NON-RECIPROCAL FERRITE PHASE SHIFTERS FOR MILLIMETER APPLICATIONS

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ABSTRACT

The design, fabrication and evaluation of 35 GHz, 65 GHz and 94 GHz non-reciprocal, ferrite latching phase shifters is described. These devices are waveguide structures which utilize the novel arc plasma spray (APS) process for fabricating the lithium ferrite toroids used in these phasors in order to achieve low cost and high performance. Currently, APS techniques are being developed to produce hybrid integrated phasor assemblies for use in millimeter phased array radars operating up to 94 GHz and possibly higher.

Introduction

The arc plasma spray (APS) process provides the technological innovation which makes the development and production of millimeter-wave, non-reciprocal ferrite phase shifters (phasors) both technically and economically feasible.[1] Whereas conventional fabrication techniques used to produce ferrite phasors up to 50 GHz[2] have proven to be very expensive, difficult to produce, and performance limited, the APS technique offers great potential for cost-effective, high performance devices throughout the millimeter range (up to 94 GHz and possibly higher). Moreover, the possibility of a rugged, low cost integrated structure employing APS at various stages to deposit ferrite, dielectric and metalization, places millimeter phased array radar antenna systems into the realm of feasibility.

APS Fabrication Procedure

Figure 1 pictures the basic non-reciprocal latching ferrite phase shifter configuration in waveguide design. Conventional techniques presently used to fabricate the dielectrically-loaded ferrite toroid for operating at microwave frequencies require material processing, tooling and machining whereby numerous time consuming steps are required to meet stringent dimensional tolerances required to minimize air voids both at the ferrite-dielectric interface and at the ferrite-waveguide wall interface. Air gaps or voids tend to launch unwanted waveguide modes which result in inadequate performance. The small size and critical tolerances are responsible for the high cost of conventional millimeter phasors.

The APS process, on the other hand, involves the deposition of ferrite powder around the dielectric, thus forming the basic dielectrically loaded toroid. This process can be accomplished very quickly (less than two minutes) and yields a toroid with intimate contact between ferrite and dielectric. The outer dimensions of the toroid are readily machined to the required tolerance.

Device Design

A lithium ferrite powder was selected for spraying millimeter phasors, since this composition can be tailored to exhibit high saturation magnetizations up to 5000 G. The hysteresis loops of these lithium ferrites are square and yield high differential phase shift.

Lithium titanate ($\epsilon = 26$) is one of the dielectric core materials around which the lithium powder is arc plasma sprayed. This particular dielectric was utilized because the high dielectric constant concentrates the r.f. energy in the ferrite region thereby maximizing the differential phase shift and, secondly, the thermal coefficient of expansion of this dielectric matches that of the ferrite, a necessity in APS fabrication to avoid stresses and cracks in the toroid.

Figure 2 is a cross-sectional schematic of the basic phasor-test fixture configuration used at 35 GHz, 65 GHz and 94 GHz. Each waveguide housing was designed to be slightly undersized ($\sim$ .001") and fitted with a spring-loaded top wall to insure a tight toroid fit in the housing. Figure 3 is a photo of the 35 GHz, 65 GHz and 94 GHz toroids. A cost-effective, simple fabrication technique was employed to form the small hole in the toroid required for the placement of the phasor switching wire. This technique involved bonding a thin sliver of boron nitride to the dielectric core material. The boron nitride remains intact during the APS operation but sublimes during the toroid anneal cycle, leaving a hole for inserting the drive wire.

Phase Shifter Operating Characteristics

Phasors operating in each of the three frequency bands of interest have been evaluated. The internal structure of each of these phasors is shown in Fig. 4. Figure 5 indicates the insertion loss and reflection loss of a 35 GHz unit utilizing a 1.35" APS toroid sample. This unit yields less than .7 dB insertion loss over a .6 GHz bandwidth exhibiting 422° of differential phase shift (i.e. figure of merit = 649°/dB). Data on a 65 GHz phasor (APS toroid length = .31") is shown in Figure 6. The insertion loss as shown is less than .9 dB over a 1 GHz bandwidth while the differential phase shift is 87° (i.e. figure of merit = 97°/dB). Both of these units exhibit reflection loss $>$ 18 dB (i.e. VSWR $<$ 1.3:1) over the designated bandwidths. Preliminary data on a 94 GHz phasor indicates a nominal insertion loss of 1.5 dB over a 1 GHz bandwidth as shown in Figure 7 when using a .25" length APS toroid. The reflection loss of this unit is $>$ 16 dB and the differential phase shift measured was found to be 38°. Switching times less than 1 μsec are possible with each of these three devices.

