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BROADBAND FERRITE TOROIDAL PHASE SHIFTER

M. L. Reuss, Jr.

Naval Research Laboratory
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

There are applications requiring nonreciprocal phase shifters with flat differential phase shift over waveguide bandwidths. This report covers the development of a X Band phaser operating over the 8.2 to 12.4 GHz bandwidth of RG 52/U waveguide. The principal emphasis is placed on the matching procedure employed since computer analysis techniques for determining phaser dimensions for flat differential phase shift are well developed.

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BROADBAND FERRITE TOROIDAL PHASE SHIFTER

Toroidal ferrite loaded waveguide configurations producing frequency independent differential phase shift over waveguide bandwidths are readily obtainable via use of the twin slab model such as reported by Ince and Stern.[1] Figure 1 depicts the configuration employed and the calculated performance of such a configuration capable of producing a flat differential phase shift from 8.2 to 12.4 GHz. Note that this ferrite loaded waveguide is reduced in width (0.500") relative to the normal 0.900" width of RG 52/U waveguide. The dispersive characteristics of the loaded line differ, over the operating frequency band, from those of normal waveguide thereby resulting in a frequency dependent mismatch between these sections of transmission line. Principal emphasis of this report will be the design approach employed to match these sections of line over the range of interest.

The impedance (Z_{TE}) of uniformly filled rectangular waveguide is given by:

$$Z_{TE} = \frac{Ex}{Hy} = \frac{j\omega\mu}{\gamma} = \frac{\omega\mu}{\beta}$$

where ω is the angular frequency, μ the permeability and β the propagation constant.[2] For two sections of transmission line filled with different dielectric constant material,

$$Z_1 = \frac{\omega\mu_1}{\beta_1} \quad \text{and} \quad Z_2 = \frac{\omega\mu_2}{\beta_2}$$

where the subscripts indicate the characteristics of the respective region. At a given frequency $Z_2/Z_1 = \beta_1\mu_2/\beta_2\mu_1$ which for nonmagnetic materials reduces to:

$$Z_2/Z_1 = \beta_1/\beta_2 \tag{1}$$

since $\mu_2 = \mu_1$.

Note: Manuscript submitted February 10, 1975.

If to a first approximation the assumption is made that equation (1) is also valid for rectangular waveguide center loaded with a full height dielectric rod, computer generated curves of β vs. frequency can be utilized to obtain dielectric loaded sections to serve as impedance transformer sections. The propagation constant β can be determined over a frequency range as a function of dielectric rod dimensions, dielectric constant and waveguide "a" dimensions. The agreement between calculation of β and experimentally determined β is quite good. Appendix I contains preliminary data obtained for broadband matching of a dielectric rod in rectangular waveguide.

When the waveguide is partially loaded with ferrite, the effective permeability is not unity. The computer analysis employed for this region is satisfactory for determining regions of flat differential phase shift with frequency; however, due to approximations used to obtain the initial permeability, it does not predict the absolute electrical length with a high degree of accuracy or compute the effective permeability of the ferrite loaded section. For these reasons the relative impedance is determined experimentally.

Experimentally the relative impedance of the ferrite loaded waveguide to the standard waveguide can be determined as a function of frequency via use of a thin film resistance card attached to the ferrite toroid as shown in Figure 2. This approach, when properly implemented, simulates a semi-infinite ferrite loaded region. Measurement of the signal reflected back into the standard waveguide can thus be used to determine the relative impedance.

Analysis of the twin slab model of a toroidal phase shifter indicates a relatively small change in β and thus presumably the impedance, as the "a" waveguide dimension is changed from 0.9 to 0.5 inches. The deviation over this range appears greatest at the low end of the band where it is on the order of 2%. The relative impedance of the reduced width ferrite toroid loaded section was determined by:

1) determining the relative impedance of the toroid in standard width waveguide via use of thin film resistance material applied to the side of the toroid, and

2) assuming the ferrite loaded waveguide impedance is relatively independent of waveguide width as per the computer analysis.

After the impedance was determined as a function of frequency, three-step Tchebycheff transformer impedances were calculated at several frequencies within the frequency band of interest. For convenience, these relative impedances for the transformers over the desired frequency range are expressed in terms of β (degrees per inch) to be compatible with computer printout for different dielectric loaded sections which are to be used as the impedance transformers. In order to minimize the reactive effects of changing the "a" waveguide dimension between the standard and loaded waveguide, the "a" dimension of the transformer sections was stepped in equal increments between the ferrite loaded section and the standard waveguide.

The next step was to find dielectric loaded waveguide sections with the same impedance (expressed in terms of β) vs. frequency characteristics as determined by the transformer calculations. Curve A of Figure 3 denotes the experimentally determined impedance for the toroid loaded waveguide; the circles denote the experimental points used to generate the curve. Curves I, II and III denote the impedance characteristics for selected dielectric loaded waveguide configurations to be used as transformers. The calculated values for the transformers at indicated frequencies are denoted by an "x". Curve C of Figure 3 is shown to illustrate that the proper impedance can be obtained at the center frequency but can have undesirable dispersion characteristics so that the required transformer impedance is not present at the band edges. Table I shows the dimensions for the quarter wave transformers determined via this analysis approach.

