A DIELECTRIC AMPLIFIER

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Carroll E. Weller

1954

This is to certify that the

thesis entitled

"A Dielectric Amplifier"

presented by

Mr. Carroll E. Weller

has been accepted towards fulfillment
of the requirements for

M.S. degree in E.E.

J A Strelzoff
Major professor

Date August 24, 1954

A DIELECTRIC AMPLIFIER

By

Carroll E. Weller

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Electrical Engineering

1954

THESIS

ACKNOWLEDGMENT

The author wishes to express his thanks to Dr. J. A. Strelzoff for his valuable suggestions throughout the development of this thesis.

A DIELECTRIC AMPLIFIER

By

Carroll E. Weller

AN ABSTRACT

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Electrical Engineering

1954

Approved ________________________

PREFACE

This thesis is concerned with barium-titanates used as electronic circuit elements.

Some of the characteristics and applications of these ceramics as used in circuit components are described.

A laboratory model of a dielectric amplifier was built. The experimental operation of this amplifier is reported upon and accompanied with a mathematical analysis of the circuit.

TABLE OF CONTENTS

CHAPTER I

Introduction

Shortcomings of electron tubes in certain applications have been listed and relisted in the literature. Although tubes hold a prominent place in electronics, people have done a lot of research toward the development of alternative devices for such functions as amplification.

Among the various amplifiers that have been developed are resistor and crystal amplifiers, magnetic amplifiers, transistors and dielectric amplifiers.

The dielectric amplifier can probably best be described by pointing out the duality that exists between it and the magnetic amplifier. The dielectric amplifier seems like a good device to supplement the magnetic amplifier in that it is a relatively high impedance device, and it requires the same type alternating-current supply and rectifiers used in a magnetic amplifier. In each case a low-power change in one circuit causes a high-power change in another.

In the magnetic amplifier a change in control current changes the permeability of a core material, and in the case of the dielectric amplifier the reactance of the nonlinear capacitor is changed by applying a control voltage across the dielectric. These changes in reactance are in turn used to produce changes in the current flowing in an alternating-current power circuit.

Non-Linearity

Before describing the materials themselves, let us define terms and present a general discussion of non-linearity. It is convenient to consider a capacitor in the form of a thin sheet with metal electrodes on its opposing faces.

Non-linearity refers to the fact that the total charge induced on this capacitor does not change proportionally with a voltage applied to it if the thin sheet is of non-linear dielectric material. The curve of charge versus voltage, or, more fundamentally of polarization of electric displacement versus field strengths, is not a straight line, that is, it is non-linear. If a complete cycle of positive and negative voltages is applied, the result is a hysteresis loop similar to Figure 1.[1] While the hysteresis loop is not included in the definition of non-linearity, it is exhibited by all the non-linear dielectrics and thus may be considered an inherent condition.

---

[1] Glenco Corporation. Phamphlet, Metuchen, New Jersey, p. 2-3.

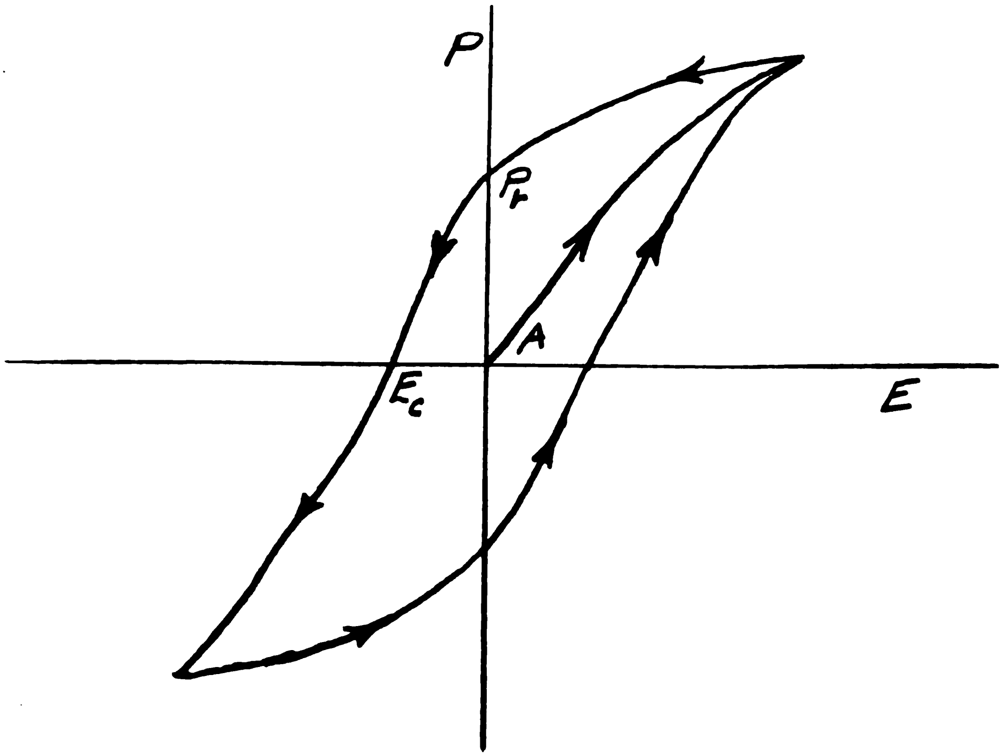


Fig. 1. Ferroelectric Hysteresis Loop

The hysteresis loop can be explained by considering the behavior of the barium-titanate crystal.

At room temperature this crystal has a tetragonal form which is similar to a distorted cube in which one axis, the c axis, is elongated by a spontaneously occurring electric dipole along that direction, while the other two axes, both a axes since they are identical, are shortened. The dielectric constant along the a axes is several times greater than that along the c axes.

Along the <u>c</u> axis the polarization may have two directions, oppositely oriented, which may be called positive and negative. When the voltage along the <u>c</u> axis is varied in sign, the dipole switches from one stable position to the other in turn. Since a finite field is necessary to re-orient the dipole, there is little change in polarization until this critical field is reached. Then there is a rapid change in polarization after which subsequent increase in field strength produces little further change. Upon reversal of the field there is again little change until the field is large enough to switch the dipoles, then the change is large, and then there is little change once more with increases in field in the new direction.

This follows the general pattern of Figure 1.

In the ceramic of which the thin sheet capacitor mentioned above is formed, the barium-titanate crystals are a multitude of tiny particles whose spontaneous dipoles are randomly oriented. Therefore, there is no favored <u>c</u> direction and the statistical average of the elemental orientations cancels to zero. With no biasing electric field, the dielectric constant lies between that characteristic of the <u>c</u> direction and that of the <u>a</u> directions. It is somewhat closer to the <u>a</u> value since the <u>a</u> axes are more abundant.

Referring to Fig. 1 and beginning at point A, there is initially no net polarization before voltage is applied. When a Direct Current bias is placed on the electrodes, some of the dipoles originally oriented otherwise now follow the field and a partial c axis is induced perpendicular to the electrode faces. As a consequence the dielectric constant decreases. As the biasing voltage is increased, more and more dipoles are re-oriented and the dielectric constant continues to decrease as the polarization in the new c direction increases. This proceeds until saturation is approached when a further increase in bias no longer yields a proportionate increase in polarization since the supply of randomly oriented dipoles is becoming exhausted.

In the polycrystalline ceramic many of the elemental dipoles are incapable of being oriented perpendicular to the electrode faces by their position in the ceramic matrix surrounding them. At best they can be electrically strained in the direction of the field.

When the field is reduced these strains relax and some polarization is lost. However, since a large number of dipoles were oriented into a stable condition, they remain so and the charge stored in this manner is not recovered. This makes up the remanent polarization, P_r. When the field is reversed, it requires a certain field strength, E_c, to reduce the polarization to zero and further increase in field switches the dipoles to the reverse direction.

Upon a second reversal of field the curve of polarization versus field duplicates the upper path. It is seen therefore that the point A is not traversed again and that the process is not reversible.

