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THIRD INTERIM DEVELOPMENT REPORT
FOR
FERRITE COMPONENTS PROGRAM

THIS REPORT COVERS THE PERIOD 17 JANUARY 1954 TO 17 APRIL 1954

SPERRY GYROSCOPE COMPANY
DIVISION OF THE SPERRY CORPORATION
GREAT NECK, NEW YORK

NAVY DEPARTMENT, BUREAU OF SHIPS, ELECTRONICS DIVISION
CONTRACT NO. NObsr 66312, INDEX NO. NE-111616
SUBTASK 14

SPERRY REPORT
NO. 5224-1339-3

COPY NO. 11
JUNE 1954

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ABSTRACT

This third interim report summarizes the work accomplished in the research and developmental phases of the ferrite components program during the period of 17 January 1954 to 17 April 1954. In this period data was obtained on the microwave properites of twelve commercially available ferrites, each located in rectangular waveguide, with a d-c magnetic field applied parallel to the E vector of an incident microwave signal. The frequency sensitivity of the microwave properties of four of these ferrite samples was investigated. The temperature sensitivity of two ferrite samples was also investigated, each located in circular waveguide with a magnetic field applied parallel to the direction of propagation. In addition, the various definitions of the Curie temperature, as applied to ferrites, were considered. A broadbanding technique for ferrite components employing tuned cavities was examined. Information was obtained on the properties of a microwave component containing two ferrite slabs located at the planes of circular polarization in rectangular waveguide, with magnetic fields applied parallel to the microwave E vector. Also investigated was a microwave component employing a ferrite cylinder in rectangular waveguide, with the magnetic field applied parallel to the direction of propagation.

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[1]Illustrations are grouped in numerical order at the rear of this report.

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PART I

SECTION A

PURPOSE

1. PURPOSE OF PROGRAM

This program is concerned with the study of the microwave properties of commercially available ferrites, and the development of microwave components using these ferrites as the active element. This work is conducted in the frequency range of 8500 to 9600 mc.

2. BREAKDOWN INTO WORKING PHASES

a. Research Phase

The properties of existing ferrites will be studied and data obtained on the following characteristics:

(1) specific rotation

(2) absorption loss of ferrite

(3) phase-shift properties

(4) axial ratio of emergent radiation

(5) hysteresis effects

(6) any other pertinent properties discovered

(7) reproducibility of characteristics

The shapes of the ferrite samples to be investigated are cylinders and plates. The parameters to be varied are the following:

(1) dimensions of sample

(2) dimensions of waveguide

(3) frequency of microwaves

(4) level of microwave power

(5) strength of magnetic field

(6) orientation of magnetic flux with respect to waveguide axis

(7) temperature of sample

b. Developmental Phase

With the aid of the data supplied in the research phase, the following components are to be developed in 1" x 1/2" waveguide for use in the frequency range of at least 8500 to 9600 mc:

(1) low-power modulator
(power level of 1 watt or less)

(2) high-power modulator
(power level as much above 1 watt as possible)

(3) nonbilateral transmission unit
(power level as high as possible)

(4) phase shifter

(5) variable attenuator having a loss dependent upon the applied magnetic field

(6) microwave switch

SECTION B

GENERAL FACTUAL DATA

3. REFERENCES

First and second Interim Development Report for Ferrite Components Program, furnished by Sperry Gyroscope Company to Bureau of Ships under Contract No. NObsr 63312.

Gelbard, E., "Magnetic Properties of Ferrite Materials," Tele-Tech, Vol. 11, pp. 50-52, May 1952.

Goldsmith, H.A., "Ferromagnetic Ceramics", Product Engineering, Vol. 22, pp.97-102, April 1951.

Hogan, C.L., "The Ferromagnetic Faraday Effect at Microwave Frequencies and Its Applications," Reviews of Modern Physics, Vol. 25, pp. 253-263, January 1953

Rowen, J.H., "Ferrites in Microwave Applications," Bell System Technical Journal, Vol. 32, pp. 1333-1369, November 1953.

Snyder, C.L., E. Albers-Schoenberg, and H.A. Goldsmith, "Magnetic Ferrites," Electrical Manufacturing, Vol. 44, p. 86, December 1949.

SECTION C

DETAIL FACTUAL DATA

4. SUMMARY OF PREVIOUS INTERIMS

Four test systems for studying ferrites have been described. Two systems were used for measuring microwave properties of ferrites symmetrically located in circular waveguide and subjected to an applied longitudinal magnetic field: one of these two was especially suited for precise measurements, and the other for rapid evaluation of a large number of samples. A third system was used for the precise measurement of the microwave properties of ferrites located in rectangular waveguide and subjected to an applied perpendicular magnetic field. The fourth system was used to measure percent harmonic distortion of a ferrite modulator. Theory and data have been presented on the microwave properties of ferrites located in waveguide and subjected to an applied magnetic field. Possible applications of portions of this data to component development were presented. Experimental versions of a modulator, attenuator, and switch were built and some performance data was obtained.

5. THEORETICAL CONSIDERATION OF TEMPERATURE EFFECTS IN FERRITES

In any ferromagnetic material, such as a ferrite, there exists a temperature above which the material loses its ferromagnetic properties. This point is known as the Curie temperature and may range from ambient temperature to several hundred degrees centigrade. The Curie temperature is a function of composition and method of processing of the ferromagnetic material. Its dependence on other factors has not been determined. In practice, it is difficult to determine an exact Curie temperature. Since the change from a ferromagnetic to a nonferromagnetic state is gradual.

Since, at the Curie temperature, a ferrite loses its ferromagnetic properties, those microwave properties of the ferrite which depend on its ferromagnetism, such as rotation of plane of polarization and axial ratio, are expected to undergo extreme changes near this temperature. The rotation of plane of polarization of the guided waves should approach zero at the Curie temperature, and the axial ratio should approach infinity. Changes in the rotation of plane of polarization and axial ratio can be explained in terms of the changes which take place in the effective permeabilities seen by the circularly polarized components of the wave.

The rotation of plane of polarization can be determined by an equation given by Rowen[1]:

$$\theta = \frac{\omega l}{2c} \sqrt{\epsilon} \left\{ \sqrt{\mu_-} - \sqrt{\mu_+} \right\} \qquad (1)$$

where

l = length of ferrite sample

c = velocity of light in free space

ω = angular frequency of incident microwave energy

ϵ = dielectric constant of ferrite

μ_+ = effective permeability seen by positive circularly polarized component of the wave

μ_- = effective permeability seen by negative circularly polarized component of the wave

At the Curie temperature $\mu_+ \simeq \mu_-$, and the rotation of plane of polarization approaches zero.

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[1]J.H. Rowen, "Ferrites in Microwave Applications, "Bell System Technical Journal, Vol. 32, pp. 1333-1369, November 1953.

The change in axial ratio in the region near the Curie temperature can be explained in a similar manner. The axial ratio of a ferrite has been previously defined in terms of power (see first interim report). It also can be defined in terms of voltage, as given by Rowen[1]:

$$M = 20 \log \frac{|E_+| + |E_-|}{|E_+| - |E_-|} \qquad (2)$$

where

E_+ = voltage amplitude of positive circularly polarized component of the wave

E_- = voltage amplitude of negative circularly polarized component of the wave

A finite axial ratio is caused by the differential attenuation of the circularly polarized components of the wave. At the Curie temperature, the circularly polarized components of the wave see the same effective permeability, and the differential attenuation approaches zero. This decrease in differential attenuation results in a decrease in the denominator of equation (2) toward zero, and a corresponding increase in the axial ratio toward infinity. The

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[1] Ibid.

predicted changes in the rotation of plane of polarization and the axial ratio of a ferrite near its Curie temperature have been observed in the laboratory, as well as a large increase in the ferrite absorption loss. Additional studies of this latter effect are in progress; results will be included in a later report.

It has been found by Gelbard, Goldsmith, and others[1], that the initial permeability of some ferrites, measured at one frequency, will increase from its value at ambient temperature (25°C) to a maximum value and then approach unity as the temperature is further increased. (Initial permeability is that permeability which is exhibited by a ferromagnetic material for a negligibly small applied magnetic field.) In other ferrites, as the temperature is raised above 25°C, the initial permeability drops abruptly to unity from some value above that at 25°C. In either case, one

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[1]E. Gelbard, "Magnetic Properties of Ferrite Materials," Tele-Tech, Vol. 11, pp. 50-52, May 1952.

H.A. Goldsmith, "Ferromagnetic Ceramics," Product Engineering, Vol. 22, pp. 97-102, April 1951.

C.L. Snyder, E. Albers-Schoenberg, and H.A. Goldsmith, "Magnetic Ferrites," Electrical Manufacturing, Vol. 44, p. 86, December 1949.

manufacturer (General Ceramic and Steatite Corporation) has defined the Curie temperature as that temperature at which the value of initial permeability (measured at 1 mc) equals that at ambient temperature (25°C)[1]. In this and subsequent reports, a temperature so defined will be referred to as the "manufacturer's Curie temperature".

Since ferrites have a permeability greater than unity at the manufacturer's Curie temperature, this temperature will always be less than the true Curie temperature. The more abruptly the initial permeability drops to unity, the more closely should the manufacturer's Curie temperature approximate the true Curie temperature.

Since the true Curie temperature is higher than the manufacturer's Curie temperature, it is expected that ferrites will exhibit microwave properties which are characteristic of ferromagnetic materials above the latter temperature. These properties will occur to some extent up to the true Curie temperature.

It has become evident from measurements of the temperature sensitivity of the microwave properties of ferrites, that a maximum operating temperature near the Curie

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[1] Private communication with E. Gelbard, General Ceramic and Steatite Corporation, Keasby, New Jersey.

temperature should be defined which will give the microwave operating range of a ferrite component. This definition is under consideration and will be included in a later report.

6. MICROWAVE PROPERTIES OF FERRITES IN CIRCULAR WAVEGUIDE

Data on the microwave properties of ferrites in circular waveguide, with a static magnetic field applied parallel to the direction of propagation and with temperature as a parameter, is presented for two samples of ferrites (figures 1 and 2). This information consists of VSWR, axial ratio, ferrite absorption loss, and rotation of plane of polarization, each taken as a function of the applied magnetic field, with temperature as the parameter. These microwave properties were measured in Ferramics A-106 and D-216 at frequencies of 9600 mc and 9000 mc, respectively, using 0.250" x 3" cylindrical samples.

The Curie temperature of Ferramics A-106 and D-216, as given by the manufacturer, is 300°C and 165°C, respectively. The temperature coefficient of initial permeability, measured at 1 mc and expressed in percent change in initial permeability per °C, is given by the manufacturer as 0.30 for Ferramic D-216 and 0.15 for Ferramic A-106. From figures 1 and 2, it is noted that the properties of Ferramic A-106 are much less sensitive to temperature than are those of Ferramic D-216. Thus, for these two cases, a direct relationship appears to exist between the temperature stability of the microwave properties at X-band frequencies and the behavior of the initial permeability at 1 mc as listed by the manufacturer.

In each of these cases, the rotation of plane of polarization increased with increasing temperature to some maximum value and then decreased to zero at a temperature above the manufacturer's Curie temperature. For Ferramic A-106, this temperature was approximately 475°C; for Ferramic D-216, this temperature was approximately 225°C. Also noted in each case was the fact that as the rotation of plane of polarization increased as a function of temperature, the ferrite absorption loss decreased, with the minimum value of ferrite absorption loss occurring at approximately the same temperature as that at which maximum rotation occurred; for both ferrites, this temperature was approximately midway between room temperature and the manufacturer's Curie temperature.

