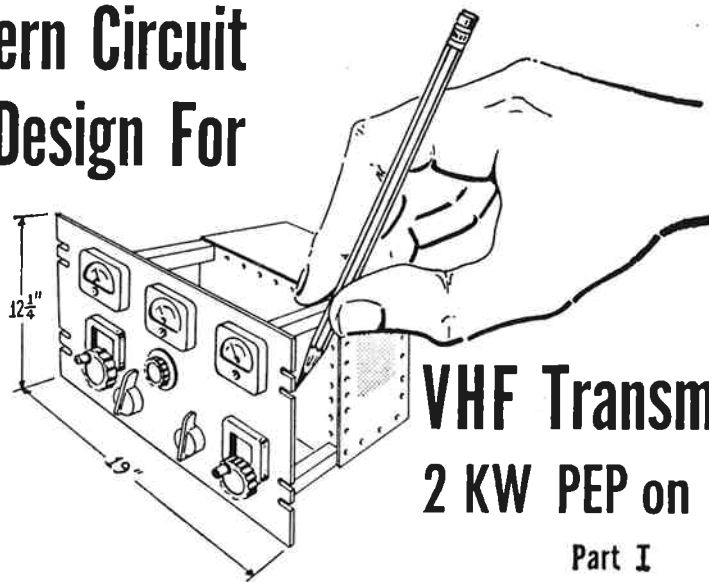




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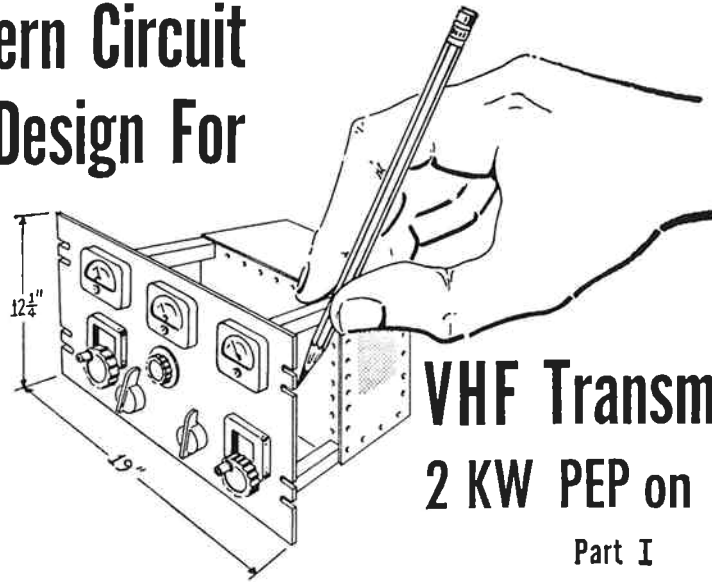
Modern Circuit
Design For



VHF Transmitters
2 KW PEP on 144 mc

Part I

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VHF Transmitters 2 KW PEP on 144 mc

Part I

BY H. C. BARBER,* W6GQK; W. I. ORR,† W6SAI; R. RINAUDO,†
W6KEV AND R. SUTHERLAND,† W6UOV

Part I describes the design of a two kilowatt p.e.p. amplifier for the serious 2 meter operator. Requiring less than 10 watts of driving power, this efficient amplifier loafs along at the legal amateur power level. Designed for continuous service, a lot of power is packed behind a 12¼-inch relay rack panel. Construction details of this "powerhouse" will be featured in Part II of this two part series.

THE would-be designer of transmitting equipment for the v.h.f. spectrum soon finds that he is operating in a twilight area that falls between microwave techniques and practices associated with the high frequency (h.f.) bands. He realizes, sooner or later, that at some broad, undefined wavelength peculiar things start to happen to h.f. circuitry that otherwise looks deceptively simple on paper. As he progresses from the h.f. into the v.h.f. region, the attentive amateur soon is aware that bypass capacitors no longer exhibit the normal characteristics they possess at lower frequencies. Short bits of wire assume importance beyond their size. R.f. tends to "leak" through small chassis holes. Components that seemingly are a passive part of normal communications hardware become complex devices that bedevil, and bear little resemblance to the comfortable components that make up h.f. gear.

Viewing the microwave (u.h.f.) region, the amateur finds a new world of waveguides and plumbing. Circuit techniques, equipments, and vocabulary fall into a strange category, and engineering philosophy and hardware of this

frequency region are alien to h.f. concepts and techniques.

Between the comfortable world of kilocycles and the alien world of gigacycles are the amateur v.h.f. bands of 144, 220 and 432 mc. What techniques and practices should be used at these frequencies? Are microwave techniques applicable, or is this portion of the v.h.f. spectrum

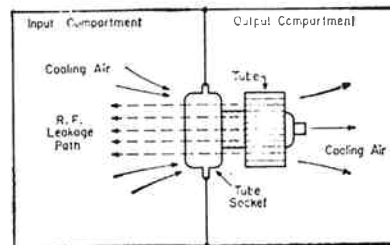


Fig. 1—Socket orifices to permit cooling air to pass across base seals of tube and through anode cooler may also create r.f. leakage path from output to input compartment. Simple "receiving type" sockets have little r.f. attenuation, while most "air-system" sockets afford 20 decibels or so of intra-stage isolation. The new Eimac SK-820 socket and 4CX1000K tube achieve better than 50 decibels of intra-stage isolation below 450 megacycles.

