博士論文要旨 (2016 年度)

Dielectric Permittivity Estimation at Microwave Frequencies

中央大学大学院理工学研究科博士課程後期課程
情報セキュリティ科学専攻
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1. Introduction

Dielectrics or insulators is one of the three groups of substances categorized according to the ability to conduct electricity, namely dielectrics, semiconductors and conductors. Dielectrics or insulators do not conduct electric currents or have a poor conductivity. Meanwhile, conductors allow electric current to flow easily.

Dielectric materials show their presence everywhere in our daily life and the dielectric permittivity is a characteristic parameter of dielectrics. This parameter draws very much attentions of researchers and the industries. The main reason is knowing the permittivity or how it changes at certain frequencies provides us with crucial information that shed insights and enables important applications.

Some applications are shown in Fig. 1. Such examples can be numerous but all of them confirm the importance of permittivity estimation and lead to the development of many methods in past several decades [1].

Various complex permittivity measurement methods designed for different materials, frequencies and other requirements have been proposed with comprehensive reviews by many authors found in the literature [1, 2, 3]. Well-known techniques are the capacitor, the resonant cavity, the open resonator, the waveguide, the coaxial probe and the free space methods. The configurations of some methods can be seen in Fig. 2.

These methods can be divided broadly into two groups of techniques, namely the resonance methods and the transmission line methods [2, 3]. The resonance methods are capable of conducting nondestructive measurements of very low loss materials with high accuracy at narrow frequency bands. The transmission line methods, on the other hand, are able to make fast, broadband measurements and are capable of measuring medium and high permittivity [3]. In this group, the waveguide methods, the open-ended coaxial probe methods and the free space transmission and/or reflection methods are well known. Given the increasing need of material characterization in a wide range of frequencies in material science and electronics, as well as in large scale environment monitoring system, the free space techniques emerge as a powerful solution with many striking features among the mentioned methods. They allow broadband measurements, safely reserve the material sample and they are capable of assessing the material from afar or under extreme conditions.

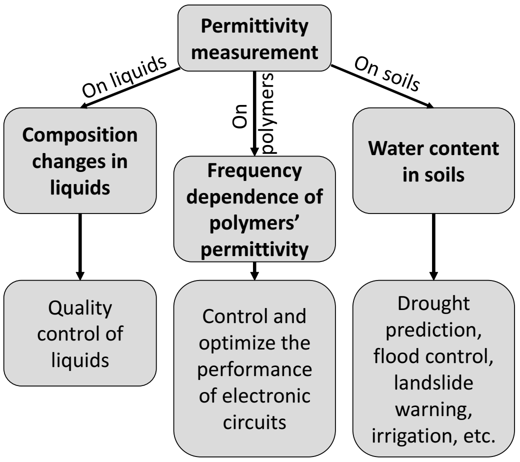


Figure 1: The potentials of dielectric permittivity measurement in some applications.

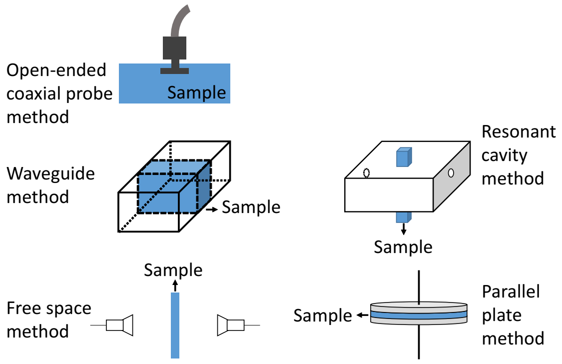


Figure 2: Some current dielectric permittivity measurement methods.

The abilities of the free space methods have been verified by several authors with different variations [4, 5, 6, 7]. These authors use various settings and parameters to estimate the relative permittivities and permeabilities. For example, they have used two S-parameters, samples with different thicknesses, PEC plate termination, time domain gating technique and measurement at the Brewster angle. Efforts have been made to improve the estimation accuracy.

In general, these techniques will face an ambiguity in determining the true value of the relative permittivity, since there are numerous complex permittivity values which satisfy the equation of the reflection/transmission coefficient as described by Redheffer [8] and Hasar [9].

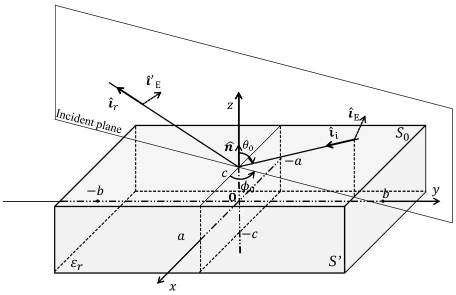


Figure 3: Scattering from a rectangular cuboid.

