Undergraduate Project Report 2020/21

Permittivity reconstruction of samples in rectangular waveguide

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Table of Contents

Abstract

Material characterization is an important issue in many material production, processing, and management applications. All kinds of microwave technology were introduced to characterize the performance of the material. Recent studies have shown that the complex permittivity, ε, of materials can be measured using scattering parameter measurements. This project is to design and implement a dielectric measurement software to accurately compute the dielectric data of samples inside rectangular waveguides and then validate the developed software by simulations with measurements performed in UPV lab. There are three transmission line methods measuring the complex permittivity of dielectric materials included in this software, which are transmission/reflection method, propagation constant method and microwave nonresonant method. The software is programmed in MATLAB and has a graphical user interface so that the software is easier to operate. The software calculates the complex permittivity value by reading the parameter value file and plots the result into a diagram to show to the user. By reading the data files of two measurements, TEFLON and PVC, provided by my supervisor, we obtain the value of the real and imaginary part of permittivity of three methods. Among these three methods, transmission/reflection method performs best through comparison.

摘要

材料表征是许多材料生产、加工和管理应用中的一个重要问题。各种微波技术已被引入来表征材料的性能。近年来的研究表明，材料的复介电常数 ε 可以用不依赖于校准的散射参数测量。本项目旨在设计并实现一款介电测量软件，以精确计算矩形波导内样品的介电数据，并通过 UPV 实验室的测量进行仿真验证开发的软件。本软件包括三种测量介电材料复介电常数的传输线方法:透射/反射法、传播常数法和微波非共振法。软件采用 MATLAB 编程，具有图形化用户界面，易于操作。该软件通过读取参数值文件来计算复介电常数值，并将结果绘制成图表显示给用户。通过读取导师提供的 TEFLON 和 PVC 两种测量方法的数据文件，我们得到了三种方法的介电常数的实部和虚部值。通过比较，在这三种方法中，透射/反射法表现最好。

Chapter 1: Introduction

Relative complex permittivity (ε_r) is a required parameter to describe the frequency dependence as well as energy storage (and dissipation) capacity of dielectric materials. In this project, we set out to analyse, design and implement a dielectric measurement software system which can be used to characterise the dielectric properties of samples inside rectangular waveguides. The developed software system is complemented with comparisons from commercial measurements to validate the results.

At the beginning of the project, we did background research of dielectric measurements and made research summary. After that, we focused on dielectric measurements of samples inside rectangular waveguides. We chose three representative transmission line methods out of various dielectric measurements to programme in MATLAB. The three methods are transmission/reflection method, propagation constant method and microwave nonresonant method. Then we developed a software to accurately compute the dielectric data by reading measurement data files, calculating complex permittivity in three different methods and displaying results in the coordinate area. We also designed user panel to make the software more convenient for users to choose files to read and enter input parameters. User can select any one out of three methods by clicking the corresponding tab on the top of the panel to do the simulation. After that, we validated the developed software with measurements performed in UPV lab. In the end, we summarised the results into final report.

In this report, for the background part, we explain the permittivity characterization and overview different kinds of permittivity measurement methods. Then we specially delve into transmission line methods because the measurements that we have are using rectangular waveguide. As to design and implementation part, we introduce the algorithm of the three methods used and the design of the software. When it comes to result analysis part, we display all the simulation results with two measurements, TEFLON and PVC, and analyze the results and uncertainty. We compare results of these three methods separately with two different measurements. We write down the overall summary and achievements of the project in the conclusion part.

Chapter 2: Background

2.1 Permittivity Characterization

As the article [1] describes: "The goal of dielectric measurements is to report the relative permittivity of a specimen under test for a specified orientation of electric field and frequency. The constitutive parameter in dielectrics is permittivity, ε. This is a complex valued parameter that is generally dependent on frequency and temperature."

We often express permittivity as a relative value ε_r: $\varepsilon = \varepsilon_0\varepsilon_r = \varepsilon_0(\varepsilon_{r'} - j\varepsilon_{r''})$, where $\varepsilon_0 \cong 8.854*10^{-12}$ F/m. Often, engineering applications refer to the real part of the relative permittivity $\varepsilon_{r'}$ as the dielectric constant (often D_k). The ratio of the imaginary part to real part is called the loss tangent, $\tan\delta = \varepsilon_{r'}/\varepsilon_{r''}$ (often called the material dissipation factor, D_f).

2.2 Overview of Permittivity Measurement Techniques

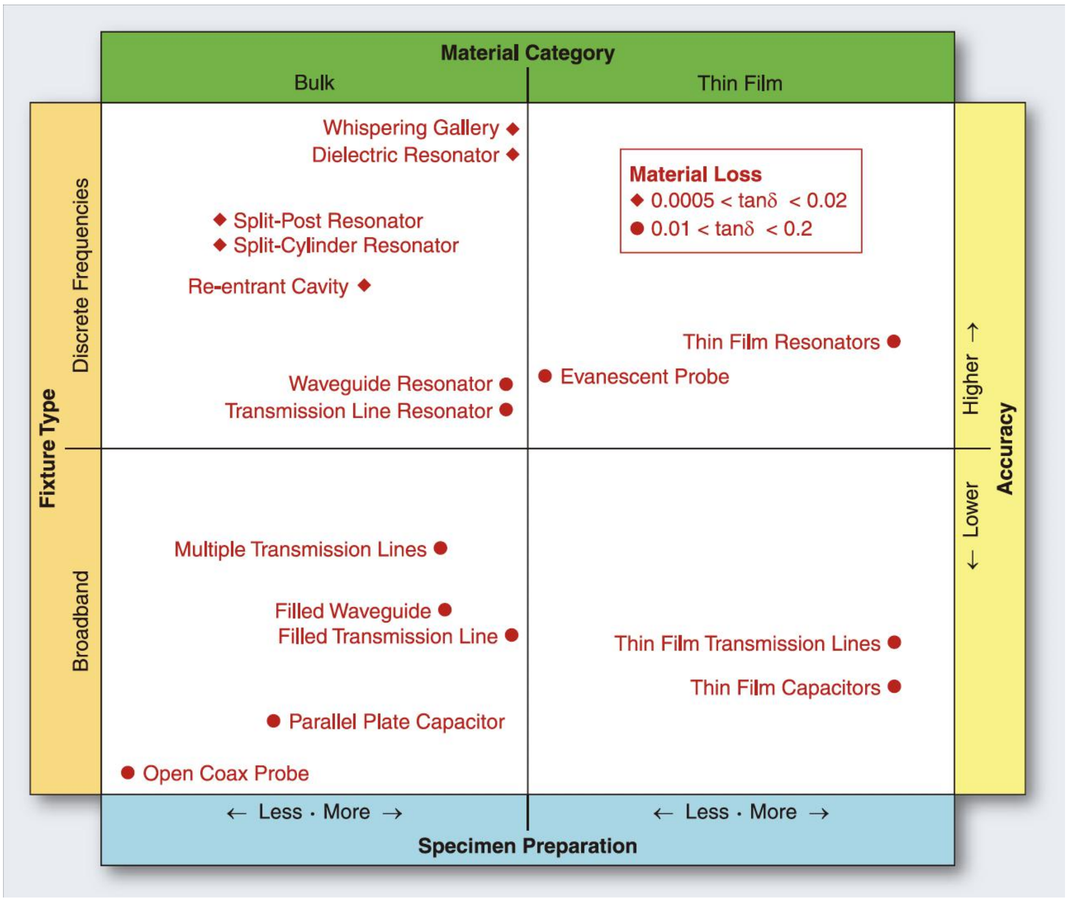


Figure 1. Matrix of dielectric measurement methods grouped and organized according to material category / sample preparation and frequency band / relative accuracy. The matrix also identifies valid material loss ranges. [1]

Permittivity reconstruction of samples in rectangular waveguide

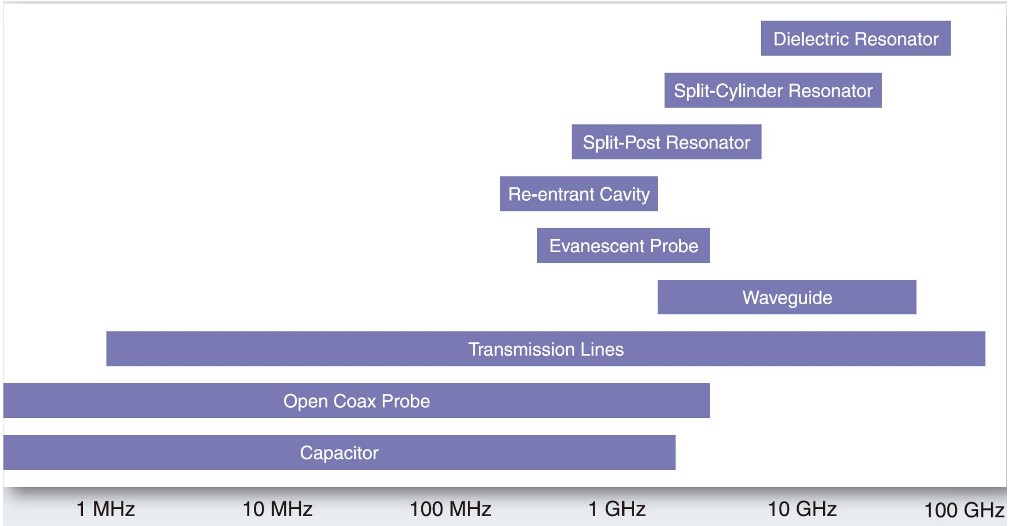


Figure 2. Frequency range of various dielectric test fixture categories. Each category may include both discrete frequency resonators and broadband structures. [1]

Usually, in order to accurate measurement, high frequency technology will impedance through the test fixture or vector network analyser (such as probes, cavity, or a transmission line) connected to the material being tested. In dielectric measurements, the instrument reports values of its intrinsic measurand, impedance or scattering parameters. After that, the test fixture model turns test fixture parameters to material permittivity, as shown in Figure 3.

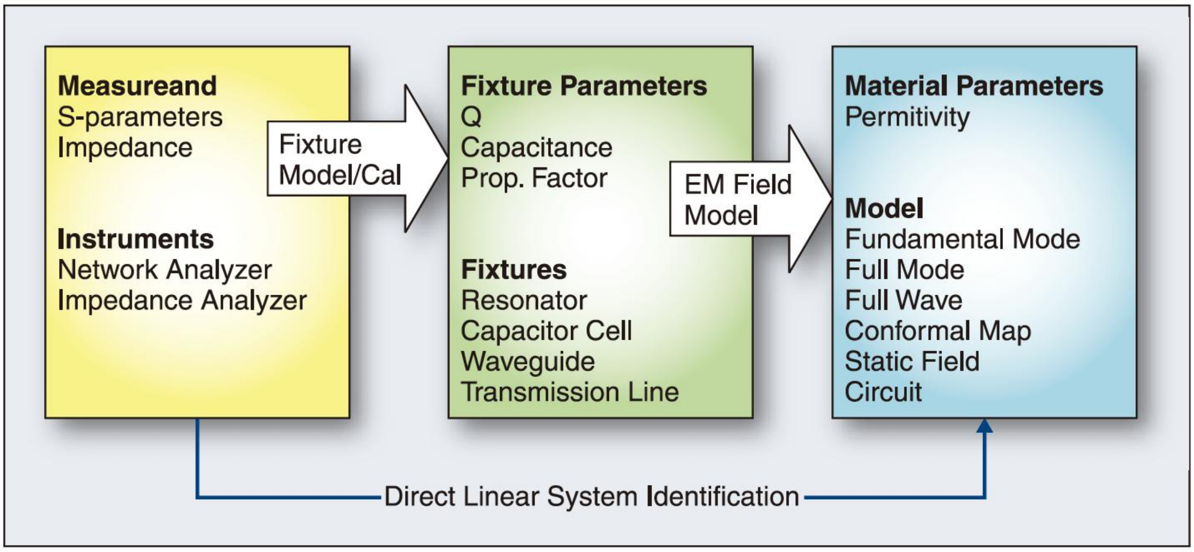


Figure 3. The general flow of the permittivity measurement process showing instruments measuring response of fixture with material under test and the field models required to go from fixture response to material parameters. [1]

Here are four common dielectric test fixture categories, which are introduced in article [2] in detail.

Permittivity reconstruction of samples in rectangular waveguide

a) Coaxial probe

Table 1: Method features of coaxial probe

Suitable for broadband measurement.
It’s very convenient and won’t cause destruction.
Accuracy of ε_r and loss resolution (tanδ) are low.
Suited for liquids or semi-solids.

Table 2: Material assumptions of coaxial probe

The sample is semi-infinite thick.
The sample is non-magnetic.
The surface of the sample is flat.
There are no air gaps in the sample.

The open-ended coaxial probe is a cut off section of transmission line. To measure the material, the probe is immersed into liquid or touched to the solid (or powder) fixture’s surface. “The fields at the probe end “fringe” into the material and change as they come into contact with the MUT (Figure 4). The reflected signal (S_{11}) can be measured and related to ε_r^*.” [2]

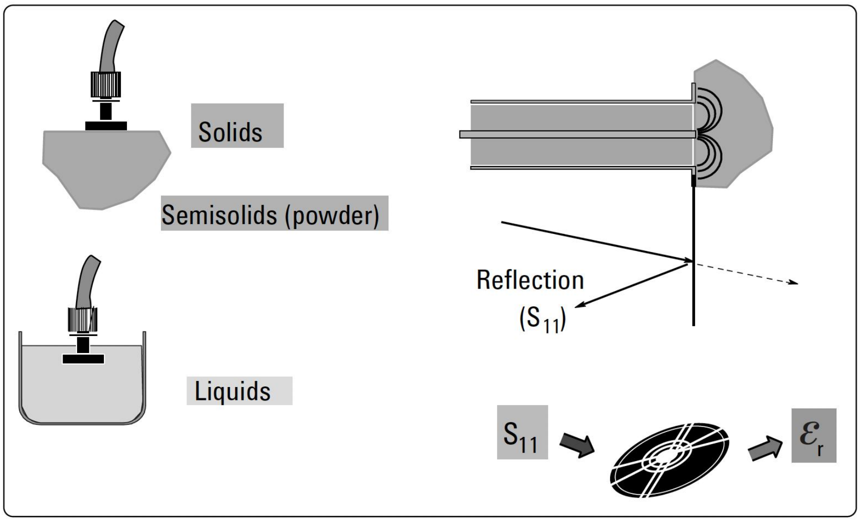


Figure 4. Coaxial probe [2]

Permittivity reconstruction of samples in rectangular waveguide

Calibration of the probe needs to be done before measuring for the accuracy of measurement. As mentioned in article [2] : "A three-term calibration corrects for the directivity, tracking, and source match errors that can be present in a reflection measurement. In order to solve for these three error terms, three well-known standards are measured, which are air, a short circuit, and distillate and de-ionized water. Even after calibration, there are still existing errors which affect the accuracy of measurement." Details are shown in Table 3.

Table 3: Three main sources of errors and corresponding solutions of coaxial probe method [2]

Sources of errors	Corresponding solutions (The solutions are found from article [2].)
Cable stability	"It is important to allow enough time for the cable (that connects the probe to the network analyser) to stabilize before making a measurement and to be sure that the cable is not flexed between calibration and measurement. The automated Electronic Calibration Refresh feature recalibrates the system automatically, in seconds, just before each measurement is made. This virtually eliminates cable instability and system drift errors."
Air gaps	"For solid materials, an air gap between the probe and sample can be a significant source of error unless the sample face is machined to be at least as flat as the probe face. For liquid samples air bubbles on the tip of the probe can act in the same way as an air gap on a solid sample."
Sample thickness	"The sample must also be thick enough to appear infinite to the probe. There is a simple equation to calculate the approximate thickness of the sample for the high temperature probe sample and suggested thickness for the slim probe sample. A simple practical approach is to put a short behind the sample and check to see if it affects the measurement results."

b) Transmission line

Table 4: Method features of transmission line

Suitable for broadband measurement.
It's very convenient and won't cause destruction.

Permittivity reconstruction of samples in rectangular waveguide

Accuracy of ε_r and loss resolution (tanδ) are low.
Suited for liquids or semi-solids.
It can measure magnetic materials.

Table 5: Material assumptions of transmission line

Fixture's cross section is filled by sample.
Fixture is smooth and perpendicular to long axis.
Fixture walls don't have air gaps.
Material is homogeneous.

