8. Mixer

<u>Chapter 8 Goals</u>

- Become familiar with how a mixer works
- Analyze the mixer in LTspice, generating a spectrum using the FFT function
- Build and test a mixer

8.1 Mixing Theory

The mixer, as depicted in Figure 8.1, multiplies an RF signal with an oscillator signal (the *local oscillator*, or LO) to produce a number of signals at different frequencies. The desired output is known as the difference frequency, which in our radio is also termed the intermediate frequency, or IF.

The mixing action occurs because of nonlinearity in the mixing element, be it a diode or a transistor. A transistor-based mixer, though slightly more complicated, has the advantage of providing signal gain, whereas the diode mixer does not.

Referring to Figure 8.2, the total current i_C through an npn BJT biased in the forward active mode is a function of the total base-emitter voltage, v_{BE}, by the equation

$$i_C = I_C + i_c = I_S \exp\left(\frac{v_{BE}}{V_T}\right) \qquad (8.1)$$

where V_T is the thermal voltage, approximately equal to 25 mV at room temperature, and I_S is the saturation current, typically $10^{-13} - 10^{-16}$ A. In (7.1) the total current consists of a DC component, I_C, and an AC component, i_c. Breaking v_{BE} into its DC and AC parts and rewriting (8.1),

$$i_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \exp\left(\frac{v_{be}}{V_T}\right) \qquad (8.2)$$

or

$$i_C = I_C \exp\left(\frac{v_{be}}{V_T}\right) \qquad (8.3)$$

An exponential term can be written as a MacLaurin Series expansion,

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots \frac{x^n}{n!}$$

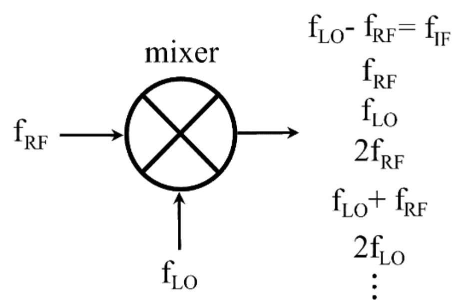

Figure 8.1: block diagram of mixer showing the various frequency components

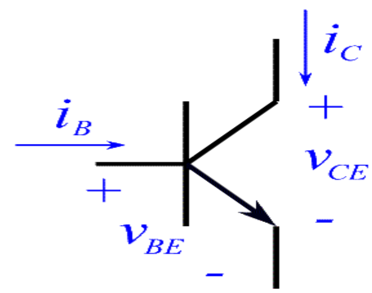

Figure 8.2: the npn BJT

Applying this expansion to (7.3), we have

$$i_C = I_C + \frac{I_C}{V_T} v_{be} + \frac{I_C}{2V_T^2} v_{be}^2 + H.O.T. \qquad (8.4)$$

where, for small values of v_{be}, we can ignore the *higher order terms* (H.O.T.). Comparing (8.4) and (8.1), it is apparent that

$$i_c = \frac{I_C}{V_T} v_{be} + \frac{I_C}{2V_T^2} v_{be}^2 + H.O.T. \qquad (8.5)$$

This result is reassuring in that the first term relates i_c to v_{be} via the transconductance g_m ($g_m = I_C/V_T$).

The second term in (8.5) is the one responsible for mixing. To see how this is so, consider that v_{be} consists of a pair of signals,

$$v_{be} = v_{RF} \cos(\omega_{RF} t) + v_{LO} \cos(\omega_{LO} t) \qquad (8.6)$$

where RF and LO subscripts refer to the RF signal and the local oscillator signal, respectively. Squaring v_{be}, we get

$$\begin{aligned}(v_{be})^2 &= (v_{LO})^2\cos^2(\omega_{LO}t) \\ &+ (v_{RF})^2\cos^2(\omega_{RF}t) \\ &+ 2v_{LO}v_{RF}\cos(\omega_{LO}t)\cos(\omega_{RF}t)\end{aligned} \tag{8.7}$$

Considering the half-angle identity,

$$\cos^2\theta = \frac{1}{2}(1+\cos 2\theta)$$

we see that the first and second terms of (8.7) give us the following radian frequency components: DC, $2\omega_{LO}$ and $2\omega_{RF}$. For the last term, the identity

$$\cos\alpha\cos\beta = \frac{1}{2}\cos(\alpha-\beta)+\frac{1}{2}\cos(\alpha+\beta)$$

shows that the product $\cos(\omega_{LO}t)\cos(\omega_{RF}t)$ gives us two more terms: the difference $\omega_{LO} - \omega_{RF}$ and the sum $\omega_{LO} + \omega_{RF}$.

