CornellEngineering
Electrical and Computer Engineering

ECE 4880: RF Systems

Fall 2016

Lab 5: Oscillators and Mixers

1 Learning Objectives

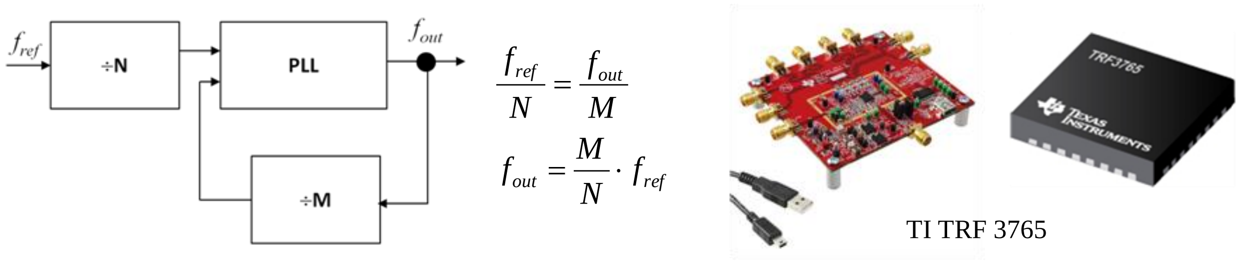
The students will learn to:

1) Understand the functions of oscillators and mixers with small signal power.
2) Explore the nonideal characteristics (noise and nonlinearity) of oscillators and mixers with non-perfect analyzers.
3) Practice the analysis and tracing of spurs (undesirable frequency components) in a signal chain with some frequency strategy.

2 Background Information

2.1 The Oscillator

The local oscillator (LO) is of ultimate importance to the radio transceiver in performing frequency conversion and in frequency strategy. As the transmitter-to-receiver link is at two locations with different manufacturing time (and possibly two different temperatures), the modulation and demodulation will ONLY work accurately if the two LOs are very much the same (a process called synchronization). The amplitude and phase noises of LO are also critical, as those are directly added to the signal chain as well. The frequency synthesizer becomes even more important for the "cognitive radio" (i.e., the channel select is done after evaluation of the present situation), as LO may need to change frequency even faster than the conventional frequency hopping scheme. Classical frequency synthesizer is made by the rational divider-PLL feedback loop as shown in Fig. 1. A **reference frequency** f_{ref} (around 1MHz or the channel bandwidth for the particular application) is often derived from mechanical oscillations that have minimal manufacturing and temperature variations such as a quartz oscillator, or from clock tower/satellite broadcast. The output frequency f_{out} can **inherit** the high quality in f_{ref} for this rational synthesizer. The divider can be implemented digitally with counter circuits. Changing f_{out} frequency by digital control of N and M often takes a delay more than 1,000 cycles of f_{out} (for 1GHz, this is about 1μs), which needs to be taken into consideration during channel selection by mixers.



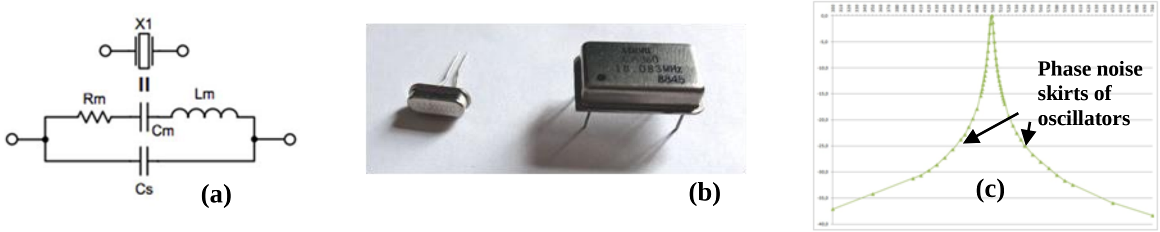
$$\frac{f_{ref}}{N} = \frac{f_{out}}{M}$$

$$f_{out} = \frac{M}{N} \cdot f_{ref}$$

Fig. 1. Classical rational frequency synthesizer.

