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MINIATURE NONLINEAR CAPACITORS

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ABSTRACT

Very small ferroelectric capacitors have been constructed which have the property of wide changes in capacity with applied dc voltage. These tiny capacitors have relatively low losses up to a few hundred megacycles and can be employed in voltage tuned oscillators up to 400 megacycles. Special techniques were developed for the construction of these capacitors to reduce the losses at high frequency, and prevent voltage breakdown.

MINIATURE NONLINEAR CAPACITORS

1. INTRODUCTION

Nonlinear ferroelectric capacitors have been commercially available for several years. A typical commercial capacitor consists of a circular ferroelectric ceramic wafer 1/4 inch in diameter and 20 to 40 mils[1] thick.

The ceramic usually used is a buffered barium-strontium titanate. The addition of about 20% strontium lowers the Curie temperature to about 30° C., and the buffer material is added to reduce the capacitance variation[2] over the design temperature range, 0° C. to 100° C.

The sides of the wafer are plated or printed with circular silver electrodes. These do not extend to the edges of the wafer, but a clear margin of one or two mm is generally left. Electrode wires are attached, usually by soldering, and the entire unit is coated with an insulating jacket which gives mechanical strength to the unit.

Because of a fundamental property of all ferroelectric materials, these capacitors show a variation of capacitance with electric field, the maximum capacitance being obtained at zero field. As a DC voltage is applied, the capacitance is reduced.

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1. One mil = .001 inch.
2. Adding buffer material also lowers the tuning range of the capacitor, unfortunately.

With the application of a field of 100 volts per mil[1] the capacitance is reduced in some cases to as much as 10% of the initial value.

This property is the basis for the electric tuning of resonant circuits, and commercial capacitors have been used for several applications including electric tuning and dielectric amplifiers[2]. However, for wide range electric tuning at very high frequencies (20 to 400 mc) the presently available commercial units are not satisfactory.

First, the minimum starting value of capacity for these units is of the order of 100 μμf, whereas much lower capacities are desirable for some applications. Also, the active electrode area does not completely cover the dielectric and this results in a capacitor which is more lossy than one in which the dielectric faces are completely covered by the electrodes. In addition, the field sensitivity of capacity is increased when the electrodes completely cover the active material; this is due to the reduction of the high capacity strays. When the electrodes do not extend to the edges, the voltage sensitivity of the fringing capacity is not as great as thatfor the material between the electrodes (due to the longer field path required) so that the effective tuning is reduced.

In addition to the above, it may be noted that for some applications starting capacities of the order of 10 μμf are required, together with a 5 to 1 change in capacity for an applied field of 100 volts per mil. Also, it is desirable to limit the thickness of the dielectric to about 20 mils (.020") so that large tuning voltages are not required. Since the nonlinear dielectrics have

1. This greatly exceeds the voltage rating set by the manufacturer. Commercial capacitors are so constructed and so rated that little change is observed in capacitance within the ratings.
2. Diamond, H. and Orr, L. W., "Interim Report on Ferroelectric Materials and Their Applications," Technical Report No. 31, Electronic Defense Group, University of Michigan, July, 1954.

dielectric constants of the order of 5,000, and since very low capacities are required, it can readily be realized that the capacitors will be extremely small in size.

It has been found to be most convenient to fabricate the capacitors in our own laboratories and to do so in sufficient quantity to implement a large number of experiments and applications. The fabrication techniques have been developed in order to optimize the use of presently available materials for specific applications and specific experiments.

Two types of units which have been constructed for special applications are:

1) The single, low capacity unit, and

2) the multi-unit or "stack", for use in applications where a large RF field is encountered.

Both types are described in detail below. The tools and instruments used for their construction are those commonly found in the laboratory.

2. FABRICATION PROCEDURE FOR SINGLE UNITS

In view of the requirements pointed out in Section 1, it has been found that the optimum thickness of the dielectric is between 10 and 20 mils. On the other hand, the initial capacity required is often in the range 10 to 20 μμf. That the completed units will occupy an extremely small volume can be understood from the above requirements and the fact that the dielectric constant of the material is of the order of 5,000.

Commercially available ferroelectric ceramics are used. This material is available in slips 10 to 20 mils thick and one or two centimeters square, or in discs about one centimeter in diameter with silver electrodes on opposite faces, each electrode being about one mil thick. In making the electrodes a silver

conducting paint is fired onto the ceramic surface at about 800° C. for fifteen or twenty minutes to remove the organic binders in the paint. This leaves the surface of the ceramic with a metallic silver electrode--usually with a small oxidized layer which must later be removed[1]. For convenience, the step by step fabrication procedure is given.