(Note: the neglected higher order terms generate even more frequency components in the output. The components can be important and are considered in more advanced discussions on mixers.)

8.2 Mixer Simulation in LTSpice

1. Build the mixer circuit displayed in Figure 8.3. The RF and LO sources are VSIN sources with the properties. Place the voltage marker on the load resistance as shown.

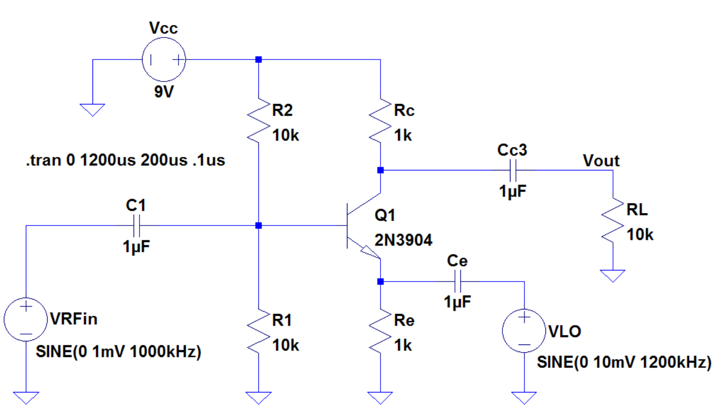

Figure 8.3: The first attempt at a mixing circuit

2. In the simulate – edit simulation cmd, set the following under Transient simulation:
   Stop Time: 1200us
   Time to Start Saving Data: 200us
   Maximum Timestep: .1us
   Simulate and view Vout.

Delay of 200us before saving data will help get rid of start-up noise in the data, allowing the circuit to reach steady state. You can play with the maximum timestep. The goal is to get a nice sharp fourier transform. Speaking of which…

3. In the plot window, View menu, select FFT (see Test & Measurement Lab 1 for a refresher) and again choose Vout. This will generate an output spectrum, a portion of which is shown in Figure 8.4.

- Notice the output at 200 kHz!
- Placing the cursor over either the x or y axis text will show as a little ruler. Right-clicking and choosing 'manual limits' will allow change to the axes. Figure 8.4 displays the result after zooming in to a frequency range of interest.

4. Carefully analyze the output spectrum to estimate the RF signal gain. This is the voltage output amplitude at the RF frequency divided by the input RF signal amplitude. Table 8.1 shows the estimated gain of the RF signal and the LO signal. Note that a direct gain calculation for the IF signal cannot be determined since there is no input signal at IF!
   We can, however, calculate a *conversion gain*, defined as CG = $v_{IF}/v_{RF(in)}$, or in dB as

$$CG(dB) = 20\log\left(\frac{v_{IF}}{v_{RF(in)}}\right) \tag{8.8}$$

Calculate the conversion gain, in dB, for this default case.

