Gilbert Cell Mixers: A Final Project

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1 Gilbert Cell Mixer as a Multiplier

The Gilbert cell mixer analyzed here is a an active circuit consisting of six matched nMOS transistors. These are arranged into three differential pairs. The Gilbert Cell Mixer is a multiplier, taking two input signals and multiplying them together preserving elements of their frequencies and amplitudes. Because of this, it has many use cases including in RF applications.

In a RF communications setup, the mixer is one of the primary components. This is used in transmitters for modulating data signals with carrier frequencies as well as in receivers for demodulation and phase locking.

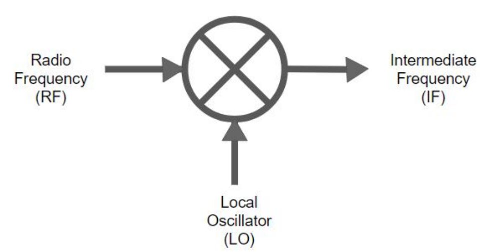

Figure 1: Block diagram mixer showing input signals relationship to output signals. The "X" enclosed by a circle is the traditional symbol used for mixers in block diagrams.

This circuit relies on the behavior of the differential amplifier. The gain of the differential amplifier is a function of the the bias current. For the differential pair consisting of Q_1 and Q_2, the bias current is I_1. For the differential pair consisting of Q_3 and Q_4, the bias current is I_2. For the differential pair consisting of Q_5 and Q_6, the bias current is I_7.

In a Gilbert cell the outputs of the top two differential pairs are connected together into a common set of loads. Here resistors are used as loads to aid in measuring voltage and current. In the Gilbert cell we analyzed, the current through the each resistor is equivalent to the sum of the current going through the nMOS transistors connected to it as determined by Kirchoff's Current Law. By combining this with Ohm's Law gives us the following equations.

$$V_{dd} - V_{IF+} = R(I_3 + I_5)$$

$$V_{dd} - V_{IF-} = R(I_2 + I_4)$$

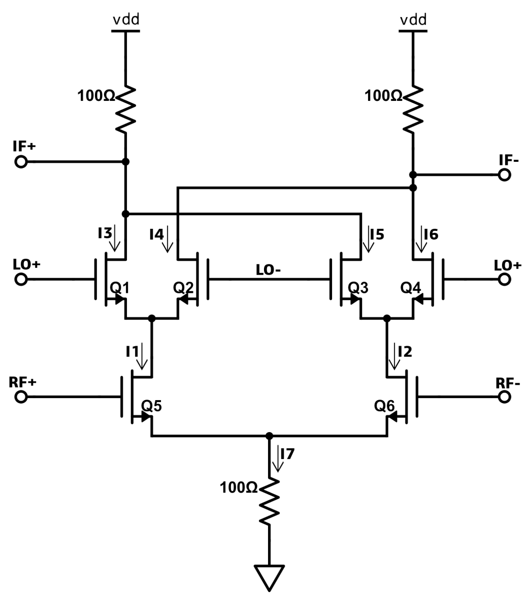

Figure 2: nMOS implementation of Gilbert Cell Mixer.

The gates of the nMOS transistors are cross connected; Q_1 is connected to Q_4 and Q_2 is connected to Q_3. The input here is denoted as the Local Oscillator, LO. The differential gain is proportional to the difference between I_1 and I_2. Depending on whether $I_1 > I_2$ the signal will be noninverting or if $I_1 < I_2$ then it will be inverting. The inputs to the lower differential pair RF determine the current split between I_1 and I_2. The output differential voltage is proportional to the input voltage difference of both LO and RF.

The output differential voltage can be written as the below equation where κ is a scaling factor.

$$V_{IF} = \kappa V_{LO} V_{RF}$$

This is seen when the input signals are compared to the output signals of the circuit in the time domain. We simulated the circuit in LTspice, performing a transient response with a bias voltage set to 2.5 V. The RF differential voltage was set to a sine wave with a frequency of 1000 Hz (high frequency), an amplitude of 0.1 V, and an offset of 0 V. The LO differential voltage was set to a sine wave with a frequency of 50 Hz (low frequency), an amplitude of 0.2 V, and an offset of 0 V. Multiplying the high frequency signal by the low frequency signal resulted in a high frequency signal with the high frequency waves' amplitude modulating at the low frequency. This behavior is seen in figure 3 and 4.

