DESIGN AND DEVELOPMENT OF A MICROSTRIP SENSOR FOR MEASUREMENT OF MOISTURE CONTENT IN RICE GRAINS

FARIBA JAFARI

T FS 2007 64
DESIGN AND DEVELOPMENT OF A MICROSTRIP SENSOR FOR MEASUREMENT OF MOISTURE CONTENT IN RICE GRAINS

FARIBA JAFARI

MASTER OF SCIENCE

UNIVERSITI PUTRA MALAYSIA

2007
DESIGN AND DEVELOPMENT OF A MICROSTRIP SENSOR FOR MEASUREMENT OF MOISTURE CONTENT IN RICE GRAINS

By

FARIBA JAFARI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

July 2007
To
My lovely Mother,
The most wonderful gift from God.
A Microstrip moisture sensor is developed based on microwave attenuation and is used for measuring moisture content of rice grains. This sensor is suitable for a broad range of moisture content ranging from 0% to 40% (wet basis). It was fabricated using RT-Duriod with dielectric properties of 2.2-j0.002 as the substrate, with operating frequency at 9.0 GHz. In this technique only the small part of sample is needed to contact with the microstrip line, therefore the measurement can be done with more accuracy and in a shorter time.

Theoretical analysis based on quasi-transverse electromagnetic mode (TEM mode) in four layered microstrip is carried out to evaluate design parameters such as microstrip characteristic impedance, effective dielectric constant, length and
thickness due to the sensitivity of the sensor. The analysis of the complex electromagnetic waves in this system is presented using signal flow graphs and solved by Mason's non-touching loops rules. To this end Visual Fortran programs is written and documented to evaluate all the design parameters needed and to estimate the microstrip patterns.

In the other part of this study, investigation was made to find the relation between the dielectric properties and moisture content of rice grains. The dielectric mixture theory has been derived to solve the problem of non homogenous medium. In the purpose of verifying the mixture theory the theoretical results has been compared with the empirical results. It was found that the dielectric properties of dried rice samples were in the range of 1.20 to 1.88 for $\varepsilon'$ and 0.065 to 0.23 for $\varepsilon''$ and even can increased up to 30-j18 in maximum moisture content, respectively. A close and good agreement to theoretical expectation values is found. A computer program EMIX is written to predict the dielectric properties of wet basis rice grain by knowing the values of physical properties for dry basis.

In this study, analyzes of the sensor and various type of the rice grain samples with the effect of density and temperature of rice grains to the total attenuation of the sensor has been studied and the predicted results are compared with experimental results. The effect of air inside the medium and the compactness of the material under the test has been studied and the errors of ± 0.16 dB has been calculated for the measured reflected attenuation of the sensor.

The microstrip sensor was tested on five types of rice grains in the range of 1% to
40% moisture content. The sensor has predicted moisture contents with standard error of ±0.22 dB and accuracy of 1.5% MC wet basis compared to standard oven drying method. Moisture contents of rice grain samples were found in the range of 11 to 12.5% at room temperature (25°C).

A new proposed moisture sensor which can measure the moisture content of grains contained in a sack manner has been given. The slim and sharp geometry of the sensor enable it to measure the mean volumetric values of moisture content of rice since it penetrates deep into the sack. Therefore, this method can be so useful in industry for moisture content measurement of rice grains and even some other grains like wheat, corn barley and so on, to determine the proper time of harvest, safe storage and quality control of grains.
PEMBANGUNAN DAN REKABENTUK SENSOR/MICROSTRIP KELEMBAPAN BAGI BIJIRIN BERAS

Oleh
FARIBA JAFARI

Julai 2007

Pengerusi: Profesor Kaida Khalid, PhD

Fakulti: Sains

Sensor kelembapan microstrip telah direcabentuk berdasarkan pengecilan gelombang mikro dan digunakan untuk mengukur kandungan kelembapan bijirin beras. Pengesan ini sesuai bagi pelbagai julat kandungan kelembapan bermula dari 0% hingga 40% (asas basah). Pengesan ini direka menggunakan RT-Duriod dengan sifat dielektirk, 2.2-j0.002 sebagai ‘substrak’ dan frekuensi operasi pada 9.0 GHz. Melalui teknik ini yang hanya memerlukan bahagian kecil sampel untuk menyentuh dengan