In transmission line methods, the fixture is placed inside a section of an enclosed transmission line which is normally a part of rectangular waveguide or coaxial airline (Figure 5). ε_r is computed from the measurement of the reflected signal (S_{11}) and transmitted signal (S_{21}).

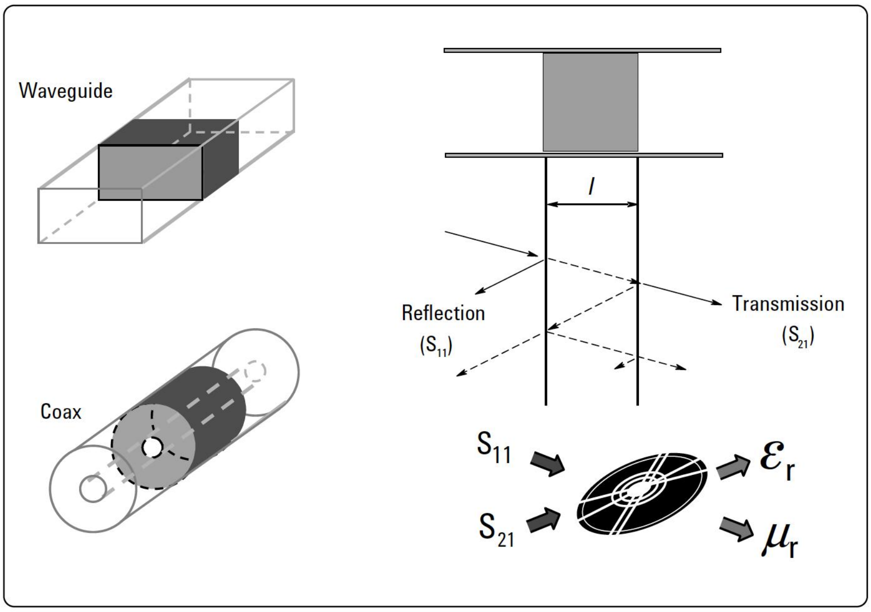


Figure 5. Transmission line; waveguide and coaxial line case [2]

There are various kinds of transmission line methods. Here are several methods from papers I read:

1. Measurement of the Intrinsic Properties of Materials by Time-Domain Techniques [6]

The authors are A. M. Nicolson and G. F. Ross.

Permittivity reconstruction of samples in rectangular waveguide

This paper proposes a single time domain measurement method in frequency domain are used to determine the complex permittivity and permeability of the linear materials; The frequency band generally extends from VHF to the X band. The technique consists of placing an unknown sample in a microwave TEM mode fixture and exciting the sample with a subnanosecond baseband pulse. The fixture is used to measure the forward scattered energy S_{21} (t) and the backscattered energy S_{11} (t) respectively. In this paper, it has been proved that the time domain "characteristics" of the forward and backward scattering are uniquely related to the eigenproperties of the material, i.e., ε* and μ*. By properly interpreting S_{21} (t) and S_{11} (t), we can determine the real and imaginary parts of ε and μ as functions of frequency.

2. Improved Technique for Determining Complex Permittivity with the Transmission /Reflection Method [7]

The authors are James Baker-Jarvis, Eric J. Vanzura and William A. Kissick.

This paper presents a new robust algorithm for determining the permittivity which eliminates the undesirable properties of the commonly used methods corresponding to half-wavelength integer multiples in the sample. In addition, a formula for calculating the complex permittivity independent of the reference plane position and the sample length is derived.

3. Calibration-Independent and Position-Insensitive Transmission/Reflection Method for Permittivity Measurement with One Sample in Coaxial Line [8]

The authors are Zhao Caijun, Jiang Quanxing, and Jing Shenhui.

This paper presents a simple method based on the transmission/reflection method. In this method, the uncalibrated scattering parameters can be measured twice using a sample and a straight line, and the high precision measurement results without singularities can be obtained. One method of measurement is to make a measurement of an empty fixture, the other is to make a measurement of the same fixture that keeps the sample in a single position. In addition, the principle of the method ensures its independence from the fixture and sample position.

4. A New Microwave Method for Electrical Characterization of Low-Loss Materials [10]

The author is Ugur Cem Hasar.

An effective microwave method for the determination of complex dielectric constant of low loss dielectric materials is presented. The method uses an empty element and a measuring element (a waveguide or coaxial cross part) for the measurement of the original scattering parameters and a sample for its two configurations. The proposed method has three advantages. Firstly, microwave measurements do not require any calibration. Secondly, the measurement errors required by other methods due to the sample thickness and the inhomogeneity of the second sample are eliminated. Thirdly, the pure transmission scattering parameter of the sample is used in the theoretical formula, so as to reduce the measurement error caused by the phase uncertainty in the reflection scattering parameter.

5. Thickness-Invariant Complex Permittivity Retrieval from Calibration-Independent Measurements [12]

The author is Ugur Cem Hasar.

A calibration-independent method is proposed to accurately determine the complex permittivity (ε_r) of dielectric samples by measuring the original scattering parameters, especially for thin samples. Two polyethylene samples with X-band waveguide measurements were carried out to verify our method. From the analysis of the results, it can be found that although the ε_r of the two samples extracted by this method is similar (the thickness is not changed), the accuracy of the test method is greatly reduced due to the inaccurate L measurement.

c) Free space

Table 6: Method features of free space

Do not contact or destruct the sample.
Suited for high frequency and high temperature.
It can measure magnetic materials.
Antenna polarization may be varied for anisotropic materials

Table 7: Material assumptions of free space

Material is homogeneous.
The sample is flat, large and parallel-faced.

As mentioned in article [2] :"Free-space methods use antennas to focus microwave energy at or through a slab of material without the need for a test fixture. This method is non-contacting and can be applied to materials to be tested under high temperatures and hostile environments. An exemplary measurement system using a free-space method consists of a vector network analyser, a “fixture” (antennas, tunnels, arches, etc.), software, and a computer.” The work of network analyser calibration for a free space measurement is full of difficulties. Free space calibration standards have special problems due to their “connector-less” feature. Based on the convenience and accuracy needed, a calibration can be as easy as a response calibration or as complex as a full two-port calibration.

High temperature measurement is simple to operate in free space because in high temperature environment, the sample is never touched or contacted. “The sample can be heated by placing it within a furnace that has windows of insulation material transparent to microwaves.” [2] The basic set up is illustrated in Figure 7.

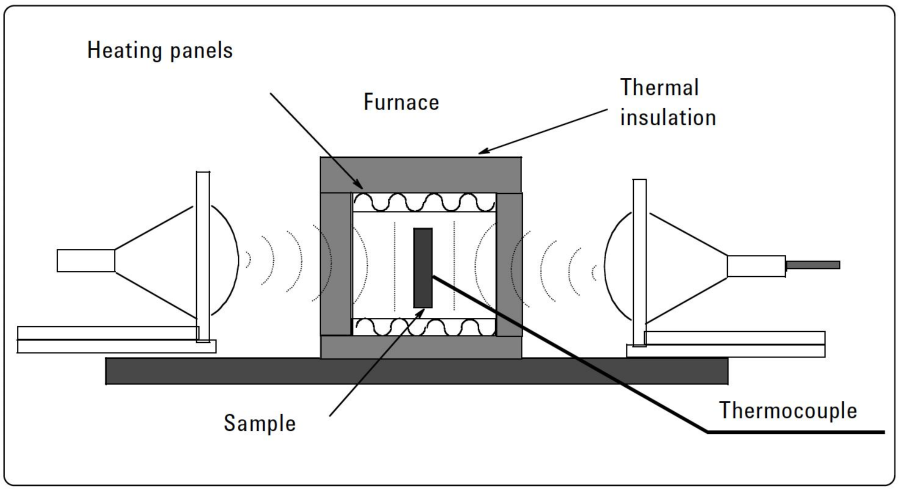


Figure 6. High temperature measurement in free space [2]

d) Resonant cavity

Table 8: Method features of resonant techniques

Suited for high impedance environment.
Suited for low loss materials.
Can use small samples to realize reasonable measurements.
Can measure one or a few frequencies.

Table 9: Material features of broadband techniques

Suited for low impedance environment.
Can use large samples to realize reasonable measurements.

Permittivity reconstruction of samples in rectangular waveguide

Can measure any frequency.

"Resonant cavities are high Q structures that resonate at certain frequencies. A piece of sample material affects the centre frequency (f) and quality factor (Q) of the cavity. From these parameters, the complex permittivity (ε_r) of the material can be calculated at a single frequency", described in article [2]. There are various kinds of cavity methods, among which the most widely considered one is cavity perturbation method. This method uses a rectangular waveguide with iris-coupled end plates, operating in TE_{10n} mode (Figure 8). "For dielectric measurement, the sample is placed in a maximum electric field. The sample is inserted through a hole in the middle of the waveguide length, then an odd number of half wavelengths (n = 2k + 1) will bring the maximum electric field to the sample location, so that the dielectric properties of the sample can be measured.", described in article [2].

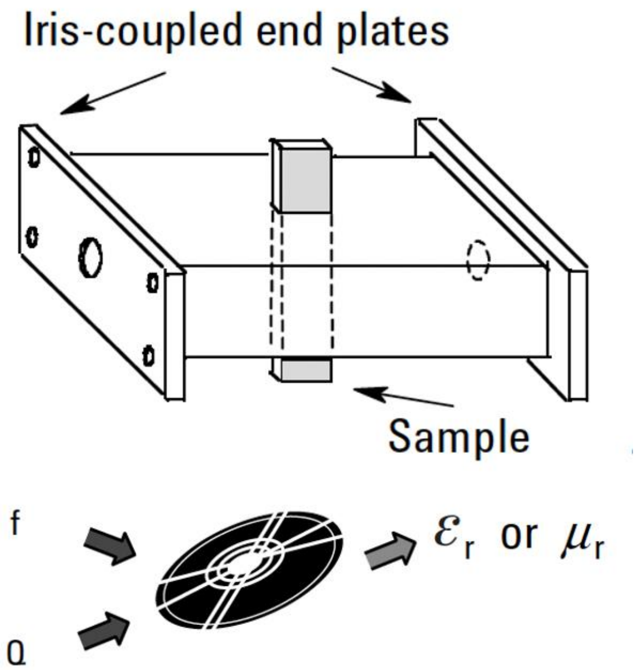


Figure 7. Resonant cavity measurement [2]

2.3 Calibration-independent Methods

As mentioned in article [11] : "In recent decades, the calibration-independent methods have successfully been employed to determine the complex permittivity of dielectric materials without the need of calibration before measurements. The accuracy of calibration-dependent techniques is not good enough, so calibration-independent techniques are more attractive. The accuracy of calibration-dependent methods is limited by the requirement of a full two- or one-port calibration which bring error due to imperfections.

a) Calibration-independent methods can be categorized into two different types:

1. Multiline methods

In the multiline methods, the permittivity of dielectric materials is derived from the propagation constant obtained by measuring two identical transmission lines (waveguide or coaxial airline) with different lengths, which are totally filled with sample material. Despite the fact that the process of calculating permittivity is simple, the multilines methods suffer from the thickness uncertainty in the second line.

2. Multiposition methods

The multiposition methods utilize measurements of one sample at different positions in its measurement cell. Although these methods can effectively solve the problems in the multiline methods, they require precise location of the sample in the cell or distance between different positions, the uncertainty of which will cause serious measurement errors. Additionally, the airgaps between the sample and its cell, which are necessary to move the sample within the cell.

To keep the sample position invariant, two modified methods have been presented based on multiposition methods. One method introduces an extra cell which is connected to two terminals of the measurement cell, respectively, in two measurements [3]. The other method loads the sample asymmetrically in the measurement cell and makes the second measurement with the inverse connection of the same cell [4], [5]. However, the first method experiences the problems rising from the length uncertainty of the extra cell and any discontinuity between the extra cell and the measurement cell, and the second method requires the precise knowledge on the sample location and the length of the measurement cell.

b) In calibration-independent methods, multiposition methods are more attractive than multiline methods for two reasons.

1. They eliminate any inhomogeneity and/or impurity present in the second sample.
2. They decrease any thickness uncertainty that can arise from using the second sample. Despite some methods can solve these problems, they ask for precise location or precise shifting distance of the sample inside a waveguide or coaxial-line portion.

c) However, these calibration-independent methods have their own respective problems:

The requirement of two samples.

The movement of the sample.

The introduction of extra assistant transmission lines.

2.4 Comparison of Methods

Many factors are important in selecting the most appropriate measurement technique, for example, accuracy, material shape and convenience. Some main factors are displayed here:

Table 10: Significant factors to select measurement technique

Factors	Description
Frequency range	
Sample size restrictions	
Expected values of ε_r and μr	
Destructive or non-destructive	
Required measurement accuracy	
Contacting or non-contacting	
Material properties	i.e., homogeneous, isotropic
Temperature	
Form of material	i.e., liquid, powder, solid, sheet
Cost	

Figure 9 makes a conclusive comparison between the measurement methods that are introduced.

Permittivity reconstruction of samples in rectangular waveguide

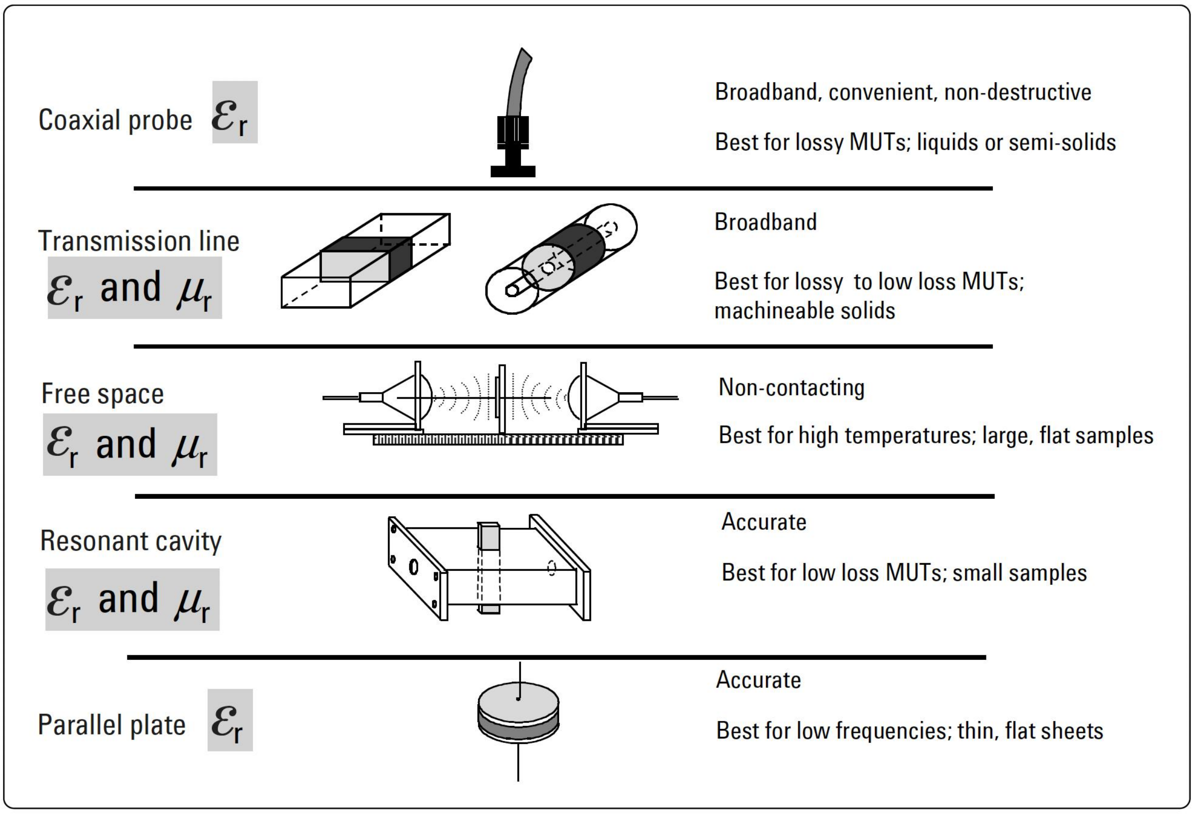


Figure 8. Comparison between the measurement techniques [2]

Chapter 3: Design and Implementation

3.1 Select suitable methods for the project

Here are the factors to consider:

a) Why choose transmission line method?