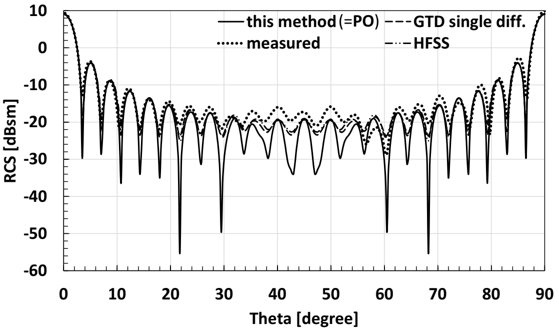


Figure 4: Monostatic RCS of aluminum cube ($2a = 2b = 2c = 100.0$ mm) when $\phi = \phi_0 = 90.0^\circ$ at 24.0 GHz.

The problem is often fixed by limiting the sample thickness, knowing the range of permittivity in advance or measuring with different initial conditions, etc. Additionally, people often use more than one S-parameter in the conventional permittivity estimation using the transmission measurements. However, this practice requires more equipment, which may cause more uncertainty, than when only the reflection parameter is used. Currently, solving this difficulty requires laborious procedures and reduces convenience. Therefore, a new free space method to solve this difficulty is meaningful in the research perspective and will improve industrial efficiency. This new method is the purpose of this research.

In this research, a new free space method is proposed to estimate the relative permittivity of solid materials and water-based liquids. An algorithm was developed to help selecting the proper permittivity value of solid materials. In the case of water-based liquid, an analytical formula to calculate the permittivity was derived. In order to derive the algorithm and the analytical formula, an analytical formula for scattering far field from the material sample has been developed.

Firstly, the analysis on scattering far field from the material sample was presented. Then the scattering analysis is applied to the permittivity estimation method for solid material. Later, the method to deal with water and water-based liquids was introduced. Measurements on real samples were conducted to confirm the validity of the proposed method.

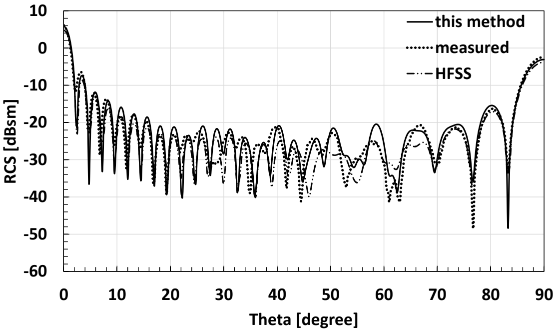


Figure 5: Monostatic RCS of the polymer cuboid ($2a = 100.0$ mm, $2b = 150.0$ mm, $2c = 40.0$ mm) when $\phi = \phi_0 = 90.0^\circ$ at 24.0 GHz.

2. High frequency electromagnetic scattering analysis of rectangular dielectric cuboids [10]

Scattering is a classic topic of electromagnetics with a rich history with several canonical problems solved. However, there has been no known exact analytical solution for the particular problem of rectangular cuboids. There are approximation methods, such as the Geometrical Theory of Diffraction (GTD) or the Physical Optics method (PO) but are limited to conducting cuboids. Other methods are numerical methods like Finite-Difference Time-Domain method, Method of Moments or Finite Element Method. However, they return only numerical values which are hard to utilize in permittivity calculation. Therefore, before solving the inverse problem to find the dielectric permittivity of dielectric cuboids, it is required to solve the forward scattering problem to establish an analytical relation between known information and the wanted permittivity.

This research proposes a high frequency method based on Kirchhoff approximation for electromagnetic scattering. The case of a cuboid illuminated by a TE polarized electromagnetic plane wave was considered. Equivalent currents were presumed from the reflected wave and electromagnetic scattering far fields were calculated from them through the vector potentials. In the case of dielectric cuboids, a ray tracing technique was used to include the effect of the multiple internal bouncing effect. Several PEC and dielectric cuboids were used to verified the proposed scattering analysis as shown in Figs. 4, 5. Good agreements between my method, measurement and other references have been observed around the specular reflection direction ($\theta = 0.0^\circ$ and 90.0°) in both examples.

The proposed method has proved to be quite accurate around the specular reflection direction. By using the reflected wave to estimate the equivalent currents, the method is able to calculate scattering far field from dielectric objects, where classical methods such as PO and GTD cannot be applied. This scattering analysis has provided an analytical relation between the scattering field obtained from measurement and the permittivity of the sample and opened a way for the analysis for permittivity estimation on solid materials.

3. Dielectric permittivity estimation for solid materials using free space method [11]

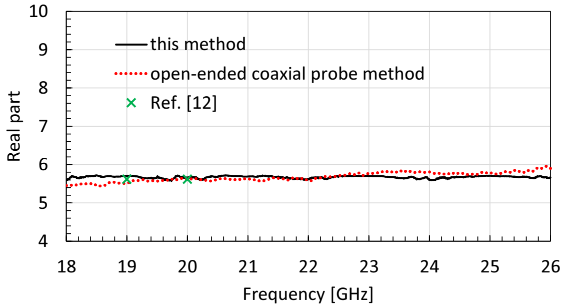
The scattering analysis is used to reveal the relation between the complex scattering quantity and the dielectric permittivity of solid samples and other known information. The relation is further analyzed to devise an iterative process in order to extract the relative permittivity from the measured scattering data. An algorithm was developed to calculate the relative permittivity without knowing much about the material's dielectric property in advance and solved the multiple value difficulty. This algorithm is based on the observation that the multiple reflection coefficient oscillates around the surface reflection coefficient.

