Ultra Wideband Microwave Multi-Port Reflectometer in Microstrip-Slot Technology: Operation, Design and Applications

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1. Introduction

A microwave reflectometer is an instrument to measure a complex ratio between reflected and incident waves at an input port of a uniform transmission line terminated in a Device Under Test (DUT). The conventional reflectometer is formed by a four-port network with two ports connected to a microwave source and DUT, and the remaining ports coupled to a heterodyne receiver which acts as a Complex Ratio Detector (CRT). By using the heterodyne receiver technique, the two microwave signals are converted in the linear manner to an Intermediate Frequency (IF) of hundreds of kHz where they are processed using digital means. The use of the heterodyne technique enables a very large dynamic range of 100 dB or more for this type of reflectometer. However, as the ratio of two original microwave signals has to be preserved at IF, a very advanced electronic circuitry is required to accomplish the linear conversion process. This complicated electronics leads to a large size of the conventional reflectometer and its high price tag. Many applications require compact-size and low-cost reflectometers. They can be built using N-port networks, with N being greater than 5, equipped only in scalar (power) detectors. This chapter describes the concept of a multi-port reflectometer which employs scalar instead of complex ratio detector to determine the complex reflection coefficient of DUT. It is shown that such a device requires a suitable calibration and mathematical transformations of the measured power at selected ports of the N-port to obtain the complex reflection coefficient of DUT. Because of this requirement, the multi-port reflectometer uses a computer to perform calibrations and measurements. The use of a computer accelerates the calibration and measurement procedure and at the same time it does not create a considerable overhead to the total cost of this measurement instrument. The challenge is to obtain a low-cost fully integrated N-port network operating over an ultra wide frequency band, which can be used to develop a fully operational reflectometer. This challenge is addressed in the present chapter. Practical configurations of this measurement instrument are described and the design of a compact fully integrated N-port network in microstrip-slot technique to build a reflectometer operating over an ultra wide microwave frequency band of 3.1 to 10.6 GHz is given.
2. Multi-Port Reflectometer Concept

A multi-port reflectometer is a passive linear circuit with two input ports allocated for a power source and Device Under Test (DUT) and at least three output ports terminated in scalar power detectors to obtain the information about a complex reflection coefficient of DUT. A particular case of this device is a six-port reflectometer with four scalar detectors to determine in precise manner, the reflection coefficient of DUT. Having one more port with a power detector makes it less prone to power measurement errors than its five-port counterpart. Being introduced in 1970s, a six-port, or in more general case, N-port reflectometer provides an alternative method to the conventional network analyser employing heterodyne receiver principle to measure impedance, phase or complex reflection coefficient of passive or active circuit (Hoer, 1975). For the six-port reflectometer, these parameters are obtained from the measured power at its four output ports.

Accuracy of six-port measurements is a function of linearity of the power detectors and the properties of the six-port network (Hoer, 1975). Because the six-port reflectometer can provide phase information by making only power (scalar) measurements of four different linear combinations of the two electromagnetic waves (incident and reflected at DUT), the requirement for phase information at the output ports of six-port is avoided. The other advantage of this technique is the reduced frequency sensitivity (Engen, 1977). Consequently, the phase locked source is no longer necessary in the design. As a result, the concept of six-port reflectometer can easily be extended to millimetre frequencies (Engen, 1977). The general block diagram of a six-port reflectometer is shown in Fig. 1.

![General block diagram of a reflectometer employing six-port network.](image)

As shown in Fig. 1, the microwave source is connected to Port 1, while Port 2 acts as the measurement port for Device Under Test (DUT). Here, variable \( b \) represents an incident signal while variable \( a \), indicates a reflected signal. The other four ports (Port 3 to 6) are connected to scalar power detectors. The power reading from these 4 ports can be written as in (1) – (4) from the assumption that the network is arbitrary but linear (Engen, 1969; Engen, 1977):

\[
P_3 = |b_3|^2 = |Aa + Bh|^2
\]  
\[
P_4 = |b_4|^2 = |Ca + Db|^2
\]  
\[
P_5 = |b_5|^2 = |Ea + Fb|^2
\]  
\[
P_6 = |b_6|^2 = |Ga + Hb|^2
\]
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\[
\begin{align*}
|a|^2 &= \Sigma_{i=3}^{6} \alpha_i P_i \\
|b|^2 &= \Sigma_{i=3}^{6} \beta_i P_i \\
|ab|\cos\psi &= \Sigma_{i=3}^{6} c_i P_i \\
|ab|\sin\psi &= \Sigma_{i=3}^{6} s_i P_i 
\end{align*}
\]

From these 4 unknowns, the general equation of reflection coefficient can be written as the ratio of reflected signal, \( a \) to incident signal, \( b \) (Engen & Hoer, 1972; Hoer & Engen, 1973; Hoer, 1975):

\[
\Gamma = \frac{a}{b} = \frac{\Sigma_{i=3}^{6} (c_i + js_i)P_i}{\Sigma_{i=3}^{6} \beta_i P_i}
\]

3. Geometrical Interpretation of Reflection Coefficient and Design Considerations

3.1 Geometrical Interpretation of Reflection Coefficient in Complex Plane

As presented in equation (9), the unknown reflection coefficient of measured load (DUT) is related to the power measurements by a set of complex constant \( A - H \). These eight complex constants \( A - H \) and/or 12 real constants \( c_i, s_i \) and \( \beta_i \) can be determined from a suitable calibration procedure by applying 5 to 6 standards (Somlo & Hunter, 1982; Hunter & Somlo, 1985).

