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TRANSISTOR RECEIVER VIDEO AMPLIFIERS

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Approved

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During the last two years the improvement in high-frequency transistors has been significant. Transistors suitable for video output stages have been made with large increases in collector breakdown voltage and power dissipation. While these units are now of an experimental nature, they represent only minor modifications of commercial transistors.

The design of the receiver video amplifier is a function of the television system and the transistor. In the receiver, the video amplifier must drive the kinescope, supply the horizontal and vertical sync separators, sound i-f and a-g-c circuits with suitable signals and provide an associated gain control for the signal to the kinescope. The transistor amplifier must fulfill these requirements while presenting the additional design problem of temperature compensation.

The work reported in this bulletin attempted to integrate the transistor into the television receiver. There are many possible designs with transistors because of the three-circuit configurations and the possibility of p-n-p or n-p-n type units. The general design problems are discussed and a practical amplifier is described.

Transistors for Video Amplifiers

Until recently, it was difficult to use transistors for driving a kinescope in a conventional television receiver. Special circuitry was needed to overcome the collector voltage and power limitations of transistors to obtain the 80 to 150 volts normally available from tubes.

High-frequency transistors are normally made by decreasing the base width and the area of the collector and emitter dots or contacts. Also, low resistivity material is used in the base pellet to reduce the base lead resistance. The low resistivity and narrow base widths cause the collector breakdown voltage to be lower as the frequency response is improved. Because of the small geometry involved, low power dissipation seemed a limitation to high-frequency transistors.

The drift transistor[1,2] and other transistors using diffusion techniques in their manufacture appear to have made a major breakthrough in the transistor art. It is now possible to improve the frequency response of a given transistor geometry by an order of magnitude by using diffusion techniques. This is achieved with an increase in collector voltage breakdown. The diffusion process allows a variation of impurity between the base and collector so that low resistivity is achieved at the base and high resistivity at the collector side of the junction. Since the breakdown is proportional to the resistivity of the material, collector breakdown voltages for drift transistors run two or three times those of normal high-frequency transistors such as the 2N139 type used in 455-kc i-f amplifiers.

Fig. 1 shows a comparison of a conventional 2N139 alloy junction high-frequency transistor with two drift transistors. The 2N247 drift transistor has geometry similar to that of the 2N139 except that diffusion techniques are used in its manufacture. The type A drift

TYPE	DESCRIPTION	$f_{max.}$ MC	$f_{\alpha CE}$ MC	$r_{bb'}$ OHMS	$C_{b'c}$ $\mu\mu f$	$V_{CE\ max.}$ VOLTS	COLLECTOR DISSIPATION AT 70°
2N139	ALLOY p-n-p	14	4.7	75	9.5	16	35 MW
2N247	DRIFT p-n-p	136	30	40	1.7	>40	35 MW
TYPE A	DRIFT p-n-p	136	30	40	1.7	>100	≈200 MW

Fig. 1 – Transistor characteristics.

transistor has electrically similar characteristics to the 2N247 with the exception of the increased breakdown voltage and higher collector dissipation. The dissipation rating is increased by lowering the thermal resistance of of the unit.

The drift transistors have reduced base resistance $r_{bb'}$ in the order of 40 ohms compared to 75 ohms for the 2N139. The f_{max}, maximum frequency of oscillation, and $f_{\alpha b}$, the frequency at which the common base current gain falls to 70 percent of its low-frequency value, are both increased by an order of magnitude. Since the depletion layer between the collector and base is much wider in the drift transistor, the depletion layer capacity $C_{b'c}$ is also greatly reduced.

The 2N247 transistor has frequency characteristics that are suitable for low-power video application. The type A units can dissipate over 200 milliwatts with a maximum peak-to-peak voltage of 100 volts with the same bandwidth as the 2N247.

