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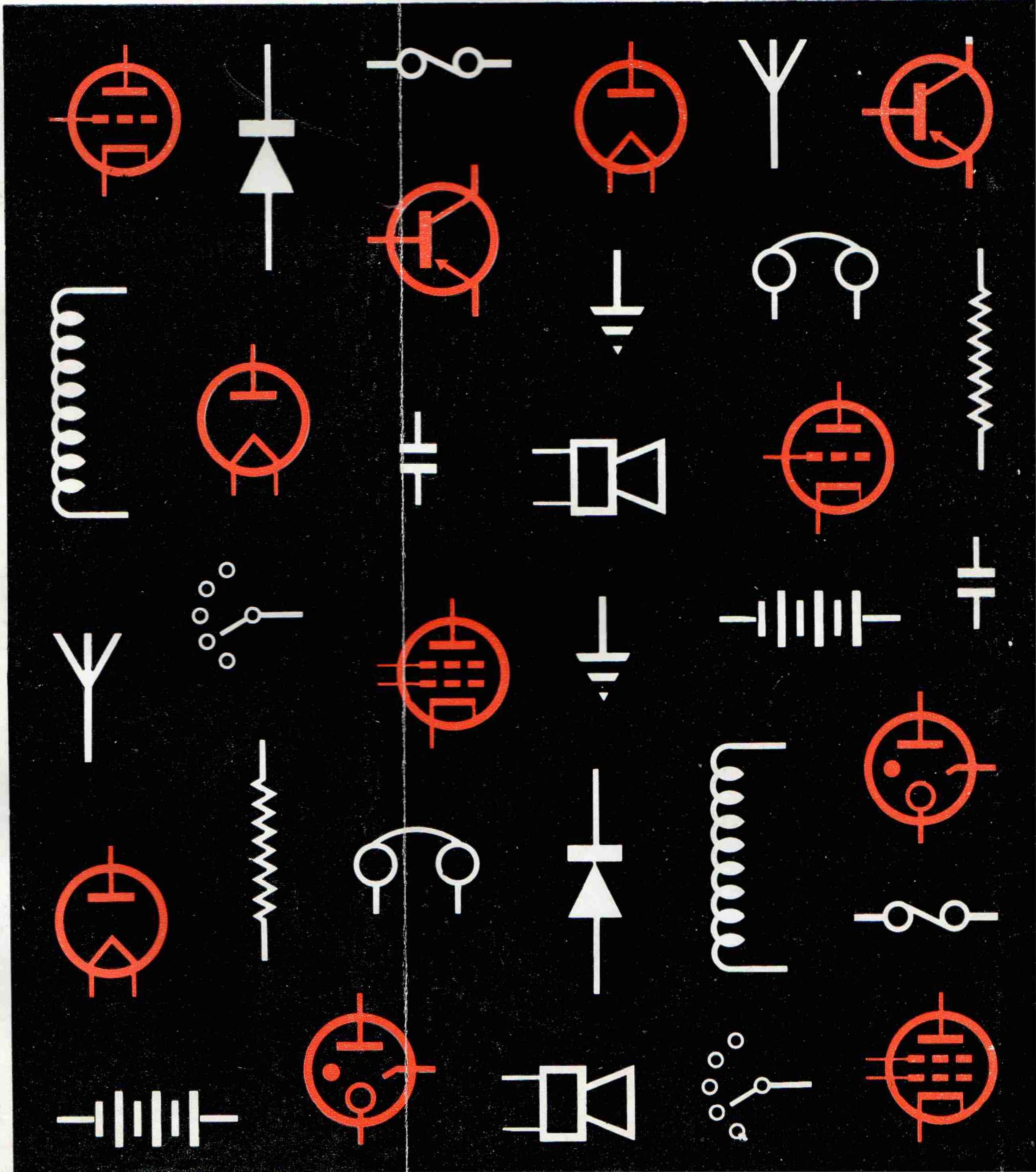

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RADIOTRONICS

Vol. 26, No. 12, 1961

Editor, Bernard J. Simpson

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NUVISTOR PREAMPLIFIER

For Amateur Receivers

By M. Adams, WA2ELL, and P. Boivin, Jr., K2SKK

RCA Electron Tube Division, Harrison, N.J.

A comment frequently heard on the amateur bands is, "This receiver is fine on 80 up through 20 meters, but on 10 and 15 it seems to lose sensitivity." The problem is a common one, especially with older, general-coverage communications receivers which tune from 0.55 to 35 megacycles in four bands. Because the 10-meter band is near the upper limit of this tuning range, sensitivity often drops off as a result of stray capacitance and a less than optimum LC ratio for this frequency.

One solution to the problem is a ham-band-only receiver optimized for each band. However, on some older models of this type, 10-meter sensitivity still is not satisfactory. All-band preselectors are also available, but these are expensive, elaborate, and bulky; also the extra boost is usually not needed on the lower frequencies. This article describes a preamplifier that adds 25 to 35 db gain ahead of the receiver on the desired band and can be built from readily available parts.

TABLE I: PERFORMANCE DATA

Band—meters	Frequency—Mc	Gain—db
15	21.0 21.5	30 30
10	28.0 29.0 30.0	27 29 26
6	50.0 51.5	17 16

Design Features

The unit is built around a pair of 6CW4 nuvistor triodes. These tiny high-mu triodes, designed for use as TV-tuner rf amplifiers, work exceptionally well at 30 Mc. The preamplifier provides ample gain ahead of the receiver and improves the signal-to-noise ratio. The resulting overall sensitivity is equal to that of many higher-priced receivers. Gain measurements for the unit are shown in Table I.

Top view of the nuvistor preamplifier designed around two 6CW4 high-mu triodes.

TABLE II: COIL DATA

Band—meters	Coil	C_1	C_2	Links
15	L_1—18 turns #32 enameled wire on ¼-inch slug-tuned form L_2—18 turns #32 enameled wire on ¼-inch slug-tuned form	15 $\mu\mu f$	15 $\mu\mu f$	1½ T
10	L_1—18 turns #32 enameled wire on ¼-inch slug-tuned form L_2—18 turns #32 enameled wire on ¼-inch slug-tuned form	5 $\mu\mu f$	5 $\mu\mu f$	1½ T
6	*L_1—10 turns #32 enameled wire on ¼-inch slug-tuned form *L_2—10 turns #32 enameled wire on ¼-inch slug-tuned form	5 $\mu\mu f$	6.8 $\mu\mu f$	1½ T

As an example of what can be expected from this preamplifier, a 10-meter unit was used ahead of a 10-year-old, general-coverage, single-conversion receiver. At 29 Mc, the receiver alone has a 10-db signal-to-noise ratio at an input of 20 microvolts. With the preamplifier ahead of the receiver, a 10-db signal-to-noise ratio is obtained at a 2.5-microvolt input. This improvement represents a sensitivity increase of 8 times at an equivalent signal-to-noise ratio. The preamplifier output impedance is 75 ohms, while the receiver input impedance may vary from 100 to 300 ohms depending on the design of the input network. If the unit is properly matched to the receiver, sensitivity can be improved even more.

An improvement in signal-to-noise ratio results from the lower noise factor of the nuvistor circuit as compared to that of older pentode amplifier designs. A noise figure of 4.5 db was measured for the nuvistor preamplifier by means of the noise-generator method. With the added gain of the preamplifier, the receiver front-end contributes negligible noise to the system. The noise factor of the preamplifier could be improved an additional 1 db by precise adjustment of the input link and proper tuning. However, the simplicity of alignment would be lost, and the resulting improvement in performance would be difficult to detect in actual use.

Construction and Alignment

Similar to the cascode amplifier in the ARRL Amateur Handbook, the circuit, shown in Figure 1, is used in many TV tuners. It has been reduced to its basic form to simplify construction and alignment. As indicated in Table II, a 1½-turn link around the hot end of L_1 matches a 75-ohm coaxial transmission line to the high-impedance input of a conventional grounded-cathode amplifier V_1. The output of V_1 is fed to the cathode of V_2, a grounded-grid amplifier in which the output appears across plate coil L_2. Another link around L_2 couples the output signal to a 75-ohm line to the receiver. Even though this type of amplifier is inherently stable, ample decoupling and bypassing have been included in the design. V_1 and V_2 are operated in a stacked arrangement in series with the B+ supply. Proper bias for V_2 is maintained by tying the grid back to the plate of V_1 through R_3. Because V_2 receives a larger signal than V_1, additional bias for V_2 is obtained across R_2.

