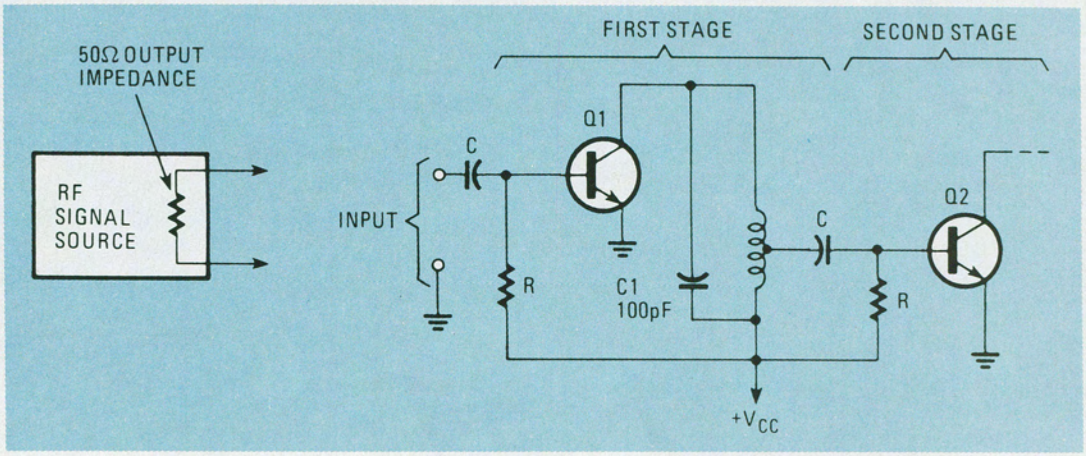

How to Design High Frequency Analog Circuits

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Many factors that up to now could be ignored when designing a circuit become critical at high frequencies. This month, we'll look at those factors and the role they play in designing a successful circuit.

UP TO NOW, WE'VE BEEN DISCUSSING CIRcuits that operate at fairly low frequencies. As operating frequencies become higher, however, factors that were previously unimportant become critical. That's because the effects of stray capacitance, both of the components and the circuit itself, become more pronounced as the frequency increases. Thus, any successful design must take into consideration the selection of the components as well as their placement in the circuit.

Before we begin, let's review a couple of points. It was previously stated that a resonant circuit in an oscillator consists of a capacitor and an inductor. The capacitor in that circuit has a reactance, X_C, equal to $1/2\pi fC = 1/6.28fC$, where f is the frequency of the signal applied to the component and C is its capacitance in farads. Obviously then, as frequency increases the reactance of the capacitor is reduced. In the case of an inductor, however, its reactance, X_L, is equal to $6.28fL$, where L is the inductance in henrys; thus, the reactance increases with increasing frequency.

Figure of merit

Inductors and capacitors store energy. That energy is applied to those components when a voltage is placed across their terminals and a current is fed through them. If the capacitor or inductor were ideal, all of the energy stored in them would be returned to the circuit eventually regardless of the operating frequencies. Of course, the components we are dealing with are real, not ideal. They all have some element of resistance associated with them that causes losses. Consider, for instance, a capacitor. Under DC conditions that component is considered an open circuit with infinite resistance. That being the case, no current should get through. We all know, however, that some small leakage current almost always exists. The effect is the same as if a large valued resistor were in parallel with the capacitor as shown in Fig. 1. That figure illustrates the model used when analyzing the behavior of a real capacitor.

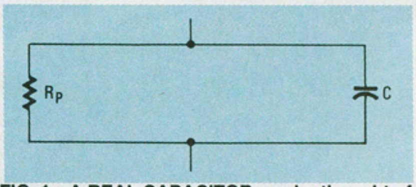

FIG. 1—A REAL CAPACITOR can be thought of as an ideal capacitor in parallel with a very large resistance.

Inductors, on the other hand, are treated as short circuits under DC conditions. Since they theoretically present no resistance, there should be no voltage drop across them. Of course, that is not what happens. There is a voltage drop that is caused by the resistance of the wire that makes up the inductor. Although that resistance is distributed along the length of the wire, the effect is the same as if that resistance were in series with an ideal inductor. That is the model used in analyzing the behavior of a real inductor and is shown in Fig. 2.

