A TEN CENTIMETER MICROWAVE OSCILLATOR

Thesis for the Degree of M. S.

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Ronald Lavern Martin

1948

This is to certify that the

thesis entitled

"A 10-cm Microwave Oscillator"

presented by

Ronald Lavern Martin

has been accepted towards fulfillment
of the requirements for

M.S. degree in Physics

Thomas H. Osgood.
Major professor

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A TEN CENTIMETER MICROWAVE OSCILLATOR

by

Ronald Lavern Martin

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Ronald L. Martin

I. INTRODUCTION

The purpose of this thesis was to construct a micro-wave oscillator with suitable detectors to be used in the laboratory to demonstrate some of the optical phenomena in a simpler manner than is possible with the much shorter visible light rays.

In order to achieve a frequency in the neighborhood of 3000 mc ordinary radio circuits must be modified considerably. The resonant frequency for the usual tuned circuit of a coil and condenser (neglecting resistance) is $f = \frac{1}{2\pi\sqrt{LC}}$. Decreasing the inductance or capacitance will increase the frequency until we have a capacitance of two parallel plates and an inductance of one turn of wire. With this circuit frequencies up to 200 mc can be obtained but it is very difficult to tune properly. With such small values of L and C in the tuned circuit the inductance of the lead wires both in and out of the tube, and the electrode capacitances are large in comparison and have a very great effect upon the performance of the tube and the tuning. The base of the tube is an insulator to ordinary frequencies, but a conductor to ultra high frequency currents. At such high frequencies as we are to achieve the stray radiation from open wire circuits becomes excessive. This tuned circuit of a small coil and condenser will also have a low Q where $Q = \frac{\omega L}{R}$ since the resistance of the circuit will be large compared to L. Q is a measure of the selectivity of a circuit and for an oscillator we want a high selectivity in order to have it oscillate at only one frequency. Q can also be defined as the energy stored in the field per cycle divided by the energy lost per cycle and is therefore a measure of the efficiency of the oscillator. Finally transit time of the electron from cathode to plate is very important with frequencies in the range of 1000 mc or greater since it is of the same order of magnitude as the period of oscillation. This will change the phase relation between the grid voltage, which is controlled by the oscillations of the tuned circuit, and the output current. The tuned circuit does not receive energy at the proper time of the cycle and the efficiency of the tuned circuit is reduced until it fails to oscillate.

The high frequency oscillator of the type constructed overcomes these difficulties of the ordinary radio oscillator circuit in the following manner:

(1) The tube is a disk-seal type triode which has large but short external connections to plate, grid, and cathode, and has very small elements within the tube spaced very close together. Therefore the lead inductances to the tube are negligible, interelectrode

capacitances are reduced considerably by the small area of the tube elements, even with their close spacing, and transit time is greatly reduced by the close spacing between cathode and plate.

(2) The entire radio frequency circuit is contained within the outer shell and takes place in the resonant cavities so that stray radiation is negligible.

(3) All metalic parts of the circuit are silver plated to reduce resistance to radio frequency currents.

(4) The lumped elements of the tuned circuits are replaced by the distributed elements of cavity resonators which have a very high Q so that efficiency is high and selectivity is extremely sharp.

With these modifications the oscillator can attain a frequency of over 3000 mc.