As the temperature was further increased to that value which gave zero rotation of the plane of polarization, the ferrite absorption loss was found to increase far above the db level recorded at room temperature. For Ferramic A-106, the maximum ferrite absorption loss recorded was 34 db (figure 1). The loss may be still larger for even higher temperatures. From figure 3 measurements (at 498°C) of ferrite absorption loss vs applied magnetic field, using frequency as a parameter, showed that the ferrite absorption loss increases with increasing frequency; this is a reversal of the frequency behavior of this ferrite at 23°C (refer to second interim report). Similar results were obtained for Ferramic D-216.

The VSWR of the ferrites, taken as a function of applied magnetic field, was found to vary irregularly over the range from 1.10 to 1.80 in Ferramic A-106 and from 1.10 to 2.35 in Ferramic D-216, as the temperature was increased from 23°C to the Curie temperature (figures 1 and 2). Above the Curie temperature, the VSWR remained practically constant at 1.50 for Ferramic A-106, but still varied over a large range for Ferramic D-216. This behavior of VSWR in Ferramic A-106 can be explained as being the result of the ferrite exhibiting a VSWR due only to the reflection at its interfaces since only negligibly small multiple reflections can exist in the system due to the large absorption loss of the ferrite. Conversely, the absorption loss is not sufficiently large in D-216 to prevent multiple reflections. In Ferramic A-106, the axial ratio decreased with increasing temperature from a value of 18 db at 498°C (figure 1). In Ferramic D-216, the axial ratio increased from 11 db at 23°C to 19 db at 56°C, decreased to 14 db at 138°C, and then increased to 24 db at 211°C (figure 2). In Ferramic D-216, these values of axial ratio are the values obtained at saturation rotation at fixed temperatures and do not necessarily represent the maximum and minimum values obtainable as a function of temperature. In Ferramic A-106, the data indicates that the axial ratio has one minimum which occurs at approximately 400°C.

7. MICROWAVE PROPERTIES OF FERRITES IN RECTANGULAR WAVEGUIDE

The ferrite absorption loss and the VSWR of ferrite cylinders located at one of the planes of circular polarization in rectangular waveguide, with a static magnetic field applied parallel to the incident microwave E vector, have been investigated for several types of ferrites. These types include Ferramics A-106, B-90, C-159, D-216, I-141, J-472, R-1 (formerly 1331), and Ferroxcubes 102, 103, 104, 105, and 106.

(The latter ferrites are manufactured by the Ferroxcube Corporation of America, Saugerties, New York.) The ferrite absorption loss and the VSWR were measured at a frequency of 9000 mc for each ferrite sample and, in addition, at 8500 and 9600 mc for Ferramics A-106, B-90, C-159, and R-1. The tests were made using 0.125" x 3.00" cylinders of ferrite, and the results are shown in figures 4 through 9.

In all of the Ferroxcube samples the differential attenuation for the two directions of propagation was found to be 39 db or greater, with a minimum attenuation of 5 db or less (figure 4). In the case of Ferroxcube 105, the maximum attenuation was greater than 50 db, with a minimum attenuation of less than 4 db (figure 4). The maximum attenuation at resonance in Ferramic J-472 was greater than 50 db and the minimum attenuation was less than 2 db (figure 5). In Ferramics B-90, C-159, H-419, and I-141, the differential attenuation was much less than in the other ferrites tested (figures 5, 6, and 8).

The differential attenuation at resonance is 20 db for Ferramic C-159, 16 db for Ferramic H-419, and 12 db for Ferramics B-90 and I-141. In all cases, the minimum attenuation is greater than 10 db. However, in these Ferramics, a differential attenuation of 10 to 15 db with a minimum attenuation of 3 db or less is obtained for the relatively small applied magnetic field of 1400 to 2000 gauss, as compared with 4000 to 5000 gauss at resonance. If the ferrite is moved 0.010" to 0.020" out of the plane of circular polarization of the H vector, the minimum attenuation is decreased. For Ferramic H-419, the decrease is 1.6 db, with a resulting minimum attenuation of 0.2 db and a differential attenuation of 11.6 db (figure 8).

In figures 6 and 7 are shown the effect of frequency on transmission loss of Ferramics B-90, C-159, A-106, and R-1. Each sample was located in rectangular waveguide in one of the planes of circular polarization of the H vector. With Ferramics A-106 and R-1, maximum differential attenuations of 24 and 30 db, respectively, have been obtained for the frequency range of 8500 to 9600 mc. For Ferramics B-90 and C-159, the differential attenuation is much less.

The effect of a change in the diameter of a cylindrical sample of Ferramic A-106, located in one of the planes of circular polarization in rectangular waveguide, is shown in figure 9. With increasing sample diameter, the maximum differential attenuation properties of the ferrite increase to a maximum and then begin decreasing. The optimum diameter was found to be approximately 0.125".

In addition to the change in differential attenuation with a change in sample diameter, the VSWR increases from 1.05 to 1.60 for a change in the diameter of the ferrite from 0.076" to 0.188".

For some of the 0.125"-diameter samples tested, as the applied magnetic field is increased from zero to above the value required to bring the ferrite into gyromagnetic resonance, the VSWR ranges from 1.05 to 1.30. However, for most ferrites, this range is from 1.05 to 1.20.

8. COMPONENT DEVELOPMENT

a. Rotation of Plane of Polarization in Rectangular Waveguide

Figure 10 shows a cross section of waveguide with a ferrite sample placed in the center, along the axis of the waveguide. When a d-c magnetic field is applied parallel to the direction of propagation, rotation of the plane of polarization will occur. Thus, the electric-field vector rotates to E'. This vector may be resolved into two perpendicular waves: E_1 corresponding to the TE_{01} mode, and E_2 corresponding to the TE_{10} mode. Wave E_1 exists in a waveguide beyond cutoff frequency, hence this configuration should result in increased losses as a result of multiple reflections.

Such a device can be useful in many applications. Results of tests on the unit shown in figure 10 are given in figure 11, using Ferramic R-1 (formerly 1331). The high total transmission loss of the unit is accompanied by a VSWR of approximately 19. Thus, this unit may be successfully used as a reflected-power switch. This type of switch was described in the second interim report.

Since the reflection and total transmission losses of this structure are known, the total absorption loss can be calculated from the following formula:

$$\alpha_a = \alpha_t - \alpha_r \quad (3)$$

where

α_t = total transmission loss

α_r = reflection loss

In the case just described, $\alpha_t = 26.4$ db and $\alpha_r = 7$ db; therefore $\alpha_a = 19.4$ db. This would indicate that a large amount of the power is being lost in the ferrite.

This unit has proven to be very sensitive to frequency changes, since its properties depend upon the electrical length of the ferrite sample as well as the frequency sensitivity of ferrite with respect to the rotation of plane of polarization.

b. Ferrites in Rectangular Waveguide with Applied Transverse Magnetic Field

The arrangement shown in figure 12 has been described in the second interim report: it requires large applied magnetic fields to make it useful for the design of components. Applied magnetic fields of 3000 gauss are usually needed to cause gyromagnetic resonance. An electromagnet which was used to obtain these fields had a 0.5" air gap and external dimensions of 7" x 7" x 9". As has been pointed out, such a magnet is too large to be a practical part of a microwave component. However, figure 15 of the second interim report shows that the axial ratio of Ferramic H-419 is very low at small values of applied magnetic field. This indicates that Ferramic H-419 can be exhibiting gyromagnetic resonance at low field strengths, since in general, low axial ratio can be identified with the presence of resonance. Low-field resonances would mean that magnets of practical size could be designed for components operating at this level.

To test the unidirectional properties of such an arrangement, a low-field magnet was built around a section of rectangular waveguide, as shown in figure 12. The magnetic circuit contains no air gaps; hence, higher fields are possible with smaller magnet mass. The ferrite sample used was in the form of a rectangular slab with the same cross section as the pole pieces.

Figure 13 shows the results of tests made on the unit shown in figure 12. Evidently, no significant unidirectional properties appear at low fields. According to the data previously taken on Ferramic H-419, unidirectional properties should have been observed beginning at 20 gauss. An isolation of 13 db is obtained at approximately 3 amperes coil current which is about 700 gauss. This is considerably smaller than the 3000 gauss necessary for gyromagnetic resonance in other ferrites. It should be noted that unlike most other Ferramics, H-419 exhibits a high attenuation in the absence of an applied magnetic field, with the attenuation dropping approximately 14 db with 2 amperes coil current (approximately 500 gauss). As yet, no explanation has been found for this behavior.

c. Broadbanding Techniques

Work has begun on developing techniques for broadbanding the microwave characteristics of ferrites with respect to their rotation of plane of polarization. Several techniques exist at the present time.

A method described by Rowen[1] relies on the change in rotation caused by multiple reflections in the ferrite chamber. Since, in general, the rotation of the plane of polarization increases with frequency, the length of the ferrite sample is made an integral number of half wavelengths at the low end of the band; since the additional rotation provided by multiple reflections is a maximum at an integral number of half wavelengths, compensation is effected. Rowen reports that a 10-degree rotation with a change in rotation of 9 degrees over the band was broadbanded to a 10-degree rotation with a 2-degree change over the same band (8000 to 9500 mc). This data was taken on a 1/8"-diameter sample 2" in length.

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[1] Rowen, "Microwave Techniques."

There are several other factors, which must be considered in evaluating the applicability of this method. Measurements made in our laboratory on cylindrical samples of Ferramic R-1 (1331), 3.00" in length and 0.250" in diameter, show that this ferrite produces large rotations for very small applied magnetic fields, but exhibits 60-degree changes in rotation over the frequency band of 8500 to 9600 mc. Application of Rowen's method would probably not meet with much success in this case. Thus, in selecting ferrite dimensions, frequency sensitivity must be considered as well as the magnitude of the magnetic field used. Another factor is the over-all length needed to give 90 degrees of rotation at a given applied magnetic field. Specifically, the aforementioned sample of Ferramic R-1 gives 90 degrees of rotation at an applied magnetic field of only 40 gauss. In contrast, Hogan[1] reports a sample giving 90 degrees of rotation at approximately 1000 gauss, but which exhibits only 10 degrees of change in rotation over a frequency band of 8500 to 9600 mc. It is believed that this sample was also 1/8" in diameter. Thus, it appears that less frequency sensitivity can be obtained with higher applied magnetic fields on smaller samples of the proper ferrites.

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[1]C.L. Hogan, "Ferromagnetic Faraday Effect at Microwave Frequencies and Its Applications," Reviews of Modern Physics, Vol. 25, pp. 253-263, January 1953.

