Radio-Frequency IC Design

Lecture 14:
Transmitters

ELEC 404

Acknowledgement: *RF Microelectronics*, B. Razavi

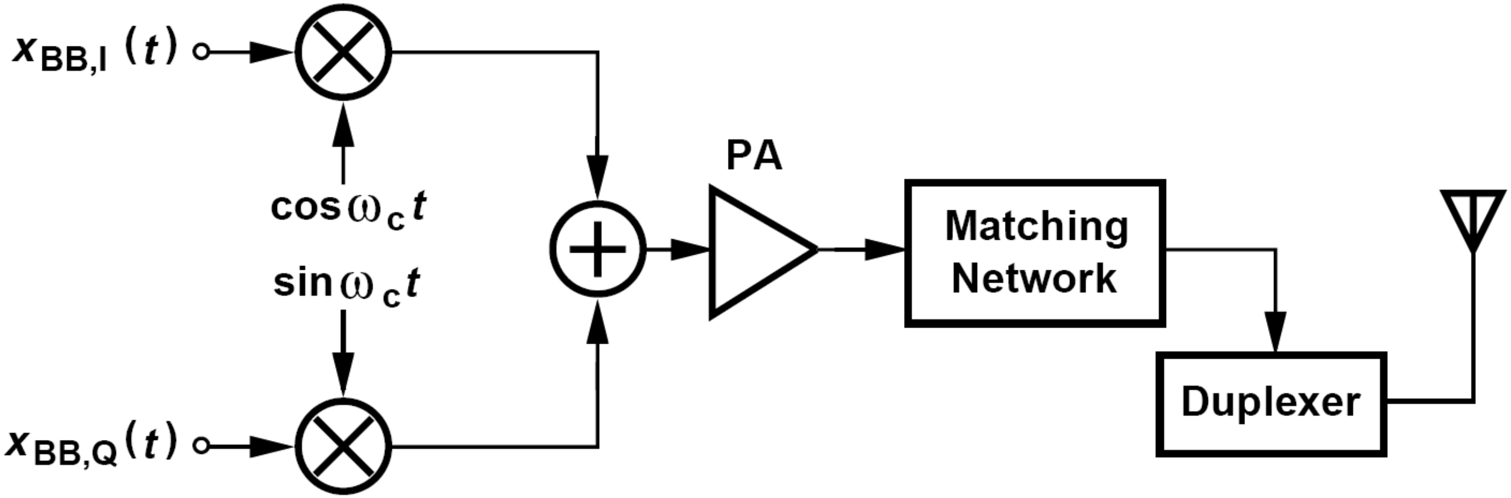
Direct-Conversion TX

A narrowband modulated signal:

$$\begin{aligned} x(t) &= A(t)\cos[\omega_c t + \phi(t)] \\ &= A(t)\cos\omega_c t\cos[\phi(t)] - A(t)\sin\omega_c t\sin[\phi(t)] \end{aligned}$$

Quadrature baseband signals:

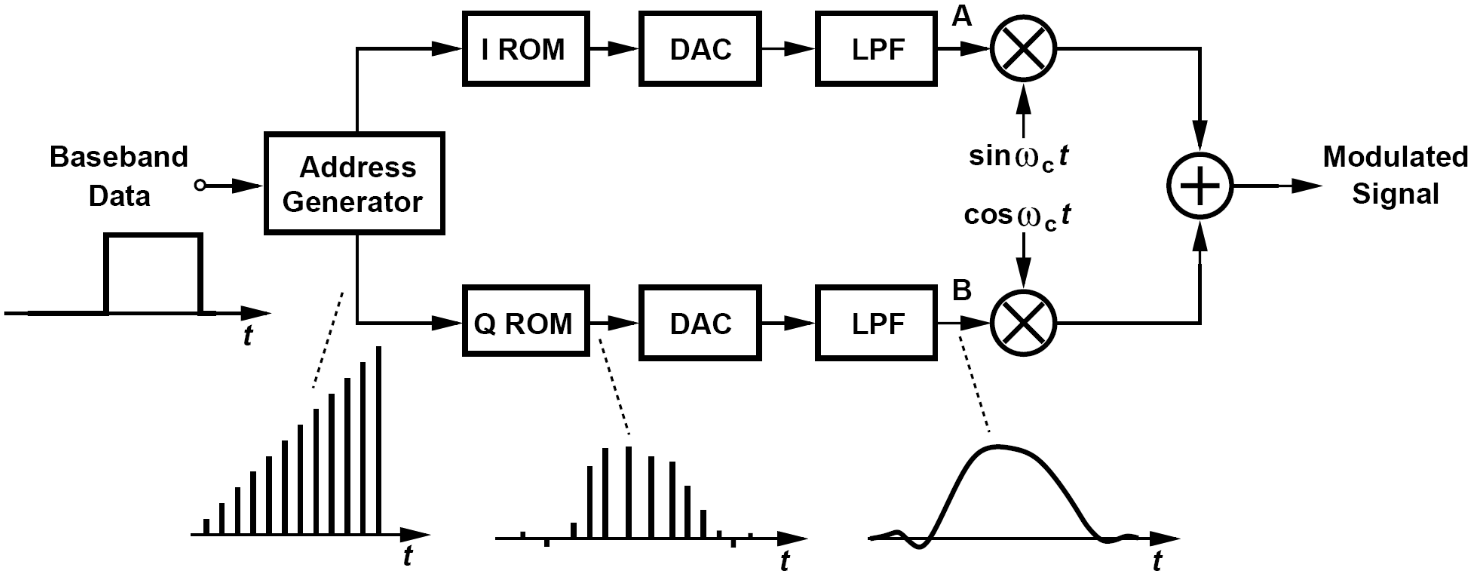
$$\begin{aligned} x_{BB,I}(t) &= A(t)\cos[\phi(t)] \\ x_{BB,Q}(t) &= A(t)\sin[\phi(t)] \end{aligned}$$



