The Application of Periodic Loading to a Ferrite Phase Shifter Design

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Abstract—**The use of a class of periodic structures in the design of low-cost ferrite remanence phase shifters is reported. A loading factor is developed to show the relation of device characteristics to the degree of periodic loading. Results of measurements on a subarray of 64 phase shifters are given to illustrate the repeatability of a described simultaneous assembly technique.**

I. Introduction

The evolution of the phased array radar antenna, requiring a microwave phase shifter for each of four to six thousand radiating elements, has led to considerable interest in the cost and efficiency of the remanence ferrite phase shifter. After the early recognition of the advantages of using a "latching" toroid in the phase shifter [1], the majority of the devices and the analysis that followed utilized rectangular waveguide and the "twin slab" approximations to the toroid geometry [2]–[10]. An exception to this was the work of Stern and Hair [11], who applied the concept to a helical transmission line.

The necessity for device geometries and drive schemes which are inherently low cost was recognized early by Frank *et al.* [12] and some of the more recent work is oriented toward these explicit objectives [13], [14]. Techniques of dielectrically loading [15] the center of the ferrite toroid with a high dielectric constant material have been very successful in reducing the device dimensions and drive requirements.

The work reported here is related generically to the ferrite phase shifters of the nonreciprocal remanence class discussed above. Unlike the previous devices, the basic transmission line is a periodic circuit. This serves to enhance the phase shift per unit length of device, reducing the volume of the ferrite material required, the switching energy, and driver cost. In addition, the simple geometry of the toroid and laminated construction of the circuit allow simultaneous assembly of an entire subarray of phase shifters. As in the conventional devices, the differential phase shift is frequency compensated and has temperature characteristics as determined by the toroid material. The figure of merit, differential phase shift divided by insertion phase, can be increased on the order of three times (dependent on frequency and degree of loading) using the periodic circuit. Results have indicated that the figure of merit, phase shift per decibel of loss, can be maintained to at least that of the nonperiodic phase shifter for periodic circuits yielding the other desirable characteristics already discussed.

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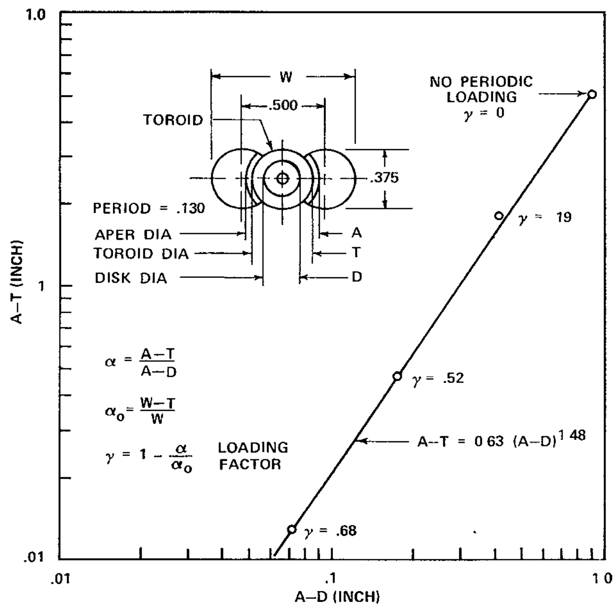

Fig. 1. Geometry of periodic loading required for frequency compensation. Loading factor is defined as shown.

II. Approach

The cross section of the waveguide and ferrite toroid used is shown in the inset of Fig. 1. The intersecting circular boundaries are machined in aluminum plates and provide captivation of a perfectly circular ferrite toroid. The dimensions of this cross section were chosen to provide frequency compensation of the differential phase shift for a conventional phase shifter; e.g., one without periodic loading. The compensation of the cross section is not necessary for the periodic devices to be discussed, since this can be accomplished through selection of the periodic circuit. However, it is a logical geometry to use as a starting point and reference in determining the merit of this technique.