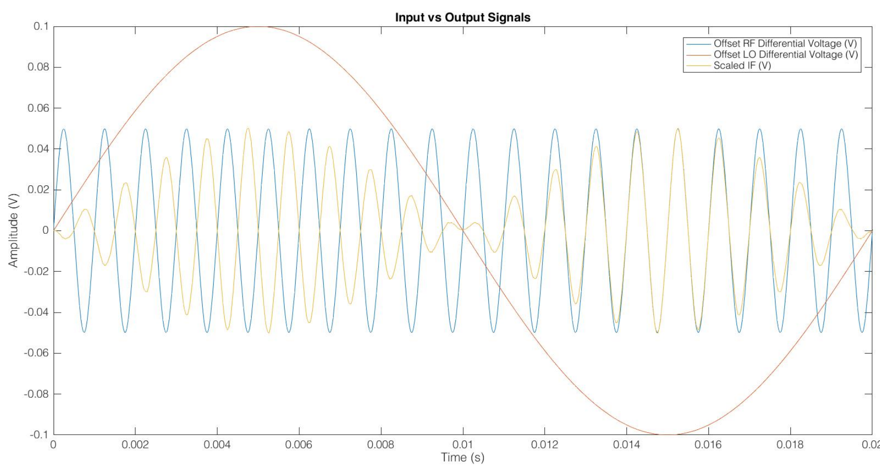

Figure 3: Input and Output differential voltages over time.

In figure 4, this is examined further when the actual output of the LTspice modeled circuit is seen closely following the theoretical MATLAB generated signal that is the product of the sine wave inputs. This shows that the Gilbert Cell mixer multiplies the two input signals. In this figure however, the theoretical is multiplied by a scalar to align with the experimental results. This scalar is the κ value from the equation above.

Also note that the theoretical output is actually inverted in order to align with the output from our LTspice simulation. This also matches with the behavior seen in our Voltage Transfer Characteristic (see later section).

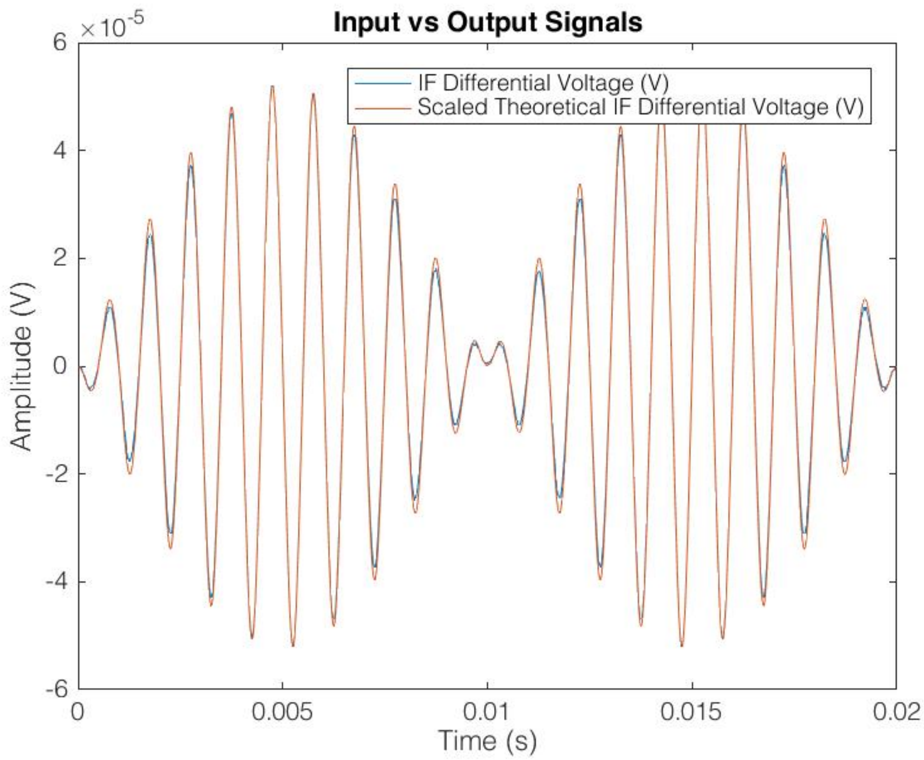

Figure 4: The differential output voltage (IF) of two time varied signal inputs (RF and LO).

