Synthesizing Vacuum Tubes

Put that old tube-type receiver back to work by replacing the burnt-out tubes with JFET circuits.

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Some wag once said that a vacuum tube was just an N-channel depletion-mode FET with a light in it to tell you when it was good. There is enough truth in the comparison to warrant exploring the use of FETs in hard-to-fill receiver tube sockets. Of course, a one-to-one replacement isn't possible, but with a little headscratching, an FET-based substitute may be built for either a pentode or triode vacuum tube. The substitute costs less and has a longer life expectancy than a tube, and there's no penalty in performance.

Comparing Tubes and JFETs

A pentode vacuum tube has five elements: cathode, control grid (G1), screen grid (G2), suppressor grid (G3) and plate. The plate current is essentially independent of plate voltage; the dynamic plate resistance is very high. This high plate resistance does not load a resonant output tank, so simple tuned output circuits can be used. And the low capacitance between G1 and the plate results in little coupling from output to input, so no special circuitry is needed for stable amplification at RF.

A triode has only three elements: a cathode, a control grid and a plate. The plate current is a function of plate voltage and grid voltage; the dynamic resistance is relatively low. The coupling between output and input through the plate-to-grid capacitance is relatively tight, which usually restricts triodes to use in untuned applications. They can be used at RF with special circuits or under special conditions, but are more often found in audio or other low-frequency applications.

A receiving tube typically requires plate voltages of 100 V or so, positive with respect to the cathode. The grid is operated negative with respect to the cathode, and plate current increases as the grid-to-cathode voltage becomes less negative. Grid current is typically a few microamps when the grid is negative but can be several milliamps when the grid is driven positive with respect to the cathode. Plate currents in receiving tubes are a few milliamps, and output power is normally not a significant consideration.

The major parameters of tubes that we'll be concerned with are μ, r_p and g_m, which are related by:

$$\mu = g_m r_p \qquad \text{Eq 1}$$

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where g_m (transconductance) is the change in plate current for a change in grid voltage, with plate voltage held constant; r_p (plate resistance) is the change in plate current for a change in plate voltage, with grid voltage held constant; and μ is the change in plate voltage needed to hold plate current constant for a change in grid voltage—in a word, gain. Pentodes usually specify g_m and r_p, while triodes specify μ and r_p. g_m is typically in the range of 1000 to 10,000 μmhos. [The more modern term for the mho is the *siemens*. Receiving tube databooks, however, are likely to give g_m in μmhos rather than in μS.—*Ed.*] r_p is in the range of 1 MΩ for pentodes and less than 100 kΩ for triodes.

The N-channel depletion mode JFET has features in common with vacuum tubes. The drain (equivalent to the plate) operates with a voltage that's positive with respect to the source (equivalent to the cathode). Drain current is essentially independent of drain voltage; the dynamic drain resistance is very high. The gate (equivalent to the control grid, G1) operates at a voltage that's negative with respect to the source. Gate current is a nanoamp or so (essentially zero) when the gate is negative with respect to the source, and maximum drain current occurs with 0 V gate-to-source. The gate current can be several milliamps when the gate is positive with respect to the source. Of course, the JFET operates with much lower voltages than tubes, from a few volts to 25 or 50 V maximum.

The JFET has only a single gate, and the gate-to-drain capacitance is relatively large, like the triode grid-to-plate capacitance, which limits its RF applications to special circuits or operation under special conditions. There are dual-gate MOSFETS (eg, 3N200, 3N201, 3N140, 3N187) that have low output-to-input coupling and are used in TV front ends without special circuits. While their RF characteristics may match a pentode, their transconductances may not. A JFET can have a transconductance much greater than any tube, and its operating point can be adjusted to produce various values of g_m.

Two discrete JFETs or tube triodes connected in cascode, as shown in Fig 1, have excellent RF properties. In the JFET cascode, Q1 is a common-source amplifier that drives the source of the common-gate amplifier Q2. The voltage gain of Q1 is $g_{fs(1)}R_s$, where $g_{fs(1)}$ is the common-source transconductance of Q1, and R_s is the source impedance of Q2, which is approximately $1/g_{fs(2)}$. When the g_{fs} values of both transistors are equal, the voltage gain of Q1 is g_{fs}/g_{fs}, and Q1 is unconditionally stable. Since the current in Q2 is the same as the current in Q1, the gain of Q2 is $g_{fs}R_L$, where R_L is the impedance in the drain of Q2 (the load). The cascode amplifier is stable, even though the gain of Q2 (and thus the overall gain) may be high, because the grounded gate of Q2 effectively shunts its C_{gd} to ground. The capacitance between output and input is generally in the range of femtofarads.

