Extracting the Electrical Properties of Polymeric Composite Materials through Circuit Simulation and Optimization

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Abstract **–** The electrical properties of polymeric composite materials were extracted from measured data using optimization techniques in Advanced Design System (ADS), a circuit simulation tool. A vector network analyzer was used to measure the S-parameters of the composite materials. The materials were inserted in an X-band waveguide and measured from 8 GHz to 13 GHz. The measured data was used to reconstruct the relative permittivity and loss tangent against a modeled setup in ADS. Two techniques were implemented in the reconstruction of the permittivity, one with the permittivity and loss tangent assumed to be constant and the other with them considered to be a function of frequency. The results show that for both techniques the modeled data does converge to the measured data yielding an optimized permittivity and loss tangent.

Keywords**:** Permittivity, loss tangent, optimization, and composite materials.

I. INTRODUCTION

Polymeric composite materials have gained a growing interest in the electromagnetic community. These materials can be tailored to provide desired effects, such as being transparent or conductive in the microwave frequency range. In order to make these composites with the desired effects, one must know the electrical properties of such materials. Thus, it is important to find new ways to take more accurate and efficient measurements from these materials in the microwave frequency range.

Material measurements are a broad and growing field in the microwave community. There are many methods for measuring electrical properties of materials such as resonant cavity methods or reflection methods [1].

In the experimental setup for this study, a reflection/transmission waveguide method was used to measure the S-parameters of the composite material. The Nicholson Ross Weir (NRW) algorithm and other variation of this method have been traditionally used to reconstruct the permittivity and/or permeability from the measured data [2-7]. Instead of using one of those approaches, ADS was used to extract the permittivity and loss tangent of these materials through optimization.

The measurement setup and ADS layouts will be shown and discussed in detail in the experimental setup section. A comparison between the optimizing permittivity and loss tangent as a constant and as a function of frequency will be made in the results and discussion section. Then, conclusions will be drawn from the results about the extraction of the permittivity for these low loss composite materials.

II. EXPERIMENTAL SETUP

The S-parameters of the composite materials were measured with an HP 8510C vector network analyzer. Composite materials were placed in a brass waveguide. The waveguide itself was X-band, with a length of 15.88 cm. A relatively low loss composite that was made with E-glass fiber and polyester resin was used as the material under test (MUT) for this investigation. This composite filled the entire 15.88 cm of the test fixture. Having a MUT of this length is known to cause difficulties with the NRW algorithm, but there is not a problem using the optimization technique. A Thru-Reflect-Line (TRL) two port calibration was done on the network analyzer. Once the composite was measured, the data was imported into ADS to find the permittivity and loss tangent.

The goal of the design was to determine values for permittivity and loss tangent so that the measured S-parameters matched the S-parameters from a circuit simulation model. The modeled setup consisted of a dielectric filled waveguide that has the same dimension as the actual waveguide that was used to take the measurements. For the electrical properties, it was assumed that the composite material was homogenous and isotropic, only the reflection and transmission are needed to satisfy the experimental goals.

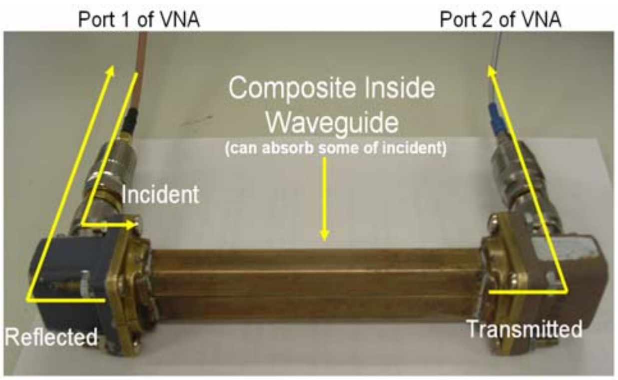

Fig. 1. Photograph of the waveguide used to measure the reflection/transmission behavior of the composite samples [8].

