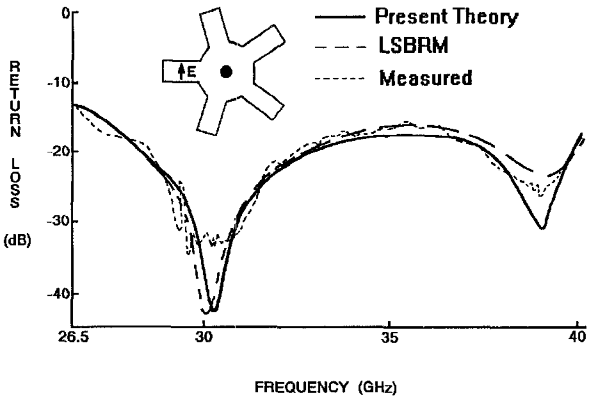

Fig. 4. Return loss versus frequency for a symmetrical 5-port consisting of a coaxial cavity and E-plane coupled rectangular waveguides. Cavity dimensions: height a = 11.0 mm, inner radius r_i = 0.50 mm, outer radius r_o = 4.50 mm. Waveguide dimensions: width a = 11.0 mm, height b = 3.56 mm. Experimental and LSBRM points taken from Cullen *et al.* [3].

band, the power delivered to port 1 is almost equally divided between the remaining four ports. At the same time, the phase difference between the signals at ports 2 and 3 stays approximately constant and is close to 120 degrees. According to the theory [1], the analysed five-port is suitable in the design of a broadband six-port reflectometer.

Fig. 4 shows a comparison between theoretical and experimental results for the return loss of the symmetrical five-port, now incorporating a coaxial cavity. The theoretical results were obtained by using LSBRM [3] and the non-standard field matching technique developed here. It can be seen that both LSBRM and the field-matching technique provide very similar results and both agree well with the experiment.

CONCLUSIONS

Based on the non-standard field matching technique which exploits both, circular and rectangular, natural boundaries, the analysis of an n-port comprising a radial or coaxial cavity and E-plane coupled rectangular waveguides has been presented. A computer algorithm for determining the scattering matrix of the n-port has been developed.

The validity of the new analysis and the algorithm have been verified by comparing numerical results with experiment and the alternative analysis which was based on the least-squares boundary residual method.

The new analysis produces results in good agreement with those produced by the least-squares boundary residual method and experiment. In comparison with the LSRBM, the new analysis is less complicated.

The analysis is easily implemented on an IBM PC. The analysis and computer algorithm can be of help to the designers of E-plane n-port circuits.

ACKNOWLEDGMENT

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REFERENCES

[1] G. P. Riblet, "An E-plane coupled matched waveguide 5-port for making 6-port measurements over a full waveguide band," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1983, pp. 372–374.
[2] A. L. Cullen and S. P. Yeo, "Using the least-squares boundary residual method to model the symmetrical five-port waveguide junction," *Inst. Elec. Eng. Proc. H, Microwaves, Antennas & Propag.*, 1987, vol. 134, no. 2, pp. 116–124.
[3] A. L. Cullen and S. P. Yeo, "Designing a symmetrical five-port waveguide junction," *Inst. Elec. Eng. Proc. H, Microwaves, Antennas & Propag.*, 1988, vol. 135, no. 1, pp. 17–22.
[4] K. Chang, M. Li and K. A. Hummer, "High-power four-way power divider/conbiner," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1990, pp. 1329–1332.
[5] M. Abramovitz and I. A. Stegun, Handbook of Mathematical Functions New York: Dover, 1965.

Experimental Study of Multihole Directional Couplers Providing a Rippled Response

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Abstract—**The directivity versus frequency of a multihole waveguide coupler may be expressed as a polynomial whose complex roots, if placed off the unit circle, provide the opportunity of a rippled response. Two designs using seven equispaced holes, one each with 3.0 and 0.5 dB ripple, were implemented at *X*-band and experimental validation of the theory has been excellent.**

INTRODUCTION

In 1985, Orchard *et al.* [1] introduced an iterative design technique used to synthesize shaped beam patterns for antenna array applications, with a specified ripple tolerance in the shaped region and sidelobes in the unshaped region at individually specified heights. Experimental verification followed quickly. In 1990, this method was extended to the design of multihole directional couplers by Elliott and Kim [2] who showed, for two rectangular waveguides with a common narrow or broad wall, how to determine coupling values so that the directivity response in the passband would be at a controlled ripple level rather than lobed, as in a Chebyshev design. The purpose of the present study was to use their technique to design two distinctly different narrow wall couplers, undertake their construction, and attempt an experimental confirmation of the theory.

