

# Developments in Double-Modulated Terahertz Differential Time-Domain Spectroscopy

by

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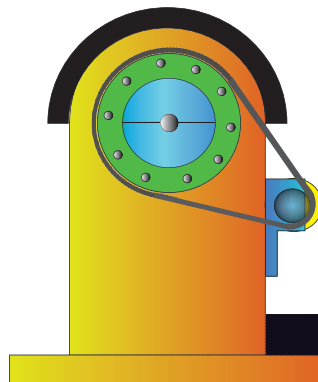
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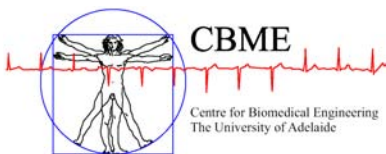
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# Contents

Heading	Page
Contents	iii
Abstract	ix
Statement of Originality	xi
Acknowledgments	xiii
Thesis Conventions	xv
Publications	xvii
List of Figures	xix
List of Tables	xxv
<b>Chapter 1. Introduction and Motivation</b>	<b>1</b>
1.1 Introduction . . . . .	2
1.2 Thesis overview . . . . .	3
1.3 Original contribution . . . . .	5
<b>Chapter 2. Electromagnetic spectrum</b>	<b>7</b>
2.1 Introduction . . . . .	8
2.1.1 Objectives and framework . . . . .	9
2.2 In the Beginning . . . . .	9
2.2.1 Radiowaves . . . . .	9
2.2.2 Microwaves . . . . .	9
2.2.3 T-rays . . . . .	11
2.2.4 Infrared . . . . .	13

2.2.5	Visible light . . . . .	14
2.2.6	Ultraviolet (UV) . . . . .	14
2.2.7	X-rays . . . . .	16
2.2.8	$\gamma$ -rays . . . . .	17
2.3	Chapter summary . . . . .	19
<b>Chapter 3. Terahertz time-domain spectroscopy (THz-TDS)</b>		<b>21</b>
3.1	Introduction . . . . .	22
3.1.1	Objectives and framework . . . . .	22
3.2	Principles of terahertz pulse emission and detection . . . . .	23
3.2.1	Terahertz pulse emission using photoconductive emitters . . . . .	23
3.2.2	Terahertz pulse detection using a photoconductive detector . . . . .	25
3.2.3	Photoconductive antennas . . . . .	27
3.2.4	THz-TDS configuration . . . . .	27
3.2.5	Novel antenna mounts . . . . .	33
3.3	Data analysis . . . . .	35
3.3.1	Assumption and method of extraction . . . . .	36
3.4	Chapter summary . . . . .	42
<b>Chapter 4. THz dielectric properties of polymer materials</b>		<b>43</b>
4.1	Brief introduction on macromolecules or polymers . . . . .	44
4.1.1	Objectives and framework . . . . .	45
4.2	Polymers today . . . . .	46
4.3	Polymer T-ray spectroscopy . . . . .	47
4.3.1	High density polyethylene (HDPE) . . . . .	48
4.3.2	Polytetrafluoroethylene (PTFE) . . . . .	50
4.3.3	TOPAS Cyclic-olefin copolymer (COC) 5013L10 & 6013S04 . . . . .	51
4.3.4	Poly(methyl methacrylate)-(PMMA) . . . . .	56
4.3.5	Polycarbonate (PC) . . . . .	56
4.4	Chapter summary . . . . .	60
<b>Chapter 5. Sensing the hygroscopicity of polymer and copolymer materials</b>		<b>61</b>

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5.1	Introduction . . . . .	62
5.1.1	Objectives and framework . . . . .	62
5.2	Polar and non-polar polymers . . . . .	63
5.2.1	Polymer hygroscopicity . . . . .	63
5.3	Sample preparation . . . . .	63
5.4	Analysis . . . . .	64
5.5	Results and discussion . . . . .	66
5.6	Chapter summary . . . . .	70
<b>Chapter 6. THz-TDS sample cells for liquid spectroscopy</b>		<b>71</b>
6.1	Introduction . . . . .	72
6.1.1	Objectives and framework . . . . .	74
6.2	Window cell geometries . . . . .	74
6.2.1	Single-thickness window cell geometry . . . . .	74
6.2.2	Air tight window cell geometry . . . . .	80
6.2.3	Dual-thickness window cell geometry . . . . .	83
6.2.4	Reflection window cell geometry . . . . .	87
6.3	Chapter summary . . . . .	88
<b>Chapter 7. THz material parameter extraction using a spinning wheel</b>		<b>91</b>
7.1	Introduction . . . . .	92
7.1.1	Objectives and framework . . . . .	92
7.2	THz-DTDS and Double-modulated THz-DTDS . . . . .	93
7.3	Spinning wheel . . . . .	95
7.4	Simulation . . . . .	97
7.5	Experimental Method . . . . .	101
7.5.1	Lock-in amplifier configuration . . . . .	101
7.6	Analysis . . . . .	103
7.7	Results and discussion . . . . .	105
7.7.1	Polyvinyl chloride: PVC . . . . .	105
7.8	Chapter summary and recommendation . . . . .	109