Directly translates the BB spectrum to the RF carrier by means of a "quadrature upconverter".

Baseband Pulse Shaping

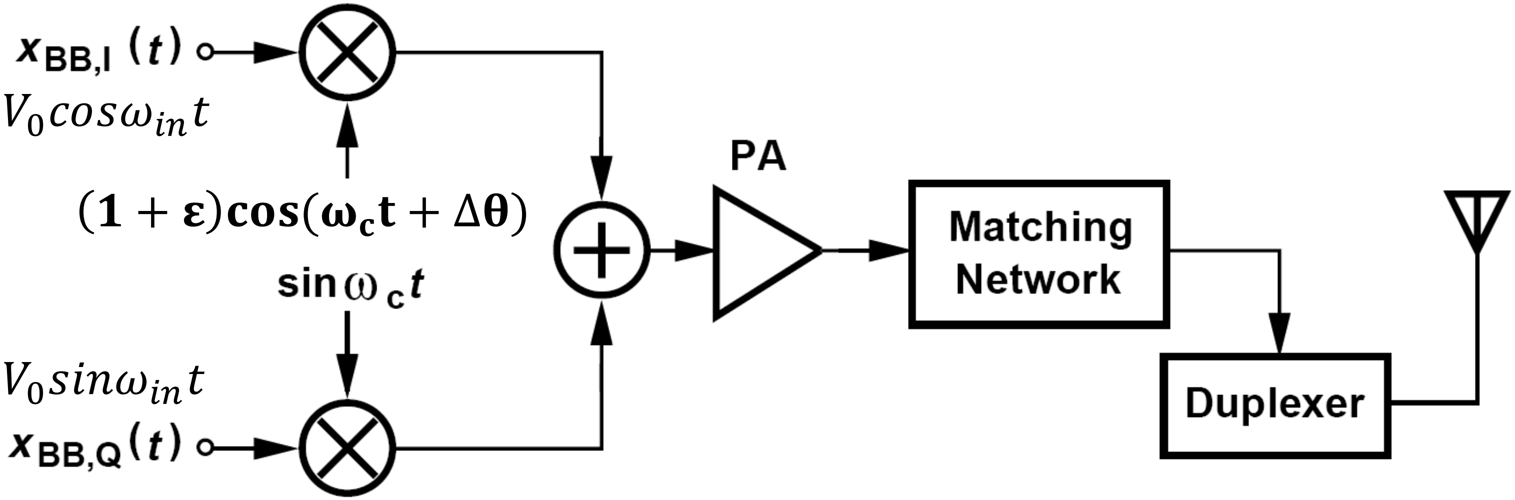
- RF TX performs modulation, upconversion, and power amplification.
- Quadrature BB signals generated by the digital BB processor & converted to analog form by D/A converters.
- Each incoming pulse is smoothened (shaped) to reduce BW
- Mapping to the desired shape preferred in digital domain to avoid bulky analog filters at low BB frequency.



