ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

# STUDY OF CIRCUIT APPLICATIONS OF SOLID STATE DEVICES TO ECM EQUIPMENT

## PROGRESS REPORT NO. 17, TASK ORDER NO. EDG-4

Period Covering January 1, 1956 to July 1, 1956

Electronic Defense Group
Department of Electrical Engineering

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July, 1956

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# ABSTRACT

The progress of the Electronic Defense Group on Task EDG-4 is reviewed for the first half of 1956. New ceramic compositions have been developed by the Solid State Devices Laboratory which have much higher Q's than previously used commercial compositions. Tuning with parallel and perpendicular biasing fields is being attempted. Receiver noise due to properties of the ferroelectric material has been studied. Petr-Pan has been modified to some extent. Test results of the EDG HS 24F1 Hi-Q capacitors are presented. A panoramic electric tuned monitor receiver which will be used to identify target signals in the EDG Task 8 CMJS has recently been completed. A preliminary analysis of resonant circuits in the UHF region is presented. Recent developments of ferrite material by the Solid State Devices Laboratory which are suitable for use in the VHF-UHF range are discussed. Problems connected with microwave applications of ferrites are discussed.

# TASK ORDER NO. EDG-4 (Amendment No. 1)

Title: STUDY OF CIRCUIT APPLICATIONS OF SOLID STATE DEVICES TO ECM EQUIPMENT

Starting Date: 1 July 1955　　　　Completion Date: Continuing

## Purpose of Task:

To perform applied research and engineering investigations in order to familiarize SCEL engineers with possible applications of solid state materials suitable for use in improved or advanced ECM equipment.

## Procedure:

1. Determine theoretically and/or experimentally the application of solid state devices to ECM equipment which offer advantage over the use of conventional circuit elements.

2. Prepare technical reports and technical memoranda presenting the results of the investigations in a form suitable for direct application by SCEL engineers to the design of equipment. It is expected that design data, charts, and formulas will be tailored to the objective of immediate reduction to practice.

3. When it is considered desirable, simple breadboard models of circuits shall be fabricated and submitted to SCEL for study, evaluation, and familiarization with novel promising techniques.

4. Consultation and guidance will be furnished by SCEL to establish priorities of application to be exploited.

## Personnel:

| Electronic Defense Group: | Evans Signal Laboratory |
|---|---|
| Task Engineer<br>T. W. Butler, Jr. | Project Engineer<br>Maurice S. Blum |

# STUDY OF CIRCUIT APPLICATIONS OF SOLID STATE DEVICES TO ECM EQUIPMENT

PROGRESS REPORT NO. 17, TASK ORDER NO. EDG-4
Period Covering January 1, 1956 to July 1, 1956

## 1. PURPOSE

The purpose of this report is to review the progress made by Electronic Defense Group Task 4 in the study of the circuit applications of solid state devices to ECM equipment.

## 2. VISITORS AND TRAVEL

January 4-5, 1956. Mr. Howard Diamond visited the Hexagon at Fort Monmouth and Rutgers University Ceramics Department to obtain information on the properties and processing of newly developed nonlinear materials suitable for tuning applications in connection with Task EDG-4.

January 30, 1956. Mr. Howard Diamond attended the IRE Committee on Solid State Devices meeting and the solid state physics sessions of the American Physical Society Meeting in New York City.

February 27-29. Mr. B. F. Barton visited the Hexagon, Fort Monmouth, to discuss the crystal circuit of the Brett receiver with ESL personnel and attend the Microwave Crystal Symposium.

March 6-7. Mr. Howard Diamond attended the Symposium on Ferroelectricity at Rutgers University and visited Prof. E. Banks at Brooklyn Polytechnic

Institute to obtain information relative to the Task EDG-4 investigation of nonlinear dielectric materials.

March 19-22, 1956. Dr. L. W. Orr and Messrs. B. F. Barton and T. W. Butler, Jr., attended the National IRE Convention in New York City.

April 2-4, 1956. Dr. C. B. Sharpe attended the Symposium on Microwave Properties and Applications of Ferrites at Harvard University.

May 10-12. Messrs. T. W. Butler, Jr., and Howard Diamond visited General Electric Company, Syracuse, to discuss the practical application of ferroelectric materials in electronic circuitry.

June 8, 1956. Mr. Maurice S. Blum, Evans Signal Laboratory, visited EDG to discuss problems related to ferroelectric tuning.

## 3. FACTUAL DATA

### 3.1 Ferroelectric Materials

3.1.1 New Ceramic Compositions. Several ferroelectric ceramic compositions have been prepared during this period. These generally have been of the $BaTiO_3$-Sr $TiO_3$ class of materials with certain additives employed in an attempt to improve upon presently available commercial ceramics. The properties which are of most importance for this particular application are: (1) large non-linearity with low losses, and (2) a minimum of temperature sensitivity.

Some of the promising compositions have been used in fabricating nonlinear capacitors, and further tests have been made on these compositions (see Section 3.2.1.4). In addition, several types of conventional units have been constructed. These include $BaTiO_3$ coaxial wave guide filters, $TiO_2$ quarter-wave matching plates, and sub-miniature non-linear capacitors. Also, a special dual non-linear capacitor unit which is contained in an evacuated envelope is now being prepared by the Electron Tube Laboratory of the Electrical Engineering Department.

Some specific ferroelectric compositions are described in greater detail in Section 3.2.1.4.

3.1.2 Tuning with Parallel and Perpendicular Biasing Fields. A simple analysis presented in the previous progress report shows that the tuning ratio (R) of a ferroelectric material can be improved from the value of about 8:1 for fields of 100 volts/mil to a theoretical upper limit of about 25:1. The success of this method depends upon pre-aligning as large a number of ferroelectric domains as is possible, perpendicular to the signal field direction. In addition, this domain orientation should remain "frozen", as much as possible, which implies that the material should be prepared in such a way as to have large internal strains, small grains, etc.

At present, an attempt to align the domains by means of pressure forming is being made. As shown in QPR No. 16, the domains will tend to align in a plane perpendicular to the applied pressure (for a one dimensional pressure). It has been decided that the electric forming and the firing should be done in one process. Samples of this type are being prepared for EDG by the Carboloy Corp., Detroit, Mich. These samples are fired at 1320°C while under 2000 psi pressure. In the meantime, we have prepared samples of the same compositions as those sent into Detroit for pressure forming. Samples of the same composition have been prepared, formed and fired in the conventional way and will be used as control samples in the experiment. The results of the experiment should be available for the next progress report.

In the event that pressure forming does not prove to be successful, an attempt will be made to polarize the ceramics by means of cooling the material through its Curie temperature (of about 40°C), insuring the existance of oriented ferroelectric domains at room temperature. However, assuming the success of the pressure forming technique each composition thus formed is then divided into three parts, the first two of which are fired conventionally and the third part is crushed after it is fired, passed through a 300 mesh screen and this part is then reformed by hot pressing. The latter procedure has been adopted to assure that the compositions have undergone a solid state reaction prior to the hot pressing. The $\epsilon$ vs T characteristic, the tuning ratio, R, and the 50 mc Q's of each part of each composition will be determined and compared.

3.1.3 High-Q Nonlinear Ferroelectric. While investigating compositions which simultaneously have high $\epsilon$ and $\mu$ values, it was discovered that certain $BaTiO_3$ - $SrTiO_3$ materials with several percent additions of $Fe_2O_3$ gave phenomenall large values of Q compared with the typically available commerical non-linear ceramic. At the same time these compositions enjoyed the same degree of non-linearity as some of the lower Q materials. Table 1 shows some of the data for these new compositions, compared with some commerical materials which have been employed here. The last three materials listed are of our own manufacture. It can be seen that the Q's range from about five to ten times as high as for the usual commercial materials. The product of the Q and the tuning ratio minus one is used here as an indication of the suitability of a given dielectric for application to non-linear devices.

| Sample | Type | Zero Field 50 mc Q | 50 V/mil Tuning Ratio (R)[1] | (R-1)Q | Curie Temp[2] | $\epsilon_{max}$ |
|---|---|---|---|---|---|---|
| A-20-7 | Aerovox "Hi-Q"-20 | 40 | 1.8:1 | 32 | 40°C | 2600 |
| $B_1K50$-3 | Aerovox $B_1K50$ | 31 | 2.6:1 | 50 | 30°C | 3300 |
| $B_2K45$-1 | Aerovox $B_2K45$ | 29 | 3.2:1 | 64 | 25°C | 4000 |
| A-40 | Aerovox "Hi-Q-40" | 23 | 3.7:1 | 63 | 25°C | 6500 |
| GE-214ER | Gen. Elect. body 214ER | 34 | 2.2:1 | 41 | 30°C | 3000 |
| D-51 | Centralab body D-51 | 29 | 3.1:1 | 61 | 40°C | 5600 |
| HS24F1 | EDG | 205 | 3.0:1 | 410 | 30°C | 4100 |
| HS22F1X | EDG | 102[3] | 2.1:1 | 110 | 40°C | 2500 |
| HS23F2 | EDG | 305[3] | --- | --- | -5°C | ---- |

TABLE 1 COMPARISON OF VARIOUS MATERIALS

1. R is taken at the Curie temperature
2. The temperature of maximum dielectric constant.
3. The Q is taken at room temperature for these materials.

3.1.4 The $BaTiO_3$ - $SrTiO_3$ - $Fe_2O_3$ Ternary. The three EDG materials listed in Table 1 contain varying quantities of $Fe_2O_3$. In addition, a rather high temperature firing procedure has been used. Small quantities of iron have been previously added to $BaTiO_3$ materials by investigators interested primarily in producing single crystals of $BaTiO_3$. The addition of .2 mole percent of iron considerably enhances the formation of rather large, nearly perfect crystal plates. The iron, however, also has an extremely large effect in lowering the curie temperature for both iron and strontium additives in $BaTiO_3$.[1]

Figure 1 shows the effect on Curie temperature of $BaTiO_3$ of adding various amounts of $Fe_2O_3$ and $SrTiO_3$. It can be seen that the $Fe_2O_3$ is much more effective in lowering the Curie temperature than is $SrTiO_3$. In order to determine the behavior in the system of three components, $BaTiO_3$, $SrTiO_3$, $Fe_2O_3$ a ternary diagram is being constructed. At this time there is insufficient data to present a complete picture of the effects of the $Fe_2O_3$ additions. The present work consists of establishing the line in the ternary diagram along which the Curie transitions are at 25°C. Then a series of samples are to be fired having compositions given along the 25°C line and the values of Q and R will be determined. With the limited data available a tentative ternary diagram has been prepared and is shown in Fig. 2. As more data become available, the diagram will be revised. One important point to mention here is that the data for the Curie temperatures of the $BaTiO_3$ - $Fe_2O_3$ join are in agreement with the data given by Niohioka.[1]

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[1] The data for iron additives is after A. Niohioka, K. Sekikawa, M. Owaki, Jour. Phys. Soc. of Japan, 11, 1956.

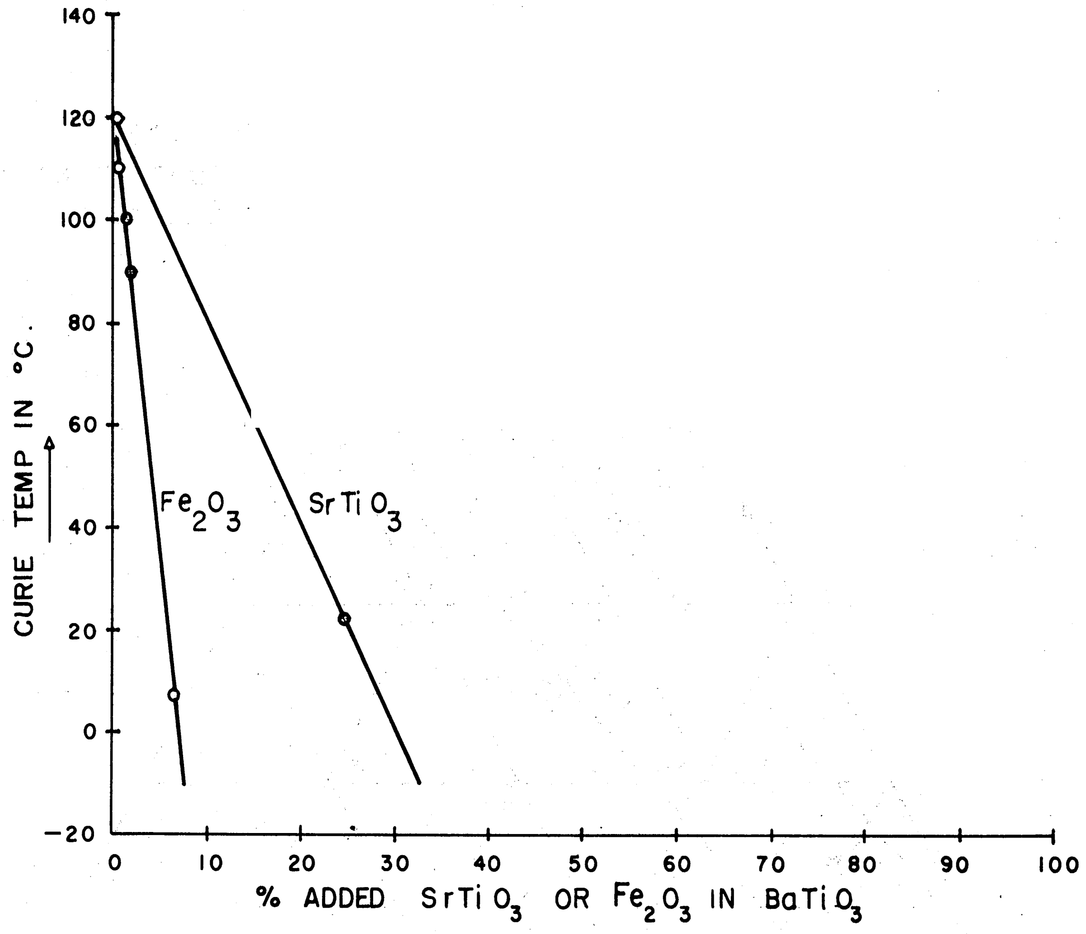

FIG. I CURIE TEMPERATURE OF $BaTiO_3$ VS $Fe_2O_3$ AND $SrTiO_3$ ADDITIVES

However, in a test on ceramics along the $BaTiO_3$-$Fe_2O_3$ join we were unable to find any pronounced peaks in the dielectric constant in compositions ranging from two to eight mole percent of iron additions, except an extremely small and broad "hump" at 120°C (the Curie temperature of pure $BaTiO_3$). It is possible, then, that in our particular samples the iron did not enter into the composition as a solid solution with the $BaTiO_3$. The empirical equation governing the diagram based on our limited data has been determined as: $T_c = 125-400S-1800F$ and $B + F + S = 1$, where S is the mole fraction of $SrTiO_3$, F is the mole fraction of $Fe_2O_3$, and B is the mole fraction of $BaTiO_3$.