1. The first step in the fabrication is the removal of the oxide layer from the silver electrode on the ceramic plate. This is done by burnishing the electrode surface with a stiff wire brush or burnishing tool.

2. After the oxide layer has been removed, and the silver electrode appears rather bright, an ordinary lead-tin solder is rubbed onto the surface until the surface becomes dull in appearance. A microscopic examination of the surface at this point in the procedure shows that the solder forms into many small dark areas. It has been found that the solder applied to the electrode surface in this manner greatly facilitates the adhesion of the lead wires that are ultimately to be attached to the electrodes. The above processes are shown in Figures 1 and 2.

3. After the solder has been applied the ceramic is cemented onto a microscope slide in order to facilitate further handling. It has been found that a glass or porcelain cement is the most suitable; however, polystyrene cement and wax have been used successfully.

4. After the cement has hardened, the ceramic plate is cut up into dice, the size being dependent on the capacity desired (See Figure 3). The cutting tool is either a diamond or carborundum saw, although an ultrasonic cutting device has

1. Electrodes may also be applied using vacuum plating techniques, with a considerable improvement in the apparent dielectric properties (see, e.g., Technical Report No. 31, Diamond, H. and Orr, L. W., "Interim Report on Ferroelectric Materials and Their Applications," Electronic Defense Group, University of Michigan, July, 1954). However, certain technical details involved have not yet been completely worked out so that these techniques will not be considered here.

