Undergraduate Project Report
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Dielectric Measurement of Tissues

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Abstract

Dielectric is widely used in life, industry and military. As the most important property of dielectric, the measurement of permittivity is of great significance. In order to achieve more accurate and simple measurement, I study the model of measuring dielectric property(permittivity) based on coaxial reflection method. Compared with other models, this scheme is cheap, accurate, occupies a small space, and non-destructive to the tested material. In this study, I have implemented two complex coaxial models for calculating permittivity, one is the model for multilayer dielectric measurements under ideal conditions, and the other is a more realistic model with the introduction of an air-gap layer. Both models discuss the situations of using metal short-circuit terminals and air short-circuit terminals (depend on different experiment situations). I not only verify the validity and accuracy of two models, but also put forward a feasible scheme to determine the relationship between the reflection coefficient and the permittivity, so that it is possible to determine the permittivity under complex situations. At the same time, I also designed a relevant software and a graphical user interface for the friendly-use. Subsequently, I verified and analysed our proposed scheme through the combination of physical experiment and software calculation, and proved its feasibility. The end result is a publishable paper and a commercial software package.

摘要

介电质在生活，工业以及军事中均有广泛的应用，作为介电质最重要的属性，介电常数的测量具有非常重要的意义。为了实现更加准确，简便的测算，我们针对基于同轴线反射法测量介电常数的模型展开了研究。该种方案相比于其他模型具有便宜，准确，占地空间小，对待测物体没有伤害等优势。在这个研究中我们实现了两种复杂的同轴线计算反射系数的模型，一种是理想状态下对于多层介电质测量的复杂模型，一种是引入空气层的更加真实的模型。两种模型都讨论了使用金属短路终端以及空气短路终端两种情况。我们不仅实现并验证了模型的准确性，也提出了一种可行性的方案来确定反射系数与介电常数的关系，使复杂反射模型确定介电常数成为可能。同时我们还设计了软件以及图形界面方便用户使用。随后，我们通过物理实验与软件测算相结合的方式对我们提出的方案进行了验证与分析，证实了方案的可行性。最终，我们产出一篇可发表的论文以及一套可以商业化的软件。

Chapter 1: Introduction

1.1 Project Main Goal

The main objective of our project is to develop a model based on coaxial reflection method to measure the permittivity of multilayer dielectric materials, write a set of commercial software and related development documents, measure the experimental data, and finally evaluate and analyse our model. In order to make our model more universal and accurate, I chose to use a multilayer dielectric model and a dielectric measurement model with air-gap layer, which posed a challenge for us to determine the relationship between the reflection coefficient and the permittivity.

1.2 Project Tasks

1.2.1 Background Knowledge Learning

In order to effectively complete this project, I have done a lot of background knowledge research since the beginning of the project. I first learned electromagnetism, microwave theory, transmission line theory and other knowledge related to this project by reading papers and books such as *Electromagnetic Field and Microwave Theory* [1]. Then through the network resources and the book *MATLAB object-oriented programming - from the introduction to the design patterns* [2], I learned the MATLAB grammar and the way doing mathematical calculation. Later on, I also learned MATLAB Graphic User Interface (GUI) design, which make our software's function richer and more friendly to use.

1.2.2 Project Thesis Research

In addition to basic knowledge supplement, my tutor and I conducted a large number of literature survey, including papers on mainstream calculation of permittivity, papers on calculation of reflection coefficient through coaxial line, papers on verification scheme of permittivity, etc., and selected two papers and their models for our major research according to our needs. After a thorough study of these two models and a certain understanding of domain knowledge, I also put forward a plan for how to transform the model to calculate the reflection coefficient.

1.2.3 Software Design and Implementation

Then I design and implement two thesis models, our own model and establish a software for commercial use. During the implementation, I keep validating and verifying the formula and model.

1.2.4 Conduct Experiments and Analysis

After the completion of the code and software design, I carried out the research part. This part was supposed to be carried out by me in Spain, but due to the Covid-19, it was turned into cooperation between me and my supervisor in Universidad Politécnica De Valencia (UPV) of Spain. My supervisor sent the data measured in the laboratory to me, and I calculated the data through software and analysed it. Finally, I produced a feasible report and a paper that could be published.

1.3 Project Achievements

In the end, our project had two major outcomes. First of all, I have designed a set of feasible software system based on MATLAB. In this software, I not only provide the operation mode based on script, but also provide a relatively good graphical user interface for users to use. I have written detailed guidelines to facilitate users to flexibly use script mode, and I have provided corresponding interfaces for experienced programmers to modify and adjust our model conveniently. The graphical user interface also provides a wealth of functions, users can arbitrarily choose their favourite model, flexible processing of parameters, and even batch operation to generate analysis graphs and save data, and so on. The second major achievement is that I have proposed a scheme to obtain the permittivity of dielectric in reverse based on the model, verified the theoretical model in the practice process, analysed and discussed the experimental results, and formed a report and a publishable paper.

1.4 Report Structure

Our report will consist of seven main parts:

1. The first part is the Introduction, which will briefly introduce the main work, content and results of our project.

2. The following background section will introduce some of the terminology I need to understand in the project, the principle of our model implementation, what previous methods have been used to accomplish this task, and what are the advantages and disadvantages of these methods, etc.

3. The next part is the introduction of the theoretical model. In this part, I will focus on how our theoretical model is used for reference and design.

4. The fourth part is the design and application part, in this part I will introduce our program

Object-Oriented design, UML diagram, concept, as well as GUI design, simple use of the introduction and some of our software renderings.

5. The fifth part is the verification part. After the theoretical model is practiced, I designed a series of verification methods and experiments to ensure the accuracy of our results. This part will focus on our verification and revision process.

6. The sixth part is the processing and analysis of the experimental data based on the cooperation with UPV, and what improvements I can make.

7. The last part is the summary of the project.

1.5 Brief Conclusion

To sum up, our project has verified two kinds of complex dielectric models through research and implementation. One is the model of Reflection Coefficient calculated by multi-layer dielectric. One is the model to calculate Reflection Coefficient after the introduction of air-gap layer and TM mode. I put forward a scheme to determine the complex relationship between Reflection Coefficient and Permittivity. Through the collaboration between UPV and BUPT, my supervisor measured the Reflection Coefficient with the open-ended coaxial line and I calculated the permittivity with my scheme. Contrast and analyse the experimental results with those in the National Physical Laboratory Report and form a paper. At the same time, I also completed a software with GUI, as well as writing related development documents, user manual, etc.

Chapter 2: Background

1. Why are we interested in dielectric?

Dielectric properties are widely used in civil, industrial and even military applications. The permittivity is a very important physical property of dielectric, and the research on it has been playing a very important role in academic circles. In the fields of biomedicine, microwave technology, electronic technology, geological exploration and so on, the measurement of permittivity has put forward certain requirements. Cheap and accurate permittivity measurements make it easy to measure the hardness of a building, the moisture content of a fruit or even the salinity of sea water.

2. What is dielectric and permittivity?

Dielectric is an insulator that can be polarized in an electric field (as Figure 1) [1]. Some non-insulators are also classified as dielectric due to the process of polarization. The dielectric does not exhibit electrical properties at the macroscopic level, but polarizes at the microscopic level. Although as complicated as it sounds, dielectrics are actually common substances in our life, such as air, glass, and mica. Dielectric includes a wide range of substances such as gas, liquid and solid, and even vacuum. In this project, we mainly focus on the measurement of liquid dielectric properties, but also involve solids and gases. The four main type material we focus on are: Dimethyl sulphoxide, Ethanol, Methanol, Propan-2-ol.

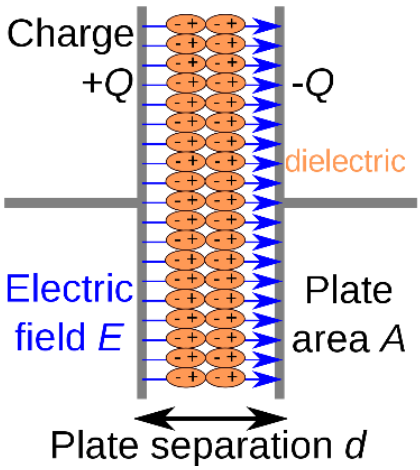


Figure 1 Dielectric Polarization Diagram [18]

The permittivity describes the polarity of the dielectric. When the dielectric is polarized in the electric field, it weakens the current electric field. The ratio of the strength of the original electric field to the strength of the internal electric field in the dielectric is the permittivity. The ratio of the permittivity to the vacuum permittivity is the relative permittivity. The smaller the permittivity is, the more difficult it is for the material to be polarized, the smaller the electric field intensity inside the dielectric is, the stronger the ability to store electrostatic energy is, and the higher the insulation is.

Substance	ε	σ (μS/cm)
Air	1.00	0.0
Silicone Oil	2.78	0.0
Diethyl Ether	4.27	0.0
Isopropanol	19.74	0.1
Glycol	40.56	1.5
Deionized Water	79.86	2.5
Water + Salt	79.86	13.1

Figure 2 Common Material's Permittivity and Conductance [18]

In addition, permittivity is usually a complex number with real part and imaginary part. The different values of these two parts play different roles in the model [2]. In general, the real part of permittivity determines the dielectric's ability to be polarized, or the strength of its ability to store charge. In general, the substance with the larger real part of permittivity has the better ability to store charge. The imaginary part determines the loss of the signal as it passes through the dielectric. The smaller the imaginary part of permittivity, the less influence it has on the passing signal. On the contrary, the higher imaginary permittivity, the greater the loss and the higher the heat it produces. Knowing exactly the permittivity can help us make better use of different substances.

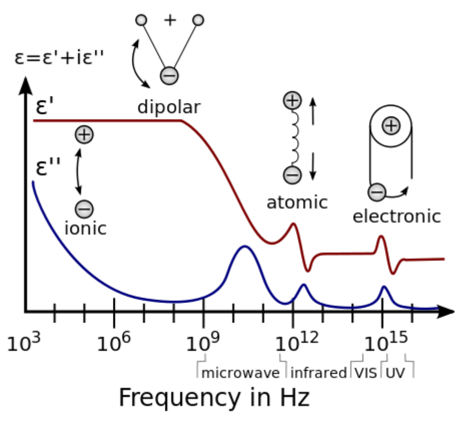
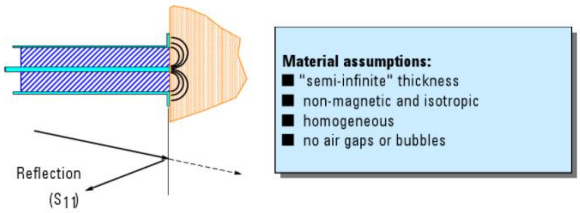


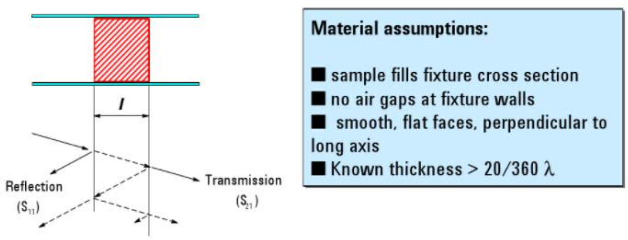
Figure 3 The graph of the real part and imaginary part of permittivity changing with frequency [18]

3. What are the common methods to calculate permittivity?

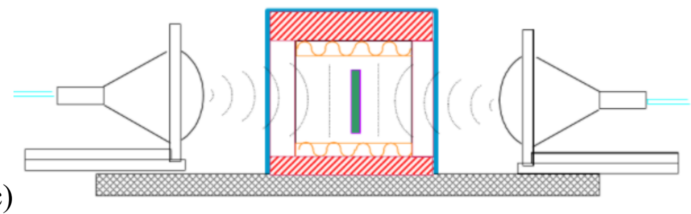
There are various methods to measure the permittivity of the dielectric, and there are corresponding appropriate measurement methods for the dielectric in different states and frequencies. The main measurement methods are centralized circuit method, transmission line method, resonance method and free-space wave method, etc. The method I will use in this project is one of the transmission line methods. (1) Lumped parameter method is a method to fill the capacitor with lossless material at low frequency and calculate the permittivity by using the capacitance parameters. This method can only be applied to low frequency bands to ensure its effectiveness. For example, liquids, semi-fluids and solids are suitable for this method. (2) The Network (Transmission Line) method is to put the tested medium into one network system (two-port network or four-terminal network) to obtain the reflection coefficient of microwave by measuring the single port or double port network, and then obtain the relative permittivity through the equation. The method has high accuracy and simple operation, but it is unstable and has multiple values at partial measurement frequencies. (3) Resonance method is to measure the material as a part of the resonance structure. This method can basically measure the permittivity of the material in all frequency range, but it is only applicable to low loss medium, and extract the transcendental equation of the relative permittivity with multiple valued solutions, etc. In addition to these three mainstream methods, we also have free space method, six port measurement technology and other methods, in the practice of measuring the permittivity have their own advantages and disadvantages.



(a)



(b)



(c)

Figure 4 Diagram of (a) coaxial probe method (b) Network Method (Transmission Line Method) (c) Free-Space Wave Method [3]

In our project, I used the reflection method based on the transmission line method theory to measure the permittivity. According to our investigation, I propose a model based on coaxial reflection coefficient analysis to obtain the permittivity of the tissues. Coaxial probe is a guide system formed by two coaxial cylindrical conductors, a transmission line filled with air or high-frequency medium between the inside and outside conductors. As indicated of Figure 4, the coaxial line is composed of four layers of structure, from the inside to the outside are the inner conductor, insulating medium layer, outer conductor and sheath. Such a design can mitigate electromagnetic attenuation and shield external disturbance, thus passing us more real and accurate data which facilitating the analysis. Compared with the methods mentioned above, the coaxial reflection method has several advantages in measuring electrolyte: 1. Lower cost 2. Nondestructive on material 3. Small space occupation 4. Higher accuracy.

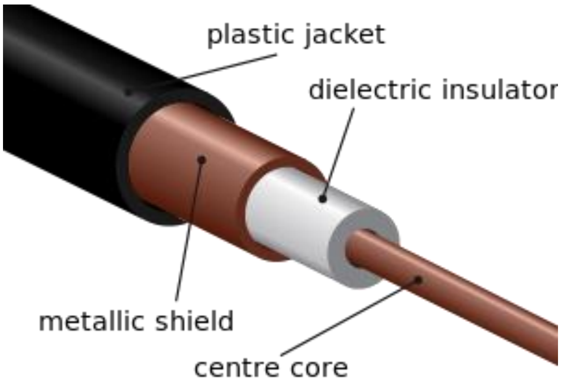


Figure 5 Basic Structure for a Coaxial Line (Probe)[20]

I use coaxial lines mainly to measure the reflection coefficient. The reflection coefficient is closely related to permittivity. The reflection coefficient in the coaxial line refers to the ratio of the electric field intensity of the reflected wave to the electric field intensity of the incident wave. In the course of electromagnetic wave propagation through different media, such as from the dielectric into the coaxial line, or the multi-layer dielectric model I will discuss below, the electromagnetic wave reflection occurs, so the final reflection coefficient at the coaxial line is closely related to the permittivity of the dielectric passing through. Our basic idea is as follows: Firstly, establish a model to calculate the reflection coefficient in the coaxial line according to the permittivity of material; And then determine the relationship between the reflection coefficient and the permittivity through the model. Based on the above model, I can use the coaxial line to measure the reflection coefficient and calculate the permittivity.

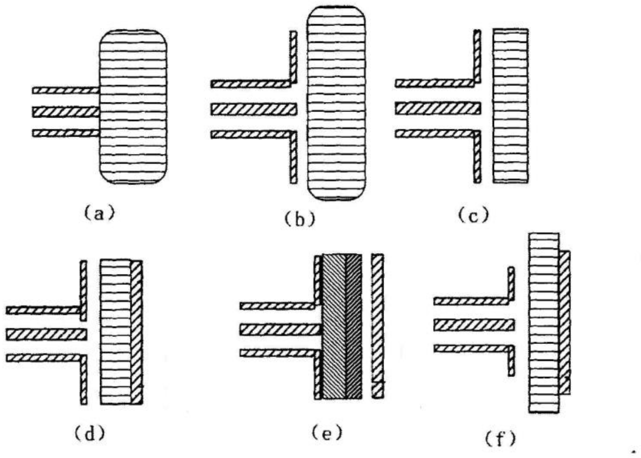


Figure 6 Common Open-Ended Coaxial Probe Model [19]

Finally, our project is the external project cooperated by BUPT, QMUL and UPV of Spain. According to the original plan, I was supposed to go to the laboratory of UPV in Spain on January 16, 2021 to complete the work of measuring the reflection coefficient of objects, but due to the epidemic, I could not go there. Therefore, the cooperation turned to online. My tutor measured in the laboratory and sent the data back to me. I processed and analyzed the data through the model established by MATLAB and completed our report.

Chapter 3: Theoretical Models and Methods

As shown in Fig. 6, the basic coaxial model and the measuring model of monolayer dielectric are presented [11] [12]. Due to the simple structure of the model, it is easy to calculate the relationship between the reflection coefficient and the permittivity, so it has been well studied and applied. I will build on this model and discuss two more complex models. The first model will study the multilayer dielectrics with different permittivity [6]. In this model, it is assumed that the coaxial line fits perfectly with the material surface and there is only the ideal TEM mode electromagnetic wave inside. However, in reality, it is difficult for us to achieve such a perfect state because there is often a gap between the coaxial line and the material and TM mode electromagnetic wave will be introduced which can result in a great error. Therefore, the second model I discussed introduces an air-gap layer and brings TM_{0n} wave, which makes the situation more complicated, but also closer to reality [7]. I expect the second model to have a better performance.