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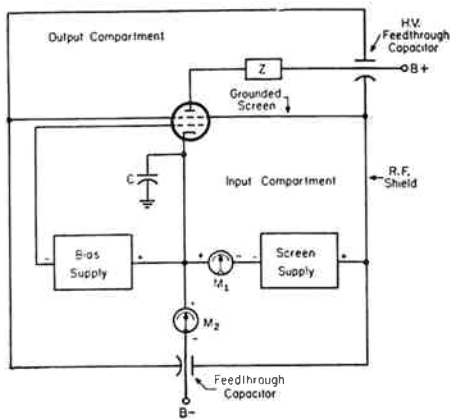


Fig. 2—To achieve maximum isolation between input and output compartments, the screen of the tube may be grounded, with bias and screen supplies placed below d.c. ground potential as shown in this circuit. The screen bypass capacitor is thereby omitted and a cathode bypass capacitor (C) substituted in its place. The B-minus lead is "negative" to the chassis by the amount of the screen voltage. Meter M_1 measures screen current and meter M_2 measures plate current.

merely an extension of the h.f. spectrum, with suitable modifications applied to equipment design and construction?

The answer to both these questions is obscured by realities. The v.h.f. amateur bands can and do use components designed for h.f. service, but these bands fall on the doorstep of the u.h.f. region wherein the components start to assume the size of the radio wave that is being generated. This physical congruence of wave and component calls for techniques and circuitry not normally associated with h.f. equipments.

One obvious solution to this problem is to reduce the size of the v.h.f. hardware so that the dimension of the radio wave is great compared with that of the components. This is commonly

done; but there is a limit to this reduction technique, however, since no one has ever invented a way to shrink the *watt* in a corresponding manner. A limiting factor in the design of v.h.f. gear, therefore, is the ability of small components to radiate or otherwise dissipate the heat generated by the power dissipation of active components.

This natural law of thermodynamics becomes a limiting factor at v.h.f. in the design of a one kilowatt (2 kilowatt p.e.p.) amplifier for linear and c.w. service. To begin with, the number of tubes that will accept this power level at this frequency are but a handful. Tank circuits tend to disappear within the tubes, and the problem of dissipating five hundred watts or so within a shielded enclosure containing small tubes and tiny components poses a difficult mechanical design problem. Even at the relative "low" frequency of 144 mc, the use of "garden-variety" tubes and tank circuits provides a marginal solution.

Special tubes and hardware have been designed to work well at v.h.f., and by the proper combination of tube, hardware and circuitry, a reliable amplifier having the aforementioned power capability may be built that "tunes up just like 20 meters" and is capable of continuous, 24 hour-a-day operation. The design of such an amplifier is covered in this article, with some interesting asides directed to problem areas encountered in the construction of a practical amplifier.

Socket-Tube Intra-Stage Coupling

One source of potential trouble in the v.h.f. amplifier is *intra-stage r.f. coupling* (fig. 1). Passage of r.f. energy between two sealed metal compartments placed side by side is zero, but the introduction of power leads and cables in the compartments permits r.f. leakage; and the placement of a tube between the compartments allows the coupling of energy through the socket

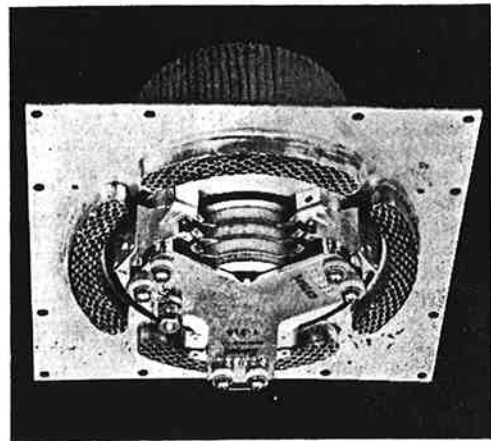
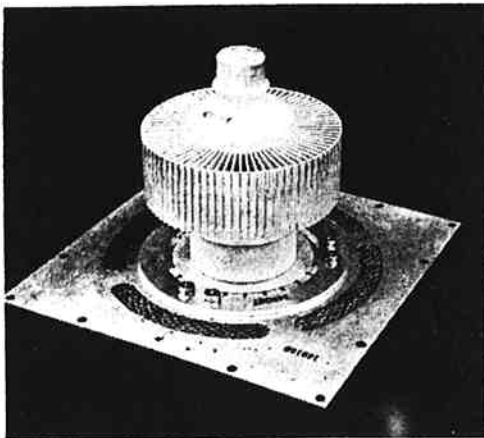


Fig. 3—(Left) Screen terminal of 4CX1000K tetrode is a ring that completely encircles the upper portion of the base structure of the tube. Flexible tabs on matching socket ring insure low impedance ground path from screen element as screen is run at d.c. ground. Cooling air is passed through the socket structure by means of "honeycomb" section of expanded metal (Right) built into socket plate which acts as a waveguide beyond cutoff frequency and provides high degree of attenuation below 450 mc. The socket provides 50 decibels or better intra-stage isolation in the v.h.f. region.

orifices, impairing the erstwhile perfect isolation between the compartments. It is possible to reduce intra-stage coupling via the power leads by proper bypassing and termination of the individual wires. Combining these techniques with the use of a new, improved tube socket and tube base, an intra-stage isolation of -50 decibels or higher may be achieved.

