北京邮电大学

Queen Mary
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Undergraduate Project Report 2017/18

[Electric field distribution in microwave ovens with MATLAB]

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Date [Submission date]

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Abstract

This paper aims to simulate the electromagnetic field inside the microwave ovens based on the MATLAB using FDTD method through the software called openEMS. Obtaining the S-parameter through the FDTD and then do the "inverse engineering", which means receive the permittivity of the sample inside the microwave oven by calculating the S-parameter, which is accurate and reliable.

The paper also introduces several methods to do the calculating and analyses them. To prove the value of the permittivity, the comparison of the value from HFSS and the value from FDTD are made. By amending the boundary condition of the waveguide, the results from FDTD finally nearly matched with the HFSS.

[Electric field distribution in microwave ovens with MATLAB]

摘要 (Chinese translation of the Abstract)

Chapter 1: Introduction

1. 1 Motivation

Nowadays, microwaves oven is an essential part of the modern kitchen due to their ability to quickly and easily heat food and drink. Analyzing the electric field distribution inside the microwave oven contributes to the improvement of the design of the microwave oven, which better lives up to user requirements. Besides this, analyzing the electric field distribution inside the microwave oven also has another function- to analyse the permittivity of the sample inside, which is easily and accurately.

In electromagnetism, the absolute permittivity, often referred to simply as the dielectric constant ε, is a measure of the resistance encountered when forming an electric field in a particular medium. More specifically, the dielectric constant describes the amount of charge required to produce a unit of electrical flux in a particular medium. Correspondingly, the charge will generate more electric flux in a medium with a low dielectric constant than in a medium with a high dielectric constant. Therefore, the dielectric constant is a measure of the material's resistance to electric fields. It is of great importance to have a broad understanding of the properties, especially the dielectric constant, which is the real part of complex permittivity and loss tangent at the processing conditions.

Because of the large amount of water content and the structure of the biomaterials, permittivity property is also a crucial characteristic of the fruits and plant. The dielectric properties of these materials not only provides valuable information about the cache and dissipation of magnetic and electric fields in it, but also offers insight into the feasibility of the use of the material in potential applications.

The idea of the project is to have a tool in MATLAB to model dielectrics inside the microwaves oven which simulated in the MATLAB in order to do the “inverse engineering”: to calculate permittivity from the scattering parameters.

1.2 Novelty

[Electric field distribution in microwave ovens with MATLAB]

When creating 'phantom' materials for systems that use absorbers to measure specific absorption rates, and when applying ferrite materials to manage electromagnetic field propagation, the media properties play a role when the antenna is made using PCB traces.

It’s quite common to use a rectangular waveguide to model the electromagnetic properties of materials. A rectangular piece is then inserted into the waveguide, the S-parameters are then measured. The electromagnetic complex-valued permittivity ε can be then extracted from the “inverse function”.

Several methods have been created for the “inverse calculating”, which gets the permittivity ε by measuring the S-parameter. Nicolson-Ross-Weir（NRW）is a method that typically used for this inverse calculating. An alternative way to perform inversion is to use a reliable physical model with changeable parameters, which follows the causal relationship of frequency dependent parameter ε. For example, one or more Debye or Lorentz-type models. The optimization software is then applied to receive the dielectric parameters ε and μ.

The project consists of the use of a FDTD software based on MATLAB to model a microwave oven with a dielectric sample inside and to plot the electric and magnetic field inside the oven depending on the permittivity of the material.

In contrast, FDTD is a very simple method, which can easily simulate non-homogeneous and anisotropic materials and arbitrarily shaped geometry; it can also provide time and frequency analysis, which are crucial for microwave heating problems, such as field distribution, scattering parameters and the consumption of various materials and geometries, as well as scatterring power distribution.

1.3 Technical context

The project consists of the use of a free FDTD software based on MATLAB to model a microwave oven with a dielectric sample inside and obtain the permittivity of it by “inverse engineering”- to get the permittivity by calculating the S-parameter.

Operating System: Windows 8

Simulation method: FDTD(Finite-Difference Time-Domain)

FDTD Software: openEMS

[Electric field distribution in microwave ovens with MATLAB]

Validation software: HFSS

1.4 Structure of the report

Chapter 1 is an introduction to the project. It leads to the motivation of the project and analyses the novelty of the methods.