The behavior of a given capacitor can be pictured since its capacitance is proportional to the dielectric constant, K, which is the slope of the hysteresis loop.

Ferroelectric Effect

The hysteresis loops produced by the electric field in dielectric materials are quite like the hysteresis loops produced by magnetic fields within magnetic materials. Therefore, dielectrics are said to exhibit a ferroelectric effect. This is rather confusing as dielectric amplifiers are often referred to as ferroelectric amplifiers although no iron is involved.

Curie Point Dependence

The temperature at which the dielectric constant is the highest is known as the Curie point. This is a major consideration when working with ceramics, as the greatest gain is obtained very near this point. If the Curie point varies with temperature, it follows that the gain is also affected.

The ceramics used in the construction of the amplifier described later in this report had a Curie point occurring near room temperature and no attempt was made to stablize the gain drift due to this cause.

A leveling of temperature response could be achieved by placing in parallel two non-linear capacitors, one with a Curie point above and the other below the intended temperature. Where larger variations in temperature are expected, an operating temperature could be chosen above the highest ambient temperature expected, and maintained with a heater-thermostat arrangement.

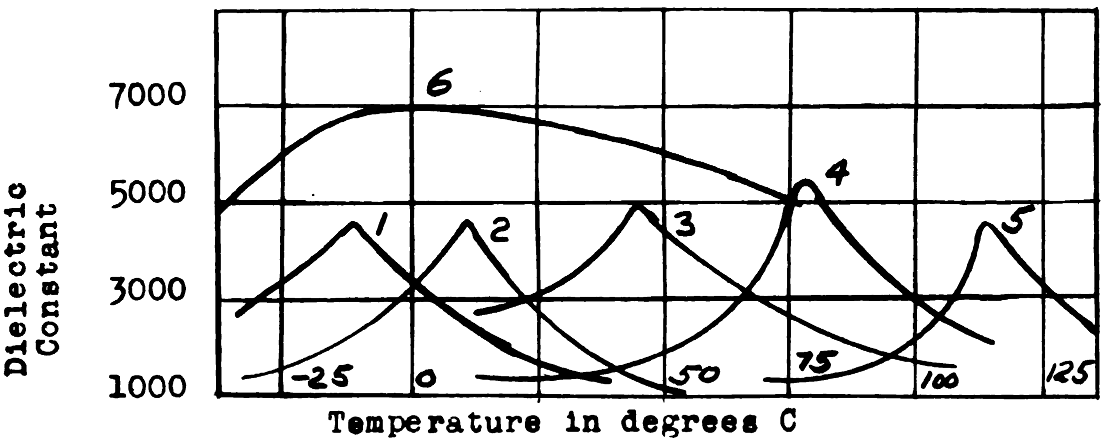
One arrangement might be to apply temperature stabilization by using a piece of the dielectric whose temperature is to be controlled as the temperature-sensitive element in an automatic thermostat.

Shifting the Curie point by changing the ratio of ingredients also provides a means of controlling temperature effects. Strontium-titanate has proved useful for this application.[2]

---

[2] A. M. Vincent, "Dielectric Amplifier Fundamentals," Electronics, 24; December, 1951, 84-88.

Some materials do not depend on the Curie point operation. Barium-lead-zirconate is an example of a material with a stable dielectric constant. These effects can be seen in the curves of Figure 2 plotted at General Electric.[3]



1. 69% Barium-titanate - 28% Strontium-titanate
2. 71% " " - 29% " "
3. 80% " " - 20% " "
4. 87.4% " " - 12.6% " "
5. 100% " "
6. 35% Barium-zirconate - 65% Lead-zirconate

Fig. 2. Temperature Effect on Curie Point

---

[3] <u>Ibid</u>.

The lead-zirconate compositions have a high dielectric constant compared to the titanate compositions. This causes this material to have a slightly lower possible gain, but a more stable gain than the titanate combination.

Vincent reports that indications are that lead-zirconate compositions will be used in many applications now dominated by the titanates particularly where stability is important.[4]

Material

The (Ba-Sr) Ti O_3 is available in the form of small sheets from 2 to 30 mils thick. They can be obtained either as bare ceramic or painted on both sides with a special silver paint. This paint is made of finely divided silver, plastic, thinner and constituents for a vitreous binder. After drying, the painted ceramic is fired at about 1,300°F. The plastic binder is driven off, while the silver and glass constituents form a combination having nearly the conductivity of silver but vitreous enough to adhere firmly to the titanate ceramic. In this form, the electrode will take solder. However, great care must be taken since the silver is likely to go into solution with the lead and tin if the molten solder is kept in contact with the electrode for more than a few instants.

---

[4] Ibid.

There is available a plastic-cored solder consisting of lead and tin with about 4 percent of silver. The presence of the silver helps to reduce the tendency to dissolve the electrode.

Dielectrics suitable for circuit applications at the higher frequencies and with small signal voltages must have small capacitance values and must be made from very thin materials so that the signal voltage gradient will be adequate.

This immediately presents a problem since a capacitor having a value of 100 $\mu\mu$fd. with a dielectric material 0.005 inches thick and having a dielectric constant of 4,000. would be approximately 0.0236 inches square or less than 1/32 inch on each side.

CHAPTER II

Basic Principles of Non-Resonant Amplifiers

The fundamental principles underlying the operation of a dielectric amplifier which doesn't make use of a resonant circuit may be illustrated by means of Figure 3.

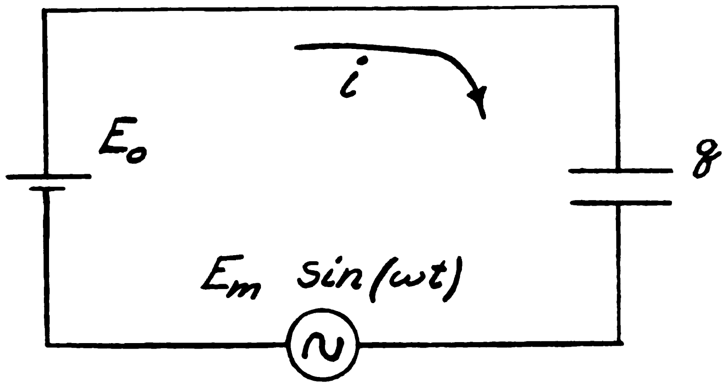


Fig. 3. Fundamental Circuit

This type of amplifier was not actually constructed because of the advantages obtained by making use of the steep slope of a fairly high Q resonant circuit. However, since the early dielectric amplifiers operated on this principle this description is included for purposes of contrast and is accompanied by a mathematical analysis by L. A. Pipes.[5]

---

[5]L. A. Pipes, "A Mathematical Analysis of Dielectric Amplifiers," Journal of Applied Physics, 23; 818-824, August, 1952.

The elementary dielectric amplifier consists of a capacitor in series with high-frequency carrier source and a constant potential source. The amplitude of the current that flows in the circuit is controlled by varying the impedance of the capacitor. This is provided by changing the degree of saturation of its dielectric by varying the magnitude of the direct potential E_0.

The dielectric constant of a non-linear dielectric material decreases with its degree of saturation. The capacitance, and therefore, the admittance of a non-linear capacitor is diminished by saturation. Therefore, the current in the circuit may be reduced by saturating the dielectric of the capacitor.

The saturation curve of a non-linear capacitor is shown in Figure 4.

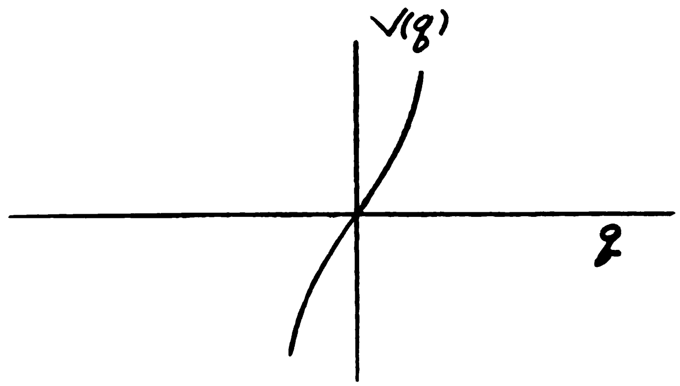


Fig. 4. Saturation Curve

This is a curve expressing the potential drop across the plates of the capacitor when it carries a charge q.