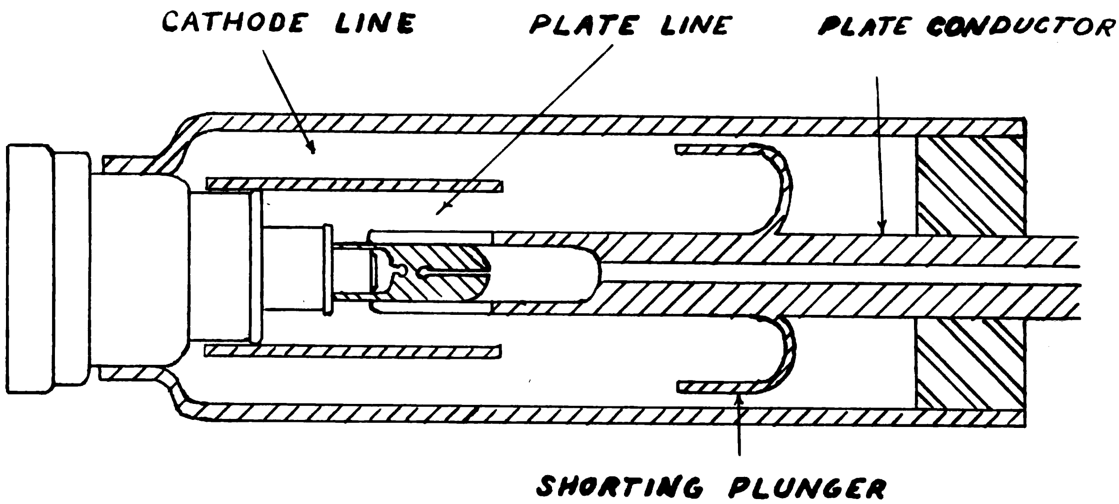

CATHODE LINE
PLATE LINE
PLATE CONDUCTOR
SHORTING PLUNGER

Fig. 1a

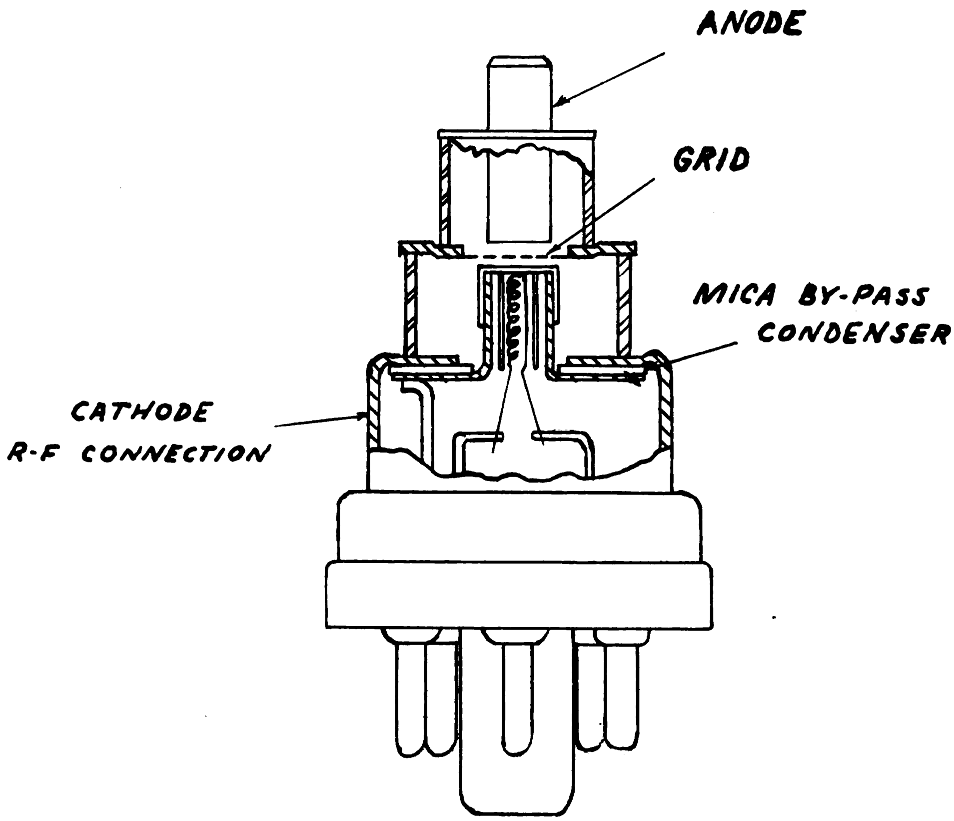

ANODE
GRID
MICA BY-PASS CONDENSER
CATHODE R-F CONNECTION

Fig. 1b

II. CONSTRUCTION OF THE OSCILLATOR

The oscillator uses a single type 2C40 disk-seal triode which is known as a lighthouse tube because of its appearance as seen in Fig. I(b). All r-f connections are made directly to the outside of the tube without going through the octal base. These external connections are all silver plated. The tube was designed as a class A radio-frequency amplifier or as a CW local oscillator at the higher frequencies, and therefore does not have a very large power output. It was used for the latter purpose in an aircraft radar set for which this cavity resonator was designed. Some of the tube characteristics are listed below:

Cathode - Indirectly heated	
Heater voltage	6.3 volts
Heater current	0.75 amperes
Average amplification factor	36
Grid-plate transconductance, Ib 17 mil.amps.	4850 microhms
Direct interelectrode capacitances	
Grid-plate	1.3 $\mu\mu f$
Grid-cathode	2.1 $\mu\mu f$
Plate-cathode, maximum	0.05 $\mu\mu f$
Cathode-r-f connection, Cathode	100 $\mu\mu f$
Maximum frequency	3370 mc
Type cooling - Convection	

Maximum Seal Temperature	200° C

Typical operating conditions for d-c plate voltage

D-c plate voltage	250 volts
D-c grid voltage	-5 volts
D-c plate current	30 mil. amps.
Plate input	8 watts
Plate dissipation	7 watts
D-c grid-current, approximate	0.7 mil amp.
Power output	75 milliwatts

Referring to Fig. I(a), the oscillator consists of three coaxial cylindrical conductors. The inner conductor makes contact with the plate, the next with the grid, and the outer with the shell which is connected externally to the cathode. Capacitance within the tube provides a r-f connection from shell to cathode. The resonant cavity between the shell and grid cylinder is called the cathode line and the resonant cavity between the grid and plate is called the plate line. Both lines are short circuited at the end away from the tube by an adjustable plunger. A connector is securely clamped to the plate lead of the tube and slides within the plate conductor as the latter is adjusted along with the plunger. The plate conductor is hollow to allow air to be circulated for cooling since with the high speed of the electrons and the small area of the plate there is considerable heating. However with the relatively low voltages used on this particular oscillator it is not necessary to use air cooling. The hollow space inside the plate conductor is restricted in one place to form an approximate quarter wave length choke which looks like infinite impedance to r-f currents and therefore prevents r-f oscillations from going into the d-c plate supply.

The shorting plunger and the plate conductor are fastened rigidly together and are moved by adjustment of the tuning screw. The d-c connection to the grid cylinder is made by three symmetrically-placed prongs which are insulated from the shell as they emerge and are connected to the shell through a 10,000 ohm resistor. The output is taken from a probe in the cathode line through a short coaxial line to the half wave dipole which is backed by an eight inch parabolic reflector. The reflector may be removed by pulling out the center half of the dipole, loosening the screws holding the reflector to the coaxial line and removing the reflector leaving the grounded half of the dipole intact. The coaxial line is connected to the output probe with a slip joint and can therefore be removed. It is not necessary to remove the reflector to remove the coaxial line, reflector, and dipole as a unit from the resonator.

A transformer is used which has outputs of 6.3 volts to the tube heater and pilot light, and 300 volts rms between the plate conductor and the shell. The shell is also connected to the internal cathode through the base of the tube to form a path for d-c currents. The primary of the transformer is to be connected to a 110 volt, 60 cycle line. The rod emerging from the end of the resonator near the plate conductor is a mechanical stop to the tuning mechanism and has the same voltage as the plate so must not be touched when the oscillator is turned on. The mechanical stop may be adjusted by an Allen wrench to stop the tuning rod at any desired wave length.

The entire unit is mounted in a metal box to eliminate stray radiation. The bakelite screw on the tuning rod must be removed when removing the oscillator from the box. All connections to the oscillator including the power lead, switch, fuse, and pilot light are connected to the front cover of the box so that once the tuning rod screw is removed the oscillator and front cover may be removed from the box.

III. [illegible]

(a) Direct Current Circuit

A d-c connection from grid to cathode is made through the grid-leak resistor R_g of 10,000 ohms. Grid-cathode interelectrode capacitance and capacitance between the three external grid leads and the shell form the other parallel part of the grid-leak so that the grid has a d-c bias similar to any grid leak in ordinary radio circuits. Instead of a steady d-c plate voltage a 60 cycle a-c voltage is impressed upon the plate so that the output is modulated at 60 cycles and may be detected by an audio amplifier.

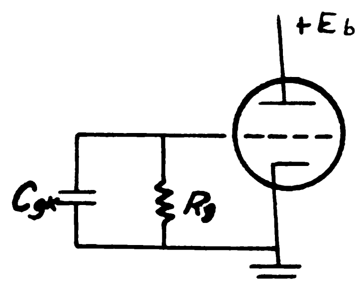


FIG. 2

(b) Radio Frequency Circuit

Both the cathode cavity and the plate cavity form tuned circuits and can be represented by an inductance and capacitance in parallel. In addition there is interelectrode capacitance between grid and plate, grid and cathode, and plate and cathode. These elements are shown in an equivalent circuit of Fig. 3(a). L_k and C_{gk} are combined into the reactance X_k and L_p and C_{gp} are combined into the reactance X_p in the second equivalent circuit of Fig. 3(b). X_k, C_{pk}, and X_p must form a resonant tank circuit and return a voltage to the grid in proper phase and magnitude to sustain oscillations. This is a form of the simple Colpitts oscillator. In order to do this X_k must be capacitative so that it and C_{pk} can form a voltage divider that will return a voltage to the grid out of phase with the plate voltage. Oscillations would not be sustained if X_k were inductive. And so X_p must be inductive in order to form a tank circuit. The final equivalent circuit is that of Fig. 3(c).

