MICROWAVES

Part III—Tubes for the microwave frequencies, giving special notice to the lighthouse triode, velocity-modulated tubes, and the magnetron

By C. W. PALMER

THE early investigators of microwave frequencies above 3,000 mc soon discovered that conventional vacuum tubes with the grids operated at a negative bias were inadequate or entirely inoperative for several reasons.

First, interelectrode capacitance between the elements of the tubes was large enough to bypass the high-frequency currents so that they went around the tube instead of through it.

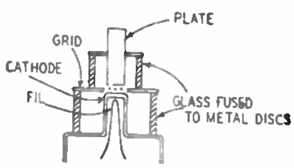


Fig. 1—Cross-section of a lighthouse tube.

Second, the internal leads from the tube elements to the external connections were often first-class inductances at the desired frequencies. This combination of L and C limited the highest frequency at which the tube could operate.

However, even before this theoretical limit was reached, it was found that tubes would not oscillate because of losses in the insulation, electronic emission from the grids, and (perhaps most important) the *transit time* of electrons from cathode to plate.

As an example of this transit-time trouble, let us consider a conventional tube operating at 1,000 kc (in the broadcast band). A typical transit time of .001 microsecond at this frequency is only one thousandth of a cycle of the r.f. current, and would have little effect on the flow of electrons. At 500 mc, however, the same transit time would become a half cycle, which would make the tube entirely inoperative.

The upper limit of oscillation of tubes of ordinary construction is about 150 to 175 mc or even lower. Special acorn, door-knob, and miniature tubes were developed to reduce the capacitance and inductance of the leads in an effort to increase the maximum operating frequency.

Next, tubes were made with the grid-cathode spacing cut to as little as .005 inch to reduce transit time and still maintain control of the electron flow. By these methods the maximum operating frequency was raised to about 800 mc.

Another trick—using multiple leads to the tube elements—provides additional gains. The grid and plate leads are run right through the glass envelope on both sides of the tube, forming terminals at each side which are connected to the ends of the tuning inductances, providing resonant circuits with the tube capacitance and inductance included in the over-all values. This serves to divide the shunting capacitance between the two circuits (grid and plate), and, since the inductance of the leads is then part of the resonant line, it becomes a distributed, instead of a lumped, constant. Of course, there is no effect on the transit time.

Lighthouse triodes

Up to this point, microwave tubes were of conventional design with wrinkles added to make them operative at higher frequencies.

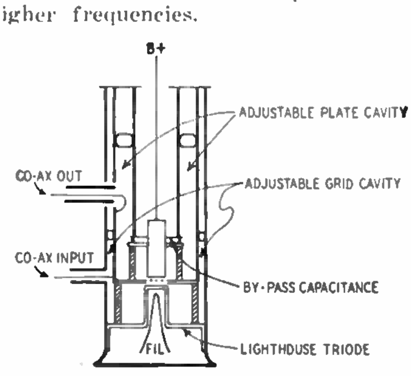


Fig. 2—Lighthouse tube in co-axial circuit.

One tube that is truly a microwave design instead of a modification of conventional forms is the Lighthouse tube or Megatron. In this tube the cathode, grid, and plate are mounted in parallel planes instead of co-axially. This can be seen in Fig. 1. The cross section shows how glass cylinders are fused to metal discs and cylinders to form the housing and the control elements. This coplanar electrode design and disc-seal construction permits really low interelectrode capacitances.

In addition, the construction permits the tube to become a part of a resonant cavity for providing high-Q resonant circuits at microwaves. Fig. 2 is a typical cross section of a lighthouse tube mounted in co-axial cavity resonators to form a grounded-grid amplifier of microwave signals.

The lighthouse tube is used in local oscillators for superhet receivers, in detectors and amplifiers, and as a signal source for microwave measurements. Its main limitation is its low power output for transmitting purposes, compared to some other microwave tubes to which we will turn our attention.

Orbital beam tube

Secondary electron emission plays an important part in several of the microwave tube designs. One of these is the orbital beam tube. Fig. 3 shows a cross section (looking down from the top) of such a tube. A small electrode structure of cathode and two grids with a secondary electron emitter raises the transconductance of the tube above the level obtainable in the usual direct-emission construction.

