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AD828635

TECHNICAL REPORT

HIGH POWER C BAND PHASE SHIFTERS

SEMIANNUAL REPORT

11 July 1967 To 10 January 1968

ARPA ORDER NO. 550-PRA-7-1207
PROGRAM CODE NO. HJ-D5

RADC CONTRACT NO. F30602-68-C-0006

Air Force Systems Command
Research and Technology Division
Rome Air Development Center
Griffiss Air Force Base, New York

Sponsored By
Advanced Research Projects Agency (ARPA)
Department of Defense
Washington, D.C.

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RADC-TR-68-88



HIGH POWER C BAND PHASE SHIFTERS

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Sperry Rand Corporation

TECHNICAL REPORT NO. RADC-TR-68-88

January 1968

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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

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SYNOPSIS

This is the First Semiannual Report on this program.

This report outlines the present status of the program and includes techniques developed in attaining the high power performance of ferrite digital phase shifters. Test results confirming these techniques are also given.

Structural studies have been carried out to assure compatibility of designs with phased array requirements. Cross sections have been reduced to a minimum by careful location of cooling passages.

Driving techniques for phased arrays were studied to determine trigger mode, repetition rates, switching rates, switching accuracy, and primary power requirements. A scheme for triggering a single bit phase shifter is outlined in detail.

Magnetostrictive high power effects of YIG and CVB materials are under investigation and the present status of materials investigation as related to this program is given.

A discussion of remaining tasks of this program is made, followed by conclusions and recommendations.

1. INTRODUCTION

1.1 PROGRAM OBJECTIVE

The purpose of this program includes the design and fabrication of high power digital phase shifters capable of continuous operation at 100 kw peak, 1000 watts average, 100 microsec. pulse width with size and performance compatible with operation in a phased array radar. A comparison study of multibit (4 bit) units to single programmable phase units is also included.

Such a program of necessity includes the following broad categories.

- Evaluation of system needs
- Materials considerations
- Construction and Assembly techniques
- Reproducibility

1.2 IMPLEMENTATION OF OBJECTIVES

After careful evaluation of the state of the art in phase shifter design the following tasks were determined to be included as part of this program.

- Evaluation of microwave performance of ferrite (garnet) materials in their partially magnetized state with emphasis on peak power performance.
- The study of techniques to reduce and suppress arcing in the phase shifter structure due to high peak powers and/or wide pulse widths.
- Attainment of stable differential phase at all average powers up to the maximum specified under this program. This task includes the study of magnetostriction in various materials when subjected to non-uniform temperatures.
- Attainment of the above goals in a package compatible with phased array requirements.
- Evaluation of driver requirements for phase shifters with emphasis on compatibility of large numbers of units in a single radar.
- Design, construct and compare single and multibit phase shifters with emphasis on relative cost of fabrication, assembly, and accuracy of microwave parameters.

These objectives are now being implemented. This semiannual report of a one year program includes the methods being employed and includes test data obtained on test structures.

2. MATERIALS STUDY

2.1 GENERAL

The materials phase of this program does not include the manufacture of new materials but rather includes the study of microwave parameters of existing materials (YIG and CVB) for compatibility with the needs of this program.

2.2 YIG MATERIALS

YIG materials possess excellent properties for digital phase shifters in that limiting thresholds and $4\pi M_s$ can be readily adjusted by proper gadolinium and aluminum doping. In addition, their combined properties of Curie temperature, coercive field, and remanence qualify this family of materials as excellent for high average power performance.

From the curve of Figure 1, a value for m_s was chosen for this program using YIG with 15% gadolinium plus aluminum doping. The value of $4\pi M_s$ chosen was 625 gauss based upon this value of m_s .

It should be noted that h_{crit} (left hand side of Figure 1) is a function of material parameters only whereas the values of peak power equivalent (right hand side of Figure 1) are those values of peak power that will produce h_{crit} in the cross section of Figure 2. This cross section has been obtained from careful study of computer data for phase shifter loading and involves a compromise of length, loss, toroid wall thickness and toroid slot width for zero phase/frequency slope.

It can be shown, however, that a slightly lower loss per inch (and lower overall loss) can be obtained at the sacrifice of increased phase shifter length if the toroid wall thickness is reduced to $0.036 \lambda_c$. To ease the problem of dissipation/heating per inch, this reduced wall thickness was chosen. An extra benefit from such a reduction in wall thickness is an increase in the peak power equivalent of h_{crit} by decreased waveguide loading.

The value of limiting for the cross section of Figure 3 (with wall thickness of $0.036 \lambda_c$) obtained was estimated at 125 kw, a value sufficiently above that required to allow for variations in $4\pi M_s$ with garnet manufacture.

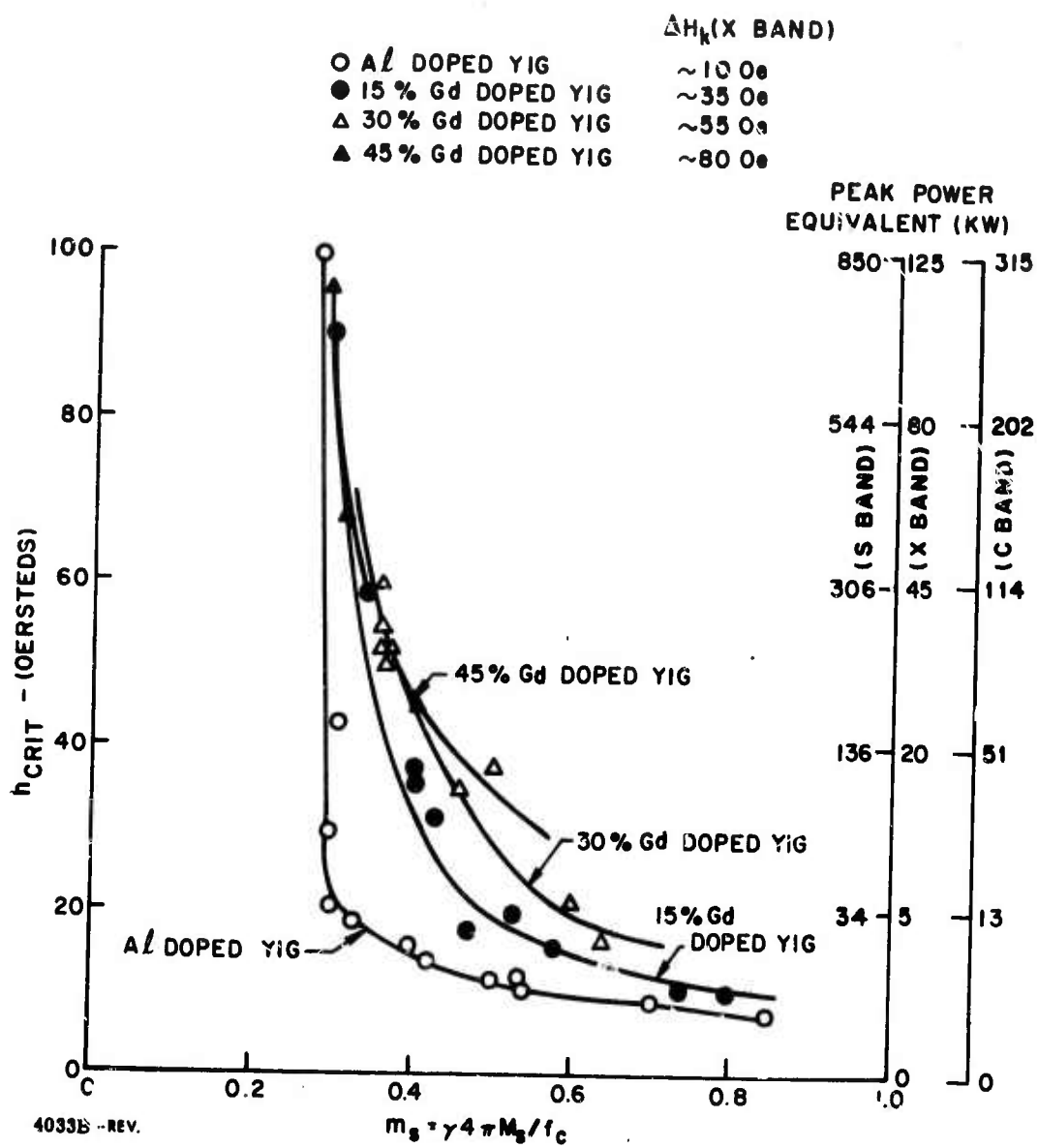


Figure 1. m_s Vs h_{crit} For Various Gd Dopings

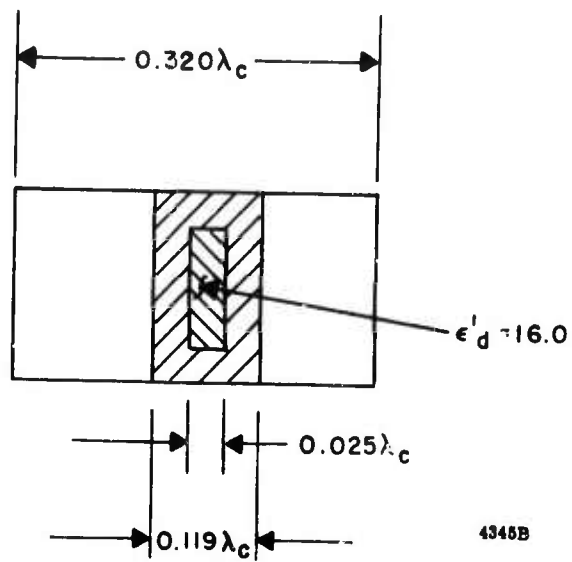


Figure 2. "Optimum" Cross Section of Digital Phase Shifter

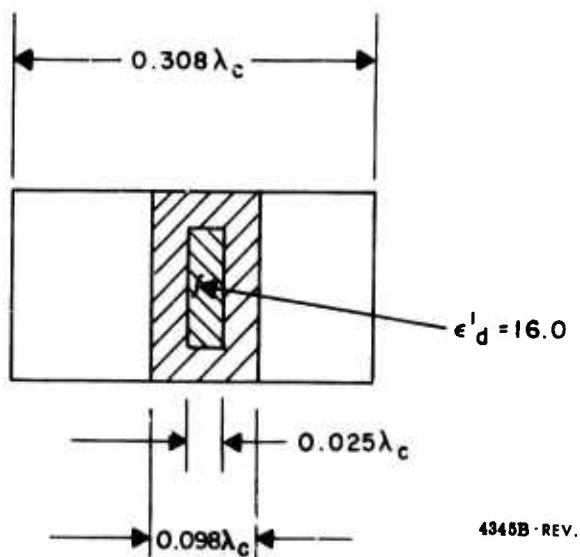


Figure 3. Modified Cross Section For Minimum Loss

Although the above discussion indicates an "ideal" material in YIG, there is one difficulty, magnetostriction. Magnetostriction manifests itself as a change in remanence of a YIG material when this material is placed in tension, the change being a decrease in remanence.

In high average power phase shifters this stress on the toroid can be a purely mechanical factor due to improper fit of the phase shifter components or what is more common and the most difficult to control, this stress results from non-uniform temperatures in the toroid generated from RF dissipation.

