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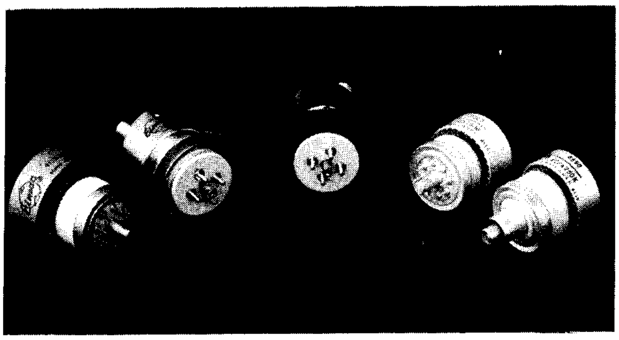

vhf/uhf effects in gridded tubes

Here is a rundown on the characteristics you should understand to get the most out of gridded tubes at uhf

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The technically-minded amateur has known for some time that a vacuum tube becomes progressively less effective as the frequency of operation is increased. Amplifiers require greater driving power, output power drops off, and the manufacturer may be obliged to derate the tube at the high-frequency end of the operable range. If the frequency is raised high enough, the gain of the amplifier will drop to an unusable level. Upon further increase in frequency, the gain will drop to unity or less. At the same time this is happening, the input impedance of the amplifier drops as does the maximum impedance realizable in the plate circuit.

Numerous factors contributing to the reduction of amplifier output at vhf and uhf can be listed and divided roughly into three groups:

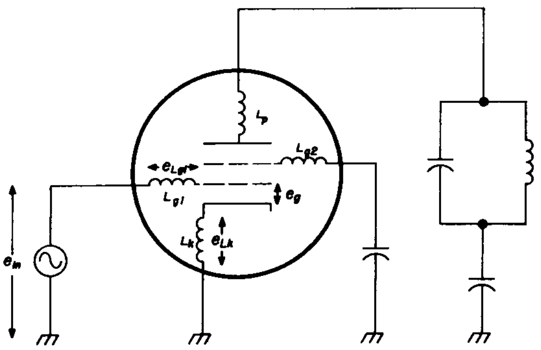
1. Circuit-reactance limitations
2. Circuit and tube loss limitations
3. Electron transit-time limitations.

circuit-reactance limitations

At the very-high and ultra-high frequencies there exists a situation which is quite different from that which exists at low frequencies. At low frequencies the electrical circuits and the tube are quite distinct. As frequency increases, this ceases to be true, and it is found that part of the resonant circuit exists within the tube (**fig. 1**). The electrode leads, while they are normally short and have large surface area in modern tubes, have a small but finite inductance. As the frequency of operation is raised, the reactance of the **lead inductance** will become quite appreciable, often reaching undesirable proportions in the vhf-uhf regions. The effect of lead inductance is to create a voltage drop such that the applied voltage across the external terminals of the tube will not entirely appear across the electrodes. Driving voltage is thus lost across the lead inductance.

In addition, while the interelectrode capacitances may be small, at ultra-high frequencies they approach a large fraction of the capacitance required to establish resonance in an external circuit. As such, the interelectrode capacitances represent a limitation in terms of actual operation as the external tank circuit may "disappear" within the tube. The combination of the electrode-lead-inductance and the interelectrode capacitance may cause an **internal resonance** in the uhf region.

fig. 1. The total input voltage does not act upon the grid-to-cathode electron stream because of grid and cathode lead inductance—the voltage across them subtracts from the input voltage.



A typical internal resonance experienced in a large power tube is the circuit consisting of the control-grid cage and mounting cone, and the screen-grid and cone. These two assemblies can form a quarter wavelength long tuned-line circuit shorted at the tube envelope by the capacitor consisting of the two contact rings and the dielectric material used in the envelope. The internal resonant frequency could be in the range of 1400 MHz for a five- to ten-kilowatt tube. This could lead to a 1400-MHz parasitic oscillation.

