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Development of Compact P-Band Vector Reflectometer

Yi Lung Then[1], Kok Yeow You[2], Ming Hao Lee[3], Chia Yew Lee[4]
[1]Electrical and Electronic Engineering Department, Faculty of Engineering, Computing and Science, Swinburne University of Technology, Sarawak Campus, 93350 Kuching, Malaysia
[2,3,4]Communication Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81300 UTM Skudai, Malaysia

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ABSTRACT

A compact and low cost portable vector reflectometer is designed for a reliable measurement of reflection coefficient, S_{11}. This reflectometer focuses on return loss measurement of frequency ranges from 450 MHz to 550 MHz. The detection of magnitude and phase is based on the utilization of surface mount Analog Devices AD8302 gain/phase detector. The data acquisition is controlled by using Arduino-Nano 3.0 microcontroller, with the use of two analog to digital converter (ADC) and a digital to analog converter (DAC). One port (Open, short and matched load) calibration technique is used to eliminate systematic errors prior to data acquisition. The evaluation of the reflectometer is done by comparing the result of the measurement to that of vector network analyzer.

Corresponding Author:

Kok Yeow You,
Communication Engineering Department,
Faculty of Electrical Engineering,
Universiti Teknologi Malaysia, 81300 UTM Skudai, Malaysia.
Email: kyyou@fke.utm.my

1. INTRODUCTION

The demand for analysis and measurement equipment for microwave device is rather promising due to the rapid development of communication devices. Existing equipment for measuring parameters, specifically the S-parameters in high frequency circuits or radio frequency (RF) devices, such as network analyzers are too costly and bulky to be portable for handheld measurement purposes. As an alternative to this matter, a more compact and low cost reflectometer is developed for reliable measurement of reflection coefficient, S_{11} or so-called return loss.

Reflection coefficient is the complex ratio of reflected voltage, V_r to incident voltage V_i, from which the operating frequency and response of a device under test (DUT) over a range of frequency is determined. In other words, reflectometer measures how much power is reflected from the DUT with reference to the incident power.

Some of the earlier researches were on the development of six-ports vector reflectometers for industrial purposes covering frequency from 2.2 GHz to 2.7 GHz, especially for determining operating frequency of microwave device and assist in impedance matching [1]. The six-port reflectometer obtained phase reading by deducing from the power measurement readings at several ports based on the idea of phase-shift interferometry. However, there are some of crucial issues with six-port reflectometer, such as complicated calibration and requirement of complex computation to obtain the actual measurement. Therefore, some modifications are implemented by simplifying the complexity of circuit to fewer ports, which lead to four-port reflectometer which utilizes a single detector [2] and able to operate in both reflection and transmission modes.

After that, research continued for the design of reflectometer applicable for higher frequency, at millimeter wave up to 100 GHz [3] due to the fact that not many existing network analyzers at that time are capable of measurement up to such a high frequency. Recent works show an increase interest on researches on design of reflectometers for specific applications. Some of the applications include aqueous concentration measurement [4], moisture monitoring of building [5] and soil quality processing [6]. At the same time, computer interfaces and LCD displays are implemented together with the reflectometer system to ease data analysis and interpretation [7-9]. Surface mounted device (SMD) are started to be implemented in the design of reflectometer especially for industrial, scientific and medical (ISM) band applications [8-9]. Another highlight is self-calibrating reflectometer system introduced to obtain more consistent and accurate measurement without the need for manual calibration [5].

This paper proposed a compact single port reflectometer with only one output port for DUT and one detector for magnitude and phase measurement. The reflectometer utilizes surface mounted integrated circuit AD8302 for the detection of magnitude and phase of the reflection coefficient. Frequency range for this reflectometer is from 450 MHz to 550 MHz. A microcontroller Arduino Nano 3.0 controls the analog to digital converters (ADC) and digital to analog converter (DAC) for data acquisition. Hardware implementation for this project involves fabrication of reflectometer prototype by assembling voltage controlled oscillator, bidirectional coupler and detector. Two ADC and a DAC are fabricated to enable controlling by using microcontroller, followed by fabrication of main board for the microcontroller and its peripherals. Software implementation includes programming of microcontroller to obtain measurement result.

