TRANSMISSION PHASE MEASUREMENTS WITH A SINGLE SIX-PORT

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Abstract

It is well known that two six-ports can be used to measure the S matrix parameters of a two port network. In this paper the point is emphasized that a single six-port is sufficient to measure the transmission phase of such a two port network. The transmission phase is frequently the quantity of most experimental interest. Two methods of measuring transmission phase with a single six-port are described and experimental confirmation is provided at X band (8.2-12.4 GHz) and Ku band (12.4-18.0 GHz).

Introduction

Transmission phase is one of the more attractive quantities to measure with the six-port measurement technique. This is particularly true above 12.4 GHz where no commercial swept measurement equipment is available for measuring phase. On the other hand , six-port techniques can be expected to be useful for measuring transmission phase into the millimeter region of the spectrum. Although it is well known that two six-ports can be used to measure the S matrix parameters of a two port[1], it is perhaps less well appreciated that a single six-port is sufficient for measuring transmission phase. In this paper two methods for measuring transmission phase in this way are described. Experimental results are presented at X band (8.2-12.4 GHz), where they can be compared with those of a commercial network analyser, and at Ku band (12.4-18.0 GHz).

Method I

The first method uses a single six-port to measure four reflection coefficients. The transmission phase is then calculated from these reflection coefficients within an uncertainty of 180°. The reflection coefficients that have to be measured are that of an appropriate mismatch, that of the test device with a load on the output, and those with this mismatch and the mismatch shifted through a known length of transmission line on the output of the D.U.T.. The method is only applicable to reciprocal devices with relatively low loss (<10 dB) and gives an uncertainty of 180° in the phase. An important point is that if the only information required is the phase differences between various output ports with a common input port (one of the most common applications) , then nothing need be known about the actual reflection coefficient of the mismatch.

The basic idea is to try to determine the transmission matrix element S_{12} from the signal reflected back through the device by a standard on the output after the reflection coefficient with a load on the output has been measured. Let Γ be the reflection coefficient of a device with scattering matrix parameters S_{11}, S_{12}, S_{22} (this approach applies to reciprocal devices for which $S_{12}=S_{21}$) with a standard with reflection coefficient Γ' on the output. Then

$$\begin{pmatrix} V_1' \\ V_2' \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{12} & S_{22} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} \Rightarrow \begin{array}{ll} V_1' = S_{11}V_1 + S_{12}V_2 & (1) \\ V_2' = S_{12}V_1 + S_{22}V_2 \quad . & (2) \end{array}$$

Now $V_2 = \Gamma' V_2'$. Substituting into (2) and solving for V_2 yields

$$V_2 = \frac{\Gamma' S_{12} V_1}{1-\Gamma' S_{22}} \quad .$$

Substituting into (1) ,

$$V_1' = \left\{ S_{11} + \frac{\Gamma' S_{12}^2}{1-\Gamma' S_{22}} \right\} V_1 \text{ or } \Gamma = S_{11} + \frac{\Gamma' S_{12}^2}{1-\Gamma' S_{22}} \quad .$$

$$\therefore\ S_{12}^2 = \frac{(\Gamma - S_{11})(1-\Gamma' S_{22})}{\Gamma'} \quad . \tag{3}$$

Clearly the transmission phase can be determined within an ambiguity of 180° by measuring the four reflection coefficients S_{11} , S_{22} , Γ , and Γ'.

One undesireable feature is that the output reflection coefficient S_{22} must be measured requiring the D.U.T. to be removed from the line. Furthermore, for certain networks this output reflection coefficient will be large although the input reflection coefficient is small. Likewise, the reflection coefficient of the standard must be measured. These difficulties can be overcome by including a second measurement at the input port with the standard at the output port shifted through a known length ℓ_i of transmission line. If the reflection coefficient of the path length shifted standard is called Γ'' and the reflection coefficients at the input port for the two cases are called Γ_1 and Γ_2 respectively, then from (3)

$$\frac{S_{12}^2}{\Gamma_1 - S_{11}} = \frac{1}{\Gamma'} - S_{22} \quad ; \quad \frac{S_{12}^2}{\Gamma_2 - S_{11}} = \frac{1}{\Gamma''} - S_{22} \quad .$$

Eliminating S_{22} between these equations gives

$$S_{12}^2 = \frac{(S_{11}-\Gamma_1)(S_{11}-\Gamma_2)}{(\Gamma_2 - \Gamma_1)} \left\{ \frac{1}{\Gamma'} - \frac{1}{\Gamma''} \right\} \quad . \tag{4}$$

Note that if the same standard is used for all measurements, then the magnitude of Γ' and Γ'' will be the same and need not be known or measured to determine the phase of S_{12}. In most cases one is making relative amplitude and phase measurements between various output ports. The term $\left\{\frac{1}{\Gamma'} - \frac{1}{\Gamma''}\right\}$ will be common to all such measurements and nothing at all need be known about the standard in order to make such measurements!