As explained above, the output signal is the multiplication of the two input signals (specifically, the amplitude of the output signal is the product of the amplitudes of the input signals at each time point). However, this is scaled by a κ value. In order to determine this κ value, we plotted the actual vs unscaled (and not inverted) theoretical value, as seen in figure 5,

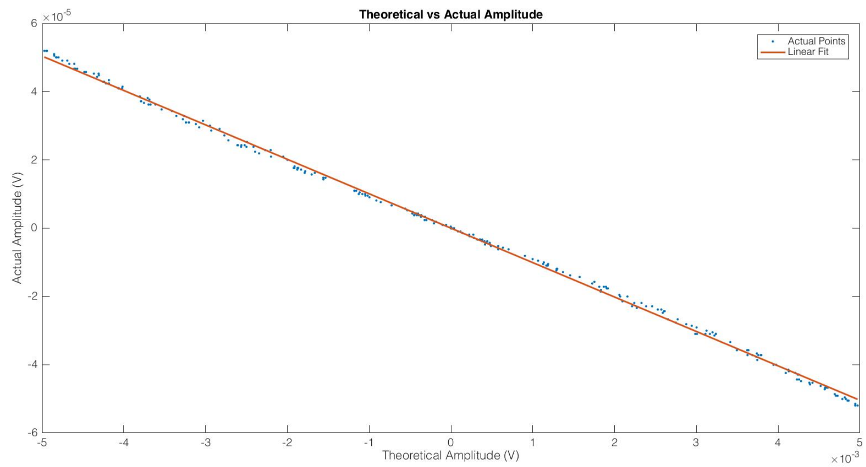

Figure 5: The actual vs theoretical linear fit to determine the κ value.

We then performed linear regression, yielding a slope of -0.0101 and a y-intercept of 2.34e-9 V, a near zero value (compared to the scale at which we are operating). This slope is the value at which the theoretical amplitude has to be multiplied by to reach the actual amplitude achieved by the simulation - aka, the κ value. Hence, -0.0101 is the κ value. Note the negative sign on the slope corresponds with the fact that we had to invert the theoretical signal (in addition to scaling it) in order to get it to align in figure 4.

2 Current-Voltage Characteristics of Gilbert Cell Mixer

As an implementation of an RF mixer, typically sinusoidal signals are input as the differential voltage between the LO- and LO+, and RF- and RF+ input terminals. In order to fully realize the performance of the Gilbert Cell Mixer, we also elected to generate current-voltage characteristics with the differential voltage at LO swept around a RF held at a constant differential voltage. This was done around a constant bias voltage of 2.5 V. The results are seen in figure 6.

We used three static RF differential voltages: 1.5 V, 2.5 V, and 3.5 V. We swept LO from -2.5 V to 2.5 V. When running the simulation, we probed the output currents at both the IF+ and IF- terminals.

The current across the IF- node increases as the differential voltage $(LO_{+} - LO_{-})$ increases. This is contrary to the behavior of the IF+ node, which decreases as the