A very useful analytical expression which can be adjusted to fit the usual experimental V (q) curve closely is the hyperbolic sine curve.

$$V(q) = \frac{S_o}{a} \sinh(aq) \qquad (2.1)$$

Others have also used binomial expressions with coefficients which were characteristic of the particular material. In expression (2.1), S_o is the initial elastance of the capacitor defined by

$$S_o = \left(\frac{dV}{dq}\right)_{q=o} \qquad (2.2)$$

S_o is the reciprocal of the initial capacitance which is defined by

$$C_o = \left(\frac{dq}{dV}\right)_{q=o} \qquad (2.3)$$

The constant (a) is a measure of the non-linearity of the saturation curve of the capacitor. The slope of the V(q) curve is given by

$$\frac{dV}{dq} = S_o \cosh(aq) = V^1 \qquad (2.4)$$

Therefore the curve V (q) has a constant slope and is a straight line only when a = o.

If 2.4 is divided by 2.1 the result may be written in the form

$$a = \frac{V^1}{V} \tanh (aq) \tag{2.5}$$

For large values of q, tanh (aq) = 1 and

$$a = \left(\frac{V^1}{V}\right)_{q \to \infty} \tag{2.6}$$

Equation 2.6 may be used to obtain an estimate for (a) from the empirical saturation curve of the non-linear capacitor.

In order to accentuate the most important features of the elementary dielectric amplifier shown in Figure 5 and to keep the mathematical complexity of the analysis to a minimum, the resistance was neglected.

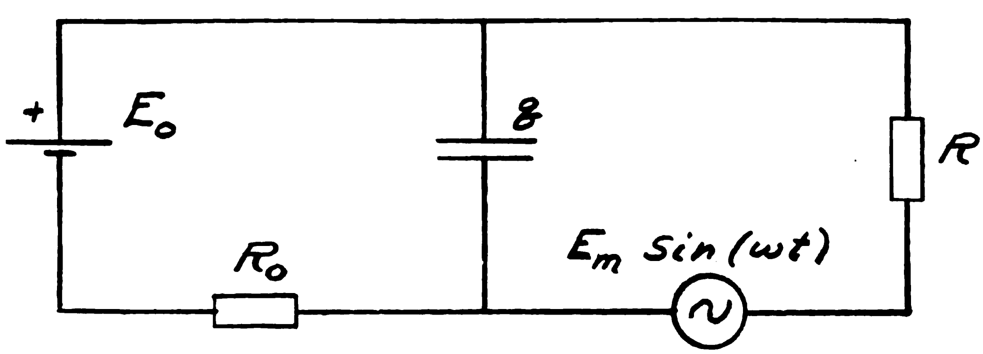


Fig. 5. Elementary Circuit

For a more complete mathematical treatment the reader is referred to a report by L. A. Pipes.[6]

The equation of the circuit shown in Figure 5 may be obtained by equating the applied potential of the circuit to the potential drop across the plates of the capacitor V (q) in the form

$$V(q) = \frac{S_o}{a} \sinh (aq) = E_o + E_m \sin(wt) = E(t) \quad (2.7)$$

therefore,
$$q = \frac{1}{a} \sinh^{-1} \left(\frac{aE}{S_o}\right) \quad (2.8)$$

Differentiating (2.8) with respect to t, yields the following expression for the circuit i:

$$i(t) = (a^2 E^2 + S_o^2)^{-\frac{1}{2}} \frac{dE}{dt} \quad (2.9)$$

If it is assumed that the control potential, E_o, is much greater than the maximum value of the applied harmonic potential of the circuit, so that

$$E_o >> E_m \quad (2.10)$$

Then the expression (2.9) may be written in the form

$$i(t) = A_o \cos wt \quad (2.11)$$

---

[6] *Ibid.*

where

$$A_o = w E_m (a^2 E_o^2 + S_o^2)^{-\frac{1}{2}} \tag{2.12}$$

a measure of the gain of the amplifier is

$$\mu_o = \left(\frac{\partial A_o}{\partial E_o}\right)_{E_o} = - w a^2 E_m E_o (a^2 E_o^2 + S_o^2)^{-3/2} \tag{2.13}$$

The gain of the amplifier which Pipes has designated as μ_o is comparable to the familiar term of transconductance used so extensively with electron tubes. A small increase ΔE_o of the control potential is accompanied by a change of ΔA_o in the amplitude of the current given by

$$\Delta A_o = \mu_o \quad \Delta E_o \tag{2.14}$$

Since the gain of the amplifier u_o is negative, a slight increase of the control potential corresponds to a decrease in the amplitude of the current in the amplifier.

Variocaps

A variety of forms of the small titanate capacitors were considered and tried for fabrication by Mr. Silverstein and others late in the year 1953.[7] A form called a variocap proved to be a superior type, in point of convenience and ease of production.

---

[7]Abraham Silverstein, "Building and Using Dielectric Amplifiers," Electronics, p. 150-153, February, 1954.

Except for variations in the method of production and of mounting the non-linear capacitors used in this thesis were similar to this type called a variocap. They will be referred to as such for convenience.

The variocaps used here were made by soldering a small square cut from a silvered sheet of ceramic to the end of a brass screwhead. One of these capacitors is shown in Figure 6. The small brass screwhead had previously been turned down in a lathe so that the driver slot was removed from the head and a flat plane left.

With the ceramic soldered to the screwhead, the assembly was again placed in a lathe and the capacitor was worn down at the sides by light strokes from the top down with number 2/0 sandpaper.

This method of mounting was used for damping out piezoelectric resonances and seemed to provide for good heat conduction from the ceramic. To make connections to the capacitor one lead was connected to the screw while the other was connected through spring contact to the upper edge of the variocap. An example of this type of mounting is shown in Figure 7.

Fig. 6. Non-linear Capacitor

Fig. 7. Mounted Capacitor

Resonant Amplifier Operation

The basic resonant dielectric amplifier is shown in Figure 8.

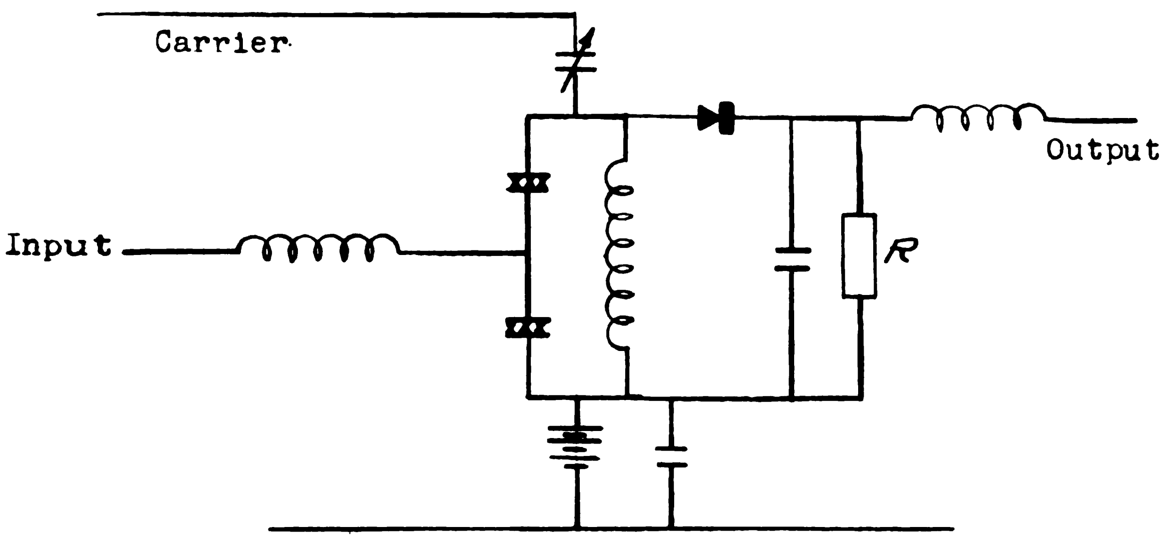


Fig. 8. Basic Resonant Circuit

It involves using the titanate capacitor as part of a resonant tank circuit. Signal voltage applied to the variocap serves to shift the resonant frequency. The response of the tank circuit to a fixed frequency carrier source then changes by a greater voltage than that of the signal. This operation is represented schematically in the block diagram of Figure 9.[8]

