Some Applications of Analog Multiplier MPY634

MPY634 is a wide-bandwidth (10 MHz), four-quadrant[1] analog multiplier with several applications such as analog signal processing, modulation and demodulation, voltage-controlled amplifiers, filters, and oscillators [1]. It is the purpose of this experiment to use the MPY634 multiplier for (a) true rms measurement, (b) phase detection. To begin with, let us consider the Gilbert multiplier cell to see how analog multiplication is achieved in the MPY634.

Gilbert cell [2]

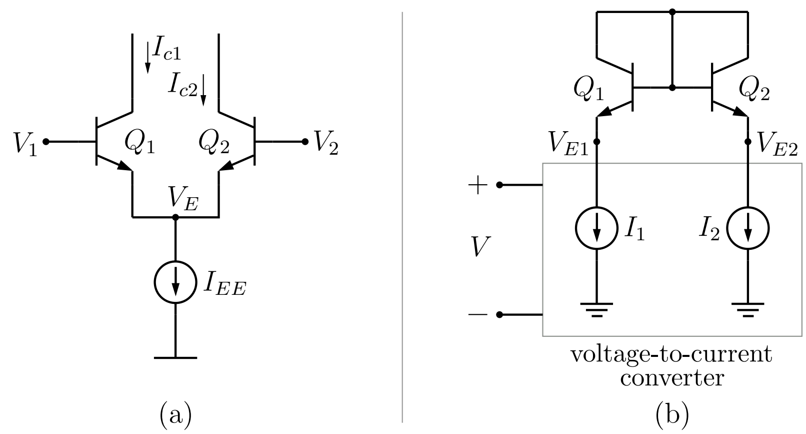

Figure 1: (a) Emitter-coupled pair, (b) Inverse hyperbolic tangent circuit.

At the heart of the Gilbert cell is the matched BJT pair, with identical transistors operating at the same temperature. Fig. 1 shows two blocks consisting of matched BJT pairs. For the emitter-coupled pair, we have

$$I_{c1} = I_s\, e^{(V_1 - V_E)/V_T}, \quad I_{c2} = I_s\, e^{(V_2 - V_E)/V_T}. \tag{1}$$

Using $I_{c1} + I_{c2} = I_{EE}$, we get

$$I_{c1} = \frac{I_{EE}}{1 + e^{-\Delta V/V_T}}, \quad I_{c2} = \frac{I_{EE}}{1 + e^{\Delta V/V_T}}, \tag{2}$$

where $\Delta V = V_1 - V_2$. The difference between I_{c1} and I_{c2} can be written as

$$I_{c1} - I_{c2} = I_{EE}\, \tanh\left(\frac{\Delta V}{V_T}\right). \tag{3}$$

For the circuit of Fig. 1 (b), we assume that the input voltage V is converted to currents I_1 and I_2 such that

$$I_1 = I_0 + K\, V, \quad I_2 = I_0 - K\, V. \tag{4}$$

[1] "Four-quadrant" operation means that both input voltages are allowed to take positive and negative values.

Using these equations and the relationship $I_C = I_s\, e^{V_{BE}/V_T}$, we get

$$V_{E2} - V_{E1} = V_T \,\log \left(\frac{I_0 + KV}{I_0 - KV} \right). \tag{5}$$

We now use the identity, $\tanh^{-1} x = \dfrac{1}{2}\, \log \left(\dfrac{1+x}{1-x} \right)$, and obtain

$$V_{E2} - V_{E1} = 2\, V_T \,\tanh^{-1} \left(\frac{KV}{I_0} \right). \tag{6}$$

With the functional blocks of Figs. 1 (a) and 1 (b), the complete four-quadrant multiplier cell can be constructed, as shown in Fig. 2. By using Eqs. 3 and 6 for this circuit, it can be shown that