A computer program was used to predict the theoretical phase shift which could be expected for various phasor design parameters. This program was found to be very useful since the test results agreed reasonably well with that of the theoretical predictions.

The insertion loss of each of these phasors could be further reduced through the use of a lower loss dielectric loading material. The lithium titanate presently being used exhibits a dielectric loss tangent of $\sim$.0025. Loss measurements made at millimeter wavelengths indicate a significant amount of loss contributed by this dielectric, particularly at the higher frequencies (65 GHz and 94 GHz) where the dielectric material represents a greater proportion of the phasor cross-section. Further improvement in lithium ferrite powders and APS techniques will result in improved figures of merit for these millimeter phasors. Also, broadband impedance matching transformers together with mode suppression techniques will allow broadband operation.

Advanced Design Concepts and Techniques

The APS technology offers great potential at 35 GHz and at substantially higher frequencies for fabricating phasors and also other millimeter components such as switches, circulators, and modulators which use the basic ferrite phasor as the essential building block. It should be possible to produce rugged, low cost integrated assemblies via the arc plasma spray application of dielectric, ferrite and metal in sequential phases of fabrication. Novel design approaches are now being investigated at ECOM for application in these frequency regions. One such concept is the dual toroid design[3] which was first demonstrated in the X-band frequency region at ECOM. A cross sectional schematic view of this configuration is shown in Figure 8. Although this structure employs two toroids, the active region of the phasor (region of dielectric loading) functions in the same way as that of the single toroid configuration. The dual toroid concept, however offers several advantages over that of the single toroid approach. First, the fabrication of the phasor becomes simplified since the ferrite is no longer formed around a very small sliver of dielectric, thus, the dielectric may be APS deposited between the two toroids. Second, the latching wire is removed from the high r.f. field region, thereby eliminating undesirable interaction. Third, by APS deposition, a metal waveguide can be bonded directly around the outer phasor circumference effecting an intimate contact with the ferrite. An example of metalization is shown in Figure 9 where this process was successfully accomplished at microwave frequencies. Through the use of the APS process together with unique techniques such as mentioned above, the possibility exists of fabricating integrated multi-component arrays at millimeter wavelengths such as a composite line source and/or other types of phased array antennas. Such systems would offer low cost, high performance, and size and weight minimization.

References

1. Richard W. Babbitt, "Arc Plasma Fabrication Phase Shifter Elements, "Proceedings of 12th Electrical/ Electronics Insulation Conference, 11-14 May 1975.

2. Richard A. Stern and John P. Agrios, "A Fast Millimeter Ferrite Latching Switch" IEEE International Microwave Symposium, May 1966.

3. Richard A. Stern and John P. Agrios, "A 500 kW X-Band Air-Cooled Ferrite Latching Switch," IEEE International Microwave Symposium, May 1968.

