THE USE OF A MATCHED SYMMETRICAL FIVE-PORT JUNCTION TO MAKE SIX-PORT MEASUREMENTS

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ABSTRACT

A new configuration for six-port measurements is proposed. It consists of a symmetrical five-port junction and a directional coupler. Assuming the components to be ideal,it is shown that the proposed six-port has optimal properties for accurate determination of complex reflection coefficients. An experimental coaxial five-port junction has been designed and used in a six-port measurement system. After calibration, using five impedance standards, measurements on precision loads indicate good measurement accuracy over the frequency band where the five-port is well matched.

Introduction

In a six-port measurement system the complex reflection coefficient,Γ, is given by the intersection of three circles in the complex plane, whose radii are related to the readings of four power detectors. In a paper by Engen[1] it was argued that, ideally, one power detector should be used to determine the power incident to the unknown load, while the complex numbers , q_1 , q_2 and q_3 , associated with the remaining three power detectors should be symmetrically distributed around the origin, i.e. separated by 120°. The numbers q_1 , q_2 and q_3 then represent the centers of the three circles, see Fig.1.

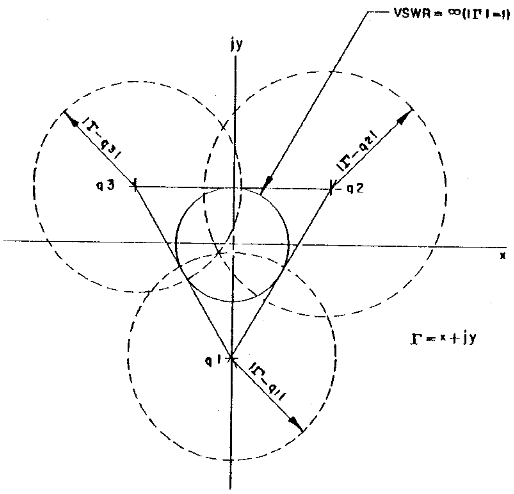

FIGURE 1: OPTIMUM LOCATION OF q_1 , q_2 AND q_3 FOR A SIX-PORT, AFTER ENGEN.

Most six-port networks reported on have been based on the use of several standard four-port networks connected together , enabling broadband frequency coverage e.g.[2,3]. These six-ports are,however, rather complicated and the q-points have a non-ideal distribution even if the four-port networks are assumed to be perfect. Some attempts have been made to find simple six-port structures with ideal q-point distribution , so far resulting in narrow-band devices[4,5].

A simple six-port configuration will here be described consisting of a symmetrical five-port junction and a directional coupler, Fig.2. It will be shown that an ideal distribution of the q-points is obtained using perfect components and that an operational bandwidth of about an octave is readily realized.

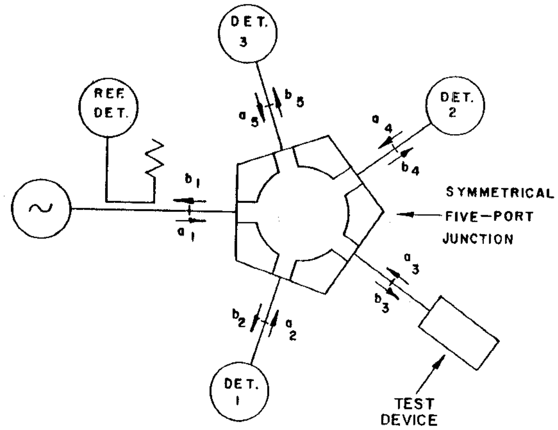

FIGURE 2: PROPOSED SIX-PORT CONFIGURATION.

Properties of a matched five port junction

The scattering matrix element-eigenvalue relations for a symmetrical,reciprocal five-port junction are[6]:

$$S_{11} = (S_1+2S_2+2S_3)/5 \tag{1}$$

$$S_{12} = (S_1+2S_2 \cos(\tfrac{2\pi}{5})+2S_3\cos(\tfrac{4\pi}{5}))/5 \tag{2}$$

$$S_{13} = (S_1+2S_2 \cos(\tfrac{2\pi}{5})+2S_3\cos(\tfrac{2\pi}{5}))/5 \;. \tag{3}$$

The scattering matrix eigenvalues S_1, S_2, and S_3 represent the reflection coefficients for the three different eigen-excitations of the junction. For a lossless five-port junction all power entering the junction is radiated out, which means that $|S_1|= |S_2|= |S_3|= 1$. Assuming, in addition, that the five-port is matched there are only two combinations of eigenvalues, except for a common arbitrary phase angle,that satisfy Eq.(1). With $S_1= -1$, $S_2= \mathrm{Exp}[\pm j \cos^{-1}(.25)]$ and $S_3= \mathrm{Exp}[\mp j \cos^{-1}(.25)]$. Insertion of these eigenvalues into Eq.(2) and (3) implies that

$$|S_{12}| = |S_{13}| = .5 \tag{4}$$

and

$$\angle S_{13} = \angle S_{12} \pm \tfrac{2\pi}{3}\ (120^{\circ}) \tag{5}$$

The matched symmetrical five-port junction thus works as a 4-way equal power divider. These results agree with the ones published by Dicke.[6]

Derivation of q_1 , q_2 and q_3 for the proposed six-port assuming ideal performance.