These transformers were fabricated and attached to the toroid with crude thin film mode suppressors employed. Figure 4 shows the insertion and return losses of the completed phaser as a function of frequency. The maximum VSWR over the band is 1.37:1. The differential phase shift (Figure 5) is within ± 5 degrees of 239 degrees. No attempt was made to improve this value via minor modification of the loaded section "a" dimension. The relatively high insertion loss is primarily attributed to nonoptimized suppression of modes.

This approach for achieving broadband matching was suggested by a previous study aimed toward development of a broadband fixed phase difference between two parallel waveguides. Results of this study are included as Appendix II.

SUMMARY

A "flat" differential phase shift toroidal phaser was constructed to operate over the full bandwidth of RG 52/U waveguide. The maximum VSWR of less than 1.4:1 is obtained with a three-step transformer designed via a combination of experiment and analysis.

ACKNOWLEDGMENT

The author expresses his appreciation to Mr.C.W.Young,Jr., who developed the computer program utilized to calculate the relative impedances and to both Mr.Young and Dr.B.E.Spielman for stimulating discussions. The efforts of Mr.M.Finnley and Mr.C.Banks who ably assisted in taking the experimental data are also greatly appreciated. This report documents some of the tasks completed during the period 1969 through 1973.

TABLE 1

Transformers for TT390 Toroid
Toroid outer dimensions: 0.172 x 0.400 x 2.000"
Toroid hole dimensions: 0.052 x 0.280 x 2.000"
Center Loading: $\epsilon = 10$

TRANSFORMER	ϵ	LENGTH (IN)	WIDTH	WAVEGUIDE WIDTH
I	9	0.125	0.170	0.6
II	6	0.200	0.100	0.7
III	4	0.310	0.050	0.8

REFERENCES

[1] William I. Ince and Ernest Stern, Nonreciprocal Remanence Phase Shifters in Rectangular Waveguide, IEEE Transactions on Microwave Theory & Techniques, Vol.MTT-15, February 1967, pp.87-95

[2] Roger F. Harrington, Time-Harmonic Electromagnetic Fields, McGraw-Hill Book Co., 1961, p.69