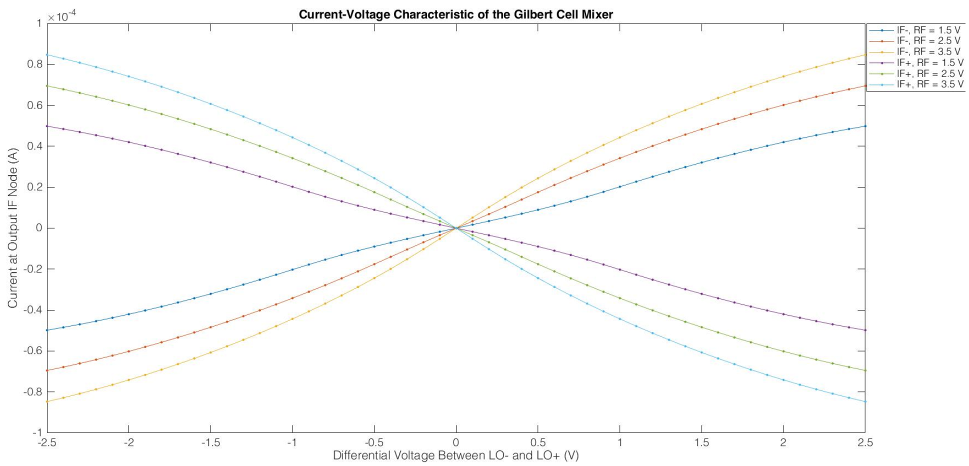

Figure 6: The current-voltage characteristic of the Gilbert Cell Mixer with LO swept around a static RF, at threshold.

differential voltage ($LO_+ - LO_-$) increases. However, if the differential voltage were instead taken so that it was ($LO_- - LO_+$), these behaviors would be reversed. So, the general rule for the Gilbert Cell Mixer output IF currents is that if the LO differential voltage increases, one of the output IF node currents increases, and the other decreases.

Both the IF- and the IF+ node currents increase in magnitude when the static RF voltage increases. The rate of change is also greater. This means that as the RF voltage increases, the current leaving or entering (depending on the set-up - see explanation in previous paragraph) the IF- and IF+ nodes also increases.

3 Voltage Transfer Characteristics of Gilbert Cell Mixer

In the LTspice simulation we held LO at six discrete points as we swept RF from -2.5 V and 2.5 V. This was done in order to understand the inverting and non inverting behavior of the circuit. This was then plotted in MATLAB.

As seen in figure 7, at negative differential LO voltages, there is a upward trend in the output differential IF voltage. At positive differential LO voltages, there is a downward trend in the output differential IF voltage. Note that due to the κ value being negative, the multiplication of the amplitudes are inverted on this graph. For instance, the combination of a negative LO differential voltage and a negative RF

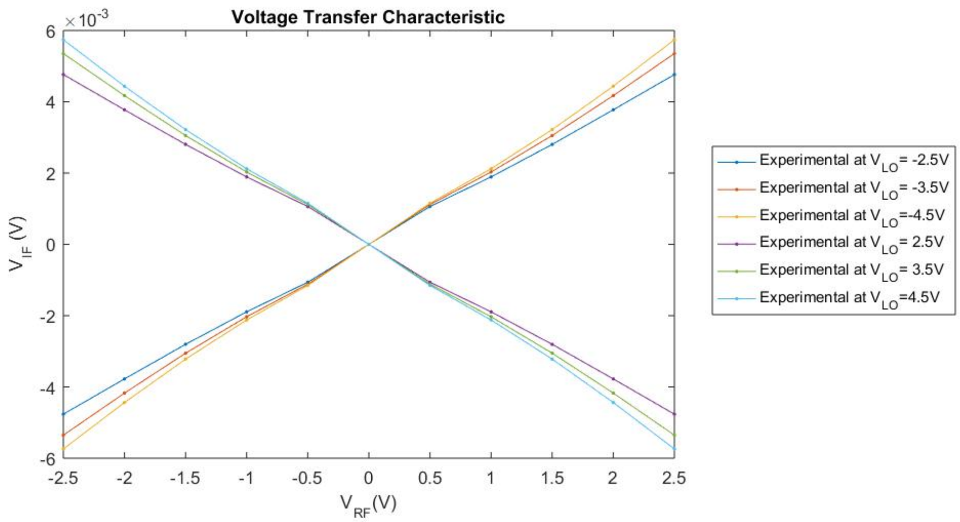

Figure 7: The voltage transfer characteristic of the Gilbert Cell Mixer at six discrete values for V_{LO}.

differential voltage actually outputs a negative IF differential voltage. The output is also scaled down by a magnitude of two - which matches our κ value of 0.0101.

As the RF differential voltage increases in magnitude, the rate of change of the output also increases. The range of the LO differential voltages from -0.5 V to 0.5 V correspond with all values of the RF voltages, but past that point they differ significantly - especially with RF voltages at 2.5 V and -2.5 V.

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