

HIGH PRECISION TECHNIQUE OF MEASURING THE REFLECTANCE OF
REFLECTIVE MATERIALS

LIM BOON HAN

A thesis submitted in fulfilment of the requirement for the award of
the degree of Doctor of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

OCTOBER, 2001

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN STATUS TESIS*

JUDUL: HIGH PRECISION TECHNIQUE OF MEASURING THE
REFLECTANCE OF REFLECTIVE MATERIALS.

SESI PENGAJIAN: _____

Saya LIM BOON HAN
 (HURUF BESAR)

mengaku membenarkan tesis (PSM/Sarjana/Doktor Falsafah)* ini disimpan di Perpustakaan Universiti Teknologi Malaysia dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Teknologi Malaysia.
2. Perpustakaan Universiti Teknologi Malaysia dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (✓)

SULIT

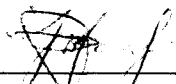
(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

TERHAD

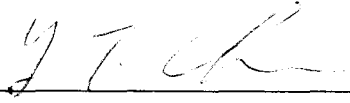
(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

TIDAK TERHAD

Disahkan oleh



(TANDATANGAN PENULIS)



(TANDATANGAN PENYELIA)

Alamat Tetap:

18, Jalan Machang Subst 24,
Taman Machang Subst
14000 Bukit Mertajam.


Prof. Dr. Y. T. CHEN

Nama Penyelia

Tarikh: 02/02/2003Tarikh: 06/02/2003

- CATATAN:
- * Potong yang tidak berkenaan.
 - ** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh tesis ini perlu dikelaskan sebagai SULIT atau TERHAD.
 - ◆ Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

“~~Saya/Kami~~* akui bahawa saya telah membaca karya ini dan pada pandangan
saya/~~kami~~* karya ini adalah memadai dari segi skop dan kualiti untuk tujuan
penganugerahan ijazah Sarjana Muda/Sarjana/Doktor Falsafah
.....”

Tandatangan : 
Nama Penyelia I : Prof. Dr. Che Yig. Tan
Tarikh : 24/10/2013

Tandatangan :
Nama Penyelia II :
Tarikh :

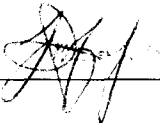
Tandatangan :
Nama Penyelia III :
Tarikh :

* *Potong yang tidak berkenaan.*

DECLARATION

“I hereby declare that this thesis entitled “High Precision Technique of Measuring the Reflectance of Reflective Materials” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and it is not concurrently submitted in candidature of any degree.”

Signature

:  _____

Name of Candidate : Lim Boon Han

Date : 21 September, 2001.

BAHAGIAN A – Pengesahan Kerjasama*

Adalah disahkan bahawa projek penyelidikan tesis ini telah dilaksanakan melalui kerjasama antara _____ dengan _____

Disahkan oleh:

Tandatangan : Tarikh :

Nama :

Jawatan :
(Cop rasmi)

** Jika penyediaan tesis/projek melibatkan kerjasama.*

BAHAGIAN B – Untuk Kegunaan Pejabat Sekolah Pengajian Siswazah

Tesis ini telah diperiksa dan diakui oleh:

Nama dan Alamat : **Prof. Dr. Mohd Yusof bin Sulaiman**
Pemeriksa Luar : **Timbalan Pengarah**
Institu Teknologi Maju
Universiti Putra Malaysia
43400 Serdang
Selangor

Nama dan Alamat : **Prof. Madya Dr. Jasmy bin Yunus**
Pemeriksa Dalam I : **Fakulti Kejuruteraan Elektrik**

Pemeriksa Dalam II : **Prof. Dr. Noordin bin Ibrahim**
Institut Kajian Sains Fundamental Ibnu Sina

Nama Penyelia lain :
(jika ada)

Disahkan oleh Timbalan Pendaftar di SPS:

Tandatangan :  Tarikh :

Nama : **DAHARI BIN HJ. DERANI**

Dedicate to my beloved mother
Madam Tan Soo Hwang

ACKNOWLEDGEMENTS

First of all, I feel eternal gratitude to my supervisor, Prof. Dr. Chen Ying Tian, for his teaching and patient guidance in various aspect including academic, technical, philosophy, psychology, moral and social, his valuable criticism, his help in getting financial support and his embedded love. I would like to thank Chong Kok Keong, Lim Chern Sing, Tan Kien Kia, Chen Lee Chuin, Omar Aliman, Tan Boon Kok and other friends for their help, discussions and information sharing. Besides, I would like to thank the technicians, Sahar Salehan, Abd Khalid Lipot and Shariezaniel Salim for technical support. I also would like to thank Faculty of Electrical Engineering and Universiti Teknologi Malaysia for their support. I owe my gratitude to Ministry of Science, Technology and Environment for the financial support in tuition fees and livings for the past two years and three months through NSF fellowship. Last but not the least, thank you to my mother and brothers for their spiritual support, care and love. . .

