MICROWAVE SYSTEMS

REFLEX OSCILLATORS

1. GENERAL

1.01 The development of radio equipment to provide broad-band circuits over which video (television) signals or carrier channels may be transmitted has led to the use of frequencies commonly referred to as microwaves. For purposes of this section, microwaves may be considered as electromagnetic radiation having a frequency greater than 1,000 megacycles (1,000 million cycles) per second.

1.02 Equipment components which operate at microwave frequencies are vastly different from those used at lower frequencies such as in broadcasting or mobile radio service. Transmission lines are replaced by waveguides, tuned (LC) circuits are replaced by resonant cavities, and conventional electron tubes are replaced by special triodes, velocity-modulated tubes, or magnetrons.

1.03 A form of velocity-modulated tube known as a reflex oscillator, or Klystron, is used almost exclusively in Bell System equipment as a generator of microwave energy. Since operation of this device on proper frequency requires the adjustment of three separate controls, a knowledge of its theory is of help in tuning the microwave apparatus, and in locating trouble in connection with maintenance work.

1.04 The following sections are devoted almost exclusively to a non-mathematical description of the theory of operation of the reflex-oscillator tube. A thorough, broad knowledge of electron tube theory is assumed at least to the extent outlined in B.S.P. AB46.001, Vacuum Tubes.

2. MICROWAVE OSCILLATORS

2.01 An analogy to other types of electron tube oscillators may be helpful in understanding the operation of a reflex oscillator. In Figure 1 are shown picture schematics of a conventional triode oscillator (a), a dual-cavity Klystron (b), and a magnetron (c). Figure 1 (d) is an equivalent circuit schematic which may be considered applicable to all three oscillators.

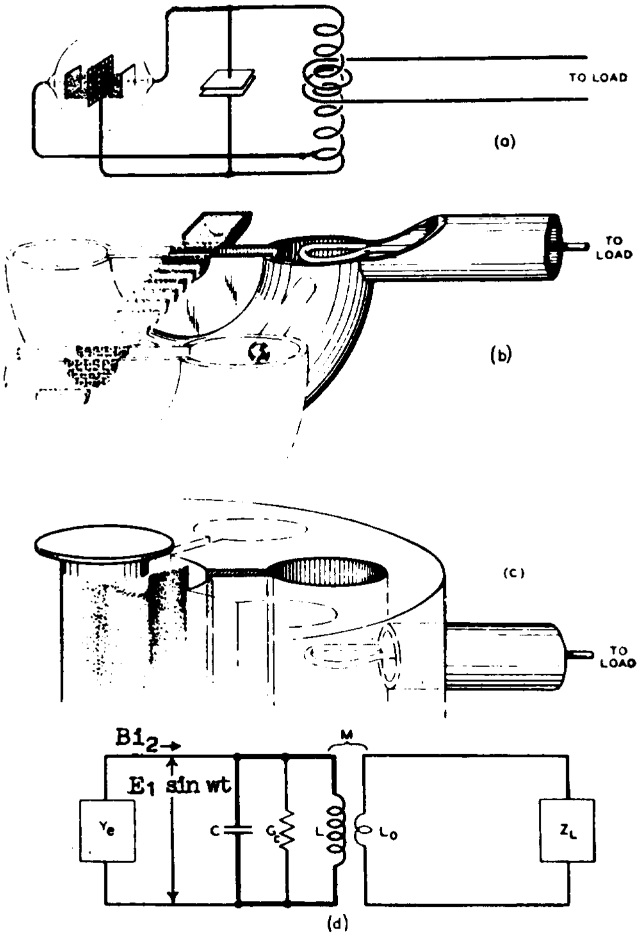


Fig. 1 —A schematic diagram depicting the parallelism among the conventional triode oscillator, the velocity variation oscillator, the centimeter wave magnetron and an equivalent lumped constant circuit. In the figure an attempt is made to align corresponding parts vertically above one another.