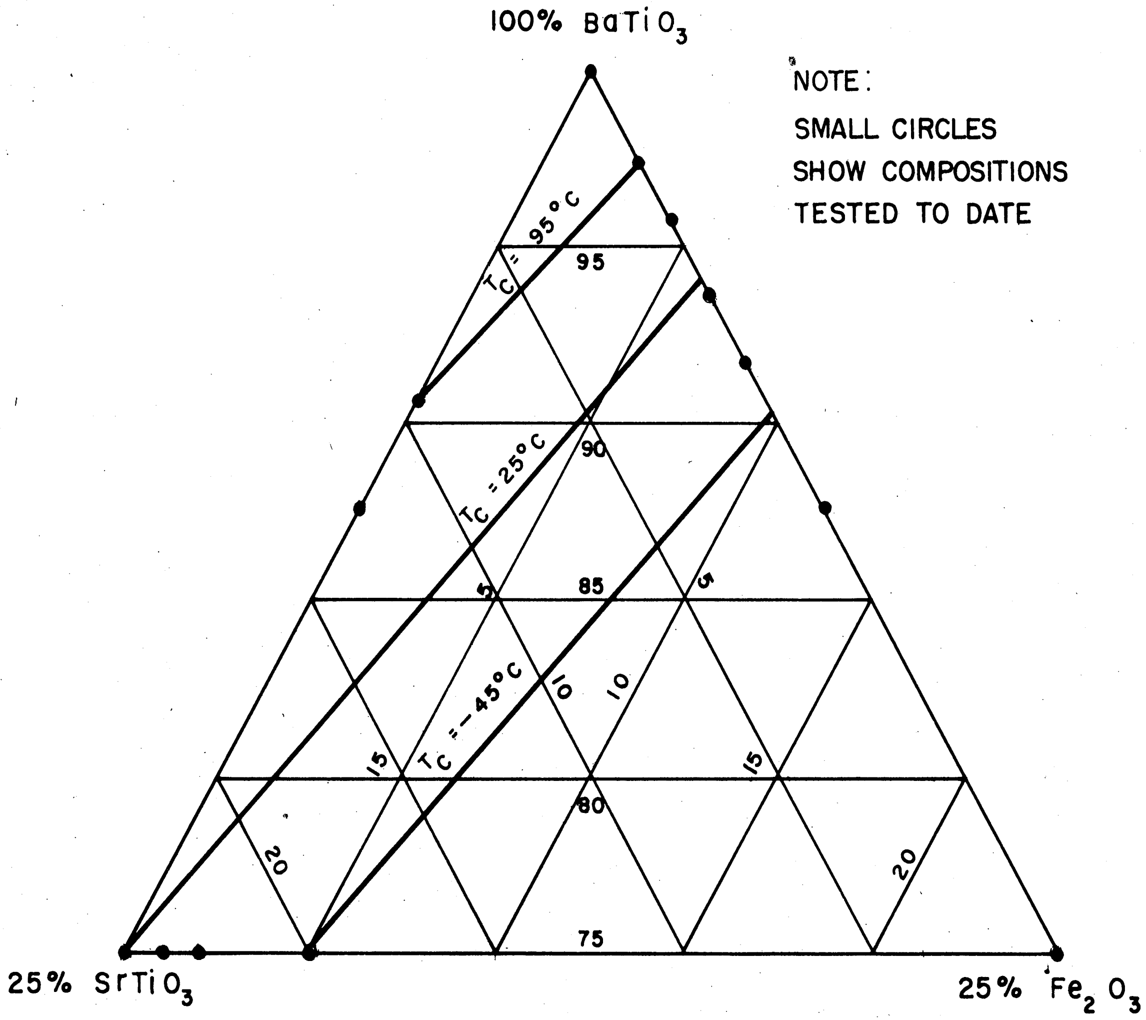

FIG. 2 TERNARY DIAGRAM (TENTATIVE) OF $T_C$ IN $BaTiO_3-SrTiO_3-Fe_2O_3$

The compositions on the $BaTiO_3$ - $Fe_2O_3$ join will be reproduced and re-examined for peaks of dielectric constant versus temperature.

3.1.5 Further Consideration. It has been speculated that one of the contributions to the dielectric losses, at least at low frequencies, is made by a loss of oxygen due to over-firing. It is known, for instance, that properly fired $TiO_2$ is a very good insulator, but upon overfiring the $TiO_2$ (rutile) reduces to TiO, which is a semiconductor. The conduction there would take place by means of the electrons left behind in the material upon loss of the oxygen. That is to say, the overfired material is an n type semiconductor. Now if some means were employed to produce electron traps, or to bind the oxygen in the material, it would be possible for the dielectric to retain its low conductivity. Remeika[1] has shown that upon the addition of .2 mole percent $Fe_2O_3$ in $BaTiO_3$ single crystals, the n type crystals become intrinsic semiconductors. Upon further addition of $Fe_2O_3$ the crystals become p type semiconductors. That is, the effect of the $Fe_2O_3$ is to supply acceptor ions.

Although a detailed study of the conductivity vs. $Fe_2O_3$ additions in our Ba-Sr-$TiO_3$ ceramics has not been made, the limited data available appear to show a discrepancy over what is expected from data published for the single crystals. We have noted that materials containing $Fe_2O_3$ additions even in excess of one percent have much lower conductivities (higher resistivities) than even the pure $BaTiO_3$ ceramics. Thus:

Sample HS34F1 (1% $Fe_2O_3$) $P = 10^{12}$ Ω/cm.
Sample H13-2 (100% $BaTiO_3$) $P = 10^{11}$ Ω/cm.

In view of the rather high firing temperatures employed (1400°C for two hours) it is possible that the oxygen lost at these temperatures is being replaced by oxygen from the $Fe_2O_3$. The iron may then drop from a valence state of +3 to +2 and may even occupy a lattice site of Ba(+2). That is to say, a phase of $FeTiO_3$ may exist in the Ba-Sr-$TiO_3$ ceramic.

Another point worth noting is that in all our ceramics with as little as 1 mole percent $Fe_2O_3$ additive, the color is jet-black. This color change in this normally light ceramic is certainly indicative of a chemical change, expecially since it occurs at very low percentages of the iron additives.

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[1] J. P. Remeika, Jour. Amer. Chem. Soc., 76, 940, Feb. 1954.

As a further check on the question of chemical change, both chemical and X-ray analyses have been initiated. Preliminary chemical analysis for the percentage of the iron in the +2 valence state has been inconclusive. In the meantime X-ray analysis has been started, and preliminary indications are that most of the change in structure (due to iron additives) is taking place within the first one percent addition.

It was further found that the dark black ceramic became white again by reheating to moderate temperatures for two or three hours. Also, some of our older samples (those that have been fired six months to a year ago) are beginning to turn brown. These phenomena indicate that the black ceramic is only a metastable composition. Analysis of the situation is being continued.

## 3.2 Applications of Ferroelectric Materials

### 3.2.1 Pandu Program.

**3.2.1.1 Receiver Noise.** It has been known for some time that there is an increase in the pandu receiver noise figure when the receiver is switched from manual tuning to electronic tuning. Most of the noise observed can be traced to properties of the ferroelectric material used to manufacture the tuning capacitors.

There are several possible mechanisms of noise generation in dielectric materials[1], such as noise associated with ionic conduction through the volume and over the surface of the specimen, noise resulting from imperfectly applied electrodes, noise as a function of temperature, noise as a function of electrical stress, etc.

Noise as a function of electrical stress plays a most important part in the contribution of noise when the receiver is switched from manual to

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[1] A. C. Kibblewhite, "Noise Generation in Crystals and in Ceramic Forms of Barium Titanate When Subjected to Electric Stress," Inst. Elec. Eng., Vol. 102, Part B, pp.59-68.

electronic tuning. When a slowly varying electric field (e.g., 60 ~ sine wave) is applied to a ferroelectric material, discontinuous changes occur in the polarization due to domain wall jumps which give rise to pulses of current. It is felt that these pulses of current constitute the major part of the noise in the ferroelectric material.

The P-E loop (polarization versus electric field) in Fig. 3 shows the relationship between polarization and applied electric field for a typical ferroelectric ceramic operated below its Curie temperature. Because of the rapid changes in polarization on the steep portions of the loop, a large noise output is generated. Conversely, nearer the tips of the loop the noise output is much smaller and frequently absent altogether. Thus, it can be seen that the noise in the ferroelectric material is a varying quantity; its magnitude being dependent upon four main parameters. These parameters are: (1) rate of change of the applied electric field, (2) instantaneous value of the driving voltage, (3) the characteristics of the material, and (4) the temperature at which the sample is being operated. Figure 4 shows qualitatively the noise (central trace) in a typical ceramic capacitor as a function of the rate of change of the applied electric field. It should be noted that the maximum noise output does not occur at the maximum value of dE/dt but some time later at max dp/dE.

Under actual operating conditions the receiver is not cycled around a complete P-E loop, but is cycled over the portion of the P-E loop as shown by the solid lines of the curve of Fig. 3. To determine the additional noise output of the receiver due to its being cycled around the minor loop shown the following test was run. The noise figure of the receiver (using FE-10, 2262 A-S4-79 BM 8-2-56

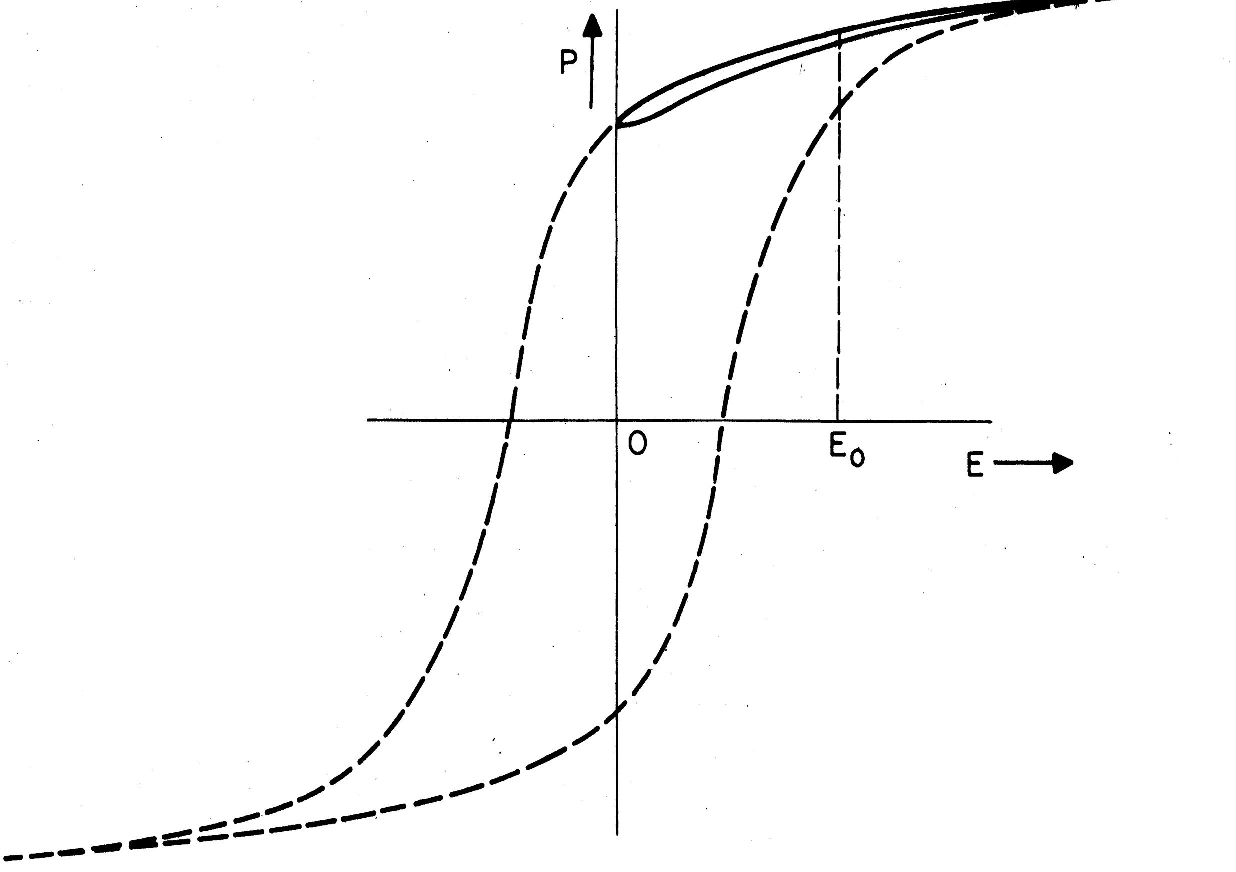

FIG. 3 POLARIZATION AS A FUNCTION OF ELECTRIC FIELD IN A TYPICAL TITANATE CERAMIC.

