AN OPTIMISATION APPROCH TO DETERMINE THE ELECTROMAGNETIC PROPERTIES OF LANTHANUM IRON GARNET FILLED PVDF-POLYMER COMPOSITE AT MICROWAVE FREQUENCIES.

HASSAN SOLEIMANI[a*], Z. ABBAS[b], N. YAHYA[a], HOJJATOLLAH SOLEIMANI[b], M. SABET[c], A. OECHSNER[d], C. POLITIS[e]
[a]*Department of Fundamental and Applied Science, Universiti Teknologi PETRONAS, 31750 Seri Iskandar.*
[b]*Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia.*
[c]*Department of Petroleum and Chemical Engineering, Jalan Tungku Link, Gadong BE1410, Institut Teknologi Brunei (ITB), BRUNEI DARUSSALAM*
.[d]*School of Engineering, Griffith University, Gold Coast Campus, Australia.*
[e]*School of Engineering, University of Patras, Greece.*

In this study, an optimization approach is shown to improve the accuracy of the Nicholson and Ross Weir (NRW) method to determine both the complex permittivity and permeability of the lanthanum iron garnet-filled PVDF-polymer nanocomposite loaded in a rectangular waveguide. The complex permittivity and permeability values were in turn used in Finite Element Method to calculate the S-parameter and were found to be in good agreement with the measured values.

(Received April 21, 2015; Accepted August 7, 2015)

Keywords: Optimization Technique, Microwave Measurements; RW-90 waveguide; LIG; PVDF; FEM; NRW

1. Introduction

Ferrite loaded polymer nanocomposites with permittivity less than 10 are increasingly used in microwave devices such as isolators, filters and circulators [1–3] .At X-band frequencies, simultaneous and determination of both the complex permittivity ε* and permeability μ* of materials are usually calculated using Nicholson and Ross Weir (NRW) method [4] based on the measured S-parameter of samples loaded either in a coaxial sensor or a waveguide. Unfortunately, the NRW solution diverges at frequencies corresponding to integer multiples of one half-wavelength in the sample when simultaneously calculating ε* and μ* [5].

This paper presents an improved technique for the NRW method by applying optimization technique by fitting the values obtained from the theoretical complex transmission and reflection coefficients to the measured values with ε*, μ* and thickness d as the arguments. Comparison results with finite element method are presented to illustrate the flexibility and usefulness of the optimization technique.

As a soft ferrite material, lanthanum iron garnet ($La_3Fe_5O_{12}$) has been used in various applications in electronic devices. This is because of its efficient absorption of electromagnetic waves, low saturation flux density, low losses at high frequencies, high resistivity and easy to magnetize and demagnetize. As a result, polymer-based composites filled with ferrite particles, such as cobalt-ferrite, NiZn-ferrite, and MnZn-ferrite [6, 7] have attracted considerable attention over the years.

Many methods have been used for measuring the S-parameters as electromagnetic properties of the materials [8, 9]. In our previous works [10, 11,12], the transmission reflection rectangular waveguide technique (T/R) was conducted in order to obtain the S-parameters of the materials [13]. Moreover, in our previous studies, the Nicholson-Ross-Weir (NRW) method was applied to calculate simultaneously the complex permittivity and permeability of the lanthanum iron garnet-filled PVDF-polymer as nanocomposite sample [10]. The calculations were based on measured the S-parameters of mentioned sample which positioned in rectangular waveguide at X-band frequencies. Furthermore, The NRW method was introduced in order to calculate the S-parameters of the mentioned sample by applying obtained complex permittivity and permeability as well as [10, 13]. The comparisons of the results obtained by rectangular waveguide in conjunction with an Agilent N5230A PNA-L Vector network analyzer (VNA) and NRW method were presented to show the validation of obtained complex permittivity and permeability of sample [10].

The Finite Element Method (FEM) was applied to simulate the rectangular waveguide with three dimension of the geometry [14, 15]. The model consists of a rectangular waveguide with microwave propagation transition through it. This model applies the RF Module's Port boundary condition for the wave propagation problem.

2. Methodology

2.1 Finite Element Method

In the FEM formulation, the electric field in the rectangular waveguide was discretized using tetrahedron elements [16, 17, 18]. Hence, within each tetrahedron, the unknown field can be interpolated from each node value by using the first order polynomial [19] as follows:

$$\rho^e(x, y, z) = a^e + b^e x + c^e y + d^e z \quad (1)$$

The electric field in the rectangular waveguide is

$$\mathrm{E}^e = \sum_{i=1}^{6} \mathrm{N}_i^e \, \mathrm{E}_i^e(x, y, z) \quad (2)$$

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 $\mathbf{E}_i^e\,(x, y, z)$ is the vector basis function associated with the i^{th} edge of the tetrahedron. Using boundary condition and integration over the volume of one tetrahedron

$$[S_{el}].\{N_i^e\} = \{v^e\} \quad (3)$$

These element matrices can be assembled over all the tetrahedron elements in the sample region to obtain a global matrix equation

$$[S] \times \{N_i\} = \{v\} \quad (4)$$

The solution vector$\{N_i\}$ of matrix equation (7) is then used to determine both the scanning Parameters S11 and S21 [21].