2. SINGLE PORT REFLECTOMETER

The design of the reflectometer is done by utilizing a voltage controlled oscillator (VCO), a bidirectional coupler and an AD8302 gain/phase detector. The VCO is capable of generating signals with frequency ranges from 450 MHz to 550 MHz, by supplying tuning voltage from 0.5V to 5.0V. The bidirectional coupler operates with low mainline loss of 0.02 dB under normal conditions and a maximum of 0.2dB in worst case. AD8302 enables detection of both magnitude and phase at the same time, with scaling slope of 28.7mV/dB and 10.1mV/Degree respectively [10].

The expression of the magnitude output voltage and phase output voltage in ideal cases are shown in Equation (1) and Equation (2) respectively.

$$V_{mag} = V_{SLP} \log\left(V_{INA} / V_{INB}\right) \quad (1)$$

$$V_{PHS} = V_{\Phi} \left[\left|\Phi\left(V_{INA}\right) - \Phi\left(V_{INB}\right)\right|\right] \quad (2)$$

where V_{SLP} is the slope of voltage to magnitude, V_{Φ} is the slope of voltage to phase, V_{INB} is the incident voltage and V_{INA} is the reflected voltage [10].

The tuning voltage of the VCO is controlled by the microcontroller Arduino Nano 3.0 with the aid of a DAC. The magnitude and phase voltages detected by AD8302 are input to the microcontroller through ADCs for analysis. In this project, 24-bit resolution LT2440 is used as ADC and 1024-position AD5292 is used as DAC to obtain precise measurement. The data transfer between the microcontroller with DAC and ADCs is achieved by using master in slave out (MISO) and master out slave in (MOSI) ports within the serial peripheral interface (SPI) of Arduino. The prototype of the fabricated reflectometer is illustrated in the block diagram in Figure 1.

During measurement of reflection coefficient using the prototype, microcontroller will apply a tuning voltage to the VCO through DAC so as to generate signal with a certain frequency. The incident voltage of the generated signal, V_i will have a portion of it coupled to the detector through bidirectional coupler, while the rest of it will be guided to the DUT. Some of the signal will be transmitted and propagated at the DUT whereas some will be reflected back to the port, according to the performance of the DUT. The reflected signal, V_r will be coupled to the detector through bidirectional coupler. At AD8302 gain/phase detector, the output voltages proportional to the ratio of the reflected voltage to incident voltage in decibels, V_{MAG} as well as the phase difference, V_{PHS} will be generated based on the incident and reflected voltages input. The output voltages V_{MAG} and V_{PHS} are then input to the microcontroller through two individual ADCs via SPI interface of the Arduino microcontroller. The process of data acquisition is controlled by computer USB interface using microcontroller.

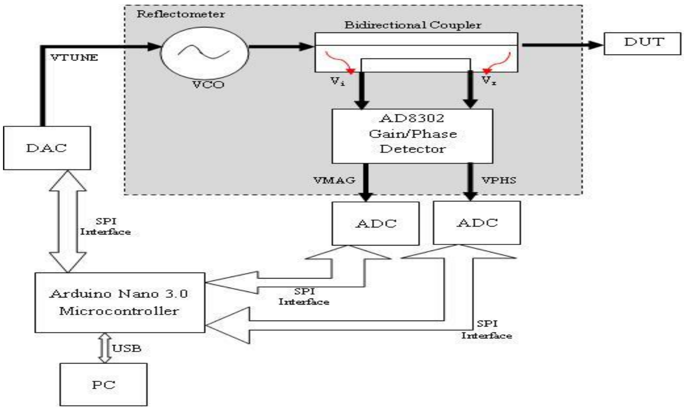

Figure 1. Block diagram of the fabricated reflectometer prototype

In this project, V_{INA} is used as incident voltage and V_{INB} is used as reflected voltage. Therefore, the magnitude of reflection coefficient can be derived from Equation (1) as shown in Equation (3).

