

## Chapter 9: FM Receivers

### Chapter 9 Objectives

At the conclusion of this Chapter, the reader will be able to:

- € Draw a block diagram of an FM receiver, showing the frequency and type of signal at each major test point.
- € Explain the operation and alignment of Foster-Seeley/Ratio, PLL, and quadrature FM detector circuits.
- € Describe the features of noise-suppressing circuits in an FM receiver.
- € Draw a block diagram of a frequency-synthesized FM receiver.
- € Trace the signal flow through FM stereo and SCA decoder circuits.
- € Describe the alignment procedures unique to FM receivers.
- € Apply basic troubleshooting methods to FM receivers.

FM is popular as a communications mode because of its superior noise performance and fidelity, when compared to AM. The operation of AM and FM receivers is very similar; the same familiar circuit techniques are used in both. The primary differences in an FM receiver stem from the relatively high frequencies used for FM transmission (the VHF and UHF bands), and the differences in detector circuitry. FM receivers tend to be more "feature-laden." The addition of circuitry to support FM stereo, SCA, automatic (microcomputer-driven) tuning, and other features adds complexity to the set.

FM is a fundamental technology, like AM. Its techniques are used in satellite and data communications, telemetry (remote measurement), and a score of other non-broadcast applications. A professional with a strong knowledge of FM can go far in communications!

### 9-1 FM Superheterodyne Receivers

FM receivers use the superheterodyne principle as shown in Figure 9-1. Recall that a superhet receiver operates by converting the desired incoming RF carrier frequency down to the *IF* or *intermediate frequency*, where most of the amplification is provided and receiver bandwidth is defined. The sections of the receiver that are new or different compared to an AM receiver are in blue.

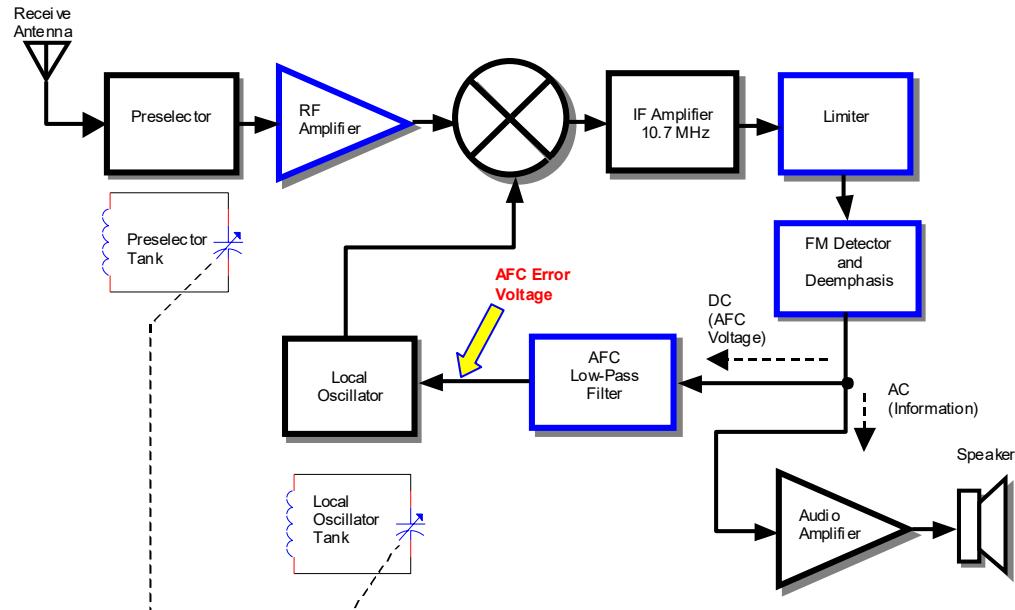


Figure 9-1: An FM Superheterodyne Receiver

An FM receiver contains several stages that are new or different from those in an AM set. These include the *detector*, *limiter*, *RF amplifier*, and *AFC stages*.

#### FM Detector

Naturally, detecting an FM signal requires different circuitry than that for demodulating AM. There are several popular types of FM detectors. All them can be thought of as *frequency to voltage converters*. That is, they take a varying input frequency (a frequency-modulated carrier wave) and convert that into a varying output voltage. This is exactly the opposite of the action of the modulator in an FM transmitter, so the output of an FM detector is a replica of the original information signal.

#### Limiter

In FM the information is encoded by changing the frequency of the carrier wave. Ideally, the carrier wave amplitude remains constant; in other words, the transmitter does not amplitude-modulate the carrier, and the envelope carries no information.

However, between the transmitter and receiver are various sources of external noise, such as atmospheric noise and man-made noise sources. These noise sources add at random to the voltage of the FM signal envelope, as shown below in Figure 9-2(a). An AM receiver is affected quite strongly by noise because an AM receiver recovers the envelope of the modulated wave. Not so with FM!