Dalam bahagian lain kajian ini, penyelidikan telah dijalankan untuk mencari hubungan di antara sifat-sifat dielektrik dan kandungan kelembapan bijirin beras. Teori campuran dielektrik telah diterbitkan untuk menyelesaikan masalah medium tidak homogen. Bagi tujuan mengesahkan teori campuran ini, keputusan teori telah dibandingkan dengan keputusan empirik. Didapati, sifat-sifat dielektrik sampel beras kering adalah di dalam julat 1.20 hingga 1.88 bagi \( \varepsilon' \) dan 0.065 hingga 0.23 bagi \( \varepsilon'' \) dan akan ditingkatkan dengan kandungan kelembapan maksimum. Suatu persetujuan yang baik dan hampir kepada nilai jangkaan teori telah dikesan. Program komputer ditulis untuk meramal sifat-sifat dielektrik bijirin beras basah dengan mengetahui nilai sifat-sifat fizikal bagi bijirin beras kering.

Dalam kajian ini, analisis sensor pelbagai jenis sampel bijirin beras dengan kesan...
kepadatan dan suhu bijirin beras kepada jumlah pengecilan pengesan telah dikaji dan keputusan yang dijangka telah dibandingkan dengan keputusan eksperimen. Kesaran udara di dalam pengantaraan dan kepadatan sampel di bawah ujikaji telah dikaji dan ralat bagi ±0.16 dB telah dihitung bagi pengecilan sensor yang telah diukur.

Sebagai contoh aplikasi, sensor microstripm telah diuji ke atas 5 jenis bijirin beras dalam jualat kandungan kelembapan minimum dan maksimum. Sensor telah meramal kandungan kelembapan dengan ralat piawai kepadatan sebanyak ±0.22 dB dan kejituan sebanyak 1.5% kandungan kelembapan berasaskan basah berbanding dengan kaedah pengeringan ketuhar biasa. Kandungan kelembapan sampel bijirin beras dikesan dalam jualat 11 hingga 12.5% dalam suhu bilik (25°C).

Dengan persetujuan yang rapat antara nilai yang diramal dan nilai eksperimen, cadangan baru sensor kelembapan yang dapat mengukur kandungan kelembapan bijirin yang terkandung di dalam suatu karung dalam keadaan pantas dan praktikal telah diusulkan. Geometri sensor yang halus dan tajam itu membolehkan ia mengukur nilai min volumetrik bagi kandungan kelembapan beras oleh kerana ia menembusi ke dalam karung. Oleh itu, kaedah ini sangat berguna dalam industri pengukuran kandungan kelembapan bijirin beras dan juga bijirin-bijirin lain seperti gandum, jagung, barli dan lain-lain untuk menentukan masa yang sesuai bagi penanaman, keselamatan simpanan dan kawalan kualiti bijirin.
ACKNOWLEDGEMENTS

"All praise to Almighty Allah, for his bounties and providences."

I would like to express my sincere gratitude to my supervisor, Professor Dr. Kaida bin Khalid for his parentally guidance and advice during this research. His encouragement, moral and technical support made this work possible.

I am also grateful to my supervisory committee, Associate Professor Dr. W. Mohamed. Daud W. Yusoff, Associate Professor Dr. Jumiah Hassan and for their advice and helpful discussion during this period of study.

I would like to thank:

- Mr. Mohd. Roslim who has helped in fabricating the patch and provided technical support in the Laboratory.

- All the staff in physics department, UPM for their cooperation given to me throughout my work.

- All of my lovely friends in Malaysia for enjoyable social life in a wonderful country.

Last but not least, I wish to express my gratitude to my family for the support they gave throughout my studies. Long absent years from home are often found with a warm and hopeful words.
I certify that an Examination Committee has met on 25th July 2007 to conduct the final examination of Fariba Jafari on her Master of Science thesis entitled “Design and Development of a Microstrip Sensor for Measurement of Moisture content in Rice Grains” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

**W. Mahmood Mat. Yunus, PhD**  
Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(Chairman)

**Mohd. Maaroof H. A. Moksin, PhD**  
Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(Internal Examiner)

**Zaidan Abd. Wahab, PhD**  
Associate Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(Internal Examiner)

**Mazlina Esa, PhD**  
Associate Professor  
Faculty of Electrical Engineering  
Universiti Teknologi Malaysia  
(External Examiner)

