL ESTIMATE, d (mm)	FINAL OBJECTIVE VALUE, F	OPTIMIZATION		
		ε'	ε''	THICKNESS, d_{opt} (mm)
13.0	5.4424	2.06	0.20	15.4
13.5	3.6162	2.08	0.21	15.2
14.0	2.1226	2.11	0.22	15.1
14.5	1.0692	2.04	0.19	15.5
15.0	0.4862	2.05	0.19	15.4
15.5	0.3265	2.04	0.19	15.4
16.0	0.5030	2.04	0.19	15.4
16.5	0.9476	2.05	0.19	15.4
17.0	1.5856	2.04	0.19	15.4

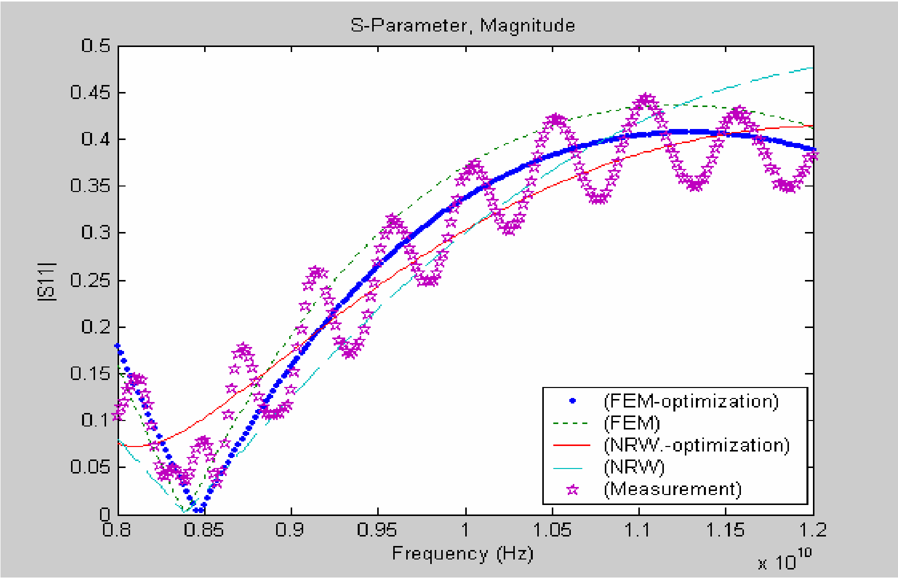

Figure 7: Magnitude S11 for PTFE in X-band by using NRW ($\varepsilon = 2.03 - j0.005, d = 15mm,$) and FEM ($\varepsilon = 2.03 - j0.005, d = 15mm,$) method and optimization ($\varepsilon = 2.04 - j0.19, d = 15.4mm,$) solution.

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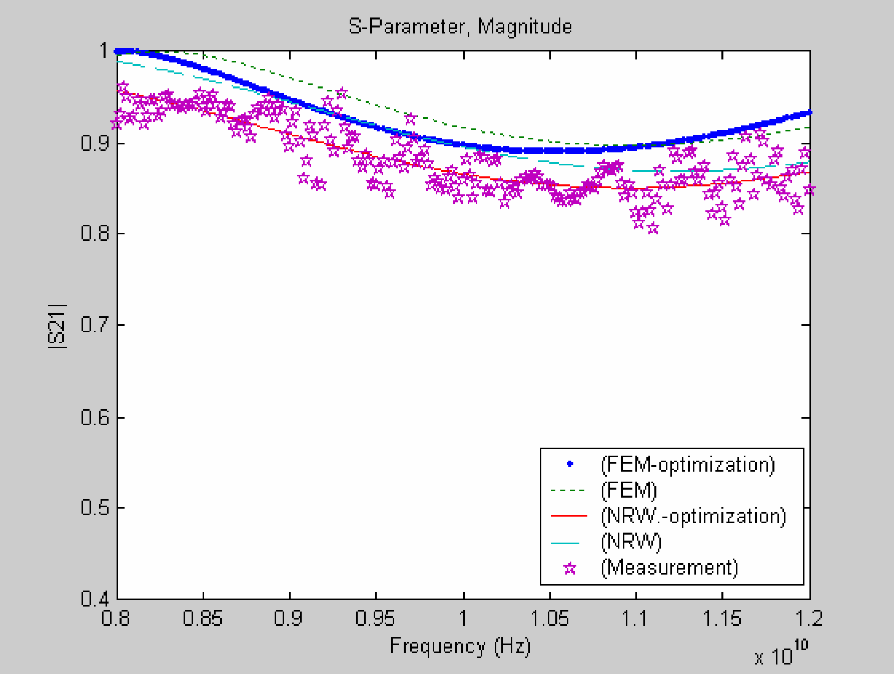

Figure 8: Magnitude S21 for PTFE in X-band by using NRW ($\varepsilon = 2.03 - j0.005, d = 15\mathrm{mm}$) and FEM ($\varepsilon = 2.03 - j0.005, d = 15\mathrm{mm}$) method and optimization ($\varepsilon = 2.04 - j0.19, d = 15.4\mathrm{mm}$) solution.