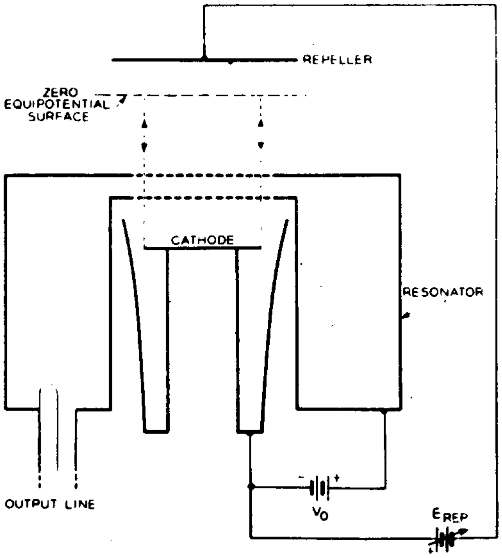
2.02 In the triode of Figure 1 (a), as in the gap of the second cavity of the velocity variation tube of Figure 1 (b) and in the interaction space of the magnetron oscillator of Figure 1 (c), electrons are driven against r.f. fields set up by the resonator or "tank circuit", to which they give up energy absorbed from the primary DC source. In each type of oscillator there is operative a mechanism of "bunching" which allows electrons to interact with the r.f. field primarily when the interaction will result in energy transfer <u>to</u> the r.f. field.

2.03 In the triode oscillator energy transfer is accomplished by the grid, whose r.f. potential is supplied by the "tank circuit" in proper phase with respect to the r.f. potential on the anode (plate). In the velocity variation oscillator, bunching is accomplished by variation of the electron velocities in the gap of the first cavity, followed by drift through the intervening space to the second gap. The first cavity is driven in proper phase by a feed back line from the second cavity. In the magnetron oscillator, electron interaction with the r.f. fields is such as to group the electrons into bunches or "spokes" which sweep past the gaps in the anode, in phase for favorable interaction with the r.f. fields across the gaps.

2.04 In the reflex type of velocity variation oscillator a single cavity is used both as "buncher" and "catcher" where the electrons after traversing the gap once, are turned back in the proper phase in the drift space so as to pass through the gap again in the opposite direction.

3. REFLEX OSCILLATORS

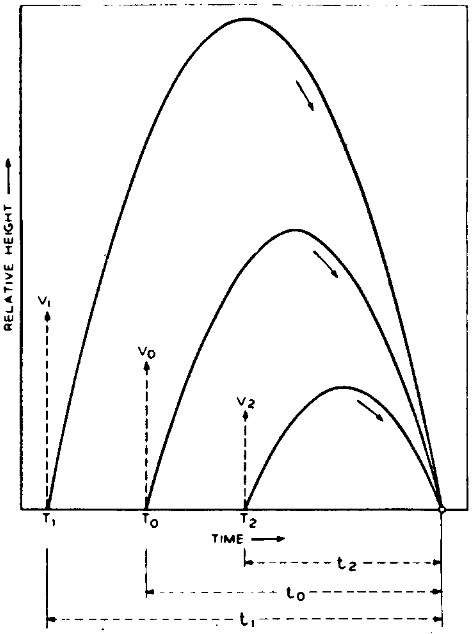
3.01 An idealized reflex oscillator is shown schematically in Figure 2. It has, of course, a resonant circuit or "resonator". This may consist of a pair of grids forming the "capacitance" of the circuit and a single turn toroidal coil forming the "inductance" of the circuit. Such a resonator behaves just as do other resonant circuits. Power may be derived from it by means of a coupling loop linking the magnetic field of the single turn coil. An electron stream of uniform current density leaves the cathode and is shot across the "gap" between the two grids, traversing the radio-frequency field in this gap in a fraction of a cycle. In crossing the gap the electron stream is velocity modulated; that is, electrons crossing at different times gain different amounts of kinetic energy from the radio-frequency voltage across the gap. The velocity modulated electron stream is shot toward a negative repeller electrode which sends it back across the gap. In the "drift space" between the gap and the repeller the electron stream becomes "bunched" and the bunches of electrons passing through the radio frequency field in the gap on the return transit can give up power to the circuit if they are returned in the proper phase.



An idealized reflex oscillator with grids, shown in cross section.