A second method, based on the use of resonant cavities containing ferrites, has been devised which may be capable of broadbanding those cases having greater frequency sensitivities. This technique was developed to broadband the characteristics of a typical curve of rotation vs frequency (figure 14a) for 1/4"-diameter ferrites. The configuration used is shown in figure 14b. The broadband rotation value to be obtained is θ_o (figure 14a). The following description of operation is made with reference to figure 14. If cavities C_1 and C_2 are tuned to frequencies f_1 and f_2, respectively, energy from the main line can be made to couple into these cavities selectively. The ferrite in the cavity will then introduce rotation into the coupled wave which recombines with the uncoupled wave. Thus, any rotation in the uncoupled energy will be modified by the addition of the coupled component, giving the output rotation (θ') the following values:

$$
\begin{aligned}
\theta' &= \theta_1 + R_1 && \text{at } f_1 \\
\theta' &= \theta_o && \text{at } f_o \qquad (4) \\
\theta' &= \theta_2 - R_2 && \text{at } f_2
\end{aligned}
$$

where

R_1 = rotation caused by cavity C_1

R_2 = rotation caused by cavity C_2

θ_1 = uncorrected rotation of main-line wave at frequency f_1

θ_2 = uncorrected rotation of main-line wave at frequency f_2

The sense of the current in the coil wrapped around each cavity determines whether θ and R will add or subtract. As shown, the addition is vectorial and depends on the phasing of the coupled and uncoupled waves. Note also that R is a function of such factors as the cavity coupling, length of ferrite, and applied magnetic field. These values of R must be picked from a curve like that shown in figure 14a. Under these conditions, a broadband output-rotation characteristic similar to the dashed-line curve might be expected. The operation of such a device is beset with difficulties, such as phase shift in the resonant cavity and perturbations due to the presence of the ferrite. However, a preliminary test was made to see if the rotation could be changed selectively at certain frequencies.

The results of tests on a component with a single cavity are shown in figure 15. The VSWR was large, since no attempt was made to reduce it. The total transmission loss was approximately 10 db. This high value was anticipated because of the power stored in the cavity.

The idea of selectively tuned ferrite cavities can be extended to a component consisting entirely of tuned cavities. Such a component could have a new broadband rotation characteristic as shown in figure 14c.

Another possible broadbanding technique may be effected by applying a tapered magnetic field to a ferrite in the region of its gyromagnetic resonance. Since the applied magnetic field and the resonant frequency are linearly related, a tapered magnetic field will produce a broadbanding effect on the absorption-loss characteristics of the ferrite. Thus, for every frequency of the r-f field near resonance, there will exist a corresponding value of applied magnetic field for which resonance will occur at some point along the ferrite.

9. PROJECT PERFORMANCE AND SCHEDULE

See figure 16 for a chart showing the project performance and schedule.

SECTION D

CONCLUSIONS

10. CONCLUSIONS

The information obtained on Ferramics A-106 and D-216 indicates that the manufacturer's Curie temperatures (300°C and 165°C, respectively) are below the true Curie temperatures (approximately 475°C and 225°C, respectively). In addition, this data shows that, at some temperature between 20°C and the manufacturer's Curie temperatur , the rotation of plane of polarization reaches a maximum and, at approximately this same temperature, the ferrite absorption loss reaches a minimum. Also, with respect to the microwave properties of the two Ferramics tested in the temperature range of 25 to 225°C, Ferramic A-106 is less sensitive to temperature changes than Ferramic D-216.

A study of the nonreciprocal properties of ferrites located in rectangular waveguide, with the magnetic field applied parallel to the microwave E vector, indicates that several types of ferrites exhibit good nonreciprocal-attenuation properties.

The initial results of the study of rotation of plane of polarization in rectangular waveguide show characteristics applicable to switch design of the "power-passed-power-reflected" type. The operation of this component is extremely narrowband. If the high VSWR's can be matched, this configuration will be useful in many other components, such as attenuators and modulators.

The study of Ferramic H-419 located in rectangular waveguide showed very small unidirectional properties at low levels of applied magnetic field, with a maximum isolation of 19 db occurring at a field of approximately 700 gauss.

The techniques under development for broadbanding the rotation characteristics look promising. The broadband resonant-circuit configuration tested proved capable of influencing the rotation of the plane of polarization of a given ferrite at a selected frequency, but the successful operation of this technique requires control of many more factors and thus a great deal of additional development.

PART II

PROGRAM FOR THE NEXT INTERVAL

11. PROGRAM FOR THE FOURTH INTERIM

a. Research Phase

A system for measuring transmission phase shift will be assembled, and phase-shift measurements will be made. This system will permit more accurate measurements to be made than the system described in the first interim report. Also, additional data will be obtained on the microwave properties of ferrites in circular and rectangular waveguide as a function of temperature.

b. Developmental Phase

Work will continue on developing simpler broadband configurations. If time permits, the tapered magnetic field and series-cavity rotator will be studied. Rowen's[1] technique will be tried for larger changes in rotation.

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[1] Rowen, "Microwave Techniques."

Work will be continued with the ferrites having low axial ratios. The position and size of the ferrite in the waveguide will be varied in an attempt to obtain unidirectional properties at low levels of applied magnetic field.

Attempts will be made to find a method of attenuating the high VSWR's produced by the cutoff wave. The change in characteristics as a function of length of ferrite will also be investigated.

Preliminary considerations will be given to the design of a phase shifter.

Several tests on Ferramic I-141 indicate a large change in total transmission loss with a small change in applied magnetic field. Application to modulators and attenuators will be attempted.

Final design and construction of a low-power modulator and nonbilateral transmission unit will be started.

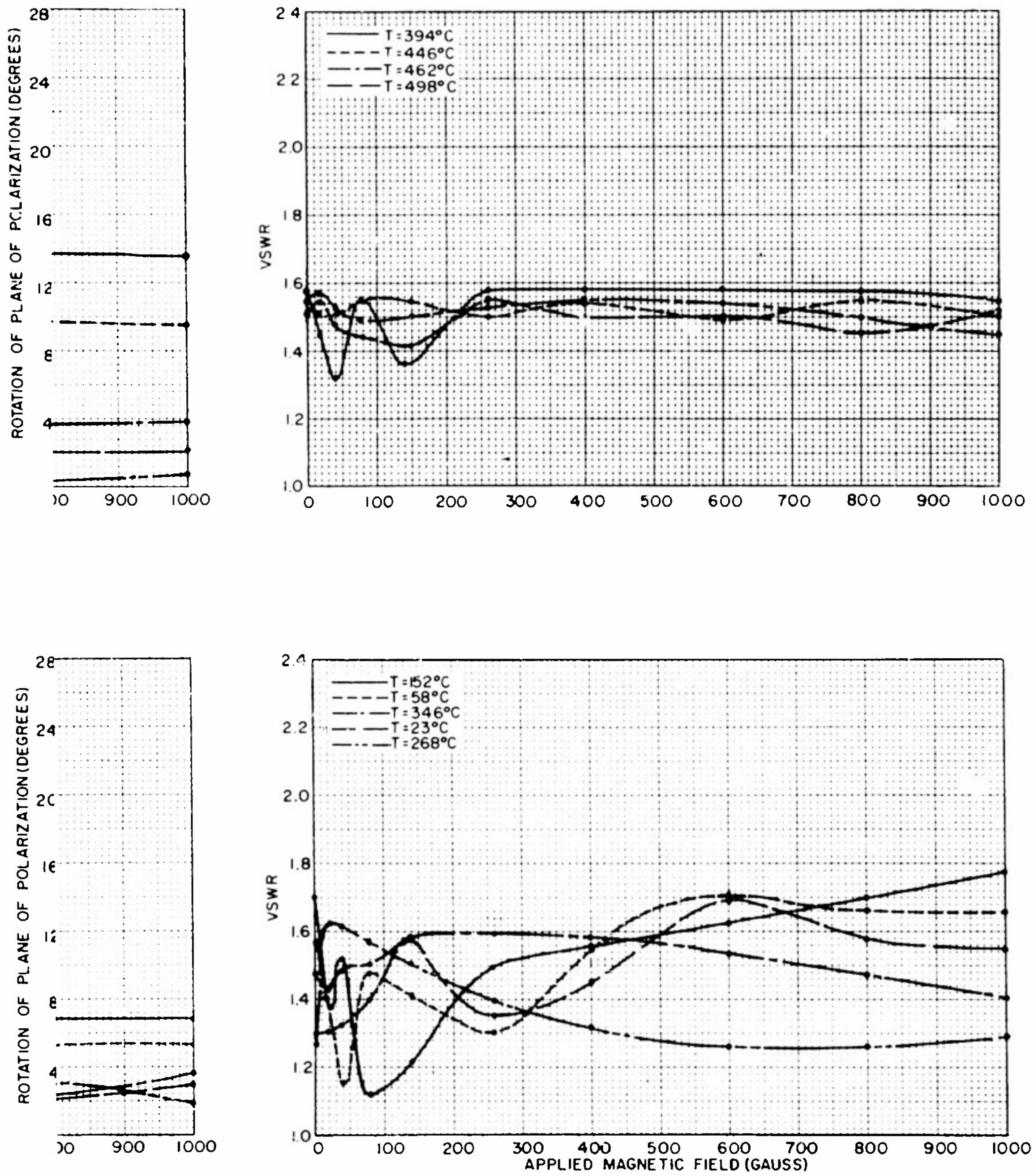

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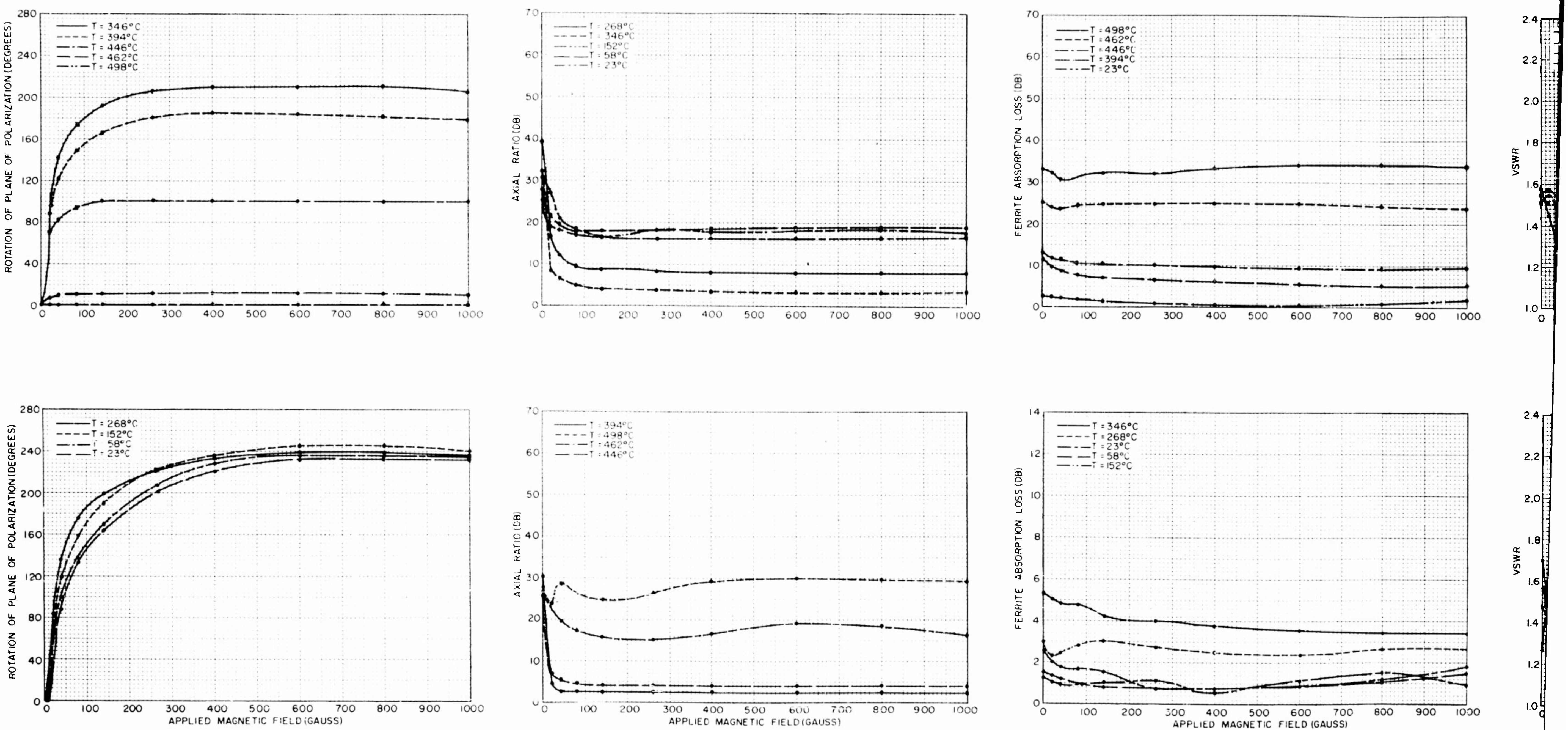
FIGURE 1