Electrons emitted by the cathode K1 are accelerated through the control grid G1 by a screen grid G2 which has a high positive bias. The electrons enter a strong electrostatic field set up by electrodes J1 and J2 causing them to follow a circular path at high speed until they strike the secondary emitter K2. Here they "bounce off" about 10 secondary electrons for each primary electron in the cathode stream. The

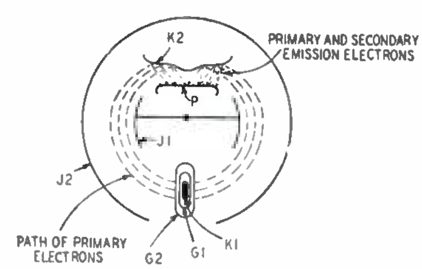


Fig. 3—Operation of the "orbital-beam" tube.

greatly multiplied electron stream proceeds to the plate P, causing a considerably greater plate current to flow than would be possible by direct emission. The result of this beaming effect is a tube having a high transconductance without increasing transit time or internal capacitance effects. Transconductances of 15,000 at higher than 500 mc have been measured.

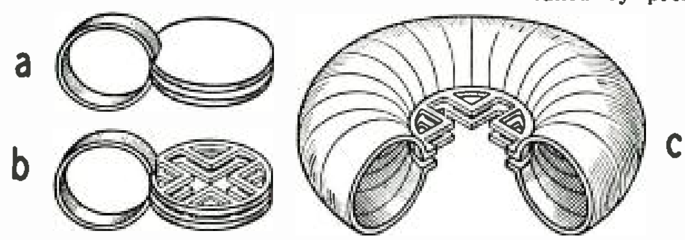


Fig. 4—Evolution of the resonant cavity and grid system of the Klystron.

This tube finds application in amplifiers where high voltage gain is needed with small input loading effects. In both transmitters and receivers it is desirable to have high-gain amplifiers in the low-level parts of the circuit. R.f. and i.f. amplifiers, detectors, and oscillator circuits are typical examples of this, particularly at frequencies under 1,000 mc.

Velocity-modulated tubes

In conventional negative-grid tubes, the control grid restricts the flow of electrons when it becomes negative and increases the flow when it becomes positive. Thus, the electrons, after passing the control grid, tend to separate into groups. Those which pass the grid during the negative half-cycle are collectively slowed down while those passing during the positive half-cycle are speeded up.

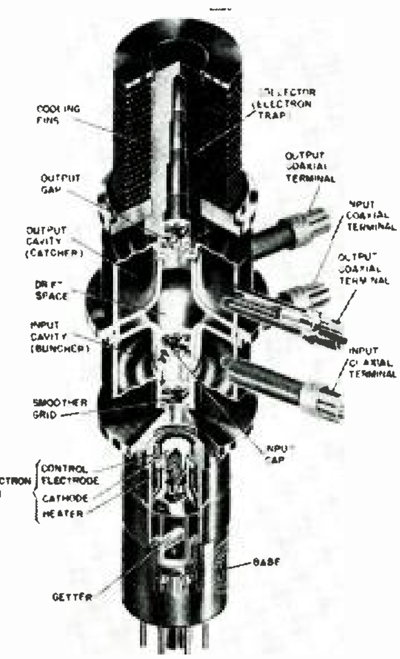
However, because of incomplete control of the electron stream, only part of the electrons reach the plate in the alternating slowed-down and speeded-up groups, the remainder reaching the plate at random speeds, thus contributing nothing to the tube action. The efficiency of the tube is thus reduced in proportion to the variation in velocity and reaches zero when the transit time approaches a half-cycle, as we mentioned before.

A velocity-modulated tube has been developed, in which this effect serves a useful function. In this tube, the input signal on the grid is used to control the velocity of the electrons in a constant-current beam instead of varying the intensity of a constant-velocity flow.

A specialized form of velocity-modulated tube, which is extensively used for wide-frequency operation because it can be readily tuned over a wide range, is the Klystron.

The Klystron depends on the resonant cavity discussed in our last installment. There are two of these in the standard Klystron. Each of them has two grids, which may be considered the capacitor plates of a greatly modified coil-capacitor circuit. See Fig. 4, which is developed in a little different way from the resonator of Fig. 4 in last month's installment. At *a* we see a single turn with a capacitor across it. At *b* the capacitor plates are made of mesh so they can also act as grids. At *c* a large number of turns are joined together to suggest how the resonant cavity can be built up. In the complete resonant cavity, as seen in the Klystron of Fig. 5, one end of the cavity is made flat, of corrugated flexible metal, so the circuit can be tuned by pressing the two grids closer together. This is the same as turning the plates of a variable capacitor further "in."

If r.f. is introduced through the input terminal, any part of the wall and



Courtesy Sperry Gyroscope Co.