---

**HASANAH MOHD.GHAZALI, PhD**  
Professor/Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 24 October 2007
This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

**Kaida Khalid, PhD**  
Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Chairman)

**W.Mohamed Duad W. Yusoff, PhD**  
Associate Professor  
Faculty of Forestry  
Universiti Putra Malaysia  
(Member)

**Jumiah Hassan, PhD**  
Associate Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Member)

---

**AINI IDERIS, PhD**  
Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia  

Date: 15 November 2007
DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

FARIBA JAFARI

Date: 30 April 2007
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>ii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>vii</td>
</tr>
<tr>
<td>APPROVAL</td>
<td>ix</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xvi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xvii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xx</td>
</tr>
</tbody>
</table>

## CHAPTER

1 **GENERAL INTRODUCTION**

1.1 Introduction 2
1.2 Microwave Energy 3
1.3 Advantages and Limitations of Microwave Sensing 4
1.4 Microwave Aquametry of Grain 6
1.5 Classifications of Microwave Moisture Sensors 8
1.5.1 Reflection Sensors 8
1.5.2 Resonant Sensors 10
1.5.3 Transmission/Reflection Sensors 12
1.5.3.1 Free-Space Transmission Method 13
1.5.3.2 Waveguide Transmission Method 13
1.6 Objectives 14
1.7 Thesis Outline 15

2 **THEORETICAL ANALYSIS BASED ON MICROSTRIP STRUCTURE**

2.1 Semi-Infinite Double Covered Microstrip as Sensing Area 18
2.2 The Total Attenuation of the Microstrip Sensor 19
2.2.1 Reflection and Transmission at Multiple Interfaces 20
2.2.2 System Signal Flow Graph 21
2.3 Microstrip Structure 25
2.4 TEM Analysis of Double Covered Microstrip with Semi-infinite Layer 26
2.5 Stripline 31
2.6 Computed Results for Microstrip Structure 34
2.7 Dielectric Loss in Microstrip 36
2.8 Dielectric Mixture Theory 40
2.9 Results and Discussion 43
2.10 Summary 45
### SENSOR DEVELOPMENT

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Microstrip Sensor</td>
<td>48</td>
</tr>
<tr>
<td>3.2</td>
<td>Properties of Materials</td>
<td>51</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Frequency Dependence</td>
<td>52</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Complex Dielectric Spectrum of Water</td>
<td>54</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Complex Dielectric Spectrum of Rice Grains</td>
<td>56</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Bulk Density of Grain Dependence</td>
<td>57</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Temperature Dependence</td>
<td>58</td>
</tr>
<tr>
<td>3.3</td>
<td>Summary</td>
<td>60</td>
</tr>
</tbody>
</table>

### METHODOLOGY

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Determination of Dielectric Properties</td>
<td>61</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Calibration Procedures</td>
<td>62</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Methodology</td>
<td>62</td>
</tr>
<tr>
<td>4.2</td>
<td>Standard Methods of Measuring Moisture Content</td>
<td>64</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Direct Methods</td>
<td>64</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Indirect Methods</td>
<td>66</td>
</tr>
<tr>
<td>4.3</td>
<td>Measurement of Moisture Content</td>
<td>67</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Sample Preparation</td>
<td>67</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Calibration Procedure for Attenuation Measurement</td>
<td>70</td>
</tr>
<tr>
<td>4.4</td>
<td>Experimental Set-up</td>
<td>71</td>
</tr>
<tr>
<td>4.5</td>
<td>Summary</td>
<td>72</td>
</tr>
</tbody>
</table>

### RESULTS AND DISCUSSION

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>How Does Rice Dry?</td>
<td>74</td>
</tr>
<tr>
<td>5.2</td>
<td>Dielectric Properties of Rice Grain</td>
<td>76</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Variation with Frequency</td>
<td>77</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Variation with Moisture Content</td>
<td>79</td>
</tr>
<tr>
<td>5.3</td>
<td>Attenuation of Microwave Power in Rice Medium</td>
<td>81</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Variation with Thickness of Protective Layer</td>
<td>81</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Variation of Attenuation with Moisture Content</td>
<td>83</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Effect of Operating Frequency</td>
<td>85</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Effect of Temperature</td>
<td>88</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Effect of Density</td>
<td>89</td>
</tr>
<tr>
<td>5.4</td>
<td>Comparison between Compactness and Noncompactness Sample</td>
<td>90</td>
</tr>
<tr>
<td>5.5</td>
<td>Standard Errors of Experiments</td>
<td>92</td>
</tr>
<tr>
<td>5.6</td>
<td>Summary</td>
<td>93</td>
</tr>
</tbody>
</table>