Cooling structures are added to the structure as in Figure 4 but they can only reduce the effect of magnetostriction, not eliminate the cause.

2.3 CALCIUM-VANADIUM-BISMUTH MATERIALS (CVB)

This family of garnet materials is similar to the YIG family but possesses a very small positive magnetostrictive factor. Remanence increases slightly when the toroid is placed under radial tension.

This material is somewhat limited in that $4\pi M_s$ max. ≈ 700 gauss and $H_c \approx 1$ at $4\pi M_s \approx 650$ gauss to approximately 4.5 for $4\pi M_s = 300$ gauss. Loss tangent is approximately equal to YIG ($\tan \delta \approx .0005$) and remanence ratio $\approx .35$ (R_R YIG $\approx .45$).

Measurements of ΔH_k for this material indicate values of h_{crit} similar to that of Al doped YIG (no other rare earth doping).

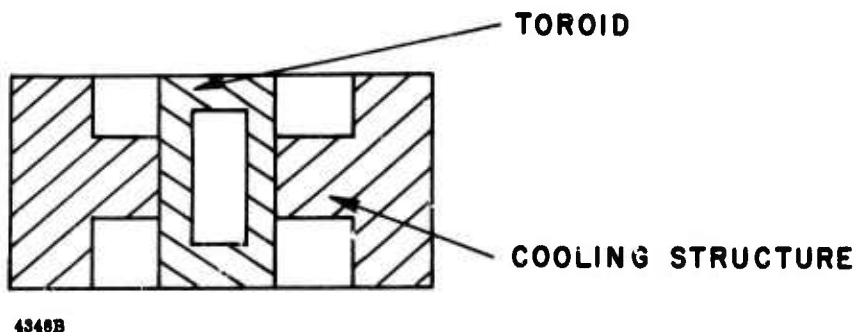


Figure 4. Phase Shifter Cross Section With "T" Cooling Structure

This material is now under evaluation for use in high power phase shifters at C band and will be used in a full four bit unit if preliminary testing is satisfactory.

2.4 LIMITING THRESHOLD VS PARTIAL MAGNETIZATION

The original proposal for this program indicated a potential problem area associated with reduction (or change) in h_{crit} for different levels of magnetization of a given material. Such changes would be quite noticeable in a phase shifter employing our 337 degree bit which is trimmed to lower phase shift increments by a reduction in magnetization level.

Tests to determine if such a phenomenon exists in YIG materials (especially for those associated with this C band program) were conducted early in this program.

Figure 5 is a plot of peak power out vs peak power in for G311, YIG with $4\pi M_s = 625$ gauss, and also gives relative insertion loss vs peak power in. It can be seen that the loss of the device for saturation conditions +M and -M differs only slightly below limiting level (approximately 120 kw). The limiting value for a demagnetized toroid and for the partially magnetized state in +M and -M directions all fall within the spread of the saturation conditions.

No such difficulty as originally speculated, exists for designs being incorporated into this program.

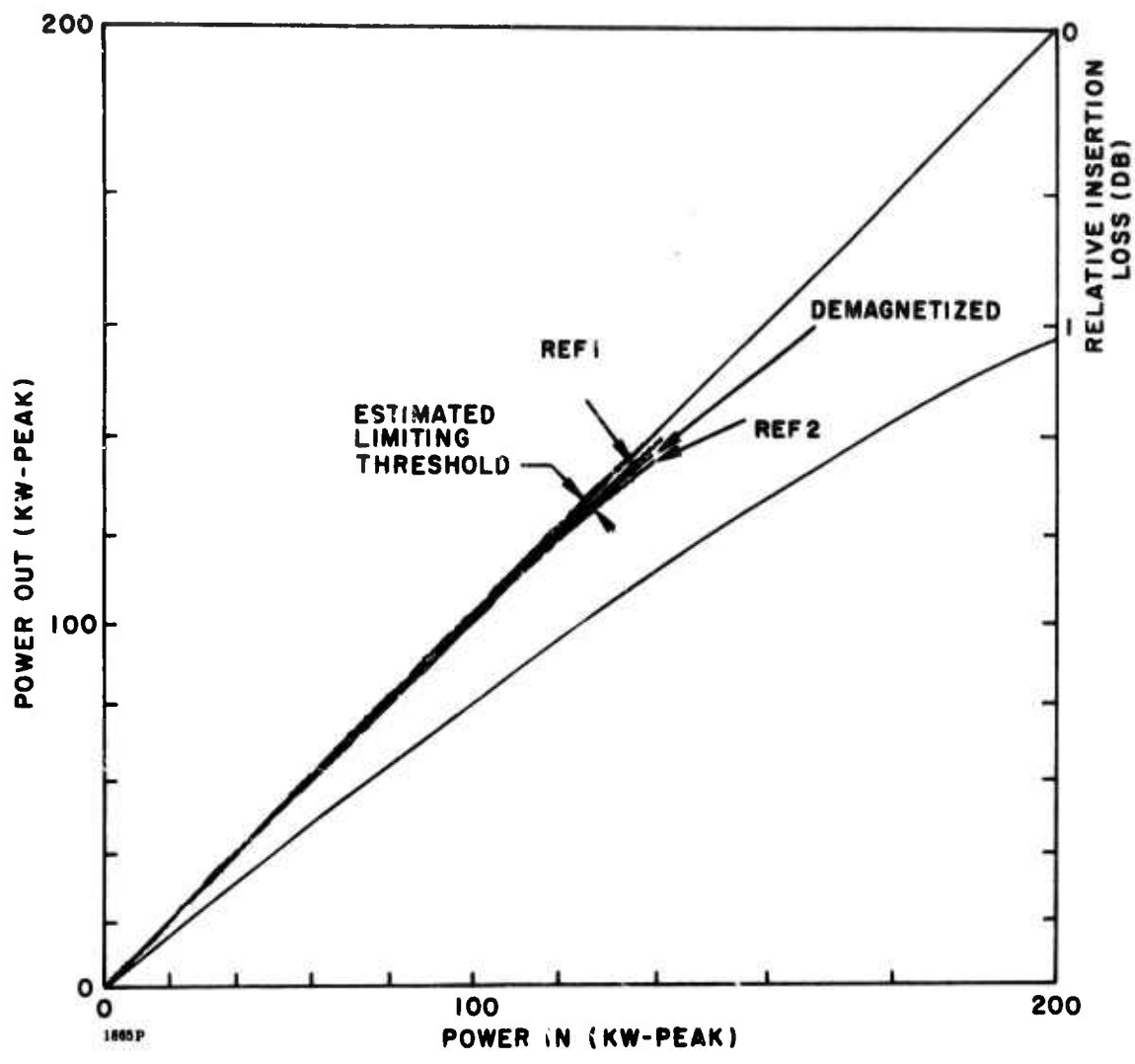


Figure 5. Power Out Vs Power In G311

3. PHASE SHIFTER DESIGN

3.1 GENERAL

Design of phase shifters for this program is determined by the following categories and is discussed in detail in the following section.

- High peak power breakdown
- Long pulse width effects
- High average power dissipation/cooling
- Cross section limitations for phased array use
- Ease of fabrication and assembly

3.2 PEAK POWER BREAKDOWN

A very general statement can be made that peak power breakdown in heavily loaded waveguide of reduced height, as commonly employed in phase shifter design, is appreciably below that of air filled unloaded waveguide.

The term "appreciable" in the above statement covers a range of values dependent heavily upon the degree of fit attained between all components in the loaded guide. Applying this concept to phase shifter design, it is absolutely necessary to eliminate all air gaps between toroid and walls and toroid and dielectric core and between core, toroid, and charging wire. It is also desirable to reduce, as far as is feasible, any break in the toroid assembly which is continuous from broad wall to broad wall (parallel to E field) of the waveguide.

The material chosen to fill these air gaps in the C band phase shifter is Sylgard 184 (Dow-Corning), a two part potting compound which readily penetrates into open spaces and remains flexible after curing.

Tests were run with this sealant used in varying degrees in the phase shifter structure with the following results and conclusions.

- Use Sylgard 184 liberally on all toroid-core-charging wire surfaces.
- Take extreme care at input (and output) junctions of toroid structure where mating with matching transformers occurs.

- Allow excess Sylgard 184 within the structure to cure normally, no wiping necessary. This excess material in no way degrades the phase shifter and does enhance high power performance.
- The ultimate design appears to be to completely fill the waveguide in the loaded region with Sylgard 184. This, however, is a difficult task because Sylgard flows quite easily.

Breakdown tests were performed on a test structure and will be discussed in a later section of this report. It should be mentioned at this point, however, that arc-over always occurred at the junction of the toroid and matching transformer on the input end of the phase shifter. This is a point where an impedance transformation occurs in the presence of heavy dielectric loading, a combination that creates a higher probability of arc-over.

Careful application of Sylgard in this region to eliminate all air pockets proved successful in suppressing arcs.

3.2.1 Short/Long Pulse Operation

Accurate data on pulse width/arc-over between 1 μ sec and 100 μ sec is not available. In addition, a high power source at 100 μ sec was not available for test evaluation, the longest available pulse length being 10 μ sec.

Some form of scaling factor was required for short-medium pulse evaluation. A curve was derived for arc-over vs pulse length for WR 2100 waveguide as shown in Figure 6. This curve was for waveguide with no special provisions (such as rounding corners) for suppressing arc-over. It is also obvious that with only three points, the precise shape of the curve is unknown.

Taking this curve at face value, however, to attain 125 kw minimum arc-over at 100 microseconds would require testing to approximately 270 kw at 10 microseconds and 550 kv at 2.5 microseconds.

All testing at 2.5 or 10 microseconds, therefore, should be made and be successful at power levels in excess of these values.

3.3 HIGH AVERAGE POWER REQUIREMENTS

Although not specified under this program, a phase shifter capable of operation from zero to 1000 watts average should not vary more than 5% from nominal differential phase shift over this power range.