CG(dB) = ___________dB

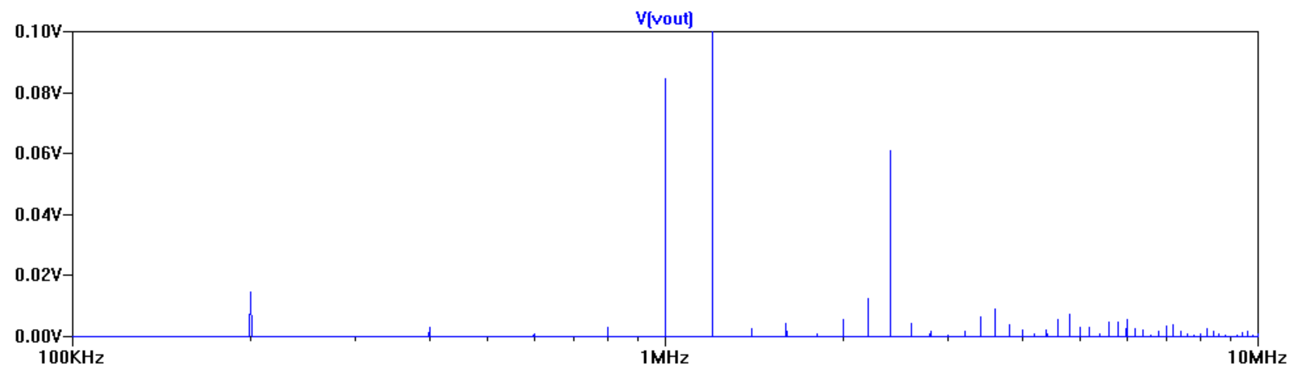

Figure 8.4: A portion of the FFT output from simulation of the circuit in Figure 8.3

5. Change the simulation to a DC Op Pnt and determine the Q point for the transistor in this configuration. Enter the results in Table 8.1 for the default case.

6. Change R_E to 470 Ω , simulate and fill in Table 8.1 for this case. Your value for V_{CE} should be close to 0.1 V or so, meaning the transistor is operating in the saturation mode. How do these results compare with the default case?

7. Return to the default case, with R_E = 1 kΩ. Now add an RFC ("RF Choke", or large value inductance) to hide the Rc resistor from the AC circuit, as shown in Figure 8.5. Simulate and fill in Table 8.1 for this case. What is the effect of adding the RFC?

Table 8.1 Data for LTspice analysis of mixer circuit

	Default	R_E = 470 Ω	add RFC to default	Add BPF and RFC to default
V_{CE}				
I_C				
1200 kHz:				
v_{LO}	850 mV			
$A_{vLO} = v_{LO}/10mV$	85 V/V			
1000 kHz				
v_{RFout}	85 mV			
$A_{vRF} = v_{RFout}/1mV$	85 V/V			
200 kHz				
v_{IFout}	14 mV			
$CG = v_{IFout}/1mV$	14 V/V			

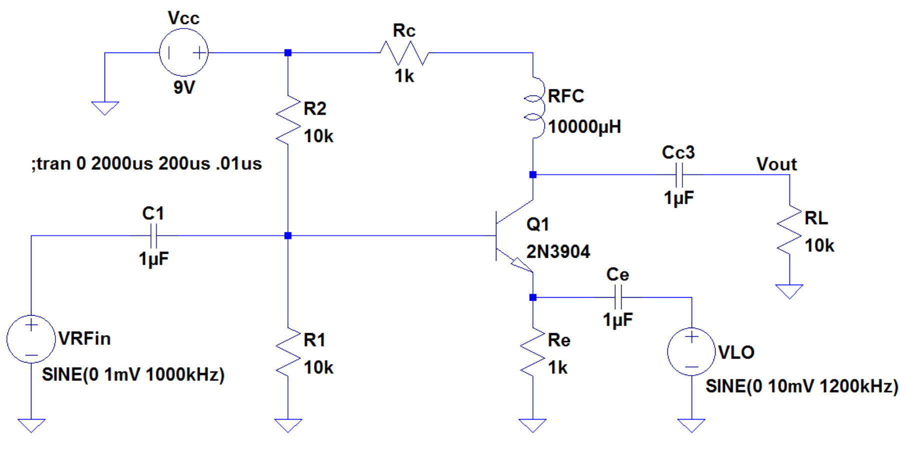

Figure 8.5 Mixer including an RFC

8. Let us now place the bandpass filter (from section 7) between our mixer and our load. Your new circuit should appear as in Figure 8.6.