Chapter 2 is the background of the project, it firstly introduces the concept of the related knowledge and 3 methods which use S-parameter to calculate the permittivity.

Chapter 3 is the design and implementation of the project, which gives the overall review of the whole system, and the way to realize it.

Chapter 4 is the result and discussion of the project, which displays the result directly from the MATLAB

Chapter 5 is the conclusion and further work of the project, which concludes the whole work and further work that aims to optimize the project.

Chapter 2: Background

2.1 FDTD method

The project consists of the use of a free FDTD software based on MATLAB to model a microwave oven with a dielectric sample inside and to plot the electric and magnetic field inside the oven depending on the permittivity of the material and then do the “inverse calculating”, which means obtaining the S-parameter from the FDTD and then calculating the permittivity of the sample inside, which process is easily and accurately.

2.1.1Deeper familiarization of FDTD

Firstly, a deeper familiarization of FDTD is needed. FDTD (Finite-Difference Time-Domain) was established in 1966 by K.S. Yee in a paper published in the AP. It was later called the Yee grid space discrete method. The core idea is to transform Maxwell's curl equation with time variables into a differential form to simulate the time-domain response of the electronic pulse and ideal conductor action. Known as the most fashionable algorithm in the field of computational electromagnetics, but it is still in development.

In general, the FDTD method differentiates the Maxwell equations in the time and space domain. Leap frog algorithm is used to calculate alternately the electric field and magnetic field in the space domain, and the time field is updated to imitate the change of the electromagnetic field to achieve the purpose of numerical calculation.

2.1.2 Analyzing FDTD method

When analyzing the problem with this method, the geometric parameters, material parameters, calculation accuracy, computational complexity, and computational stability of the object must be considered. Its advantage is that it can directly simulate the distribution of the field, and the accuracy is relatively high. It is one of the methods that currently use more numerical simulations. All in all, the advantage of FDTD can be summarized as: wide applicability, saving computing and storage space, suitable for parallel computing, versatility of calculation programs, easy and intuitive. And the three key elements of FDTD are difference format, stability of the solution, and absorption of boundary conditions.

2.2 Permittivity

[Electric field distribution in microwave ovens with MATLAB]

Then, learn more broadly about the permittivity. The dielectric properties of a material, the dielectric constant, is usually measured as a function of frequency and are referred to as dielectric/ impedance spectroscopy, which influences the propagation of the electric fields. The dielectric constant values show the interaction of the external field with the sample's electrical dipole moment (Griffiths 1999, Baker-Jarvis et al., 2010, Yaw 2012). Dielectric measurement is an important tool for understanding the behavior of the material, especially at high frequencies, since it provides an electrical or magnetic properties of the material, which is critical to achieve the desired parameters of the material in many applications. In electrodynamics, the situation is more complex, and the dielectric constant, in general, is complex, where the real part is the polarization discussed earlier, and the imaginary part represents the absorptivity of the substance; that is, how much energy is absorbed and Loss of heat or other processes, which offers insight into the feasibility of using the material in potential applications.

2.3 OpenEMS

OpenEMS is a free and open electromagnetic field solver using the FDTD method. It included CSXCAD, which is a C++ library to describe geometrical objects and their physical or non-physical properties; AppCSXCAD- a visualization program, capable of showing the structure defined inside a CSXCAD xml-file; QCSXCAD- the visualization library used by AppCSXCAD.
Besides, it is fully 3D Cartesian and cylindrical coordinates graded mesh. And it is multi-threading, SIMD(SSE) and MPI support for high speed FDTD. Therefore, openEMS based on MATLAB that using FDTD to model the electromagnetic field inside the rectangular waveguide is a more reliable way to measure the transmission and reflection act between the two ports.

2.4 Related work done before

Owing to the importance of measuring the permittivity of the material, there exits various ways to do the inverse calculating. A common way to do the inverse calculating is the Nicolson-Ross-Weir (NRW) method.

The Nicolson Ross Weir method is used to obtain the dielectric constant and permeability from S-parameters. This method combines the values of S11 and S21 to establish an equation system to calculate the complex electromagnetic constants. This method works well for frequencies far away from TEM mode. However, the method is not sensitive to low-loss materials near resonance range.