ABSTRACT

A new method of reflectivity measurement is proposed and tested in this Ph.D. study. The method employs fast rotating reference mirror and certain geometry configuration to alternately deliver the light via a sample mirror or by passing it to a photo detector. It has proved to reach a precision of 2×10^{-4} reflectance unit. The precision is at least ten times better than that of conventional reflectometer used in solar energy applications. With good repeatability, the durability test of mirrors is carried out for only one month enabling significant specular reflectance losses of mirrors to be observed instead of more than a year in the conventional case. The reflectometer has provided solutions to few problems that limit the conventional reflectometer. Firstly, the time interval between the collection of reference signal and sample signal is short, therefore, this can reduce the effect due to the changes of environment conditions, particularly, the intensity fluctuation of light source and others. Secondly, by taking advantage of the short measurement time, a large number of readings can be made to suppress the noise level. Thirdly, the value of the reflectance of the reference mirror is not required. In the system, an accurate positioning of laser beam on the photo detector is achieved by a position sensor using a pair of dual cells that acts as an optical lever as well as a position transducer for the feedback system.

ABSTRAK

Teknik baru untuk mengukur pemalar pantulan telah dikemukakan dalam tesis ini. Teknik ini menggunakan cermin rujukan yang boleh berputar dengan laju dan konfigurasi geometri yang tertentu untuk menghantar cahaya ke cermin sample atau terus ke pengesan cahaya secara berselang-seli. Ketepatan pengukuran yang dicapai ialah 2×10^{-4} unit pantulan. Keputusan ini adalah sekurang-kurangnya 10 kali ganda lebih baik daripada keputusan yang dicapai oleh pengukur pemalar pantulan konvensional yang digunakan dalam bidang tenaga suria. Dengan keboleholuan yang baik, ujian ketahanan pemantul suria yang hanya dijalankan sepanjang satu bulan telah dapat memerhatikan pengurangan pemalar pantulan yang jelas berbanding dengan ujian yang sepanjang satu tahun diperlukan bagi keadaan konvensional. Pengukur pemalar pantulan yang baru ini telah menyelesaikan beberapa masalah yang menjadi penghalang kepada pengukur konvensional. Pertama, masa perantaraan semasa mengukur isyarat rujukan dan isyarat sampel telah dipendekkan supaya kesan pengolakan keamatan laser dikurangkan. Kedua, bilangan pengukuran yang banyak dapat dijalankan untuk mengurangkan hingar dalam sistem. Ketiga, pemalar pantulan muktamad bagi cermin rujukan tidak perlu diketahui. Dalam sistem pengukur ini, penempatan sinaran laser yang tepat pada pengesan cahaya dicapai oleh satu pengesan kedudukan yang mengandungi satu pasang pengesan cahaya. Pengesan kedudukan itu boleh berfungsi sebagai tuil optik dan juga sebagai transduser kedudukan untuk sistem suapbalik. Untuk mencapai keputusan yang dinyatakan di atas, selain daripada cara yang pengarang berjaya menggunakan, pengarang juga mengkaji cara lain yang tidak begitu berjaya, sebagai rujukan masa depan.

CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	CONTENTS	vii
	LIST OF TABLES	xiii
	LIST OF FIGURES	xiv
	LIST OF SYMBOLS	xxi
	LIST OF APPENDICES	xxii
CHAPTER I	INTRODUCTION	1
	1.1 Introduction	1
	1.2 Objective and Scope of Study	3
	1.3 Thesis Overview	3
CHAPTER II	LITERATURE REVIEW	6
	2.1 Theory of Specular Reflectance	6

LIST OF TABLES

TABLE NO.	SUBJECT	PAGE
2.1	Precision of reflectometers and their suitability for use in solar energy applications.	55
3.1	Range of θ , β , and ϕ for the four possible configurations of mirrors and photo detector in Figure 3.2.	84
3.2	DC motor rotation direction at the four regions according to the received signals and the flag set.	138
4.1	Measurement parameters and measurement result using dual-cell position sensor method.	151
4.2	Measurement parameters and measurement results using stoppers method.	153
4.3	Amount of specular reflectance losses of sample candidates studied by Fend.	160
4.4	Parameters used for calculating error induced by background signal variation.	173
4.5	Reflectance measurement results in the presence and absence of spider webs.	177
4.6	Results of reflectivity measurement at flat region and V region.	182
4.7	Contribution of various sources to the measurement error.	183
5.1	Reflectance of two identical gold-coated mirrors.	185