The smaller the tube, the higher the resonant frequency. All tubes will have internal resonances and the designer must move them out of the normal usable frequency range or load the circuit in such a way as not to degrade the performance within the rated frequency range. Even if resonances do not occur, the combination of reactances within the tube may constitute an undesired network that creates a mismatch between the driver and the tube electrodes.

magnitude of lead inductance

The most important reactance encountered in a vacuum tube is that associated with the lead inductance. An estimate of the magnitude of lead inductance may be made using the following equation:

$$L = 1.00508\ell\left(2.303\log_{10}\frac{4\ell}{d} - 1 + \frac{d}{2\ell}\right)$$

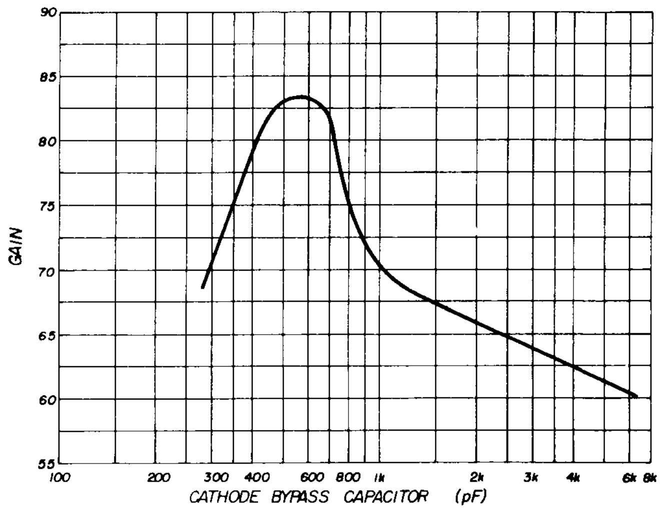
where L = inductance (microhenries)
ℓ = wire length (inches)
d = wire diameter (inches)

This equation assumes no mutual inductance with some other nearby lead or wire.

As an example of how great lead inductance can be, consider the case of a lead that is 0.1-inch in diameter and one-inch long. This lead will have an inductance of 0.015 μH and an inductive reactance of 47 ohms at 500 MHz. An inductive reactance of this magnitude, for example, between the screen element and the screen by-pass capacitor outside the tube can cause stability problems. A voltage drop exists across the screen reactance caused by the current flowing through it which is the vhf current charging the output capacitance of the tube. This voltage is impressed upon the screen, which thereby is removed from ground potential, disturbing the grid-plate isolation normally afforded by this element.

This source of positive input resistance can be better understood by realizing that it results from a signal appearing across the cathode lead inductance, driving the cathode a small amount, as in a cathode-driven amplifier. (In a cathode-driven amplifier, the alternating current component of the plate current has to flow through the cathode lead inductance to reach the cathode. Since the driving signal is in series with the output load through the cathode-to-plate resistance of the tube, some of the power in the load is supplied by the driver.) Unwanted feedthrough power is thus supplied by cathode lead inductance in a grid-driven stage.

fig. 2. Gain of a 5CX1500A 100-MHz class-B amplifier with different values of cathode bypass capacitance. Gain peak occurs when bypass capacitor is series resonant with tube, socket and cathode lead inductance.



cathode lead inductance and input loading

Tube gain will also be adversely affected due to a reduction in input resistance because of the cathode-lead inductance. A small amount of cathode-lead inductance in conjunction with the grid-to-cathode capacitance of a vacuum tube will cause a resistive load to appear across the input of the tube. The magnitude of this added shunt input resistance is:

$$R \cong \frac{1}{\omega^2 L_k C_{gk} g_m}$$

R = input resistance due to cathode-lead inductance

$\omega = 2\pi f$ where f is frequency (hertz)

L_k = cathode lead inductance (henries)

C_{gk} = Grid-to-cathode capacitance (farads)