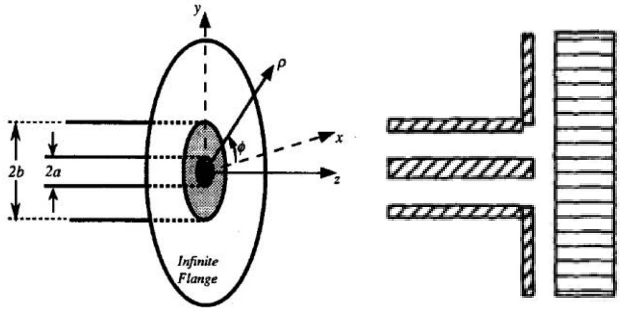


Figure 7 Basic Coaxial Probe Diagram [6]

Overall, both of the model will follow a basic steps: determine the boundary conditions between the layers; calculate each layer's electric field intensity and magnetic field intensity and the corresponding value of them after Hankel transformation; using Hankel transformed electric field and magnetic field on the border to meet the continuous characteristics on the tangent direction; Combined with other theorem such as Paseval theorem to help us to establish the relationship between different layer's electric and magnetic fields, and ultimately determine the value of the reflection coefficient.

3.1 Variable List

Table 1: Variable List

Symbol	Meaning
ϵ	Permittivity, ϵ_0 is the permittivity of vacuum. ϵ^* is

	the relative permittivity.
μ	Permeability, μ_0 is the permeability of vacuum. $\mu_*$is the relative permeability.
d_n	The thickness of the n_{th} layer
ρ, θ, z	Polar coordinate system of coaxial line.
n	The order of the layer
Π	Potential Vector
E	Electric Field
H	Magnetic Field
$\tilde{\Pi}$	The symbol after transformation of Hankel
J_n(x)	The nth order of first-kind Bessel Function
N_n(x)	The nth order of second-kind Bessel Function
k_n	The nth layer's wave number
R	Reflection Coefficient
γ_n	The nth layer's propagation constant.
ω	The angular velocity of transmission wave
v_{cav}	The velocity of light within vacuum

3.2 Multilayer Dielectric Model

In this model [6] I will analyze the reflection coefficients within the coaxial line as the electromagnetic wave enters the multilayer dielectric layer from the coaxial line to the terminal layer. In the figure 7, a) and b) were all the models I discussed. The leftmost part was the plane graph of the coaxial line, in which the relative permittivity was ϵ_{r_c}, and the vacuum-permeability was μ_0.The middle layer is multilayer dielectric, where ϵ_{r_c} is the nth layer relative permittivity $d_n$is the dielectric thickness. The difference between the two models is that (a) the terminal uses an open-circuit, while (b) the terminal uses a metal short-circuit. Two different terminal methods will have a great impact on the results, and I have also implemented them in experiments and programs respectively. Users can choose either model to use according to the situation in the laboratory.

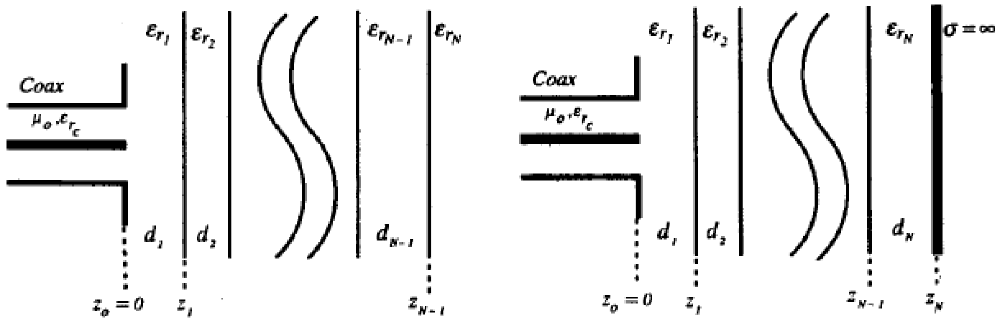


Figure 8 Multilayer Dielectric Model a) with open-circuit b) with short-circuit termination [6]

In this ideal model, I assume that only TEM mode waves in the coaxial line enter the material layers, That is, the electromagnetic wave has no component in the ϕ direction in the coaxial line, and Hertz Potential can be simplified as: $\overline{\Pi}(\rho, \phi, z) = \Pi_n^{\phi}(\rho, z)\hat{a}_{\phi}$, where n represents the internal condition of the nth layer dielectric. It can be obtained by plugging it into the Helmholtz wave equation, so we can get [1]:

$$\left[\frac{\partial^2}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial}{\partial \rho} + \frac{\partial^2}{\partial z^2} + \left(k_n^2 - \frac{1}{\rho^2}\right)\right]\Pi_n^{\phi}(\rho, z) = 0 \tag{1}$$

After vector potential formulation, electric field component $\overline{\boldsymbol{E}}_{\boldsymbol{n}}$and magnetic field component $\overline{\boldsymbol{H}}_{\boldsymbol{n}}$ of each layer can be obtained, where $\boldsymbol{k_n}$ is the wavenumber of dielectric electromagnetic waves of the nth layer. Then we formulated vector potential formulation by Hankel transform, and we could obtain:

$$\tilde{\Pi}_n^{\phi}(\rho, z) = \int_0^{\infty} \rho\, \Pi_n^{\phi}(\rho, z) J_1(\mathbb{R}_{\rho}) d\rho \tag{2}$$

There should be some writing errors in (6b) of this part of the original thesis [1], which should be corrected here. Where R is the converted variable representing the wave number, $\tilde{\Pi}$ is the vector potential after the Henkel transform, and 3 is the first-order Bessel equation of the first kind. The wave number $k_{z_n} = \sqrt{k_n^2 - \mathbb{R}^2}$. According to the vector potential after transformation, we can easily get the electric field component $\tilde{\mathrm{E}}$ and magnetic field component $\tilde{\mathrm{H}}$ after Hankel transformation. In an ideal state, the boundary transformation of electric field and magnetic field should be continuous. So we can get the expression $\tilde{E}_n^{\rho}(\mathbb{R}, z = z_n) = \tilde{E}_{n+1}^{\rho}(\mathbb{R}, z = z_n)$, and $\tilde{\mathrm{H}}_n^{\rho}(\mathbb{R}, z = z_n) = \tilde{\mathrm{H}}_{n+1}^{\rho}(\mathbb{R}, z = z_n)$, where $\boldsymbol{z_n}$ is the distance from the coaxial line to the nth layer dielectric.

Based on the premise that only TEM mode wave exists in the coaxial line, we can write the electric field and magnetic field components in the coaxial line [14]:

$$E_0^p(\rho, z) = \frac{A_0}{\rho}\left(e^{jk_c z} + Re^{-jk_c z}\right) \tag{3}$$

$$H_0^\phi(\rho, z) = \frac{Y_0\sqrt{\epsilon_{r_c}}A_0}{\rho}\left(e^{jk_c z} - Re^{-jk_c z}\right) \tag{4}$$

where $k_c = k_0\sqrt{\epsilon_{r_c}}$, $R = \Gamma e^{j\Phi}$ is the reflection coefficient, that's what our model ultimately wants to get, A0 is a constant that represents the amplitude, and we don't have to worry about its magnitude because it will get rid of it later in the calculation. Given the initial electromagnetic field component of the coaxial line and the condition that the electromagnetic field intensity between each layer is continuous, we also need Poynting Theorem, a conservation of electromagnetic field energy, to help us establish the connection between the electromagnetic field intensity of each layer. According to Parseval Theorem, we can obtain the density of energy flow flowing out of the coaxial line [15]:

$$\vec{P}^*_{z=0} = \pi Y_c * A_0^2(1 + \mathrm{R}) * (1 - R)\ln\left(\frac{a}{b}\right) \tag{5}$$

And the first layer of dielectric received the density of energy flow is:

$$\tilde{E}_0^\rho = -A_0(1 + R)\frac{J_0(\mathrm{R}b) - J_0(\mathrm{R}a)}{\mathbb{R}} \tag{6}$$

According to Poynting Theorem, they should be equal and substituted into the Hankel transform of the electric field component in the coaxial line:

The calculation method of Aperture Admittance is obtained, which is the core algorithm of our model [6]:

$$y_s = \frac{\epsilon_{r_1}}{\sqrt{\epsilon_{r_c}}\ln\left(\frac{a}{b}\right)}\int_0^\infty \frac{[J_0(k_0\zeta b) - J_0(k_0\zeta a)]^2}{\zeta}F(\zeta)d\zeta \tag{7}$$

$F(\zeta)$ is a part we extracted from the algorithm, has no actual physical meaning, but its calculation needs to be implemented through recursive functions.

$$F(\zeta) = \frac{1}{\epsilon_{r_1} - \zeta^2}\left(\frac{1 + \rho_1}{1 - \rho_1}\right) \tag{8}$$

$$\rho_i = \frac{1 - K_i\beta_{i+1}}{1 + K_i\beta_{i+1}}e^{-j2k_0 z_i\sqrt{\epsilon_{r_i} - \zeta^2}} \tag{9}$$

$$K_i = \frac{\epsilon_{r_i}\sqrt{\epsilon_{r_{i+1}} - \zeta^2}}{\epsilon_{r_{i+1}}\sqrt{\epsilon_{r_i} - \zeta^2}} \tag{10}$$

$$\beta_{i+1} = \frac{1 - \rho_{i_+1} e^{j2k_0 z_i \sqrt{\epsilon_{r_{i_+1}} - \zeta^2}}}{1 + \rho_{i_+1} e^{j2k_0 z_i \sqrt{\epsilon_{r_{i_+1}} - \zeta^2}}} \tag{11}$$

$$\rho_N = \begin{cases} 0, for\ a\ open - circuit\ termiantion \\ e^{-j2k_0 z_N \sqrt{\epsilon_{r_N} - \zeta^2}}, for\ a\ close - circuit\ termination \end{cases} \tag{12}$$

With the help of this algorithm, we can easily get the admittance with the info of multilayer's dielectric's property.

We have the relationship between admittance and reflection coefficient as $y_s = \frac{1-R}{1+R}$, so we can get reflection coefficient easily with this algorithm. For now, our basic multilayer dielectric model has been established. Later on, I will introduce our method to calculate permittivity via this model.

3.3 Dielectric Analyzing Model with Lift-off

Our first model helps us understand the effect of multilayer dielectric mass on the reflection coefficient in the coaxial line. However, it is established in the ideal case that coaxial line and material perfectly fit and only TEM mode wave exists. In reality, there will be a certain gap between our coaxial line and material, and the introduction of TM mode makes the situation more complicated. Therefore, in the second model, I will discuss the influence of dielectric parameters on the reflection coefficient in the coaxial line with the introduction of the air-gap layer (lift-off layer) [7]. Since the basic principles are the same, I will focus on the following issues when discussing this model: 1. After introducing air layer, what are the boundary conditions of the air layer and the material layer, and how should the electromagnetic field intensity be expressed as? 2.How the TEM mode wave and TM mode wave in the coaxial line interact and how they should calculate? 3.How to calculate the reflection coefficient under the new situation.

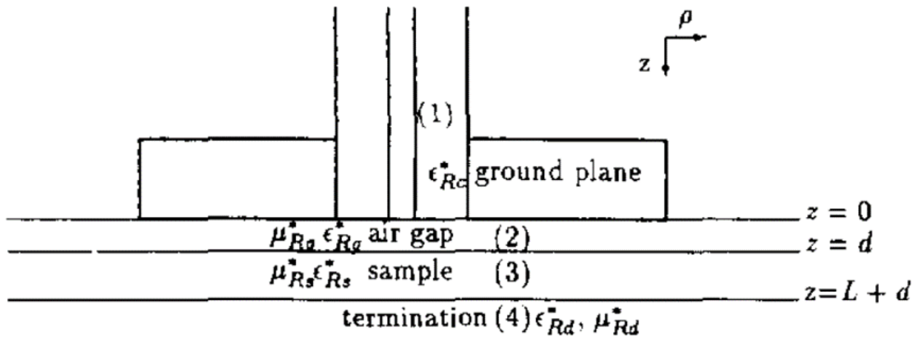


Figure 9 Dielectric Model with an air-gap(lift-off) layer [7]

As in Model 1, we can easily obtain the Potential Vector Π_ϕ by Helmholtz Theorem, and similarly, we can obtain the electric and magnetic field components E and H of each layer by it. Meanwhile, according to the model, we can obtain the boundary conditions of magnetic field:

$$\mathrm{H}_{\phi(i)}(\rho \to \infty, z) \to 0, (i = 2,3,4).$$

$$\mathrm{H}_{\phi)2}(\rho, 0_+) = \mathrm{H}_{\phi(1)}(\rho, 0_-)$$

$$\mathrm{H}_{\phi(3)}(\rho, d_+) = \mathrm{H}_{\phi(2)}(\rho, d_-) \tag{13}$$

$$\mathrm{H}_{\phi(4)}(\rho, d + L_+) = \mathrm{H}_{\phi(3)}(\rho, d + L_-)$$

In addition, for a material termination, $\Pi_{\phi(4)}(\rho, z \to \infty) \to 0$, for a short-circuit termination $E_{\rho(3)}(\rho, d + L) = 0$

Then we can make Hankel transformation on the E and H and the corresponding boundary conditions. The above equation (1) can be converted to

$$\left[\frac{d^2}{dz^2} + (k_i^2 - \zeta^2)\right]\tilde{\Pi}_{\phi(i)} = 0 \tag{14}$$

Firstly The converted electric field component can be expressed as $\tilde{E}_{\rho(i)}(\zeta, z) = -\frac{1}{jw\epsilon_i^8}\frac{\partial \tilde{H}_{\phi(i)}}{\partial z}$, and the converted magnetic boundary conditions turned to be:

$$\tilde{H}_{\phi(2)}(\zeta, z) = Aexp\big(-\gamma_2(z-d)\big) + Bexp\big(\gamma_2(z-d)\big)$$

$$\tilde{H}_{\phi(3)}(\zeta, z) = Cexp\big(-\gamma_3(z-d)\big) + Dexp\big(\gamma_3(z-d)\big)$$

$$\tilde{H}_{\phi(4)}(\zeta, z) = Fexp\big(-\gamma_4(z-d)\big) \tag{15}$$

Where A, B, C, D, F are constants, $\gamma_i = j\sqrt{k_i^2 - \zeta^2}, i = 2,3,4$ is propagation constant. Suppose that R_0 represents the reflection coefficient of TEM mode, and Ri, i = 1, 2, ..., n represents the reflection coefficient of TM_{0n} mode. The electric field component within the coaxial line can be expressed:

$$E_{\rho(1)}(\rho, z) = [exp(-\gamma_1 z) + R_0 exp(\gamma_1 z)]R_0(\rho) + \sum_{n=1}^{\infty} R_n\, exp(\gamma_{n(c)z})R_n(\rho)$$

$$E_z = \frac{1}{jw\epsilon^*}\left[\frac{\partial \Pi_\phi(\rho, z)}{\partial \rho} + \frac{1}{\rho}\Pi_\phi(\rho, z)\right] \quad (16)$$

In the coaxial line, two propagation constants are involved in calculation. One is the transmission constant of TEM mode, which is defined as $\gamma_1 = \frac{jw\sqrt{\epsilon_{Rc}^* \mu_{Rc}^*}}{c_{vac}}$. The propagation constant of Tm_{0n} mode is $\gamma_{n(c)} = j\sqrt{(w/c_{cav})^2 \epsilon_{Rc}^* \mu_{Rc}^* - k_{n(c)^2}}, n = 0,1,2, \dots, N$, Where c_{cav} is the speed of light, we use the subscript n(c) specially to refer to the properties within the coaxial line, when n=0 indicates TEM mode, other cases indicate TM0n mode, that is, $\gamma_{0(c)} = \gamma_1$. $k_{i(c)}$ is the wave number in the coaxial line $k_{0(c)} = k_1$, When i = 1, 2, ..., n, and $k_{i(c)}$ is the i_{th} solution of equation (16) [8], [16]:

$$\left[J_0\left(k_{n(c)}a\right)N_0\left(k_{n(c)}b\right) - N_0\left(k_{n(c)}a\right)J_0\left(k_{n(c)}b\right)\right] = 0 \quad (17)$$

where J is the first kind Bessel function and N is the second Bessel function.

