유전알고리듬을 이용한 도체 입자가 함유된 복합물질의 복수유전율 측정

정회원 이 상 일*

Complex Dielectric Constant Measurements for Conductor-Loaded Composite Materials Using Genetic Algorithms

Sang-il Lee* ***Regular Member***

요 약

본 논문에서는 전송방식과 유전알고리듬을 이용하여 간단하지만 빠르고 신뢰성 있는 복수유전율 측정 기법을 제안한다. 측정된 S-파라메터 중 전파계수만을 이용하여 복수 유전율을 얻었으며, 그 이유는 전파계수만을 이용한 복수유전율 측정기법이 반사 계수를 이용한 방법보다 측정오차에 대해 안정적인 결과 값을 제공하였기 때문이다. 또한 역추출 방식으로 유전알고리듬을 적용함으로써 매우 효율적이고 정확한 측정결과 값을 얻을 수 있었다. 제안된 방법을 이용하여 도체입자가 함유된 복합유전체 및 PCB 기판의 복소유전율을 측정하였다.

Key Words : Complex permittivity(dielectric constant) measurement, S-parameters, Transmission method, Genetic algorithms, Conductor-loaded composite materials

ABSTRACT

In this paper, a simple but fast and reliable technique for the complex dielectric constant measurement of non-magnetic materials is introduced using a measured transmission coefficient (S21) and a genetic algorithm as an inversion process at microwave frequencies. In this experiment, it has been found that the transmission method is less susceptible with the measurement errors than that of the reflection method and the genetic algorithm can be efficiently used as a search technique. The suggested technique is validated with known and unknown conductor-loaded lossy materials and the conductor-loaded PCB at X-band.

Ⅰ. Introduction

There has been an increasing interest in artificial composite materials due to the market demands on low-loss high dielectric constant materials and highly lossy dielectric materials at microwave frequencies hence intensive research has been made on this topic. Low loss high dielectric constant materials can be effectively used to minimize the size of the microwave devices, such as substrates of antennas and resonators. If the effective wavelength inside the material is decreased with a high dielectric constant of the material, and the decreased effective wavelength reduces the physical dimension of the devices. Although there are high dielectric materials in nature, such as *Barium-tetratitanate* (*r* = 37, tan = 0.0001) and *Titania* (*r* = 96, tan = 0.001), they can be used in limited condition as antenna substrates. Therefore, new composite materi-

* 목포대학교 정보공학부 초고주파공학 연구실(leesi@mokpo.ac.kr)
※위 논문은 2004년도 jcci에서 우수 논문으로 추천된 논문입니다

als with low loss and high dielectric constant are desired. Lossy dielectric materials also have many usages at microwave frequencies, such as absorbing materials, conducting coaters, EMI shielding materials, conductive adhesives hence the cheaper and more reliable composite materials are desired. [1]

It is known that conductor-loaded composite materials have lossy or high dielectric properties depending on the fractional volume of the including conductors [2]. One of the techniques to control the material characteristics is making a composite with the conducting particles inside a dielectric material. The loaded conductor particles increase either the real or the imaginary part, or both parts of the complex dielectric constant depending on the fractional volume of the inclusions. However, it has been found that the estimation of the electrical properties of the composite material is very difficult and the complex dielectric constant measurement may not be a simple problem, especially in high volume fraction and at microwave frequencies. Although numerous measurement techniques have been reported, each technique has its own limitations. Therefore, a reliable complex dielectric constant measurement technique for conductor-loaded composite materials has been developed. In Chapter II, scattering parameters for both transmission and reflection coefficients are reviewed. Scattering parameters are only a function of complex dielectric constant and permeability. Both can be determined by the measured scattering parameters and using an inversion process. A genetic algorithm is presented as a proposed inversion process in Chapter III. In Chapter IV, experimental results are evaluated for the conductor-loaded composite samples and the conclusions are discussed in Chapter V.