MICROWAVE PROPERTIES OF FER :AMIC A-106
IN CIRCULAR WAVEGUIDE
WITH TEMPERATURE AS PARAMETER



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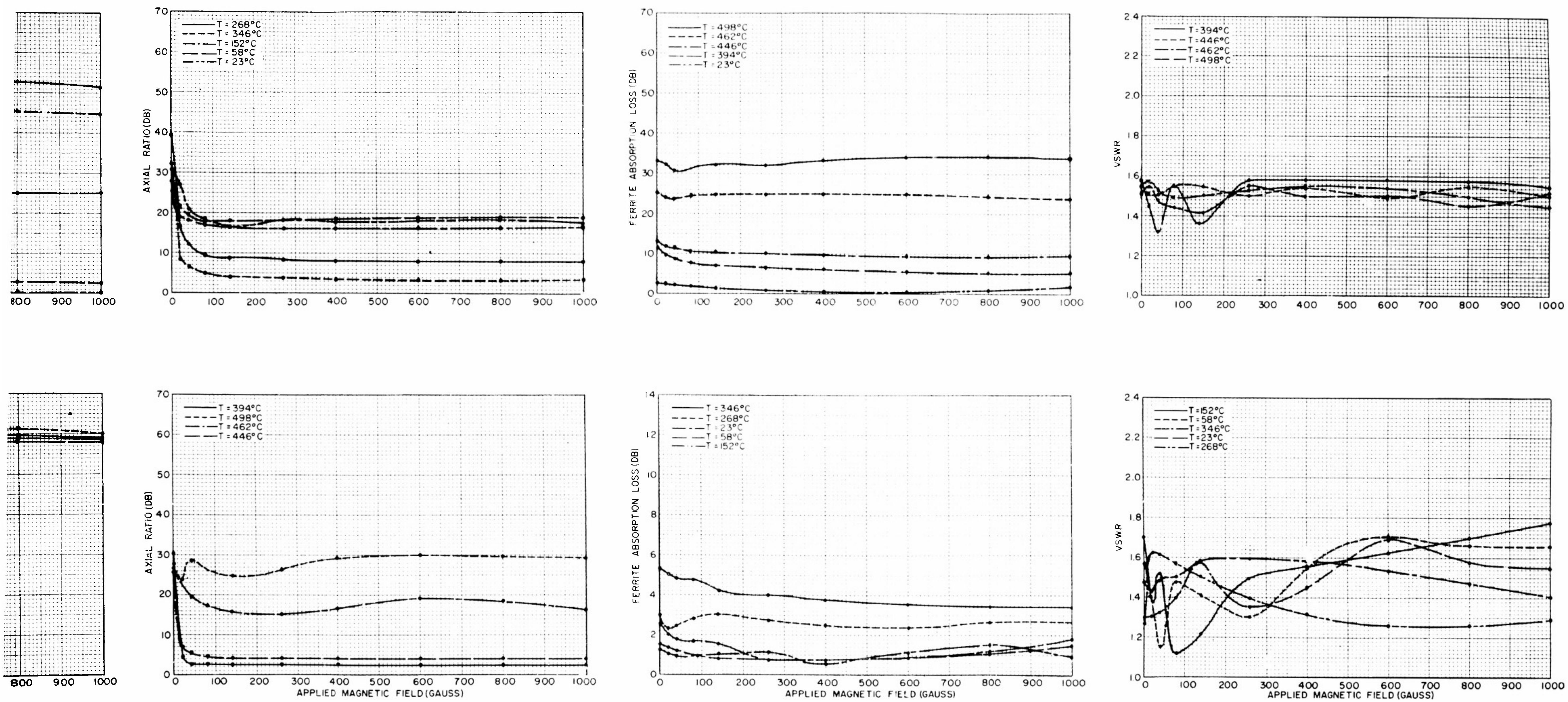

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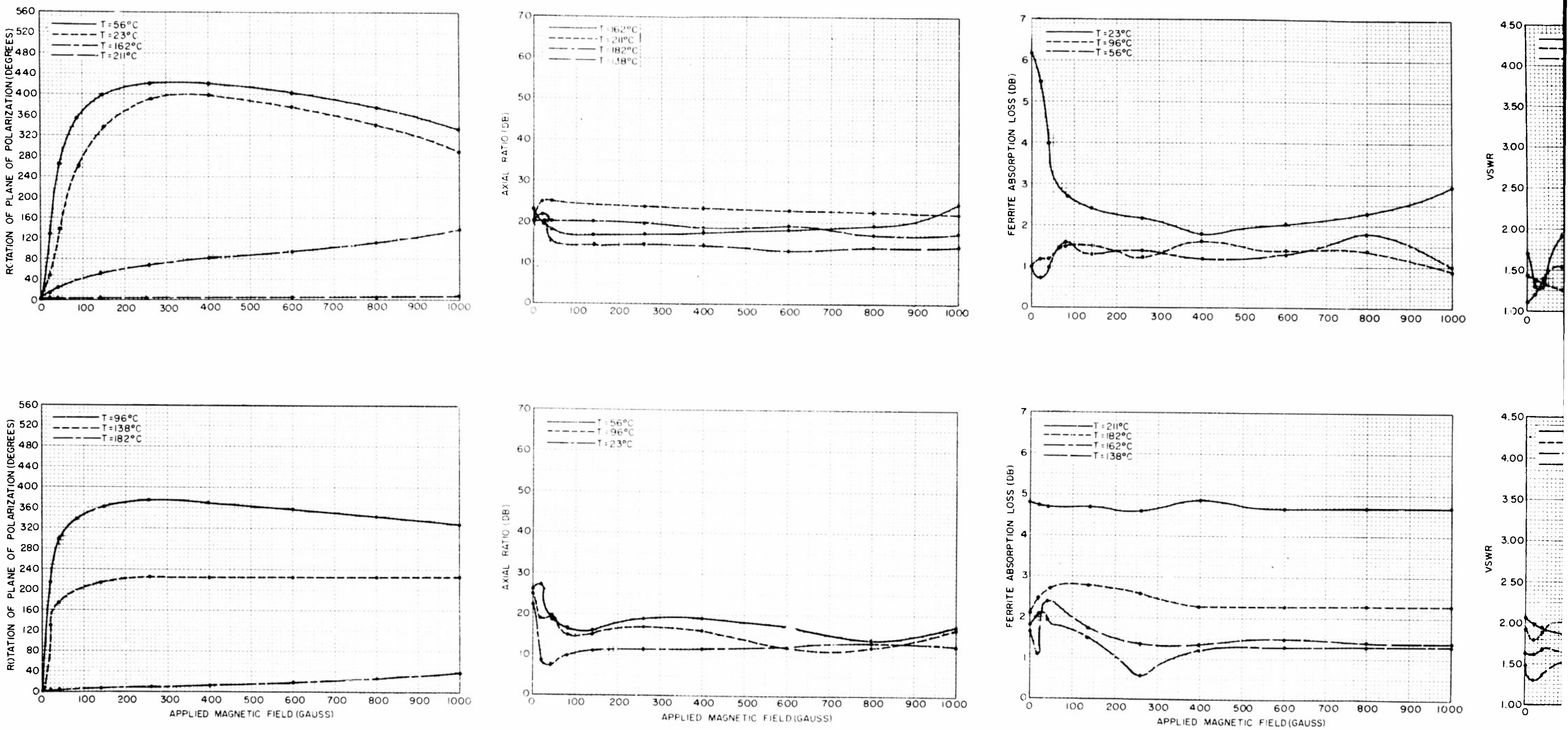
FIGURE I

MICROWAVE PROPERTIES OF FERRAMIC A-106
IN CIRCULAR WAVEGUIDE
WITH TEMPERATURE AS PARAMETER



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LENGTH = 3.00"
DIAMETER = 0.242"

