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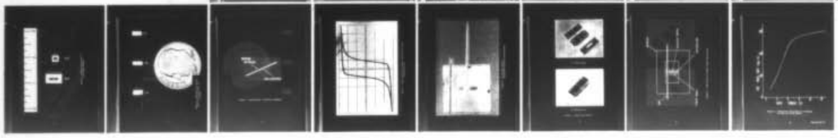

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Research and Development Technical Report

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MILLIMETER FERRITE PHASE SHIFTERS USING ARC PLASMA SPRAY FABRICATION TECHNIQUES

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Richard W. Babbitt
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Electronics Technology & Devices Laboratory

July 1977

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Arc plasma spray techniques have previously been developed for fabricating low microwave frequency non-reciprocal ferrite phase shifters, 3 GHz to 6 GHz. Currently, spraying techniques are being developed for the arc plasma fabrication of ferrite phasers for millimeter frequencies 35 GHz to 95 GHz. It is expected that the arc plasma process will have a significant impact on the cost of millimeter phasors, since they are difficult and expensive to fabricate by conventional techniques. Also, arc plasma millimeter phasors are expected to produce an improved device performance. However, for the arc plasma process

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to be suitable for fabricating millimeter phasors, new techniques and modifications of arc plasma spraying procedures were required. This report presents the techniques developed and the device performance of arc plasma fabricated 35 GHz non-reciprocal ferrite phasors. Projected costs and future fabrication concepts are also presented.

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INTRODUCTION

This investigation is to demonstrate the feasibility of the arc plasma spray (APS) process for fabricating low-cost, high-performance, non-reciprocal, millimeter wave ferrite phase shifters. The ferrite phasor, Figure 1, for operating at 35 GHz, has a dielectric thickness which was varied between 9 mils and 18 mils and a ferrite wall thickness which was varied between 15 mils and 22 mils. This design produces maximum differential phase shift and minimum insertion loss per unit length for a ferrite composition.

Conventional fabrication techniques which are used to produce millimeter ferrite phasors are difficult to reproduce, are expensive and generally provide inadequate performance characteristics. Conventional techniques require material processing, tooling and machining whereby numerous time consuming steps are required to meet stringent dimensional tolerances in order to minimize air voids at the ferrite-dielectric interface. The small size and tight tolerance of the ferrite toroid and dielectric insert are responsible for the high cost of millimeter phasors, and unavoidable air gaps at the ferrite-dielectric interface produce inadequate device performance.

The APS process has been successfully used to fabricate lower frequency, 3 GHz to 6 GHz phasors[1,2]. During the low frequency effort, it was recognized that the greatest economic impact of the APS process would be realized for higher frequency phasors[3]. The APS deposition of a ferrite around a dielectric is a simpler and more economical process for producing phasors than the current conventional fabrication procedure. Also, the process produces a bonded ferrite-dielectric interface which enhances device performance. The tolerance of the center of the ferrite toroid is exactly the dimension of the dielectric insert, while the outer dimensions of the ferrite are readily machined to within ±0.001 in. After machining, the APS phasor is annealed to reduce microwave losses and coercive force, prior to device testing.

APS PROCEDURE

a. Fabrication Techniques: A lithium ferrite powder was selected for spraying millimeter phasors, since a lithium ferrite composition can be tailored to have a high saturation magnetization ($4\pi M_s$), to 5000 G, with a square hysteresis loop, and is annealed at relatively low temperatures. The arc plasma spray equipment and procedure used to spray millimeter phasors was the same as that used for the lower frequency, C and S-band phasors. Even though the same spray procedure was used for millimeter phasors, the

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1. Richard W. Babbitt, "Arc Plasma Sprayed C-Band Lithium Ferrite Phase Shifters," IEEE Transactions on Magnetics, Vol. Mag-11, No. 5, Sep. 1975.
2. W. Wade and R. Babbitt, "S-Band Lithium Ferrite Phase Shifters by Arc Plasma Spraying," AIP Conference Proceedings, No. 34, Magnetism and Magnetic Materials, 1976.
3. Richard W. Babbitt, "Arc Plasma Fabricated Phase Shifter Elements," Proceedings of 12th Electrical/Electronics Insulation Conference, 11-14 Nov. 1975

thin dielectric of millimeter phasors necessitated a modification of the arc plasma spray parameters and a new technique for placing a drive wire.

It has been observed that thin dielectrics, less than 0.020 in., are very susceptible to warping during spray procedure. The APS parameters modified to avoid warping were spray distance, arc current and plasma velocity (arc gas); Table 1 compares the APS parameter used for C-band with the parameters used to spray K_a (35 GHz) phasor. This table shows an increase in spray distance, a decrease of arc current and arc gas. The low arc gas decreases the plasma velocity which increases the dwell time, thus compensating for the lower arc current. The spray distance was the most critical parameter, with variations of $\frac{1}{4}$ in. having a significant bearing on warpage. However, it was desirable to have the spray distance as short as possible since this parameter also has a significant effect on the ferrite deposition rate.

Table 1. Modification of APS Parameters for Millimeter Phasors

Freq. Band	Arc Current Amperes (A)	Arc Gas argon/helium cubic feet per hour (cf/h)	Spray Distance (inches)
K_a	300	30/2	2-3/4 ± 1/8
C	350	40/6	2-1/2 ± 1/4
C	330	75/3	2 ± 1/4

The larger dielectrics used for C and S-band phasors, Figure 2, were sprayed as two slotted halves joined together, forming a center hole for a drive wire. The dielectric used for millimeter phasors is too thin for this technique to be practical. Two techniques investigated for placement of the drive wire were 1) to spray with the drive wire bonded to the dielectric and 2) to form a hole for the drive wire, Figure 3. Two approaches, Figure 3, A and C, were considered for the drive wire bonded to the dielectric. One approach A) was to spray with stops set the desired length apart, in order that the wire extend beyond the ends of the phasor. The other approach C) was to spray the dielectric-wire combination without stops, cut to length after machining, and weld lead wires to the exposed surface of the conductor. A gold conductor was found to be the most satisfactory for this technique, and low-loss millimeter phasors were fabricated. The second technique, Figure 3 B, was to form a hole for the drive wire during the fabrication of the phasor. An inexpensive and simple procedure was developed which required bonding a thin piece of boron nitride to the dielectric, Figure 4. The boron nitride maintained its size and shape during spraying but was completely burnt out during the anneal cycle, leaving a hole for inserting a drive wire. There may be an improvement of device performance with the dielectric-wire technique since no air voids will exist around the drive wire to produce insertion loss spikes. However, further work will be required with the dielectric-wire technique to perfect it and also to determine the degree of improvement. The technique of forming a hole was used on the vast majority of APS millimeter phasors fabricated and tested. It was also possible to determine hysteresis properties when the hole was large enough for two wires.