Two different types of setups were made in ADS to reconstruct the permittivity of the materials. In these two setups, it was also assumed that these composite materials were not magnetic. The first setup considered the complex permittivity to be constant along the span of the tested frequency range. The second setup allowed the permittivity and loss tangent to vary linearly or quadratically as a function of frequency. Equations (1) and (2) are the permittivity and loss tangent for the linear setup, respectively. Equations (3) and (4) are the permittivity and loss tangent for the quadratic setup. This allowed the permittivity and loss tangent to be unique in the given frequency range. Note that constants A, B, C, D, E, and F were considered as variables that ADS was solving for in the optimization process. The variables were optimized to meet the goal requirements at each frequency. These goals, which are seen in Fig. 2, were to minimize the difference between the measured and modeled reflection (S11) and transmission (S21) coefficients. The weights of each goal could be varied, and this could be of importance for a lossy composite, but for this investigation, the weights were equal.

$$Er = 1 + \left| A + B * (freq / 10^9) \right|, \tag{1}$$

$$TanD = \left| C + D * (freq / 10^9) \right|, \tag{2}$$

$$Er = 1 + \left| A + B * (\tfrac{freq}{10^9}) + C * (\tfrac{freq}{10^9})^2 \right|, \tag{3}$$

$$TanD = \left| D + E * (\tfrac{freq}{10^9}) + F * (\tfrac{freq}{10^9})^2 \right|. \tag{4}$$

ADS has several built-in optimization types available such as the random, gradient, or genetic algorithm methods. Random optimization was applied first to help narrow the optimization range. It also was important to use this optimization technique because it is not susceptible to convergence to a local maximum or minimum solution. Once the optimization range was reduced, the gradient technique was applied to further satisfy the goals. The gradient technique was also chosen because of its speed in converging to the minimum.

III. RESULTS AND DISCUSSION

A comparison between the measured and modeled S-parameters will be made in the following figures. The permittivity and loss tangent will also be shown for each method to finalize the results.

Figures 3 and 4 show the optimized real permittivity and loss tangent of an air filled waveguide using a linear model for the frequency dependence.

This data was generated to insure that the program was working properly by investigating air as a known standard. As it can be seen in Fig. 3, the program optimized the real permittivity to one. The loss tangent was optimized from 0.00034 to 0.00056, which is relatively close to zero. This test provided expected results and insured that our measurements and modeling were working properly.

Figures 5 and 6 show the reflection and transmission when both the permittivity and loss tangent of the material is considered to be constant, thus assuming the material under measurement is perfectly homogenous and not frequency dependent. In both these figures, the reflection and transmission from the modeled data does converge to the measured data. Looking at the figures, it shows the transmission does not match up quite as well as the reflection. There seems to be a few discrepancies between the modeled and measured data at the peaks for both goals. In both graphs there seems to be no more than a 0.5 dB in error which is almost negligible.

Figures 7 and 8 show the results where the permittivity and the loss tangent were allowed to vary linearly over the frequency range. For both the transmission and reflection, the modeled results compare better to the measured data than the previous method. This can be seen more clearly in Fig. 11 which compares the measured data against both the constant and frequency dependent real permittivities. This would indicate that the material itself is not ideally frequency independent.

Figures 9 and 10 illustrate the case when the permittivity and loss tangent vary in a quadratic fashion. From the figures one can see that the goals matched up just as well as the linear case, if not better. The profile of the modeled data is almost mirrored to the measured data for both goals. Seen in Fig. 11 one can see that both the linear and quadratic goal for the transmission is in close proximity to the measured data. It should also be noted that both the quadratic/linear method satisfied the goals better than the constant method thus considering the frequency dependent methods to be the correct approach on optimizing the electromagnetic properties for this type of composite material.

The resulting permittivity and loss tangent for both methods can be seen in Figs. 12 and 13. The constant setup yielded a real permittivity of 4.26 and loss tangent of 0.0106. While for both the frequency dependent cases yielded a real permittivity in the range of 3.4 to 3.7 and loss tangent of 0.0123 to 0.01257. It should also be pointed out that the ranges for the permittivity and loss tangent are considerably small for the frequency dependent methods. If one would enlarge the ranges the permittivity and loss tangent would appear to be constant.