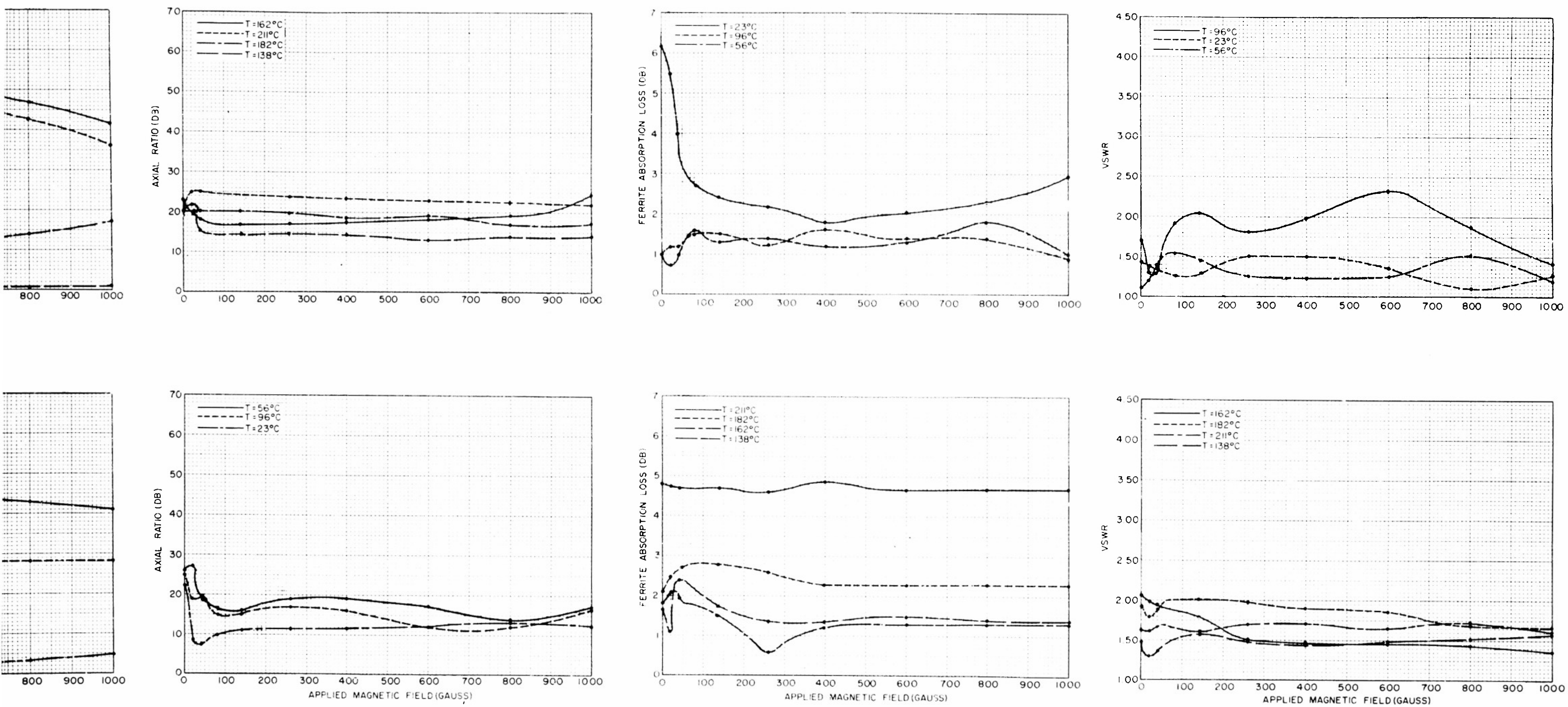
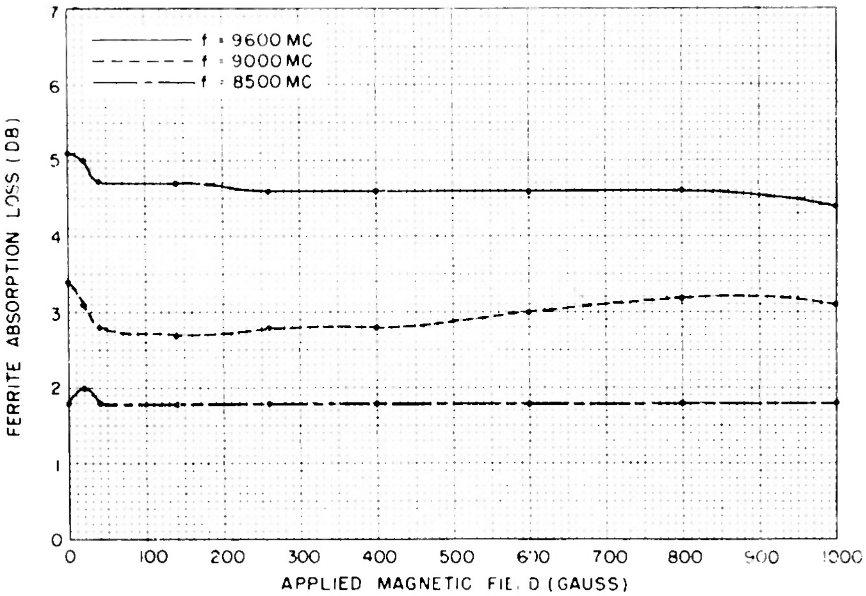
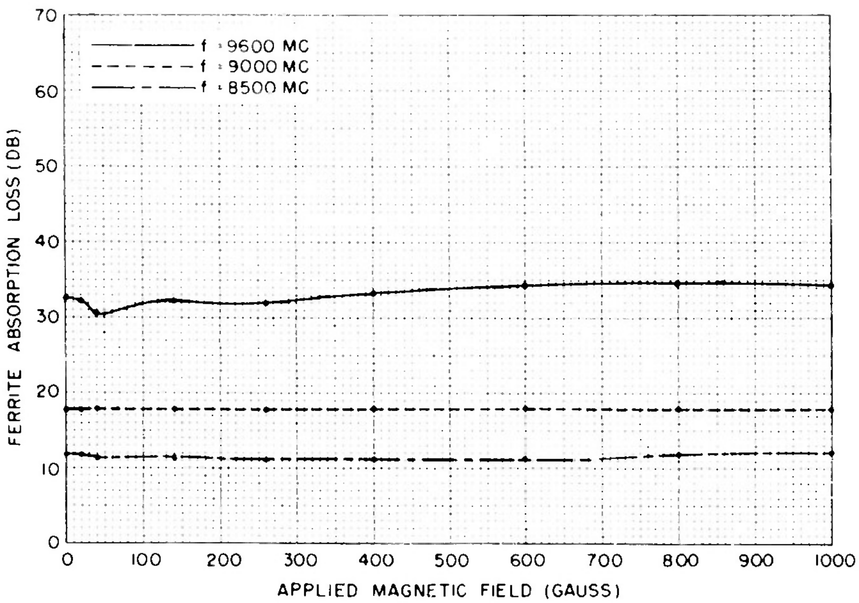


FIGURE 2

MICROWAVE PROPERTIES OF FERRAMIC D-216 IN CIRCULAR WAVEGUIDE WITH TEMPERATURE AS PARAMETER



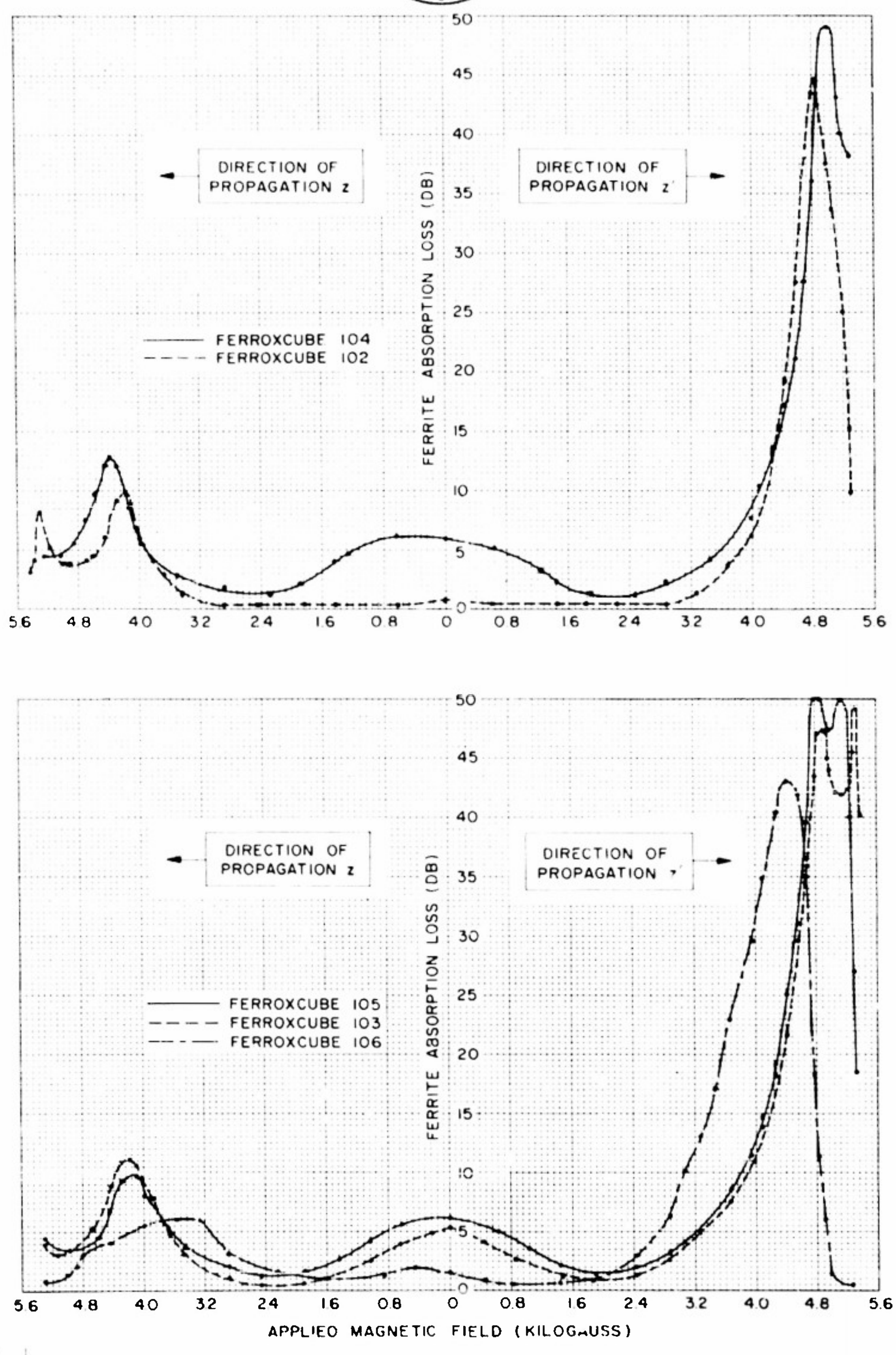
FERRAMIC D-216
TEMPERATURE = 180°C
LENGTH = 3.00"
DIAMETER = 0.242"

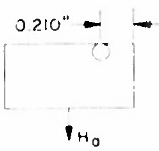


FERRAMIC A-106
TEMPERATURE = 498°C
LENGTH = 3.00"
DIAMETER = 0.262"

FIGURE 3

MICROWAVE PROPERTY OF FERRAMICS A-106 AND D-216 IN CIRCULAR WAVEGUIDE WITH FREQUENCY AS PARAMETER AND TEMPERATURE NEAR CURIE POINT