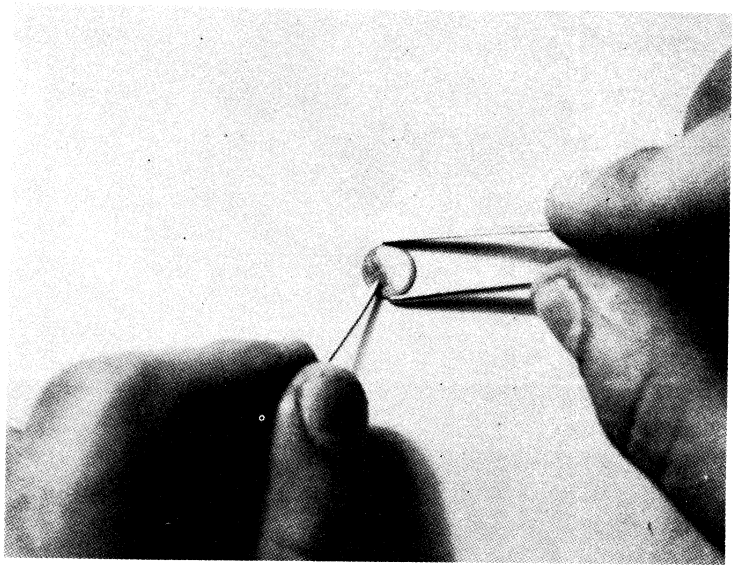


FIG. 1

BURNISHING ELECTRODE SURFACE

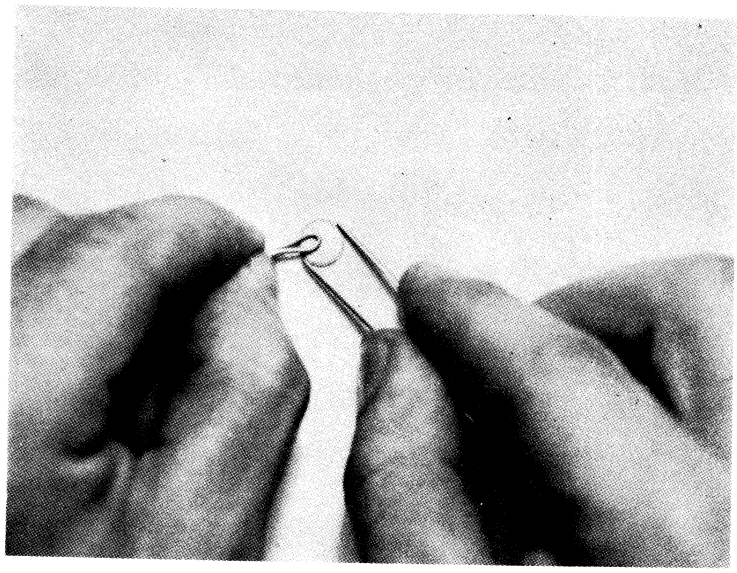


FIG. 2

APPLYING SOLDER TO ELECTRODE SURFACE

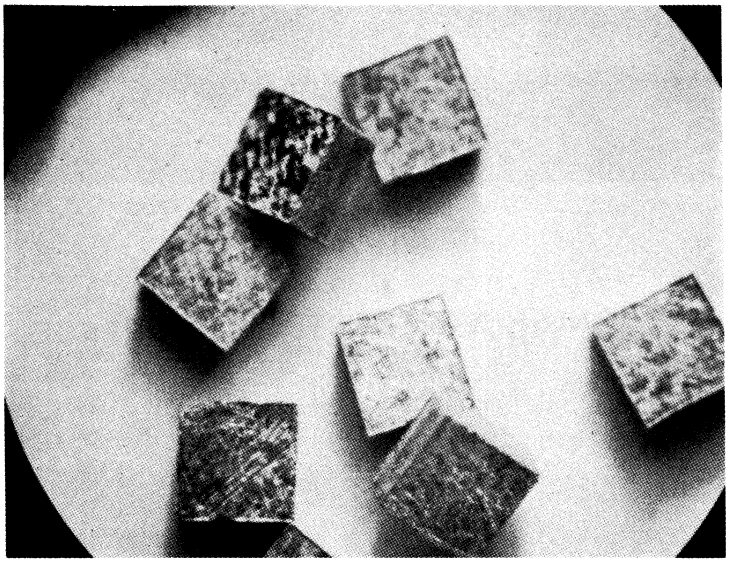


FIG. 3

CERAMIC DICE

been suggested and should serve very well. Examination of the dice shows that the entering edge of the cut is usually very clean and smooth, but the saw pulls out ceramic grains as it leaves the far surface. This can be eliminated, or considerably minimized, by requiring the saw to take a large number of passes in cutting through the material. An ultrasonic cutter would probably eliminate this difficulty.

5. The dice are then removed from the microscope slide by a solvent for the cement used. After the cement has been removed from the dice, they are ready for assembly.

6. In attaching leads to the electrodes it has been found convenient to start with a short piece (about 6 inches) of No. 18 or 20 stranded hook-up wire. About one inch of the insulation is removed from one end of the piece of wire. The strands are then fanned out as seen in Figure 4. The ends of the strands are then dipped in flux and are tinned by dipping in molten solder.

7. The small cubes of ceramic are spread out over the working area and are picked up one at a time with the ends of the stranded wire. This is accomplished as shown in Figure 4. The end of a wire strand is held against the electrode area of a die while heat is applied to the wire, about 1/4" away from the electrode, by means of a small soldering pencil. This procedure is continued until each strand of the wire is attached to a cube of ceramic. The work must be done under a microscope[1] for the very small samples.

8. Leads are attached to the electrodes on the opposite face. This is done in the same manner in which the first leads are placed onto the electrodes. About one inch of insulation is again stripped off the end of the stranded wire and the individual strands are separated and tinned as before. Each strand is sweated onto the other electrode, as described above, and is then cut free of the

1. A low power steroscopic microscope having an erect image is the most satisfactory for performing these operations.

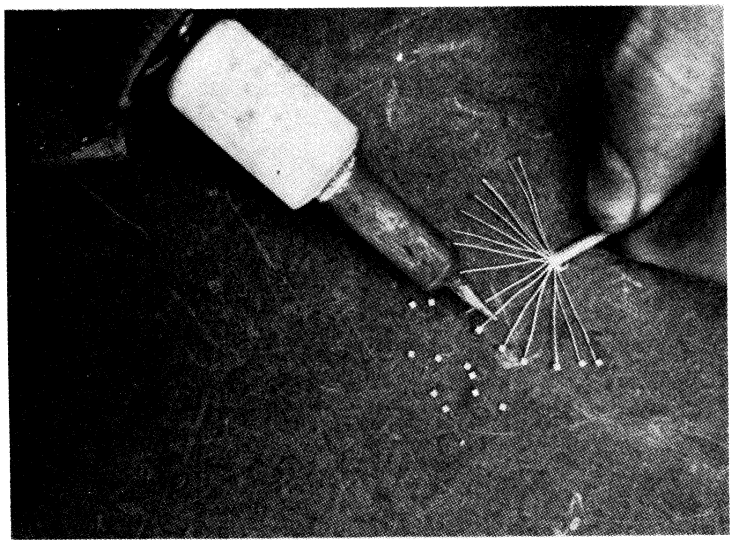


FIG. 4

ATTACHING LEADS TO DICE

main body of the wire leaving a lead length of about one inch. This procedure is continued until all the ceramic dice have been provided with their second lead wire (see Figures 5 and 6).

