# WAVEGUIDE STAR JUNCTION USED IN Ka BAND DUAL SIX PORT MEASUREMENTS

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## ABSTRACT

An automatic dual six port network analyzer has been designed and tested over the frequency band of 26.5 to 40 $GHz$. The six port design utilizes a matched symmetrical five port waveguide junction. A method of matching avoiding the use of tuning screws is discussed, and an analysis of the sensitivity of six port parameters to the matching of the star junction is presented.

## INTRODUCTION

It has been shown by Hansson and Riblet [1] that a matched lossless reciprocal five port can be used together with a perfect directional coupler to construct an ideal six port for microwave measurements. Some practical results have been reported using this scheme in microstrip and stripline media for frequencies up to 18 $GHz$ [1][2]. In this paper the design of a waveguide five port junction suitable for broad band measurements in millimeter wave bands is discussed and practical results over the frequency band of 26.5 to 40 $GHz$ are presented.

## MACHED STAR JUNCTION

The key observation leading to the design of the matched five port was that a star junction fabricated and tested here * demonstrated to be inherently matched with a return loss greater than 15 $dB$ over a frequency range covering the lower portion of the waveguide band and extending outside the band. Expressed in terms of the cutoff frequency $f_c$ of the waveguide, the region of inherent match extended approximately from $1.14 f_c$ to $1.66 f_c$ The task of designing a matched five port was then reduced to the alteration of the size of the junction such that the range of inherent match is shifted up in frequency to cover the entire waveguide band. This was achieved by reducing the size of the waveguides forming the junction. For operation in $Ka$ band (26.5 to 40 $GHz$), the size of the smaller waveguides characterized by the cutoff frequency $f_c'$ was obtained from the requirement $1.66 f_c' = 40 GHz$. Leading to $f_c' = 24.1 GHz$ and the corresponding waveguide size of $0.24 \times 0.12 in$. These dimensions were then tapered out to $0.280 \times 0.140 in$ for connection with WR28 waveguide used in $Ka$ band. Figure 1 shows the value of $S_{11}$ for both tapered and untapered star junctions over the entire $Ka$ band.

* This junction consists of the intersection of five waveguides in the $H$ plane, maintaining a five fold rotational symmetry about the common axis, and sharp intersection edges.

## SIX PORT SENSITIVITY TO THE MATCHING OF THE STAR JUNCTION

A star junction with five fold rotational symmetry has three distinct $S$ parameters, namely $S_{11}$, $S_{12}$, and $S_{13}$ ($S_{15} = S_{12}, S_{14} = S_{13}$). It has been shown that if such a lossless junction is completely matched, i.e., $S_{11} = 0$, then $|S_{12}| = |S_{13}| = .5$ and the phase angle between the two is 120° [3]. A five port with these properties can be used with a perfect directional coupler to make an ideal six port for $S$ parameter measurements [1]. In practice, of course, the magnitude of $S_{11}$ is never zero, and the properties of the five port are less than ideal. The following analysis is aimed at quantifying this, by finding the relationship between $S_{12}$ and $S_{13}$ when $S_{11}$ is not zero.

The three independet $S$ parameters of the star junction are given in terms of its three scattering matrix eigenvalues $S_1$, $S_2$, and $S_3$ as follows [3]

$$S_{11} = (S_1 + 2S_2 + 2S_3)/5, \quad (1)$$
$$S_{12} = (S_1 + 2S_2\cos(2\pi/5) - 2S_3\cos(\pi/5))/5, \quad (2)$$
$$S_{13} = (S_1 - 2S_2\cos(\pi/5) + 2S_3\cos(2\pi/5))/5. \quad (3)$$

The magnitude of each eigenvalue is unity for a lossless junction. The phase angle of one of the eigenvalues can be set arbitrarily. This corresponds to the choice of the reference plane at each port. The choice we make here is

$$S_1 = -1, \quad S_2 = e^{i\theta_2}, \quad S_3 = e^{i\theta_3}. \quad (4)$$

Since the reference planes are now fixed, $S_{11}$ has well defined real and imaginary parts. Given real and imaginary parts of $S_{11}$, the values of $\theta_2$ and $\theta_3$ can be determined from (1). Written more explicitly, $\theta_2$ is determined from the quadratic equation

$$\cos^2(\theta_2) - \frac{1}{2}(5Re(S_{11}) + 1)\cos(\theta_2) + \frac{1}{16}F(S_{11}) - \frac{25(Im(S_{11}))^2}{F(S_{11})} = 0, \quad (5)$$

where $F(S_{11}) = (5Re(S_{11}) + 1)^2 + (5Im(S_{11}))^2$. The other angle $\theta_3$ is obtained by direct substitution into (1), and the other two $S$ parameters are found from (2) and (3). Exceptionally simple results are obtained if we assume that $S_{11}$ is real:

$$Re(S_{12}) = Re(S_{13}) = -0.25(1 + S_{11}),$$
$$Im(S_{12}) = -Im(S_{13}) = 0.25(3 - 2S_{11} - 5(S_{11})^2)^{1/2}. \quad (6)$$