Periodic loading, as discussed here, refers to the use of two types of shunt susceptances which are placed at regular intervals down the guide in the direction of propagation. The first is an aperture, consisting of a thin aluminum sheet in a plane normal to the direction of propagation, with a round hole concentric to the ferrite toroid. The other is a disk, also a thin conductor in

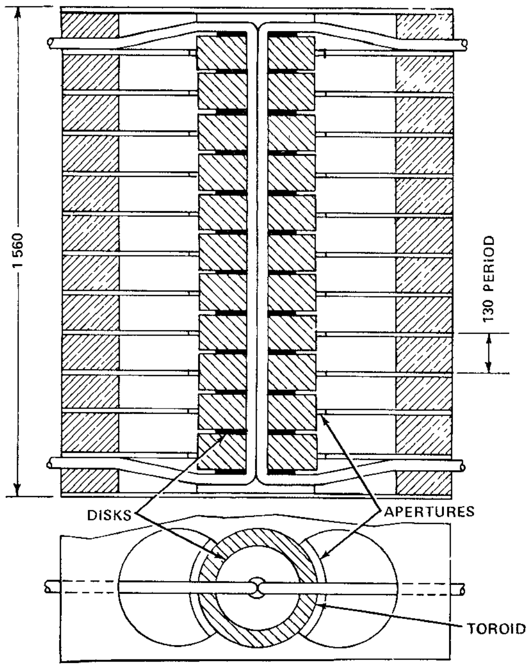

Fig. 2. Periodic ferrite phase shifter assembly for single-bit flux-drive control.

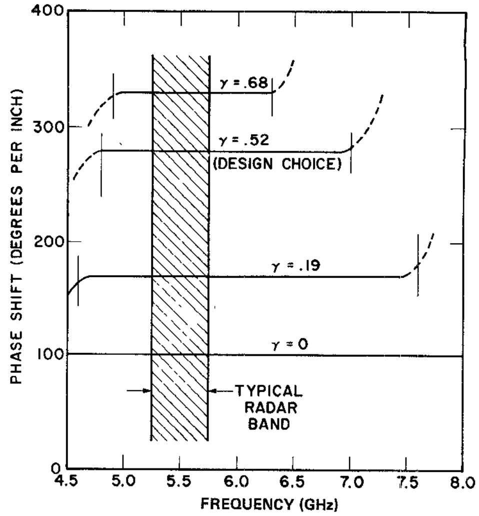

Fig. 3. Differential phase shifter versus frequency **for** various periodic loading (TT1-105).

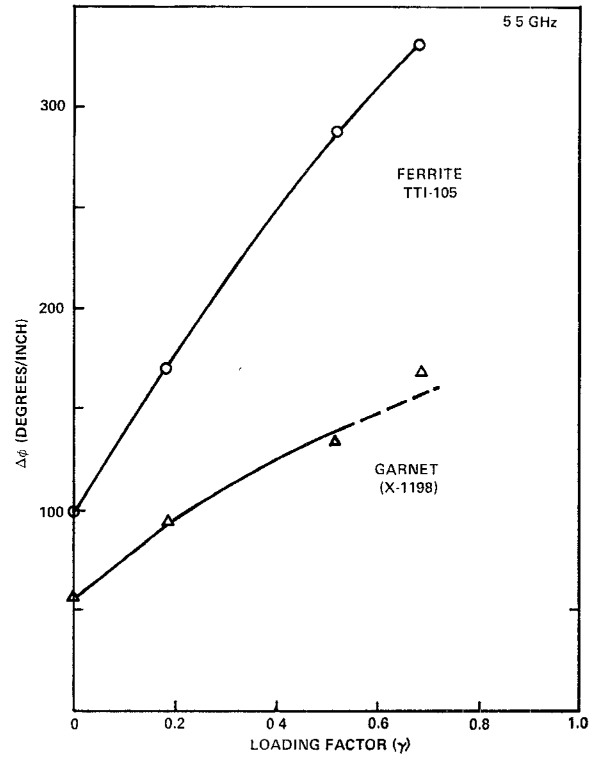

Fig. 4. Frequency-compensated differential phase shift obtained for various periodic loading factors (note that $\gamma=0$ represents the nonperiodic device).

a plane normal to the direction of propagation. It is of the same circular shape as the ferrite toroid, except that its outer diameter is less than the diameter of the toroid. The disk and the toroid are also concentric and have center holes of the same diameter. The disks are placed between segments of the toroids with the switching wire, used for the magnetization of the toroids, threaded through both. The apertures have diameters larger than the toroid and, therefore, segment the air-filled guide outside the toroid.