9. The units, still attached to the main cable by one lead, are then washed to remove the solder fluxes, and to clean up the edges of the ceramic, preparatory to "potting" the capacitors in plastic beads. It has been found that a good washing procedure is to swirl the units first in a beaker containing acetone (see Figure 7) for about five minutes and then to repeat the process in a beaker containing a solvent (such as toluene) for the rosin. The units are again washed in acetone and are then allowed to dry.

10. It has been found that even a very slight amount of moisture potted into the capacitor causes a very lossy unit and often results in a voltage breakdown at the surface. Therefore, it is necessary to make sure that the units are extremely dry before the potting material is applied. This is accomplished by heating the units to about 110° C. for fifteen or twenty minutes prior to potting. Also it is helpful to keep the ceramic pieces stored in a dessicator while awaiting fabrication.

11. The capacitors are then removed from the oven and the potting material is applied while the units are still warm (Figure 8), or after they cool in a dessicator. Since the electrode area comes to the edge of the ceramic material, it is essential that a potting material be applied to prevent an air-path breakdown. For experimental purposes, polystyrene "Q-dope" has proved satisfactory, although special potting resins and thermosetting plastics have been used whenever the moisture conditions (e.g., due to high humidity) become particularly troublesome. The polystyrene dope is first applied by brush in a thin coat to seal out any moisture. A heavier second coat is applied after the initial coat has dried.

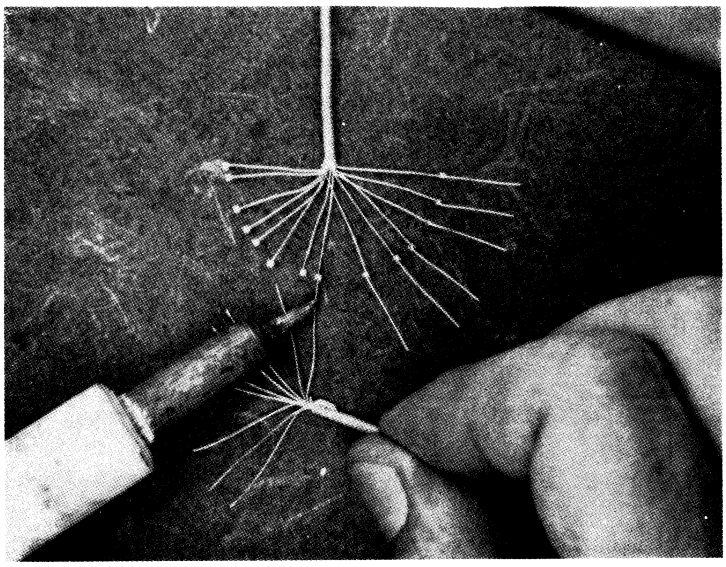


FIG. 5

ATTACHING SECOND LEAD TO DICE

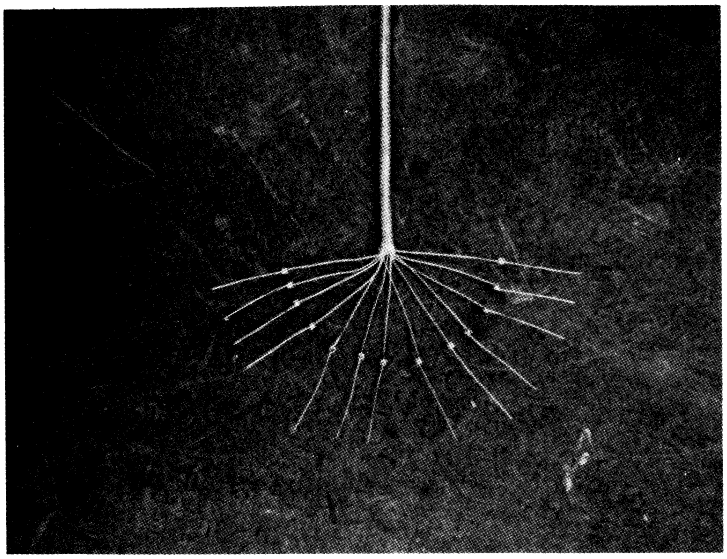


FIG. 6

DICE WITH BOTH LEADS ATTACHED

FIG. 7
WASHING THE UNITS

FIG. 8
POTTING THE UNITS

It has been found convenient to color code the finished capacitor to aid in identification.