M-970 A-P4-11 BM 8-1-56

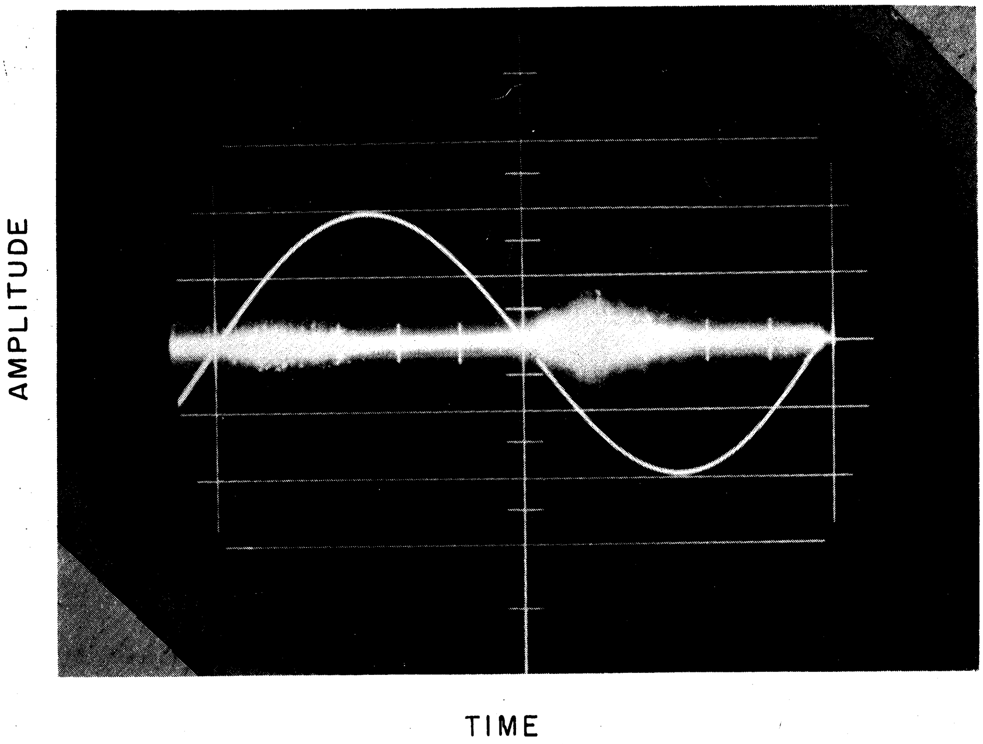

FIG. 4 NOISE AS A FUNCTION OF ELECTRICAL STRESS IN A TYPICAL TITANATE CERAMIC AT 27° C.

having a frequency range 55-130 mc) was obtained[1] at a bias level of 1000 volts (i.e., $E_0$ = 1000 v) and with zero sweep. The sweep (60 ~ AC) was applied in 100 volt steps and the noise figure of the receiver measured with each incremental increase in sweep. The results of this test are shown by the graph of Fig. 5.

It is interesting to note that the noise figure of the receiver is increased approximately 3 db when the receiver is switched from manual tuning to full electronic tuning.

3.2.1.2 Packaged Receiver (PETR-PAN). The packaged electric tuned panoramic receiver (PETR- PAN) has been modified as indicated by the block diagram of Fig. 6. The major changes were made in the display circuit. The fence generator was eliminated and a method of determining the frequency of displayed signals which does not depend upon a completely linear sweep was designed and built. These changes will not be explained in detail in this report since a technical report on the design and construction of the entire receiver will be published in the next report period. However, a sketch indicating the final display is presented in Fig. 7. Frequency determination is obtained by moving the step (left edge of the expanded sweep) into coincidence with the unknown signal by means of a precalibrated slide rule dial. The unknown frequency is then read directly off the dial.

Front end unit FE-P-3 (130-240 mc) has been completed and tested. The construction of the unit is very similar to FE-10 (described in Task EDG-6 Progress Report No. 16). Tests indicate that the unit compares very favorably with FE-P-2 (55-130 mc) in that the sensitivity is $\cong 2$ $\mu$-volts the image rejection $\cong 50$ db, and the noise figure $\cong$ 15-18 db.

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[1] T. W. Butler, et. al., "Study of Circuit Applications of Solid State Devices to ECM Equipment," Progress Report No. 16, January, 1956. See page 35 for schematic diagram of FE-10.

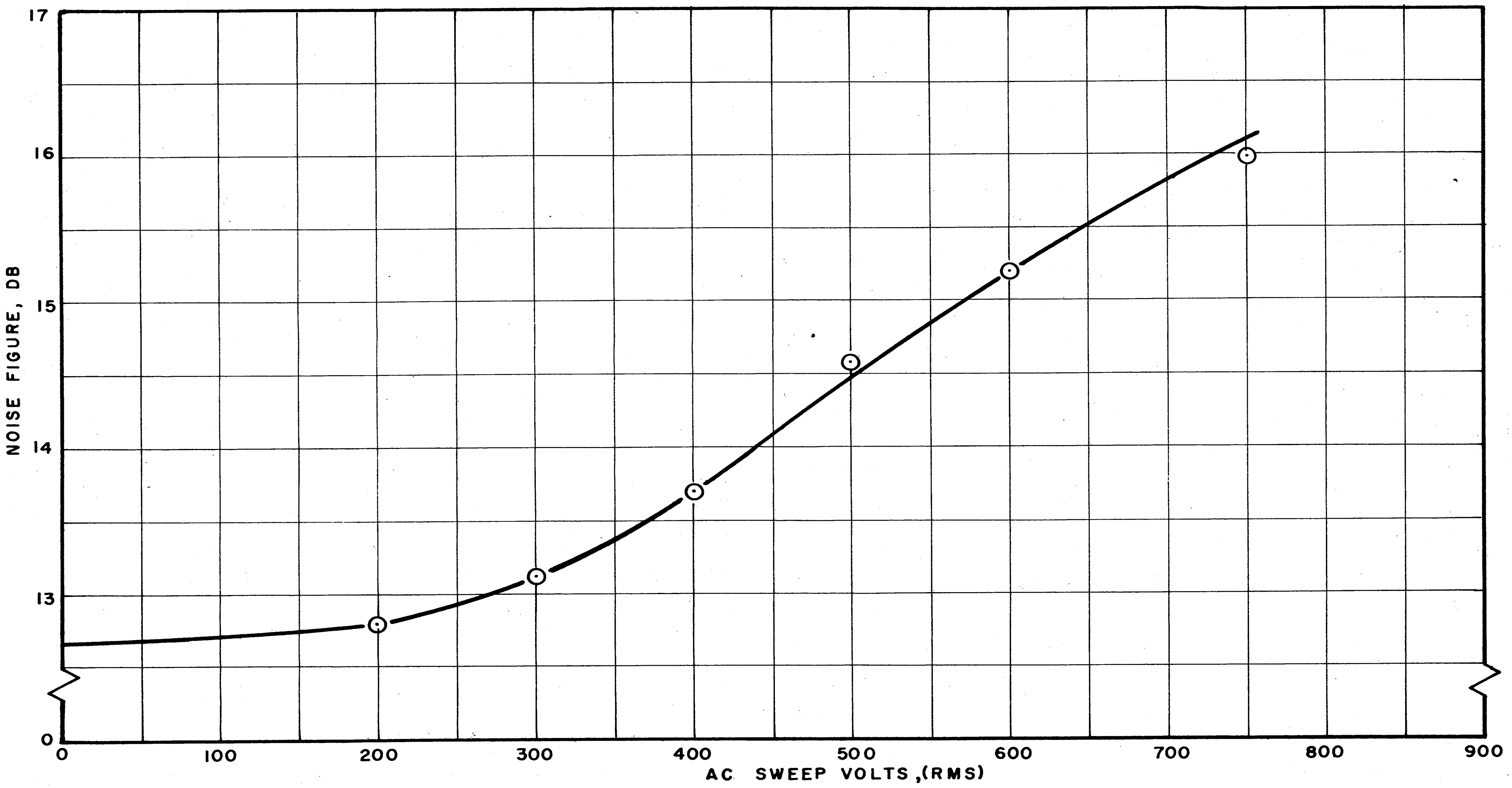


FIG. 5 RECEIVER NOISE FIGURE
FE-10 (55 – 130MC)
$E_0$ = 1000V (DC BIAS LEVEL)