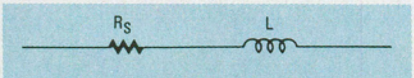

FIG. 2—A REAL INDUCTOR can be represented as an ideal inductor in series with a resistor.

When discussing such components, it is useful to know how close to ideal they are. To do that, a value Q, called the figure of merit, can be determined for each component. That value relates the amount of energy returned to the circuit to the amount of energy lost in the component due to its inherent resistance. A high value of Q indicates a more ideal component, and hence less loss than one with a low Q rating.

The Q of an indicator or capacitor is related to the reactance and series resistance of the component through the equation $Q = X/R_S$; and is related to the reactance and parallel resistance by $Q = R_P/S$. Thus (using the equivalent circuits shown), for an indicator, $Q = 6.28fL/R_S$, while for a capacitor it equals $6.28fCR_P$.

While we represented a real inductor as an inductance in series with a resistance, and a real capacitor as a capacitance in parallel with a resistance, those are not necessarily the only ways those components can be shown. For instance, there is no reason why an inductor could not be shown as an inductance in parallel with a resistance. After all, it is the same component so the impedance and the Q will be the same. When the way that the component is shown changes, the only thing that changes is the way in which Q is calculated. Instead of $6.28fL/R_S$, it is now found from $R_P/6.28fL$. But since the value of Q is identical, $6.28fL/R_S = R_P/6.28fL$. After rearranging the terms and simplifying, that equation yields the relationship $R_P = Q^2R_S$. That relationship also holds true for capacitors.

Dissipation factor

Instead of Q, the quality of a capacitor is frequently described by the dissipation factor, or DF. That is a quantity indicating a loss of energy, usually due to the conversion of that energy to heat and is equal to 1/Q. Thus, the quality of a capacitor is best when the dissipation factor is at a minimum.

Although most frequently used when specifying the quality of a capacitor, the dissipation factor can also be used to describe the quality of an inductor. Such use is rare, however.

Resonance

Inductors and capacitors are used to tune a circuit so that it is resonant at a specific frequency such that $X_L = X_C$. By substituting and rearranging terms it can be shown that that frequency, f_O, is equal to $1/6.28\sqrt{LC}$. Resonant circuits can take one of two forms: series or parallel. If the inductor and capacitor are in series, the circuit presents a low impedance at resonance. If the inductor and capacitor are in parallel, the circuit presents a high impedance at resonance.

Let's first consider a series L-C circuit, such as the one shown in Fig. 3. The current in any series circuit is the same through all the components in the circuit. In a series L-C circuit, however, the phase of the voltage across the capacitor is 90° ahead of the current through it, while the voltage across the inductor is 90° behind the current through that component. Thus, the voltages across those components are 180° out of phase. What that means is that when the reactive voltages are equal, the voltage across the capacitor will completely cancel the voltage across the inductor. That happens when $X_L = X_C$, which is the condition at resonance.

If the circuit were ideal, at resonance it would present zero inductance, zero reactance, and zero impedance. Real capacitors generally do resemble the ideal model and have negligible series resistance associated with them, but that is not the case with inductors. As previously mentioned, those components are coils of wire and as such generally have a substantial series resistance associated with them. Thus, since the resistance of the inductor can be drawn as a discrete component in series with it, Fig. 3 can be redrawn as shown in Fig. 4, where R_S is the series resistance of the inductor.

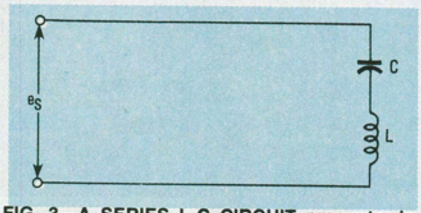

FIG. 3—A SERIES L-C CIRCUIT presents, in theory, zero impedance at resonance.

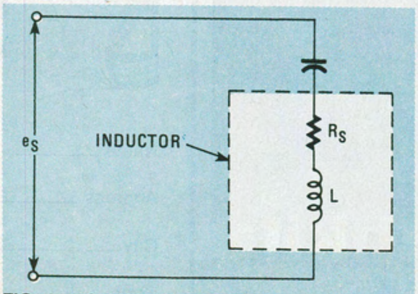

FIG. 4—TO ANALYZE a series L-C circuit's behavior, redraw the circuit as shown.