The degree of r.f. coupling between compartments may be determined by injecting a signal into the input compartment at the operating frequency of the gear, and then measuring the residual signal developed in the output compartment. For example, assume each compartment in the illustration has zero r.f. leakage other than the path through the tube and socket. This coupling path has an attenuation of -20 decibels, that is, the signal measured in the output compartment is 20 decibels lower in power than the signal injected in the input compartment. The particular tube in the socket has a power gain of 25 decibels, so it can be seen, without even turning the equipment on, that $+5$ decibels of positive coupling occurs through the socket-tube path and that the circuit will sustain self-oscillation at the frequency in question.

If the attenuation of the path is increased to greater than -25 decibels, oscillation may still occur under certain conditions of equipment tuning and loading wherein the tube gain may momentarily rise over the nominal figure. Many combinations of tubes and sockets normally used in the v.h.f. region exhibit a high degree of internal coupling since the screening of the tube is not perfect. Also, leads within the tube are long, bypass capacitors are imperfect at the design frequency, and the necessary air path through the socket permits the plate of the tube to "see" the input circuitry.

To provide the proper degree of isolation, the socket-tube intra-stage coupling should provide a degree of attenuation that is at least 20 decibels greater than the circuit gain of the stage, and the internal screening of the tube should be as excellent as the state of the art permits.

The "Grounded" Screen

In order to increase screen isolation at v.h.f. and to insure that the screen is as close to ground potential as possible, it is expedient to ground the screen to the chassis and to supply bias and screen potentials "below ground" as shown in fig. 2. The screen bypass capacitor is thereby eliminated and a cathode bypass capacitor substituted in its place. The screen capacitor usually employed in a tetrode stage is in a critical location in the v.h.f. circuit as it carries almost all of the plate circuit r.f. circulating current and, in addition, introduces regeneration in the circuit if the capacitor exhibits inductive reactance. When this cranky component is removed, the tetrode screen can be physically grounded, and the burden is transferred to the cathode bypass capacitor which carries little circulating current and tends to be a *degenerative* element if it exhibits inductive reactance.

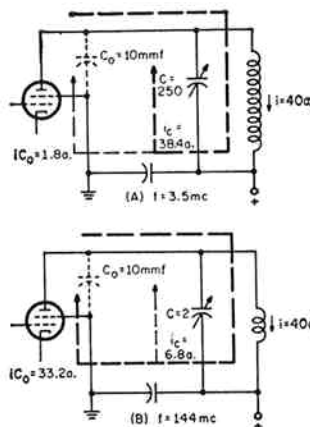


Fig. 4—At v.h.f., the output capacitance of the vacuum tube constitutes a larger proportion of the total tank circuit capacitance than in the h.f. region. Circulating r.f. tank current (i) divides through tube capacitance (C_0) and tuning capacitor (C) in proportion to capacitance of each. At 144 mc, current flowing through tube output capacitance (iC_0) is almost twenty times as great as at 3.5 mc.

Intra-stage r.f. leakage through the socket may be reduced by modifying the air vents between input and output terminations while allowing cooling air to pass across the base seals and through the tube anode.

A "Grounded Screen" Tube and Socket

Shown in fig. 3 are the new Eimac 4CX1000K tetrode and the companion SK-820 socket. The "K" tube is an improved version of the 4CX1000A having a low impedance screen grid terminal ring that completely encircles the upper portion of the base structure of the tube. The 4CX1000K is designed for improved input-output isolation and the screen terminal ring presses snugly against a circular spring-like grounding plate built into the top portion of the SK-820 socket. The screen is thus completely and securely grounded around its circumference by an extremely low impedance path, reducing r.f. intra-stage leakage through the socket to -50 decibels or better at 450 mc.

Cooling air is passed through the socket assembly by means of "honeycomb" sections of expanded metal built into the socket which act as simple waveguides beyond cutoff frequency, and provide a high degree of attenuation to r.f. currents passing between the grid and plate compartments.

Use of the 4CX1000K in the improved socket permits construction of a high power v.h.f. amplifier having excellent intra-stage isolation and that does not require neutralization. Thus, one of the big "trouble makers" in v.h.f. equipment design has been conquered!

The V.H.F. Plate Tank Circuit

The purpose of the v.h.f. plate tank circuit is twofold: First, it provides an impedance match between the tube and the load; and second, it

