ERROR CORRECTION METHOD OF WIDEBAND MULTI-PORT REFLECTOMETER USING LEAST MEAN SQUARE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
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Specially and dedicated to my mother and late father,

Hjh. Chik Mahamed and Hj. Che Yob Othman

My beloved husband and daughter,

Alif Bahari Abu Bakar and Rabia'tul A'dawiyyah Alif Bahari

My supported parents-in-law,

Abu Bakar Lajis and Ruhana Dollah

My understanding and inspirational supervisor,

Dr. Norhudah Seman

&

Brothers, sisters, friends, lecturers and WCC staffs

For your infinite and unfading love, patience, encouragement, sacrifice, endless support, motivation, and best wishes throughout my journey of education.

Thanks you for all the support that was given to me.

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ABSTRACT

The microwave imaging applications have a great demand in recent years by having considerable interest such as in medical, industrial and military aspects. Particularly, in most research of microwave imaging applications, Vector Network Analyzer (VNA) is frequently been used to act as transmitter and receiver to allow the measurement of complex ratio between two microwave signals and also provide accurate measurement of reflected and scattering parameters, but it is bulky and expensive. Therefore, in this research, a portable low-cost measurement device namely multi-port reflectometer is proposed as an alternative to VNA in the imaging system. The configuration of this device is formed by four couplers and two power dividers over the operating wideband frequency range between 1 and 6 GHz. The investigation of the characteristics and operation of such reflectometer are accessed via simulation using existing components in Agilent's Advance Design System (ADS) software and measurement of real components in the laboratory. The real components used are Krytar 90º hybrid coupler and Aeroflex two-way in-phase power divider. Each component constituting the multi-port reflectometer is not operated in error-free state in wideband frequency range. Thus, in order to offer accurate measurement of any Device Under Test (DUT) using wideband multi-port reflectometer, a suitable error correction procedure or known as calibration is implemented. A variety of loads have been used as DUT in order to verify the proposed error correction method. A one-port error model with three standards and Least Mean Square (LMS) technique have been applied to the proposed multi-port reflectometer. Through that, any imperfect operation of the wideband multi-port reflectometer is removed. By implementing the proposed error correction method, the imperfect operation of the multi-port reflectometer has successfully been corrected and an accurate wideband performance with fully error correction can be offered. Therefore, the multi-port reflectometer achieves the desired value of its operation.

ABSTRAK

Aplikasi pengimejan gelombang mikro mempunyai permintaan yang besar dalam beberapa tahun kebelakangan ini dengan mempunyai kepentingan seperti dalam bidang perubatan, perindustrian dan ketenteraan. Dalam kebanyakan penyelidikan aplikasi pengimejan gelombang mikro, Rangkaian Penganalisis Vektor (VNA) sering digunakan untuk bertindak sebagai pemancar dan penerima bagi membolehkan pengukuran nisbah kompleks antara dua isyarat gelombang mikro dan juga menyediakan ukuran tepat untuk parameter yang terpantul dan berselerak, tetapi ia bersaiz besar dan mahal. Maka, dalam kajian ini, peranti pengukuran mudah alih kos rendah iaitu reflektometer pelbagai-*port* dicadangkan sebagai alternatif kepada VNA dalam sistem pengimejan. Konfigurasi peranti ini dibentuk oleh empat pengganding dan dua pembahagi kuasa dalam julat operasi frekuensi jalur lebar di antara 1 dan 6 GHz. Penyelidikan operasi reflektometer dicapai melalui simulasi menggunakan komponen-komponen yang sedia ada di dalam perisian Agilent's *Advance Design System* (ADS) dan pengukuran komponen sebenar dalam makmal. Komponen sebenar yang diguna adalah 90º hibrid pengganding Krytar dan pembahagi kuasa dalam fasa Aeroflex. Setiap komponen yang membentuk reflektometer pelbagai-*port* tidak beroperasi dalam keadaan bebas ralat dalam julat frekuensi jalur lebar. Oleh itu, dalam usaha untuk menawarkan pengukuran tepat bagi Peranti Yang Diukur (DUT), prosedur pembetulan ralat atau dikenali sebagai kalibrasi yang sesuai dilaksanakan. Pelbagai beban telah digunakan sebagai DUT untuk mengesahkan cadangan kaedah pembetulan ralat. Model ralat satu-*port* dengan tiga piawaian dan penggunaan teknik Min Kuasa Dua Terkecil (LMS) telah digunakan untuk reflektometer pelbagai-*port* yang dicadangkan. Melalui itu, mana-mana operasi yang tidak sempurna pada jalur lebar reflektometer pelbagai-*port* disingkirkan. Dengan melaksanakan prosedur pembetulan ralat yang dicadangkan, operasi yang tidak sempurna bagi reflektometer pelbagai-*port* telah berjaya dibetulkan dan prestasi jalur lebar yang tepat dengan pembetulan ralat sepenuhnya boleh ditawarkan. Oleh itu, reflektometer pelbagai-*port* mencapai nilai operasi yang dikehendakinya.