A parallel L-C circuit is shown in Fig. 5. In all parallel circuits, the voltage across each branch is identical. In a parallel L-C circuit however, the phase of the current leads the voltage by 90° in the capacitor, while the current lags the voltage by 90° in the inductor. At resonance, since the reactances are equal, whatever current is flowing upward in the capacitive branch of the circuit, is flowing downward in the inductive branch, and vice versa.

Let's examine what the importance of that is a little more closely. From Kirchoff's current law we know that the sum of the currents flowing into a junction of circuit branches must equal zero. Looking at the point labeled A in Fig. 5, we see that at resonance the same current flowing into it from one of the reactive elements is flowing out of it into the other. That means that there is no current drawn from the source, which means that the impedance presented by the circuit is infinite ($Z = e_S/I_S = e_S/0 = \infty$).

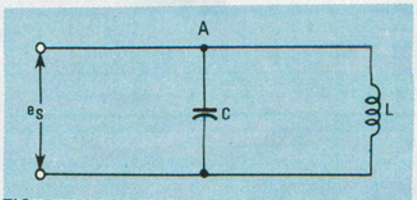

FIG. 5—AN IDEAL PARALLEL L-C CIRCUIT will present an infinite impedance at resonance.

That, of course, assumes ideal components. If those components were indeed ideal, and the source were disconnected, the current would flow back and forth between the reactive elements indefinitely. Of course, that never would happen because of the losses introduced by the series resistances of the components. Here, we once again can consider the series resistance of the capacitor to be negligible and concern ourselves just with the series resistance of the inductor. Thus, Fig. 5 can be redrawn as shown in Fig. 6, where R_S is the series resistance of the inductor.

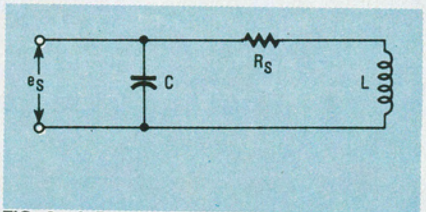

FIG. 6—A PARALLEL L-C CIRCUIT can be redrawn as shown here.

Before we go any farther, let's look at one other aspect of inductors that's important, especially when dealing with higher frequencies. As inductors are composed of turns of wire, stray capacitances can form between turns, whether or not they are adjacent; between the coil and ground; between the leads connected to the terminals of the coil, and so on. Thus, any inductor is in essence a large inductor in parallel with a very small capacitor. At lower frequencies, those *distributed capacitances* are rarely important, but at higher frequencies, they can make the inductor self resonant. That effect must be considered in high-frequency designs because if the signal frequency exceeds the inductors self-resonant frequency, that device will behave like a capacitor rather than an inductor. Thus, those distributed capacitances place an upper limit on the frequencies at which the inductor can be used. Self-resonance can also occur if the self-resonant frequency is a harmonic of the signal frequency.

Filters

Since series L-C circuits present a low impedance at the resonant frequency, but high impedance at others, they make excellent bandpass filters. Such an application is shown in Fig. 7-a. In it, the input signal e_S, is fed to a series L-C circuit. Assuming that the circuit is designed to be resonant at e_S's fundamental frequency, only that frequency will be passed; all other frequencies will be sharply attenuated. Finally, the signal appears across R_L as e_{OUT}.

In the circuit shown in Fig. 7-b, all frequencies except the resonant frequency are shorted by the L-C circuit. The resonant frequency, however, appears across L. From there it is coupled into L2 and on to the output. Ideally, only the resonant frequency should pass through those L-C circuits to the output. In most cases, however, a band of frequencies is passed. The width of that band can be determined from the circuit Q, and through use of a graph of the frequency response of a circuit similar to the one shown in Fig. 8. Looking at that curve, the maximum output of a circuit is e_{OUT}, and f_H and f_L are the −3-dB points. The bandwidth of the circuit, $f_H - f_L$, is equal to the resonant frequency divided by Q. Thus the bandwidth is inversely proportional to Q.

As an example, assume a circuit where C = 10pF, L = 25.4µH, and Q = 20. Using the equation for the resonant frequency, we find that f_O = 10 MHz. If Q = 20, $f_H - f_L$ = (10 MHz)/20 = 500 kHz. Because f_L should be the same distance below f_O as f_H is above that resonant frequency, f_L = 10 MHz − 250 kHz = 9.75 MHz, and f_H = 10 MHz + 250 kHz = 10.25 MHz. Signals with frequencies between 9.75 MHz and 10.25 MHz are passed rather easily by that circuit.

