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A Quadrature Demodulator Tutorial

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ABOUT THE AUTHORS

Massachusetts Institute of Technology in 1996 and 1997, respectively.

Eric Main joined Motorola Semiconductor Products Sector in 1970. Since then, he has worked in the area of analog integrated circuit design and development. He received his B.Sc.(Eng) in electrical engineering from the University of Aberdeen, Scotland in 1965. He holds 41 patents and has seven pending.

In an FM signal, the modulation is the deviation of a carrier from its nominal frequency. The conventional method to demodulate this signal is to convert frequency deviation to phase and detect the change of phase. In the quadrature demodulator, the modulated carrier is passed through an LC tank circuit that shifts the signal by 90° at the center frequency. This phase shift is either greater or less than 90° depending on the direction of deviation. A phase detector compares the phase-shifted signal to the original to give the demodulated baseband signal. You use quadrature demodulators not only for frequency modulation, but also with digital modulation schemes such as FSK (frequency shift keying) and GFSK (Gaussian frequency shift keying).

FM Quadrature Demodulator Block Diagram

shift network. This phase shift network includes an LC tank *(L, R_p , and C_p)* and a series reactance *(C_s).* The network gives a frequency-sensitive 90° phase shift at the center frequency. The phase detector discussed here is the bipolar double-balanced multiplier popularized by Bilotti [2]. The output of the multiplier (I_o) is filtered, which results in a DC level that changes as the input frequency changes.

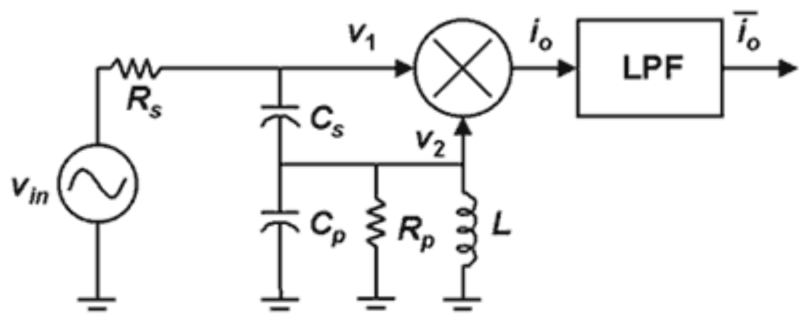

Figure 1: Quadrature demodulator block diagram

Quadrature Demodulator Transfer Function

To derive the transfer function of the quadrature demodulator, the phase shift network is first drawn as a small-signal circuit model (**Figure 2**). The impedance

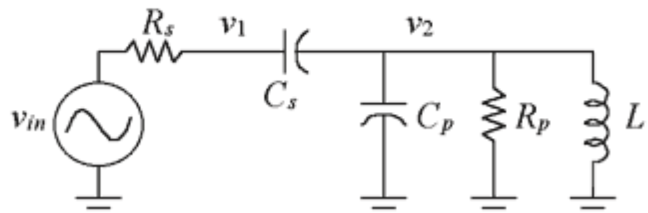

Figure 2: Small-signal model of the quadrature phase-shift network

The ratio of v_2 over v_1 is the ratio of impedances Z_p (s) over (Z_p (s) + 1/sC_s). Simplifying this ratio,

$$\frac{v_2}{v_1} = \frac{C_s L \cdot s^2}{(C_p + C_s)L \cdot s^2 + \frac{L}{R_p} \cdot s + 1}. \qquad (2)$$

The resonant frequency ω_n of this filter is:

$$\omega_n = \frac{1}{\sqrt{L(C_s + C_p)}}. \qquad (3)$$

The quality factor Q of the phase shift network is $R_p/(\omega_n L)$. Next **Equation 2** is

$$\frac{v_2}{v_1} = \frac{jQ \cdot \frac{C_s}{C_s + C_p} \cdot \frac{\omega}{\omega_n}}{1 + jQ\frac{\omega_n}{\omega}\left(\frac{(\omega+\omega_n)(\omega-\omega_n)}{\omega_n^{\ 2}}\right)} \approx \frac{jQ \cdot \frac{C_s}{C_s + C_p}}{1 + \frac{jQ}{\omega_n}(2\Delta\omega)} . \qquad \textbf{(4)}$$