Mimicking the Tube's Parameters with JFETs

As you can see the basic nature of a pentode or triode vacuum tube can be matched using JFETs. The next step is to make our JFET circuit exhibit the same parameters—from Eq 1—as the vacuum tube we're trying to replace. What we'll do is trim the transconductance of a JFET to the particular value needed by adjusting the JFET's operating point.

To simulate the 6SK7 (Fig 2) requires a device with a transconductance of about 2000 μmhos and a dynamic output resistance greater than 800 kΩ.[1] The g_{fs} of a JFET can be expressed as:

$$g_{fs} = \frac{2I_D}{\left(V_{off} - V_{gs}\right)} \qquad \text{Eq 2}$$

where I_D is the drain current, V_{gs} is the gate-to-source voltage that causes I_D, and V_{off} is the value of V_{gs} that reduces I_D to zero.

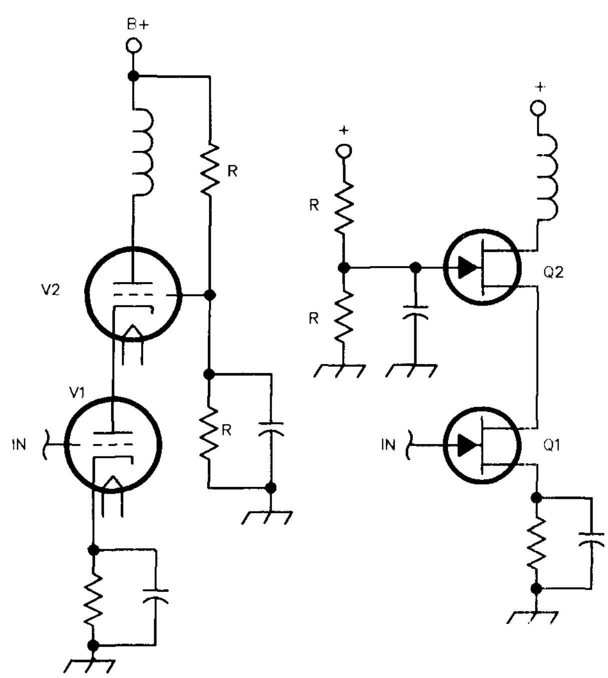

Fig 1—The cascode uses triodes as an RF amplifier.

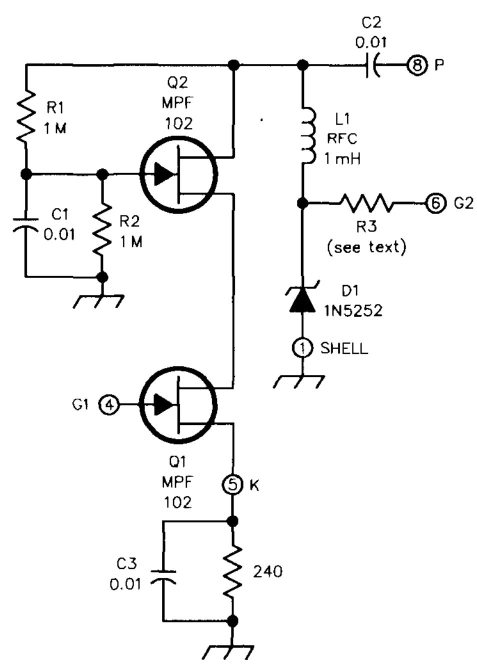

Fig 2—A JFET cascode synthesizes a 6SK7 pentode.