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LIST OF ABBREVIATIONS

MRI	-	Microwave Resonance Imaging
VNA	-	Vector Network Analyzer
DUT	-	Device Under Test
ADS	-	Agilent’s Advance Design System
WHO	-	World Health Organization
CT	-	Computerized Tomography
LMS	-	Least Mean Square
CRMU	-	Complex Ratio Measuring Unit
CRD	-	Complex Ratio Detector
TLS	-	Total Least Square
TLMS	-	Total Least Mean Square
RLS	-	Recursive Least Square
MSE	-	Minimum Mean Square Error
NLMS	-	Normalised LMS
BLMS	-	Block LMS
SLMS	-	Sign LMS
EDA	-	Electronic Design Automation
RF	-	Radio Frequency

MDIF	-	Measurement Data Interchange Format
CITI	-	Common Instrumentation Transfer and Interchange
IC-CAP	-	Integrated Circuit Characterization and Analysis Program

LIST OF SYMBOLS

Q	-	Coupler
D	-	Power divider
Γ	-	Reflection coefficient
a	-	Reflected signal
b	-	Incident signal
A-H	-	Unknown complex constants
b_i	-	Signal voltages at output ports
P_i	-	Power values
α_i	-	Real constants
c_i	-	Real constants
s_i	-	Real constants
β_i	-	Real constants
q_i		Centre of power circles (q-points)
V_o	-	Input voltage
μ	-	Learning rate
R	-	Output of the perceptron
C_j	-	Current test inputs
$y(k)$	-	Estimated output
$X(k)$	-	Input signal

W(k)	-	Weight vector
d(k)	-	Desired output
e(k)	-	Error
W(k+1)	-	Weight update
C_N	-	Voltage coupling coefficient
C_0	-	Voltage coupling vector
Z_{oo}	-	Odd-mode Characteristic Impedance
Z_{oe}	-	Even-mode Characteristic Impedance
L_N	-	Length
W_N	-	Width
S_N	-	Spacing
λ	-	Wavelength of transmission line
c	-	Speed of light
f	-	Frequency
ε_e	-	Effective relative permittivity
ε_r	-	Relative permittivity
d	-	Substrate thickness
Z	-	Impedance
E_D	-	Directivity error
E_R	-	Reflection signal path error
E_S	-	Source match

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter discusses the basic overview with regard to the error correction method study of the wideband multi-port reflectometer for microwave imaging application. The problem statements and motivations, research objectives, scope and contributions, and the thesis outline are presented.

1.1 Introduction

Particularly, in most reviewed research of the microwave imaging applications, [1-8] Vector Network Analyzer (VNA) was frequently used to act as receiver and transmitter in purpose to measure the complex ratio between two microwave signals. As can be seen in Figure 1.1, the developed working prototype of microwave imaging system using conventional Vector Network Analyzer (VNA) has been demonstrated in [3].

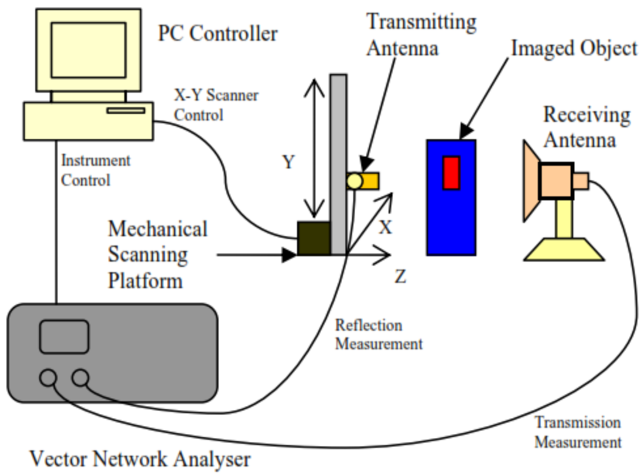

Figure 1.1: The configuration of the microwave imaging system using conventional Vector Network Analyzer (VNA) [3]