$$|\Gamma|_{dB} = \frac{V_{mag} - 0.9V}{V_{SLP}} = \frac{V_{mag} - 0.9V}{-28.7mV} \quad (3)$$

However, due to the limitation of the detector, the phase values detected are in the form of absolute phase, without positive or negative sign. The absolute phase was calculated using Equation (4).

$$|\angle\Gamma| = \frac{V_{phs} - 1.8V}{V_{\Phi}} = \frac{V_{phs} - 1.8V}{-10.1mV} \quad (4)$$

Therefore, in order to determine the sign of the measured phase, an algorithm is required to be implemented in MATLAB. In that algorithm, the phase of next frequency was compared with the phase of current frequency as shown in the program code below.

```
for n=1:1:sample-1
if (phaseact(n+1)-phaseact(n))>=0

        M_prePhase3(n,1)=-phaseact(n);

else (phaseact(n+1)-phaseact(n))<0

        M_prePhase3(n,1)=phaseact(n);
end
end
```

If the phase of the next frequency is greater than the current frequency, the sign of negative phase will be assigned. On the other hand, if the phase of the next frequency is smaller than the current frequency, the sign of positive phase will be assigned. Figure 2 shows the fabricated single port reflectometer.

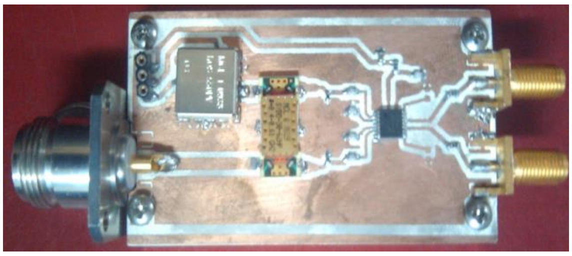

Figure 2. The fabricated single port reflectometer

Figure 3 shows the reflectometer system which include microcontroller, ADC and DAC.

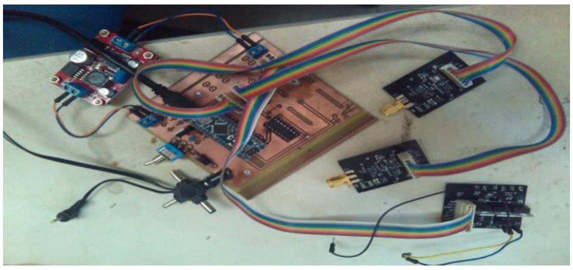

Figure 3. The reflectometer system which include microcontroller, ADC and DAC

3. ONE PORT (OPEN, SHORT AND LOAD) CALIBRATION

The reflection coefficient measured at the DUT port without calibration may not be accurate as it takes all the reflections in the system and the components into account [12]. Therefore, in order to obtain accurate reflection coefficient considering the DUT solely, calibration is essential to eliminate or minimize systematic errors due to the components of the reflectometer. One port calibration is done by taking the reflection coefficient measurement of three known standards, namely open, short and matched load (OSL), and then obtains three correction factors for the calculation of the actual reflection coefficient.

OSL calibration standard is the most common standard for one port measurement. In order to achieve precise measurement through calibration, the three open, short and matched (50Ω) load, are connected to the DUT port progressively and the respective measurements of reflection coefficient are recorded. After that, the known actual values of reflection coefficient for the three standards are used in the calculation of the three correction factors as shown in Equation (6). The actual reflection coefficient, Γ_A is expressed in terms of measured reflection coefficient, Γ_M as shown in Equation (5) below.

$$\Gamma_A = \frac{\Gamma_M - B}{-C\Gamma_M + A} \tag{5}$$

where Γ_A is the actual reflection coefficient, Γ_M is the measured reflection coefficient, while A, B and C are the three correction factors.