Also, due to the thin ferrite wall, less than 0.022 in., stresses from a coefficient of expansion mismatch and machining stresses, are more critical than experienced for the C and S-band phasors.

b. Ferrite Powder and Dielectric: Initially, an Ampex 1200 Gauss (G) lithium ferrite powder, used for C-band phasors, was sprayed to develop the fabrication techniques for millimeter phasors. Although the $4\pi M_s$ of this composition was far from optimum for 35 GHz, the spraying parameters, anneal cycle and matching dielectric were known and available. Based on C-band results, this powder when arc plasma deposited and annealed, had a $4\pi M_s$ of 1100 G and a remanent magnetization (B_r) of 700 G. The powder had a matching coefficient of expansion with both a lithium titanate dielectric with dielectric constant (K) of 26 and a non-magnetic lithium ferrite dielectric with a K of 19. The basic spraying techniques for millimeter phasors were developed with this powder using both dielectrics. Millimeter phasors had B_r's of 660 G when driven at 3 A.

The techniques developed with the 1200 G powder were continued with a 4100 G lithium ferrite composition, Trans Tech TT-4100, which had a reported B_r of 3000 G. The $4\pi M_s$ of arc plasma deposited samples was between 3800 G and 3950 G. However, the B_r's of stress free toroids were only 2100 G, even though relatively high B_r/Bm ratios (0.92) were measured. Figure 5 is the hysteresis loop of a typical arc plasma, stress free, toroid. The low B_r of arc plasma deposited samples may be a result of the powder not being fully reacted prior to arc plasma spraying. This is based on a low B_r, 700 G, measured on a 1200 G powder, which when the same compositional powder was presintered at a 100° C higher temperature and fully reacted, produced a B_r of 780 G. A fully reacted powder is desirable for arc plasma spraying, since the time it takes the powder to travel through the heat of the plasma is not long enough to complete a homogeneous reaction. APS millimeter phasors had measured B_r of 1800 G for 4 A drives. The reduced B_r value, as compared to 2100 G for the stress free samples, is attributed to a small mismatch in the coefficient of expansion with the lithium titanate dielectric. This was the only dielectric available which could be reasonably matched to the 4100 G composition. A 4100 G composition, presintered at a higher temperature, is planned for future work.

The high K 26 of the lithium titanate dielectric necessitated spraying around very thin, less than 12 mils, dielectric in order to achieve a suitable match with the quarter wave boron nitride transformer, with a K of 4.1. An ideal match is achieved when the K of the transformer equals the square root of the effective K of the ferrite-dielectric composite. Effective K of the composite is determined from the K of the ferrite, which for 4100 G lithium ferrite is 15, and the K of the dielectric. Since the ideal effective K for boron nitride is 16.8, the dielectric with a K of 26 must be thin in respect to ferrite wall thickness, in order to contribute only a minor portion to the effective K of the composite. A close match between transformer and composite results in a phasor with a broad frequency bandwidth of operation. Lower K dielectrics can be thicker and physical tolerances are not as critical. However, high K dielectrics produce more differential phase shift ($\Delta\phi$) than lower K dielectrics for the same ferrite toroid. The versatility of the APS process made it possible to easily vary the dielectric dimension from one phasor to the next. During this development on K_a-band phasors, two different designs were alternately APS fabricated, Figure 6. One was a Navy designed, reduced, waveguide phasor, while the other was a full waveguide phasor which was tested and evaluated.

APS PHASOR DEVICE PERFORMANCE

The APS process is expected to produce improved phase shifter performance, since there is a minimum of air voids within the phasor structure. However, it is also necessary that voids between the ferrite and waveguide housing be eliminated to realize an improved device performance. Figure 7 shows the parts of a spring loaded test fixture (waveguide housing) used to device test the phasors. The top of the waveguide has a 5 mil metal shim, which is free to give in the center when the phasor is inserted. The height of the ferrite is cut approximately 2 mils oversize with respect to the waveguide height. This insures a tight fit between the phasor and waveguide, minimizing the generation of spurious modes due to air voids. A cross sectional schematic of the ferrite phasor and test fixture is shown in Figure 8.

[illegible] first phasors tested were those fabricated from the 1200 G lithium ferrite. Both the non-magnetic lithium ferrite, K=19, and the lithium titanate, K=26, dielectrics were used to arc plasma fabricate these phasors. Typical device performances of these APS phasors are given in Table 2. The 1200 G composition has a relatively high dielectric constant, 17, thus it is not possible to achieve an ideal match to the quarterwave boron nitride transformer, especially with the high K lithium titanate dielectric. This accounts for the relatively narrow bandwidth achieved for these phasors. Bandwidth is also restricted by spurious modes generated when the phasor is heavily dielectrically loaded. The greater phase shift with the higher K dielectric is due to the greater concentration of RF energy in the phasor. The insertion loss is relatively low, and a significant amount of the reported loss, 0.3 dB, is attributed to the waveguide housing. The losses of the waveguide can be reduced by shortening and silverplating the structure.

Table 2. Device Characteristics of 1200 G
APS Phasors

Dielectric (K)	Br (G)	Differential Phase Shift	Insertion Loss	Bandwidth*
19	660	80°/in.	0.5 dB	1 GHz
26	660	105°/in.	0.6 dB	0.6 GHz

*Bandwidth is defined as the frequency region of operation exhibiting a VSWR $< 1.3:1$.