The NRW method obtains the permeability and permittivity by using the following constants:

$$K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}^2}$$

Then, the reflection and transmission coefficients, Γ and T respectively.

$$\Gamma = K \pm \sqrt{K^2 - 1} \qquad T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \qquad K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}^2}$$

After knowing the the coefficiets of both reflection and transmission, it is possible to obtain the value of the permittivity.

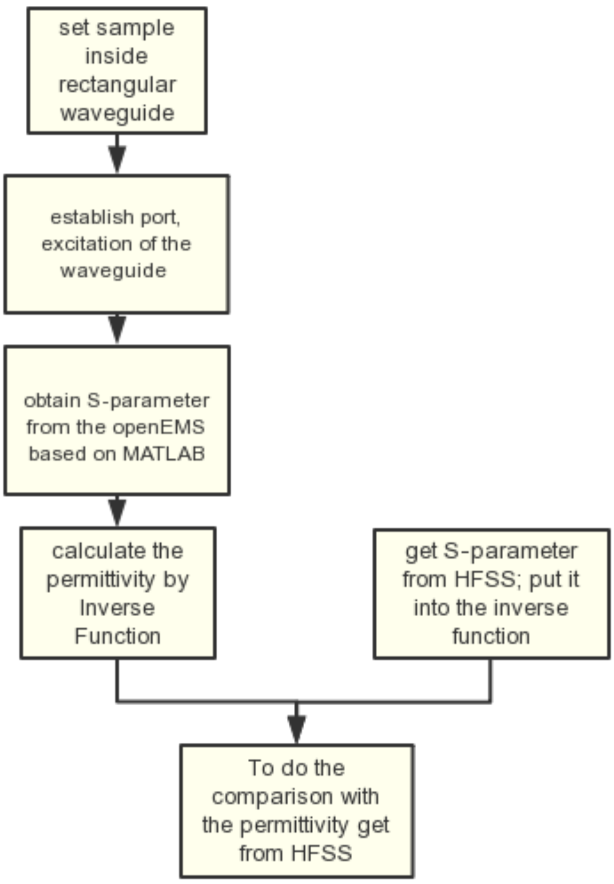
Another way to perform the inverse calculating is to use the model of Debye or Lorentz and obey the causal relationship between frequency of ε and μ.

Also, Short path (SCL) method is a single port measurement method for coaxial cable or waveguide. It is calculated by the same Newton Raphson numerical method. It is only applicable to dielectric constant calculation, just like NIST iteration method. It only uses the S11 parameter of MUT to calculate the reflection coefficient, which requires a good prediction to come to the conclusion. The method also needs to enter the sample length and position for accurate measurement.

Chapter 3: Design and Implementation

3.1 Overview

The first step of the project is to expand the outline from specification to more detailed plan, I prepared for this project since I was in BUPT. Since I was unfamiliar about the use of openEMS and had limited knowledge about FDTD method, I searched on the Internet, read related published book in the library and also asked my tutor for help. During the process of preparation of the work, I also sketch a script for the whole project and set up correlation among tasks. The overview of the project can be describes as follow:



3.2 Get S-parameter from FDTD method

The work needs to be done before inverse calculating is to get the S-parameter from the given permittivity using the FDTD methods, simulate the electromagnetic field inside microwave oven and put sample with given permittivity inside it, and then get the S-parameter. Make the comparison between S-parameter from FDTD and S-parameter from HFSS (will be explained more later).

3.2.1 Dimension of the waveguide and the sample inside

The first step of the design of the project is to define the waveguide dimensions including basic parameters like height, length and width;

Description	Symbol	Value
Length of waveguide		
Width of waveguide		
Height of waveguide		