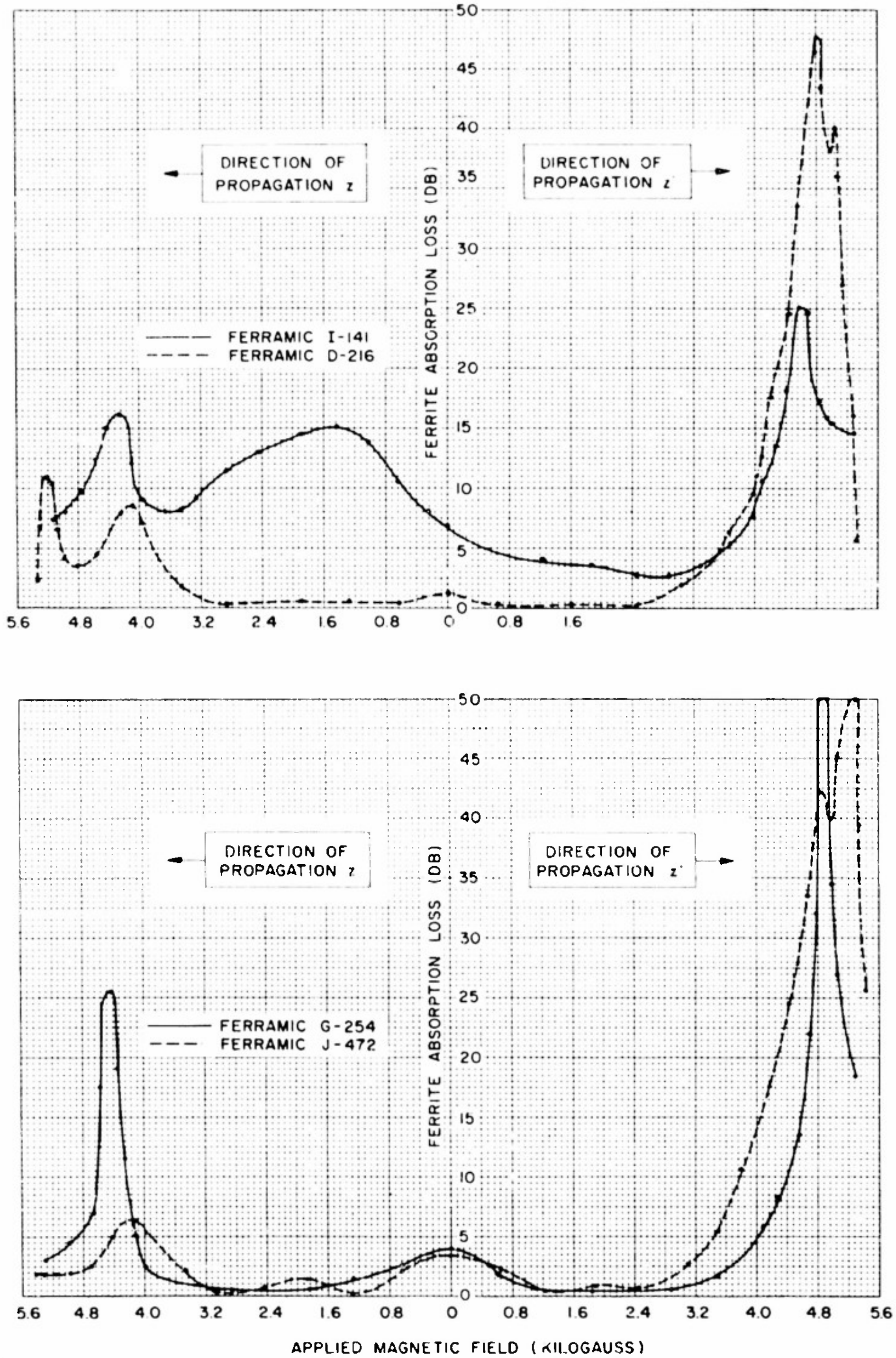


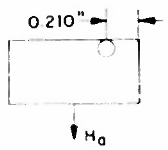


FREQUENCY = 9000 MC
LENGTH = 3.00"
DIAMETER = 0.125"
TEMPERATURE = 23° C

FIGURE 4

MICROWAVE PROPERTY OF FERROXCUBES 102, 103, 104, 105, AND 106 IN RECTANGULAR WAVEGUIDE

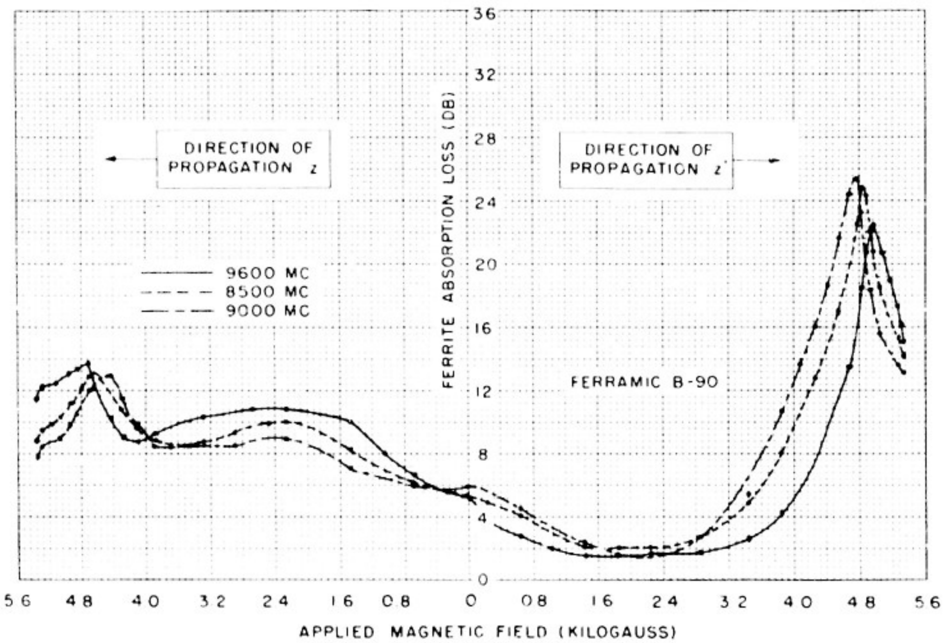


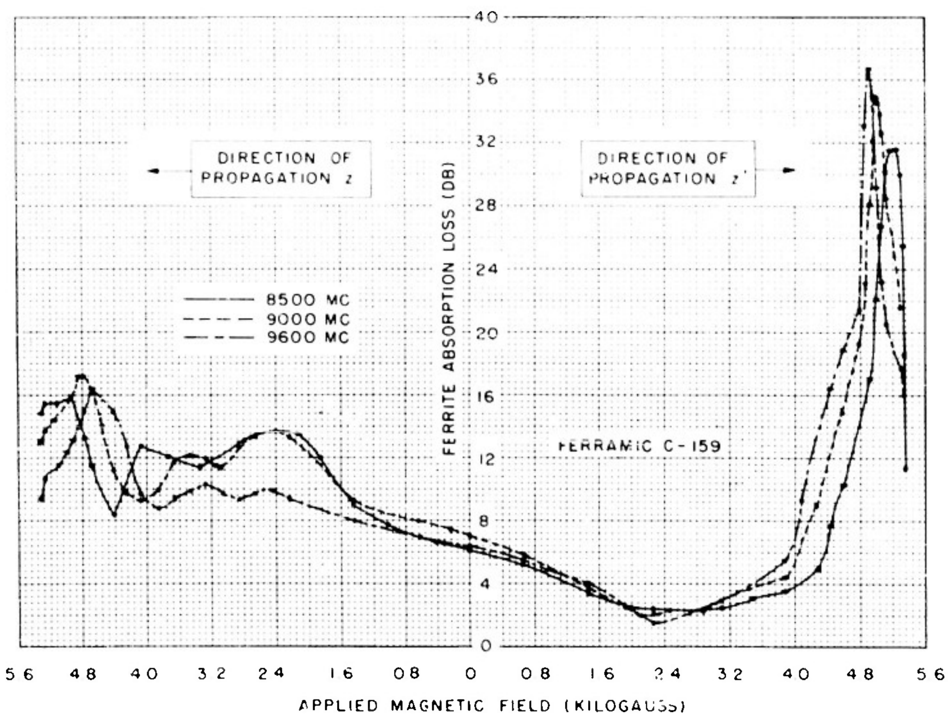


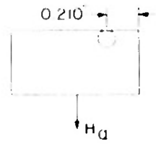
FREQUENCY	=	9000 MC
LENGTH	=	3.00"
DIAMETER	=	0.125"
TEMPERATURE	=	23°C