The radial eigenfunction could be:

$$R_n(\rho) = \begin{cases} \frac{C_0}{\rho}, & n = 0, TEM\ Mode \\ C_n[J_1(k_{n(c)}N_0 k_{n(c)}a - N_1(k_{n(c)}\rho)J_0(k_{n(c)}a)], & n > 0, TM\ mode \end{cases} \quad (18)$$

By acquiring orthogonality, $\int_a^b \zeta\, R_m(b\zeta)R_n(a\zeta)d\zeta = \delta_{mn}, m, n = 0,1, \dots, n$, we can obtain:

$$C_n = \begin{cases} \frac{1}{\sqrt{\ln\left(\frac{b}{a}\right)}}, n = 0 \\ \frac{\pi k_{n(c)}}{\sqrt{2}} \frac{1}{\sqrt{\frac{J_0^2\left(k_{n(c)}a\right)}{J_0^2\left(k_{n(c)}b\right)} - 1}} \end{cases} \quad (19)$$

By applying Hankel Transformation on the electronic field on the coaxial probe, we can obtain the transformed electronic field : $\tilde{E}_{\rho(1)}(\rho, z) = D_0[exp(-\gamma_1 z) + R_0 exp(\gamma_1 z)] + \sum_{n=1}^{\infty} R_n\, D_n exp(\gamma_{n(c)} z)$, where $D_n(\zeta) = \int_a^b \rho J_1(\zeta\rho) R_n(\rho) d\rho$. The transformed magnetic field is:

$$\tilde{H}_{\phi(1)}(\zeta, z) = -\frac{D_0 jw\epsilon_0\epsilon_{Rc}^*}{\gamma_1}[-exp(-\gamma_1 z) + R_0 exp(\gamma_1 z)] - jw\epsilon_0\epsilon_{Rc}^* \sum_{n=1}^{\infty} \frac{1}{\gamma_{n(c)}} R_n exp\left(\gamma_{n(c)} z\right) D_n \quad (20)$$

er calculating all the electronic and magnetic field, we need to meet the boundary requirement and establish their relationship. Between layer 1 and layer 2, the converted electric field is continuous in the tangential direction. Combining with the impedance relation of TM mode, the relation can be obtained as follows:

$$(1 + R_0)D_0 + \sum_{n=1}^{\infty} R_n\, D_n = -\frac{\gamma_2}{jw\epsilon_g^*}\left(\mathrm{A}\exp(\gamma_2 d) + Bexp(-\gamma_2 d)\right) \quad (21)$$

The magnetic field is also continuous in the tangent direction, so we can get:

$$A + B = E(1 + \Theta), \qquad \frac{\gamma_2}{\epsilon_{Rg}^*}(B - A) = \frac{\gamma_3 E}{\epsilon_{Rs}^*}(\Theta - 1) \quad (22)$$

$$\Theta = \begin{cases} exp(-2\gamma_3 L), for\ a\ shorted\ termination \\ \dfrac{exp(-2\gamma_3 L)(1 - \Theta_2)}{1 + \Theta_2}, \Theta_2 = \dfrac{\epsilon_{Rs}^*\gamma_4}{\epsilon_{Rd}^*\gamma_2}, \quad for\ material\ termination \end{cases} \quad (23)$$

To obtain the reflection coefficient Rn, we can take the inverse transform of the above boundary equation and get the target equation [6]:

$$\frac{jw\epsilon_0\epsilon_{Rc}^*}{\gamma_m} R_m = -\int_0^{\infty} \zeta\, D_m[Ae^{\gamma_2 d} + Be^{-\gamma_2 d}]d\zeta + \frac{jw\epsilon_0\epsilon_{Rc}^*}{\gamma_1}\delta_{m0} \quad (24)$$

So that we can obtain reflection coefficient R_m where m = 0 for TEM mode[7], and m = 1, 2, 3, ..., n for TM_{0n} modes.

3.4 Nelder-Mead determine the permittivity

For now, I have established two models to calculate the reflection coefficient. However, in practice, reflection coefficient is easy to be identified by the help of coaxial line rather than the permittivity. Now I have to focus on how to obtain the permittivity via these two models. Due to the influence of multilayers and introducing of air-gap layer, the relationship between reflection coefficient and permittivity could be complex and hard to be determined. Therefore, I want to refer to one method to update permittivity through iteration until it reaches a value similar to the reflection coefficient measured in the laboratory and stops updating. At this time, the permittivity is the final value measured by us.

3.4.1 Model Feasibility

First of all, I need to verify the feasibility of this method to see whether our scheme will produce multi-value problem, that is, whether multiple permittivity can obtain the same reflection coefficient, or analyze the monotony of the relationship between reflection coefficient and permittivity. Since it is difficult to determine their mathematical relationship, I choose to draw analysis on the basis of the model I have implemented.

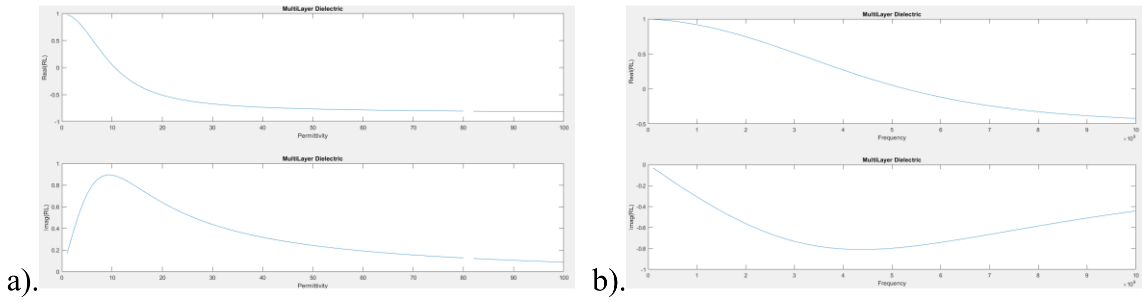


Figure 10 Model 1 a) Graph of Reflection Coefficient (RC) changing with permittivity (1-100); b) Graph of RC changing with frequency (100MHz – 10GHz)

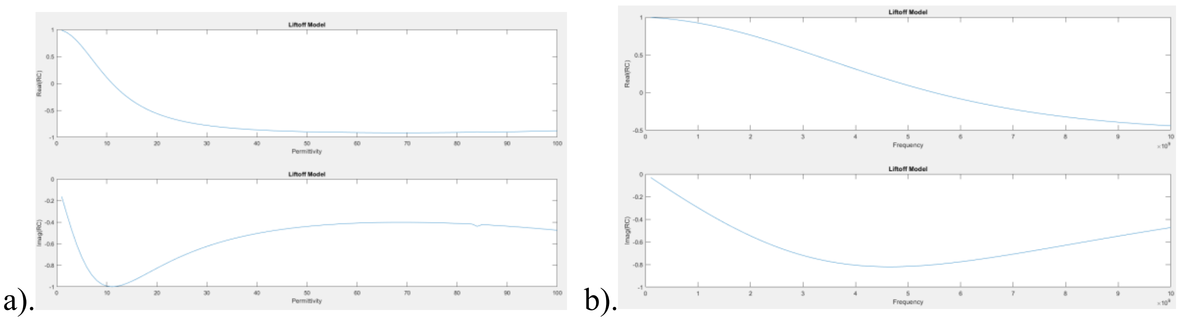


Figure 11 Model 2 6 a) Graph of Reflection Coefficient (RC) changing with permittivity (1-100); b) Graph of RC changing with frequency (100MHz – 10GHz)

I used the established two models to simulate the change of the Reflection Coefficient with the increase of Permittivity and Frequency, respectively. I found that the real part of the obtained Reflection Coefficient decreased monotonically with the increase of Permittivity and Frequency, so there would be no multi-value problem. Obviously, the imaginary part of Reflection Coefficient will produce multiple value problems. This problem is often existing in reflection method and to be solved, but it actually will have little impact on the effect of permittivity. In the later analysis I also can see the value of the real component of predicting permittivity is far better accurate than that of imaginary part. Although the imaginary part (error is less than ten percent) is greater, in the end of the overall effect depends on the value of the real part. So according to this analysis, I can use the search method to find the appropriate permittivity. For multi-valued cases, I usually go to the smaller one.

3.4.2 Parameter Renew Method — Nelder-Mead Algorithm

Loss function was simply defined as the distance between the measured reflection coefficient and our calculated reflection coefficient:

$$f_{loss}(\epsilon_n) = |R_{calculated} - R_{measured}|$$

In order to achieve our purpose, I chose a relatively simple algorithm, Nelder-Mead[4]. This is an algorithm for finding the local minimum of multivariate function. The advantage is that the function does not need to be differentiable and it can quickly converge to the local minimum. So, this algorithm is very well suited to solving this kind of complex relationship. But this algorithm can only solve the local minimum, so I need to determine whether this property will affect the performance of our model. I don't want to be stuck at a local minimum when I update our permittivity and not get to the point where I expect it to. In order to verify our idea, I drew the image of the real and imaginary parts of the reflection coefficient changing with the permittivity. As shown in the figure, the surface of the image is very smooth and there are no local concave points, so the local optimal point I have solved is the global optimal point. Therefore, this algorithm can help us determine permittivity through reflection coefficient.

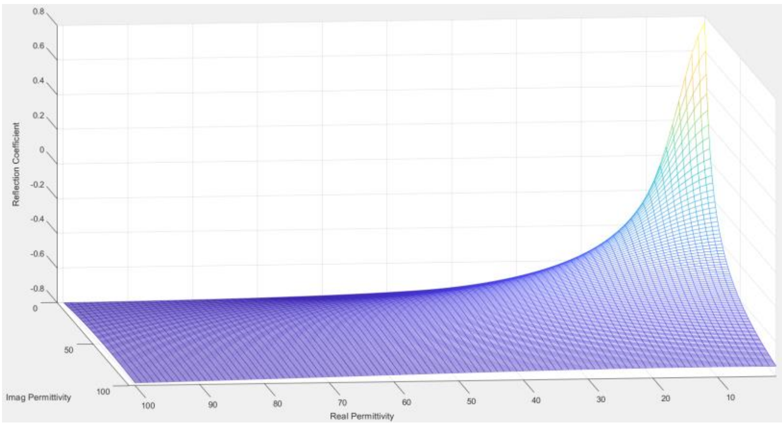


Figure 12 The real part of RC with changing of permittivity

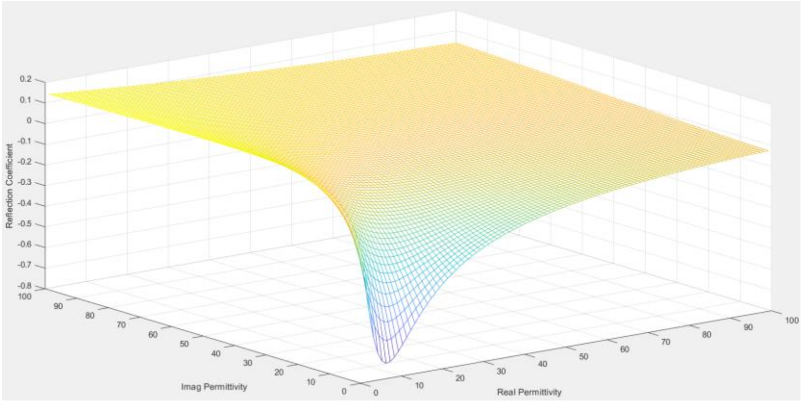


Figure 13 The imaginary part of RC with changing of permittivity

According to the thesis[4], I want to basically describe the process of Nelder-Mead updating parameters:

0. Suppose we wish to calculate two layers of dielectric permittivity, we have four unknown parameters (N=4), the real and imaginary parts of the first layer of permittivity, and the real and imaginary parts of the second layer of permittivity.

1. We generate N new points from the initial point, x_i, i = 1, 2, 3, ..., N, x_i is 5% larger in the i component than the initial point, so we have N+1 point, and then we sort these points by the value of $f(x_i)$. We assign these points with new name from x_1, x_2, ... x_n, x_{N+1}.

2. We calculate the mean of first N points: $m = \frac{1}{N}\sum_{\{i=1\}}^{N} x_i$

3. Calculate the reflection point of x with respect of m: $r = 2m - x_{N+1}$

4. If $f(x_1) \leq f(r) < f(x_N), let\ x_{N+1} = r$, entering the next iteration.

5. If $f(r) < f(x_1)$, we calculate the extending point as $s = m + 2(m - x_{N+1})$. If $f(s) < f(r)$, let x_{N+1} = s and entering the next iteration, or let x_{N+1} = r and entering the next iteration.

6. If $f(x_N) \ll f(r), then\ c_1 = m + \frac{r-m}{2}$, if $f(c_1) < f(r)$, let xN+1 = 5 and entering the next iteration. Or go to the last step.

7. If $f(x_{N+1}) \ll f(r)$, let $c_2 = m + \frac{x_{N+1}-m}{2}$. If $f(c_2) < f(x_{N+1}), let\ x_{N+1} = c_2$, and entering the next iteration. Or go to the last step.

8. Last Step: Let $v_i = x_1 + \frac{x_i - x_1}{2}\ i = 2, 3, \dots, N+1, let\ x_i = v_i$

When one of the points meets the accuracy requirement, we exit the loop. According to the analysis of the algorithm, when the position of the local minimum is outside the region surrounded by N+1, the graph accelerates to move towards the minimum. When the minimum position is inside the graph, the graph tends to shrink and eventually close together.

3.4.3 Basic Structure for Calculating Permittivity

Let us introduce the specific process of measuring permittivity according to our model:

First of all, since we don't know the value of the permittivity of the substance, we're going to set a random value like 10 - 1i. Other values, such as the magnitude of the axis and the frequency of the wave, are known values. Then I can choose one of the two models that have been built to calculate the reflection coefficient. Use this instrument in the lab, I can measure the reflection coefficient inside the coaxial line, then I can put our model and measured reflection coefficient in the Nelder-mead algorithm, using our calculation of reflection coefficient and measurement of the difference of the reflection coefficient of the update as loss material permittivity, until their difference is less than 1 e - 6, I will stop the iteration permittivity at this time as the final result.

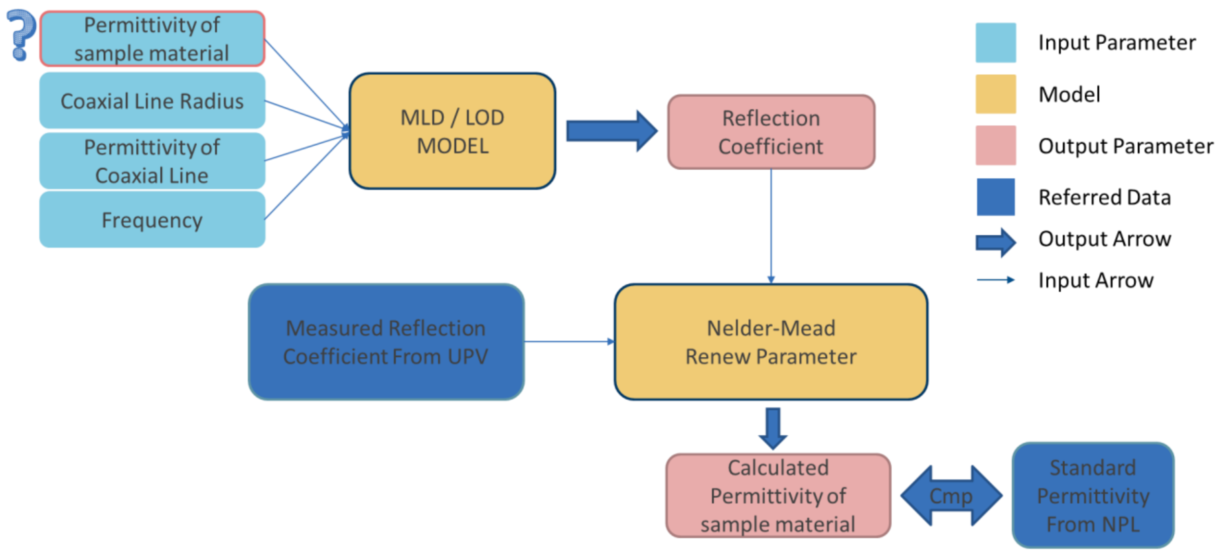


Figure 14 Structure of calculating permittivity

For now, the whole established has been established. I will introduce the procedure I design and implement the model and the software.

Chapter 4: Design and Implementation

4.1 Object-Oriented Design

The two Model programs are designed based on object-oriented programming and the concept of MVC(Model-View-Control) framework in the Internet. I use the MVC model mainly to separate the data, processing logic and interface, reduce the randomness of the program, and provide convenience for development and later extension.

Model: Treat each layer of substance in our two models as a business Model to store the attributes belonging to this substance. I set up an empty BasicData class to be the parent of all of our Models, and the Data class inherits Handel and handles the getter and setter methods of the Data.

Control: For each model I have a Control class that is responsible for the implementation of the model algorithm. The Control class in the first model is MultilayerDielectric and the Control class in the second model is LiftOffDielectric. They are responsible for extracting data from the Model and performing calculations, and they also provide interfaces to the outside world to retrieve the data.

View: In this project, I use MATLAB App Designer as the GUI of the program to provide users with a user interface and a variety of Settings and choices to help users calculate the results more conveniently. I also support batch operation by setting one factor as a variable and calculating it. For more detailed instructions, see the User Manual in additional materials.

4.1.1 Multiple layer Dielectric Model Design

We designed the Model pattern as shown in the figure according to the MLD Model. BasicData is the abstract parent of all data classes. The CoaxialLineData holds the data associated with the coaxial line layer, the MultilayerDielectricData holds the n layers dielectric property data, and the ConstantData holds the physical constants that we will use.