2262 A-G4-166 BM 8-2-56

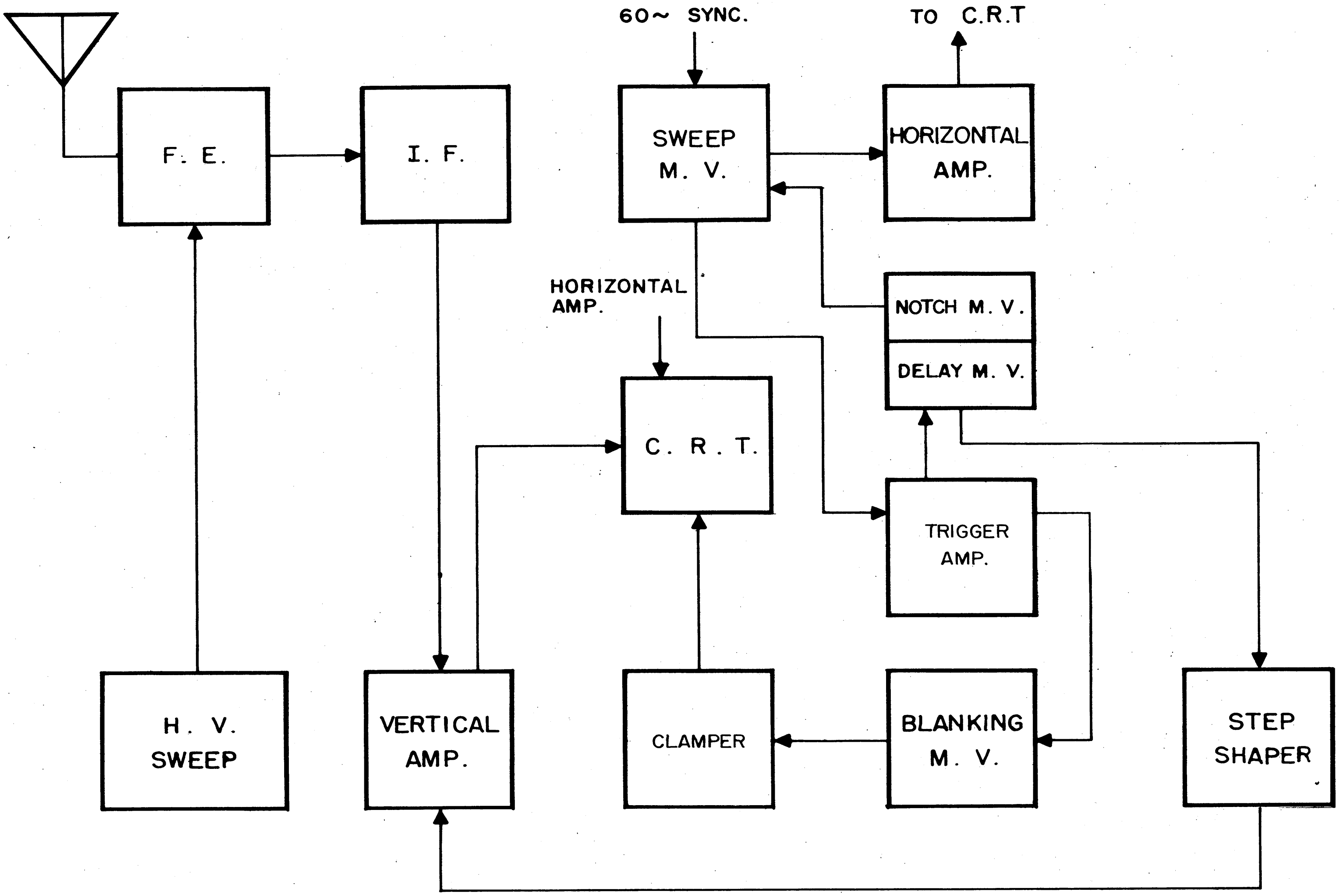
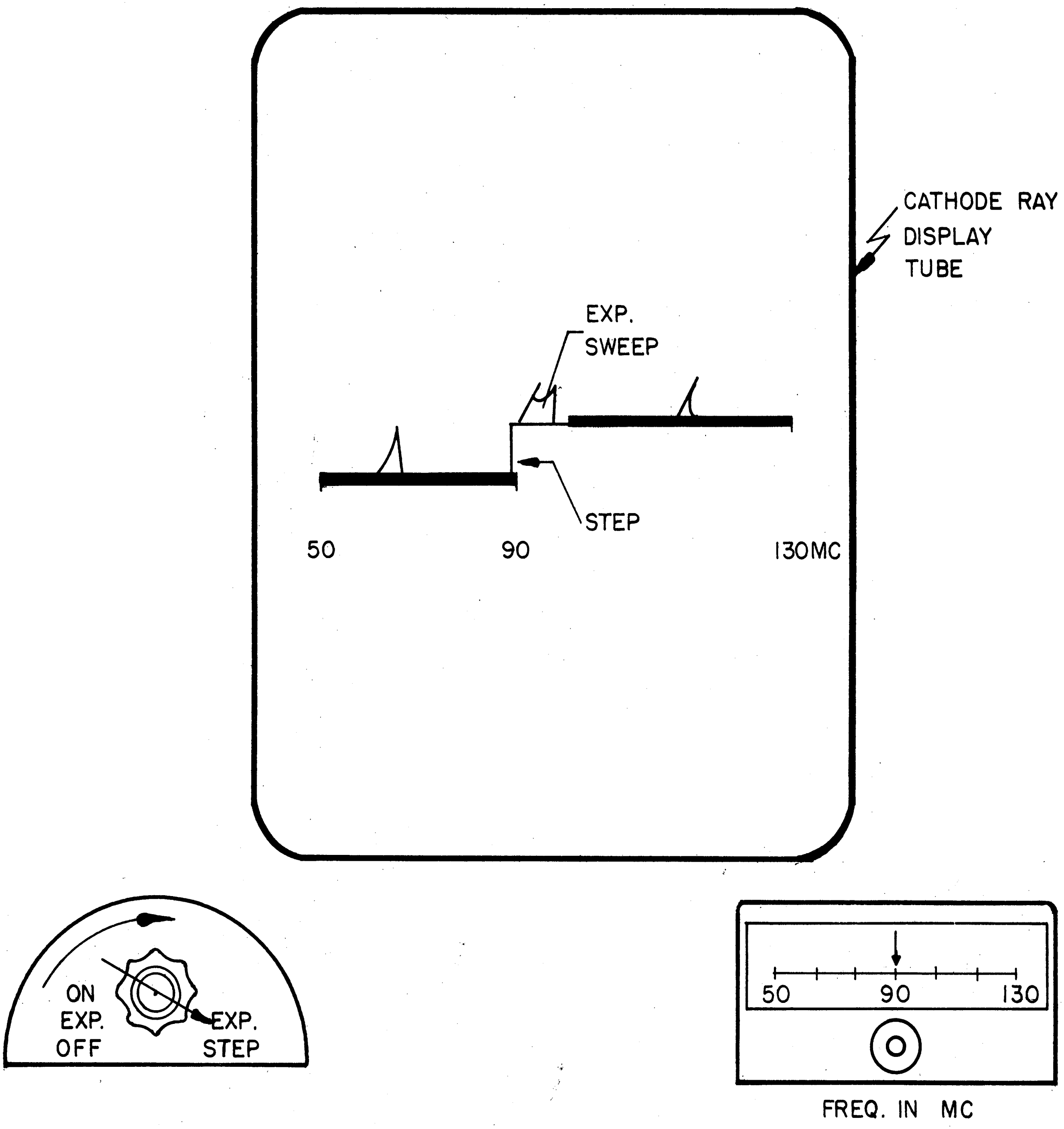


FIG. 6 BLOCK DIAGRAM

2262 A-S4-76 JF 6-29-56

2262 A-S4-80 JF 8-2-56



THE ABOVE CONTROL OPERATES AS FOLLOWS:

(a) "OFF" STRAIGHT SWEEP

(b) "ON" EXP. STRAIGHT SWEEP WITH EXPANSION

(c) "EXP." STEP STEP AT BEGINNING OF EXPANDED SWEEP – VARIABLE IN AMPLITUDE

FIG. 7 PETR PAN DISPLAY

It is not advisable to continue designing FE units at a frequency much in excess of ≅ 250 mc using presently available dielectric body materials and lumped constant design techniques, since the losses become too great for satisfactory operation of a swept receiver. However, the development of new materials (e.g., HS-24-Fl described in Sections 3.1.3 and 3.2.1.4) which have vastly improved properties, and the use of transmission line techniques (see Section 3.2.2.1) will undoubtedly make possible the design of FE units for use at much higher frequencies.

3.2.1.3 Panoramic Electric Tuned Monitor Receiver. The design and construction of the first phase of a receiver which will be used to identify target signals in the EDG Task 8 Continuous Monitor Jamming System has recently been completed and is presently being tested. A complete description of the receiver will not be presented in this report; however, a block diagram of the receiver is shown in Fig. 8. The requirements of the Electric Tuned Panoramic receiver are shown in the table below:

| | |
|---|---|
| Frequency Range | 35-45 mc. |
| Sensitivity | 1 μv for visible signal-to-noise ratio = 2/1 |
| Noise Figure | 10-13 db |
| Resolution | 20 KC |
| Sweep Rate | 60 ~ |
| Spurious Responses | down ≅ 60 db |
| Dynamic Range | 20 db |

Additional requirements are to provide linear frequency response with time, provide for sweep expansion, and for frequency determination within 100 kc.

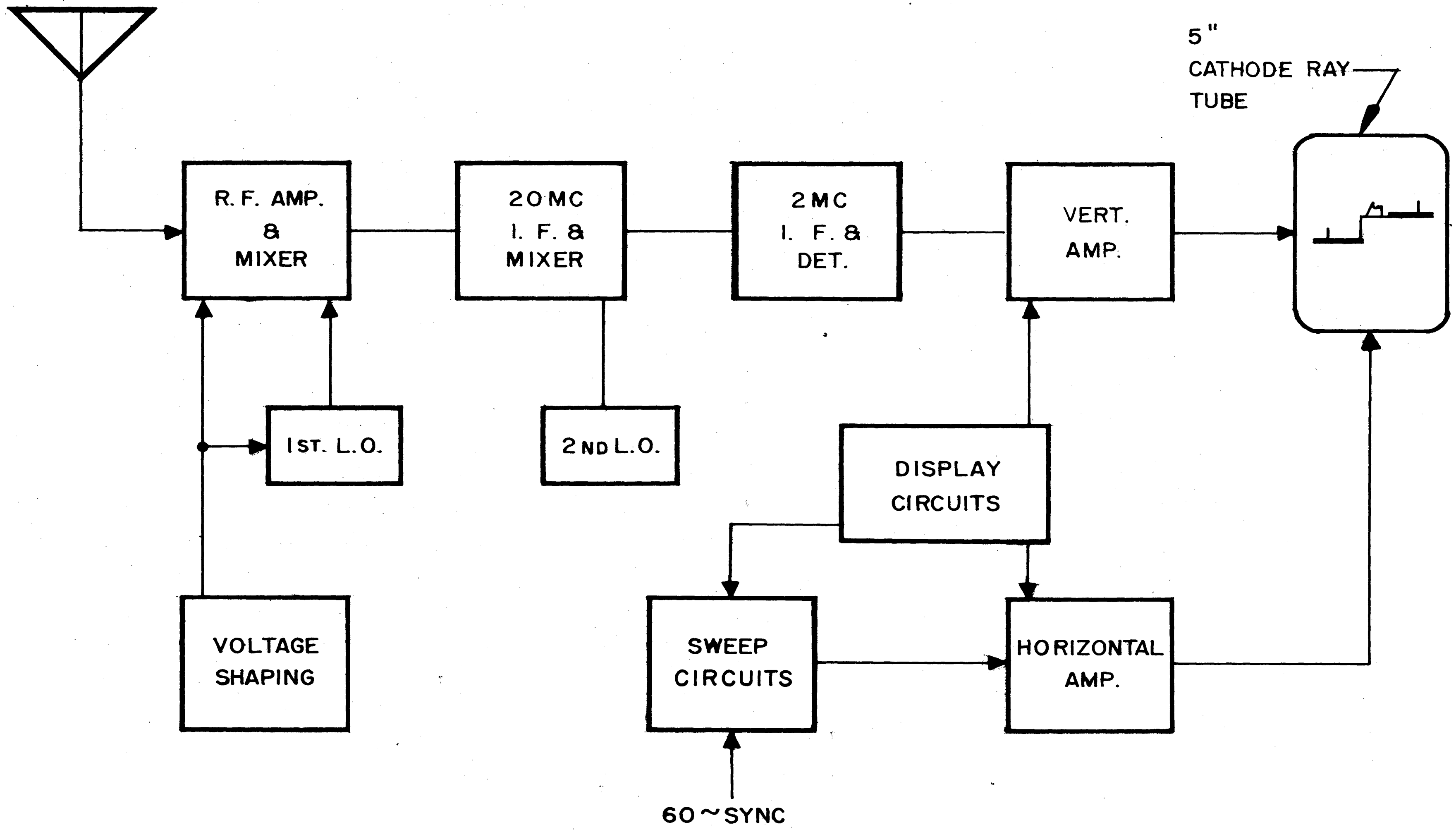


FIG. 8 PANORAMIC ELECTRIC TUNED MONITOR RECEIVER
(35 – 45 MC)

2262 A-S4-81 JF 8-2-56

3.2.1.4 Test Results of EDG HS24F1 Hi-Q Capacitors. The development of the new Hi-Q capacitors by the Solid State Devices Laboratory will have a decided effect upon the design of future FE assemblies. To compare the performance of Aerovox Hi-Q 40 material with the new Michigan HS24F-1 Hi-Q material, a one stage pentode amplifier was constructed as shown in Fig. 9. The circuit was constructed using capacitors made of A-40 material. Tests were then run to determine bandwidth, voltage gain, and tuning range. The A-40 capacitors were replaced by the Michigan Capacitors and the tests rerun. The results of the tests are tabulated below.

| | Bias | Freq. (mc) | Bandwidth (mc) | Voltage Gain |
|---|---|---|---|---|
| A-40 | 0-1300 v | 21-41 | 1.8 | 18 |
| HS-24F1 | 0-1300 v | 23-39 | .7 | 28 |

From the table it can be seen that the Michigan material afforded an improvement in gain of 1.6:1 over the A-40 material while the bandwidth of the Michigan material is less than that of the A-40 material by a factor of 2.5:1. The tuning range of the Michigan material is 9% less than the range of the A-40 material for the same change in bias voltage.

These results indicate that a definite improvement in gain and bandwidth (with some loss in overall tuning range) may be realized by the use of the Michigan material. Although these improvements will lead to the design of FE assemblies with improved image frequency rejection, greater rejection against undesired signals, greater gain, and improved signal-to-noise ratio, they will also lead to increased tracking problems and greater difficulty in eliminating general FE instability.

It was noted also that the Michigan material has a large positive temperature coefficient of dielectric constant at the operating temperature. This indicates that the material is being operated somewhat below the Curie point.

Operation of the material at the Curie temperature would give a decided increase in tuning range and greater stability for small temperature changes. Although it is desirable to use titanate materials which have a small temperature coefficient of dielectric constant over a wide temperature range (if the FE assembly is to be used over an extended temperature range) it is not essential because thermostating or compensating techniques can be used to good advantage. The Michigan Solid State Devices Laboratory is presently developing a Hi-Q material which has a broad Curie over an extended temperature range, thus eliminating the need for thermostating or compensating techniques when operating the FE over a wide range of temperatures.

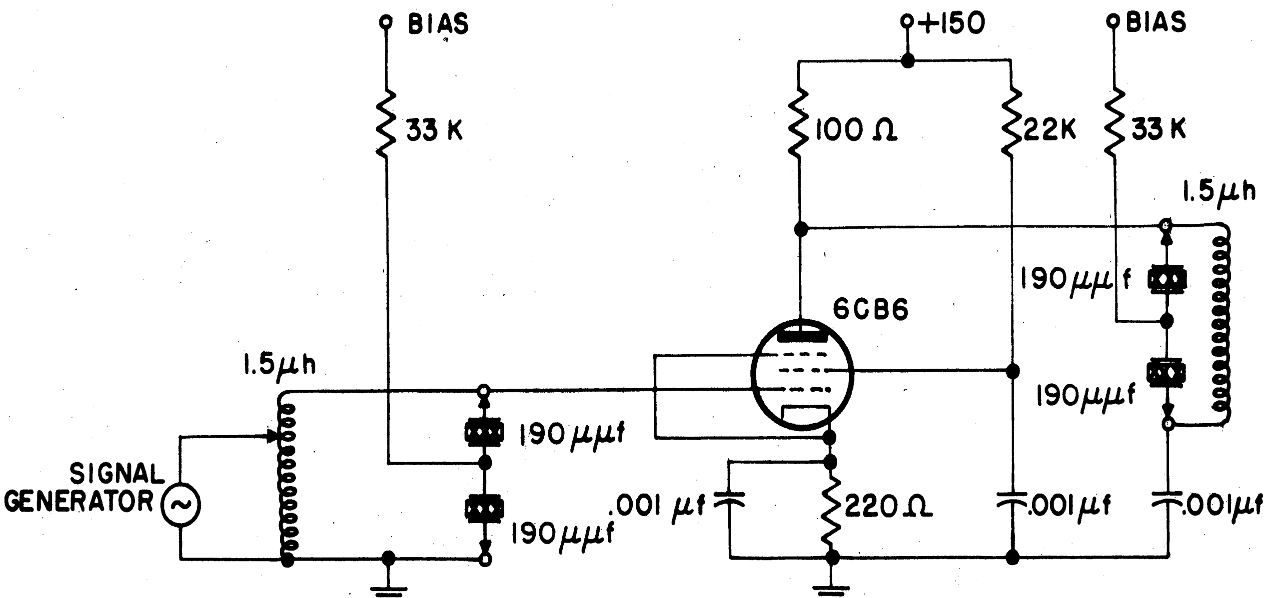


FIG. 9 COMPARISON AMPLIFIER

### 3.2.2.1 Analysis and Construction of Resonant Circuits in the U.H.F. Region.

Two methods for constructing tunable resonant circuits in the UHF region are under consideration.