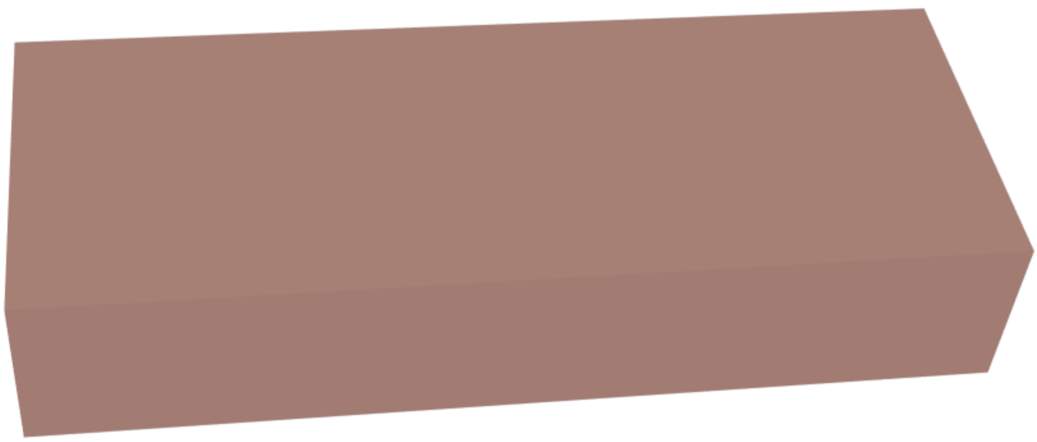


Figure1. the whole view of the waveguide

Description	Symbol	Value

Length of sample		
Width of sample		
Height of sample		
Location of the sample		

3.2.2 Boundary conditions and Excitations

The frequency measured is chosen from 2GHz to 3GHz. The excitation port option was specified in two steps. Firstly, the sample model area was selected to define the port location and assign a port number. The port number assigned must between 1 and 50. For an exterior port, after assigning the port number, the port type was specified as a rectangular waveguide of TE10- Transverse electric mode. Boundary conditions are set to

BC = {'PEC' 'PEC' 'PEC' 'PEC' 'PML_10' 'PML_10'} PEC-Perfect Electrical Conductor and PML can be used for the remaining boundaries,

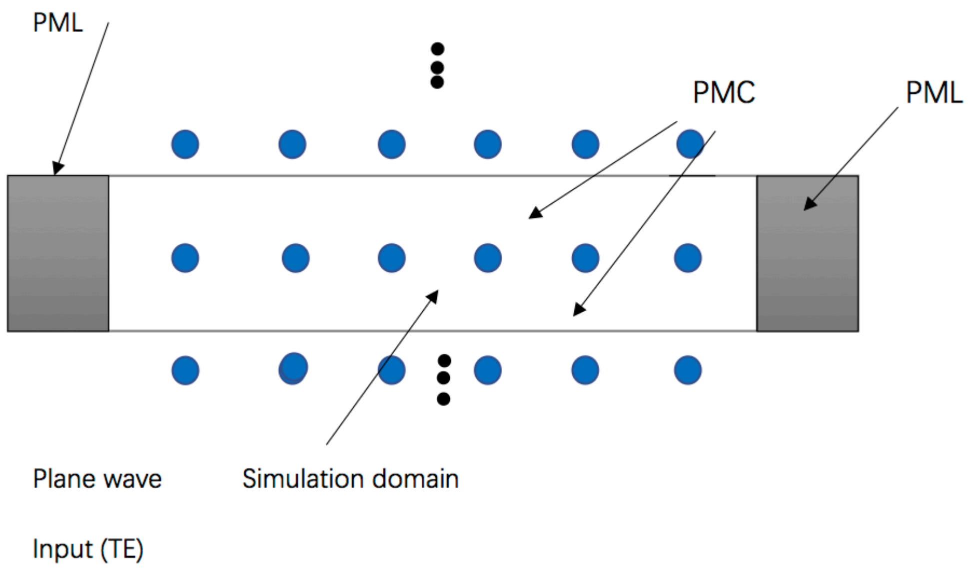


Figure2. Figure of the boundary condition

For a 2D TE10 simulation, the edge of transverse plane should be set to the PMC boundary condition to realize the plane wave.