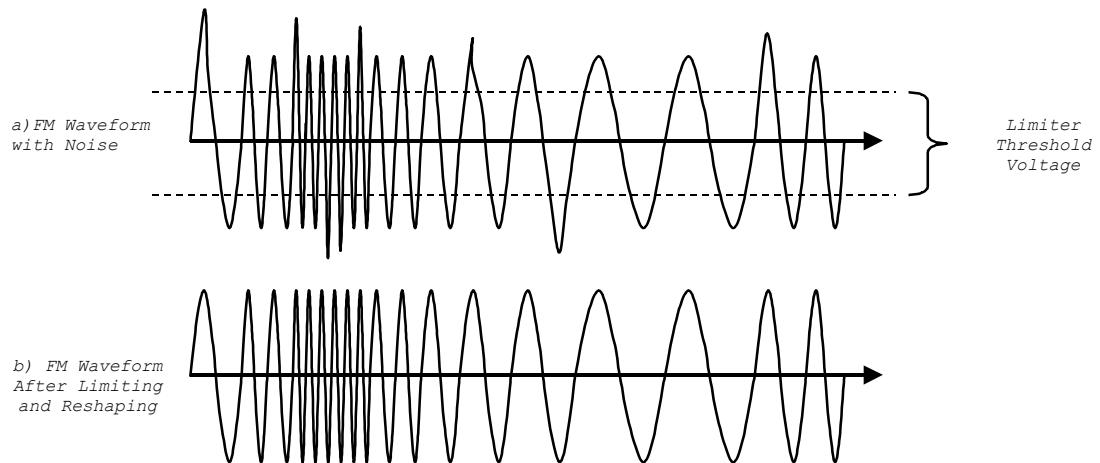


Figure 9-2: An FM signal Before and After Limiting

Because an FM signal contains information only in the wave's frequency, an FM receiver can safely ignore all amplitude changes without losing any information. The *limiter* in an FM receiver is a stage that essentially flattens the top and bottom of the modulated waveform prior to detection, as shown in Figure 9-2(b).

Flattening or clipping the waveform eliminates most of the noise, but preserves the information. This is why FM reception is virtually free of all sorts of static interference, even in the immediate presence of very strong noise signals (thunderstorms, nearby electric motors, and so on). Because the limiter removes most of the amplitude changes, the detector sees only frequency changes in the modulated waveform, and therefore, the output of the detector is only the original information signal.

#### RF Amplifier

In an AM broadcast receiver, there is seldom an RF amplifier in the front end. In an FM broadcast receiver, an RF amplifier provides two important actions, *amplification* and *local oscillator energy suppression*. The signal from the antenna in a VHF receiver (such as an FM broadcast receiver) can be very tiny. A "strong" signal may be only 50  $\mu$ V, and often signals are only a few microvolts in strength. This is due to the high frequencies (VHF and UHF) that are being used, combined with the small antennas employed for reception at these frequencies (recall that wavelength and antenna size decrease as frequency increases). When such a small signal is mixed with the local oscillator (for conversion down to the IF frequency), it can be easily lost in the noise from the mixer. The mixer adds a considerable level of *internal noise* to signals that pass through it. In an AM broadcast receiver, this is not a problem; signal levels at the antenna are in the hundreds of microvolts. An RF amplifier is not needed. *The RF amplifier provides sufficient gain for the incoming RF signal to overcome the noise floor of the mixer*. The noise floor of the mixer is the noise power level, in dBm (decibels with respect to 1 mW), that the mixer produces by itself with no RF input from the antenna.

The RF amplifier serves a second purpose: *local oscillator energy suppression*. The local oscillator in a receiver operates at a typical power level of 0 dBm (1 mW) to 10 dBm (10 mW). This doesn't sound like much

energy, but think about what could happen if the local oscillator's output were coupled to an antenna. The receiver would become a *transmitter*! The wavelength at VHF is short compared to the MF frequencies used for AM broadcast. This means that even the telescoping rod antenna of a portable receiver can be a fairly effective transmitting antenna. If the local oscillator energy is allowed to couple to the antenna, the receiver can become quite a potent interference source. *The RF amplifier prevents local oscillator reradiation by allowing signals to flow in only one direction, from the antenna to the mixer circuit.* This prevents most of the energy from leaving the receiver.

### Example 9-1

What is the wavelength of a 100 MHz FM broadcast signal? Compare this to the length of a typical rod antenna (20").

*Solution*

From Chapter 1, we know that:

$$\lambda \mid \frac{v}{f} \mid \frac{3\Delta 10^8 M/S}{100 \text{ MHz}} \mid \underline{\underline{3 \text{ meters}}}$$

To compare these lengths, let's convert the wavelength into inches:

$$\lambda_{\text{inches}} \mid \lambda_{\text{meters}} \Delta \frac{39.37''}{1M} \mid 3M \Delta \frac{39.37''}{1M} \mid \underline{\underline{118.11''}}$$

Only about one-quarter of a wavelength is needed for an antenna to be an efficient radiator. One quarter of 118.11" is 29.5". You can see that the rod antenna isn't nearly this long, but it is in the ballpark (20"), and therefore could radiate significantly! (We will discuss the theory of antennas in much more detail in a later chapter.)

#### AFC Stages

The local oscillator in an FM receiver operates at very high frequencies. Before the advent of frequency synthesizers, the frequency of the local oscillators in FM receivers was controlled by discrete LC resonant "tank" circuits, just like in an AM receiver. Using an LC tank allows the oscillator to drift off frequency and as luck would have it, drift becomes much more difficult to control in a VHF oscillator. In addition, receiver frequency drift rapidly degrades the quality of FM reception. The signal becomes distorted quickly as tuning degrades. *The automatic frequency control or AFC system is built into analog FM receivers to correct local oscillator drift.* The receiver local oscillator is essentially frequency-locked onto the carrier frequency from the transmitter, which is crystal controlled.

The AFC control voltage is developed at the FM detector, which is a frequency-to-voltage converter. As the receiver drifts off frequency, a positive or negative DC voltage is produced at the FM detector. This DC voltage is fed back to the local oscillator, which pushes the local oscillator back in the correct direction. A low-pass filter is included so that only steady DC is sent back to the local oscillator circuit. The local oscillator contains a *reactance modulator*, not shown in Figure 9-1, which converts the DC AFC voltage into a varying capacitance or inductance, which corrects the oscillator frequency. The AFC system operates almost exactly like the control method in a Crosby FM transmitter.

Many modern receivers are *digitally synthesized*. They lack the mechanical tuning capacitors of older sets; instead, they sport keypads, buttons, and digital frequency displays. In synthesized receivers, there is no need for AFC, since the local oscillator is actually a PLL or DDS frequency synthesizer, and is locked to a stable quartz frequency reference.

There's one other difference between AM and FM receivers that you may have already noticed. The standard IF frequency for AM is 455 kHz, and FM it is 10.7 MHz. Why is a higher IF frequency used?