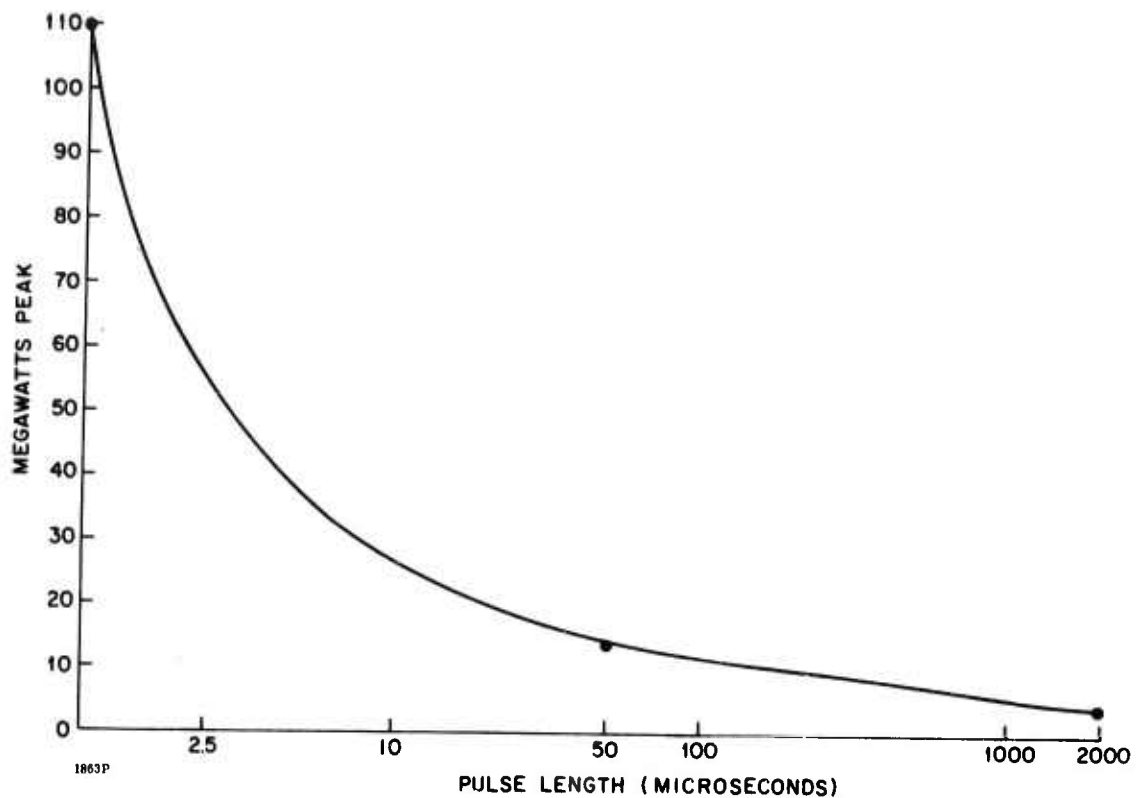


Figure 6. Arc-Over Of WR 2100 Waveguide Vs Pulse Width

To attain this degree of stability it is necessary to remove heat produced by RF power dissipation for two reasons.

- Drop in $4\pi M_s$ with increased temperature
- Magnetostriction

To reduce the temperature of the toroid in the microwave structure it is necessary to introduce additional thermal paths from the toroid to the waveguide walls since garnets have very low coefficients of thermal conductivity. This is attained by adding boron nitride T structures to the assembly as previously shown in Figure 4.

Calculations of temperature of the toroid at 1000 watts when boron nitride thermal sections are employed indicate a rise of approximately 20 degrees F, which would produce a change in differential phase of approximately 1%.

The remainder of the change in phase shift so commonly found in high power devices can be attributed to magnetostriction resulting from temperature gradients across the material.

As previously stated in Section 2, CVB materials are only slightly magnetostrictive and their response is such that it will normally partially compensate for the normal drop in $4\pi M_s$ with temperature.

Data included in a later section of this report indicates that CVB truly responds as described above and if properly controlled, can result in a C band unit capable of operation to powers well in excess of 1000 watts average. This data also indicates that, as predicted, the largest percentage of the drop in phase shift experienced on YIG devices is a result of magnetostriction and not temperature rise of the toroid.

3.4 CROSS SECTION

To meet the spacing requirements of phased array radars, a spacing similar to that shown in Figure 7 is required.

This cross section is compatible with the cross section of the active region of the phase shifter being developed under this program.

The unit being developed, however, will have waveguide (unloaded) input and output.

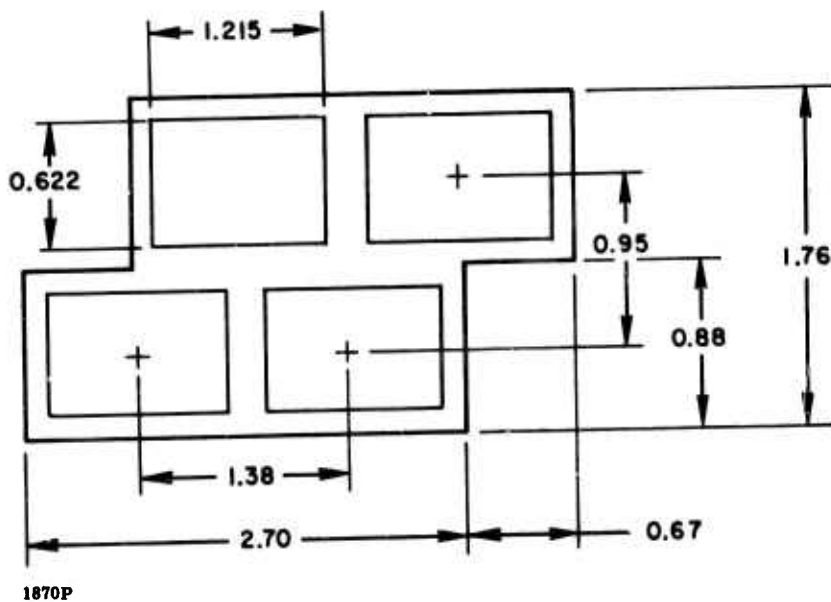


Figure 7. Typical Element Spacing For C Band Array

In order to meet spacing requirements in the region of input and/or output waveguides, the use of ridged waveguide sections appears attractive. Such a cross section is shown in Figure 8.

Although such a feed is not specifically reflected in the scope of this program, a structure will be designed and tested at a future date if time permits since there is a need to develop a practical means of feeding a phased array radar.

Areas of special consideration will be arc-over in the ridged area and development of a satisfactory transformer from ridged guide to toroid structure.

3.5 ASSEMBLY

The phase shifter being developed employs a four piece housing that is screwed together. A cross section is shown in Figure 9. This cross section permits adjustment in the direction marked A in Figure 9, thus allowing for easy assembly with accurate fit of the boron nitride sections (required for good thermal transfer).

3.6 SPECIAL CROSS SECTIONS

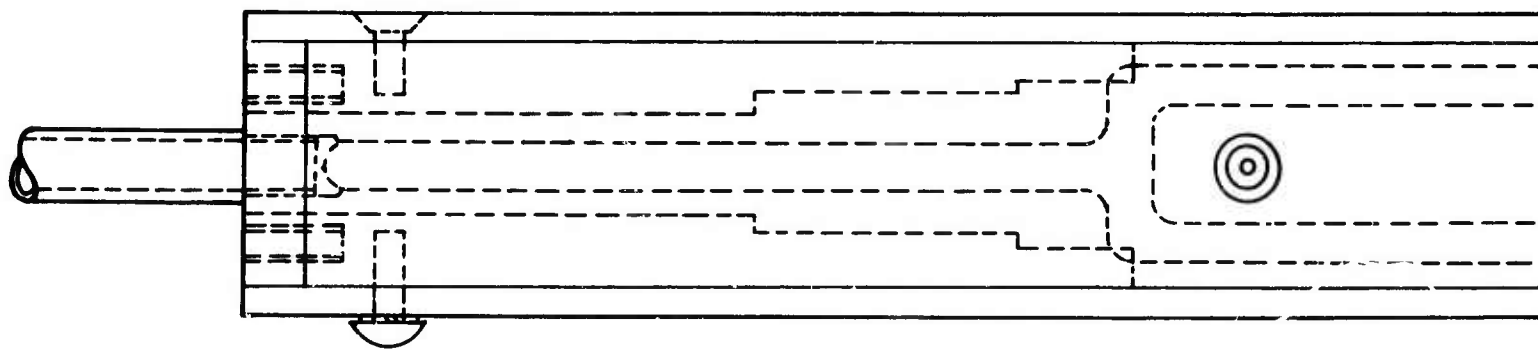
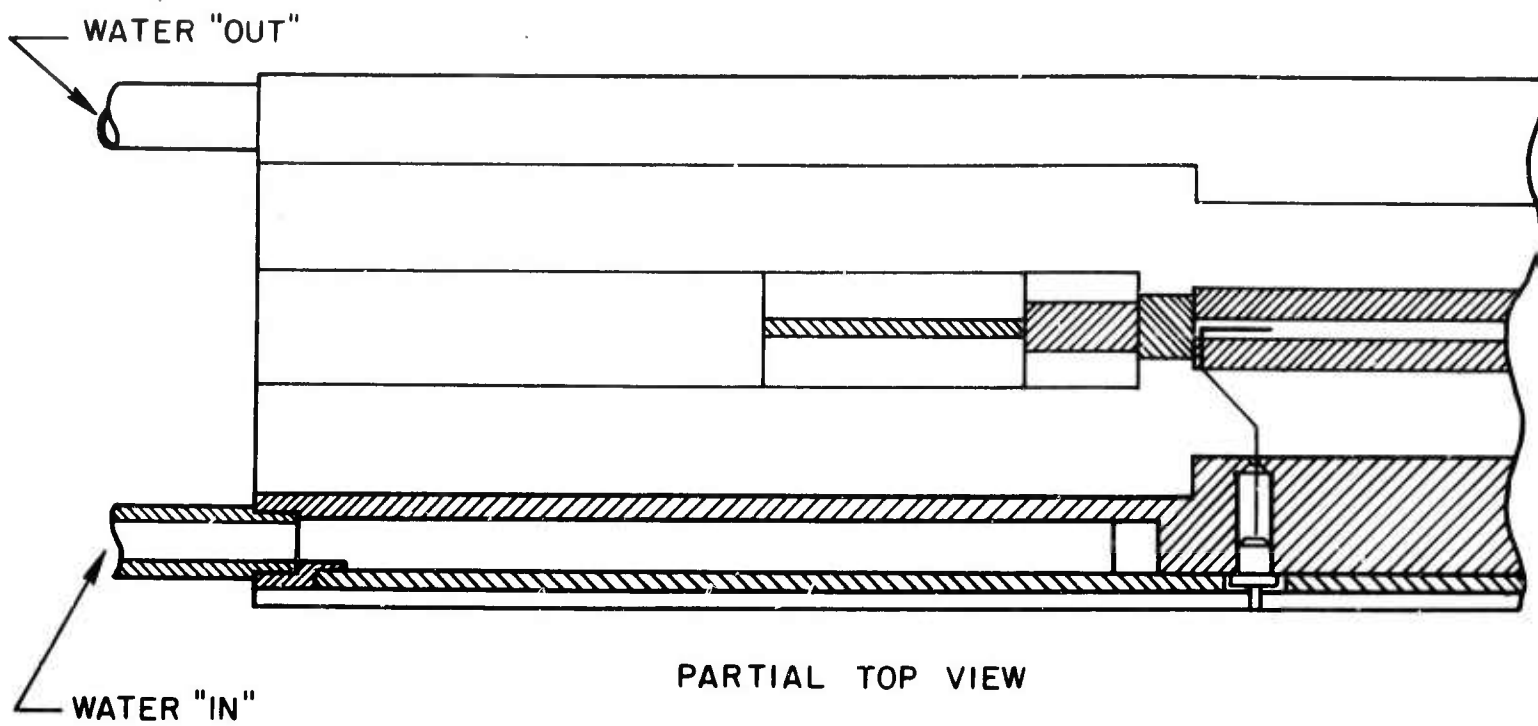
A unique design, previously developed on Sperry funding, has been extended to potential use on this program. In an attempt to design a low cost, low power phase shifter, a unit was designed as in Figure 10, where close fit between "waveguide" and toroid is attained not by precision grinding of the toroid assembly to fit the waveguide, but by forming the thin film foil "waveguide" to conform to the toroid.

