IN5240
Review: Mixers and Oscillators

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Frequency Conversion

- RF wanted signal is down-converted by a mixer i.e., multiplication with a local oscillator (LO), $f_{LO}$ in time domain.
- Multiplication in time domain $\rightarrow$ convolution in frequency domain (shift of RF signal)
Image is the unwanted signal that lies symmetrically to the RF signal of interest with respect to the $f_{LO}$.
Hartley Receiver

Spectrum of sine and cosine are asymmetrical → image
Noise Mixing

• Receive mixer down converts wanted and the image bands to IF frequency $\rightarrow$ folding of noise at image frequency on top of wanted band at IF, and is:
  – Noise at desired and image RF bands down converted $\rightarrow$ IF
  – Added noise from mixer circuit

• If the mixer is noiseless, SSB NF is 3 dB because of the image noise folding
SSB and DSB Noise

- SSB NF assumes no signal at the image frequency except source noise
- DSB NF assumes image band w/ noise and an image signal equal to the wanted signal
RF Mixers
Performance Metrics

• Noise
• Linearity: P1dB, input inferred intercept points (IIP3, IIP2)
  – OP1dB = IP1dB + (G − 1)
  – IP1dB + 10.6 dB = IIP3
• Voltage conversion gain/loss
• Port-to-port isolation (LO-RF, RF-LO and LO-IF)
  – Leakage from a port to another is undesirable
• Supply voltage
• Power dissipation
Passive and Active Mixers

• Current and voltage mixers $\rightarrow$ transistors are switches
• What is the ideal LO waveform?
  – RF signal is multiplied by square wave not sinusoidal
Single and Double Balanced Mixers

- LO-RF Feedthrough
- RF-LO Feedthrough
- LO-IF Feedthrough
- All other combinations...

What is the ideal LO waveform? [Razavi, EE215C]
Passive Voltage Mixer

- Active devices (transistors) operate in triode
- Large signals at input/output → difficult to completely turn on/off transistors

\[ V_{out}[\omega] = \frac{2}{\pi} V_{RF}[\omega - \omega_{LO}] \]
Passive Current Mixer

- Active devices (transistors) operate in triode
- Low input impedance of transimpedance amplifier input → small voltage swings at source/drain
Active Current Mixer

- Transconductor stage $\rightarrow$ input voltage to current
- Switches (transistors) operate in saturation (i.e., cascades coupling/de-coupling RF to IF)

$$I_{RF} = g_m V_{RF}/2$$

$$V_{out}[\omega] = \frac{2}{\pi} (g_m R) V_{RF} [\omega - \omega_{LO}]$$
## Mixer Comparison

<table>
<thead>
<tr>
<th>Type</th>
<th>Transistor Operation</th>
<th>Signal Swing</th>
<th>Conversion Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Passive</td>
<td>Triode</td>
<td>Limited by switch topology</td>
<td>$\frac{2}{\pi}$</td>
</tr>
<tr>
<td>Current Passive</td>
<td>Triode</td>
<td>Limited by TIA impedance</td>
<td>$(\frac{2}{\pi}) \times R$</td>
</tr>
<tr>
<td>Active</td>
<td>Saturation</td>
<td>Limited by bias current and load</td>
<td>$g_m (\frac{2}{\pi}) \times R$</td>
</tr>
</tbody>
</table>
What is an Oscillator?

- Converts dc power $\to$ sinusoidal waveform
- High-Q LC tank or a resonator (crystal, cavity, …)
  - Lossy LC-tank $\to$ amplitude of the oscillator decays
- Oscillation frequency, power, phase noise/jitter, stability, tuning range
Oscillator Design

• Amplitude and frequency stability
• Concept of negative resistance
• Oscillator topologies (Colpitts, Hartley, Clapp, Cross-coupled, …)
• Injection locked oscillators
  – Locking range, injection pulling,
Positive Feedback

- Oscillators \(\rightarrow\) feedback systems
- Fraction of the output signal is fed back to sustain oscillations \(\rightarrow\) ‘injected’ energy required to compensate for lossy tank
Barkhausen’s Criterion
Loop Gain ($|A\beta|$)

• Magnitude of the product of open loop gain and the magnitude of the feedback factor of the amplifier is unity
  - $|A\beta| = 1$

• System poles are on $j\omega$-axis $\rightarrow$ constant amplitude oscillations
  - $|A\beta| < 1 \rightarrow$ decay
  - $|A\beta| > 1 \rightarrow$ amplitude increases exponential to steady-state

• Phase shift around the loop is 0 or integral multiples of $2\pi$
Connect a test current source as before. Performing KCL,

\[ i_x = g_m v_1 + (v_1 v_x) j\omega C_1 + (v_1 g_m + g_m v_1) = 0 \]

Where \( C'_2 = C_2 + C' \). Notice that \( C_\mu \) can be absorbed into the tank.

Using the above result we have

\[ G_x = \frac{i_x}{v_x} = -\frac{g_m}{n} + j\omega \frac{C_1 C'_2}{C_1 + C'_2} \]
Clapp

\[ g_m > R_s \omega^2 C_1 C_2 \]
Single-MOS Oscillators

A. M. Niknejad
University of California, Berkeley

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Cross-Coupled Resistance

\[ G_x = \frac{i_x}{v_x} = -\frac{g_m}{2} \]
Cross-Coupled Resistance

DC 1/f noise contributes to the 1/f³ region!
Varactor: ‘p’ of the diode is connected to virtual ground

\[ TR = 2 \frac{f_{max} - f_{min}}{f_{max} + f_{min}} \]

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Injection Locking in LC Tanks

In order to determine the lock range (the range of

\[ \begin{align*}
|H|_0 &= \frac{\omega_0}{\omega_1} \quad \omega_0 < \omega_1 \\
\angle H_0 &= \phi_0 \\
\omega_0 &= \frac{2Q I_{inj}}{\omega_{osc}} \\
\phi_0 &= \tan^{-1}\left(\frac{I_{inj}}{2Q I_{osc}}\right)
\end{align*} \]

Source: [Razavi]
Phase Noise

- Phase noise spectral density (PN) units \(\rightarrow\) dBc/Hz and measured at \(\Delta f\) from the \(f_c\)
- Low spectral purity \(\rightarrow\) convolution of blocker (\(\Delta f\)) & \(f_{LO}\) \(\rightarrow\) noise contribution in RF BW (reciprocal mixing)

\[
PN(\Delta f) = \frac{P_{\text{noise}}(f_{LO} \pm \Delta f)}{P_{\text{carrier}}}
\]

[Liscidini, ISSCC, 2015]
Harmonics $\rightarrow$ Phase Noise
Key References

1. A. M. Niknejad, EECS 142, 242 and 105
3. E. Kim, EEE 194
4. B. Razavi, EE215C