# THRU-REFLECT-LINE (TRL) CALIBRATION ON MULTILAYER SUBSTRATE INTEGRATED WAVEGUIDE (SIW) FOR X-BAND FREQUENCY RANGE

**by**

**CHA HONG YE**

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ADS | Advanced Design System |
| DUT | Device under test |
| FE | Finite element |
| HFSS | High Frequency Structural Simulator |
| mm-wave | Millimetre-wave |
| MSL | Microstrip line |
| MT | Microstrip transition |
| MTRL | Multiline TRL |
| NA | Network analyser |
| OSL | Open-Short-Load |
| PCB | Printed circuit board |
| RF | Radio frequency |
| RS | Rectangular slot |
| RWG | Rectangular waveguide |
| S-parameters | Scattering-parameters |
| SIW | Substrate integrated waveguide |
| SMA | Surface mount adaptor |
| SOLT | Short-Open-Load-Thru |
| TE | Transverse Electric |
| TM | Transverse Magnetic |
| TRL | Thru-Reflect-Line |

## LIST OF SYMBOLS

**Greek Symbols**

| | |
|---|---|
| $\gamma$ | Complex propagation constant |
| $\varepsilon_{eff}$ | Effective permittivity of dielectric |
| $\varepsilon_r$ | Permittivity of dielectric |
| $\alpha$ | Attenuation loss |
| $\lambda_c$ | Cut-off wavelength |
| $\lambda_g$ | Guided wavelength |

**Variables**

| | |
|---|---|
| $A_g$ | Width of waveguide |
| $a_r$ | Centre to centre distance between vias of parallel rows |
| $c$ | Speed of light |
| $f_c$ | Cut-off frequency |
| $h$ | Height of substrate |
| $l_{t\text{-}v}$ | Taper-via's length |
| $p$ | Separation distance between vias |
| $p_1$ | Distance between taper- via and SIW via |
| $R$ | Resistor value |
| $r$ | Radius of vias hole |
| $T_A$ | Fixtures of port A in T-parameters |
| $T_B$ | Fixtures of port B in T-parameters |
| $T_M$ | Measurement matrix of the product of error boxes and the unknown DUT |
| $w_1$ | Distance between taper-via |

| | |
|---|---|
| $W_m$ | Width of MSL |
| $w_{t\text{-}v}$ | Taper-via's width |
| $Z_0$ | Characteristic impedance |

**PENENTUKARAN TERUSAN-PANTULAN-GARISAN UNTUK PELBAGAI LAPISAN SUBSTRAT BERSEPADU PANDU GELOMBANG BAGI JARAK FREKUENSI KUMPULAN-X**

## ABSTRAK

Parameter S (S-parameter) adalah penting untuk dinilai untuk memastikan prototaip boleh direka mengikut spesifikasi. Pelbagai kaedah penentukuran telah digunakan untuk penganalisis rangkaian untuk mendapatkan parameter S, seperti pendek-buka-beban-terusan (SOLT) dan terusan-pantulan-bebanan (TRL). Substrat bersepadu pandu gelombang (SIW) menunjukkan kehilangan yang rendah, saiz padat, dan kemudahan untuk integrasi dengan litar planar. Dalam kajian ini, penentukuran MTRL dicadangkan untuk meramalkan lapisan tunggal dan pelbagai lapisan SIW. Parameter S bagi prototaip diukur oleh MTRL kit dicadangkan dan dibandingkan dengan kit komersial SOLT, dan disahkan oleh keputusan FE. Lima parameter reka bentuk yang berlainan bagi prototaip SIW lapisan tunggal dan satu pelbagai lapisan SIW dengan slot segi empat telah diukur dan dianalisis. Hasil perbandingan antara model MTRL, SOLT dan FE untuk satu lapisan SIW dibincangkan dan dianalisis. Penentukuran MTRL pada satu lapisan SIW menunjukkan sisihan 0% - 5.0% dari frekuensi pusat, jalur lebar operasi yang lebih besar dan kehilangan sisipan yang lebih dekat dengan model FE. Selain itu, persetujuan yang baik dicapai antara model FE dan keputusan percubaan menggunakan penentukuran MTRL untuk dwilapisan SIW dengan slot segi empat. Model dwiapisan SIW menunjukkan empat frekuensi resonan yang berbeza dengan kehilangan sisipan 2.71 dB. Pengukuran yang diperoleh menggunakan kaedah SOLT memaparkan tiga kekerapan resonans yang berbeza dengan kehilangan sisipan 3.41 dB. Sebaliknya, pengukuran yang diperoleh menggunakan penentukuran MTRL memaparkan empat frekuensi resonan yang berlainan dan kehilangan sisipan 2.87 dB. Berdasarkan penemuan ini, kalibrasi MTRL meramalkan lebih tepat berkaitan dengan SIW tunggal dan multi lapisan dengan kekerapan resonan yang hampir dan kehilangan sisipan yang rendah berbanding dengan kaedah SOLT.