In many applications it is desirable to attenuate signals at frequencies below and above the active band. To achieve that, L-C circuits can be placed in series with the signal. The circuit shown in Fig. 9-a is a simple *low-pass filter*. It is called that because it will only pass frequencies less than a certain cut-off frequency, f_C. The values of L and C can be found from $L = R/4\pi f_C$ and $C = 1/4\pi f_C R$, where R is the impedance of the source and the load.

The circuit shown in Fig. 9-b is a simple *high-pass filter*. It will only pass frequencies that are higher than the cut-off frequency. The appropriate values of L and C can be found from $L = R/\pi f_C$ and $C = 1/\pi f_C R$.

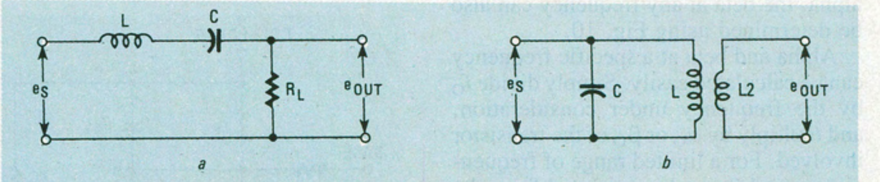

FIG. 7—TWO BANDPASS FILTERS. The one in *a* uses a series L-C circuit and presents a high impedance at all frequencies except the resonant one. The one in *b* uses a parallel L-C circuit; at resonance, only the resonant frequency appears across L.

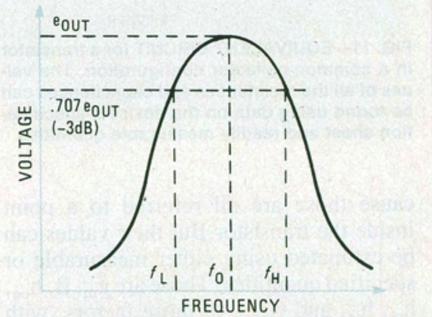

FIG. 8—THE LIMITS OF A BAND are defined by its upper and lower −3-dB points. Those are the frequencies at which the signal has dropped 3 dB from its level at resonance.

Bipolar transistors

Inductors, capacitors, and resistors are not perfect components at high frequencies. We saw that an inductor has stray capacitances associated with it. Similarly, a capacitor has stray inductances. Resistors also exhibit some capacitance and inductance; some types of resistors cannot be used at high frequencies.

Such imperfections are not limited to passive components alone; transistors, for instance, exhibit stray capacitance between their terminals. Those capacitances are their primary imperfections when they are used at high frequencies. Because of that, many types of transistors can only be used in low-frequency circuits. On the other hand, some devices have been developed that are capable of operating in the high GHz range. We will start this part of our discussion by describing the use of bipolar devices in RF circuits and by noting how those devices limit the performance of those circuits. The discussion continues by describing how FET's behave under similar situations.

Alpha and beta

When describing a transistor's characteristics, and the effect of those characteristics on a circuit, the alpha and beta of the transistor were treated as constant values. The only deviation from the stated constants was to note how they varied with collector current. But alpha and beta also vary with frequency; they become smaller as the frequency becomes higher. As a result, the input impedance of a particular transistor circuit, equal approximately to βR_E, is much higher at low frequencies than at high ones.

If we consider α_O as the low-frequency current gain between the collector and emitter, α decreases 3 dB to .707 of α_O at what is referred to as the *alpha cutoff frequency*. Several symbols are used to denote that frequency, including f_α, f_{hbo}, and $f_{\alpha b}$. Once the frequency is determined from the transistor's specifications, α at any frequency can be determined using the curve in Fig. 10. At f_O, alpha is 1/1.4 of its specified low-frequency value; at $2f_O$, alpha is 1/2.24 of α_O, and at $4f_O$, alpha drops to ¼ of its low-frequency figure. From that frequency on, every time the frequency doubles, alpha drops by one-half. Thus at $8f_O$, or double the $4f_O$ frequency, alpha dropped from ¼ of α_O to ⅛ of α_O. That relationship remains constant on up to extremely high frequencies.