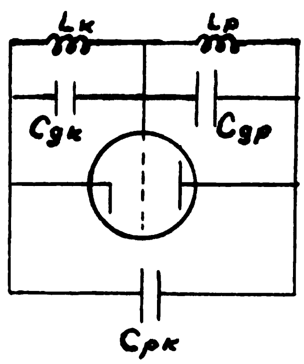


FIG. 3a

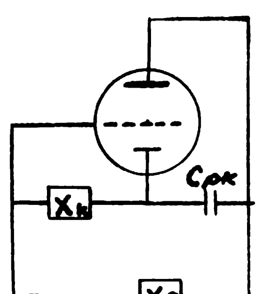


FIG. 3b

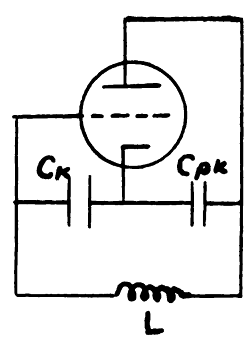


FIG. 3c

Consider now the Colpitts oscillator with the grid lead disconnected and an external voltage E_g applied between grid and cathode.

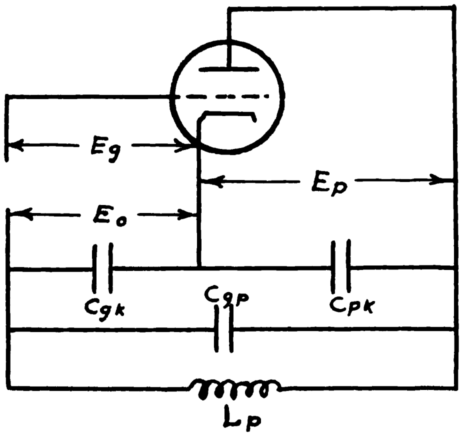


Fig. 4

If the frequency of the applied voltage is the resonant frequency of the tank circuit then the tank circuit will behave as a resonant transformer and will appear as a pure resistance in the plate circuit. Then E_p will be of opposite polarity to E_g. The polarity of E_o will be opposite to that of E_p since C_{gk} and C_{pk} act as a voltage divider. Therefore E_o is in phase with the original voltage E_g. They must also be of equal magnitude or the amplification of the tube must compensate for the attenuation of the voltage divider. When these conditions occur the external source may be removed and the grid lead can be reconnected. The circuit is now an r-f amplifier supplying its own input voltage and oscillations will continue unchanged.

The frequency of the oscillator must be the resonant frequency of the tank circuit. At any other frequency the tank circuit does not present a pure resistance load to the tube. Thus E_p is not exactly 180° out of phase with E_g and the phase of E_o is not correct so that the tube cannot supply its own input.

If the amplification of the tube is less than the ratio C_k/C_{gk} the returned voltage is too small and the circuit cannot oscillate. If the amplification is initially greater than this ratio, oscillations start and grow in amplitude until the non-linearities of the tube characteristics reduce amplification to the correct value.

Returning to our oscillator--

In order to make X_k capacitative the current in C_{gk} must be greater than the current in L_k. That is--the frequency of oscillation must be higher than the resonant frequency of the cathode line. Similarly the frequency of oscillations must be lower than the resonant frequency of the plate line to make X_p inductive. So the plate circuit must be tuned to a higher frequency than the cathode circuit. To make this clearer consider an ordinary tank circuit with resonant angular frequency $w_0 = \frac{1}{\sqrt{LC}}$. If w is greater than w_0 then $z = \frac{-jwL}{w^2LC-1}$ which is a capacitative reactance, whereas if w is less than w_0 then $z = \frac{jwL}{1-w^2LC}$ which is an inductive reactance.

X_k and X_p do not vary with frequency in the same way as would the reactance of simple capacitances and inductances since they contain a number of separate elements lumped together. Therefore one can only determine circuit relations from the equivalent circuit at the oscillation frequency but cannot calculate the frequency from circuit parameters.

Tuning the cathode line controls the amount of voltage fed back to the grid by the tank circuit since C_k is part of the capacitative voltage divider. C_k is normally much larger than C_{pk} in order to provide the proper voltage divider ratio for feedback so it may be necessary for the cathode line to be slightly greater than 5/4 wave length in which case L_k would be capacitative rather than inductive.

Tuning the plate line determines L and therefore determines principly the frequency of oscillations and to a small degree feedback since the ratio C_k/C_{pk} changes with frequency. The plate line must always be slightly less than a full wave or half wave since X_p must always be inductive.

Maximum output indicates the condition of correct feedback voltage, since if the feedback is too small the oscillations are weak, and if the feedback is too large the power consumed in the grid circuit is large and output correspondingly reduced. (This is due to transit time loading and actual grid currents when the grid is positive.)

(c) Excitation of Cavity Resonator

The resonant cavities form a coaxial cavity and are excited in the following manner:

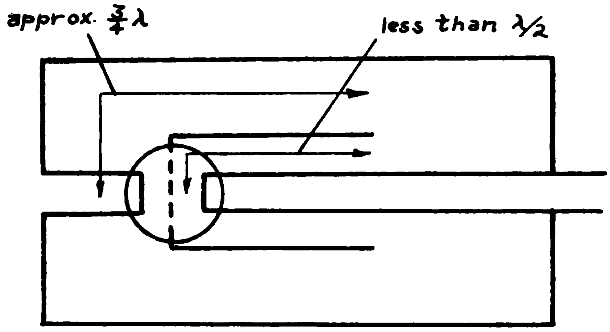


FIG. 5

Electrons going from cathode to plate induce a voltage on the grid. The first surge of electrons makes the grid slightly positive. While the grid is positive it will collect electrons and current will flow in the grid-leak which biases the grid negative but not beyond cutoff. Now when electrons flow from cathode to plate they induce a positive voltage on the grid superimposed on the grid bias. The grid is still negative however and this slows the electrons down between the cathode and the grid. The grid gains the amount of energy lost by the electrons and sets the cavities to resonating which sets up an ultra high frequency voltage on the grid independent of the other sources of grid bias. Thus ultra high frequency voltage on the grid serves to bunch the electrons if transit time is not too large. After oscillations have begun in the resonant cavities they will be sustained in the manner described for the Colpitts oscillator. When the uhf voltage on the grid is most negative it will take the maximum energy from the electrons. The grid will lose relatively little energy to the electrons when the electrons are between grid and plate since the distance is shorter and the voltage on the plate is highly positive and contributes most of the energy gained by the electron during this part of its transit.

When the plate voltage is too high the electrons have a higher speed and there are more of them so that the voltage induced on the grid by them swings the grid more positive than before. The grid draws more current, which represents energy lost, and is also biased beyond cutoff. The grid remains biased beyond cutoff for a comparatively long period so that oscillations cease. This result is noted in the section on adjustment and tuning.

Resonant cavities excited in this manner will have the electric vector perpendicular to the walls of the cavities so the dominant mode of oscillation will be the TM_{01} mode as shown in Fig. 6. For this reason the output probe extends radially inward from the shell, that is, it is parallel to the electric vector. The magnetic field is concentric with the axis of the cavities as shown. There is obviously interaction between the two fields at the end of the grid cylinder since the fields must be continuous here. Thus we have feedback from the plate line to the cathode line.