The principle of operation of a six-port reflectometer can be gathered by considering a simplified case of this device. The following representation can serve this purpose (Engen, 1977):

\[
\begin{align*}
P_3 &= |A|^2 |b|^2 |\Gamma - q_3|^2 \\
P_4 &= |C|^2 |b|^2 |\Gamma - q_4|^2 \\
P_5 &= |E|^2 |b|^2 |\Gamma - q_5|^2 \\
P_6 &= |G|^2 |b|^2 |\Gamma - q_6|^2 
\end{align*}
\]
where \( q_3 \) - \( q_6 \) are as follows:

\[
q_3 = -\frac{B}{A}, \quad q_4 = -\frac{D}{C}, \quad q_5 = -\frac{F}{E}, \quad q_6 = -\frac{H}{G}
\]  \hspace{1cm} (14)

The above expressions (10) – (13) represent circles in the complex reflection coefficient plane which can be used as geometrical interpretation in determining the reflection coefficient. The circle centres are given by the unknowns \( q_3 \) to \( q_6 \), also branded as \( q \)-points, while the circle radii are given by the \( |\Gamma - q_i| \) where \( i=3, 4, 5, 6 \).

The operation of the six-port reflectometer can also be described in terms of scattering parameters of a multi-port network. Complex constants \( A \) - \( H \) are first replaced by common complex constants \( m_i \) and \( n_i \) and then the incident signals at ports, \( b_i \) (\( i=3, 4, 5, 6 \)) can be rewritten as the following equation in terms of the incident and emergent signals at Port 2 (Somlo & Hunter, 1985):

\[
b_i = m_ia + n_ib
\]  \hspace{1cm} (15)

Complex constants, \( m_i \) and \( n_i \) can then be expressed by the scattering parameters as follows (Somlo & Hunter, 1985):

\[
m_i = S_{i2} - \frac{S_{i1}S_{22}}{S_{21}} \quad \text{and} \quad n_i = \frac{S_{i1}}{S_{21}}
\]  \hspace{1cm} (16) \hspace{1cm} (17)

The general equation of circle centre is given by the negative ratio of \( n_i \) and \( m_i \) which is analogous to the expression (14) (Somlo & Hunter, 1985):

\[
q_i = -\frac{n_i}{m_i} = -\frac{S_{i1}}{S_{i2}S_{21} - S_{i1}S_{22}}
\]  \hspace{1cm} (18)

By assuming that approximately ideal components are used to construct the network, the parameter \( S_{22} \) is very close to zero. This simplifies the equation (18) to (Somlo & Hunter, 1985):

\[
q_i = -\frac{S_{i1}}{S_{i2}S_{21}}
\]  \hspace{1cm} (19)

According to Probert and Carrol in (Probert & Carroll, 1982), the characterisation can be made more general for the multi-port network case. With the above assumption and the use of known input voltage, \( V_i \) at Port 1, the incident signal \( b_i \) (\( i=3...,N \)) and reflection coefficient, \( \Gamma \) can be written as:

\[
b_i = V_o(S_{i1} + S_{12}S_{2i}\Gamma)
\]  \hspace{1cm} (20)
The general equation of circle centre is given by the negative ratio of complex constants, (Engen, 1977):

\[ \Gamma = \frac{b_i}{V_0 s_{21} s_{i2}} - \frac{s_{i1}}{s_{i2} s_{21}} \]  

(21)

Since \( q_i \) are given by (19), then the radius is \( |\Gamma - q_i| \) and thus the circle radius can be calculated as:

\[ \text{radius} = \left| \frac{b_i}{V_0 s_{21} s_{i2}} \right| \]

(22)

where \( i=3, 4, 5, \ldots, N \) (\( N \) = number of port) and \( b_i \) is proportional to \( \sqrt{P_i} \).

An important characteristic of the properly selected six-port network is insensitivity of a reference port to the reflected signal from the DUT at Port 2. This port is in general assigned the special function of the incident signal power measurement. Since this port gives a good indication of the source power, the output of power detector connected to this port can be used to stabilize the signal source against power fluctuations or maintain the power at some set level (Woods, 1990). The inclusion of this special port does not therefore compromise the overall design of the six-port measurement system.

An alternative representation that can be used in the six-port analysis is through the use of the power ratio, \( p_i \) given by power at Port \( i \) to that at a reference port (Port 6 is selected in this analysis case) is (Somlo & Hunter, 1985):

\[ p_i = r_i \left| \frac{\Gamma - q_i}{\Gamma - q_6} \right|^2, \quad i = 3, 4, 5 \]

(23)

In (23) constant \( r_i \) is related to the scattering parameters and a real constant, \( K_i \) by the following equation (Somlo & Hunter, 1985):

\[ r_i = K_i \left| \frac{s_{i1} s_{22} - s_{i2} s_{21}}{s_{61} s_{22} - s_{62} s_{21}} \right|^2 \]

(24)

The ratio of \( p_i \) to constant \( r_i \) can be written as:

\[ e_i = \frac{p_i}{r_i} \approx \left| \frac{\Gamma - q_i}{q_6} \right|^2 \]

(25)

The reflection coefficient of DUT can be identified from the geometrical representation as the intersection of power circles. Fig. 2 illustrates this concept showing the intersection of the two circles that determine the reflection coefficient, \( \Gamma \). The centres of the two circles are given by \( q_3 \) and \( q_5 \) (Engen, 1977).
Fig. 2. Determination of the reflection coefficient, $\Gamma$ from the intersection of two power circles.

This case is found for the five-port network configuration which does not make use of circle with centre $q_4$. The example presented in Fig. 2 shows that one intersection point falls within the region of reflection coefficient unit circle while the second point is outside it. In this case, the ambiguity in the proper choice of $\Gamma$ is removed and a unique value is chosen on the basis that the reflection coefficient of a passive load is less than or equal to one. The passive load termination assumption has to be supported by the condition of a straight line connecting $q_3$ and $q_5$ that does not intersect the unit circle (Engen, 1977).

