## **Table of Contents**

page

| Acknowledgement  | iii  |
|--|------|
| Abstract in English  | v    |
| Abstract in Thai   | vii  |
| List of Tables   | xii  |
| List of Figures  | xiii |
| Chapter 1 Introduction and Background                        | 1    |
| 1.1 Proton Exchange Membrane Fuel Cell and Its Water Problem | 1    |
| 1.2 Review of Methods for Water Dynamics Observations        | 3    |
| 1.2.1 Visible Imaging  | 3    |
| 1.2.2 Terahertz Imaging                                      | 4    |
| 1.3 Proton Exchange Membrane Fuel Cell Design                | 6    |
| 1.4 Scope of Thesis  | 8    |
| Chapter 2 Theoretical Framework for Terahertz Measurement    | 9    |
| 2.1 Interactions of Electromagnetic Wave with Materials      | 9    |
| A 2.1.1 Absorption hts reserved                              | 9    |
| 2.1.2 Reflection   | 10   |
| 2.1.3 Refraction   | 11   |
| 2.2 Matrix of Light Transport                                | 11   |
| 2.2.1 Propagation Matrix                                     | 12   |
| 2.2.2 Transfer Matrix  | 13   |
| 2.3 Terahertz Response of Proton Exchange Membrane Fuel Cell |      |
| Structures   | 15   |

| 2.4 Frequency Selection by Filter                                   | 20 |
|---|----|
| Chapter 3 Visible Imaging Measurement                               | 23 |
| 3.1 Visible Imaging System  | 23 |
| 3.2 Performance of Proton Exchange Membrane Fuel Cell               | 25 |
| 3.3 Water Distribution Response to Changes in Current Density       | 27 |
| 3.3.1 Transient Response  | 27 |
| 3.3.2 Steady State Response   | 30 |
| 3.4 Characteristics of Droplet Formation and Water Removal at       |    |
| Fixed Current Density   | 31 |
| 3.4.1 Droplet Formation Process                                     | 31 |
| 3.4.2 Water Removal Process   | 33 |
| 3.5 Summary   | 35 |
| Chapter 4 Terahertz Imaging Measurement                             | 37 |
| 4.1 Terahertz Generation and Detection                              | 37 |
| 4.1.1 Terahertz Generation from Short Electron Bunches              | 37 |
| 4.1.2 Terahertz Detection   | 38 |
| 4.2 Terahertz Imaging System  | 39 |
| 4.3 Reflective Terahertz Images                                     | 41 |
| 4.4 Quantitative Identification of Water Presence using a Line-Scan |    |
| Coplotright <sup>©</sup> by Chiang Mai University                   | 43 |
| 4.5 Improvement of Image Resolution                                 | 45 |
| 4.5.1 Using a Polarizer   | 45 |
| 4.5.2 Using a Metal Mesh Filter                                     | 50 |
| 4.6 Summary   | 55 |
| Chapter 5 Conclusion and Future Work                                | 56 |
| 5.1 Conclusion and Discussion                                       | 56 |
| 5.2 Future Work   | 58 |

| Bibliography               | 59 |
|----------------------------|----|
| Appendix Focused Beam Size | 62 |
| Curriculum Vitae           | 63 |



**ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่** Copyright<sup>©</sup> by Chiang Mai University All rights reserved

## **List of Tables**

| Table |  | page |
|-------|--|------|
| 1.1   | Dimensions for the transparent PEM fuel cell   | 8    |
| 2.1   | Reflective indices of materials in multilayer of PEM fuel cell   | 17   |
| 2.2   | Geometry of copper meshes  | 22   |
| 4.1   | Transmission wavenumber of THz radiation obtain from mesh filter   | 51   |
| A.1   | Focused beam diameter for different wavelength   | 62   |
|       | <b>ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่</b><br>Copyright <sup>©</sup> by Chiang Mai University<br>All rights reserved |      |

xii

## **List of Figures**

| Figure |   | page |
|--------|---|------|
| 1.1    | The diagram of PEM fuel cell structures                                 | 2    |
| 1.2    | The THz spectrum  | 4    |
| 1.3    | THz image of fresh and dry leaves                                       | 6    |
| 1.4    | The PEM fuel cell components designed with machine-through flow         |      |
|        | channel made of nickel-coated brass enclosed with THz window            | 7    |
| 2.1    | Interactions of light with matter                                       | 10   |
| 2.2    | Electric field propagated between two positions in space                | 13   |
| 2.3    | Field across an interface   | 14   |
| 2.4    | Schematic diagram of a cross section of PEM fuel cell structure at the  |      |
|        | cathode   | 16   |
| 2.5    | Forward and backward electric fields at multistructure of the fuel cell | 16   |
| 2.6    | Spectral reflectance of the PEM fuel cell structure with PMMA           |      |
|        | windowลิทธิ์มหาวิทยาลัยเสียงใหม่  | 18   |
| 2.7    | Spectral reflectance of the PEM fuel cell structure with Si window      | 18   |
| 2.8    | Schematic diagram of a cross section of PEM fuel cell structure with    |      |
|        | filled water and unfilled water   | 19   |
| 2.9    | Spectral reflectance of the air PMMA air and air PMMA water             |      |
|        | structures  | 19   |
| 2.10   | Spectral reflectance of the air Si air and air Si water structures      | 20   |
| 2.11   | Spectral reflectance of the air Si water and air PMMA water structures  | 20   |
| 2.12   | Inductive mesh geometry and its equivalent circuit                      | 21   |
| 2.13   | Transmission spectra of THz radiation obtain from the equivalent        |      |
|        | circuit method  | 22   |