Equation (5) can be expanded into the form of:

$$\Gamma_A A + B - \Gamma_A \Gamma_M C = \Gamma_M \tag{6}$$

The three correction factors are determined by solving the matrix of OSL standards as shown in Equation (11).

$$\Gamma_{AO} A + B - \Gamma_{AO} \Gamma_{MO} C = \Gamma_{MO} \tag{7}$$

$$\Gamma_{AS} A + B - \Gamma_{AS} \Gamma_{MS} C = \Gamma_{MS} \tag{8}$$

$$\Gamma_{AL} A + B - \Gamma_{AL} \Gamma_{ML} C = \Gamma_{ML} \tag{9}$$

$$\begin{pmatrix} \Gamma_{AO} & 1 & \Gamma_{AO}\Gamma_{MO} \\ \Gamma_{AS} & 1 & \Gamma_{AS}\Gamma_{MS} \\ \Gamma_{AL} & 1 & \Gamma_{AL}\Gamma_{ML} \end{pmatrix} \begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{pmatrix} \Gamma_{MO} \\ \Gamma_{MS} \\ \Gamma_{ML} \end{pmatrix} \tag{10}$$

$$\begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{pmatrix} \Gamma_{AO} & 1 & \Gamma_{AO}\Gamma_{MO} \\ \Gamma_{AS} & 1 & \Gamma_{AS}\Gamma_{MS} \\ \Gamma_{AL} & 1 & \Gamma_{AL}\Gamma_{ML} \end{pmatrix}^{-1} \begin{pmatrix} \Gamma_{MO} \\ \Gamma_{MS} \\ \Gamma_{ML} \end{pmatrix} \quad (11)$$

After the values of the three correction factors are found, they are substituted into Equation (5) in order to calculate for the actual value of the reflection coefficient for a given measured value.

According to literatures [7, 12], the actual value of reflection coefficients for open, short and matched loads were assumed to be ideal in the calculation as shown in Table 1. However, in real case, the loads of the three standards were not ideal as claimed, where Γ_{AO}=1+j0, Γ_{AS}=-1+j0, Γ_{AL}=0+j0. In order to obtain a precise value of actual reflection coefficient of DUT, the actual values of the three OSL standards need to be obtained by measuring using VNA. Curve fitting was done to the new actual values, and then they were used as the actual reflection coefficient of OSL to calculate the actual reflection coefficient of DUT.

Table 1. Actual value of reflection coefficients for known OSL standards

Type of Load	Magnitude, $\|\Gamma\|$	Phase, Φ
Open	1	0^o
Short	1	$\pm 180^o$
Matched 50Ω	0	Arbitrary

4. RESULTS AND ANALYSIS

4.1. Measurement of Reflection Coefficient Magnitude

Calibration was done prior to data acquisition. A set of measurements have been taken for the reflection coefficient magnitude and phase of DUT using the reflectometer prototype. The responses of measurement obtained using reflectometer were compared to the measurement using vector network analyzer. The magnitude and phase of reflection coefficient measured using the two devices were plotted and shown in Figure 4 and Figure 6 respectively.

Based on the MATLAB plot as illustrated in Figure 4, it was found that the magnitude measurement after calibration was only acceptable for certain range of frequency, specifically from 490 MHz to 550 MHz. This was due to the reason that the measurement dropped to lower than -10 dB for frequency below 490 MHz. There were too many variables which may lead to the partial faulty measurement. Several possible factors in causing the issue are incorrect design of transmission line, imperfect OSL loads, surrounding noise, thermal noise and weak detected signals. However, the main factor was believed to be incorrectly designed transmission line at the two bi-directional couplers as shown in Figure 5.