A typical assembly is shown in Fig. 2 where the waveguide was machined from plates of aluminum 0.125 in thick stacked in a laminated fashion. The apertures are machined in sheets 0.005 in thick and fit between the plates. The disks are die-cut from adhesive backed 0.002-in thick aluminum foil and are stuck to the toroids before assembly. The switching wire is brought out to the side of the assembly through a groove in the end plates. To launch a wave down the experimental assemblies, it was found that a 50-Ω coaxial to 50-Ω double-ridged guide transition [16] served adequately for the variety of structures studied.

The differential phase shift is adjusted to be constant with frequency by the selection of disk and aperture diameters. If only periodic disks are used, the phase shift has a positive dispersion with increasing frequency. If the disks are omitted and the periodic circuit consists of apertures only, the resultant phase shift dispersion is negative. A combination of disks and apertures will yield a phase shift that is constant with frequency change.

Fig. 1, showing a plot of geometries that were experimentally adjusted for frequency compensation, indicates that the process is orderly enough to be described by the empirical equation shown. A similar log–log plot should yield an equation for other waveguide boundaries. To quantitatively describe the extent of periodic loading, a loading factor, γ, is defined in Fig. 1. Note that for no loading $D=0$ and $A=W$, therefore, $\gamma=0$. When the aperture and the toroid diameters are equal, $A=T$ and $\gamma=1.0$, representing a closed guide or maximum loading. The range of practical values for γ is therefore between 0 and 1.0.

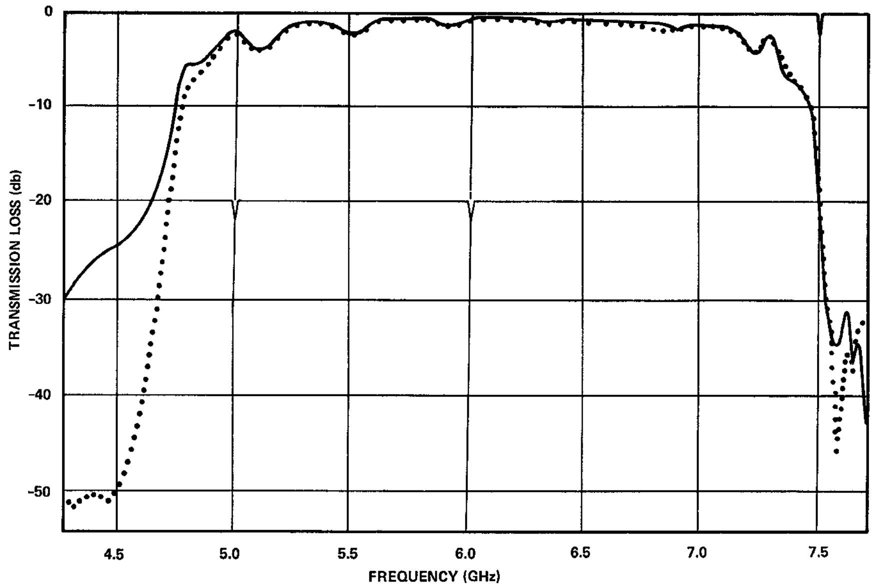

Fig. 5. Filter characteristics of a typical periodically loaded phase shifter. Dotted and solid lines represent opposite states of remanent magnetization maxima.

III. Periodic Phase Shifter Characteristics

The phase shift per unit length of device is enhanced considerably through periodic loading. This is illustrated in Fig. 3 which applies to the geometry shown in the inset of Fig. 1 utilizing TT1-105 ferrite (Trans-Tech Inc., Gaithersburg, Md.). For the nonperiodic structure, indicated by $\gamma=0$, the phase shift is moderate and the bandwidth is very broad. The broad-band characteristics of a similar device have been previously reported [17]. As the periodic loading is made more severe (γ is increased), the differential phase shift is increased and the bandwidth is reduced. Fig. 3 illustrates that the reduction in bandwidth is not a serious hinderance for most radar system applications.