Current and Power Gain

The performance as a video amplifier can be evaluated from the curves given in Fig. 2. The common emitter (beta) current gains and power gain for three typical type A units show a frequency response that is constant up to a given cut-off frequency. Above this frequency the curves roll off at a 6-db-per-octave rate. As a rough approximation the 3-db cut-off frequencies of both curves will be the same. The beta cut-off frequency $f_{\alpha e}$ is easily measured since its cutoff is in the video frequency range. The unilateralized power gain curve can be determined by two measurements (1) a low-frequency measurement at audio frequencies, and (2) a measurement in the order of ten times the 3-db cut-off frequency. In the curves given in Fig. 2 a 40-mc measurement was used to determine the high-frequency portion of the curve. The 6-db-per-octave slope has been checked by a series of power gain measurements including f_{max} data. The 2N247 transistors have beta cut-off frequencies in the order of 0.5 mc.

The power-gain curve is obtained by conjugately matching and unilateralizing the transistor. The power gain of the transistor as a video amplifier will be related to the curve of Fig. 2.

Assume a given bandwidth such as 3.5 mc. From the power-gain curve the maximum power gain would be 28 db for a single conjugately-matched stage. Generally, it is not possible to conjugately match the transistor over a wide frequency range and the maximum power gain is not realized. However, using a low-impedance generator in the order of 50 ohms and shunt series peaking with a 5 K load, gains of 22 db are possible with a 3.5-mc bandwidth.

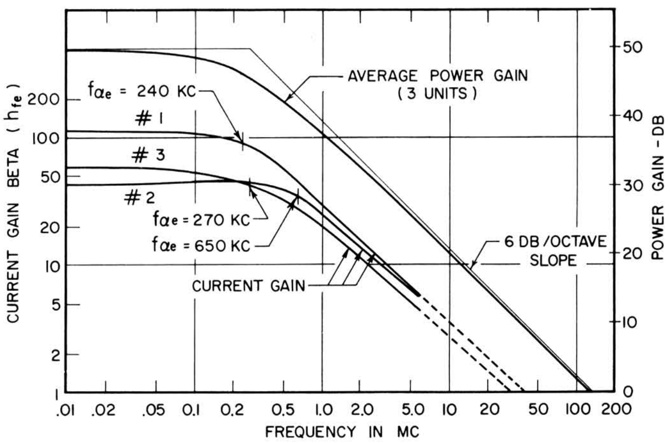


Fig. 2 – Common emitter current and power gain vs frequency.

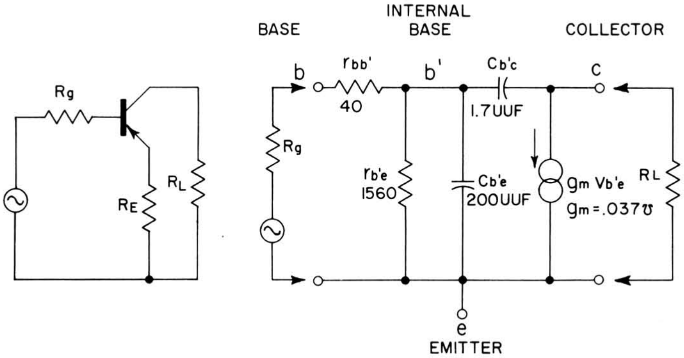
The maximum power gain of available transistors varies greatly over the video spectrum. In order to overcome this limitation, gain must be traded for bandwidth. Feedback offers a solution to this problem and most transistor video amplifiers use feedback.

The Common Emitter Amplifier

The common emitter is the most commonly used transistor configuration. As an amplifier it has the highest power gain of the three possible arrangements and gives both voltage and current gain. The amplifier and its hybrid pi equivalent circuit[3] are given in Fig. 3. This equivalent circuit uses a current generator similar to the pentode and for drift transistors using a low generator impedance, the low-frequency gain is approximately.

$$A_{LF} = g_m R_L. \tag{1}$$

It can be seen from the equivalent circuit that for small



VALUES FOR I_E = Ima

Fig. 3 – Common emitter amplifier and hybrid pi equivalent circuit.

values of load resistance the input circuit and the emitter capacitance are combined in $C_{b'e}$, and the equivalent shunt resistance R_{eq} across it determines the cut-off frequency.

$$R_{eq} = \frac{r_{b'e}\,(r_{bb'} + r_g)}{r_{b'e} + r_{bb'} + r_g} \qquad (2)$$

and the 3-db cut-off frequency neglecting $C_{b'c}$ the feedback capacity, is

$$f_{3db} = \frac{1}{2\pi\, R_{eq}\, C_{b'e}} \qquad (3)$$

These equations show the importance of using a low source impedance for wideband amplifiers. Two examples will be given to show this relationship using the equivalent circuit values and again neglecting $C_{b'c}$ the feedback capacitance.