The first consists of a shorted transmission line terminated at the open end by ferroelectric capacitors.

The resonant frequency of this configuration is plotted as a function of capacity for various values of $Z_0$ in Fig. 10. As can be seen, the principle line requirement is a low $Z_0$ in order to allow lines of practical length to be used with reasonably large values of capacity. The larger capacity is desirable, both to offset the effects of wiring, inter-electrode capacity, etc., and to facilitate fabrication of the capacitors. Longer lines could be used with operation in higher modes. This presents the possibility of undesirable operation in lower modes and reduces the possible tuning range. Also, the losses due to skin effect, radiation, etc., are increased.

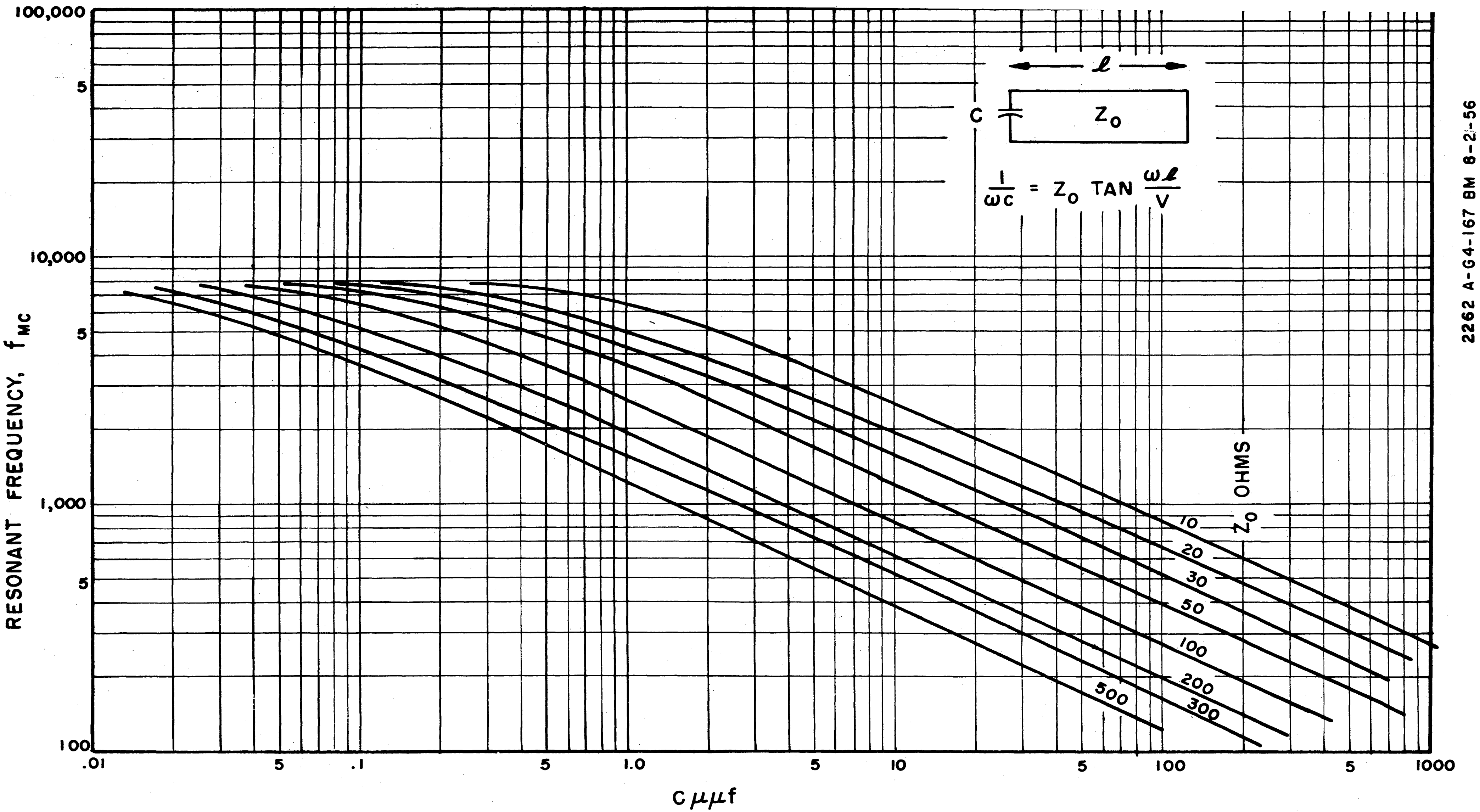
A second requirement which takes precedence over tunability in this frequency range is that of a high Q.

An 800 mc oscillator was constructed using the Aerovox Hi-Q-40 ($Q \cong 20$). Though the unit oscillated, the output was too low to be of any practical value. It is felt that a Q in the neighborhood of 100 would be satisfactory.

The second method consists of a shorted quarter-wave line operating in the TEM mode and utilizing ferroelectric materials as the propagating medium. The resonant frequency of such a line would vary as $\sqrt{\epsilon}$.

The characteristic impedance of the line must be as high as possible in order to present, at resonance, a reasonably high impedance for a given material Q. The input impedance of such a line is:

$$Z_{in} = Z_0 \coth \frac{\pi}{4Q} \cong Z_0 \frac{4Q}{\pi} \qquad Q \geqq 10$$



C FOR RESONANCE AT GIVEN f FOR ℓ = 1 CM
FOR OTHER ℓ MULTIPLY C BY ℓ IN CM AND DIVIDE f BY ℓ IN CM

FIG. 10 TUNED LINE RESONANCE CURVES

where Q is defined as the reciprocal of the dielectric loss tangent, and $Z_0$ is the characteristic impedance of the line for a lossless dielectric and equals the $Z_0$ for an air-filled line divided by $\sqrt{\epsilon}$. Since for ferroelectric materials $\epsilon_{max}$ varies from 3600-5000 it can be seen that $Z_0$ will be quite low. This restricts the usable lines to those having relatively high characteristic impedances.

Another result of the high $\epsilon$ is that the physical length of a $\lambda/4$ line becomes very small at the higher frequencies ($\epsilon$ = 3600, f = 300 mc, $\lambda/4$ = 4.2 mm). This could be helped by using the 3 $\lambda/4$ mode instead. However, the possibility of undesirable $\lambda/4$ mode operation occurring, higher losses, and attendant lower resonant impedance negate the apparent advantage so gained.

A further consideration in selecting the particular line to be used involves the tuning. Some means must be provided for applying fields of the order of KV/cm. These fields should be fairly uniform. Variations would cause variations in dielectric constant and increase the possibility of modes other than TEM occurring and thus increasing the losses.

A configuration which seems to afford the best compromise is the parallel plate or strip line. The characteristic impedance is relatively high and the flat plate construction affords a means of applying a fairly uniform field. A construction suitable for a balanced line is shown in Fig. 11. The assumptions made are that the bias field in the dielectric is rigorously uniform, that the propagating electric vector resides wholly in the dielectric, and that the effect of terminating the center strip ahead of, instead of at, the short is negligible. The extent to which these assumptions are justifiable will have to be determined by measurement. The above line is now in the process of manufacture.

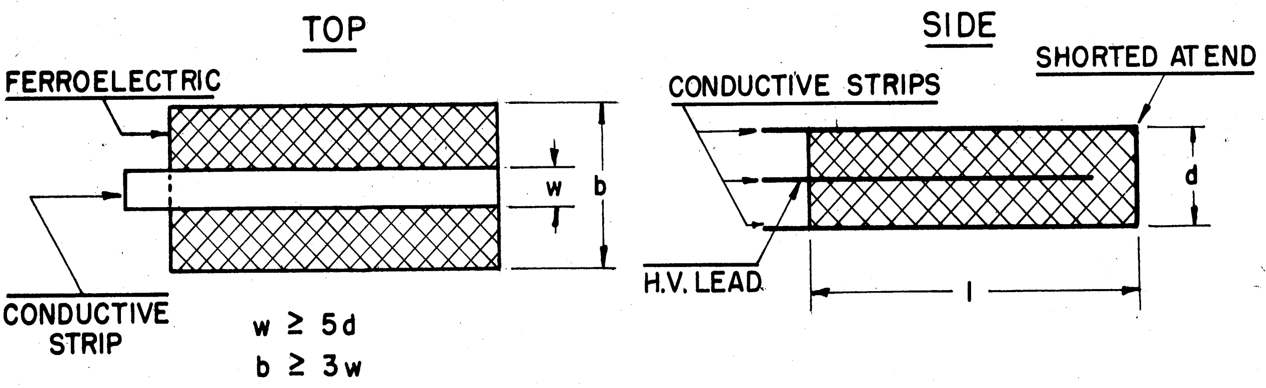


FIG. 11 λ/4 STRIP-LINED TANK CIRCUIT

The high ε of the ferroelectric material would be a definite advantage in certain applications. Much interest has been shown of late in stripline components. Directional couplers, power splitters, hybrid rings, filters, attenuators, etc., have been fabricated from this type of line. By using high ε materials the usable frequency range of these components could be extended well below 100 mc with reasonable physical sizes. Though the losses in present day commercial materials are too high for most of these applications, results from our materials laboratory indicate that a considerable improvement can be expected and additional investigation is being carried out to determine the feasibility of this application.

3.2.2.2 Duo-Tuned[1] VHF Oscillator. An investigation has been initiated to determine the feasibility of combining both ferrite and ferroelectric tuning to extend the tuning range of VHF oscillators. It is possible to obtain tuning ratios of 2:1 using ferroelectric tuning alone and about 1.5:1 using ferrite tuning alone in the VHF range. Thus, it is expected that tuning both tank

---

[1] Duo-tuned: L and C are both electronically tuned.

capacitance and inductance simultaneously should increase the overall tuning ratio to about 3:1.

Initial experiments were carried out using the test setup shown in Fig. 12 to determine whether or not the Q of the ferrite-ferroelectric combination would be sufficient for proper operation of the oscillator. An oscillator utilizing the simple tank circuit structure shown in the figure gave the following qualitative results.

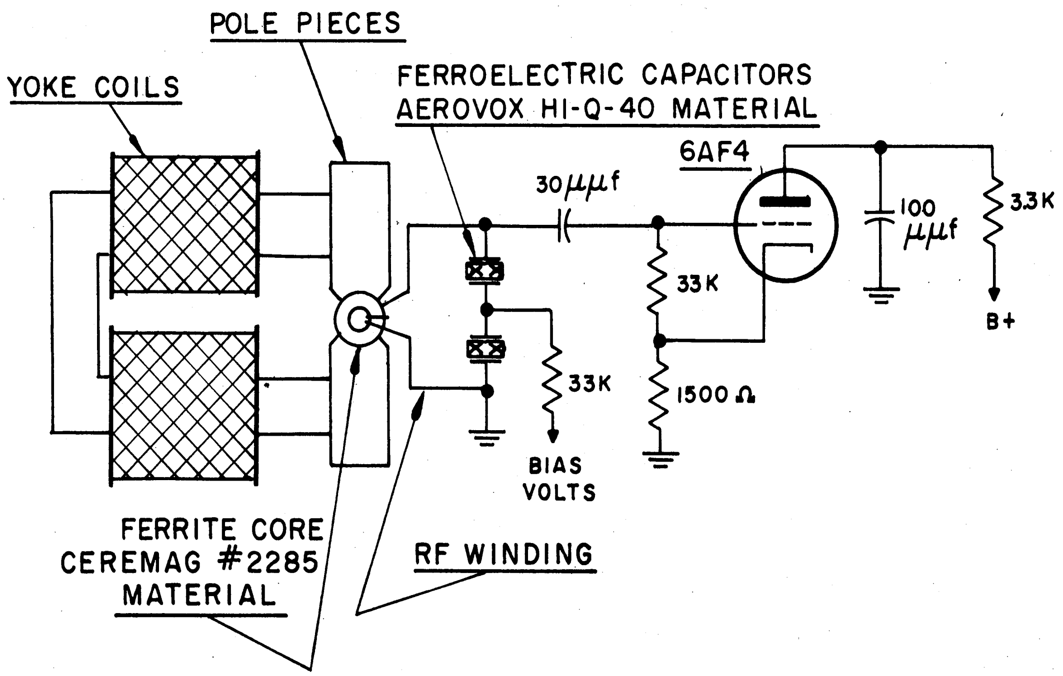


FIG. 12 DUO-LINED VHF OSCILLATOR

| Inductance | Capacitance | Tuning Range in Mc. |
|---|---|---|
| max inductance | max to min cap. | 140-170 mc |
| max to min inductance | max | 140-210 mc |
| max to min inductance | max to min cap. | 140-230 mc |

Although the test results were not startling they did indicate that tank circuit Q's high enough for proper operation of a duo-tuned oscillator could be obtained. The stray capacity and inductance due to lead length, and the large mass of the yoke, considerably reduced the tuning range.