2.2 Sample Preparation

LIG was prepared according to the previous our work [22]. Amorphous LIG was synthesized by sol-gel method. The pure phase crystalline cubic LIG was obtained by the heattreatment of the as-prepared amorphous material at 700 ˚C for 2h in air atmosphere. PVDF-13%LIG as a nanocomposite sample was prepared by solvent method with 13 % filler and 87 % of PVDF in the form of a rectangular sheet with 3 mm thickness.

2.3 Experimental Method

PVDF-13%LIG as nanocomposite sample was snugly fitted into a WR-90 waveguide then the scattering Parameters were measured in the frequency range of 8 -12 GHZ by using an Agilent N5230A PNA-L network analyzer. In this technique the fundamental transverse electromagnetic (TEM) mode is the only mode that propagates in rectangular waveguide. Network analyzer was calibrated by implementing a standard full two-port calibration technique (SOLT) for 201 frequency points. The experiments carried out at room temperature.

3. Results and Discussion

3.1 Material characterization

Characterization of the sample was carried out by various techniques which the results have been reported in our previous work [22].

3.2 Complex Permittivity and Permeability

In our previous study, The NRW method was applied to determine simultaneously the real and imaginary parts of complex permittivity and permeability of PVDF-13%LIG based on measured the scattering parameters. The results indicated that the decreasing in real and imaginary part of complex permeability and real part of complex permittivity resulted in increasing the frequency; meanwhile imaginary part of permittivity tends to become constant when frequency increased. The mean values of real and imaginary parts of the complex permittivity and permeability of mentioned sample at X-band frequencies were (4.33-j0.09) and (1.24-j0.15) respectively [10].

3.3 Optimization Technique.

This study suggests the use of an optimization method [23,24] which should be able to provide a more accurate way to determine permittivity and permeability as well as their uncertainties. In this case, all the possible errors are lumped into an error term included in an objective function to be minimized by an optimization technique. The objective function to be minimized is the sum of squared difference between the measured and calculated values of the Scattering Parameters. The variation in S11 and S21 with frequency for PVDF-LIG composite is shown in Figure 1. It can be clearly seen that both the measured S11 and S21 values were in between the FEM and NRW results.

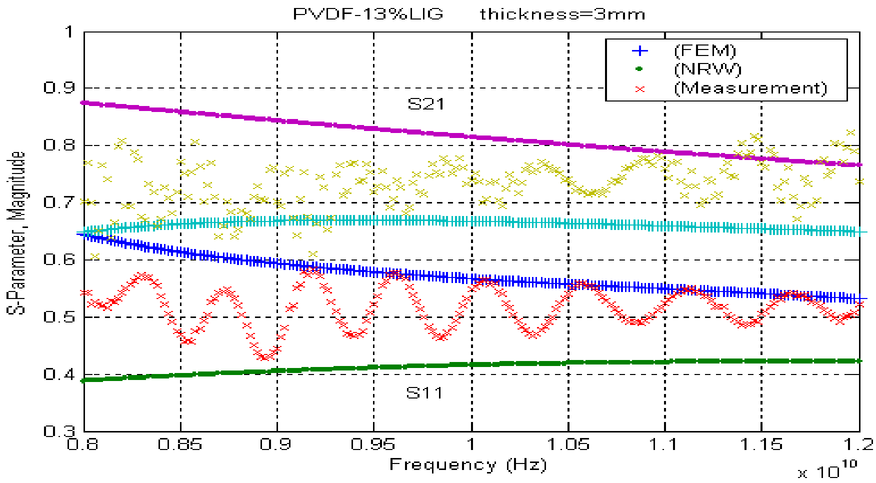


Fig. 1. The Variation of S11 and S_{21} with frequency for LIG-PVDF composite

using FEM for S11 and S21 indicate that the mean relative error were 0.118 and 0.109 whilst NRW were even higher at 0.182 and 0.132, respectively.We introduced NRW-optimization technique with objective functions F to reduce the relative errors between the measured (S11 and S21) and calculated parameters (R and T).