Recall from Chapter 8 that the bandwidth allocated for each FM broadcast station is 200 kHz, including guard bands. An AM broadcast uses only 10 kHz. FM uses a *lot* more bandwidth than AM! By raising the IF frequency, the IF bandwidth increases accordingly. Accommodating a 200 kHz-wide signal in a 455 kHz IF would be tough!

#### Choice of IF Frequency

**In general, the wider the bandwidth of a receiver, the higher the IF frequency will be.**

## Example 9-2

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Calculate the range of local oscillator frequencies required for an FM broadcast receiver (88.1 to 107.9 MHz) with an IF of 10.7 MHz, assuming high-side injection.

*Solution*

From Chapter 5, we know that when high-side injection is being used:

$$f_{LO} \mid f_c 2 f_{IF}$$

So this same relationship will be applied at bottom and top of the FM broadcast band. At the bottom of the band, we get:

$$f_{LO(MIN)} \mid f_c 2 f_{IF} \mid 88.1MHz 2 10.7MHz \mid \underline{98.8MHz}$$

And at the top of the band:

$$f_{LO} \mid f_c 2 f_{IF} \mid 107.9MHz 2 10.7MHz \mid \underline{118.6MHz}$$

118.6 MHz falls within the *aviation* band. This is one reason why you can't play a portable FM radio onboard a commercial aircraft. The local oscillator energy may leak out and interfere with the sensitive communication receivers onboard the plane!

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### Annoy your Friends!

Even though an FM receiver uses an RF amplifier to prevent local oscillator energy leakage, a tiny amount of RF *does* leak out of an FM receiver. You can easily demonstrate this by "listening" to the local oscillator of a receiver with a second receiver. Analog sets in plastic cases work best:

- € Place the two receivers close together (a few inches is best).
- € Tune one receiver to a blank spot *high* on the FM dial (such as 107.3 MHz).
- € Tune the second receiver *10.7 MHz below* the frequency of the first (96.6 MHz, for example). This is the "transmitter."

If your second receiver is a good "leaker," you'll hear the sound of *dead air* in the first receiver. The local oscillator is an unmodulated carrier, after all!

Feeling adventuresome? If you've picked up the carrier, *carefully* turn up the volume on the first receiver (107.3 MHz) and at the same time, tap on the case of the second unit. What do you hear, and why?

### No Need for AGC

FM receivers don't respond to amplitude variations, thanks to the operation of the limiter circuitry. Because the relative amplitude of the signal going into the limiter and detector is unimportant, most FM receivers don't have any automatic gain control (AGC) circuitry. The exceptions to this rule are certain communications-grade FM receivers that must operate over a very wide range of antenna signal voltages. In these receivers, a modified AGC called *delayed AGC* or *DAVC* is often used.

## Section Checkpoint

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- 9-1 What type of receiver is used for both AM and FM?
- 9-2 An FM detector converts \_\_\_\_\_ into \_\_\_\_\_.
- 9-3 What is the purpose of the *limiter* in an FM receiver?
- 9-4 Give two reasons for the use of an RF amplifier in an FM receiver.
- 9-5 Why is AFC needed in analog FM receivers?
- 9-6 What type of FM receivers don't require AFC?
- 9-7 What governs the choice of IF frequency in a receiver?
- 9-8 Why isn't AGC used in most FM receivers?

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## 9-2 Detection of FM Signals

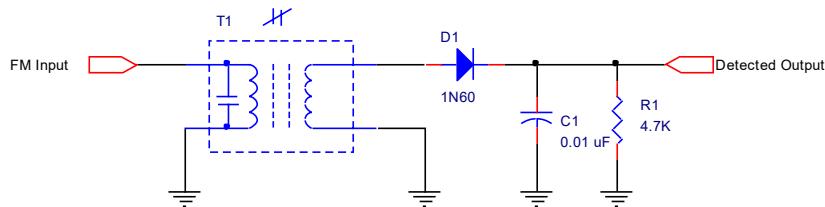
Over the years, many different circuits have been developed for the detection of FM signals. FM demodulation is a little more complicated than that for AM, and as technology has evolved, new FM detector circuits have been developed. The latest circuits can be almost entirely contained on an IC chip; additionally, use of digital signal processing techniques can entirely eliminate the FM detector.

### Slope Detection

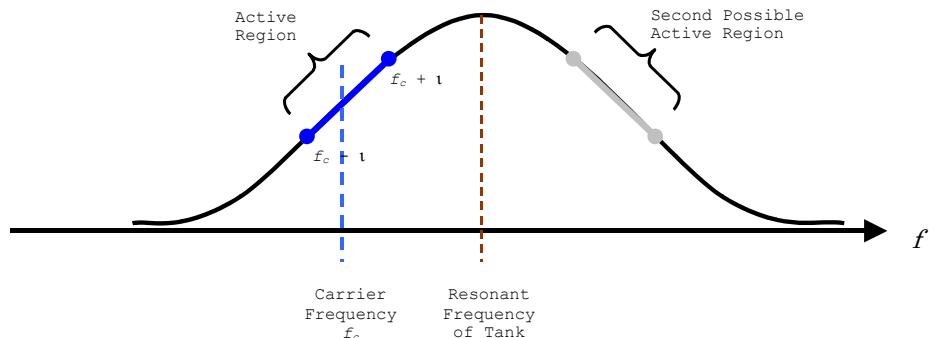
The oldest and least practical FM detector is the *slope detector* of Figure 9-3. This detector relies on the frequency response of a tuned circuit.

The slope detector works by utilizing the *slope* of a tuned circuit's frequency response. It can be best understood as a two-step detector. First, the FM signal is converted into an AM signal, and then the resulting AM signal is envelope detected.