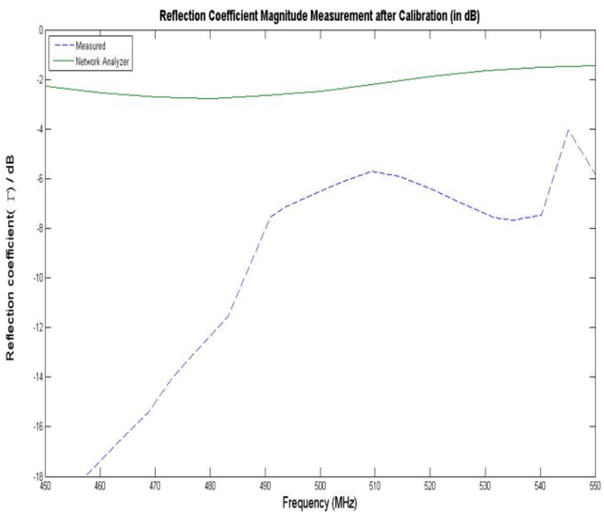

Figure 4. Comparison of measured reflection coefficient magnitude using reflectometer prototype and vector network analyzer

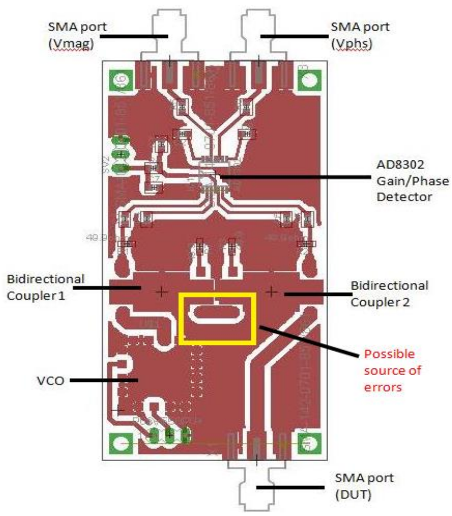

Figure 5. Possible source of errors due to incorrect design of transmission line length

The circled portion of the reflectometer in yellow box as shown in Figure 5 was believed to be the main reason of errors in the data obtained for OSL loads and DUT. As a matter of fact, the phase difference between input A with input B to the detector has to be 180^o in order for optimum measurement. Unfortunately, based on the datasheet of the bi-directional couplers, there was no information regarding the phase difference of the input/output ports and forward/reverse coupled ports. Therefore, the transmission line connecting output of bi-directional coupler 1 to input of bi-directional coupler 2 could induce a certain phase shift which was hardly determined [13]. In order to ensure the condition of 180^o as stated previously to be met, the electrical length of the part of transmission line between the two bi-directional couplers have to be designed so that the phase difference of input A with input B to the detector is 180^o[14]. However, this is just a speculation as the remaining time did not allow more alternatives to be implemented to correct the flaws. More future works were required to justify the hypothesis and improvements were required to obtain a better measurement.

In the range of applicable measurement, from 490 MHz to 550 MHz, it was found that the measured response correlates with the VNA measurement, with some error and fluctuations. The maximum deviation from the VNA measurement was recorded as 5.95dB for the applicable frequency range. It was suspected that these errors were due to the erroneous measured readings of reflection coefficient for the OSL loads, which in turn, caused by the incorrectly designed transmission line as discussed previously.

4.2. Measurement of Reflection Coefficient Phase

By referring to the phase response plot in Figure 6, it was found that the measured phase difference of the DUT correlates well with the VNA measurement throughout the frequency range of 450 MHz to 550 MHz, with minor fluctuations and errors in the acceptable range. The maximum error of measured phase was found to be 35^o, with a significant improvement compared to measurement before calibration. It was believed that the transmission line design issue stated previously had certain impact on the phase measurement result.

Apart from that, the magnitude and phase measurement of reflection coefficient before and after calibration were determined and summarized in Table 2 below. It was noticed that there was a slight rise in the maximum error from 3.18 dB to 5.95 dB for magnitude after calibration, but with significant improvement in the maximum phase error, which dropped from 171.57^o to 35^o.