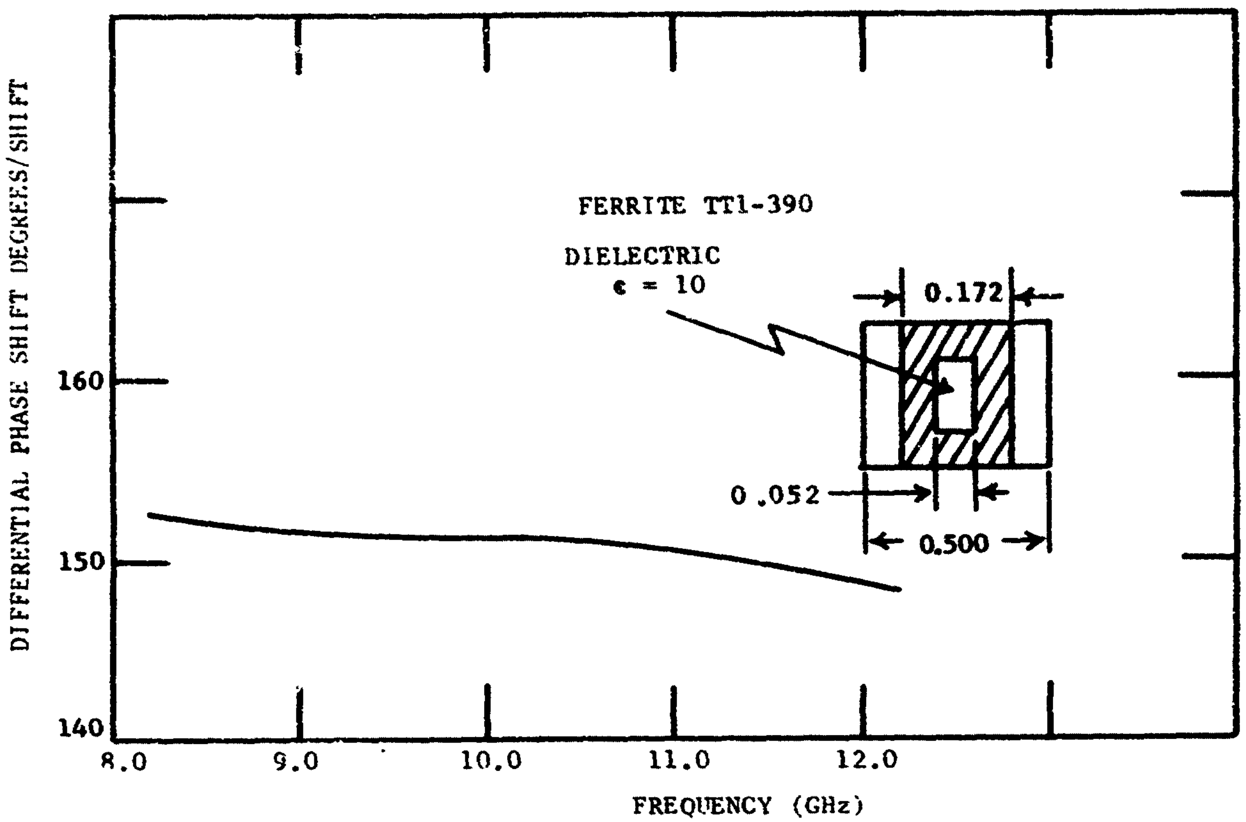


Fig. 1 — Calculated differential phase shift as a function of frequency

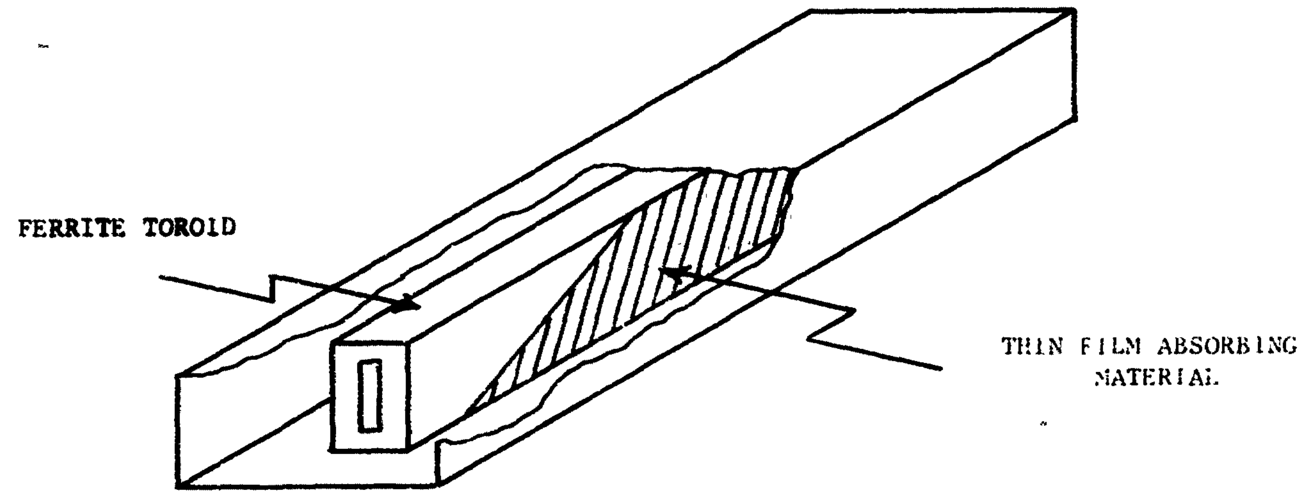


Fig. 2 — Ferrite toroid with thin film absorbing material in place

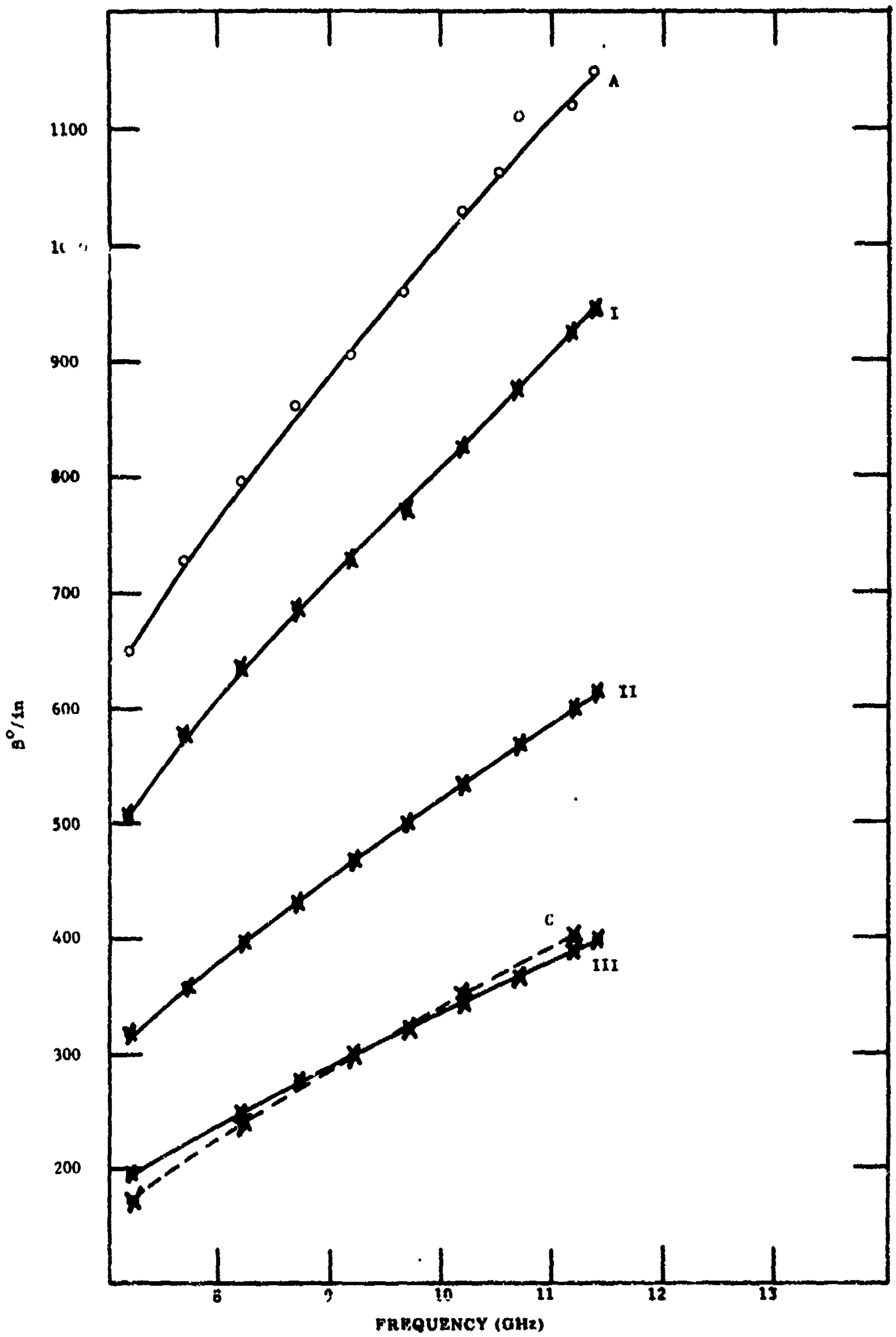


Fig. 3 — Matching transformer characteristics as a function of frequency

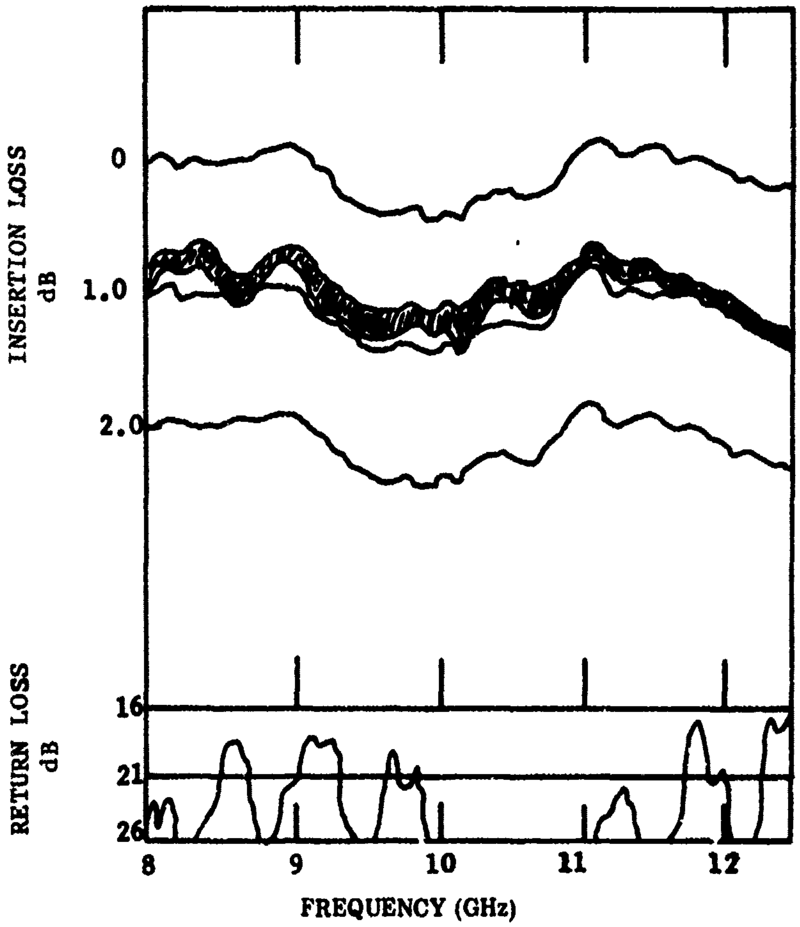


Fig. 4 — Insertion loss and return loss as a function of frequency

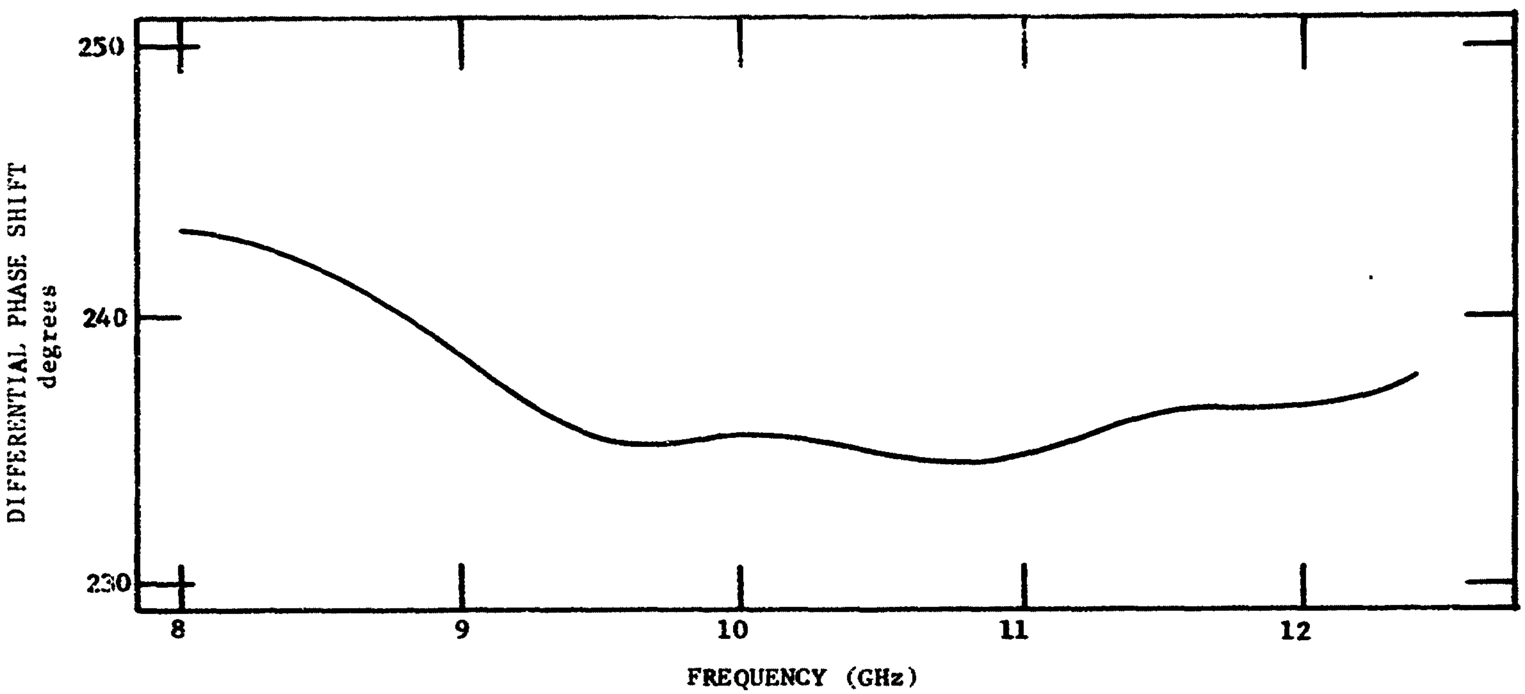


Fig. 5 — Differential phase shift as a function of frequency

APPENDIX I

Broadband Dielectric Rod Matching

An $\epsilon = 10$ dielectric rod 0.225" wide filling the waveguide height was centered in RG 52/U waveguide. Thin film resistance material was attached to the side of the