In Figure 9-3(a), the tuned circuit consists of transformer  $T_1$  and its internal capacitor, and the AM portion of the detector is built from  $D_1$ ,  $R_1$ , and  $C_1$ . This is in fact a standard AM detector circuit! In normal operation (AM detection), the input signal would be at the resonant frequency of the tank. In FM operation, the tank is deliberately mistuned, as shown in Figure 9-3(b).



a) Slope Detector Circuit



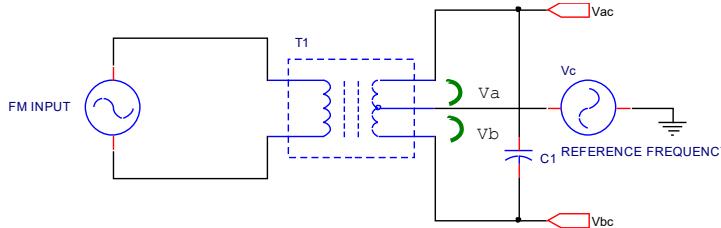
b) Slope Detector Operation

Figure 9-3: The Slope Detector

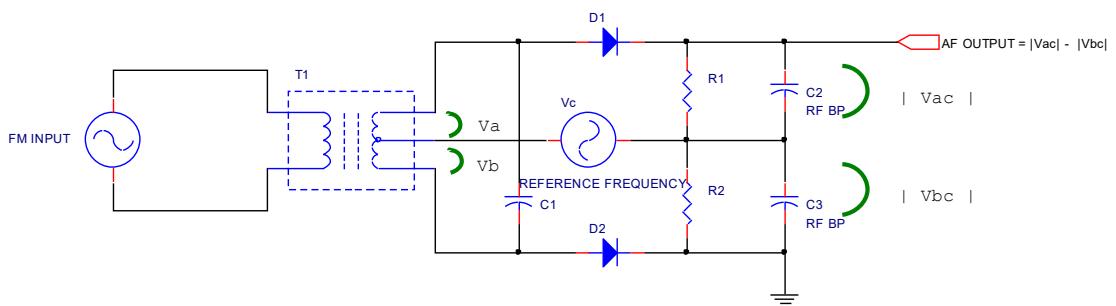
By moving the tank frequency up, the carrier frequency now falls on the left-hand slope of the tuned circuit's frequency response. As the carrier frequency increases, the amplitude of the tuned circuit output increases; as the carrier frequency decreases, the amplitude falls. The amplitude of the circuit's output depends on the frequency of the FM signal! By passing the resulting AM signal into the diode detector, the information is recovered.

The slope detector isn't an entirely practical FM detector for two reasons. First, this detector has a *dual response*. There are two points on the tuning curve of the tuned circuit that will provide a detected output. This will result in ambiguous tuning characteristics (a station will appear at two adjacent points on the tuning dial). Second, the shape of the tuned circuit's frequency response is not very linear, unless only a very small portion of the curve is used. For wideband FM detection, this would not work very well; the resulting carrier frequency swings are quite large (+/- 75 kHz), and considerable distortion of the sound would result.

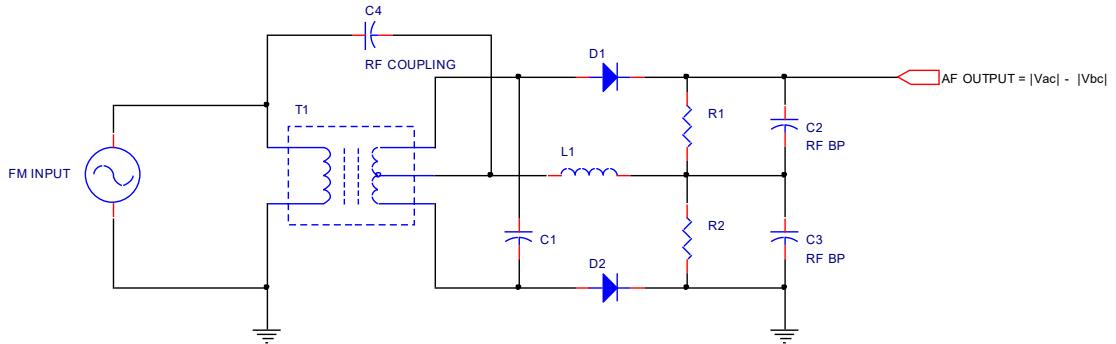
The Foster-Seeley detector circuit is a vast improvement over the slope detector. It provides a single response, and reasonably linear characteristics for wideband FM detection. This circuit can be best understood if developed in steps, as shown in Figure 9-4.



a) Converting Frequency Changes to Phase Shifts



b) Summing the Magnitudes of  $|V_{ac}|$  and  $|V_{bc}|$



c) Eliminating the Reference Frequency Source

Figure 9-4: Development of the Foster-Seeley Detector

The operation of the Foster-Seeley detector is a two-step process, just like the slope detector. Instead of converting input frequency changes to AM, the Foster-Seeley circuit converts the incoming FM signal into a series of *phase shifts*. The resulting signal, though not a true PM signal, is then phase-detected to produce a varying output voltage. The circuit can be developed in three steps.

Figure 9-4(a) shows the first step. The FM signal is coupled into transformer T1, whose secondary is parallel-resonated by C1 at the IF center frequency (usually 10.7 MHz). Capacitor C1 and the secondary inductance of T1 form a phase shifter circuit. A steady sine wave at the IF frequency of 10.7 MHz, voltage  $V_c$ , is applied to the center tap of T1.