LIST OF FIGURES

FIGURE NO.	SUBJECT	PAGE
2.1	Reflection and refraction at the boundary separating two media with refractive indices n_0 and n_1 , respectively	7
2.2	Fractional Amplitudes of s-polarisation and p-polarisation reflected from a dielectric medium of refractive index of $n = 1.50$	8
2.3	Reflectances for dielectric medium of refractive index of $n = 1.50$	10
2.4	Phase change of the electric vectors of plane-polarised light externally reflected from a dielectric medium	11
2.5	Reflectances of plane-polarised white light for gold and silver mirrors	14
2.6	Reflectances at normal incidence of aluminium, silver, gold, copper and steel for wavelength range from 200 nm to 800 nm	15
2.7	Normal-incidence Reflectometer with Two Identical Beam Splitters	19
2.8	Reflectometer with rotary beam splitter. (a) Measurement of the reflected intensity I_s . (b) Measurement of the compensated intensity of the direct beam I_o .	21
2.9	Optical diagram of PE-621 spectrophotometer. S1, S2 – slits; Source – Nernst glower	23
2.10	Experimental setup of double beam reflectometer modified from spectrophotometer. Source optics –	24

	specular reflectance. θ = incident angle; ψ = viewing angle; $\theta = \psi$ at specular direction.	
2.11	Schematic setup of the high-speed reflectometer.	26
2.12	Schematic diagram of the bi-directional reflectometer showing the collimation optics, collection optics, and the location of the sample mirror	28
2.13a	General scheme of the NBS specular reflectometer showing the relationship of the sample turntable and beam-tracking turntable and detector systems	31
2.13b	Horizontal x section through the plane of the sample beam, specular sample, and the tracking mirror that orbits the sample.	32
2.13c	Vertical x section through the plane of the sample beam, specular sample, tracking mirror, averaging sphere, and the detector	32
2.14	Schematic diagram of the optical arrangement for one of the Perkin-Elmer dual VW absolute reflectance unit	36
2.15	Optical arrangement of double beam double reflection reflectometer	39
2.16	Rectangular waves obtained at the detector output for double reflection double beam reflectometer: (a) during the recording of 100% line; and (b) during the measurement on the sample. Φ_1 , Φ_2 , Φ_s and ϕ_1 have the meanings reported in the text, and T is the signal period.	41
2.17	Modified White cell used as a multiple-pass reflectometer	43
2.18	Field mirror shows image locations and centre of curvature locations for the two objective mirrors. The diagram shown is the case of nine images, which corresponds to twenty reflectometer passes	44
2.19	Experimental data for aluminised mirrors and radiation at 546.1 nm. From the slope the absolute reflectance is $\bar{R} = 0.9095 \pm 0.0002$	46

2.20	Reflectometer layout shows the sample-out and sample-in configurations. Depending on the mirror parameters, the angle of incidence can be 15° or less	47
2.21	Physical layout of the optic train and phase shift measurement equipment used to measure the average lifetime of photons in the optical resonator	50
2.22	Three-mirror configuration for measurement of photon lifetime	51
2.23	Conceptual schematic of time decay measuring device. Optical switch shuts off light when detector output reaches a preset threshold level	52
2.24	Solar radiation at the surface of the earth	57
2.25	Schematic diagram of the structure of typical mass-produced silver mirrors	58
2.26	Schematic sketch of the float glass manufacturing process	59
2.27	Wet chemistry mirror production sequence	61
2.28	Transmittance for normal clear glass (thickness 3mm)	62
2.29	Relationships between solar reflectance for back-silvered 3 mm glass, total iron content and ferric efficiency	64
2.30	Transmittance for low iron 3 mm glass (A) and normal 3 mm glass (B)	65
2.31	Metallised polymer reflector construction	67
2.32	Spectral hemispherical reflectances $\rho_{2\pi}(\lambda)$ of an aluminium material additional PVD oxide layer (Miro 2) after different exposure times	73
2.33	Specular reflectance losses of uncorroded (solid lines), outdoor exposed (CM1 and CM2, dashed and chain-dashed lines, respectively) and accelerated aged (CM3, dotted lines) mirrors. CM1 and CM2 are the mirrors at two regions of a heliostat at Livermore, CA. The outdoor exposure test had been carried out for seven	73

