NBS TECHNICAL NOTE 642

Summary of WR15 Flange Evaluation at 60 GHz

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Summary of WR15 Flange Evaluation at 60 GHz

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ABSTRACT

The measurement results of flange loss and reflection coefficient magnitude at 60 GHZ (WR15 waveguide) of various flange configurations are presented. Included are the effects of alignment pins, surface finish, metallic contact surface, contact area, and flange bolt torque.

Key words: Attenuation, Flange measurements, Reflection coefficient, VSWR.

1. Introduction

The purpose of the evaluation summarized herein was to examine the effect of variations such as contact surface material (gold, rhodium, etc.), contact surface area and pressure (flange bolt torque), and flange alignment on the flange dissipative loss and reflection coefficient magnitude in the WR15 waveguide size. A knowledge of these effects is necessary in order to specify flange dimensional tolerances, protective plating material for standards applications, and proper flange bolt tightening procedures to obtain repeatable measurements. Also, possibilities for an improved flange design might be suggested from the results of the measurement data.

In addition, the NBS is proceeding to establish measurement services in the frequency range of 55 to 65 GHz (WR15 waveguide). Thus, in order to establish error analyses for these services a knowledge of the dissipative and reflected power losses and repeatability of these quantities is essential.

The measurement frequency chosen for this evaluation was 60 GHz. Although further investigation at other frequencies in the WR15 waveguide band would give a more complete bound on the measured quantities, the results given are considered typical for the 55-65 GHz range.

2. Background

The major parameters of interest are the dissipative loss (the component of attenuation associated with dissipation) of a flange pair and the reflection coefficient magnitude.

The dissipative loss (L) is mathematically related to the two-port efficiency (η) of the flange pair, by the equation [1, p. 63 and 91][1]

$$L = 10 \log_{10} \frac{1}{\eta}, \tag{1}$$

where [1, p. 49]

$$\eta = \frac{Z_{02}}{Z_{01}} \cdot \frac{|S_{12}|^2 (1 - |\Gamma_T|^2)}{|1-S_{11}\Gamma_T|^2 - |(S_{12}S_{21}-S_{11}S_{22})\Gamma_T+S_{22}|^2}. \tag{2}$$

Γ_T is the reflection coefficient of the element or device terminating the two-port, the S_{ij} are the scattering para-

[1]Figures in brackets indicate the literature references at the end of this note.

meters of the junction, and Z_{01}/Z_{02} is the ratio of the characteristic impedances of the input and output ports.

Techniques for the measurement of efficiency or dissapative loss are well known [2,3,4]. The more general approach [4] gives the efficiency for a particular terminating element Γ_T. This method is appropriate for obtaining the efficiency for specific terminations but may be tedious if the loss for all Γ_T is required. A more expeditious technique is to use the tuned reflectometer method [5], a special case of the above, which gives the efficiency for a non-reflecting termination, $\Gamma_T = 0$. In this case eq. (2) reduces to

$$\eta_o = \frac{|S_{12}|^2}{1 - |S_{22}|^2}, \; (\Gamma_T = 0). \tag{3}$$

Equation (3) assumes equal input and output characteristic impedances for the flange pair. Then, if the reflection coefficients of the pair are small ($|S_{11}|$ and $|S_{22}| << 1$), which is the case, eq. (2) reduces to

$$\eta \simeq \eta_o \frac{1 - |\Gamma_T|^2}{1 - \eta_o |\Gamma_T|^2} \tag{4}$$

which can be used to adequately approximate the efficiency for various terminating elements. This latter approach was used for the loss measurements. A more exact method than described above is given by Beatty [6].

In addition, the tuned reflectometer technique was chosen since it allows the measurement of the reflection coefficient magnitude of the flange pair immediately proceeding or following the loss measurement.

A measurement system, method, and results for the measurement of the reflection coefficient magnitude of WR12 (60-90 GHz) flanges is given in reference [7].

3. Measurement System and Techniques

The basic measurement system consists of a tuned reflectometer (fig. 1) and uses a sliding short circuit for measuring the flange loss and a sliding termination ($|\Gamma_T| \simeq 0.01$) for obtaining the reflection coefficient magnitude. Details for implementing a millimeter reflectometer and the associated components are given in reference [8].

The loss measurements are performed by sliding a short circuit from section A (fig. 1), through the flange pair, and into section B. A typical detected output response from the reflectometer is shown in figure 2. When the ordinate axis (fig. 2) is calibrated in decibels, the difference between the ordinate intercepts of the straight-line responses (average of the periodic variations in section B) at the plane of the flange pair is the dissipative loss of the flange pair when terminated by a non-reflecting element. (Section A is incorporated in the reflectometer, thus the detected response shows little or no variation due to initial reflectometer tuning operations.) The loss for any terminating element $|\Gamma_T| > 0$ can be obtained by applying eqs. (1) and (4).

The reflection coefficient magnitude is measured with the same configuration (fig. 1) except a sliding termination ($|\Gamma_T| \leq 0.01$) replaces the sliding short circuit. Figure 3 is a typical detected response when the termination is moved from section A to section B.