SYNTHESIS

Reference [2] contains a full description of the design procedure, embodied in (21)–(24), which permits calculation of coupling coef-

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TABLE I
COUPLING COEFFICIENTS FOR SEVEN HOLE SIDE WALL COUPLERS YIELDING RIPPLED RESPONSE

Hole No.	1	2	3	4	5	6	7
Plate 1	0.0146	0.0054	0.0054	0.0047	0.0037	0.0024	0.0016
Plate 2	0.0144	0.0037	0.0039	0.0038	0.0034	0.0030	0.0055

fients to obtain a desired rippled response in the passband of a multihole coupler. These equations have been used to design two seven hole couplers with the following specifications:

Plate number	1	2
Desired Coupling (dB)	28.47	28.47
Average Directivity (dB)	10.0	10.0
Ripple (± dB)	0.5	3.0

These response specifications were chosen in order to show the accuracy of the Orchard technique, while avoiding overly tight construction and meaurement tolerances.

For a seven hole coupler the design procedure yields four unique sets of coupling coefficients c_n, $n = 1, 2, \cdots, 7$. The solution with minimum $c_{\max}/c_{\min}$ was chosen in order to minimize the effects of mutual coupling, which were not taken into account in the design. Listed in Table I are the final desired coupling values needed to realize the above-stated response specifications.

EXPERIMENT

The next design task was to determine the hole diameters that would provide the desired coupling coefficients. An analytical approach, to be useful, would involve the solution of integral equations for round holes and finite wall thickness—a formidable task. Since the sole objective of the present study was to demonstrate the feasibility of constructing multihole couplers that would exhibit a rippled response based on Orchard's procedure, it was decided that the relation between holesize and coupling coefficient would be found experimentally. Thus the approach adopted was to fabricate seven 0.020″ thick side wall sections, one blank and six containing seven equispaced holes of a common size, with hole diameter graduated from one test piece to the next. The total coupling would be measured for each piece with the result divided by seven to obtain the coupling coefficient for a single hole.

A. Fixture Design

First a fixture was built that would accommodate successive insertion of the seven test pieces. A side view of this fixture is shown in Fig. 1. The final fixture design consisted of three sections; a straight guide section, a dual guide section with H-bends to allow access to all four ports, and the plate to be measured. The straight section was machined from a single block of aluminum to minimize RF leakage. The dual H-bend section consists of four parts: a base, two corners, and a flat cover. Once assembled, the H-bend waveguide section need never be taken apart.

As this fixture was used to generate the final coupler design curve, machining tolerances were quite tight (±0.001″). The length of the fixture was designed with a coupling window 9.0″ long and 0.400″ wide. In order to maintain adequate distance from discontinuities at the corners, yet still be assured adequate bandwidth, it was decided to make plates with seven holes, quarter-wave spaced at 10 GHz (0.3913″).

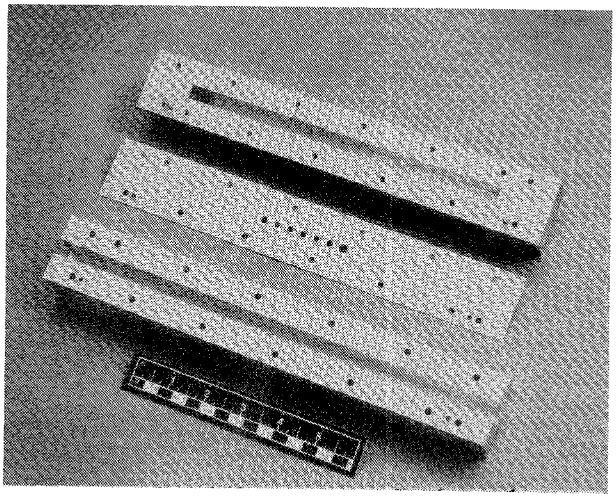

Fig. 1. Coupling test fixture with 3 dB ripple test plate. Top section is fed through H-bends to allow access to all ports.

B. Coupling Curve Plate Selection

The choice of hole diameters for these initial test plates was based on two criteria: we desired to obtain a fairly uniform data spacing in the coupling range and it was sensible to pick readily available bore sizes.