The measurement of magnitude was acceptable for frequency of 490 MHz onwards to 550 MHz, but not for below 490 MHz. However, the phase response was considered as relatively precise as it correlates well with the VNA measurement.

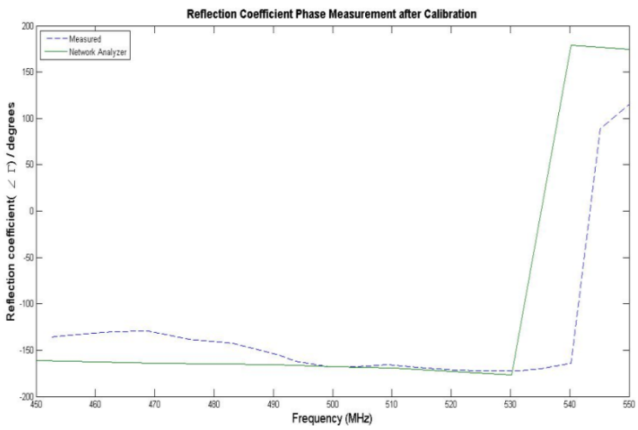

Figure 6. Comparison of measured reflection coefficient phase using reflectometer prototype and vector network analyzer

Table 2. Comparison of maximum magnitude and phase error before and after calibration

Error	Before Calibration	After Calibration
Maximum magnitude error	3.18 dB	5.95 dB
Maximum phase error	171.57^o	35.00^o

5. CONCLUSION

To conclude, a complete reflectometer prototype system is developed and implemented in terms of hardware and software. Based on the comparison of the measurement obtained using the reflectometer prototype with the measurement using Agilent E5071C VNA, the results show good correlations between the two sets of measurements in general, especially in the phase measurement. However, there are concerns on the measurement error for magnitude below frequency of 490MHz, where the readings fall below the expected precision level. Primary inspection has been done and hypothetically, it is inferred that the issue is due to some flaw in the design of transmission line connecting the two bi-directional couplers. Unfortunately, the limitation of time does not allow more corrections or improvement to be implemented in order to obtain more precise measurement. Therefore, future works are required to justify the flaw so as to enhance the precision of measurement. In general, the objectives of this project are achieved.

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BIOGRAPHIES OF AUTHORS

Yi Lung Then was born in Kuching, Malaysia in 1988. He received both his bachelor degree and Ph.D. in electrical engineering from Universiti Teknologi Malaysia (UTM), Skudai, Malaysia. He is currently a lecturer in Faculty of Engineering, Computing and Science, Swinburne University of Technology (SUTS), based in Sarawak, Malaysia. His research interests include RF and microwave engineering, passive microwave components design and fabrication, antenna design and fabrication, and microwave sensors and reflectometer for modern agriculture.

Kok Yeow You was born in 1977. Hereceived the B.Sc. degree in physics (Hons.) from Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia, in 2001, the M.Sc. degree in microwave from the Faculty of Science in 2003, and the Ph.D.degree in wave propagation from the Institute for Mathematical Research, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia, in 2006. He is currently a Senior Lecturer with the Communication Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Skudai, Malaysia. His current research interests include theory, simulation, and instrumentation of electromagnetic wave propagation at microwave frequencies focusing on the development of microwave sensors for agricultural applications.

Ming Hao Lee was born in Ipoh, Malaysia in 1990. He received the B. Eng. degree in electrical - telecommunications engineering (Hons.) from Universiti Teknologi Malaysia (UTM) Skudai, Malaysia, in 2014. He is currently a wireless product engineer in Network Design and Bidding Department, Huawei Technologies (Malaysia) Sdn Bhd. He currently works on the wireless network design for GSM, UMTS, LTE projects for network operators and service providers in Malaysia.

Chia Yew Lee was born in 1988. He received the bachelor's degree in electrical engineering (computer) from Universiti Teknologi Malaysia, Skudai, Malaysia in 2012. He involved in research on biomedical sensor designs for his Ph.D. degree in biomedical engineering.