The reflection coefficient magnitude of the flange pair, $|\Gamma_F|$, is given by (see Appendix A)

$$|\Gamma_F| = \left(\frac{1-R}{1+R}\right) |\Gamma_T| \; (1+\varepsilon), \; |\Gamma_F| < |\Gamma_T| \tag{5}$$

or

$$= \left(\frac{1+R}{1-R}\right) |\Gamma_T| \; (1+\varepsilon), \; |\Gamma_F| > |\Gamma_T| \tag{6}$$

where $|\Gamma_T|$ is the reflection coefficient of the sliding termination ($|\Gamma_T|$ is assumed known) and R is given in terms of the decibel variation (L_R) in the detected response (fig. 3) by the equation

$$L_R(\mathrm{dB}) = 20 \log_{10} \frac{1}{R}. \tag{7}$$

Tables [9] are available to facilitate the calculation of R.

The term ε is of third order and can usually be neglected. For completeness it is given by

$$\varepsilon = \frac{|\Gamma_T|^2 - |\Gamma_F|^2}{1 - |\Gamma_T|^2}. \tag{8}$$

4. Type of Flanges Measured

The type of flange used for the major portion of the measurements was an altered UG-385/U (this is a JAN designation) flange with an enlarged bossed surface. To explain the term altered, first consider the standard UG-385/U flange (fig. 4(a)) which consists of a raised or bossed connecting surface encircled by a groove of approximately 0.070 inch width. The alteration to the UG-385/U flange is to omit the groove and enlarge the bossed surface (fig. 4(b)) by approximately the groove width. The reason for choosing the enlarged bossed flange for this study was because experience has shown that the WR 42, WR 28, and WR 15 circular grooved flanges are susceptible to a bending distortion (at the groove) due to flange bolt tightening, and thus, effects the long-term repeatability of millimeter standards. It was found after 250 connect-disconnect operations that this type of distortion was negligible with the enlarged bossed flange.

Two other altered flange types were tested for contact surface effects. One was a flat (bossed surface removed) circular flange of 0.75 inch diameter and a thickness of 0.20 inch (fig. 5(a)). The other was a circular flange with a rectangular bossed surface of 0.050 inch wall thickness (fig. 5(b)) and height of 0.010 - 0.020 inch.

Loss and reflection coefficient magnitude measurements of standard UG-385/U flanges (fig. 4(a)) are included for comparison.

5. Types of Flange Loss Measurements

Measurements of flange loss were made to determine individually the effect of variations in: 1) alignment pins and holes, 2) contact surface finish, 3) contact surface material, 4) contact surface area, and 5) flange bolt torque.

Type 1 measurements (alignment pins and holes) consisted of comparisons of: a) standard pin (0.0625 inch diameter) and hole (0.064 inch diameter) dimensions, b) standard pins in holes oversized (0.0655-0.066 inch), c) larger pins (0.125 inch diameter) and holes (0.127 inch diameter), d) larger pins in oversized holes (0.130-0.1305 inch), and e) no pins. The loss measurement results are tabulated in Table I. As an example on how to read data from the table, the no pin measurement results (type 1e above) are found in the row with the left column label: Type 1, row e, "No Pins."

Type 2 measurements (contact surface finish) consisted of comparisons of: a) machined surface finish on enlarged bossed flanges (fig. 4(b)), b) machined surface finish on flat flanges (fig. 5(a)), c) lapped surface finish on enlarged bossed flanges, and d) lapped surface finish on flat flanges.

Type 3 measurements (surface material) consisted of comparisons between pairs of metallic contact surfaces of a) brass, b) silver plate (approximately 50 microinch, equivalent to at least one skin depth), c) tarnished silver (20 - 50 microinch thickness), d) rhodium plate (50 microinch thickness), e) rhodium flash (20 microinch thickness), and f) gold plate (50 microinch thickness).

Type 4 measurements (contact surface area) consisted of comparison of the four flange connecting surfaces discussed previously. They are the: a) standard UG-385/U flange (fig. 4(a)), b) enlarged bossed flange, (fig. 4(b)), c) flat flange (fig. 5(a)), and d) rectangular bossed flange (fig. 5(b)).

Type 5 measurements (flange bolt torque) consisted of applying various torques to a variety of flange pairs. The torques were: a) 2, b) 3, c) 4, and d) 5 pound-inch.

The enlarged bossed flange was used exclusively for Type 1 and 3 measurements.