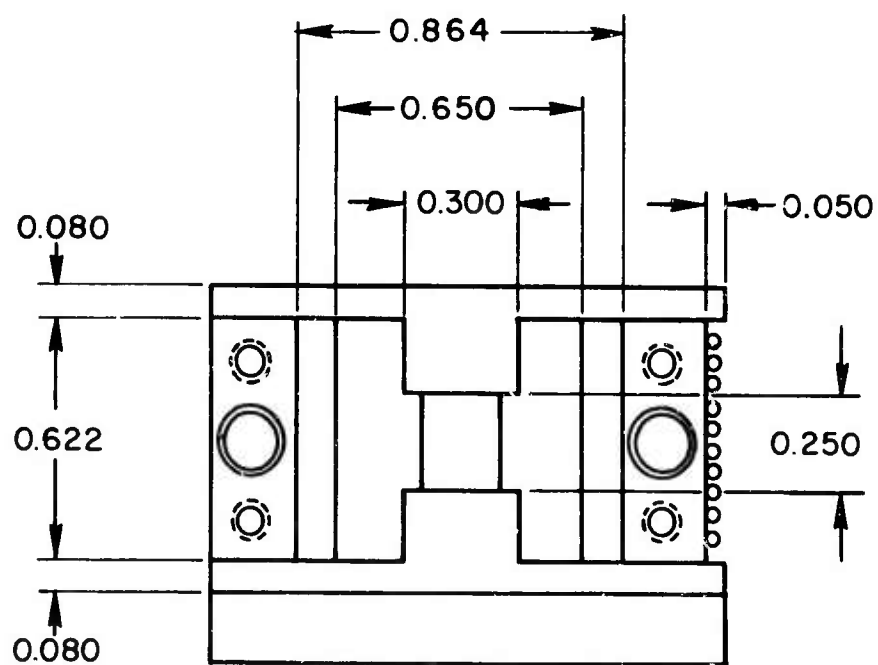
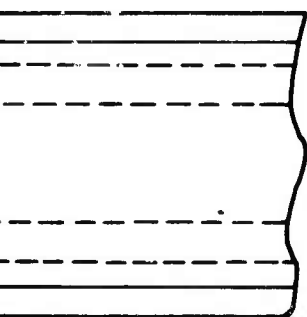
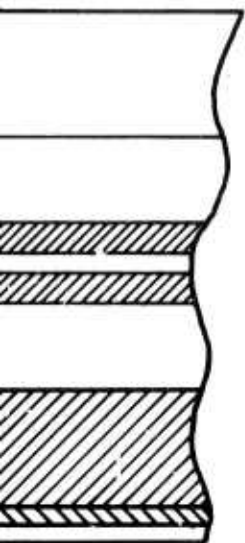
This design has led to simple techniques in assembly with component tolerances that normally would produce loss spikes in the operating band. In the low power configuration, the air spaces were replaced with a low dielectric constant material, Rexolite, as a base for the foil "waveguide" wrap.

For high power use, the Rexolite has been replaced by boron nitride. Again, to insure a solid base for the foil wrap, the boron nitride was in the form of a solid rectangular block rather than the conventional "T" structure used in high power phase shifters.

As shown in cross section in Figure 11, metallic heat sinks with cooling water passages were added to the structure, external to the foil.

This unit was high average power tested; the characteristics are given under the data section of this report.





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INPUT END VIEW

Figure 8. C Band Phase Shifter with
Ridged Waveguide Input

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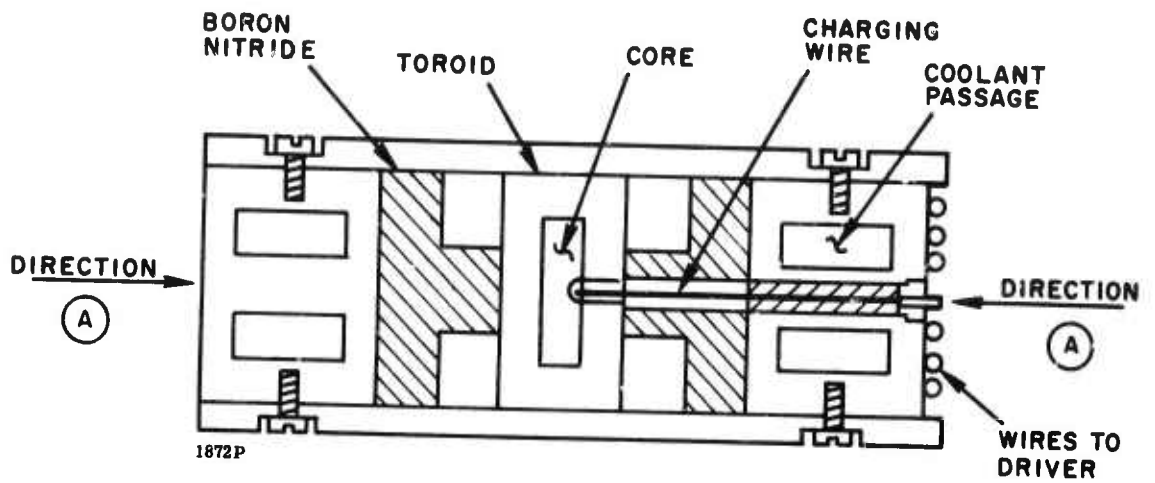


Figure 9. Cross Section of C Band Phase Shifter with Four Piece Housing

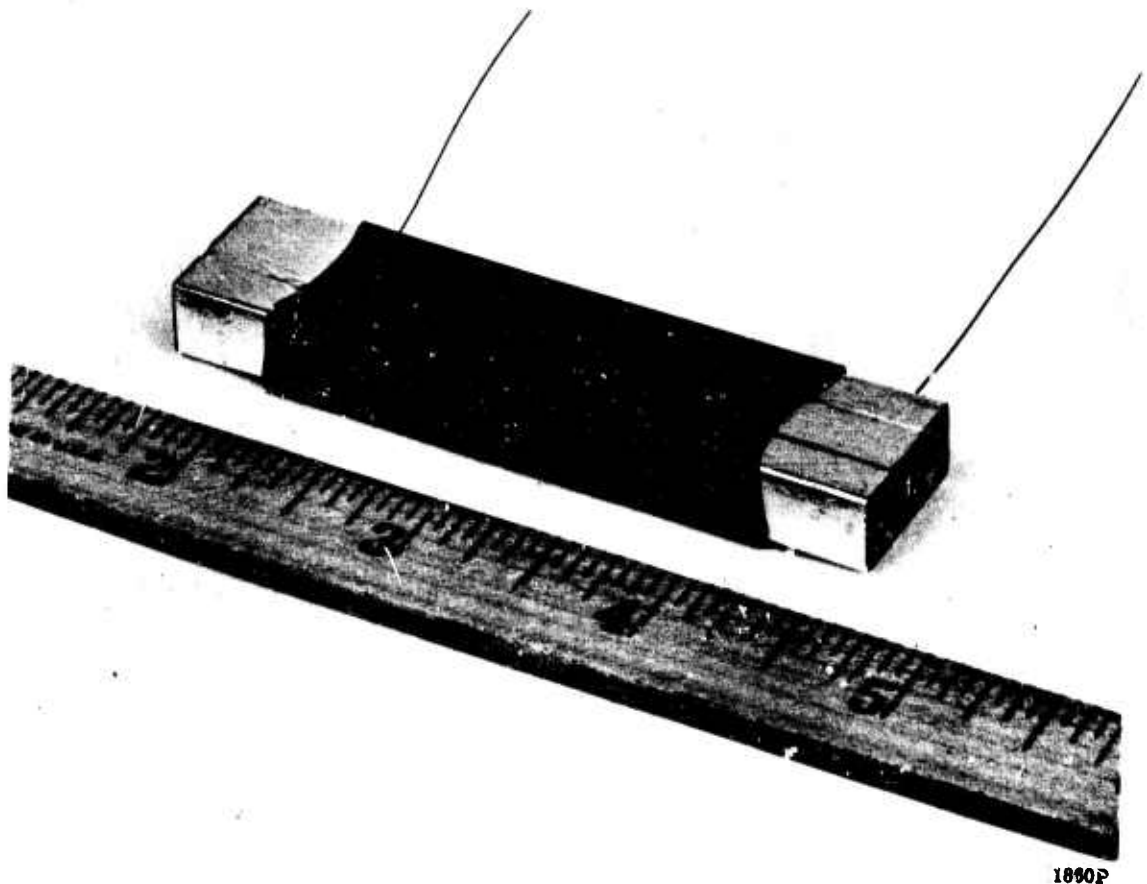


Figure 10. Low Power Foil "Waveguide" Phase Shifter

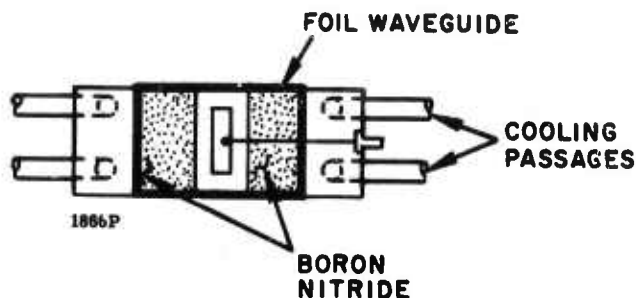


Figure 11. Foil 'Waveguide' Phase Shifter Modified for Improved Cooling at High Average Powers

This structure has the following advantages:

- **Smaller cross section - a reduction in height can be attained**
- **Reduced fabrication costs - housing machining costs are greatly reduced**

This structure also has the following disadvantages:

- **Difficulty in attaining suitable adapters for waveguide input and output - the unit is especially suited for space-fed applications.**
- **Attainment of a reliable thermal path to the coolant structure - this is greatly influenced by the method of attaching the coolant structures to the phase shifter.**
- **Operation at high peak powers - sharp edges on the foil wrap are prone to arcing at high peak powers.**

Work is continuing at a reduced level on this design. It is intended under this program to study the feasibility of such a design and assemble and test simple, one bit structures. No attempt will be made on this program to construct a multibit unit.

4. MULTIBIT PHASE SHIFTER DESIGN

4.1 GENERAL

The multibit design C band phase shifter being designed, fabricated, and tested under this program uses techniques similar to those previously developed by Sperry for high power phase shifter operation as described in Sections 2 and 3.

Parallel efforts in development are being carried out to reduce costs of fabrication, increase quality of microwave performance, and reduce the cross section for better fit into phased arrays. The requirements, however, for delivery of usable hardware within the budget specified under this program, dictate the construction of a conventional unit meeting specification as the prime requirement of this program.

Section 4 of this report discusses, in detail, the design parameters governing this "conventional" unit.

4.2 CROSS SECTION

The cross section of this phase shifter is shown in Figure 9. As previously discussed, a waveguide height of .622 inches (conventional, small C band waveguide height) was chosen. This height is greater than that normally employed but has been chosen primarily in an effort to reduce arc-over in the structure normally associated with waveguide discontinuities and increase the peak power associated with the value of h_{crit} for the garnet material, thereby permitting an increase in $4\pi M_g$ for a given value of limiting threshold.