The approach can be expected to work well as long as the magnitude of the signal reflected back through the unit is larger than the magnitude of the reflected signal at the input port. This means that it should work well for devices with losses ≤ 6 dB since then the signal reflected by an O.C. or S.C. on the output will have a magnitude corresponding to a loss of at most

12 dB. This is less than almost all input return losses. The method can work well for single path losses up to 12 dB provided that the input port is sufficiently well matched. A good application for this technique is to the measurement of the relative output port phases of a comparator. The transmission loss from any input to any one of the four output ports of a comparator will be close to 6 dB. Consequently, the signal reflected back to the input by a short circuit at the output will be 12 dB down. With one of the three input channels of the comparator (SUM,DIFF-1,DIFF-2) bolted onto the line, the relative phases of the four output ports can be measured using this method without unbolting the unit. This allows for a mechanically simple measurement procedure.

Transmission phase measurements were made from 8.5-9.6 GHz on a WR90 comparator and the results compared with phase measurements made with a commercial network analyser. A picture of the experimental arrangement is given in Figure 1. The six-port used was actually a five port waveguide resolver which was described briefly in last years Proceedings and which can be used to make accurate reflection coefficient measurements provided that the magnitude of the reflection coefficient $|\Gamma|<1/3^2$. With each of the four output ports, a measurement is made with a load on the output, a short circuit on the output, and a short circuit shifted through a length of transmission line on the output. The length of transmission line corresponded to a quarter wavelength at mid-band to maximize the factor in brackets in equation 4. Figure 2 gives the relative phases 1-2, 1-3, 1-4 for the DIFF-1 channel which was out of specification. The continuous curves are the results for a commercial network analyser. The agreement between the two is within 1°. The system repeatability is less than $.3^\circ$.

Method II

The second method is a more general one applicable to nonreciprocal devices and devices with attenuation >10 dB. A schematic diagram of the experimental arrangement is given in Figure 3. The signal from the generator is divided along two paths as in a phase bridge. Along one path the signal goes through an isolator to one input of the six-port. Along the second path the signal goes to the D.U.T. through a second isolator to the other input of the six-port. The importance of the isolators can be illustrated by considering the behaviour of the ideal six-port. Engen has suggested that the ideal six-port should have q values q_1, q_2, q_3 separated by 120° in the complex plane as in Figure 4.[3] If the equilateral triangle formed by these q values encloses the unit circle, then the input and output of this ideal six-port will only be isolated from each other by 6 dB. This contrasts with the case of the ideal correlator circuit for which the input and output are perfectly isolated from one another.[4] Consequently, ideal isolators should in principle be inserted at the input and output to prevent transmitted signals from being reflected back into the six-port. This point is perhaps implicit in the work of Hoer and Roe[5] but is worth re-emphasizing.

The picture of an experimental arrangement to measure transmission phase in Ku-band (12.4-18.0 GHz) is given in Figure 5. Once again the resolver is used in place of an actual six-port. Furthermore, a precision attenuator was used in place of an isolator at the output. If a low loss component is being measured, such as the compact isolator in the figure, then at least 10 dB of loss must be inserted via the precision attenuator to reduce the amplitude of the signal at the output. This is necessary because the resolver and directional coupler together constitute a five port and with a five port one is not able to make unambiguous measurements under all circumstances. In this case the measurements will only be unambiguous if the amplitude at the output is sufficiently small. The precision attenuator then provides 20 dB or more of isolation by itself. The data is collected and processed with the PMI 1045 power meter and PET 2001 personal computer, which provides for a quite economical system.

References

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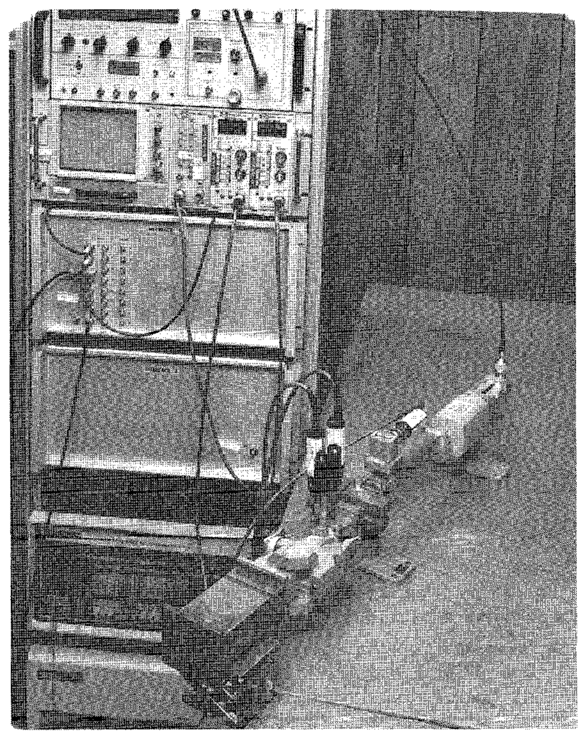

Figure 1 Experimental set-up for measuring the relative output port phases 1-2,1-3,1-4 of a WR90 comparator.