Since beta decreases at the same rate as

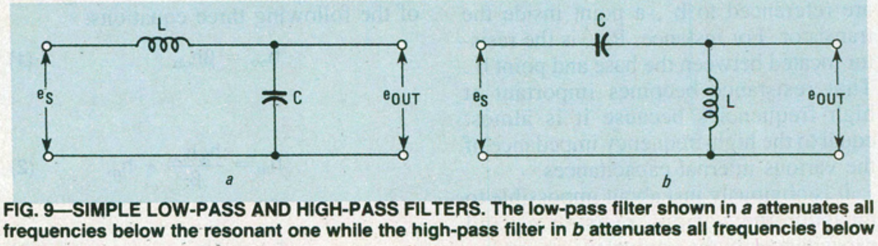

FIG. 9—SIMPLE LOW-PASS AND HIGH-PASS FILTERS. The low-pass filter shown in *a* attenuates all frequencies below the resonant one while the high-pass filter in *b* attenuates all frequencies below resonance.

alpha, the beta at any frequency can also be determined using Fig. 10.

Alpha and beta at a specific frequency can be calculated easily. Simply divide f_O by the frequency under consideration, and multiply by α_O or β_O of the transistor involved. For a limited range of frequencies, α and β can be estimated from the curve in Fig. 10.

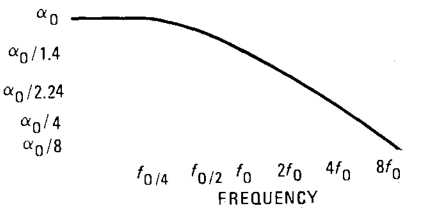

FIG. 10—HOW ALPHA VARIES with frequency. The value of beta varies in an identical manner.

Finally, the *gain-bandwidth product*, f_T, a value found on most transistor spec sheets, is useful in determining β at any operating frequency. That quantity, f_T, is defined as the product of beta and the upper 3-dB limit of a band. By simply considering the band here to stretch from 0 Hz to the operating frequency, it is possible to find beta by dividing f_T by the operating frequency. For example, if the f_T for a transistor is specified as 100 MHz, and you want to find the beta at 10 MHz, it is 100/10 = 10.

Equivalent circuits

At low frequencies, the equivalent circuit of a transistor was considered to be composed of two diodes. One diode, located between the base and collector terminals, was reverse biased. The second one, located between the base and emitter terminals, was forward biased. That circuit can be simplified farther by replacing the diodes with their internal on- and off-state resistances. The forward-biased diode could be replaced with a low value resistor connected from the base to the emitter, r_{be}, and the reverse-biased diode could be replaced with a large resistor connected between the base and collector, r_{ce}. There are, of course, also capacitances between the various terminals of the equivalent circuit. At low frequencies, those can be ignored; that, of course, is not true at high frequencies. An equivalent circuit including those capacitances, is shown in Fig. 11.

In that circuit, almost all components are referenced to b′, a point inside the transistor. For instance, R_{bb}' is the resistor located between the base and point b′. That resistance becomes important at high frequencies because it is almost equal to the high-frequency impedance of the various internal capacitances.

It is obviously just about impossible to measure the various resistances and capacitances in the equivalent circuit be-

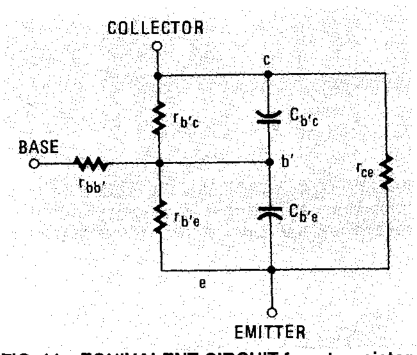

FIG. 11—EQUIVALENT CIRCUIT for a transistor in a common-collector configuration. The values of all the resistances and capacitances can be found using data on the device's specification sheet and readily measurable quantities.

cause those are all referred to a point inside the transistor. But their values can be estimated using either measurable or specified quantities. Those are g_m, β, h_{oe}, h_{re}, h_{ie}, and C_{ob}. All those factors, with the exception of g_m, can be found on most complete specification sheets. Let's look at them briefly.

The transconductance of a transistor, g_m, relates the collector current to the base-emitter voltage; in an FET it relates drain current to gate voltage. Transconductance is roughly equal to the quiescent collector current, in amperes, divided by 0.026.

Beta, of course, is the low-frequency current gain as specified by the manufacturer of the device. The no-load admittance seen when looking back into a transistor is h_{oe}. Since admittance is the inverse of resistance, the output resistance of the transistor is given by $1/h_{oe}$.