Fig. 5—Cutaway of a typical Klystron tube.

the two grids act like the single turn of Fig. 4-a, electrons flowing along the wall and voltages building up on the grids at the frequency of operation.

Electrons are attracted by the grids, which are maintained at a higher positive d.c. voltage than the cathode. Those which pass through the two grids at a part of the r.f. cycle when the first grid is at a higher voltage than the second are slowed down somewhat by the relatively more negative second grid. Those electrons which pass through the grids when the second is at a higher voltage are speeded up. Thus there is a tendency for the electrons to *bunch.*

The bunching effect is increased by letting the electrons travel through a "drift space" where the faster-moving electrons gradually overtake the slower-moving ones. The electrons emerging from the pair of grids are separated into groups or bunched along the direction of motion. This *velocity-modulated electron* stream is passed into a *catcher* cavity similar to the one that bunched the electrons. As the groups of electrons approach each of the two grids in turn, they induce positive charges in them by capacitor action, causing r.f. currents to flow in the catcher cavity at the frequency set by the input r.f. In other words, the catcher cavity is tuned or made resonant to the frequency of the velocity-modulated electron beam so that oscillations are set up in it by the passage of the electron bunches through the grid aperture. If a feedback loop is provided between the catcher cavity and the bunches, oscillations will occur at a frequency determined by the electrode voltages and the dimensions of the cavities. The Klystron is tuned by varying the supply voltages and altering the size of the cavities by means of their bellows or "rhumbatron" construction.

The bunched-beam current in a Klystron is rich in harmonics, but the output wave is remarkably pure because of the high Q of the cavity resonators which suppresses the unwanted harmonics.

Klystrons may be tuned through several modes of the cavity resonators and thus are "wide-range" devices covering a wide band of frequencies. They are, however, designed for a specific band of frequencies and are applicable only to that band.

Klystrons are perhaps the most widely used vacuum tubes for microwave measurement work, as oscillators. However, they find many applications also as amplifiers, frequency multipliers, and as detectors or mixers in superheterodyne receivers.

The reflex Klystron differs from the type described above in that only one cavity resonator is used instead of two. The electrons are reflected back from the drift space into that cavity by a reflector electrode. The action is otherwise very similar.

Positive-grid oscillators

If a triode tube is arranged in a circuit in which the grid, rather than the plate, is at a high positive voltage with respect to the cathode, it will oscillate at higher frequencies than the conventional circuits.

Electrons emitted by the cathode are accelerated toward the positive grid, some striking it and some passing between its meshes. Those that pass through are repelled by the negative

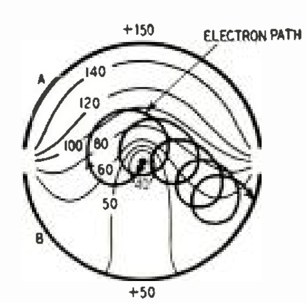


Fig. 6—Electrons in split-plate magnetron.

plate and return, passing once again between the grid meshes. In this process, the electrons induce high-frequency voltages in the grid at a frequency depending directly on the electron transit time.

Some electrons may pass through the grid structure several times while others strike the grid on the first trip. The former lose energy, but the latter gain energy. However, since the former are free for a longer period of time, there is a net transfer of energy that maintains oscillation.

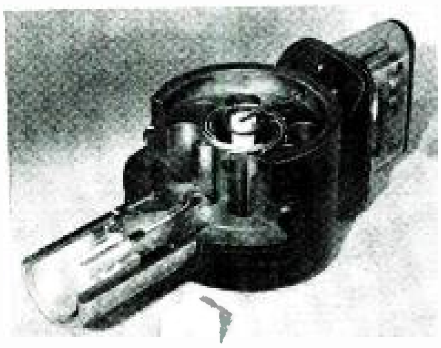


Fig. 7—Cutaway view of W.E. 5J23 magnetron.

In this type of oscillator the frequency is controlled by the grid voltage and the tube-element spacing as well as by the external resonant circuit into which the oscillation energy is fed.

Positive-grid oscillators can be operated at frequencies approaching 10,000 mc (3 cm) but are low in efficiency—only 2 or 3%—and are useful mostly for laboratory experimental and research work.

The Magnetron

Perhaps the tube with the most exciting of all careers is the magnetron. Invented many years ago, the early split-plate type was known only as a cranky but efficient laboratory oscillator. The demand for a high-power, high-frequency radar oscillator speeded research to the point where the present cavity magnetrons were born.

The magnetron is fundamentally a diode with one, two, or a number of anodes placed in a cylinder around the cathode. The tube is placed in a strong magnetic field, with the lines of force parallel to the elements (N and S poles at ends of tube). Magnetron oscillators operate in two different ways—with negative-resistance (dynatron), or transit time.