The toroid wall thickness has been reduced over the "optimum" cross section derived from computer studies to the value shown in Figure 3. This reduced loading increases limiting threshold for any value of $4\pi M_g$ chosen from Figure 1. In addition, a reduction in insertion loss/inch and total insertion loss of the device is attained at cost of increased length.

This reduced wall thickness also permits an increase in waveguide height (up to 0.622 inch in this case) without hybrid moding within the structure.

The reduced waveguide width of the loaded structure (used to attain zero phase-frequency slope) permits placement of the cooling structure in the side walls of the waveguide where they are quite efficient, that is, close to the source of heat generation and to the heat transfer structure, while maintaining the cross section desired for phased array use.

4.2.1 Driver Phase Shifter Relationship

Each phase shifter requires its driver to switch the garnet material between two magnetization states. In the case of the multibit unit, each bit is switched between two magnetization states independently of other bits, bit length and drive trim being used to attain the desired phase shift of each bit.

Charging wires are passed through the narrow wall of the waveguide in a manner to minimize charging wire rf coupling. Location of charging wire terminals is shown in Figure 9.

Because of physical dimensions of the driver and phase shifter relative to available array cross section, it is necessary to remote the driver at some distance from the phase shifter.

The design layout chosen under this program was to locate the driver some distance behind the microwave portion of the array. The driver cross section, therefore, should be equal to or less than that of the phase shifter.

Interconnection between driver and phase shifter will be accomplished through flexible cable of a suitable impedance to maintain driver efficiency.

This cable will be permanently attached to the phase shifter and will connect to the driver assembly through a suitable connector located at the driver.

Signal trigger and power leads will enter the driver assembly at the opposite end from the phase shifter connector.

The driver will be similar to that shown in the artist's sketch of Figure 12.

4.2.2 Phase-Temperature Characteristics

The phase shifter is designed to function at all power levels between 0 and 1000 watts average.

Water cooling of the phase shifter is necessary to maintain the toroid temperature constant within the limits of thermal gradients within the RF structure.

This water cooling decouples the phase shifter from its surrounding temperature medium. It is necessary, however, to maintain the proper phase shift of each bit over all water temperatures.

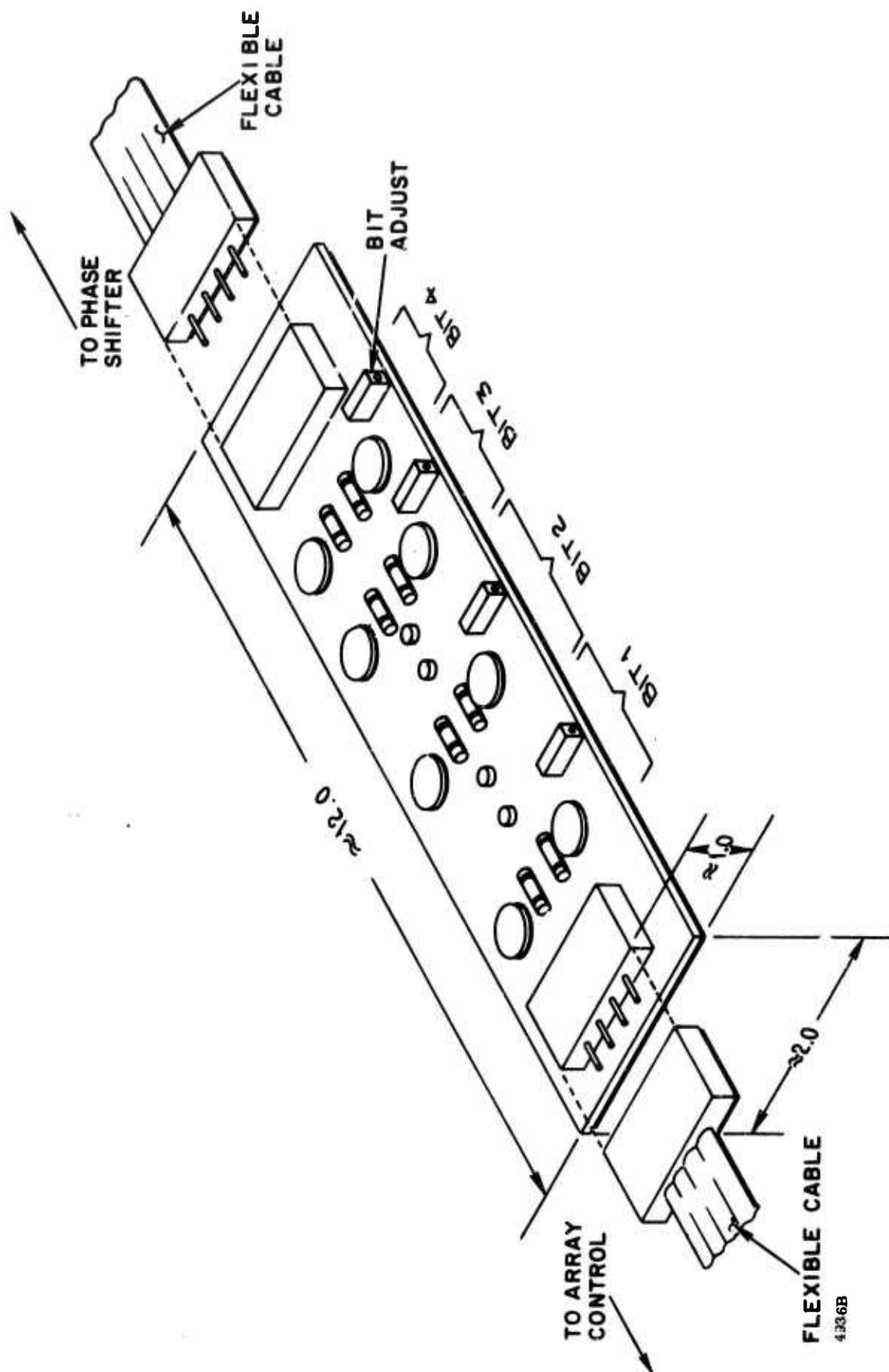


Figure 12. Remote Driver With Cross Section Compatible with Phase Shifter Cross Section

The unit under development will be designed to operate with a nominal water temperature of 25°C.

The water temperature can be allowed to increase, however, if the following conditions are satisfied.

- The unit is designed such that the garnet materials remains out of saturation (at least in one state) for all temperatures.
- The phase shifter is driven "flux drive".

Sufficient length has been incorporated into the phase shifter to permit flux drive to approximately 50°C. The precise upper limit, however, will be determined by driver capability to maintain flux drive.

Within reasonable tolerances, it is anticipated that this unit will function in the desired manner from 20° to 50°C water temperature.

Ambient temperatures surrounding the phase shifter can exceed these limits and are limited only by the capability of the coolant system to maintain the phase shifter temperature within acceptable limits.

4.2.3 Insertion/Differential Phase Stabilization

Although all parameters are not fully understood at this time, experimental data indicates that differential phase shift is not necessarily the same through a non-reciprocal phase shifter if non-symmetrical drive is employed.

This statement, in essence, implies that if one saturates the material in the +M direction for transmit signals (-M not saturated or flux driven), the differential phase shift obtained under the two transmit conditions may be different from that obtained under receive conditions, wherein the -M direction of magnetization is saturated.

This condition, if proved correct, is unfortunate since insertion phase can be best controlled if the material is driven to saturation at one point.

Use of symmetrical drive results in minor loop operation as shown in Figure 13-a, if the two currents (for +M and -M) are equal. However, if either current is allowed to increase slightly, then the loop may change as shown in Figure 13-b. Figure 13-b points up the difficulty that the insertion phase may vary while differential phase is maintained within close tolerances.

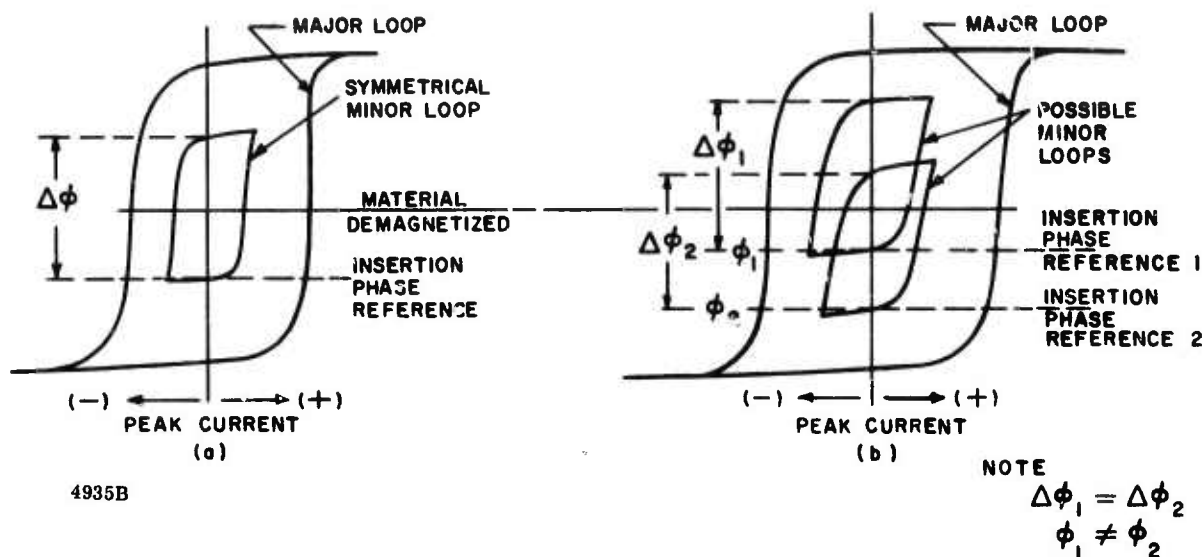


Figure 13. Minor Loop Operation of Phase Shifter

Further analysis, both of the data obtained on phase shifters in general and of the theory, is necessary before it can be determined if it is possible to design this differential phase error out of the phase shifter by proper choice of cross section. Preliminary data indicates a dependence on cross section (i. e. loading) and, also, that the error is dependent upon the degree of non-symmetry in driving.

Further work is also necessary to determine if a practical method of attaining minor loop symmetrical drive coupled with insertion phase stability is feasible.

This work is considered an intrinsic part of this program and will be explored in detail.

Because of this requirement of better understanding of phase shifter needs, development of the driver is progressing slowly and with caution, in close liaison with microwave design.

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5. SINGLE BIT PHASE SHIFTER

5.1 GENERAL

The single bit phase shifter is quite similar to the multibit design except that a single section of garnet material is allowed to operate at several levels of magnetization, the number of levels determined by the number of phase shift positions desired. The reader, therefore, is referred to Section 4 of this report for cross section information.

The microwave performance of this phase shifter is dependent to a more severe degree, on driver design and stability. This section will therefore concentrate on a discussion of expected performance of such a unit.

5.2 MAGNETIZATION ANALYSIS

A suitable set of specifications can be derived for a single bit unit from those normally considered for a multibit unit, but with variations.

Each bit of the multibit unit operates in only two states which can be called for convenience, 0 and 1 states.