A computer program was utilized to predict the theoretical differential phase shift based on the physical phasor design and material properties. The program, using a 700 G remanence, projected a maximum differential phase shift of 100°/in. and 117°/in. for dielectric loading of 19 and 26 respectively. The experimental values of phase shift, Table 2 , allowing for the lower B_r, are approximately 90% of the theoretical value. This is a good approximation of the theoretical, since it is based on a three slab geometry (ferrite-dielectric-ferrite) which only approximates a toroid phasor. The theoretical model would yield a higher value of differential phase shift, because of the absence on any horizontal component of magnetization along the top and bottom walls of the ferrite toroid.

Evaluation of APS phasors, fabricated with a 4100 G lithium ferrite was initiated after the evaluation of several of the 1200 G APS phasors had been completed. The phasor from this initial, small batch of 4100 G powder, had maximum B_r's of 1800 G. A computer program based on an 1800 G B_r and a dielectric insert with a K of 26, predicted a theoretical differential phase shift of 336°/in. The APS phasors produced 300°/in. differential phase shift, which is approximately 90% of theoretical. Figure 9 shows the relationship of differential phase shift as a function of drive current for an APS phasor.

The device characteristics of an initial 4100 G APS phasor is compared to a conventionally assembled 35 GHz phasor[4] in Table 3. The conventional phasor consists of a nickel zinc ferrite toroid, which is loaded with a K of 13. The ferrite composition, dielectric loading and physical dimension of the conventional phasor has been optimized for maximum device performance. The waveguide housing for the conventional phasor was silver plated, and this accounts for its slightly lower insertion loss. The bandwidth of the APS phasor was significantly less than the conventional phasor. Much of this difference in bandwidth can be accounted for by the lower K loading in the conventional phasor. It has been observed that when very thin dielectrics, less than 10 mils, and a very small hole is present, bandwidths in excess of 2.4 GHz have been achieved with APS phasors. The size of the hole is determined by the size of the boron nitride; in the phasor with a 2.4 GHz bandwidth, the hole was just large enough to insert an 8 mil diameter wire. This apparent improvement with a close wire fit, which minimizes voids around the wire, is additional justification for future development of the dielectric-wire spraying technique.

Table 3. Conventional and APS 35 GHz Ferrite Phasors

	Conventional	APS
B_r	1955 G	1715 G
Phase Shift	130°/in.	295°/in.
Switching Time	0.5 µ sec	0.5 µ sec
Insertion Loss	0.4 dB	0.6 dB
Bandwidth	2.2 GHz	0.75 GHz

It should also be noted in Table 3 that, although the conventional phasor possesses a higher B_r than that of the APS toroid, the APS phasor produces more than twice the differential phase shift. This is due to the fact that the APS phasor is loaded with a higher K dielectric and lacks air gaps at the ferrite dielectric interface.

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

It can be projected, that as the 4100 G lithium ferrite powder is modified for the APS process, remanences approaching 3000 G will be realized. A remanence of this magnitude will produce 500°/in. differential phase shift.

PROJECTED APS MILLIMETER PHASOR COST

The cost projections for an arc plasma fabricated 35 GHz phasor are based on a phasor 1 inch in length. This is a reasonable length, since with future ferrite powder modifications, differential phase shift in excess of 400°/in. should be achieved.

Table 4. APS Operating Cost

Item		Cost/Min.
Arc Gas (200 cf @ $30)	80 cfh	0.20
Ferrite Powder (1 lb. @ $50)	12 gm.s/min	1.32
Labor & Overhead ($28/hr)		0.47
		$1.99/min.

Currently, it takes less than 2 minutes to spray a 1 inch phasor. Based on the APS operating costs, Table 4, the spraying costs are less than $4 per phasor. A $10/lb powder cost has been quoted for large batches of powder, in excess of 1000 lbs, which would reduce spraying costs to less than $2 per phasor. Using the $4 per phasor spraying cost, and including the dielectric cost, $5 is the cost projection for arc plasma spraying a 35 GHz phasor. The machining cost for the APS 35 GHz phasor is estimated to be less than $10. This cost figure is based on our machining experience and a current $18 cost for machining an APS C-band phasor, which requires significantly more machining. Allowing $5 for profit and an 80% yield, a 35 GHz APS phasor should cost less than $25. This estimate is based on no significant improvement in the APS technology, and more important, this estimate should be realistic for small quantities, i.e. one hundred or more phasors. This estimated cost, $25 for an arc plasma fabricated 35 GHz phasor, can be compared to a current price in the range of $100 for a conventional ferrite toroid. There are still significant costs associated with inserting the dielectric, and a questionable yield.