	months. The painted surface of CM3 had been exposed to water at 77°C for 625 hours.	
2.34	Specular reflectance versus weathering outdoors at Golden, Colorado, 8 mrad full-cone acceptance angle, 650 nm wavelength. ECP-305 (silvered-PMMA) mounted on glass.	74
3.1	Basic principle of the new scheme. (a) Diagram shows measurement of reference beam intensity. (b) Diagram shows measurement of sample beam intensity.	80
3.2	Various configurations of mirrors and photo detector for the new reflectivity measurement scheme.	82
3.3	Dynamic range of incident angle to sample mirror for fixed beta.	85
3.4	Irradiance profile of a Gaussian TEM ₀₀ mode	96
3.5	Detail of the beam waist at the diffraction-limited convergence of a Gaussian beam.	96
3.6	Focusing of Gaussian beam by a lens.	99
3.7	Beam expander using two-lens system.	99
3.8a	Experimental setup of reflectivity measurement. The diagram shows sample beam measurement.	104
3.8b	Experimental setup of reflectivity measurement. The diagram shows reference beam measurement.	105
3.9	Simplified drawing of new method for reflectivity measurement. The reference mirror is attached to a motor so that it can be rotated to direct the laser beam to the required positions. (a) Reference beam measurement. (b) Sample beam measurement.	106
3.10	Mirror holding system with two freedom of rotation controlled by two differential micrometers.	108
3.11	Beam Expander System. The slider is used for fine adjustment of the location of the beam waist.	110
3.12	The experiment setup for the new reflectivity measurement. The system is enclosed in dark during	112

	operation.	
3.13a	Laser intensity fluctuation just after powered up.	114
3.13b	Laser intensity fluctuation after 8 minutes powered up	114
3.13c	Laser intensity fluctuation after 60 minutes powered up. The fluctuation cycle is longer than 128 seconds but the amplitude of fluctuation is still the same.	115
3.14	Inversed of laser beam profile after reflection. The two sides of the beam are represented as dashed line and centred dashed line respectively. Sample beam has been reflected one time more than the reference beam, therefore, the beam profile is inversed compared to that of reference beam	116
3.15	Photo detector uniformity (with window). The saw-tooth shape is the effect of interference which is resulted from multiple reflections between the surfaces of the window	120
3.16	Uniformity of Planar Photo Detector (not uniform)	121
3.17a	Planar photo detector with good uniformity	122
3.17b	Planar photo detector with good uniformity	123
3.17c	The shaded area is the region where photo detector uniformity is good. Laser beam is positioned at the intersection region for detection	124
3.18	Lens Law effect when DC motor stops. The laser beam will pass across photo detector (caused by momentum of the motor) and then inverse direction before it stops. The reverse of direction may place the beam back to the photo detector region but the position is not accurate	126
3.19	Position sensor with dual cells. (a) Two photo detectors are attached side by side. (b) Laser beam is positioned exactly at the centre of the sensor.	127
3.20	Block diagram of the beam-positioning feedback controlling system	129
3.21	Control beam position without proportional part in	130

	differentiator circuit	
3.22a	Photo detectors amplifying and summing circuit	131
3.22b	Motor controlling circuit	132
3.23	Flow Chart of the Reflectivity Measurement Procedure for Dual-Cell Position Sensor Method	134
3.24	Regions defined to overcome the overshoot of laser beam position due to momentum of the motor rotation	137
3.25	Modification of holding system to increase rigidity. (A) Before modification (B) After modification	142
3.26a	Experimental Setup of Reflectometer using Mechanical Stoppers- Sample Beam Measurement. The dashed line is the portion of beam reflected by the protective coating of photo detector.	143
3.26b	Experimental Setup of Reflectometer using Mechanical Stoppers- Reference Beam Measurement. The dashed line is the portion of beam reflected by the protective coating of photo detector.	144
3.27	Flow Chart of the Reflectivity Measurement Procedure for Mechanical Stoppers Method	145
3.28	Motor Controlling Circuit and Photo Detector Amplifier for Mechanical Stoppers Method	147
4.1	1 hour 30 minutes reflectance measurement of silver mirror with dual-cell position sensor method. Each point corresponds to 25 measurements.	149
4.2	425 measurements (1 hour 30 minutes) of silver mirror using position sensor method.	150
4.3	Repeatability of the new reflectivity measurement system. The specular reflectance is taken on a silver mirror which is stored in cabinet for 19 days. Each point corresponds to 100 measurements.	152
4.4	5.5 hours reflectance measurement of silver mirror (stoppers method with beam expander). Each point corresponds to 100 measurements.	154

4.5	4.5 hours reflectance measurement of silver mirror (stoppers method without beam expander). Each point corresponds to 100 measurements.	155
4.6	2100 measurements (5.5 hours) of silver mirror using stoppers method.	156
4.7	Reflectance of front-coated silver mirror under 28 days of durability test.	159
4.8	Reflectance of front-coated silver mirror under 28 days of durability test. Second point is omitted.	163
4.9	Reflectance drift of acrylic mirror within 3 hours 30 minutes.	164
4.10	Durability of second surface aluminised acrylic mirror for 28 days.	165
4.11	Distribution of background signals captured over typical measurement time.	173
4.12	Spectrum of laser intensity without filtering.	174
4.13	Spectrum of laser intensity after filtering with 8-pole, low-pass filter at 20Hz.	175
4.14a	Laser intensity fluctuation due to spider web.	176
4.14b	Laser intensity fluctuation due to spider web (less).	176
4.14c	Laser intensity fluctuation in the absence of spider web.	177
4.15a	Measurement in the presence of spider webs.	178
4.15b	Measurement in the absence of spider webs.	178
4.16	Intensity fluctuation due to airflow excitation	179
4.17a	Intensity drift of reference signal (0.8% in amplitude)	181
4.17b	Intensity drift of reference signal (0.04% in amplitude)	181