<b>Chapter 8. Fixed dual-thickness terahertz liquid spectroscopy</b>	<b>111</b>
8.1 Introduction . . . . .	112
8.1.1 Objectives and framework . . . . .	113
8.2 Spinning wheel . . . . .	113
8.3 Experimental configuration . . . . .	115
8.3.1 Lock-in amplifier setting . . . . .	116
8.3.2 Sample preparation . . . . .	117
8.4 Mathematical formula . . . . .	117
8.4.1 Spinning wheel accuracy verification . . . . .	118
8.5 Results and discussion . . . . .	119
8.5.1 Water . . . . .	121
8.5.2 Methanol . . . . .	121
8.5.3 Ethanol . . . . .	121
8.6 Chapter summary . . . . .	126
<b>Chapter 9. Thesis conclusion and recommendation</b>	<b>127</b>
9.1 Introduction . . . . .	128
9.2 Thesis conclusions . . . . .	128
9.2.1 Review of Electromagnetic spectrum . . . . .	128
9.2.2 Review of THz dielectric properties of polymer materials . . . . .	128
9.2.3 Review of THz-TDS sample cells for liquid spectroscopy . . . . .	128
9.2.4 Review of THz material parameter extraction using a spinning wheel . . . . .	129
9.2.5 Review of Fixed dual-thickness terahertz liquid spectroscopy . . . . .	129
9.3 Recommendation and future directions . . . . .	130
9.4 Summary of original contributions . . . . .	131
9.5 In closing . . . . .	131
<b>Appendix A. Modelling terahertz signal extraction using lock-in amplifier</b>	<b>133</b>
A.1 Terahertz signal recovery using lock-in amplifier . . . . .	134
A.1.1 Objectives and framework . . . . .	135

A.2	Terahertz signal extraction for a THz-TDS . . . . .	135
A.2.1	Mathematical expression of the THz-TDS signal recovery using a single lock-in amplifier . . . . .	136
A.3	Terahertz signal extraction for a double-modulated THz-DTDS . . . . .	138
A.3.1	Mathematical expression of the double-modulated THz-DTDS signal recovery using two lock-in amplifiers . . . . .	139
A.4	Chapter summary . . . . .	143
<b>Appendix B. Terahertz detection of substances</b>		<b>145</b>
B.1	Introduction . . . . .	146
B.1.1	Objectives and framework . . . . .	146
B.2	Methodology . . . . .	147
B.3	Experimental Setup . . . . .	148
B.4	Results and discussion . . . . .	149
B.5	Conclusion and recommendation . . . . .	151
<b>Appendix C. Experimental Equipment</b>		<b>153</b>
C.1	Conventional THz time-domain spectrometer . . . . .	154
C.1.1	Modelocked femtosecond laser . . . . .	155
C.1.2	XPS Motion controller . . . . .	156
C.1.3	Lock-in amplifier configuration . . . . .	157
C.1.4	SR540 chopper controller . . . . .	158
C.1.5	Optical components . . . . .	159
C.1.6	Mechanical components . . . . .	159
C.2	Data acquisition for conventional THz-TDS . . . . .	160
C.3	Double-modulated THz-DTDS spectrometer . . . . .	160
C.3.1	Double-modulated THz-DTDS . . . . .	162
C.3.2	Dual lock-in amplifier configuration . . . . .	162
C.3.3	Spinning wheel . . . . .	163
C.4	Data acquisition for double-modulated THz-DTDS . . . . .	164
<b>Appendix D. Matlab Algorithms</b>		<b>167</b>

## Contents

---

D.1 Conventional THz-TDS analysis program . . . . .	168
D.2 Double-modulated THz-DTDS analysis program . . . . .	175
D.3 Modelling conventional THz-TDS signal extraction . . . . .	183
D.4 Modelling double-modulated THz-DTDS signal extraction . . . . .	187
<b>Bibliography</b>	<b>199</b>
<b>Symbols &amp; Glossary</b>	<b>207</b>
<b>Index</b>	<b>209</b>
<b>Résumé</b>	<b>211</b>
<b>Scientific Genealogy</b>	<b>213</b>



# Abstract

Recent years have seen a plethora of significant advances in terahertz (THz or T-ray) technology with the rapid development of the ultrafast femtosecond laser system. By definition, THz refers to an electromagnetic wave located between the microwave and infrared regions of the electromagnetic spectrum.