The single bit unit will operate in the conventional 0 state but the 1 state is divided into many substates. For equivalency to a four bit phase shifter, it is necessary to establish 15 sublevels of the 1 state. It is therefore necessary to establish not only the end points of the magnetization loop but the shape of the loop at intermediate points (see Figure 14).

Position of intermediate points can best be controlled in a useful manner if one assumes that discrete amounts of flux are used to drive the phase shifter. A plot of differential phase vs flux is given in Figure 15.

To a first approximation, the plot of phase shift vs flux for most garnet materials is a straight line over a large portion of its useful range. If one assumes that material parameters are constant, then it is possible to supply a predetermined amount of flux to the phase shifter and obtain a known amount of phase shift. This is definitely a superior method of drive to programming current, since current is heavily dependent upon material and ambient parameters, and phase shift is not linear with current.

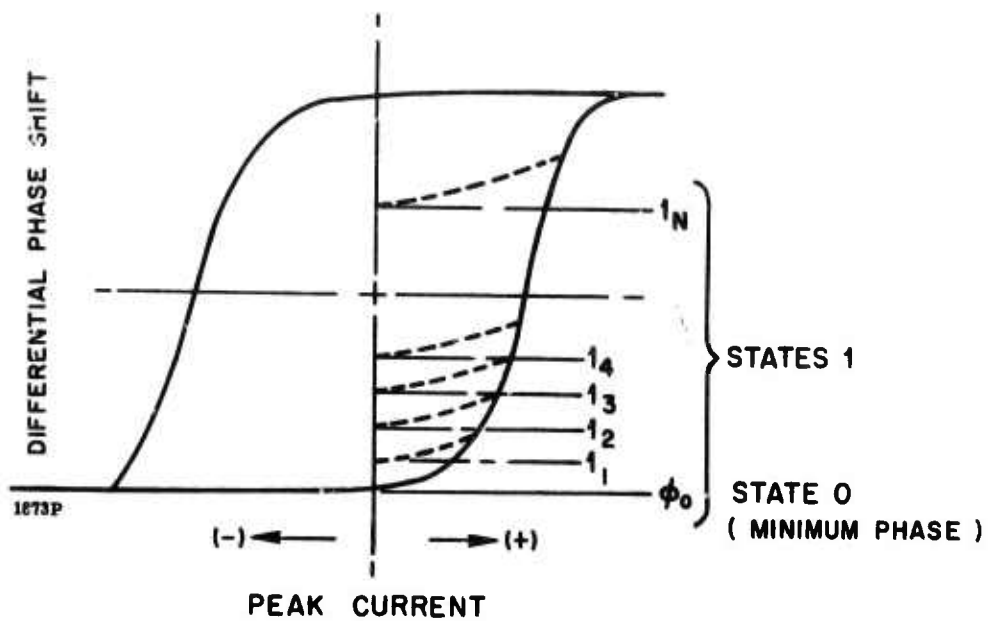


Figure 14. Magnetization Loop With Intermediate Phase Points

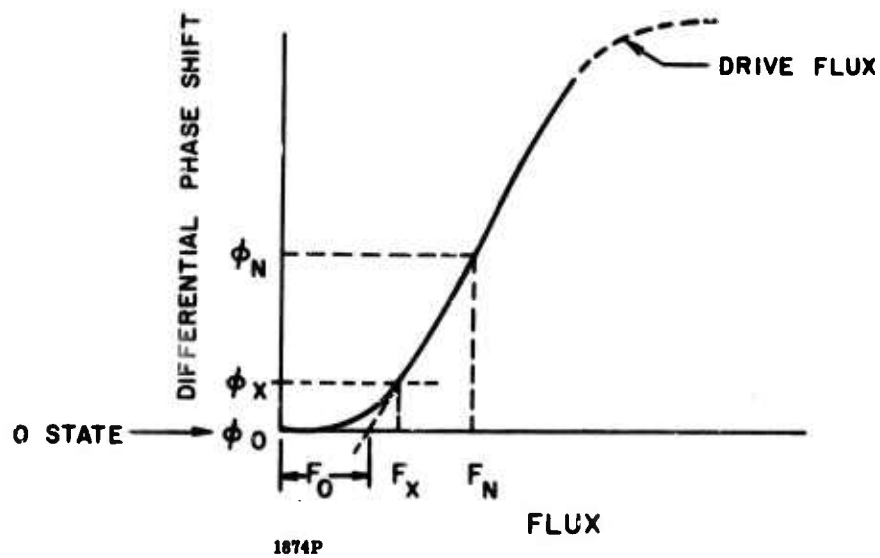


Figure 15. Flux Vs Differential Phase Shift

Over the linear portion of the flux-phase shift curve, one may write some simple approximate expressions:

$$\text{Flux} = \int E(t) dt$$

assuming $E = \text{constant}$

$$\text{then Flux} = E \Delta T$$

If one considers the curve of Figure 15 as composed of two straight lines then

$$\Delta\phi = \phi_n - \phi_o = F_o + E\Delta T = (ET_o + E\Delta T)$$

$$\Delta\phi = E(T_o + \Delta T)$$

This equation states that there is a flux F_o which accounts for the non-linear effects of the material and if the applied charging voltage remains constant with time, then phase shift can be directly related to charging time plus a fixed time T_o . In practice, this curve is essentially true. However, the approximation of the curve to two straight lines is only true if one applies a total flux F_x minimum (see Figure 15). This is a limiting case of the smallest allowable bit for the phase shifter.

One may also allow E to vary with time in the above analysis. It should be noted also that peak current does not enter the above analysis. If the voltage E is maintained, the current I will reach the value required to satisfy the loop parameters in a specified amount of time.

The single bit phase shifter can now be conveniently programmed:

- A reset pulse drives the unit to saturation and return to remanence results in the 0 state phase shift.
- A variable length pulse drives the phase shifter to the desired 1_n state.
- Because of material parameter variations (variations in H_c , coercive field and R_p remanence ratio, and $4\pi M_s$, saturation magnetization) the programming time pulse will be extended by a time T_o internally to the driver, and the voltage E will be adjusted to produce a value of $\Delta\phi_{15}$ equal to the maximum desired value in a time interval specified by the customer.

All phase shifters in an array, therefore, can be programmed in a similar manner.

5.3 SPECIAL COMMAND PROVISIONS

As an extension of the above analysis, the phase shifter/driver being developed under this program, will be designed to incorporate Alpha-Beta set triggers.

Referring to Figure 16, each column and row of an array or sub-array requires an equal value of phase shift. If an array were steered only in the α direction then each α column would have a fixed value of phase shift which can be related to a time interval when using the driving method described in previous sections. Alpha values become timing intervals. Beta steering follows a similar method. If simultaneous alpha-beta steering is desired, then the phase/time of any element is the sum of alpha and beta times.

x	x	x	x	x	β_M	β Commands (Rows)
x	x	x	x	x	β_2	
x	x	x	x	x	β_1	
α_N	α_4	α_3	α_2	α_1		
α Commands (Columns)						

Figure 16. Alpha-Beta Array Steering

In practice, alpha and beta pulses are generated by proper electronics-computer circuitry; one as a start pulse and one as a stop pulse for the set timing of the phase shifter.

A typical timing sequence is shown in Figure 17 where every element in the array receives a reset trigger simultaneously at time t_1 . This pulse t_1 drives all phase shifters into a reset condition which corresponds to a phase shift reference of zero degrees if α and β arrive simultaneously at time t_4 . α_N and β_N pulses arrive at each phase element (on a row-column basis) about the time element t_4 .

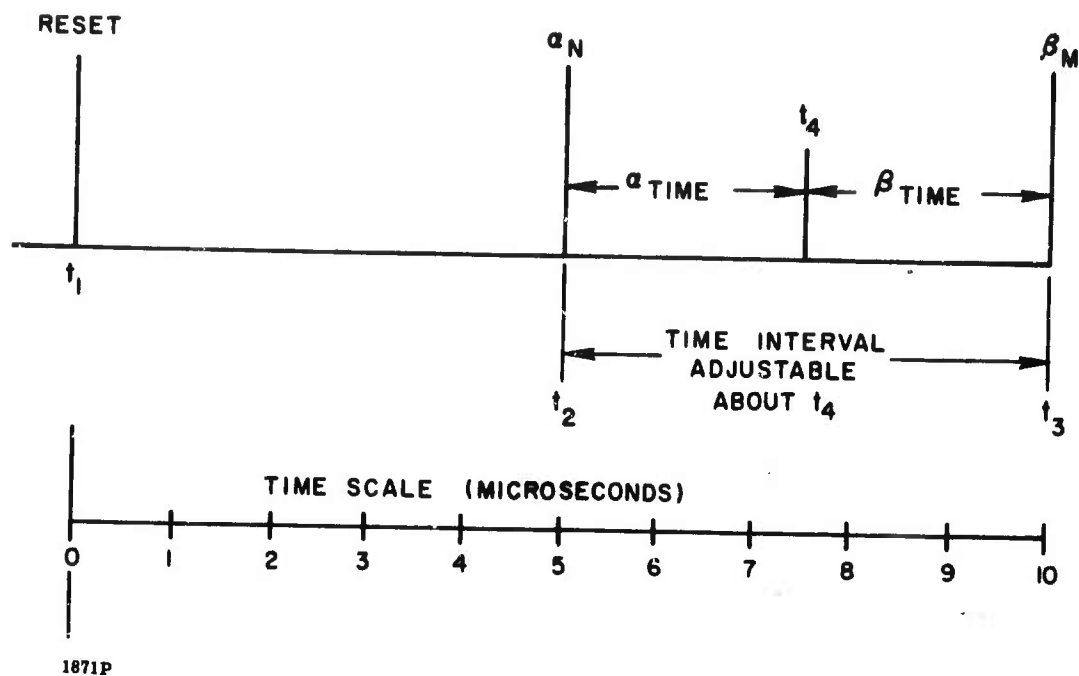


Figure 17. Typical Alpha-Beta Timing Sequence

The total switching sequence was selected at 10 microseconds to assure a minimum of 5 microseconds for $(\alpha + \beta)$ max. thus permitting reasonable resolution of times for the 16 possible values of $(\alpha + \beta)$.

The first 5 microseconds have been allotted to reset, 3 microseconds for the charging current to drive the toroid to saturation, 2 microseconds to permit all currents to return to zero (the microwave element returns to remanent magnetization).

For such a 10 microsecond timing sequence, the maximum switching time of the RF signal will be approximately 11 microseconds, allowing for an increased T_0 (see F_0 of Figure 15) and time for the set current to return to zero.

Such a triggering scheme does require 3 separate inputs to each array element but these can be corrected on a row-column basis, which is much reduced in complexity to the input signal circuitry in multibit element methods.

For equivalent steering on transmit and receive, each element is set to its complementary time. An example would be:

For element MN

$$\text{Transmit Set Time} = \alpha_M + \beta_N$$

$$\text{Receive Set Time} = (\alpha + \beta) \text{ max.} - (\alpha_M + \beta_N)$$

Again as for the multibit phase shifter, accuracy between individual phase elements of an array will be dependent upon original insertion phase of each element and tolerances in setting the desired phase of each element.