A duo-tuned oscillator utilizing the ultra-audion principle, and featuring a miniaturized tank circuit, is being built and will be tested in the near future. The materials used for the ferrite and ferroelectric elements will be obtained from the Solid State Devices Laboratory.

3.3.1 Development of VHF and UHF Tunable Devices. The investigation of ferrite materials developed by the University of Michigan Solid State Devices Laboratory which may be useful as magnetic tuning elements in the VHF range is being continued. A plot of Q vs frequency for a ferrite core Michigan Material G-58 under no-field condition, and before exposure to a biasing field is shown in Fig. 13. A plot of Q vs frequency for the same core under-no-field conditions, but after the core was exposed to a field strong enough to saturate it is also shown in Fig. 13. The Q vs frequency of this material compares favorably with Michigan G-10 and Ceremag 2285 materials before exposure to a biasing field, but is much poorer than these materials after exposure to biasing fields. Figure 14 is a plot of Q vs frequency under field-on conditions for a ferrite core G-58. The Q vs frequency of this material compares favorably with Michigan Material G-10 but is still not as good as the Ceremag material at higher frequencies.

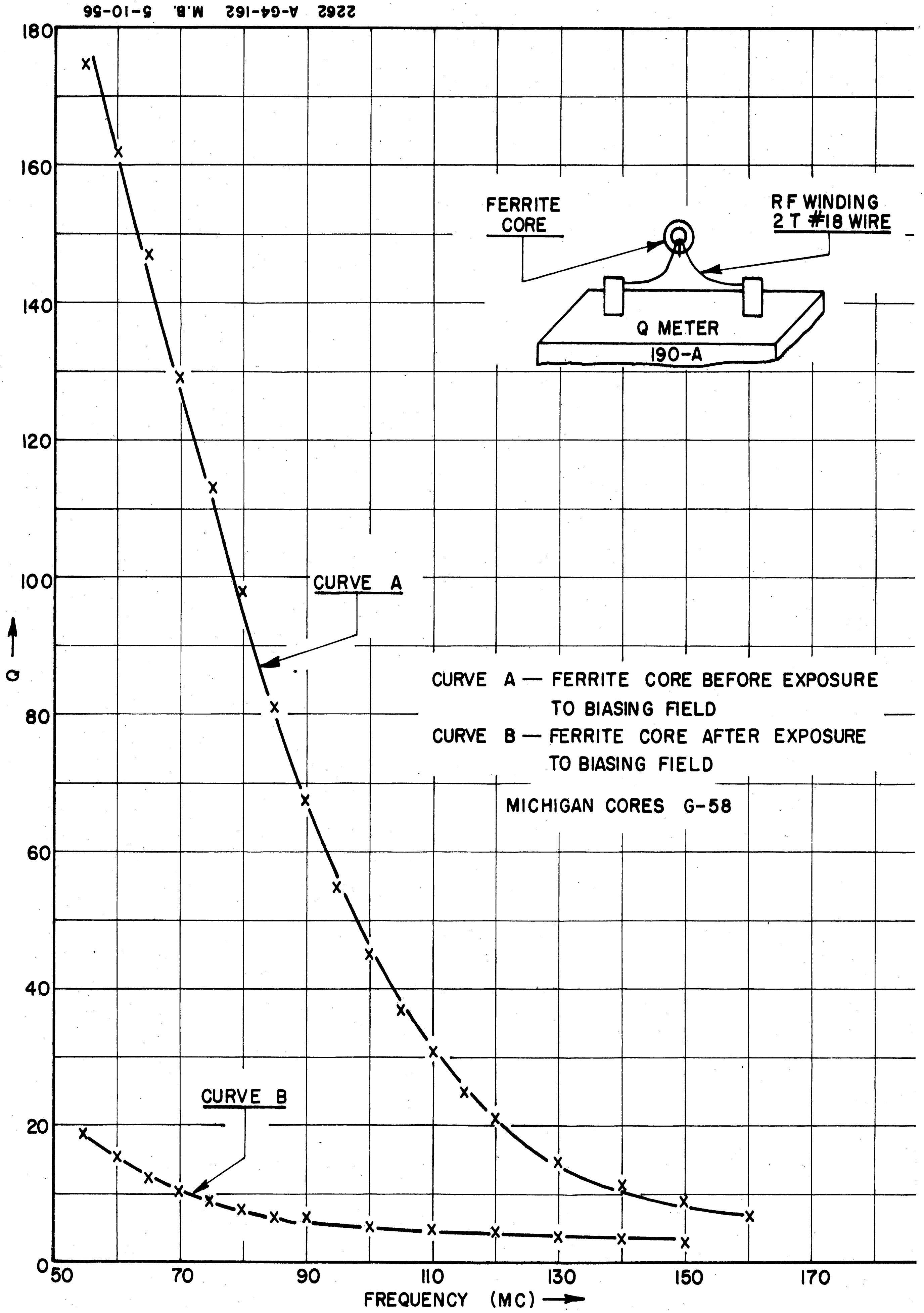


FIG. 13 VHF FERRITE CORES

Q VS FREQUENCY FOR CORES WITH ZERO APPLIED FIELD

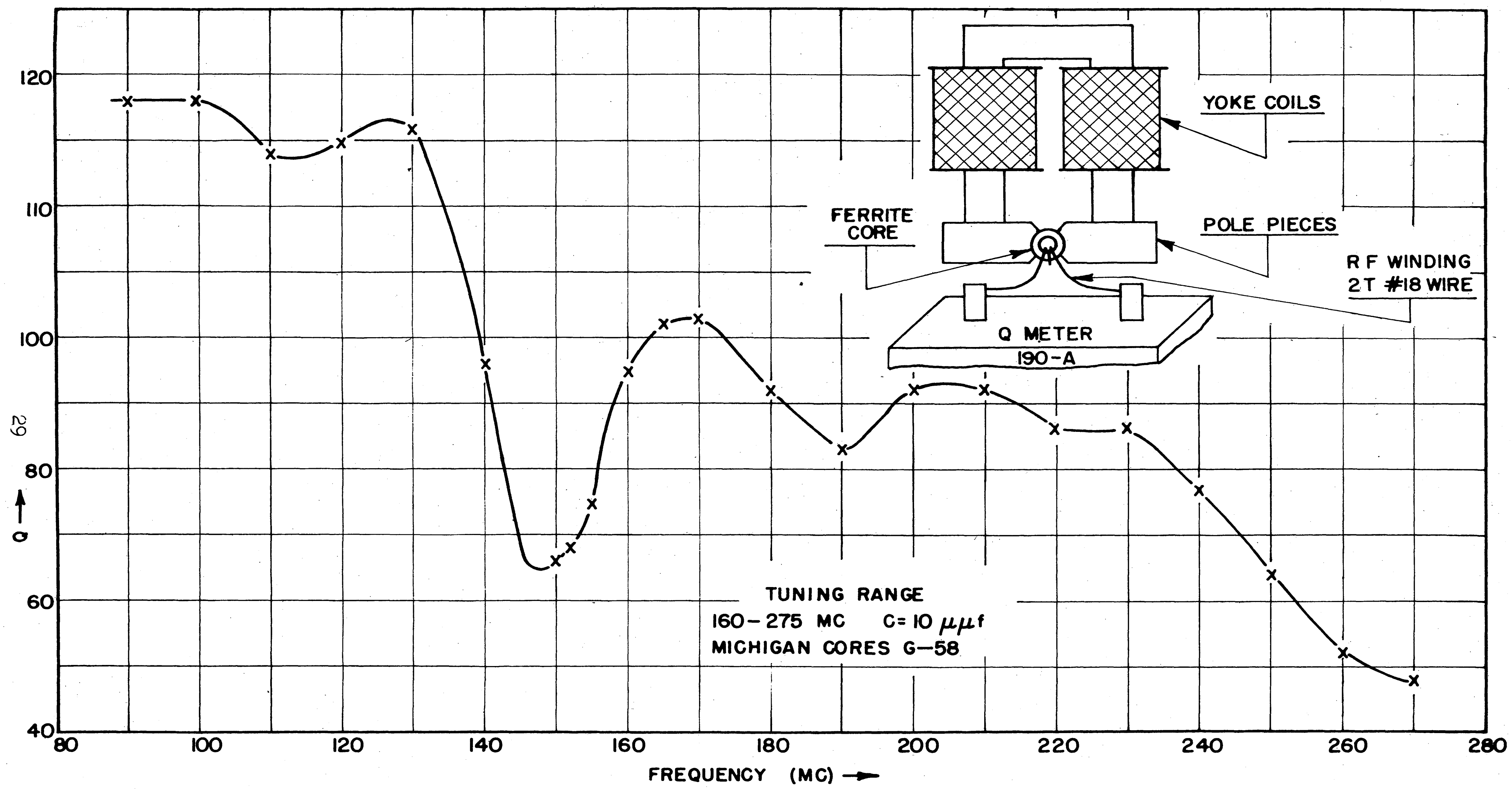


FIG. 14 VHF FERRITE CORES

Q VS FREQUENCY FOR CORES BIASED TO SATURATION

Figures 15, 16 and 17 are plots of frequency vs bias and Q vs bias for three different materials (i.e., Ceremag No. 2285, Michigan G-10, and Michigan G-58) using the test set up shown on the figures. It should be noted that the Ceremag No. 2285 material tuned from 160-258 mc with Q's ranging from 15 to ≅ 100 while the Michigan G-58 material tunes from 160-275 with Q's ranging from ≅ 2 to 55. In each case the zero bias, or starting Q, is quite low. To achieve a reasonable starting Q (e.g., Q = 30) for a tunable circuit in the VHF range using Ceremag No. 2285 material it would be necessary to bias the core (see Fig. 15) to ≅ 4 ma which would reduce the range over which the circuit could be tuned from 160-258 mc to 205-258 mc, or a reduction of ≅ 50 percent.

Figure 18 indicates the frequency ranges over which it has been possible to operate a ferrite tuned oscillator using Michigan G-58 material in the circuit shown. It should be noted that below a bias level of ≅ 15 ma the Q of the oscillator tank circuit is too low for proper operation of the oscillator. It is estimated that the necessity for biasing to this level (i.e., raising the Q of the tank circuit to a level which will cause the oscillator to break into operation) reduces the tuning range by a factor of 60-70 percent.

Work is presently being carried out in the Solid State Devices Laboratory in an effort to raise the zero bias values, or starting Q, in the VHF and UHF ranges. Details concerning the methods used to carry out this work will not be considered in this report.

3.3.2 Development of Microwave Devices. The Faraday Rotation experiment described in the previous Progress Report has been set up and a series of preliminary measurements have been made. The equipment is now undergoing modification which will improve its precision and versatility. The modification will include the addition of two wide-band quarter-wave plates