3.2.3 Waveguide port application

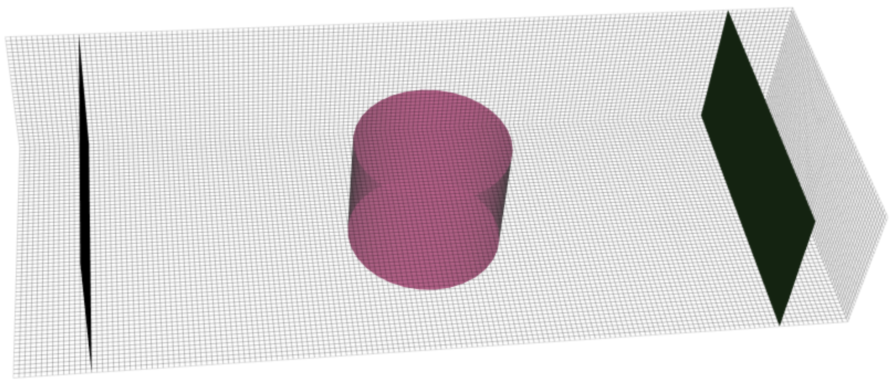
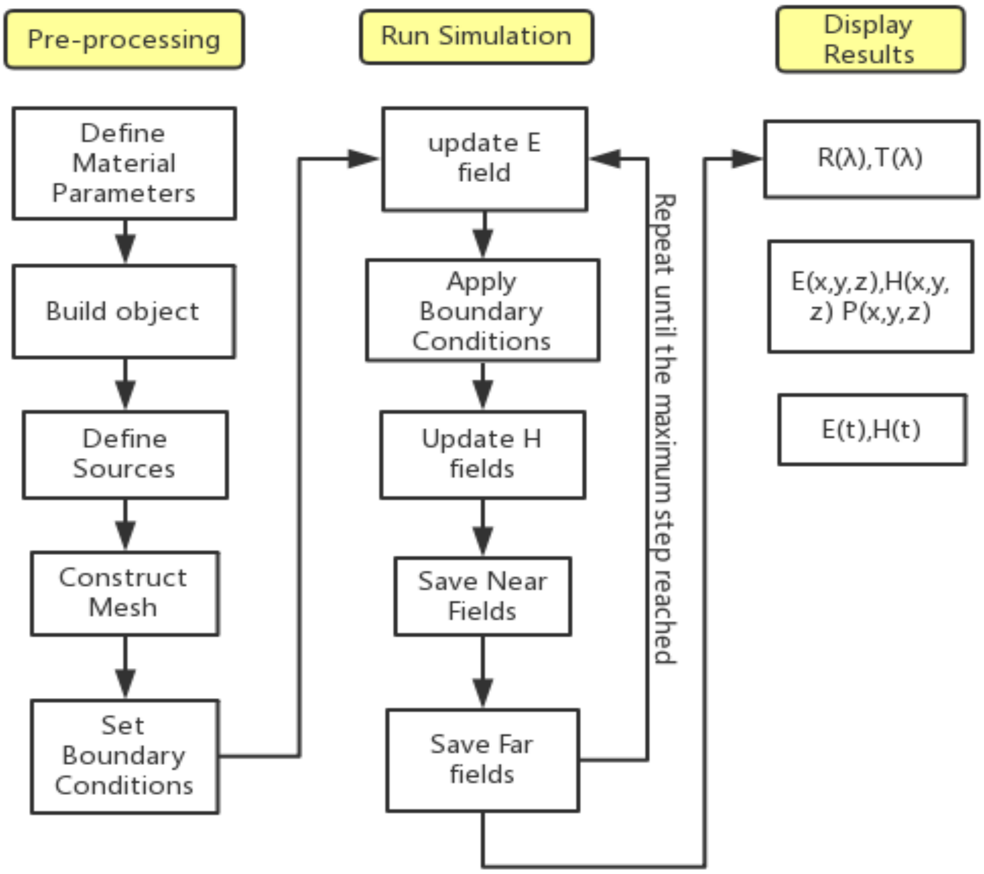


Figure3 sample inside the waveguide



Flow diagram of FDTD simulation process

A measurement using the Transmission line method involves placing a sample in a section of waveguide and measuring the two ports complex scattering parameters with a vector network analyzer(VNA). The method involves measurement of the reflected (S11 or S22) and transmitted signal (S21 or S12). The relevant scattering parameters relate closely to the complex permittivity and permeability of material by equations. The two ports are selected with concrete distance.

3.2.4 Permittivity

Firstly, for the cavity and waveguide, the permittivity is chosen being the same as vacuum.