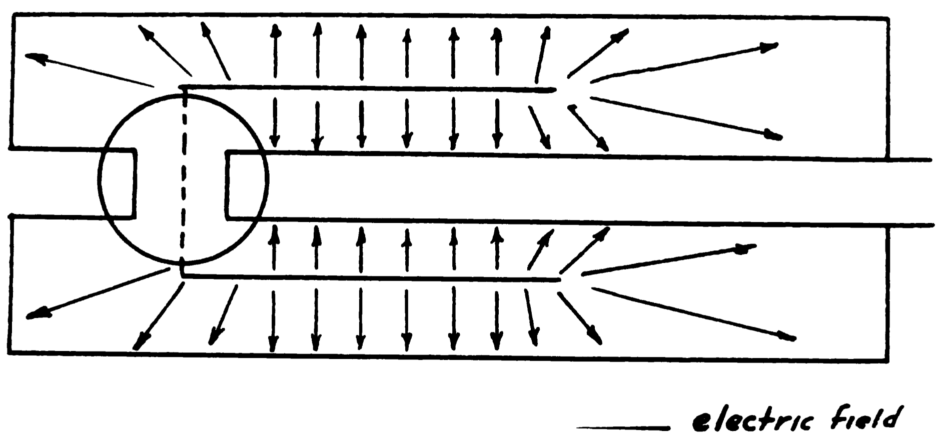


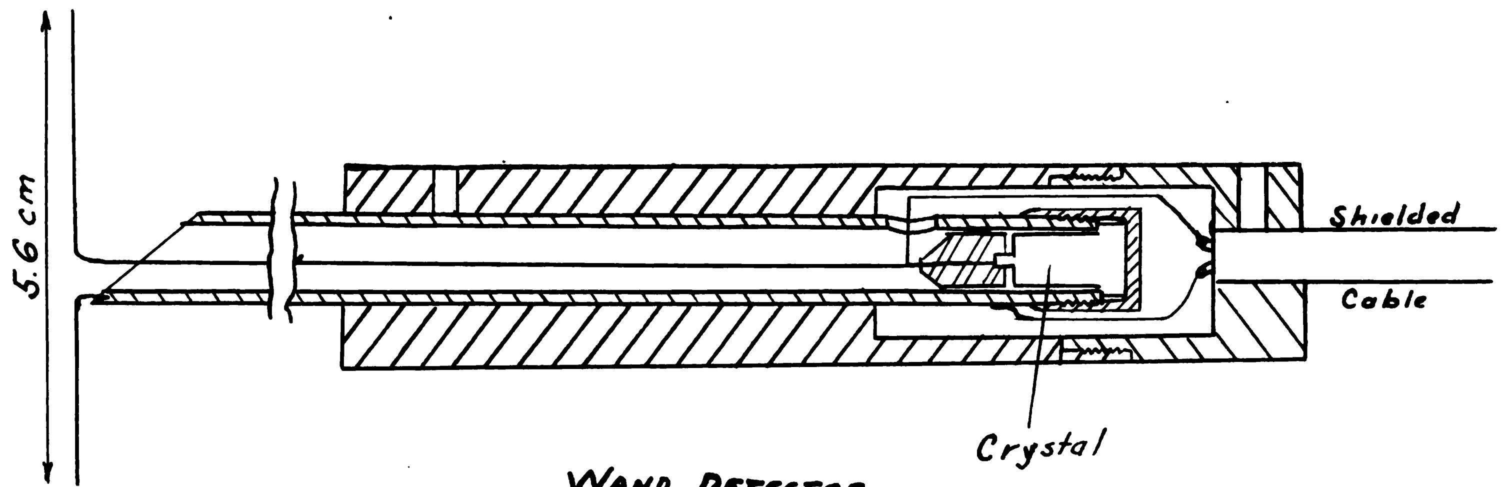
FIG. 6

IV. DETECTORS

The output radiations have been modulated at 60 cycles by impressing an a-c voltage on the plate so all that is needed for detection is a simple crystal detector to cut off the lower half of the wave, or convert it to direct current. The oscilloscope then shows the envelope of the waves, the ammeter gives the average value, and the audio amplifier gives a 60 cycle hum.

Two detectors were built. The microammeter detector simply consists of a crystal mounted between the posts of the meter. The crystal acts as the antenna in addition to rectifying the current. Much experimenting was done with other types of microammeter detectors but were given up when it was found that the metal cylinder in which the ammeter was placed had become a resonant cavity which was not of the right size to sustain oscillations at that frequency.

The wand detector is shown in Fig. 7. The lead from the wand detector to the oscilloscope or audio amplifier is a ten foot, two wire shielded cable with the shield connected to the ground wire. The ground wire is taped at the prong end so as to be distinguishable from the other wire.



WAND DETECTOR

FIG. 7

V. MEASUREMENT OF FREQUENCY

The simplest method of measuring the frequency of the oscillator is by observing the distance between the nodes of the standing wave pattern. For this purpose the wand detector was clamped in a fixed position in the beam and the reflecting plate mounted rigidly in a wooden block slotted to slide along a meter stick. In this manner one's body is completely behind the reflecting plate and does not interfere with the reflections nearly as much as if one were holding the wand detector and moving it between the oscillator and the reflecting plate. As the reflecting plate is moved along the meter stick readings are taken when the output as shown on the oscilloscope is zero or at least a minimum.

All frequency measurements were made in this manner, most of them with four to six readings and a few at intervals of the tuning with ten readings for greater accuracy. Readings from a sample frequency measurement are given below. Larger readings were given greater weight since they represent the distance between the reading and the first reading divided by the number of half wave-lengths between the two readings and should be more accurate.

Readings in cm	$\frac{\lambda}{2}$	Weight	
25.2			
30.6	5.400	1	5.4
36.2	5.500	2	11.0
41.8	5.533	3	16.6
47.4	5.550	4	22.2
52.9	5.540	5	27.7
58.7	5.583	6	33.5
64.2	5.571	7	39.0
69.8	5.575	8	44.6
75.3	5.567	9	50.1
80.8	5.560	10	55.6
		55	305.7

Average $\lambda/2$ = 5.558
Wave length = 11.12 cm

VI. ADJUSTMENT AND TUNING

Several tests were run on the oscillator to determine the effects of variation in voltage, tuning rod, length of grid cylinder, length of dipole of oscillator and detector, and the length of the output probe.

(a) Voltage

The plate voltage was fed from a 700 volt transformer whose primary was connected to a Variac transformer. Plate voltage was varied through the complete range from 0-800 volts and effects on the intensity of output, wave shape, and wave length were noted. For this purpose the wand detector was clamped in a fixed position in the beam and was connected to a cathode ray oscilloscope. Wave length measurements were taken as previously described and are believed to be within an error of 1 mm.