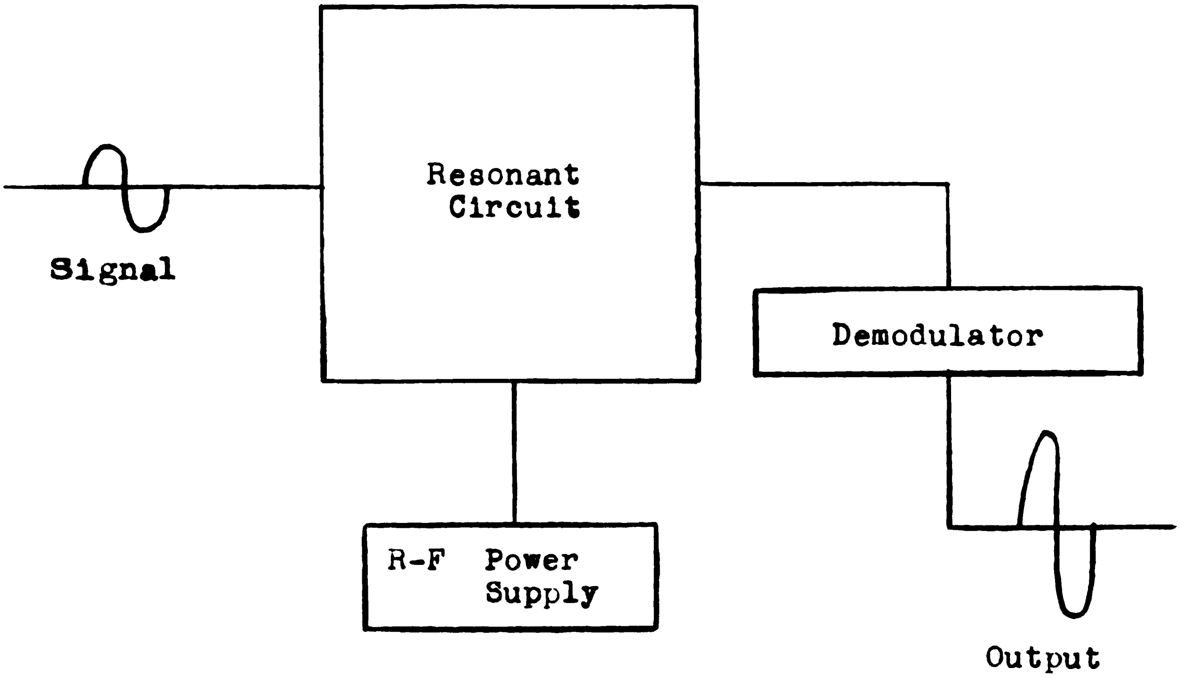


Fig. 9. Block Diagram

---

[8]George S. Shaw and James L. Jenkins, "Non-Linear Dielectrics for Dielectric Amplifiers," Electronics, 26; p. 166-167, October, 1953.

A bias voltage can be used to adjust the no-signal capacitance. A value of capacitance is chosen such that an operating point is established on one side of the resonance curve. If the capacitance is varied by some means such as a small signal voltage applied, the voltage E will vary. Thus there is produced an amplitude modulated r-f voltage which can be demodulated to recover the amplified signal. This voltage versus capacitance curve is as shown in Figure 10.

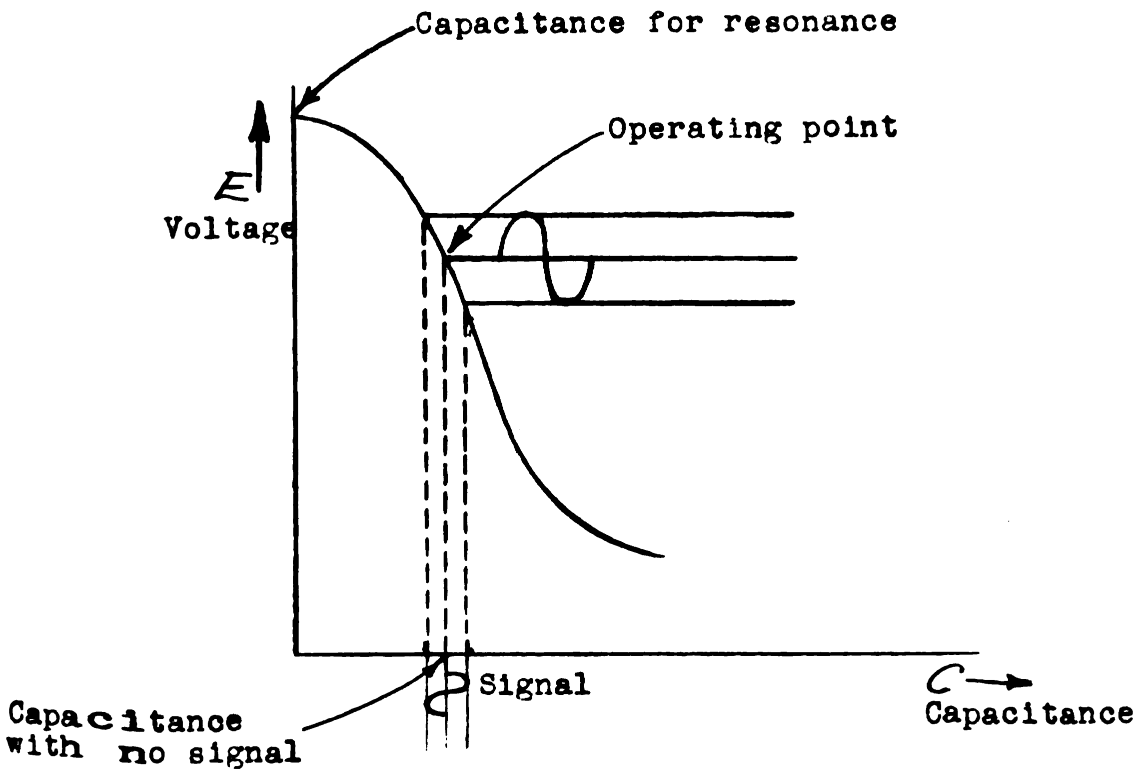


Fig. 10. Voltage versus Capacitance

No energy is required from the signal except to replenish the small capacitor losses since all of the energy supplied to the load comes from the r-f carrier supply. It is evident that the higher the Q of the circuit, the greater will be the change in voltage E for a small change in capacitance.

Looking into the input terminals the small capacitors would look like a very high impedance at low frequencies and nearly infinite for direct-current voltages. Since the input current would be nearly zero in this case, the power gain would theoretically be infinite for direct current applications.

The direct voltage gain is very moderate per stage unless at least four very thin variocaps are placed in series. The power gain is very high, however, whether a single variocap is used or several are stacked. With more variocaps in the resonant circuit the carrier voltage can be divided among them in series and the signal can be applied to the parallel combination. Then the applied carrier can be increased and a voltage gain is achieved. A circuit which accomplished this is shown in Figure 11.

This principle cannot be extended indefinitely since the loss in the chokes used to separate the carrier from the signal would limit the gain.