5.4 DIFFICULTIES

The single element phase shifter does offer many advantages over its multibit companion such as reduced complexity in phase shifter assembly and smaller (and less costly) driver but does introduce the following difficulties.

- Because of present limitations on maximum current of moderately priced flux drivers, the usable phase shift of such an element is approximately 60% as compared to approximately 90% for multibit units. An increase in phase shifter length results from this reduction in usable phase shift.
- Reproducibility of materials as related to flux - phase shift linearity is unknown. The setability of all phase shift points may not be within present customer requirements.
- Increased loss due to increased length of the phase shifter. An approximate increase in loss is estimated at 25%.
- Longer phase shifters also result in higher machining, grinding and material costs.
- Increased switching time from approximately 3 microseconds to 11 microseconds. Second generation drivers may be capable of switching times of 6 to 7 microseconds but accuracy of timing pulses and phase setability will become acute.

Resolution of the above difficulties must await further testing and a critical comparison of the two units now being fabricated under this program. One of the goals of this program is just such a comparison of properties.

6. DATA

6.1 GENERAL

This section of the report has been reserved for general data obtained on materials in a test structure. Since this structure does not correctly qualify as single or multiple bit, data was not included in Sections 4 and 5.

6.2 DATA

An area of great concern to overall performance was arc-over. Since these tests are primarily "go-no go" tests, the data is given in tabular form with comments.

TEST NUMBER	PEAK POWER	ARC- OVER	PULSE WIDTH (μ sec)	COMMENTS
#1	300 kw	Yes	2.5	Input toroid-transformer interface, insufficient Sylgard
#2	500 kw	Yes	2.5	Section of D16 added on input to relocate toroid relative to start of mode suppression arc-over at D16-toroid interface
#3	650 kw	No	2.5	Toroid-transformer same as #1, generous amounts of Sylgard
#4	309 kw	No	10	Test performed at MIT-Lincoln Labs by D. Temme, Sperry and RADC personnel present, same assembly as #3
#4	1050 kw	Yes	2.5	Arcing at toroid-transformer-charging wire interfaces, same assembly as #3

The final arc-over at 1050 kw peak, 2.5 microseconds pulse width indicated that, with liberal use of Sylgard 184 and care in attaining a good toroid-transformer interface fit, the peak power handling of the unit could be increased to values well in excess of those required on this program, and approaching that of WR 137 waveguide.

Figure 18 is a plot of phase shift as a function of average power for G311 (YIG). This material is to be incorporated into the two phase shifter^s being manufactured under this program.

Available average power was 700 watts maximum at the time of this evaluation. The curve has been extrapolated to 1000 watts. By additional cooling of the

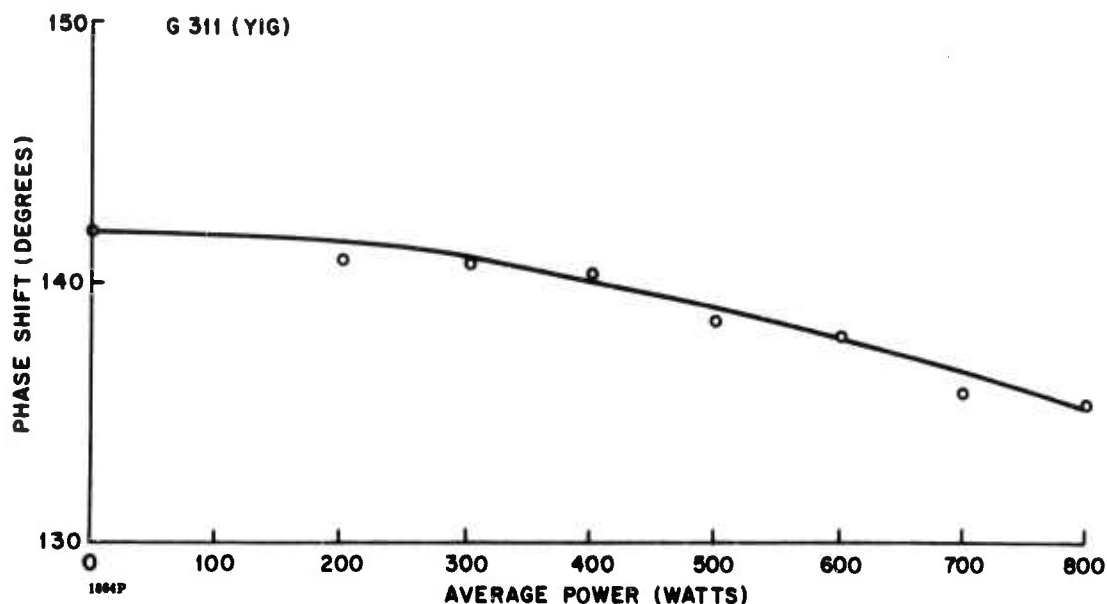


Figure 18. Phase Shift Vs Average Power, G311 (YIG)

microwave power source, it is hoped that extension to 900 watts average can be attained on the final phase shifters. Although a drop in phase shift with average power occurs, it is within normal acceptable limits for phased array applications.

Figure 19 is a plot of phase shift as a function of average power for G444 (CVB). It was found after evaluation that the toroid was placed under compression during test due to improper fit. The increase in phase shift with average power is not expected on future tests with proper toroid fit.

It is interesting to note that within the limits of toroid bending, it is possible to stress the toroid in a manner that will offset normal drop in $4\pi M_s$ with power/temperature.

The probability of attaining the degree of stress necessary to precisely offset the normal changes in $4\pi M_s$ is not high at this time since such compensation would require extreme precision in all toroid dimensions and prestressing of the entire phase shifter. Such compensation would be useless if the unit were in any way subjected to nonuniform stresses or temperatures along its length.

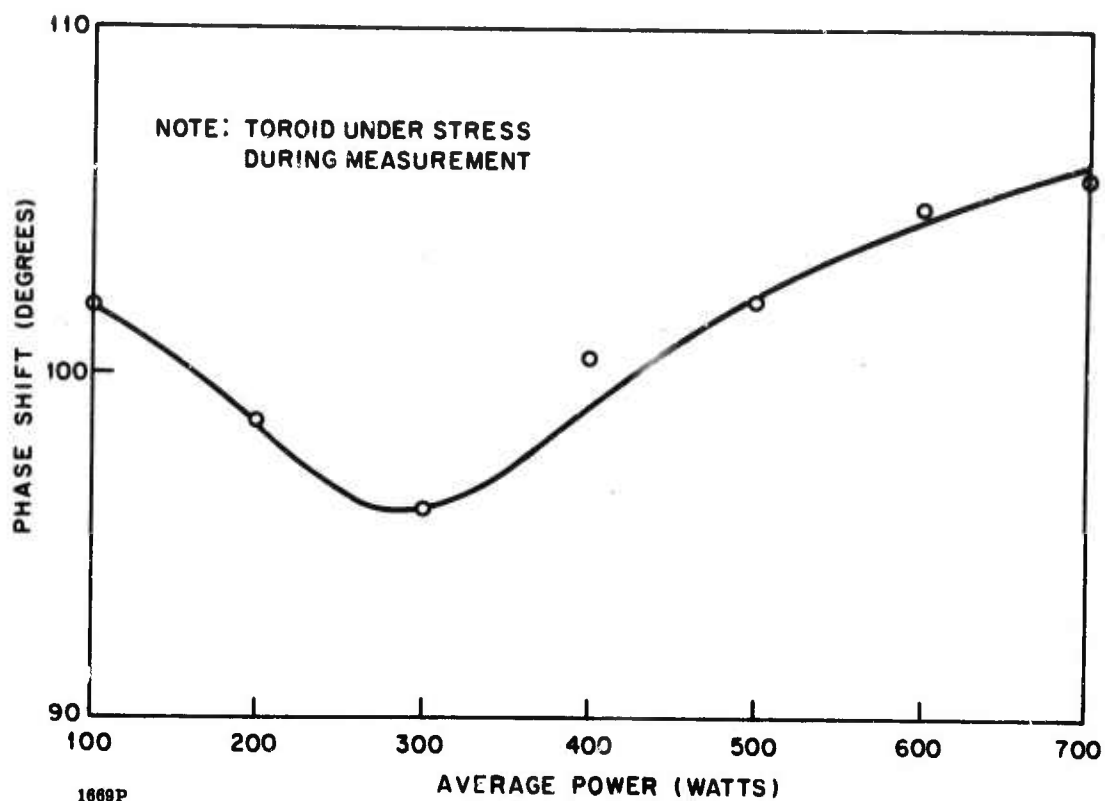


Figure 19. Phase Shift Vs Average Power, G444 (CVB)

Figures 20 and 21 are plots of loss for G311 and G444 as measured in a test structure. In each case the toroid length was 3,280 inches.

From previous sections, the active length of the multibit phase shifter using G311 is approximately 12 inches while the single bit unit is approximately 15 inches (increased length due to flux drive and required phase linearity). Extrapolating the curves of Figure 19 to these lengths, it is anticipated that the loss of the final units will be:

multibit phase shifter - 0.8 db nominal
 single bit phase shifter - 1.1 db nominal

When one considers normal variations in loss encountered on such phase shifters, maximum loss for these units will probably be 0.2 to 0.3 db above nominal.

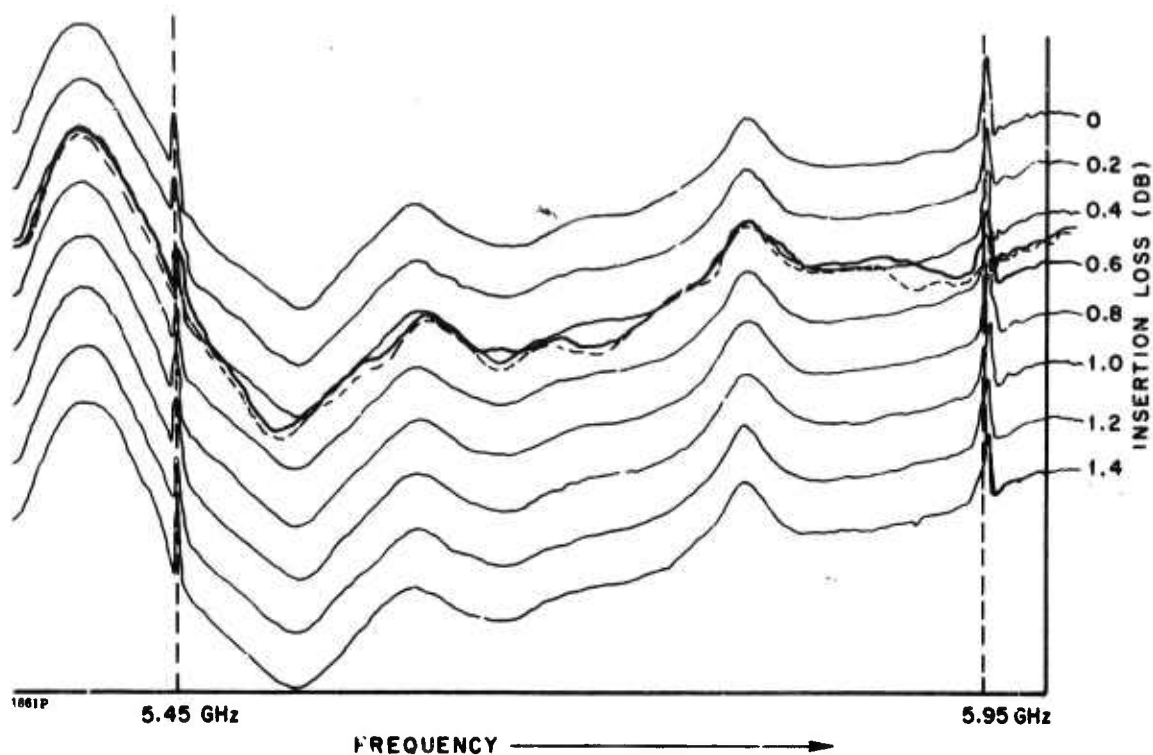


Figure 20. Insertion Loss Vs Frequency G311 (YIG)