(a) $$R_g = 10\text{ k}$$

then substituting in Eq. (2)

$$R_{eq} = \frac{1560\,(40 + 10{,}000)}{1560 + 40 + 10{,}000} = 1350\text{ ohms}$$

so that f_{3db} from (3) gives

$$f_{3db} = \frac{10^6}{2\pi\; 1350 \times 200} = 0.56\text{ mc} \approx f_{\alpha E}$$

(b) $$R_g = 40$$

$$R_{eg} = \frac{1560\,(40 + 40)}{1560 + 40 + 40} = 76.2\text{ ohms}$$

$$f_{3db} = \frac{10^6}{2\pi\; 76.2 \times 200} = 10.5\text{ mc}$$

The above relations are useful when small values of load resistance are used, making it possible to neglect $C_{b'c}$. For the more general case $C_{b'c}$ cannot be neglected and accounts for most of the bilateral nature of the transistor. This has been analysed by Bruun[4] and compared to the Miller effect in tubes. The feedback capacitance $C_{b'c}$ is multiplied by the gain of the amplifier and added to $C_{b'c}$. This gives an equivalent capacity

$$C_{eq} = C_{b'e} + g_m R_L C_{b'c}. \qquad (4)$$

The cut-off frequency of the input then would be

$$f_{3db} = \frac{1}{2\pi\, R_{eq}\, C_{eq}} \qquad (5)$$

In a practical amplifier this feedback capacitance may reduce the frequency response to one half the value without feedback, depending on the load.

In the video output stage where the transistor has a large resistive load shunted by a capacitance of 20 or 30 $\mu\mu$f the output circuit may limit the frequency response and cannot be neglected in determining the amplifier bandwidth. The feedback capacity becomes important since its effect is to reduce the output impedance at high frequencies. The load resistance R_L will then be shunted by a transistor impedance of the same order of magnitude. The cut-off frequency of the output circuit will then always be greater than the frequency at which the load resistance equals the shunt capacity.

Video Amplifier Configurations

A transistor may be operated common emitter, common base, or common collector.[5] These arrangements correspond roughly to the vacuum tube grounded cathode, grounded grid, and grounded plate or the cathode follower. Each configuration has advantages and disadvantages for a particular application. The common emitter amplifier is the most commonly used and is the only one suitable for a single-stage video amplifier in a receiver using a diode detector. This is because of the two configurations giving voltage gain, common emitter, and common base; the input impedance at low frequencies is at least ten times higher for the common emitter amplifier. At low frequencies the input impedance of the common base amplifier is approximately

$$R_{IN_B} \approx \frac{1}{g_m} \qquad (6)$$

For one milliampere this is roughly 27 ohms. This low input impedance limits the use of the amplifier considerably, but it may be used where no phase reversal is desired.

The common collector or emitter follower is used where high input and low output impedance is required.

Its input and output impedance are approximately

$$Z_{IN_c} \approx h_{fe} R_L \tag{7}$$

$$Z_{OUT_c} \approx \frac{1}{g_m} + \frac{R_g}{h_{fe} + 1} \tag{8}$$

where

h_{fe} is beta, the common emitter current gain (Fig. 2)
g_m is the transconductance in mhos,
R_L is the emitter load resistance, and
R_g is the generator resistance.

Since its voltage gain is always less than one, it must be used with another configuration to obtain voltage gain.

Fig. 4 gives the four practical two-transistor amplifiers that can be used in a receiver. These four were selected from the nine possible combinations for the following reasons:

(1) The input impedance should be 1000 ohms or larger to allow efficient diode detection.

(2) The amplifier must have a voltage gain of at least 15 and preferably more to drive a conventional kinescope.