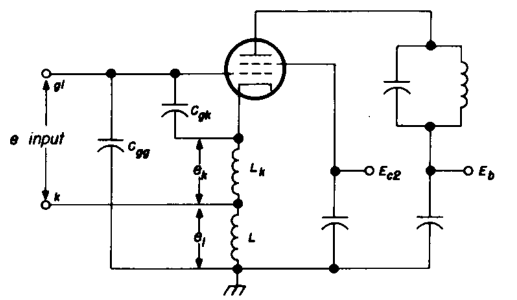
g_m = transconductance (mhos)

The above equation shows that as the frequency is increased, the grid-loading due to cathode-lead inductance increases. For example, if the frequency of the amplifier is tripled from 144 to 432 MHz, the input resistance of a particular tube at 432 MHz would be one-ninth the resistance at 144 MHz. If it is desired to drive the 432 MHz tube to the same maximum grid voltage swing, then nine times the power is required just to cover the input loading due to cathode-lead inductance.

There will be other losses such as skin

effect, dielectric, radiation, transit time and the circuit reactance effects shown in **fig. 1.** The amount of grid loading due to cathode-lead inductance may be reduced somewhat by separating the input and output circuit paths back to the cathode. Some miniature tubes and low power transmitting tubes, such as the 4CX250B, 6146 and others, have multiple cathode leads to minimize the cathode-lead inductance effects. Transistors also have this problem, only it is called emitter-lead inductance instead of cathode-lead inductance.

fig. 3. Cathode lead neutralization.



vhf/uhf cathode-lead inductance neutralization techniques

It is possible to neutralize the effects of the cathode-lead inductance by choosing the value of cathode by-pass capacitor so it will be **approximately** series resonant with the total lead inductance (tube, socket and circuit inductance). This technique is particularly effective in low noise stages of vhf/uhf receivers.

Fig. 2 illustrates stage gain as a function of cathode by-pass capacitance value in a high power vhf amplifier. This particular graph was obtained from an experimental 100-MHz, 5CX1500A amplifier running in class B. The 5CX1500A cathode lead, socket and circuit lead inductance was measured to be just over four nanohenries. A capacitance of 637 picofarads was calculated to be necessary for cathode lead inductance neutralization. The graph agrees fairly well with the calculated data.

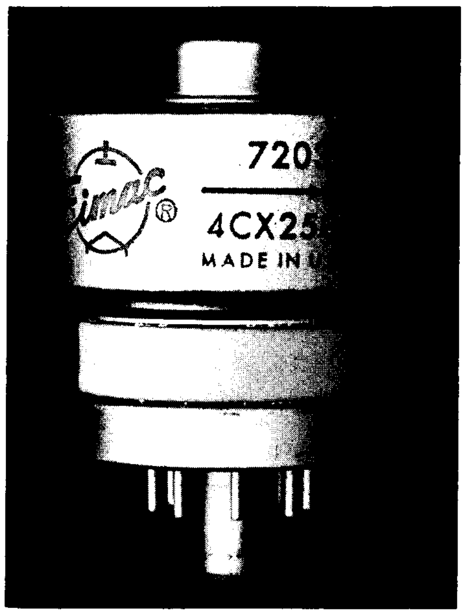
A neutralization technique described in the October 1939 issue of **Electronics** is of interest (**fig. 3**). I have had no personal experience with this technique, but it does appear to have merit. The voltage drop e_L across L, caused by the cathode current, is reversed in polarity with respect to e_k in the sense that C_{gg} and L are in series between grid 1 and the cathode. Thus, the current flowing back to the grid through C_{gg} is 180 degrees out of phase with the applied voltage, e_{input}. For a certain value of L the currents through C_{gk} and C_{gg} will be equal as well as opposite in phase; thus, the conductance between grid 1 and the cathode is zero. For neutralization of the cathode lead inductance the following ratio must be met:

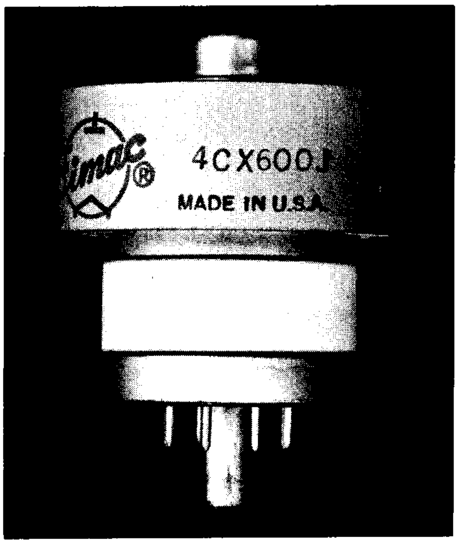
$$\frac{L}{L_k} = \frac{C_{gk}}{C_{gg}}$$

For the 5CX1500A 100-MHz amplifier component values for neutralization of the cathode lead inductance could be:

L_k = 4 nanohenries
C_{gk} = 35.8 picofarads
C_{gg} = 10 picofarads
L = 14 nanohenries

The well known 4CX250B—rated to 500 MHz.





This tube has twice the cathode area of the 4CX250B and provides better than —40 dB intermodulation distortion.

L_k and C_{gk} are typical characteristics of the 5CX1500A and SK840 socket while C_{gg} and L are added components.

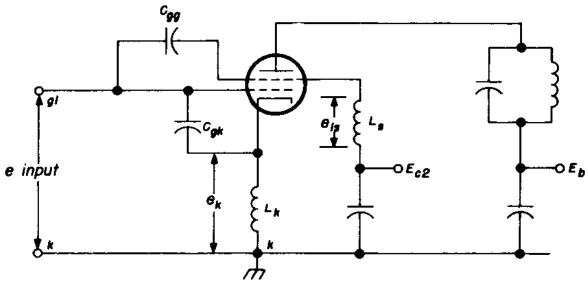
A very similar method of neutralizing that part of input resistance caused by the cathode lead inductance uses an inductance in the screen-grid lead and has been often used in 6146-type gear at 144 MHz (**fig. 4**). Basically, this circuit is the same as **fig. 3.** There are two differences: the point K (cathode pin) is now at ground potential and only screen current flows through the inductance L_s.

Other circuits may be used to minimize the effects of the cathode-lead inductance. The grounded-grid, cathode-driven (or probably more correctly called the "grid-separation" circuit), is often used (**fig. 5**). In this case the cathode is driven while the grid in a triode, or the grid and screen grid in a tetrode, are operated at some low rf potential. The grid structures then act like a shield between the input and output circuits. The main advantage, as far as cathode-lead inductance is concerned, is that this inductance is now just another inductor in series with, and therefore a part of, the input tuned circuit. There are other advantages that can be credited to the "grid separation" amplifier which will be discussed in the section on interelectrode capacitances.

intermodulation distortion and input loading

An appreciable amount of input loading can increase intermodulation distortion. Any tube plate-characteristic non-linearity will cause a variation in this input loading with signal level and thereby present a varying load to the driver, thus causing increased distortion in the drive voltage.

fig. 4. Neutralizing cathode lead inductance with an inductor in the screen lead on the tube side of the screen bypass capacitor.



screen lead inductance

The screen lead inductance between the screen element and the screen by-pass capacitor may help or hinder the operation of an amplifier. Below the **self-neutralizing frequency**[1,2] of the tube, the screen lead inductance is usually detrimental to the stability of the amplifier, as the rf current flowing through this inductance will cause an unwanted rf voltage to be developed. The point where the screen bypass is connected to the screen terminal may very well be at rf ground potential, but the potential of the screen itself may be varying above and below ground by the magnitude of voltage developed across the screen lead inductance, eL_s (**fig. 4**).

The magnitude of the developed voltage depends on the inductance of the screen lead and the frequency of operation. The higher the frequency, the greater the inductive reactance and the greater the rf current through this inductor. The current is greater because the capacitive reactance of the output capacitance of the tube will be smaller, and the capacitor will be charging to the same rf plate voltage swing each cycle.