6. Measurement Results

6.1. Flange Loss Measurements

Table I is a summary of the measured average loss for a measurement set, estimated standard deviation of the mean of

TABLE 1

	Average Measured Loss x 10^{-3} dB	Estimated Standard Deviation of the Mean x 10^{-3} dB	Number of Flange Pairs	95% Confidence Interval x 10^{-3} dB
Type 1				
a. Standard pin and hole	6.0	.71	12	4.46 - 7.60
b. Standard pin and oversized hole	9.6	.537	4	7.91 - 11.32
c. Large pin and hole	6.1	.554	4	4.38 - 7.9
d. Large pin and oversized hole	7.2	.49	4	5.66 - 8.79
e. No pins	12.7	.74	4	10.37 - 15.07
Type 2				
a. Machined-enlarged boss (1a)	6.0	.71	12	4.46 - 7.60
b. Machined-flat	11.7	1.5	6	7.83 - 15.57
c. Lapped-enlarged boss	6.44	.18	6	5.98 - 6.90
d. Lapped-flat	9.6	.67	6	7.86 - 11.34
Type 3				
a. Brass (2c)	6.44	.18	6	5.98 - 6.90
b. Silver plate	7.0	.359	4	6.02 - 8.01
c. Tarnished silver	13.46	1.35	4	9.16 - 17.75
d. Rhodium plate	24.8	3.05	8	17.59 - 32.02
e. Rhodium flash	10.7	2.51	4	2.42 - 19.02
f. Gold plate	6.7	.292	8	6.03 - 7.41
Type 4				
a. UG-385/U flange	6.27	.57	8	4.91 - 7.62
b. Enlarged bossed flange (2c)	6.44	.18	6	5.98 - 6.90
c. Flat flange (2d)	9.6	.67	6	7.86 - 11.34
d. Rectangular bossed flange	3.8	.31	8	3.07 - 4.53
Type 5				
a. 2 pound-inch	13.75	4.49	4	0.0 - 28.0
b. 3 pound-inch	7.16	1.7	4	1.70 - 12.6
c. 4 pound-inch	6.96	1.36	4	2.60 - 11.3
d. 5 pound-inch	7.24	1.90	4	1.20 - 13.29

the set, number of flange pairs in the set, and the 95 percent confidence interval for the flange pair measurements. The data for some of the flange pairs have been duplicated in Table I for comparison purposes. These pairs are shown in parentheses and are referenced to the first entry of the data (e.g., see type 2a).

All of the measurement data given in Table I were obtained using flanges carefully finished at NBS (pin and hole alignment and surface finish).

Also measured for loss were a sample of twelve various commercially manufactured flanges. The average loss for these flanges was 0.016 dB with a range of 0.007 to 0.045 dB. This relatively high loss is probably attributed to two factors; first, that some flanges were rhodium plated (see Type 3 results), and second, the flange alignment holes and pins were not compatible between flange pairs resulting in a forced misalignment or an incomplete closing between the connecting surfaces. In comparison, the measurement data (1e) for the loss measurements with no pins (brass flanges) is approximately 0.013 dB with a range of ± 0.002 dB.

The following statements summarize the conclusions drawn from the data of the loss measurement comparisons.

Type 1. Alignment Pins and Holes

1. Oversized holes (0.067 inch) when used with 0.0625 inch pins increased the loss by 0.003 to 0.004 dB.

2. The large pins (0.125 inch) in the 0.127 inch hole did not affect the loss.

3. If oversized holes (0.130 inch) are used with large pins (0.125 inch), the loss appeared to increase by 0.001 dB (this amount of loss difference is considered negligible).

4. The flanges with no pins resulted in an approximate doubling of the loss.

Type 2. Contact Surface Finish

1. Lapping of the enlarged bossed flange did not decrease the loss (if the machined surface is relatively flat), but the standard deviation <u>between</u> pairs (not to be confused with the standard deviation of the mean) of the lapped flanges was near zero (i.e., all randomly selected flange pairs appear to have the same loss).

2. Lapping of the flat flange gave a moderate reduction in loss and a significant reduction in the estimated standard deviation of the mean. (Here, lapping has improved the surface flatness. Refer to Type 4 measurements for a discussion of flatness versus loss).

Type 3. Contact Surface Material

1. Silver plated, gold plated, and brass contact surfaces have similar loss characteristics.

2. Tarnished silver flanges had approximately twice the loss as the untarnished flanges.

3. Rhodium flashing almost doubled the loss.

4. Rhodium plating quadrupled the loss.

Type 4. Contact Surface Area

The larger the contact surface the greater was the loss (all flanges used in this test were lapped). Comparison of the contact surfaces of the four types of flanges showed a direct relation between flatness and loss (e.g., the flat-faced flange was flat to approximately 200 microinch, the enlarged bossed and UG-385/U flanges to 100 microinch, and the rectangular bossed flange to less than 50 microinch). The average loss for these flanges was 0.0096, 0.0064, 0.0063, and 0.0038 dB, respectively.

Type 5. Flange Bolt Torque

The flanges in this group consisted of a random sample of the various flanges (i.e., flat flange, silver plated flange, etc.) used previously so the results of the loss and standard deviation measurements given in Table I is only an indication of the torque effects and not an exact measure of a particular type of flange. It was found that a 2 lb.-in. torque, which is equivalent to finger-tight, did not apply a sufficient amount of contact pressure;

however, a tightening of 3 to 4 lb.-in. appeared to give adequate contact pressure. A torque of 5 lb.-in. was considered to exert too much strain on the threads of the flange connecting holes (5 lb.-in. is approaching torsional failure). A recommended tightening procedure is to use a hexagonally-tipped screw driver (most commercially available flange bolts are of the Allenhead type). Then, it is almost impossible to obtain manually a torque of 5 lb.-in. The 3-4 lb.-in. torque can be obtained by applying a firm rotational pressure.