### CONCLUSION AND FUTURE WORK

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Conclusion</td>
<td>95</td>
</tr>
<tr>
<td>6.2</td>
<td>Future work</td>
<td>97</td>
</tr>
<tr>
<td>6.3</td>
<td>Microstrip Moisture Sensor</td>
<td>98</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Geometrical and Electrical Parameters of Microstrip sensor</td>
<td>50</td>
</tr>
<tr>
<td>4.1 Measured Values of Some Physical Properties for Each Five Types of Rice Grain</td>
<td>69</td>
</tr>
<tr>
<td>5.1 Dielectric Properties with Density and Bulk Density for Dried Rice Samples at Operating Frequency 9 GHz</td>
<td>77</td>
</tr>
<tr>
<td>5.3 Measured Attenuation with Residuals at Operating Frequency 9 GHz, for 22% MC rice sample</td>
<td>91</td>
</tr>
<tr>
<td>5.4 Standard Error of MC Measurement with Residuals at Operating Frequency 9 GHz, for Rice Sample C</td>
<td>93</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>The Electromagnetic Spectrum</td>
<td>3</td>
</tr>
<tr>
<td>1.2</td>
<td>Typical Reflection Sensor</td>
<td>9</td>
</tr>
<tr>
<td>1.3</td>
<td>Typical Resonators with Different Coupling Schemes</td>
<td>11</td>
</tr>
<tr>
<td>1.4</td>
<td>Typical Transmission sensor</td>
<td>13</td>
</tr>
<tr>
<td>2.1</td>
<td>Sensor configuration, (a) Moisture Sensor, (b) Cross Section of Semi-infinite Microstrip as a sensing area of the Sensor</td>
<td>19</td>
</tr>
<tr>
<td>2.2</td>
<td>Multiple Reflection and Transmission Propagation Paths for Plane Wave through Different Media</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>Microstrip Sensor with Sample Inserted</td>
<td>21</td>
</tr>
<tr>
<td>2.4</td>
<td>The Sensor as a Two-port Network</td>
<td>22</td>
</tr>
<tr>
<td>2.5</td>
<td>Flow Graph of the Sensor as a Cascaded Two-port Network</td>
<td>23</td>
</tr>
<tr>
<td>2.6</td>
<td>Figure 2.6: Simplified Signal Flow Graph Using Mason’s Nontouching Loop rule, (a) Simplified Signal Flow Graph, (b) Final Form in Terms of Scattering Parameters of The Input and Output Ports</td>
<td>24</td>
</tr>
<tr>
<td>2.7</td>
<td>Microstrip Transmission Line</td>
<td>25</td>
</tr>
<tr>
<td>2.8</td>
<td>Semi-infinite Double Covered Microstrip Line</td>
<td>27</td>
</tr>
<tr>
<td>2.9</td>
<td>The Cross Section of Stripline</td>
<td>32</td>
</tr>
<tr>
<td>2.10</td>
<td>Characteristic Impedance versus W/h for Stripline at various s/h for (a) Dielectric constant $\varepsilon_{r1} = 2.2$ and (b) $\varepsilon_{r1} = 10.5$ as a substrate with $\varepsilon_{r2} = 2.6$ and $\varepsilon_{r3} = 30.0$</td>
<td>33</td>
</tr>
<tr>
<td>2.11</td>
<td>Characteristic Impedance versus W/h for Semi-infinite Microstrip at various s/h for (a) dielectric constant $\varepsilon_{r1} = 2.2$ and (b) $\varepsilon_{r1} = 10.5$, with $\varepsilon_{r2} = 2.6$ and $\varepsilon_{r3} = 30.0$</td>
<td>34</td>
</tr>
<tr>
<td>2.12</td>
<td>Effective dielectric constant versus W/h for semi-infinite microstrip at various s/h for (a) dielectric constant $\varepsilon_{r1} = 2.2$ and (b) $\varepsilon_{r1} = 10.5$, with $\varepsilon_{r2} = 2.6$ and $\varepsilon_{r3} = 30.0$</td>
<td>35</td>
</tr>
</tbody>
</table>
2.13 Microstrip; (a) Semi-infinite 4-layer Microstrip, (b) Semi-infinite Covered Microstrip with the Same Dielectric Constants