The fundamental electrical parameters of a JFET, I_D, V_{off} and V_{gs} are related as follows:

$$I_D = I_{DSS}\left(1-\frac{V_{off}}{V_{gs}}\right)^2 \quad \text{Eq 3}$$

where I_{DSS} is the drain current when V_{gs} is 0. Eq 1 can be rewritten to solve for V_{off} or V_{gs}:

$$V_{gs}/V_{off} = 1-\sqrt{I_D/I_{DSS}} \quad \text{Eq 4}$$

$$V_{off} = V_{gs}/\left(1-\sqrt{I_D/I_{DSS}}\right) \quad \text{Eq 5}$$

$$V_{gs} = V_{off}\left(1-\sqrt{I_D/I_{DSS}}\right) \quad \text{Eq 6}$$

The values of V_{off}, V_{gs} and I_{DSS} given in the data sheets are often only maximum and minimum values and are quite broad. For circuit design, either typical values are assumed or actual values are measured.

The actual values can be measured with simple test equipment: a power supply (something between 9 and 24 V), a multimeter and a resistor in the range of 20 kΩ. Connect the N-channel transistor's drain to the positive side of the power supply, the gate to the negative side of the power supply, and the source to the negative side through the resistor. Measure the voltage *E* across the resistor *R* and calculate or measure I_D. *E* is V_{gs}. Short the resistor and measure I_{DSS}. Measured values for a particular MPF102 were found to be: I_{DSS} = 4 mA, V_{gs} = 2.62 V for I_D = 0.131 mA. Plugging these values into Eq 5 and solving for V_{off} yields V_{off} = 3.2 V.

The value of g_{fs} corresponding to I_D and I_{DSS} can be found by substituting Eq 6 into Eq 3:

$$g_{fs} = \frac{2\sqrt{I_D I_{DSS}}}{V_{off}}$$

Rewriting to solve for I_D yields:

$$I_D = \frac{\left(g_{fs}V_{off}\right)^2}{4I_{DSS}} \quad \text{Eq 7}$$

Eq 7 shows that g_{fs}, the parameter we're trying to synthesize, is related to I_D. Eq 6 shows that I_D is related to V_{gs}. Thus if we establish the proper value of V_{gs}, we should get the value of g_{fs} we want. For the typical 6SK7 g_m of 2000 µmhos, Eq 7 shows that the I_D that produces a V_{gs} of 2000 µmhos in the MPF102 measured earlier is 2.56 mA. Using Eq 6, the V_{gs} corresponding to that I_D of 2.56 mA is calculated to be 0.64 V. For this particular JFET, a 0.64-V V_{gs} should produce the desired g_{fs} of 2000 µmhos.

A 242-Ω source resistor will produce this V_{gs}. A standard 240-Ω part is used. The typical cathode bias for a 6SK7 used in an IF amplifier is 3 V, which is provided by 270 Ω bypassed with a 0.1-µF capacitor. 270 Ω is pretty close to 242 Ω and may be used with only a moderate change in performance, within the limits of the tube. It is serendipitous that the same value of bias resistor can be used for either the FET or the tube. A different FET would probably require a different resistor.

The gain of the synthesized tube is probably the most important characteristic to be developed, but the input and output capacitances can be important, too. The input capacitance of a common-source amplifier is greater than the gate-to-source capacity by virtue of the *Miller effect*:

$$C_{in} = C_{iss} + C_{rss}|A_v|$$

where C_{iss} is the capacitance from gate

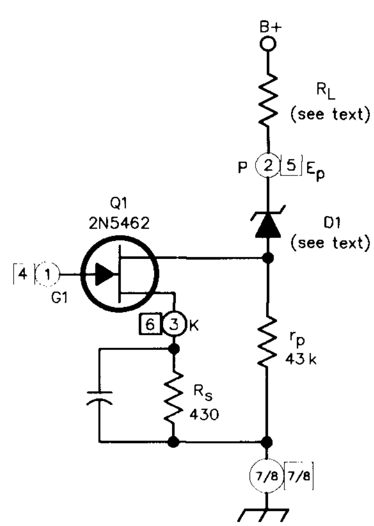

Fig 3—A JFET synthesizes one half of a 6SL7.