My supervisor offered two projects to choose. One is coaxial probe, and the other one is transmission line. Therefore, my project is assigned to focus on transmission line method.

b) Calibration-independent or calibration-dependent transmission line methods?

Both are ok, since the measurement system has been calibrated already.

c) Why use rectangular waveguide instead of coaxial line?

As mentioned in paper [8] : "The measurement using coaxial line is less accurate than using waveguide. It is because the airgaps in coaxial line bring larger errors than in waveguide. But the principle of the proposed method is also applicable to waveguide. Then, more accurate results will be obtained by the measurement using waveguide." And also, it is more difficult to put material inside coaxial line than rectangular waveguide.

d) Why choose these three methods?

First of all, they come from very distinguished papers that are generally accepted. Secondly, these three methods are different. The first method only uses the data of one sample at one location, the second method requires the data of two samples of different lengths, and the third method requires the data of one sample at two different locations. Thirdly, they are easy to implement in MATLAB.

e) Uncertainty analysis, need or not?

Uncertainty analysis requires very deep mathematical derivation. Also, the uncertainty has a lot to do with instrumental errors, which I could not fix because I was in China, away from UPV in Spain. Considering the limited time and ability, after careful literature reading and situation analysis, we gave up this part.

3.2 The algorithm of the three methods used

3.2.1 Transmission/reflection method

The transmission/reflection method [7] for complex permittivity and permeability determination is introduced. The main objective function is:

$$S_{21}S_{12} - S_{11}S_{22} = \exp\left[(-2\gamma_0)(L_{air} - L)\right]\frac{z^2-\Gamma^2}{1-z^2\Gamma^2} \tag{1}$$

where we need scattering matrix to calculate value on the left side, and γ_0, L_{air}, L, z, Γ has their relation equations:

$$\gamma = j\sqrt{\frac{\omega^2\mu_R^*\varepsilon_R^*}{c_{vac}^2} - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{2}$$

$$\gamma_0 = j\sqrt{\left(\frac{\omega}{c_{lab}}\right)^2 - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{3}$$

$$z = \exp\left(-\gamma L\right) \tag{4}$$

$$\Gamma = \frac{\frac{\gamma_0}{\mu_0} - \frac{\gamma}{\mu}}{\frac{\gamma_0}{\mu_0} - \frac{\gamma}{\mu}} \tag{5}$$

Finally, we find when the function

$$\left|\exp\left[(-2\gamma_0)(L_{air} - L)\right]\frac{z^2-\Gamma^2}{1-z^2\Gamma^2} - (S_{21}S_{12} - S_{11}S_{22})\right| \tag{6}$$

has its minimum value. The value of permittivity ε_r is the corresponding zero point.

3.2.2 Propagation constant method

A new method [9] that uses measurements of the propagation constant rather than calibrated scattering parameters for determining the complex permittivity of a sample. In this method, two waveguide transmission lines of different lengths are filled completely with a dielectric material.

First, we calculate measured cascade matrix:

$$M^i = \frac{1}{S_{21_i}}\begin{bmatrix} (S_{12_i}S_{21_i} - S_{11_i}S_{22_i}) & S_{11_i} \\ -S_{22_i} & 1 \end{bmatrix} \tag{7}$$

$$M^{ij} = M^j[M^i]^{-1} \tag{8}$$

Then, we get the two eigenvalues of M^{ij}:

$$\lambda_{1M}^{ij}, \lambda_{2M}^{ij} = \frac{(M_{11}^{ij}+M_{22}^{ij}) \pm \sqrt{(M_{11}^{ij}-M_{22}^{ij})^2+4M_{12}^{ij}M_{21}^{ij}}}{2} \tag{9}$$

Then, we use following equations to get value of real and image part of permittivity ε_r:

$$\gamma = \frac{\ln(\lambda^{ij})}{l_i - l_j} \tag{10}$$

$$\gamma(\omega) = \alpha(\omega) + j\beta(\omega) \tag{11}$$

$$\varepsilon_s' = \frac{\beta^2 + \left(\frac{\pi}{a}\right)^2}{\omega^2 \mu_0 \epsilon_0} \tag{12}$$

$$\varepsilon_s'' = \frac{2\alpha\epsilon_s'}{k}\sqrt{1-\left(\frac{\lambda}{2a}\right)^2} \tag{13}$$

3.2.3 Microwave nonresonant method

A method called microwave nonresonant method [11] is proposed to use uncalibrated-parameter measurements of an extra cell (empty) and the cell, in which the sample is arbitrarily located.

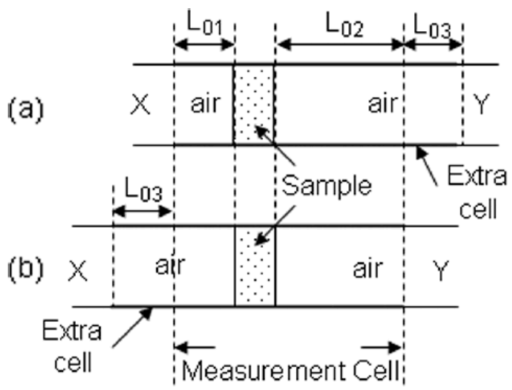


Figure 9. Microwave nonresonant method graphical introduction [11]

First, we calculate two measured cascade matrixes M_a and M_b:

$$M^i = \frac{1}{S_{21_i}}\begin{bmatrix}(S_{12_i}S_{21_i} - S_{11_i}S_{22_i}) & S_{11_i} \\ -S_{22_i} & 1\end{bmatrix}, \quad i = a, b \tag{14}$$

Then, we use following equations to get value of Λ matrix and k_0.

$$T_S = \frac{1}{(1-\Gamma^2)T}\begin{bmatrix}T^2 - \Gamma^2 & \Gamma(1-T^2) \\ -\Gamma(1-T^2) & 1-\Gamma^2T^2\end{bmatrix} = \begin{bmatrix}\Lambda_1 & \Lambda_2 \\ -\Lambda_2 & \Lambda_3\end{bmatrix} \tag{15}$$

$$\Gamma = \frac{\gamma_0 - \gamma}{\gamma_0 + \gamma}, \quad \mathrm{T} = e^{-\gamma L} \tag{16}$$

Permittivity reconstruction of samples in rectangular waveguide

$$\gamma = jk_0\sqrt{\varepsilon - (f_c/f)^2} \quad , \quad \gamma_0 = jk_0\sqrt{1 - (f_c/f)^2} \tag{17}$$

$$k_0 = \frac{2\pi f}{c} \quad , \quad f_c = \frac{1}{2a\sqrt{\mu_0\varepsilon_0\varepsilon_r}} \tag{18}$$

Finally, we find when the function

$$\left|2\left(\Lambda_1\Lambda_3 + \cos\left(2k_0\sqrt{1 - (f_c/f)^2}L_{03}\right)\Lambda_2^2\right) - T_r(M_b M_a^{-1})\right|$$

has its minimum value. The value of permittivity ε_r is the corresponding zero point.

3.3 Software Design

a) Program Logic

% read measurement data file measured by laboratory related instruments

% assign value of some input parameters

% for ff=1:length(measurement_data_file) %use the loop to run all the combination of [frequency, scattering matrix].

% code of transmission/reflection method / propagation constant method / microwave nonresonant method

% end

% plot each method's computation results respectively.

b) GUI Panel

GUI panel has been designed to make the software more user friendly. User needs to first enter several length parameters. Then user can browse the computer and choose one folder to read all the measurement data files inside. Click the "Confirm and Run" button to let the program run. The result will be displayed in the coordinate area.

Permittivity reconstruction of samples in rectangular waveguide

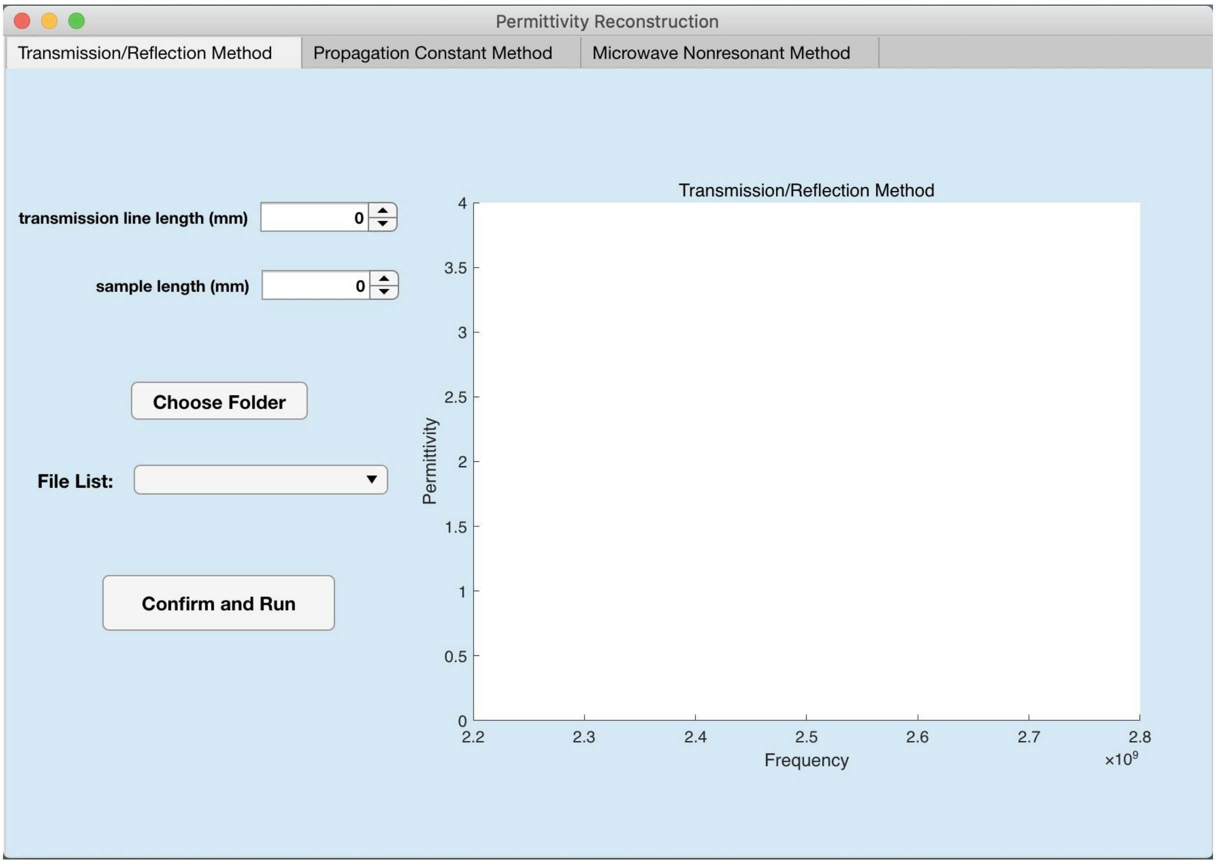
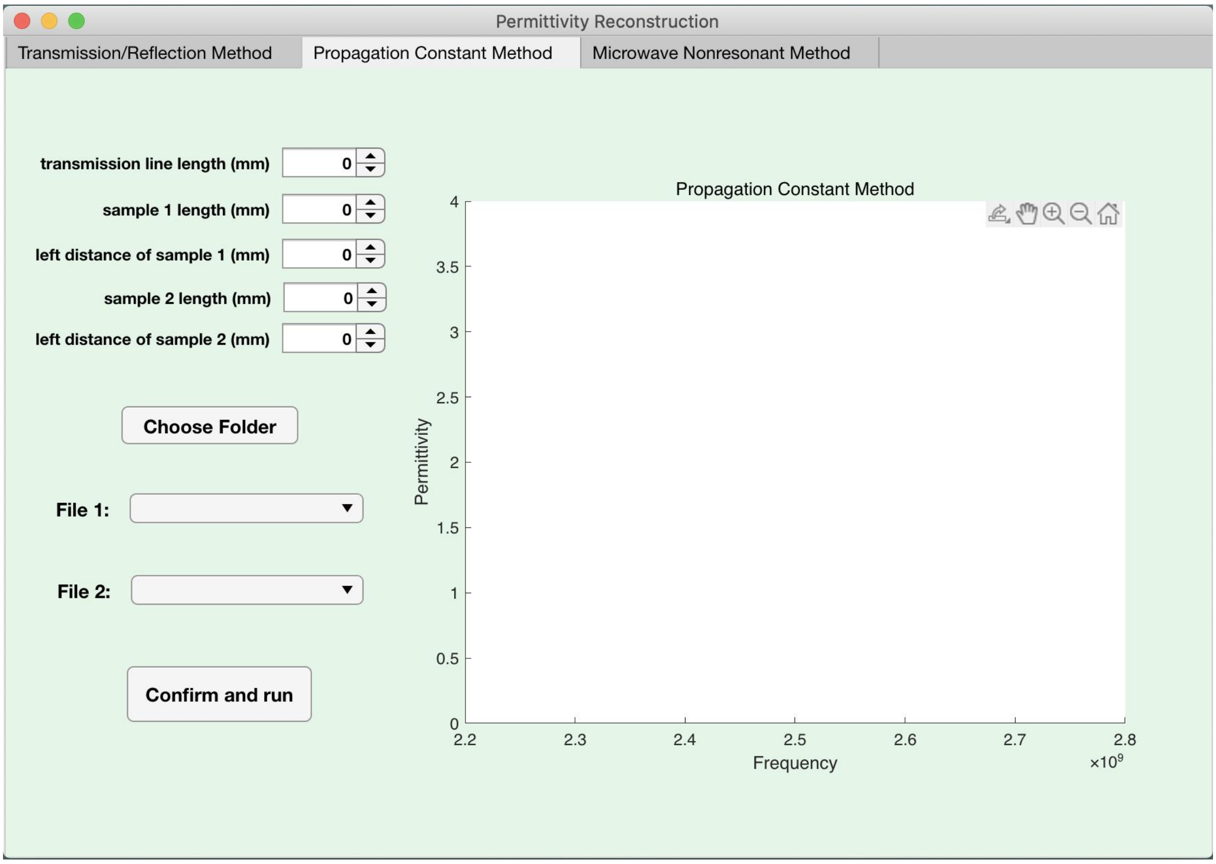