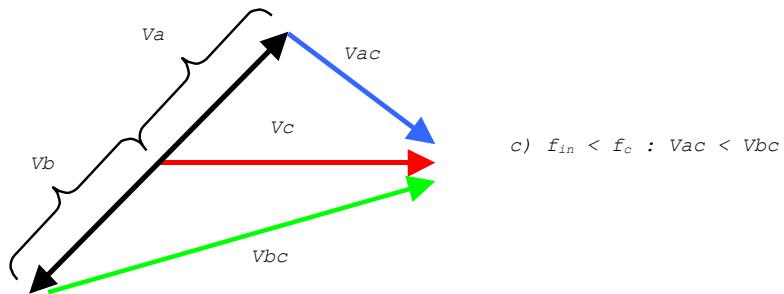
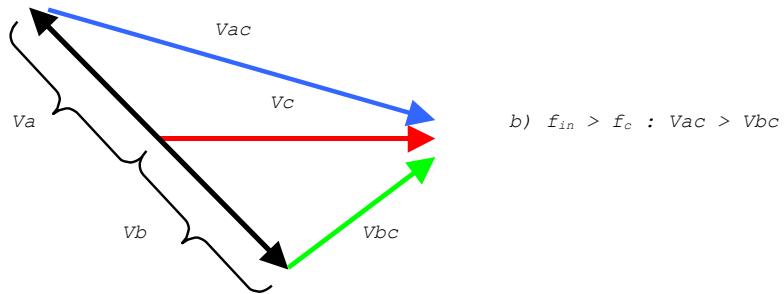
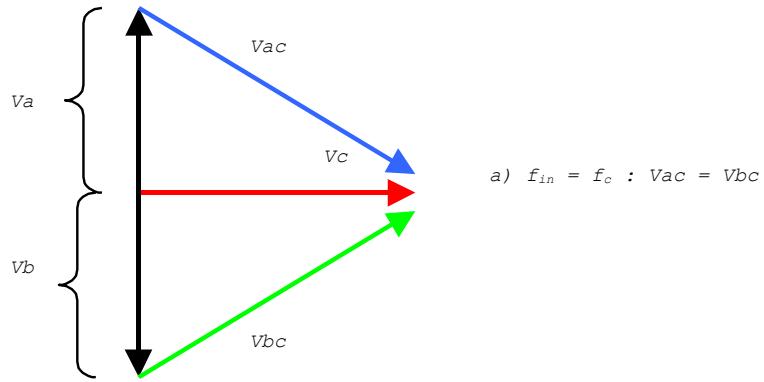


Figure 9-5: Phasor Relationships in the Foster-Seeley Detector

The phase shift produced at the secondary of  $T_1$  depends on the instantaneous frequency of the FM signal being applied. At rest ( $f = f_c$ ), the phase shift adjusted to be 90 degrees by tuning  $T_1$ . The phasors appear as in Figure 9-5(a). Notice that the *top* output of the circuit is the phasor sum of the voltages  $V_c$  (the reference) and  $V_a$  (the voltage from the top of  $T_1$ ). This voltage is  $V_{ac}$ . The same happens at the bottom side of  $T_1$ , and the voltage  $V_{bc}$  is developed here. Note the phase relationship between  $V_a$  and  $V_b$ : They are 180 degrees out of phase. This is true due to the center-tap on the secondary of  $T_1$ . *When  $f = f_c$ , the circuit is balanced.* The outputs  $V_{ac}$  and  $V_{bc}$  are equal in magnitude, and if their absolute values are subtracted, the result is zero.

What happens when the FM carrier frequency deviates upward? The phasor result is shown in Figure 9-5(b). Again,  $V_a$  and  $V_b$  maintain their 180 degree relationship; they both rotate in a counter-clockwise direction. Since  $V_c$  is the reference, it does not move. As you can see, the phasor results  $V_{ac}$  and  $V_{bc}$  are now out of balance;  $V_{ac}$  is much larger. To detect the out-of-balance condition, the circuit of 9-4b is used. Diodes  $D_1$  and  $D_2$  serve to rectify the AC voltages  $V_{ac}$  and  $V_{bc}$ . The algebraic output of 9-4(b) is  $(|V_{ac}| - |V_{bc}|)$ .

Therefore, in Figure 9-4(b), when the input frequency *rises*, the rectified output  $V_{ac}$  is larger than the  $|V_{bc}|$  output, and a positive output voltage results. The opposite effect occurs when the carrier frequency is *lowered*; now  $|V_{bc}|$  becomes larger, and the output voltage becomes *negative*. The circuit has effectively converted voltage into frequency.

The final refinement of the circuit is shown in Figure 9-4(c). The first two circuits require an oscillator to provide a reference frequency, and this oscillator must be phase-locked to the FM carrier signal. This is not very convenient, so the oscillator is replaced with a sample of the RF carrier voltage in Figure 9-4(c). The carrier voltage is coupled into the circuit through  $C_4$ , and inductor  $L_1$  (which is usually adjustable) serves to allow an RF voltage drop to be developed to serve as the reference voltage.

Why does this work? The answer is that *two* rates of phase change occur in the circuit. The portion of the circuit containing  $L_1$  changes phase relatively slowly when the input frequency changes, because it contains only  $L_1$ . The resonant circuit consisting of  $T_1$ 's secondary and  $C_1$  changes phase more quickly because it has two reactive parts ( $T_1$  and  $C_1$ ). Therefore, for practical purposes, the phase change across  $L_1$  is small enough to consider that portion of the circuit to have an approximately constant phase angle. The voltage across  $L_1$  is approximately a "reference" voltage.

The Foster-Seeley detector can reproduce a high-quality information signal, but has one limitation. In Figure 9-5, the size of the vectors  $V_a$  and  $V_b$  determines the magnitude of voltage output from the detector. If the input voltage of the FM signal changes, these vectors will change in size, and the detector's output voltage will change accordingly. In other words, a Foster-Seeley detector doesn't reject AM. Since most noise is in the form of amplitude disturbances, it will pass through a Foster-Seeley detector and be reproduced in the audio. To prevent this, a limiter stage must precede a Foster-Seeley detector to prevent AM noise from reaching the circuit.

## The Ratio Detector

A modification to the Foster-Seeley circuit results in the *ratio detector* circuit of Figure 9-6. One thing most people notice immediately about this circuit is that "one of the diodes is in backwards!"