Over the last two decades, there has been an enormous interest in improving the sensitivity of spectroscopic measurements on liquids in the terahertz regime. Liquid studies at terahertz frequencies (0.1 - 10 THz) allow analysis of chemical composition and provides a better understanding of the solvation dynamics of various types of liquids. This Thesis focusses on developing a novel spinning wheel device using a double-modulated terahertz differential time-domain spectroscopy (double-modulated THz-DTDS) scheme coupled with a simultaneous dual-waveform acquisition technique for increasing the sensitivity and repeatability of liquid studies. The spinning wheel device promises a rapid succession of measurements, requiring one mechanical delay scan for the sample and reference signals.

The double-modulated THz-DTDS scheme with simultaneous dual-waveform acquisition was first introduced by Mickan *et al.* (2004). This Thesis builds upon this former work with a modification in the signal extraction technique. In this work, a step-by-step systematic engineering approach has been employed for the development of the spinning wheel device.

The Thesis is categorised into several parts leading to the development of the spinning wheel device. The first part provides a review on the historical development of the electromagnetic spectrum and a review of the state-of-the-art regarding THz generation and detection based on transient photoconductivity. Identifying an optimal polymer window material forms the second part of this Thesis. Here, a range of polymer materials are tested for low hygroscopicity and high transmission coefficient. The third part of the Thesis reviews various window cell geometries used in liquid spectroscopy measurements. A detailed data analysis technique is described for each geometry. The fourth part of the Thesis presents a prototype of the novel spinning wheel mechanism for THz material parameter extraction using the double-modulated THz-DTDS scheme. A proof-of-principle showing that the amplitude noise of a THz

system decreases as a function of the spinning wheel modulation frequency is demonstrated. Preliminary experiments indicate the potential of this technique for achieving a better noise performance, which is of significance particularly for THz spectroscopy of polar liquids where the signal-to-noise ratios are typically low due to high absorption coefficient. The initial demonstration of the spinning wheel technique leads to THz spectroscopy of liquids based on a fixed dual-thickness window geometry. Here, a rapid switching between two fixed liquid sample thicknesses is introduced.

# Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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28 February, 2010

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Signed

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Date



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# Thesis Conventions

The following conventions have been adopted in this Thesis:

1. **Definitions.** The T-ray band is defined in this Thesis to span from 0.1 to 10 THz (where 1 THz is  $10^{12}$  cycles/s). This is an emerging definition in the literature (Abbott and Zhang 2007).
2. **Notation.** The acronyms and symbols used in this Thesis are defined in the Symbols and Glossary on page 207.
3. **Spelling.** Australian English spelling conventions have been used, as defined in the Macquarie English Dictionary (A. Delbridge (Ed.), Macquarie Library, North Ryde, NSW, Australia, 2001).
4. **Typesetting.** This document was compiled using  $\text{\LaTeX}2\text{e}$ . TeXnicCenter was used as text editor interfaced to  $\text{\LaTeX}2\text{e}$ . Adobe Illustrator CS2 was used to produce schematic diagrams and other drawings.
5. **Mathematics.** MATLAB code was written using MATLAB Version R2007b/R2008a; URL: <http://www.mathworks.com>.
6. **Referencing.** The Harvard style has been adopted for referencing.
7. **URLs.** Universal Resource Locators are provided in this Thesis for finding information on the world wide web using hypertext transfer protocol (HTTP). The information at the locations listed was current on 17 December 2009.





# Publications

## Journal Articles

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- BALAKRISHNAN-J.**, FISCHER-B. M., AND ABBOTT-D. (2009). Low noise spinning wheel technique for THz material parameter extraction, *Optics Communications*, DOI: 10.1016/j.optcom.2010.01.042.
- BALAKRISHNAN-J.**, FISCHER-B. M., AND ABBOTT-D. (2009). Fixed dual-thickness terahertz liquid spectroscopy using a spinning sample technique, *IEEE Photonics Journal*, **1**(2), pp. 88–98.
- BALAKRISHNAN-J.**, FISCHER-B. M., AND ABBOTT-D. (2009). Sensing the hygroscopicity of polymer and copolymer materials using terahertz time-domain spectroscopy (THz-TDS), *Applied Optics*, **48**(13), pp. 2262 – 2266.
- WITHAYACHUMNANKUL-W., PNG-G. M., YIN-X. X., ATAKARAMIANS-S., JONES-I., LIN-H. Y., UNG-B. S. Y., **BALAKRISHNAN-J.**, NG-B. W.-H., FERGUSON-B., MICKAN-S. P., FISCHER-B., AND ABBOTT-D. (2007). T-ray sensing and imaging, *Proceedings of the IEEE*, **95**(8), pp. 1528–1558 (Invited).