Although lower-cost valve types may be used for V_1 and V_2, only the 6CW4 provides all the advantages of small size, low power drain, and excellent performance. In addition, two separate valves provide better isolation and a more stable amplifier. The 6CW4 and sockets are now available.

A 1½- by 2- by 4-inch aluminium box, shown in Figure 2, provides more than enough room for construction. As in any circuit at this frequency, leads should be kept short and the input isolated from the output. Although the circuit is not especially critical, a shield has been placed between the two triodes for maximum isolation. Oscillation, which should not occur if the input and output are connected to the proper impedances, may be encountered if the antenna is not connected.

TABLE III: ALIGNMENT DATA

Band	Tune L_1 to	Tune L_2 to
15 M	21.25 Mc	21.25 Mc
10 M	32.00 Mc	29.50 Mc
6 M	51.00 Mc	50.00 Mc

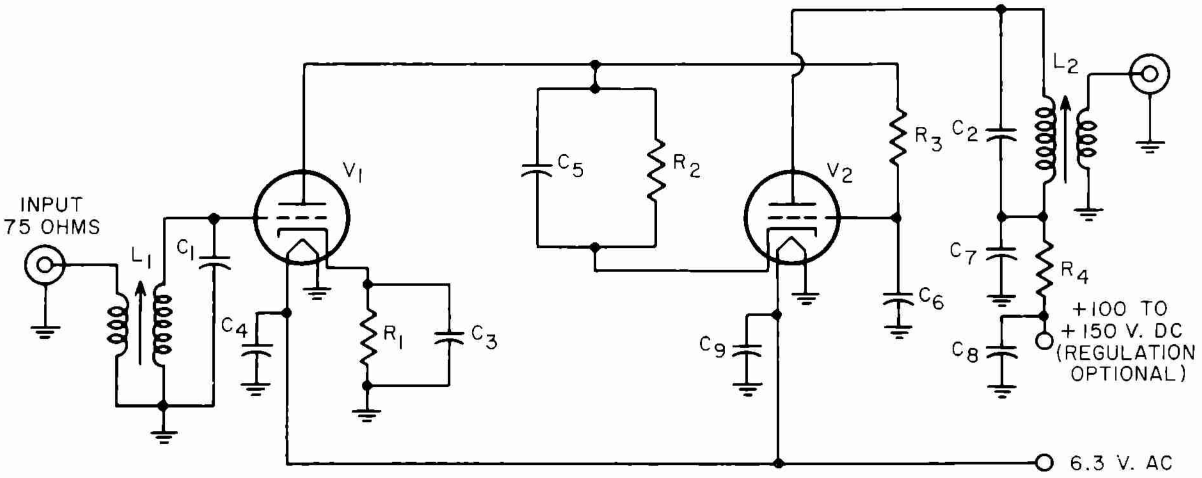
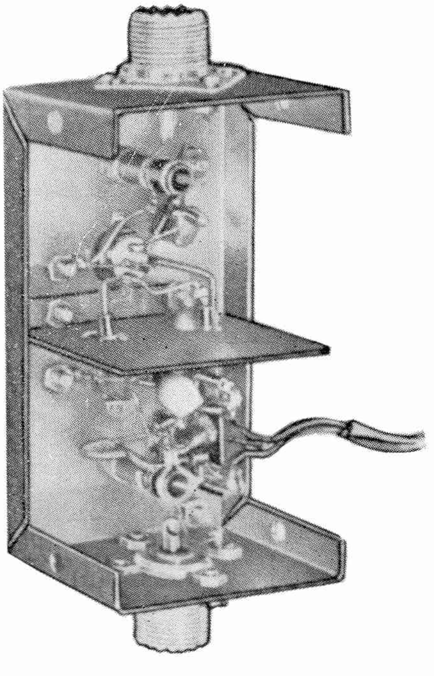


Fig. 1—Schematic diagram of the nuvistor preamplifier. C_1, C_2, see Table II; C_3 - C_9 inc., 0.001 mfd., ceramic, 500 volt working; L_1, L_2, see Table II (link is 1½ turns No. 32 enam. wire on form over other turns); R_1, R_2, 100 ohms, ½ watt; R_3, 470K ohms, ½ watt; R4, 1K ohms, ½ watt; V_1, V_2, 6CW4.

The original 10-meter unit was designed to use high-Q tuned circuits to obtain a flat-topped response over the band, and required careful tuning with the aid of a sweep generator and 'scope to obtain the desired response. The unit described in this article uses lower-Q tuned circuits which have a broader response. This arrangement is not only easier to align initially, but is also less sensitive to changes in supply voltage and loading. Alignment data for three bands are listed in Table III. The difference in gain over the band is not sufficient to degrade performance.

A grid-dip oscillator may be used to pre-set the coils at the correct frequency. For 15 meters, adjust L_1 and L_2 to a maximum indicated signal on the S-meter of the receiver with the preamplifier connected and a 21.25 Mc input signal. For 10 and 6 meters, adjust L_1 and L_2 with a grid-dip oscillator to the frequencies indicated in Table III, with no power connected to the preamplifier. The grid-dipper frequency should be checked against a reliable standard to insure correct alignment. The preamplifier cannot be tuned for 10 and 6 meters with a grid-dip oscillator if the heaters are on because grid current in V_1, due to the signal from the dip oscillator, will result in a false indication or no dip at all. If a sweep generator and 'scope are available, alignment is no problem. Simply tune the coils so that the edges of the band fall at the -3 db points on the response curve. The links should not have to be adjusted during alignment.

The preamplifier may be mounted inside the receiver cabinet, but should be more convenient to disconnect if mounted on the back near the antenna terminal. The maximum length of coaxial cable between the receiver and the preamplifier should not exceed 12 inches. The small power requirements (5 milliamperes at 150 volts and 0.26 amperes at 6.3 volts) may be obtained from the receiver through the accessory plug. The unit described uses 75-ohm coaxial connectors for easy changeover to bands where the preamplifier is not needed. If a balanced antenna system is used, terminal strips for the twin-lead may be used instead of coaxial connectors. In this case, the input link around L_1 would not be grounded.



Bottom view of the nuvistor preamplifier.

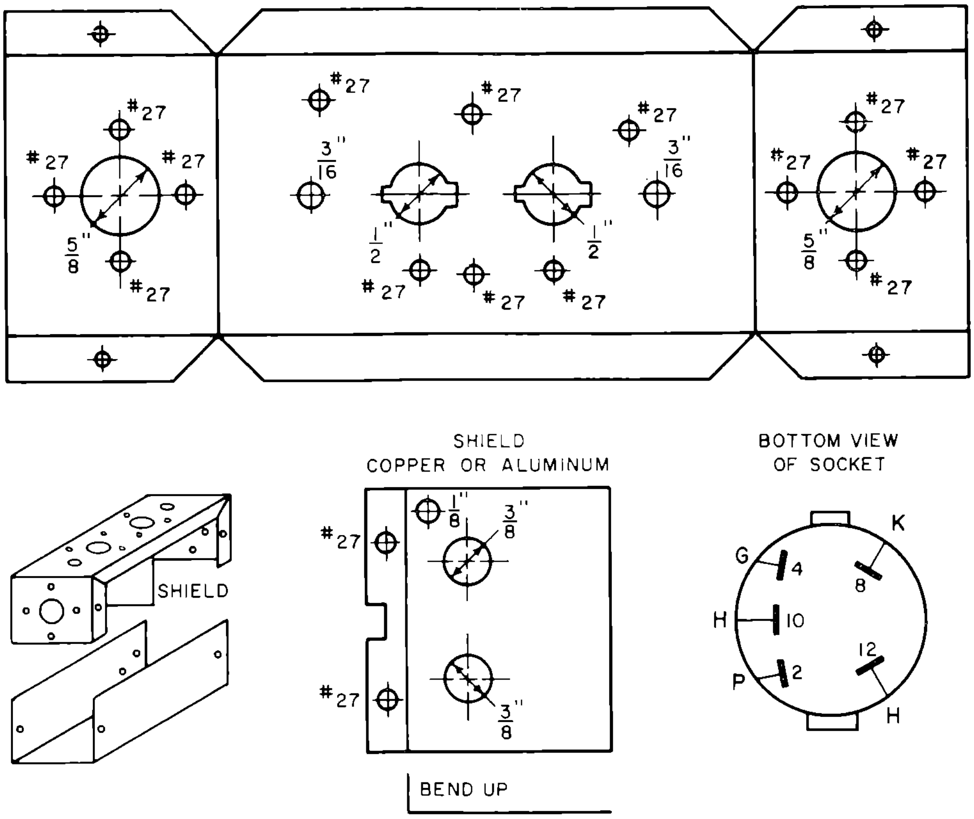


Fig. 2—Diagram of the box used for the preamplifier, and details of the socket connections for the 6CW4.