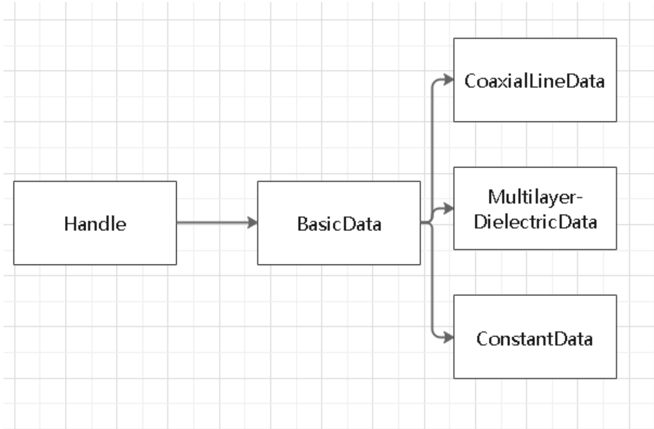


Figure 15 Model Part of MLD

MLD's MVC pattern is shown in the following figure: User can use script to input data to controller, controller can transmit data to Model part and store them. In the meantime, Controller can invoke the data from Model and conduct calculation and send the result to View part. View part is also a Data Class which store the information related to result. User can invoke relevant script to view the result. In the following the view part is been replaced by GUI.

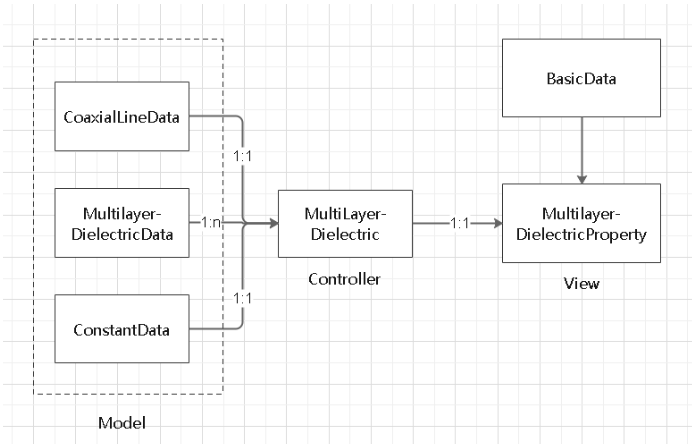


Figure 16 MVC of MLD

4.1.2 Lift-off Dielectric Model Design

Due to the different structure of MLD, we design a new Model structure for LOD model. Firstly, for the similar part, we reuse the code of BasicData and ConstantData classes. And then we design a LayerData class which is responsible for store the data of sample layer and air-gap layer. In the meantime, we have CoaxialLayerData and TerminationLayerData as the subclass of LayerData. They expand some specific properties based on LayerData.

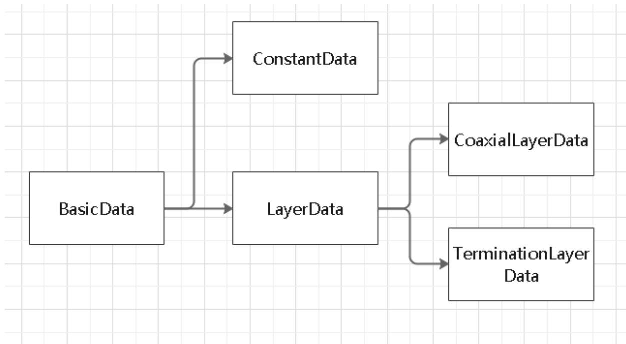


Figure 17 Model Part of LOD

The basic design logic of LOD is quite similar to MLD. The controller can store and get data from Model part. Also, controller takes the responsibility to calculate results and send them to View part. View part has specific methods to show the result to users.

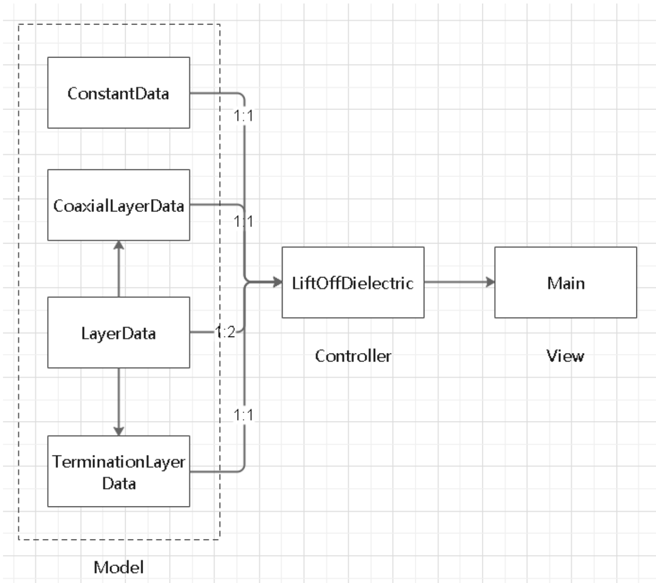


Figure 18 MVC structure for LOD

4.2 Implementation

Written using a test-driven Development approach. In the whole process of writing software to pass the test for the purpose of code writing.

The Model part mainly stores two types of data: one is directly read and write data, such as frequency, coaxial radius, etc., which is directly stored in member variables and read; the other is dependent data, such as wave number, angular velocity, etc., which relies on the values of other member variables for calculation every time it is read. In the implementation, I will first write the instantiated Model class, and then check the correctness of read and write data by comparing write and read values. Secondly, I will design some inputs and manually calculate the results to compare the correctness of the formula implementation with the results calculated by the program. Secondly, in this way, it can also detect whether the missing dependent data will give corresponding prompts instead of reporting errors when the dependent data is read.

The Control part is mainly to realize the model formula. In the implementation mode of TDD, I will take the final objective function as the test, and decompose the required quantity in the objective function into small test units as the function to realize. Two important questions to consider when implementing each function are whether it will produce a singularity point, and at what range it will produce null values, and what to do about them.

The speed of the program depends largely on the amount of computation in the formula, which is the algorithm I use. In this model implementation, I mainly used two optimization methods. The first scheme is that there is a large amount of integral calculation in the formula, but many calculation parts need to be repeatedly calculated during integration, which has nothing to do with the integral variable. I can calculate these parts in advance and save them in temporary member variables to reduce the amount of calculation. The second is that many formulas have the same part in the integral, and I can say that these formulas are calculated together, and use the result of one integral to calculate the value of more formulas.

Every time I do an integral it's always going to produce singularities as I do the computation, and I need to test, when I write an integral function, if we integrate from 0 to infinity to see if that integral produces singularities. If there are singularities, I need to deal with them, otherwise it will affect our further calculations. And the way that I normally deal with singularities is to make it equal to the value of the left limit and the right limit, and make it continuous. (In the figure, it's kind of like adding a value to the image to make it complete and continuous.)

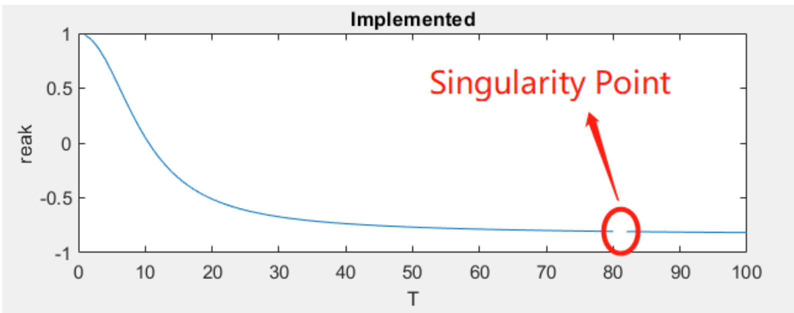


Figure 19 Singularity Example exists in the integral

When writing each formula, I should also consider whether the formula produces Nan values in the range of possible inputs. Such a value is usually produced by INF/INF or 0/0 results. The most common solution is to use l 'Hospital’s rule to help the program figure out what the value should be when the region is limited and modify it with conditional judgment. For example, in the formula (11) I presented above, $\beta_{i+1} = \frac{1-\rho_{i+1}e^{j2k_0 z_i\sqrt{\epsilon r_{i+1}-\zeta^2}}}{1+\rho_{i+1}e^{j2k_0 z_i\sqrt{\epsilon r_{i+1}-\zeta^2}}}$, it can be easily to generate a form of inf/inf when ζ approach to a larger value, so in MATLAB it will produce Nan value(as indicated in Figure 12). So, I have to manually correct it to 1 when it reaches to a large value.

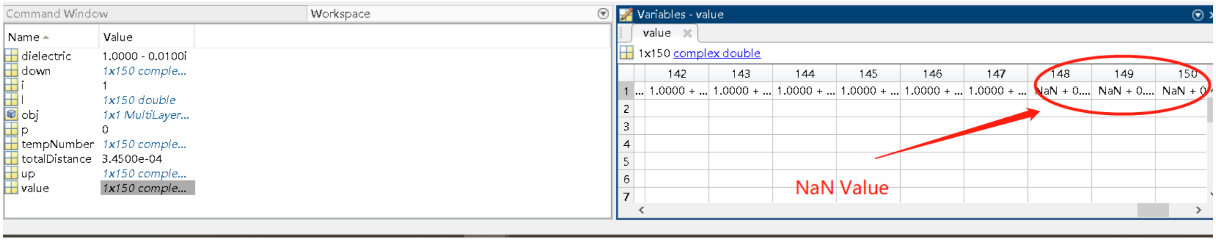


Figure 20 Nan-Value Situation Exits in Formula

Finally, I also completed the writing of program documents and user manuals, in which I marked the meaning and use methods of objects and methods of each class. In the user manual is introduced all the interface use methods, as well as the use of script-based rules.

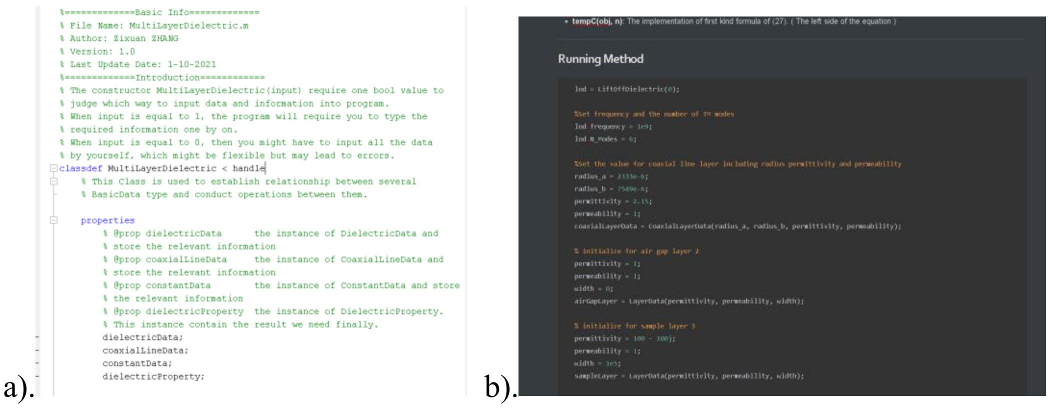


Figure 21 a) Code Doc Screenshot b) User Manual Screenshot

4.3 Formula Validation

I have to make sure that the formula is valid before I can translate it into code. As we all know, when writing related papers, due to the large number of corner marks and the similarity of various symbols for each variable, it is easy to make mistakes in transcription. For example, the formula (6b) in the paper [7] and [8] describes the Hankel transformation with the wrong symbols. In fact, in the process of our application of the paper, I also found many problems, which means that the manual inspection of the formula between the line of sight is particularly important. Once it's all done and it doesn't work, I still have to revisit the formula from scratch, which wastes a lot of time.

$$\Pi_n^{\phi}(\rho, z) = \int_0^{\infty} \mathcal{R}\tilde{\Pi}_n^{\phi}(\mathcal{R}, z) J_1(\mathcal{R}\rho)\, d\mathcal{R} \qquad (6a)$$

where

$$\tilde{\Pi}_n^{\phi}(\rho, z) = \int_0^{\infty} \rho \Pi_n^{\phi}(\rho, z) J_1(\mathcal{R}\rho)\, d\rho. \qquad (6b)$$

Figure 22 The typo exists in the thesis (on the left side of 6b should be R rather than ρ [7]

For another example, both Equation (14) and Equation (27) in the paper describe a regularization constant formula, but their representations in one part are reciprocal to each other. This formula affects the electric field intensity of TM mode. If it is wrong, the accuracy of our second model will be seriously affected. Therefore, I must derive C_N from the nature of Formula (17).

$$N_0 = 1/\sqrt{\ln(b/a)}. \qquad (11)$$

For the higher order TM_{0n} modes, $n > 0$:

$$f_n(\rho) = N_n[J_1(p_n\rho)Y_0(p_na) - Y_1(p_n\rho)J_0(p_na)] \qquad (12)$$

where $J_m(x)$ is the Bessel function of the first kind and $Y_m(x)$ is the Bessel function of second kind of order m. The eigenvalues $p_n (n \neq 0)$ are computed from

$$Y_0(p_na)J_0(p_nb) = J_0(p_na)Y_0(p_nb), \quad n > 0 \qquad (13)$$

and the normalizing factor N_n is given by

$$N_n = \frac{\pi p_n}{\sqrt{2}}\left[\frac{J_0^2(p_na)}{J_0^2(p_nb)} - 1\right]^{1/2}. \qquad (14)$$

The propagation factors (4) will be equal to

$$\gamma_0 = j\beta_0 = j\sqrt{\epsilon_c}(\omega/c_0), \quad n = 0 \quad \text{(propagated)} \qquad (15)$$

$$\gamma_n = \alpha_n = \sqrt{p_n^2 - \epsilon_c(\omega/c_0)^2}, \quad n > 0 \quad \text{(evanescent)}. \qquad (16)$$

VIII. Resolution for the Coaxial Line

Therefore

$$C_0 = \frac{1}{\sqrt{\ln(b/a)}} \qquad (26)$$

and

$$C_n = \sqrt{\frac{1}{\int_a^b \rho R_n^2(\rho) d\rho}} = \frac{\pi k_{n(c)}}{\sqrt{2}} \frac{1}{\sqrt{\frac{J_0^2(k_{n(c)}a)}{J_0^2(k_{n(c)}b)} - 1}}. \qquad (27)$$

Unless stated otherwise we will assume that the radial eigenfunctions are normalized. The eigenvalues $k_{n(c)}$ are obtained from the condition of vanishing tangential electric field on the conductor walls. The tangential electric field is given by (23). These are the nth solutions of

$$[J_0(k_{n(c)}a)N_0(k_{n(c)}b) - N_0(k_{n(c)}a)J_0(k_{n(c)}b)] = 0. \qquad (28)$$

Figure 23 The conflicting formulas in the paper

Secondly, I can compare the results of the formula generated by our recursive algorithm with the simplified formula graph written by the author in the paper. If the values are consistent, it can prove the correctness of our algorithm. For example, formula (7) to (11) are the recursive method I proposed to calculate multiple layer's dielectric's reflection coefficient. However, the author also proposed formula $F(\zeta) = \frac{1}{\sqrt{\epsilon_{r_1} - \zeta^2}}\left[\frac{k_1 + j\tan(k_0 d_1\sqrt{\epsilon_{r_1} - \zeta^2})}{1 + jk_1\tan(k_0 d_1\sqrt{\epsilon_{r_1} - \zeta^2})}\right]$ [6], for two layers without termination. If I can prove we have the same value, then our algorithm has been implemented correctly.

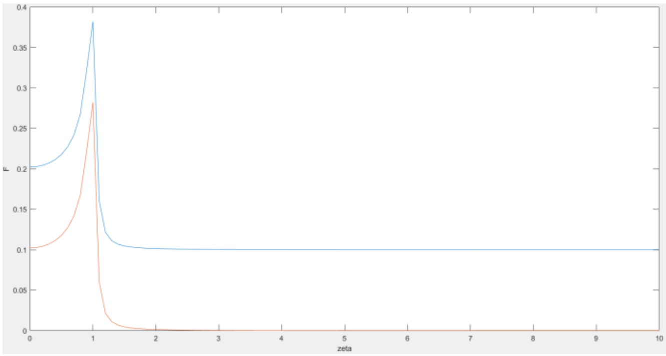


Figure 24 The comparison of our algorithm's value plus 0.1 with thesis's formula

4.4 Program Validation

After the completion of the model implementation, I still need to test the effect of the whole model, because the model implemented in this part is based on the model of Reflection Coefficient obtained by permittivity in others' papers, so the simplest solution is to repeat the experiment[6] used by the author in validation and compare whether the results are consistent or similar. Through comparison in the following Figures, it is obvious that I have perfectly restored the model used by the author.

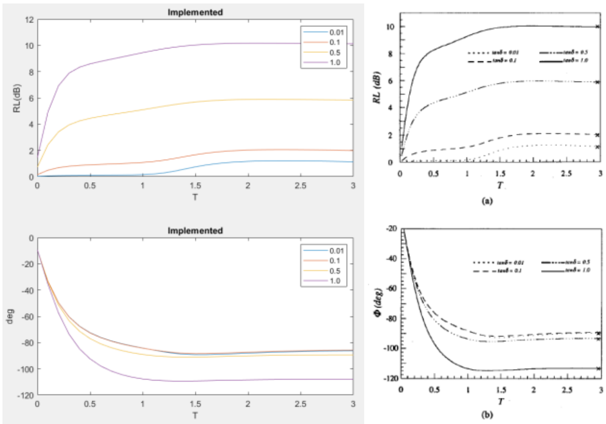


Figure 25 The comparison of return loss and phases changing with respect to T under the situation of 1 dielectric layer without termination. frequency f = 5GHz, $\epsilon_{r_1} = 10$. T is the dielectric slab thickness with respect to the coaxial line's outer radius.