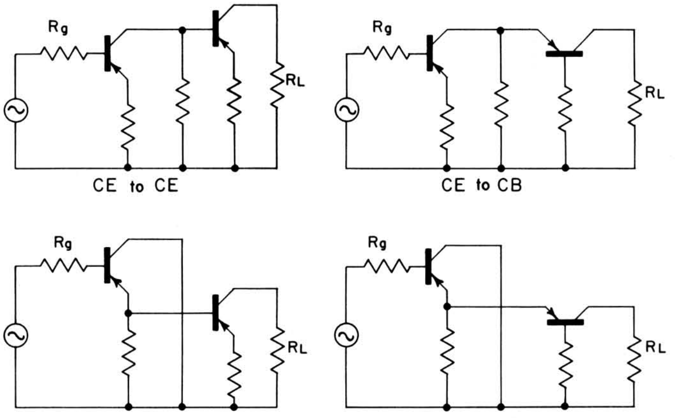


Fig. 4 – Two-transistor amplifiers.

In Fig. 4 all the transistors are shown as p-n-p types. Since no d-c conditions are shown either p-n-p or n-p-n units could be used. The p-n-p units are more readily available. The choice between the four arrangements shown will depend on a number of factors such as

(1) the gain bandwidth product for the given load and generator impedances,

(2) d-c considerations including n-p-n or p-n-p types supply voltages available, temperature stability, and a-c or d-c coupling, and

(3) the associated system requirements such as a-g-c, sync, and sound take-off points, noise limiting, contrast control, and output polarity.

The requirements of the amplifier in the receiver are complex and a compromise is generally necessary when trying to solve the overall problem.

In order to meet the high input impedance requirement the common collector circuit is best as a first stage since it has the highest impedance. However, if the common emitter circuit is used with an emitter resistance, the input impedance will be

$$Z'_{IN} = Z_{IN} (1 + g_m R_e) \tag{9}$$

where

Z is the input impedance without feedback,
Z is the input impedance with feedback,
g_m is the transconductance in mhos, and
R_e is the external emitter resistance.

The gain of the amplifier is sacrificed to obtain this increase in input impedance. The gain reduction factor F is

$$F = \frac{1}{1 + g_m R_e} \tag{10}$$

Either circuit can be used to meet the input requirement.

The output circuit must be operated with high voltage gain because little if any voltage gain can be realized in the first stage since either the common emitter or common collector will have large amounts of feedback. For high voltage gain, both of the possible output circuits, common emitter, and common base will present a low impedance to the first stage. In a practical amplifier the common emitter output stage usually gives more power gain than the common base circuit even though they will be identical for zero source impedance. The grounded base stage may still be preferred with its lower power gain in order to meet some of the previous conditions mentioned, such as amplification without a phase reversal.

Bias Considerations

Transistors require forward bias on the emitter junction and reverse bias on the collector junction. The emitter-to-base voltage will always be in the order of a few tenths of a volt while the collector voltage may be anything from a few volts to a hundred volts depending on the supply voltage, load resistance, and collector current. Many methods of biasing the transistor are possible, and Fig. 5 shows a method that has been found suitable for receiver applications. The four resistances are considered in the d-c circuit only, and the transistor may be operated in any of the three configurations by suitable location of the a-c ground points.

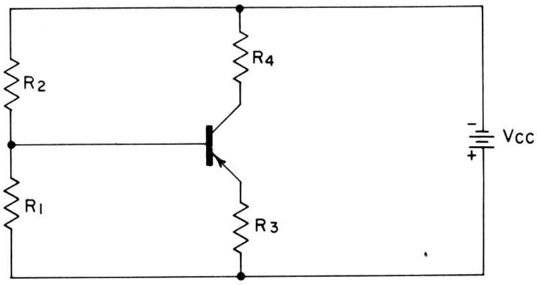


Fig. 5 – Transistor biasing circuit.

A suitable bias circuit designed to operate over a wide temperature range must include compensation for two temperature effects exhibited by the transistor.[6] The first is the increase of the collector-to-base saturation current, I_{cbo}, that increases approximately 10 percent per degree centigrade. The second is the increase in emitter base conductance with temperature at a rate of approximately 10 percent per degree centigrade. These two effects make it necessary to define a stability factor for a transistor circuit which is the incremental increase of collector current for an incremental change in I_{cbo}. The stability factor must be low enough to maintain the operating point within a specified voltage and current range for a given temperature increase.