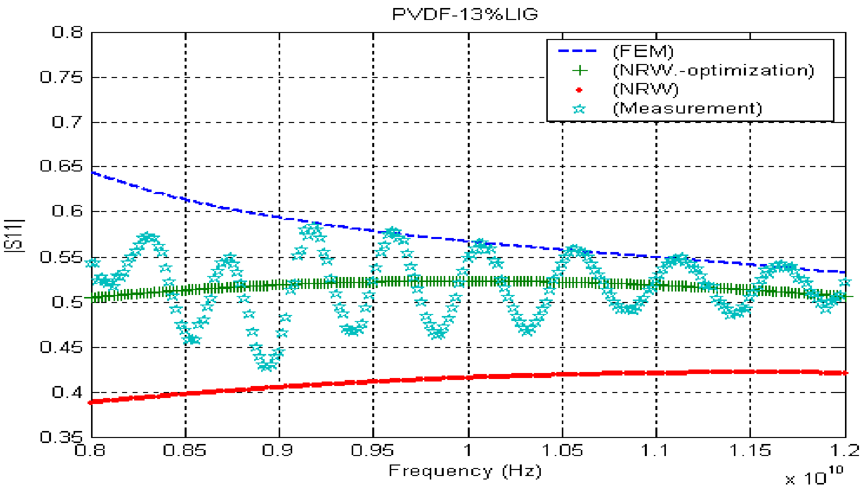
$$F\,(\varepsilon_r,\mu_r,\,d)=\sum_{i=1}^{N}[(R(\varepsilon_r,\mu_r,d)-S11))^2+(T(\varepsilon_r,\mu_r,d)-S21)^2\;] \tag{5}$$

where

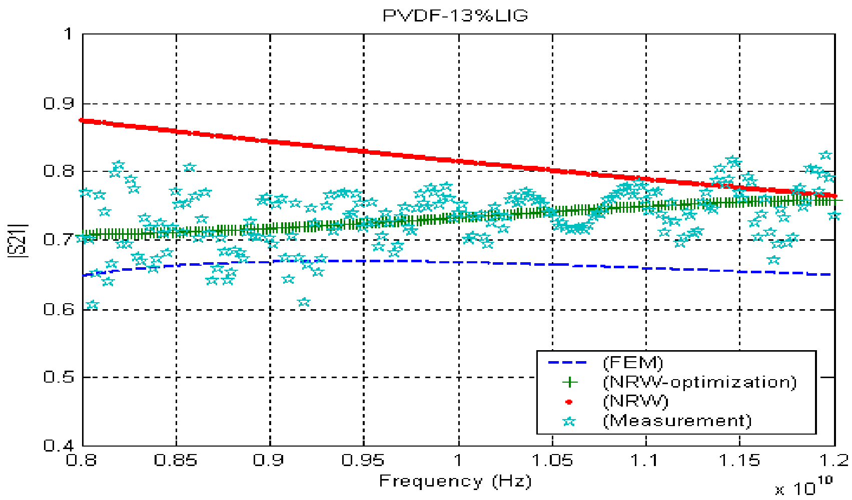
$$T(\varepsilon_r,\mu_r,d)=\exp\,(-j\left(\frac{\omega}{c}\right)\sqrt{(t(1)-j\,t(2)).\,(t(3)-j\,t(4))\,.\,t(5))} \tag{6}$$

$$R(\varepsilon_r,\mu_r,d)=\frac{(\sqrt{\frac{t(3)-jt(4)}{t(1)-jt(2)}}-1)}{(\sqrt{\frac{t(3)-jt(4)}{t(1)-jt(2)}}+1)} \tag{7}$$

where t (1) and t(2) are the real and imaginary parts of the permittivity, t(3)), and t(4) are the real and imaginary parts of permeability and t(5) is the sample thickness to be determined from the optimization program running . It was found that the relative mean errors between the measured and calculated S-parameter were 0.033 and 0.001 when using objective functions represented by eq. 6 and eq.7, respectively. The latter gives optimum values of ε_r , μ_r and d equal 4.05-j0.037, 1.72-j0.068 and 3.091 mm, respectively. The increase in the thickness d value was due to sample expansion when fitted tightly into the waveguide.



(a)



(b)

Fig. 2. Magnitude S11 a) and S21 b) for PVDF-YIG in X-band frequency by using NRW, FEM and optimization technique

Figures 2 shows the improved results obtained when using the NRW-optimization technique where the mean relative error. Also shown in the figure were the improved values of FEM-optimization using the optimized valuesε_r , μ_r and d. However it should be noted that the FEM is an expensive and time consuming method which is usually never used in practice to determine both the complex permittivity and permeability of materials. Our results suggest the NRW-optimization technique provides a powerful and efficient technique for simultaneous determination of both ε^*, μ^* as well as providing a true thickness d of sample tightly loaded in a waveguide.