2.14 Dielectric Loss as a Function of Ratio $W/h$ for Semi-infinite Double Covered Microstrip at Various Thicknesses of Covered Layer with $\varepsilon_r1 = 2.2$, $\varepsilon_r2 = 3.0$ and $\varepsilon_r3 = 30.0$

2.15 Model of Rice Compact Volume and Specimen with Moisture Content

2.16 Variation in Total Attenuation with moisture content of 3-layer Semi-infinite Microstrip sensor

2.17 Comparison of Total Attenuation Between 4-layer Microstrip and 3-layer Semi-infinite Microstrip Sensor

3.1 Photo of Microstrip Moisture Sensor

3.2 The Cross Section of Microstrip’s Sensing Area

3.3 Variation of Dielectric Constant and Loss factor of Rough Rice, *Oryza Sativa* L., at 24 °C, with Moisture Content for Frequencies of 20 MHz, 300 MHz and 2.45 GHz

3.4 Real and imaginary part of the complex permittivity, $\varepsilon$ of water plotted Versus frequency

3.5 The Variation of Effective Dielectric Constant and Loss Factor for Rice and Air Mixture as Functions of Volume fraction of Rice

3.6 Moisture content and bulk-density dependence of (a) the dielectric constant and (b) the dielectric loss factor of rough rice, brown rice, and barley samples at 10.5 GHz and 24±1 °C

3.7 The temperature dependencies of relative permittivity for wheat Grains variety at 2 MHz for moisture contents wet basis

4.1 Field Lines for an Open-ended Coaxial probe

4.2 Rice Grain Samples Have Been Used for Measurement

4.3 Experimental Setup for Microwave Attenuation Measurement Using HP 8270B Vector Analyzer

5.1 Drying Process of Rice sample Type M

5.2 Variation in Mass of dried rice at Different Temperatures
5.3 Frequency Independence of Dielectric Properties of Dried Rice Samples

5.4 Dielectric Properties of Dried Grain Versus Moisture Content

5.5 Comparison between Predicted and Measured Values of Dielectric Properties as a Function of Moisture Content in Medium Rice M

5.6 Comparison between Predicted and Measured Values of Attenuation as a Function of Moisture Content for Sample Rice A

5.7 Comparison between Predicted and Measured Values of Attenuation as a Function of Moisture Content for Rice Samples A and B

5.8 Comparison between Predicted and Measured Values of Attenuation as a Function of Moisture Content for Rice Samples C,D and B

5.9 Comparison between Predicted and Measured Values of Attenuation as a Function of Frequency for Rice Samples A and B

5.10 Comparison between Predicted and Measured Values of Attenuation as a Function of Frequency for Rice Samples C and D

5.11 Comparison between Predicted and Measured Values of Attenuation as a Function of Temperature for Rice Sample M

5.12 Variation of the Attenuation versus Moisture Content for Five Types of Rice Samples

5.13 The Effect of Compactness and Non-Compacted Material

5.14 Comparison between Standard and Measured Moisture Content of Rice Grain

6.1 Sensor Structure (a) Cross Section of sensor Layers, (b) Front and Side view of the Microstrip Moisture Sensor

6.2 Proposed application of the Sensor System to Measure Moisture Content of Grain Commodities

B1.1 Flow chart to Compute the Characteristic Impedance for Different Values in width of Conducting Line of a Two Port Network

B2.1 Flow chart to Compute the Dielectric of the Microstrip Line for Different Values in width of Conducting Line

B4.1 Flow chart to Compute the Scattering Parameters and Total Attenuation of the Sensor in 0% to 50% Moisture Content
LIST OF ABBREVIATIONS