ACKNOWLEDGEMENTS

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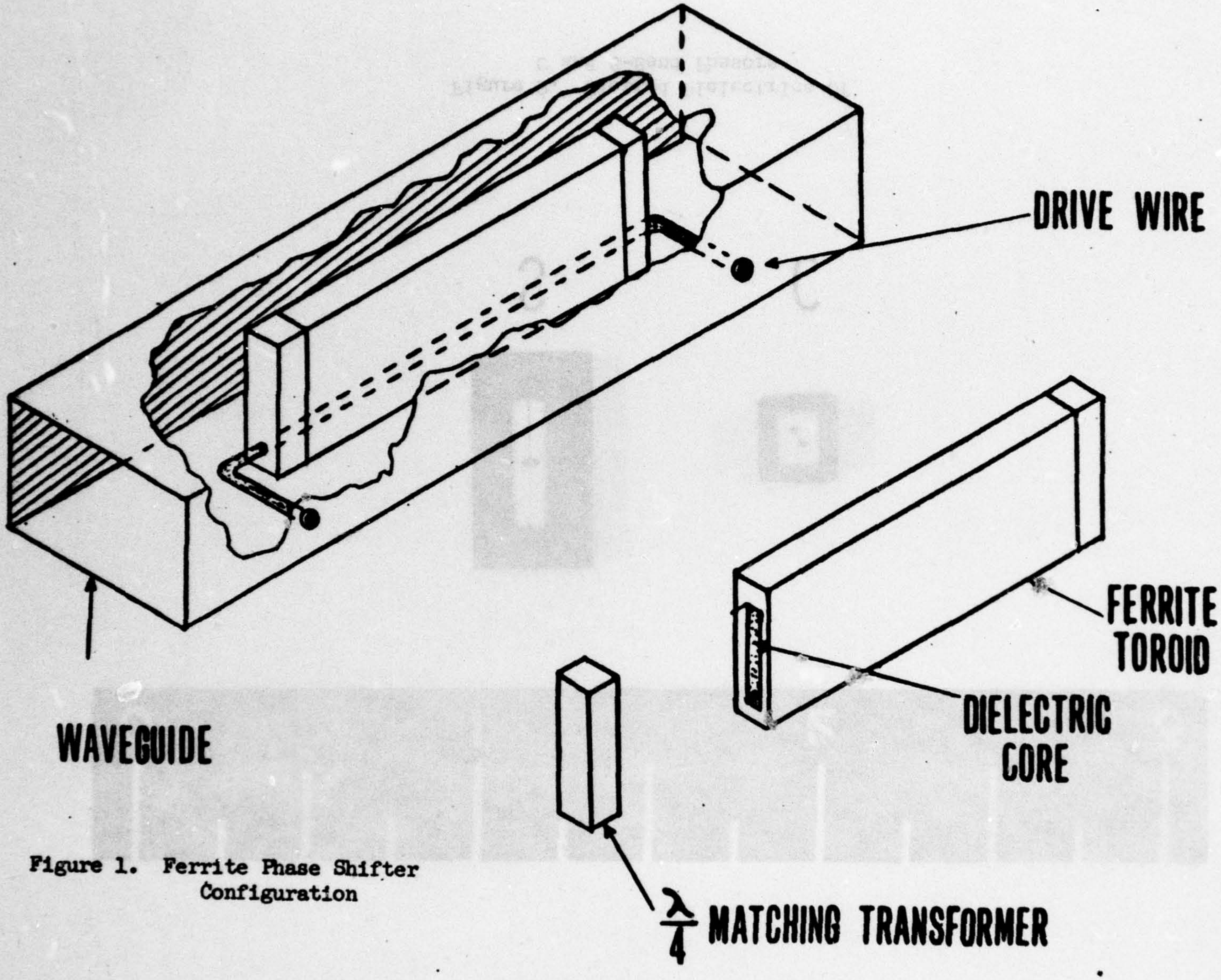