rod as shown in Figure AI-1 so that effectively only reflections from the front face of the dielectric would be detected in the standard input waveguide. Table A-1 compares these measurements with computations based on computer analysis of dielectric loaded waveguide. The relative impedance of the dielectric rod in reduced width waveguide was calculated at points over the waveguide band using the assumptions described in the preceding text. At each of these points the impedance of three-step Tchebycheff transformer was calculated. Equal changes in waveguide width between the reduced width waveguide and standard waveguide were chosen for the transformer waveguide section to reduce junction effects. Calculated performance of different dielectric constant and dimension rods was used to determine the configuration whose performance characteristics best fit over the frequency band the points determined for each transformer. Figure AI-2 shows the data obtained for the reflected signal from the 0.225" $\epsilon = 10$ rod centered in 0.5" wide waveguide with the three-step transformer--determined by the above approach--in place. Considering tolerances on the physical dimensions and dielectric constants, it was felt that this preliminary data justified applying this approach to ferrite loaded waveguide.

TABLE A-1

Return Loss (dB) for 0.225" Wide ϵ=10 Rod Located in Rectangular Waveguide

Frequency (GHz)	Calculations		Measured
	a = 0.9	a = 0.5	a = 0.9
8.2	4.14	4.2	4.2
9.2	4.72	4.76	4.5
10.2	5.05	5.07	4.9
11.2	5.26	5.27	5.1
12.2	5.40	5.39	5.2