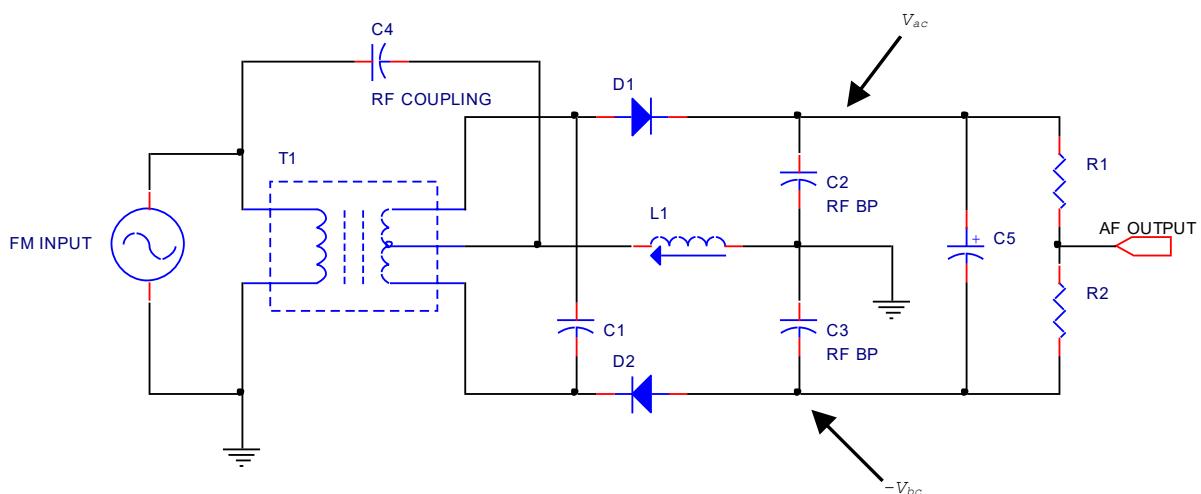


Figure 9-6: A Ratio Detector Circuit

The operation of the ratio detector is very similar to that of the Foster-Seeley circuit. The *difference* involves how the audio output voltage is developed. Notice that the voltages  $V_{ac}$  and  $-V_{bc}$  are developed on the top and bottom legs of the circuit, and that both of these voltages are *ground referenced*. The bottom voltage  $-V_{bc}$  appears as a negative value because  $D_2$  is reversed. Resistors  $R_1$  and  $R_2$  form a voltage divider. When the two voltages  $V_{ac}$  and  $V_{bc}$  are equal, the output from the divider will be *zero*, since  $R_1$  and  $R_2$  are equal values. When  $V_{ac}$  and  $V_{bc}$  become unequal, the voltage divider unbalances, and a positive or negative voltage output is produced, depending upon which voltage ( $V_{ac}$  or  $V_{bc}$ ) is larger, which in turn depends upon the input frequency.

In this manner, the operation is very similar to the Foster-Seeley circuit. The primary *addition* is capacitor  $C_5$ , which sees the total voltage ( $|V_{ac}| + |V_{bc}|$ ). Even when the circuit unbalances, the sum of these two voltages is constant (when one gets smaller, the other becomes larger to compensate). Capacitor  $C_5$  is a large electrolytic, usually around  $10\text{ }\mu\text{F}$ , and tends to stabilize the total voltage across the circuit. The benefit of capacitor  $C_5$  is that the circuit has a *built-in limiting action*, but only for short-term (less than a second or so) amplitude changes. The ratio detector does a better job of rejecting AM noise than the Foster-Seeley Circuit, but must still be preceded by a limiter amplifier circuit.

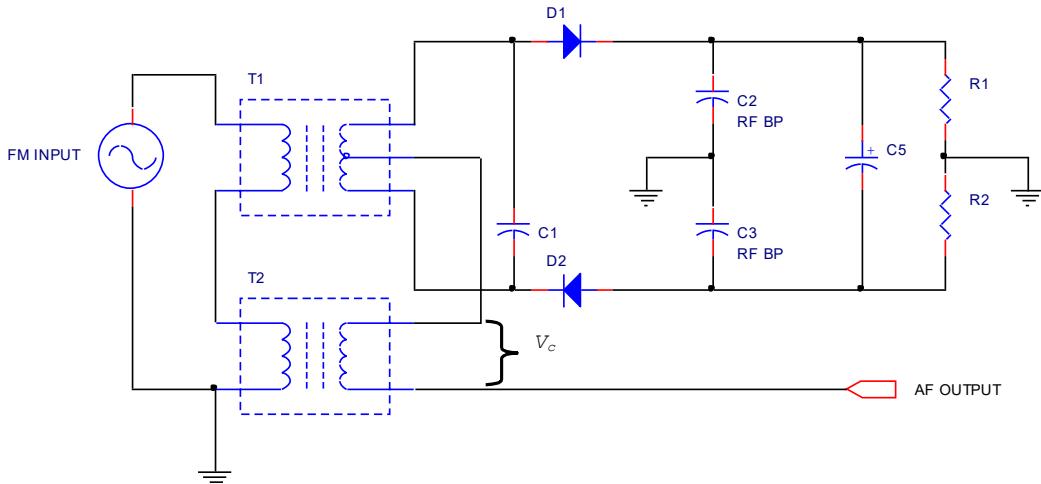


Figure 9-7: A Very Common Form of the Ratio Detector

Figure 9-7 shows a very common form of the ratio detector that uses two adjustable transformers. The operation is identical to Figure 9-6, except that the secondary of  $T_2$  is used to provide the reference voltage  $V_c$ . Usually  $T_1$  and  $T_2$  are a matched set of transformers designed especially for ratio detector duty, and may even be contained in one metal can (with the two screw adjustments visible).