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Equations (6) show that even a poorly matched junction is a good power divider under these conditions. However, the condition on the phase of $S_{11}$ can not be practically enforced and it is necessary to find the behavior of the $S$ parameters as a function of both magnitude and phase of the reflection coefficient. This is done numerically using (5), with the results given in figures 2 and 3. These results show the extent of deviation from ideal behavior that can be expected from a junction with a given magnitude of $S_{11}$. Also, if the magnitudes of $S_{11}$, $S_{12}$ and $S_{13}$ are known, the phase angles of $S_{12}$ and $S_{13}$ can be estimated from figures 2 and 3.

## EXPERIMENTAL SYSTEM

A dual six port network analyzer using tapered waveguide star junctions has been assembled and tested in the frequency range of $Ka$ band. The magnitude of $S_{11}$ for the star junction is $-15dB$ or less over the entire band. The differnce between the magnitudes of $S_{12}$ and $S_{13}$ is $2dB$ over most of the band, and the phase angle between them can vary from 105 to 145 degrees (Fig. 3). The detectors used are Schottky diodes preceded by isolators in order to keep the six port under optimum operating conditions. Each six port is calibrated separately as a reflectometer using a matched load and five offset shorts (or four offset shorts and a standard mismatch). The resulting twelve equations in eleven unknowns [4] are solved using least squares analysis. This analysis allows for the use of a higher number of standards leading to more equations if necessary. Extra equations reduce the effect of experimental errors on calibration, at the expense of some numerical complexity. After the calibration of each six port, the dual six port is calibrated using the method suggested by Woods [5]. This method involves switching each six port to active and passive modes of operation. Two waveguide switches are used for this purpose. The calibration method for the dual six port has not been finalized. Other calibration procedures are being tested for the best combination of measurement speed and accuracy.

## CONCLUSIONS

It was shown that waveguide star junctions can be matched over the entire waveguide band using a simple taper in each arm. The analysis of the lossless five port star junction showed the extent of ideal behavior that can be expected from the junction when it is not perfectly matched. Finally, a dual six port network analyzer utilizing waveguide star junctions was built and successfully tested over the frequency range of 26.5 to $40GHz$.

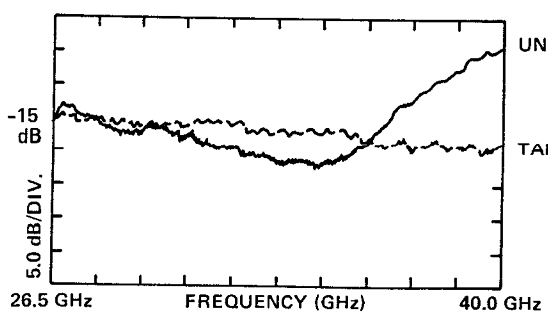


**Figure 1.** $S_{11}$ for tapered and non-tapered junctions. Vertical scale is $5dB$ per division.

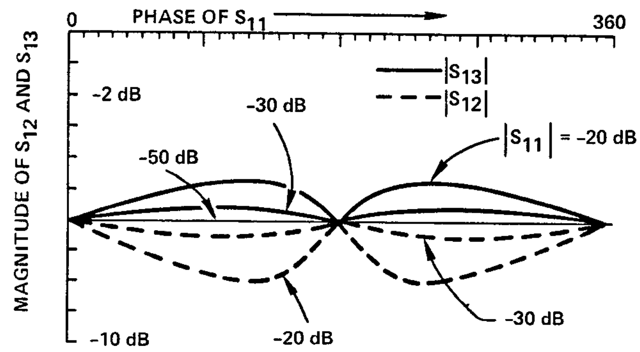


**Figure 2.** Magnitudes of $S_{12}$ and $S_{13}$ vs. phase of $S_{11}$, for three magnitudes of $S_{11}$.

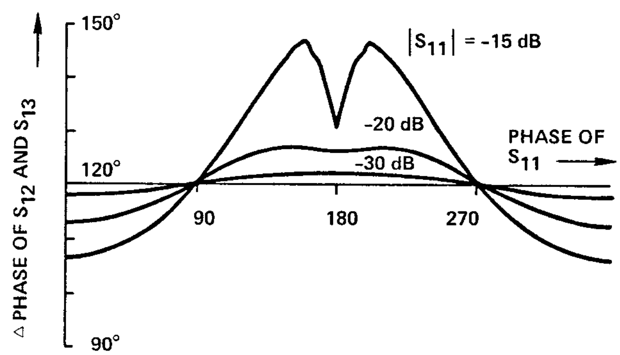


**Figure 3.** Phase difference between $S_{12}$ and $S_{13}$ as a function of magnitude and phase of $S_{11}$.

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