To verify the proposed method, dielectric permittivites were successfully estimated from a Macor ceramic sample and compared to the results by the commercially available open-ended coaxial probe method and Ref. [12] as shown in Fig. 6. The real part of ε_r by our method agreed well with the result measured by the probe method and the Ref. [12]. In term of the imaginary part, there is a significant difference between our method and the probe method. However, our method and Ref. [12] have good agreement at 19 and 20 GHz. Therefore, it can be concluded that in this case of Macor ceramic the result by our method is more reliable than the result by the probe method. The erroneous negative imaginary part obtained by the probe method may be due to an air gap between the probe and the sample's surface due to imperfection on the sample surface or bad positioning.

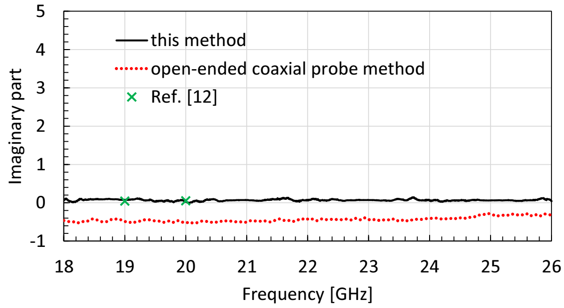
With the proved accuracy, stability and feasibility in dealing with non-magnetic solid materials, the method is being used to provide material information for other studies involving radar target reconstruction, propagation estimation and other scattering analysis in the same laboratory. Further upgrades of the method may include stability improvement.

4. Dielectric permittivity estimation for liquids

The proposed scattering analysis was applied to deal with water and water-based liquids. Since liquids need containers, the effect from a container was included in the scattering analysis. A decomposition was proposed to separate unwanted scattering contributions from the measured scattering quantities. Based on the structure of the container and the lossy nature of water in liquids, two reflection coefficient models were proposed to calculate the scattering quantities and to establish a direct analytic relation between the dielectric permittivity of water and known information.



(a) Real parts of ε_r



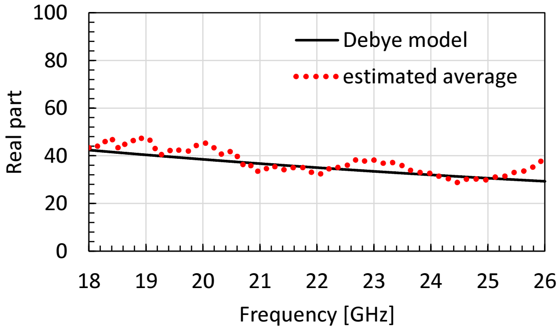
(b) Imaginary parts of ε_r

Figure 6: Relative permittivity ε_r extracted from a Macor ceramic cuboid ($2a = 2b = 100.0$ mm, $2c = 30.0$ mm) at 21.0°C.

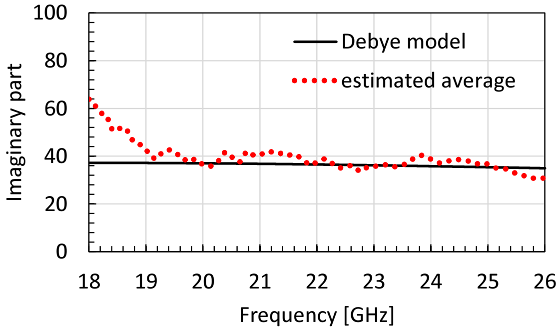
Being aware of the lossy nature of water and water-based liquids, proper thickness of the container was decided so as to simplified the reflection coefficient. This simplified coefficient provides us with an analytical formula to calculate the dielectric permittivity of the liquids. Later, a procedure for dielectric permittivity estimation on water and water-based liquids is described. The procedure is verified by estimating water permittivity from an acrylic container and inversely. The measured results contain measurement errors so they oscillates strongly and needs to be averaged. The average values show close agreement with the Debye model [13] as seen in Fig. 7.

5. Conclusions

A new free space dielectric permittivity estimation method has been developed successfully. This new



(a) Real parts



(b) Imaginary parts

Figure 7: Complex relative permittivity of pure water at 22.0°C estimated from the fully filled container.

method is based on the scattering analysis using Kirchhoff approximation. It is promising in areas where dielectric permittivity characterization of solid material is required. With further improvements, this method also can be used in practice to deal with liquids. From a different point of view, the scattering analysis developed as the foundation for the estimation process is also a new way to calculate the scattering far field from dielectric objects that can be applied in many other areas.

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