**THRU-REFLECT-LINE (TRL) CALIBRATION ON MULTILAYER SUBSTRATE INTEGRATED WAVEGUIDE (SIW) FOR X-BAND FREQUENCY RANGE**

## ABSTRACT

Scattering-parameters (S-parameters) are important to be evaluated in order to ascertain the hardware prototype can be designed according to the specifications. Various calibration methods have been applied to the network analyser to obtain the S-parameters, such as *short-open-load-thru* (SOLT) and *thru-reflect-line* (TRL). Substrate integrated waveguide (SIW) demonstrates low loss, compact size, and ease for integration with the planar circuits. In this research, MTRL calibration is proposed to predict the single- and multilayer- SIW. The analytical modelling of MTRL calibration, and the FE models of the prototypes are discussed and simulated. The S-parameters, such as insertion loss, bandwidth, and resonant frequency, can be measured in the frequency range of 8.0 GHz – 13.0 GHz. The S-parameters of the prototype are measured by the proposed MTRL kits and compared with commercial SOLT kits, and validated by FE results. The comparison results between MTRL, SOLT and FE models for single layer SIW are discussed and analysed. MTRL calibration on single layer SIW shows deviation of 0 % - 5.0 % of centre frequency, larger operating bandwidth and closer insertion loss with respect to FE models. Moreover, a good agreement is achieved between the FE model and experimental results using MTRL calibration for double layer SIW with rectangular slot. A finite model of double layer SIW with rectangular slot shows four different resonant frequencies with 2.71 dB insertion loss. The measurement obtained using the SOLT method displays three different resonant frequencies with 3.41 dB insertion loss. In contrast, the measurement obtained using MTRL calibration displays four different resonant frequencies and 2.87 dB insertion loss. Based on these findings, MTRL calibration predicts more accurately pertaining to single- and multi- layer SIW with close resonant frequencies and low insertion loss as compared with that of the SOLT method.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

The development of millimetre-wave (mm-wave) integration technologies is essential for the evolution of wireless system and utilised electromagnetics in future. In fact, a variety of application has been proposed in GHz frequency range, which are wireless network [1], automatic radar [2], imaging sensors [2], and biomedical device [3]. In many of these systems, there are several aspects such that the availability of cost effective technology which is suitable to mass production of wireless system [4]. It is predictable that ease of integration technique together with cost effective fabrication process should offer solution for commercial planar circuit application. Planar mm-wave circuits that commonly explored by researcher are microstrip [5], waveguide [6] , and substrate integrated waveguide (SIW) [7].

Microstrip components such as antennas, filters, and power divider are widely used, owing to their advantages of electrical properties in broadband frequency, i.e., MHz frequency range [5]. Besides that, industrial sector has high interest in microstrip for commercial purposes because microstrip are generally economical to be fabricated and advantage of interconnection with other active or passive circuits [8]. Moreover, microstrip features compact size and lightweight which considerable by industrial sector for reduce packaging and assembly problems that are major concern in current mm-wave equipment [2].

Other than microstrip components, metallic waveguides are typical transmission medium for radar, radio astronomy, imaging systems, medical diagnosis, spectral analysis, and high-bandwidth wireless communications [9]. This is because waveguides exhibit low insertion loss, low return loss, and high power capability when compared with planar transmission line at GHz frequency range [10]. The metallic waveguides can be fabricated by utilizing electrical discharge machining equipment with extremely high precision [11]. This fabrication accuracy requirements become more strict when dealing with resonant structures of waveguides [12].

From the findings, SIW technology provides new approach in the mm-wave applications which are the emerging of the advantages of waveguides and microstrip [4]. Bozzi et al. (2009) reported that the SIW with the whole systems, combining passive components (filters, couplers, and antennas), active components (amplifiers, oscillators, and mixers) can be integrated on same substrate. This solution gains high interest in different market sectors, especially in aerospace and industrial [6]. Then, this solution allows the components to be designed in a significant reduction in size; moreover, the losses are lower than that in microstrip component, especially in GHz frequency [13]. Furthermore, there are no radiation and packaging problems in SIW technology [13].