This instrument provides an accurate measurement of the reflected and scattering parameters but it has large size and high cost. In contrast, the demands of many applications nowadays are requiring compact size and low-cost measurement instruments. Therefore, in this research there is a need to replace it by a portable low-cost measurement instrument namely multi-port reflectometer [4-8]. It is considered to have a long-term stability of operation with no requirement of the phased locked source [7].

Multi-port reflectometer is a low-cost measurement instrument that formed by passive components of couplers and power dividers that accomplish such measurement of a complex ratio between reflected and incident waves known as reflection coefficient, Γ at an input port of a uniform transmission terminated line. Two ports of the multi-port reflectometer are allocated for a power source and device under test (DUT) and at least having three output ports, which are terminated in scalar power detectors [7]. With this characteristic, the information of reflected and scattering parameters of an object that is to be detected and imaged can be obtained [9]. The configuration of the microwave imaging system in which a multi-port reflectometer replaces the conventional VNA is shown in the following Figure 1.2.

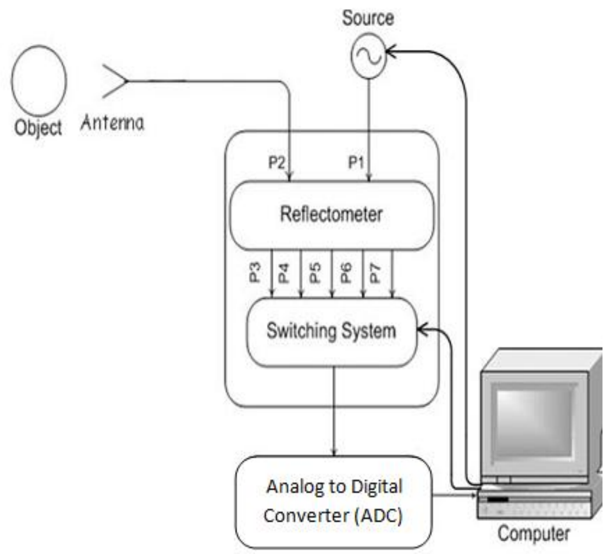

Figure 1.2: Microwave imaging system with the use of a stand-alone multi-port reflectometer replacing conventional VNA [9]

In this research, the multi-port reflectometer is aimed to operate in the wideband frequency band, which is 1 to 6 GHz. Particularly, the concerned application in this research is the microwave imaging for human head. In microwave imaging, a microwave image can be obtained by generating and receiving short pulses at the various locations of the probe antenna at many viewing angles and frequencies [1]. These short pulses can be produced in frequency domain by applying the step-frequency pulses synthesis technique. This principle can be explained as the Fourier Transform of a signal that having a constant power spectral density in certain bandwidth. This constant power spectral density is equivalent to the pulse signal of sinc function shape in time domain [1]. The frequency operation of the multi-port reflectometer has been decided based on this application of the human head.

The operation of such multi-port reflectometer is accessed via simulation using existing components in Agilent's Advance Design System (ADS) software and real practical hardware measurement in laboratory. The chosen real components are Krytar 90º hybrid coupler and Aeroflex two-way in-phase power divider.

The performances of the multi-port reflectometer are investigated based on S-parameter, phase characteristics, centre of the power circle (q-points) and magnitude of the complex reflection coefficients. The proposed configuration of multi-port reflectometer in this research is formed by four 3-dB couplers (Q) and two power dividers (D). The multi-port reflectometer needs to be operated in error-free state condition in order to offer accurate measurement of any DUT. Any imperfect operation of the characteristic of an individual components that forming multi-port reflectometer can be removed by implementing a suitable error correction method or known as calibration. There are various methods for correcting error of such device. Therefore, the study of the error correction method of the multi-port reflectometer is important, that will be presented and discussed. The differences between these error correction methods are including the number of standards, restrictions on the type of standards and also the amount of computational effort needed [10].