Figure 10. Tab 1 of the software panel



Permittivity reconstruction of samples in rectangular waveguide

Figure 11. Tab 2 of the software panel

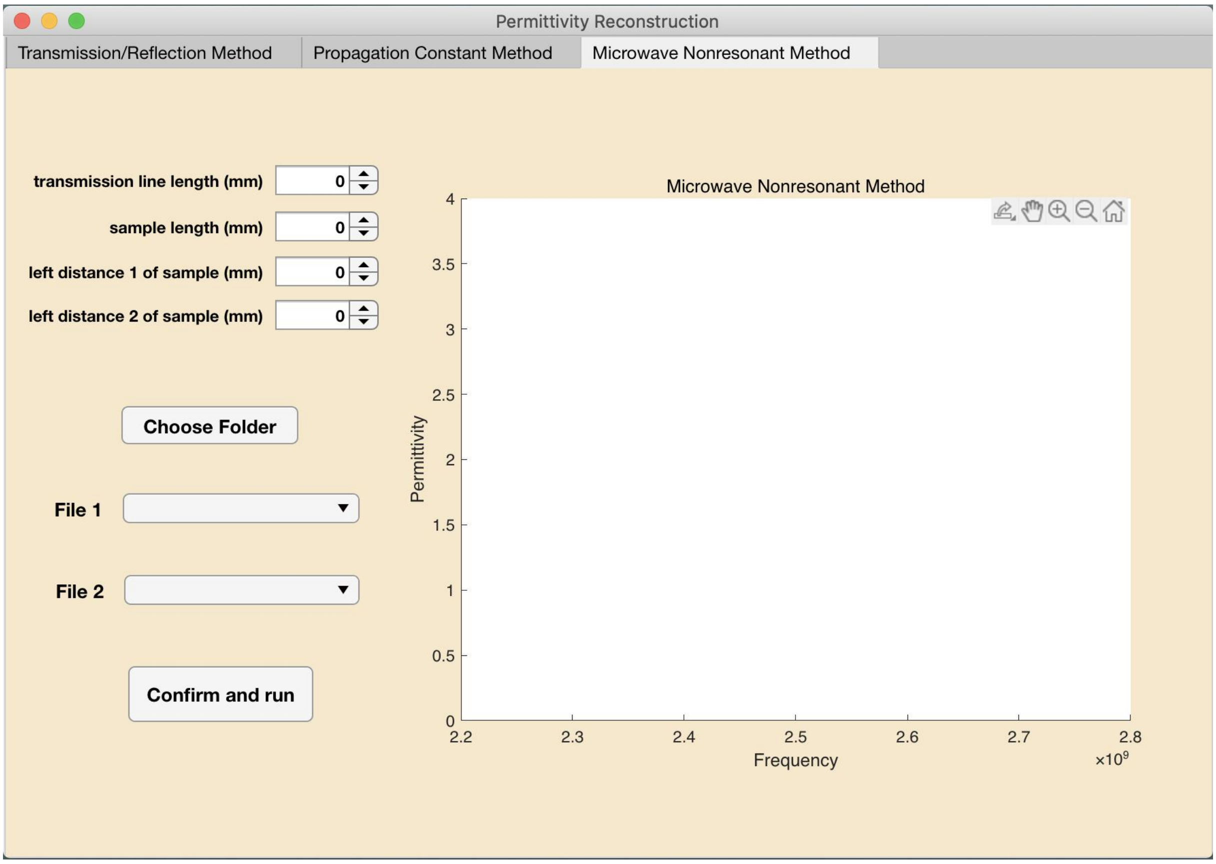


Figure 12. Tab 3 of the software panel

c) Function Introduction

Permittivity reconstruction of samples in rectangular waveguide

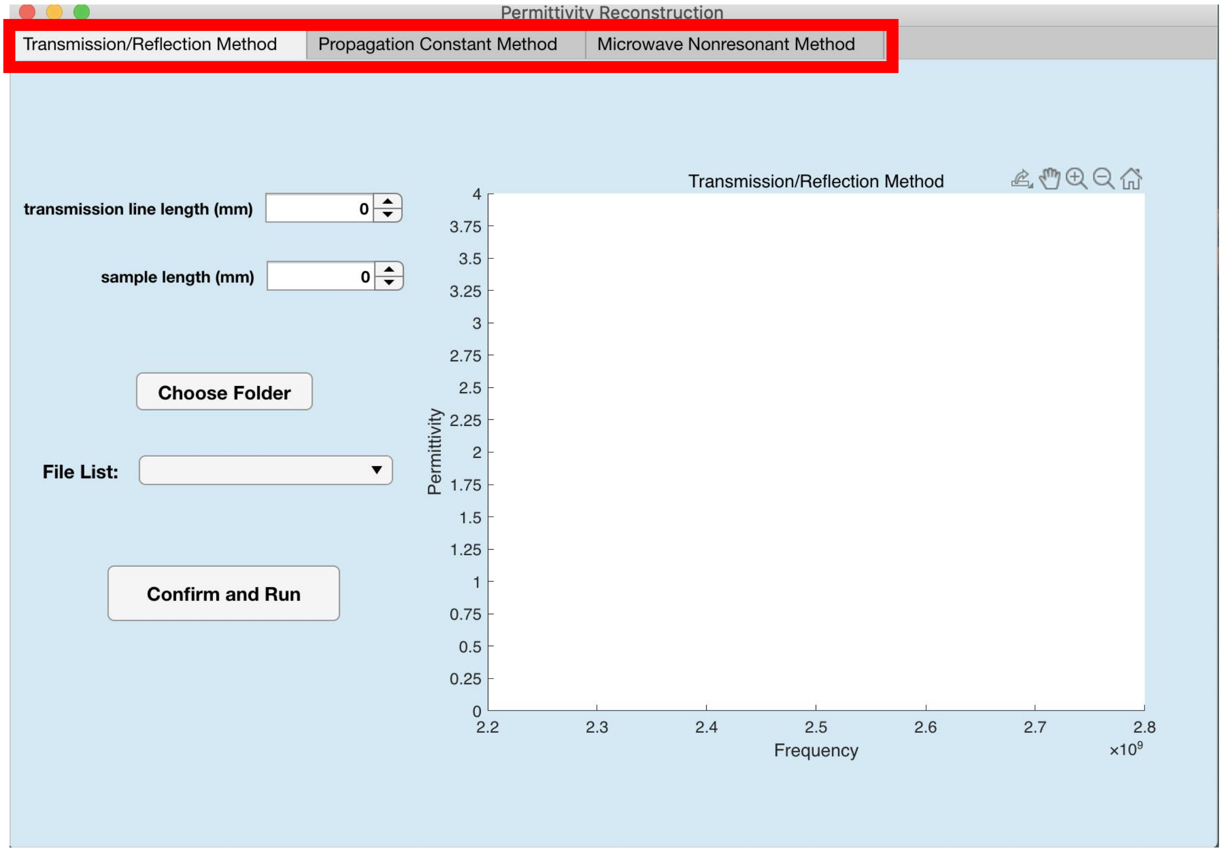
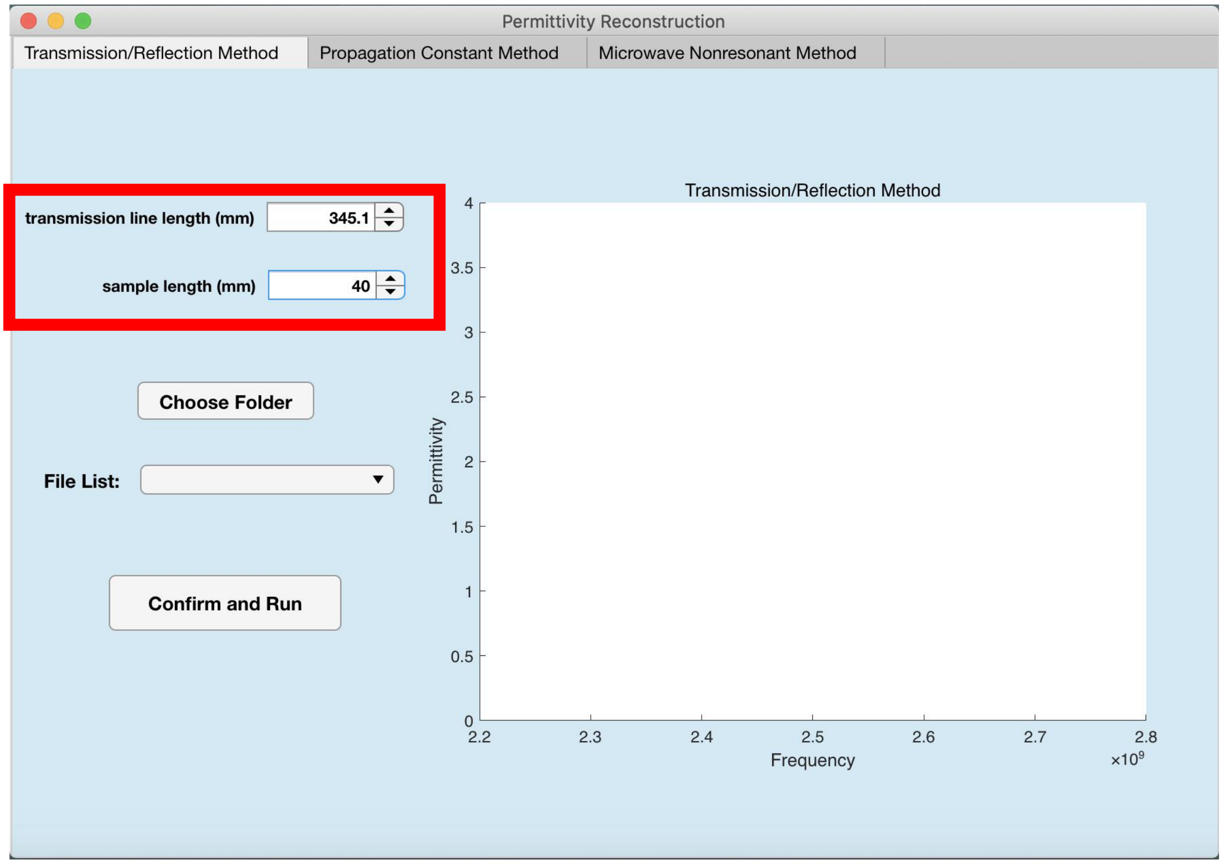


Figure 13. Enter length parameters in the numerical boxes.



Permittivity reconstruction of samples in rectangular waveguide

Figure 14. Enter length parameters in the numerical boxes.

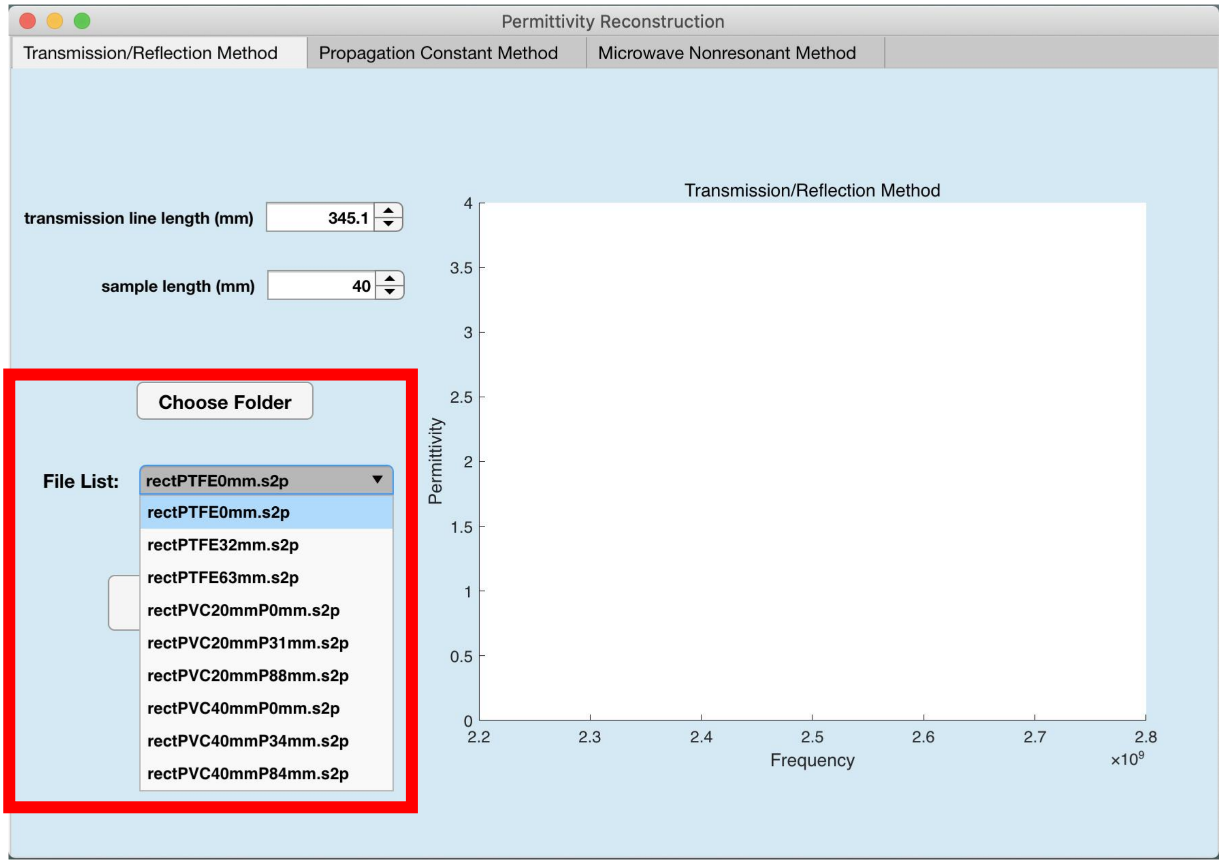


Figure 15. Click 'Choose Folder' bottom to browse the computer and choose one folder to read all the measurement data files inside. Then all the files will be listed.

Permittivity reconstruction of samples in rectangular waveguide

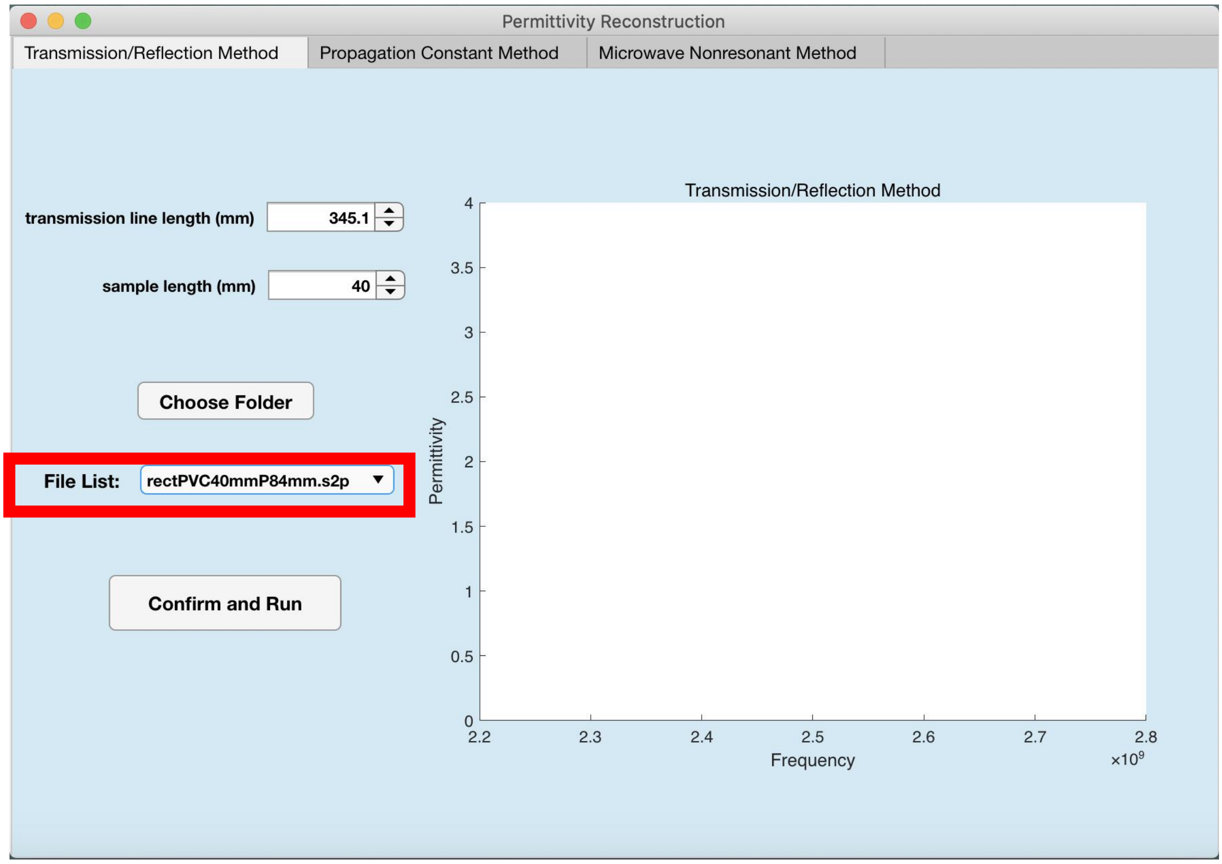
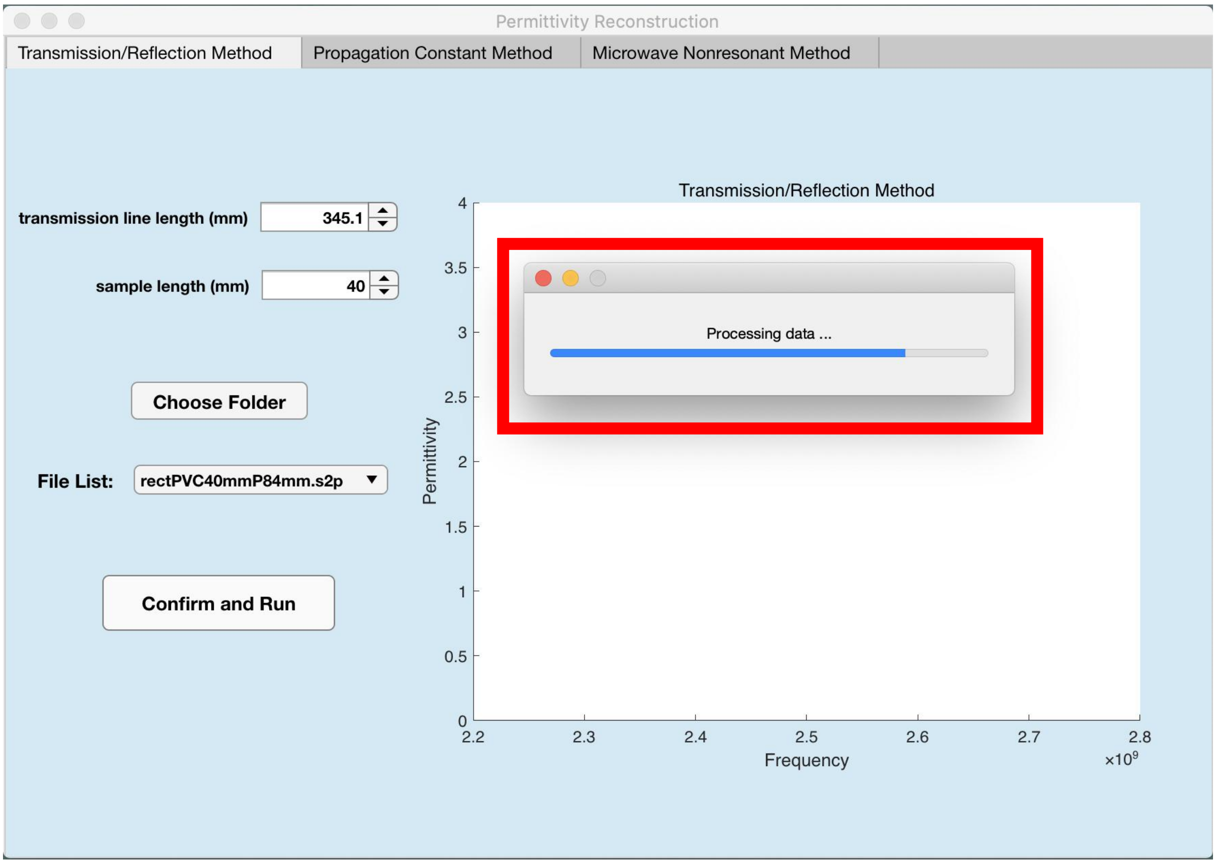


Figure 16. In the file list, we select the file we need.