Concerning the passive circuits, the most common measurement task in radio frequency (RF) and mm-wave engineering involve the analysis of electrical performance for passive circuit using a network analyser (NA) [14]. The electrical performances of experimental passive circuits can be evaluated through the scattering-parameter (S-parameters) from the NA [15]. The S-parameters are chosen because they are easy to derive at high frequencies, and related to measurement parameters such as bandwidth, resonant frequency, and insertion loss which gain interest to RF engineers [14]. However, planar circuits without fixtures are difficult to be measured by network analyser (NA) for the reason that fixtures are required to provide electrical and physical connection between the planar circuits and the network analyser (NA) [16]. Additionally, ideal fixtures allow direct measurement of planar circuits, without any losses and mismatch from fixtures [17]. Nevertheless, ideal fixtures are impossible to be realised in reality because it allows other signals from the surrounding to interfere the measurement [18]. Subsequently, the S-parameters of fixtures are introduced into the experimental result as errors [19].

The aforementioned S-parameters without the effects of fixtures are preferred [20]. The S-parameters of fixtures are mathematically removed from entire measurement of the prototype by calibration process [21]. Calibration process employed technique called calibration method, which the fixture effects are characterized using known standards [22]. There are two types of calibration methods which are *short-open-load-thru* (SOLT) method and *thru-reflect-line* (TRL) approach. Hence, this thesis focus on the research of different calibration methods applied to NA in order to separate the effects of fixtures from the measured S-parameters of the prototype.

## 1.2 Problem Statement

Conventionally, SOLT method has been widely used by researcher as standard calibration technique to predict the S-parameter of entire prototype [23]. However, the entire S-parameters of the prototype are measured that include the device under test (DUT) and its complimentary fixtures [19]. Moreover, SOLT method produced extremely high return loss and inaccurate experimental results in microstrip, especially in GHz frequency [12], [23], [24].

In the literature, many research studies relating to TRL aprroach were found in [17], [22], [25]. That approach has been employed for coaxial, on-wafer, and waveguide [25]. Nevertheless, TRL calibration predicted significantly high insertion loss result in microstrip [23]. Additionally, the implementation of waveguide on TRL calibration are expensive, bulky volume, and difficult to be integrated with the planar circuits [18], [26].

In contrast, the substrate integrated waveguide (SIW) exhibited low loss, compact size, and ease for integration with the planar circuits [4], [13]. Hence, SIW shown better electrical and physical properties as compared with microstrip and waveguide component [4], [13]. Interestingly, Kumar et al. (2012) reported that the TRL approach produced an accurate result with low insertion loss for single layer SIW [27]. However, the approach cannot be employed to predict the result in multilayer SIW, owing to the high insertion loss [27].

As pointed out in [28]–[30], the complex propagation constant, $\gamma$, of *line* standards of TRL approach provide more accurate result in locating the location of reference plane precisely. Different *line* standards produce various complex propagation constants in diversify frequency ranges [28]. It was reported that the more complex propagation is considered, the result predicted by TRL calibration will be more accurate [29]. Thus, additional *line* standards in TRL calibration formed Multiline TRL (MTRL) calibration [30].

Therefore, MTRL calibration that utilized to predict the S-parameters of single- and multi- layer SIW are proposed in this research. The motivation on our work hinges on de-embedding the S-parameters of the DUTs without consider the fixtures by employing the proposed MTRL calibration.

### 1.3 Aims and Objective

The aim of this research is to demonstrate the MTRL calibration for single- and multi- layer SIW within X-band frequency range that can predict the S-parameters result of DUT accurately. In order to achieve this aim, several objectives listed below have to be carried out. The objectives are listed as below:

- To propose and model equivalent circuit of MTRL standards, single- and multi-layer SIW that operates in multiband frequency range.
- To design and simulate the FE models of MTRL standards, single- and multi- layer SIW using ANSYS HFSS software.
- To fabricate and measure the experimental S-parameters result obtained by MTRL calibration with that obtained by SOLT method, and justify by FE simulated results.

### 1.4 Research Scope

The scope of this research mainly is confined on the equivalent circuit models of MTRL standards, single- and multi- layer SIW for predicting and evaluating their electrical properties that can be employed to determine the best performances for FE models. This is an emerging research topic, and has attract a lot interest among radio frequency (RF) engineers. In this thesis, MTRL calibration that utilized in predicting the S-parameters of single- and multi- layer SIW are proposed, their simulated and experimental results are analysed and discussed. Moreover, the simulated FE results of DUTs include different physical dimension of single layer SIW and multilayer SIW with rectangular slot are designed and simulated within 8.0 GHz – 13.0 GHz frequency range.

Next, the DUT for two-port network with desired performance are necessary to interconnect with fixtures at both port before characterization process. Fixtures such as surface mount adaptor (SMA) and microstrip transition are commonly employed in planar design. The hardware prototypes to be measured are including DUTs with fixtures are fabricated on PCB. Moreover, the proposed MTRL calibration kits that include fixtures are fabricated on the same material as the DUT. That calibration requires known definition standards before de-embedding process. Lastly, the result predicted by hardware prototypes using proposed MTRL calibration kits and commercial SOLT kits are compared, which are then justified by FE models and equivalent circuit models. The comparison results are important to ascertain the precision and effectiveness of proposed MTRL calibration with commercial calibration kits.