When no magnetic field is applied, the magnetron acts like an ordinary diode. Electrons leaving the filament are drawn directly to the positively charged plate. Upon application of a magnetic field, the electron is acted on by two forces—the electrostatic force attracting it to the plate, and the magnetic force urging it in a direction at right angles to its path from cathode to anode. Therefore, the electron moves in a curved path, the curvature of which increases with the magnetic field strength, until a point is reached at which the plate is missed altogether, and the electron—carried on by its own momentum—curves back toward the filament.

To make the tube act as a negative-resistance magnetron oscillator, anode voltage and field strength are so adjusted that the tube acts as a negative resistance. The magnetic field force is increased to a point which prevents practically all electrons from reaching the anodes. If, however, one of the split sections is at a higher voltage than the other, the electrostatic field in the vicinity of the slot between sectors will be distorted as shown in Fig. 6. Any electron whose circular path causes it to move parallel with the plate and in the direction of the one with lower voltage is retarded by the opposing field and no longer has momentum enough to carry it clear of the plates and back to the cathode. Consequently, it comes to rest on the lower-voltage anode.

This is a true case of negative resistance. A lowering of voltage results in an increase of current, and vice versa.

The action is more completely described in RADIO-CRAFT, February, 1946, from which the above description is taken.

In the transit-time oscillator, the electrostatic and magnetic fields are so adjusted that all the electrons rotate in circles and never reach the plates, but form a strong space charge between cathode and anodes.

If an alternating current is now applied between the plates, they alternately draw electrons from the space charge, causing momentary plate current to flow. If the frequency of the alternating voltage applied between the plates equals the time it takes for an electron to rotate once round the cathode in the magnetic field, the a.c. component of the plate current changes direction twice for each electron rotation. The result is a sustained oscillation due to transfer of energy from the electrons to the electric field in the tube.

In the early magnetrons, the plates were semicircles surrounding the cylindrical cathode and the output of the plates was fed to a resonant transmission line. Modern magnetrons have built-in cavity resonators as shown in Figs. 7 and 8. At extremely high frequencies the plate structure is divided into as many as six or eight segments, each with its own resonant cavity coupled to the cathode by slots of critical dimension. Sometimes, further to increase efficiency, the segments are cross-connected with wires. The magnetron is then said to be "strapped." See Fig. 7.

The efficiency of multisegment magnetrons may be as high as 70%. The frequency of high-order modes of oscillation can be as high as 120,000 mc (0.25 cm) at power outputs of 100 watts or more. Thus it can be readily seen why magnetrons are almost exclusively used as high-power oscillators and transmitters in the microwave regions.

The above descriptions cover most of the microwave tubes now in use. We have not covered some of the specialized types such as the Micropup, which is a special triode of English origin in which the plate is part of the external tube envelope and is equipped with radiating fins to dissipate heat and permit it to produce higher power; the Zahl internal-circuit tube, which contains four triodes in one envelope connected directly to resonant quarter-wave lines and can develop up to 200 kw of pulsed microwave power; or the ring triodes in which separate triodes are mounted around the periphery of a circular mounting with their elements connected in parallel. These and other special types are either outmoded or have little general application and are interesting only from a purely academic viewpoint.

Fig. 8—A 270-kw magnetron, the W.E. 728-AJ.

INSECTS ARE RADAR "ANGELS"

Many a GI who sat at a radar screen in the South Pacific during the war can attest to the harassing power of flying (and lighting) insects. But he never dreamed that these insects were responsible for the "angels" which confused his observations when they appeared on his radar scope.

"Angels" is the nickname applied to the short, sharp echo "blips" that have been noted on radar equipment for years. These little spots of light defied all the laws of aerodynamics and bewildered all the experts, who were at a loss to explain them.

Recently, however, tests and observations conducted jointly by Bell Telephone Laboratories and the Naval Electronics Laboratory confirmed that high-flying insects were the source of the "angels." Working at night, researchers threw out a strong searchlight beam and stationed observers at different levels of a 200-foot tower. While the observers counted insects, the radar operators counted "angels." In one 15-minute period, for instance, 20 were counted, 15 of which coincided with the sighting of an insect.

A. B. Crawford of Bell Laboratories, who reported the discovery, points out that insects fit most of the descriptions applied to the mysterious reflections. They are small, move at a speed around that of the wind (sometimes with and sometimes against the wind), are present both day and night, and increase in warm weather.