The close inspection of Fig. 2 indicates that solution offered by the five-port is prone to the power measurement errors. These power errors may result in a substantial error in the position of the reflection coefficient perpendicular to the line joining the circle centres of $q_3$ and $q_5$ (Woods, 1990). As explained in (Engen, 1977), a one percent error in the experimental measurement of $|\Gamma-q_3|$ and $|\Gamma-q_5|$ can cause the uncertainty of 10 percent in the measured reflection coefficient result.

The deficiency of the five-port reflectometer can be overcome by employing an extra power detector reading that is available in the six-port network. This is illustrated by introducing the third power circle, as shown in Fig. 3.

Fig. 3. Circle intersection failure when three circles are used to determine reflection coefficient, $\Gamma$. 
From Fig. 3 it is apparent that the solutions for reflection coefficient are restricted more than in the case of five-port and a unique value can be determined without the assumption of the load being passive. This procedure can be interpreted as finding the intersection of three circles. Therefore, three circles solve the ambiguity when choosing between the two intersections given by two circles (Waterhouse, 1990). When the measured power values include errors, the three circles will not have a common point of intersection but will define a quasi-triangular area in the complex plane. Engen explained in (Engen, 1997) that this intersection failure is an indicator of the power meter error. Moreover, the measurement noise, nonlinearity in power measurement and imperfections in the calibration can also contribute to this phenomenon (Somlo & Hunter, 1985). Hence in practical cases, the multi-port measurement system being prone to power errors changes the ideal circles radii (Woods, 1990). A suitable configuration of multi-port has to be decided upon to counter this effect. The solution to this problem is related to the choice of locations of the \( q_i \)-points which characterize the multi-port. As can be observed in Fig. 3, locations of the \( q_i \)-points in the complex plane are important in keeping the area of the quasi-triangle to minimum. By making the proper choice of the \( q_i \)-points, the uncertainty of value for the \( \Gamma \) can be marked small (Somlo & Hunter, 1985).

Engen proposed that for the six-port reflectometer the \( q_i \) amplitudes should be in the range of 1.5 to 2.5 and their angular separation should be about 120°. The reasons for such conditions are explained in detail in the next section. When the multi-port with a larger number of ports is used more than three circles are available and the improved measurement accuracy is possible in situations where intersection failure occurs. The whole circle equation system can be solved simultaneously in a least-squares sense where statistical averaging or weighting can lead to the best solution (Engen, 1969; Engen, 1980).

It is apparent that the use of additional detectors can significantly improve the device performance and make it less sensitive to power measurement errors. Following this general concept, the system can be extended to seven or more ports. With the possible exception of a seven port, however, the accuracy improvement does not ordinarily warrant additional complexity (Engen, 1977).

### 3.2 Optimum Design Considerations

It has already been shown that the operation of six-port reflectometer is governed by the constants \( A - H \) which determine the coupling of the waves to the detectors (Woods, 1990). A set of the design rules for the six-port network can thus be formulated by establishing preferred values of these constants. A practical network can then be designed which conforms to these preferred values. The main parameter to be considered is the accuracy of the complex reflection coefficient measurement. However, as the detectors output voltages are processed by Analogue to Digital Converters, the other important factor which also needs be taken into account is the required voltage meters dynamic range.

The following are the considerations which lead to the guidelines for the six-port (or in a more general case, multi-port) reflectometer design.

From the graphical interpretation of operation of six-port reflectometer, the optimum design is related to selection of locations of the \( q_i \)-point circle centres, which correspond to the values of \(-B/A, -D/C, -E/E\) and \(-G/H\) in the complex plane. When the measurement accuracy of reflection coefficient is of concern, an optimum six-port reflectometer is the one that is least susceptible to detector power measurement errors. In the previous considerations, it
has been pointed out that for the optimum design the \( q \)-points have to be separated evenly in phase and magnitudes. This six-port design strategy has been suggested by many researchers.

Somlo and Hunter explained in (Somlo & Hunter, 1985) that for the case of passive terminations with \(|\Gamma| \leq 1\), the network has to be chosen in such a way that for the reference Port 6 \(|q_6|\) has to be greater than 1. This geometrically means that \( q_6 \) is located outside the unit circle in the complex \( \Gamma \) plane. A similar choice they also suggested for the remaining \( q \)-points. This is to reduce the sensitivity of the power measurement to noise. If the opposite condition of \(|q_i| \leq 1\), \( i = 3, 4, 5 \) is chosen, then there are values of \( \Gamma \) which make the numerator in equation (23) and \( p_i \) small. In particular, the value of \( \Gamma = q \) sets \( p_i = 0 \), which is greatly influenced by noise.

The restriction \(|q_i| > 1\) \((i = 3, 4, 5)\), also avoids the case \( q_i = 0 \) which has been argued against in detail by Engen in (Engen, 1977) on the basis of noise sensitivity when measuring a termination near a match, which is likely to be the one of the most important uses of the reflectometer. This condition can be explained using the example of having \( q_3 = 0 \), \( q_4 = 2 \) and \( q_5 = 2 \) (Engen, 1977). In such a case, \( P_3 \) almost does not contribute to the determination of \( \Gamma \) when measuring \( |\Gamma| \) with small magnitude such as 0.01. As a result, the most inaccurate power measurement (worst signal to noise ratio, SNR) occurs as the power incident on a detector approaches zero. Based on this argument the \( q \) values should be such that \(|q_i| \neq 0\).

However in contrast to the discussed \(|q_i| > 1\), Engen in (Engen, 1977; Engen, 1997) suggested the optimum value of \(|q_i|\) to be chosen around 0.5. Their argument is valid if the measurement region is within \( 0 \leq |\Gamma| \leq 0.3 \).