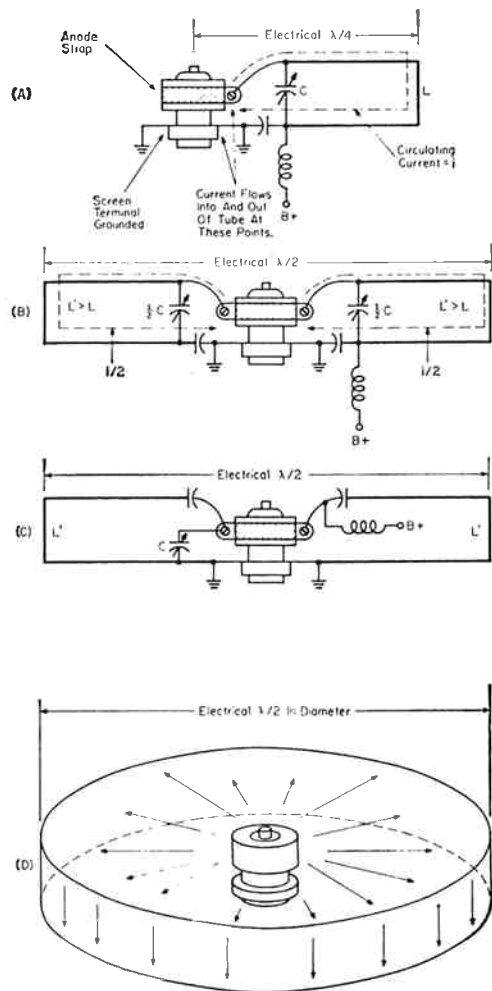


Fig. 5—Simple "quarter-wave" loaded tank (A) may be used as resonant circuit at 144 mc. However the circulating r.f. tank circuit flows into tube at one point and overheating of screen lead and vacuum seal may result from the high concentration of current. Divided tank circuit (B and C) places tube at the high potential point in half-wave line and divides circulating r.f. tank circuit between two sides of the tube. Limiting case is circular cavity (D) with tube placed at center and with circulating r.f. current evenly spread over inner surface of cavity. At 144 mc, the circuit of (C) is an efficient and practical compromise.

attenuates undesired spurious emissions. As the v.h.f. region is approached, the popular h.f. resonant tank composed of a parallel coil and capacitor shrinks in size until it is more practical to employ a different, larger resonant configuration. A capacitance-loaded section of transmission line may be used as a resonant circuit, since v.h.f. short-circuited transmission lines can efficiently replace inductances in tank circuits.¹ Such transmission line circuits exhibit considerably higher impedance at resonance and better

¹"Fields and Waves in Modern Radio", by Ramo and Whinnery, Chap. 10. John Wiley and Sons.

Q than can be obtained with "lumped" circuitry. In general, the transmission line tank circuit may be designed for maximum efficiency, for maximum bandwidth, or for mechanical convenience. That is to say, given a reasonable efficiency and line impedance, the physical constants may be "juggled" about to permit a satisfactory circuit to be constructed of the material at hand so that odd sizes of tubing or unusual construction techniques need not be used.

Output Capacitance

In passing, it should be noted that the output capacitance (C_o) of a vacuum tube assumes great importance in the v.h.f. region as compared to the h.f. spectrum since it constitutes a larger percentage of the total tank circuit capacitance (fig. 4). At 3.5 mc, for example, a reasonable value of plate tuning capacitance (C) might be 250 mmf, of which 10 mmf (or 4%) represents the output capacitance (C_o) of the tube. At 144 mc, the total plate tank capacitance may be 12 mmf, and the tube contributes 83% of this capacitance. In a high- Q tank circuit, the circulating r.f. plate current may reach the order of 40 amperes at the kilowatt level and this current divides through the tube output capacitance and tuning capacitor in proportion to the capacitance of each. Thus, in the case of the 3.5 mc amplifier, 4% of the r.f. plate circuit current (1.6 ampere) flows through the output capacitance of the tube, whereas at 144 mc 83% of the current (33.2 amperes) flows through the tube output capacitance! In the case of a tetrode, the circulating current flows through the screen circuit as shown in fig. 4. The screen leads and screen bypass capacitor must carry this extraordinarily heavy r.f. current. Elimination of the screen bypass capacitor removes this cranky component from the high current density path; however, the circulating r.f. current flowing through the tube terminals tends to heat the vacuum seals, often to such a temperature that the tube may be damaged. The current cannot be eliminated, but it may be distributed in such fashion as to minimize seal heating consistent with the shortest possible return path from plate to screen. Placing the screen at absolute ground potential, and using a low inductance screen terminal on the tube aids this task.

The Modified Coaxial Tank Circuit

The condition for resonance of a capacitance loaded transmission line is:

$$X_c = Z_o \tan L$$

Where X_c is the reactance of the loading capacitor, Z_o is the impedance of the transmission line, and L is the electrical length of the line in degrees: ($\lambda/4 = 90^\circ$).

In the general v.h.f. situation, the loading capacitance is the output capacitance of the tube, and line parameters (Z_o and L) are adjusted so as to establish circuit resonance with this capacitance.

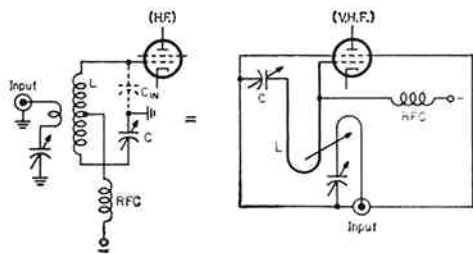


Fig. 6—"Split-stator" h.f. grid tank circuit may be duplicated at v.h.f. by the use of a loaded half-wave line. Input capacitance of tube makes use of quarter-wave line impractical, as the line tends to "disappear inside the tube".