Fig. 2

3.02 The vital features of the reflex oscillator are the bunching which takes place in the velocity modulated electron stream in the retarding field between the gap and the repeller and the control of the returning phase of the bunches provided by the adjustment of the repeller voltage. The analogy of Figure 3 explains the cause of the bunching. The retarding drift field may be likened to the gravitational field of the earth. The drift time is analogous to the time a ball thrown upwards takes to return. If the ball is thrown upward with some medium speed v_0, it will return in some time t_0. If it is thrown upward with a low speed v_2 smaller than v_0, the ball will return in some time t_2 smaller than t_0. If the ball is thrown up with a speed v_1 greater than v_0, it returns in some time t_1 greater than t_0. Now imagine three balls thrown upward in succession, evenly spaced but with large, medium, and small velocities, respectively. As the ball first thrown up takes a longer time to return than the second, and the third takes a shorter time to return than the second, when the balls return the time intervals between arrivals will be less than between their departures. Thus time-position "bunching" occurs when the projection velocity with which a uniform stream of particles

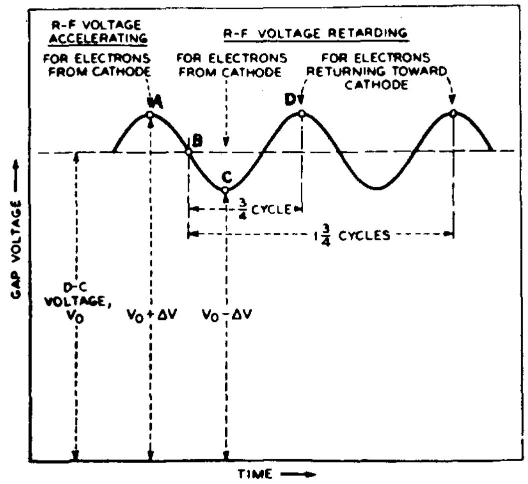


The motion of electrons in the repeller space of a reflex oscillator may be likened to that of balls thrown upward at different times. In this figure, height is plotted vs time. If a ball is thrown upward with a large velocity of V_1 at a time T_1, another with a smaller velocity at a later time T_0 and a third with a still smaller velocity at a still later time T_2 the three balls can be made to fall back to the initial level at the same time.

Fig. 3

enters a retarding field is progressively decreased.

3.03 Figure 4 demonstrates such bunching as it actually takes place in the retarding field of a reflex oscillator. An electron crossing the gap at phase A is equivalent to the first ball since its velocity suffers a maximum increase, an electron crossing at phase B corresponds to the ball of velocity v_o where for the electron V_o corresponds to the d.c. injection velocity, and finally an electron crossing at phase C corresponds to the third ball since it has suffered a maximum decrease in its velocity. The electrons tend to bunch about the electron crossing at phase B. In this process no energy is taken from the cavity since as many electrons give up energy as absorb it.



The drift time for transfer of energy from the bunched electron stream to the resonator can be deduced from a plot of gap voltage vs time.

Fig. 4

3.04 The next step in the process is to bring back the grouped electrons in such a phase that they give the maximum energy to the r.f. field. Refer to Figure 4. At point B the gap voltage is changing most rapidly from accelerating to retarding for electrons going from the cathode toward the repeller. Three-quarters of a cycle later, such as point D, the gap voltage has a maximum retarding value for electrons returning thru the gap. Under this condition maximum energy is transferred from the bunched beam to the r.f. field existing in the gap. This is true also for 1-3/4 cycles, 2-3/4 cycles, n + 3/4 cycles. Hence as Figure 4 shows if the time electrons spend in the drift space is n + 3/4 cycles, the electron bunches will return at such time as to give up energy to the resonator most effectively.

3.05 We may summarize as follows: A reflex oscillator consists essentially of a source of electrons (filament or cathode) which are formed into a beam and accelerated by a positive voltage, V_o, on a pair of grids between which a radio-frequency voltage exists. As the electrons pass through the grids they are accelerated or retarded depending on whether the r.f. voltage aids or opposes the direction of motion. After the electrons pass through the grids they tend to group into bunches as the faster electrons catch up with the electrons which have been slowed down. Since an electric current is measured by the number of electrons which pass a given point at a given instant, it is seen that the electron beam has become an alternating current (superimposed on a direct current) which rises and falls at the same frequency as the r.f. voltage across the grids.

3.06 Beyond the grids the electron current comes under the influence of a negative voltage, E_{rep}, applied to a plate called the repeller. This voltage reverses the direction of the negative electrons and causes them to pass again through the space between the two grids, traveling in the opposite direction. By properly adjusting the repeller voltage the electron stream will return to the grids at a time when it will assist in building up the r.f. voltage which exists across them. This occurs when the time interval in cycles between leaving the grids and returning is 3/4, 1 + 3/4, 2 + 3/4, n + 3/4, where n is any integer.

