# A Simple Low Cost Three-Probe Waveguide Reflectometer in 7 GHz Band

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**Abstract - The reflection coefficient measurement technique using a three-probe reflectometer was analyzed. Based on the results of the theoretical analysis, a very simple and low cost automated stepped frequency six-port reflectometer in the 7 GHz band was designed and manufactured. A six-port network was fabricated using a simple three-probe hybrid waveguide-coaxial structure and "off the shelf" waveguide components. An automatic measuring system was implemented by adding sweep generator and commercial power meters controlled by a PC computer. Calibration was implemented using the modified Neumeyer method. Measurements were made using few unknown loads and the achieved accuracy was 3% in magnitude and 1° in the phase in the whole waveguide band. It was in good agreement with the theoretical prediction.**

## I. INTRODUCTION

A six-port measurement technique, first introduced by Engen [1] in the late seventies is now well established and adopted in the microwave community. Many different six-port designs have been published so far. Among them, three-probe reflectometer is probably the oldest and the simplest one. This method is not widely used because of its narrow bandwidth and large dynamic range on the power detectors. On the other hand, three-probe reflectometer structure is very simple. Reflectometer can be fabricated at very low cost, which makes it convenient for narrow band measurements in calibration laboratories. In this paper, analysis and design of a waveguide three-probe reflectometer in the 7 GHz band, is described.

## II. THEORETICAL ANALYSIS

The basic structure of the three-probe reflectometer [2,3] is shown in Fig 1. It consists of a main line, a reference directional coupler, three nondirectional probes which sample a standing wave in three points and an optional attenuator connected in front of measured load for limiting the dynamics on the detectors. This circuit can be described using a basic six-port equation:

$$\frac{P_k}{P_3} = \frac{|A\Gamma + B|^2}{|C\Gamma + 1|^2} \qquad k = 4,5,6 \quad , \qquad (1)$$

where $\Gamma$ is unknown reflection coefficient, $P_i/P_3$ are measured powers normalised to the power at the reference port, and A, B and C are complex system constants which must be determined by calibration. Three measured normalised powers describe three circles in a complex plane whose intersection gives an unknown reflection coefficient [1]. Analysis of the three-probe reflectometer is usually done assuming that the coupler has infinite directivity, lossless main line, perfectly matched power meters and generator. Coupling between power meters and the line is considered to be weak, so the probes do not disturb field configuration. Power meters are considered as ideal devices, without any measurement errors. In such a case location of the circle centres in the complex plane is only function of the frequency and reflectometer can be used as long as the circles intersection exists i.e. two circle centres do not coincidence. [8]. Theoretically, reflectometer could be used in the almost octave frequency bandwidth. In practice power measurement is affected by errors. Therefore, the three circles will not intersect at only one point, but there will be few mutual intersections which bound the region of uncertainty. In order to minimize errors Engen [1] suggested circle centre (q-points) locations with 120° angular separations on a central circle of radius 1.5. This can be achieved by choosing $d_1=d_2=\lambda/6$ at centre frequency and L=1.76 dB. If the frequency of the operation is varied, the distribution of the circle centres and therefore errors are varied. By defining reflectometer bandwidth using predetermined error margins, it has been shown [4] that in a practical reflectometer, errors are dependent both on power measurement accuracy and reflectometer parameters (finite probe coupling, finite coupler directivity). It has also been shown [5] that hardware imperfections cause narrowing of frequency bandwidth compared to the bandwidth in an ideal reflectometer.

Therefore, main design task is optimization of the reflectometer parameters (probe coupling, reference coupler coupling and directivity, attenuator value). Reflectometer bandwidth can be predicted [5] using computer simulation which uses worst case error analysis. Simulation showed that if reference coupler has directivity better than 20 dB and probe coupling of -20 dB or more, their influence on errors can be neglected. In this case reflectometer bandwidth is primarily determined by the magnitude of a measured reflection coefficient and power measurement errors. Probe coupling is limited by detector sensitivity and available signal generator power, particularly in the millimetre frequency band. It seems that a probe coupling of around 20 dB is a good compromise between the errors introduced and detector sensitivity. Some three-probe reflectometer designs do not include an attenuator. It causes infinite SWR for purely reactive loads and theoretically infinite dynamics on detectors. Introducing an attenuator (L=1.76 dB, $|q|=1.5$), decreases power at the measurement port and causes larger errors in the measurement of loads with small reflection coefficients but decreases dynamics on detectors [7] to 14 dB. An attenuator also introduces isolation between a measured load and generator. This is very important if the measured load is highly reactive, because generator power and frequency could be pulled by the load. In practice, this isolation is usually not enough and it is recommended that a ferrite isolator is inserted between the generator and the reflectometer.