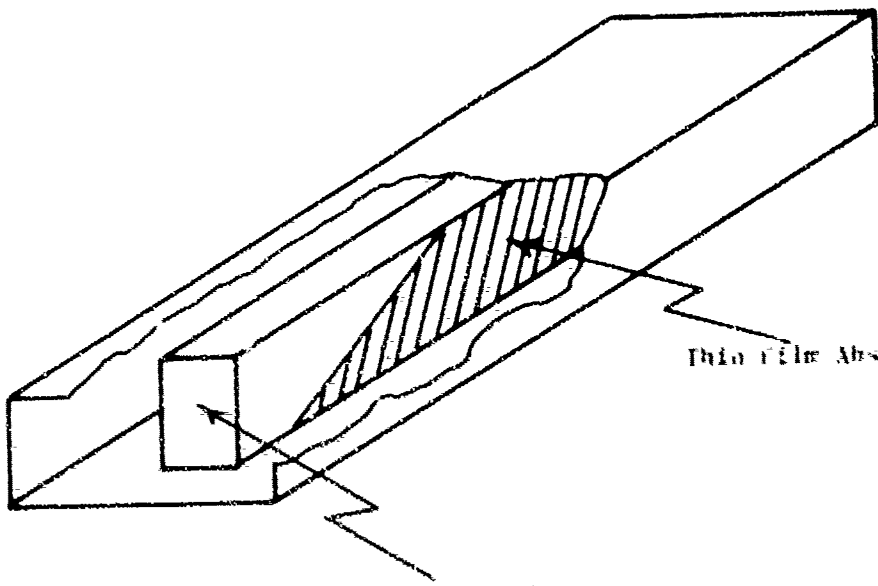
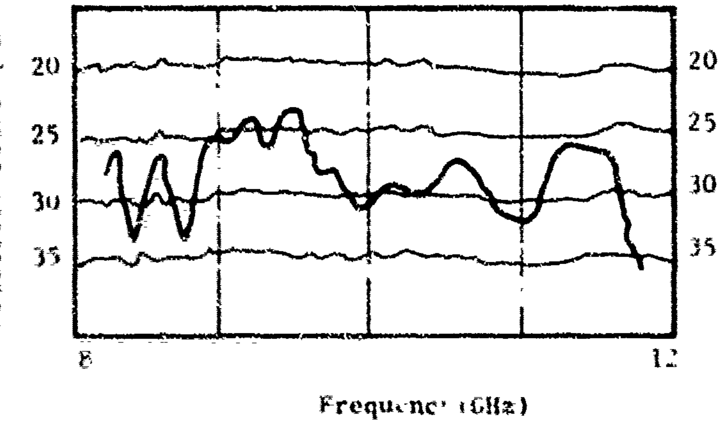


Figure AI-1



Reflected Power from ε = 10 centered Rod with 3-Step Transformers.

Figure AI-2

APPENDIX II

Broadband Fixed Phase Difference Between Two Parallel Waveguides

In certain applications, employment of a broadband fixed phase difference between parallel lines can be utilized to improve component performance or to make a particular type of broadband waveguide component feasible. An example of the first case can be seen in a ferrite switch employing similar hybrids (either quadrature or 180°) and ferrite phasers (180° differential phase shift required). Use of a fixed phase difference between the two paths connecting the hybrids allows reduction of the required differential phase shift to 90° in each arm. Phase errors associated with 90° differential phase shift are generally one-half of those associated with 180°, thus overall performance can be improved. Construction of a broadband waveguide Butler matrix can be an example of the second case.

A feasibility model of one approach to obtaining a fixed phase difference between two sections of RG 52/U waveguide was constructed and evaluated. The design goal of 90° over the full waveguide bandwidth was met within ±4° while the insertion loss was less than 0.5 dB and VSWR better than 1.5:1.

The approach utilized was that of determining dielectric loaded waveguide configurations that have similar changes of phase shift per unit length per change of frequency. The initial analysis employed centered dielectric rectangular rods filling the waveguide height. Both width and dielectric constant were varied and phase shift per unit length calculated as a function of frequency. Results of some of these calculations can be seen in Figure AII-1 where phase shift (degrees per inch) is plotted as a function of frequency for several configurations. It is evident from this figure that there is essentially a constant difference in phase shift over the frequency band when considering the $\epsilon = 6$, $w = 0.250''$, and $\epsilon = 8$, $w = 0.100''$ configurations. These configurations were selected for experimental investigation. When using waveguide as heavily loaded as these are, there is a strong probability that higher order modes would be present, so resistive mode suppressors orthogonal to the electric field were utilized in each line.

Different impedances relative to the empty waveguide are presented by the two dielectric sections, thus the required matching transformers will differ, thereby affecting the phase difference between the two loaded waveguide sections. Two section dielectric rod transformers were selected. The impedance of these transformers relative to the empty waveguide was assumed to be of the form

$$\frac{Z(\text{loaded})}{Z(\text{empty})} = \frac{\beta e}{\beta \ell}$$

where βe and $\beta \ell$ refer to the propagation constants of the empty and loaded waveguides respectively. Using the phase shift per unit length for the loaded waveguide sections plus the quarter wavelength transformers, the desired phase difference (in this case 90°) was determined by considering the difference in phase between two physically equal length sections of waveguide; one fully loaded lengthwise and one partially loaded lengthwise. If βi represents the phase shift per unit length of a loaded section and li represents the length of that section then

$$\left(\sum_{j=1}^{n} \beta_{T_j} \ell_j + \beta_\epsilon l_\epsilon + \beta_a l_a \right) -$$

$$\left(\sum_{k=1}^{n} \beta_{T_k} l_{T_k} + \beta_{\epsilon 2} l_{\epsilon 2} \right) = \theta$$

where θ is the desired phase difference, the subscripts T, a, ϵ refer to the transformer, air and main dielectric regions respectively. Calculations of this type are required at selected intervals over the frequency band of interest.