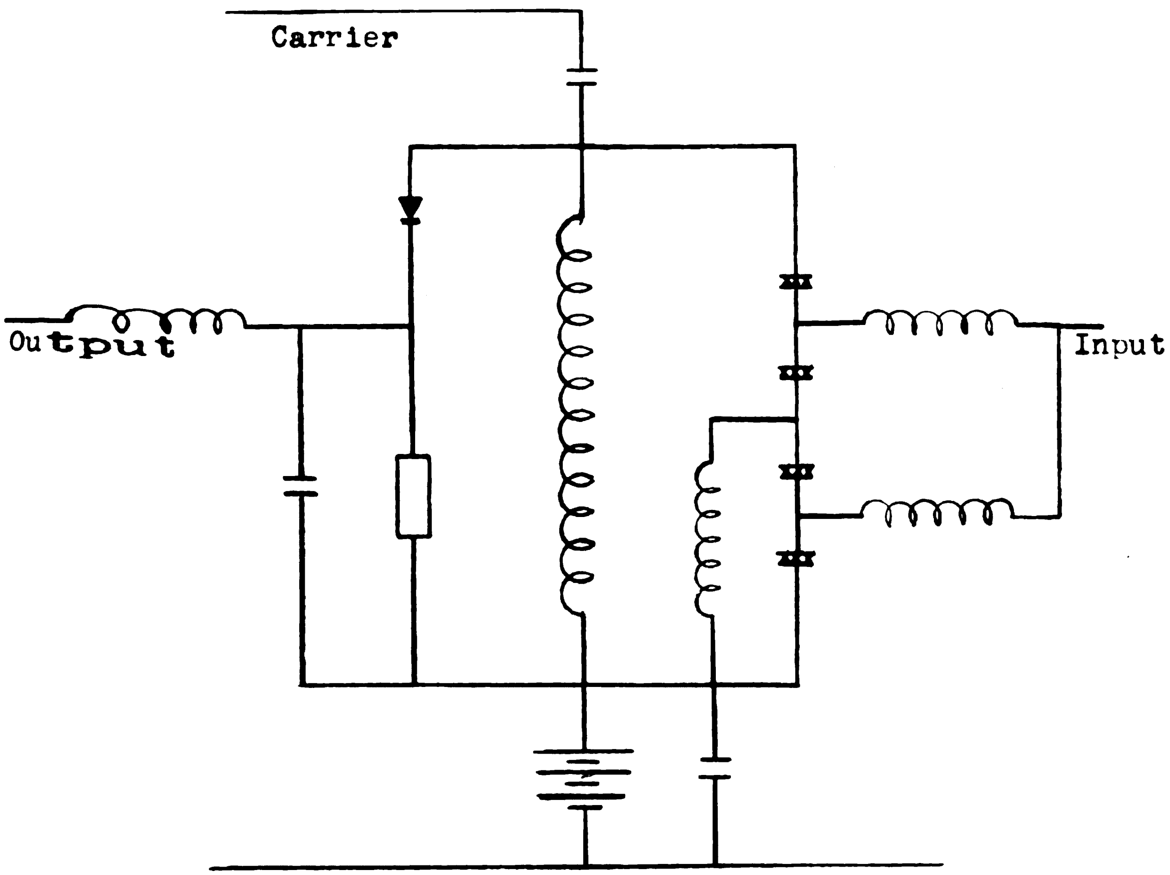


Fig. 11. Circuit with 4 Variocaps

Power Amplifiers

The voltage amplifier circuits are not adapted to driving a loud speaker because the output energy is dissipated in heating the load resistor. If a high-inductance transformer with a resistive load were substituted for the resistor, the load would be determined by the resistor for audio frequencies, but for very low frequencies and direct-current the transformer would be a short circuit. This is not permissible in the dielectric amplifier since the energy lost in direct current flow would destroy the Q and hence the amplification of the stage. This condition can be avoided by using an R-C limiter for direct current, as shown in Figure 12.[9]

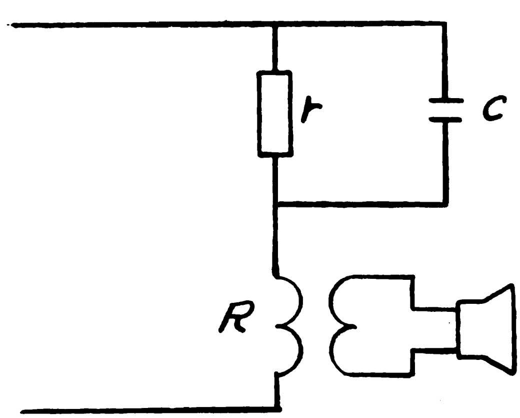


Fig. 12. Direct-Current Limiter

---

[9] Silverstein, Op Cit.

Calculation shows an interesting property of this circuit. It is desired to have the combination always look like a resistance of value R, which is the transformed voice coil resistance. Figure 12 is actually equivalent to Figure 13 where the transformer and load have been replaced by R & L.

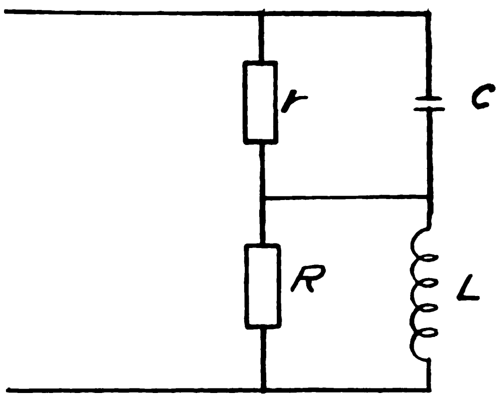


Fig. 13. Equivalent Limiter Circuit

At very low frequencies the inductance L looks like a short circuit across R and at very high frequencies the capacitance $\underline{c}$ acts to short out the resistance $\underline{r}$.

These high and low limits therefore, impose the condition that $\underline{r}$ must equal R and it remains to calculate the ratio of inductance to capactiance in terms of R required to satisfy the necessary conditions at medium frequencies.

This can be done directly by combining the impedances as follows:

$$\frac{jwRL}{R + jwL} + \frac{\frac{R}{jwc}}{jwCR + \frac{1}{jwc}} \qquad (2.15)$$

which can be put into the form:

$$\frac{jwLR\,(jwCR + 1) + R\,(R + jwL)}{jwCR^2 + R + j^2 w^2 CLR + jwL} \qquad (2.16)$$

This is equated to R:

$$\frac{j^2 w^2 CLR^2 + jwLR + R^2 + jwLR}{j\,wCR^3 + R^2 + j^2 w^2 CLR^2 + jwLR} \qquad (2.17)$$

and solving for L:

$$L = CR^2$$

$$\text{or} \quad L/C = R^2 \qquad (2.18)$$

This type of direct-current limiting circuit was incorporated in the power amplifier which is described in this paper.

Vincent suggests that more voltage gain could be realized by use of a push-pull circuit. Although he doesn't give a description of what is meant by a push-pull dielectric amplifier, the circuit in Figure 14 could possibly be classified as such.