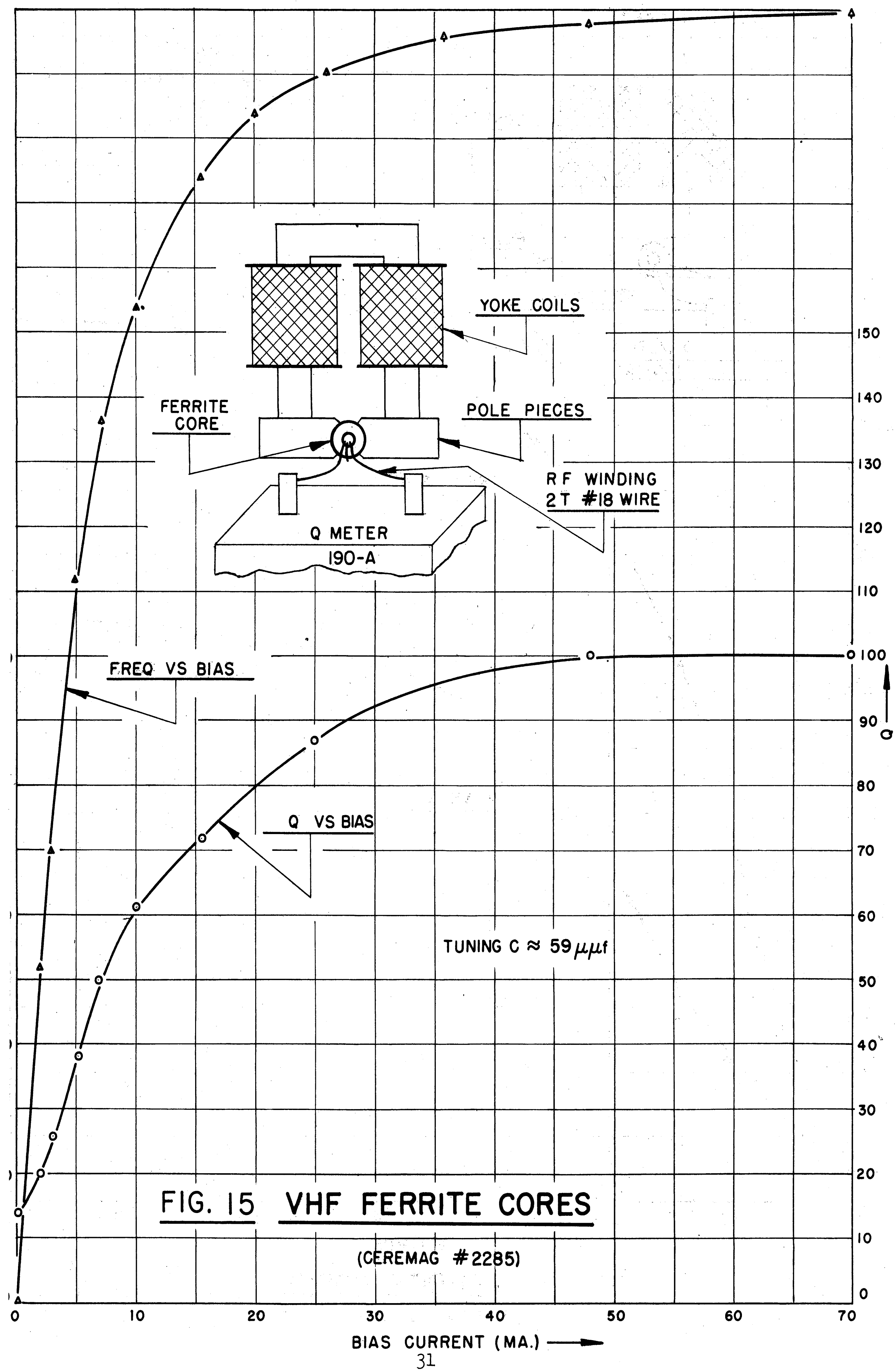


FIG. 15 VHF FERRITE CORES

(CEREMAG #2285)

2262 A-64-138 JF 2-9-56

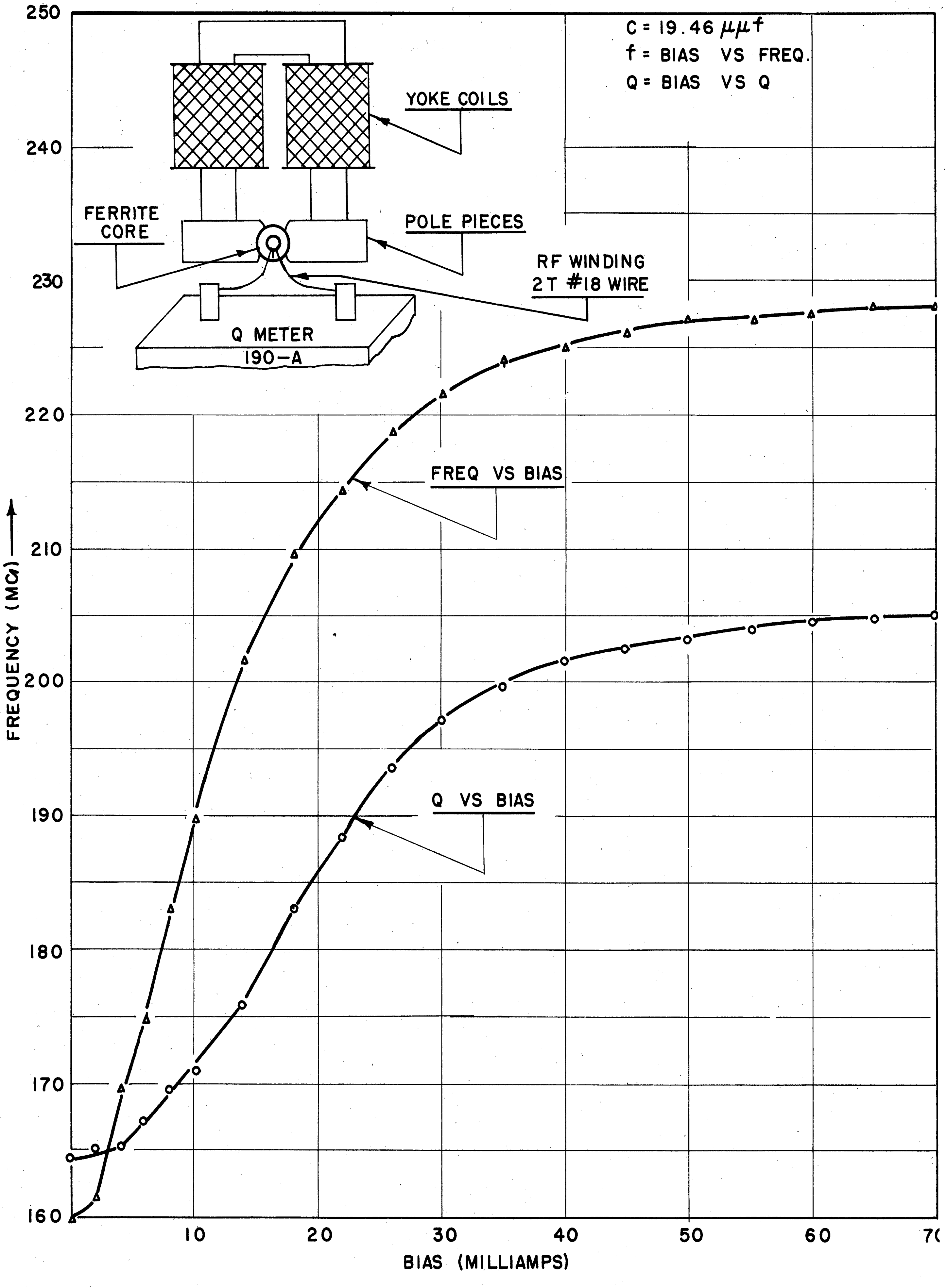


FIG. 16 VHF FERRITE CORES
(MATERIAL G-10)

2262 A-G4-158 M.B. 5-10-56

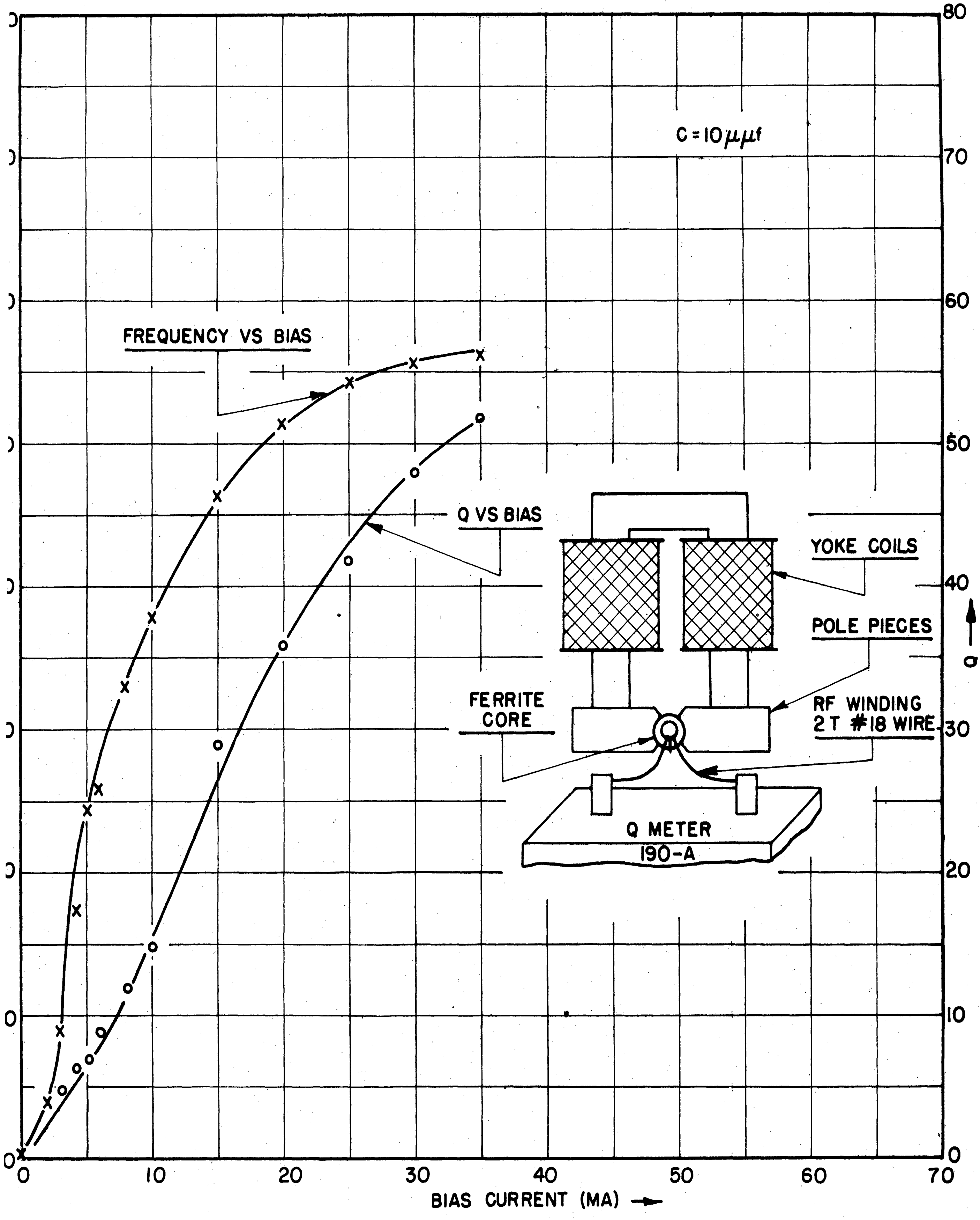


FIG. 17 VHF FERRITE CORES

(MATERIAL G-58)

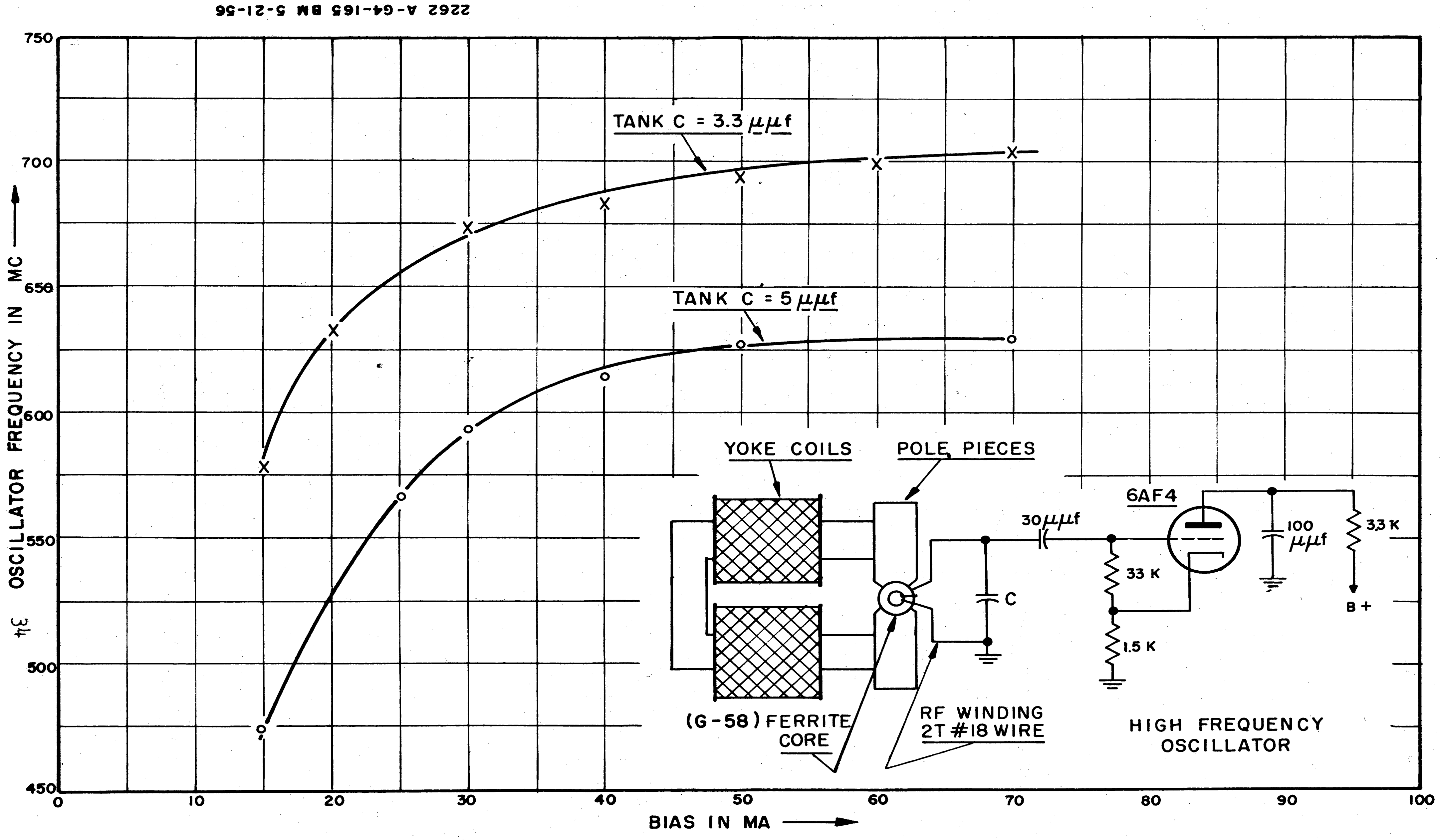


FIG. 18 FERRITE TUNED OSCILLATOR

which will make it possible to measure independently the phase rotations of both the positive and negatively polarized circular waves. It is expected that this device will be useful in the evaluation and comparison of ferrites produced experimentally for this task by the Solid State Devices Laboratory of this University. In this connection Lax[1] has shown that the Faraday Rotation angle per db insertion loss may be defined as a figure of merit for a wide variety of ferrite microwave devices. Although his theory has not been applied to the ferrite tuning of cavities and microwave filters, one can argue intuitively that the concept is probably applicable to tuning devices as well.