## Conference Articles

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- BALAKRISHNAN-J.**, FISCHER-B. M., AND ABBOTT-D. (2009). Low-noise terahertz material parameter extraction using a spinning wheel, *Proceedings IRMMW-THz*, Busan, South Korea, DOI: 10.1109/ICIMW.2009.5325568.
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# List of Figures

Figure		Page
1.1	The electromagnetic spectrum . . . . .	2
1.2	Thesis structural flow chart . . . . .	5
<hr/>		
2.1	The electromagnetic wave . . . . .	8
2.2	Heinrich Rudolf Hertz (1857 - 1894) . . . . .	10
2.3	Hertz's laboratory apparatus . . . . .	10
2.4	Microwave radiation sources: Reflex klystron and magnetron . . . . .	11
2.5	Generation and detection of THz radiation using photoconductive antennas . . . . .	12
2.6	Sir William Frederick Herschel (1738 - 1822) and his experimental setup	13
2.7	Sir Isaac Newton (1643 - 1727) . . . . .	14
2.8	Isaac Newton's experimental setup to illustrate visible spectrum of light generated from sunlight . . . . .	15
2.9	Johann Wilhelm Ritter (1776 - 1810) . . . . .	15
2.10	Wilhelm Konrad Röntgen (1845 - 1923) . . . . .	16
2.11	X-ray of Röntgen's wife's hand with a ring . . . . .	17
2.12	Paul Ulrich Villard (1860 - 1934) . . . . .	18
2.13	Experimental setup for $\gamma$ -ray generation . . . . .	18
<hr/>		
3.1	Transmitting photoconductive switch . . . . .	24
3.2	Photocurrent and electric field amplitude of the THz radiation as a function of time . . . . .	25
3.3	H-structured photoconductive detector switch . . . . .	26
3.4	Illustration of repetitive sampling with variable delay . . . . .	28
3.5	Photoconductive antennas . . . . .	29

## List of Figures

---

3.6	THz time domain spectrometer . . . . .	30
3.7	Custom built THz time-domain spectrometer . . . . .	30
3.8	Typical temporal profile and spectral amplitude . . . . .	32
3.9	Novel custom-built antenna mount module . . . . .	35
3.10	Homogeneous sample test . . . . .	36
3.11	Terahertz data analysis procedures for a 3 mm PMMA polymer sheet . . . . .	41
<hr/>		
4.1	Hermann Staudinger (1881-1965) . . . . .	44
4.2	Monomer and polymer structures of ethylene . . . . .	45
4.3	Structure of polyethylene . . . . .	45
4.4	Molecular chain representation of thermoplastic and thermoset polymers . . . . .	46
4.5	Classification of linear chain thermoplastic polymers . . . . .	47
4.6	Absorption coefficient ( $\alpha$ ) and refractive index ( $n$ ) spectra of HDPE . . . . .	49
4.7	Repeating units of PTFE . . . . .	50
4.8	Absorption coefficient and refractive index spectra of PTFE . . . . .	52
4.9	Repeating units of TOPAS™ COC copolymer . . . . .	53
4.10	Absorption coefficient ( $\alpha$ ) and refractive index ( $n$ ) of COC 5013L10 . . . . .	54
4.11	Absorption coefficient ( $\alpha$ ) and refractive index ( $n$ ) of COC 6013S04 . . . . .	55
4.12	Repeating units of PMMA . . . . .	56
4.13	Absorption coefficient ( $\alpha$ ) and refractive index ( $n$ ) of PMMA . . . . .	57
4.14	Repeating units of PC . . . . .	58
4.15	Absorption coefficient ( $\alpha$ ) and refractive index ( $n$ ) of PC . . . . .	59
<hr/>		
5.1	Process diagram of the experiment . . . . .	64
5.2	Absorption spectra of PMMA . . . . .	66
5.3	Absorption spectra of PC . . . . .	67
5.4	Absorption spectra of COC 6013S04 . . . . .	69
<hr/>		
6.1	Transmission notation for a single-thickness window cell geometry . . . . .	77