6.2 Reflection Coefficient Magnitude Measurements

The following is a summary of the reflection coefficient magnitude measurements made on the various types of flanges.

A sample of 66 flange pairs were measured, all of which were machined (alignment pins and holes and surface finish) at the NBS. The waveguide to which the flanges were attached was obtained commercially and was not of exact WR 15 dimensions (approximately 0.0002 inch undersized and an 0.008 inch corner radius), although it was uniform to at least 0.0001 inch. Since the reflection coefficient magnitude is referenced to the waveguide dimensions, the inexactness of the dimensions will be reflected as an inaccuracy (± 0.003 with respect to WR15 waveguide of exact dimensions) in the measurement values obtained. The reflection coefficient measurements were performed with respect to such commercial waveguide sections because precision waveguide sections of exact WR15 dimensions with the different flange configurations would be difficult and expensive to obtain.

The average reflection coefficient magnitude of 66 flange pairs was 0.0023 as referenced to the commercial waveguide sections. From this sample 50 percent of the pairs ranged between 0.002 and 0.003, 25 percent between 0.0015 and 0.002, and 15 percent between 0.003 and 0.0035. Except for one pair (magnitude of 0.0037) the remaining 10 percent of the reflection coefficient magnitudes of the pairs were less than 0.0015. (The above percentages are approximate.)

The sample of 66 flange pairs consisted of all types of flanges used for the loss measurements, and were pooled together to obtain an average since the average reflection coefficient of the various types did not differ significantly from the grand average except as discussed below.

In the sample two types of flanges exhibited a noticeably higher reflection coefficient that the average. These were the flanges with no pins (≃ 0.003 average) and the rhodium plated flanges (≈ 0.0033 average). It was expected that the flanges without pins would have a higher reflection coefficient, but this result was not expected for the rhodium plated flanges. The cause for this is not obvious and cannot be explained at this time.

When a sample of six average valued (reflection coefficient) flanges were measured with respect to the NBS WR15 precision waveguide (dimensions are fabricated to 50 microinch tolerance), the average reflection coefficient magnitude was 0.0036 with a range of 0.0015 to 0.0075. This is in agreement with theory [8, pp. 52-53, 10] for the tolerances of the commercial waveguide used.

A sample of commercially manufactured waveguide section and flanges was also tested; the measurements were performed with respect to the commercial waveguide. The average reflection coefficient was 0.006 with a range of 0.0033 to 0.009. This large value of reflection coefficient is largely attributed to the fact that the alignment holes and pins were not sufficiently perpendicular to the flange face, thus, proper alignment was not obtained. Also, several of the flanges varied widely in the placement of the alignment pins and holes resulting in improper mating and alignment. When these results are compared with those where no alignment pins were used, it appears that a forced misalignment resulted in a higher reflection coefficient than the random alignment obtained without pins. Since the two samples were small (8 pairs), a definite conclusion (in reference to the last statement) cannot be reached, but a more detailed testing would probably resolve this question.

A set of twelve NBS machined enlarged bossed flange pairs were tested (eight measurements per pair) for repeatability. The pin and hole tolerances of this set were approximately 0.0005 inch. The average reflection coefficient was 0.0018 with an estimated standard deviation of the mean of 0.00015. The estimated standard deviation between pairs (11 degrees of freedom) was 0.0005.

7. Conclusion

The flange measurements of loss and reflection coefficient magnitude which have been presented are exemplary of the results obtainable under a rigorous control of pin and hole alignment tolerances (within 0.0005 inch when applicable). Thus, it is necessary that care be exercised in the handling of the contact surfaces and pins since any damage will effect the loss and reflection characteristics. Further, contact surfaces and alignment pins and holes must be made to appropriate dimensions and tolerances by all manufacturers and suppliers in order to achieve precision (repeatable) measurements.

Appendix A

A derivation of eqs. (5) and (6) follow.

Denote the magnitude of the maximum and minimum detected reflectometer responses by $|b|_{max} = c\ |\Gamma|_{max}$ and $|b|_{min} = c\ |\Gamma|_{min}$ [11], respectively. Then,

$$\frac{|b|_{min}}{|b|_{max}} = \frac{|\Gamma|_{min}}{|\Gamma|_{max}} = R. \qquad (9)$$

Also, it can be shown for the lossless[2] case [12, 13] that

$$|\Gamma|_{max} = \frac{|\Gamma_F| + |\Gamma_T|}{1 + |\Gamma_F \Gamma_T|} \qquad (10)$$

and

$$|\Gamma|_{min} = \frac{|\Gamma_T| - |\Gamma_F|}{1 - |\Gamma_F \Gamma_T|}, \quad |\Gamma_T| > |\Gamma_F| \qquad (11)$$

or

$$= \frac{|\Gamma_F| - |\Gamma_T|}{1 - |\Gamma_F \Gamma_T|}, \quad |\Gamma_T| < |\Gamma_F|. \qquad (12)$$