A simple "quarter-wave" loaded line may be used as a resonant tank circuit (fig. 5A) but the circulating r.f. tank current flows through the tube via one small area and overheating of the screen terminal and vacuum seal in this particular area may result. It is possible, however, to achieve the same resonant frequency with one-half the tuning capacitance and a somewhat longer transmission line section (L') as shown in fig. 5B. Combining two of these circuits (fig. 5C) permits the use of the longer line (an electrical half-wavelength long) with the tube placed at the center. Circulating r.f. plate currents now flow through both sides of the tube, providing somewhat better current distribution than before. The longer line is easier to extract energy from because of its greater length, and it is less critical of construction. In addition, the physical mass of metal in the long line can dissipate heat more readily than can the smaller mass of the shorter quarter-wave line. The limiting design, of course, is when the tank circuit completely surrounds the tube in the form of a cavity (fig. 5D), wherein r.f. plate current is equally divided around the circumference of the tube. Such an approach is necessary in the upper regions of the v.h.f. spectrum, but at 2 meters, the simple half-wavelength line discussed here works well, and is simpler and cheaper to construct than the cavity configuration.

An optimum value of line impedance exists, which is a function of the dimensions of the resonant line. In the design of 5C the line is made in coaxial fashion, composed of a circular center conductor (made of a section of readily obtainable copper water pipe) and the outer walls of the shielded plate circuit enclosure. The impedance of a line of these rough dimensions is approximately 60 ohms, and the enclosure dimensions and spacing of the line are chosen to provide minimum surface area of the elements consistent with maximum volume, thus reducing the surface "skin resistance" of the elements.

The V.H.F. Grid Input Circuit

It is possible to use a quarter-wave line for the input circuit in the lower portion of the v.h.f. spectrum. However, the law of diminishing re-

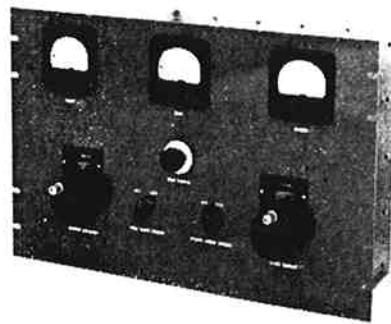
turns is at work: since the tube input capacitance does not shrink as the operating frequency is raised, the line must necessarily be drastically reduced in length to maintain resonance. Broad, low resistance circuits and wide contact areas are very fine for heat radiation but, by their very area, they add residual capacitance to any circuit built around them. Input capacitance of tubes designed for the v.h.f. region tends to run into a respectable figure, and some of the better tubes have input capacitances in the range of 50 to 100 mmf. The input capacitance is the sum of the grid-cathode, grid-screen, and grid-plate capacitances. Considerable ingenuity is demanded of the v.h.f. engineer to construct a high impedance tank resonated by such a value of capacitive loading, but it can be done, even though the quarter-wave tank tends to disappear within the tube!

An effective solution to this problem is to add a capacitance-shortened quarter wave line to lengthen the tank assembly to an electrical half wavelength (fig. 6). A form of "split stator" resonant circuit is achieved, and the driving signal may be easily coupled to the added tank section, as shown in the illustration. Low inductance leads are required, and the tank circuit may advantageously be made of wide copper strap, with multiple strap connections to the grid terminals of the tube to insure proper division of circulating current. A simple series tuned inductive loop can be used to efficiently couple the driving signal into the grid circuit of the v.h.f. amplifier. At best, grid drive is hard and expensive to obtain at v.h.f. and it is poor engineering practice to waste it!

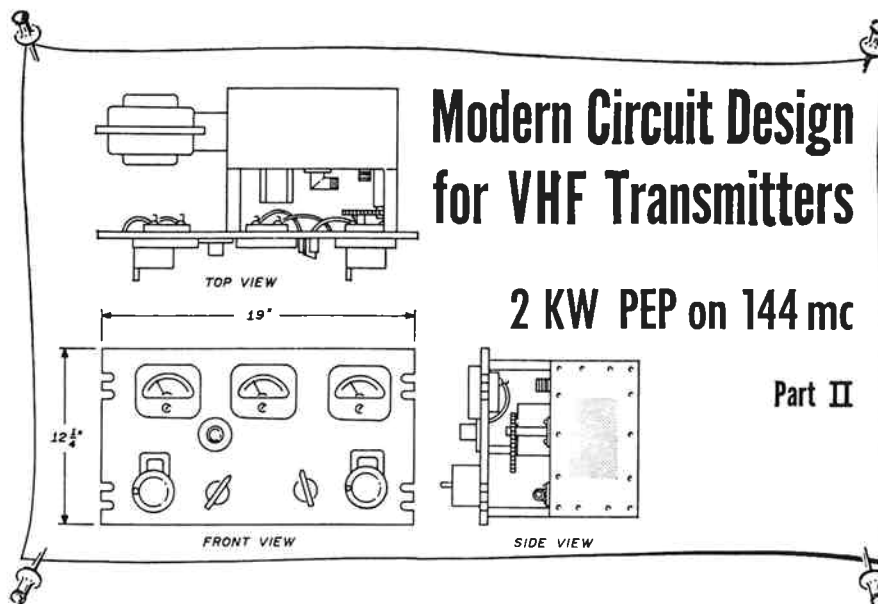
A Practical V.H.F. Amplifier

A high power 144 mc amplifier making use of these design techniques and featuring the 4CX1000K and SK-820 socket will be described in the second part of this article.