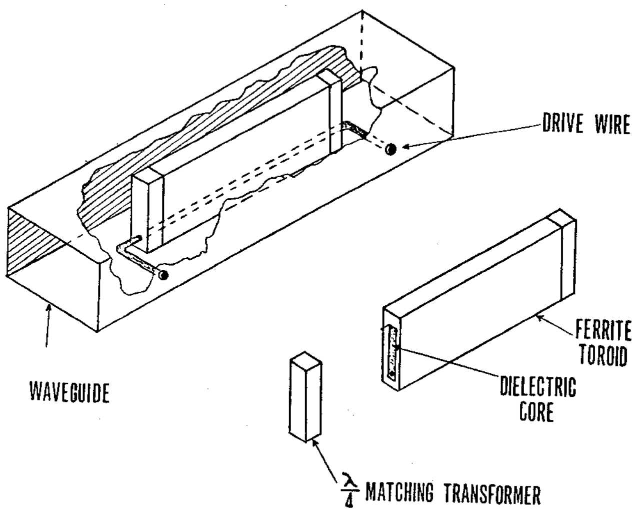

FIGURE 1: PHASE SHIFTER CONFIGURATION

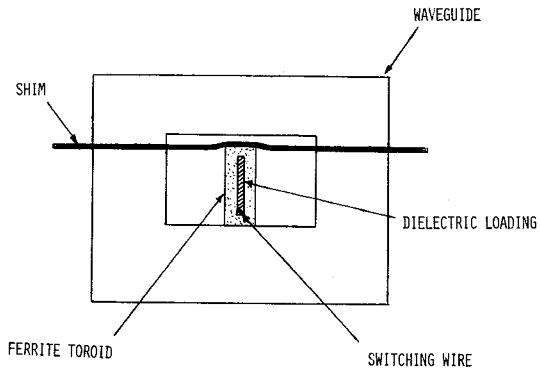

FIGURE 2: CROSS-SECTION OF PHASOR TEST FIXTURE WITH FERRITE TOROID

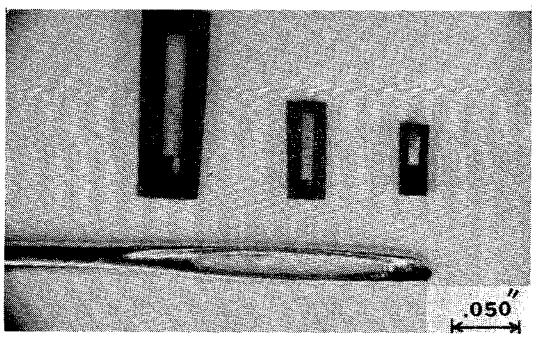

FIGURE 3: 35 GHz, 65 GHz, AND 94 GHz FERRITE TOROIDS

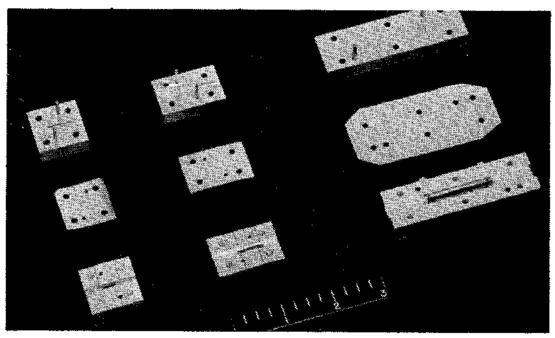

FIGURE 4: INTERNAL VIEW OF 94 GHz, 65 GHz AND 35 GHz PHASORS

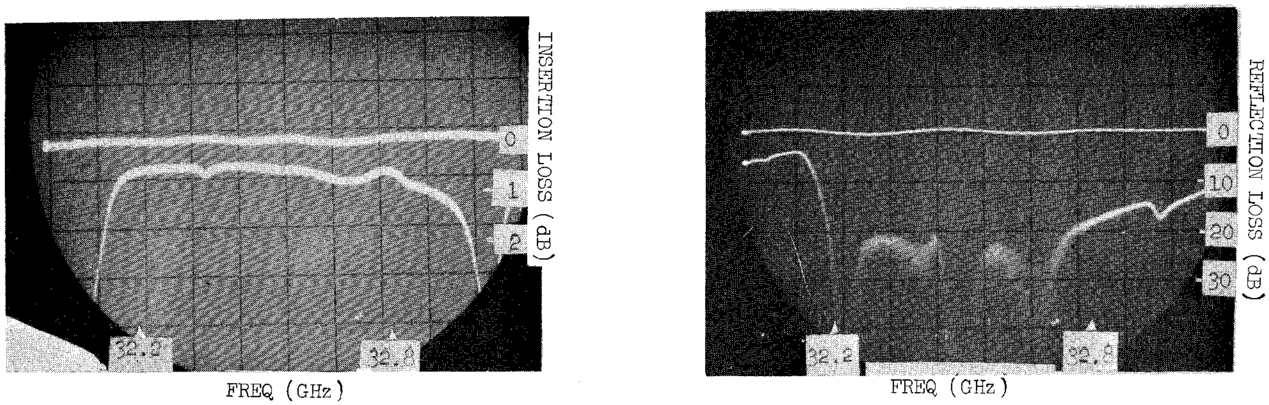