The choice of \(|q_i| > 1\) \((i = 3, 4, 5)\) postulated by Somlo and Hunter in (Somlo & Hunter, 1985), is also beneficial with regard to the voltage meters dynamic range. This range has to be not too large. If the conditions of \(|q_6| >> 1\) and \(|q_i| > 1\), \( i = 3, 4, 5 \) are implemented, the approximated dynamic range required for the power meters can be calculated as given by (Somlo & Hunter, 1985):

\[
\text{Dynamic range } [dB] = 20 \log_{10} \left( \frac{|q_i| + 1}{|q_i| - 1} \right) dB \tag{26}
\]

With the condition of \(|q_i| > 1\) \((i = 3, 4, 5)\) and \(|q_6| > 1\), one can pose the question whether the magnitudes of all the \( q_i \)-s have to be equal. If it is the case, complex constants, \( c \) and \( s \), are equal to zero. It is therefore essential that, geometrically, the \( q_i \) do not all lie on the circle with centre \( \Gamma = 0 \) on the complex \( \Gamma \) plane (Somlo & Hunter, 1985). This means that \(|q_i|\) \((i = 3, 4, 5)\) have to be less than \(|q_6|\) to meet the preferable design.

In addition to the above argument, the magnitude of \( q \) should not be too near to unity because \( p_i \) could be small for the fully reflecting terminations (Somlo & Hunter, 1985). Small values of \( p_i \) resulting from \(|q_i| \approx 1\) decrease the measurement accuracy (Engen, 1977).

The remaining condition concerns the upper bound for the distance of the \( q \)-points with respect to the complex \( \Gamma \) plane origin. Since \( \Gamma \) is determined from its distances from \( q_3, q_4 \) and \( q_5 \) (Engen, 1977), it is proven that an ill conditioned situation will result if these distances become large in comparison with distances between \( q_3 \) and \( q_4, q_5 \) or \( q_4 \) and \( q_5 \) (Engen, 1977). If the \(|q_i|\) are too large, it can be seen from equation (25) that a small change...
to \( p_i \) represents a large change in \( \Gamma \). Choosing \( |q_i|, i=3, 4, 5 \) to be large also places high resolving demands on the power meters (Somlo & Hunter, 1985). Based on these argument, (Engen, 1977) postulated that magnitude of \( q_i \) should be in the range of \( \sqrt{2} \) to 2. In turn, Yao in (Yao, 2008) made suggestion for using the range between 1 and 3. Additionally, Bilik in (Bilik, 2002) postulated the choice of magnitude of \( q \)-points approximately 2. It is worthwhile mentioning in the practical circuits these magnitudes of \( q \)-points fall to some extent short of the optimum design aims in (Engen, 1977). However, they are easier to achieve. Moreover, it appears that the theoretical loss in performance between such practical circuits and “ideal” ones may be small in comparison with the performance degradation which results from the use of non-ideal components (Engen, 1977).

With respect to the \( q \)-points spacing, the even spacing in the complex plane is postulated (Engen, 1977; Somlo & Hunter, 1985; Bilik, 2002). For the six-port reflectometer this requirement leads to \( 120^\circ \) separation of \( q \)-points. For the more general case of multi-port network with \( N>6 \), the \( q \)-points are suggested to be separated by \( 360^\circ/(N-3) \) (Probert & Carroll, 1982). Because practical circuits are unable to keep constant angular separation of \( q \)-points, Yao in (Yao, 2008) added the tolerance conditions. For the case of \( N=6 \) he suggested the phase separation range should fall between \( 100^\circ \) and \( 140^\circ \) with the \( \pm 20^\circ \) from the optimum \( 120^\circ \).

4. Integrated UWB Reflectometer

4.1 Reflectometer Design

The configuration of reflectometer chosen for practical development is shown in Fig. 4.

![Reflectometer Configuration](image)

**Fig. 4.** Reflectometer configuration formed by five quadrature hybrids (Q) and one power divider (D).
The device is constructed using a seven-port network and includes five 3-dB couplers (Q) and one power divider (D). In this configuration, Port 1 is allocated for a microwave source while Device Under Test (DUT) is connected to Port 2. Five power detectors terminate Ports 3-7. Part of the reflectometer within the broken line is given the special name of Complex Measuring Ratio Unit (CMRU) or Correlator. It plays a similar role to the Complex Ratio Detector in the conventional four-port reflectometer based on the heterodyne receiver technique. The two couplers (Q) outside the CMRU are used to redirect the signals, a and b to measure the complex reflection coefficient of DUT. Note that in a more basic design, a single coupler is sufficient to perform this function. However, the use of two couplers provides a better signal balance which is of importance to achieving a better quality measurement of the reflection coefficient. A scalar detector terminating Port 3 of the divider D, outside the CRMU monitors the signal source power level.

The advantage of this seven-port configuration is that it allows for a real-time display of DUT complex reflection coefficient (Engen, 1977; Engen, 1977; Hoer & Roe, 1975; Hoer, 1977). In this case, the detector at Port 3 can be used in a feedback loop to maintain a constant power level from the source. The chosen configuration meets the condition of $|q_3| > 1$ and $|q_i| < |q_3|$ where $i = 4, 5, 6, 7$ and represents an optimal reflectometer configuration, as pointed by (Probert & Carroll, 1982), as its $q_i$ ($i = 4, 5, 6, 7$) points are spread by $90^\circ$ in the complex reflection coefficient plane.

While undertaking a rough assessment of operation of the seven-port reflectometer of Fig. 4 it is important to find out by how much it diverges from the one using ideal components. The following mathematical expressions can be applied in this evaluation process.