Additional differential phase shift measurements were made using X-1198 garnet (Harshaw Chemical Co., Columbus, Ohio) as the toroid material. The results are shown in Fig. 4 where the same geometries were used for both the ferrite and garnet. The difference in phase shift obtained between the two materials is predictable from the proportionality

$$\Delta\phi \sim B_r$$

where B_r is the remanent magnetic flux density resulting from a given switching field. The B_r of TT1-105 is 1220 G and for X-1198 it is 642 G. The ratio of these values, 0.53, is approximately the ratio of the amounts of the phase shift obtained.

The passband characteristics of the $\gamma=0.52$ geometry using TT1-105 are shown in Fig. 5 where both remanent states are indicated. The excessive ripple within the passband is due to a poor match. However, the data do show that the band edges are clearly defined and that they are fairly stable with change of magnetization.

Fig. 6 indicates that, by periodic circuit selection, the designer can trade off peak power handling capability

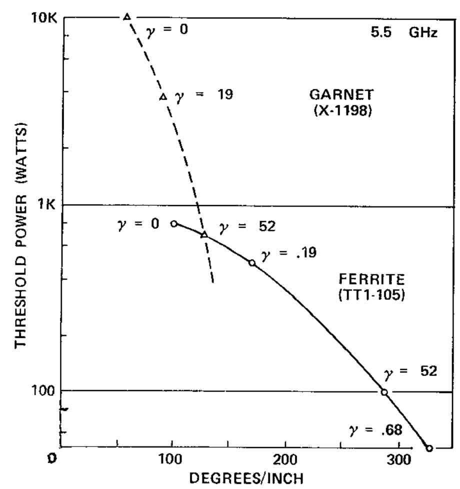

Fig. 6. Threshold power versus differential phase shift for ferrite and garnet material in several periodic phase shifter geometri es.

for increased phase shift per unit length. For most phase shifter applications the peak power is not a severe criterion; therefore, this is a reasonable tradeoff. The ordinate of Fig. 6 is the peak power level at which the threshold of increased insertion loss occurs. These data were taken at a 2-μs pulsewidth and a 0.001 duty cycle. The point of nonlinear effect was assumed when the insertion increased by 0.3 dB.

The difference in the threshold power of the ferrite and garnet generally agrees with the proportionality

$$P_{\text{crit}}^{1/2} \sim \frac{\Delta H_K}{4\pi M_s}$$

where P_{crit} is the critical power threshold, ΔH_K is the spin-wave linewidth, and $4\pi M_s$ is the saturation magnetization of the material. Substituting the appropriate quantities for these materials yields

TABLE I

Periodic Loading	γ	A (in)	D (in)	$\Delta\phi$ (degree/in)	Loss (dB/in)	$\frac{1}{\lambda g}$ (degree/in)	$\frac{\Delta\phi}{\Phi \text{ Total}}$	$\frac{\Delta\phi}{\text{dB}}$
None	0			100	0.24	554	0.18	416
Light	0.19	0.562	0.158	170	0.3	362	0.47	570
Medium	0.52	0.422	0.250	277	0.5	362	0.79	576
Heavy	0.68	0.388	0.316	330	1.0	446	0.75	330

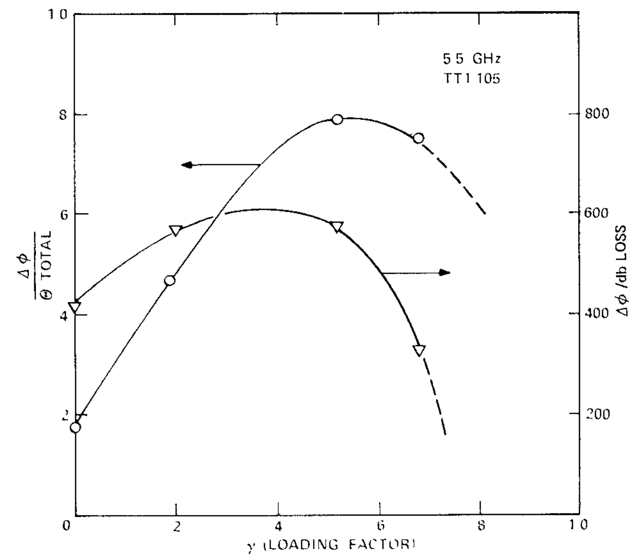

Fig. 7. Two figures of merit plotted versus periodic geometry.