[To be continued]



The next part will deal with the construction of the above amplifier. This is a front view of a compact two kw p.e.p. linear amplifier suitable for s.s.b., a.m., f.m., or c.w. It requires less than ten watts of drive to reach the maximum legal power.



law" of Child and Langmuir is theoretically valid for uniform tube geometry and holds true for any space-charge-limited electron flow under the influence of an external field (Fig. 1). The $3/2$ -power law is not a linear function, and in practical tubes the cathode current is not a straight-line function of grid voltage. Further, practical tubes depart from the $3/2$ -power law to some extent, depending upon tube geometry, space charge, electron interception by grids, and emission limitations.

The relationship between the electric field and cathode-current flow within the tube described by this natural law plays an important role in the establishment of tube linearity. In practical amplifiers, for example, the magnitude relationship between input and output signals is not perfectly constant at all signal levels within a given range. The relationship defining amplifier linearity is termed the *envelope transfer function*, and ideal and typical transfer functions are shown in Fig. 2. The fundamental cause of a non-ideal, nonlinear amplifier transfer function may be traced directly to the nonlinear relationship between the plate current and grid voltage of the tube employed in the amplifier. This relationship approximates the $3/2$ -power law throughout the operating region above cutoff.² An examination of intermodulation distortion reveals the importance of significant cathode-current departure from this fundamental law as regards amplifier linearity.

Intermodulation Distortion Measurement Techniques

Leaving the vacuum tube for a moment, it is useful to examine means of testing tuned linear amplifiers for distortion. One such means is to apply two equal-amplitude r.f. signals of different frequency to the input circuit and then to measure the relative strengths of the output signals and the accompanying intermodulation products.³ This combination of input signals is often called a *two-tone test signal*. The action of the test signals beating with each other in the typical "nonlinear" linear amplifier having amplitude distortion produces intermodulation distortion, and the purpose of the two-tone test is to create this action under controlled conditions and to measure it. Maximum limits of intermodulation distortion have become an important specifica-

² Cutoff may be thought of as that amount of grid bias required to reduce the idling plate current of a vacuum tube to virtually zero.

³ "The Grounded Grid Linear Amplifier," Orr, Rinaudo, Sutherland; *QST*, August, 1961, pages 16-21.

Fig. 3—QST authors and prominent DXers W6KEV (standing) and W6UOV examine data plotted by Eimac Intermodulation Distortion Analyzer. General-purpose equipment permits IMD measurements to be made on a wide variety of transmitting tubes in either grid- or cathode-driven configuration. IMD products are seen on screen of panoramic analyzer.

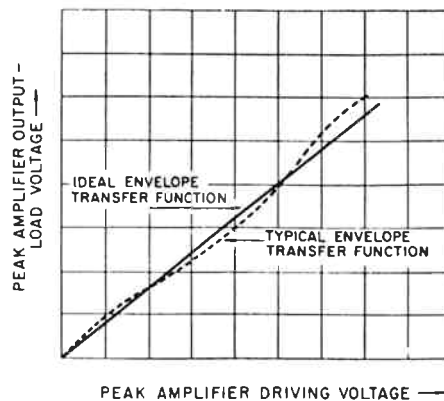
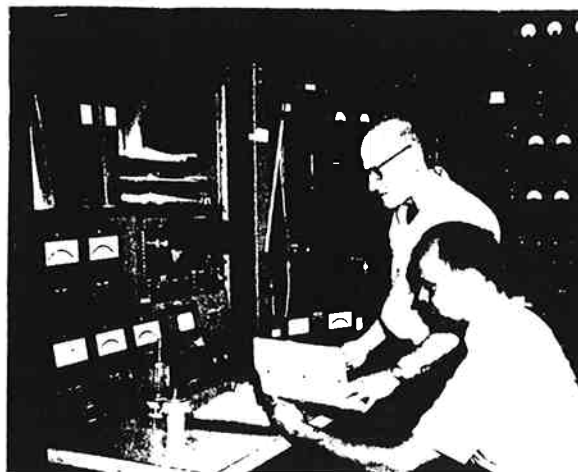


Fig. 2—Amplifier linearity is defined by the envelope transfer function. Departure from linearity is illustrated by curvature of the function (dotted curve) and may be traced directly to the nonlinear relationship between cathode current and electrode voltage shown in Fig. 1.

tion determining the excellence (or lack thereof) of linear amplifiers and tubes.

A practical test technique is to employ a two-tone, low-distortion test signal to drive a linear amplifier, and to use a spectrum analyzer to display a sample of the output signal of the amplifier (Fig. 3). A spectrum analyzer is a precision panoramic receiver having high resolution and capable of resolving signals separated in frequency by only a few kilocycles. The presentation of a portion of the spectrum in which the tests are taking place is given on a long-persistence cathode-ray tube. If the IMD products of the two-tone test signal are known and the amplifier under test is run with no feedback, at a frequency low enough to remove side effects due to circuit uncertainties, the IMD products of the tube under test may be readily determined by visual inspection of the picture on the screen of the spectrum analyzer. Equally important is the fact that the test is reproducible, and that the tube may be operated under any combination of electrode voltages and loads.