Consider two voltages. One, V1, is the voltage at the input due to voltage present at the output of the transistor. The other, V2, is the voltage at the output. The ratio V1/V2 is equal to h_{re}. That again assumes no load at the output. The impedance seen by looking into the input when the output is short circuited is called h_{ie}. The collector-to-base capacitance of a transistor's common-base equivalent circuit is C_{ob}.

All of the above parameters, with the exception of C_{ob}, are for a common-emitter circuit. If the specification sheets should list the h-factors for the common-base circuit, h_{ob}, h_{rb} and h_{ib}, rather than the h-factors for the common-emitter circuit as noted above, the common-base factors can be converted back to common-emitter parameters through use of the following three equations:

$$h_{oe} = \beta h_{ob} \quad (1)$$

$$h_{re} = \frac{h_{ie}h_{oe}}{\beta} + h_{rb} \quad (2)$$

$$h_{ie} = \beta h_{ib} \quad (3)$$

In each case, all factors should be altered to conform with the emitter current and collector-emitter voltage conditions under which the transistor is being used. Curves are usually supplied by the manufacturer of the device to help in that task. If no such curves are available, the data can be used as supplied but the circuit will have to be tweaked up once it is built. (More on that later.)

Using the h-factors, the values of the resistances and capacitances in the high-frequency equivalent circuit can be found from the following:

$$r_{bb}' = h_{ie} \quad (4)$$

$$r_{b'e} = \frac{\beta}{g_m} \quad (5)$$

$$r_{b'c} = \frac{r_{b'e}}{h_{re}} \quad (6)$$

$$r_{ce} = \frac{1}{(h_{oe} - g_m h_{re})} \quad (7)$$

$$C_{b'e} = \frac{g_m}{2\pi f_T} \quad (8)$$

$$C_{b'c} = C_{ob} \quad (9)$$

At low frequencies, the voltage gain can be found without resorting to complex mathematics. But like α and β, voltage gain drops at higher frequencies. The frequency at which the voltage gain has dropped to 1/1.414 of its low-frequency level (3 dB) is:

$$f_O = \frac{\beta + g_m(\beta R_E + r_{b'b} + R_S)}{2\pi\beta(C_T)(R_T)} \quad (10)$$

where:

$$C_T = (C_{b'e} + C_{b'c}g_mR_L + C_{b'c}g_mR_E)$$

$$R_T = (R_E + r_{bb'} + R_S)$$

In that equation, all factors, with the exception of R_E, R_L, and R_S, are found as shown above. As for the exceptions, R_E is the emitter resistor, R_L is the load resistance, and R_S is the resistance of the signal source. The gain of the device varies as shown in Fig. 10.

The above details apply to a common-emitter circuit. To find the high-frequency voltage gain of a transistor in a common-base or common-collector circuit, proceed as you would in a low-frequency situation, except use the values of α and β, and the effective load on the transistor, at the frequency in question.

Let's now apply what we've learned. Assume you have a 10-MHz signal source with an output impedance of 50 ohms.

That source is feeding a transistor in a common-emitter circuit. In order to get good gain, a transistor with a high f_T should be used. Use a 2N5354; it has an f_T of 250 MHz. In that transistor, $C_{ob} = 8$ pF, beta at low frequencies is 100, $h_{ie} = 1300$, $h_{oe} = 24 \times 10^{-6}$, and $h_{re} = 1.5 \times 10^{-4}$. If we assume that the idling current, I_E, is 2 mA (.002 amperes), then $g_m = 0.002/0.026 = 0.077$ mhos. We can use the common-emitter h-factors as supplied by the manufacturer without modification. The various components in the high-frequency equivalent circuit of the transistor are found by substituting into equations 4 through 9:

$r_{bb'} = 1300$ ohms

$r_{b'e} = 100/0.077 = 1300$ ohms

$r_{b'c} = 1300/1.5 \times 10^{-4} = 870 \times 10^{-4}$ ohms

$r_{ce} = 1/[24 \times 10^{-6} - 0.077(1.5 \times 10^{-4})] = 28000$ ohms

$C_{b'e} = 0.077/6.28(250 \times 10^6) = 49$ pF

$C_{b'c} = 8$ pF

As for the load, assume there is a parallel resonant circuit in the collector circuit consisting of a 100-pF capacitor and a 2.5-μH inductor. The series resistance of the inductor is 0.2 ohms. That circuit resonates at 10 MHz. The Q is primarily equal to that of the inductor, which is $6.28fL/R_S = (6.28 \times 10^7)(2.5 \times 10^{-6})/2 = 80$. Thus the series resistor, when converted to the parallel resistance across the L-C circuit, is equal to $Q^2R_S = 80^2 \times 0.2 = 1280$ ohms. Because the impedance of the inductor cancels the impedance of the capacitor at resonance, R_L is equal to that parallel resistance. Use 1300 ohms as a close approximation.