Figure 1. Ferrite Phase Shifter Configuration

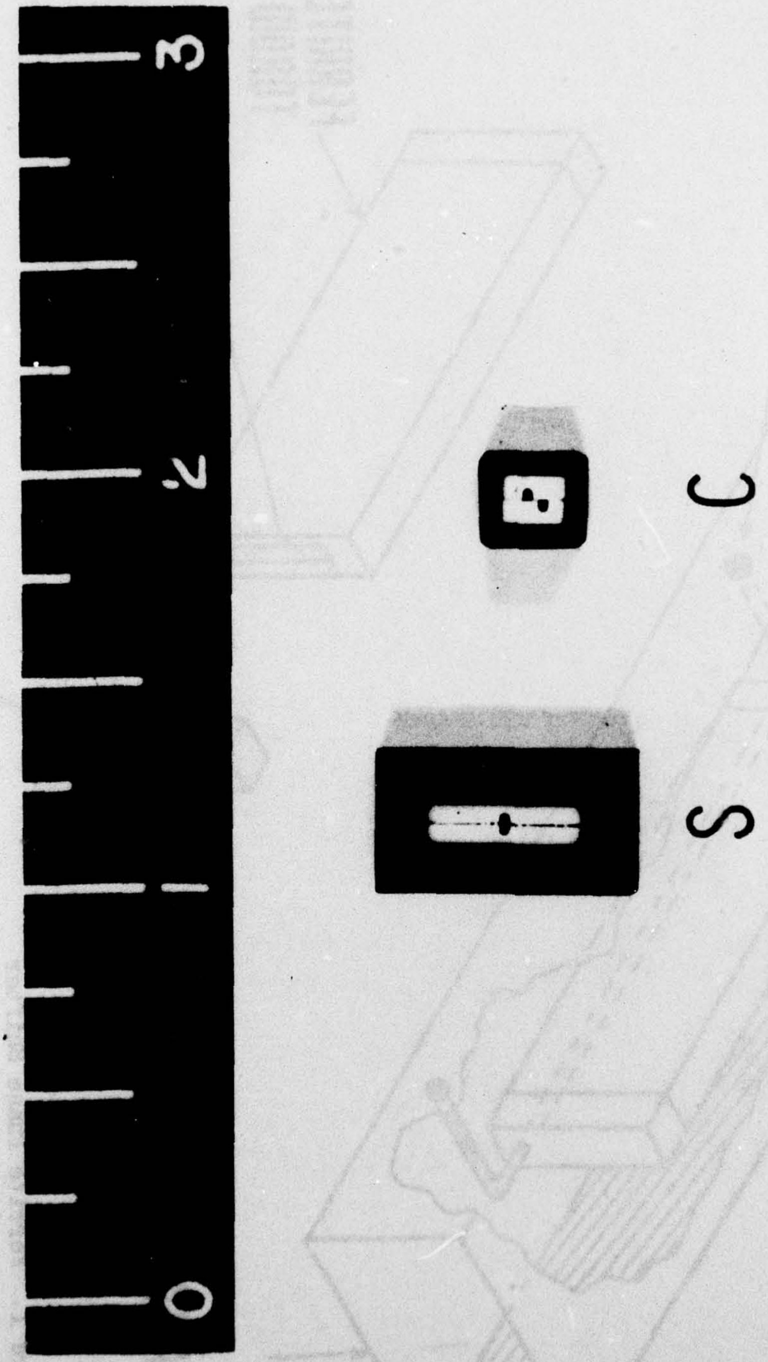


Figure 2. Slotted Dielectrics of C and S-Band Phasors

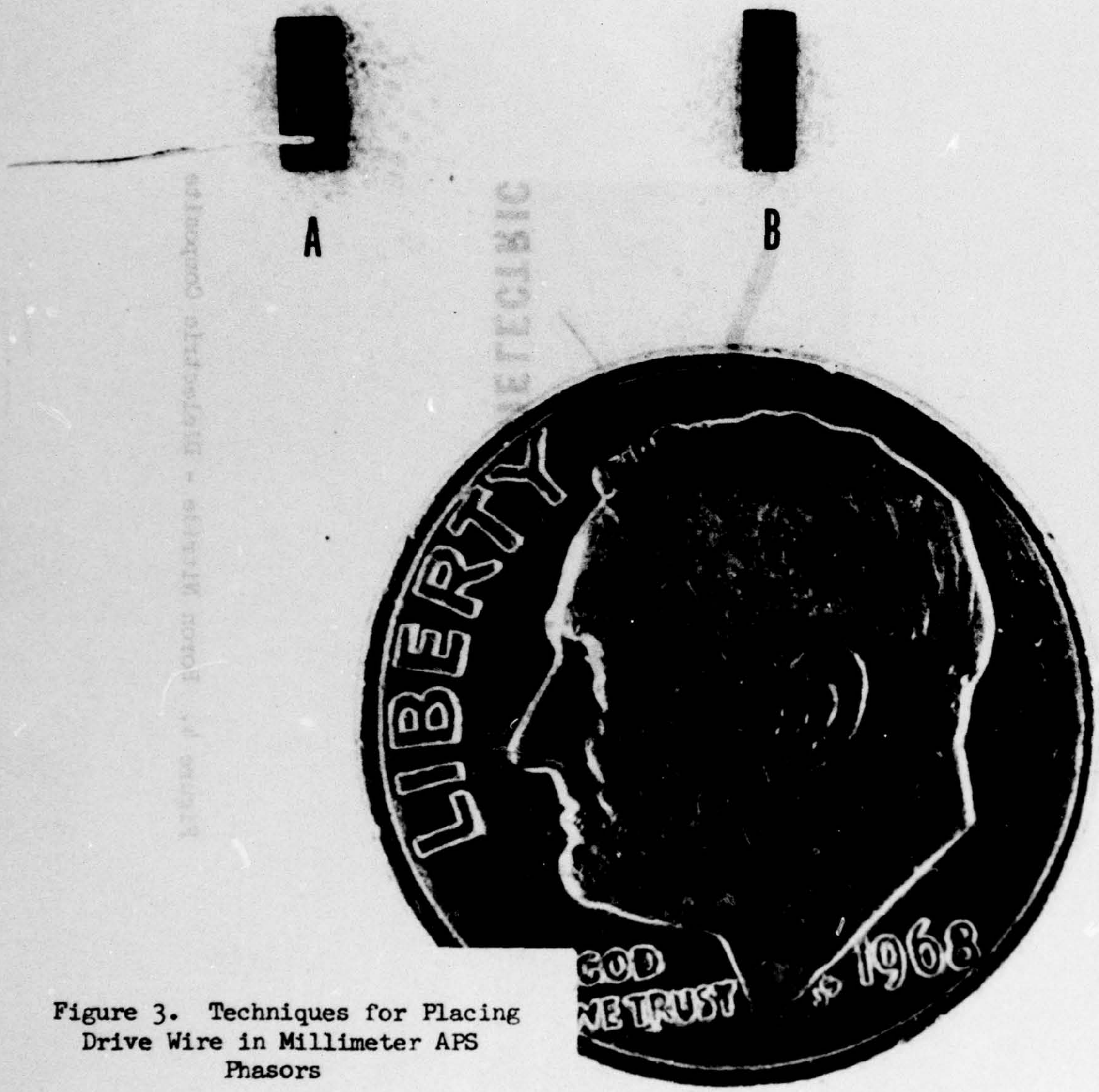