A block diagram of a typical IMD test experiment is shown in Fig. 4. The low-distortion signals are generated by separate stable r.f. oscillators operating on 2000 and 2002 kc., respectively, their outputs being carefully combined in a special isolator which prevents the oscillators



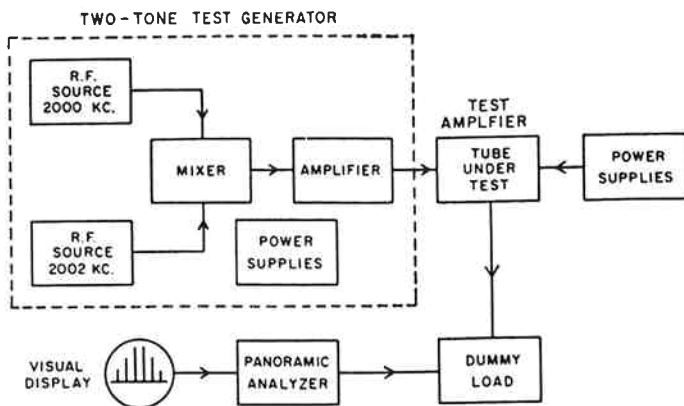


Fig. 4—Block diagram of Intermodulation Distortion Analyzer of Fig. 3. Low distortion two-tone r.f. signal is generated at 2 Mc. and applied to test amplifier. The output of the amplifier is dissipated in a dummy load and a portion of the output signal is examined on the screen of a high resolution panoramic analyzer. Distortion products as low as -60 decibels below peak power may be seen and studied.

from "seeing" each other. The resultant two-tone signal is amplified by successive class A stages until the desired driving level is reached. The two-tone generator shown in the photograph is capable of delivering a test signal having IMD products more than 60 decibels below the two-tone signals, at a power level up to 700 watts.

The tube under test is placed in a test amplifier operating at 2000 kc., and capable of permitting various electrode voltages and r.f. loads to be

impressed upon the tube at the convenience of the operator. The output of the test amplifier is dissipated in a dummy load and a small portion of the output signal is applied to a panoramic analyzer having a dynamic range of 60 decibels. The two-tone test signal, along with spurious IM products, may be seen on the screen of the instrument, separated on the horizontal frequency axis by the difference in frequency between the two test signals (Fig. 5). A reading is made by comparing the amplitude of a specific intermodulation product with the amplitude of the two equal test tones in the output signal. For convenience, the ratio between one of the test signals and one of the IM products (there are always two of the same order) is read as a power ratio expressed in decibels below the test-signal level. It is equally correct, and the absolute answer is the same, if the ratio of the sum of the powers of the two test tones to the sum of the powers of the two IM products of the same order is used. It is equally valid to express IM relative to peak-envelope power, (p.e.p.) provided it is done by taking the ratio of p.e.p. to the square of the sum of the two IM products of the same order.⁴ Referring IM to p.e.p. carries the additional information that the IM is specified for conditions of maximum signal level. Peak envelope power occurs when the two test tones are instantaneously in phase.

Measurements made on a wide variety of power tubes, from small to large, filamentary types and oxide cathode, triodes and tetrodes, in grid- and cathode-driven service, have shown conclusively that the magnitudes of the intermodulation distortion products are significantly affected by almost everything: changing heater or filament voltage by only a few per cent; slight shifts in bias voltage, idling current, screen voltage, plate or grid tuning; neutralization, loading — all these factors and others even more obscure enter into the determination of intermodulation distortion.

This might be a melancholy and discouraging picture, but it is a fact of life and is one of the

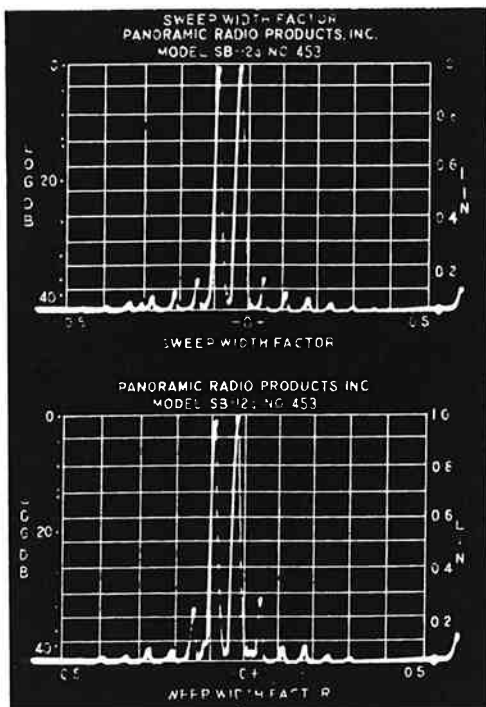
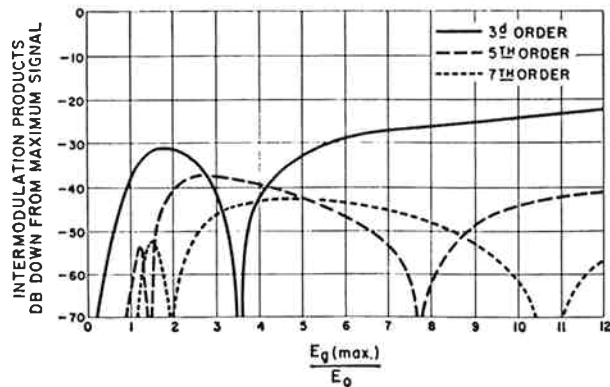


Fig. 5—Typical display on screen of IMD Analyzer. Top: Two test tones are seen at the center of the screen, with IMD products evenly displaced on either side of test signals. Third-order products are 35 db. down in amplitude from two-tone signal, and 5th-order products are 40 db. below test signals. Higher-order distortion products may also be seen. Bottom: Equipment parameters adjusted to raise third-order products and to drop fifth-order products. The linear amplifier may be adjusted to enhance or reduce various distortion products, if desired.