If 300-ohm twin-line is used for the input, one extra turn should be added to the input link to match the line.

When to Use

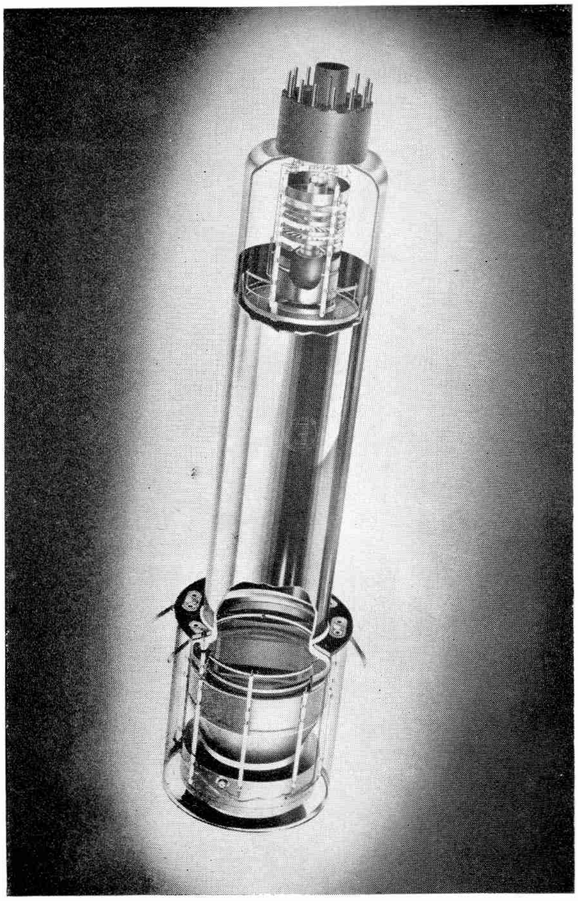
The nuvistor preamplifier is not intended to improve the image rejection of a single conversion receiver. Because response is intentionally made broad to eliminate tuning during operation, images will be present whether the unit is used or not. The increased sensitivity of the receiver due to the nuvistor unit will be apparent from the rise in background noise level. In addition, signals that were previously about equal to the background noise in strength will be 3 or 4 S-units above the noise with the preamplifier connected, due to the improvement in signal-to-noise ratio in the front-end. The greatest improvement will be noticed in receivers having poor sensitivity initially. Little advantage is gained in receivers which have 1.5 to 3 microvolt sensitivity and a good signal-to-noise ratio. If it is desired to use this circuit on 6 meters, the design can be incorporated in a crystal-controlled or tunable-type converter. This arrangement would eliminate tracking problems because the rf section would not have to be tuned after initial alignment.

The nuvistor preamplifier has been designed for best performance consistent with simplicity and ease of construction and alignment. If you have not been hearing those signals on ten, here is the opportunity to obtain top performance from your receiver with a minimum investment.

(With acknowledgements to RCA)

DEVELOPMENT OF THE ENGLISH ELECTRIC AWARD-WINNING IMAGE ORTHICON

TELEVISION'S SILVER JUBILEE FEATURE



The Silver Jubilee year of British Television is especially significant for EEV as it is the year in which the company received the American National Academy of Television Arts and Sciences "Emmy" Award for its work in the development of the $4\frac{1}{2}''$ Image Orthicon pick-up tube. The award recognises the pioneer achievement in the commercial development of this type of tube; it is the first year that this award has been presented to a company outside the United States, and is therefore an appropriate tribute to the industry which twenty-five years ago gave the world the first regular television transmissions.

An all electronic television system was first proposed by Campbell Swinton in a letter in "Nature" in 1908, but 15 years elapsed before John Logie Baird demonstrated his mechanical scanning system, the first serious attempt at television. Swinton's idea, of using cathode ray tubes at both transmitting and receiving ends of the system was years in advance of the existing technology and, even when Baird began his experiments, was far from reality. The controversy that raged around the Baird 250 line mechanical and the 405 electronic system was resolved in 1936 when the B.B.C. adopted the latter after comparative trials with the two methods had been undertaken over a long period.

To obtain satisfactory pictures from the electronic system the iconoscope pick-up tube demanded particularly high illumination of the subject. Furthermore, spurious signals were unavoidably generated and had to be corrected. Such correction was not difficult when the scene was well and evenly illuminated, but at low light levels correction became increasingly difficult and was practically impossible if the illumination was not uniform.

In 1937 E.M.I. added an image section to the iconoscope and the new tube had a considerable increase in sensitivity, although the problem of spurious signals still remained.

Co-incident with the image iconoscope development, the orthicon tube was being developed in the United States, and so at the outbreak of war there were the iconoscope or emitron and image iconoscope or super emitron in Britain, and the orthicon in America. The orthicon represented a remarkable departure from iconoscope tradition because the mosaic was scanned by a beam of low-velocity electrons. Under these conditions the mosaic was driven down to approximately the potential of the thermal cathode and was stable at that value, so ensuring a true black reference level.

Although spurious shading signals are almost eliminated by the use of low velocity scanning beams, the early orthicons were far from trouble free. The most serious trouble was the tendency of the mosaic to charge up positively under strong local illumination causing loss of image, restoration of which could only be achieved by reducing the anode potential to zero for a short time, a considerable circuit inconvenience. Recent orthicons (S.C.P.S. Emitrons) have overcome this defect.

The perfection of the double sided mosaic by RCA during the war allowed an image section to be built on to the orthicon, so increasing its sensitivity and at the same time ensuring stability.

When the television service was resumed in Britain in 1946, the iconoscope was the only working tube available, but it was recognised that a considerable amount of development work would be necessary if this tube was to reach the full theoretical sensitivity possible. Theile, then of Cathodeon, indicated the direction of approach and the fruits of this development is the Riesel-iconoscope of Fernseh GMBH.

In the United States, the end of the war saw the image orthicon firmly established, and its potentialities as a high definition tube were being seriously considered in this country.

In development work on the 3″ tube, the English Electric Valve Company undertook to reduce its noise, the ballooning of whites, and the black halo around highlights, and to improve its definition and the inability to produce true edge transition, etc. These drawbacks tended to offset the high sensitivity of the tube.

Ballooning of whites and diffuse edges were reduced by the incorporation of an additional mesh in the reading section of the image orthicon. This field mesh, as it has been called, increased the target decelerating field of the scanning beam,

Test studio of the Photoelectric Tubes Division of EEV. Image Orthicon and Vidicon tubes receive a thorough electrical test to stringent specifications, and an optical test under studio conditions in a TV camera.

and prevented the displacement of the beam which gave rise to the faults. This move gave considerable improvement in the picture quality. The next step was taken by Otto Schade of RCA, who demonstrated a larger version of the 3″ tube. This — the 4½″ image orthicon — allowed a larger target area and produced considerable improvements in signal/noise ratio, resolution, true edge reproduction, black halo elimination and grey scale reproduction.

In order to retain the optical convenience of the 3″ tube the English Electric Valve Company redesigned the electron image section. This operated at higher potentials and so had the added advantages of higher target sensitivity and reduced picture sticking.

As stated above, the used area of the photocathode in the 4½″ tube remained identical with that of the 3″ tube, but it also provided the possibility of using a size equal to that of the target if needed. To fill the target with the electron image from the smaller standard photocathode it was necessary to arrange in the camera a divergent magnetic field from photocathode to target in such a way that the linear photocathode dimensions were multiplied by approximately 1.5 times.

The first operational 4½″ tubes were used in Marconi Mark III cameras in the B.B.C.'s Lime Grove studio in London in 1954. From that date the 4½″ image orthicon has been accepted in no fewer than 20 countries, and is fast becoming the standard tube for quality television presentation throughout the world.

The new Marconi Mark IV camera incorporating the 4½″ tube was designed to provide simpler operation and greater stability, and with the Mark III, both using English Electric pick-up tubes, forms the basis of the majority of good quality pictures throughout the television world of today.

NEW RELEASES

1N110-A, 1N1200-A, 1N1202-A, 1N1203-A, 1N1204-A, 1N1205-A, 1N1206-A

These units together with their reverse-polarity versions (designated by suffix "RA") represent an addition of fourteen 12-ampere silicon rectifiers in the JEDEC DO-4 package to the expanding line of diffused-junction silicon rectifiers for military and industrial power supplies. These silicon rectifiers, which directly replace all corresponding prototypes, are designed to meet the stringent environmental and mechanical requirements of critical power-supply applications. These industrial rectifiers feature peak inverse-voltage ratings from 50 to 600 volts, low thermal resistance, low-leakage current and low forward voltage drop.