Graphical technique has been used to finding mean relative error in FEM and NRW, Variation mean relative error with thickness of sample for S11 and S21 has been shown in Figures 9 and 10, the figures show that the minimum mean relative error in simulation (FEM) are 0.2082 and 0.0731 for S11 and S21 respectively that they occur at 14.8 mm and the minimum mean relative error for calculation (NRW) are 0.2253 and 0.0435 for S11 and S21 respectively that they occur at 15.2 mm .and also Mean relative error for optimization has been done, 0.1903 and 0.0258 are mean relative error for optimization S11 and S21 respectively that occur at 15.4 mm, this thickness that has been found from mean relative error on optimization is in good agreement with thickness from the optimized on thickness in table II, therefore 15.4 mm is the best choice to use as thickness to finding best fitting between experimental measurement and theoretical results.

comparison between Figures 9 and 10 show the mean relative error of S21 is less than 0.0731 that means in S21the results of FEM and NRW are more agreement with measurement than results of S11 and also these Figures show to finding transmission coefficient, NRW method is more accurate than the results of FEM method and to finding reflection coefficient, FEM method is more accurate than NRW method.

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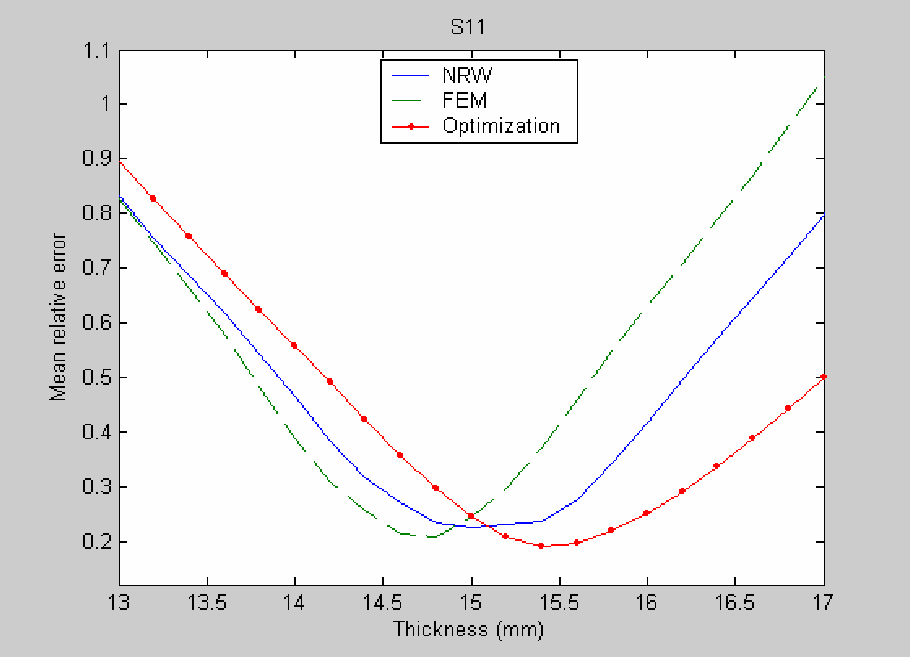

Figure 9:Variation mean relative error with thickness of PTFE in NRW and FEM and optimization for S11 Fig (a) and S21 Fig (b)

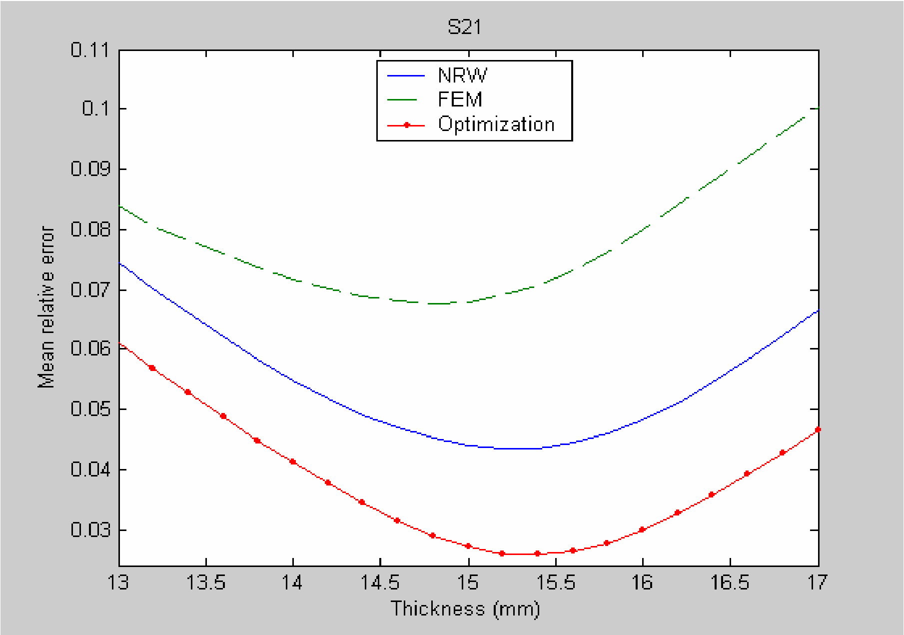

Figure 10: Variation mean relative error with thickness of PTFE in NRW and FEM and optimization for S11 Fig (a) and S21 Fig (b)

CONCLUSION

In this work a Finite Element Method (FEM) procedure has been presented to determine reflection and transmission coefficients of PTFE as dielectric material that are in good agreement with result by measured data found using vector network analyzer and (NRW) method. optimization technique has been used to reduced error, the least squares curves was used to produced the beast fitting line through the measurement data.

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