At operating frequencies below the self-neutralizing frequency of a tetrode, screen inductance may be added in order to neutralize the amplifier. That is, the self-neutralizing frequency is lowered to the operating frequency.[3] At operating frequencies above the self-neutralizing frequency of the tube, a series capacitor is sometimes added to move the self-neutralizing frequency up to the operating frequency (**fig. 6**). As was briefly touched upon previously, sometimes it is desirable to add a certain amount of screen lead inductance to neutralize the number of leads to use to provide the inductance he needs for his design.

In a cathode-driven (grounded-grid) amplifier, control-grid inductance is very important. Just as in the case of the screen-lead inductance in a grid-driven tetrode amplifier, the control-grid inductance in a cathode-driven amplifier may aid or hinder the designer. The control-grid inductance may cause instability, a loss in drive voltage due to the voltage divider effect (**fig. 1**) or it may be used to provide a method of neutralizing the amplifier.[2]

plate lead inductance

The plate in modern tubes used for vhf/uhf operation is usually designed with a

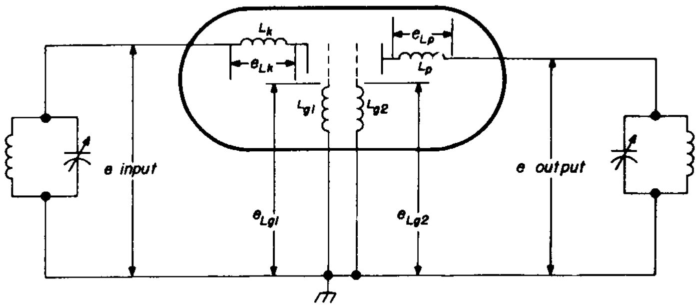


fig. 5. Cathode-driven or grid-separation amplifier.

cathode-lead inductance portion of the input resistance.

control-grid lead inductance

The **control-grid lead inductance** in a grid-driven amplifier is usually not of much concern as the relative magnitude of the tube lead inductance as compared to the external inductance added to it to attain resonance is very small. The control-grid lead inductance is wholly a part of the input resonant circuit with no current being induced from the output circuit, and it becomes part of the input tuned circuit. An exception to this is in the case of a vhf/uhf **distributed amplifier.** In this application an active filter is designed using all of the tube lead inductances and interelectrode capacitances. The control-grid inductance is important in this case, and modern distributed amplifier tubes are made with four grid leads available to the equipment designer. He then has the choice of the

massive anode structure in order to dissipate the heat that is generated in this element of the tube. For this reason, plate lead inductance is usually low enough so it is not of any great concern. If normal good engineering practice is followed in designing vhf/uhf circuitry, the plate lead inductance becomes inconsequential.

interelectrode capacitance

In addition to lead inductance, interelectrode capacitance plays an important role in the operation of tubes in the vhf/uhf regions. Interelectrode capacitances due to active parts of the tube structure are incapable of reduction beyond a certain point. However, in many tubes the interelectrode capacitance results largely from capacitance between leads in areas of the tube where electrons do not flow. It is the job of the tube designer to reduce this unnecessary capacitance to a minimum.

input capacitance

The input capacitance of a grid-driven tube is the sum of the grid-to-cathode and grid-to-screen capacitances. The larger the input capacitance, the greater the drive power must be. This can be explained by the very large increase in input charging current necessary to charge the input capacitance. As the frequency increases the reactance of the input circuit becomes smaller, and for the same peak grid voltage, the charging current must increase. As power is proportional to the square of the current, the power lost in the input circuit necessarily increases as the charging current rises. The driver must supply this extra power.

To reduce this loss, the circuit designer must keep the input capacitance down and may limit the magnitude of the peak grid voltage. Peak grid voltage can also be minimized by operating with less bias. Quite often in certain amplifiers the class-B mode is more desirable than class-C operation. Reducing the peak grid voltage and the charging current will reduce the amount of power that must be dissipated by the control grid. Radio frequency power dissipated by the control grid unfortunately cannot be measured by the dc meters on the front panel of the amplifier, so the operator has no means of knowing if charging currents cause excessive grid temperature. High input capacitance also limits the bandwidth of the input circuit. For those applications requiring large instantaneous bandwidth, great care must be taken in the design of the equipment.