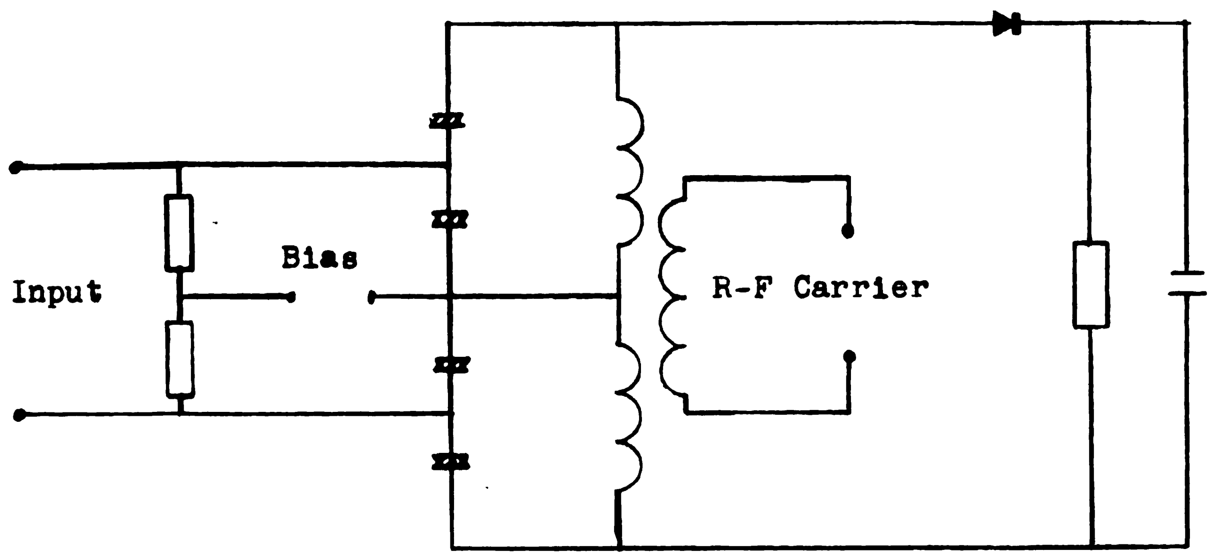


Fig. 14. Push-Pull Circuit

Here two resonant tank circuits are tuned to identical frequencies, but slightly off the RF source frequency. When an audio signal is applied, the polarities are such that the resonant frequency of one tuned circuit is raised while the other is simultaneously lowered, and an output voltage is produced which is the difference of these responses.

Phase Consideration

The output phase of a dielectric amplifier is determined by three factors (1) whether the carrier is above or below resonance of the tank circuit; (2) the polarity of the rectifier used to detect the carrier modulation; and (3) the polarity of the bias voltage on the non-linear capacitors.

The reversal of either one of the three above factors would result in reversing the sign of a feedback factor.

Feedback

Positive feedback has been easily achieved by many of the people working with dielectric amplifiers. It can be achieved in a simple stage with only R-C components. With an increase in β, the portion of output voltage fed back, there is an increase in gain. When the feedback voltage equals the input voltage, the amplifier will oscillate at the peak frequency. However, because of the low voltage gain, it is more convenient to use a transformer for positive feedback.

Negative feedback can be applied to any degree without oscillation provided cumulative phase shifts do not reverse the phase of the output signal.

In working with two stage amplifiers Silverstein has encountered a kind of oscillation in which no signal frequency component is fed back.[10] If the first and second stages are tuned to opposite sides of resonance position feedback results across the common r-f impedance in the carrier source. A rise in carrier current due to a signal in the second stage will reinforce a corresponding drop in the output of the first. This type of oscillation was unwanted and was eliminated by changing the impedance of the r-f carrier source.

---

[10] *Ibid*.

CHAPTER III

Experimental Amplifier

Am amplifier was built using four non-linear capacitors connected in series for the tank circuit capacitance. For experimental reasons the bias and inductance were made variable and no attempt was made to miniaturize the assembly.

The amplifier is shown in Figure 15.

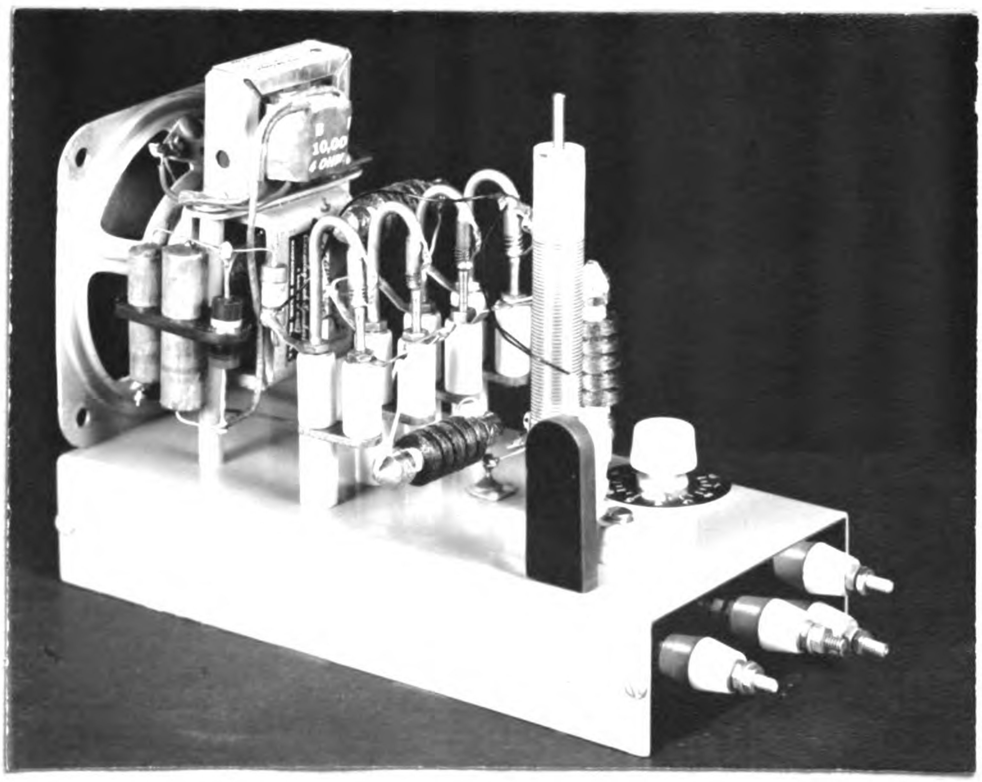


Fig. 15. Laboratory Model of the Dielectic Amplifier

The circuit of this amplifier is shown in Figure 16. This is basically the same as the power amplifier described by Silverstein.[11]

The modulation of the carrier source by the input signal can be seen in the photographic recording of an oscillograph's trace in Figure 17.

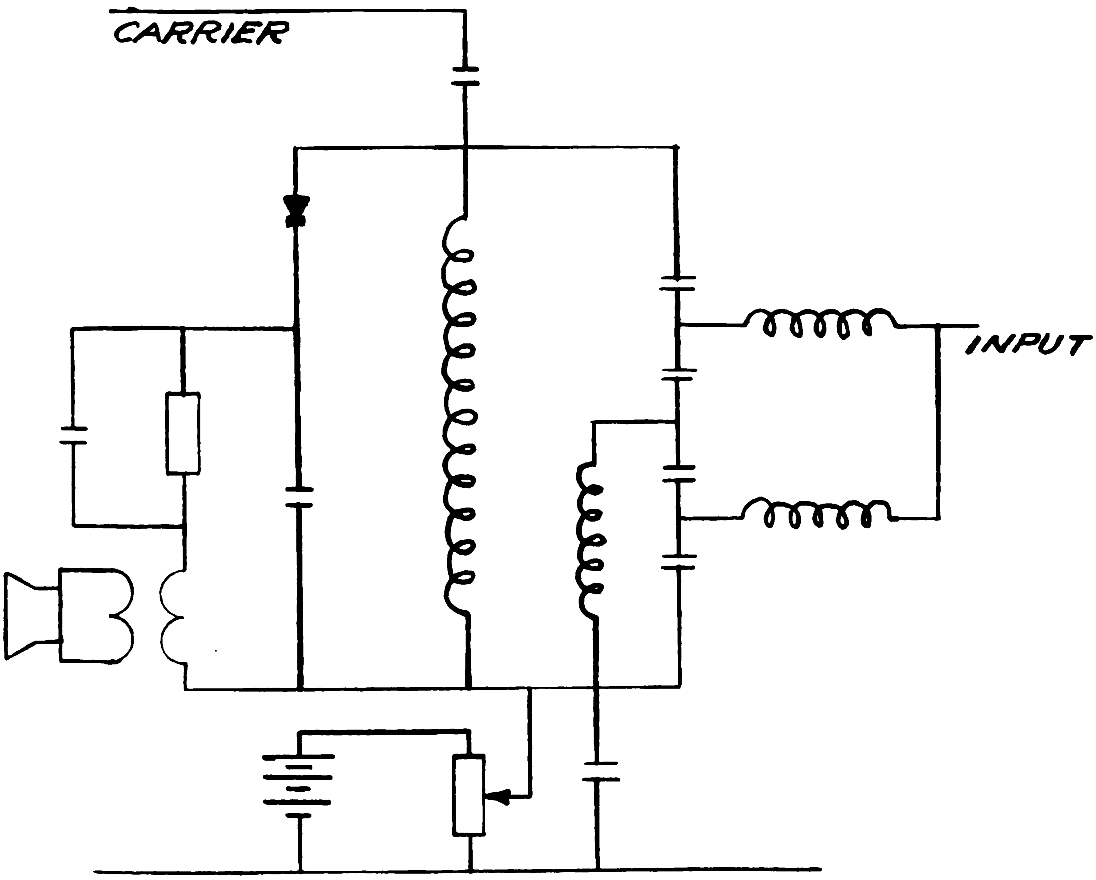


Fig. 16. Power Amplifier Circuit

---

[11] Ibid.