VNA  Vector Network Analyzer
MUT  Material Under Test
MC   Moisture Content
HPBW Half-Power Beam Width
BW   Bandwidth
PLF  Polarization Loss Factor
SEC  Standard Error of Calibration
NDT  Non Destructive Testing
VSWR Voltage Standing Wave Ratio
TEM  Transverse Electric Magnetic Fields
RF   Radio Frequency
HF   High Frequency
VHF  Very High Frequency
UHF  Ultra High Frequency
d.b. Dry Basis Moisture Content Determination
w.b. Wet Basis Moisture Content Determination
## LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Electric Field Intensity</td>
<td>(V/m)</td>
</tr>
<tr>
<td>H</td>
<td>Magnetic Field Intensity</td>
<td>(A/m)</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Permittivity of Vacuum</td>
<td>(F/m)</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Permeability of Vacuum</td>
<td>(H/m)</td>
</tr>
<tr>
<td>$\varepsilon^*_{r}$</td>
<td>Relative Permittivity (Complex)</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$\mu^*_{r}$</td>
<td>Relative Permeability (Complex)</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$\eta^*$</td>
<td>Medium Impedance (Complex)</td>
<td>(Ω)</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
<td>(H)</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>(F)</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>Characteristic Impedance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>Y</td>
<td>Admittance</td>
<td>(S)</td>
</tr>
<tr>
<td>$\gamma^*$</td>
<td>Propagation Constant (complex)</td>
<td>(1/m)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Dielectric constant</td>
<td>(1/m)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Phase Constant</td>
<td>(rad/m)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Conductivity</td>
<td>(S/m)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular Frequency</td>
<td>(rad.Hz)</td>
</tr>
<tr>
<td>$\varepsilon'$</td>
<td>Dielectric Constant</td>
<td>(F/m)</td>
</tr>
<tr>
<td>$\varepsilon^*''$</td>
<td>Loss Factor</td>
<td>(F/m)</td>
</tr>
<tr>
<td>$\tan\delta$</td>
<td>Loss Tangent</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$\Gamma^*$</td>
<td>Reflection Coefficient (complex)</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>$\tau^*$</td>
<td>Transmission Coefficient (Complex)</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$D$</td>
<td>Directivity</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$G$</td>
<td>Gain</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$e$</td>
<td>Efficiency</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$Q_T$</td>
<td>Quality factor</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>RL</td>
<td>Return Loss</td>
<td>(dB)</td>
</tr>
<tr>
<td>$h$</td>
<td>Substrate Thickness</td>
<td>(mm)</td>
</tr>
<tr>
<td>$s$</td>
<td>Thickness of Protective Layer</td>
<td>(mm)</td>
</tr>
<tr>
<td>$d$</td>
<td>Height of Sample or Wet Media</td>
<td>(mm)</td>
</tr>
<tr>
<td>$W$</td>
<td>Width of Line</td>
<td>(mm)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Phase Constant</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>(gr/cm³)</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
<td>(cm³)</td>
</tr>
<tr>
<td>$v_a$</td>
<td>Volume Fraction of air</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$v_g$</td>
<td>Volume Fraction of grain</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$v_w$</td>
<td>Volume Fraction of water</td>
<td>(dimensionless)</td>
</tr>
<tr>
<td>$m_a$</td>
<td>Mass of air</td>
<td>(gr)</td>
</tr>
<tr>
<td>$m_g$</td>
<td>Mass of Grain</td>
<td>(gr)</td>
</tr>
<tr>
<td>$m_w$</td>
<td>Mass of water content</td>
<td>(gr)</td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>Scattering Parameter (Port 1 to Port 1)</td>
<td>(dB)</td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>Scattering Parameter (Port 2 to Port 1)</td>
<td>(dB)</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>Scattering Parameter (Port 1 to Port 2)</td>
<td>(dB)</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>Scattering Parameter (Port 2 to Port 2)</td>
<td>(dB)</td>
</tr>
<tr>
<td>$C$</td>
<td>Capacitance of the structure</td>
<td>(F)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>$C_a$</td>
<td>Line Capacitance</td>
<td>(F)</td>
</tr>
<tr>
<td>$V_p$</td>
<td>Phase Velocity</td>
<td>(m/s)</td>
</tr>
<tr>
<td>$A$</td>
<td>Attenuation</td>
<td>(dB/cm)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Electrostatic Potential</td>
<td></td>
</tr>
<tr>
<td>$\rho(x,y)$</td>
<td>surface Charge Density</td>
<td>(C/m²)</td>
</tr>
<tr>
<td>$\rho(\beta)$</td>
<td>Fourier Transform of $\rho(x,y)$</td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>Total Charge</td>
<td>(C)</td>
</tr>
</tbody>
</table>