Potentiometric mixers

Basic idea:

\[
\begin{align*}
&\text{triode region MOSFET} \\
&I_D = I_{DS} = \frac{V_{DS}}{R_{DS}} \\
&\text{set } R_{DS} \propto \frac{1}{V_{RF}} \\
&\text{if } V_{DS} = \text{fixed}, \quad I_D = \frac{V_{DS}}{R_{DS}} \propto V_{RF} \\
&\text{if } V_{DS} \propto V_{LO}, \quad I_D \propto V_{RF}, V_{LO}
\end{align*}
\]

Diagram:

- Mixing
- Filter out sum & higher freq. components
Double-balanced structure
+ cancels CM DC
+ cancels non-linear dependence on $g_{ds}, V_{ds}$

$C_N$ & $C_F$ - filter out high-frequency components

GHz input stage (MOSFETs)

Opamp operates @ low freq. (IF, MHz)
+ virtual ground only @ IF

$C_V$ ⇒ signal ground @ high freq.

$M_1-M_4$ in linear region

\[ I_1 = \beta_1 \left[ V_{RF} - V_{L0,DC} - V_{T1} - \frac{(V_{L0} - V_{L0,DC})}{2} \right] (V_{L0} - V_{L0,DC}) \]

\[ I_2 = \beta_2 \left[ V_{RF} - V_{L0,DC} - V_{T2} - \frac{(V_{L0} - V_{L0,DC})}{2} \right] (V_{L0} - V_{L0,DC}) \]

\[ I_3 = \beta_3 \left[ V_{RF} - V_{L0,DC} - V_{T3} - \frac{(V_{L0} - V_{L0,DC})}{2} \right] (V_{L0} - V_{L0,DC}) \]

\[ I_4 = \beta_4 \left[ V_{RF} - V_{L0,DC} - V_{T4} - \frac{(V_{L0} - V_{L0,DC})}{2} \right] (V_{L0} - V_{L0,DC}) \]

\[ I_{01} = I_1 + I_2 \]

\[ I_{02} = I_3 + I_4 \]

\[ V_{out+} - V_{out-} = R_F (I_{02} - I_{01}) = \beta R_F (V_{RF} - V_{RF})(V_{L0} - V_{L0}) \]
* can offer very good linearity e.g. $I_{IP3} \approx 40$dBm
* very high NF (e.g. 30dB)
  → resistive noise of $M_{1-4}$
  → overall DC around the same as
  Gilbert mixer

**Passive mixer**
* extremely low-power operation
* use MOS as switches
* avoids $V \Rightarrow I$ conversion

![Passive Mixer Diagram](attachment:image.png)

+ve phase $\Rightarrow M_1, -M_4$ conducting $\Rightarrow V_{IF} = V_{RF}$
-ve phase $\Rightarrow M_2, -M_3$ conducting $\Rightarrow V_{IF} = -V_{RF}$

$$V_{RF} \rightarrow \times \leftrightarrow \begin{cases} +1 & \text{for } s(t) = 1 \\ -1 & \text{for } s(t) = 0 \end{cases} \rightarrow T_{LO} = \frac{1}{f_{LO}}$$
\[ S(t) = \frac{2}{\pi} \left[ \sin(w_{\text{LO}}t) + \frac{1}{3} \sin(3w_{\text{LO}}t) + \ldots \right] \]

\( \Rightarrow \) output has \( w_{\text{LO}} \pm w_{\text{RF}}, 3w_{\text{LO}} \pm w_{\text{RF}} \) etc.

\[ g_c = \frac{2}{\pi} \left( = -3.92 \text{ dB} \right) \]

practical implementations: \( g_c \sim -6 \text{ dB} \)

* Sinusoidal LO can give larger gain

\[ g_c, \sin = \frac{\pi}{4} \left( = -2.1 \text{ dB} \right) \left[ \text{Ref. Thomas Lee} \right. \]

2nd edition, page 430

* Load filtering T.F.

\[ H(s) = \frac{1}{\frac{sC_L}{g_0,av} + 1} \]

\( \{ g_0,av = \text{average value} \} \)

\( \{ \text{of output conductance} \} \)

* Can use L-match to boost input voltage

( offset conversion loss )

* NF, \( 11 P_3 \) - strong functions of LO drive

\( \text{e.g.} \) NF \( \sim 10 \text{ dB} \) (SSB), \( 11 P_3 \sim 10 \text{ dBm} \)

* no DC current \( \Rightarrow \) can still have \( 1/f \) noise

\( \Rightarrow P_{\text{min}} < 1 \text{ mW is common} \)

\( \Rightarrow \) power consumption only in LO buffers
**Tx Architecture**

Reminder: Bandpass signal $x(t)$ can be written as:

- **Polar:** $x(t) = a(t) \cos(\omega_0 t + \phi(t))$
  - AM
- **Cartesian:** $x(t) = x_I(t)\cos\omega_0 t - x_Q(t)\sin\omega_0 t$
  - $x(t)\cos\phi(t)$ (in-phase)
  - $a(t)\sin\phi(t)$ (quadrature)

**Complex envelope:**

- $x(t) = \Re \left[ x'(t) e^{j\omega_0 t} \right]$
- $x'(t) = x_I(t) + j x_Q(t) = a(t) e^{j\phi(t)}$

$x_I(t)$ & $x_Q(t)$ are real signals

$\Rightarrow x_I(t) \rightarrow x_I(t); x_I(t) = x_I^*(-t)$ etc.