3.07 A resonant cavity, of which the two grids form a part, determines the frequency at which the Klystron will oscillate. A mechanical adjustment of the spacing between the grids varies the capacity of the resonant cavity and provides a coarse method of tuning the Klystron. A fine control of frequency is obtained by varying the repeller voltage slightly. This causes the electron beam to either lag the r.f. voltage (inductive effect) or lead the r.f. voltage (capacitive effect). A change of either inductive or capacitive reactance will change the frequency.

3.08 Figure 1(d) gives an equivalent electrical circuit which may be used to represent the action of a reflex oscillator. Z_L denotes the impedance of the load, i.e., antenna, crystal mixer or other device to which energy is delivered. In a properly adjusted circuit this will be a pure resistance, R_L. G_c represents the conductance of the resonator and is the reciprocal of R_c, the equivalent resistance causing copper losses and other resonator losses. C is the capacitance of the resonator gap and may be computed from the cross-sectional area and spacing of the resonator grids. L is the equivalent inductance which will make the resonant frequency $1/(2\pi\sqrt{LC})$ equal to that of the cavity. Y_e, the admittance of the electron beam, is the reciprocal of the impedance seen by the electron beam. It is somewhat analogous to the reciprocal of the plate resistance in a conventional triode.

3.09 An equation for the beam admittance is:

$$Y_e = \frac{-Bi_2}{E_1} = \frac{2BI_oJ_1\ (x)}{E_1}\ (-\cos \phi + j \sin \phi)$$

where B = beam coupling coefficient of the gap and equals 1, or less.

$x = B\pi N\frac{E_1}{V_o}$ = bunching parameter.

I_o = Direct beam current.

$i_2 = 2I_oJ_1(x)\sin(wt_2 - 2\pi N)$ = r.f. component of beam current.

$N = n + 3/4$ = no. of cycles during transit time in reflection space.

E_1 = peak value of r.f. voltage at resonator gap.

$J_1(x)$ = Bessel function of the first kind.

t_2 = Arrival time of returning electrons.

$\phi = 2\pi N = 2\pi(n+3/4)$ = phase angle of i_2

n = any integer.

3.10 A plot of the equation for Y_e is given as Figure 5:

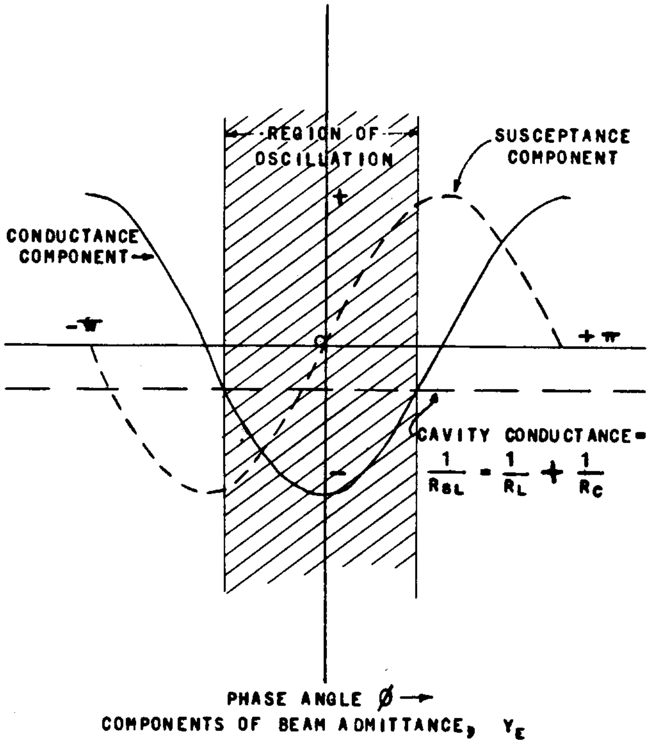


FIGURE 5

The real part or conductance component (reciprocal of resistance) is plotted as a solid curve, while the imaginary, or susceptance component (reciprocal of reactance) is plotted as a dashed curve, against the phase angle ϕ. Two features are evident from Figure 5: (1) oscillation will take place whenever the negative conductance of the beam equals and cancels the cavity conductance which causes energy losses in the oscillator circuit, and (2) oscillation will still take place although a susceptive (reactive) component of beam admittance is present. This susceptive component will change the frequency of oscillation by adding either inductance or capacitance to the reactance of the resonator alone.

4. TUNING CONTROLS

4.01 From the equivalent circuit of Figure 1(d) and the equation for Y_e it is evident that the frequency of oscillation may be changed by adjusting three variables, as follows:

(1) The value of C or L of the resonator may be varied.