The bias circuit can reduce these two temperature effects most easily for a class A amplifier by means of d-c feedback. In Fig. 5 the emitter resistance improves the temperature stability by negative current feedback. Since the base voltage is fixed by the voltage divider R_1 and R_2, increases in current due to increased temperature add to the drop across R_3. This reduces the forward bias on the emitter base junction. Thus the current variations with temperature are reduced.

Another commonly-used bias method uses collector-to-base feedback. If the top of R_2 is moved to the collector, this type of feedback[7] results. The needed temperature stabilization is thus provided. The arrangement is generally unsuitable for the common collector amplifier since no collector resistance is used. With common emitter amplifiers, the collector-to-base feedback will reduce the maximum output voltage swing available since the d-c load line of the feedback resistor will be in shunt with the load resistor. The feedback resistor can be bypassed to eliminate a-c feedback, but the direct current will prevent the output voltage swing from reaching the full supply voltage. The collector-to-base feedback resistance should not be used when the absolute maximum output voltage is desired.

Collector Load and Dissipation

The video output stage of the receiver should supply the kinescope with a peak-to-peak signal in the order of 100 volts. This allows for kinescope variations and allows the screen of the kinescope to be operated at a sufficiently high voltage to give a bright picture under most normal conditions. Tube amplifiers have ratings of several watts or more to meet this requirement. Transistors are much more efficient than tubes in that they can be operated satisfactorily with only a few volts on their collectors. This allows a transistor video amplifier to deliver an output voltage that is only a few volts less than its collector-to-emitter voltage. The collector curves showing voltage and current relations for a type A drift transistor are shown in Fig. 6. Five constant dissipation hyperbolas are drawn on the collector curves for ratings of 100 to 500 milliwatts. If it is assumed that 100 volts of output are required, load lines can be drawn from the 100 volt supply with slopes of typical load resistances. It can be seen then that with a 10 K load, the transistor must be rated at a minimum of 250 milliwatts to meet the dissipation requirement. If loads of 7.5 K or 5 K are used, the minimum dissipation will be 375 and 500 milliwatts respectively. These data assume satisfactory stability factors for the amplifier. As the load resistance is reduced, the frequency response will be improved if the amplifier is limited by the output circuit.

The maximum and minimum voltage range can be seen from Fig. 6. The maximum collector voltage is the break-

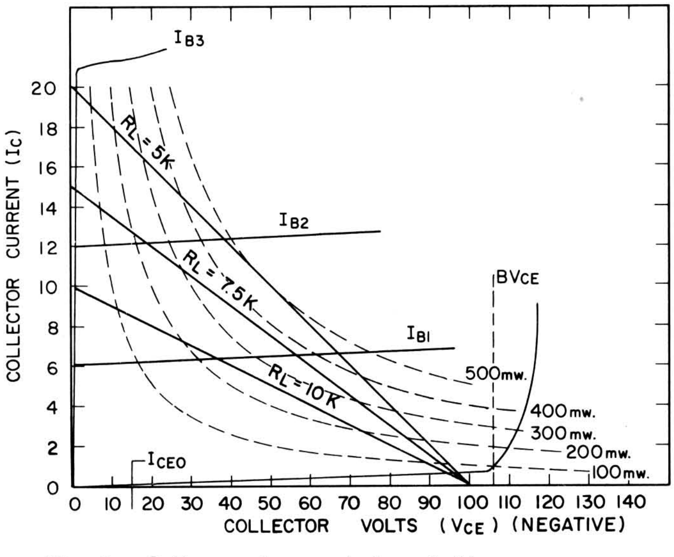


Fig. 6 – Collector characteristics of video output stage.

down voltage BV_{CE} which is shown at 106 volts. This is the voltage at which the collector current of the transistor begins to increase rapidly and is usually specified at a fixed value of current such as 50 μamps.

The low voltage limit can also be seen from the nearness of the knee of the curves to the current axis. The output voltage swing can come within a volt or so of the d-c emitter voltage.