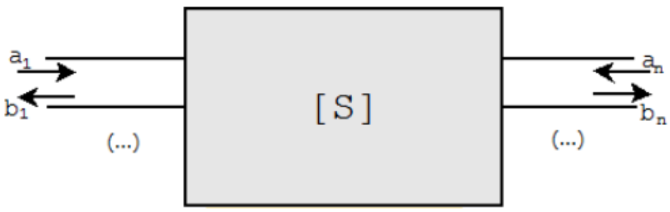
Secondly, set the permittivity of the sample inside the rectangular waveguide. In electromagnetism, the absolute permittivity, often referred to simply as the dielectric constant ε, is a measure of the resistance encountered when forming an electric field in a particular medium. More specifically, the dielectric constant describes the amount of charge required to produce a unit of electrical flux in a particular medium. Correspondingly, the charge will generate more electric flux in a medium with a low dielectric constant than in a medium with a high dielectric constant. Therefore, the dielectric constant is a measure of the material's resistance to electric fields. This step for this project is setting the parameter to unknown value which will be calculated in the inverse function.

3.2.5 Scattering parameters

Scatter parameters, also called S-parameter, defines the relationship between the transmitted and incident power of a group of incident waves in one device. Furthermore, these parameters are related to the voltage and the current in the device port, they are frequency dependent and they are useful to characterize linear active and passive devices.

[D. M. Pozar, "Microwave Engineering", 2nd edition, John Wiley & sons, 1998.]

These S-parameters can be calculated on the openEMS by using network analysis techniques or a vector analyzer (VNA). The figure below presents the two port network.



For a device like the figure*.*, the an is the incident wave and bn represents the reflected wave, the relationship between these two waves is characterized by the S-parameters[S] by using the matrix product below.

$$B=[S]\bullet A\rightarrow\begin{bmatrix}b_1\\b_2\\\vdots\\b_n\end{bmatrix}=\begin{bmatrix}s_{11}s_{12}\cdots s_{1n}\\s_{21}s_{22}\cdots s_{2n}\\\vdots\ddots\\s_{n1}s_{n2}\cdots s_{nn}\end{bmatrix}\begin{bmatrix}a_1\\a_2\\\vdots\\a_n\end{bmatrix}$$

The development of this equation could be simplified doing the analysis for a specific device, the quadripole also called two-port network, which can be seen in (Fig. 2.7). The two-port matrix is the most common scattering matrix, and this is the one that is going to be used in the experimental part. The two-port network will be completely defined by its S-parameters, S_{11}, S_{12}, S_{21} and S_{22}.

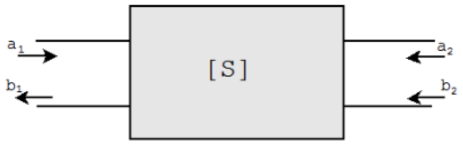


FIGURE 2.7: TWO-PORT ELEMENT OR NETWORK

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \quad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} \quad S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \quad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

where S_{11} is the reflection coefficient looking into first port and S_{21} is the transmission coefficient from second port to first port.

These S_{11} and S_{21} are determined by measuring the amplitude and the phase of the incident, reflected and transmitted signals when the output is terminated in a matched load so a_2 is 0. Likewise, by placing the source at port 2 and terminating port 1 in a matched load, it is possible to obtain S_{12} and S_{22}. S_{22} is the reflection coeficient for second port and S_{12} is the transmission coeficient from first port to second port.

From these particular results of the two-port network, it is easy to extrapolate the results for a N ports device. A specific element of this generalized scattering matrix could be seen in the following equation:

(2.31)

In (Eq. 2.31), S_{ij} is the transmission coefficient from port i to port j when all other ports are terminated in matched loads. For i=j the S-parameter, S_{ii}, is the reflexion coefficient in the i^{th} port when all the other ports are terminated in matched loads.

S-PARAMETERS CHARACTERISTICS

For different kinds of components or networks, the S-parameters present different useful properties [28].

In the case of a reciprocal n-port network, normally made of different passive components, the S-matrix present the relation $S_{ij}=S_{ji}$ for all i and j. If the n-port network is passive and lossless, the S-matrix is unitary, so in this case the S-matrix satisfies the relation $([S]^*)^T \cdot [S]=1$.

In the specific case of a two-port network, it is symmetric when it is reciprocal ($S_{21}=S_{12}$) and when the output reflection coefficient are equal ($S_{11}=S_{22}$). In this specific case, if the network is passive and lossless,

$|S11|=|S21| \quad |S22|=|S12|$

3.3 Inverse calculating

The main idea of the project is to do the inverse calculating, which means obtaining the S-parameter from the given permittivity, and then put the S-parameter to the inverse function, an original value of permittivity will be calculated. And then do the comparison between the value get from this program and the value from the HFSS.