## III. REFLECTOMETER DESIGN

The six-port network was designed using a hybrid waveguide-coaxial technique. Three collinear 3.6 mm holes at the mutual distance of 9 mm ($\lambda_p/6$ at the 7.025 GHz) were made in the middle of the wider wall of the standard J band (5.8 - 8.2 GHz) waveguide. The probes were fabricated using three pieces of semi rigid cables. On the one side of the cable SMA connectors were mounted, and on the other side shielding and insulation is removed in 5 mm length. These cables were inserted into the holes in a such way that only the central wire penetrate in the waveguide making capacitive coupling. A cable shield was soldered to the waveguide. A cross section of the three-probes network is shown in figure 2. The length of the probes (central wire) was trimmed using "cut and try" method until a coupling of 22 dB (waveguide terminated with a matched load) was achieved. It was found that a length of the central wire of 2 mm is required to achieve this coupling. For the reference coupler a standard cross waveguide coupler with coupling of 20 dB, and 20 dB directivity was used. A waveguide circulator was used for isolation between the measured load and the generator. A commercially available waveguide attenuator adjusted to 1.76 db, was connected in front of the measured load. An RF generator HP 86320, and power meters HP 437B (maximal relative power measurement error 0.5%), were used. Using the error model described in [4] a reflectometer bandwidth with error margins of 2% (magnitude) and 2° (phase) was calculated. Simulation results gave a bandwidth of 42% for a load with reflection coefficient of magnitude 0.5. That bandwidth exceeds the waveguide bandwidth (32%). Therefore, it is expected that reflectometer may be used in a whole waveguide band. All instruments were connected to a PC computer using IEEE-488 bus. Appropriate software for calibration and measurement was developed. Modified Neumeyer calibration method developed in [5] was implemented. This method enables usage of different types of connectors in the six-port to four-port reduction and in the error-box calibration. Therefore, reduction can be achieved using five positions of waveguide sliding short, and then error box calibration by using two sliding short positions and a waveguide matched load. After that, the six-port is prepared for measurement of waveguide loads. If one wants to measure coaxial loads, after reduction is accomplished, adapter waveguide to coax can be mounted on the reflectometer measuring port. Then, error-box calibration can be achieved using three coaxial standards.

## IV. MEASUREMENT RESULTS

Measurements were performed using coaxial loads. Six-port to four-port reduction was done using waveguide sliding short. After that the waveguide to coax adapter was mounted and error-box calibration was performed using three coaxial calibration standards from a HP 85032D calibration kit. Location of the centres of constant normalised power (q-points) were calculated from calibration parameters. These values are shown in Fig. 3 (magnitude) and Fig. 4 (phase difference). It can be noted that magnitudes of q-points are fairly constant and show only small variations. At higher frequencies these variations increase but magnitudes are in no case smaller than 1.3 and greater than 1.9. Phase differences vary from 80° to 240°. These values are still large enough to produce unique intersections for $\Gamma$ within a whole waveguide band. Three different loads were measured: short, 3 dB attenuator terminated with short and 6 dB attenuator terminated with short. Load reflection coefficients measured by a HP 8720B network analyzer were taken as a reference. It must be mentioned that HP 8720B accuracy declared by manufacturer is 1.15% for magnitude and 0.5° in phase. Results are shown in Fig. 5 and Fig. 6. The magnitude error was less than 3%, and the phase error less then 1° in whole band (5.8 to 8.2 GHz). This is in very good agreement with simulation which gave worst case errors of 2.8% in magnitude and 1.8° in phase.

## V CONCLUSION

The three-probes method is convenient for application in waveguide reflectometer because the intrinsic bandwidth determined by error margins exceeds the waveguide bandwidth. The reflectometer can be fabricated relatively easily and at low cost. Using this reflectometer accuracy of 3% in magnitude and 1° in phase was achieved. It was limited primary on the accuracy of power meters. The main drawback of this design is the large insertion loss between feeding port and power detectors caused by weak probe coupling.