Neglecting wall thickness, Bethe [3] has provided a formula for predicting the coupling through small circular apertures, viz.,

$$|c_n| = 20 \log \left[\frac{4}{3} r_n^3 \left(\frac{\pi}{a} \right)^2 (\beta_{10} ab)^{-1} \right] \tag{1}$$

where r_n is the radius of the nth hole. This formula is approximate but accurate enough for the selection of hole sizes. The choices made are listed in Table II.

At the time that the plates were machined it was unknown how sensitive the coupling would be to variations in diameter. For this reason the hole diameters were machined to ±0.0001″ of nominal.

C. Measurements

The first measurement of the coupling fixture was made with a blank plate. Data were taken to calibrate through loss and return loss in each waveguide section. At the center frequency (10 GHz) the through loss of the straight section was 0.079 dB. The through loss of the dual H-bend waveguide was 0.100 dB at this frequency. At none of the four ports did the VSWR exceed 1.004 : 1; this level approaches the limit of measurement accuracy. The difference of 0.021 dB between the two waveguide sections is thought to be due to the addition of the two H-bends. This difference is typical across the band of interest and is considered trivial since it approaches the measurement uncertainty of the network analyzer. The power con-

TABLE II
HOLE SIZES USED IN TEST PLATES

Plate No.	1	2	3	4	5	6	7
Diameter (in)	0.0625	0.0938	0.1250	0.1563	0.1875	0.2500	0.3125

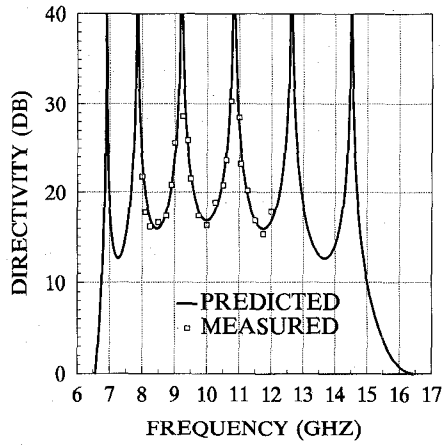

Fig. 2. Uniform distribution coupler directivity.

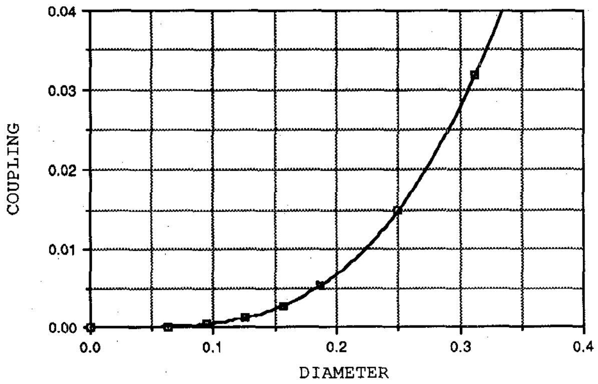

Fig. 3. Coupling versus diameter.

TABLE III
COUPLING PER HOLE FOR SEVEN TEST PLATES

Plate No.	1	2	3	4	5	6	7
Diameter (in)	0.0625	0.0938	0.1250	0.1563	0.1875	0.2500	0.3125
Coupling (ratio)	0.0001	0.0004	0.0012	0.0027	0.0053	0.0149	0.0310

TABLE IV
DIAMETERS FOR SEVEN-HOLE SIDE WALL COUPLERS YIELDING RIPPLED RESPONSE

Hole No.	1	2	3	4	5	6	7
Plate 1	0.2485	0.1878	0.1876	0.1812	0.1689	0.1512	0.1353
Plate 2	0.2480	0.1697	0.1713	0.1701	0.1662	0.1595	0.1892

served is calculated by summing the squares of the S-parameters (unitary referenced voltages) of the ports. This calculation reveals 98 percent of the power to be conserved in the device across the band. The other 2 percent can be attributed to waveguide attenuation. This conservation of power is typical of the other plates.

D. Coupling Curve

The seven plates were measured to determine coupling level from 8 to 12 GHz. To obtain the value of the coupling coefficient c_n through each individual hole the measured resonant frequency cou-

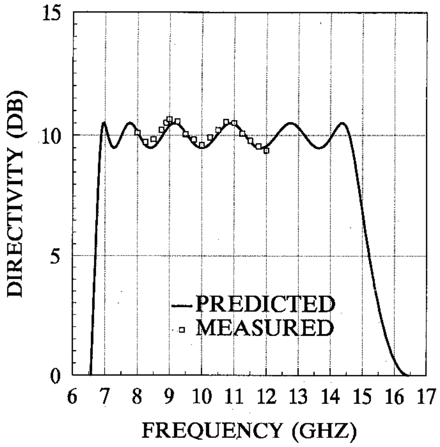

Fig. 4. Orchard distribution with ±0.5 dB ripple.