FIGURE 5

MICROWAVE PROPERTY OF FERRAMICS G-254, D-216, I-141, AND J-472 IN RECTANGULAR WAVEGUIDE







LENGTH = 3.00"
DIAMETER = 0.125
TEMPERATURE = 23° C

FIGURE 6

MICROWAVE PROPERTY OF FERRAMICS B-90 AND C-159 IN RECTANGULAR WAVEGUIDE, WITH FREQUENCY AS PARAMETER

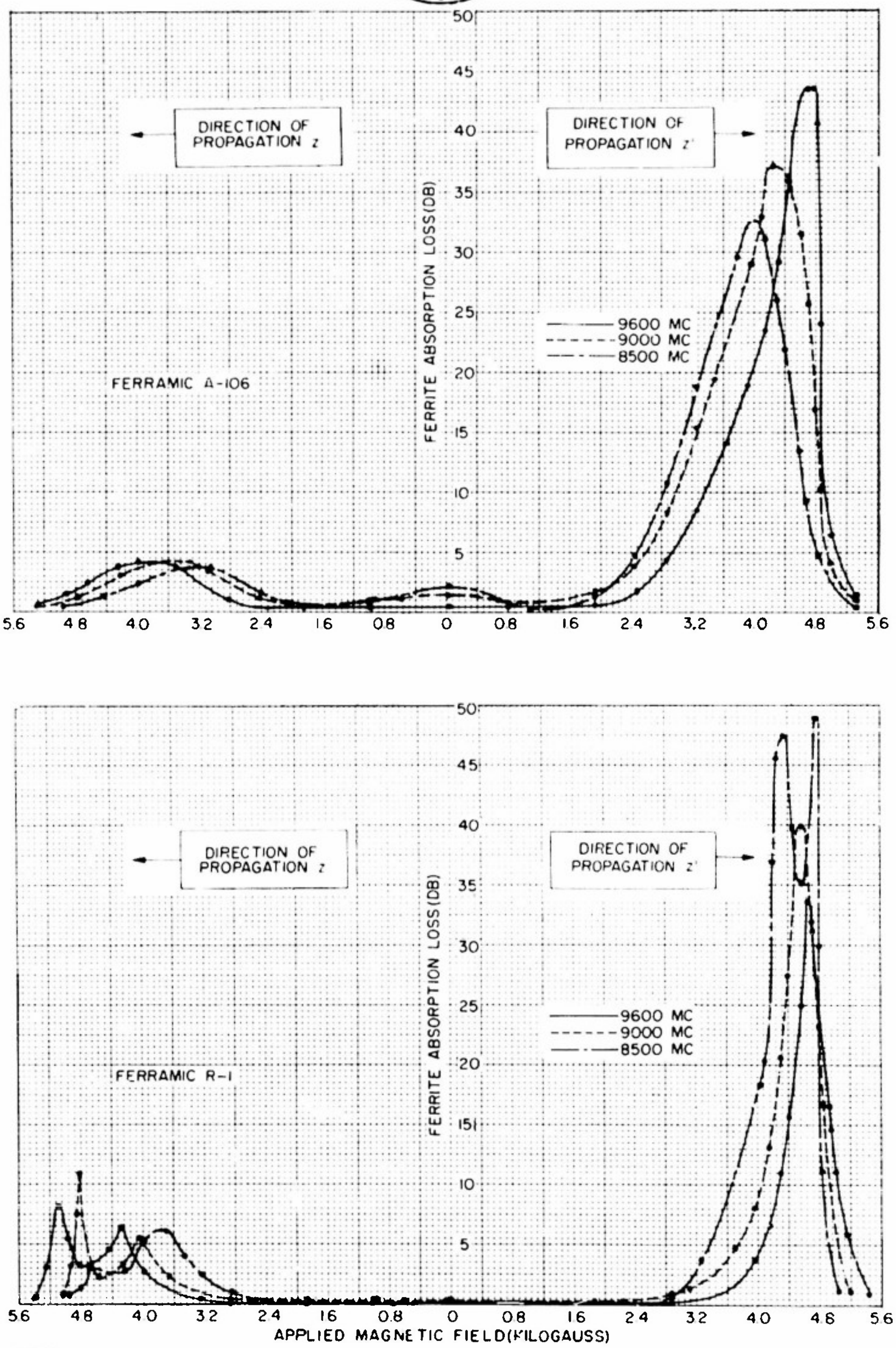


FIGURE 7

MICROWAVE PROPERTY OF FERRAMICS A-106 AND R-1 IN RECTANGULAR WAVEGUIDE WITH FREQUENCY AS PARAMETER

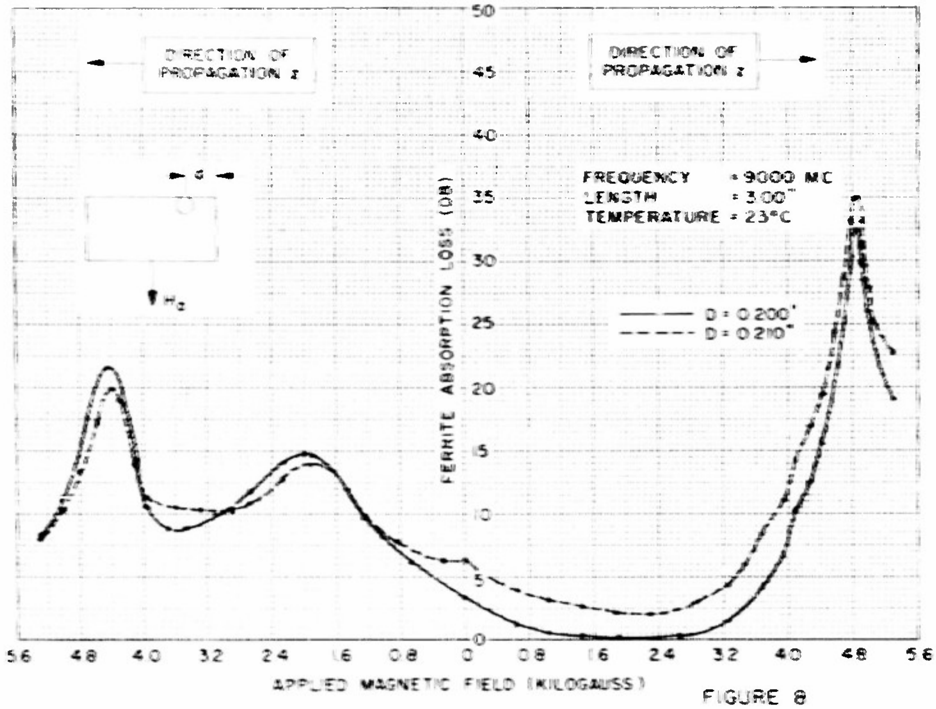


FIGURE 8

MICROWAVE PROPERTY OF FERRAMIC H-419 IN RECTANGULAR WAVEGUIDE WITH LOCATION AS PARAMETER

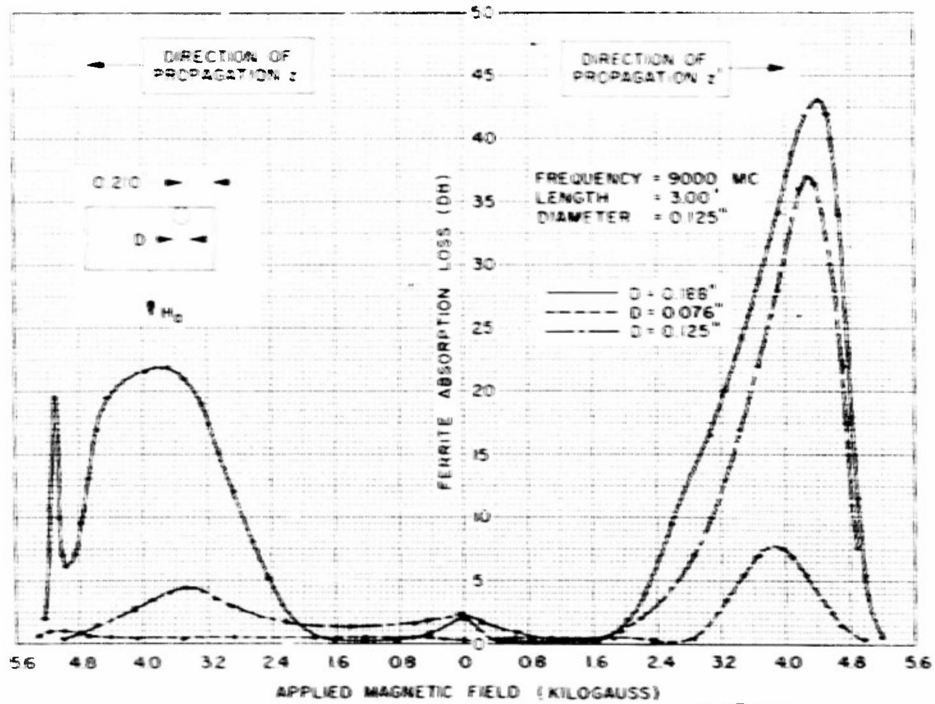
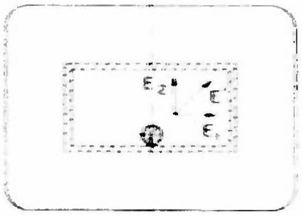