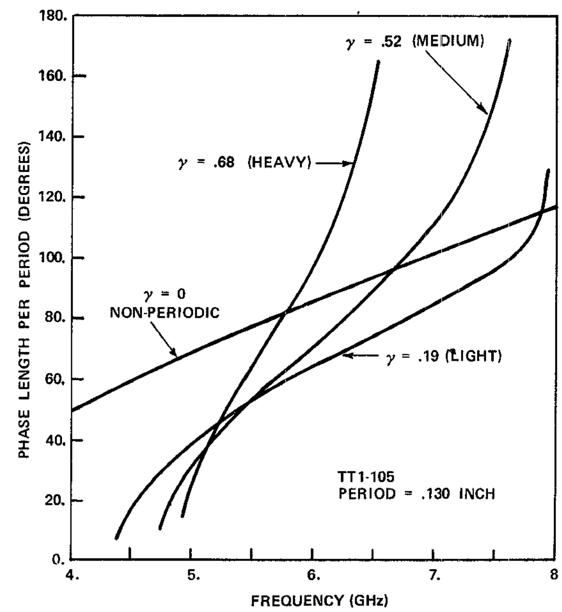

Fig. 8. The mean insertion phase length per section versus frequency.

$$\frac{P_{\text{crit}} \text{ garnet}}{P_{\text{crit}} \text{ ferrite}} \sim 7.9.$$

This is the approximate ratio of the threshold powers of the two materials given in Fig. 6 for the cases of $\gamma = 0.19$ and $\gamma = 0.52$. The $\gamma = 0$ case does not agree as well, but the results are reasonably within the measurement error and approximations involved.

The intrinsic loss [18] of the TT1-105 geometries was measured at 5.5 GHz. The data, shown in Table I, indicate that the insertion loss per unit length increases with γ, the loading factor. However, the phase shift per unit length also increases; therefore, the device length required for a 360-degree phase shifter is reduced. The net effect can be assessed by the figure of merit, phase shift per decibel of loss, which is plotted in Fig. 7. This plot shows that for TT1-105 the loss of a device required for a specific phase shift can be reduced through periodic loading. This is true up to about $\gamma = 0.65$, where the figure of merit is roughly the same as that of a nonperiodic device of $\gamma = 0$.

An advantage of periodic loading is the reduction obtained in the insertion phaselength. A given absolute phase variation tolerance should be easier to meet in a production lot because the allowable variation is a larger percentage of the total. The insertion phaselength per section is plotted versus frequency in Fig. 8 for the same geometries as previously described. This plot summarizes computed results from experimental data to be described in a later paper. The above data yield the figure of merit differential phase shift divided by insertion phase which is shown in Fig. 7. The plot indicates that an improvement by a factor of 4 times the nonperiodic ($\gamma = 0$) value is possible. These quantitative results are dependent on frequency, with the best results always obtained at the lower edge of the band; however, significant improvement occurs throughout the passband of all the geometries of Table I.

IV. Application Considerations

The amount of phase shift obtained for a given drive level is described by the drive characteristic curve. The phase shift is the change in insertion phaselength, measured in degrees, between a reference state and some other "set" state of remanent magnetization. The drive level is obtained from the integral of the switching pulse required to switch the toroid remanent magnetization from the reference state to the set state. Before the measurement of each point on the drive characteristic curve, the toroid is returned to the reference state by a large pulse of opposite polarity to that of the set state. A typical characteristic obtained for the periodic phase shifter is shown in Fig. 9. Note that if either the reference state polarity or the direction of RF propagation