For any one setting of the tuning rod it was found that a variation of the voltage did not affect the frequency of oscillations to the extent that any change in frequency could be detected. This result could have been predicted since the Q of the resonant cavities is extremely high (of the order of 70,000) so that they tune at one frequency very sharply. A voltage which would have the effect of changing the frequency of the oscillations to any great extent will cause oscillations to cease.

That this actually happens can be seen from the results below.

Since the frequency is independent of voltage a complex supply circuit to give constant voltage is unnecessary and the oscillator is an ideal type for use in demonstrating optical phenomena where a single wave length is necessary. It also permits the use of a-c plate voltage which modulates the output so that it can be fed into an audio amplifier to give a 60 cycle hum.

This effect of variation of voltage was tested at several settings of the tuning rod with the same result but complete readings were taken when the wave length was 11.2 cm. Oscillations first began when the plate voltage was 75 volts rms. The intensity built up rapidly with increase of voltage as shown by Fig. 8, until a voltage of 165 volts rms was reached. With further increase in voltage the intensity remained constant but the top of the curve began to flatten out indicating that the intensity did not increase with higher voltages. At 200 volts rms the intensity at the peak of the voltage was even less so that the oscilloscope showed two humps. This change continued until at 280 volts rms or 396 volts peak value the oscillations ceased at the peak voltage and two separate humps appeared on the oscilloscope with zero intensity between the two. Further increase in voltage only separated the humps since the 396 volts occured at an earlier time in the cycle and lasted longer. These results are all shown graphically on the charts of Fig. 9.

The voltages at which oscillations begin, intensity reaches maximum, and the upper limit where oscillations cease are not the same when the oscillator is tuned for different frequencies. They should not be the same for different frequencies since the resonant frequency of the cavities and the feedback has been changed.

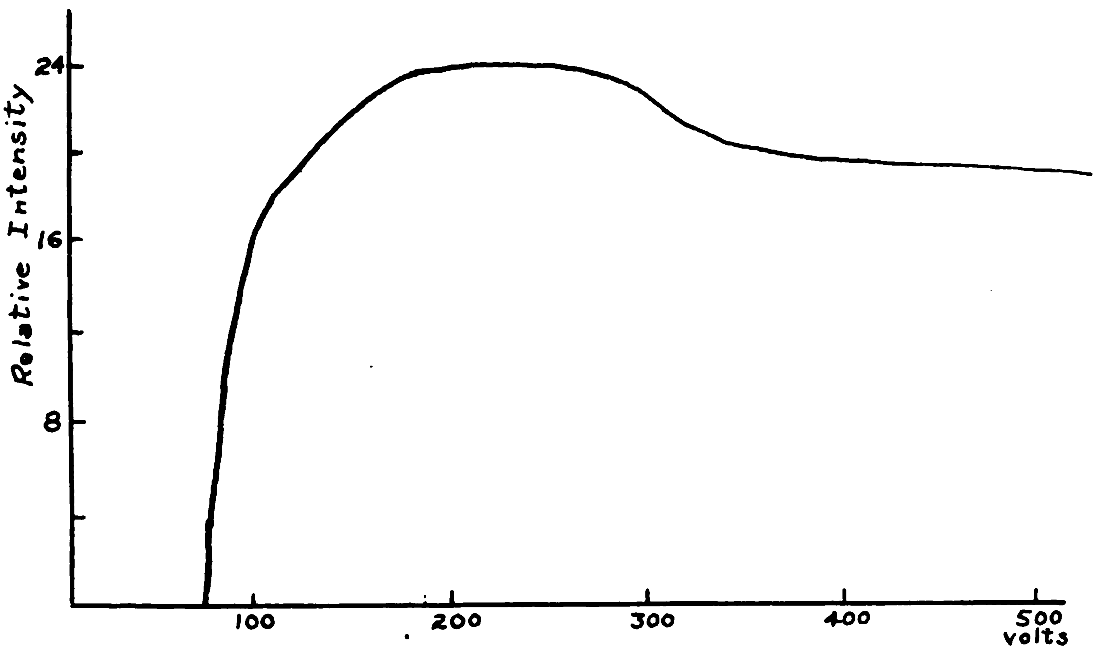
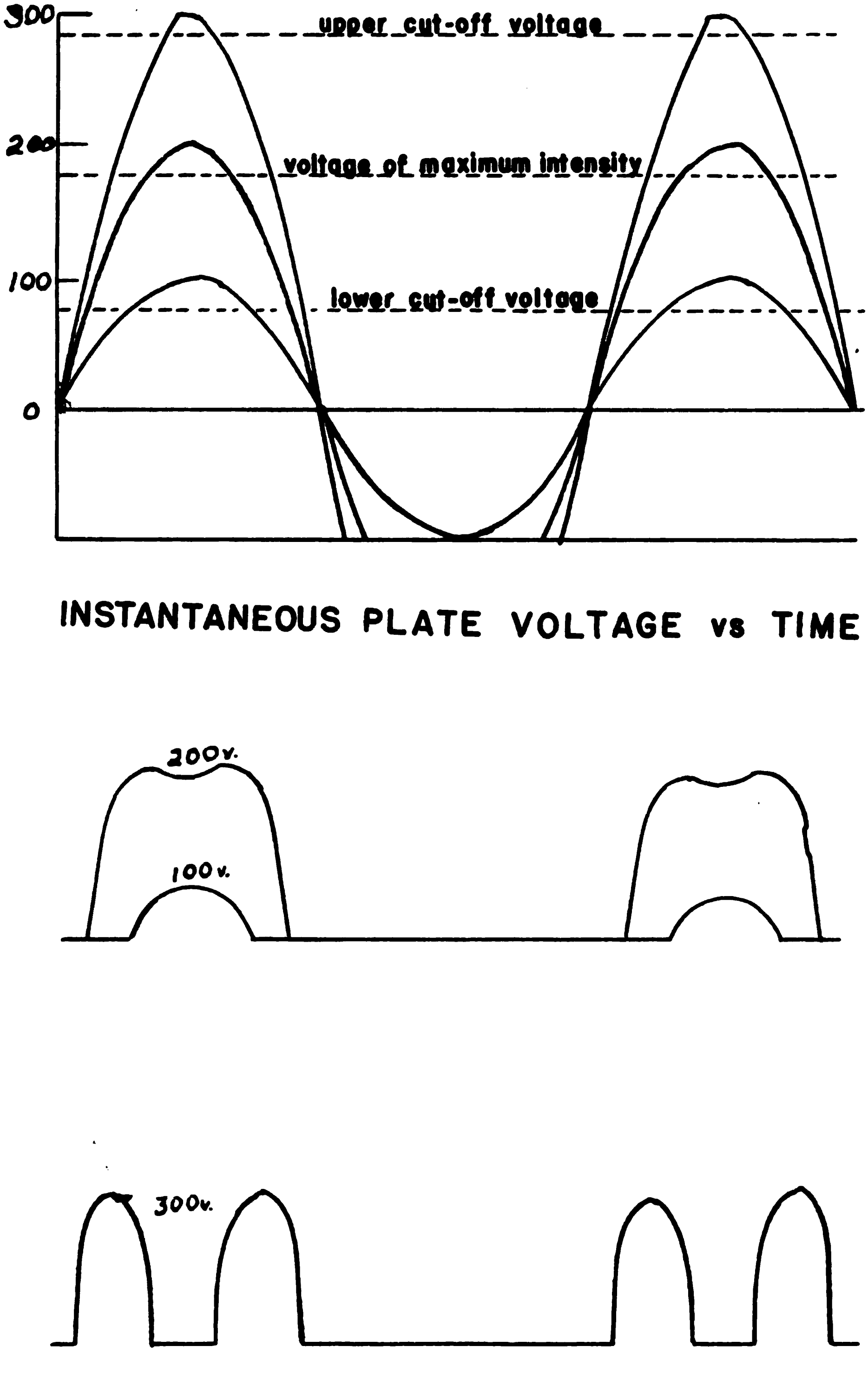