Permittivity reconstruction of samples in rectangular waveguide

Figure 17. After clicking 'Confirm and Run' bottom, the software will process data.

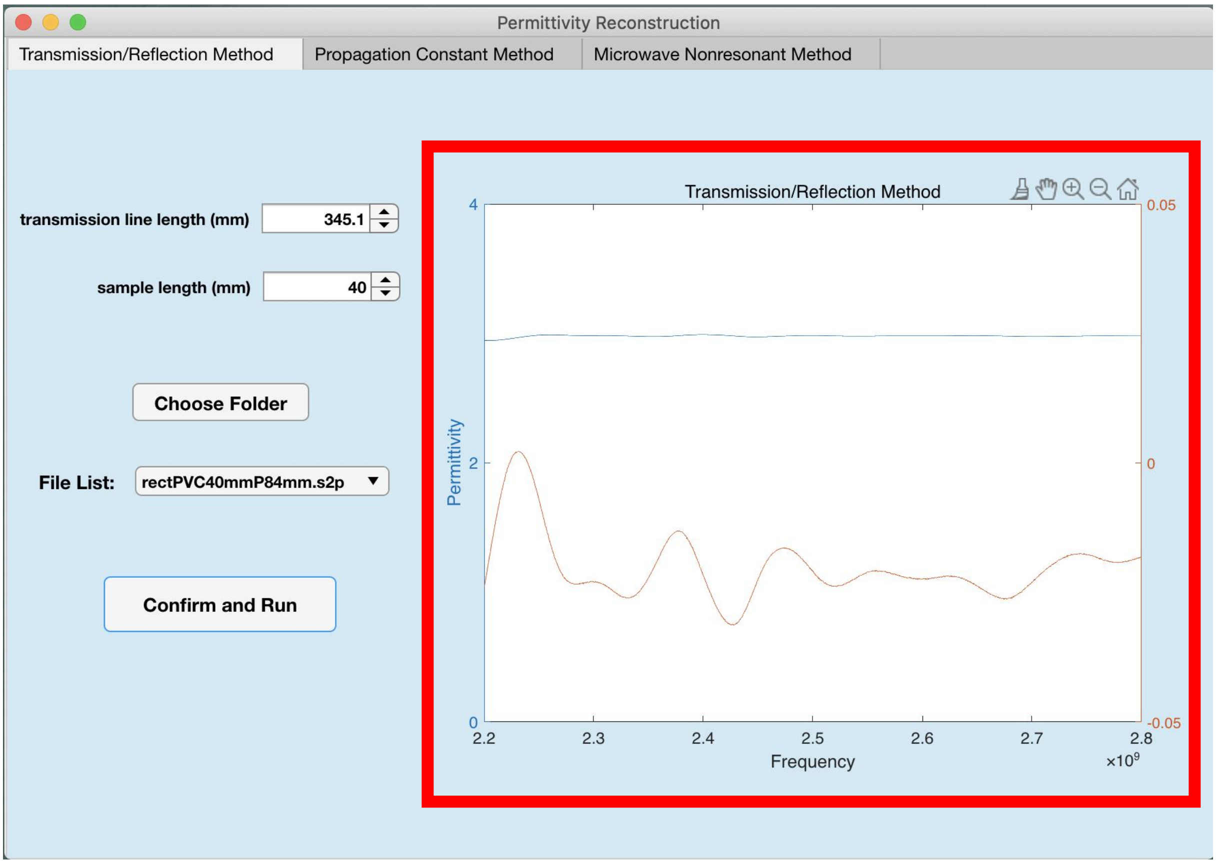


Figure 18. Finally, the results will be shown as a diagram.

3.4 Software testing and simulation

To run the software and make analysis and comparison, supervisor offered me two measurements. One measurement is TEFLON, and the other one is PVC. There are altogether nine measurement data files. Three TEFLON files and six PVC files. The total length of the transmission line is the same (345.2156mm). The difference between three files inside each group is that, as Figure 17 shown below, L_1 and L_2, the distances from two ports to the sample are different.

Figure 19. TEFLON measurement with 40mm long sample

Permittivity reconstruction of samples in rectangular waveguide

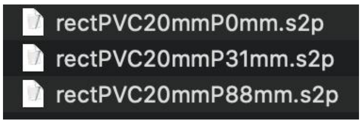


Figure 20. PVC measurement with 20mm long sample

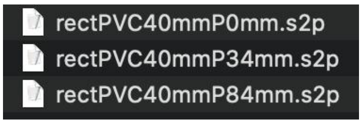


Figure 21. PVC measurement with 40mm long sample

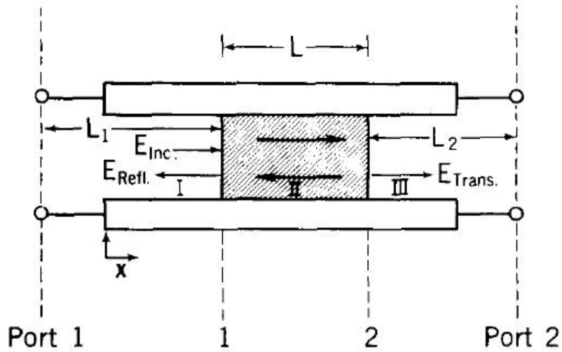


Figure 22. Rectangular waveguide structure (shaded part is sample) [7]

Chapter 4: Results and Discussion

4.1 TEFLON results

The x-axis is frequency, changing from $2.2*10^9$ to $2.8*10^9$, and the y-axis is the real part and imaginary part of permittivity. Blue line is the real part of permittivity, while orange line is the real part of permittivity. The ideal value of permittivity of TEFLON measurement is 2.00-j*0.0001.

There is one thing to mention. TEFLON measurement has only one sample length, but the propagation constant method needs two samples of different lengths. Therefore, TEFLON was not used in the simulation of propagation constant method.

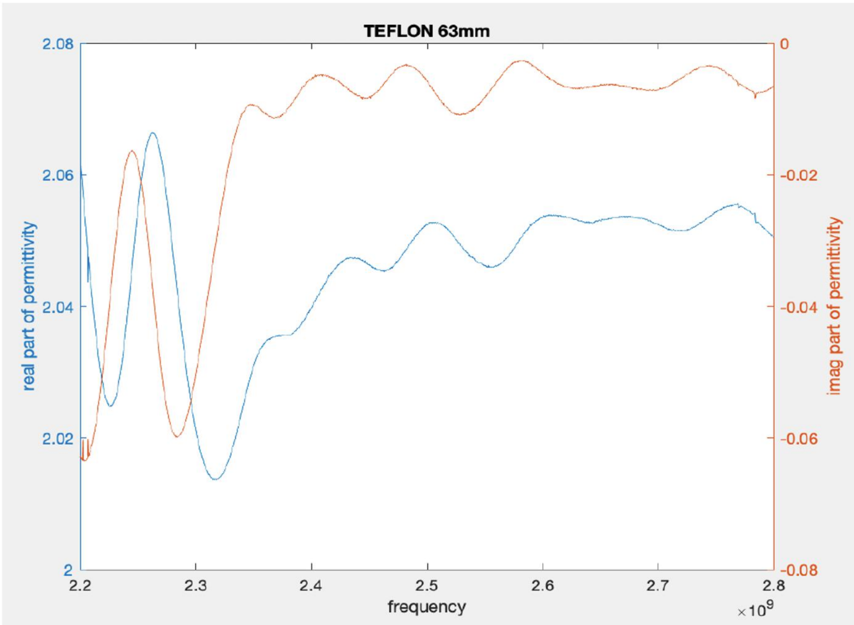


Figure 23. Transmission/Reflection method for TEFLON

Permittivity reconstruction of samples in rectangular waveguide

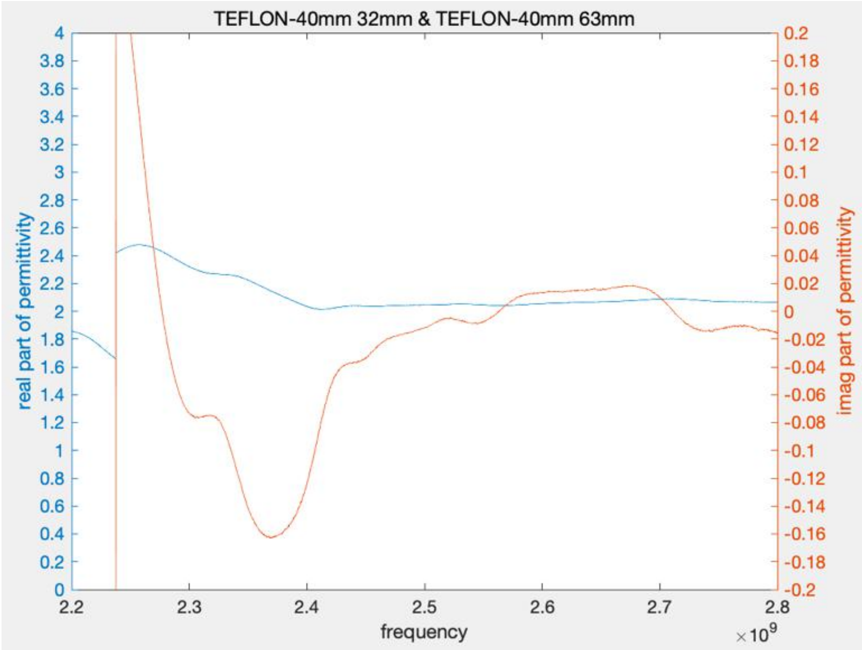


Figure 24. Microwave nonresonant method for TEFLON

4.2 PVC results

The x-axis is frequency, changing from $2.2*10^9$ to $2.8*10^9$, and the y-axis is the real part and imaginary part of permittivity. Blue line is the real part of permittivity, while orange line is the real part of permittivity. The ideal value of permittivity of PVC measurement is 2.95-j*0.02.

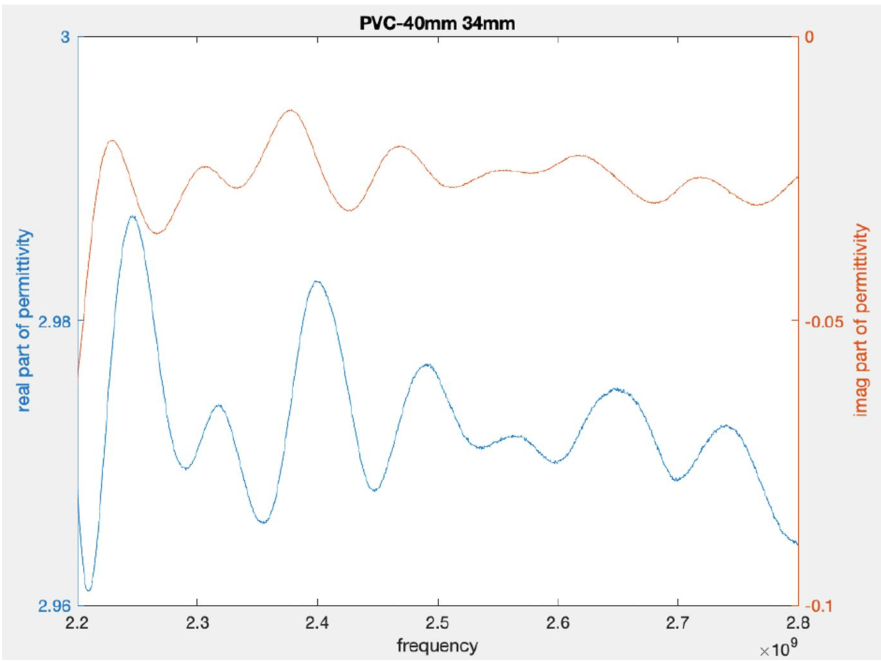


Figure 25. Transmission/reflection method for PVC

Permittivity reconstruction of samples in rectangular waveguide

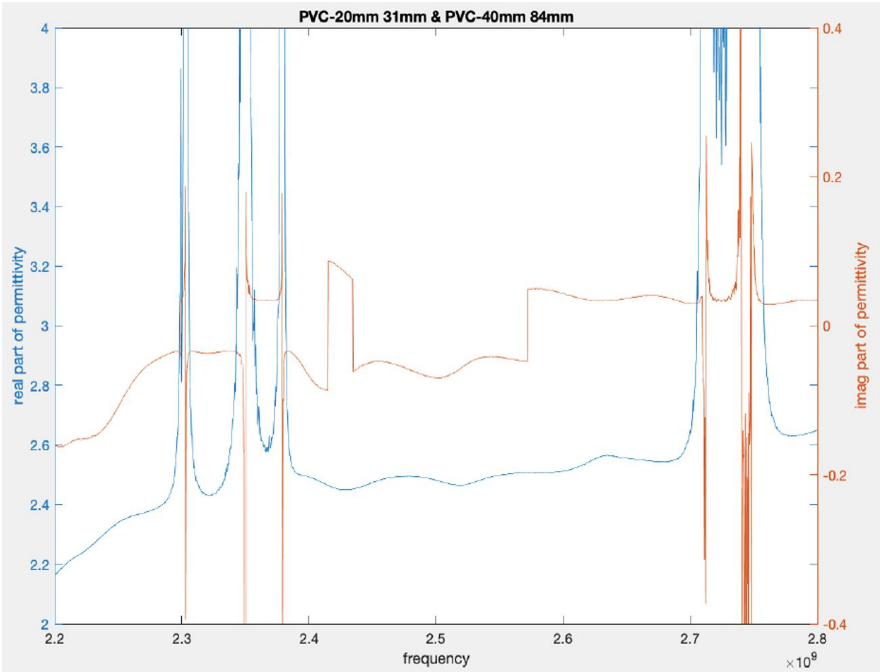


Figure 26. Propagation constant method for PVC

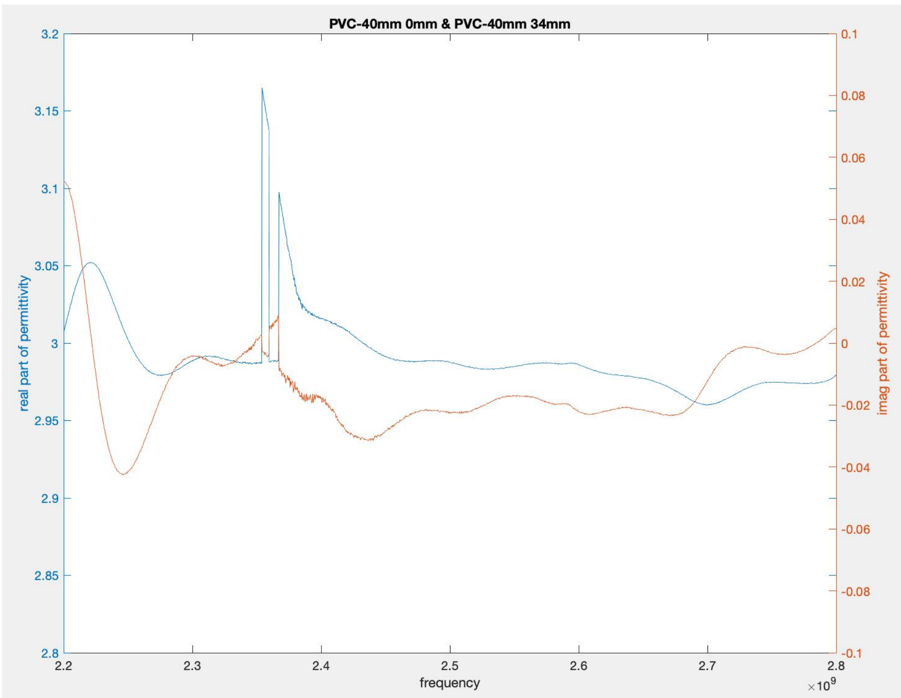


Figure 27. Microwave nonresonant method for PVC

4.3 Result analysis

a) Lower frequency (2.2-2.3 kHz) is closer to the cut-off frequency, so the result is worse.