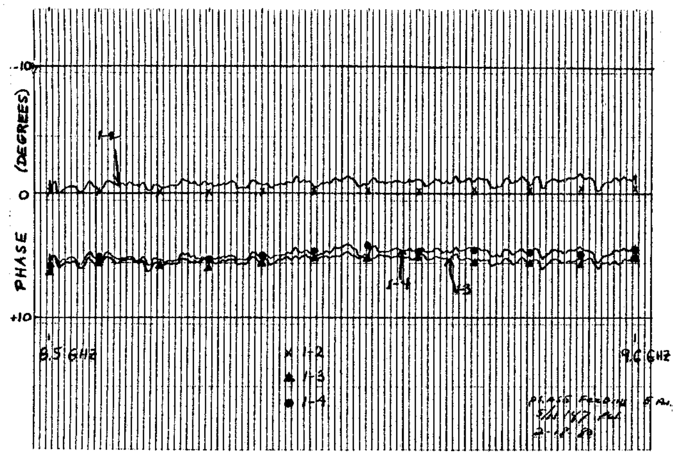

Figure 2 The relative output port phases 1-2, 1-3, and 1-4 of the DIFF-1 channel of a WR90 comparator as measured with a resolver (x,Δ,o)and with a commercial network analyser(continuous curves).

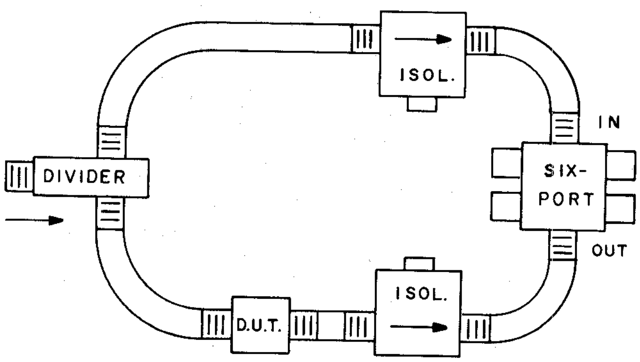

Figure 3 Schematic diagram of the experimental arrangement for measuring transmission phase with a single six-port.

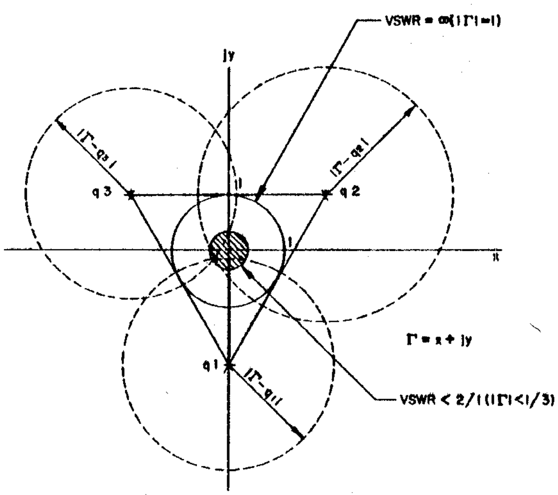

Figure 4 Engen diagram giving the location of the q values q_1 , q_2 , and q_3 in the complex plane for the ideal junction 'six-port'.

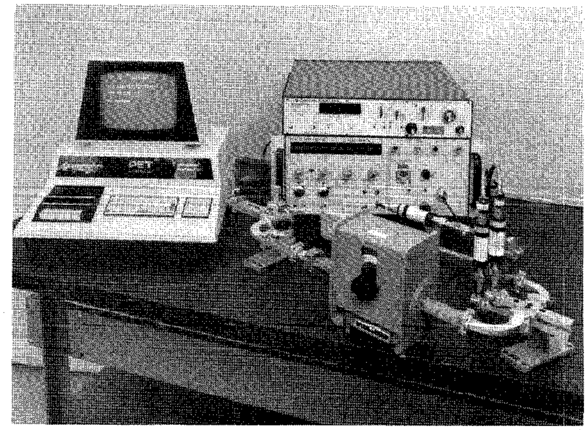

Figure 5 Experimental arrangement for measuring transmission phase in WR62 waveguide.

Table I Phase tracking of matched pair of Ku band miniature isolators as measured with the experimental arrangement of Figure 5.

Frequency(GHz)	Phase Difference(Degrees)
15.5	-1.0
15.7	-1.1
15.9	-1.4
16.1	-1.7
16.3	-1.9
16.5	-2.0
16.7	-2.1
16.9	-1.7
17.1	-1.5
17.3	-0.8
17.5	-1.2