xiii

| 3.1  | Schematic diagram of our visible imaging system incorporated in the     |    |
|------|---|----|
|      | fuel cell test station  | 24 |
| 3.2  | The front view of the transparent fuel cell assembly                    | 24 |
| 3.3  | Generalized polarization curve for a PEM fuel cell                      | 26 |
| 3.4  | Polarization curve and power curve for a PEM fuel cell                  | 26 |
| 3.5  | Current density profile adopted for the experiment on the transient     |    |
|      | response of the PEM fuel cell   | 27 |
| 3.6  | Dynamic response of the cell voltage with respect to a step current     |    |
|      | change  | 28 |
| 3.7  | Image of water distribution in the flow channels with time after a step |    |
|      | increase in the current density   | 29 |
| 3.8  | Photographs of water buildup at the cathode with different current      |    |
|      | densities   | 30 |
| 3.9  | Photographs of empty flow channel, and water-clogged flow channel       | 31 |
| 3.10 | Droplet formation in the flow channel for transparent cell              | 32 |
| 3.11 | Visualization of water removal process in the flow channel for          |    |
|      | transparent cell  | 34 |
| 3.12 | Photographs of water buildup in the flow channel at current density of  |    |
|      | 0.6 A/cm <sup>2</sup>   | 35 |
| 4.1  | Schematic diagram of the THz generation system via coherent             |    |
|      | transition radiation by Chiang Mai University                           | 38 |
| 4.2  | A photograph of the reflective THz imaging setup                        | 39 |
| 4.3  | Preparation of a flow channel plate used in a model cell for THz        |    |
|      | imaging   | 40 |
| 4.4  | Photographs of a flow channel plate before and after covering with Si   |    |
|      | window and THz image of it  | 41 |
| 4.5  | THz image of machine-through-brass flow channel plate with PMMA         |    |
|      | window  | 42 |
| 4.6  | THz image of machine-through-brass flow channel plate with silicon      |    |
|      | window  | 42 |

| 4.7  | Gradient THz image with PMMA window includes the dashed line, and              |    |
|------|--|----|
|      | THz-signal line-scan along the dashed line in gradient THz image with          |    |
|      | PMMA window  | 43 |
| 4.8  | Gradient THz image with silicon window includes the dashed line, and           |    |
|      | THz-signal line-scan along the dashed line in gradient THz image with          |    |
|      | Silicon window   | 44 |
| 4.9  | Diagram of the flow channel plate with spot of THz radiation across an         |    |
|      | arc of the flow channel, and using a line scan profile of region in left to    |    |
|      | define a resolution of the image   | 44 |
| 4.10 | The polarizer and Insertion of the polarizer to our reflective THz             |    |
|      | imaging setup  | 45 |
| 4.11 | P-polarization and S-polarization of THz radiation beam                        | 46 |
| 4.12 | Reflectance spectra of the air Si air structure at 30 degree incident angle    |    |
|      | as a function of polarization  | 47 |
| 4.13 | THz image using p-polarized THz radiation                                      | 47 |
| 4.14 | THz image using s-polarized THz radiation                                      | 48 |
| 4.15 | Line scans illustrate real profile of the flow channel groove at the arc of    |    |
|      | the cell compared the THz signal by using p-polarized and                      |    |
|      | s-polarized THz radiation  | 49 |
| 4.16 | Measurement of THz power spectrum after mesh filtering via                     |    |
|      | Michelson interferometer   | 50 |
| 4.17 | Transmission spectra of THz radiation obtain from measurement                  |    |
|      | Michelson interferometer   | 51 |
| 4.18 | Photo of copper mesh filter with opening size $180 \times 180 \text{ mm}2$ and |    |
|      | Reflective THz imaging system with inserting metal mesh                        | 52 |
| 4.19 | THz image of machine-through-brass flow channel plate without mesh             | 52 |
| 4.20 | THz image of machine-through-brass flow channel plate with mesh-40             | 52 |
| 4.21 | THz image of machine-through-brass flow channel plate with mesh-80             | 53 |
| 4.22 | Line scans illustrate real profile of the flow channel groove at the arc of    |    |
|      | the cell compared to THz signal with mesh and without mesh                     | 54 |