Now, substitution of eq. (10) and (11) into eq. (9) gives

$$R = \frac{(|\Gamma_T| - |\Gamma_F|)(1 + |\Gamma_F \Gamma_T|)}{(|\Gamma_T| + |\Gamma_F|)(1 - |\Gamma_F \Gamma_T|)}. \qquad (13)$$

Next, performing the indicated algebra one obtains,

$$\frac{1-R}{1+R} = \frac{|\Gamma_F|}{|\Gamma_T|} \cdot \left(\frac{1 - |\Gamma_T|^2}{1 - |\Gamma_F|^2}\right) \qquad (14)$$

---

[2]Since the efficiency of the flanges was greater than 0.999, losslessness has been assumed.

or

$$|\Gamma_F| = \left(\frac{1-R}{1+R}\right) |\Gamma_T| \left(\frac{1-|\Gamma_F|^2}{1-|\Gamma_T|^2}\right) \tag{15}$$

$$= \left(\frac{1-R}{1+R}\right) |\Gamma_T| (1+\varepsilon) \tag{16}$$

where

$$\varepsilon = \frac{|\Gamma_T|^2 - |\Gamma_F|^2}{1 - |\Gamma_T|^2}, \tag{17}$$

Likewise, substitution of eq. (10) and (12) into eq. (9) gives

$$|\Gamma_F| = \left(\frac{1+R}{1-R}\right) |\Gamma_T| \left(\frac{1-|\Gamma_F|^2}{1-|\Gamma_T|^2}\right) \tag{18}$$

$$= \left(\frac{1+R}{1-R}\right) |\Gamma_T| (1+\varepsilon) \tag{19}$$

where ε is given by eq. (17).

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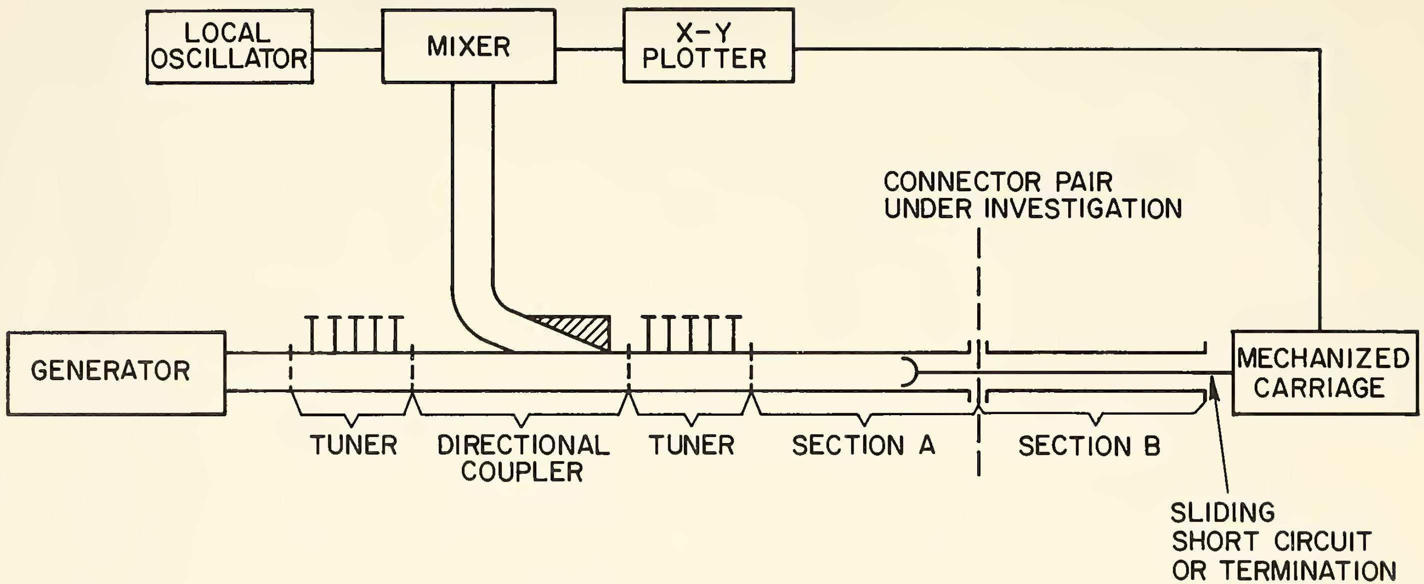

Figure 1. Block diagram of the flange loss and reflection coefficient magnitude measurement system.