12. The individual capacitors are clipped off from the main wire cable and are tested. This test consists of subjecting the units to a 60 cycle ac field of about 75 volts per mil (peak). The polarization - vs.- electric field hysteresis loop is observed on an oscilloscope as the field is applied. If the loop remains steady and thin, and the "horns" of the loop are sharp, the unit is considered satisfactory. Moisture or dielectric surface conduction effects can give rise to almost eliptical hysteresis loops even at low fields. Usually such a unit will break down upon application of high electric fields. Figure 9(a) shows the hysteresis loop of a unit with an equivalent of 100 megohms leakage resistance. Some samples are also subjected to a life testing schedule using alternating fields of 75 volts per mil peak superimposed on a DC biasing field of 75 volts per mil giving a maximum field of 150 volts per mil. Figure 10 shows the schematic of the life-testing unit.

3. FABRICATION PROCEDURE FOR "STACK" UNITS

For applications in which the nonlinear capacitors are required to handle a large amount of power, or where the radio frequency fields are rather high (e.g., in power oscillators), several capacitors may be placed in series across the RF field with the series "stack" being subjected to a parallel biasing field. A schematic diagram of a circuit utilizing a stack unit is shown in Figure 11.

In order to keep the multi-unit physically compact, and at the same time to allow for rapid heat dissipation, the capacitors are assembled as shown in Figure 12. Multi-units of from two to sixteen sections have been constructed.

Construction of the multi-units is very simple. The individual capacitors are prepared as described in Section 2 but are not potted. Flat copper strips

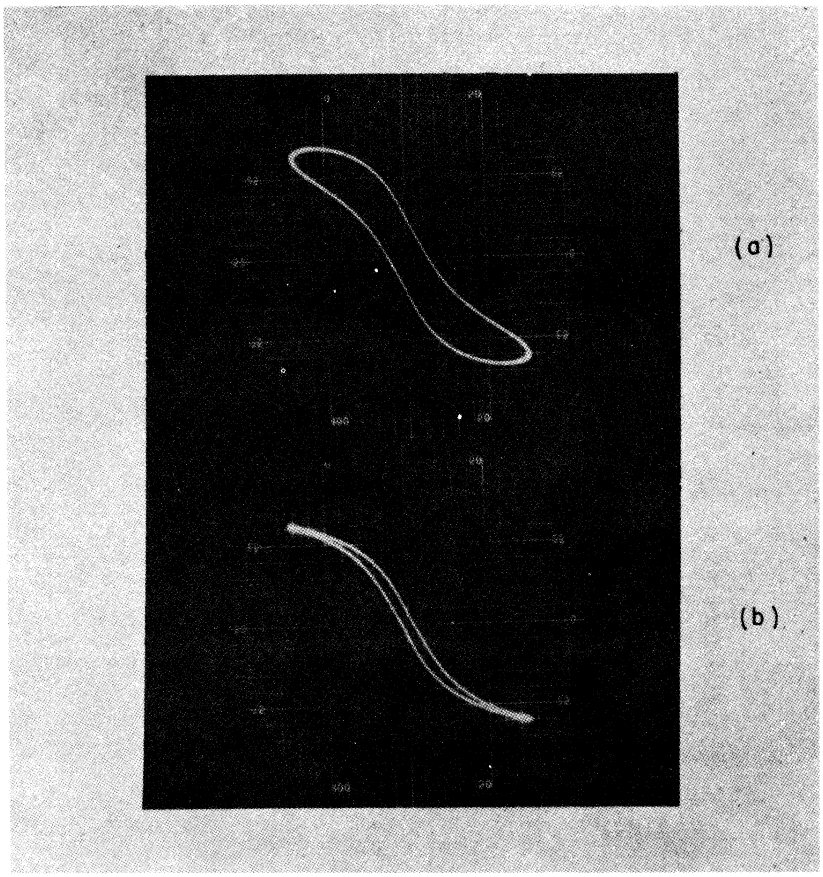


FIG. 9

P-E AND HYSTERESIS LOOP FOR A TYPICAL MINIATURE FERROELECTRIC CAPACITOR
(a) UNSATISFACTORY CAPACITOR
(b) SATISFACTORY CAPACITOR