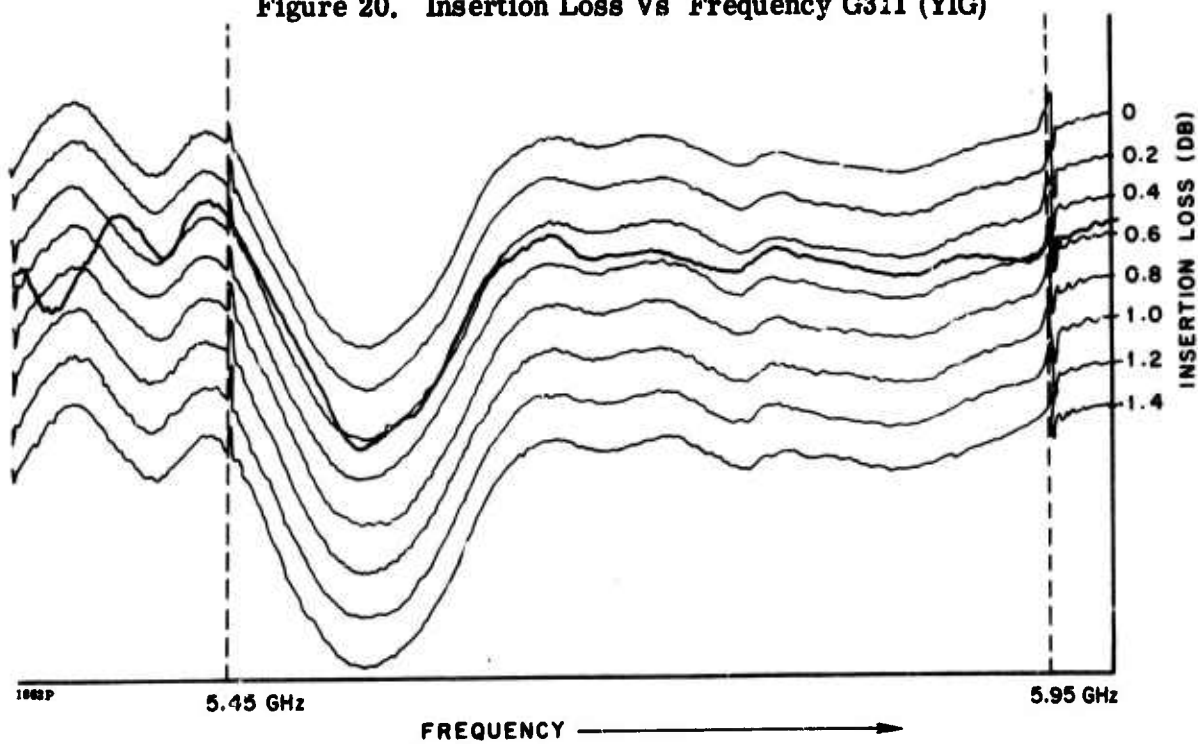


Figure 21. Insertion Loss Vs Frequency G444 (CVB)

Figure 22 is a plot of phase shift as a function of average power for the "foil waveguide" previously discussed in this report. It can be seen that power handling is below that obtained for the same material (G311) in a conventional housing.

This can be attributed to two sources:

- Poor fit between boron nitride, foil, and water cooling structure.
- Changes in magnetostrictive pattern due to use of solid boron nitride cooling sections rather than the conventional "T" structure.

Of the two sources of error, the first is most probable. Further tests will be made using a unit that has been carefully assembled for optimum heat transfer.

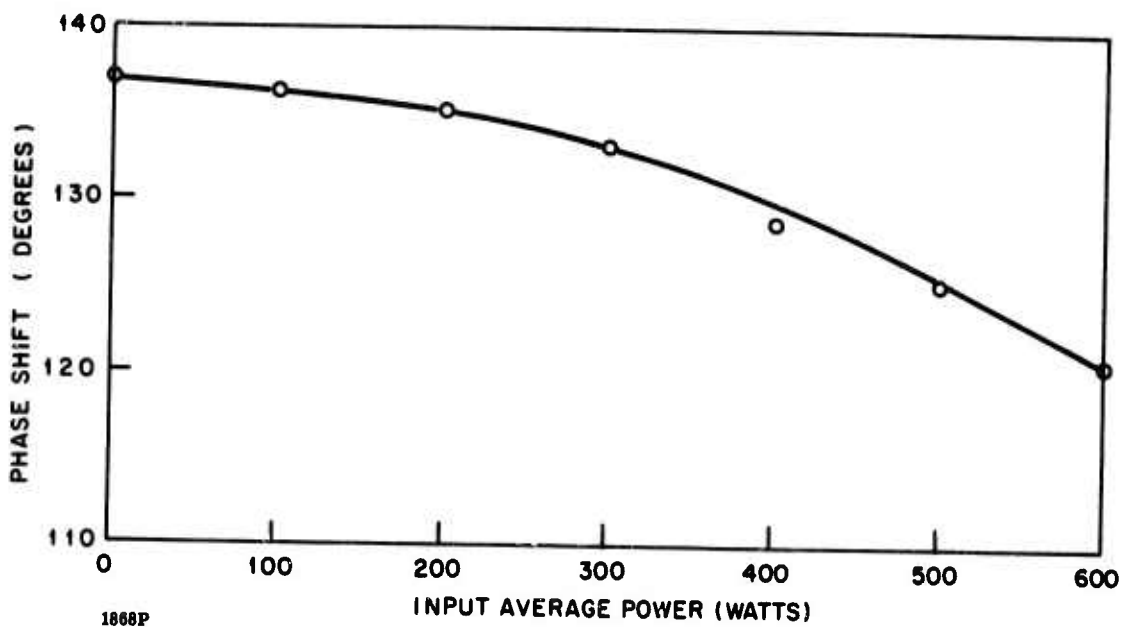


Figure 22. Phase Shift Vs Average Power Foil "Waveguide" Structure With Cooling G311 (YIG)

7. WORK SCOPE FOR REMAINING PROGRAM

The remaining 6 months of this program will concentrate on the following areas:

- Fabrication and assembly of two phase shifters using G311 material, one unit a single bit model, one unit a multibit model.
- Test of the above units with emphasis on comparison of the performance parameters and relative merits of the two units.
- The units will be evaluated to 700 watts average and 500 kw peak (2.5 μ sec pulse width).
- Study of phase shift reciprocity properties of the multibit phase shifter when operated under various conditions of symmetrical or nonsymmetrical drive.
- Further evaluation of CVB materials for phase shifter use, especially G444, the material chosen as a possible substitute for the YIG family of garnets. This evaluation will concentrate on microwave performance and will probably be centered on a test structure evaluation rather than full phase shifter model.
- Evaluation of the "foil waveguide" model under high average power for possible reduction in structure cross section for phased arrays. If successful under average power, tests will be performed to determine feasibility under high peak power conditions.
- Study of the problem of matching a high power phased shifter into ridged waveguide for use in waveguide fed phased arrays.

The above tasks have been stated in order of importance. Since the first tasks mentioned will satisfy the letter of this program although not necessarily its intent, the remaining tasks are placed on an "if time and cost permits" basis.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Although this program is only partially complete, some very important conclusions can be drawn which will influence ferrite high power phase shifter design in the future.

- It is completely feasible to design a practical high power C band phase shifter that meets the requirements of this program.
- It is feasible to construct a C band phase shifter with limiting threshold well in excess of 100 kw.
- Limiting factors will be arc-over of the waveguide structure which is dependent upon pulse length. Operation to 1 megawatt has been attained with 2.5 μ second pulse width, no pressurization.
- Average power operation will be extended at C and S band frequencies by the use of CVB materials.
- A C band phase shifter can be developed for operation to 500 kw peak, 2.5 μ sec pulse width, 1000 watts average with insertion loss of approximately 1 db.
- Operation to average powers in excess of 1000 watts can be attained by the use of CVB materials. However, present state of the art materials have remanence ratio values below those of typical YIG materials and this would introduce additional phaser length and thus higher insertion loss.

8.2 RECOMMENDATIONS

It is recommended that, if feasible, this program be expanded or a new program be initiated to include development of integrated circuit hardware for multibit drivers. Such a program would of necessity, to be most useful, require great emphasis on attaining a driver design that is compatible with a large number of phase shifter designs in different bands.

At present, driver costs are a sizable percentage of the cost of high power phasers and are a prohibitive percentage of the cost of low power units.

Such a program should also include introduction of logic circuitry into the integrated circuit which would simplify and improve interconnection of phase elements in an array. An example of such logic would include the $\alpha - \beta$ programming method as is planned for the single bit phase shifter under this program.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

SPERRY RAND
Sperry Microwave Electronics Division
Clearwater, Florida

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

HIGH POWER C-BAND PHASE SHIFTERS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Semiannual Report - 11 July 1967 to 10 January 1968

5. AUTHOR(S) (First name, middle initial, last name)

L. J. Lavedan, Jr

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J. Brown, Jr

6. REPORT DATE

January 1968

7a. TOTAL NO. OF PAGES

45

7b. NO. OF REFS

None

8a. CONTRACT OR GRANT NO.

F30602-68-C-0006

b. PROJECT NO.

ARPA Order 550

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

(Proj No. 0-0200-2122-D102)
SJ 220-4970-3

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

RADC-TR-68-88

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES

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12. SPONSORING MILITARY ACTIVITY

Advanced Research Projects Agency
Department of Defense
Washington, DC

13. ABSTRACT

This report outlines the present status of the program and includes techniques developed in attaining the high power performance of ferrite digital phase shifters. Test results confirming these techniques are also given.

Structural studies have been carried out to assure compatibility of designs with phased array requirements. Cross-sections have been reduced to a minimum by careful location of cooling passages.

Driving techniques for phased arrays were studied to determine trigger mode, repetition rates, switching rates, switching accuracy and primary power requirements. A scheme for triggering a single-bit phase shifter is outlined in detail.

Magnetostrictive high power effects of YIG and CVB materials are under investigation and the present status of materials investigation as related to this program is given.

A discussion of remaining tasks of this program is made, followed by conclusions and recommendations.

DD FORM 1473

1 NOV 68

UNCLASSIFIED

Security Classification

14.

KEY WORDS

None

LINK A

LINK B

LINK C

ROLE

WT

ROLE

WT

ROLE

WT

UNCLASSIFIED

Security Classification