LIST OF SYMBOLS

θ	-	Angle of incidence
λ	-	Wavelength
ρ	-	Measured reflectance of sample mirror
ε		Photometric conversion efficiency of photo detector
d	-	Distance from the reference mirror to photo detector
ΔA	-	Area different of reference beam and sample beam
A_r	-	Area of reference beam
A_s	-	Area of sample beam
ΔL	-	Area shifted due to misalignment
α	-	Divergence angle of Gaussian beam
w_0	-	Radius of laser beam waist
z_0	-	Length parameter of Gaussian beam
S	-	Distance of lens from laser beam waist
f_1	-	Focal length of the first lens of beam expander
f_2	-	Focal length of the second lens of the beam expander
\bar{V}_s	-	Mean value of sample signal
\bar{V}_r	-	Mean value of reference signal
\bar{V}_b	-	Mean value of background signal
N		Number of measurements
σ	-	Standard deviation of measurement results

LIST OF APPENDICES

APPENDIX	SUBJECT	PAGE
A	Instrument Specifications and Operating Conditions	194
B	Programme Code for Dual-Cell Position Sensor Method	198
C	Programme Code for Mechanical Stoppers Method	219
D	The Uniformity Region of Measurement Photo Detector (PD3)	235
E	Experiment to Determine the Humidity Effect on Aluminised Acrylic Mirror	241

CHAPTER I

INTRODUCTION

1.1 Introduction

In the age of energy crisis, solar energy as a renewable and environmental friendly energy has gained its importance to become the next alternative energy. High power, high temperature solar concentrator systems generally depend on the use of large area of highly reflective materials. Although second surface silvered float glass mirror has long been recognised to have good solar reflectance, good specularly, good rigidity and long time span etc., it is not commercially competitive due to its weight that require strong structure in heliostat designs. Metallised polymers offer the potential advantages of low cost, lightweight and ease of installation (Berry and Dursch, 1980, Alpert *et. al.* 1990, Alpert *et. al.* 1991 and Schissel *et. al.* 1994). However, metallised polymers suffer from several problems such as unknown lifetime, and low surface abrasion resistant. Much effort has been paid in the search of good protective coating, which has good surface abrasion resistant and high transmittance. At present, researchers still seek for good alternative materials in order to let solar concentrator system commercially attractive. A precise knowledge of the reflectance characteristics of potential solar device materials is required in the choice of materials and to determine the extent of environmentally induced changes in such materials as a function of outdoor exposure conditions and duration.

Specular reflectance loss with time is one of the important determinants of reflective material lifetime. A durable reflective material deteriorates slowly. Hence,

the outdoor exposure test period for candidate mirror will depend on the capability of a reflectometer to measure a small change of material reflectance. Presently, the reflectometer used in solar energy applications has measurement uncertainty of 2×10^{-3} reflectance unit. The precision level is limited by the fluctuation of light intensity during the interval of measuring reference signal and sample signal (the reflectance is calculated from the ratio of the sample signal to the reference signal). The interval is long because of the need to reinstall the sample mirror for each measurement. This process is necessary because the optical path lengths for both reference beam path and sample beam path should be the same to achieve high accuracy. Due to the low precision achieved for conventional reflectometer, the period of outdoor weatherability test of mirror is usually more than a year. Such a long period of testing has affected the progress of developing solar energy concentrator that can provide inexhaustible energy to mankind.

On the other hand, scientists have thought of an alternative way to accelerate exposure test using weatherometer. But, the accelerated weatherability test does not always reflect actual environmental conditions. For example, Isakson (1972) tested polymethylmethacrylate (PMMA) and polyvinylidene fluoride (VDF) modified with PMMA with accelerated weathering devices and by outdoor exposure. The $12.7 \mu\text{m}$ thick samples were coated on matte-finished, bright aluminium panels. Nine months exposure in Florida produced only minor band broadening in the IR spectrum for PMMA, while only 31 hours in a Dew Cycle Weatherometer totally obliterated the IR spectrum.