4 pairs of signals can be considered “complex” if they satisfy:

$c = a + jb \quad \& \quad z = x + jy$

$\Rightarrow c + z = (a + x) + j (b + y)$

$\& \quad cz = (ab - xy) + j (bx - ay)$

**Tx Architecture**

- Noise, interference rejection, band selectivity are more relaxed (compared to Rx)
- Obviously, linearity & power efficiency are concerns
1) **Direct-conversion Tx**: (Homodyne)

\[ x(t) = x_I(t) \cos(\omega_0 t) - x_Q(t) \sin(\omega_0 t) \]

**BB signals**

\[ x_I(t) \]

\[ x_Q(t) \]

\[ \text{matching network} \]

\[ \text{Duplexer} \]

\[ R_x \]

*BB signal is produced in the Tx (i.e. it is strong) \Rightarrow noise of mixers is not critical*

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**PA pulling**:

\[ \text{VLO} \]

\[ \text{BPF} \]

\[ \text{PA} \]

*"Injection Locking": PA corrupts VLO spectrum*

\[ \text{High power} \]

\[ \text{VLO} \]

*EM coupling\n*Supply coupling\n*Pulling gets worse if PA is turned on & off periodically (e.g. GSM)
solution: \( \omega_{\text{VCO}} \neq \omega_{\text{LO}} \)

a) Offset LO freq.

\[ \omega_1 \]

\[ \omega_2 \]

\[ \omega_1 + \omega_2 \]

b) LO frequency dividers (very common in modern systems)

\[ \frac{\text{VCO}}{2} \] or \[ \frac{\text{VCO}}{4} \]

\( \div 2 \) circuit can be easily designed to produce 0°, 90° signals

\( \div 2 \) can still have pulling from harmonics of PA output (e.g. 2nd or 4th harmonic)

2) Two-step Tx: another solution to pulling (Heterodyne)
\[ A \]
\[ B \]
\[ C \]
\[ D \]

\[ W_{pa} = W_1 + W_2 \Rightarrow W_1, W_2 \]
\[ W_1 = \text{IF} \text{ (intermediate freq.)} \]
\[ \text{BPF}_1 \Rightarrow \text{remove} W_1 \text{ harmonic} \]
\[ \text{BPF}_2 \Rightarrow \text{remove} (W_1-W_2) \text{ sideband} \]

Remember: \((W_1+W_2) \& (W_1-W_2) - \text{equal amplitudes}\)

\[ \text{BPF}_2 - \text{difficult to realise, off-chip passive device (expensive)} \]

Unwanted Emissions

1) Emission Mask

Very strict regulations on radiated Tx signal
(from wireless standard \& regulating authority)

- negligible radiation in adjacent channels
  \Rightarrow “Emission mask”

- Tx output spectrum must lie below the mask.

India: TRAI vs: FCC
2) Adjacent Channel Power (ACP)
   
   ACP = relative adjacent channel power for modulated signal (dBc)

   $\rightarrow$ ratio of powers integrated over a certain BW

   $\rightarrow$ usually limited by Tx linearity performance (low freq. offsets)

   CDMA - ACPR (ACP ratio)

   WCDMA - ACLR (AC Leakage Power Ratio)

   GSM $\rightarrow$ ORFS (output radio freq. spectrum)

3) Spurs: unwanted freq. components, harmonics, mixers, VCO/PLL, PA non-linearities etc.

   * FDD: spurs in Rx band are very troublesome

   * can act as interferers for other users
4) **Noise**:

* Output thermal noise is critical → raises Rx band noise floor in FDD-based systems (Tx & Rx on simultaneously)

* $P_{SMS} = -174 \text{dBm} + 10 \log B + N_F + SNR \leftarrow \text{is affected}

* (Noise @ Rx input) = (Rx-band noise @ Tx output) - (Duplexer Rejection)

![Diagram](image)

From A to B @ Rx-freq. offset from Tx

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*Example:* Duplexer rejection = 50 dB; $f_{Tx} = 824 \text{ MHz}; f_{Rx} = 869 \text{ MHz}$

*Tx noise @ 45 MHz offset = $-160 \text{ dBc/Hz}; P_{Tx} = +27 \text{ dBm}$

$B = 3.84 \text{ MHz}$

$\Rightarrow N_{Tx} @ B = -160 \text{ dBc/Hz} + 27 \text{ dBm} - 50 \text{ dB}$

$= -183 \text{ dBm/Hz}$

We want $N_{Tx} \ll -174 \text{ dBm/Hz}$ so that noise floor is not raised $10 \log kT$

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**Note:** Rx $\rightarrow$ in-band noise matters most

Tx $\rightarrow$ in-band noise matters less

$\Rightarrow$ Rx-band noise matters most