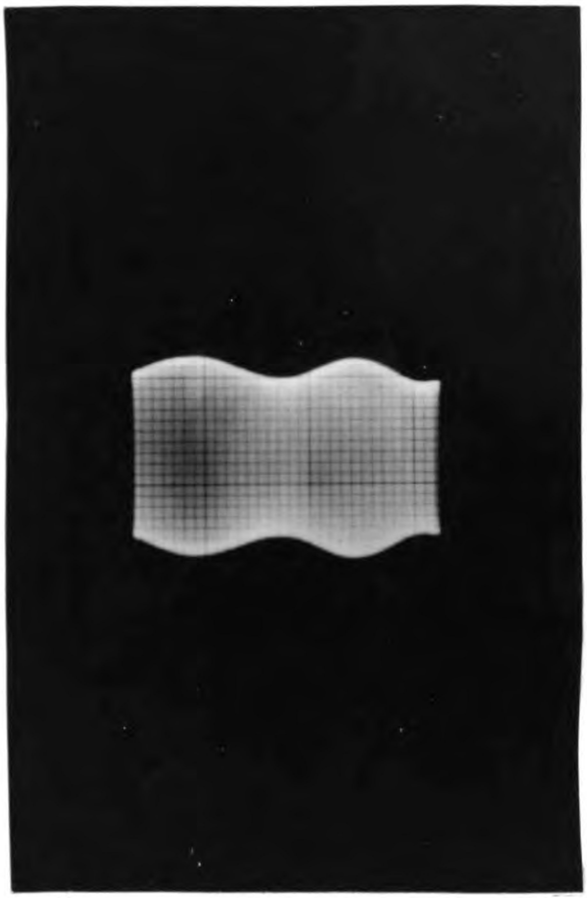


Fig. 17. Carrier Modulation

As shown on page 27, the value of (L/C) should equal (R) and (R) should equal (r) in the direct-current limiter circuit. A transformer was used with approximately 10 henries inductance and capable of matching the 4 ohm voice coil to an ordinary plate load of 10,000 ohms. Thus, satisfying the above conditions c had a value of 0.1 μfd and r was 10,000 ohms.

The four capacitors used in the amplifier each had a value of approximately .002 μfd with no bias voltage applied. This uniformity in size was accomplished by decreasing the plate area of each one with sandpaper until the desired capacity was reached.

Since the capacitors were connected so as to present a series combination to the radio-frequency carrier the total capacity was one-fourth of .002 μfd or 500 $\mu\mu$fd. Using an R-F solenoid design chart it was found that for a winding one-half inch in diameter and two inches long to resonate at 3 megacycles with the 500 $\mu\mu$fd capacitance it must be six micro-henries and have 50 turns.

The coil was wound on polystyrene by cutting a groove with a lathe screw-thread attachment for the wire to rest in.

It was assumed that with a 10,000 Ω load coupled to the resonant circuit the energy consumed in the circuit itself was negligible as compared with that consumed by the load. Under these conditions the Q of a parallel resonant circuit loaded by a resistive impedance is $Q = \frac{R}{X}$ where Q = quality factor, R = parallel load resistance (ohms) and X = reactance of one of the resonating elements (ohms).

Since the 6 μ hy. inductance presents a reactance of approximately 113 ohms to a frequency of 3 Mc. the Q of the loaded circuit is then about 88.

The impedance that the carrier sees can be expressed as

$$Z = \frac{R}{1 + jR\left(wc - \frac{1}{wL}\right)} \qquad (3.1)$$

by simply combining the parallel combination of R, L, and C. Here R is the equivalent parallel loss resistance of the tank circuit, L is the inductance of the tank coil, and C is the series capacitance of the non-linear capacitors. The expression can be simplified by letting

$$x = R\left(wc - \frac{1}{wL}\right) \qquad (3.2)$$

Now the expression for Z is seen to have an absolute magnitude of

$$\left| Z \right| = \frac{R}{\sqrt{1 + x^2}} \qquad (3.3)$$

Multiplying through by R and substituting Q, Equation (3.2) can be written in the form of

$$x = (wRC - Q) \qquad (3.4)$$

In Figure 18 is shown a curve of % change in capacitance versus electric field in volts per mil. This curve was furnished by the manufacturer of the material used in the amplifier described here.[12]

---

[12] Glenco Corporation, Op. Cit.