Permittivity reconstruction of samples in rectangular waveguide

Theoretically the result should be feasible, but we need measurements which are more careful.

b) The sources of uncertainty in measurement include

1. Gaps between sample holder and sample, sample holder dimensional variations, gap correction formulas' errors.

2. Sample length uncertainty.

3. Connector mismatch and line losses.

4. Reference plane positions uncertainty. In paper [7], it's explained like this: "Generally, when experiments are carried out, the sample is placed flush with the end of the sample holder and hence coincident with a calibration reference plane. This placement procedure leaves room for positioning errors, particularly when the sample is loose. One way to minimize this is to use equations that are invariant to reference plane position."

c) Calibration error comes from the reason that we should have used a Short-Open-Load and Through. The flange needs screws, but we use clips instead, so the results are not accurate.

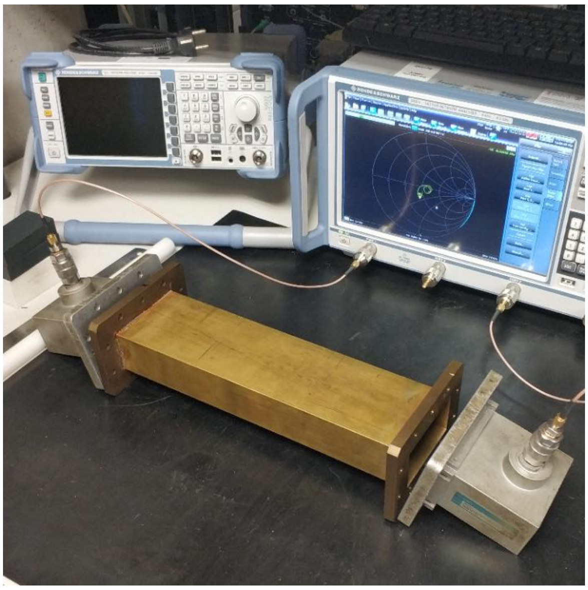


Figure 28. Measuring apparatus

d) We can see from the diagrams that the performance of propagation constant method in both real and imaginary parts is bad. The reason may be as follows:

a) This method needs two sample's parameter value, so the error is larger. And this method is very sensitive to the measurement error.

b) Still need other kinds of measurements to test the performance of this method. TEFLON measurement has only one sample length, but the propagation constant method needs two samples of different lengths. Therefore, TEFLON was not used in the simulation of propagation constant method.

e) For fminsearch function in MATLAB, there may be more than one zero point to be found and chosen to be the result. Figure 24 is the result with initial guess [2, 0.01], while Figure 25 is the result with initial guess [3, 0.01].

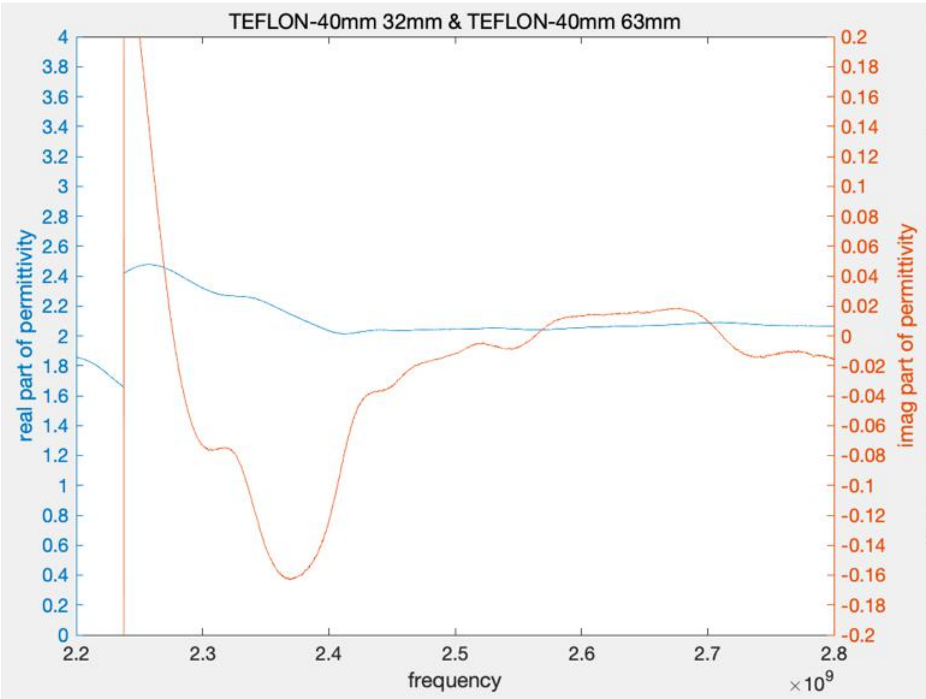


Figure 29. TEFLON result of microwave nonresonant method with initial guess [2, 0.01]

Permittivity reconstruction of samples in rectangular waveguide

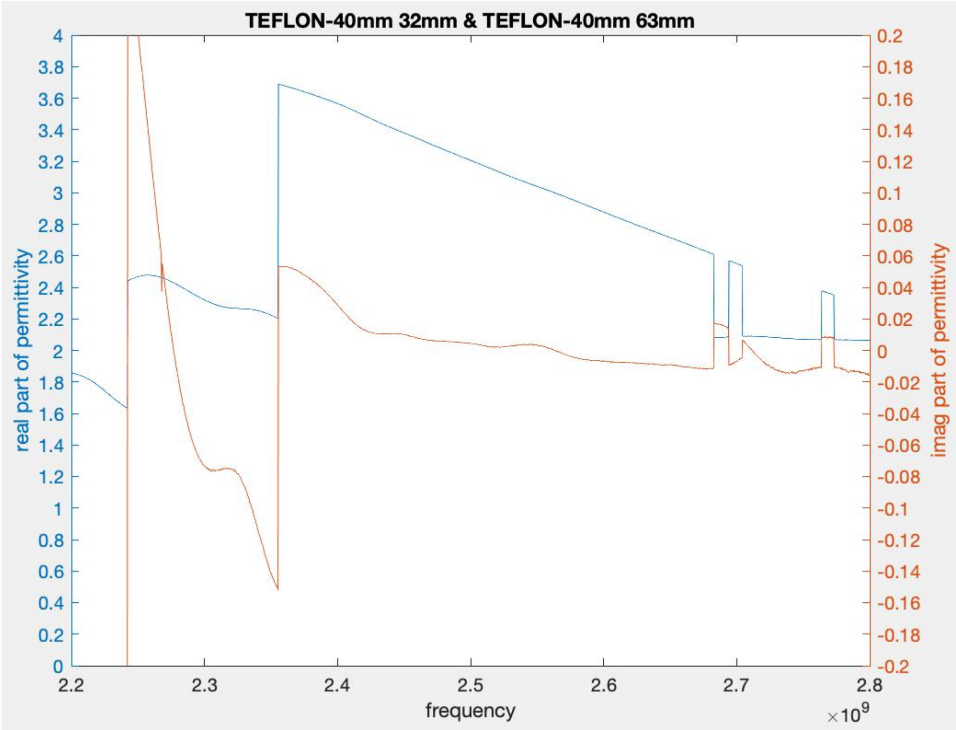


Figure 30. TEFLON result of microwave nonresonant method with initial guess [3, 0.01]

Chapter 5: Conclusion and Further Work

A software system for measuring the complex permittivity of dielectric materials based on three calibration-independent transmission line methods with rectangular waveguide has been designed, implemented and validated. Focused on dielectric measurements of samples inside rectangular waveguides, we chose three representative transmission line methods out of various dielectric measurements to programme into code with MATLAB. The three methods are transmission/reflection method, propagation constant method and microwave nonresonant method. The software accurately computes the dielectric data by reading measurement data files, calculating permittivity in three different methods and displaying results in the coordinate area. The software has GUI panel which makes it more convenient for users to choose files to read and enter input parameters. To validate the software, some experiments were made for measuring the permittivity of TEFLON and PVC using rohde and schwarz VNA, model ZNB 8 (rohde and schwarz: company's name; VNA: type of network analyser; model ZNB 8: model number). Nine measurements with two samples with different length (20mm, 40mm) at nine different positions in the cell were made to testify the validation of this software. The comparison between the results of the proposed three methods indicates that, transmission/reflection method can determine the permittivity of the sample more accurately than the other two methods.

For the further work, after implementing two methods, instead of focusing on the error correction, we choose to add one more method to improve the performance of the software. Therefore, an analysis of the errors incurred due to the uncertainty in scattering parameters, length measurement, and reference plane position can be done in the future.

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[1] James Baker-Jarvis, Michael D. Janezic, and Donald C. DeGroot, “High-Frequency Dielectric Measurements”. IEEE Instrumentation & Measurement Magazine, April 2010, pp. 24-31

[2] “Agilent Basics of Measuring the Dielectric Properties of Materials”. Agilent Technologies, Inc. 2005, 2006. Printed in USA, June 26, 2006. 5989-2589EN

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[7] James Baker-Jarvis, Eric J. Vanzura and William A. Kissick, "Improved Technique for Determining Complex Permittivity with the Transmission /Reflection Method". IEEE MTT, Vol. 38, NO. 8, AUGUST 1990, pp. 1096-1103

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[9] Michael D. Janezic and Jeffrey A. Jargon, "Complex Permittivity Determination from Propagation Constant Measurements". IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 9, NO. 2, FEBRUARY 1999, pp. 76-78

[10] Ugur Cem Hasar, "A New Microwave Method for Electrical Characterization of Low-

Loss Materials". IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 19, NO. 12, DECEMBER 2009, pp. 801-803

[11] Ugur Cem Hasar, "A New Calibration-Independent Method for Complex Permittivity Extraction of Solid Dielectric Materials". IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 18, NO. 12, DECEMBER 2008, pp, 788-790

[12] Ugur Cem Hasar, "Thickness-Invariant Complex Permittivity Retrieval from Calibration-Independent Measurements". IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 27, NO. 2, FEBRUARY 2017, pp, 201-203

Acknowledgement

The author would like to thank Dr. FELIPE L. PENARANDA - FOIX (UPV) and Dr. Yan SUN (QMUL) for their helpful discussions and guidance. Also, many thanks to Microwave Group (DIMAS) at ITACA Institute at UPV.

Appendix

Specification Part 1

--Title:

Permittivity reconstruction of samples in rectangular waveguide

--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 samples inside rectangular waveguides. The developed software system should be complemented with comparisons from commercial software, or measurements to validate the results.

--Requirements:

The applicant should be familiar with microwave theory and MATLAB (or other programming languages).

--application area

Software development

--Project Type:

research

--Project Nature:

Simulation

--Target students:

Telecom Engineering with Management
IoT Engineering

-- Four Main tasks:

1. Background research of samples inside rectangular waveguides.
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.

----Expected output for exams:

1. Research summary of dielectric measurements of samples inside rectangular waveguides.
2. Functional software tool to assess the dielectric data.
3. Validation of the developed software against simulations using commercial software, or using measurements.

Permittivity reconstruction of samples in rectangular waveguide

北京邮电大学 本科毕业设计（论文）任务书

Project Specification Form

Part 2 - Student

<table>
<tr><td>学院
School</td><td>International School</td><td>专业
Programme</td><td colspan="3">Telecommunications Engineering with Management</td></tr>
<tr><td>姓
Family name</td><td>HAO</td><td>名
First Name</td><td colspan="3">HAO</td></tr>
<tr><td>BUPT 学号
BUPT number</td><td>2017212567</td><td>QM 学号
QM number</td><td>171044717</td><td>班级
Class</td><td>2017215101</td></tr>
<tr><td>论文题目
Project Title</td><td colspan="5">Permittivity reconstruction of samples in rectangular waveguide</td></tr>
<tr><td>论文概述
Project outline

Write about 500-800 words

Please refer to Project Student Handbook section 3.2</td><td colspan="5">Project Overview:
Broad-band measurements of complex permittivity and permeability are required for a multitude of applications. In most applications the reflection and transmission coefficients are measured and used to determine the permittivity of the sample. In this project, we will analyze, design and implement a dielectric measurement software system which can be used to characterize the dielectric properties of samples inside transmission lines (coaxial line, rectangular waveguides, …). The developed software system should be complemented with comparisons from commercial software, papers, and measurements to validate the results.

In the past few years, a large number of theoretical methods have been proposed to solve and optimize this problem. Therefore, we want to implement them with MATLAB, and test them with the data generated by simulation software. We get scattering matrix values, which are provided by commercial software simulations, as input parameters of our nonlinear function, which is in the form of $F([S], L, a, f, \varepsilon r, \mu r) = 0$. Then we use minimum value search algorithm to solve the value of ε_r and μ_r. Finally, we will compare the results of these methods and conclude the advantages and disadvantages of them.

Four main tasks:
1. Background research of samples inside rectangular waveguides.
At this stage, we will investigate the existing theoretical methods with good performance and select three to four optimal methods to summarize the objective function of them.
2. To develop a software code to accurately compute the dielectric data.
We aim to develop a software based on the methods provided by the papers. The data involved in our project will be generated by commercial software's simulation.
In the first half of the project, we will develop the basic command line to control our script. Later on, if time permits, we will develop the GUI for our program to let it become more friendly.
We will use MATLAB to programme the methods we select.
3. To validate the developed codes with commercial software simulations and with measurements.
We will use commercial software to simulate data to test the code we develop, and also will perform measurements.
4. To summarize the results into meaningful set of publishable paper.</td></tr>
</table>

1

<table>
<tr><td></td><td>Eventually we will summarize the results we get from our simulations, analyse them and conclude it 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] A. M. NICOLSON and G. F. ROSS, "Measurement of the Intrinsic Properties of Materials by Time-Domain Techniques". IEEE TRANSSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. IM-19, No. 4. NOVEMBER 1970, pp. 377-382
[2] James Baker-Jarvis, Eric J. Vanzura and William A. Kissick, "Improved Technique for Determining Complex Permittivity with the Transmission /Reflection Method". IEEE MTT, Vol. 38, NO. 8, AUGUST 1990, pp. 1096-1103
[3] Zhao Caijun, Jiang Quanxing, and Jing Shenhui, "Calibration-Independent and Position-Insensitive Transmission/Reflection Method for Permittivity Measurement With One Sample in Coaxial Line". IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, VOL. 53, NO. 3, AUGUST 2011, pp. 684-689
[4] Michael D. Janezic and Jeffrey A. Jargon, "Complex Permittivity Determination from Propagation Constant Measurements". IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 9, NO. 2, FEBRUARY 1999, pp. 76-78
[5] Ugur Cem Hasar, "A New Microwave Method for Electrical Characterization of Low-Loss Materials". IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 19, NO. 12, DECEMBER 2009, pp. 801-803
[6] Ugur Cem Hasar, "A New Calibration-Independent Method for Complex Permittivity Extraction of Solid Dielectric Materials". IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 18, NO. 12, DECEMBER 2008, pp, 788-790
[7] Kwang-Hyun Baek, Ho-Young Sung, and Wee Sang Park, "A 3-Position Transmission/Reflection Method for Measuring the Permittivity of Low Loss Materials". JEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 5, NO. 1, JANUARY 1995, pp. 3-5
[8] Ugur Cem Hasar, "Thickness-Invariant Complex Permittivity Retrieval from Calibration-Independent Measurements". IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 27, NO. 2, FEBRUARY 2017, pp, 201-203</td></tr>
<tr><td>道德规范
Ethics</td><td>Please confirm that you have discussed ethical issues with your Supervisor using the ethics checklist (Project Handbook Appendix 2).