The reference frequency f_{ref} also needs to have very small phase noise to avoid polluting the signal chain. Often the electromechanical quartz or crystal oscillator is based on the piezoelectric resonance of a specially cut quartz as shown in Fig. 2. The operation can be reasonably modeled by the van Dyke resonator circuits also as shown. The quality factor Q is often above 1,000 and the temperature coefficient is typically very small ($<10^{-7}\ {}^{o}\mathrm{C}^{-1}$).

$$f = f_0\left(1 - 0.04ppm(T - T_0)^2\right) \qquad (1)$$



Phase noise skirts of oscillators

Fig. 2. Crystal oscillators based on piezoelectric quartz crystal vibration: (a) Circuit symbols and van Dyke equivalent circuits; (b) Hermetic packaging to reduce the influence from ambient air; (c) Typical resonator response with $Q > 1{,}000$.

2.2 The Mixer

Frequency mixer circuits generate $\omega_1 \pm \omega_2$ frequency components from input of ω_1 and ω_2. This can be achieved with any nonlinear elements when the signal $s_1(\omega_1) \pm s_2(\omega_2)$ goes through a quadratic nonlinearity (seen as the Taylor expansion of the nonlinear transfer function), or an active multiplier (such as the Gilbert multiplier which comes with a gain as well), or by switching. The basic function of the multiplier is the prosthaphaeresis (product to sum) identity:

$$\sin(\omega_1 t)\sin(\omega_2 t) = \frac{\cos((\omega_1 - \omega_2)t) - \cos((\omega_1 + \omega_2)t)}{2} \qquad (2)$$

Mixers are typically done in lumped elements (diode or transistors) when the signal level is relatively small, and therefore, mixer description often contains the cutoff frequency f_T. The input and output are often taken differentially, with or without impedance match (as the reflection will be small as well). The most common RF mixer in a superhyterodyne receiver has f_{RF} (radio frequency, i.e., carrier tone from the antenna) and f_{LO} (local oscillator from the frequency synthesizer) as the input, and f_{IF} (intermediate frequency) as output, by

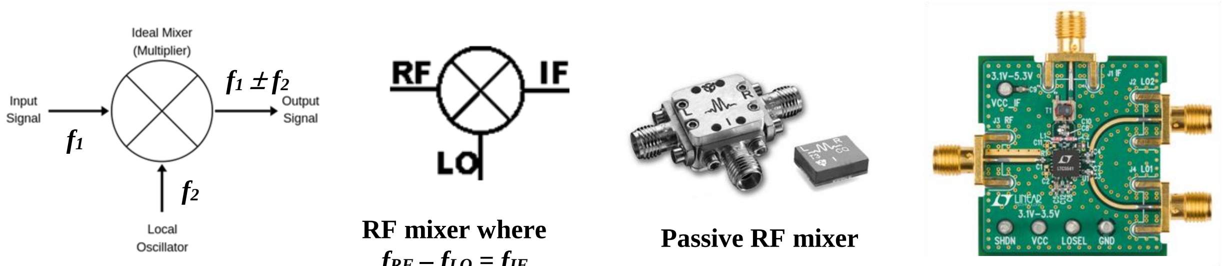
$$f_{RF} - f_{LO} = f_{IF} \qquad (3)$$

where the sum of $f_{RF} + f_{LO}$ is discarded by low-pass filters. Typical mixers are illustrated in Fig. 3. Surely we have more than just $\omega_1 \pm \omega_2$ frequency components being generated from the nonlinear mixer function. Other harmonics such as $2\omega_1$, $2\omega_2$, $2\omega_1 - \omega_2$, $2\omega_2 - \omega_1$ $2\omega_1 - 2\omega_2$, and $2\omega_2 - 2\omega_1$are also important in the signal chain. Such unwanted frequencies, some out of band and some in band, are called the “spurs”. After interaction of noise and nonlinearity (notice that mixers are by definition nonlinear), spurs from mixers are hard but important to trace out.