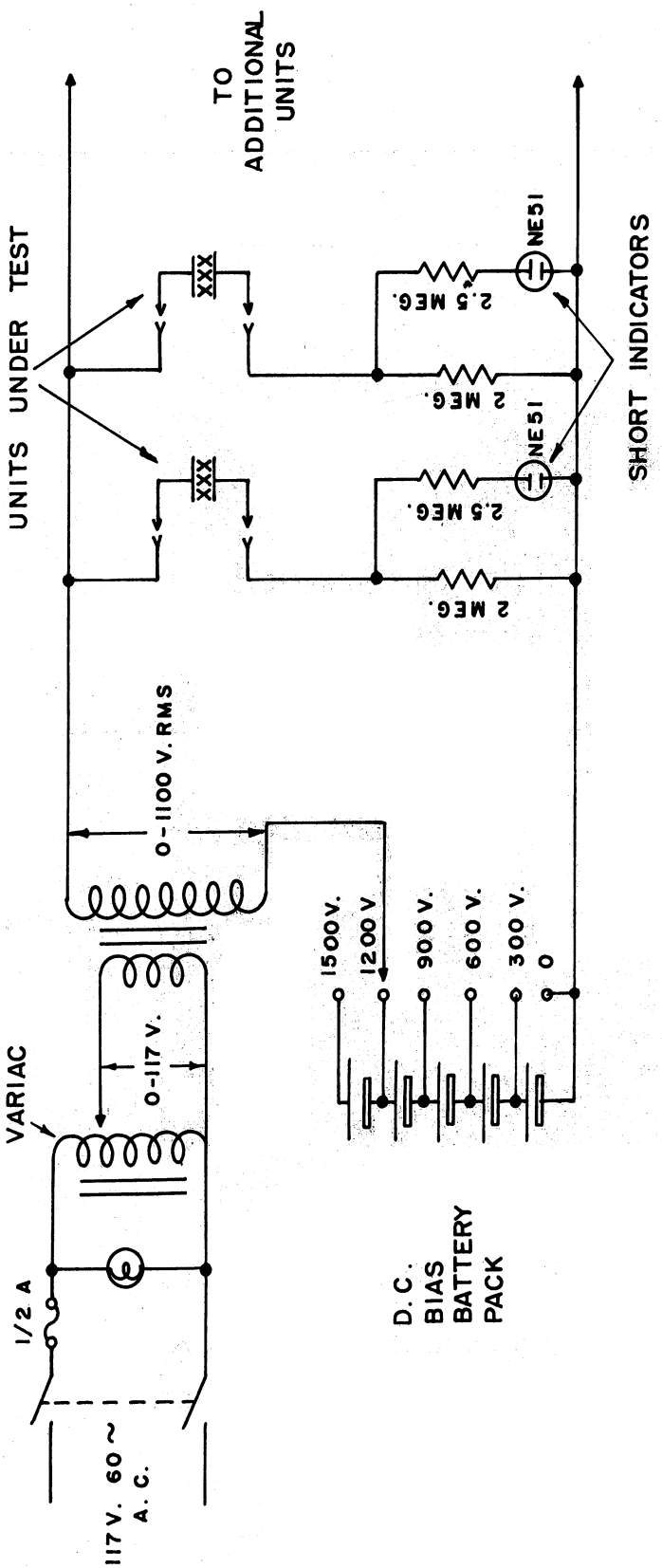


FIG. 10

CAPACITOR LIFE TEST UNIT

FIG. 11

CIRCUIT OF A LOW CAPACITY STACK
UTILIZING DECOUPLING RESISTORS

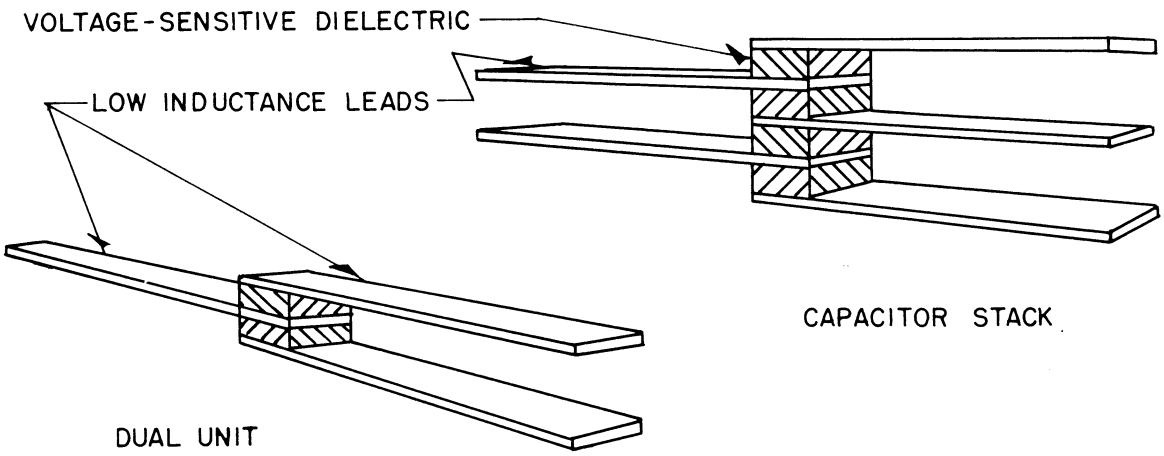


FIG 12

CONFIGURATION OF STACK CAPACITOR

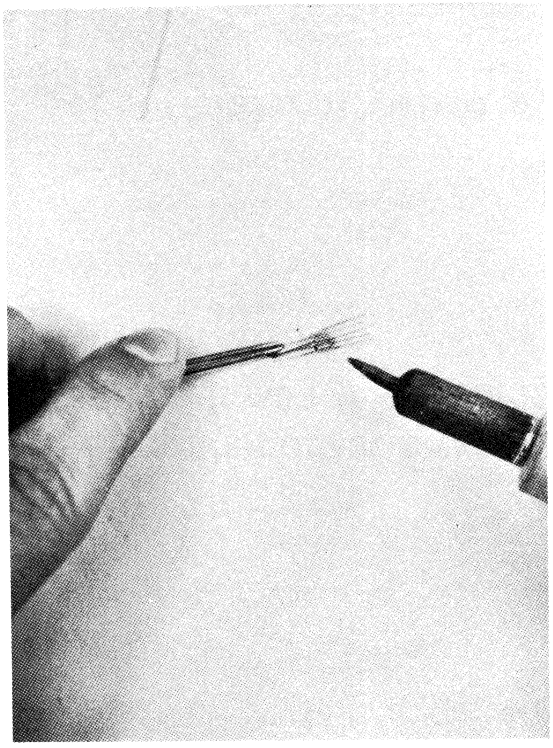


FIG. 13

ASSEMBLY OF STACK CAPACITOR

are then cut to the width of the ceramic squares and to about three or four times the length. These strips are tinned with solder. The ceramic squares are then placed against the metal strips and the solder is melted by holding a small soldering iron against the metal strip about an eighth of an inch away from the ceramic, until the metal strip and the capacitor are "sweated" together. Two methods of assembling the units have been tried. First, the ceramic and metal strips are assembled by clamping the stack together prior to soldering. Second, the units are assembled by soldering one ceramic square into place before proceeding to the next one. These methods seem to work equally well.