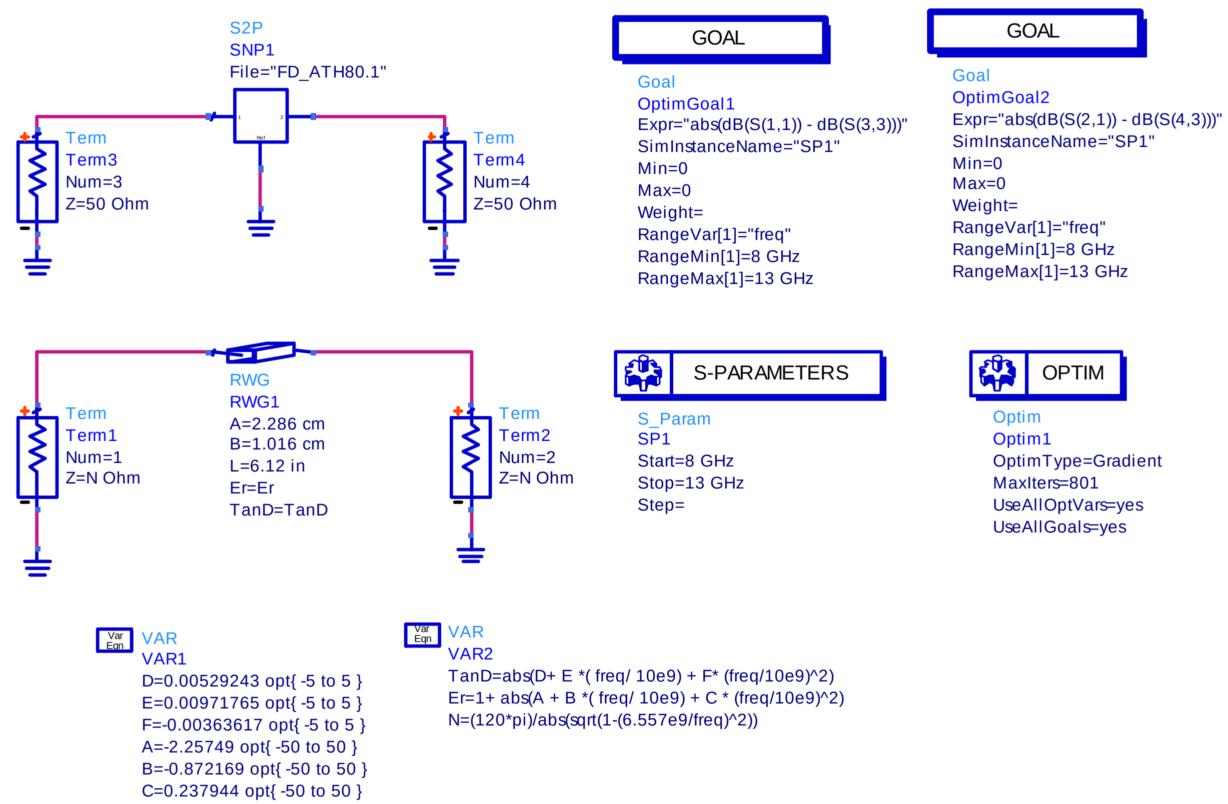

Fig. 2. ADS schematic layout for optimizing permittivity and loss tangent.

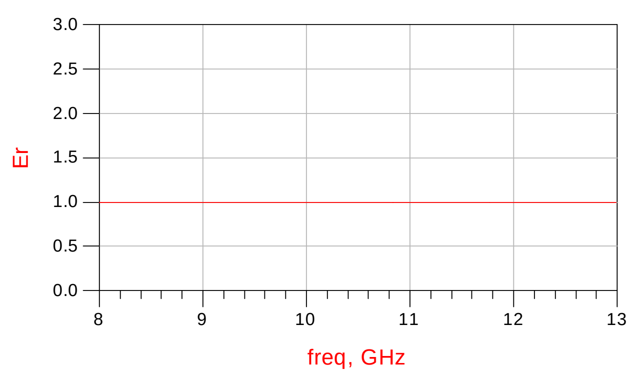

Fig. 3. Real permittivity for air filled waveguide using the linear model.

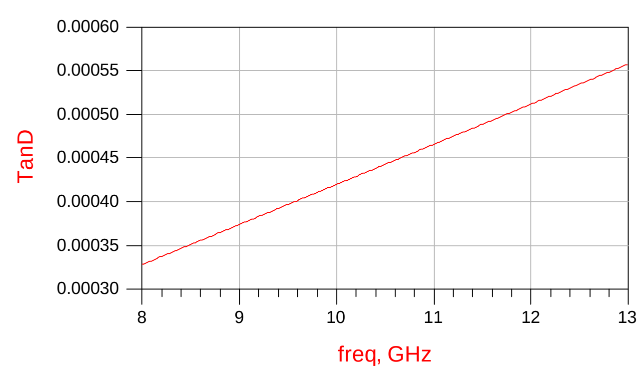

Fig. 4. Loss tangent for air filled waveguide using the linear model.