FIGURE 5: OPERATING CHARACTERISTICS OF 35 GHz PHASOR

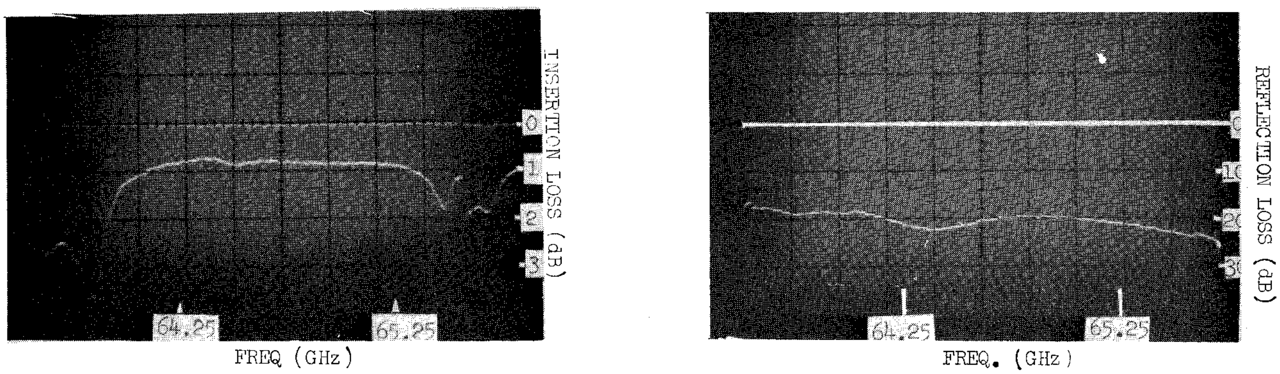

FIGURE 6: OPERATING CHARACTERISTICS OF 65 GHz PHASOR

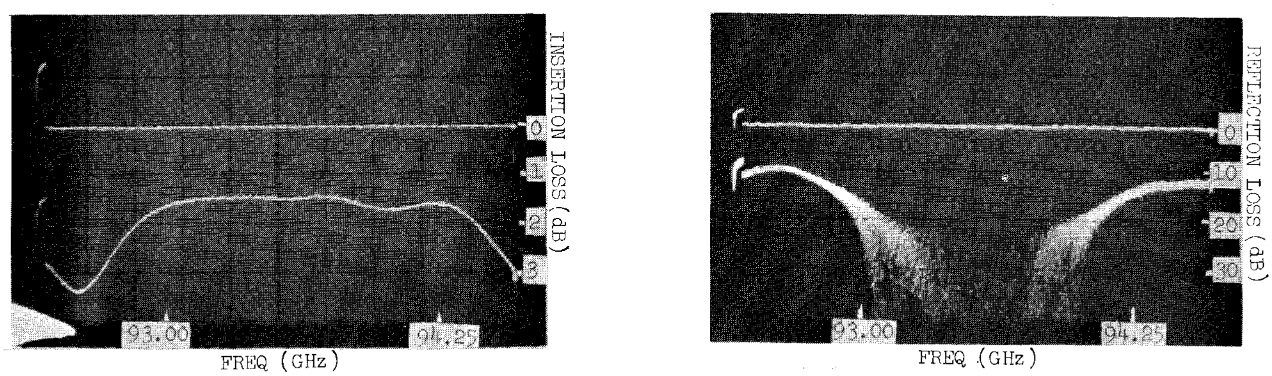

FIGURE 7: OPERATING CHARACTERISTICS OF 94 GHz PHASOR

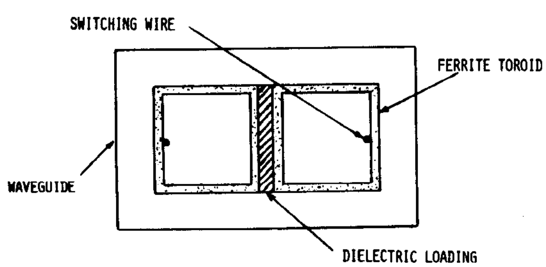

FIGURE 8: CROSS-SECTION OF DUAL TOROID PHASOR

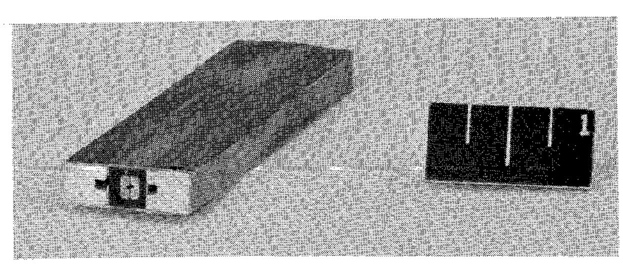

FIGURE 9: METALIZED PHASOR