The mixer is used in the transmitter signal chain as well. Assume that the baseband data rate can be represented by ω_{base}, the mixing in the transmitter signal chain with f_{LO} closed to the intended carrier frequency is:

$$\sin(\omega_{base}t)\sin(\omega_{LO}t) = \frac{\cos((\omega_{LO} - \omega_{base})t) - \cos((\omega_{LO} + \omega_{base})t)}{2} \qquad (4)$$

where $f_{LO} - f_{base}$ is called the lower side band and $f_{LO} + f_{base}$ the upper side band. Although they can be used together, most often for data-heavy wireless communication only one side is used to minimize the spectral cost. However, during the receiver down mixing, the noise from the other side (called the image frequency) will still be coupled to the receiver chain.



Generic mixer

RF mixer where $f_{RF} - f_{LO} = f_{IF}$

Passive RF mixer

Active RF quadrature mixer

Fig. 3. Mixer schematics and examples

2.3 Tracing spurs

The frequency strategy has been the heart of multi-access wireless communication from Day 1 of radio development history. Frequency division or the orthogonality in the trigonometry functions, thanks to the foundation laid out by geniuses Leonhard Euler and Joseph Fourier, has been the key concept behind sharing the free space and affordable/realistic electronic components. However, the main component to realize the mixer has to be nonlinear by definition, and spurious frequencies, or spurs, can be generated as a side product. When the mixer nonlinearity interacts with the noise, especially when the power is strong for f_{RF} (in case of jamming) or f_{LO} (in case of obtaining RF gains from the mixer), it may take the RF engineers a long time to debug these spurs.

Measuring spurs from mixers is often not straightforward. Similar to measuring intermodulation distortion in amplifiers, when you are measuring spurs your measurement equipment itself can mislead you into thinking the mixer is causing spurs, when it is really coming from the equipment itself, such as the Spectrum or Network analyzers, which are transceivers with mixers inside anyway.

The first confusion in spur testing comes from not filtering the output of the synthesizers. Any tunable synthesizer will produce some amount of spurious content (in addition to producing f_{IF} for example, it will also produce f_{2IF} and f_{3IF}) and if these higher order terms are not filtered out they will significantly affect the number and levels of spurs.

Every spectrum analyzer has a mixer at the front end, and this mixer can cause intermodulation distortion such as IM2 and IM3. This distortion can be reduced by placing the attenuator in front of it. You might ask: “why not just turn down the IF power into the mixer down to get the output power down?” The answer is that spurious products do NOT increase or decrease linearly with an increase or decrease in power the way the fundamental does. Higher order IF spurs (i.e. $2f_{IF} + f_{LO}$ and $3f_{IF} + 2f_{LO}$ but not $f_{IF} + 3f_{LO}$, which is third order in LO) will increase with power according to the IF orders in input power. For example, if the IF power increases by 3 dB, the $2f_{IF} + f_{LO}$ will increase by 6 dB. This is why it is easier to see the spurs by putting a larger power into the mixer and then attenuate the output.

One possible way to help determine if observed spurs are generated in the mixer or in the spectrum analyzer is to swap the 10dB attenuator for a 20dB attenuator. If the observed spurs drop 10db like the fundamental does, then the spurs were likely from the mixer. If they drop by 20 or 30dB or more, then they are likely generated in the spectrum analyzer.

An example of the signal chain to trace spurs is shown in Fig. 4. The two chains contain optional bandpass filter, amplifier and attenuator. The amplifier and attenuator pair not only gives more freedom in choosing the power of f_{IF} and f_{LO} into the mixer, but also increases the number of spurs. For example, even if the gains of the amplifier and the attenuator cancel each other for the fundamental frequency, the spurs out of the amplifier will still be shown at the output of the attenuator.

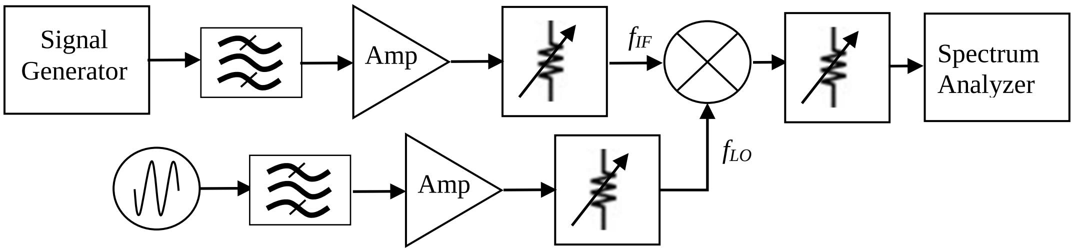


Fig. 4. An example of the signal chain to practice tracing the spurs.