In this research, one-port error model with three standards of match, open and short can be used as initial step of the error correction procedure for multi-port reflectometer. Then, it will be followed by adopting the Least Means Square (LMS) algorithm. These two types of the error correction methods will take the responsibility in removing the imperfect operation of the multi-port reflectometer. The details of the error correction methods will be reviewed in the Chapter 2. Meanwhile, the next section will discuss the problem statements of this research.

1.2 Problem Statements and Motivations

Commonly, the conventional Vector Network Analyzer (VNA) was frequently been used [4-7] in the working prototypes of the microwave imaging applications in purpose to act as the receiver and transmitter. This measurement instrument allows the measurement of the complex ratio between two microwave signals (reflection coefficient) in microwave imaging application but, it has large size, expensive and limited used in some laboratory environment only. Meanwhile, many microwave imaging applications in medical, industrial and military [1] currently require low-cost measurement instrument and compact-size. Therefore, in this research; the multi-port reflectometer is proposed as an alternative measurement instrument to the common VNA.

One potential application that can used multi-port reflectometer as an alternative measurement in its systems is microwave imaging. A significant interest has been shown in applying a microwave imaging technique for imaging of human body in medical application as an alternative approach to X-ray mammography and Microwave Resonance Imaging (MRI) [2], [11-13]. In microwave imaging system, the multi-port reflectometer can act as a transmitter and receiver to offer measurement of scattering parameters of an object that is to be detected or imaged. By using the multi-port reflectometer, the image of target (object) can be constructed through the information of the reflected and scattering parameters. For example, in the application of breast cancer detection, the ground for imaging is difference in the electrical properties of normal and malignant breast tissues. The different electrical property of the malignant tissue to the normal tissue is responsible for the reflection and scattering of an incident signal. From these reflected and scattered signals, the image is constructed at many frequencies and viewing angles [14]. With regard to the works reported in [9] and [21-38], the chosen frequency range that is used in this research is 1 to 6 GHz.

The example setup of the microwave imaging of the human head, which consist of the transmitter or receiver, antenna and phantom can be illustrated as in Figure 1.3 [26]. While, the phantom head with the top half omitted in purpose to show the high detail of the brain matter is illustrated in Figure 1.4.

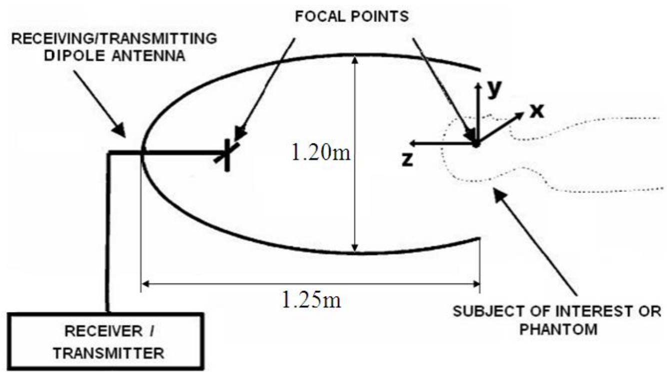

Figure 1.3: Example setup of microwave imaging for human head [26]

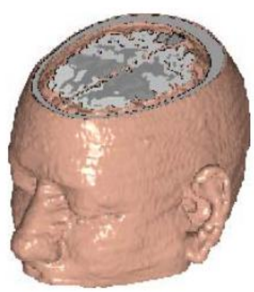

Figure 1.4: Phantom head with the top half omitted to show the high detail of the brain matter [16]

Furthermore, multi-port reflectometer is a measurement instrument device that can be accomplished with two input port for power source and device under test (DUT) and at least three outputs terminated ports in scalar power detectors. It has long-term stability of operations and no longer necessary need the phased locked source [7].

Practically, each of the components constituting multi-port reflectometer does not operate in the ideal state across wideband frequency range. In purpose to eliminate this imperfect characteristic and phase of the wideband multi-port reflectometer, a suitable error correction method or can be known as calibration should be applied. When the multi-port reflectometer operates in wideband frequency range, the overlap of the phase characteristics of the used standards in error correction procedure will be occurred as reported in [33]. With the overlapping phase characteristics of the used standards loads as illustrated in Figure 1.5, the error correction procedure is unable to remove the imperfect characteristics of the wideband multi-port reflectometer. Therefore, inaccurate performance is expected to be occurred at some frequency range.