HFSS is a commercial finite element method solver for electromagnetic structures from Ansys. The acronym stands for High Frequency Structure Simulator. It is one of several commercial tools used for antenna design, and the design of complex RF electronic circuit elements including filters, transmission lines, and packaging.
[https://en.wikipedia.org/wiki/HFSS]

With the given permittivity, S-parameter can be obtained from HFSS, then put the S-parameter into the matlab, by calling the inverse function, a value of permittivity will be obtained.

```
function F=Inverse_Rectangular_Shape(x,S11m,S21m)

Er=x(1)-j*x(2);


[S11,S21]=Rectangular_Shape(Er);

F=sqrt(abs(S11-S11m).^2+abs(S21-S21m).^2);
F=mean(F);

function Example

Er=2.08-j*0.001;


[S11m,S21m]=Rectangular_Shape(Er);


Seed=[1,1e-4];
Options=optimset('Display','iter');
X=fminsearch('Inverse_Rectangular_Shape',Seed,Options,S11m,S21m)
```

(a concrete description of the method)

3.4 Plot electric field distribution inside the cavity

Results and Discussion

The results from the inverse function has been nearly matched with the real value from, which deeply proved that using FDTD method based on the openEMS software gives a new way to do the inverse engineering. It is acknowledged to us all that measuring the permittivity of a sample is of crucial importance to predict the use of it. Instead of measuring the permittivity directly, which is hard to implement and design. However, the use of FDTD method makes this engineering easier and realiable.

```
Create FDTD operator (compressed SSE + multi-threading)
FDTD simulation size: 32x16x81 --> 41472 FDTD cells
FDTD timestep is: 5.47994e-012 s; Nyquist rate: 30 timesteps @3.0414e+009 Hz
Excitation signal length is: 1046 timesteps (5.73202e-009s)
Max. number of timesteps: 10000 ( --> 9.56023 * Excitation signal length)
Create FDTD engine (compressed SSE + multi-threading)
Running FDTD engine... this may take a while... grab a cup of coffee?!?
[@        4s] Timestep:         1878 || Speed:   19.4 MC/s (2.133e-003 s/TS) || Energy: ~1.37e-027 (-51.59
Time for 1878 iterations with 41472.00 cells : 4.01 sec
Speed: 19.45 MCells/s
    42          100         0.771093         contract inside

Optimization terminated:
 the current x satisfies the termination criteria using OPTIONS.TolX of 1.000000e-04
 and F(X) satisfies the convergence criteria using OPTIONS.TolFun of 1.000000e-04


x =

    4.5913   -0.0001
```

Figure() The given permittivity is 4.6000

```
Create FDTD operator (compressed SSE + multi-threading)
FDTD simulation size: 32x16x81 --> 41472 FDTD cells
FDTD timestep is: 5.47994e-012 s; Nyquist rate: 30 timesteps @3.0414e+009 Hz
Excitation signal length is: 1046 timesteps (5.73202e-009s)
Max. number of timesteps: 10000 ( --> 9.56023 * Excitation signal length)
Create FDTD engine (compressed SSE + multi-threading)
Running FDTD engine... this may take a while... grab a cup of coffee?!?
[@        4s] Timestep:         1818 || Speed:   18.8 MC/s (2.207e-003 s/TS) || Energy: ~2.05e-026 (-39.86dB)
[@        8s] Timestep:         3702 || Speed:   19.5 MC/s (2.123e-003 s/TS) || Energy: ~1.79e-026 (-40.46dB)
[@       12s] Timestep:         5586 || Speed:   19.5 MC/s (2.131e-003 s/TS) || Energy: ~8.75e-027 (-43.56dB)
[@       16s] Timestep:         7476 || Speed:   19.6 MC/s (2.116e-003 s/TS) || Energy: ~4.61e-027 (-46.34dB)
[@       20s] Timestep:         9282 || Speed:   18.7 MC/s (2.218e-003 s/TS) || Energy: ~6.10e-027 (-45.13dB)
RunFDTD: Warning: Max. number of timesteps was reached before the end-criteria of -50dB was reached...
    You may want to choose a higher number of max. timesteps...
Time for 10000 iterations with 41472.00 cells : 21.54 sec
Speed: 19.26 MCells/s
    28           63        0.0122148         shrink

Optimization terminated:
 the current x satisfies the termination criteria using OPTIONS.TolX of 1.000000e-04
 and F(X) satisfies the convergence criteria using OPTIONS.TolFun of 1.000000e-04


x =

    2.1873    0.0001
```

Figure() The given permittivity to be calculated is 2.200

Again, most projects will have results, especially for a research project. But again you should talk to your supervisor about it.