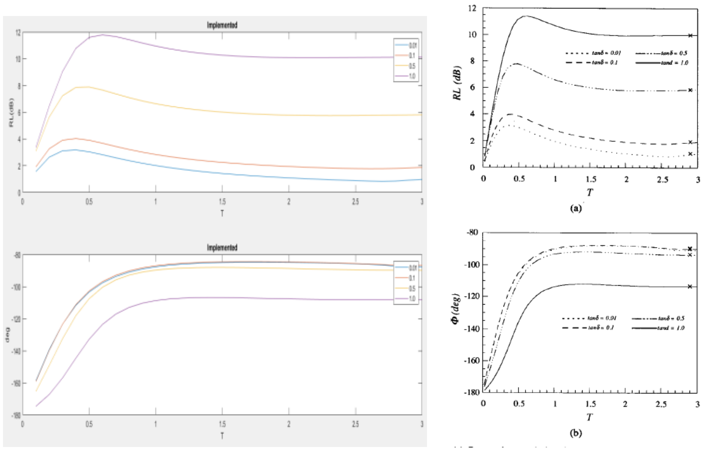


Figure 26 The comparison of return loss and phases changing with respect to T. under the situation of 1 dielectric layer with a conducting termination. frequency f = 5GHz, $\epsilon_{r_1} = 10$. T is the dielectric slab thickness with respect to the coaxial line's outer radius.

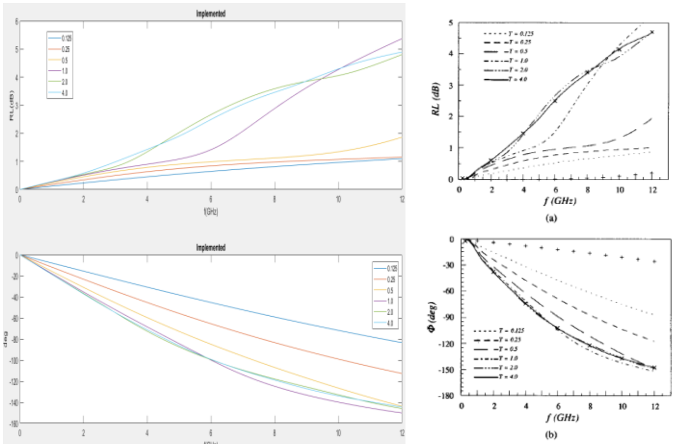


Figure 27 The comparison of return loss and phases changing with respect to the frequency under the situation of 1 dielectric layer without termination. $\epsilon_{r_1} = 10, tan\delta_1 = 0.1, T = \frac{d_1}{ar}$

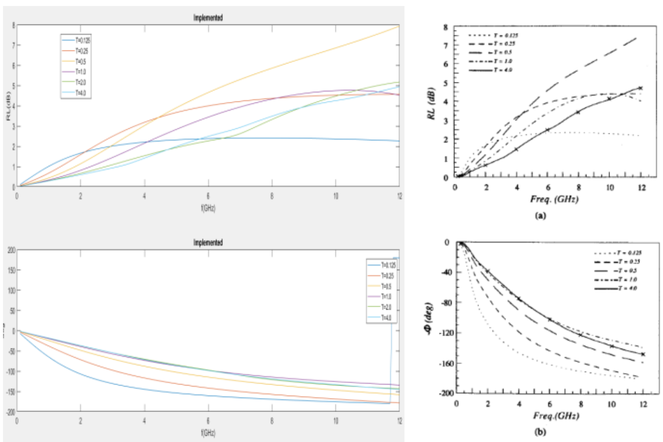


Figure 28 The comparison of return loss and phases changing with respect to the frequency under the situation of 1 dielectric layer with termination. $\epsilon_{r_1} = 10, tan\delta_1 = 0.1, T = \frac{d_1}{ar}, r = \frac{b}{a}$

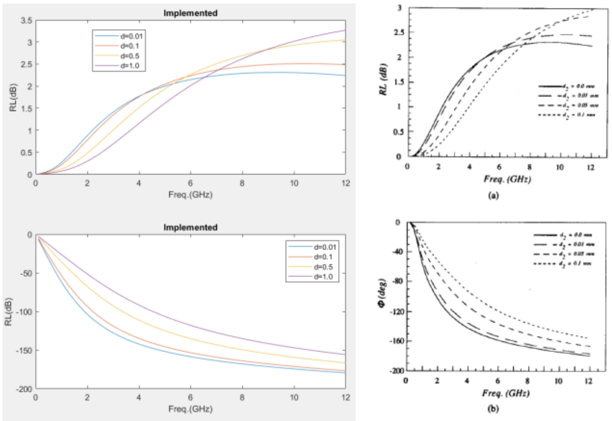


Figure 29 The comparison of return loss and phases changing with respect to the frequency under the situation of 2 dielectric layers with conducting termination. $\boldsymbol{\epsilon_{r_1} = 10, tan\delta_1 = 0.1, T = \frac{d_1}{ar}, r = \frac{b}{a}}$

Second, I can validate the two models against with each other. For example, the second model introduced air-gap layer and TM mode on the basis of the first model. As long as I set the modes number equal to 0, the test results of the LOD should be similar with MLD. The experimental results indicate that the two models perform similarly under the ideal conditions. This reinforces our confidence that the second model will be more suitable for practical use.

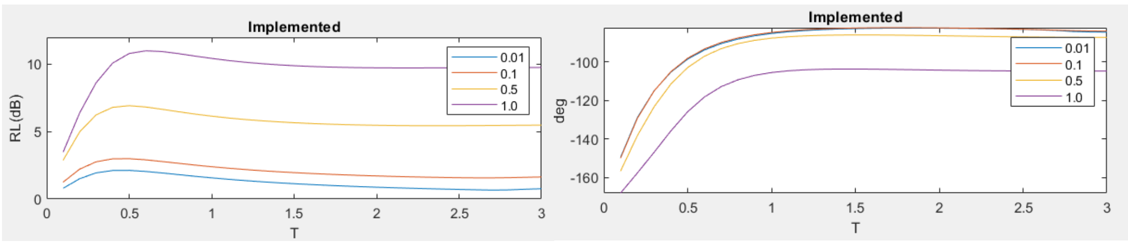


Figure 30 The result of the repeated test of the first model, which can be compared with Figure 26

4.5 Graphic User Interface

After the GUI is introduced, the basic operation logic of the system is that users operate on the graphical interface, and the corresponding response will be conducted by the GUI logic unit and conduct storing data, calculating results, drawing pictures and other operations. The logic unit will interact with one of the two models depending on the setting. At the same time, in addition to using the basic interface provided by the model, we also implemented more complex functions, such as batch manipulation of data, in the logic unit through these interfaces to make users have a better experience.

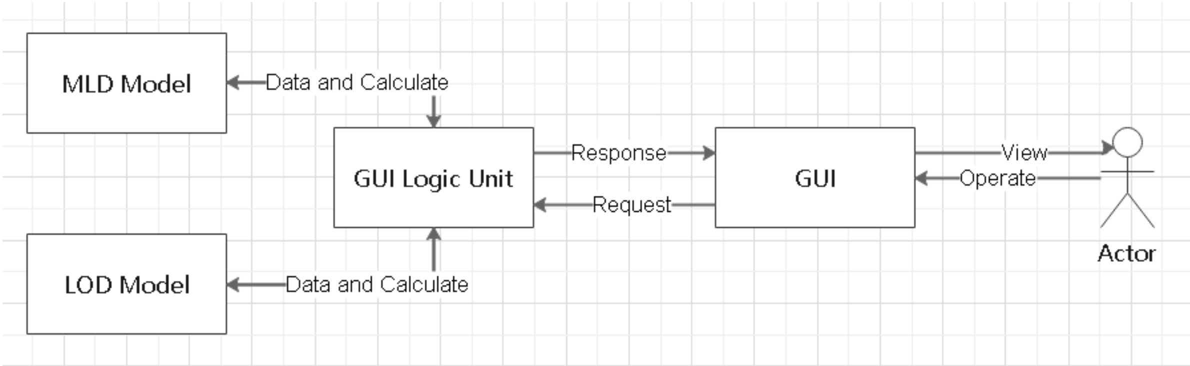


Figure 31 The interaction between GUI and Models

In order to ensure a better user experience, I also designed a GUI for our program. I provided as more functions as I can. On the left side is setting panel and the right side is the data panel. On the left side: we can select the model between multilayer dielectric model and lift-off layer model. If we select normal mode, the software will get permittivity and calculate the reflection coefficient for you. If we select the inverse mode, we can calculate the permittivity from reflection coefficient. If we chose the button "Batch Operation", then we can select a batch parameter below, which means we can get a batch of this parameter and calculate a series of results and display them in below graph. On the right part, we only have to input the data according to the model and select calculate. The batch file only support you select .mat file which store the batch values in a vector called "data".

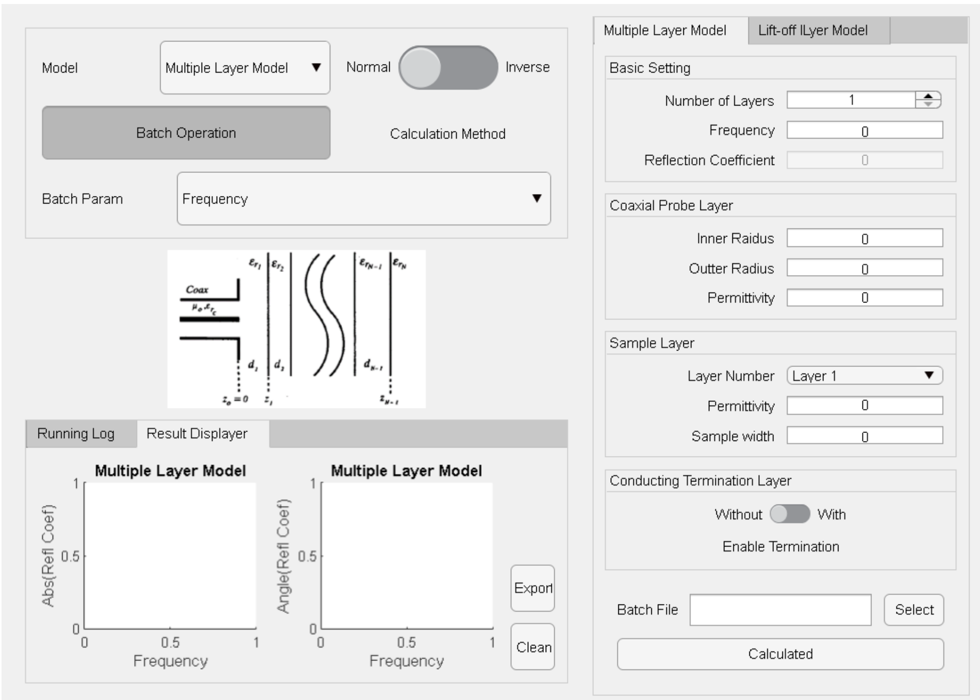


Figure 32 The screenshot of our software GUI

Chapter 5: Results and Discussion

5.1 Data source

For the experimental data, I collaborated with UPV in Spain. In this external project, I was supposed to go to Spain in 2021 and complete the data measurement in person, but I couldn't go there because of the epidemic, so I have to conduct the project remotely. The data measurement part was conducted and sent to me by my supervisor. The detailed data is listing in the appendix. The measured data are mainly based on the coaxial line inner diameter is 155e-6 m, outer diameter is 5e-3 m, and inner dielectric is 2.07. Our data is the coaxial line reflection coefficient (S11) corresponding to the changing of frequency. We select four main types material: A, B, C, D. And my supervisor doing the test under the situation of temperature at 23° C, testing it at frequency from 10MHz to 4GHz.

At the same time, the benchmark data we selected came from the National Physical Laboratory Report. This report lists the results and uncertainty of permittivity measured by NPL during the period from 1997 to 2000.Very few revisions have been made since the report was released, except for some high frequency revisions. The method used in the report is mainly derived from CETM33, which is also the algorithm we used as Benchmark. Not only that, the data in this report are not measured in just one way. Instead, the algorithms that are most suitable for this frequency band are adopted respectively, and the final results are obtained by averaging the results obtained by multiple algorithms. In this report, a large number of fluid substances (reported for use in our laboratory) were tested. They used frequencies ranging from 30MHz to 5GHz and temperatures ranging from 10 ° C to 50 ° C. Unlike our test of permittivity based on coaxial line, NPL mainly uses a micrometre-driven parallel-electrode admittance cell. And it was modified to include a temperature control scheme. The uncertainty of the data is measured based on the scheme proposed in the paper [c5 c6]. Almost all the uncertainties are less than 10%, which is a very reliable report. So, we finally chose the data of this report as our benchmark

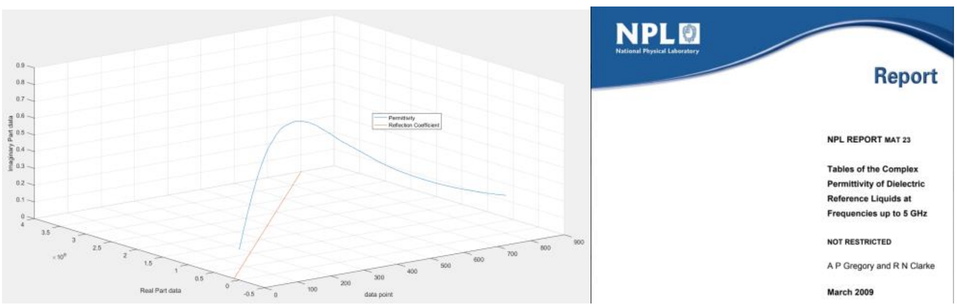


Figure 33 Overview of lab data and NPL report

5.2 Experiments

The basic process of our experiment was to substitute the reflection coefficient measured in the laboratory at different frequencies into the model to calculate the corresponding permittivity, compare it with the permittivity of the same substance in NPL at the same frequency, and calculate the loss value. I used models for the above mentioned Multilayer Dielectric model and Lift-Off Layer model. In the lift-off model, I calculated the number of modes as 1,2,3,4, and 6 with TM Mode respectively. I defined the Loss Function as:

$$F_L = Avg\left(\frac{\left|\epsilon_{calculated} - \epsilon_{report}\right|}{\epsilon_{report}}\right) \tag{25}$$

5.3 Results

More detailed experimental data will be posted in the appendix. Here I will simply present them in the form of graphs and indicate the more critical data.

For the reflection coefficient measured in the laboratory for the four substances, I obtained the corresponding permittivity in our model and compared it with the calibration data in NPL to calculate the error. Since the permittivity I obtained is mainly expressed in the form of plural numbers, I will compare the real part, imaginary part, absolute value and phase four dimensions. The most important thing I care about is the real part, followed by the imaginary part. Since the value of the imaginary part is usually very small, the absolute value reflects the size of the real part to some extent, and the phase reflects the size of the imaginary part to some extent.

The first substance that I tested was Dimethyl sulphoxide. See Table 2 in Appendix 2 for detailed data. In the Multilayer Dielectric Model, the data performance deviation is large, with a loss of 12% in the real part and 26% in the virtual part. In the lift-off Model, when the number of TM Modes is 0 (ideally), the real part loss is 11.8% and the virtual part loss is 25%, similar to the first Model data. However, when one TM Mode is introduced, the real part loss is reduced to 1% and the imaginary part loss is reduced to 9%. As the number of introduced modes increases, the loss begins to increase gradually.

Table 2: Loss of Performance of Different Model Related to NPL for Material Dimethyl Sulphoxide

%	MLD	LOD (0 Mode)	LOD (1 Mode)	LOD (2 Modes)	LOD (4 Modes)	LOD (6 Modes)

Real Value	12.85	11.85	1.00	7.18	11.61	13.61
Imaginary Value	26.27	25.86	9.16	8.31	9.83	10.84
Absolute Value	13.43	12.45	8.53	7.36	11.82	13.82
Phase (Angle)	14.97	15.45	8.65	7.93	8.11	8.18

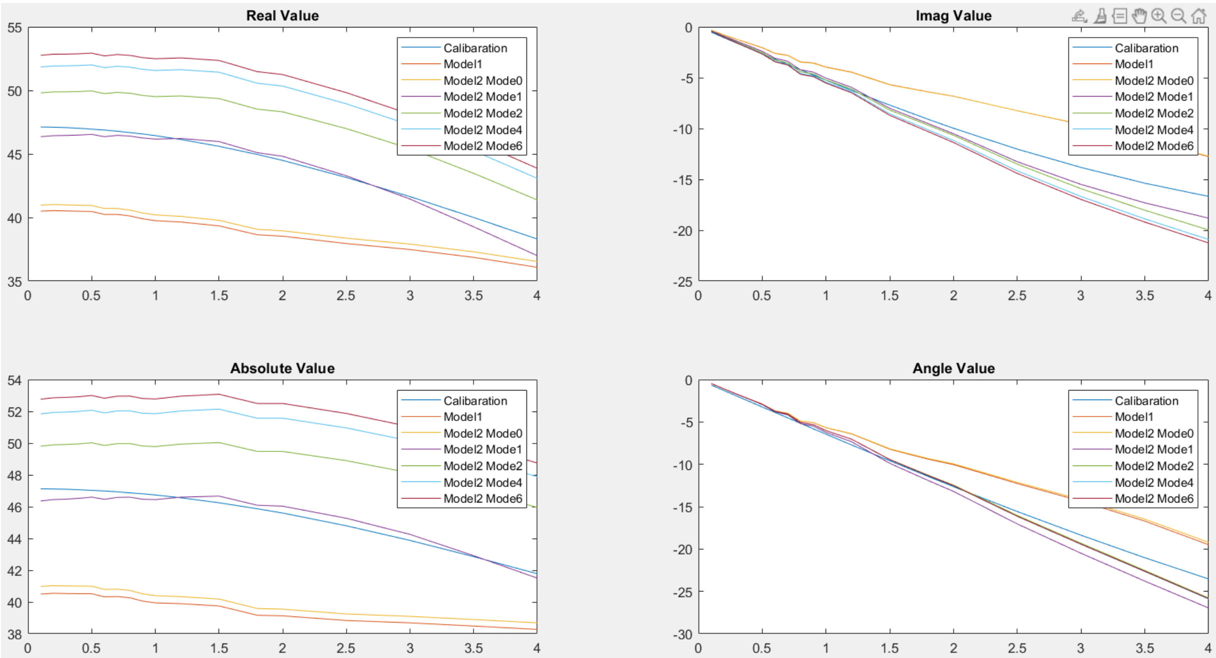


Figure 34 Figure of Dimethyl Sulphoxide experimental data

The second substance I tested was Ethanol. The data are shown in the appendix. Different from the data in the first set of experiments, the result of Multilayer Dielectric Model is better in the real part, while the result of Lift-Off Dielectric Model with the number of modes of 0 is the best. The result of LOD of 1 Mode is slightly worse (but has the best performance in absolute value), and the result of 1 Mode in the virtual part is the best. Subsequently, as the number of MODES increases, the performance gets worse.