In an effort to find a proper solar beam reflective material for the new invented Non-imaging Focusing Heliostat (Chen *et. al* 2001, and Chen *et. al* 2002), the author and Prof. Dr. Y. T. Chen have proposed and tested a new idea to measure reflectivity with high precision. The merits of the system are:

- (a) Fast measurement that reduces the effect of light intensity fluctuations.
- (b) Good repeatability without the need to know the reflectance of the reference standard.

Fast measurement can be done because reinstallation of the sample mirror for each measurement is not required in the new experimental setup. A reference mirror,

which is attached on a DC motor, can rotate at high speed to direct the laser beam to the desired position. High beam-positioning precision is accomplished by a novel method which apply dual cells as a position sensor. The position sensor acts as an optical lever as well as position transducer for feedback system.

The measurement precision achieved is 2×10^{-4} reflectance unit. With this result, a durability test is carried out for a front-coated silver glass mirror and a back-coated aluminised acrylic mirror. Results show that obvious degradations are observed within one-month of exposure. This has greatly shortened the typical outdoor test of more than a year. Therefore, the desired reflective material property can be determined in a short time.

1.2 Objective and Scope of Study

The objective of my study is to carry out specular reflectance measurement at precision level of 10^{-4} reflectance unit for ordinary mirror. The constructed reflectometer will be used in solar collector system for development of high reflectance and long durability reflective material. Although the new reflectometer can be used in other application such as material science to study the optical properties of material, it is beyond the scope of my study. Besides, diffuse reflectance measurement is also beyond the scope of my study because specular reflectance are emphasised in solar collector system.

1.3 Thesis Overview

This thesis is divided into five chapters. Chapter 1 discusses the importance and necessity to have high precision measurement of reflective materials for solar energy applications. Chapter 2 is the literature review section. The theory of specular reflectance is first outlined. Then, various kinds of reflectometers for specular reflectance measurement are given. They are grouped into single-reflection, double-

reflection and multiple-reflection systems. However, some of those reflectometers are not suitable for use in durability test. Therefore, a summary is provided together with the discussion of the criteria of reflectometer for used in solar energy field. The following section introduces the reflective material for solar collector system: the silver-coated float glass mirror and thin film reflectors. Glass mirror has long durability whereas thin film reflectors are easier subjected to environmental degradation. Various types of degradation and their protection methods are also given. Finally, two different mirror durability tests are studied, that is, the outdoor weatherability test and accelerated test. Accelerated test can be simulated weatherability test or other specific tests such as the durability test of mirror under the corrosion of acid, abrasion of sand etc. Durability test involves the use of many types of equipment of which reflectometer is the most important instrument.

Chapter 3 describes the principle of the new reflectometer and the experimental setup. Firstly, I will explain that my research work is mainly focused on the precision and repeatability of the reflectivity measurement as long as the accuracy achieved is sufficient for solar energy applications. Then, the principle of the design of the reflectometer is illustrated including all the considerations and calculations. The experimental setup is described in detailed subsequently, which covers the optical scheme, the optical alignment, the electronic circuits and the data acquisition methods. Experimental set up issues such as beam size, uniformity of photo detector, fluctuation of laser intensity, performance of DC motor and design of position sensor are given. The last part of the chapter describes the experimental setup using mechanical stoppers for beam positioning.

Result and analysis are provided in Chapter 4. The first section gives the precision and repeatability achieved by the reflectometer. The verification of the good performance of the constructed reflectometer is confirmed by weatherability test of a silver front-coated mirror and an aluminium back-coated acrylic mirror. The noises of the reflectometer system are analysed in the subsequent section. The major contributions that limit the measurement precision are beam positioning precision, photo detector uniformity and laser intensity fluctuation. The laser intensity fluctuation arose from the laser system itself, the effect of particle flow and the effect of 50 Hz noise.

REFERENCES

- Abdulkadir, A. and Birkebak, R. C. (1974). "Optical Surface Roughness and Slopes Measurements with a Double Beam Spectrophotometer." *Review of Scientific Instruments*. **45** (11). 1356-1360.
- Alpert, D. J., Houser, R. M., Heckes, A. A. and Erdman, W. W. (1990). "The Development of Stretched-Membrane Heliostats in the United States." *Solar Energy Materials*. **21**. 131-150.
- Alpert, D. J., Mancini, T. R., Houser, Grossman, J. W., Schissel, P., Carasso, M., Jorgensen, G. and Scheve, M. (1991). "Solar Concentrator Development in the United States." *Solar Energy Materials*. **24**. 307-319.
- Anderson, D. Z., Frisch, J. C., and Masser, C. S. (1984). "Mirror Reflectometer Based on Optical Cavity Decay Time." *Applied Optics*. **23**. 1238-1245.
- Arnon, O. and Baumeister, P. (1978). "Versatile High-Precision Multiple-Pass Reflectometer." *Applied Optics*. **17**. 2913-2916.
- Assink, R. A. (1980). "Abrasion Resistant Polymer Reflectors for Solar Applications." *Solar Energy Materials*. **3**. 263-275.
- Berry, M. and Dursch, H. (1980). "Exposure Testing of Solar Collector Plastic Films." *Solar Energy Materials*. **3**. 247-261.