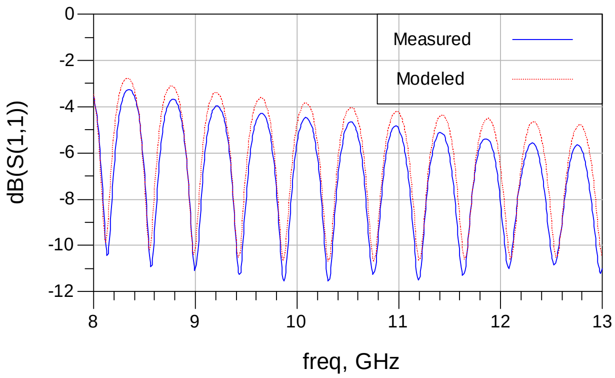

Fig. 5. Return loss for the constant permittivity setup.

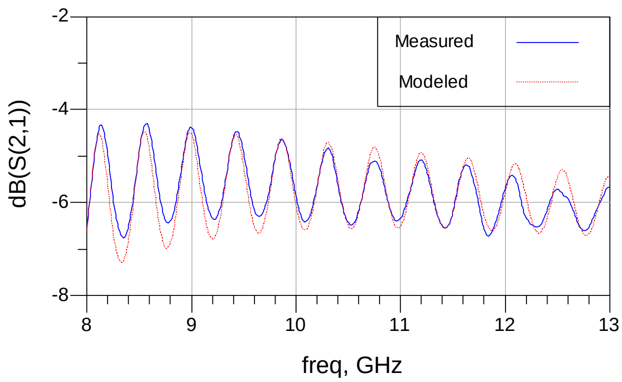

Fig. 6. Insertion loss for the constant permittivity setup.

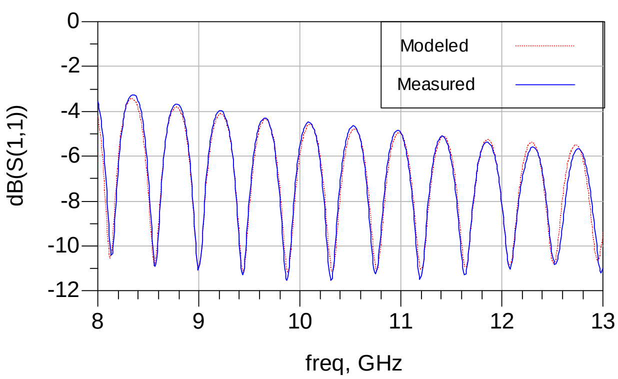

Fig. 7. Return loss for the linear permittivity setup.

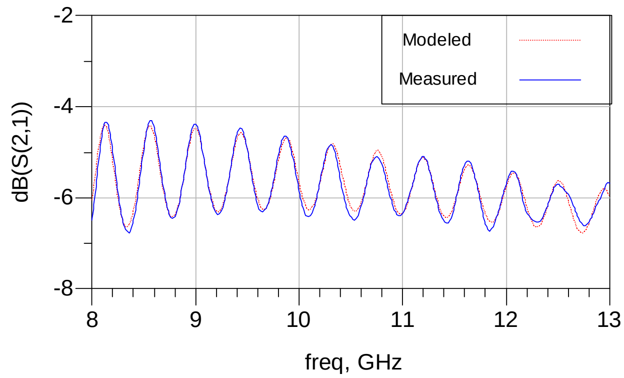

Fig. 8. Insertion loss for the linear permittivity setup.

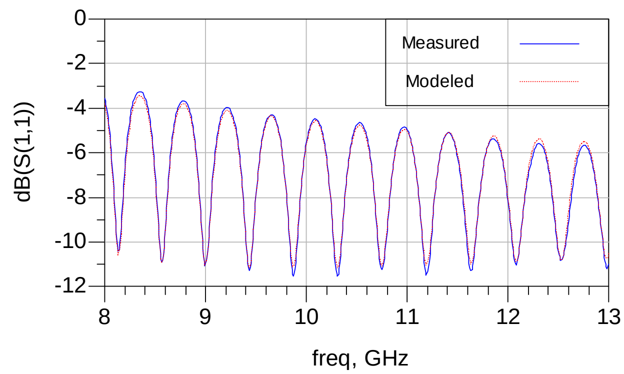

Fig. 9. Return loss for the quadratic permittivity setup.

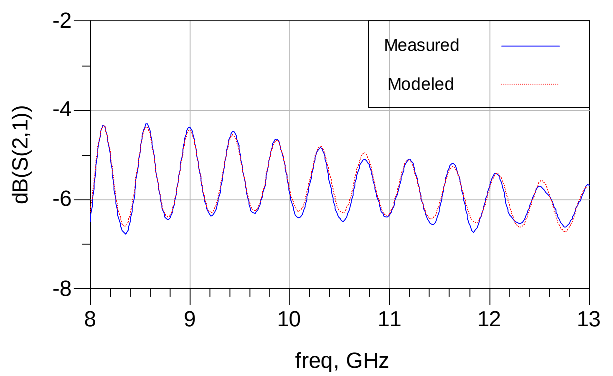

Fig. 10. Insertion loss for the quadratic permittivity setup.