Ⅱ. Scattering parameters: Transmission Method

Determining the dielectric constant of an unknown material is one of the most important tasks for the material properties. Several measurement techniques have been investigated but many researchers are still trying to develop more correct and reliable method for both the complex dielectric constant and the complex permeability measurements. In general, the scattering parameters are equated as shown in equation (1)~(8). [3]

$$S_{11}(\omega) = \frac{\Gamma(1-Z^2)}{1-\Gamma^2 Z^2} \tag{1}$$

$$S_{21}(\omega) = \frac{Z(1-\Gamma^2)}{1-\Gamma^2 Z^2} \tag{2}$$

$$\Gamma = \frac{\gamma_0 - \gamma}{\gamma_0 - \gamma} \tag{3}$$

$$Z = exp(-\gamma d) \tag{4}$$

$$\gamma_0 = j\sqrt{\frac{\omega^2}{C_0^2} - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{5}$$

$$\gamma = j\sqrt{\frac{\omega^2 \mu_r \epsilon_r}{C_0^2} - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{6}$$

$$\epsilon = [\epsilon_r' - j\epsilon_r'']\epsilon_0 = \epsilon_r \epsilon_0 \tag{7}$$

$$\mu = [\mu_r' - j\mu_r'']\mu_0 = \mu_r \mu_0 \tag{8}$$

Here, $j = \sqrt{-1}$, ω is angular frequency, γ_0 is propagation constant in the air, γ is propagation constant in the material, C_0 is speed of light in vacuum, λ_c is cut-off frequency, and d is sample thickness.

The scattering parameters are only a function of the complex dielectric constant and the complex permeability of the sample material, if the rest of the parameters, such as operating frequency, cutoff frequency of a waveguide and the sample thickness are given. Thus the complex dielectric constant and the permeability can be determined by the measured scattering parameters. There are four unknowns, a real and an imaginary part of the complex dielectric constant and the complex permeability. If more than four equations are given, the problem may be able to be solved. Both S_{11} and S_{21} measurements may be enough for four equations, because each scattering parameter contains both amplitude and phase information. If the desired material is non-magnetic, only one measurement, either reflection or transmission measurement may be enough to determine the complex dielectric constant[4]. However, the dielectric constant is related to the scattering parameters in very complicated way and the solution may not be solved analytically. Therefore, the inversion process is required to achieve the dielectric constant from the measured scattering parameters in many cases. In general, the measured scattering parameters include some measurement errors and the errors may drive the iteration to wrong conversion values. To obtain correct result, better measurement techniques and more reliable inversion process are required. It is also recommended to measure the sample several times to verify the obtained dielectric constant.

Ⅲ. Inversion Process: Genetic Algorithms

Nicolson and Ross combined the S_{11} and S_{21} equations and made analytic forms for the complex dielectric constant and the complex permeability [3]. However, the amplitude of S_{11} becomes very small at frequencies corresponding to integer multiples of one-half wavelength then the phase uncertainty is too large to obtain the correct results. Thus, an iterative inversion process has been widely used to obtain the complex dielectric constant and the complex permeability. There have been approaches to solve the complex dielectric constant and the complex permeability from the measured scattering parameters using an iterative method with various combinations, and the achievements have been reported [4]~[7].

One of the simplest inversion processes is an exhaustive search. All the possible amplitudes and the phases of the S_{21} are calculated in the range of the estimated complex dielectric constant. The point that shows minimum differences between the calculated and the measured S_{21} may be the complex dielectric constant of the sample. If we can estimate the possible range of the complex dielectric constant, we may set the search area around the estimated solution. Then, the exhaustive search may be useful as an inversion process. However, in many cases, it is not possible to estimate the complex dielectric constant of the unknown materials and also, the fine resolution for the search area may help not to be converged into a wrong direction of the inversion process. Thus, we may need to set very large search area with fine resolution then the search time may take too long or the iteration may not be able to be done. We may need faster but robust search algorithms.

There are several search techniques commonly used for the optimal solution or the inversion process such as optimization technique, random search algorithms, and genetic algorithms. A genetic algorithm is one of the most robust search algorithms widely used in complex optimization problems, which is based on the mechanics of natural selection and natural genetics [8]~[9]. The genetic algorithm's main search strategy is the survival of the fittest and an interbreeding population. Populations of strings represent possible solutions for a specified problem, which make the algorithm a parallel search. Populations are initially assigned with random numbers and then developed with a fitness function iteratively. First, the new populations are selected from the old populations with a selection rule. The probability to be selected for the next generation is decided by the fitness function. Then, cross over and mutation is performed to be free from the local minimum. Therefore, the fitness function is very important for a convergence to the correct answer. Finally, the best population gives the solution after enough iteration. The genetic algorithm is a form of randomized search and a stochastic process determined by a fitness function.