#### PLL FM Detection

The Foster-Seeley and ratio detectors are excellent FM detectors but require the use of bulky RF transformers. A phase-locked-loop, or PLL can be used as an FM detector by extracting the audio signal at the low-pass filter output, as shown in Figure 9-8.

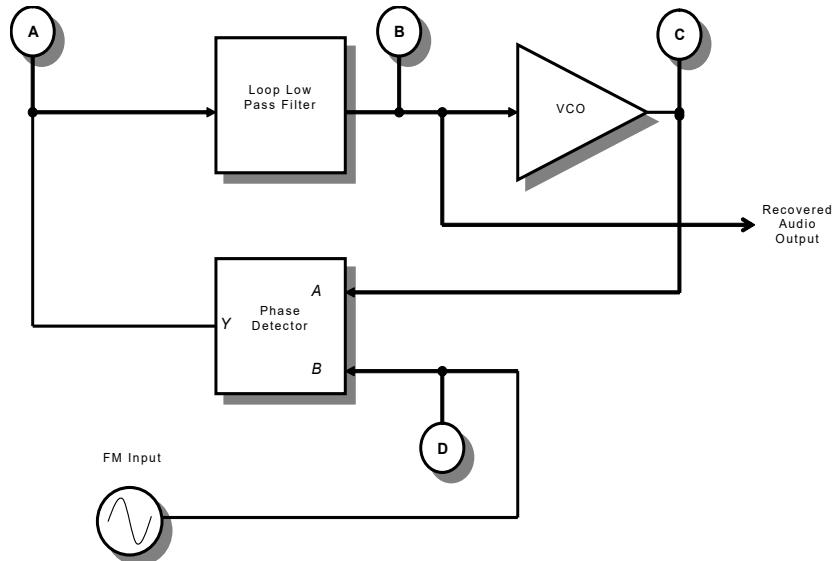


Figure 9-8: The PLL FM Detector

The PLL FM detector looks too good to be true. How can such a simple circuit detect FM? The answer comes from looking at the basic action of a phase locked loop.

You might recall that the basic function of a PLL is to lock the VCO frequency *exactly* onto the input frequency. In the PLL circuits we discussed in Chapter 7, the input frequency was called the *reference*, and because of Finley's law, the phase detector gave appropriate commands to the VCO (through the loop filter) to keep the VCO frequency *exactly* the same as the reference frequency (test points  $D$  and  $C$ ). In other words, the loop causes the VCO frequency to follow the input frequency. What will happen if an FM signal is substituted for the steady *reference* frequency of the PLL? You're right -- the loop will "imitate" (follow) the input frequency. That doesn't seem to be especially useful; after all, we are now putting an FM signal in, and getting an identical FM signal out of the VCO. But wait! Figure 9-9 offers a hint about how this circuit works.

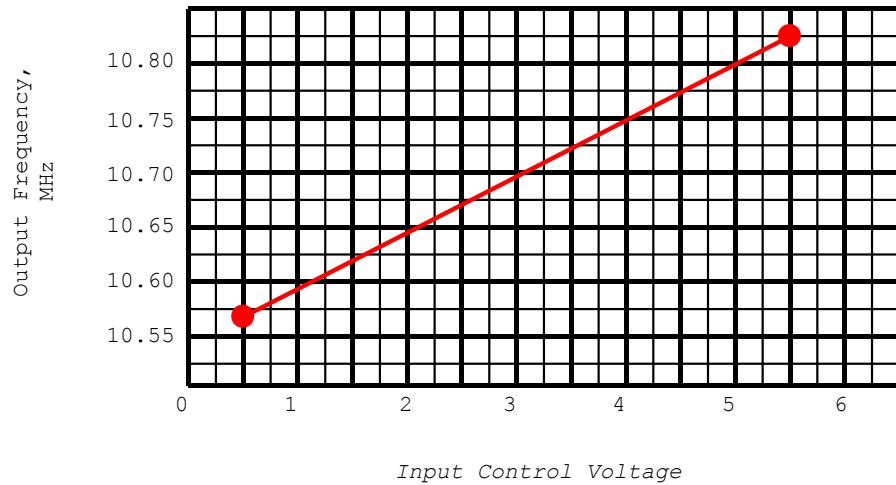


Figure 9-9: The VCO Transfer Characteristic

Figure 9-9 tells us that for the VCO frequency to change, its *control voltage* must change. The phase detector and low-pass filter in the loop will determine the correct control voltage for any applied input frequency. The "correct" voltage, of course, is the one that makes the VCO frequency *exactly* equal to the FM input frequency.

Suppose the input frequency is 10.7 MHz (the IF center frequency). What VCO control voltage will result? According to the graph in Figure 9-9, the VCO requires approximately 3 volts DC to produce 10.7 MHz out, so the DC control voltage will be 3 volts. *An input of 10.7 MHz is converted to a DC voltage of 3 volts.*

When the carrier frequency increases in a positive direction, the loop must follow. Suppose that an input frequency of 10.775 MHz (+75 kHz deviation) is applied. What VCO control voltage will result? Again, Figure 9-9 suggests that the VCO "needs" 4.5 volts for this to happen. *An input of 10.775 MHz is converted to 4.5 volts.*

Can you see what is happening? The loop *must* follow the input frequency changes. We're taking advantage of that behavior by "peeking" inside the loop to extract the DC control voltage for the VCO. The information signal will be riding on top of the DC control voltage; we simply block the DC with a capacitor to extract the information!

The PLL is an excellent FM detector and can be built without any RF transformers at all. In fact, all of the circuitry can be built onto a chip. This makes it well suited for miniature circuitry. Since the input to the PLL is a digital input, it can be equipped with a Schmitt trigger, which provides automatic *limiting* action. The PLL can provide true limiting action on its own without the addition of a limiter amplifier.