Temperature Limitations

Another design consideration of the transistor as an output video amplifier is its power limitation with temperature. Normally a maximum safe junction temperature is established by the manufacturer based on life test data. This temperature is usually given at 85 degrees C though there are indications that a higher value maybe practical. The 85 degrees C value is used in Fig. 7, and the relation between collector dissipation and the ambient operating temperature is shown. Less dissipation is allowed as the ambient temperature is increased. The five curves correspond to different values of thermal resistance. A thermal resistance of 50 degrees C per watt means that the junction temperature would rise 50 degrees above the ambient operating case temperature for 1 watt dissipation. Thus for a given maximum junction temperature the curves will appear as in Fig. 7.

The case temperature of a transistor may be reduced with a heat sink. The high dissipation region shown in Fig. 7 for high-frequency transistors can be realized only with a heat sink such as a metal clip on a chassis. The 2N139 and 2N247 transistors have thermal resistances in free air of 500 degrees C per watt while the type A units will be 80 degrees C per watt or less. Special heat conducting materials and heat sinks make increased dissipation possible. Fig. 7 shows that if a transistor must dissipate 250 milliwatts and operate at a case temperature as high as 55 degrees C, a thermal resistance of 125 degrees C per watt or less would be required. At a room temperature of 20 degrees C, 520 milliwatts could be dissipated with this transistor. This assumes a maximum safe junction temperature of 85 degrees C. If this value were increased to 100 degrees C, then a thermal resistance of 200 degree C per watt would meet the original specification of 250 milliwatts at 55 degrees C.

Two-Stage Receiver Video Amplifier

The two-stage amplifier of Fig. 8 shows a practical amplifier circuit that provides the basic requirements for a television receiver. The circuit uses a common collector to common emitter combination with two supply voltages, + 12 and + 300 volts. The common collector input circuit allows a large detector load resistor to be used assuring maximum efficiency and highest detector output voltage. The low output impedance makes large voltage gains possible in the second stage with an overall bandwidth of 3.5 mc. AGC voltage is supplied from the emitter of the first stage. The detector is direct coupled so that no coupling capacitor is required, and the d-c component is carried through to the a-g-c circuit. The bias for the first stage is supplied from the 1000-ohm and 220-ohm voltage divider. Sound is taken from the collector circuit.

The inductance load in the collector of the first stage has the advantage of raising the input impedance due to the feedback provided by the collector depletion capacitance $C_{b'c}$. The second stage is a-c coupled since it

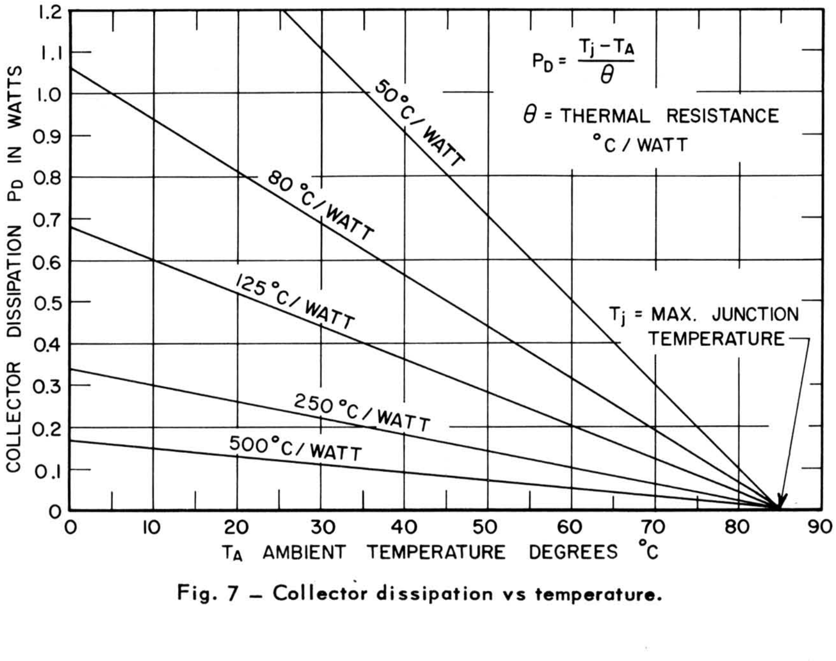


Fig. 7 – Collector dissipation vs temperature.