2N1905, 2N1906

The 2N1905, 2N1906 are two new diffused-collector graded-base power transistors of the germanium p-n-p type. These drift-field types utilise a combination of diffusion and alloying techniques to provide a built-in accelerating field in the base region. This field makes possible a wide frequency response and a linearity of characteristics over the entire operating collector-current range not available in conventional power transistors. 2N1905, 2N1906 are particularly useful as high-power, high-speed switches in dc-to-dc converters, inverters and computers for data-processing equipment, as ultrasonic oscillators and as large-signal, wide-band linear amplifiers. Other features which make the 2N1905 and 2N1906 especially useful in industrial and consumer-type equipment are 50 watts dissipation at 25° C, extremely short rise and fall times at high values of I_C—less than 1 microsecond, a high typical-gain bandwidth product and low base resistance for high-power sensitivity.

6EW7

The 6EW7 is a dual triode containing a medium-mμ unit and a low-mu unit in a t-9 envelope with a nine-pin base. The medium-mu unit ($\mu=15$) is designed for use in vertical-deflection-oscillator applications. The low mu unit ($\mu=6$) is designed for use in vertical-deflection-amplifier applications and in suitable circuits will fully deflect picture tubes having deflection angles up to 110 degrees.

6HS8

The 6HS8 is a sharp-cutoff twin pentode of the nine-pin miniature type, having a common cathode, common grid No. 1 and common grid No. 2. In addition, grid No. 1 and grid No. 3 have separate base-pin terminals, permitting either to be used independently as a control electrode. The 6HS8 is designed primarily for use in automatic gain-control amplifier, sync, and noise-limiting circuits of TV receivers. In such receivers one pentode unit performs the function of combined sync separator and sync clipper; the other unit serves as an automatic-gain-control amplifier.

JAN-1N540, JAN-1N547, JAN-1N548

These are military versions of the diffused-junction silicon rectifiers. The JAN-1N547 meets the requirements of military specification MIL-E-1/1083A dated January 28, 1958. The rectifiers are otherwise similar to their commercial prototypes.

RADIOTRONICS BACK NUMBERS

We are frequently asked about back numbers of Radiotronics. The position at the moment is that a limited number of complete issues for 1961 is available at 10/- the set. Issues prior to January 1961 are out of print.

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THE ELECTRON-BEAM PARAMETRIC AMPLIFIER

Its Performance and Operating Characteristics

By G. O. Chalk, M.Sc.,
English Electric Valve Co. Ltd.

This article is intended to fulfil the need of providing the equipment designer with a realistic appraisal of the merits of the low-noise electron-beam quadrupole amplifier. The experimental performance of typical amplifiers at 200, 400 and 600 Mc is discussed, and various operational parameters which may influence its use in a particular application are considered. A comparison is made with other devices in the field.

Introduction

In recent years there has been a wealth of technical papers on the theory and design of the various types of parametric amplifier, but very little information has appeared on the practical use and application of these devices. The parametric amplifier is one of the most recent additions to the range of low-noise radio-frequency amplifiers, and in order to become a useful device it must compete successfully, both in performance and ease of operation, with conventional devices already in use. It is the purpose of this article to describe the practical performance that may be obtained with one particular form of parametric amplifier, the electron-beam quadrupole amplifier, and the various practical problems involved in putting it into satisfactory and reliable service. A comparison will be made with existing devices over the frequency range in which it may find its widest application, namely, from about 200 to 1,000 Mc.

The quadrupole amplifier

The quadrupole amplifier first described by Adler* is shown diagrammatically in Fig. 1. It consists of a cylindrical electron beam, which passes from an electron gun through three sets of radio-frequency electrodes to a collector. The electron beam is focused by a uniform axial magnetic field of such a value that the cyclotron frequency of electrons in the field is equal to the centre frequency of the band over which the tube is designed to operate. The relation between magnetic flux density B (gauss) and the cyclotron frequency f (Mc) is:

$$B = 0{\cdot}36\,f \qquad (1)$$

The three sets of electrodes serve to couple external radio-frequency signals on to the beam. The input coupler, immediately following the electron gun, couples rf power from the input signal source on to the electron beam. It consists of a pair of parallel plates disposed symmetrically about the axis of the beam which are tuned by an inductance to resonate at the design centre frequency. An rf signal applied to this circuit from the input signal source produces an rf electric field between the coupler plates, transverse to the axial magnetic field and the direction of motion of the beam. This transverse electric field causes individual electrons passing through the coupler to describe helical paths of radii increasing approximately linearly with distance as

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*Adler, R., Hrbek, G., and Wade, G., *Proc. Inst. Radio Engrs.*, **47**, pp. 1713-1723, (1959).

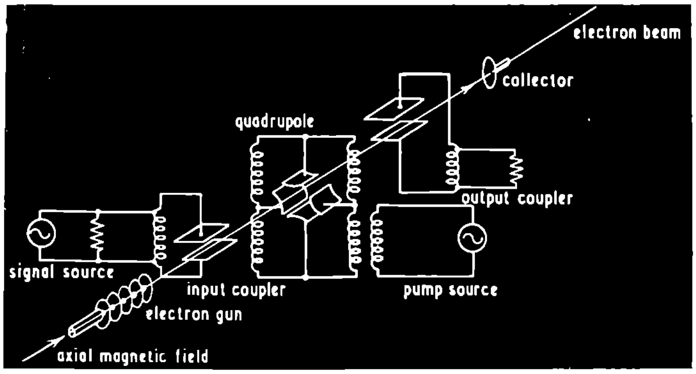

Fig. 1. Schematic diagram of the quadrupole amplifier. For clarity the straps connecting alternate quadrupole electrodes have been omitted.

energy is transferred from the signal field into kinetic energy of rotation of the electrons. The electrons rotate about the axis at a frequency equal to the cyclotron frequency. The radius of the electron orbits as they leave the coupler is proportional to the amplitude of the signal field.

The orbiting electrons from the input coupler next pass into the quadrupole section, in which parametric amplification of their orbits takes place. The quadrupole consists of four electrodes symmetrically disposed about and parallel to the axis of the beam. It is tuned by four identical inductances to a frequency equal to twice the cyclotron frequency given by equation (1). Alternate electrodes are strapped together to ensure a phase difference of 180° between the instantaneous rf polarity of adjacent electrodes. When excited by an rf source (the pump) at twice the cyclotron frequency, the electric field produced in the quadrupole region possesses azimuthal and radial components which rotate around the axis at one half the pump frequency, i.e. at the cyclotron frequency. Electrons entering the quadrupole field from the input coupler will interact with the azimuthal component of this field and, depending on their phase of entry with respect to the rotating field, some will gain energy and some will give energy up to the field. The electrons gaining energy will spiral outwards into orbits of larger radius, the ones losing energy spiralling towards the axis. The gain always exceeds the loss so that, considering the beam as a whole with electrons entering in all possible phases, there is an overall gain, the electrons leaving the quadrupole having considerably more rotational kinetic energy than when they entered. The amplitude of the quadrupole field is proportional to the radial distance from the axis, which is the necessary requirement for exponential gain. The amount of energy gained by each electron depends both on the amplitude of the quadrupole field (pump power) and on the time spent in the quadrupole. This in turn depends on the beam velocity in the quadrupole, i.e. the dc potential of the quadrupole.

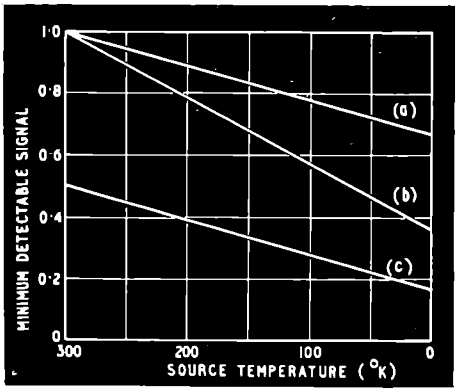

Fig. 2. Variation of minimum detectable signal with input source temperature for: (a) a triode or travelling-wave tube; (b) a non-degenerate parametric amplifier; (c) degenerate parametric amplifier.

The amplified electron orbits finally pass into the output coupler, which is usually identical to the input one. Here the rotational energy is extracted from the electrons and passed to the output load, the electron paths following a convergent conical helix as their rotational energy is reduced on passing through the coupler. If the output load resistance is of the correct value, all of the rotational energy can be extracted and passed to the load.