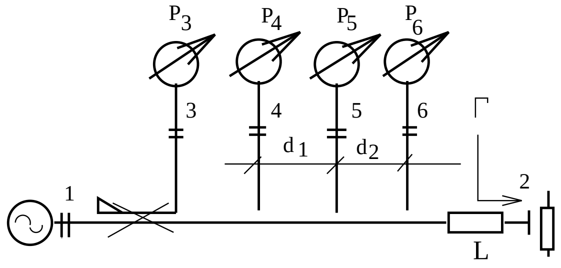

Fig. 1. A general three-probe reflectometer

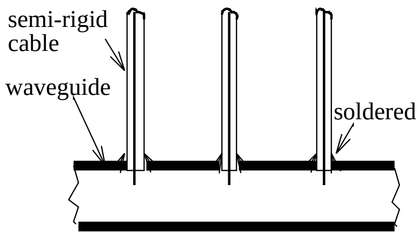

Fig. 2. A cross section of the three-probe network

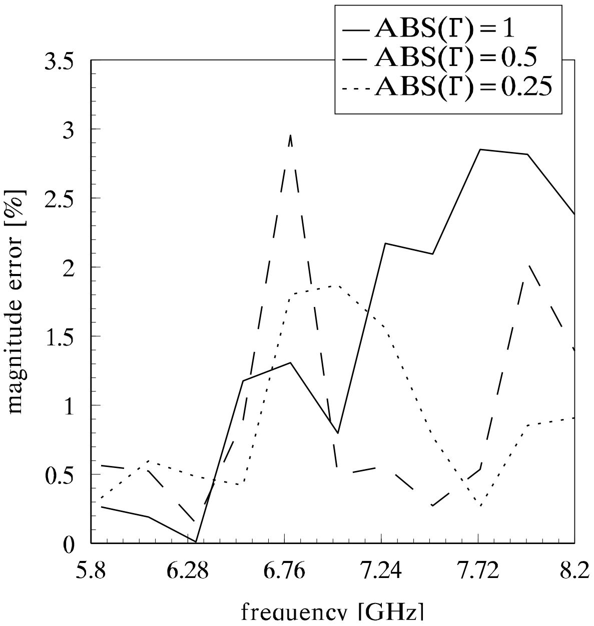

Fig. 3. Dependence of q-points magnitude on frequency

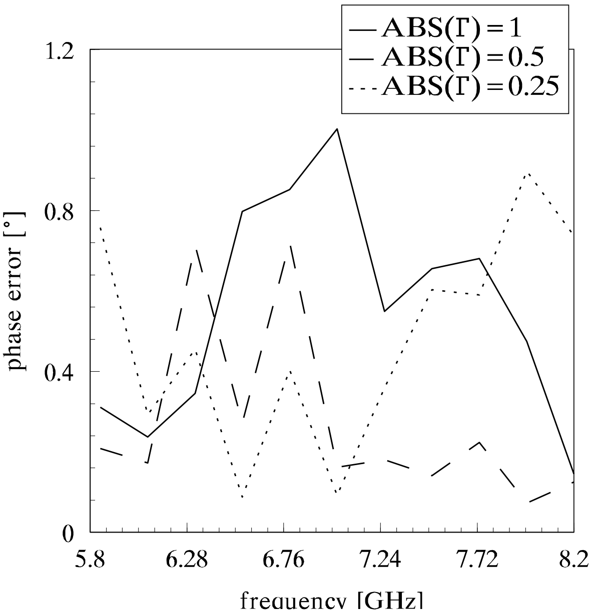

Fig. 4. Dependence of q-points phase difference on frequency

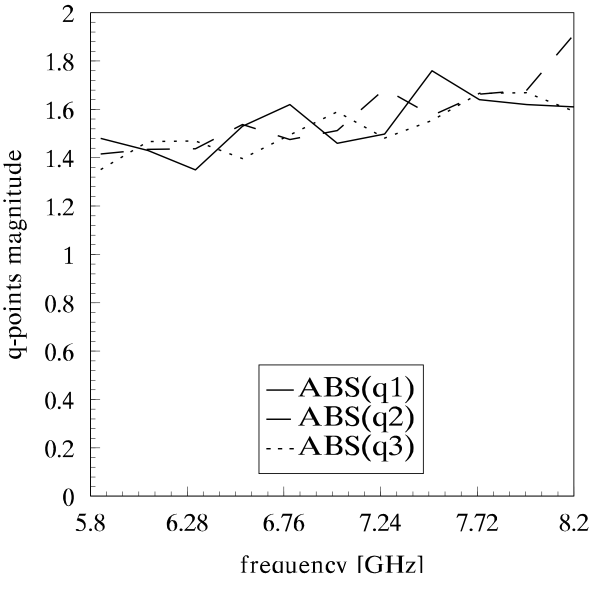

Fig. 5. Measurement results - magnitude error

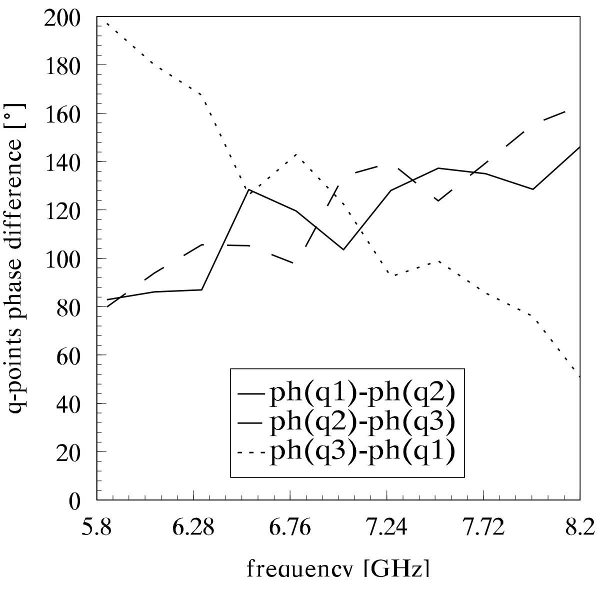

Fig. 6. Measurements results - phase error

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