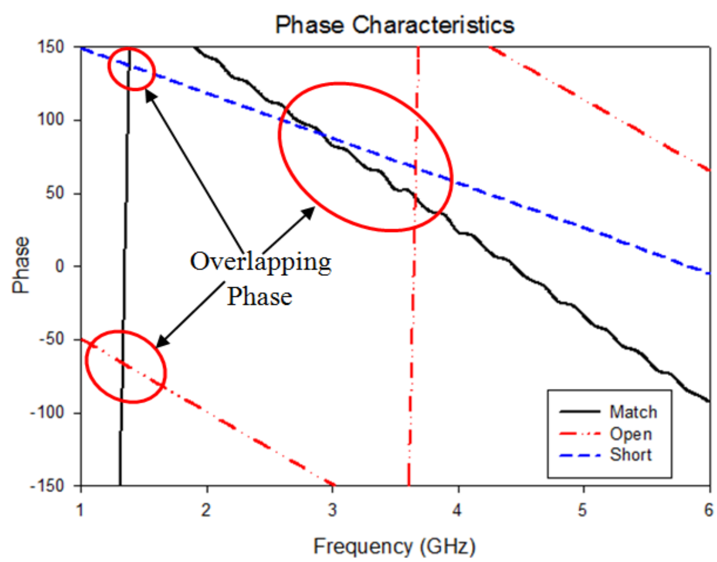

Figure 1.5: The overlapping phase characteristics of the used standards loads

Consequently, to remove the effect of overlapping phase characteristic, it is suggested to adopt Least Mean Square (LMS) technique to the proposed error correction method with the chosen standard loads. The chosen method used in this research is one-port error model with three standards of match, open and short due to its simplicity in the implementation and reliability in order to remove the imperfect operation of multi-port reflectometer [34].

Then, the adopted LMS is considered to be used because it does not required correlation function calculation, low complexity computational, matrix inversion and also easy to be implemented compared to other algorithms [35]. By using these error correction methods, the imperfect operation of multi-port reflectometer should be successfully eliminated.

1.3 Research Objectives

In this research, there are three objectives that need to be met in order to complete the research. The objectives of this research are as follows:

1. To investigate the characteristics and operation of the multi-port reflectometer as an alternative measurement instrument to the common VNA.
2. To eliminate the imperfect characteristics and operations of the multi-port reflectometer by implementing suitable error correction method.
3. To verify the proposed error correction method for multi-port reflectometer device via using a number of loads as DUTs.

1.4 Research Scope and Contributions

In this research, the scope and contributions are resulting as follows in order to achieve the research objectives:

1. Investigation the characteristics and operations of the proposed multi-port reflectometer that formed by passive components.

    i. In simulation stage, the proposed multi-port reflectometer is formed via using existing component in ADS software; which are three-section coupled-line coupler and two-stage Wilkinson power divider.

    ii. In measurement stage, the proposed multi-port reflectometer is formed via using practical measurement instrument in laboratory with real components; which are 90^{o} hybrid coupler, two-way in-phase power divider and cable.

    iii. The investigation characteristics in both simulation and measurement stage are including S-parameter, phase characteristics, and the centre of the power circles (*q*-point).

    iv. The investigation operation in both simulation and measurement stage in term of the reflection coefficients (Γ) is tested via using a number of loads as DUTs. In simulation stage, ithe used loads in ADS simulator are match (50 ohm), open and short circuit, 5, 10, 25, 40, 45, 55, 100 and 950 ohm. While, in measurement stage; the standard loads are match, open and short. Then, followed by a number of the attenuators with short termination and without termination (open-ended) for 1, 3, 6 and 10 dB.

2. Implementation the one-port error model with three standards and Least Mean Square (LMS) technique to remove the imperfect characteristics and operations of the proposed multi-port reflectometer.

3. Verification the proposed error correction method into the operations of the proposed multi-port reflectometer in term reflection coefficient that tested via using a number of loads as DUTs.