This transistor performs well without a resistor in its emitter circuit so one will not be used here. Substituting all necessary information into equation 10 to determine f_O while letting R_E equal 0 gives us $f_O = 283,419$ Hz.

Use $f_O = 250,000$ Hz as an approximation for the calculated frequency. That means that the gain at 250 kHz is 1/1.414 of what it is at low frequencies (3 dB below the low frequency gain). At 500 kHz, the gain drops another 4 dB, and at 1 MHz the gain is another 5 dB down for a total drop in gain of 12 dB. From that frequency on, the voltage gain drops an additional 6 dB each time the frequency doubles, so that it is 18 dB down at 2 MHz, 24 dB down at 4 MHz, 30 dB down at 8 MHz, and a little more, about 32 dB, down at the 10 MHz we are concerned with. The 32 dB figure indicates that the gain at 10 Mhz is about 1/40 of the gain at low frequencies.

Considering that the only resistor in the emitter circuit is the r_e of the transistor, and that r_e is equal to $26/2 = 13$ ohms when 2 mA of current flows through the device, the gain at low frequencies is $R_L/13 = 1300/13 = 100$. Because gain dropped to 1/40 of that at 10 MHz, the voltage gain of the overall circuit is 1/40 of that 100, or 2.5.

As the gain-bandwidth product equals 250 MHz, β at 10 MHz is equal to 250 MHz/10 MHz = 25. That is approximately equal to the current gain of the device at 10 MHz. Power gain is the product of the current and voltage gains at 10 MHz, or 2.5 × 25 = 62.5.

Those results must be tweaked-up in the amplifier after it has been built. There are many reasons for that. For one, approximations have be used in the design. Also, the various stray capacitances in the equivalent circuits of Q1 and Q2 were not considered. Although not shown in the equation, they do affect the resonant frequency and must be compensated for in the final design.

A basic schematic using two transistors and the components we've described here is shown in Fig. 12. In our design example, Q2 was not in the circuit, so that the complete load on the transistor was the L-C resonant tank. Should the L-C circuit feed another transistor as shown, its load should be considered to be in parallel with the calculated R_P of the tank. In the figure, the tap on the transformer is used to match the impedance of the resonant circuit to the impedance at the input of Q2. That is done to maximize the transfer of power from the first stage to the second stage.

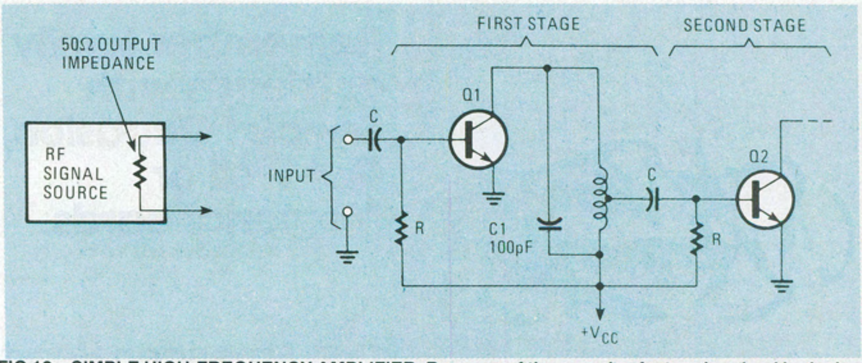

FIG 12—SIMPLE HIGH-FREQUENCY AMPLIFIER. Because of the complex factors involved in designing such a circuit, the values used for the various components will always differ from those initially calculated.

FET's

Practical circuits involving FET's do not differ radically from those using bipolar devices. There are differences, however. Because of an FET's high input impedance, the transistor does not contribute substantially to the load on a preceding stage but the various capacitances in the FET's equivalent circuit can effect the load. As for those loads, they are almost always resonant tank circuits so it's clear that those capacitances will change the tank's resonant frequency.