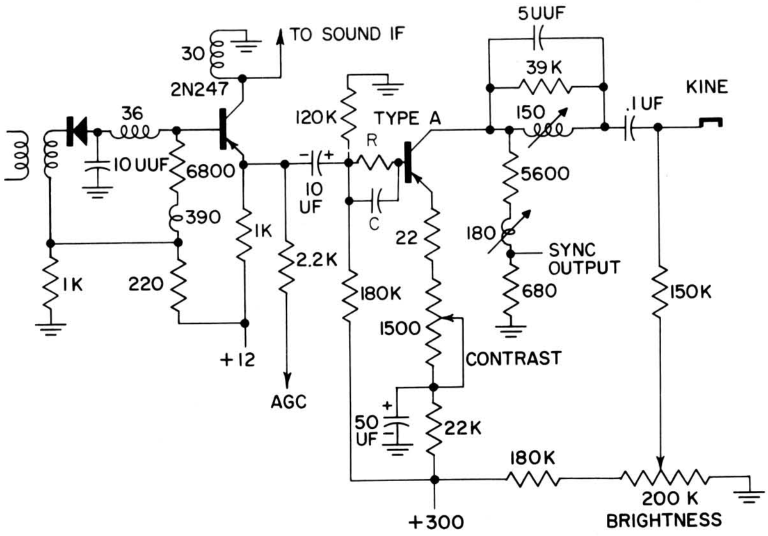


Fig. 8 – Two transistor amplifier.

must operate at a 100-volt emitter voltage and would require a high breakdown voltage for the first transistor if it were d-c coupled. The power for the output stage is taken from the 300-volt kinescope screen supply. This large voltage allows an emitter resistance of 22 K to be used, giving an essentially constant current supply to the transistor and making the circuit relatively independent of temperature variations. The stability factor for the stage is three. Conventional shunt series peaking is used and an RC peaker is added between the stages to improve the frequency response. Sync is removed across a 680-ohm resistor in series with the load. The cathode of the kinescope is driven since 15 to 20 percent less drive is required. When the cathode is driven, the signal is in the direction to cancel the screen voltage and thus increase the effective output since the drive required is proportional to the screen voltage.

The frequency response of the amplifier is shown in the curves given in Fig. 9. The voltage gain for a 3.5 mc bandwidth is 40. The curves show the effect of the emitter gain control and show that the bandwidth is slightly increased for full gain indicating some positive feedback in the output stage due to the indictive loading and internal capacity feedback. The square wave response gives a large signal rise time of 0.18 μsec and a fall time of 0.21 μsec. These results are comparable with conventional tube amplifiers.

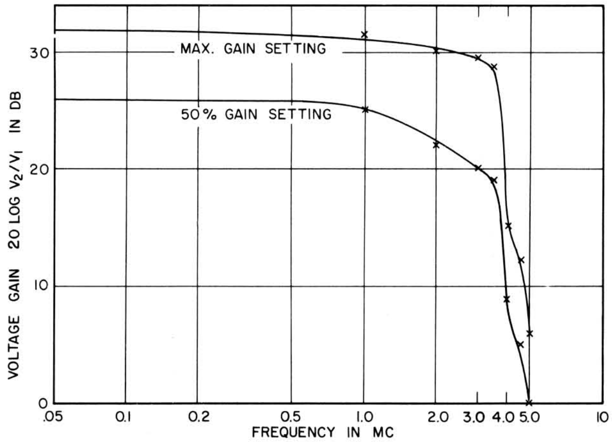


Fig. 9 – Frequency response of two stage amplifier.

Conclusions

Experimental transistors can now meet the video amplifier receiver requirements. The drift transistor with improved thermal properties is capable of driving the conventional kinescope. Practical amplifiers have been made and found to give results comparable with tube performance. The circuit designer is confronted with the special problems of the transistor such as its bilateral nature and temperature sensitivity but can achieve improved efficiency in his circuits along with reduced heat, size, and weight.

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