Figure 9-10 illustrates a PLL FM detector using the Motorola CD4046 PLL IC. This circuit is designed to operate on a carrier of 600 kHz, with nominal deviation of +/- 10 kHz. R<sub>4</sub> and C<sub>3</sub> set the free-running frequency of the loop at 600 kHz (at pin 4 of the IC, the VCO output) with no signal applied to the *FM INPUT*. There are no adjustments needed -- the loop will automatically lock onto the signal, even if it's not perfectly on frequency! The CD4046 IC contains the phase detector, VCO, and filter resistor. C<sub>5</sub> and R<sub>3</sub> form the PLL loop filter circuit and filter any residual 600 kHz RF signal from the detected FM output. C<sub>6</sub> is a DC block, which leaves only the information signal at the *AUDIO OUTPUT* terminal.

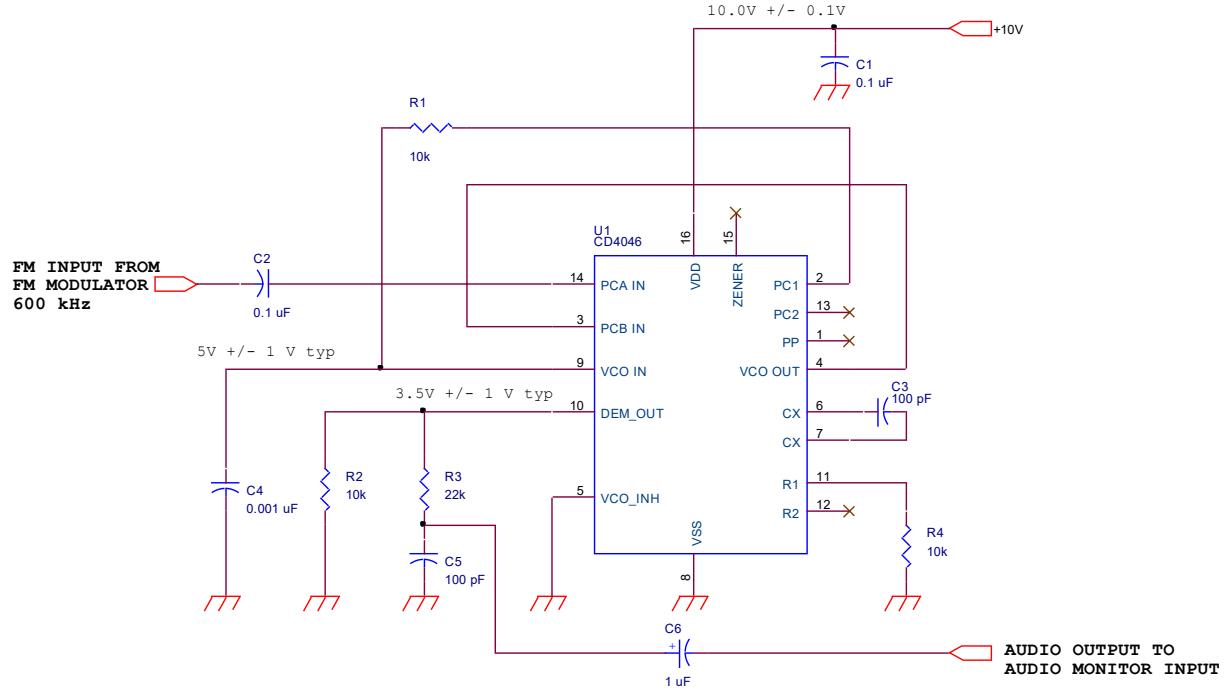


Figure 9-10: A PLL FM Detector Utilizing the CD4046

The Quadrature Detector

The quadrature detector of Figure 9-11 is a simple digital FM detector. It is perhaps the simplest of the FM detectors; like the PLL, it provides built-in limiting action through a Schmitt-trigger input, and can be implemented on an IC chip.

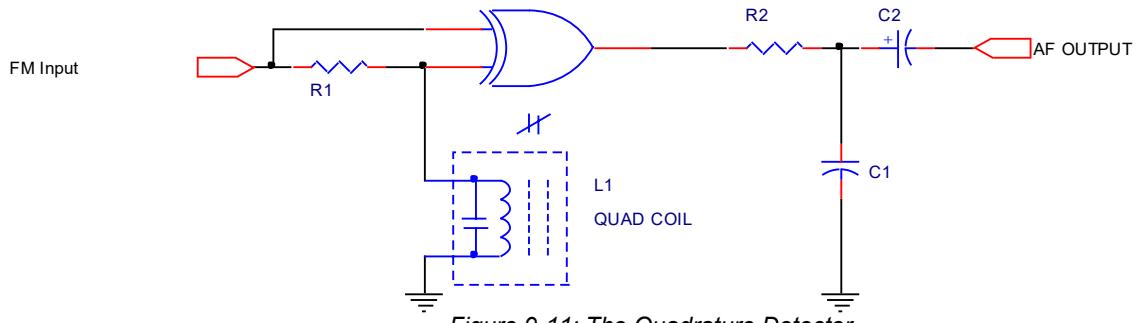


Figure 9-11: The Quadrature Detector

The quadrature detector relies on conversion of frequency to phase shift, just like a Foster-Seeley detector. In the quadrature detector above, the exclusive-OR gate functions as a phase detector. The FM input signal is applied directly to the top gate input, and indirectly to the bottom gate input through isolator resistor R1 and the *quadrature coil*, L1 (which usually contains a built-in capacitor to resonate at the IF center frequency).

R<sub>1</sub> and L<sub>1</sub> form a *phase shifter network*. As the FM input changes in frequency, the phase shift developed across R<sub>1</sub>, L<sub>1</sub>, and L<sub>1</sub>'s internal capacitor varies. This causes the phase of the two signals at the phase-detector XOR gate to vary, which in turn causes the duty cycle of the pulses at the gate's output to vary. Figure 9-12 shows the phase-versus-output frequency relationship for the XOR phase detector.