Figure 3. Techniques for Placing Drive Wire in Millimeter APS Phasors

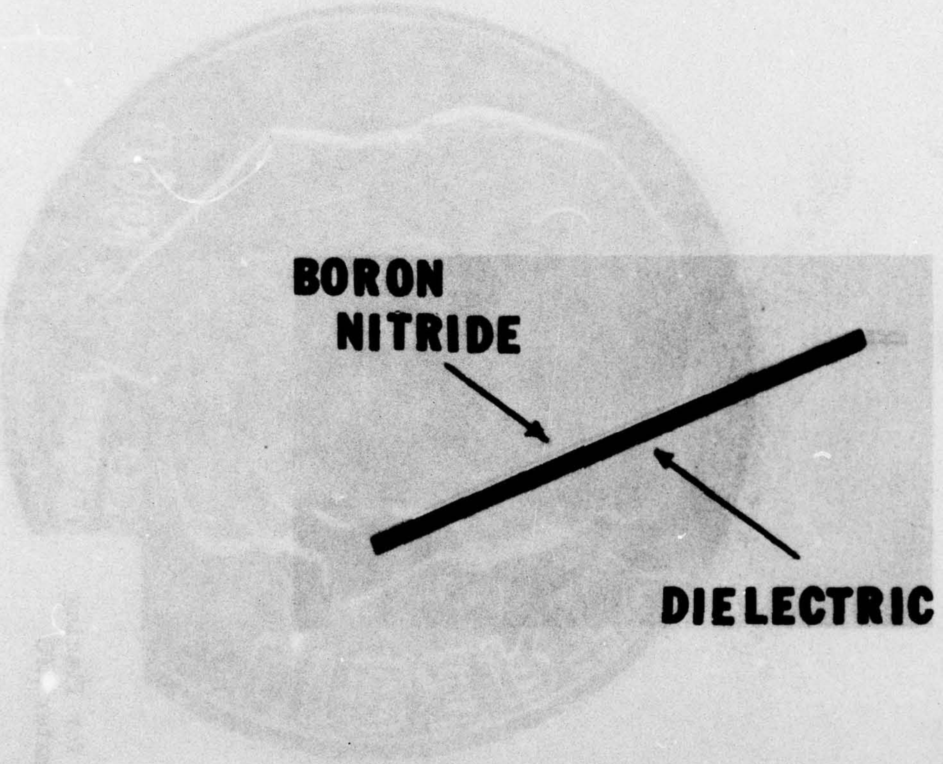


Figure 4. Boron Nitride - Dielectric Composite

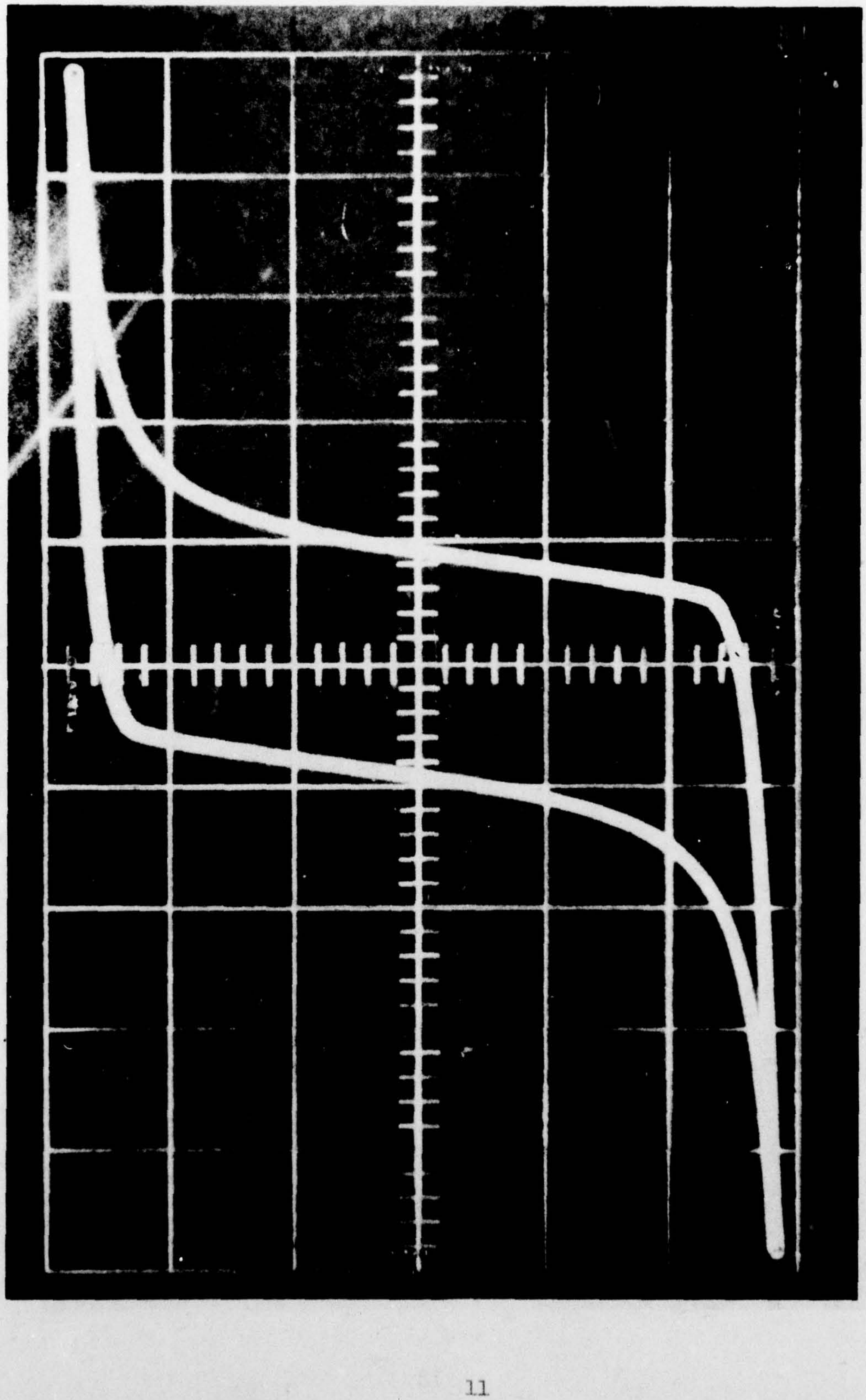