- Bieg, K. W. and Wischmann, K. B. (1980). "Plasma-Polymerised Organosilanes as Protective Coatings for Solar Front-Surface Mirrors." *Solar Energy Materials*. **3**. 301-316.
- Bittar, A. and Hamlin, J. D. (1984). "High-Accuracy True Normal-Incidence Absolute Reflectometer." *Applied Optics*. **23**. 4054-4057.
- Boivin, G. and Theriault, J. M. (1981). "Reflectometer for Precise Measurement of Absolute Reflectance at Normal Incidence." *Review of Scientific Instruments*. **52** (7). 1001-1002.
- Bouquet, F. L., Helms, R. G. and Mag, C. R. (1987). "Recent Advances in Long-lived Mirrors for Terrestrial and Space Applications." *Solar Energy Materials*. **16**. 423-433.
- Castellini, C., Emiliani, G., Masetti, E., Poggi, P. and Polato, P. P. (1990). "Characterization and Calibration of a Variable-Angle Absolute Reflectometer." *Applied Optics*. **29**. 538-543.
- Chen, Y. T., Chong, K. K., Bligh, T. P., Chen, L. C., Jasmy Yunus, Kannan, K. S., Lim, B. H., Lim, C. S., Alias, M. A., Noriah Bidin, Omar Aliman, Sahar Salehan, Shk. Abd. Rezan S. A. H., Tam, C. M. and Tan, K. K. (2001). "Non Imaging Focusing Heliostat," *Solar Energy*. **71** (3). 155-164.
- Cheng, F. Q. and Hu, J. P. (1988). "Analysis of Al/glass and Ag/glass Mirror Films." *Solar Energy Materials*. **18**. 83-86.
- Coyle, R. T., Barrett, J. M. and Call, P. J. (1982). "Durability of Silver-Glass Mirrors in Moist Acid Vapours." *Solar Energy Materials*. **6**. 351-373.
- Dennis, W. E. and McGee, J. B. (1980). "Silicone Resins for Protection of First Surface Reflectors." *Solar Energy Materials*. **3**. 285-300.

- Dietrich, J. J., Boyaner, M. R. and Pittinato, G. F. (1980). "Reflector Edge Seal Development." *Solar Energy Materials*. **3**. 335-346.
- Edwards, D. F. and Baumeister, P. (1981). "Multiple-Pass Reflectometer." *Applied Optics*. **20**. 3968-3971.
- Fend, T., Jorgensen, G., and Kuster, H. (2000). "Applicability of Highly Reflective Aluminium Coil for Solar Concentrators." *Solar Energy*. **68**. 361-370.
- Gindele, K., Kohl, M., and Mast, M. (1985). "Spectral Reflectance Measurements Using an Integrating Sphere in the Infrared." *Applied Optics*. **24**. 1757-1760.
- Goodyear, J. K. and Lindberg, V. L. (1980). "Low Absorption Float Glass for Back Surface Solar Reflectors." *Solar Energy Materials*. **3**. 57-67.
- Hanssen, L. M. (1989). "Effects of Restricting the Detector field of View when Using Integrating Spheres." *Applied Optics*. **28**. 2097-2103.
- Herbelin, J. M. and McKay, J. A. (1981). "Development of Laser Mirrors of Very High Reflectivity Using the Cavity-Attenuated Phase-Shift Method." *Applied Optics*. **20**. 3341-3344.
- Herbelin, J. M., McKay, J. A., Kwok, M. A., Ueunten, R. H., Urevig, D. S., Spencer, D. J. and Benard, D. J. (1980). "Sensitive Measurement of Photo Lifetime and True Reflectances in an Optical Cavity by a Phase-shift Method." *Applied Optics*. **19**. 144-147.
- Isakson, K. E. (1972). *Journal of Paint Technology*. **44**. 41.
- Jenkins, F. A. (1958). *Journal of Physical Radium*. **19**. 301.
- Jenkins, F. A. and White, H. E. (1981). "Fundamentals of Optics." New York: McGraw-Hill.