Assuming an ideal operation of couplers and divider and the square-law operation of detectors (the measured voltages at detector outputs are proportional to power values at the detectors inputs) and by applying mathematical derivations similar to those in (Hoer, 1975), it can be shown that the reflection coefficient, $\Gamma$, of DUT for the configuration of Fig. 4 can be determined from (27):

$$\Gamma = \frac{a}{b} = \Gamma_1 + j\Gamma_2 = \left(\frac{P_4 - P_5}{P_3}\right) + j\left(\frac{P_6 - P_7}{P_3}\right)$$  \hspace{1cm} (27)

where $\Gamma_1$ is the real component of complex reflection coefficient, $\Gamma_2$, the imaginary and $P_i = |V_i|^2$ ($i = 4, 5, 6, 7$) are measured power at 4 ports.

It is apparent that the above expression can be used to obtain a real-time display of the DUT reflection coefficient as the difference operation can be achieved using analogue means and real and imaginary parts can be displayed in the polar form on an oscilloscope.

An equivalent representation of $\Gamma$ can be obtained from knowing the scattering parameters of the seven-port constituting the reflectometer of Fig. 4. In this case, $\Gamma$ can be determined using the following expression:

$$\Gamma = \frac{\left(\left|S_{41}\right|^2 - \left|S_{51}\right|^2\right) + j\left(\left|S_{61}\right|^2 - \left|S_{71}\right|^2\right)}{\left|S_{31}\right|^2}$$  \hspace{1cm} (28)
Assuming ideal operation of couplers, dividers and square-law operation of detectors, the DUT reflection coefficient can also be obtained by geometrical means from an intersection of four circles defined by (29):

\[
V_4 = -\frac{b}{2\sqrt{2}}(\Gamma - q_4) \\
V_5 = \frac{jb}{2\sqrt{2}}(\Gamma - q_5) \\
V_6 = -\frac{b}{2\sqrt{2}}(\Gamma - q_6) \\
V_7 = -\frac{jb}{2\sqrt{2}}(\Gamma - q_7)
\]

where \( V_i \) represent the voltages measured at ports 4 to 7.

The four circles are defined here by the centres \( q_i \) and radii \(|\Gamma - q_i|\) where \( i=4, 5, 6, 7 \).

In order to design the individual couplers (Q) and divider (D) constituting the reflectometer, CST Microwave Studio (CST MS) is used. Rogers RO4003C featuring a relative dielectric constant of 3.38 and a loss tangent of 0.0027 is chosen as a microwave substrate to manufacture these components. It has 0.508 mm thickness and 17 μm of conductive coating. The design of coupler and divider follows the initial guidelines explained in (Seman & Bialkowski, 2009) and (Seman et al., 2007), followed by the manual iterative process aided with CST MS.

In the present case, a three section coupler with rectangular shaped microstrip-slot lines is chosen. The microstrip-slot technique is also applied to a divider. A special configuration of divider proposed here makes it compatible with the coupler. Their design is accomplished using CST MS. Layouts of the coupler and the divider are generated with the use of CST MS as shown in Fig. 5(a) and (b), respectively.

![CST MS layout of (a) 3 dB microstrip-slot coupler (Q) and (b) in-phase power divider (D).](image-url)
The designed coupler has the simulated characteristic of return loss at its ports better than 20 dB whilst isolation between ports 1 and 4, and 2 and 3 is greater than 19 dB in the 3.1 to 10.6 GHz frequency band. In the same band, the coupling between ports 1 and 3 and 2 and 4 is 3 dB with a ±1 dB deviation. The phase difference between the primary and coupled ports is 90.5° ± 1.5°. The designed divider offers return losses greater than 12 dB at its input port and power division of -3 dB ± 1 dB between its output ports across the same band. The phase difference between the output ports is 0° ± 1° for 3 to 7 GHz and deteriorates to -1° to -3.5° for the frequency band between 7 and 11 GHz. These results indicate good performances of individual components. Therefore they can be integrated to form the reflectometer of Fig. 4.

The task of forming a reflectometer is accomplished in two stages. First, a Complex Measuring Ratio Unit (CMRU) in Fig. 6(a) is assembled. Then, two additional couplers are added to finalize the reflectometer design. Layout of the designed reflectometer providing the details of input and output ports, match terminated ports and screw holes is shown in Fig. 6(b).

![Fig. 6. CST MS layout of the integrated CMRU (a) and reflectometer (b).](image)

### 4.2 Reflectometer Results

Fig. 7 presents a photograph of the fabricated reflectometer with the attached SMAs connectors but excluding power detectors. The device is formed by the CMRU and two additional couplers for rerouting signals to perform reflection coefficient measurements. The reflectometer uses two double-sided Rogers RO4003 PCBs.
In the fabricated prototype, the two substrates are affixed using plastic screws with diameter 3 mm to minimize air gaps between two dielectric layers. Sub-miniature A (SMA) connectors are included for detectors, a microwave source and DUT. They are also used for characterization of the seven-port using a Vector Network Analyser. The overall dimensions of this device excluding SMA connectors are 11.8 cm × 7 cm. These dimensions indicate the compact size of the developed reflectometer.

![Photograph of the fabricated reflectometer](image-url)

**Fig. 7.** Photograph of the fabricated reflectometer.

The CST MS simulated transmission coefficients at Port 4, 5, 6 and 7 referenced to Port 1 and 2 for this device are shown in Fig. 8.

![Simulated transmission coefficients](image-url)

**Fig. 8.** Simulated transmission coefficients of designed reflectometer using CST MS where \(i=4, 5, 6, 7\) and \(j=1, 2\).