Fig. 8

(b) Tuning Rod

As explained before the movement of the shorting plunger changes the amount of feedback from plate line to cathode line and therefore controls the intensity of oscillations. Movement of the plate conductor within



INSTANTANEOUS PLATE VOLTAGE vs TIME

OSCILLOSCOPE PATTERNS

Fig. 9

the grid cylinder changes the effective length of the plate line which determines I_p and thereby controls the frequency of oscillations. Plate conductor and shorting plunger are fastened rigidly together and move together when the tuning control is adjusted. Therefore by tuning the oscillator to different frequencies we also change the feedback so that due to the design of the oscillator it will operate most efficiently at a certain frequency. Intensities are read when the oscilloscope pattern has a flat top or has two peaks since this is the maximum for that frequency independent of voltage. It was necessary to change the voltage to obtain these shapes at different points but this does not introduce any error in intensity readings. Results of relative intensity and wave length against movement of the tuning rod are shown in the graph of Fig. 10.

The intensities are only relative values and depend on the efficiency of the oscillator antenna, detector, and the output probe. These efficiencies are dependent upon the length of dipoles, lengths of probe in the resonator, and the impedence match of the probe.

(c) Length of Dipoles

The dipoles of the oscillator and detector were purposely left too long in order that the effects of changing their lengths may be studied. A dipole antenna

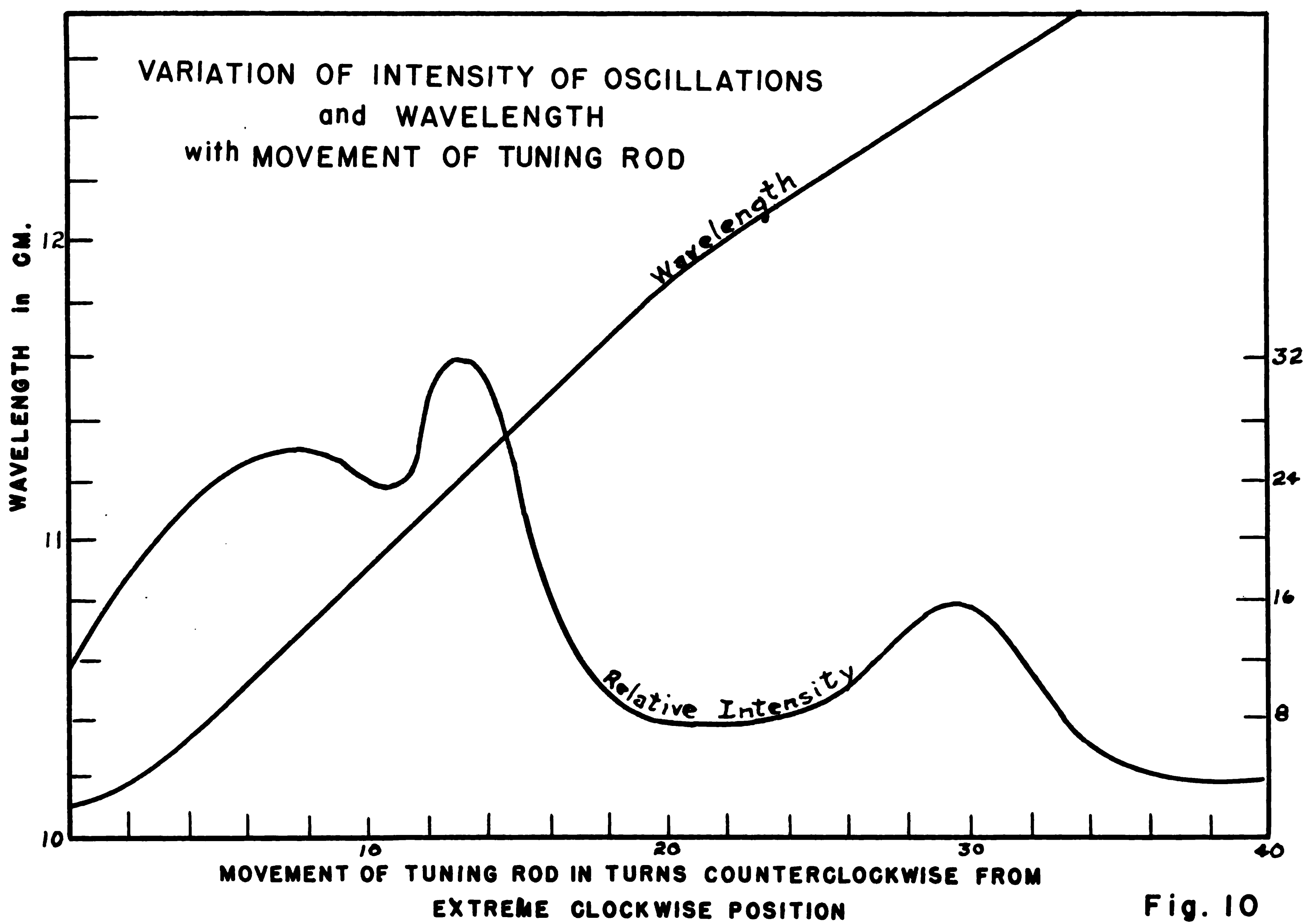

VARIATION OF INTENSITY OF OSCILLATIONS
and WAVELENGTH
with MOVEMENT OF TUNING ROD
Wavelength
Relative Intensity
WAVELENGTH in CM.
10
11
12
RELATIVE INTENSITY
8
16
24
32
10
20
30
40
MOVEMENT OF TUNING ROD IN TURNS COUNTERCLOCKWISE FROM
EXTREME CLOCKWISE POSITION

Fig. 10

should be half a wave length long (or some multiple of half a wave length) for most efficient operation. Under these conditions there will be maximum voltage at the ends, zero voltage in the center, and maximum current at the center. There is, of course, zero current at the ends of the dipole.