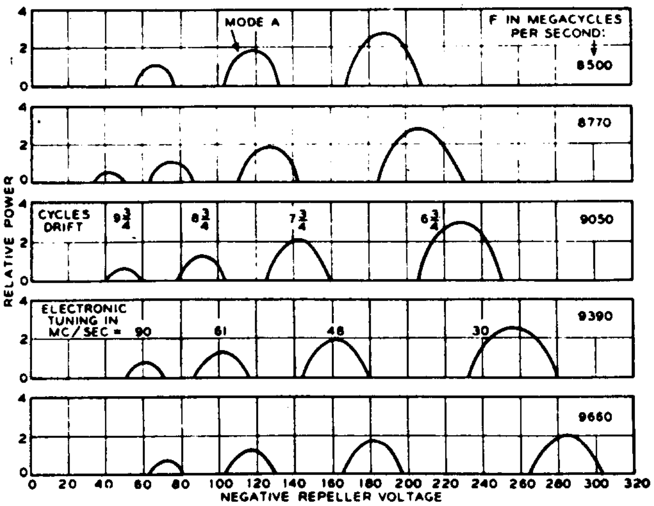
(2) The value of Y_e may be changed to provide different values of susceptance.

(3) The coupling to the load, Z_L, may be such that a reactive component is present in the oscillating circuit, i.e., load is not a pure resistance, R_L.

4.02 The value of C of the resonator is most easily changed by mechanically varying the gap between the two grids. This is performed by a tuning bow built onto the usual type of reflex oscillator tube. This tuning adjustment is usually referred to as the coarse frequency control.

4.03 Electronic tuning of reflex oscillator tubes, usually called fine frequency control, is performed by varying the negative repeller voltage. As indicated in Figure 5, small variations of phase angle, $\phi = 2\pi N$, caused by changes of repeller voltage, introduce susceptance into the tuned circuit which varies the frequency. With further changes of repeller voltage, and resultant phase angle, a value will be reached where the tube will cease oscillating. This condition will continue with changing repeller voltage until the period during which the electrons remain in the drift space is either increased or decreased by approximately one full cycle. This represents a change in value of N by unity, and oscillations will again start at approximately the frequency determined by the LC value of the resonator. Several such periods of oscillation, termed modes, may be found while the repeller voltage is varied. Each mode represents a change in drift period of one cycle from the modes adjacent. Figure 6 indicates the modes for a 2K25 oscillator for various settings of the mechanical, or coarse tuning control.

4.04 Maximum efficiency of power transfer to an external load is obtained when the external conductance is equal approximately to half the available small signal conductance, that is, half the difference between the electronic beam conductance and the resonator conductance. This means that, regardless of the mode, if the generator



Operation of the 2K25 in various repeller modes and at various frequencies when connected to characteristic admittance of a 1" x ½" guide

Fig. 6

is coupled to the load conductance for maximum output; then, if that conductance is slightly more than doubled oscillation will cease. In all presently used Bell System equipment, the coaxial output line of the reflex oscillator tube is coupled to a waveguide thru an impedance matching transducer (a form of transformer). The probe from the transducer which extends into the waveguide radiates in all directions. Reflections from the rear plunger and side walls of the waveguide establish a standing-wave pattern which determines the impedance at the point where the probe is inserted. In order that the standing-wave ratio may be close to unity and a good impedance match obtained, it is necessary in most designs that the rear plunger be made adjustable so that its distance from the probe may be varied to permit maximum power transfer at the desired frequency. Changes of position of this plunger may change the value of reactance which is reflected back into the resonator of the oscillator tube and thereby change the frequency.

5. MODULATION

5.01 A reflex oscillator tube may be frequency modulated by applying the modulating signal to the repeller plate in series with the repeller voltage, E_{rep}. As long as the maximum signal voltage is a small percentage of E_{rep} the frequency of oscillation will vary in a linear manner with the signal. Very little amplitude modulation will occur if carrier frequency has been centered at the peak of the power output curve, since the power output curve is relatively flat for several megacycles either side of the peak power.

5.02 Amplitude modulation is not desirable for reflex oscillator tubes but is sometimes used so that a single crystal rectifier may be used as a receiving detector. Amplitude modulation may be obtained by applying the modulating signal to the resonator in series with the accelerating voltage, V_o. The beam current, I_o, will vary directly with the modulating voltage and this will produce a power output which varies with the desired signal.