The complex amplitudes of waves entering into the junction, $a_1 \ldots a_5$, and waves emerging from the junction, $b_1 \ldots b_5$, at symmetrically situated reference planes, as illustrated in Fig. 2, are related through the scattering elements of the five-port. If the detectors are matched then $a_2 = a_4 = a_5 = 0$. Thus we get

$$b_2 = S_{12} a_3 + S_{12} a_1 \tag{6}$$

$$b_3 = S_{13} a_1 \tag{7}$$

$$b_4 = S_{12} a_3 + S_{13} a_1 \tag{8}$$

$$b_5 = S_{13} a_3 + S_{12} a_1 \quad . \tag{9}$$

With a_1 according to (7) the powers emerging to the detectors 1-3 are

$$P_1 = |S_{12} a_3 + \frac{S_{12}}{S_{13}} b_3|^2 = |S_{12}|^2 |b_3|^2 |\Gamma - (-\frac{1}{S_{13}})|^2 \tag{10}$$

$$P_2 = |S_{12} a_3 + b_3|^2 = |S_{12}|^2 |b_3|^2 |\Gamma - (-\frac{1}{S_{12}})|^2 \tag{11}$$

$$P_3 = |S_{13} a_3 + \frac{S_{12}}{S_{13}} b_3|^2 = |S_{13}|^2 |b_3|^2 |\Gamma - (-\frac{S_{12}}{S_{13}^2})|^2 \tag{12}$$

where $\Gamma = a_3/b_3$. In (10)-(12) we identify[1]

$$q_1 = -\frac{1}{S_{13}} \tag{13}$$

$$q_2 = -\frac{1}{S_{12}} \tag{14}$$

$$q_3 = -\frac{S_{12}}{S_{13}^2} \quad . \tag{15}$$

Using the relations for S_{12} and S_{13} according to (4) and (5) we find that

$$|q_1| = |q_2| = |q_3| = 2 \tag{16}$$

$$\angle q_2 = \angle q_1 \pm \frac{2\pi}{3} \tag{17}$$

$$\angle q_3 = \angle q_1 \mp \frac{2\pi}{3} \quad . \tag{18}$$

A more detailed study would show that only one combination of signs in (17) and (18) is in fact possible for a physical five-port junction , so that the presence of the double signs is no indication of a phase ambiguity. Thus the q-points are ideally situated for six-port measurements(see Fig.1).

A consequence of these results is that the problem of obtaining a preferable distribution of the q-points is, for the proposed six-port,essentially reduced to the problem of matching the symmetric five-port junction. The reciprocal five-port junction, used as a part of a six-port as described above or as a four way equal power divider, thus exhibits an analogy with the non-reciprocal three-port junction, where similarly, the desired function mode, namely circulation, can be obtained by simply matching the junction.

Power distribution of the proposed six-port.

By the aid of the reference detector we measure the input power, P_{in}, to the junction which with (7) gives

$$P_{in} = |a_1|^2 = |b_3|^2 / |S_{13}|^2 \quad . \tag{19}$$

From (10) - (12) we thus get

$$\frac{P_i}{P_{in}} = |\Gamma - q_i|^2 / 16 \; . \qquad i = 1, 2, 3 \tag{20}$$

The relative output powers thus range from 1/16 to 9/16. The total power to the detectors 1 to 3 is 3/4 for $\Gamma=0$, increasing to 15/16 for $|\Gamma|=1$. The remaining power emerges to the generator if $|\Gamma| \neq 0$, and to the test device if $|\Gamma| \neq 1$.

By using the properties of the ideal six-port an approximate value of Γ, suitable for visual display , is readily available:

$$\frac{3}{4} \, \mathrm{Re}\{\Gamma\} = (P_1 + P_2 - 2 P_3)/P_{in} \tag{21}$$

$$\frac{\sqrt{3}}{4} \, \mathrm{Im}\{\Gamma\} = (P_1 - P_2)/P_{in} \quad . \tag{22}$$

Experimental six-port

A symmetrical five-port junction in planar technique has been constructed, based on a series expansion of the fields in the junction subject to proper boundary conditions. By designing the junction to have large coupling to the surrounding network a relatively broadband device could be obtained without using any external matching, Fig.3.