Figure 5. Hysteresis Loop of Stress Free APS 4100 Gauss Lithium Ferrite

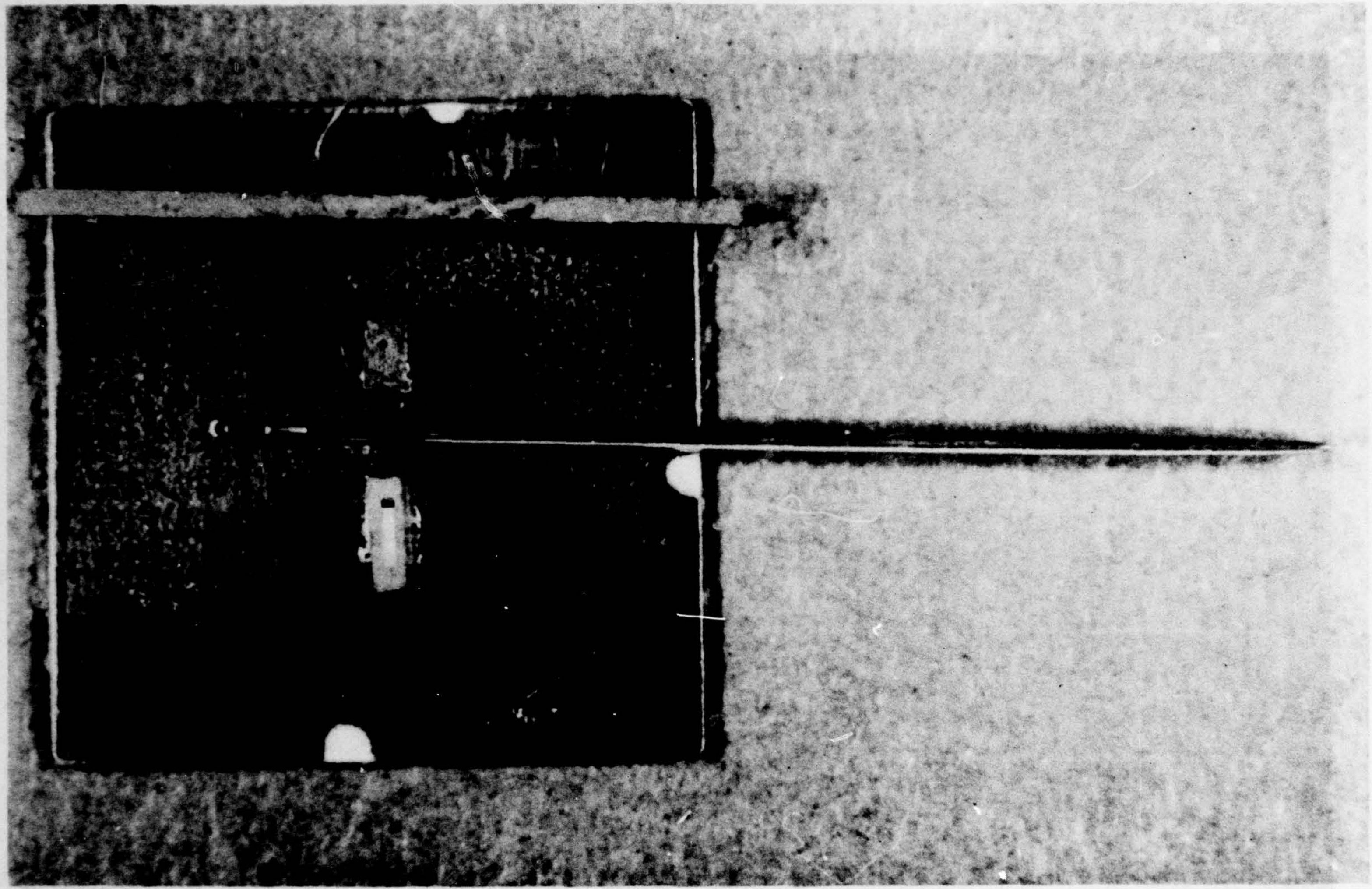
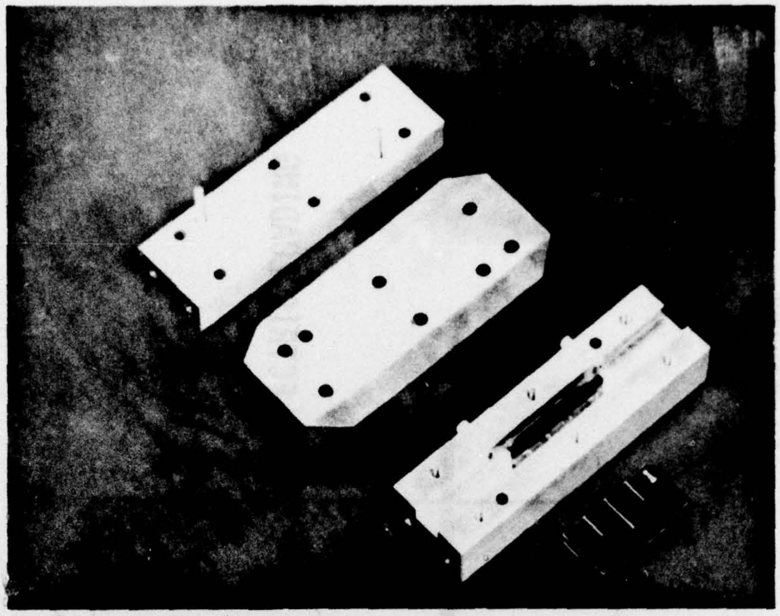
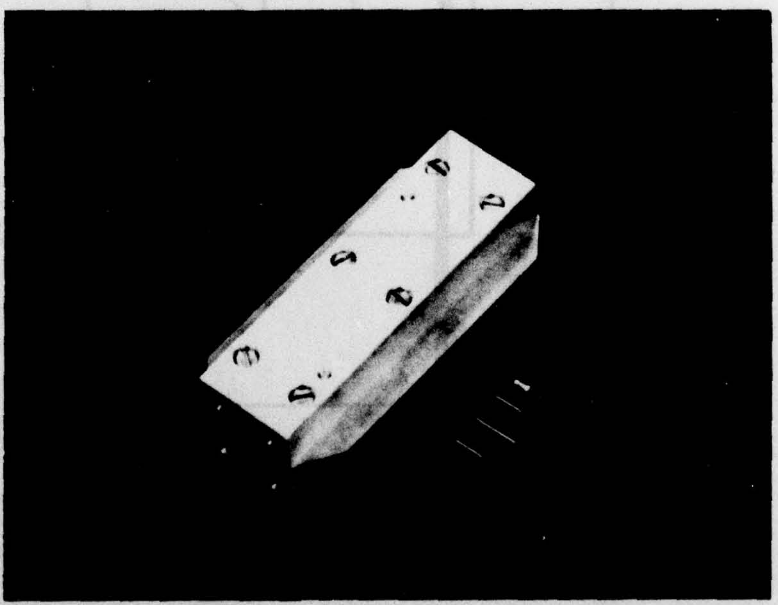