As observed in Fig. 8, magnitudes of the simulated parameters \(S_{21}\) and \(S_{31}\) are -7.3 dB ± 1.3 dB and -7.05 dB ± 1.35 dB for the frequency range of 3.5-9.8 GHz and 3.3-10.6 GHz, respectively. The simulated S-parameters \((S_{ij})\) at Port 4 to 7 with the reference to Port 1 and 2
show good performance of the seven-port network between 4 and 10 GHz. The worst case is for the parameter $S_{72}$ which starts to deteriorate above 10 GHz.

Fig. 9 shows the measured results corresponding to the simulated ones of Fig. 8.

There is similarity between the results shown in Fig. 8 and those of Fig. 9. However, the measured results exhibit larger ripples (±2 dB) between 3 and 9.5 GHz.

Fig. 10 presents the simulated and measured return loss characteristics at Port 1 and the simulated and measured transmission coefficients between Port 1 and Port 8 and 9. Similarly, Fig. 11 presents the simulated and measured return loss at Port 2 and the simulated and measured transmission coefficients between Port 2 and selected ports of the seven-port reflectometer. Comparisons between the simulated and measured characteristics presented in Fig. 10 and 11 indicate a relatively good agreement.

Fig. 12 shows the simulated and measured locations of the $q_i$-points ($i=4, 5, 6, 7$).
The simulated or measured S-parameters can be used to assess the performance of the designed seven-port in terms of its $q$-points ($i=4, 5, 6, 7$), which can be calculated using expression (18). For the ideal case, the chosen configuration of seven-port reflectometer offers the location of $q_i$ at 2, j2, -2 and -j2. The location of these points with respect to the origin of the complex plane of 2 and the angular separation of 90° indicate the optimal design of this reflectometer.

Fig. 11. Simulated and measured reflection coefficient at Port 2, and simulated and measured transmission coefficients between Port 2 and Port 3, 8 and 9.

Fig. 12 shows the simulated and measured locations of the $q$-points ($i=4, 5, 6, 7$).

Fig. 12. Polar plot of the simulated (s) and measured (m) $q_i$ - points ($i=4, 5, 6, 7$).
The simulated magnitudes of $q_4$, $q_5$, $q_6$ and $q_7$ are $2.3 \pm 0.9$, $1.9 \pm 0.8$, $2.1 \pm 0.6$ and $2.5 \pm 0.9$, while the measured ones are $2 \pm 1$, $1.6 \pm 0.6$, $2.1 \pm 1.1$ and $2.3 \pm 1.1$ in the frequency band between 3 and 11 GHz. Therefore there is a reasonable agreement between the two sets.

As observed from the polar plot in Fig. 12, the circle centres of $q_i$ for this reflectometer deviate from the ideal separations of $90^\circ$ ($0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$). The actual phase separation is given by $\pi/2+\delta_0+k\Delta f$, where $k$ and $\delta_0$ are constants and $\Delta f$ is the shift from the mid-frequency (Yao & Yeo, 2008). The measured phases of $q_4$, $q_5$, $q_6$ and $q_7$ are $180^\circ \pm 10^\circ$, $0^\circ \pm 20^\circ$, $-90^\circ \pm 18^\circ$ and $89^\circ \pm 19^\circ$, respectively from 3 to 10.6 GHz.

The measured phase characteristics $q_i$ ($i=5, 6, 7$) can be referenced against $q_4$ by the following equation of (30):

$$\text{phase } (q_{ia}) = \text{phase } (q_i) - \text{phase } (q_4) \quad i=5, 6, 7$$

The measured phase $(q_{ia})$ deviation compared to the ideal case is $\pm 20^\circ$ for frequencies from 3 to 9.9 GHz.

Although Fig. 12 shows a good behaviour of $q$-point characteristics, better results could be obtained if the factors $k$, $\delta_0$ and $\Delta f$ were included in the design specifications. In the present case, the design of seven-port reflectometer was accomplished by just integrating individually designed Q and D components.

There is one remaining criterion of performance of the designed seven-port reflectometer and it concerns the magnitude of reference point $q_3$. The simulated and measured results for $|q_3|$ are shown in Fig. 13. They are dissimilar. However in the both cases the $|q_3|$ values are greater than 4.4. These results indicate that the reflectometer fulfils the optimum design specification of $|q_3|<|q_3|$.

Fig. 13. Simulated and measured magnitude of $q_3$.

5. Calibration Procedure

Following its successful design and development, the reflectometer is calibrated prior to performing measurements. A suitable calibration procedure to the reflectometer offers high measurement accuracy that can be obtained with the error correction techniques. There are various methods for calibrating multi-port reflectometers. The differences between these
methods include the number of standards, restrictions on the type of standards and the amount of computational effort needed to find the calibration constants (Hunter & Somlo, 1985). In (Hoer, 1975), Hoer suggested to calibrate a six-port network for the net power measurement. In this case, Port 2 (measurement port) is terminated with a power standard. The known power standard can be expressed as:

\[ P_{\text{std}} = \sum_{i=3}^{6} u_i P_i \]  

(31)

Then, the procedure is repeated with connecting three or more different offset shorts to replace power standard. The sliding short or variable lossless reactance also can be used. Therefore, the real net power at Port 2 is zero.

\[ 0 = \sum_{i=3}^{6} u_i P_i \]  

(32)

The net power into unknown impedance can be measured with the known \( u_i \) real constants. \( P_i \) is also observed for two or more positions of a low reflection termination. This is an addition to the \( P_i \) for the three or more different positions of an offset or sliding short. After performing this set of measurements, all constants state which one requires to calculate reflection coefficient are determined (Hoer, 1975).