FIGURE 9

MICROWAVE PROPERTY OF FERRAMIC A-106 IN RECTANGULAR WAVEGUIDE WITH DIAMETER AS PARAMETER



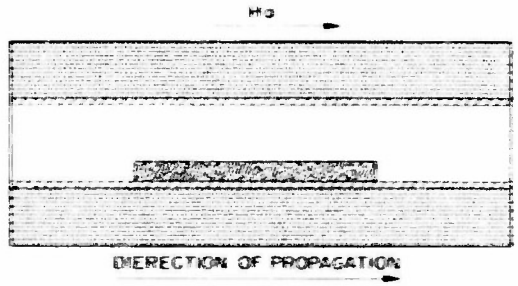


FIGURE 10

SETUP USED FOR STUDYING ROTATION OF PLANE OF POLARIZATION IN RECTANGULAR WAVEGUIDE

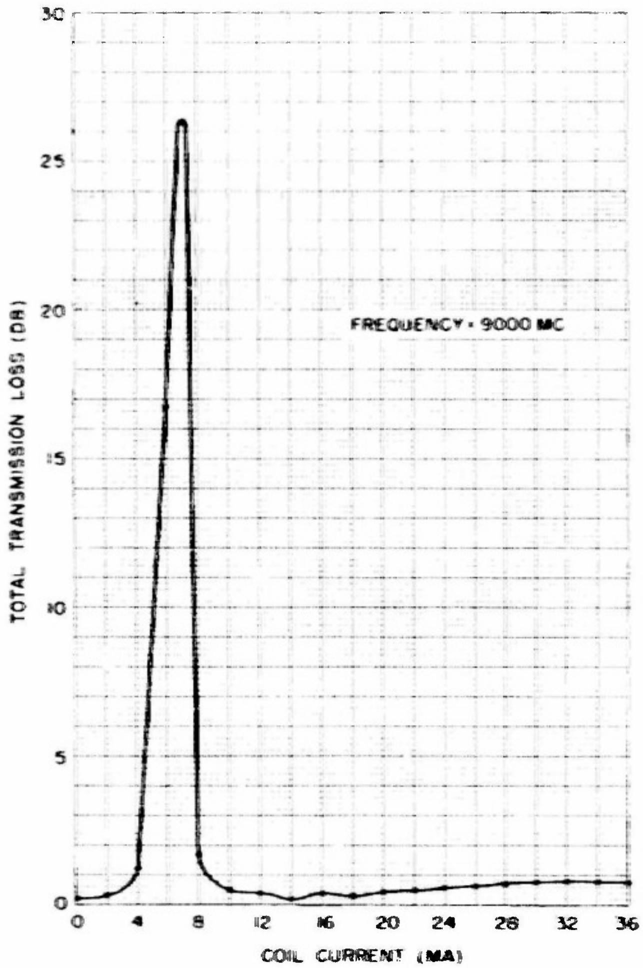


FIGURE 11

TOTAL TRANSMISSION LOSS VS COIL CURRENT FOR SETUP SHOWN IN FIGURE 10 USING FERRAMIC R-1

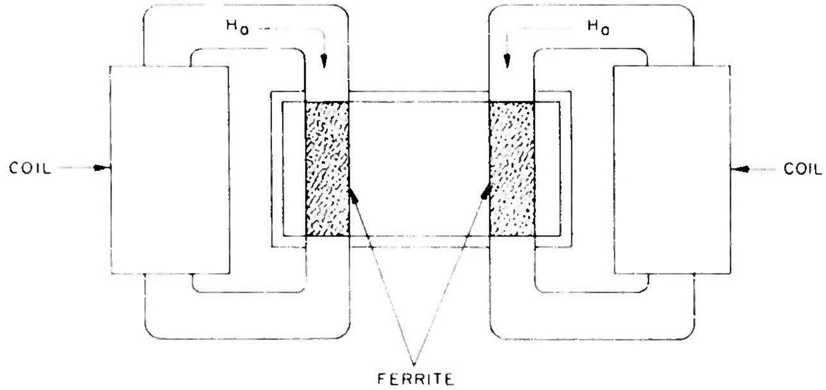


FIGURE 12
COMPONENT FOR TESTING UNIDIRECTIONAL PROPERTIES OF FERRITES IN RECTANGULAR WAVEGUIDE

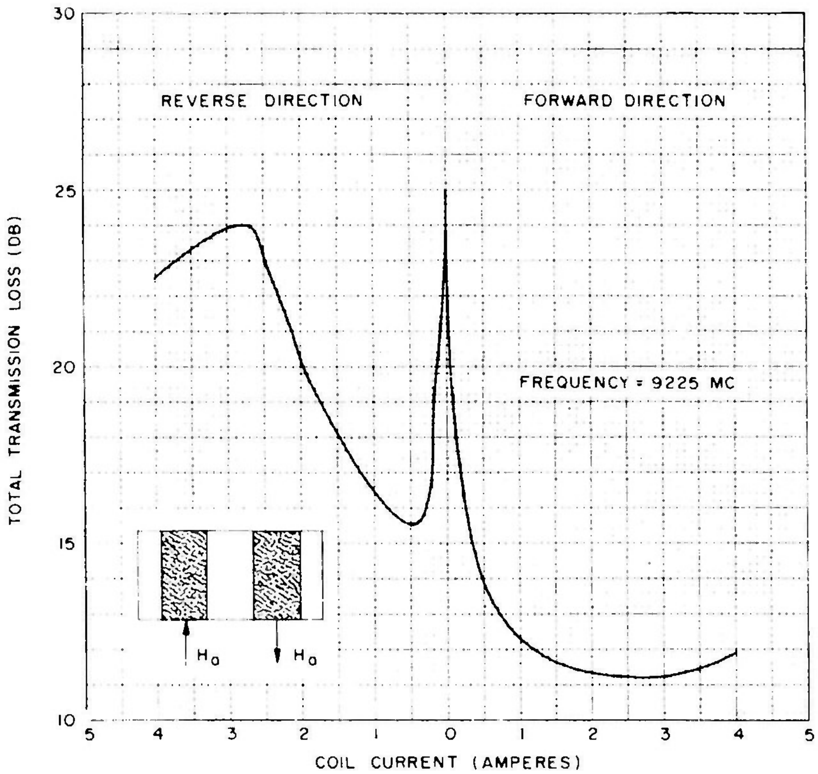


FIGURE 13
TOTAL TRANSMISSION LOSS VS COIL CURRENT FOR COMPONENT SHOWN IN FIGURE 12 USING FERRAMIC H-419

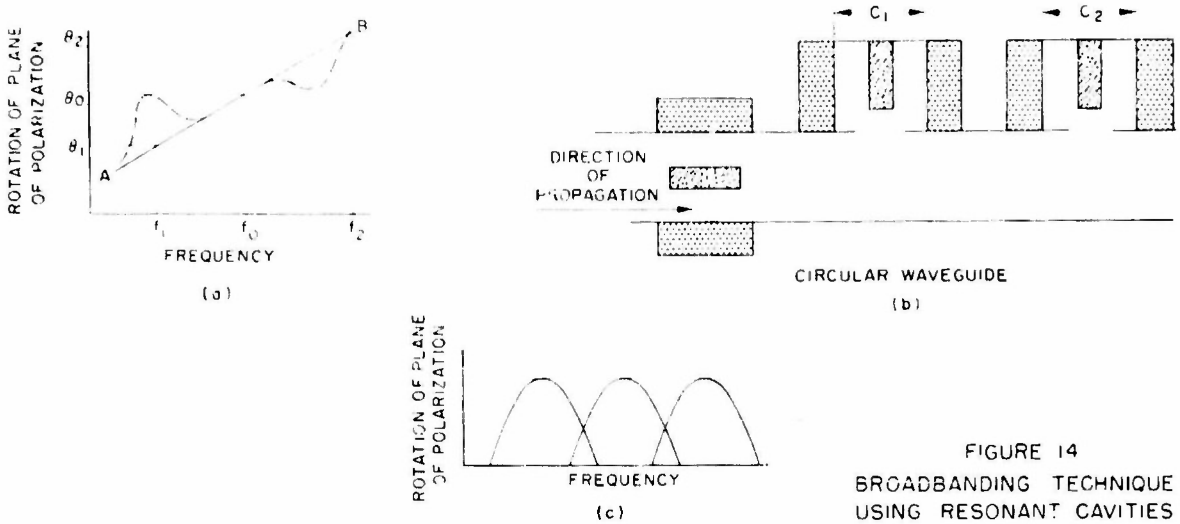


FIGURE 14
BROADBANDING TECHNIQUE USING RESONANT CAVITIES

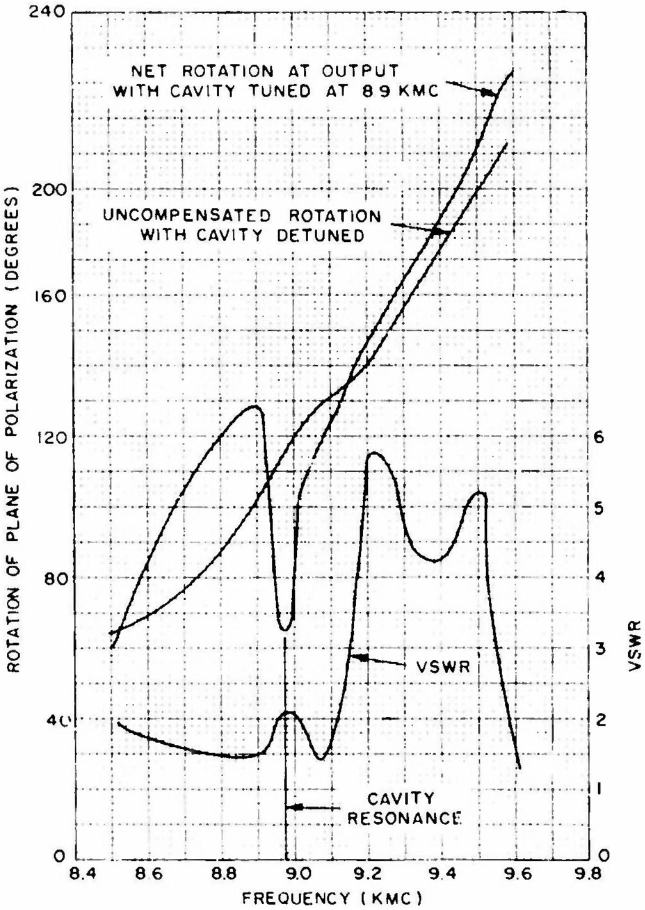
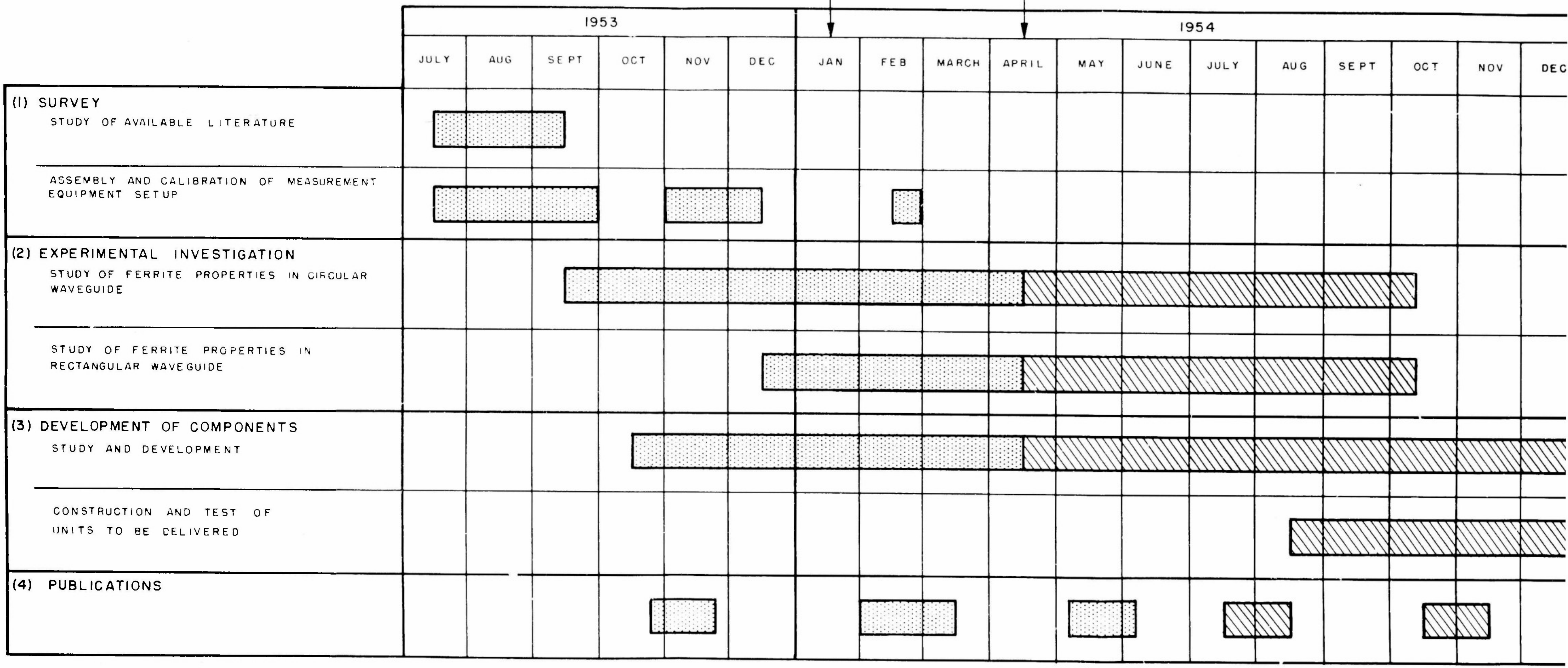
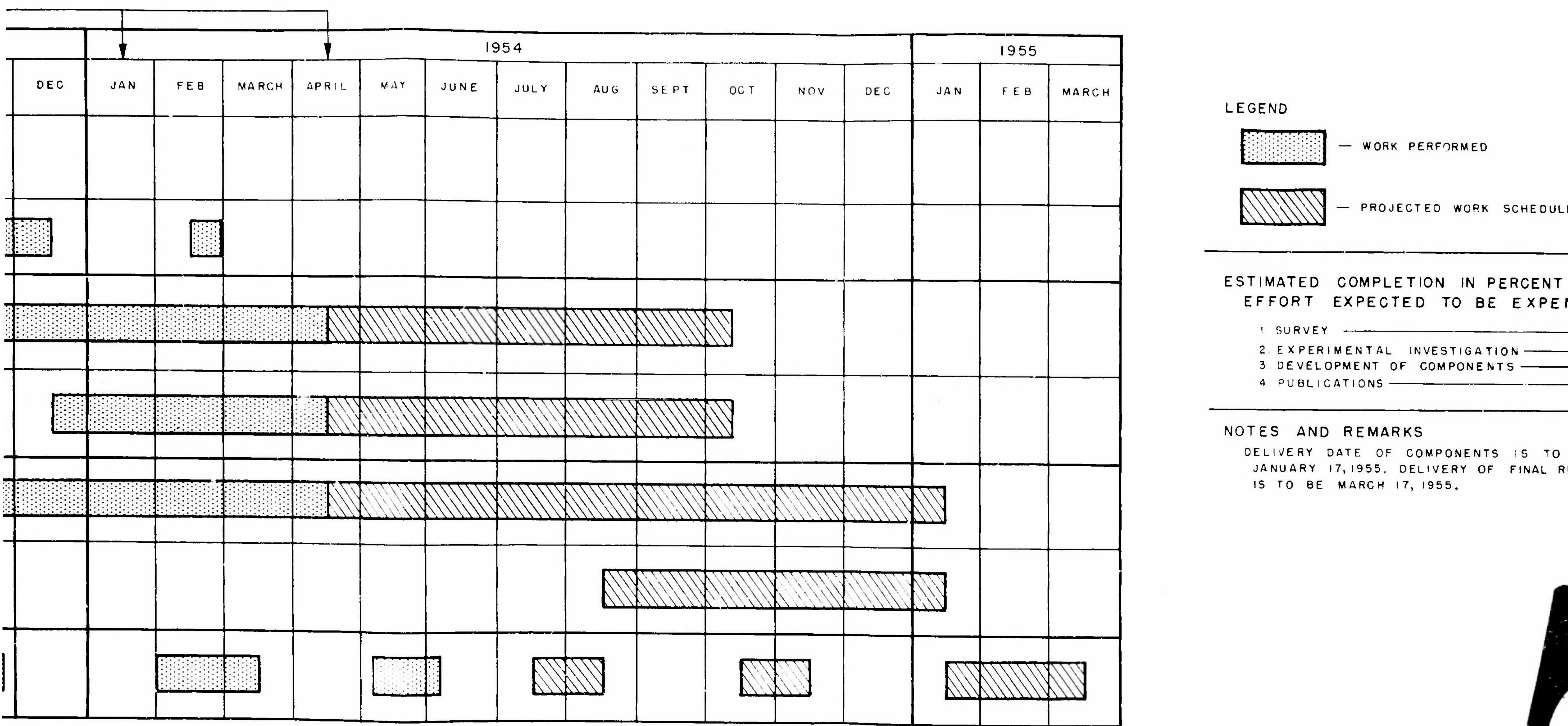


FIGURE 15

ROTATION OF PLANE OF POLARIZATION VS FREQUENCY FOR SINGLE-CAVITY BROADBANDING COMPONENT

PERIOD COVERED: 1/17/54 TO 4/17/54





ESTIMATED COMPLETION IN PERCENT OF TOTAL EFFORT EXPECTED TO BE EXPENDED

1. SURVEY — 100 %
2. EXPERIMENTAL INVESTIGATION — 75 %
3. DEVELOPMENT OF COMPONENTS — 40 %
4. PUBLICATIONS — 30 %

NOTES AND REMARKS

DELIVERY DATE OF COMPONENTS IS TO BE JANUARY 17, 1955. DELIVERY OF FINAL REPORT IS TO BE MARCH 17, 1955.

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FIGURE 16
PROJECT PERFORMANCE AND SCHEDULE