4 Conclusion and Further Work

{The conclusion is an important part of the report, as it states what you have done for the project. It also concludes the findings of your research or the outcome of implementing a system.

A good conclusion will NOT repeat what you have done, but set out the achievements very crisply (2 pages should be sufficient).

Further work can be the next step of your research, or some functionality that can be added to the implementation to make it more practical.

NOTE: The maximum length of the report up to here is 50 pages.}

Further work:

4.2 The further work:

Improved the accuracy of the permittivity

The accuracy of final permittivity calculated by the S-parameter not only depends on the inverse function, but also depends on the S-parameter obtained from the FDTD methods. Therefore, to improve the accuracy of the result, it is of great importance to enhance the accuracy of the S-parameter from the FDTD method. The work I have done to improve the accuracy of the S-parameter includes optimization of the boundary condition of the waveguide and the distance between port and excitation. After the improvement of these, the accuracy has been enhanced evidently.(seen and calculated from the similarity and data of the two curve) Further work can be done to enhance the accuracy of the S-parameter.

To make the comparison of the permittivity obtained from FDTD and HFSS for several examples, we now change the samples manually, further work can be done to make this process automatically, which means thousands of data can be calculated instead of changing each data by hand.

References

Everything you cite from other sources should be properly referenced. The QM Faculty of Science and Engineering has identified the Harvard and Vancouver referencing styles as the recommended styles for project reports. Details about the referencing style and examples can be found online at https://qmplus.qmul.ac.uk/mod/book/view.php?id=653429. Here are some examples:

Books:

Pitts, J. M., & Schormans, J. A. (2000). *Introduction to IP and ATM design and performance: with applications and analysis software.* New York: John Wiley. (047149187X)

Journals:

Chiau, C.C., Chen, X., & Parini, C. (2003). Multiperiod EBG structure for wide stopband circuits. *IEE Proceedings-Microwaves Antennas & Propagation, 150,* no.6, 489-92.

Conference papers:

Papadopoulos, S., & Parini, C. G. (1998). FDTD scattering by a dielectric strut in large geodesic space-frame radomes. In *International Symposium on Electromagnetic Theory. Proceedings. 25-28 May, 1998* (Vol.2, pp. 721-3). Thessaloniki: Aristotle University.

Online sources:

Abbott, K. (2004, May). *Finding information for Electronic Engineering, Engineering, Materials and the IRC in Biomedical Materials.* Retrieved May 27, 2004, from Queen Mary, University of London Library Web site: http://www.library.qmul.ac.uk/

Acknowledgement

During my final project done in UPV, Department of Communications of ITACA, it is really appreciated to meet so many warm people and professor in the office. My supervisor, who is a kind and enthusiastic professor that not only helps me with the project, but also leads me to my future area and builds up confidence about my further study. My colleague introduces me the way to use HFSS and also make the way to adapt to the work as soon as possible. It is truly a unforgettable experience to have the chance to work here!

Appendix

You must include the following here:

- Specification
- Early-term Progress Report
- Mid-term Check Report

NOTE: all of the above must be the final PDF versions downloaded from QMPlus.

Risk Assessment

Description of risks	Description of impact	Likelihood rating	Impact rating	Preventative actions
Break down of MATLAB	The most important foundation of this project broken	2	5	Maintain the software carefully
Slow speed of FDTD calculation	The advantage of using this method minimized	2	3	Optimization the code
Break of Inverse function of calculating the permittivity	The result of the project won’t come out	3	4	Make the loop more robust and reliable
The S-parameter from FDTD doesn’t match with the HFSS	The preparation of the inverse engineering break down	4	4	Change the excitation of the port.

[Electric field distribution in microwave ovens with MATLAB]

Environmental Impact Assessment