Calibration algorithms proposed in (Li & Bosisio, 1982) and (Riblet & Hanson, 1982) assume the use of ideal lossless standards having \( |\Gamma| = 1 \). This notion was criticized by Hunter and Somlo which claimed that this would lead to measurement inaccuracies since practical standards are never lossless (Somlo & Hunter, 1982; Hunter & Somlo, 1985). Therefore, the information on the used non-ideal standards is important when high reflectometer accuracy is required. This information has to be used in the calibration algorithm. To perform the calibration process, Hunter and Somlo presented an explicit non-iterative calibration method requiring five standards. They suggested that one of the standards should be near match. This is to ensure the improvement of the performance of the calibrated reflectometer near the centre of the Smith chart (Somlo, 1983). The other four standards are short circuits offset by approximately 90° (Hunter & Somlo, 1985). These standards are convenient because of their ready availability. Also their use is beneficial in that their distribution is likely to avoid the accuracy degradation which can occur when measuring in areas of the Smith chart remote from a calibrating standard (Hunter & Somlo, 1985).

An alternative full calibration algorithm can be also obtained using 6 calibration standards (Somlo & Hunter, 1982). The proposed standards used in the procedure are four phased short-circuits \( (\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4) \), a matched load \( (\Gamma_5) \) and an intermediate termination \((0.3 \leq |\Gamma_6| \leq 0.7)\). It is based on the general reflection coefficient six-port equation (9) and is separated into two equations of real, \( r \) and imaginary, \( x \) part as (Somlo & Hunter, 1982):

\[
\begin{align*}
  r &= \frac{\sum_{i=3}^{6} c_i P_i}{\sum_{i=3}^{6} \beta_i P_i} \\
  x &= \frac{\sum_{i=3}^{6} s_i P_i}{\sum_{i=3}^{6} \beta_i P_i}
\end{align*}
\]  

(33)
The constants are normalized by setting $\beta_6$ equal to 1. The other 11 real constants can be determined from the calibration (Somlo & Hunter, 1982). Then, equation (33) and (34) can be rewritten as:

$$\sum_{i=3}^{6} c_i P_i - r \sum_{i=3}^{5} R_i P_i = r P_6$$

$$\sum_{i=3}^{6} s_i P_i - x \sum_{i=3}^{5} R_i P_i = x P_6$$

(35)  

(36)

These two equations are used to determine 11 real constants in the calibration procedure. The matrix to calculate the constants is given by (37) (Somlo & Hunter, 1982):

$$\begin{bmatrix}
  c_3 \\
  c_6 \\
  s_3 \\
  s_6 \\
  \beta_3 \\
  \beta_6
\end{bmatrix} = \begin{bmatrix}
  P_{13} & P_{16} & 0 & \ldots & 0 & -r_1 P_{13} & \ldots & -r_{15} P_{15} \\
  \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
  P_{43} & P_{46} & 0 & \ldots & 0 & -r_4 P_{43} & \ldots & -r_{45} P_{45} \\
  0 & \ldots & 0 & P_{13} & P_{16} & -r_1 P_{13} & \ldots & -r_{15} P_{15} \\
  \vdots & \ddots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\
  P_{53} & P_{56} & 0 & \ldots & 0 & 0 & \ldots & \ldots & 0 \\
  0 & \ldots & 0 & P_{53} & P_{56} & 0 & \ldots & 0 & \ldots & 0 \\
  P_{33} & P_{66} & 0 & \ldots & 0 & -r_6 P_{63} & \ldots & -r_{65} P_{65} & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & r_6 P_{66}
\end{bmatrix}^{-1}\begin{bmatrix}
  \eta P_{16} \\
  \vdots \\
  \eta P_{16} \\
  \vdots \\
  \eta P_{16} \\
  \vdots
\end{bmatrix}$$

(37)

where $P_i$ is a measured power at $i$th port when $i$th calibrating termination is connected to the measuring port.

From the above described alternative calibration techniques, it is apparent that the use of three broadband fixed standards such as open, short and match required in the conventional heterodyne based reflectometer is insufficient to calibrate a six-port reflectometer. To complete the calibration, at least two extra loads are required. To achieve the greatest possible spacing for the best calibration accuracy, it is beneficial to phase the offset shorts by 90° (Hunter & Somlo, 1985). Woods stated in (Woods, 1990) that to apply this ideal condition at many frequency points would require repeated tuning of standards. It may be time consuming and would rely on the expert operator (Woods, 1990). Because of these reasons, it may be appropriate to ease the ideal condition on 90° phasing of the sliding loads in favour of least adjustments to the standards (Woods, 1990). Assuming the standards are phased by at least 45° to obtain sufficient calibration accuracy, fixed positions of the short could be employed over a bandwidth of approximately 5:1 (Riblet & Hanson, 1982).

To calibrate the developed reflectometer, the method using six calibration standards, as proposed by Hunter and Somlo in (Somlo & Hunter, 1982), is chosen. This method offers a straightforward solution for the reflectometer constants and employs simple equations, which lead to the easy practical implementation of the calibration algorithm.

In the chosen calibration procedure, three coaxial standard loads (matched load, open and short circuit), two phased-short circuits and an intermediate termination with magnitude of approximately 0.5 are used. For the last standard, a 3 dB coaxial attenuator open-circuited at its end is utilized. The information about the electrical characteristics of these standards in...
The frequency band of 3 to 11 GHz is obtained from measurements performed with the conventional Vector Network Analyser (HP8510C). This information is used for the values \( r \) and \( x \) in equations (33) and (34). Knowing \( r \) and \( x \), the calibration constants \( c_i, s_i \) and \( \beta_i \) are determined from solving the matrix equation similar to the one in (37).