An initial model was made using equal length (1.047) dielectric bodies ($\epsilon = 6$ and $\epsilon = 8$ rods) to determine general validity of the approach since mechanical tolerances and dielectric constant tolerances could significantly affect the results. The transformers employed for the $\epsilon = 6$ rod were nominally (a) $\epsilon = 4$, w = 0.225" and ℓ = 0.186" and (b) $\epsilon = 2.5$, w = 0.100" and ℓ = 0.295" while the transformers employed for the $\epsilon = 8$ rod were (a) $\epsilon = 6$, w = 0.090" and ℓ = 0.198" and (b) $\epsilon = 2.5$, w = 0.075" and ℓ = 0.311". Standard 0.900" x 0.400" i.d. RG 52/U waveguide was employed. Figure AII-2 is a sketch of the configuration used including the resistive mode suppressors. The calculated phase difference over a 8.2 and 12.2 GHz band indicated a variation between 95 and 102 degrees would be expected over this band. Using a Wiltron 310B Phase Indicator and 311Z Resolver, a phase difference variation of between 93 and 100 degrees was determined. Results of this measurement are found in Figure AII-3 along with the insertion loss and return loss for each section: Over most of the band, the insertion loss was less than 1/2 dB and return loss was greater than 15 dB. Agreement was considered satisfactory in light of tolerances.

Emperically the lengths of the $\epsilon = 6$ and $\epsilon = 8$ rods were reduced until the data of Figure AII-4 was obtained. The $\epsilon = 6$ rod was 0.965 inches long while the $\epsilon = 8$ rod was 0.898 inches long. As can be seen from this figure, the extreme values of phase difference are with ± 4 degrees of the desired 90 degree difference over the full band of interest. Insertion loss was no greater than 1/2 dB while the VSWR was less than 1.5:1.

<u>SUMMARY</u>

A fixed phase difference of 90 ± 4 degrees has been maintained between two waveguides over the bandwidth of RG 52/ waveguide. Insertion loss of less than 1/2 dB with VSWR of less than 1.5:1 was maintained. These results indicate the feasibility of obtaining a broadband fixed phase difference using dielectric rods of rectangular cross-section.

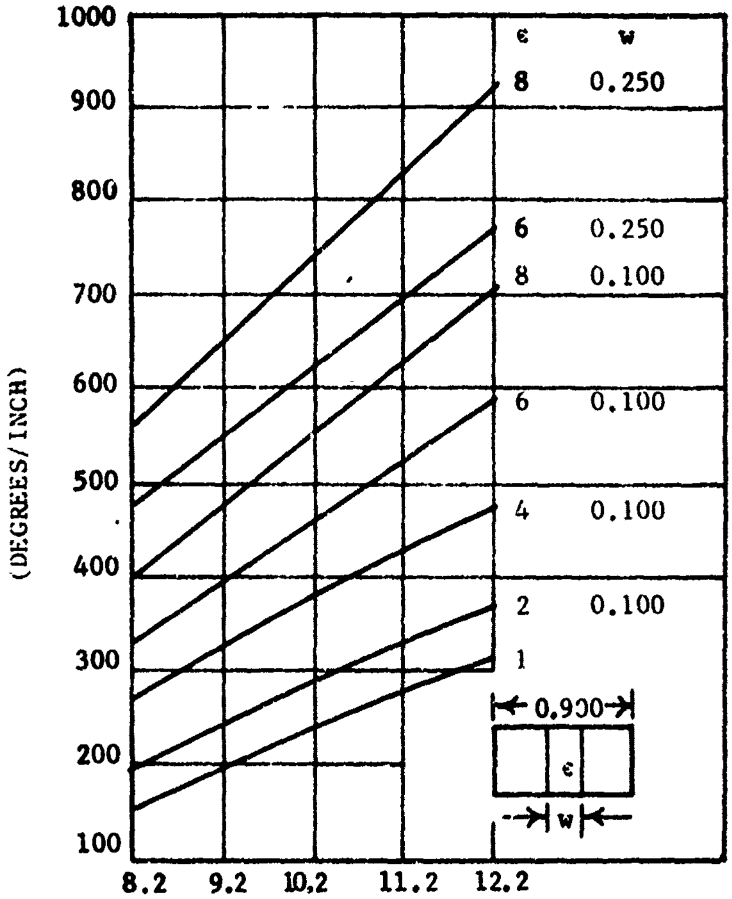


Fig. AII-1 — Electrical length for various waveguide loadings as a function of frequency