Ⅳ. Experiments

Scattering parameters are measured with a HP8719D vector network analyzer, which is connected to the X-band (8.2 ~ 12.4 GHz) waveguide and a sample holder. The transmission measurements are performed for the different sample thickness at the frequency range from 8 GHz to 12 GHz. For the transmission measurement, the system is "THRU" calibration, and "GATING" is used to eliminate multiple reflections due to unwanted impedance mismatching areas. All the measurements are repeated three times, and the measurements are averaged. To apply the genetic algorithm as an inversion process, several factors, such as a population size, the number of iterations, the probability of cross over and mutation and a selection rule should be decided. It may be obvious that a longer iteration and a bigger population size give a better or equal result at the expense of search time. In this experiment, 400 of iterations and 100 of population size are normally used, and the convergences are good in most cases. The roulette wheel method is used as a selection rule and the probability of crossover and mutation are tried for 0.8 and 0.02, respectively. Depending on the search area and the search resolution, the number of bits is decided. Seventeen bits are used for the up to 100 of the search area for both real and imaginary part, and 1/1000 of resolution in the complex dielectric constant measurement. One of most important parameters is a fitness function. Each fitness value or weight is calculated for each population depending on possibility to be a solution. In our case, the less difference between the calculated and measured value gives a higher possibility to be a solution. Thus, the reciprocity is used for the weight. The lower difference can have the higher fitness value, and the population having a higher weight may survive in the next generation.

Fig. 1 (a) and Fig. 2 (a) shows the averaged test results for the error added reflection and transmission measurement, respectively, and the standard deviations for each measurement technique are shown in Fig. 1 (b) and Fig. 2 (b). To observe the relation between the sample thickness and the inversion error due to the measurement errors, the tests are repeated for five different sample thickness ratios, from 10 % to 50 % for the reflection method and from 5 % to 30 % for the transmission method. With the error added inversion tests, interesting results are observed. First of all, the error added reflection measurements show that the inversion process itself is very unstable, and the standard deviations seriously deviate from zero as shown in Fig. 1 (b). However, the transmission method shows almost zero standard deviation for all range of the added errors, which means all the same results are obtained for the different iterations as shown in Fig. 2 (b). Another observation is the deviation of the measured dielectric constant from the expected values. In the transmission method, with 10 % errors, the real part of the complex dielectric constant swings 13.5 % of the ideal values, but more than 100 % errors can be involved with the reflection measurement depending on the sample thickness ratio. Thus, another step to decide the sample thickness ratio is required in the reflection method. In general, 10 % measurement errors are extreme cases. If 2 % errors are assumed, the estimated dielectric constant has less than 3 % of meas-

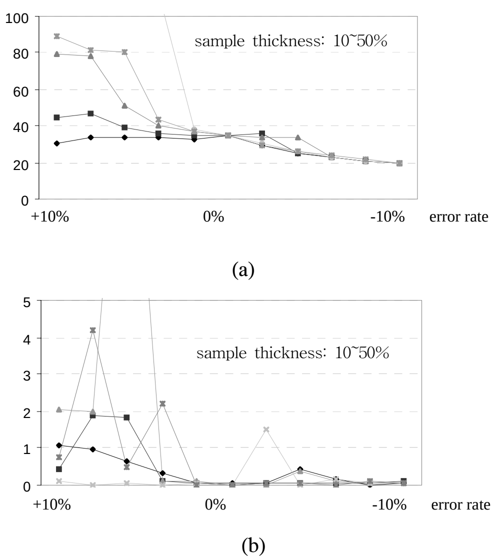

Fig. 1 Convergence and error sensitivity test for reflection method: real parts of the complex dielectric constant, sample thickness difference (4 &4.4~4 & 6 mm), (a) Average, (b) Standard deviation.

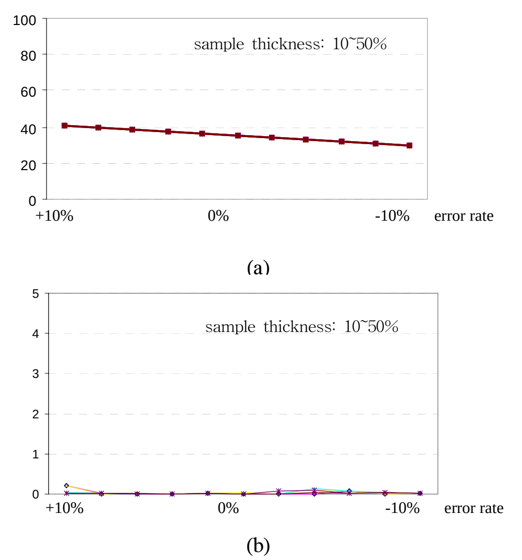

Fig. 2 Convergence and error sensitivity test for transmission method: real parts of the complex dielectric constant, sample thickness difference (2 &1.9~ 2&1.4 mm), (a) Average, (b) Standard deviation.