After the stack is assembled it is washed, heated, and potted as described in Section 3.

It should be noted that the dielectrics are tested (see step 12, Section 2) before they are assembled into the stack, and each individual section of the stack is tested after assembly. The assembly of the capacitor stack is shown in Figure 13.

4. APPLICATIONS

The Tuned Resonant Circuit

A capacitor tuning element consists of a pair of ferroelectric capacitors in series. When such an element is connected across an inductance, a voltage-tunable resonant circuit is obtained.

The resonant frequency is controlled by applying a variable dc voltage to the junction of the two capacitors with a ground return at one end of the coil.

The Tuned Low-Power Oscillator

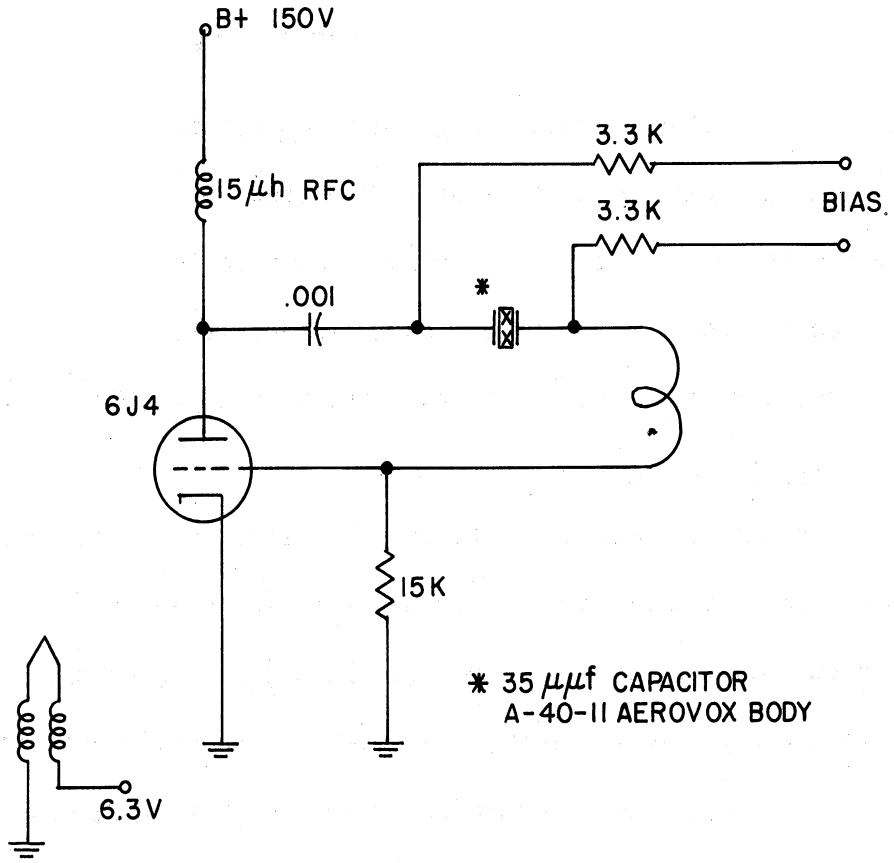
Using a circuit as described above, it has been possible to develop dielectric-tuned wide-range V.H.F. low power swept oscillators. In the 25-150 mc