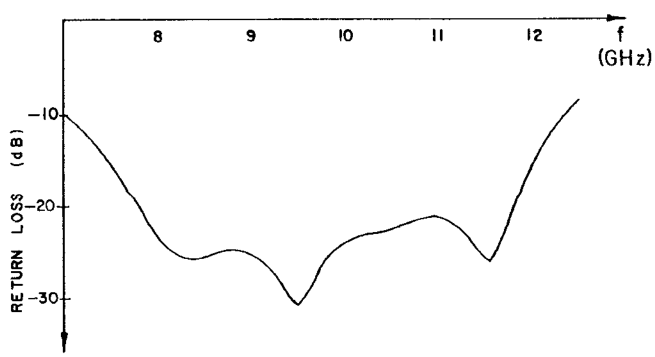

FIGURE 3: MEASURED RETURN LOSS VERSUS FREQUENCY OF A PLANAR SYMMETRICAL FIVE-PORT JUNCTION.

Measurement of some standards with the experimental six-port

Due to the imperfections of the five-port and the directional coupler an accurate determination of the eleven calibration constants for the six-port is necessary for precision measurements.[7] A calibration routine has been developed, based on the procedure proposed by Judah[8], which makes use of five standards, four with $|\Gamma|=1$ and the fifth with $\Gamma=0$. Although only the four unit modulus loads are actually necessary for determination of the calibration constants, the use of an additional precision 50Ω load has been found to improve the accuracy for small reflection coefficients. The calibration constants are calculated and stored in a form suitable for rapid calculation of Γ according to Eq.(23) below.[1]

$$\Gamma=\frac{\alpha_1+j\beta_1+(\alpha_2+j\beta_2)\frac{P_1}{P_{ref}}+(\alpha_3+j\beta_3)\frac{P_2}{P_{ref}}+(\alpha_4+j\beta_4)\frac{P_3}{P_{ref}}}{1+\gamma_1\frac{P_1}{P_{ref}}+\gamma_2\frac{P_2}{P_{ref}}+\gamma_3\frac{P_3}{P_{ref}}} \quad (23)$$

Here the ratios p_i/P_{ref} , $i=1,2,3$, were taken directly by a ratio detecting, multi-channel power meter.

Some examples of measurements made with the experimental six-port are given in Table 1. None of the standards in Table 1 were used for calibration. The calibration loads for the six-port were:

1. Open circuit at the reference plane.
2. Open circuit, offset -4.128mm.
3. Open circuit, offset +3.772mm.
4. Short circuit at the reference plane.
5. Precision 50 Ω load.

Fig.4 shows the six-port used in the measurements.

Table I

Examples of measurements with the proposed six-port.

A: Open circuit,offset 1.892mm.
B: Standard load,$|\Gamma|$=.2 nominally
Reference pl. ext. 0.000mm

Freq.(MHz)	A. Open circuit		B.Standard load	
	$\|\Gamma\|$	$\angle\Gamma$ (°)	$\|\Gamma\|$	$\angle\Gamma$ (°)
7000	.990	-.4	.214	79.7
7500	1.007	-1.0	.212	45.7
8000	1.000	.6	.206	13.2
8500	.985	.1	.195	-20.6
9000	.992	-1.1	.190	-59.3
9500	1.000	.1	.187	-94.8
10000	.992	.2	.195	-132.9
10500	.997	.9	.190	-169.6
11000	.998	-1.0	.203	155.0
11500	.990	-.3	.208	119.6
12000	.989	-.5	.209	87.0
12500	.992	-1.0	.205	52.5

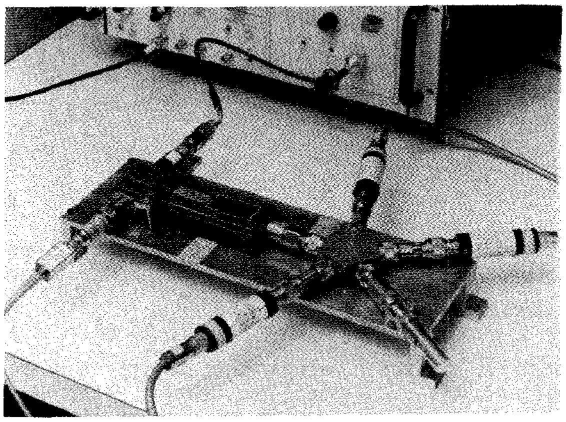

FIGURE 4: EXPERIMENTAL SIX-PORT

Conclusion

A compact and simple six-port configuration with virtually ideal properties for precision measurements has been presented. Measurements on an experimental model demonstrate the applicability of the proposed six-port. By the use of external matching networks it should be possible to increase the bandwidth of the five-port junction and thereby also the bandwidth of the six-port.

References

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