Table 3: Loss of Performance of Different Model Related to NPL for Material Ethanol

	MLD	LOD (0 Mode)	LOD (1 Mode)	LOD (2 Modes)	LOD (4 Modes)	LOD (6 Modes)
Real Value	6.12	5.00	10.1	19.95	26.06	28.9
Imaginary Value	14.38	13.43	7.64	8.59	10.60	11.79
Absolute Value	8.22	7.15	7.02	15.64	20.97	23.40

Phase (Angle)	7.46	7.52	8.99	10.46	11.42	11.89

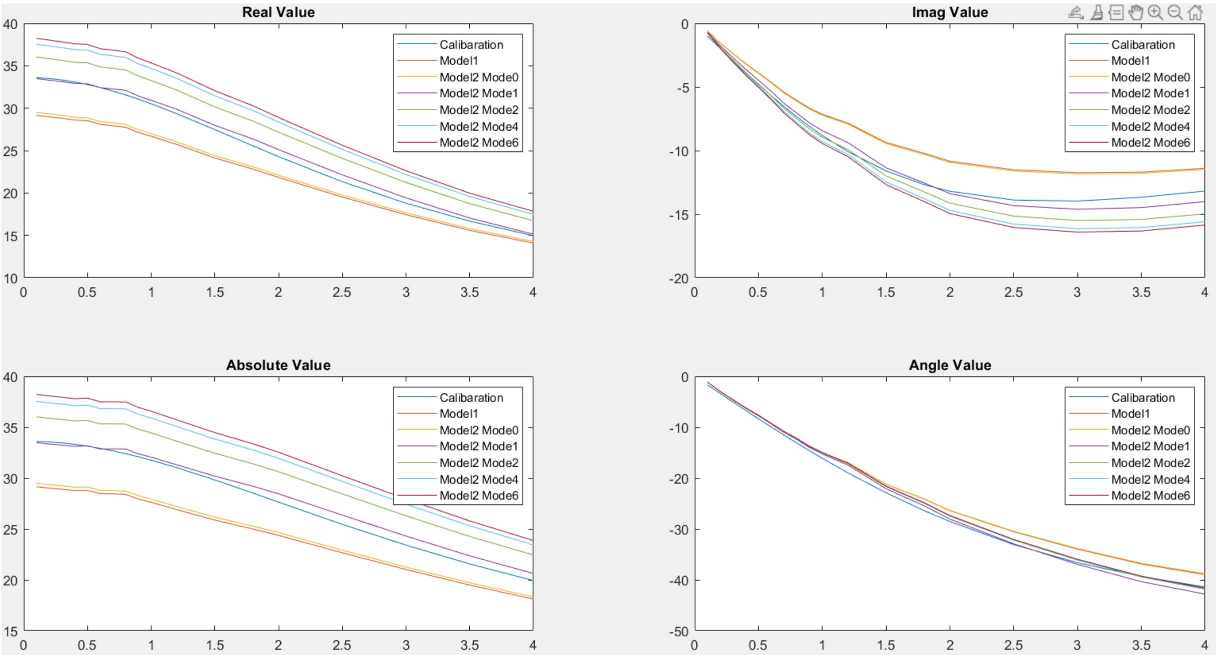


Figure 35 Figure of Ethanol experimental data

The third substance I test is Methanol. The results were similar to those of the first experiment. The LOD model with one Mode performed best, with a loss of 1.5&in the real part and 6.6% in the imaginary part. The LOD of the two modes also has a good result (has a loss about 9%), which is better than the MLD result, and the model performance gets worse as the number of modes increases.

Table 4: Loss of Performance of Different Model Related to NPL for Material Methanol

	MLD	LOD (0 Mode)	LOD (1 Mode)	LOD (2 Modes)	LOD (4 Modes)	LOD (6 Modes)
Real Value	11.31	10.25	1.56	9.53	14.25	16.41
Imaginary Value	19.43	18.62	6.65	6.04	8.76	10.18
Absolute Value	12.36	11.35	1.57	9.11	13.77	15.87
Phase (Angle)	8.41	8.56	6.35	7.11	7.38	7.55

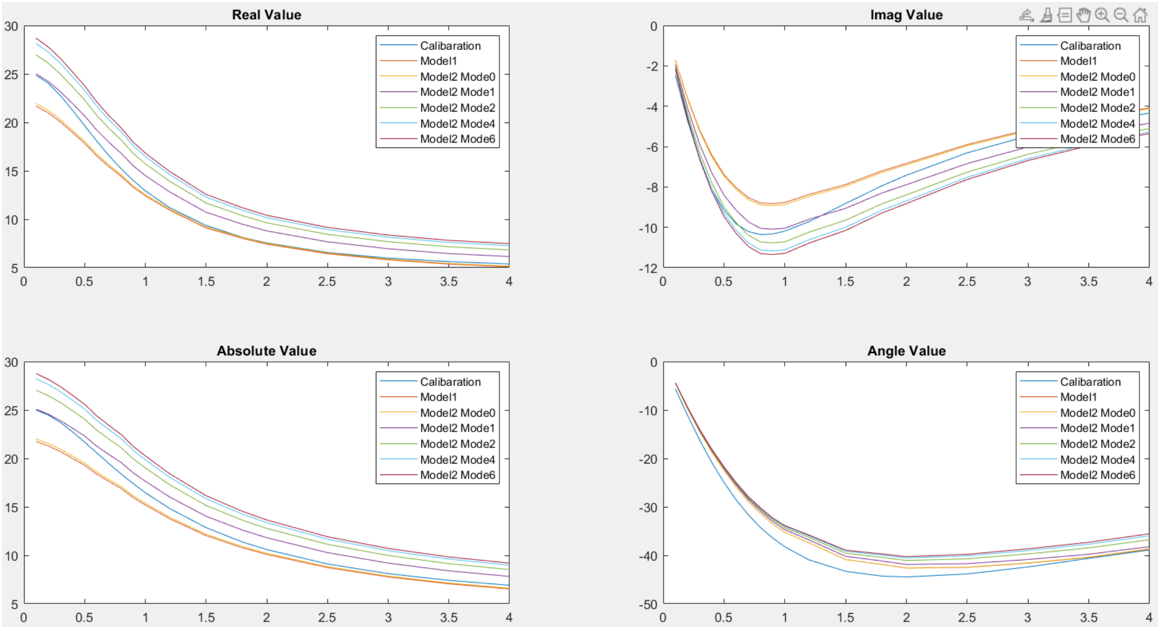


Figure 36 Figure of Methanol experimental data

The substance that I tested in our last experiment was propan-2-ol. The result of this material is quite different from the previous three. It performs best in the MLD model, with a real part loss of only 6% and an imaginary part loss of only 3%. We know that the LOD model with 0 mode quantity has the same performance as MLD, so its loss in the real part and imaginary part is 3.5% and 7.5% respectively. But when Mode is 1, the real part loses 22% and the imaginary part loses 12%. As the number of modes increases, the performance gets worse and worse.

Table 5: Loss of Performance of Different Model Related to NPL for Material Propan-2-ol

	MLD	LOD (0 Mode)	LOD (1 Mode)	LOD (2 Modes)	LOD (4 Modes)	LOD (6 Modes)
Real Value	3.96	4.53	2.25	3.47	4.29	4.68
Imaginary Value	8.60	8.24	9.69	13.66	15.92	16.99
Absolute Value	3.2	3.51	16.05	26.32	32.95	35.99
Phase (Angle)	7.55	7.54	12.30	14.48	16.43	17.35

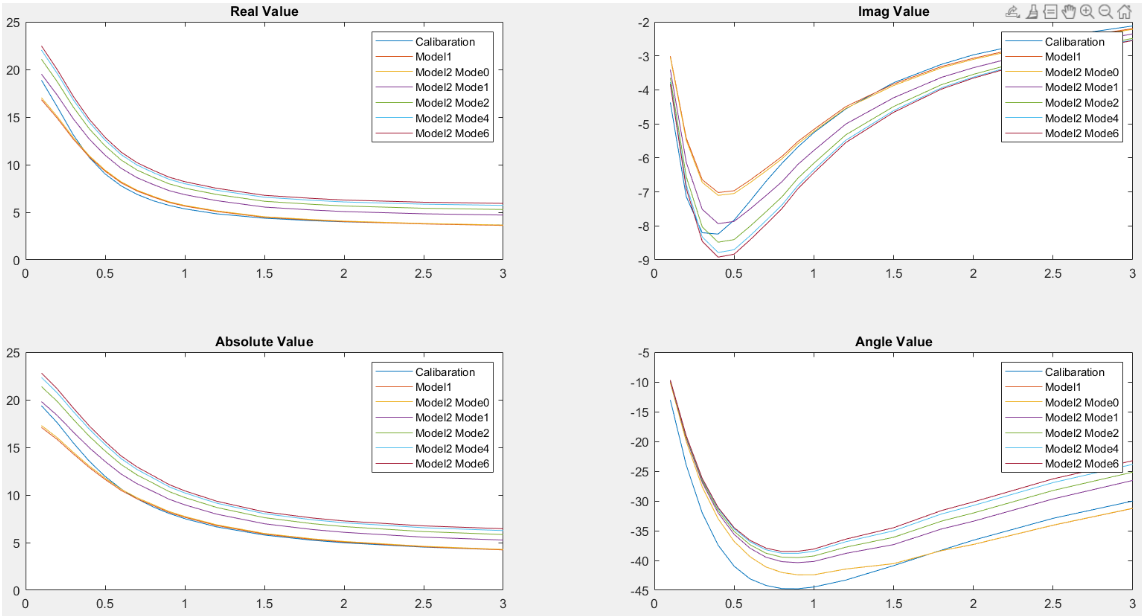


Figure 37 Figure of Propan-2-ol experimental data

5.4 Discussion

The above experimental data is of great significance, which can help us to further study and discuss the nature of dielectric and deepen our understanding of the calculation of Permittivity model by reflection method based on Coaxial line. Next, I will discuss in detail several points that the experimental data explain for us:

1. The overall performance of Lift-Off Dielectric Model (LOD) is better than that of Multilayer Dielectric Model (MLD).

   According to the above experiment, it can be seen that LOD performs much better than MLD in most cases, especially when the number of introduced MODES is 1. There are even cases where the MLD performs poorly. This can prove that it is indeed difficult to guarantee that no TM Mode wave is introduced when coaxial line is used in reality, and it is more practical to introduce TM Mode wave into coaxial line.

2. What are the connections and differences between the MLD model and the LOD model?

   The difference between MLD and LOD was clearly pointed out during the modelling, and I have the model introducing the air layer and the resulting TM mode into LOD to make it more realistic. However, they also have some connections. We can see that when the number of Tm modes in the LOD model is set to 0, its performance is almost the same as that of the LOD model, which also proves that the most important factor causing the difference between the two models is not the introduced air layer, but the existence of Tm modes

3. Why does the LOD model perform better when the number of modes is 0 or 1?

   According to our judgment, the performance of the LOD model should get better and better as the number of TM Modes increases. However, the experimental results often show that the results begin to decline rapidly after the number of TM modes exceeds 2. My supervisor and I believe that the main reason should be that after the introduction of TM mode, the integral calculation amount will increase by a factor of 2, resulting in more singular value problems. These inaccurate values will further affect each other, resulting in large deviation of the data.

4. The influence of different frequencies on the calculation of results.

   Although the performance of different models varies greatly, we can still see that they follow a basic rule and have the same shape according to the image. Through analysis, we can see that the prediction error of the model in the real part is shrinking with the increasing frequency. At the same time, with the increase of frequency, the error of the model in the imaginary part becomes larger and larger.

5. What kind of substance is our method more suitable for measuring?

   We can analyse permittivity in terms of the real and imaginary parts. From the above analysis data, we can see that we are more accurate in predicting the real part permittivity, and there will be no great deviation due to frequency changes. In the analysis of the imaginary part of permittivity, I found that the result was more accurate when the frequency was low, and there was a large deviation with the increase of the frequency. Therefore, our model is more suitable for the case where I need to use the real part of dielectric permittivity, such as designing charge storage unit. In the analysis of the virtual part of Permittivity related applications, such as signal loss, there will be a large deviation, especially in the high frequency band.

6. What are the reasons for the difference in results?

   In addition to the performance of the model itself, there are external factors that may affect the overall performance of our model. First of all, the data we used is not absolutely accurate. Our experiment was conducted at room temperature of 23 degrees, and compared with the experimental data conducted at 20 degrees in the report. Secondly, the frequency we use is also inaccurate. We do not have the data under the standard 4GHz, so we can only use the data close to its 4.023GHz for simulation, which will produce a certain error. Finally, I think manual operation may bring some errors when using coaxial line

Chapter 6: Conclusion and Further Work

In this project, our main research objective is to establish a model of measuring substance permittivity based on coaxial reflection method and analyse it. Before I summarize each achievement in detail, I want to put the most important research conclusions first:

Through our experiment, it was found that although when we modelling, we believed that the structural design of coaxial probe could bring us a stable TEM mode wave, in reality, due to many external factors, multiple TM modes would be introduced, which have a great affect on the results. Therefore, the second model I introduced is more practical and performs better in the experiment than the first ideal model.

Secondly, because there are a lot of integral calculations in the second model with the number of modes increases, so more singularities points introduced, and accurate the calculation results will be less. Although we expect models with more modes can get better results, for this reason, the loss became larger and the cost of model became larger. So the recommended number of modes of LOD is between 0 and 2.

Thirdly, when the number of TM modes is set to 0, I can find that the results are basically consistent with the MLD model, which proves that the key influencing the results is not the introduction of air layer, but the TM modes introduced by air-gap layer, which makes the situation more complicated.

Finally, our method based on open-ended coaxial line are more suitable for testing high-loss liquids. It has a better performance when testing the real part of permittivity rather than the imaginary one. So, it’s suitable for the electron capacity testing purpose.

In a period of six months, I have achieved a lot from implementation to research:

1.Completed the study and supplement of background knowledge.

2. Replicate the model in the paper; I used MATLAB to reproduce the multi-layer dielectric model and dielectric measurement model with air-gap layer introduced in the two papers; At the same time, I also verified and corrected the formula in the paper.

3. Propose a feasible schema; I put forward a scheme that takes permittivity as a parameter and constantly updates the loss reduction function to calculate permittivity by using the above model, while avoiding the analysis of the complex relationship between permittivity and reflection coefficient

4. Design experimental analysis results; I designed and completed the experiment to verify the accuracy of the model and measure the permittivity of the substance and carried out detailed analysis.

5. Completed the production of a commercial software; I introduced GUI design to transform the experimental model into convenient and practical software.

6. Completed the writing of a publishable paper.

Future Work:

Although our project has been completed, there are still many inadequacies and areas that can be improved. First of all, we know that with the increasing number of TM modes, the model effect should be better, but the occurrence of a large number of singular values leads to inaccurate data calculation. So, we should optimize our algorithm to avoid this situation or find an algorithm suitable for dealing with singular values. Second, the algorithm I used to update parameters cannot avoid the multi-value problem. In the following research work, we can find a better algorithm to determine which values is the optimal solution.

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In this part, I would like to thank all those who have helped me academically and in my life during the program.

First of all, I want to thank my mentor. As a student majoring in e-commerce and law, I hardly had any physical background before the project began, and I was not familiar with MATLAB programming. My teacher patiently answered every question and helped me to make progress. Secondly, thanks to my teacher's major, I was able to find the right tools or solutions when facing different problems. In the process of solving these problems, I also gained a lot.

Secondly, I would like to thank my high school classmate. Since I didn't have much background in physics at the beginning, thanks to him who majored in physics, he taught me a lot of basic knowledge after class, so that I could get started on my project as soon as possible without delay.

Then I would like to thank my parents, thank you for your support in my life during the winter vacation, and for giving me encouragement when I was anxious. At the same time also thank you for your continuous training, so that I can achieve my own and constantly challenge and break through myself.