The low-noise performance of the tube is a result of the fact that complete removal of electron rotational energy can be obtained in such a coupler by terminating it in the correct value of load resistance. If the input coupler is terminated in this value of load resistance, the transverse or rotational component of noise in the beam from the cathode can theoretically be completely removed and the beam leaving the coupler is then noise-free in the transverse sense in the bandwidth over which this correct resistive "match" is achieved. This particular value of resistance is also that which gives maximum transfer of signal energy from the source on to the beam, so that noise is removed from the beam and signal power impressed on to the beam simultaneously in the input coupler.

As a result of input circuit loss and a number of second-order effects, the noise figure of practical tubes when the input circuit is correctly matched is not unity. There is a small residual noise component which results in typical best noise figures of about 1 db.

If the signal frequency is not exactly equal to one half the pump frequency, an "idler" will be generated in the same way as in other parametric amplifiers. The idler frequency is given by:

$$f_i = f_p - f_s \qquad (2)$$

where f_p and f_s are the pump and signal frequencies respectively. The signal and idler are equally disposed in frequency about one half the pump frequency, i.e. the cyclotron frequency.

Noise figure

The noise figure of any amplifier may be defined as the signal-to-noise ratio at the input divided by the signal-to-noise ratio at the output, when referred to a matched input source at room temperature (290°K). It is often convenient to represent noise generated within an amplifier by a temperature T, where KTB is the available noise power of the amplifier in a bandwidth B. For a single-channel device of power gain G (e.g. a triode) we may therefore write

$$\text{output} = GP/\{G(KTB+KT_o\mathrm{B})\} \qquad (3)$$

$$\text{and } (S/N)_{\text{input}} = P/KT_oB \qquad (4)$$

where P is the signal input power and T_o is the temperature of the matched input termination (290°K). It is easily shown that

$$F = 1+(T/T_o) \qquad (5)$$

$$\text{or } F\text{db} = 10 \log_{10}\{1+T/T\}\text{db} \qquad (6)$$

Clearly when T=O (zero noise generated inside the amplifier) the amplifier is noiseless and $F = 1$ or zero db.

In the case of a parametric amplifier with the signal frequency exactly equal to one half the pump frequency, no idler is generated and the expression for the noise figure is the same as equations (5) and (6). When the signal frequency is not equal to one half the pump frequency the idler is generated, and since power is now converted from the idler to the signal frequency in the tube and *vice versa,* the expression for the output signal-to-noise ratio at the signal frequency is modified and becomes:

$$(S/N)_{\text{output}} = G_sP/G_s(KT_sB+KT_{os}B)+ G_i(KT_iB+KT_{oi}B) \qquad (7)$$

where G_s is the power gain at the signal frequency and G_i is the power gain for an input signal at the idler frequency, which is converted to an output at the signal frequency; T_s and T_i are the tube-noise temperatures and T_{os} and T_{oi} are the input-source temperatures at f_s and f_i respectively. In the quadrupole amplifier, when the gain is high, G_s and G_i are equal, and in general T_s and T_i, and T_{so} and T_{si} are also equal. Hence the noise figure becomes:

$$F = 2\{1+(T/T_o)\} \qquad (8)$$

$$\text{or } F\text{db} = 10 \log_{10}\{1+T/T\}+3\text{db} \qquad (9)$$

This assumes the bandwidth of the receiver following the quadrupole amplifier is sufficiently narrow that power at the signal frequency only is passed to the detector.

The noise figure in the non-degenerate mode ($f_p \neq 2f_s$) of operation is therefore twice that in the degenerate mode ($f_p = 2f_s$) of operation. However, as the source temperature is reduced the sensitivity of the quadrupole amplifier in the non-degenerate condition increases more rapidly than, for example, a triode with the same noise figure (sensitivity) at room temperature. This is because there are two contributions of Johnson noise, one at f_s and one at f_i from the input source impedance to the quadrupole amplifier, both of which are reduced, whereas there is only one contribution in the case of the triode. Fig. 2 shows the more rapid increase in sensitivity (decrease in minimum detectable signal) of the non-degenerate quadrupole amplifier over a single-channel device as the source (aerial) temperature is reduced. The noise figure of each is assumed to be 5 db referred to room temperature. Shown also is the characteristic for the same parametric amplifier working in the degenerate condition corresponding to a 2 db noise figure at room temperature. It is seen that for all values of source temperature the minimum detectable signal is 3 db lower in the degenerate than in the non-degenerate case.

Performance of typical quadrupole amplifiers

Fig. 3 is a photograph of packaged quadrupole amplifiers designed for operation in the region of 400 and 600 Mc. The packages consist of

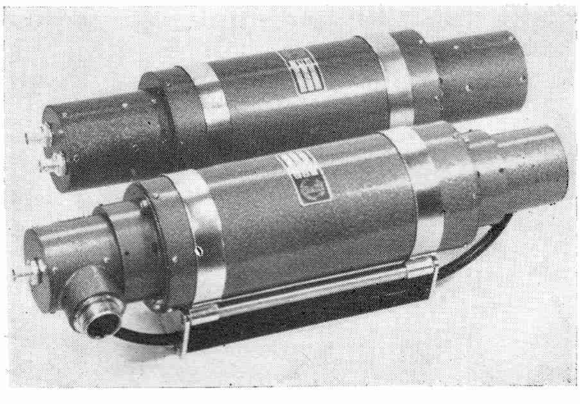

Fig. 3. Photograph of packaged 400 Mc (front) and 600 Mc (rear) quadrupole amplifiers.

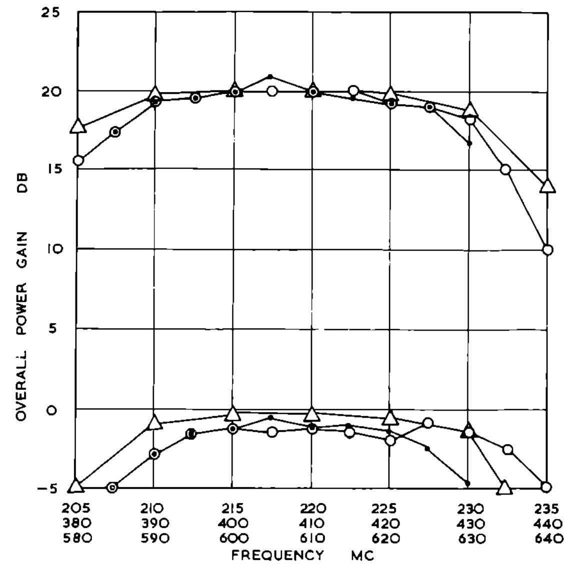

Fig. 4. Variation of unpumped transmission loss and gain versus frequency for 200 Mc, 400 Mc and 600 Mc quadrupole amplifiers.

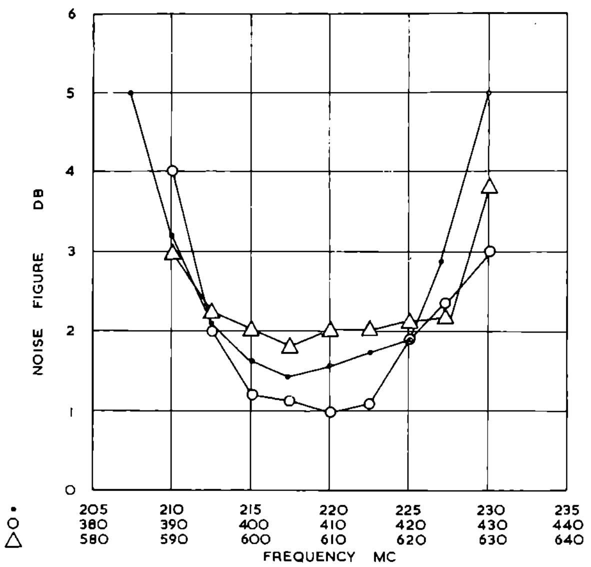

Fig. 5. Variation of noise figure with frequency at 20 db gain for 200 Mc, 400 Mc and 600 Mc quadrupole amplifiers.

the amplifier tube, electromagnet and rf matching transformers to match the tube into 50-ohm coaxial line. Three coaxial sockets provide rf connections and a multiway socket provides connection to the power unit supplying the various tube electrodes and the electromagnet. Since the adjustment of the rf matching sections for optimum performance requires considerable test equipment, the units are assembled as a complete package including the tube, so that in the case of replacement the complete package is interchanged. It is considered that this is the most satisfactory way at present to use the device to achieve optimum performance.