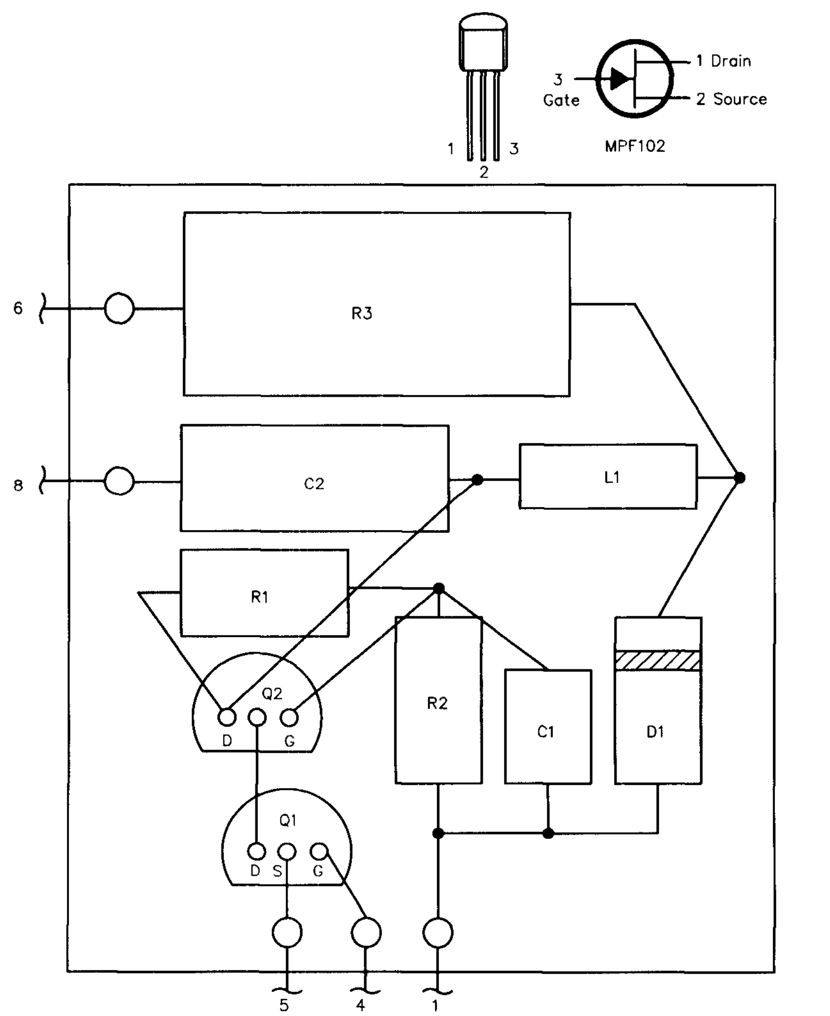

Fig 4—A perf-board layout for a synthesized 6SK7.

to source, C_{rss} is the capacitance from gate to drain, and A_v is the voltage gain of the amplifier. In a cascode amplifier, the voltage gain of the common-source part is essentially −1 (the input is inverted), so the input capacitance is simply $C_{iss} + C_{rss}$. For an MPF102, that's about 10 pF. The capacitances of a 6SK7 are: C_{in} = 6 pF, C_{out} = 7 pF, C_{gp} = 3 fF. The differences can undoubtedly be accommodated by the coupling transformer tuning. Low output-to-input capacitance C_{gp} is critical for stable RF/IF gain. Both the pentode and the FET cascode have feedback capacitance in the femtofarad range. But from a practical point of view, a stable amplifier is as dependent on the physical layout, interstage shielding and dimensions of the chassis as on the plate-to-grid capacitance.

Practical Replacement Circuits

Fig 2 shows a cascode JFET replacement for the 6SK7 pentode. The only sticky part of using JFETs to synthesize vacuum tubes is obtaining the needed low operating voltages with minimum modification of the receiver. The dc plate voltage of the 6SK7 is typically 150 V, while the maximum drain-to-source voltage of the MPF102 is specified as +25 V. The gate voltage of Q2 sets the source voltage of Q2, which is the drain voltage of Q1. The resistors R1 and R2 in the gate divide the voltage to about half the drain voltage, so a supply of 50 V would result in about 25 V across each of Q1 and Q2. Using a nominal 43-V supply allows for tolerances in R1 and R2 as well as for up to 10% variation in the supply voltage. The lower drain-supply voltage needed for the FETs can be obtained in several ways. An obvious solution is to build a suitable low-voltage supply, but that would be a major receiver modification that would be hard to justify unless all of the tubes were replaced.