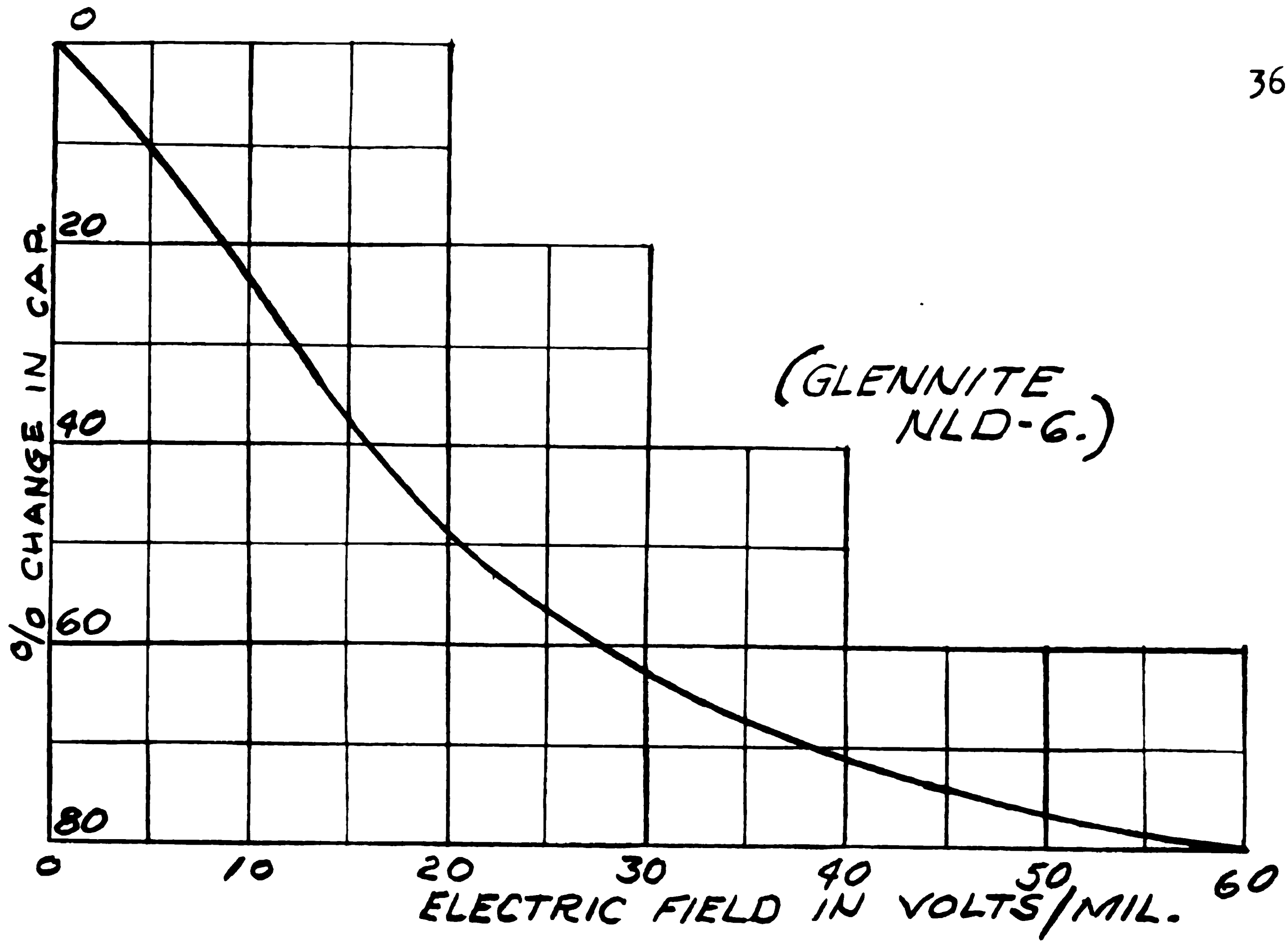


Fig. 18. Capacitance versus Electric Field

From the curve in Figure 18 it was estimated that the material used undergoes a change in capacitance of 2.5% with a change of one volt per mil of electric field. This information was taken from the linear portion of the curve.

Since these capacitors were 6 mils thick they experienced a 0.4% change in capacitance for a one volt change in control signal voltage.

Substituting the experimental values w, R, C and Q into a combined form of equations 3.3 and 3.4 yields the following expression for the absolute magnitude of the impedance.

$$|z| = \frac{10^4}{\sqrt{1 + (30\pi - 88)^2}} \qquad (3.5)$$

From this it was found that a 0.4% variation in the 30π term produces an increase in impedance from 1590 ohms to 1640 ohms which is a variation of 6.5%.

With the amplifier operating on an r-f carrier of 30 milliamperes this variation in impedance would produce an output voltage to the demodulator of 2 volts. This figure agrees closely with the measured value of voltage gain which varied from less than one to about 1.6.

The power gain was very high, however, since the ceramic capacitors had narrow hysteresis loops and practically no input power was taken from the signal.

A screenroom was not available and the induced 60 cycle signal and extraneous radiations present in the room made it impossible to obtain an accurate measurement of such a small power input.

Although this amplifier was intended to be used with a voltage pre-amplifier, a 0.9 volt signal from a phonograph cartridge produced an audible signal in the loudspeaker. The addition of 3 megohms resistance in series with the pick-up output did not noticeably decrease the power output from the amplifier. This further shows how small the input power can be.

Frequency Response

Currently available titanates have responded to frequencies as high as 10^7 cycles per second.[13] It appears therefore, that amplifiers could be built with flat frequency-response curves over very wide ranges of frequencies. This would require a choice of high quality components such as the output transformer, chokes, etc.,and a carrier source of high frequency.

The amplifier built here and described above dropped sharply in output at about 16,000 cps. This was due to the high value of capacitance at the input, the low quality components used and the simple method of separating the signal from the carrier source.

Other Possible Uses of Non-Linear Capacitors

The most obvious use of a non-linear capacitor is as the modulating device of a frequency-modulated oscillator.

M. Apstein and H. Wieder have developed a system of coupling the barium-titanate capacitor to an oscillator tank circuit operating in the 50 mc. to 500 mc. range of frequencies.[14]

---

[13] Vincent, Op. Cit., p.87.

[14] Maurice Apstein and H. H. Wieder, "Capacitor-Modulated Wide-Range FM System," Electronics, 26; pp. 190-192, October,1953.

They have concluded that the system should find application in portable uhf equipment that requires both a wide deviation and broad frequency responce.

The GLENNITE P-series of dielectrics are available with high remanent polarization and relatively square hysteresis loops. The squareness of the loops is an indication that these materials could be used as storage units in modern computers just as the square-loop ferrites have been applied.

N. Rudnick of Glenco Corporation, states that ferroelectric storage devices offer the advantages of fast switching rates small size, stability, and the fact that they are operated by voltages. His last point appears to be important since magnetic memory units are operated by short pulses of high currents and short voltage pulses may be generated much easier than short current pulses. Also, since the ferroelectrics may be made very thin, the operating voltages can be made quite low.

Non-linear capacitors also show promise for application as multivibrators, sweep generators, filters, thermostats, transducers and many others.

CHAPTER IV

Dielectric Amplifier Advantages and Disadvantages

Vincent has compiled a list of characteristics which is repeated here:[15]

Advantages

Ruggedness - practically indestructible

Efficiency - no filament to heat

Reliability - no filament to burn out

Readiness - normally requires no warm-up time

High Gain

Adaptability - small size, variety of shapes

High-Impedance Control Circuit

Size - in r-f applications, requires less space than equivalent tube amplifier

Cost - considerably cheaper than equivalent tube or magnetic amplifier. Titanate non-linear capacitors are actually cheaper than either paper or mica

Frequency Range - direct current to r-f.

Disadvantages

Frequency Limitations - present state of art indicates upper limit of 10Mc., although this is not definitely determined.

---

[15]Vincent, Op. Cit., p. 85.

Curie Effect - present materials might suffer considerable gains drift. This can be compensated.

Loading Effects - a consideration at high frequencies.

Power Factor - losses greater than mica or air dielectrics.

Impedance Ratio - somewhat limited

Power Limits - closely dependent on frequency

Aging and Lag - differ with different materials

Power Supply - requires high-frequency power supply

Perhaps it should be added to this list that although the low-level amplification probably hasn't been determined as yet, Vincent claims that electrical and thermal action will definitely set some low level limit of operation.[16]

With the model tested, no noise could be heard when the amplifier was operating without an input signal. Also this type of amplifier appears to be completely free from microphonic noise.

---

[16] Vincent, Op. Cit., p. 88.

SUGGESTIONS FOR FURTHER STUDY

Design of an amplifier with extremely high input reactance capable of continuous response ranging from D.C. to R.F. This would perhaps include the use of a very small tank capacitance and an improved method of seperating the signal from the carrier.

Investigate the possibility of imbedding a grid arrangement within the ceramic or a method of stacking the ceramic to increase the control voltage gradient.

Investigate the range of frequencies over which an L-C Filter could be tuned with a D.C. control voltage. This could be either a band-pass or band-eliminator type.

BIBLIOGRAPHY

Apstein, Maurice and H. H. Wieder. "Capacitor-Modulated Wide-Range FM System," Electronics, XXVI, October 1953, pp. 84-88.

Glenco Corporation, Phamphlet, Metuchen, New Jersey.

Pipes, L. A. "A Mathematical Analysis of Dielectric Amplifiers," Journal of Applies Physics, XXIII, August 1952, pp.818-824.

Shaw, George S. and James L. Jenkins. "Non-Linear Dielectrics for Dielectric Amplifiers," Electronics, XXVI, October 1953, pp. 166-167.

Silverstein, Abraham. "Building and Using Dielectric Amplifiers," Electronics, February 1954, pp. 150-1953.

Vincent, A. M. "Dielectric Amplifier Fundamentals," Electronics, XXIV, December 1951, pp. 84-88.

ASSOCIATED BIBLIOGRAPHY

Dranetz, A. I., G.N. Howett, J. W. Crownover. "Barium Titanates as Circuit Elements," Tele-Tech, April, May, June, 1949, pp. 29-28-36.

Penney, G. W. "Resonant Dielectric Amplifier Frequency Response," Electrical Engineer, April, 1954, p. 311.

Terman, F. E. "Parallel Circuits," Radio Engineers' Handbook. New York and London: McGraw-Hill Book Co., 1943, p. 141.