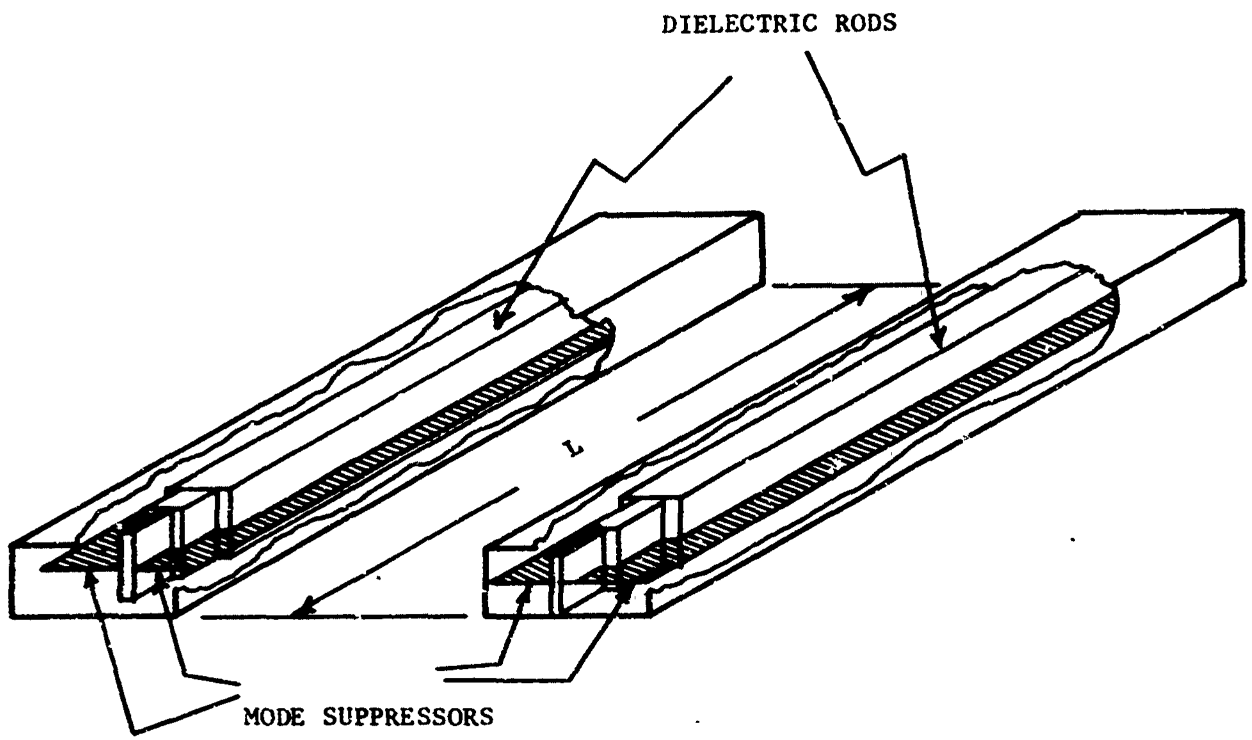


Fig. AII-2 — Dielectric loaded parallel waveguides

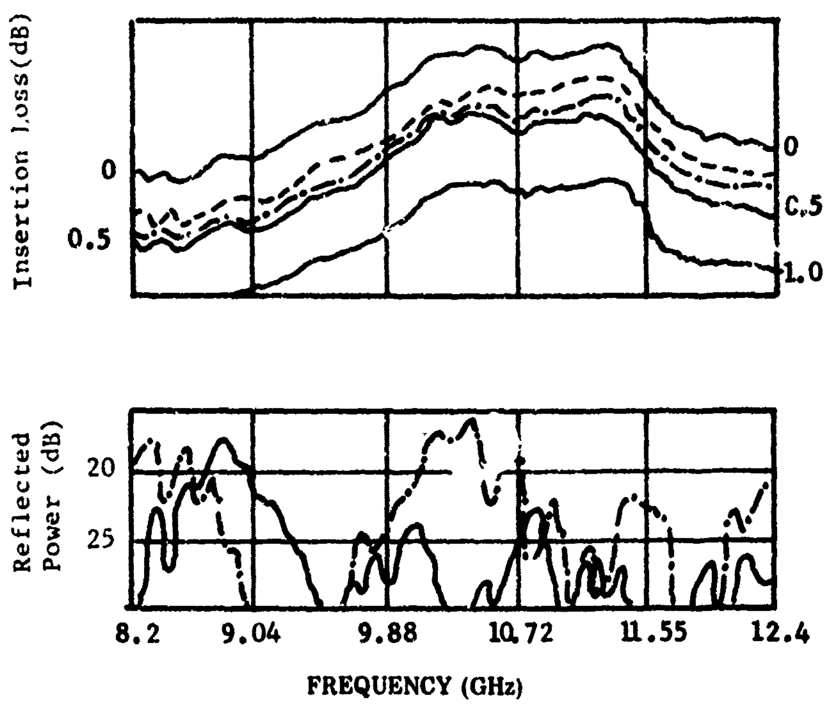


Fig. AII-3 — Insertion loss and return loss as a function of frequencies

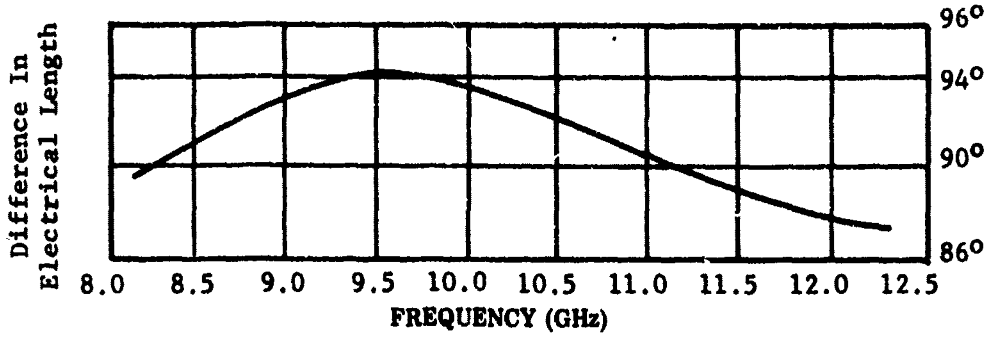


Fig. AII-4 — Difference in electrical length of the two waveguide sections over the range of RG 52/U waveguide