range, the Colpitts or Hartley circuit using a high g_m triode will give tuning ratios of better than 2:1 with power outputs in the order of 50 milliwatts. In the 150-400 mc range the most satisfactory circuit appears to be the ultra-audion using a series-tuned resonant tank circuit and a high g_m triode. Figure 14 shows schematics of typical circuits designed to tune the ranges 50-385 mc.

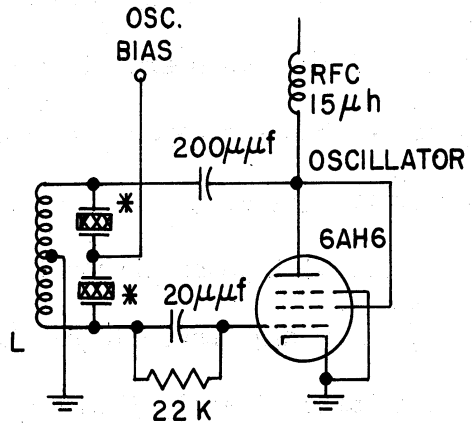
Dielectric Tunable Power Oscillators

When large signal phenomena are to be considered, as in the case of high-power oscillators, the RF voltage applied to any tuning element must be restricted in order to avoid excessive dielectric heating. In order to accomplish this, several capacitors are arranged as shown in Figure 15. Here the capacitors are in series across the RF signal and in parallel with the biasing field. The resistors are used for decoupling. With this arrangement the RF field is divided among the capacitors, but no increase in the voltage required for tuning is necessary. This push-pull circuit proved to be superior to the other circuits in the range of 40 to 100 mc. The capacitor stacks used were between 100 and 200 μμf.

The capacitors must not be allowed to heat excessively because the capacitance range, and hence tuning, is drastically reduced at temperatures much above the Curie point. When the oscillator was operated at high power but pulsed on a sufficiently small work cycle so that the capacitors remained relatively cool, the tuning range and power output were about the same as for low power cw operation; i.e., a tuning range of 2:1 with power output in the order of 100 mw. When the oscillator was operated cw at a high power level the tuning range was reduced to 1.1:1 with a power output of approximately 3 watts.



(a) ULTRA AUDION 150-385 MC



(b) COLPITTS 50-150 MC

FIG. 14 TYPICAL CIRCUITS UTILIZING MINICAPS

FIG. 15

SWEPT POWER OSCILLATOR

2262 A-S4-75 JF 12-5-55

5. CONCLUSIONS

The techniques for the fabrication and testing of miniature ferroelectric capacitors, on a laboratory scale, have been described.

It has been pointed out that dielectric tuning of lumped circuits has been achieved at very high frequencies using ferroelectric capacitors as the tuning element. In order to take advantage of the properties of the commercial dielectric material available at present, it is necessary to select the optimum material for the particular capacitor application. A method of doing this is described in Technical Report No. 53, "ϵ-T-E Surfaces of Ferroelectric Ceramics" by L. W. Orr.

A more detailed description of some applications of these non-linear materials is presented in an article appearing in Proceeding of the IRE, September, 1955, entitled, "The Application of Dielectric Tuning to Panoramic Receiver Design, Design," by T. W. Butler, Jr., W. J. Lindsay, L. W. Orr.

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