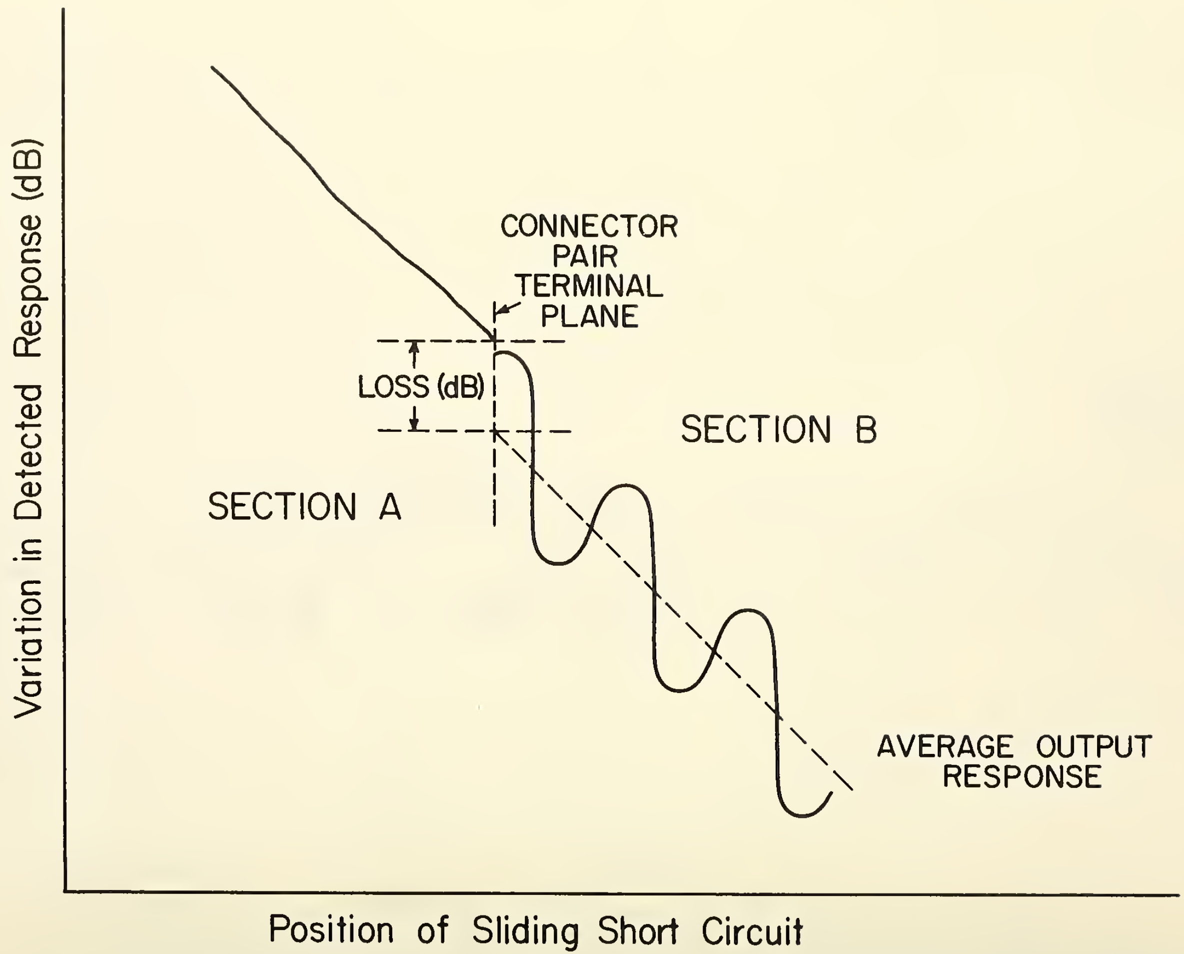

Figure 2. Illustration of the detected reflectometer response versus position of the sliding short circuit.