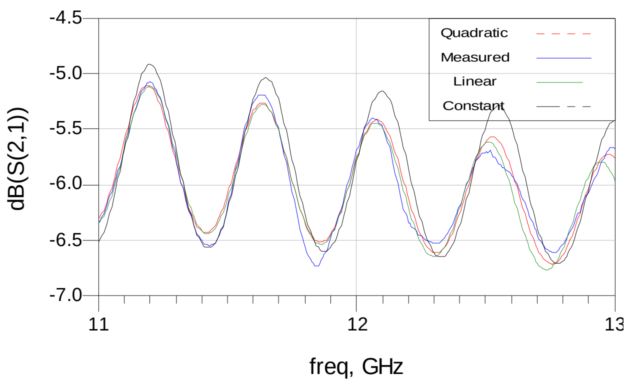

Fig. 11. Insertion loss for the constant and frequency dependent permittivity setups in a narrow frequency range.

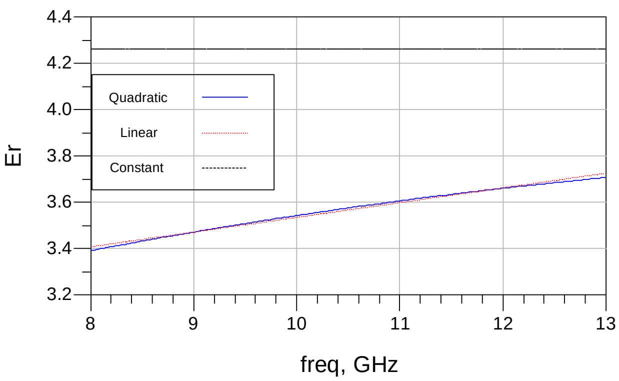

Fig. 12. The real permittivity of the constant and frequency dependent setups.

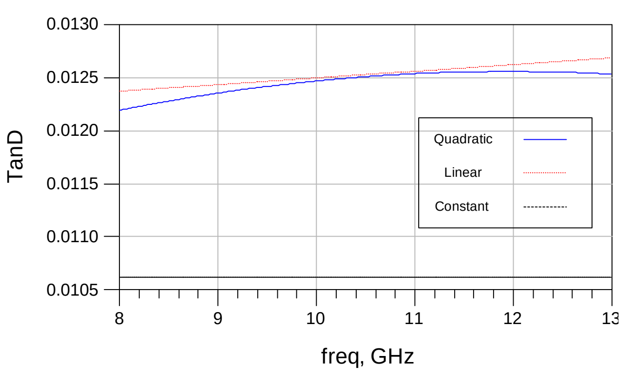

Fig. 13. The loss tangent of the constant and frequency dependent setups.

IV. CONCLUSION

The permittivity and loss tangent were found for both setups. A comparison was made for each method. Other methods consider the MUT to be frequency independent, and this technique does not require that. Allowing the frequency dependency doesn't change the outcome greatly, but it does indeed match the measured data better. In future research, this method can be improved for various other types of composite materials, such as highly conductive materials or composites made with veils. Since these materials could be very frequency dependant, a more elaborate model might be necessary.

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Lorenzo P. Bennett Jr. graduated from the University of Mississippi with a bachelor's degree in electrical engineering in 2005. Since then, he is currently pursuing his master's degree in electrical engineering with an electromagnetic emphasis at the University of Mississippi. In his study, he has been learning how to characterize EM properties of composite materials through various methods. During the summer of 2004, he interned at SPAWAR, in San Diego, California, with the telecommunications branch. While he was there he learned about mobile ad-hoc networks and radio systems. He is a member of Tau Beta Pi and Eta Kappa Nu, both academic engineering societies. He is also a member of Phi Kappa Phi. Lorenzo is an IEEE member and served as treasurer of IEEE's Ole Miss section for one year. While not in school, he enjoys working out at the gym and playing sports.

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Reid Averill is currently the Technical Sales Manager for Inspec Foams, ROHACELL, North America. Reid is in the final stages of completing his thesis in studying the behavior of low cost composite materials which absorb and reflect electromagnetic radiation. Reid has 4 years experience in the composite industry.