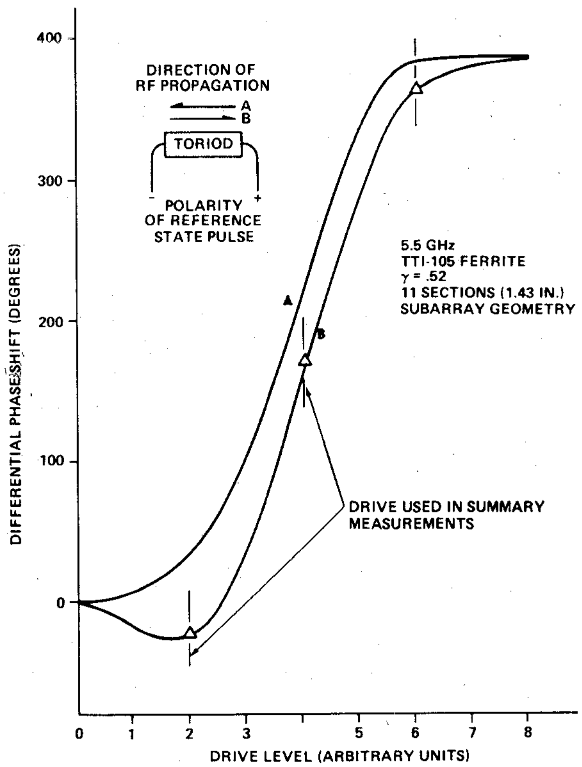

Fig. 9. Differential phase shift versus drive level for the periodic phase shifter geometry used in subarray construction.

is reversed, another drive characteristic is obtained as indicated by the two curves. This effect is typical of thick-walled toroid phase shifters and is not a result of the periodic loading. The slight phase shift reversal shown in the lower curve, however, does appear to be a characteristic of the periodic circuit. This can be enhanced considerably by increasing the inside diameter of the disk. The effect is most pronounced at the upper passband frequency limit where it is frequency sensitive. It appears to be a field displacement effect in the center of the toroid, related to the resonant frequency of the ring formed when the inside diameter of the disk is increased appreciably. The minor reversal of the extent shown is useful in increasing the phase shift availability, since its frequency sensitivity is not appreciable in this portion of the passband. In practice, both the reference state and the direction of propagation are reversed between transmit and receive; therefore, only one of the two curves of Fig. 9 is used.

As the temperature is increased, there are two primary effects on the curves of Fig. 9. The level of phase shift represented at the knee of saturation is reduced and the entire set of curves is shifted to the left toward lower switching energy. Thus, the intercept is changed, but not the slope. For wide temperature range operation the maximum of the linear portion of the curve, established by the device length, must be determined at the highest temperature expected. The intercept change can be compensated for in the driver or by assuring that the

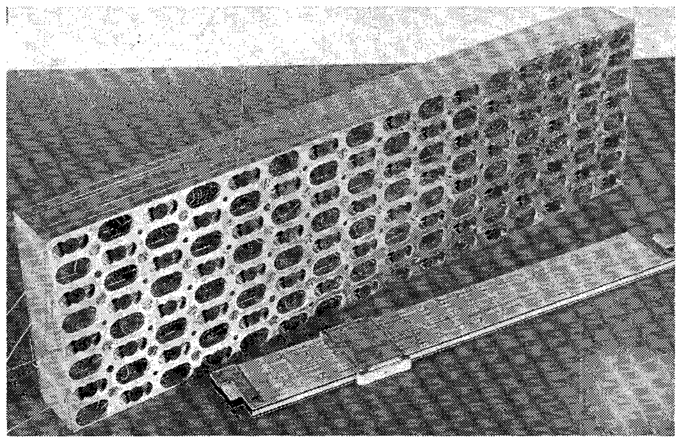

Fig. 10. Photograph of laminated subarray of 64 periodic phase shifters—oval openings alongside each element are for hybrid integrated circuit drivers.

expanse of the linearity is adequate at both temperature extremes, using a compromise intercept.

From the periodic geometries studied, the one shown in Fig. 2 was chosen for further investigation as the phase shifter to be used in a 64-element subarray. It is identified as $\gamma = 0.52$ in the preceding figures and in Table I. Eleven sections of this geometry, using TT1-105, yield approximately 400 degrees of phase shift and result in a stack 1.43 in thick. An additional half section without a toroid is used at each end for matching purposes and to allow room for the switching wire exit; therefore, the total length of the phase shifter without transitions is 1.560 in. A coaxial-to-double-ridge waveguide transition was used, which included a single quarter-wave transformer to match a 50-Ω omni spectra miniature (OSM) jack to the 110- to 120-Ω periodic structure.