4. Conclusion

The application of NRW-optimization technique provides a simple and accurate technique for simultaneous and determination of complex permittivity and permeability of YIG-PVDF nanocomposite loaded in a standard waveguide in the X-band frequency. This approach made the optimized NRW more accurate than FEM. As evidence for this statement, the mean relative error of the optimized NRW was observed to be 0.033.

Acknowledgments

The authors wish to thank for the project funding; FRGS research grant 0153AB-I46.

References

[1] P. Toneguzzo, O. Acher, G Viau, F. Fievet-Vincent, F. Fievet, J. Appl. Phys. **81**(8), 5546 (1997).
[2] M. Pardavi-Horvath, J. Magn. Magn. Mater. , **203**(1-3), 57 (1999).
[3] Y.J. Wu, H.P. Fu, R.Y. Hong, Y. Zheng, D.G. Wei, J. Alloys Compd., **470**, 497 (2009).
[4] P.P. Vaishnava, U. Senaratne, E. Buc, R. Naik, V.M. Naik, G. Tsoi, L.E. Wenger, P. Boolchand, J. Appl. Phys. **99**(8), 08G702 (2006).
[5] T. Nakamura, T. Tsutaoka, K. Hatakeyama, Frequency J. Magn. Magn. Mater., **138**, 319 (1994).
[6] O. Yavuz, M.K. Ram, M. Aldissi, P. Poddar, S. Hariharan, J. Mater. Chem., **15**, 810 (2005).
[7] N.E. Kazantseva, Y.I.; Bespyatykh, I.; Sapurina J.; Stejskal J.; Vilcáková P. Sáha, J. Magn. Magn. Mater., **301**, 155 (2006).
[8] J. Baker-Jarvis, Dielectric and magnetic measurement methods in transmission lines: An overview. Proceedings of the 1992 AMTA Workshop, Chicago, Illinios. 1992.
[9] S Simsek; C. Isik, B. Topuz, Esen, AEU-International Journal of Electronics and Communication, **60**(9), 677 (2006).
[10] H. Soleimani, Z. Abbas, N. Yahya, H. Soleimani, M. Y. Ghotbi, Measurement, **45**, 1621 (2012)
[11] H. Soleimani, Z. Abbas, N. Yahya, K. Shameli, H. Soleimani, P. Shabanzadeh International Journal of Molecular Sciences., **13**(7), 8540 (2012).
[12] H. Soleimani, N. Yahya, M. Sabet, Z. Abbas, H. Soleimani, G. Kozlowski, M.Y.Ghotbi, Digest Journal of Nanomaterials and Biostructures, **9(**1), 53 (2014).
[13] L.P. Ligthart,. IEEE Trans. Microw. Theo. Tech., **31**, 249 (1983)
[14] H. Soleimani, Z. Abbas, K. Khalid, N. Yahya, H. Soleimani, European Journal of Scientific Research, **39**(1), 105 (2010).
[15] COMSOL Multiphysics Model Library, ver. 3.3; Comsol AB, 2006.
[16] H. Soleimani, Z. Abbas, N. Yahya, H. Soleimani, M. H. Zaid, Journal of Nano Research **21** (2013) pp 151-157
[17] M. N. O.Sadiku, Elements of electromagnetic; Oxford University Press: New York, 2001.
[18] P. P. Silvester, R. L Ferrari, Finite Elements for Electrical Engineers, 2nd ed.; Cambridge Univ. Press: 1990.
[19] C. J. Reddy, M. D. Deshpande. C.R. Cockrell, F.B. Beck Finite element method for eigenvalue problems in electromagnetic. NASA Technical Paper 3485, 1994.
[20] C. J. Reddy, M. D. Deshpande, Application of FEM to esrtimate complex permittivity of dielectric material at microwave frequency using waveguide measurements. NASA Contractor Report, 1995.
[21] R. Coccioli, G. Pelosi, S. Selleri, Characterization of Dielectric Materials with the Finite-Element Method. IEEE Transactions on Microwave Theory and Techniques 1999, 4(77)
[22] H. Soleimani, Z. Abbas, N. Yahya, H. Soleimani, M.Y. Ghotbi, Journal of Composite Materials, **46**(12), 1497 (2012).
[23] L. Paul, Devries. A First course in computational physics. New York:John wiley and sons. Inc. 1994.
[24] Z.Abbas, R.D.Pollard and R.W.Kelsall. IEEE Transactions on Microwave Theory and Techniques **46**, 2011(1998).