⁴ Expressions of IM without reference to conditions of measurement and techniques are — as expressed by Poo-Bah in "The Mikado" — "merely corroborative detail, intended to give artistic verisimilitude to an otherwise bald and unconvincing narrative." Unfortunately, a trend seems to be developing in this direction. The reader is hereby warned.

Fig. 6—Intermodulation distortion products may be predicted mathematically. This universal family of IMD curves applies to all perfect tubes obeying the 3/2-power law. The curves are plots of IMD level (Y axis) referred to the driving signal expressed as a ratio of drive to operating bias. As the drive is increased, the various IMD products pass through maxima and minima. Misleading conclusions of amplifier performance may be drawn if the equipment happens to be tested near a cusp on the IMD curve, where a particular product drops to an extremely low level. The whole operating range of the equipment must be examined to draw a true picture of IMD performance.



major roadblocks in joint industry efforts (working through the auspices of the Electronic Industries Association with the active cooperation of the U.S. Navy) to set up standards and testing procedures in order to establish a common yardstick for all to follow in vacuum tube IMD testing, rating and equipment design.

Mathematical Analysis

IMD products may be calculated by several methods.⁵ The results of different valid mathematical techniques are in good agreement with each other, and also agree in general with data obtained from two-tone tests conducted with the IMD analyzer. A theoretical family of IMD curves of a perfect tube obeying the 3/2-power law is shown in Fig. 6. This universal family of curves applies to all tubes, regardless of operating parameters or tube type. Changes in electrode potentials and circuit values (and even changes in tube type) will produce characteristic curves of this general configuration, but of course the signal level at which particular value of distortion occurs will be different in each case.

In Fig. 6 intermodulation distortion products, expressed in decibels below the output level of the tube, are plotted along the Y axis. The ratio of the two-tone driving signal $E_{g(max)}$ to operating bias, E_0 (relative to cutoff voltage) is plotted along the X axis. When E_0 is zero, the tube is biased at cutoff (class B). Ratios of $E_{g(max)}/E_0$ greater than one, but less than infinity, represent the possible range of class AB operation. Starting on the curve at the no-signal point ($E_{g(max)} = 0$), the IMD products are nonexistent. As $E_{g(max)}$ is increased, the IM products increase throughout the range of class-A operation and into the class AB region, until a maximum IM distortion figure for the 3rd-order products of about -30.7 decibels is reached at an $E_{g(max)}/E_0$ ratio of about 1.7. The 3rd-order product then drops to zero (minus infinity) again for a ratio of $E_{g(max)}/E_0$ of about

⁵ "Approximate Intermodulation Distortion Analyses." Report CTR-173 by R. E. Cleary, Collins Radio Co., Cedar Rapids, Iowa; "Linear Power Amplifier Design," W. B. Bruene, *Electronics*, August, 1955; "Linearity Testing Techniques for SSB Equipment," Icenbice and Tellhaver *Proc. I.R.E.*, December, 1956, pages 1775-1782. "Intermodulation Distortion in High Powered Tuned Amplifiers," R. C. Cummings, Consultant, Eitel-McCullough, Inc., San Carlos, California.

3.5, after which the IM product again increases, gradually rising to a level near -20 decibels for class-B operation. Fifth-order and 7th-order (and higher-order) products follow this same general behavior, compressed along the X-axis, and are shown in dotted lines on the graph.

The results of this theoretical study imply that the amount of intermodulation distortion in any vacuum tube that follows the basic 3/2-power law is predictable; further, that such distortion is inescapable and is independent of tube type. Moreover, the study indicates that the perfect 3/2-power tube will provide 3rd-order IM products no better than -20 to -30 decibels below maximum power output, and that the IM product varies markedly with drive level, dropping to zero at various points in the dynamic operating range. Thus, the perfect tube, obeying a fundamental law of physics, is a mediocre performer from a linearity point of view. As far as IM distortion goes, it is a poor device to use in equipment

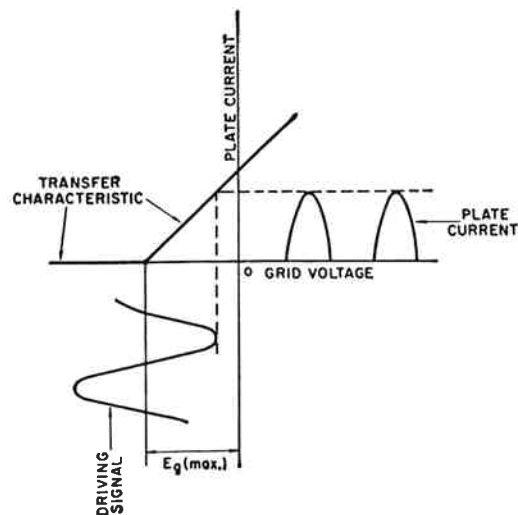


Fig. 7—An ideal tube transfer characteristic departs from the 3/2-power law. The ideal characteristic shown here consists of two linear portions, with the operating point set at the intersection. Half-wave plate current pulses are converted to sine waves by the flywheel effect of the plate tank circuit. Poor tank circuit Q, therefore, will have adverse effect on over-all linearity.