Conceivably, the plate voltage could be dropped using a bypassed resistor. The specifics of dropping the voltage would depend on the drain current and the B+ supply voltage used in the receiver. The dropping resistor can be calculated, and the drain voltage is $V_{drain} = B^{+} - RI_D$. Since I_D is constant, the voltage across R is constant, and B+ changes appear at the drain. Most tube-type receivers have an unregulated plate supply, and line voltage changes of ±10% cause a 150-V supply voltage to change ±15 V. The power supply voltage fluctuations can thus drastically change the FET's supply voltage. A simple dropping resistor in the high-voltage plate supply may be a risky solution.

A more conservative solution for RF/IF amplifiers is to regulate the screen supply down with a Zener diode and shunt feed the JFETs through an RF choke, as shown in Fig 2. (The screen supply is not otherwise needed.) The supply voltage for the cascode can be anything between 9 and 47 V. The Zener used in this example is arbitrarily chosen to be 24 V. The power dissipated in the dropping resistor, R3, is $(B^{+} - V_Z)(I_D + I_Z)$ and may be in the ½-W range. It is good practice to derate resistor power dissipation by 50%, so a 1-W part would be appropriate for R3. A 1-mH choke, similar to a J. W. Miller part number 9230-92, is adequate for L1. The coupling capacitor, C2, must have a voltage rating greater than the B+ supply; use something similar to a Sprague 5HKSS10. The gate-bypass capacitor, C1, must have a dc working voltage greater than half the drain voltage; a monolithic ceramic like Sprague's 1C10X7R103K100B rated at 100 VDCW is a convenient size.

The bias will probably need to be changed from the pentode tube's value. Changing the bias means changing the value of the cathode resistor, but keeping the cathode bypass capacitor.

Almost any pentode can be synthesized with the equations given and can be substituted for hard to find tubes. The layout of the circuit board is not especially critical. A perf board mounted on an octal header will not take up any more room than the tube and can be pin-for-pin compatible with the tube. A layout of the perf board is shown in Fig 4. The terminal numbers shown are those corresponding to a 6SK7. The shell of the tube connects to pin 1, which should go to ground. The positive supply for the FETs comes through the G2 pin, pin 6. The G2 supply, V^{+}, is typically 100 V and may come from the plate supply through a dropping resistor or from a separate supply. The value of R3 needed to drop the screen voltage to the Zener voltage can be calculated with the following equation:

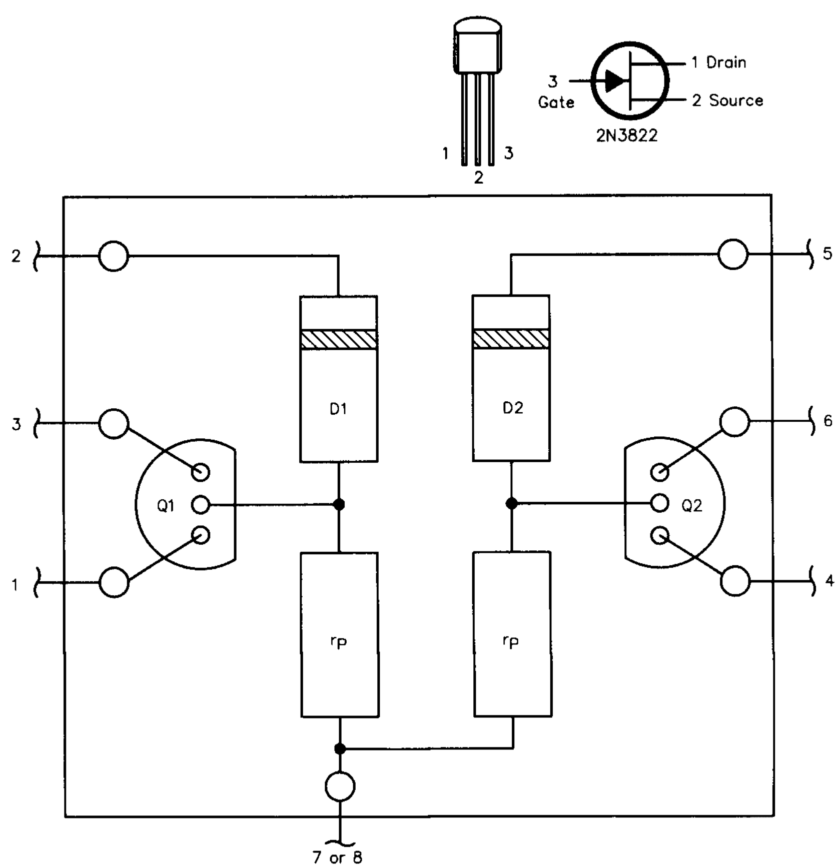

Fig 5—A board layout for a synthesized 6SL7.