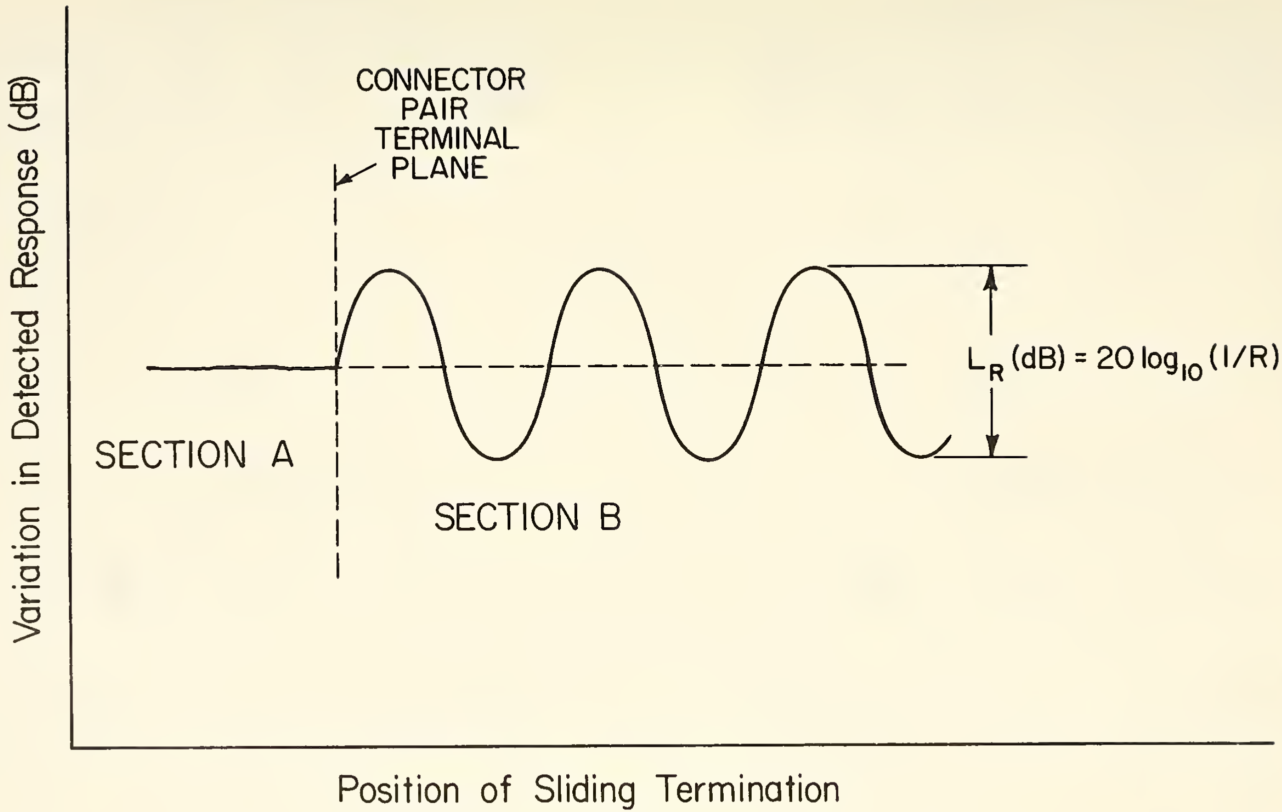

Figure 3. Illustration of the detected reflectometer response versus position of the sliding termination.

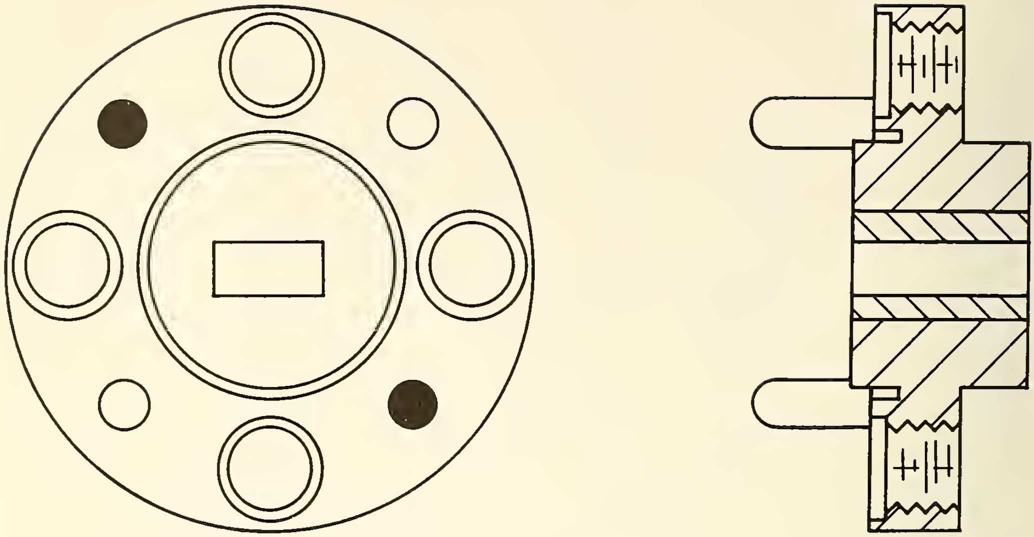

Figure 4(a). UG-385/u flange.

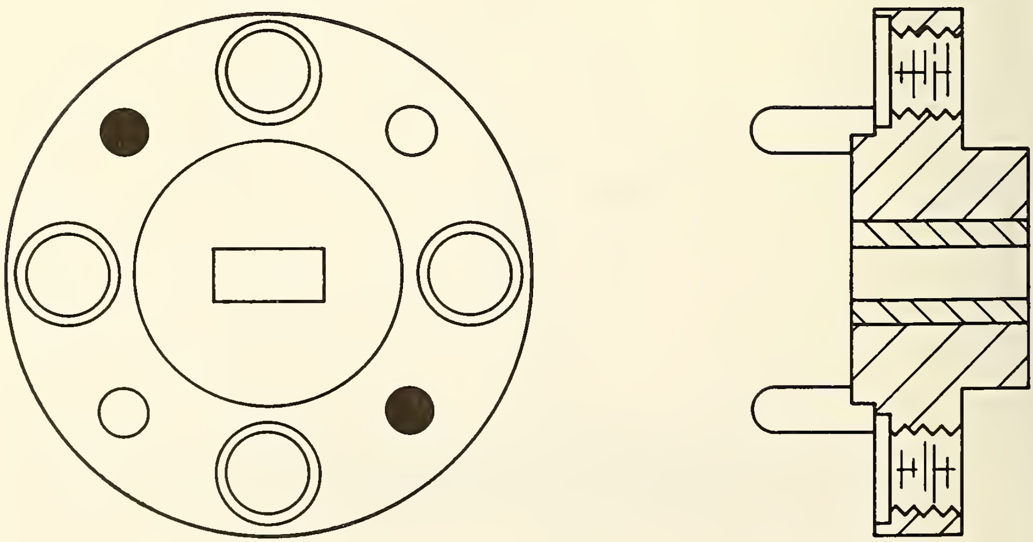

Figure 4(b). UG-385/u flange with enlarged bossed surface.