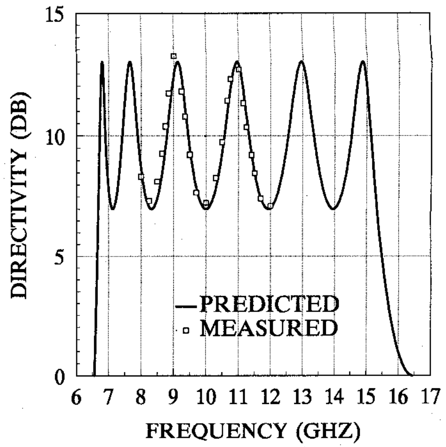

Fig. 5. Orchard distribution with ±3.0 dB ripple.

pling was simply divided by the number of holes (seven). This assumes that the coupling through each of the holes and the internal mutual coupling are uniform. This is not actually true since each of the holes, particularly the end holes, sees a different environment. It can be observed from the final measurements that this effect was not a problem. Fig. 2 shows the agreement between measured and predicted data for uniform distribution plates. Fig. 3 shows the coupling curve derived from the Table III and is quite accurate in predicting the correct diameters. If c_n is the coupling per individual hole at the resonant frequency and d_n is the diameter of that hole then the third order polynomial which fits this curve is

$$c_n = 1.486d_n^3 - 0.1538d_n^2 + 0.0053d_n + 1.644 * 10^{-5}. \quad (2)$$

The final diameters computed to yield the desired coupler characteristics are listed in Table IV.

E. Fabrication and Testing

These final diameters were submitted to the machine shop and bored to within ±0.0005″ of nominal. Special care was taken as none of the diameters could be machined with fixed bores. Instead, an adjustable bore was used. This required trial and error but provided quality results.

Once the two final plates passed mechanical inspection, they were assembled in the test fixture and measured on the automatic network analyzer. As directivity is a function of coupling and isolation, it cannot be measured directly; however, the analyzer could measure coupling an isolation separately, store one set of data in memory, and then calculate and display the difference.

F. Comparison

The results of the measurements are overlayed with the predicted patterns and are presented in Figs. 4 and 5. Both cases show directivity amplitude correlation to within 0.5 dB. Most of this error is due to an apparent frequency shift, which increases toward the lower end of the frequency band. The cause of this is not obvious and, since small, was of no great concern. One possible explanation is that the presence of holes lengthens the guide wavelength, thus shifting the band. The center frequency coupling agreed within 0.07 decibels, and again the discrepancy may be attributed to band shift.

G. Tolerance Study

For a given distribution of hole diameters, one may reverse the final design equations to predict the directivity pattern and center frequency coupling. This analysis tool can be utilized to predict the performance of existing plates or to demonstrate the effect of dimensional variation on the directivity pattern and coupling. Reference [4] examines several examples of this. Uniformly increasing the hole diameters increases the coupling and the average directivity. Uniformly decreasing the hole diameters produces the opposite effect. Unlike a uniform error in hole diameter, random errors do alter the shape of the directivity pattern. The Orchard couplers described here remain tolerance-insensitive up to ±0.003″. However, tolerances are dependent ultimately on the application.

CONCLUSIONS

The agreement between measured and predicted data is seen to be very good. Thus the physical realizability of multihole directional couplers, designed by Orchard's technique, has been established. This technique should prove invaluable in the design and realization of multihole couplers when a lobed response is to be avoided in the pass band.

REFERENCES

[1] H. J. Orchard, R. S. Elliott, and G. J. Stern, "Optimizing the synthesis of shaped beam antenna patterns," *Proc. Inst. Elec. Eng.*, vol. 132, Part H, pp. 63–68, Feb. 1985.

[2] Y. U. Kim, and R. S. Elliott, "Improved design of multihole directional couplers using an iterative technique," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 411–15, Apr. 1990.

[3] H. A. Bethe, "Theory of diffraction of small holes," *Phys. Rev.*, vol. 66, 163–82, Oct. 1944.

[4] D. L. Swartzlander, "Experimental study of multihole directional couplers providing a rippled response," Master's thesis, University of California, Los Angeles, 1991.