Curves in Figs. 4 and 5 show the variation of gain, unpumped transmission loss and noise figure with frequency for a tube designed for broad-band operation centred on 220 Mc. For these particular measurements the pump frequency was 440 Mc and about 5 mw of pump power was required to obtain a gain of 20 db. The noise figures were measured with the input terminated in a resistance of such a value that the residual vswr was less than 1·1:1. The effect of input mismatch on noise figure is discussed in a later section.

Also shown in Figs. 4 and 5 are similar results on the broad-band performance of tubes centred at 408 Mc and 600 Mc, which show similar percentage bandwidths and noise figures to the 220 Mc tube. In these tubes about 5 mw of pump power was required at 816 Mc and 50 mw at 1200 Mc respectively to obtain gains of 20 db.

In Fig. 6 is shown the power output *versus* power input characteristic of a 400 Mc tube. The characteristic is linear up to the point where there is some current interception by the plates of the output coupler, due to the increased size of the electron orbits. As more current is intercepted the gain falls until, when almost complete interception occurs, the output power falls rapidly to zero. This is the "cut-off" characteristic of the quadrupole amplifier, the importance of which is discussed in the next section. A maximum output power of about 50 microwatts is typical.

Operating characteristics of the quadrupole amplifier

Impedance matching

Unlike the low-noise grounded-grid triode amplifier, the quadrupole amplifier must operate between matched impedances to achieve minimum noise figure and maximum gain. In this case the matching conditions for maximum gain and minimum noise figure are identical. A mismatch in the output circuit affects the gain alone, but a mismatch in the input circuit affects both gain and noise figure, more particularly the noise figure. Since in any particular system the input will be connected to an aerial, either directly or through a duplexer or filter, some degree of mismatch is bound to be presented to the tube, resulting in an increase in noise figure due to incomplete noise removal from the beam. The variation of noise figure with input mismatch is therefore an important practical tube parameter, and a typical curve for a 600 Mc tube is shown in Fig. 7. In a well-designed aerial system, a vswr of better than 1·2:1 can probably be achieved, which produces a degradation in noise

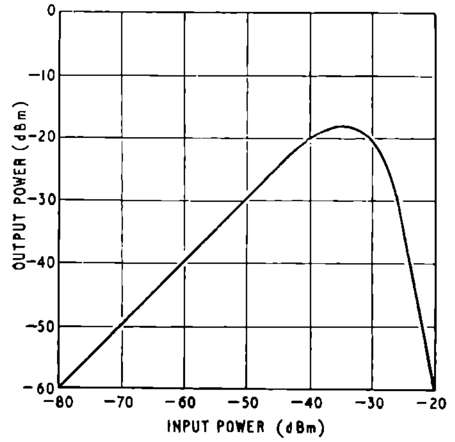

Fig. 6. Variation of output power with input power for a 400 Mc quadrupole amplifier.

figure of typically 0·3 db. The theoretical degradation in noise figure due to an input vswr s is:

$$F=(s-1)^2/(s+1)^2 T_t/T_o \qquad (11)$$

where T_t is the contribution to the overall tube noise temperature T, which may be removed by correct matching; T_t is typically about 1000°K in the tubes described here. The measured increase in noise figure due to a particular value of s appears to be greater than that predicted in equation (11) when s is small, but agrees closely for large values of s. The reason for this is not yet known.

Stability

The quadrupole amplifier is a unilateral device, the only coupling between the input and output circuits being *via* the beam. Provided that there is no feedback outside the tube, the device is completely stable and its stability is unaffected by variation in input and output impedances. This is quite unlike the majority of variable capacitance parametric amplifiers, which are regenerative and must be operated near to oscillation in order to obtain high gain. Under these circumstances the gain stability is very sensitive to operating conditions, and small changes in input or output impedances or pump amplitude or frequency may readily cause large variations in gain and possibly oscillations, making them difficult to set up and use. There is no such difficulty with the quadrupole amplifier.

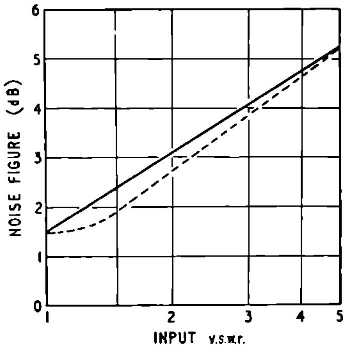

Fig. 7. Variation of noise with input vswr for a 600 Mc quadrupole amplifier.

Dynamic range

The output *versus* input characteristic of a typical quadrupole amplifier is shown in Fig. 6. The maximum output power of typically 50 microwatts corresponds to a dynamic range of about 80 db in a 1 Mc bandwidth, which may be rather low for many applications. However, this may be increased by about 20 db by a simple agc system to be described below.

In a quadrupole amplifier, with identical input and output couplers, the radius of electron orbits in the input coupler is still quite small at the time when saturation in the output coupler is reached, due to current being intercepted by the output coupler plates. The power in the input coupler at this point is the saturation output power divided by the power gain. If the gain of the tube is now progressively reduced to maintain the output power constant as the input power is increased, an increase in dynamic range may be achieved up to the point when interception by the input coupler occurs. At this point the gain is unity and an increase in dynamic range approximately equal to the original gain of the tube has been achieved.

The gain can be conveniently reduced by increasing the dc potential of the quadrupole structure, thereby decreasing the time spent by individual electrons in the quadrupole field. A typical curve of the variation of gain with quadrupole potential is shown in Fig. 8. It is desirable to provide a delay voltage in the agc circuit so that it is inoperative until normal saturation is reached.

As the gain is reduced there is a corresponding increase in the overall receiver-noise figure, due to the increasing effect of the noise of the second stage. However, under large signal conditions, when the agc operates, very low noise is not important provided that the agc time constant is sufficiently short that the amplifier is returned to the high-gain—low-noise regime immediately after the termination of the large signal that caused the agc to operate.

Large signal effects

When a very large input signal, much greater than the normal saturation power input, is applied to the tube, the electric field produced across the input coupler plates is so great that the beam is completely deflected and intercepted by the input coupler, resulting in a substantially zero output from the tube. This "cut-off" characteristic is of considerable practical importance in pulsed-radar systems when some transmitter power leakage occurs during the transmitted pulse, since it affords complete protection to the next stage of the receiver during this period. The stage following the quadrupole amplifier is likely to be either a triode or a crystal mixer, both of which are susceptible to permanent damage by large overload signals. The maximum output power of the quadrupole amplifier is typically about 50 microwatts, which is sufficiently small not to damage the subsequent stages in the receiver.

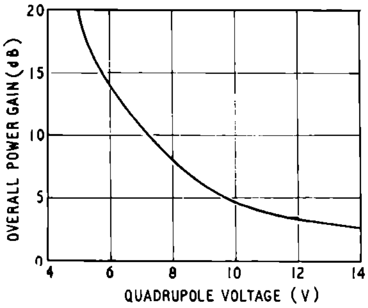

Fig. 8. Typical variation of gain with quadrupole voltage for 200 Mc quadrupole amplifier. The pump power is constant.

Since the beam power in the quadrupole amplifier is very low, typically about 250 microwatts, no damage is caused by the defocusing following normal overloads. Damage may be caused only when the input power is so great that a flashover occurs inside the tube, which normally requires pulsed power in the kilowatt region. After the removal of the overload signal the tube returns to its normal state very rapidly. Large signal paralysis is absent, the recovery time being considerably less than one microsecond.

The relatively large overload signal permissible with the quadrupole amplifier allows the duplexer design in a radar system to be simplified and makes the pulsed attenuators, commonly used in the input circuits to triodes, unnecessary. This leads to reduced input circuit loss and a correspondingly improved noise performance.

Spurious signals

One disadvantage arising from the use of the quadrupole amplifier, or any other parametric amplifier for that matter, is the number of spurious signals which accompany the desired signal in the output of the device. These must be considered carefully in the application of the amplifier to a particular use, and may necessitate a careful choice of local oscillator and intermediate frequencies and the use of filters to achieve interference-free reception. Spurious signals in this context are defined as any signal (other than the wanted one) which may beat with the local oscillator to produce an output at the intermediate frequency. The various spurious signals are discussed below.

Idler. As previously stated, an idler of frequency f_i is generated when the signal frequency is not equal to one half the pump frequency. An input signal at f_s gives rise to an output signal at f_s and f_i, and conversely an input signal at f_i gives an output at f_s (as well as f_i). An interfering signal received by the aerial at f_i will be converted to f_s by the parametric process and appear as an intermediate frequency (if) output together with the wanted signal at f_s.