- Klein, M.V. and Furtak, T. E. (1986). "Optics." New York: John Wiley and Sons.
- Kortum, G. (1969). "Reflectance Spectroscopy: Principles, Methods, Applications."
Translated by Lohr, J. E. Philadelphia: Springer-Verlag.
- Lavin, E. P. (1971). "Specular Reflection." London: Adam Hilger.
- Lind, M. A. and Hartman, J. S. (1980). "Natural Aging of Soda-Lime-Silicate Glass
in a Semi-Arid Environment." *Solar Energy Materials*. **3**. 81-95.
- Manoochehri, F. and Ikonen, E. (1995). "High-Accuracy Spectrometer for
Measurement of Regular Spectral Transmittance." *Applied Optics*. **34**. 3686-
3692.
- Park, H. S. and Day, D. E. (1986a). "Corrosion of Evaporated Ag Films on Glass by
Saturated Water Vapour." *Solar Energy Materials*. **13**. 351-365.
- Park, H. S. and Day, D. E. (1986b). "Corrosion of Chemically and Vacuum
Deposited Ag Films on Glass by Wet HCL Vapour." *Solar Energy Materials*.
13. 419-432.
- Park, H. S. and Day, D. E. (1986c). "Corrosion of Bare Ag, Ni/Ag and Cu/Ag Films
on Glass by Wet HCL Vapour." *Solar Energy Materials*. **13**. 367-372.
- Pettit, R. B. (1977). "Characterisation of the Reflected Beam Profile of Solar Mirror
Materials." *Solar Energy*. **19**. 733-741.
- Pettit, R. B. and Freese, J. M. (1980). "Wavelength Dependent Scattering Caused by
Dust Accumulation on Solar Mirrors." *Solar Energy Materials*. **3**. 1-20.
- Pitts, J. R., Thomas, T. M. and Czanderna, A. W. (1984). "Surface Analysis of Silver
Mirrors Made from Organometallic Solutions." *Solar Energy Materials*. **11**.
261-271.

- Richter, W. and Erb, W. (1987). "Accurate Diffuse Reflection Measurements in the Infrared Spectral Range." *Applied Optics*. **26**. 4620-4624.
- Schissel, P. and Czanderna, A. W. (1980). "Reactions at the Silver/Polymer Interface: A Review." *Solar Energy Materials*. **3**. 225-245.
- Schissel, P., Jorgensen, G., Kennedy, C. and Goggin, R. (1994). "Silvered-PMMA Reflectors." *Solar Energy Materials and Solar Cells*. **33**. 183-197.
- Shelby, J. E. and Vitko, J., Jr. (1980). "Weathering of Glasses for Solar Applications." *Solar Energy Materials*. **3**. 97-110.
- Shelby, J. E. Vitko, J., Jr. and Farrow, R. L. (1980). "." *Solar Energy Materials*. **3**. 185-201.
- Snail, K. A. and Hansen, L. M. (1989). "Integrating Sphere Designs with Isotropic Throughput." *Applied Optics*. **28**. 1793-1799.
- Strong, J. (1938). "Procedures in Experimental Physics." 1st ed. New York: Prentice Hall. 376.
- Susemihl, I. and Schissel, P. (1987). "Specular Reflectance Properties of Silvered Polymer Materials." *Solar Energy Materials*. **16**. 403-421.
- Taketani, H. (1980). "Reflectance and Aging Studies of Heliostat Mirrors." *Solar Energy Materials*. **3**. 127-134.
- Vitko, J. Jr., Benner, R. E. and Shelby, J. E. (1983). "Corrosion of Thin Silver Films in an Aqueous Environment." *Solar Energy Materials*. **9**. 51-67.
- Vitko, J. Jr. and Shelby, J. E. (1980). "Solarisation of Heliostat Glasses." *Solar Energy Materials*. **3**. 69-80.

- Voss, A., Plass, W. and Giesen, A. (1994). "Simple High-Precision Method for Measuring the Specular Reflectance of Optical Components." *Applied Optics*. **33**. 8370-8374.
- Weidner, V. R. and Hsia, J. J. (1980). "NBS Specular Reflectometer-Spectrophotometer." *Applied Optics*. **19**. 1268-1273.
- White, J. W. (1942). *Journal of Optical Society of America*. **32**. 285.
- Zentner, R. C. (1977). "Performance of Low Cost Solar Reflectors for Transferring Sunlight to a Distant Collector." *Solar Energy*. **19**. 15-21.
- Zerlaut, G. A. and Anderson, T. E. (1981). "Multiple-Integrating Sphere Spectrophotometer for Measuring Absolute Spectral Reflectance and Transmittance." *Applied Optics*. **20**. 3797-3804.
- Zwinkels, J. C. and Gignac, D. S. (1992). "Design and Testing of a New High-Accuracy Ultraviolet-Visible-Near-Infrared Spectrophotometer." *Applied Optics*. **31**. 1557-1567.
- Zwinkels, J. C., Noel M. and Dodd, C. X. (1994) "Procedures and Standards for Accurate Spectrophotometric Measurements of Specular Reflectance." *Applied Optics*. **33**. 7933-7944.