---

6.2	Bruker's liquid cell . . . . .	78
6.3	Starna's fixed thickness cylindrical liquid cell . . . . .	78
6.4	Custom-built variable thickness liquid cell . . . . .	79
6.5	Custom-built fixed thickness liquid cell . . . . .	80
6.6	Transmission notation for air tight window cell geometry . . . . .	81
6.7	T-ray transmission notation for dual-thickness window cell geometry . .	84
6.8	Dual-thickness liquid sample cell . . . . .	86
6.9	T-ray reflection notation for window cell geometry at normal incidence .	87
6.10	Reflection geometry liquid cell setup . . . . .	88

---

7.1	The hammer-like sample holder for a differential measurement technique	93
7.2	Spinning wheel for double-modulated THz-DTDS polymer measurements	95
7.3	Polymer sample design for a double-modulated THz-DTDS measurement	96
7.4	Flowchart of the simulation process for mean and amplitude signal ex- traction . . . . .	97
7.5	Simulated mixer output at $n$ th step of the delay stage in frequency domain	99
7.6	Time-domain simulated output signal of a mixer at $n$ th step of the delay stage . . . . .	100
7.7	Double-modulated DTDS spectrometer schematic for polymer materials measurement . . . . .	102
7.8	Lock-in amplifier configuration for mean and amplitude signals extraction	103
7.9	Mean and amplitude waveforms of PVC . . . . .	106
7.10	Absorption coefficient and refractive index of PVC . . . . .	107
7.11	Noise percentage, $\mu_x$ of the THz system detected using a spinning wheel technique as a function of modulation frequency . . . . .	108

---

8.1	Spinning wheel for double-modulated DTDS dual-thickness liquid mea- surement . . . . .	114
8.2	Fixed dual-thickness geometry of COC 5013L10 window cell . . . . .	115
8.3	A double-modulated DTDS spectrometer schematic for dual-thickness liquid measurement . . . . .	116

---

## List of Figures

---

8.4	Lock-in amplifier settings for mean and amplitude signal extraction . . .	117
8.5	Time traces of a double-modulated dual-thickness liquid spectroscopy .	120
8.6	Refractive index and absorption coefficient of distilled water . . . . .	122
8.7	Refractive index and absorption coefficient of methanol . . . . .	123
8.8	The absorption coefficient and refractive index of ethanol . . . . .	125
8.9	Sample thickness error present at random positions in the thin and thick liquid layer of the fixed dual-thickness liquid sample holder . . . . .	126
<hr/>		
A.1	Small signal hidden under a large noise signal . . . . .	135
A.2	Lock-in amplifier setup for conventional THz-TDS small signal recovery	136
A.3	Simulated terahertz signal extraction for a standard THz-TDS at the $n$ th step of the delay stage . . . . .	138
A.4	Lock-in amplifier setup for double-modulated THz-DTDS small signal recovery . . . . .	139
A.5	Simulated mixer output at $n$ th step of the delay stage in frequency domain	142
<hr/>		
B.1	Simulation of a faux suitcase and contents . . . . .	147
B.2	Picometrix™ T-Ray 2000 spectrometer . . . . .	148
B.3	Absorption curves of $\alpha$ -lactose, clean and laced samples of the faux suitcase . . . . .	150
<hr/>		
C.1	Conventional terahertz time-domain spectrometer . . . . .	154
C.2	A MiraSeed Ti-sapphire femtosecond modelocked laser . . . . .	155
C.3	XPS motion controller and motorised delay stage . . . . .	156
C.4	Photograph of SR830 lock-in amplifier . . . . .	157
C.5	SR540 Chopper system . . . . .	158
C.6	Screen shot of the LabVIEW program for conventional THz-TDS spectrometer . . . . .	161
C.7	Double-modulated THz-DTDS spectrometer . . . . .	162
C.8	Dual lock-in amplifier configuration . . . . .	163

C.9	The spinning wheel prototype . . . . .	164
C.10	Screen shot of LabVIEW program for double-modulated THz-DTDS spectrometer . . . . .	165

---





# List of Tables

<b>Table</b>		<b>Page</b>
2.1	Electromagnetic spectrum definitions . . . . .	19
3.1	Water lines in THz regime . . . . .	34
4.1	Terahertz dielectric properties of polymer materials . . . . .	60
5.1	The variation in absorption coefficient and hygroscopicity of polymer materials . . . . .	68