IF images. If the local oscillator and intermediate frequencies are given by f_o and f_{if} respectively then:

$$f_{if}=|f_s-f_o| \qquad (13)$$

Intermediate image frequencies at $f_s \pm 2\,f_{if}$ occur depending on whether the local oscillator is above or below the signal frequency. An interfering signal in the aerial at the image frequency will produce an if output. The magnitude of this if output depends on the magnitude of the image signal in the input to the mixer, which in turn depends on the gain of the quadrupole amplifier at this frequency. An interfering signal at the idler frequency $f_p-(f_s \pm 2\,f_{if})$ corresponding to the image will also produce an if output. This indicates the use of a high intermediate frequency and a quadrupole amplifier whose bandwidth is no wider than necessary.

Pump breakthrough. Since the transmission line carrying the pump power to the quadrupole circuit within the valve envelope passes close to the output coupler, some coupling between these two circuits will inevitably occur. The pump frequency, which is in the region of twice the signal frequency, may beat with the second harmonic component of the local oscillator generated in the mixer (a non-linear device) to produce an if output of frequency

$$f_{if}=|f_p-2f_o| \qquad (14)$$

Since the pump power is typically some tens of milliwatts and the output signal power at maximum sensitivity is only about 10^{-12} watts, severe interference may be caused by this effect. This may be prevented by a suitable choice of local oscillator and intermediate frequencies or by filtering.

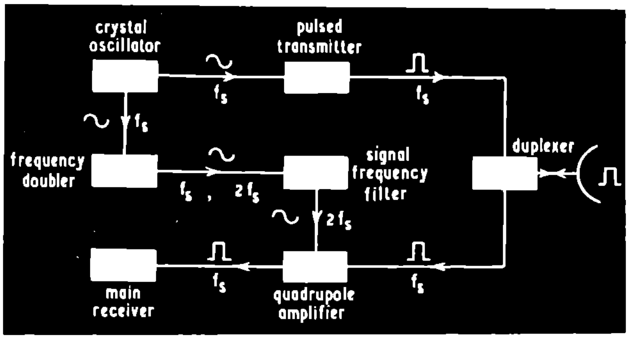

Fig. 9. Possible arrangement for degenerate operation of a quadrupole amplifier in a pulsed radar system.

Local oscillator feedback

If appreciable power at the local oscillator frequency passes into the output coupler, it may "cut-off" the tube. Since the maximum power that can be passed through the tube is about 50 microwatts before interception occurs and the local oscillator level is some tens of milliwatts. considerable attenuation is required. This can be achieved in a number of ways, for example, a signal-frequency band-pass filter, an isolator or a buffer stage between the mixer and the quadrupole amplifier.

Pump failure

Probably the most common cause of failure or reduced performance of a quadrupole amplifier system will be a gradual or complete failure of the pump oscillator. This will result in a loss of gain and a corresponding increase in the overall noise figure of the complete receiver. Even with complete pump failure, the quadrupole amplifier behaves as a low-loss transmission device (the bandwidth and gain are independent) of attenuation less than 2 db. Pump failure will therefore not cause a complete receiver failure, only a deterioration in the performance, and the protection characteristics will remain unchanged.

Life

The life of the complete quadrupole amplifier system is determined by two factors:

(1) the life of the quadrupole amplifier itself, and
(2) the life of the pump oscillator.

Apart from disastrous failures, such as heater burn-out due to a switching-on surge, the life would be expected to be determined solely by cathode emission. Insufficient life-test data is available at present to ascertain whether or not the noise figure deteriorates with life due to any other cause than failing emission.

The life of the quadrupole amplifier itself, due to emission alone, is likely to be very long. The cathode current density of a typical 200 Mc tube is less than 20 ma/cm^2, while that of a 600 Mc tube is only 50 ma/cm^2, so that even with oxide-coated cathodes (which are used in practice) the loading is very low. Low-noise travelling-wave tubes with comparable cathode current densities have achieved many thousands of hours of reliable service. Continued operation under large signal conditions should have no effect at all on the life of the tube. Since the electrode potentials employed are very low, the effect on the cathode of positive ion bombardment should be very small.

The pump oscillator is likely to have the shorter life, but by careful design in which attention is paid to operation under conditions conducive to long life, many thousands of hours of service should be achieved. This is possible since only a small amount of pump power is required.

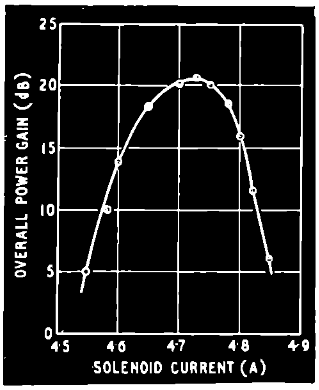

Fig. 10. Variation of gain with magnetic field (solenoid current) for a 600 Mc quadrupole amplifier. 4·72 A corresponds to 2·6 G.

Degenerate operation

This mode of operation, in which the signal frequency is exactly equal to one half of the pump frequency, has already been mentioned. The frequency condition can be met continuously in practice only when the pump frequency is obtained from the source of signal power by multiplication. This can be carried out only when the transmitter and receiver are on the same site, e.g. a radar system. The pump power may be obtained, for example, by doubling the CW source driving a pulsed transmitter amplifier. Such a system is shown in block form in Fig. 9.

The main problem that occurs in the operation of such a system is leakage of any fundamental component (i.e. signal frequency) through the doubler and into the receiver *via* coupling inside the valve between the pump circuit and the output coupler circuit. In order to prevent this, at least 110 db of attenuation is required between the input to the doubler and the output of the quadrupole amplifier. Very careful design and ample filtering is essential to obtain satisfactory performance.

Modulation

When the input signal to the device is modulated a number of precautions are necessary. First consider what happens to a CW signal passing through the quadrupole.

If the frequency of the input CW signal is exactly one half the pump frequency, a specific phase condition between the orbiting electrons leaving the input coupler and the rotating quadrupole field can be maintained, e.g. that of maximum gain when the electrons enter the quadrupole field into the maximum accleration phase. Under these conditions the beam leaving the quadrupole describes a circle about the axis of constant radius. An unmodulated input signal produces an amplified unmodulated output signal. If the signal frequency is changed slightly, the specific phase condition cannot be maintained and conditions of maximum gain and maximum loss occur alternately, the output beam motion now exhibiting beats, i.e. it appears to be amplitude-modulated at a frequency given by $2f_s-f_p$. This modulated signal can be resolved into two unmodulated signals, one at f_s, the signal frequency, and the other at (f_p-f_s), the idler frequency. This is the manner in which the idler is actually generated. Obviously the beat frequency can extend from a few cycles per second to many megacycles per second, depending on the particular pump and signal frequencies. Trouble arises when the beat frequency is so low that it may be accommodated within the pass-band of the receiver following the quadrupole amplifier. The demodulated output of the receiver now possesses an ac component as well as the normal dc component.

When the input signal is modulated, either FM, AM or pulse, it is important that the signal and idler be either coincident (degenerate operation) or separated sufficiently for the beating modulation not to affect or distort the original modulation on the signal. This means, in effect, that there is an unusable portion of the amplification bandwidth of the device, centred about the degenerate condition, which cannot be used without the risk of distortion of the modulation envelope. The width of this gap depends on the characteristics of the modulation involved.

Power supplies

The power supplies required for the operation of the quadrupole amplifier may be divided into three parts:

(1) power supplies for the tube itself;

(2) power supplies for the focusing electromagnet;

(3) pump power, including its own power supply.

Tube supply

The power requirements for the tube itself are very small, although the number of individual electrodes to be supplied may be large. Apart from the heater supply there are, in typical tubes, six gun electrodes, the input and output couplers, the quadrupole and the collector to be supplied with dc power. The voltages required by the various electrodes of a typical 600 Mc tube are as follows (with respect to cathode), the ranges in parentheses being the desirable range of adjustment for that particular electrode in the light of present evidence to enable the optimization of tube performance. The voltages are:

Anode 1	2 V	(0-10 V)
Anode 2	110 V	(0-250 V)
Anode 3	25 V	(0-50 V)
Anode 4	45 V	(0-50 V)
Anode 5	35 V	(0-50 V)
Anode 6	12 V	(0-50 V)
Couplers	6 V	(4-8 V)
Quadrupole	5 V	(4-8 V)
Collector	100 V	100 V

The couplers are usually designed to work at earth potential, being directly earthed by connection to the external rf leads so that the cathode is some 6 volts negative with respect to earth.