$$R3 = \frac{V^{+} - V_Z}{I} \quad \text{Eq 8}$$

where V^{+} is the supply voltage, V_Z is the Zener voltage and I is the current drawn from V^{+}.

The existing screen voltage must be measured and the current limiting resistance calculated using Eq 8. The current in R3 is the sum of the drain current and the Zener current. (The Zener current need not be greater than 1 or 2 mA.)

Pin 5, the cathode pin of the 6SK7, probably goes to ground through about 270 Ω. In the example cited, the cathode resistor should be 240 Ω, but for other FETs a different value of resistance may be needed.

Synthesizing a dual-triode, such as the 6SL7, in a resistance-coupled amplifier presents a different problem: enough pins to bring in ground and the high capacitance of coupling and bypassing capacitors. The six pins needed for the two sets of triode elements and two pins for the heater occupy all eight pins of the socket. The synthesized 6SL7 doesn't require a heater voltage, so one of those pins can be used to bring in ground. The technique of applying power to the FET with shunt feed as used with the pentode is not an attractive option because high-voltage coupling capacitors for low-frequency circuits are physically large. The only other choice is direct coupling and accepting the power supply changes. In Fig 3, the supply voltage is shown being series-fed through the plate load resistor R_L, with a heater pin being used for ground.

The 6SL7 data sheet shows $\mu = 70$, $r_p = 44$ kΩ, and $G_m = 1600$ µmhos. A MPF3822 JFET is chosen to simulate the triode to take advantage of its higher (than the MPF102) drain-source voltage rating and to demonstrate handling a different JFET.

The MPF3822 has only its maximum and minimum characteristics specified, so the following values were measured: $I_{DSS} = 6$ mA, $I_D = 2$ mA for $V_{gs} = 3.5$ V. The value of V_{off} is found to be 4.3 V with Eq 5. Eq 1 shows that I_D is 2 mA when G_{fs} is 1600 µmhos. The V_{gs} needed for $I_D = 2$ mA is shown by Eq 6 to be 1.8 V. The source resistance, R2, needed to produce the 1.8 V bias is 910 Ω. The equivalent r_p is obtained by shunting the FET drain with 43 kΩ (the nearest standard 5% part). The voltage, E_p, can be shown to be:

$$E_p = \left(B^{+} - R_L I_D\right) r_p \big/ \left(r_p + R_L\right) \quad \text{Eq 9}$$

B^{+} and R1 are peculiar to a particular receiver's circuit and must be measured. As an example, assume the supply is +150 V ±10% (135 V to 165 V), R_L is 20 kΩ and I_D is 2 mA. For these conditions, E_p varies from 65 V to 85 V. A 47-V Zener will drop E_p to 18 V to 38 V for the drain. If R_L were 47 kΩ, E_p would vary from 19 V to 34 V and no Zener would be necessary. Power dissipation in the 43-kΩ resistor is less than 1/4 W.

Conclusion

I've shown that a pair of JFETs in a cascode circuit can synthesize a pentode, and a single JFET can synthesize a triode. These rather simple circuits can solve the problem of finding tubes to keep the receiver operating, and the modifications to the receiver are nominal. The equations given above allow the scrounger of flea markets, yard sales and hamfests to resurrect a receiver that can be had for just a few dollars and some research to find out what tubes are missing. The older *Radio Amateur Handbooks* have summaries of receiving tube base diagrams and typical operating characteristics. Tube-type receivers don't have the pizzazz of the latest and greatest solid-state receivers, but they don't have the big price tag, either. Ham radio doesn't have to be out of reach of the ham who has to watch his pennies. □□