$$I_{c35} - I_{c46} \propto V_1 V_2. \tag{7}$$

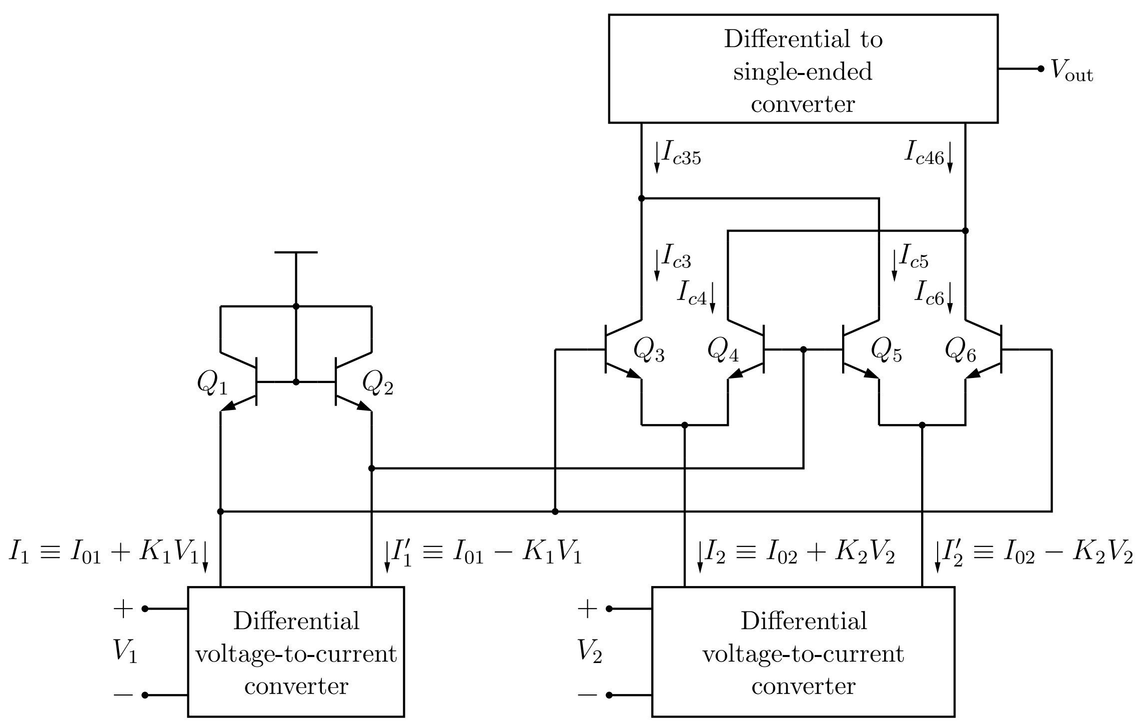

Figure 2: Complete four-quadrant multiplier cell.

The above current difference is converted to a single-ended output voltage to get $V_{\text{out}} = K\, V_1 V_2$ where K is a constant (in 1/Volts). This relationship is valid over a rather wide range, determined by the requirement that the currents I_1, I_1', I_2, I_2' in Fig. 2 must be positive. These conditions can be written in terms of V_1 and V_2 as

$$-\frac{I_{01}}{K_1} < V_1 < \frac{I_{01}}{K_1}, \quad -\frac{I_{02}}{K_2} < V_2 < \frac{I_{02}}{K_2}. \tag{8}$$

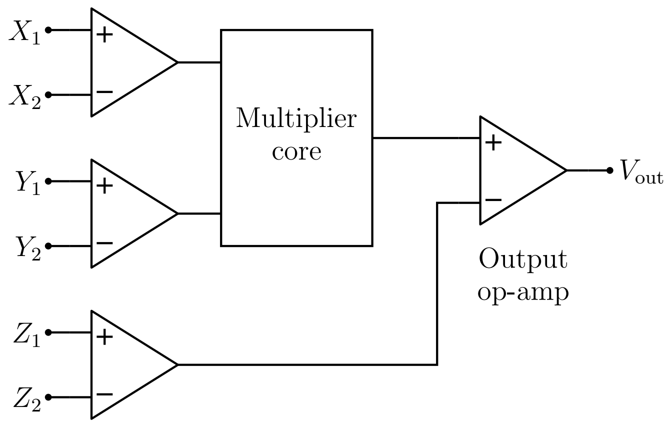

Figure 3: Simplified block diagram of the MPY634 multiplier.