The subarray, as shown in Fig. 10, was constructed by lamination of 12 identical aluminum plates, each with the holes required for the 64 phase shifters, fastener holes, and an oval cutout alongside each phase shifter for a hybrid integrated circuit driver. The plates were machined on a digital tape-controlled milling machine and then stacked, and the 0.375-in diameter hole for the ferrite toroid was reamed to size through the stack. After separation and cleaning, the stack was reassembled with the 0.005-in aperture sheets between the plates. The ferrite toroids, with the adhesive-backed die-cut disks in place were also included in this assembly. The switching wires were then threaded through the toroid stacks. Thus, the 64 phase shifters were assembled simultaneously.

Measurements were made on each of the 64 phase shifters of the subarray (Fig. 10) to determine the repeatability obtained from the laminated construction technique. Unit-to-unit insertion phase was measured at room temperature, held at $22 \pm 1°C$, for several remanent states of magnetization. A summary of the measured results for three frequencies is shown in Fig. 11.

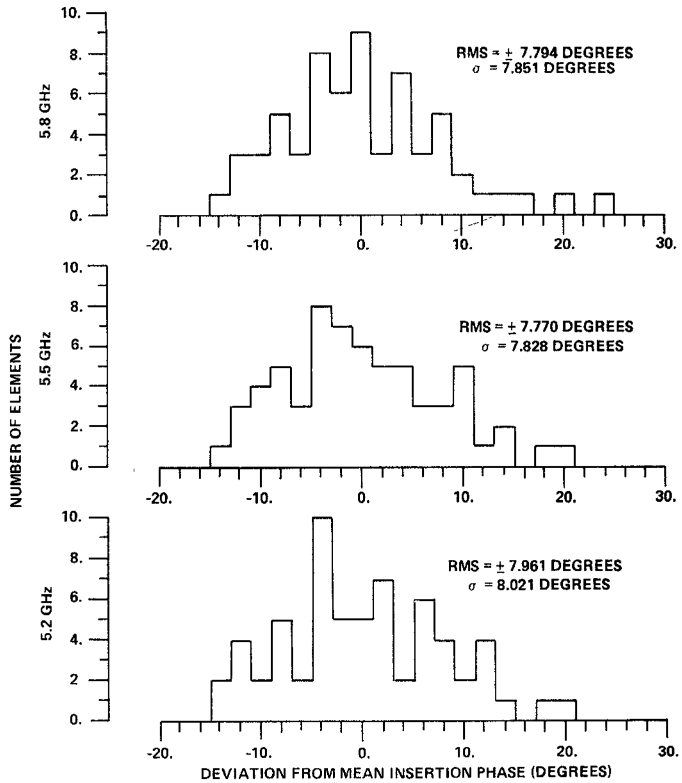

Fig. 11. Histograms of measured insertion phase error of the 64-element subarray.