YES, I have discussed ethical issues with my Supervisor. ☑</td></tr>
</table>

	Summary of ethical issues: 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. **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. **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?** No. **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. **6. Are any of your participants under the age of 16?** No. **7. Do any of your participants have an impairment that will limit their understanding or communication?** No. **8. Are you in a position of authority or influence over any of your participants?** No. 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?** Yes. 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 that 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 can ensure its security.

Permittivity reconstruction of samples in rectangular waveguide

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.**	Mid-term: 1 MAR 2021 **Background research:** 1. Reading papers 01-04 provided by Supervisor and summarize the objective function of the method in each paper. 2. Reading papers 05-08 provided by Supervisor and summarize the objective function of the method in each paper. **Develop a software:** 1. MATLAB programming for the selected three to four methods from the papers provided by Supervisor. 2. Improve code comments and write user manual for the software. **Paper Writing:** 1. Draft abstract and introduction. 2. Conclude the background research, in other word, theoretical analysis part.

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 samples inside rectangular waveguides.												
Reading papers 01-04 provided by Supervisor and summarize the objective function of the method in each paper.	X	X										
Reading papers 05-08 provided by Supervisor and summarize the objective function of the method in each paper.			X	X								
MATLAB programming supplementary learning.		X	X	X	X	X	X					
Reading other same topic papers for supplementary knowledge.				X	X	X	X	X	X	X		
Task 2 To develop a software code to accurately compute the dielectric data.												
MATLAB programming for the selected methods from the papers		X	X	X	X	X						
Test and debug for each objective function.				X	X	X	X					
Improve code comments and write user manual for the software.				X	X	X	X				X	X
Task 3 To validate the developed codes with commercial software simulations or with measurements.												
First trial of validation of the software which only contain one to two objective functions.					X							
Fully evaluate on the software and identify the drawbacks involved.								X	X	X		
Improve the performance of our model based on the simulation results.					X			X	X	X		
Task 4 To summarise the results into meaningful set of publishable paper.												
Draft abstract and introduction and modify some details in it.			X	X								X
Conclude the background research, in other word, theoretical analysis part.				X	X							
Finish comparison and conclusion.										X	X	

Permittivity reconstruction of samples in rectangular waveguide

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	Telecommunications Engineering with Management		
姓 Family name	HAO	名 First Name	HAO		
BUPT 学号 BUPT number	2017212567	QM 学号 QM number	171044717	班级 Class	2017215101
论文题目 Project Title	Permittivity reconstruction of samples in rectangular waveguide				

已完成工作 Finished work:

- Summary of material was read or researched
  I have completed the study of four papers [1][2][3][4]. Each paper introduces a method to determine the permittivity of samples inside transmission lines (coaxial line, rectangular waveguides, …).
  - In paper 01[1], a method is presented for determining the complex permittivity and permeability of linear materials in the frequency domain by a single time-domain measurement. An unknown sample is placed in a microwave TEM-mode fixture and excited with a sub nanosecond baseband pulse. The fixture is used to facilitate the measurement of the forward- and back-scattered energy, $S_{21}(t)$ and $S_{11}(t)$, respectively. By appropriately interpreting $S_{21}(t)$ and $S_{11}(t)$, we are able to determine the real and imaginary parts of ε and μ as a function of frequency.
  - In paper 02[2], the transmission/reflection method for complex permittivity and permeability determination is introduced. The main objective function is:

$$S_{21}S_{12} - S_{11}S_{22} = \exp[(-2\gamma_0)(L_{\text{air}} - L)]\frac{z^2 - \Gamma^2}{1 - z^2\Gamma^2}.$$

, where we need scattering matrix to calculate value on the left side, and γ_0, L_{air}, L, z, Γ has their relation equations:

$$\gamma = j\sqrt{\frac{\omega^2\mu_R^*\epsilon_R^*}{c_{\text{vac}}^2} - \left(\frac{2\pi}{\lambda_c}\right)^2}$$

$$\gamma_0 = j\sqrt{\left(\frac{\omega}{c_{\text{lab}}}\right)^2 - \left(\frac{2\pi}{\lambda_c}\right)^2}$$

$$z = \exp(-\gamma L)$$

$$\Gamma = \frac{\frac{\gamma_0}{\mu_0} - \frac{\gamma}{\mu}}{\frac{\gamma_0}{\mu_0} + \frac{\gamma}{\mu}}$$

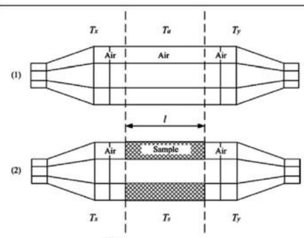
Then, we find when the function

$$\text{abs}\left(\exp[(-2\gamma_0)(L_{\text{air}} - L)]\frac{z^2 - \Gamma^2}{1 - z^2\Gamma^2} - S_{21}S_{12} - S_{11}S_{22}\right)$$

has its minimum value, the value of the corresponding permittivity ε_r.
  - In paper 03[3], a simple method is proposed based on transmission/reflection method. This method can afford high accurate measurement results without singularities by only two measurements of uncalibrated scattering parameters with one sample and one line. One measurement is for the empty fixture and the other for the same fixture holding the sample at a single position. Additionally, the principle of the proposed method ensures it independent of the fixture and the sample position.

1

Permittivity reconstruction of samples in rectangular waveguide



- In paper 04[4], a new method that uses measurements of the propagation constant rather than calibrated scattering parameters for determining the complex permittivity of a sample. In this method, two waveguide transmission lines of different lengths are filled completely with a dielectric material.
  First, we calculate measured cascade matrix:

$$M^i = \frac{1}{S_{21_i}}\begin{bmatrix}(S_{12_i}S_{21_i} - S_{11_i}S_{22_i}) & S_{11_i} \\ -S_{22_i} & 1\end{bmatrix}.$$

$$M^{ij} = M^j\left[M^i\right]^{-1}$$

  Then, we get the two eigenvalues of M^{ij}:

$$\lambda_{1M}^{ij}, \lambda_{2M}^{ij} = \frac{\left(M_{11}^{ij} + M_{22}^{ij}\right) \pm \sqrt{\left(M_{11}^{ij} - M_{22}^{ij}\right)^2 + 4M_{12}^{ij}M_{21}^{ij}}}{2}$$

  Then, we use following equations to get value of real and image part of permittivity ε_r:

$$\gamma = \frac{\ln\left(\lambda^{ij}\right)}{l_i - l_j} \qquad \gamma(\omega) = \alpha(\omega) + j\beta(\omega)$$

$$\epsilon_s' = \frac{\beta^2 + \left(\frac{\pi}{a}\right)^2}{\omega^2\mu_0\epsilon_0} \qquad \epsilon_s'' = \frac{2\alpha\epsilon_s'}{k}\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}$$

- Summary of work was done
  - Summarize the objective function of the method in paper 02[2] and MATLAB programming for the objective function.

```
function F=findAns2_FPF(x,L,L1,L2,kc,frequency,ur,S)
%  L is the sample length
%  Lair is the total length of the sample holder
%
Clab = 299792458;
Cvac = 299792458;
u0 = 4*pi*10^(-7);
w = 2*pi*frequency;

Lair = L+L1+L2;

f1 = S(2,1)*S(1,2)-S(1,1)*S(2,2); %left side value of the equation
r0 = 1j*sqrt((w/Clab)^2-kc^2); % equation 5
r = 1j*sqrt(((w/Cvac)^2)*(x(1)-1j*x(2))*ur-kc^2); % equation 4
z = exp(-r*L); % equation 15
R = (r0/u0-r/(u0*ur))/(r0/u0+r/(u0*ur)); % equation 14
F=abs(exp(-2*r0*(Lair-L))*(z^2-R^2)/(1-z^2*R^2) - f1); % equation 21
```

  - Summarize the objective function of the method in paper 04[4] and MATLAB programming for the objective function.

2

```
function x = findAns4(li,lj,frequency,Si,Sj)
% li is the length of transmission line i
% lj is the length of transmission line j
u0 = 4*pi*10^(-7);
e0 = 8.854*10^(-12);

Mi = 1 / Si(2,1) * [(Si(1,2)*Si(2,1)-Si(1,1)*Si(2,2)) Si(1,1); -Si(2,2) 1];
Mj = 1 / Sj(2,1) * [(Sj(1,2)*Sj(2,1)-Sj(1,1)*Sj(2,2)) Sj(1,1); -Sj(2,2) 1];

Mij = Mj * Mi' ;

lam_1M_ij = 0.5*( Mij(1,1) + Mij(2,2)+ sqrt( (Mij(1,1)-Mij(2,2))^2 + 4*Mij(1,2)*Mij(2,1)) );
lam_2M_ij = 0.5*( Mij(1,1) + Mij(2,2)- sqrt( (Mij(1,1)-Mij(2,2))^2 + 4*Mij(1,2)*Mij(2,1)) );

lam = 0.5*(lam_1M_ij + 1/lam_2M_ij);

r = log(lam) / (li-lj);
a = real(r);
b = imag(r);
w = 2*pi*frequency;

x(1) = (b^2+(pi/a)^2) / (w^2*u0*e0);

k = w*sqrt(u0*e0*x(1));
x(2) = 2*a*x(1) / k * sqrt(1 - (lam/(2*a))^2 );
end
```

- Write corresponding function to test and debug for each objective function code. For function in paper 02[2]:

```
function Example

Options=optimset('display','iter','tolX',1e-5,'tolF',1e-5,...
        'PlotFcns',@optimplotfval);

a=86.36e-3;
L=25e-3;
L1=137.5e-3;
L2=137.5e-3;
kc=pi/a; % for a rectangular waveguide; for a COAXIAL -> kc=0
f=2.45e9;
ur=1-j*eps;

% Empty waveguide
Module_S0=[1.4767364329153591e-03  9.9999956852990624e-01;9.9999956852990624e-01  1.4767364329153591e-03];
Phase_S0=[2.8963261404910288e+01  9.6951259984174541e+01;9.6951259984174541e+01  2.8963261404910288e+01];
S_Empty=Module_S0.*exp(j*Phase_S0*pi/180);

% Waveguide with sample inside
Module_S=[5.8602403520537016e-01 8.0607327679120466e-01;8.0607327679120466e-01 5.8602403520537016e-01];
Phase_S=[-4.4988484883825521e+01  4.5192150431552513e+01;4.5192150431552513e+01  -4.4988484883825521e+01]; % Phase in DEG
S_Er=Module_S.*exp(j*Phase_S*pi/180);

% Permittivity:
[x,fval,exitflag,output]=fminsearch('findAns2_FPF',[3,0.01],Options,L,L1,L2,kc,f,ur,S_Er);
Er_Reconstructed=x(1)-j*x(2)
```

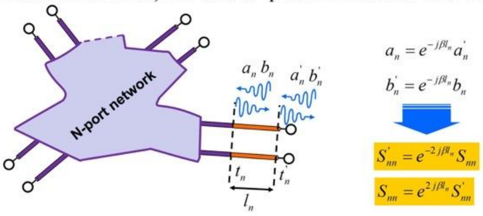
For function in paper 04[4]:

```
function Example_4

a=86.36e-3;
L=25e-3;
L1=137.5e-3;
L2=137.5e-3;
kc=pi/a; % for a rectangular waveguide; for a COAXIAL -> kc=0
f=2.45e9;
ur=1-j*eps;

% Empty waveguide
Module_S0=[1.4767364329153591e-03  9.9999956852990624e-01;9.9999956852990624e-01  1.4767364329153591e-03];
Phase_S0=[2.8963261404910288e+01  9.6951259984174541e+01;9.6951259984174541e+01  2.8963261404910288e+01];
S_Empty=Module_S0.*exp(j*Phase_S0*pi/180);

% Waveguide with sample inside
Module_S=[5.8602403520537016e-01 8.0607327679120466e-01;8.0607327679120466e-01 5.8602403520537016e-01];
Phase_S=[-4.4988484883825521e+01  4.5192150431552513e+01;4.5192150431552513e+01  -4.4988484883825521e+01]; % Phase in DEG
S_Er=Module_S.*exp(j*Phase_S*pi/180);

% Permittivity:
x = findAns4(L1,L2,f,S_Empty,S_Er);
end
```

- Problems were faced
  - Lack of code comments, which makes it difficult for others to understand the code.
  - Didn't manage *fminsearch* function (in Matlab library) on my own, which is a vital step in function *findAns2*.
  - In paper 04[4], the scattering matrix needs to be changed because if a reference plane is moved from its original location (which is common when characterizing

3

microwave networks) the waves' phase references also change.



- Solutions were found
  - Improve code comments. Explain each input parameter and constant. Comment some important line's meaning.
  - Discuss with supervisor and supervisor modified my code and shows me the correct usage of *fminsearch* function.
  - Add the code for parameter calibration of scattering matrixes before the rest of calculation in function *findAns4*.

References:
[1] A. M. NICOLSON and G. F. ROSS, "Measurement of the Intrinsic Properties of Materials by Time-Domain Techniques". IEEE TRANSSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. IM-19, No. 4. NOVEMBER 1970, pp. 377-382
[2] James Baker-Jarvis, Eric J. Vanzura and William A. Kissick, "Improved Technique for Determining Complex Permittivity with the Transmission /Reflection Method". IEEE MTT, Vol. 38, NO. 8, AUGUST 1990, pp. 1096-1103
[3] Zhao Caijun, Jiang Quanxing, and Jing Shenhui, "Calibration-Independent and Position-Insensitive Transmission/Reflection Method for Permittivity Measurement with One Sample in Coaxial Line". IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, VOL. 53, NO. 3, AUGUST 2011, pp. 684-689
[4] Michael D. Janezic and Jeffrey A. Jargon, "Complex Permittivity Determination from Propagation Constant Measurements". IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 9, NO. 2, FEBRUARY 1999, pp. 76-78

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

下一步 Next steps:

- Testing schedule:
  - Download the free simulation sample measurement software *openEMS*[5] and test two finished function (*findAns2* and *findAns4*)
- Coding schedule:
  - Summarize the objective function of the method in paper 5-8.
  - MATLAB programming for the selected methods from the papers.
  - Test and debug for each function.
  - Fully evaluate on the software and identify the drawbacks involved. Improve the performance of our software based on the simulation results.

References:
[5] https://openems.de/index.php/Tutorials

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**	**Telecommunications Engineering with Management**		
姓 **Family name**	HAO	名 **First Name**	HAO		
BUPT 学号 **BUPT number**	2017212567	**QM 学号** **QM number**	171044717	班级 **Class**	2017215101
论文题目 **Project Title**	Permittivity reconstruction of samples in rectangular waveguide				

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

NO

已完成工作 Finished work:

• **Comparison between the progress with the target**

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.**	Mid-term: 1 MAR 2021 **Background research:** 1. Reading papers 01-04 provided by Supervisor and summarize the objective function of the method in each paper. 2. Reading papers 05-08 provided by Supervisor and summarize the objective function of the method in each paper. **Develop a software:** 1. MATLAB programming for the selected three to four methods from the papers provided by Supervisor. 2. Improve code comments and write user manual for the software. **Paper Writing:** 1. Draft abstract and introduction. 2. Conclude the background research, in other word, theoretical analysis part.

This is the mid-term target we set in Specification. As shown, tasks inside green box are the ones have been done, while tasks inside red box have not.