- Notice we are selecting C3 to be 0.0633 µF, which is not the actual value of your BPF capacitor. We do this to ensure a BPF peak at 200 kHz for our simulation. The alternative would be to adjust f_{LO} until the actual BPF peak is reached.
- Students have found that replacing the 1mV amplitude of VRFin with a 20mV amplitude generates much stronger, more easily viewable signals.
- Simulate this case in LTspice and fill in the last column of Table 8.1. How do the various gains compare with the previous cases? Can you explain this?

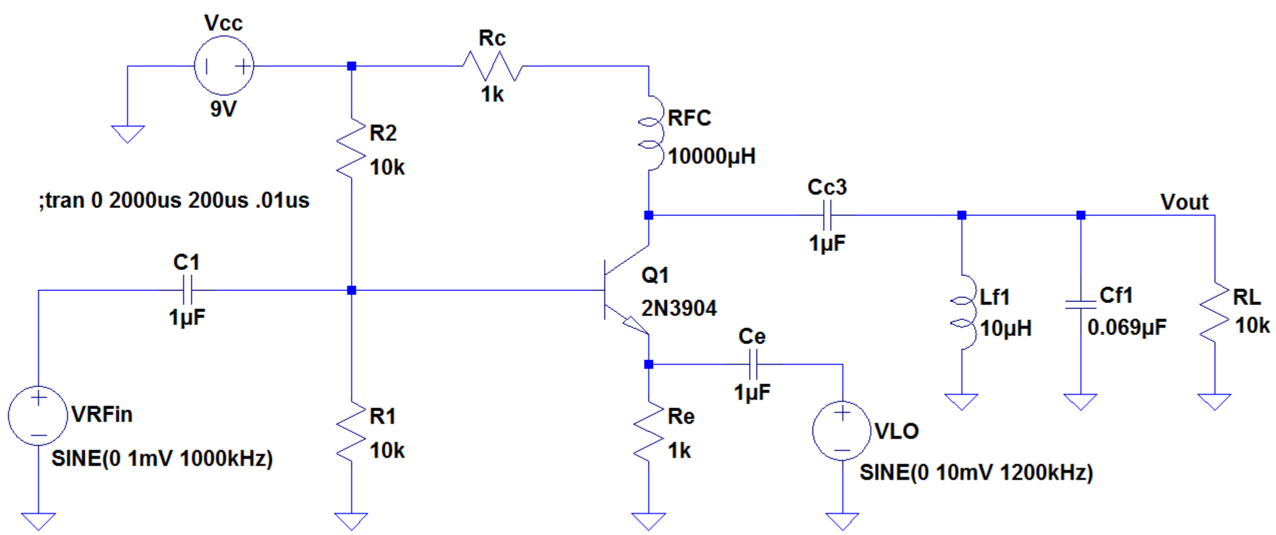

Figure 8.6: Mixer with RFC and BPF added.

8.3 Building/Testing the Mixer Circuit

This lab is best done with your partner, since you will need a second BK Precision generator to conduct the measurements.

1. Build the default circuit of Figure 8.3. Note that you will probably not be able to achieve a 0.001V amplitude for Vrf.

2. On your oscilloscope, observe the output across the load. Now take a look at the frequency spectrum by pressing the Math Menu button and selecting operation 'FFT'. You may need to adjust the time base know. *(Refer to chapter 2 of the lab manual if you have trouble with this.)*

3. Inspect the output spectrum as you vary the oscillator frequency. Are you able to see the difference frequency?

4. Repeat steps 1-3 after inserting the RFC as shown in Figure 8.5.

5. Now add the bandpass filter, realizing the circuit shown in Figure 8.6. Replace C3 with the parallel capacitors needed to achieve 0.069 μF as was done in Chapter 7.

- You will change the signal levels from Figure 8.6 since the 4040 output can't go down to 1 mV. Try VRFin = 20 mV and VLO = 200 mV.
- Since your inductors and capacitors are non-ideal you will not know the exact resonance frequency of the filter, so inspect the frequency spectrum as you slowly vary the oscillator frequency. You should be able to sweep the oscillator frequency such that the output difference frequency occurs at the filter resonance. This will be the intermediate frequency (the IF, also known as the difference frequency) of your radio. Indicate this frequency here:

IF = ___________________

(notes)