The MPY634 multiplier

A simplified block diagram of the MPY634 Multiplier is shown in Fig. 3. The output voltage is given by

$$V_{\text{out}} = A\left[\frac{(X_1 - X_2)(Y_1 - Y_2)}{SF} - (Z_1 - Z_2)\right], \tag{9}$$

where A is the gain of the output op-amp, and SF is a scaling factor which is set by the manufacturer to 10 V and can be adjusted over a 3 to 10 V range using external resistors (not shown in the figure). The circuit is to be operated in a closed-loop configuration with a negative feedback. In this situation, V_{out} is finite, and since the op-amp gain A is large, we have

$$\frac{(X_1 - X_2)(Y_1 - Y_2)}{SF} - (Z_1 - Z_2) \approx 0. \tag{10}$$

To perform multiplication, we can connect the V_{out} and Z_1 terminals together, and connect Z_2 to ground. In that case,

$$V_{\text{out}} = Z_1 = \frac{(X_1 - X_2)(Y_1 - Y_2)}{SF}. \tag{11}$$

Furthermore, by connecting X_2 and Y_2 also to ground, we can implement multiplication of two single-ended input voltages X_1 and Y_1.

Square root operation

Fig. 4 shows how the MPY634 can be used to perform the square root operation. The input, applied at Z_2, is denoted by V_i in the figure, and the output by V_o. Eq. 10 applied to this situation gives

$$-\frac{V_o^2}{SF} - (0 - V_i) = 0, \tag{12}$$

giving $V_o = \sqrt{SF \times V_i}$. The input voltage V_i is expected to be positive, and if it becomes negative (unintentionally), the diode-R_L combination prevents the circuit from getting into a "latch-up" state in which the op-amp output gets permanently stuck at $-V_{\text{sat}}$.

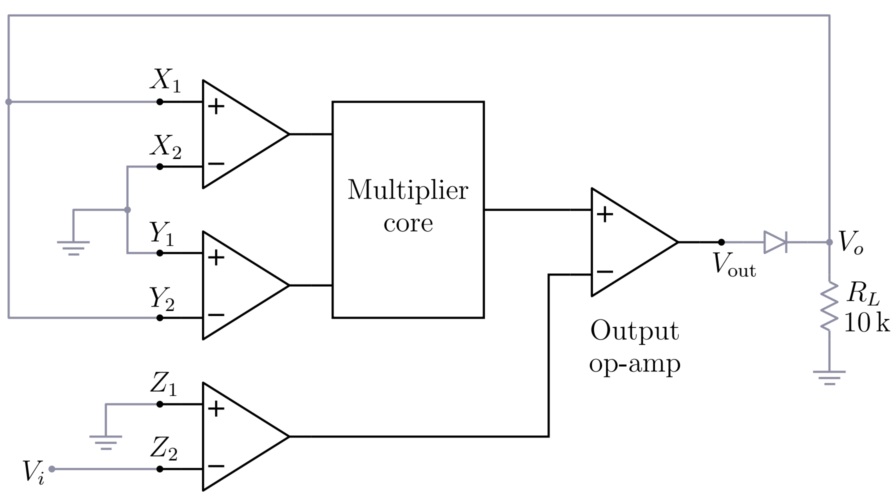

Figure 4: The MPY634 multiplier connected as a square rooter.

True rms measurement

An rms meter designed for sinusoidal inputs can be used to measure rms values of other types of periodic waveforms (square, triangle, for example) by multiplying the output by a suitable scaling factor. This approach is clearly not suitable for an arbitrary periodic waveform, and a "true" rms measurement is required in that case. One possible implementation of true rms measurement using two multipliers – one as a squarer and the other as a square rooter – is shown in Fig. 5. Note that the RC low-pass filter is being used here to average $v_i^2(t)$ by choosing its corner frequency ω_c to be sufficiently small compared to the input frequency[2]. At the same time, ω_c should not be made too small since that would increase the time required for the filter to settle to its steady-state value.

The output is given by

$$v_o = \sqrt{SF \times v_{o1}} = \sqrt{SF \times \frac{1}{T} \int \frac{v_i^2}{SF}\, dt} = \sqrt{\frac{1}{T} \int v_i^2\, dt}, \tag{13}$$

as desired.