The operation of the developed seven-port reflectometer is assessed by assuming an ideal operation of power detectors. To achieve this task in practice, the power values required in (33) and (34) are obtained from the measured S-parameters of the seven-port reflectometer with DUT present at Port 2. Therefore, \( P_i = \left| S_{i1} \right|^2 \) for \( i=4, 5, 6, 7 \), where \( S_{i1} \) is the transmission coefficient between port 1 and port \( i \) when port 2 is terminated with DUT.

The validity of the calibration method and measurement accuracy is verified by comparing the characteristics of three open-circuited coaxial attenuators of 3, 6 and 10 dB (Fig. 14) as measured by the seven-port reflectometer with those obtained using the conventional VNA (HP8510C). For the reflectometer, the complex reflection coefficient values are determined using equation (9).

Fig. 14. Photograph of the 3, 6 and 10 dB coaxial attenuators.

The two sets of measured results for the magnitudes and phases of reflection coefficient are presented in Fig. 15 and Fig. 16.

Fig. 15. Measured magnitude of reflection coefficient for three coaxial attenuators: 3, 6 and 10 dB obtained using the developed reflectometer (R) and VNA HP8510C (VNA).

As observed in Fig. 15, HP8510C provides the measured \( |\Gamma| \) of 0.51 ± 0.02 for 3 dB, 0.25 ± 0.03 for 6 dB and 0.1 ± 0.05 for the 10 dB attenuator across the investigated frequency band. The calibrated seven-port reflectometer gives comparable results for \( |\Gamma| \) which are 0.51 ± 0.02 for 3 dB, 0.22 ± 0.03 for 6 dB, and 0.1 ± 0.01 for the 10 dB attenuator.
Fig. 16. Comparison of measured phase characteristic reflection coefficients of three coaxial attenuators of 3, 6 and 10 dB obtained using the developed reflectometer (R) and VNA HP8510C (VNA).

The best agreement occurs for the 3 dB attenuator, which was used in the calibration procedure. This agreement indicates validity of the calibration procedure as well as a very high measurement repeatability of the two instruments. The worst agreement between the reflectometer and the VNA measured results looks to be for the 6 dB attenuator, which is observed for the frequency range between 8 and 11 GHz. In all of the remaining cases the agreement is quite good. The observed discrepancies are due to the limited range of off-set shorts.

Because the attenuators have the same length, it is expected that they should have similar phase characteristics of reflection coefficient. This is confirmed by the phase results obtained by the reflectometer and the VNA, as shown in Fig. 16. An excellent agreement for the phase characteristic of 3 dB attenuator obtained with the reflectometer and the VNA again confirms excellent repeatability of the two instruments. For the remaining 6 and 10 dB attenuators there are slight differences of about ± 10° between the results obtained with the reflectometer and the VNA for some limited frequency ranges. Otherwise the overall agreement is very good indicating that the designed seven-port reflectometer operates quite well across the entire ultra wide frequency band of 3 to 11 GHz. Its special attributes are that it is very compact in size and low-cost to manufacture.

6. Applications

The designed seven-port reflectometer can be used in many applications requiring the measurement of a complex reflection coefficient. There is already an extensive literature on applications of multi-port reflectometers with the main focus on six-ports.

Initially, the six-port reflectometer was developed for metrological purposes (Bilik, 2002). The metrological applications benefit from the high stability of six-port reflectometer
The metrological applications benefit from the high stability of six-port reflectometer applications of multi-port reflectometers with the main focus on six-ports. Measurement of a complex reflection coefficient. There is already an extensive literature on the designed seven-port reflectometer can be used in many applications requiring the six ports.

6. Applications

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Fig. 17. Illustration of synthesized pulse technique: frequency and time domain pulse representation.

The locating reflectometer can be used to investigate waveguide discontinuities, as shown in (Hunter & Somlo, 1985), as well as to build a UWB radar system to measure distances in free space (Noon & Bialkowski, 1993) or perform internal imaging of objects (Bialkowski et al., 2006). The image of a scattering object in time/space domain can be constructed from the scattering signal measured at different viewing angles (Lu & Chu, 1999). Such monostatic
radar systems (Edde, 1995) can be realized by connecting a UWB antenna to the port allocated for DUT in the developed seven-port reflectometer. The potential of using a reflectometer in a microwave imaging system is illustrated in Fig. 18.

In the presented setup, a UWB microwave source is connected to Port 1 while an antenna is connected to Port 2.

In the system illustrated in Fig. 18, the antenna transmits a step-frequency synthesized pulse signal to the object. The reflected signal from the object is received by the same antenna. The measured powers by scalar power detectors at Port 3-7 are converted to digital form by a precision Analog to Digital Converter (ADC). A PC included in this system provides control of the source, the reflectometer and ADC. Also it is used for data collection and post-processing. A UWB microwave system similar to the one shown in Fig. 18 aiming for an early detection of breast cancer is under development at the University of Queensland (Khor et al., 2007).

![Fig. 18. Configuration of a microwave imaging system using a seven-port reflectometer.](image)

### 7. Conclusion

This chapter has described a multi-port reflectometer which employs scalar instead of complex ratio detection techniques to determine the complex reflection coefficient of a given Device Under Test. The operation and optimum design principles of this type of microwave measurement instrument have been explained. Following that, the design of a seven-port reflectometer in microstrip-slot multilayer technology formed by five couplers and one in-phase power divider operating over an ultra wide frequency band of 3.1 to 10.6 GHz has been presented. It has been shown that the seven-port network forming this reflectometer fulfils optimum design requirements. The calibration procedure involving the use of six calibration standards of match load, open, short, two phased-shorts and an intermediate termination have been described for this reflectometer. The performance of the developed reflectometer has been evaluated for 3 different attenuators. The obtained results have
shown that the designed device can be confidently used for UWB measurements. Possible applications of the developed device in communications, microwave imaging and metrology field have been pointed out and briefly explained.

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