Figure 6. Two K_a-Band Phasors.
Designs fabricated by APS Techniques



A. Internal View



B. External View

Figure 7. Phasor Test Fixture

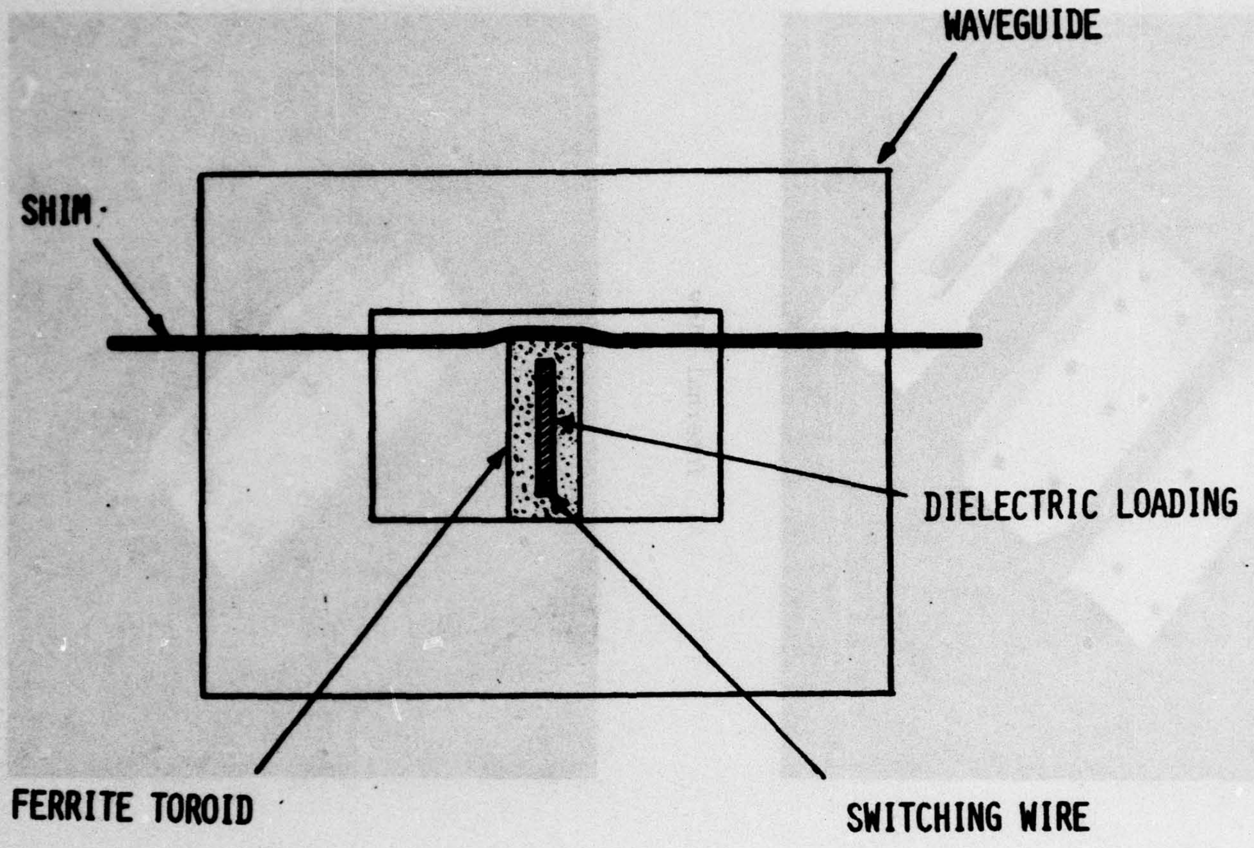


Figure 8. Cross Section of Phasor Loaded Test Fixture

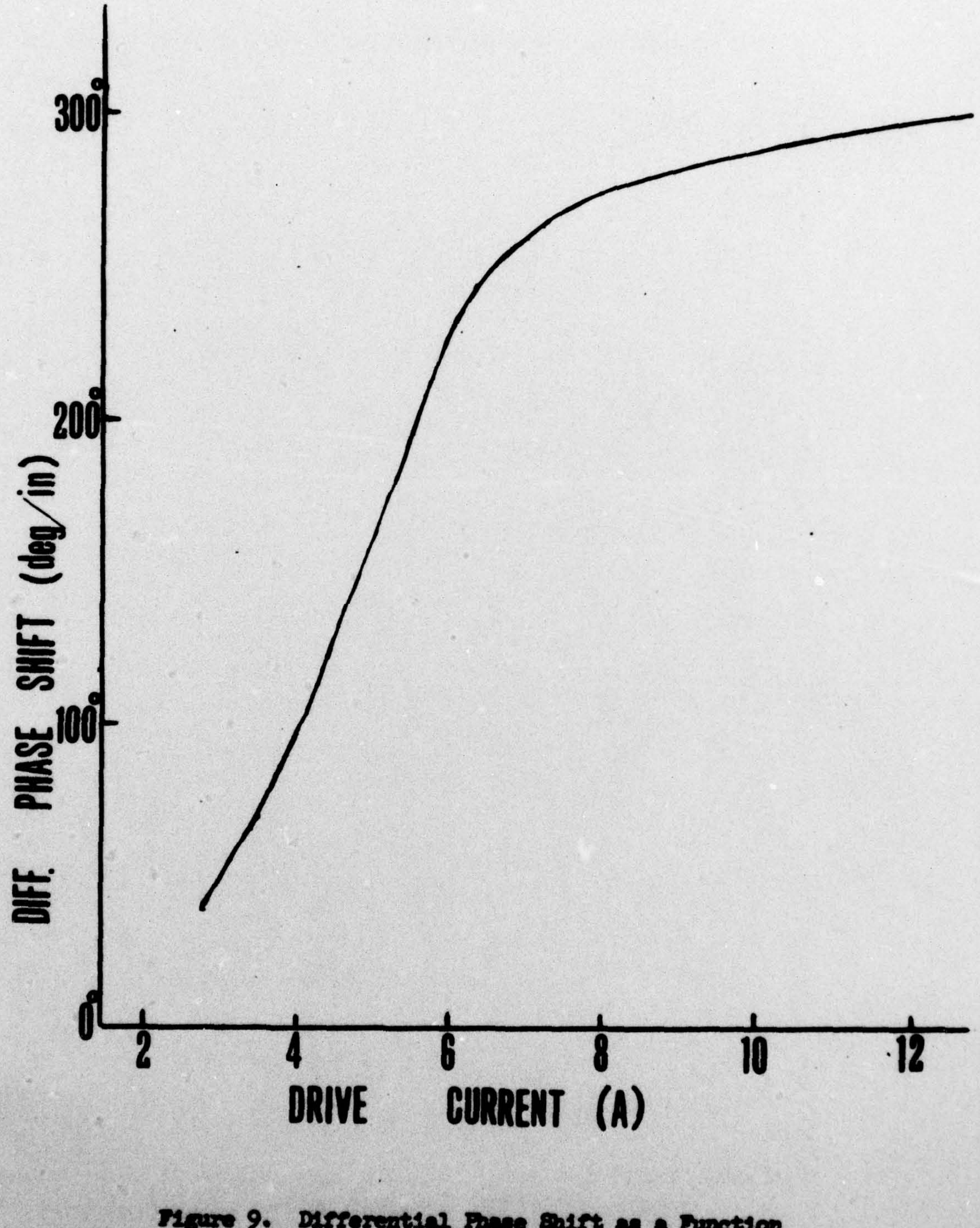


Figure 9. Differential Phase Shift as a Function of Drive for an APS Phasor.