Table. 1 The measured complex dielectric constant for the conductor loaded composite materials

sample name	Real Part				Imaginary Part				thickness (mm)
Frequency (GHz)	9	10	11	12	9	10	11	12	
AlN	8.19	8.19	8.19	8.19	0.14	0.05	0.06	0.06	3.15, 5.04
Sample A	49.7	50.4	51.1	51.6	21.0	23.5	24.7	25.4	2.05, 4.0
BeO-SiC	36.3	35.2	32.8	32.8	16.4	15.2	16.4	17.0	2.01

urement errors with the transmission method. We have observed that the transmission method provides more stable and less sensitive with the measurement errors.

Several samples for both known and unknown conductor-loaded composites have been tested with the proposed transmission method and the genetic algorithm. The complex dielectric constant of *AlN* (8.2-j0.02 at 10GHz) and *BeO-SiC* (35.24-j15.75 at 10 GHz) are known. The measured results show good agreements as shown in Table 1. *Sample A* is a new composite material recently manufactured by a local company which dielectric constant is not available yet. Thus, we have measured the complex dielectric constant of this material and we have found the results are very similar to the manufacturer's expectation.

A simple experiment for the low loss high dielectric constant material with the PCB (Printed Circuit Board) has also been tested. Particle patterns are fabricated from the copper etching on the PCB (RT/duroid6000 (PTFE/ceramic, 1 oz copper = 0.07 mm)). The dielectric constant of the host material is given with 6.5, and the dielectric loss can be ignored.

We need to make 5 % of volume fraction on a single PCB layer, and the random distribution may make the particle overlapping or clustering problem. Thus, the particles are placed periodically rather than randomly. The width and the height of the particle is the same as the simulations but the thickness of the particle is only 0.07 mm, and more particles are included for the same 5 % of volume fraction.

The transmission coefficients are measured and the complex dielectric constants are obtained using the transmission method and the genetic algorithm. As we expect, only the real part of the dielectric constant is significantly increased as shown in Fig. 3. The increment with the measurement is higher than that of the simulation because the sample used for the

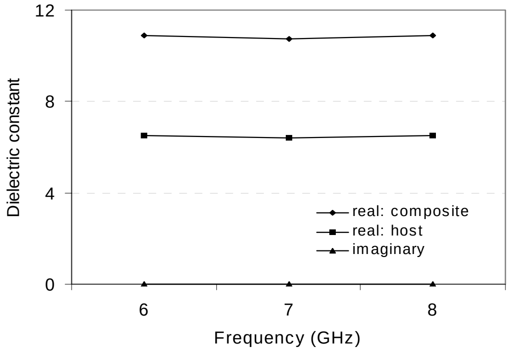

Fig. 3 Measured complex dielectric constant for the conductor loaded low loss high dielectrics at 5% of fractional volume

measurement may have the higher effective fractional volume than that of the sample used for the simulations. The effective fractional volume means, although the same 5 % of fractional volume has been tested, the sample for the experiments includes more particles with the different thickness. Hence the actual fractional volume can be different.

V. Conclusions

The complex dielectric constants for the conductor-loaded composite materials are obtained with the proposed measurement technique. It has been found that the transmission method is less susceptible with measurement errors and the genetic algorithms are efficiently used as a fast and reliable inversion process. The obtained results for the known sample are well agreed. More detailed analysis and experiments are remained as a future work.

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이 상 일(Sang-il Lee) 정회원

1991년 8월 고려대학교 전자전산공학과 졸업

1994년 1월 고려대학교 전자공학과 석사

2002년 8월 University of Washington, Electrical Engineering, Ph.D.

2002년 9월~2003년 8월 삼성전자 책임연구원

2003년 9월~현재 국립목포대학교 정보공학부 전임강사

<관심분야> 초고주파 소자 및 회로 설계, UWB 초고속실내무선망, 광무선통신