Moreover, the specifications of the material and the availability of calibration kits is considered. The material used in this research is RO4003C with relative permittivity of 3.38, thickness of 0.813 mm and loss tangent of 0.0027. The design specifications are limited by the provided specification of material in which the thickness and permittivity of material influence the physical dimension. In order to be supported by RO4003C material and SMA, the centre frequency at 10.00 GHz is chosen. Moreover, the calibration kits provided are the 85056D calibration kits with 2.40 mm SMA which are used to calibrate PNA-X N5242A, network analyser.

## 1.5 Thesis Contribution

The research present in this thesis has three contributions, as follow:

- The equivalent circuit models of single- and double- layer SIW are presented, verifed by simulated FE result, and justified by the experimental results predicted by proposed MTRL calibration and SOLT method.
- The modelling of fixtures that representing the SMA and microstrip transition are presented; the equivalent circuits that include SMA, microstrip transition and DUTs are presented and compared with the hardware prototype.
- The details to design taper-via transition together with microstrip line and DUTs are decribed and shown promising electrical performances; implementation of taper-via transition in proposed MTRL calibration are presented.

## 1.6 Outline

In this thesis, there are five main chapters covering the introduction, literature review, methodology, results and discussion, and conclusion of research.

Chapter 2 provides a comprehensive review of calibration methods. Various calibration technique applied to NA are discussed. The advantages and disadvantages of each calibration approach are compared. Additionally, this chapter provides review of previous technology which are microstrip line, waveguide and SIW. Relevant literature on previous research on SIW with details on design parameters, formulae and advantages are elucidated.

Chapter 3 explains the research methodology to achieve all the research objectives accordingly. Equivalent circuit model, finite element model, hardware prototype design, and measurement procedure with proposed MTRL calibration are included. Firstly, the equivalent circuit model represents DUTs and fixtures are stimulated in ADS software, respectively. Then the design parameters of FE model computed by mathematical formulae are simulated in ANSYS HFSS software. Subsequently, the DUTs with optimum design parameters are integrated with microstrip line and taper-via transition are characterized. The proposed MTRL calibration standards with specific requirements are also integrated with microstrip line and taper-via transition. Lastly, MTRL calibration procedures on NA are performed and achieved with the prototype of MTRL calibration kits.

Chapter 4 provides the details analyses and discussion on all results obtained from the equivalent circuit model, FE model, experimental result of SOLT method and proposed MTRL calibration. Initially, the comparison results between equivalent circuits of SMA, microstrip transition and DUT with measured hardware prototype are discussed. Besides that, the comparison results between circuit model, FE model and prototype of *thru*, *reflect* and *line* standard are analysed. Moreover, the experimental results of DUTs which are single layer SIW with different physical parameters and double layer SIW with rectangular slot are compared with circuit models, and verified by FE results. These results are obtained in form S-parameters and compared within X-band frequency range in terms of resonant frequency, bandwidth and insertion loss. Furthermore, the comparison between obtained results with conventional results are also discussed in this chapter.

Finally, conclusion are drawn in Chapter 5. A number of future work and recommendation are included in this chapter.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Introduction

In Chapter 2, the objectives of this project is to model the TRL calibration standard for de-embedding process and the equivalent circuit model for SIW for single- and multi- layer. The design of SIW start with equivalent circuit model, and then finite element (FE) model. Also, the implementing de-embedding technique throughout the research is emphasized to determine the fixture characteristics of prototype by mathematical equations. By de-embedding SIW from the prototype, the S-parameters will be obtained and plotted.

Here, details of calibration methods and standards are discussed. The equations on the designing the SIW are also discussed. Also, these expectations are used as design specifications to produce SIW model in this project. Furthermore, methods of determining the S-parameter of SIW are explained.

## 2.2 Calibration

Calibration is a process in which network analyser (NA) measures test devices and stores the vector differences between the measured values and actual values [31]. In order to ensure the accuracy of measured data, NA must be calibrated before carry out any measurement for one-, two- or more- port [26]. The types of calibration methods are different in environment and the standards used [32].

The types of calibration methods are selected accordingly with the test setup, which the required parameters provided by known standards are measured [33]. After measuring the standards according to calibration methods, the error terms are and can be removed from entire measured S-parameters [26]. Hence, calibration process de-embeds the imperfections by measuring known standard as the error terms can be isolated, quantified and mathematically removed [19].