In **Equation 4** , $\Delta\omega$ is the deviation from the carrier frequency, and 2Q $\Delta\omega/\omega_n$ is the normalized deviation. Defining:

$$a = 2Q\frac{\Delta\omega}{\omega_n}, \qquad \textbf{(5)}$$

Equation 4 can be written as:

$$\frac{v_2}{v_1} \approx jQ \cdot \frac{C_s}{C_s + C_p} \cdot \frac{1}{\sqrt{1+a^2}} \angle \tan^{-1} a \qquad \textbf{(6)}$$

Writing v_2 in terms of v_1 ,

$$v_2 = v_1 \cdot Q \cdot \frac{C_s}{C_s + C_p} \frac{1}{\sqrt{1+a^2}} \angle(90^\circ + \tan^{-1} a) \qquad \textbf{(7)}$$

Equation 7 describes the signal at one multiplier input in terms of the signal at the other input. The signal

$$\bar{i}_o = \frac{\omega}{\pi} \int_0^{\pi/\omega} v_2 \cdot g_m dt \qquad (8)$$

For a bipolar differential amplifier, g_m is I_o / V_T where $2I_o$ is the multiplier bias current. Substituting for v_2 and g_m ,

$$\frac{\bar{i}_o}{2I_o} = \frac{\omega}{\pi} \int_0^{\pi/\omega} \frac{V_1}{2V_T} \cdot Q \frac{C_s}{C_s + C_p} \cdot \frac{1}{\sqrt{1+a^2}} \cdot \sin(\omega t + 90^\circ + \tan^{-1} a) dt \qquad (9)$$

where V_1 is the peak voltage of the signal v_1 . Simplifying **Equation 9** yields the transfer function for the quadrature demodulator:

$$\frac{\bar{i}_o}{2I_o} = \frac{2}{\pi} Q \frac{C_s}{C_s + C_p} \frac{V_1}{2V_T} \frac{1}{\sqrt{1+a^2}} \frac{a}{\sqrt{1+a^2}} . \qquad (10)$$

In **Figure 3** , the term $a/(1+a^2)$ from **Equation 10** is plotted versus the normalized frequency deviation *(a).* This plot is the quadrature demodulator s-curve. As the frequency of the signal applied to the demodulator becomes more positive than the natural frequency of the phase shift network, the filtered output of the multiplier increases. Likewise, the filtered output decreases as the frequency of the input signal

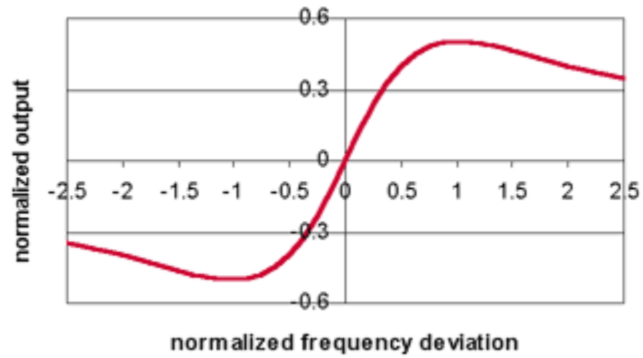

Figure 3: Plot of normalized demodulator output vs. normalized frequency deviation

Integrated Circuit Implementation

Figure 4 shows an integrated circuit implementation of the quadrature demodulator. The input signal v_{in} is supplied from a limiting amplifier and is a square wave of known amplitude. The input signal v_{in} is level shifted, and v_1 is applied to transistors Q_1 and Q_2. The amplitude of v_1 is large enough such that Q_1 and Q_2 are switched completely on or off during each cycle. Capacitor C_s is typically integrated while C_p, L, and R_p are external

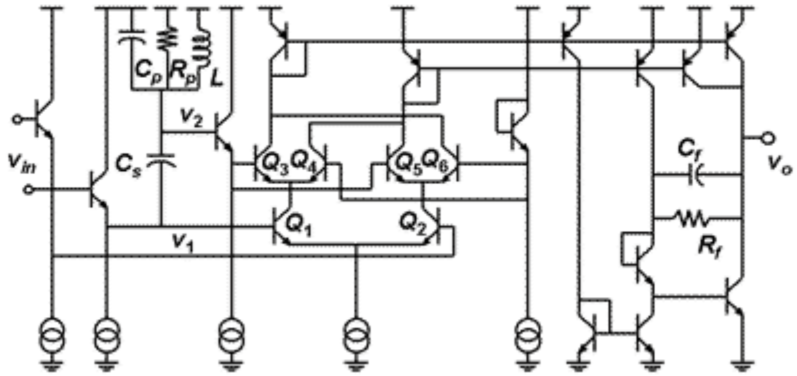

Figure 4: Integrated circuit implementation of the quadrature demodulator