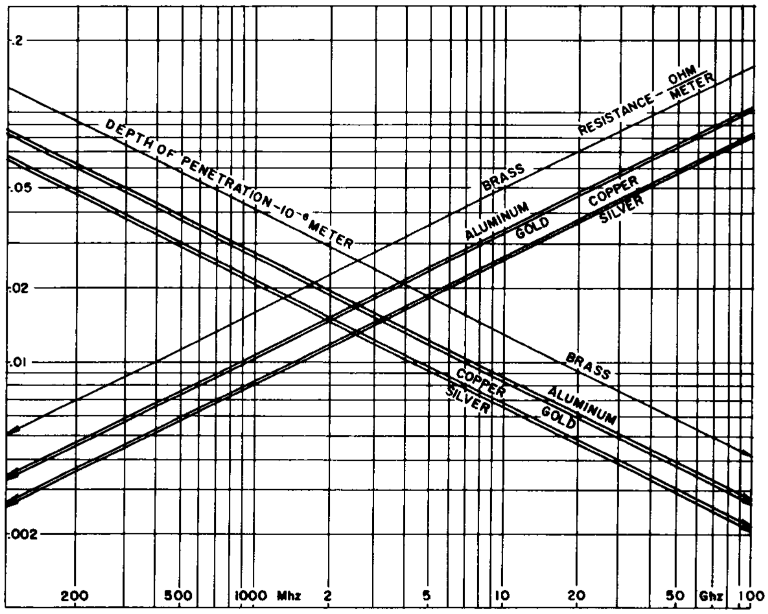
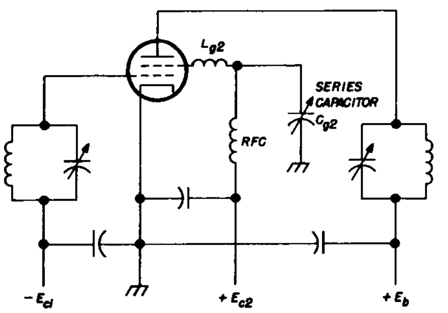


fig. 7. Chart for computing resistivity and depth of penetration for metallic conductors between 100 MHz and 100 GHz.

fig. 6. Screen neutralization at operating frequencies above self-neutralizing frequency of tube.



The grid-separation or cathode-driven amplifier offers quite an advantage as far as input capacitance is concerned. The input capacitance consists only of the cathode-to-grid capacitance. For the same tube in the cathode-driven configuration, the input capacitance will be roughly half that value in the grid-driven circuit. This is quite an advantage for applications requiring wide bandwidths.

output capacitance

The output capacitance of a power tube is an important factor in determining what plate-load resistance can be used. This in turn determines the stage gain and power output that is available. The equivalent shunt resistance (plate-load) of a parallel resonant circuit can be written as $R_L = Q/2\pi fC$ or $R_L = 2\pi fLQ$ where R_L is the plate-load resistance, Q is the loaded Q of the resonant circuit and f is the resonant frequency. For

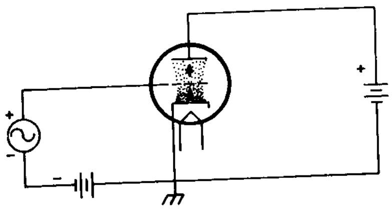


fig. 8. The effect of transit time on grid losses. At the instant shown, the grid potential is increasing in a positive direction and there is a consequent disproportionate number of electrons between grid and cathode so there is electron flow from the grid even though it may be negatively biased.

operation at a given frequency, to increase the shunt resistance it is necessary to decrease the shunt capacitance. This can be done to a point by reducing the circuit capacitance and increasing the tank coil inductance, maintaining the same frequency of resonance. Eventually, this process is limited by the fact that the capacitance external to the tube has been reduced to zero; the shunt resistance is finally determined by the tube interelectrode capacitance. The larger the interelectrode capacitance, the smaller the shunt resistance that can be realized. Accordingly, power output tends to drop off as the load resistance, or as the square of frequency, as frequency increases.