- For the software part, I have just programmed two methods which did not keep up with the original plan. However, after the latest meeting on Feb 25th, the programming process has started, which won't take long because of the experience from previous methods' programming, the good familiarity with the theory and the already-built overall software code framework.
- For the final report part, at the beginning, the plan was to draft final report in two separate time periods and scheduled this in Gantt Chart. During first period, from Dec 1st to Jan 15th, abstract, introduction and background parts should have been finished. Then since Mar 16th other parts would be completed. However, in December, more time and efforts were devoted to the paper reading and matlab programming, and supervisor allowed me to spare some efforts into preparation for final exams. Therefore, we made some changes of the initial time schedule. We speeded up the software coding and validation. Final report drafting will start from Mar 11th. Since some free time was set aside in March in the initial Gantt Chart, this part of unfinished final report drafting can be caught up as soon as possible in March.

• **Summary of material was read or researched**

We have completed the study of the papers offered by my supervisor. Each paper introduced a method to determine the permittivity of samples inside transmission lines (coaxial line, rectangular waveguides, …). After comparison and assessment, we mainly focused on paper 02[1] and paper 04[2], understanding the principle of transmission/reflection method proposed by paper 02[1] and propagation constant method proposed by paper 04[2].

a) In paper 02[1], the transmission/reflection method for complex permittivity and permeability determination is introduced. The main objective function is:

Permittivity reconstruction of samples in rectangular waveguide

$$S_{21}S_{12} - S_{11}S_{22} = \exp[(-2\gamma_0)(L_{air} - L)]\frac{z^2 - \Gamma^2}{1 - z^2\Gamma^2},$$

where we need scattering matrix to calculate value on the left side, and γ_0, L_{air}, L, z, Γ has their relation equations:

$$\gamma = j\sqrt{\frac{\omega^2\mu_R^*\epsilon_R^*}{c_{vac}^2} - \left(\frac{2\pi}{\lambda_c}\right)^2} \qquad \gamma_0 = j\sqrt{\left(\frac{\omega}{c_{lab}}\right)^2 - \left(\frac{2\pi}{\lambda_c}\right)^2}$$

$$z = \exp(-\gamma L) \qquad \Gamma = \frac{\frac{\gamma_0}{\mu_0} - \frac{\gamma}{\mu}}{\frac{\gamma_0}{\mu_0} + \frac{\gamma}{\mu}}$$

Then, we find when the function

$$\mathrm{abs}\left(\exp[(-2\gamma_0)(L_{air} - L)]\frac{z^2 - \Gamma^2}{1 - z^2\Gamma^2} - S_{21}S_{12} - S_{11}S_{22}\right)$$

has its minimum value, the value of the corresponding permittivity εr.

b) In paper 04[2], a new method that uses measurements of the propagation constant rather than calibrated scattering parameters for determining the complex permittivity of a sample. In this method, two waveguide transmission lines of different lengths are filled completely with a dielectric material.
First, we calculate measured cascade matrix:

$$M^i = \frac{1}{S_{21_i}}\begin{bmatrix} (S_{12_i}S_{21_i} - S_{11_i}S_{22_i}) & S_{11_i} \\ -S_{22_i} & 1 \end{bmatrix}.$$

$$M^{ij} = M^j\left[M^i\right]^{-1}$$

Then, we get the two eigenvalues of M^{ij}:

$$\lambda_{1M}^{ij}, \lambda_{2M}^{ij} = \frac{\left(M_{11}^{ij} + M_{22}^{ij}\right) \pm \sqrt{\left(M_{11}^{ij} - M_{22}^{ij}\right)^2 + 4M_{12}^{ij}M_{21}^{ij}}}{2}$$

Then, we use following equations to get value of real and image part of permittivity ε_r:

$$\gamma = \frac{\ln(\lambda^{ij})}{l_i - l_j} \qquad \gamma(\omega) = \alpha(\omega) + j\beta(\omega)$$

$$\epsilon_s' = \frac{\beta^2 + \left(\frac{\pi}{a}\right)^2}{\omega^2\mu_0\epsilon_0} \qquad \epsilon_s'' = \frac{2\alpha\epsilon_s'}{k}\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}$$

• **Summary of the completion of the software**

a) Before Jan 15th, based on the theory of the transmission/reflection method in paper 02 and the propagation constant method in paper 04, we did the matlab programming. For the simplicity of programming and testing, we wrote two different functions (findAns2 and findAns4) to do the computing.

```
function F=findAns2 FPF(x.L.L1.L2.kc.freauencv.ur.S)
function x = findAns4(li.lj.freauencv.Si.Sj)
```

Then, wrote corresponding function (Example and Example_4) to test and debug for each function. In these test functions, only one set of fixed value input parameters was used, so only one value of permittivity was computed. We can only test the correction of the program, not the quality and accuracy, and we could not make the comparison between the methods.

```
a=86.36e-3;
L=25e-3;
L1=137.5e-3;
L2=137.5e-3;
kc=pi/a; % for a rectangular waveguide; for a COAXIAL -> kc=0
f=2.45e9;
ur=1-j*eps;

% Empty waveguide
Module_S0=[1.4767364329153591e-03  9.9999956852990624e-01;9.9999956852990624e-01  1.4767364329153591e-03];
Phase_S0=[2.8963261404910288e+01  9.6951259984174541e+01;9.6951259984174541e+01  2.8963261404910288e+01];
S_Empty=Module_S0.*exp(j*Phase_S0*pi/180);

% Waveguide with sample inside
Module_S=[5.8602403520537016e-01 8.0607327679120466e-01;8.0607327679120466e-01 5.8602403520537016e-01];
Phase_S=[-4.4988484883825521e+01  4.5192150431552513e+01;4.5192150431552513e+01  -4.4988484883825521e+01];
S_Er=Module_S.*exp(j*Phase_S*pi/180);
```

2

b) After making sure of the validation of two separate functions, I designed the overall structure of the software and did the programming.

```
% read measurement data file measured by laboratory related instruments
% assign value of some input parameters
% for ff=1:length(f_Sample_01)
      use the loop to run all the combination of [frequency, scattering matrix]. Each
      combination is computed by all methods.
   % code of the first method
   % code of the second method
   % …
% end
% plot each method's computation results respectively.
```

c) Next step was to use real measurement files to run the software and made analysis and comparison. Supervisor offered me two measurements. One was TEFLON, and another one was PVC. The total length of the transmission line is the same (345.2156mm).

rectPTFE0mm.s2p
rectPTFE32mm.s2p
rectPTFE63mm.s2p

TEFLON measurement with 40mm long sample

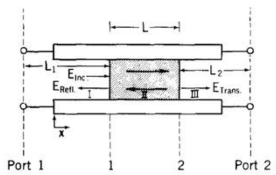
rectPVC20mmP0mm.s2p
rectPVC20mmP31mm.s2p
rectPVC20mmP88mm.s2p

PVC measurement with 20mm long sample

rectPVC40mmP0mm.s2p
rectPVC40mmP34mm.s2p
rectPVC40mmP84mm.s2p

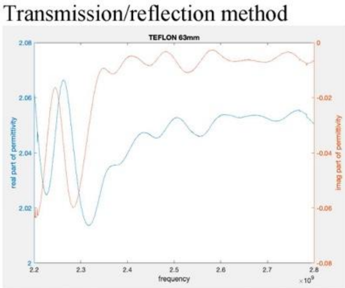
PVC measurement with 40mm long sample

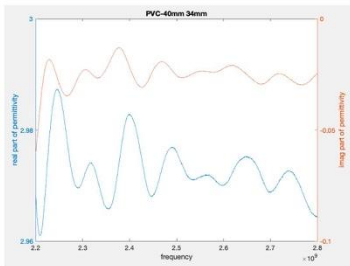
The difference between three files inside each group is that, as the diagram shown below, L_1 and L_2, the distances from two ports to the sample are different.



Here are the simulation results:

1) Transmission/reflection method



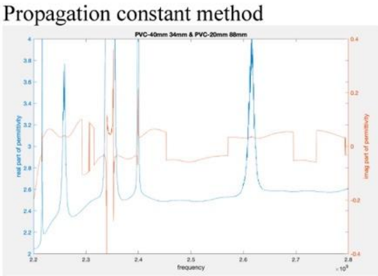


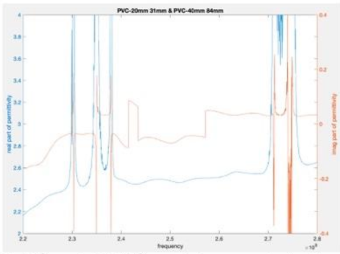
The left diagram is the result of TEFLON measurement. The x-axis is frequency, changing from $2.2*10^9$ to $2.8*10^9$, and the y-axis is the real part and imaginary part of permittivity. The ideal value of permittivity is 2.00-j*0.00.
The right diagram is the result of PVC measurement. The x-axis is frequency, changing from $2.2*10^9$ to $2.8*10^9$, and the y-axis is the real part and imaginary part of permittivity. The ideal value of permittivity is 3.00-j*0.00.

Compare two diagrams we can see that TEFLON's real part performance is better while PVC's imaginary part is better.

Overall, the simulation results of transmission/reflection method with these two measurements are good, considering the error of measurement and the slight deviation of fminsearch function used inside the program.

2) Propagation constant method





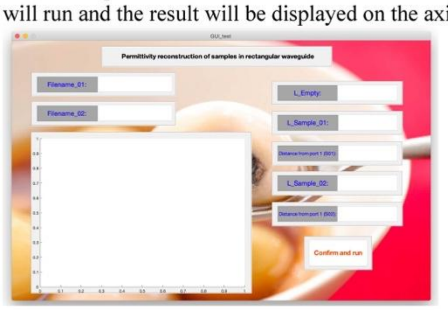
The x-axis is frequency, changing from $2.2*10^9$ to $2.8*10^9$, and the y-axis is the real part and imaginary part of permittivity. The ideal value of permittivity is 3.00-j*0.00.

We can see from the diagrams that the performance of both real and imaginary parts is bad. The reason may be as follows:

- The inevitable measurement errors
- This method needs two sample's parameter value, so the error is larger. And this method is very sensitive to the measurement error.
- Still need other kinds of measurements to test the performance of this method.

TEFLON measurement has only one sample length, but the propagation constant method needs two samples of different lengths. Therefore, TEFLON was not used in the simulation of propagation constant method.

d) What's more, GUI panel has been designed to make the software more user friendly. User can input the name of the file and several length parameters and then the program will run and the result will be displayed on the axis.



Reference

[1] James Baker-Jarvis, Eric J. Vanzura and William A. Kissick, "Improved Technique for Determining Complex Permittivity with the Transmission /Reflection Method". IEEE MTT, Vol. 38, NO. 8, AUGUST 1990, pp. 1096-1103

[2] Michael D. Janezic and Jeffrey A. Jargon, "Complex Permittivity Determination from Propagation Constant Measurements". IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 9, NO. 2, FEBRUARY 1999, pp. 76-78

尚需完成的任务 Work to do:

1. Final Report draft: (3.11 – 3.18)
   a) abstract + introduction + background+ design and implementation (3.11 - 3.14)

b) results and discussion + conclusion (3.15 - 3.18) c) Modify as suggested by supervisor and update new outcome. (3.18 - 4.8) 2. Programming schedule: a) Apply TabManager to improve GUI performance of the software. (3.4 - 3.11) b) Add one more new method into the software, design the corresponding GUI panel for it and make comparison with the existing methods. (3.11 - 3.18) c) Fully evaluate on the software and identify the drawbacks involved. (4.1 - 4.8)
存在问题 Problems: 1. We were supposed to do the simulation in the lab in UPV in Spain. Now we can not realize it. 2. There are several methods and each one needs a separate GUI panel, and better can be chosen to use at the same time. 3. The simulation outcome of the second method (propagation constant method) is not as good as expected. The problem mainly arises from the fact that only PVC measurement is used for the simulation of this method.
拟采取的办法 Solutions: 1. Supervisor offered me ready-made measurements data files. 2. Apply TabManager in matlab to meet this requirement. 3. Add different measurements for the software to run and find out whether the new outcome can be better.
论文结构 Structure of the final report: 1. Abstract 2. Introduction 3. Background 4. Design and implementation 5. Results and discussion 6. Conclusion and further work 7. References 8. Acknowledgements 9. Appendices 10. Risk and environmental impact assessment

北京邮电大学 本科毕业设计（论文）教师指导记录表

Project Supervision Log

学院 **School**	International School	**专业** **Programme**	**Telecommunications Engineering with Management**		
姓 **Family name**	HAO	**名** **First Name**	HAO		
BUPT 学号 **BUPT number**	2017212567	**QM 学号** **QM number**	171044717	**班级** **Class**	2017215101
论文题目 **Project Title**	Permittivity reconstruction of samples in rectangular waveguide				

Date: 21-09-2020
Supervision type: online meeting
Summary: introduced the project specification

Date: 24-09-2020
Supervision type: email
Summary: sent a list of papers for the project with different methods to characterize materials.

Date: 12-11-2020
Supervision type: online meeting
Summary: discussed the project progress and specification draft

Date: 20-11-2020
Supervision type: email
Summary: confirmed the final version of specification

Date: 27-11-2020
Supervision type: online meeting
Summary: mainly discussed the content of paper 2 and 4, confirmed the assignment for the next two weeks.

Date: 11-12-2020
Supervision type: online meeting
Summary: discussed the program of paper 2.

Date: 17-12-2020
Supervision type: online meeting
Summary: discussed the program of paper 4.

Date: 07-01-2021
Supervision type: online meeting
Summary: concluded the progress before and confirmed the assignment for the next two weeks

Date: 21-01-2021
Supervision type: online meeting
Summary: tested and debugged two programs with one set of fixed input parameter values

Date: 21-01-2021
Supervision type: email

1

Summary: confirmed the final version of early-term progress report

Date: 29-01-2021
Supervision type: online meeting
Summary: tested two programs with two simulation files (Sample-Length 25mm.S2P, Sample-Length 45mm.S2P)

Date: 05-02-2021
Supervision type: online meeting
Summary: introduced Lee_SnP.m file to read s2p form measurement files

Date: 09-02-2021
Supervision type: email
Summary: sent TEFLON and PVC measurement files

Date: 12-02-2021
Supervision type: online meeting
Summary: tested and debugged the first version of integrated program

Date: 17-02-2021
Supervision type: online meeting
Summary: analyzed software computing results of TEFLON and PVC measurement

Date: 25-02-2021
Supervision type: online meeting
Summary: GUI panel design, discussed theory of paper 6

Date: 01-03-2021
Supervision type: email
Summary: confirmed the final version of mid-term report and supervision log

Date: 04-03-2021
Supervision type: online meeting
Summary: discussed the program of paper 6, introduced TabManager usage

Date: 15-03-2021
Supervision type: online meeting
Summary: tested and debugged program of paper 6, analysed simulation results and reasons of error

Date: 18-03-2021
Supervision type: email
Summary: gave feedback of the simulation results of program of paper 6

Date: 22-03-2021
Supervision type: online meeting
Summary: gave feedback of the results and comparison of overall software

Date: 30-03-2021
Supervision type: online meeting
Summary: discussed final report

Date: 13-04-2021
Supervision type: online meeting
Summary: discussed details of final report

2

Permittivity reconstruction of samples in rectangular waveguide

Date: 19-04-2021
Supervision type: online meeting
Summary: discussed details of final report

3

Risk and environmental impact assessment

a) Factor: The measuring instrument in UPV lab breaks down suddenly.

- Prevents the successful completion of the project

  Level L: 1; Level C: 3; Score: 3; Low risk; Take action if easy to implement.

  Action: Discuss with my supervisor and find other ways of getting measurement data.

- Causes potential harm to people and /or animals

  Level L: 0; Level C: 0; Score: 0; No risk; No action required.

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

  Level L: 0; Level C: 0; Score: 0; No risk; No action required.

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

  Level L: 1; Level C: 3; Score: 3; Low risk; Take action if easy to implement.

  Action: Contact panel in charge of the lab to find the reasonable way, either repair the instrument or purchase a new machine.

b) Factor: Cannot go to UPV to do the measurement work in my project as scheduled in the beginning due to epidemic control.

- Prevents the successful completion of the project

  Level L: 5; Level C: 2; Score: 10; Significant Risk; Take action urgently.

  Action: Supervisor sends me the ready-made measurement data files measured in the laboratory, and the software could read these data files directly.

- Causes potential harm to people and /or animals

  Level L: 0; Level C: 0; Score: 0; No risk; No action required.

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

  Level L: 0; Level C: 0; Score: 0; No risk; No action required.

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

Permittivity reconstruction of samples in rectangular waveguide

Level L: 0; Level C: 0; Score: 0; No risk; No action required.