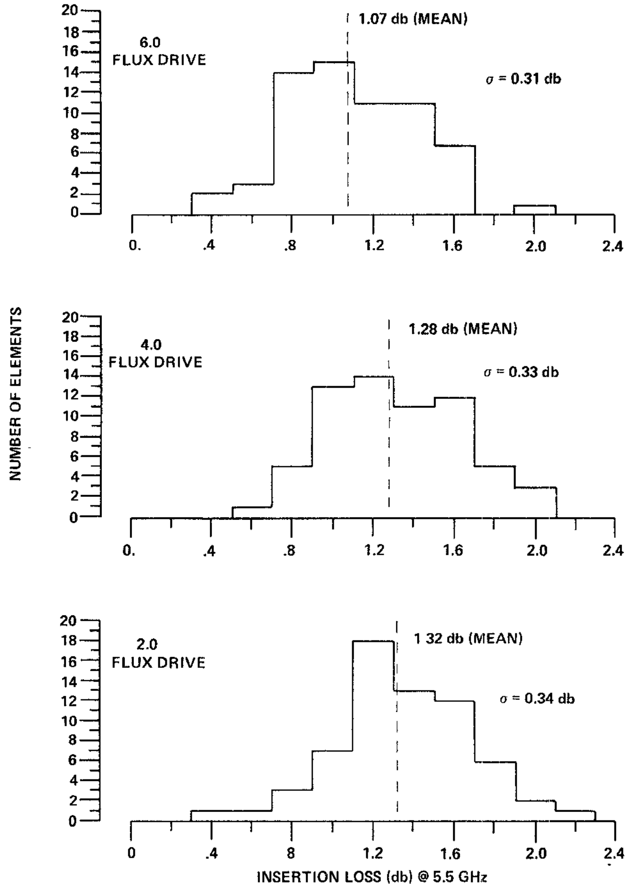

Fig. 12. Histogram of insertion loss of the 64-element subarray.

Data points for the ordinate of these histograms were obtained by averaging three different phase settings (indicated in Fig. 9) for each phase shifter.

Insertion loss of the 64 phase shifters was measured by the substitution method [18]. The histogram of the results is given in Fig. 12. These measurements were taken with a single pair of transitions moved over the array to each phase shifter. No effort was made to eliminate switching wire mode resonances or their effects. In many cases they accounted for as much as 1 dB of the total loss and up to approximately 10 degrees of phase inaccuracy. In all cases the effects that did occur were very broad and shallow; no spikes were observed on the swept frequency data. Therefore, it was decided to accept the results as a worse case study of the device. In this context, the results of Figs. 11 and 12 show significant advantage over the conventional nonperiodic phasors where resistive/reactive chokes are normally required to reduce severe switching wire loss and phase spikes.

V. Conclusions

This paper reported experimental results on a particular waveguide cross section, using an easily adjusted periodic circuit that yields a frequency-compensated device. More optimal designs of periodic structures no doubt are possible. One change that is being considered for future work is that of increasing the toroid inside diameter. It is obvious from the switching characteristic of Fig. 9 that the inside material, whose magnetization reversal is represented by the low values of flux, is not contributing significantly to the phase shift and does require switching energy. Future work is also planned toward eliminating the need for apertures by reducing the overall waveguide width and using periodic disks only. For applications other than the subarray, the laminated waveguide may not be attractive, and by this technique an extruded or smooth boundary can be used with laminated toroid and disk stack. In essence, the periodic disks form an artificial dielectric which does not have the temperature sensitivity that most high dielectric constant materials possess.

It is concluded that this work represents another approach toward improving the efficiency and reducing the cost of ferrite phasors and provides considerable lattitude toward tailoring a design toward a particular application.

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Lumped-Circuit Elements at Microwave Frequencies

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***Abstract*—This paper describes how lumped-circuit elements can be made and used at microwave frequencies. Details are given of lumped capacitors, inductors, resistors, and gyrators. Active combinations of these components and unencapsulated semiconductor chips include a 4-GHz tunnel-diode amplifier, a varactor-tuned *X*-band Gunn oscillator, a degenerate *S*-band parametric amplifier and an *X*-band Doppler radar. It is concluded that the techniques described here are useful at microwave frequencies up to *X* band.**

I. Introduction

MICROWAVE CIRCUIT functions have been performed in the past using combinations of individual components which are carefully manufactured with precision tolerances in three dimensions and which are large compared with the wavelength. Such components are described as distributed and contrast with the alternative lumped components, used at much lower frequencies, where the component dimensions are very small compared with the wavelength.

Traditionally, the transition from the use of lumped to distributed components has taken place in the region of 500 to 1000 MHz, but there is no reason why microwave components should not be constructed in lumped form—other than the possible physical inconvenience of so doing [1], [2], [3]. Recent developments in photoetching and vacuum deposition techniques have made it possible to deposit lumped-circuit elements on a suitable backing surface (substrate) by evaporation. Both high-conductivity metals such as gold and copper as well as microwave dielectric materials such as silica can be deposited.

There are five basic circuit elements which should be considered. These are the inductor, the capacitor, the resistor, the transformer, and the circulator. (It is assumed that the transmission line can be represented by a combination of these.) The successful production of some or all of these lumped components at microwave frequencies such as X band is likely to lead not only to a significant reduction in price when they are combined

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