Finally, I would like to thank my best friend for taking the trouble to listen to my complaints and give me encouragement. Thank you for always bringing surprise and joy into my life, so there is more to my life than academic. Thank you for giving me the tenderest support and keeping me moving forward.

Appendix

- Experiment Data
- Specification part 1
- Specification part 2
- Early-term Progress Report
- Mid-term Progress Report
- Supervision log

Experiment Data From UPV

Frequency	Dimethyl sulphoxide RC	Ethanol RC	Methanol RC	Propan-2-ol RC
0.1000	0.9818 - 0.1818i	0.9875 - 0.0973i	0.9887 - 0.1312i	0.9836 - 0.0751i
0.2024	0.9262 - 0.3577i	0.9499 - 0.1848i	0.9519 - 0.2580i	0.9428 - 0.1293i
0.3048	0.8395 - 0.5131i	0.8963 - 0.2540i	0.8943 - 0.3722i	0.8987 - 0.1591i
0.4023	0.7353 - 0.6367i	0.8389 - 0.3010i	0.8242 - 0.4650i	0.8631 - 0.1727i
0.5046	0.6118 - 0.7385i	0.7787 - 0.3355i	0.7393 - 0.5479i	0.8336 - 0.1809i
0.6021	0.4900 - 0.8036i	0.7271 - 0.3522i	0.6556 - 0.6036i	0.8136 - 0.1839i
0.7045	0.3629 - 0.8558i	0.6760 - 0.3642i	0.5615 - 0.6492i	0.7954 - 0.1882i
0.8020	0.2454 - 0.8741i	0.6336 - 0.3700i	0.4745 - 0.6792i	0.7815 - 0.1928i
0.9044	0.1366 - 0.8877i	0.5999 - 0.3688i	0.3955 - 0.6920i	0.7724 - 0.1966i
1.0019	0.0394 - 0.8811i	0.5710 - 0.3680i	0.3241 - 0.6986i	0.7639 - 0.2021i
1.2018	-0.1332 - 0.8477i	0.5263 - 0.3672i	0.1983 - 0.6965i	0.7513 - 0.2155i
1.5040	-0.3181 - 0.7511i	0.4728 - 0.3533i	0.0481 - 0.6428i	0.7318 - 0.2327i
1.8014	-0.4310 - 0.6603i	0.4346 - 0.3527i	-0.0595 - 0.5890i	0.7149 - 0.2569i
2.0013	-0.4893 - 0.6005i	0.4123 - 0.3497i	-0.1120 - 0.5461i	0.7021 - 0.2714i
2.5034	-0.5734 - 0.4679i	0.3690 - 0.3548i	-0.1989 - 0.4597i	0.6728 - 0.3116i
3.0006	-0.6154 - 0.3668i	0.3334 - 0.3630i	-0.2470 - 0.3894i	0.6425 - 0.3502i
3.5027	-0.6347 - 0.2874i	0.3002 - 0.3720i	-0.2754 - 0.3318i	0.6101 - 0.3847i
4.0000	-0.6411 - 0.2240i	0.2686 - 0.3849i	-0.2932 - 0.2880i	0.5749 - 0.4195i

北京邮电大学 本科毕业设计（论文）任务书

Project Specification Form

Part 1 – Supervisor

论文题目 Project Title	Dielectric Measurement of Tissues		
题目分类 Scope	Software Development	Research	Simulation
主要内容 Project description	In this project, the student will need to analyse, design and implement a dielectric measurement software system which can be used to characterise the dielectric properties of single and double layered materials. The developed software system should be complemented with comparisons from commercial software, or measurements to validate the results.		
关键词 Keywords	dielectric properties		
主要任务 Main tasks	**1** Background research of single□layer and double□layer dielectric assessments.		
	2 To develop a software code to accurately compute the dielectric data.		
	3 To validate the developed codes with commercial software simulations or with measurements.		
	4 To summarise the results into meaningful set of publishable paper.		
主要成果 Measurable outcomes	**1** Research summary of dielectric measurements of single□layer, and two-layered materials.		
	2 Functional software tool to assess the dielectric data.		
	3 Validation of the developed software against simulations using commercial software, or using measurements.		

北京邮电大学 本科毕业设计（论文）任务书

Project Specification Form

Part 2 - Student

学院 **School**	International School	**专业** **Programme**	**e-Commerce Engineering with Law**		
姓 **Family name**	ZHANG	**名** **First Name**	Zixuan		
BUPT 学号 **BUPT number**	2017212994	**QM 学号** **QM number**	171049996	**班级** **Class**	2017215114
论文题目 **Project Title**	Dielectric Measurement of Tissues				
论文概述 **Project outline** **Write about 500-800 words** **Please refer to Project Student Handbook section 3.2**	**Project Overview:** OPEN-ENDED COAXIAL PROBES are commonly used as nondestructive testing tools. In most applications the coaxial probe is pressed against a sample, and the reflection coefficient is measured and used to determine the permittivity of the sample. Over the years, the open-ended coaxial probe has been studied extensively both theoretically and experimentally. As one of the most widely used tools, sensitivity to microwave data and non-destructive to materials are the best characteristics of coaxial probes at the beginning. A good model can make use of the measured electromagnetic data to calculate the electromagnetic properties, such as electrical conductivity, of materials. In the past few years, a large number of theoretical models have been trying to solve and optimize this problem. But we think the model of testing and validation without actual data is inane. Therefore, we want to analyse the innovation points of these papers, implement them with MATLAB, and test them with the data generated by simulation software. Combining the innovation of the paper with the analysis of the actual test results, we will make a summative paper. At the same time, we will further improve the model and release a software comparable to commercial products. **Four main tasks:** 1. **Background research of single-layer and double-layer dielectric assessments.** At this stage, we will investigate the existing theoretical models with good performance, analyse and summarize the principles of them, and select two or three optimal models. 2. **To develop a software code to accurately compute the dielectric data.** We aim to develop a software based on the model provided by the papers. The data involved in our project will be generated by commercial software's simulation. Firstly, we will develop the basic command line to control our script. Later on, we will introduce the GUI for our program to let it become more friendly. We will mainly use MATLAB simulation for the two or three models we selected. We will discuss in detail the zero-value problem and boundary problem that may appear in the formula. 3. **To validate the developed codes with commercial software simulations or with measurements.**				

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	We will explore some of the papers that propose measurement schemes and use some of these schemes to evaluate our model. We also use commercial software to simulate data to test the code we develop **4. To summarize the results into meaningful set of publishable paper.** Eventually we will summarize the data that we get from our tests and put it together into a paper that can be published. At the same time, based on our data, we will further improve our software and complete the writing of user manual and other documents. **References:** 1. Bakhtiari S, Ganchev S I. Analysis of radiation from an open-ended coaxial line into stratified dielectrics[J]. IEEE Transactions on Microwave Theory & Techniques, 1994, 42(7):1261-1267. 2. Baker-Jarvis J, Janezic M D. Analysis of an open-ended coaxial probe with lift-off for nondestructive testing[J]. Instrumentation & Measurement IEEE Transactions on, 1994, 43(5):711-718. 3. Noh Y C, Eom H J. Radiation from a flanged coaxial line into a dielectric slab[J]. IEEE Transactions on Microwave Theory & Techniques, 2002, 47(11):2158-2161. 4. Gershon D L, Calame J P, Carmel Y, et al. Open-ended coaxial probe for high-temperature and broad-band dielectric measurements[J]. IEEE Transactions on Microwave Theory & Techniques, 2002, 47(9):1640-1648. 5. Ellison W J, Moreau J M. Open-Ended Coaxial Probe: Model Limitations[J]. IEEE Transactions on Instrumentation and Measurement, 2008, 57(9): p.1984-1991. 6. Weihua, Tan, Zhongxiang, et al. Efficient Analysis of Open-Ended Coaxial Line Using Sommerfeld Identity and Matrix Pencil Method[J]. Microwave & Wireless Components Letters IEEE, 2008.
道德规范 **Ethics**	Please confirm that you have discussed ethical issues with your Supervisor using the ethics checklist (Project Handbook Appendix 2). [YES]
	Summary of ethical issues: (put N/A if not applicable) Because our project mainly focusses on researching and implementation, less ethical issues will be involved. There are no participants will be involved in our project. And I will discuss every ethics issues in the following: **1. Will the participants be exposed to any risks greater than those encountered in their normal working life?** No. All the work can be done in a personal computer. There is no dangerous environment. **2. Will the participants be using any non-standard hardware?** No. In the validation process, we will use some standard hardware to test some samples and get test data. With these data, we can test our software's validity. But we don't use non-standard hardware. **3. How will participants voluntarily give consent?** The results of our project have possibility to be used after finishing this project. We will write the using statement in detail. And separate consent form will be signed by each participant. **4. Are you offering any incentive to the participants?**

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	We do not have incentive for participants if any. **5. Is there any intentional deception of the participants?** No. If there will be participants in our project, we ensure all the statements and information are honest and fair. We won't conduct any deception for those participants. **6. Are any of your participants under the age of 16?** No. We do not have any participants in our project. **7. Do any of your participants have an impairment that will limit their understanding or communication?** No. We do not have any participants in our project. **8. Are you in a position of authority or influence over any of your participants?** We don't have participants in the project. And we can ensure we won't violate anyone's willingness in this project. **9. Will the participants be informed that they could withdraw at any time?** Yes. If there are any participants involved in our project, we can ensure their liberty and withdraw from our project at any time. **10. Will the participants be informed of your contact details?** Certainly. We will publish our contact details to any participants for inquiry and emergency. **11. Will the participants be debriefed?** No. If there are any participants, we only access to those information they want to tell us. **12. Will the data collected from participants be stored in an anonymous form?** Yes. If there are any participants, their information will be stored in an anonymous form, and we will ensure data's security.
中期目标 **Mid-term target.** **It must be tangible outcomes, E.g. software, hardware or simulation.** **It will be assessed at the mid-term oral.**	1. Write the summary of papers including, *Analysis of Radiation from an Open-Ended Coaxial Line into Stratified Dielectrics, Analysis of an Open-Ended Coaxial Probe with Lift-off for Non-destructive Testing*, etc. 2. Write programs for each model presented in the papers to calculate the permittivity. 3. Write a report for the programs.

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Work Plan (Gantt Chart)

Fill in the sub-tasks and insert a letter X in the cells to show the extent of each task

	Nov 1-15	Nov 16-30	Dec 1-15	Dec 16-31	Jan 1-15	Jan 16-31	Feb 1-15	Feb 16-29	Mar 1-15	Mar 16-31	Apr 1-15	Apr 16-30
Task 1 Background research of single-layer and double-layer dielectric assessments												
Read and summary on *Analysis of an Open-Ended Coaxial Probe with Lift-off for Non-destructive Testing*	X											
Read and summary on *Analysis of Radiation from an Open-Ended Coaxial Line into Stratified Dielectrics*		X										
Read and summary on other 4 papers.			X									
Keep searching new essay and summarize the innovation			X		X		X					
Task 2 To develop a software code to accurately compute the dielectric data												
Design the flow chart for each program and analyse possible problems involved in the program.			X	X								
Implement the models for each paper				X	X	X	X					
Test and fixing bugs for each program					X	X	X					
Write a report for these programs				X	X	X	X					
Task 3 To validate the developed codes with commercial software simulations or with measurements												
Research and Design the evaluation metrics						X	X					
Fully evaluate on our models and identify the problems involved.							X	X				
To further improve the performance of our model								X	X			
Increase the friendliness of our program									X		X	
Task 4 To summarise the results into meaningful set of publishable paper												
Write a detailed user manual for our program and other related documents							X	X				
Write a paper based on the results of the research and testing									X	X	X	
Write down the final project report					X		X		X	X	X	X

Fully revised the whole project and adjust to make it perfect											X	X

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北京邮电大学 本科毕业设计（论文）初期进度报告

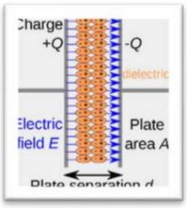
Project Early-term Progress Report

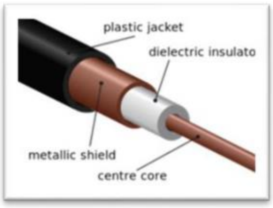
学院 **School**	International School	**专业** **Programme**	**e-Commerce Engineering with Law**		
姓 **Family name**	ZHANG	**名** **First Name**	Zixuan		
BUPT 学号 **BUPT number**	2017212994	**QM 学号** **QM number**	171049996	**班级** **Class**	2017215114
论文题目 **Project Title**	**Dielectric Measurement of Tissues**				

已完成工作 Finished work:

1. **The Summary of material I read and researched**

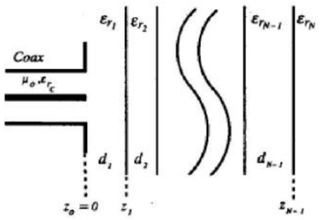
My project mainly detects the electrolyte properties of material through modelling. The material we use are mainly dielectric, which is an insulator. Common types include glass, mica and even air. But they are not absolute insulation, and can be polarized by an applied electric field to transfer charge, as is often the case with capacitors.

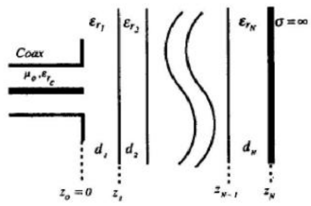




We will use coaxial line probes to measure the dielectric characteristics of the material. After we put our material in an existing electronic field and magnetic field, we will attack the coaxial line on the material and transmit the electromagnetic wave and signal. Coaxial lines bring us many benefits, such as no harm to the measurement of material, only need to occupy a small area, can transmit more valuable information and so on.

In our project, we hope to measure different dielectric properties across multiple layers using coaxial lines.





In our project, we hope to measure different dielectric properties across multiple layers using coaxial lines. Above is our basic model. We stacked a number of different dielectric materials together and placed a coaxial line above the first layer to measure the TEM mode electromagnetic waves in it and made modelling measurements. In this modelling approach, we will explore the difference between the final layer without a termination layer and with one metal termination layer. Later, we will analysis on which method will be more suitable for our measurement and verification.

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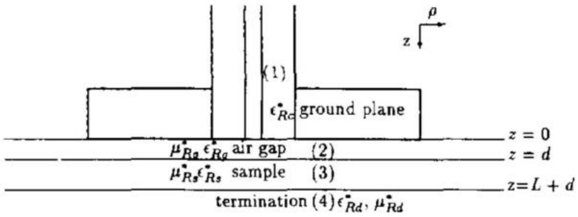

In our research, we found that in many cases we could not guarantee that our coaxial line would fit perfectly into our material, and there would be a lift-off between the coaxial line and material, which we called the air gap layer. Although air is also a common electrolyte, the situation in the air layer caused by lift-off is much more complicated than others. It is no longer a simple TEM mode electromagnetic wave, but a more complex mixed wave. So, there is another model to deal with such situation, test on one layer of material but the coaxial line cannot attach on the material perfectly. Based on these two findings, we hope that by combining the two models, we can develop software that can measure the properties of multiple electrolyte materials while perfectly handling lift-off biases.

2. Summary of work was done

2.1 Finished the reading of first three papers and did one brief summary

As of today, my tutor and I have completed the preliminary research on papers. The research results of the two papers, *Analysis of an open-ended Coaxial Probe with lift-off for non-destructive Testing* and *Analysis of Radiation from an open-ended Coaxial Line into Stratified Dielectrics*, are taken as the focus of in our final project. At the same time, we also selected other 4 papers, related to the measurement, verification schemes and so on.

Analysis of Radiation from an open-ended Coaxial Line into Stratified Dielectrics: In this paper, we can get a recursive algorithm to integrate different layers into one. We will mainly build our basic model for measuring the properties of multilayer dielectric materials.

Analysis of an open-ended Coaxial Probe with lift-off for non-destructive Testing: This paper introduces the method to handle with lift-off situation within our model. We handle the air gap layer as the mixture of TEM mode wave and TM mode wave.

We will finish the code of both these two models and see their performance. Later on, we will try to mix them up and create a brand-new model which can both handle multi-layer situation and lift-off situation.

2.2 Finished the code of first paper's code in MATLAB

Now we have completed the MATLAB code design of the first model. Under the assumption that the coaxial line perfectly fits the material, by inputting certain parameters, we can derive the conductivity formula or reflection coefficient formula of any multilayer dielectric. At the same time, through the user's choice, we can derive the model formula without the termination layer or the model formula with the metal termination layer.

Below is the UML diagram and ER diagram of my first program design. Following the design principles of SVM, I have separated the classes that store the data from the classes that manipulate the data. We first create a BasicData class that inherits Handle as the parent class of all the data. All classes that store data should inherit from this class. The data storage class is only responsible for the implementation of simple getter and setter functions. In the getter and setter functions, we will check and restrict the storage of data to give users more prompts and reduce the possibility of program errors.