The current taken by any electrode with the exception of anode 1 is at most 50 microamps, anode 1 taking typically 2·5 ma in a 600 Mc tube so that the various electrode potentials may be provided by potentiometers across a common stabilized dc supply. Voltage stabilization of the supply to ± 1% normally gives satisfactory performance for all electrodes, except perhaps the quadrupole. Since the quadrupole potential has a considerable influence on the gain of the valve (Fig. 8) the voltage stability required depends on the gain stability desired.

In order to prevent rf coupling between the dc leads and the possibility of feedback and instability, it is desirable to decouple all supplies to the tube electrodes. This has been carried out in the packages shown in Fig. 3 by means of 1,000 pf decoupling capacitors and 100 ohm resistors or rf chokes in series with the electrode leads.

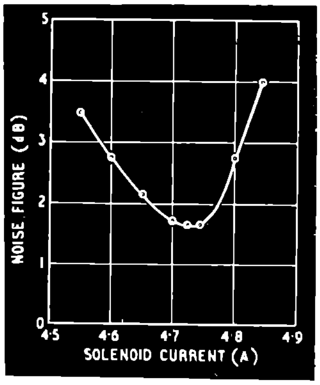

Fig. 11. Variation of noise figure with magnetic field (solenoid current) for a 600 Mc quadrupole amplifier.

Magnetic field supply

The uniform magnetic field required to focus the tube is determined by the frequency of operation (equation 1) and to maintain satisfactory performance under widely varying conditions the field supply to the electromagnet must be well smoothed and current-stabilized. Ripple on the magnetic field will cause amplitude modulation of the output signal. Typical curves of the variation of gain and noise figure with electromagnet current for a 600 Mc tube are shown in Figs. 10 and 11. They indicate that a stability of magnet current of about ± 1% is required to achieve reasonably constant performance. The achievement of stability of this order over a wide range of ambient temperature may present some difficulty and calls for a careful choice of reference element and reference resistor.

The focusing solenoids used in the packages shown in Fig. 3 are wound with aluminium foil. These require a high current at a relatively low voltage to energize them, a typical 600 Mc solenoid requiring 5 amps at 4·5 V. This is well suited to a transistorized current-stabilizing unit, in which case a Zener diode is a suitable reference element provided that its temperature coefficient of Zener voltage is carefully chosen. For the reference resistance a suitable material is constantan, which has a very low temperature coefficient of resistance in the normal ambient region of interest.

As in the case of other beam devices, a permanent magnet may have some advantages over the electromagnet. However, in the quadrupole amplifier there are three important differences over the normal case, namely:

(1) the field must be uniform to within a few per cent. over the length of the interaction region;

(2) there must be provision for a small adjustment in magnetic field about the "bogey" value;

(3) the field must be unidirectional, i.e. no reversals are permitted, hence there is a large leakage field which must be either screened or tolerated.

For normal ambient temperature ranges no temperature compensation of such a magnet should be required. The temperature coefficient of the typical Alcomax variety of magnets which would prove suitable is about —0·02% per deg C, so that to achieve a constancy of field of ±1% a range of ambient temperatures approaching 100° C is possible.

Pump sources

The possible sources of pump power depend largely on the frequency of operation of the tube. The following devices are suitable as pump suorces in the frequency ranges given:

(*a*) triode oscillator (400—4,000 Mc);
(*b*) reflex klystron ...... (800 Mc and above);
(*c*) transistor oscillator (400 Mc and above).

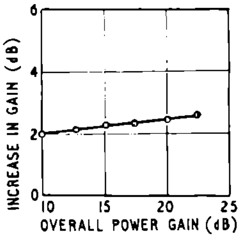

Fig. 12. Increase in gain for a 0·5 db increase in pump power at various levels of gain. 400 Mc quadrupole amplifier.

The pump power requirements for the quadrupole amplifiers shown in Fig. 3 are very low, ranging from under 10 mw at 400 Mc to about 60 mw at 1,200 Mc for a 20 db gain level. The choice between the triode and the reflex klystron is probably determined by the frequency of operation alone, since the triode oscillator is the simpler device and the power requirements are less. Therefore the triode oscillator would be preferable for pumping quadrupole amplifiers at 400 Mc to about 4,000 Mc and reflex klystrons for higher frequencies. Ample literature is available on the design of triode and reflex klystron oscillator circuits and suitable power supplies, and these will not be given here. Some form of attenuation or coupling adjustment will be required to set the correct pump level for the desired level of gain.

Rapid developments are being made in the design of uhf solid state devices, namely, transistors and tunnel diodes, providing CW sources at frequencies high enough for use as pump sources in parametric amplifiers. In the near future it should be possible to produce transistorized oscillators, together with multiplier

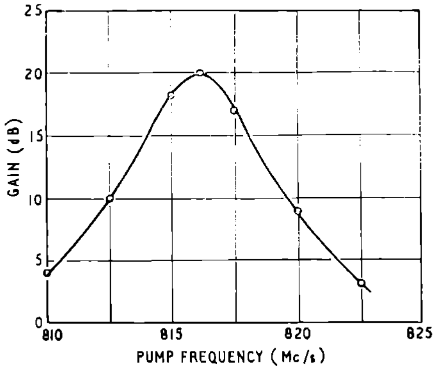

Fig. 13. Gain versus pump frequency for a 400 Mc quadrupole amplifier. The pump input power is maintained constant.

stages if necessary, to provide sufficient pump power for a wide range of quadrupole amplifier designs. Such units could be readily powered from the electromagnet supply with a considerable saving in both the size and cost of the overall unit.

One advantage of the quadrupole amplifier over the regenerative type of variable capacitance parametric amplifier is its relative insensitivity to variation in pump amplitude and frequency. A typical variation of gain with change in pump amplitude at various values of gain is shown in Fig. 12. The main effect of a change in pump frequency is a change in pump amplitude, resulting from the resonant nature of the quadrupole tuned circuit. A typical variation of gain with pump frequency for a 400 Mc tube is shown in Fig. 13.

Comparison with existing devices

Owing to a number of design factors mainly associated with the magnetic field requirements, the range of frequencies over which quadrupole amplifiers can be conveniently made is from about 200 to 4,000 Mc. Above 4,000 Mc the magnetic field requirements become excessive (equation 1) and below 200 Mc the device ceases to be competitive. Comparison, therefore, will be restricted to this frequency range.

Conventional low-noise amplifiers in this range are the triode and the travelling-wave tube. The variation of noise figure with frequency for the best triodes and travelling wave tubes is shown in Fig 14. From 200 Mc to 1,000 Mc the triode has found almost universal application in the past, owing to the unwieldy size of travelling-wave tubes below 1,000 Mc. Above 1,000 Mc low-noise travelling-wave tubes are currently available and, using new low-noise gun designs, noise figures as low as 3 db have been achieved from about 1,000 to 3,000 Mc. The variation of noise figure with frequency of typical quadrupole amplifiers is also shown in Fig. 14, both for degenerate operation and single-channel non-degenerate operation. From these considerations alone it would seem that the most competitive range of operation for the quadrupole amplifier is from about 200 to 1,000 Mc, and the majority of amplifiers so far produced have been in this region. Unless degenerate operation can be employed, and this is completely satisfactory only in the special case where the pump is derived from the signal source by frequency multiplication, the travelling-wave tube is at present superior to the quadrupole amplifier for single-channel operation above about 1,000 Mc. It has the added advantage of not requiring a pump source and its noise figure is less sensitive to input matching conditions.

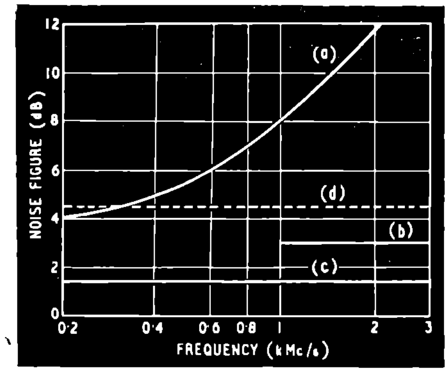

Fig. 14. Variation of noise figure with frequency for: (a), triode; (b), travelling-wave tube; (c), degenerate quadrupole amplifier; (d), non-degenerate quadrupole amplifier.

In other aspects, for example gain and bandwidth, the quadrupole amplifier has sufficient for most applications and, in addition, has a vastly superior performance to triodes under large signal conditions commonly encountered in pulsed-radar systems.

Conclusions

The performance of typical quadrupole amplifiers in the uhf region has been described and many of the problems involved in putting them into service discussed. It is hoped that this article has fulfilled its purpose of providing the user with a realistic appraisal of the merits of the quadrupole amplifier and that it will stimulate its application in many fields.

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