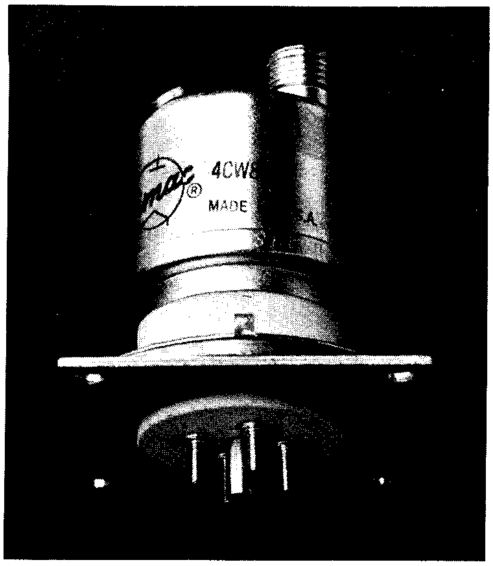
There are other problems brought about by the effect of output capacitance. The output capacitance must be charged and discharged during each cycle of the radio frequency. Again, as the frequency increases, the reactance of the output capacitance decreases. Therefore, with the same value of peak rf plate voltage, the current flowing through the output capacitance must increase as the frequency increases. The output capacitance of a tetrode is made up of the screen grid structure, the plate structure and the tube envelope.

The charging currents must flow over the surface of these components of the tube, all of which have varying degrees of rf resistance. It is possible for the charging currents to exceed the dissipation rating on the screen grid even though the dc meters indicate all is within ratings. It is advisable in vhf/uhf circuits, therefore, to try to achieve the lowest usable value of peak rf plate voltage by using the lowest plate load resistance and drawing the highest plate current consistent with desired output power and efficiency. Running the tube in this manner will lighten the rf stress on the tube seals and reduce the rf current in the scr[illegible] grid structure thus providing for a pote[illegible] longer tube life.

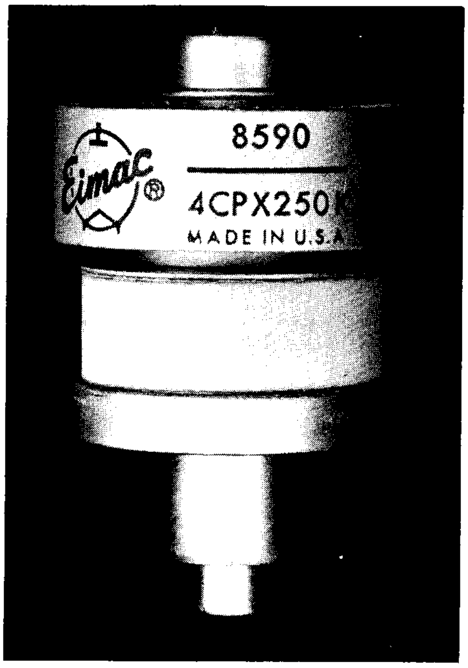
feedback capacitance

The feedback capacit[illegible] a grid-driven amplifier is the [illegible]nce from anode to the control [illegible] higher the frequency of opera[illegible] greater the chance for instabi[illegible] rf feedback from the output [illegible]ugh feedback capacitance to [illegible] circuit. In the vhf/uhf region [illegible]tance and other tube capacitan[illegible]nductance must be adjusted to [illegible]r neutralization by added circuit [illegible]nts.[4]

The grid-se[illegible] amplifier helps minimize the effect[illegible]e feedback capacitance. The feedback capacitance in this configuration is very much less than the grid-driven case since it is the capacitance from anode to cathode with the grid, or grids, shielding the output from the input. In some applications no neutralization will be required. Other applications may require quite extensive neutralization.[3,5]



Distributed-amplifier tube discussed in text. By choosing the number of control-grid leads, the designer can control lead inductance. The tube in the right-hand photo has a screen by-pass capacitor installed. Center pin is one of the heater pins; the square tab on the capacitor is the other heater connection and the cathode. The threaded pins are control-grid leads.