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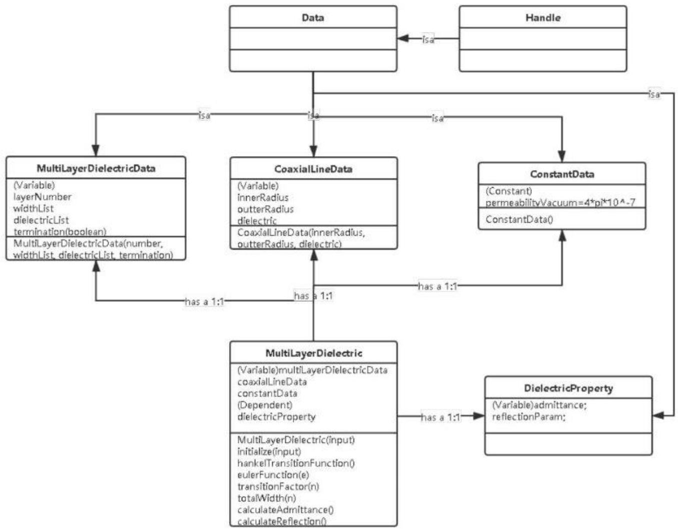
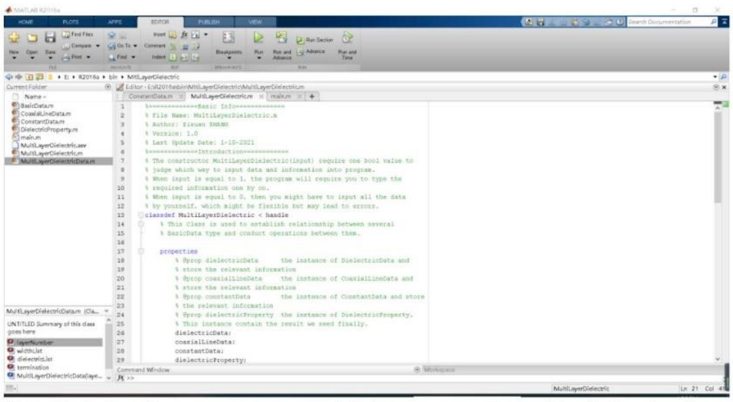
MultiLayerDielectric class is responsible for the interaction between the data, in this class, will complete the data class initialization and data storage, as well as the dielectric properties of the calculation process, and the data storage or display to the user.





When designing the program, we provide two usage patterns. One is the simple mode, in which the program guides the user to enter relevant data and perform calculations. One is a professional model, in which the user determines the order in which data is processed.

At the same time, I also made detailed notes and documents in the program to facilitate the user's understanding of this program.

2.3 *Validating on the first program*

I am currently verifying the program. Verify from two aspects respectively, the first is the stability and robustness of the program. I designed black box test and white box test according to the principle of design. Based on the input and the formulas involved, I wrote test cases and test classes to test the robustness of the program. The main areas to be tested include data types, logical validation, and mathematical formulas.

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The second part is to verify the model algorithm I implemented, which is still in progress. Mainly by using our program to constantly test the results and draw a graph and compare with the graph in the paper.

3. Problem I faced

3.1 There are two mistakes presented on the paper.

When I was researching the paper, I found that there were two formulas in the paper which should be the same but were opposite to each other. I thought the author must have made a mistake in some place, but because of the huge amount of calculation in the paper, it was difficult to verify, so I didn't know how to correct this mistake.

3.2 The results calculated by MATLAB are far from the results in the paper

After the correct application of the algorithm given in the paper, the consensus obtained by the calculation is quite different from the formula written by the author at the end of the paper. However, after careful verification, the algorithm process is OK.

3.3 Unfamiliar with MATLAB language, it is difficult to write a high-quality program

Although MATLAB can be used to simply calculate the results of various mathematical formulas, but compared with Java and other languages, I know too little about it, and find it difficult to design a functional, robust and friendly program.

4. Solutions was found

4.1 For the first question, we intend to verify the controversial formula by using other formulas. For example, we generally believe that the final conclusion is repeated verification and scrutiny, with a certain degree of credibility. In the final formula, this variable is also referred to. We can use the two kinds of consensus to calculate the result and then substitute them into the conclusion formula respectively, to see which formula can produce the same result as the author's conclusion.

4.2 For the second problem, we can do it algebraically. The author's formula is simplified after a lot of formula deduction, and the results we calculate through MATLAB are often relatively rough and unprocessed results, so at first glance, our results are more complex and greatly different. In view of this situation, we can compare whether the result of our formula is consistent with that of the author by substituting specific values. If the result is consistent for many times, the reliability of our algorithm can be indicated to a certain extent.

4.3 As for the third question, after my understanding, I found that MATLAB since the 2008RA version provides object-oriented programming features. Based on my understanding of Java, I quickly mastered the OO programming pattern of MATLAB and designed the corresponding UML diagram and ER diagram.

是否符合进度? On schedule as per GANTT chart?

YES

下一步 Next steps:

1. Make a more detailed summary of what I have read. On the basis of the brief report I made before, I will make a more detailed report on the process and innovation of each paper.

2. Complete the code for the second model. The model with lift-off condition was simulated and verified by MATLAB.

3. Do a brief summary of these two programs including the manual instructions and relevant documents. After we implement the effects of the various models, we will compare and analyse the several models. At the same time, we will also write a more detailed operation guide and related documents for our procedures.

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北京邮电大学 本科毕业设计（论文）中期进度报告

Project Mid-term Progress Report

学院 **School**	International School	专业 **Programme**	**e-Commerce Engineering with Law**		
姓 **Family name**	ZHANG	名 **First Name**	Zixuan		
BUPT 学号 **BUPT number**	2017212994	**QM 学号** **QM number**	171049996	**班级** **Class**	2017215114
论文题目 **Project Title**	**Dielectric Measurement of Tissues**				

是否完成任务书中所定的中期目标？Targets met (as set in the Specification)?
Yes

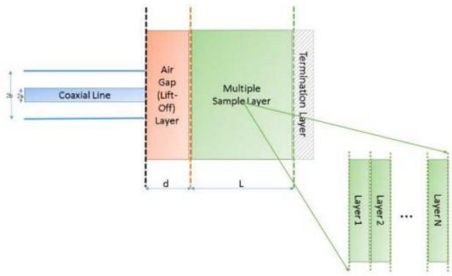
已完成工作 Finished work:

1. Background Research of Single Layer and Double Layer Dielectric Assessments

Similar to Early-Term Report

Our research based on using coaxial line to get dielectric(permittivity) property of tissues(material). Although there are many accuracy ways to measure material's dielectric, most of them are costly or can be very damaging to the material being tested. Coaxial line has the advantages of cheap, small signal transmission loss, no harm to material, small occupied area and so on. Therefore, we get two basic models which can calculate reflection coefficient (which can be measured by coaxial line) via permittivity (dielectric property).

Model Design



Based on two models (one dealing with multilayer samples, one dealing with lift-off situation), we hope to combine them and design a new model which can tackle with multilayer situation and air-gap situation at the same time.

2. Finishing the Design and Implementation of two programs

Similar with the Early-Term Report.

In accordance with the object-oriented programming mode, I completed the design of two applications through MATLAB, and they can achieve two different model functions respectively. These software are now based on the script operation, in the next development, we will introduce GUI to make it more user-friendly.

3. Writing the documentation and report for software

- initialize(obj): help you input data
- hankelTransitionFunction (obj, l): The F(l) function.
- recursiveP (obj, i, l): the function to calculate symbol p with recursive way.
- function_b (obj, i, p, l): the function to calculate symbol b
- function_k (obj, i, l): the function to calculate symbol k
- totalDis (obj, n): calculate the distance from layer 0 to layer n
- propertyCalc(obj): conduct integral to calculate admittance and reflection parameter.

- F10(obj, l): The implementation F(l) of paper under the situation of 1 layer without termination.
- F20(obj, l): The implementation F(l) of paper under the situation of 2 layer without termination.
- F21(obj, l): The implementation F(l) of paper under the situation of 2 layer with termination.

---

main.m

This script can help you quick start our software easily. (Can be used to debug)

II. Usage (Based on script)

1. Initialize MultiLayerDielectric class

```
mldd = MultiLayerDielectric(0);
```

2. Set coaxial line layer data

```
radius_a = 0.02;      # Set the inner radius of coaxial line
radius_b = 0.05;      # Set the outer radius of coaxial line
dielectric = 2.07;  # The permeability within coaxial line layer
mldd.coaxialLineData = CoaxialLineData(radius_a, radius_b, dielectric);
```

3. Set multilayer dielectric layer data

```
number = 2;        # Set the number of layers
widthList = zeros(1, number);  # Create a vector to store width
dielectricList = zeros(1, number); # Create a vector to store permeability
# Assign value for each layer
widthList(1) = 30;
dielectricList(1) = 10*(1-1j*loss_tangent);
```

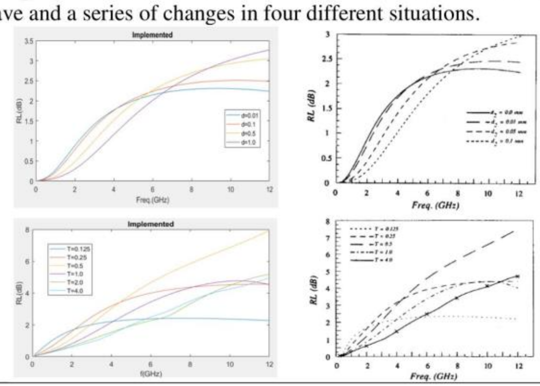
After finishing the program, I also timely added the corresponding notes, MATLAB help documents and user manual and other documents.

4. **Validate our programs**

In order to prove the correctness of our program, we carried out a verification. Our verification work is mainly divided into two parts:

The first is to verify the correctness of the formula. In order to make our model more universal, we use a recursive algorithm to derive the formula for the reflection coefficient of n-layer material. Since it is very different from the manual formula, it is difficult for us to verify it mathematically, so we substitute the unknowns to compare their images, and our formula can only be proved to be correct when their images coincide completely. In the process of debugging we can find many formula errors and adjustment timely.

After verifying the correctness of the formula, we started the data simulation. We hope to simulate the results of the model under different circumstances and compare them with the paper. Because we're going to take the integral from 0 to infinity of one of these formulas, and the formulas themselves are incredibly complicated, with multiple fractions, exponentials, and so on. In the process of integration, it is very easy to produce singularity and report error termination. We need to analyse the formula by ourselves, find out where the ambiguous value is easily generated by debug, and then make corresponding corrections according to different situations (such as 0/0, INF/INF). We spent a lot more time in this place than we had expected. In the end, we can successfully simulate the regression loss of the reflection coefficient and the change of the Angle of the reflection coefficient with the width of the material, the frequency of the microwave and a series of changes in four different situations.



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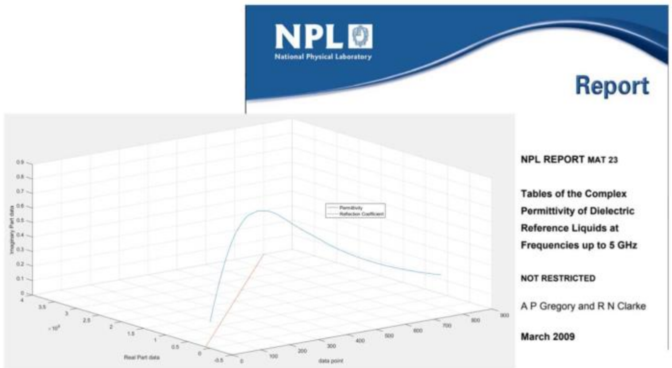
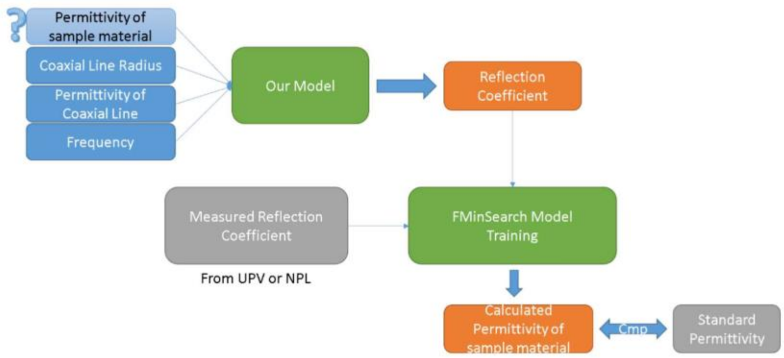
5. **Find and collect standard and practical data**

After we have designed how to obtain reflection coefficient through data such as permittivity, coaxial line radius and frequency, we need data to verify whether our method is feasible. In this phase we will work with UPV in Spain. Our data is divided into two parts. The first part comes from the National Physical Laboratory. The data in this paper have been measured by the most sophisticated instruments and authenticated by authorities, which can be used as a benchmark of our model. The second part of the data comes from UPV's laboratory. My supervisor has measured the data in the laboratory and sent it to me for calculation and comparison, so as to see its use in real life.



6. **Design our evaluation method**



The permittivity of the substance obtained by using the Coaxial line to calculate the Reflection Coefficient requires the model designed above. On the way to the model, the green part represents the abstract representation of the model we use, the blue part represents our input data, the orange part represents our output data, and the grey part represents the data we test in the laboratory. In the input data, the permittivity of the material is the data we ultimately hope to obtain, but it was unknown at the beginning, so we hope to replace it with a random number first. Through our initial design model, we will generate a random reflection coefficient. Then, the reflection coefficient calculated by us and the microwave reflection coefficient measured by the Coaxial line were introduced into a new model - FMINSEARCH. This model will adjust the permittivity of the substances we randomize so that the calculated reflectance coefficient and the tested reflectance coefficient are close to each other until the same or the difference is less than the acceptable threshold value. So, the permittivity is going to be the value that we

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want. We can compare the obtained permittivity with the standard permittivity, analyse the problem of our model and improve it.

尚需完成的任务 Work to do:

1. **Introduce GUI and further improve the programs' friendliness**
   Now our program is based on the implementation of the script, for people who do not have a computer or MATLAB foundation will be a little difficult to use. So, we'll introduce a simple GUI for the application in the next phase to make it more user-friendly and present more data to the user without having to call it one by one.

2. **Design and promote our final mode and implementation**
   We have completed the implementation of the first two models at this stage. We first needed to design a program that allowed them to calculate the permittivity of the substance and analyse its performance. At the same time, we will also fuse the two models to produce our model with more functions, and design the program and debug it.

3. **Make improvement for our final model.**
   Then we will test our three existing models to observe their performance, and revise and improve the whole model to a certain extent. For example, the selection strategy of random number of permittivity, whether there is a better training model, whether there are multiple permittivity corresponding to the same reflection coefficient, etc.

4. **Analyse our mode based on theory and practice**
   After the final determination of the model, we will carry out a large number of data calculation and analyse our final results from the theoretical and practical aspects, to find out our strengths and weaknesses, put forward the next improvement plan or opinion, to see whether it has the ability to match the results of commercial software, etc.

5. **Work out analysing report and thesis**
   Finally, we need to write a paper or a final report based on our results to report and submit.

存在问题 Problems:

1. In the second model, reflection coefficients of multiple TM modes must be calculated simultaneously for each calculation, resulting in slow running speed.

2. Where there are singular values or calculation errors in the formula cannot be fully found.

3. Our own synthetic model has no reference papers to verify it.

拟采取的办法 Solutions:

1. The approach we want to take is to look at the duplicate values in each formula and extract them as member variables rather than computations within the function, which can save a lot of computation effort. But at the same time, it also requires users to call corresponding functions to update their values after updating model parameters. The running logic of the program should also be changed accordingly to minimize the chance for users to interact with the internal functions of the program.

2. We are going to test all fractions used in the program for zero point and large number tests, and analyse the probability of such a situation and the corresponding treatment scheme.

3. We came up with a better solution. After we have successfully fused the model, it should have the characteristics of both models. The removal of the Airgap layer in our model should be consistent with Model 1, and the change of multiple layers in the material layer to one layer should be consistent with our second model. Therefore, we can test the results in special cases (the width of the AIRGAP is 0, the number of TM modules is 0, or the number of material

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layers N is 1) and compare it with the model we previously implemented, which can validate our model to a certain extent.
论文结构 Structure of the final report: Abstraction I. Introduction II. Theoretical Models and Methods III. Verification and Results IV. Practical application analysis V. Conclusion VI. References

5

Risk and environmental impact assessment

In this part, we will mainly focus on the following four questions to carry out risk and environmental impact assessment, that is:

1. Prevents the successful completion of the project

   The arrival of the epidemic has really brought great impact to our project. We are a external project with UPV of Spain, and we should go to Spain to carry out part of the physical experiment during the project. However, due to the epidemic, the visa business and flight were cancelled, so we had to turn to online cooperation. However, through my close cooperation with the supervisor, except for the communication inconvenience caused by the time difference, the results of the project did not have a significant impact. So, I consider L = 5, C = 1 and R = 5.

2. Causes potential harm to people and /or animals

   Our project is based on theoretical research and physical experiments in the laboratory (testing material's certain property), and will not cause any harm to humans and animals. So, L = 0, C = 0, R = 0.

3. Causes potential harm to the environment (for example waste disposal and recycling, energy use in service and energy savings)

   NO. Our project mainly focuses on theoretical analysis and code writing and operation. It doesn't have any impact on the environment. So, L=0, C=0, R=0.

4. Causes potential financial loss to the project or to other individuals or organisations.

   We did not use any paid products throughout the project, and all the intellectual properties were well referenced. At the same time, our results are the theoretical analysis and a software system. However, we do not plan to put our system into commercial activity. So, we will not harm the interests of any individual or institution. So, L = 0, C = 0 and R = 0.

Overall, according to the risk and environmental impact assessment, the sum of result is 5 which bring by the Coronavirus. But the impact has been well disposed by our project.