Almost all current research in the application of ferrites to the wide range tuning of cavities and filters has employed a purely experimental approach. There is good reason for this. All but the simplest boundary value problems involving ferrites in cavities and waveguides have yet to be solved. Perturbation theory has been used to give approximate solutions for cases where the anisotropic effect of the ferrite can be assumed to be relatively small. Of course, where wide tuning ranges are of interest (greater than 1%) then this theory is of little value and an exact solution is required. The approach taken here is to consider a basic experiment for which one might expect the theory to be reasonably simple and which could serve as an intermediate step in the design of more nearly optimum tuning devices. The basic experiment is diagrammed in Fig. 19. The signal generator provides an incident $TE_{10}$ wave which is reflected by the ferrite slab filling the cross-section of the X-band guide. The measuring program consists of varying the DC magnetic field and frequency so as to keep the standing-wave minimum stationary. The frequency thus measured can be termed the resonant frequency and approaches that for a resonant cavity as the Q of the ferrite increases.

---

[1] B. Lax, "Frequency and Loss Characteristics of Microwave Ferrite Devices," Symposium on Microwave Properties and Applications of Ferrites, Harvard University, Cambridge, Mass., April 3, 1956.

2262 A-S4-82 BM 8-2-56

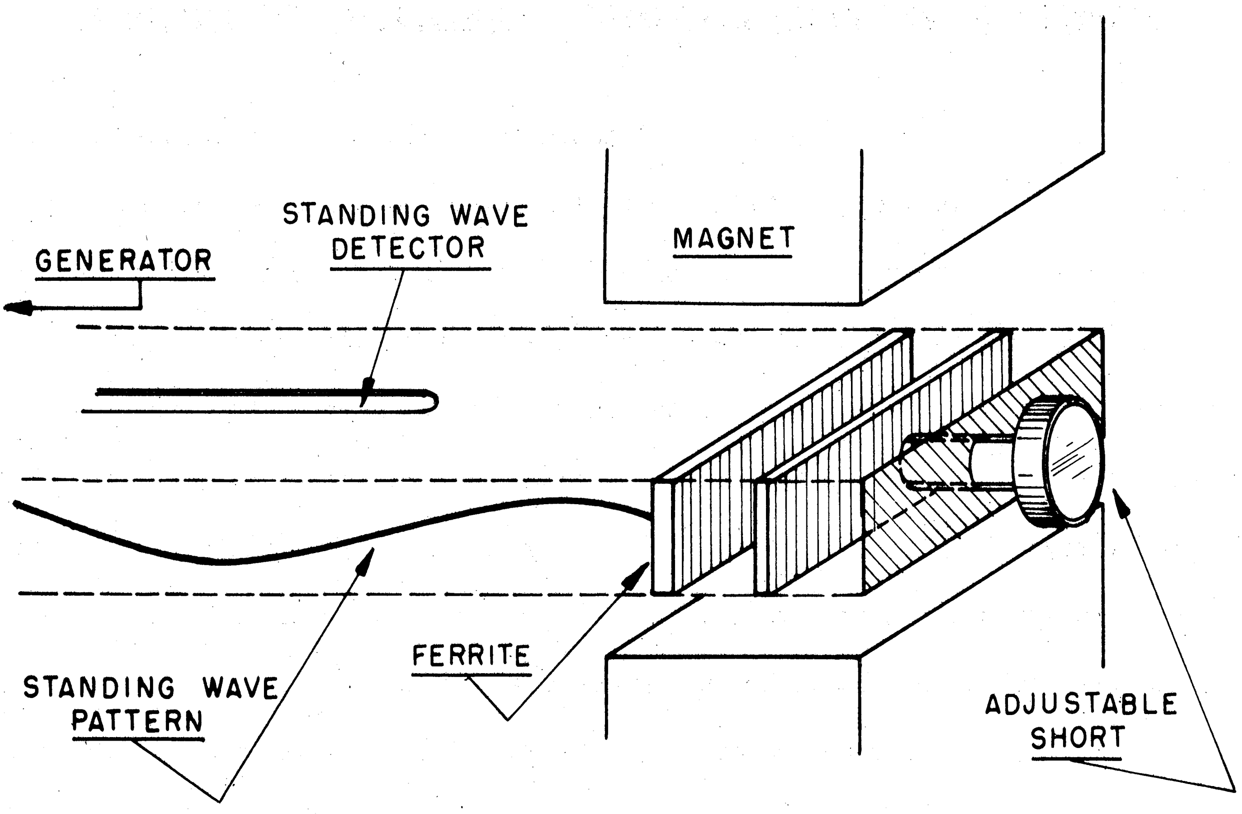


FIG. 19 BASIC TUNING EXPERIMENT

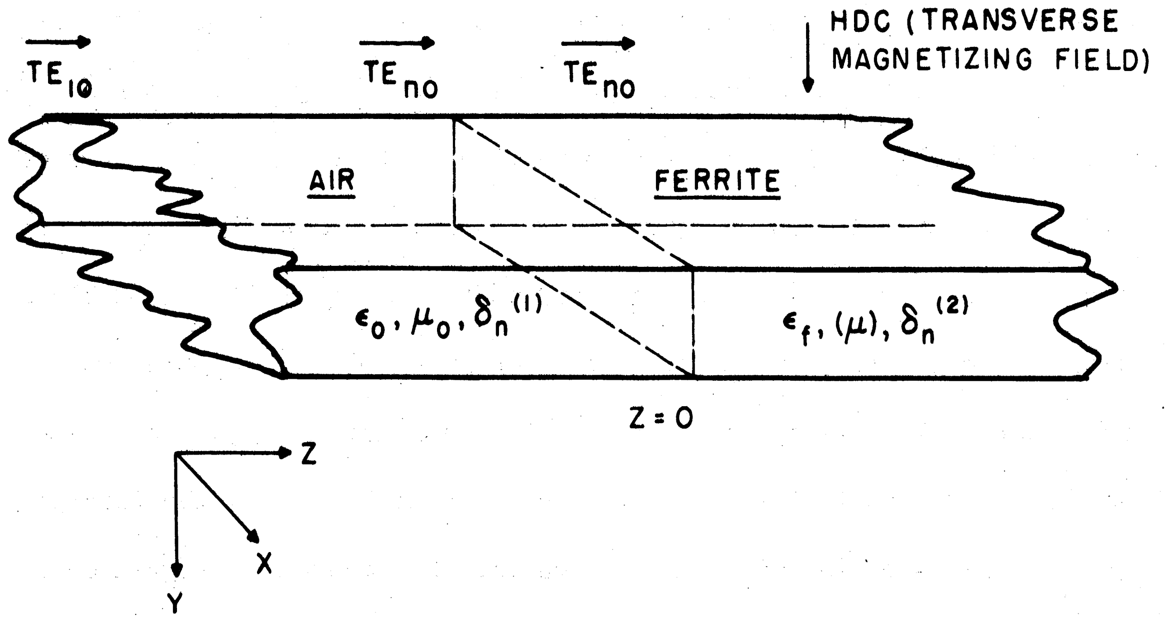


FIG. 20 REFLECTION FROM A FERRITE IN A RECTANGULAR WAVE GUIDE

The theoretical boundary-value problem which is basic to the above experiment is illustrated in Fig. 20 . The ferrite is assumed to fill the rectangular guide for all z > 0. In other words there are no waves incident to the interface from the right. The $\overrightarrow{TE}_{10}$ wave incident from the left gives rise to an infinite series of reflected and transmitted waves denoted by $\overleftarrow{TE}_{no}$ and $\overrightarrow{TE}_{no}$, respectively. Thus the effect of the ferrite appears to be similar to that of a discontinuity in an air-filled guide. However, there is an important difference in the behavior of the ferrite. The ferrite creates reflections by virtue of an "electrical" discontinuity in the character of the waves which propagate in air and in the ferrite. It can be shown that the propagation of $TE_{no}$ waves in a ferrite-filled guide with transverse magnetization takes place according to the equations[1]:

$$
\begin{aligned}
E^{(2)}_{yn} &= A_n \sin k_n x \\
H^{(2)}_{xn} &= - \frac{A_n k_n K}{\omega(\mu^2 - k^2)} \cos k_n x + j \frac{A_n \mu \ \gamma_n^{(2)}}{\omega(\mu^2 - K^2)} \sin k_n x \qquad (1) \\
H^{(2)}_{zn} & \quad \frac{A_n K \gamma_n^{(2)}}{\omega(\mu^2 - K^2)} \sin k_n x + j \frac{A_n k_n \ \mu}{\omega(\mu^2 - K^2)} \cos k_n x
\end{aligned}
$$

where $k_n = \frac{n\pi}{a}$

$$\gamma_n^2 \quad \sqrt{k_n^2 - \omega^2 \epsilon_f \frac{\mu^2 - K^2}{\mu}}$$

and $\mu$ and K are components of the permeability tensor defined by

---

[1] H. Suhl and L. R. Walker, "Topics in Guided Wave Propagation Through Gyromagnetic Media," Part II, BTSJ, Vol. 33, pp. 939-986, July, 1954.

$$(\mu) \quad \begin{pmatrix} \mu & 0 & -jK \\ 0 & \mu_o & 0 \\ jK & 0 & \mu \end{pmatrix}$$

It can be seen that each component of the magnetic field in the ferrite has a real and imaginary component each with a different spatial dependence. This will give rise to a complex electric field vector at the interface which, in contrast with result for geometric discontinuities, does not vary sinusoidally with time. Matching boundary conditions at the interface in the usual manner can be shown to lead to the following integral equation:

$$\sin\frac{\pi x}{a} = \pi/a \sum_{n=2}^{\infty} \left(Y_n^{(1)} + Y_n^{(2)}\right) \int_0^a E(x') \sin\frac{n\pi x'}{a} \sin\frac{n\pi x}{a}\, dx' + \frac{M\pi}{a} \sum_{n=1}^{\infty} n \int_0^a E(x') \sin\frac{n\pi x'}{a} \cos\frac{n\pi x}{a}\, dx' \qquad (2)$$

where $Y_n^{(1)} = \dfrac{\gamma_n^{(1)}}{j\omega\mu_o}$

$Y_n^{(2)} = \dfrac{\gamma_n^{(2)}}{j\omega}\left(\dfrac{\mu}{\mu^2-K^2}\right)$

$\gamma_n^{(1)} = \sqrt{K_n^2 - \omega^2 \epsilon_o \mu_o}$

$M = \dfrac{\pi}{a\omega}\,\dfrac{K}{\mu^2-K^2}$

E(x) is proportional to the complex electric field at the interface.

To the author's knowledge a complete solution of Eq 2 for all values of $\mu$ and K has not been found. Epstein[1] has exhibited a solution to this problem found by the method of successive approximations but this approach assumes that the anisotropy of the ferrite is small; that is, $K << \mu$. The complete solution to this basic boundary value problem is considered fundamental not only to the understanding of the tuning problem but to the understanding of other existing and contemplated devices which depend upon the interaction of a ferrite with microwave energy. Effort will be devoted to this objective during the next period.

## 4. CONCLUSIONS

The objectives for the period have been met and all phases of the work appear to be progressing satisfactorily.

## 5. PROGRAM FOR THE NEXT INTERVAL

a) Complete comparison of bead vs vacuum package for miniature nonlinear capacitors.

b) Construct receiver heads using the new Michigan Hi-Q capacitors.

c) Complete report on PETR PAN receiver.

d) Work with Task 8 group on application of ferroelectric tuning to CMJS.

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[1] P. S. Epstein, Theory of Wave Propagation in a Gyromagnetic Medium," Rev. Mod. Phys., Vol. 28, No. 1, pp. 3-17, Jan. 1956.

e) Continue investigation of distributed constant circuits for tuning between 100 and 1000 mc using ferroelectric ceramics.

f) Continue investigation of duo tuned oscillator as a means of extending the tuning range at VHF.

g) Study tuning of external cavity klystron oscillator with ferrites.

h) Attempt manufacture of ferrite with high Q at zero bias.

i) Continue improvement of Michigan Hi-Q ferroelectric material.

j) Continue study of microwave applications of ferroelectric ceramics.

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