For investigation the characteristics and operation of the proposed multi-port reflectometer in simulation stage, the preliminary study of coupler (Q), power divider (D), correlator/CRMU and reflectometer are required to be performed. In order to determine the preliminary results, the Agilent's Design Systems (ADS) software is used to simulate the chosen configurations of the components. The characteristics of coupler and power divider will influence the performance of the multi-port reflectometer across the wideband frequency range. This will demand proper design and optimization to meet the designated specifications.

Afterwards, the coupler and power divider are used to form correlator/CRMU. In purpose to construct a multi-port reflectometer, the additional circuit that consist of a coupler and power divider will be added to correlator/CRMU. The combination of the four 3-dB couplers (Q) and two power dividers (D) is proposed and the performance of the multi-port reflectometer is investigated. A number of loads have been used in order to investigate the characteristics and operations of the multi-port reflectometer in reflection coefficient measurement.

While, for measurement stage in order to investigate the characteristics and operation of the proposed multi-port reflectometer; the multi-port reflectometer is constituted by real components, which are 90^{o} hybrid coupler, two-way in-phase power divider and cable. Then, the experiment is conducted in the laboratory. A number of the attenuators with short termination and without termination (open-ended) have been used as DUT which connected to Port 2 (measurement port) in order to determine the characteristics and operations of the proposed multi-port reflectometer. Then, the obtained measurement results will be compared to the one from VNA.

In addition to that, the characteristics and operation of the multi-port reflectometer are evaluated based on S-parameter (transmission coefficients and return loss), phase characteristics, centre of power circle (*q*-points) and reflection coefficients of DUTs for both simulation and measurement stage. In order to offer a good wideband performance, it requires to be operated in error-free state condition. Therefore, the suitable error correction method needs to be implemented in purpose to eliminate the imperfect operation of the multi-port reflectometer.

In this research, the major contribution is regarding the proposed error correction method. The proposed error correction method is adopting two techniques, which are one-port error model with three standards and Least Mean Square (LMS) technique. In developing good error correction procedure, it is proposed to start with a basic procedure which involving three standards of match, open, and short. By using this error correction procedure, it will remove the imperfect operation of the multi-port reflectometer, but at some frequency points across the wideband frequency range, there are still some error cannot be eliminated due the occurred overlapped phase.

Therefore, the modified LMS algorithm is added to the error correction procedure in order to eliminate the uncorrected operation of the one-port error model with three standards. By using the proposed LMS technique, good characteristics and operation of the multi-port reflectometer can be obtained across wideband frequency range and expected to achieve the desired value.

1.5 Research Outline

A general outline of the contents in this thesis is presented as follows. The first chapter concerns the background and motivation, overview of microwave imaging, problem statements and motivations, research objectives, scope and contributions. Meanwhile, the rest of the chapters will concern the investigation of wideband multi-port reflectometer and the proposed error correction method.

Chapter 2 provides the essential background theory and literature reviews on the related topics of microwave imaging, coupler, power divider, correlator/CRMU, multi-port reflectometer and error correction method. For microwave imaging, the concern is on the human head (brain) imaging. Furthermore, the overview of the multi-port reflectometer configurations also will be reviewed. Besides that, the concepts and basic knowledge of error correction method that highlighting Least Means Square (LMS) algorithm will be described.

Meanwhile, Chapter 3 discusses the methodology and specifications characteristics and operation of the coupler, power divider, CRMU and multi-port reflectometer. Besides that, the preliminary studies of coupler, power divider, correlator/CRMU and multi-port reflectometer also will be presented. In this chapter, the study is based on the existing components of three-section coupled-line coupler and two-stage Wilkinson power divider using Agilent’s Advanced Design System (ADS) software. A number of loads are used in order to evaluate the operations of the multi-port reflectometer. Chapter 4 presents the characterizations and operation of the proposed multi-port reflectometer through the practical measurement in the laboratory. The performances of the characterization and operation of the proposed multi-port reflectometer are observed based on S-parameter responses, phase characteristics, centre of the power circles (q-points) and magnitude reflection coefficients. Meanwhile, Next, Chapter 5 discusses the error correction method for the proposed multi-port reflectometer. In this chapter, the proposed error correction method will be described. A numbers of attenuators with short termination and without termination (open-ended) are used as DUT in order to investigate the operations of the proposed multi-port reflectometer in term of reflection coefficient measurement. Last chapter which is Chapter 6 concerns the discussion and conclusion with regard to the work undertaken in this research and provides brief overview of the possible future works.

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