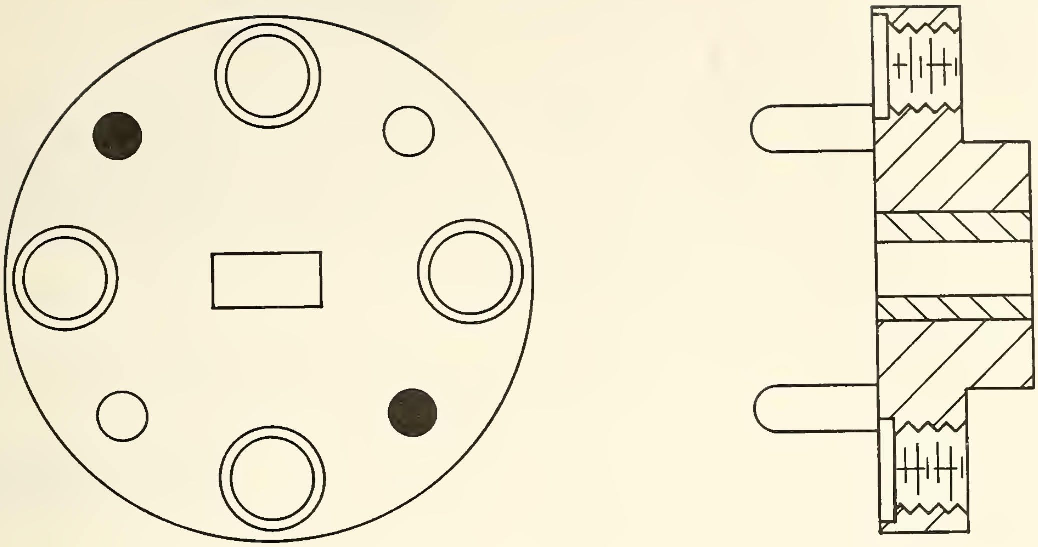

Figure 5(a). Flat flange.

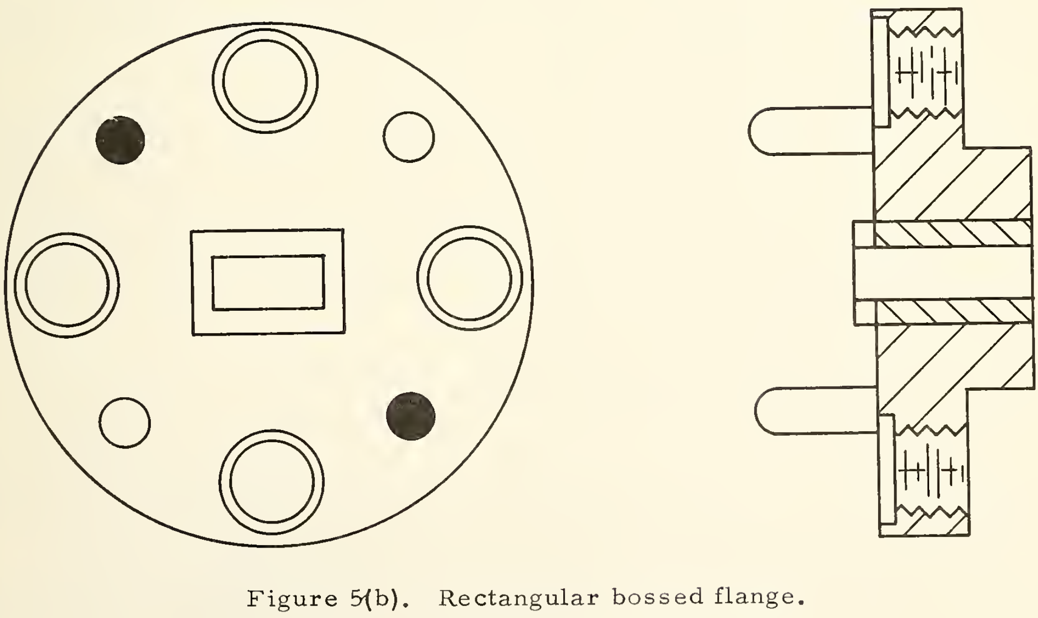

Figure 5(b). Rectangular bossed flange.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The measurement results of flange loss and reflection coefficient magnitude at 60 GHz (WR15 waveguide) of various flange configurations are presented. Included are the effects of alignment pins, surface finish, metallic contact surface, contact area, and flange bolt torque.

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