3 Lab Procedures

This lab will have a procedure different from previous labs. Please feel free to invent the signal chain connection to maximize your investigation. Do remember that the input power to the spectrum analyzer needs to be kept low. To be safe, do not exceed 20dBm ever (though the specification is 30dBm).

3.1 Component characterization

1. Obtain one oscillator (ZX95-1600W-S+), two ZX60-2510M-S amplifiers, two bandpass/lowpass filters (ZFBP-70-S+, VLF-1200+), a set of attenuators and a mixer (ZX05-42MH-S+) from TA. The specification for these components are:

   Oscillator:
   ZX95-1600W-S+:
   - Absolute max. supply voltage: 12 V
   - Frequency range, 800 to 1600 MHz
   - Maximum power output, +9 dBm
   - Phase Noise(offset frequencies),
     -72 dBc/Hz (@1 kHz), -99 dBc/Hz (@10 kHz), -122 dBc/Hz(@100 kHz)
   - Harmonics, F2: -20.7 dBc, F3: -34.6 dBc, F4: 39.1 dBc (@Vcc: 11.5V, Vtune: 10V)

   Amplifier:
   ZX60-2510M-S specifications (5V dc):
   - Noise figure, 5.4 dB @ 1.1 GHz

- BW, 0.5 – 2.5 GHz
- Gain, 12.77 dB @ 1.1 GHz
- OIP_3, 28.8 dBm @ 1 GHz
- P_{out} at 1 dB compression, 15.96 dBm @1.1 GHz

Bandpass/lowpass filter:
ZFBP-70+ (for IF)

- Center frequency, 70 MHz
- Passband, 69-71 MHz (loss<7dB)
- Insertion loss, 5.65 dB (@70 MHz)

VLF-1200 (for LO)

- Passband, DC-1200 MHz (loss<1 dB)
- Stop band, 1865 MHz (20 dB), 2-5 GHz (30 dB)

Mixer:
ZX05-42MH+

- LO Power, 13 dBm
- LO/RF, 5-4200 MHz
- IF, DC-3500 MHz
- Conversion loss (total range max.), 11.8 dB

Max power output of signal generator is 20 dBm @ 70MHz)

2. Use the spectrum analyzer to characterize the oscillator and the signal generator around the frequency for your signal chain design below. Zoom in and out of the bandwidth resolution of the spectrum analyzer to possibly identify the phase noise skirt and the spurious signals out of the oscillators and signal generators.
3. Use the network analyzer to characterize your amplifiers, attenuators and bandpass filters at a single testing power of –20dBm over the frequency from 0.4 to 3.0 GHz.

3.2 Finding spurs of the signal chain of your design.

1. Design ONE signal chain that can give at least six spurs that you can clearly identify the source (e.x., $mf_{IF} + nf_{LO}$ after the mixer).
2. When you need to isolate the source of the spurs, feel free to test your signal chains by adding or removing attenuators and bandpass filters.
3. You will be given only 1.5 hours for your trial, so that this lab does not become too long.

4. Optional Exploration

For the oscillator, mixer and amplifier, what are their DC power consumption levels at your setup? What are the ratios of the RF power outputs in ratio with the DC power inputs?

5. Report Guidelines

In your lab report, present the following information. Feel free to expand the description or explanation for your reasoning of spur tracing.

1. Describe your component characterization by the spectrum and network analyzers. Compare your test results to the given specification.

2. Describe your design rationale of the signal chain for generating and tracing the spurs as an output of the mixer.
3. Present your finding of the spurs that can be clearly identified from their sources.

For report submission, please name your lab reports as: netid_netid_ECE4880_Lab5 for two students in a lab group. Submit your final report in Word or pdf to kan@ece.cornell.edu. The report should be by each group. Submit your Matlab script or Excel sheet for the de-embedding procedure as a separate file.