Phase detection

A phase detector is an integral part of a lock-in amplifier. In this experiment, we will use a multiplier to obtain a voltage which represents the phase difference between two input voltages $v_1(t) = V_m \sin \omega t$ and $v_2(t) = V_m \sin(\omega t + \alpha)$. The experimental set-up is shown in Fig. 6.

The all-pass filter in the figure is used to generate v_2 which has the same amplitude as v_1,

[2]Think of writing $v_i^2(t)$ as a Fourier series; the only component that contribute to the average value is the zero-frequency (DC) component.

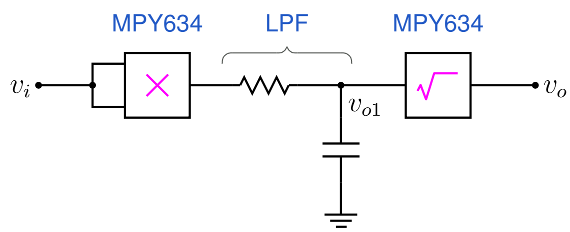

Figure 5: Implementation of true rms measurement using two multipliers.

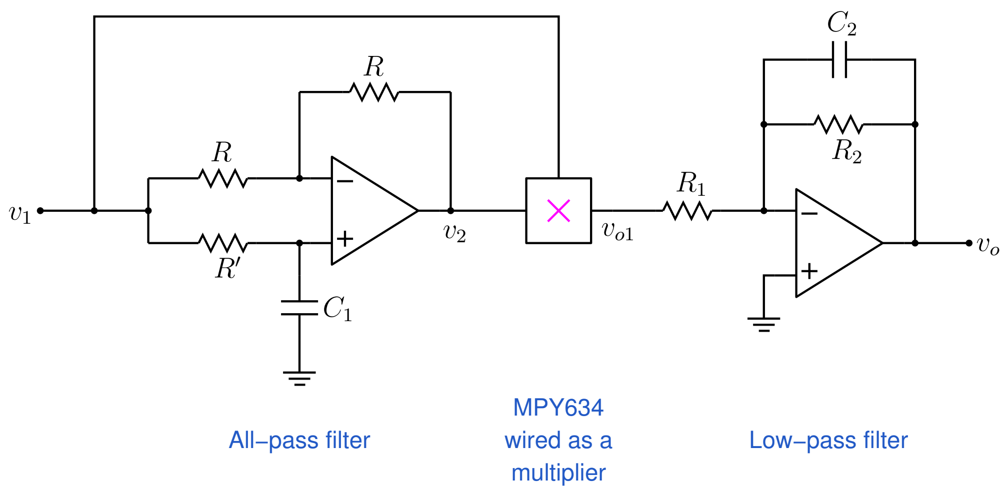

Figure 6: Experimental set-up to demonstrate phase detection using a multiplier.

but a different phase. $V_1(s)$ and $V_2(s)$ are related by

$$V_2(s) = \frac{1 - sR'C_1}{1 + sR'C_1}\, V_1(s), \tag{14}$$

and the phase difference is therefore $\alpha \equiv \angle V_2 - \angle V_1 = -2\tan^{-1} R'C_1$, which varies from 0 to $-\pi$ as $R'C_1$ is varied.

The output of the multiplier is

$$\begin{aligned} v_{o1}(t) &= \frac{1}{SF}\, v_1 v_2 \\ &= \frac{1}{SF}\, (V_m \sin\omega t) \times (V_m \sin(\omega t + \alpha)) \\ &= \frac{1}{2}\frac{V_m^2}{SF}\left[\cos\alpha - \cos(2\omega t + \alpha)\right]. \end{aligned} \tag{15}$$

The low-pass filter provides a gain $(-R_2/R_1)$ and filters out the $2\omega t$ component of $v_{o1}(t)$, giving

$$v_o = -\frac{1}{2}\frac{R_2}{R_1}\frac{V_m^2}{SF}\cos\alpha. \tag{16}$$

References

1. MPY634 data-sheet (`http://www.ti.com/lit/ds/symlink/mpy634.pdf`)
2. P.R. Gray and R.G Meyer, *Analysis and Design of Analog Integrated Circuits.* Singapore: John Wiley and Sons, 1995.