Tube designed for large phased-array radar system. Two of these tubes were used in the 1000-watt 432-MHz amplifier used by WA6LET with a 150-foot dish for moonbounce contacts in 1965.

circuit and tube-loss limitations

The power losses associated with a tube and circuit all tend to increase with frequency. In the vhf/uhf region, almost all radio-frequency current flows in the surface layers of a conductor because of skin effect (**fig. 7**). The resistance and rf losses in a conductor increase with the square root of frequency because the layer in which the current flows decreases in thickness as the frequency increases. Insulating supports in the tube and external circuit have losses associated with the molecular movements produced by the electric fields. These dielectric losses will usually vary directly with frequency. Also, there will be additional losses due to the radiation of energy from the wires and leads carrying rf current. The power radiated from a short length of wire carrying current increases as the square of the frequency.

All these factors contribute to a general reduction in tube and circuit efficiency as operating frequency is increased. In the manufacture of power tubes the resistance losses are reduced by increasing conductor surface area and by proper choice of lead materials. Dielectric losses are reduced by selection of envelope and insulating materials. Support insulators are positioned, when possible, out of high voltage fields. Radiation losses are reduced by constructing vhf and uhf tubes and circuits so as to be totally shielded. At times it is prudent to use concentric line construction techniques so that tube and circuit fields are entirely confined.

transit-time limitations

Electron transit-time effects can contribute to reduced tube output in many ways. Transit time is the finite time an electron takes in going from the cathode to the grid. If the transit time (a function of grid-to-cathode distance and grid-to-cathode voltage) is an appreciable fraction of one ultra-high-frequency cycle, then an electron in transit in the grid-to-cathode region might be still heading for what was once a more positive location than the cathode surface it just left, but now finds the grid may be less positive or perhaps even negative (**fig. 8**). As a result of transit-time effect in the cathode-grid region, there will be a dispersal of "out of step" electrons. Because of this dispersion of the electron stream, the plate-current pulses are not as sharp as the current pulses liberated from the cathode.

In addition, energy is required to accelerate the electron towards the anode, and this energy is supplied by the driver. As the operating frequency is raised, more energy is required because the grid-input resistance due to transit time varies inversely as the square of the frequency. That is, if the frequency is doubled, the input resistance due to transit time effects will be one-fourth that at the lower frequency. The extra power required to overcome transit-time loss due to grid-input resistance is supplied by the driver and appears as lost drive-power—required but put to no practical use other than to heat the tube seals and waste precious exciter output.

Paradoxically, transit-time loss and cathode-lead inductance loss (both of which cause input loading) are not all evil because they often tend to stabilize a "wild" stage. Cure of the trouble may lead to higher stage gain with the possibility of oscillation and instability!

Circuit loading can be used to achieve stability and this is often done at the lower frequencies by adding resistors across i-f transformers, for example. The circuit designer, therefore, finds that a tradeoff exists between loading and stage gain that will work to his advantage or disadvantage, depending upon his ability to analyze the circuit. There is often more than one successful path to a proper design and the good circuit engineer has several alternative paths (in his head, if not on paper) to choose from. A candid realization of uhf/vhf effects will help the circuit designer obtain maximum power, efficiency and reliability from his equipment.

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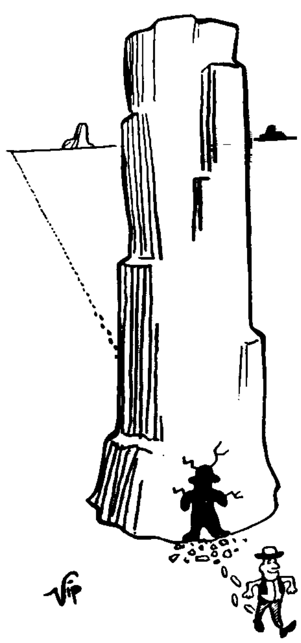
ham radio



High-power linearity with Eimac power-grid tubes.