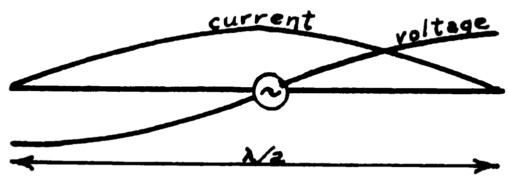


Fig. 11

The length of the antenna dipole was originally 6.4 cm long and that of the detector dipole 10.0 cm long. The antenna dipole is exactly correct for a wave length of 12.8 cm so the oscillator was adjusted to that frequency. The detector dipole was then cut down in gradual steps of about 0.5 cm until the proper length of 6.4 cm was obtained. The intensity on the oscilloscope was about 2.5 to begin with. The intensity increased slowly at first as the detector dipole was cut down and increased more rapidly as the length neared 6.4 cm. The intensity at 6.4 cm had increased to 6.5. The increase in intensity at other frequencies was as follows: for 11.7 cm, 7 to 12; for 11.7 cm, 9 to 13; for 11.2 cm, 17 to 23; and for 11.0 cm, 20 to 26. Next, with the oscillator tuned to 11.2 cm the length of the antenna dipole was reduced to [illegible] cm.

The intensity now increased from 27 to 37 and at 11.0 cm the increase was from 28 to 41. Intensities at other wave lengths were correspondingly increased. The detector dipole was then cut down to 5.6 cm and the intensity increased from 37 to 44, with corresponding increases at other frequencies.

These results show that the efficiency of the dipole is quite critically dependent upon its having the correct length.

(d) Length of Grid Cylinder

The effect of changing the length of the grid cylinders will not be treated in detail since results were inconclusive. The second grid cylinder was designed for the 2043 tube and was slightly shorter than the one designed for the 2040 tube. It reduced the intensity considerably and reduced the frequency slightly. The upper limit of the tuning range was considerably reduced as the oscillations disappeared at 20 turns and a wave length of 11.5 cm and did not reappear. The maximum efficiency is now at about 10.7 cm but the length of the dipoles is not correct for this wave length and they were not changed. The short cylinder was replaced by the correct grid cylinder.

(e) Output Probe

Adjustment of the length of output probe within the cavity showed a great effect upon the output of the oscillator. These results are shown in the graph of Fig. 12. From these results it is seen that the line containing the output probe should be one full turn from its furthest position inside the cavity. The line can be locked in this position by a nut on the coaxial line.

The length of line between the output probe and the dipole can be varied by pulling the slip joint out. However this made very little difference in the output and is therefore left at its shortest length where the connection is most solid.

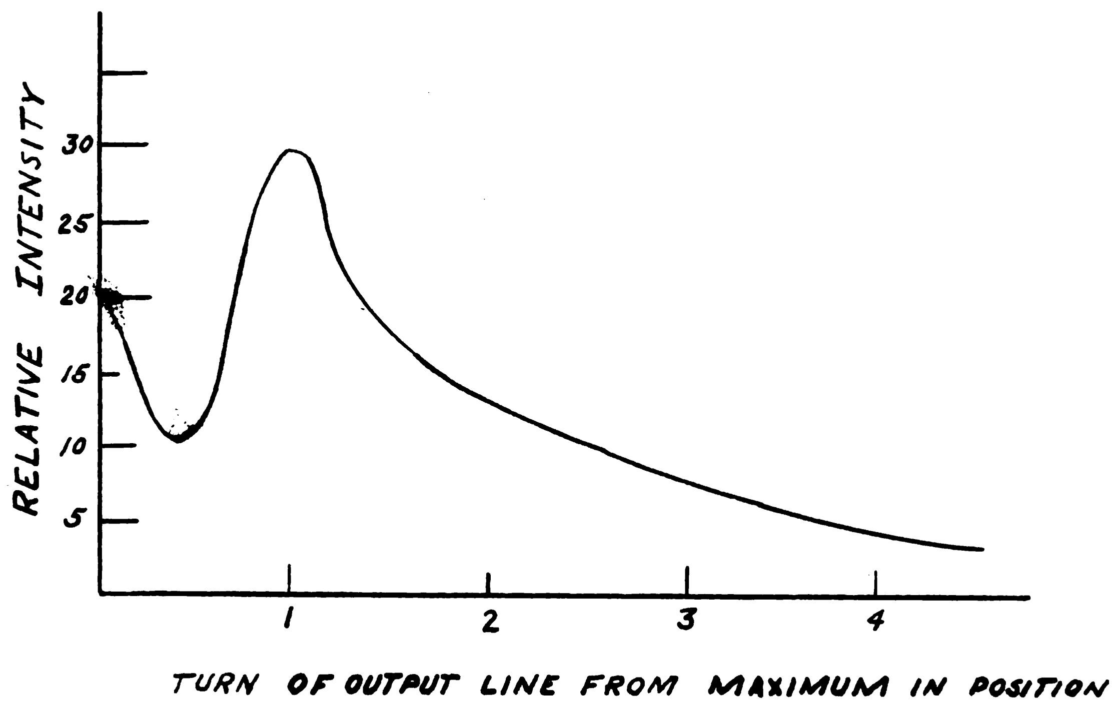
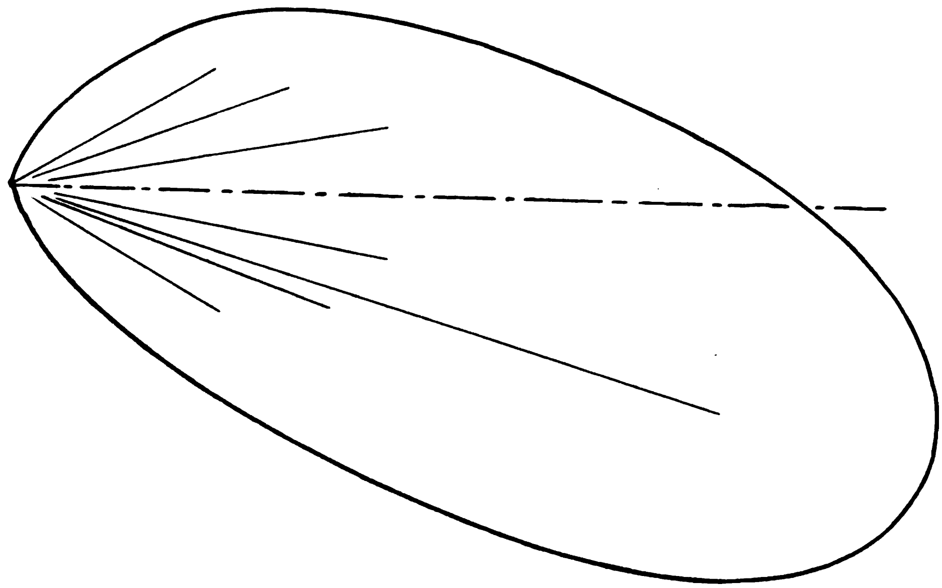