As an example, consider the circuit drawn in Fig. 13. For simplicity, we'll use the same values for L and C that were used in the previous example. Thus, L1 = 2.5 μH, C1 = 100 pF, and the parallel resistance is 1300 ohms; the tank, then, resonates at 10 MHz. The impedance of the source has no effect at high frequencies and is thus ignored.

We'll use a 2N5397 transistor here; it has excellent characteristics even at 450 MHz. That transistor's capacitance from the gate to the drain, C_{rss}, is specified as 1.3 pF. That capacitance added to the gate-to-source capacitance of the FET is specified as 5.5 pF. That sum is the C_{iss} of the device. The g_m of the transistor is about 7.5×10^{-3} ohms.

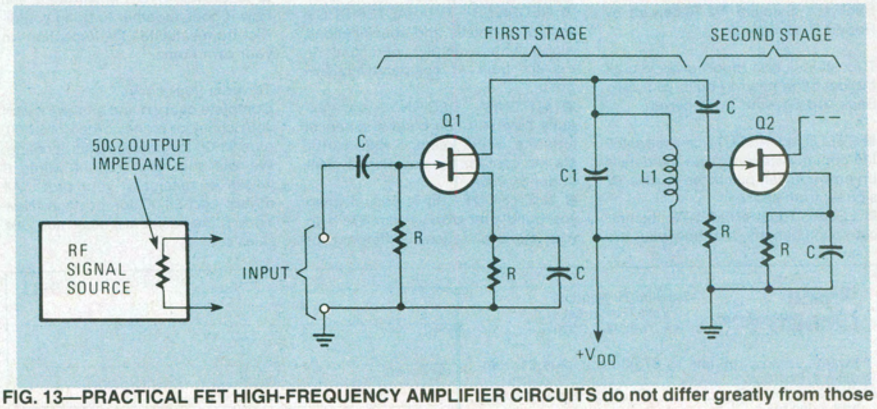

FIG. 13—PRACTICAL FET HIGH-FREQUENCY AMPLIFIER CIRCUITS do not differ greatly from those using bipolar devices.

Using this data, gain at low frequencies is $g_m R_D$ or $(7.5 \times 10^{-3})(1300) = 9.75$. Voltage gain is 3 dB down at:

$$f_O = \frac{1}{6.28\,(R_D)(C_{ds} + C_{gd})}$$

In that equation, C_{gs}, the gate-to-drain capacitance, is equal to C_{rss}. Because C_{ds} is insignificant in JFET transistors, that factor can be ignored and:

$$f_O = \frac{1}{6.28\,(1300)(0 + 1.3 \times 10^{-12})} = 94 \text{ MHz}$$

Because of that high cut-off frequency, voltage gain at 10 MHz is not reduced noticeably from its low-frequency value of 9.75. If the impedance of the signal source were comparable to the impedance of the circuit (which it is not), f_o would differ from the frequency just calculated. It would be

$$f_O = \frac{1}{6.28\,(R_S)\,(C_{iss} + g_m + R_D C_{gd})} = 175 \text{ MHz}$$

Because f_O is at a much higher frequency in that case, the effect of the transistor on voltage gain would be even less then when the source was ignored. As for the effect of Q2 on the load of Q1, it is negligible because of its extremely high input impedance as previously noted.

Stability

RF circuits have a tendency to be unstable because of undesirable positive feedback from the output back to the input of a transistor. Oscillation caused by such feedback is eliminated through a technique called neutralization. In that, a capacitor feeds a signal from a circuit at the output of an amplifier stage back to its input. The signal through the capacitor is adjusted so that it is 180° out of phase with the feedback and at the same level. When that is done, the effects of the positive feedback are cancelled.

Filters

When working at high frequencies, a considerable number of factors in the circuit must be calculated. Even so, due to stray capacitances and inductances, as well as the fact that approximations are used in some steps in the design, the values of most of the capacitors and inductors must be adjusted after the circuit has been built. The same factors occur in high-frequency filter design. There, however, the technique of approximation and trimming is not satisfactory. Therefore, more precision is required. In the next part of this series, we'll look at what's involved, as well as at the design of different types of high-pass, low-pass, bandpass, and band-rejection filters. **R-E**