FIG. 12

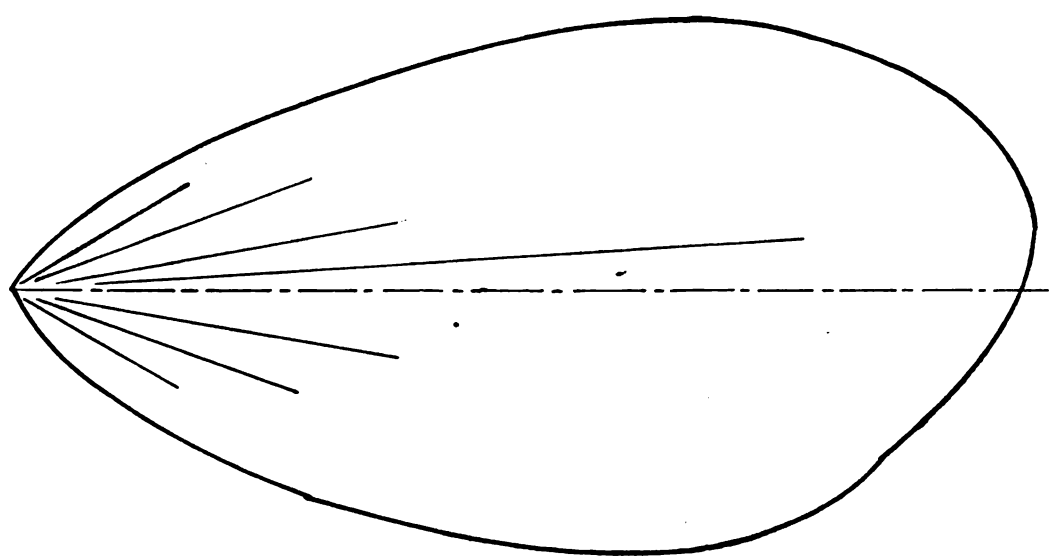
VII. RADIATION PATTERNS AND POLARIZATION

Radiation patterns were measured in a clear space out of doors in order to have as little reflection as possible. The oscillator was mounted on a turntable with the dipole directly above the center of rotation. The wand detector was clamped in a fixed position in the beam and connected to the oscilloscope so that readings were taken with the operator behind the oscillator and there was no interference in the beam. It is possible that the stand to which the detector was clamped gave some reflection and altered the pattern slightly. Readings were taken of the angles and the intensities as the turntable was rotated. The vertical radiation pattern was found in the same manner but with the reflector and dipole rotated together through 90^{o}. The diople of the wand detector was also turned until it was vertical. These radiation patterns are shown in Fig. 13. The dipole is not at the focal point of the parabolic reflector so that the line of maximum intensity makes an angle with the axis of revolution of the reflector.

By rotating the detector dipole the wave is seen to be highly polarized. These results are shown in Fig. 14.

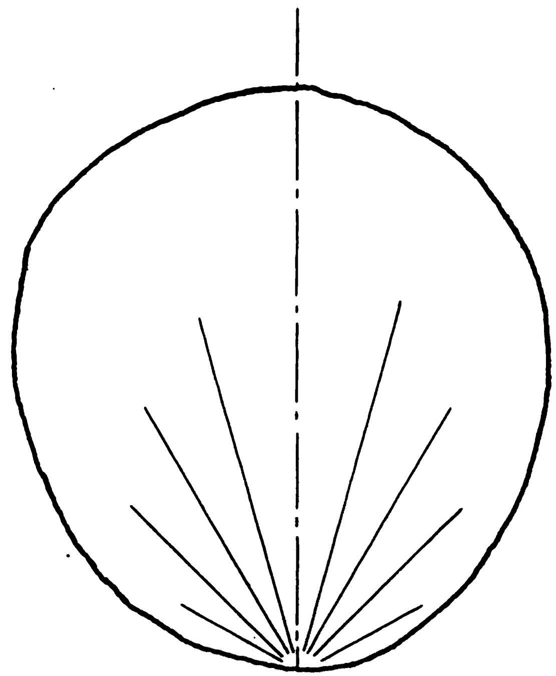


Horizontal Radiation Pattern



Vertical Radiation Pattern

Fig. 13



POLARIZATION CURVE
Fig. 14

VIII OPTICAL PHENOMENA WITH THE MICROWAVE OSCILLATOR

Microwaves are less penetrating than radio waves. The intensity of transmission and reflection is easily measured through different thicknesses of various substances. It is seen that the body reflects the wave well and must absorb the remainder since the intensity transmitted through the hand is zero. Nearly all of the intensity of the incident wave is transmitted through several inches of wood. Glass partially transmits and partially reflects the waves. If twice the optical path in glass or any other partially reflecting substance were equal to a half wave length there would be destructive interference in the transmitted wave and most of the intensity would be reflected. The wave is reflected completely from metals and shows geometrical reflection. Young's experiment is easily demonstrated with a large plane reflector by observing the maxima and minima of intensity as either the reflector or the detector is moved. There is zero intensity when the dipole is very near the surface of glass and therefore the wave has undergone a phase change of π on reflection.

Electromagnetic waves traveling in wave guides have a phase velocity which is greater than the speed of light. $v_p = \frac{c}{\sqrt{1-(\lambda/\lambda_0)^2}}$ where λ_0 is the cutoff wave length. Therefore the index of refraction $\mu = \sqrt{1-(\lambda/\lambda_0)^2}$ which is less than 1. This principle can be used to construct a lens system of a number of parallel conducting plates, which must have the dimension perpendicular to the electric vector greater than a half wave length in order to transmit waves. Since the wave speeds up when entering the wave guide the effect is the opposite to the corresponding optical phenomena and a geometrical shape of the lens which would be a divergent lens for light will be a convergent lens for microwaves. A cylindrical convergent microwave lens was built of seven plates of wire screen placed 5.8 cm apart. This lens showed considerable aberration and showed Fresnel diffraction effects from the different parallel openings since by moving the detector directly away from the lens the intensity passed through a series of maxima and minima. A spherical lens would reduce these effects and give a more striking demonstration. However the focusing property of the cylindrical lens is definitely shown in the experiment performed. Oscillator and lens were both mounted on the turntable with the lens over the center of rotation. The wand detector was clamped in a fixed position at a maxima of intensity and readings taken on the oscilloscope as follows:

Angle of rotation	Intensity with lens	Intensity without lens
0°	26	22
5°	28	21
10°	20	15
20°	15	13.5
25°	8	10.6
30°	5	9.0

One of the advantages of studying optical phenomena with microwaves is that diffraction patterns through apertures of the same order of magnitude as the wave length may be studied. These results show that the intensity in the plane of the aperture is not constant but shows maxima and minima in number dependent upon the size of the aperture.

Experiments using Fresnel zone plates and the Michelson interferometer are simple with microwaves and give the expected results. Several other experiments are listed in <u>Suggested Experiments in Microwave Optics</u>, C. L. Andrews, published by General Electric Specialties Division, 1948.

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