Direct Conversion TX Problems

- I/Q mismatch & unwanted sideband
- I/Q mismatch & constellation distortion
- Carrier leakage and constellation distortion
- Carrier leakage and power control
- Mixer nonlinearity & signal corruption or ACP increase (spectral regrowth)
- TX nonlinearity & signal distortion or ACP increase (spectral regrowth)
- Oscillator pulling
- Noise in RX band transmitted by the TX (Eg. GSM spec)

Direct-Conversion TX: I/Q Mismatch



$$\begin{aligned}
V_{out}(t) &= V_0(1+\varepsilon)\cos\omega_{in}t\cos(\omega_c t+\Delta\theta) - V_0\sin\omega_{in}t\sin\omega_c t \\
&= \frac{V_0}{2}[(1+\varepsilon)\cos\Delta\theta+1]\cos(\omega_c t+\omega_{in})t \;-\; \frac{V_0}{2}(1+\varepsilon)\sin\Delta\theta\sin(\omega_c+\omega_{in})t \\
&+ \frac{V_0}{2}[(1+\varepsilon)\cos\Delta\theta-1]\cos(\omega_c-\omega_{in})t \;-\; \frac{V_0}{2}(1+\varepsilon)\sin\Delta\theta\sin(\omega_c-\omega_{in})t.
\end{aligned}$$

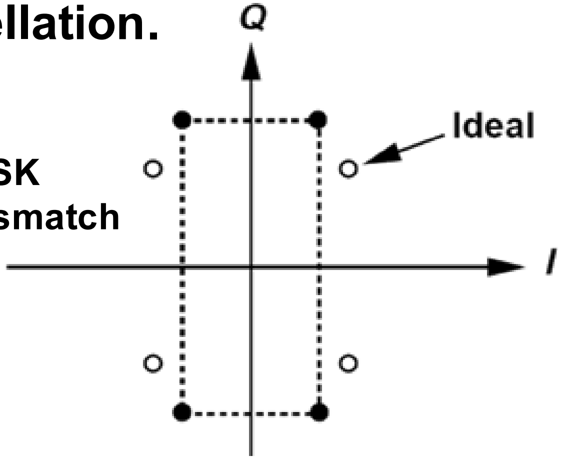
- **Results in unwanted sideband, e.g., at ω_c - ω_{in} versus wanted sideband at ω_c + ω_{in}. For amplitude error ε and phase error θ,**

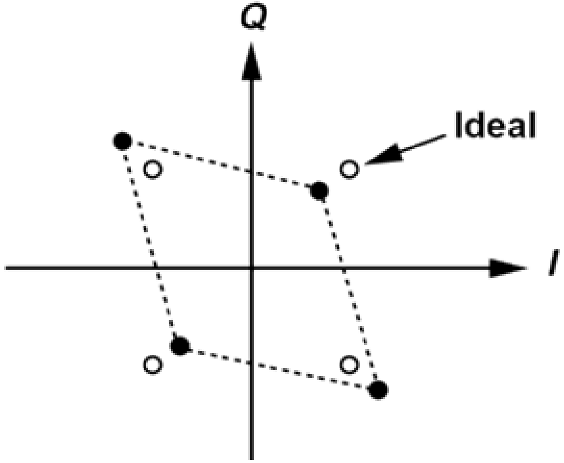
$$\frac{P_-}{P_+} = \frac{(1+\varepsilon)^2 - 2(1+\varepsilon)\cos\Delta\theta + 1}{(1+\varepsilon)^2 + 2(1+\varepsilon)\cos\Delta\theta + 1}$$

Direct-Conversion TX: I/Q Mismatch

- **Results in “xtalk” between the quadrature outputs or, equivalently, distortion in the constellation.**

QPSK
Gain mismatch





QPSK
Phase mismatch

$$
\begin{aligned}
x(t) &= \alpha_1(A_c+\Delta A_c)\cos(\omega_c t+\Delta\theta)+\alpha_2 A_c\sin\omega_c t \\
&= \alpha_1(A_c+\Delta A_c)\cos\Delta\theta\cos\omega_c t+[\alpha_2 A_c-\alpha_1(A_c+\Delta A_c)\sin\Delta\theta]\sin\omega_c t.
\end{aligned}
$$

For the four points in the constellation:

$$
\begin{aligned}
\beta_1 &= +\left(1+\frac{\Delta A_c}{A_c}\right)\cos\Delta\theta,\ \beta_2=1-\left(1+\frac{\Delta A_c}{A_c}\right)\sin\Delta\theta \\
\beta_1 &= +\left(1+\frac{\Delta A_c}{A_c}\right)\cos\Delta\theta,\ \beta_2=-1-\left(1+\frac{\Delta A_c}{A_c}\right)\sin\Delta\theta \\
\beta_1 &= -\left(1+\frac{\Delta A_c}{A_c}\right)\cos\Delta\theta,\ \beta_2=1+\left(1+\frac{\Delta A_c}{A_c}\right)\sin\Delta\theta \\
\beta_1 &= -\left(1+\frac{\Delta A_c}{A_c}\right)\cos\Delta\theta,\ \beta_2=-1+\left(1+\frac{\Delta A_c}{A_c}\right)\sin\Delta\theta.
\end{aligned}
$$

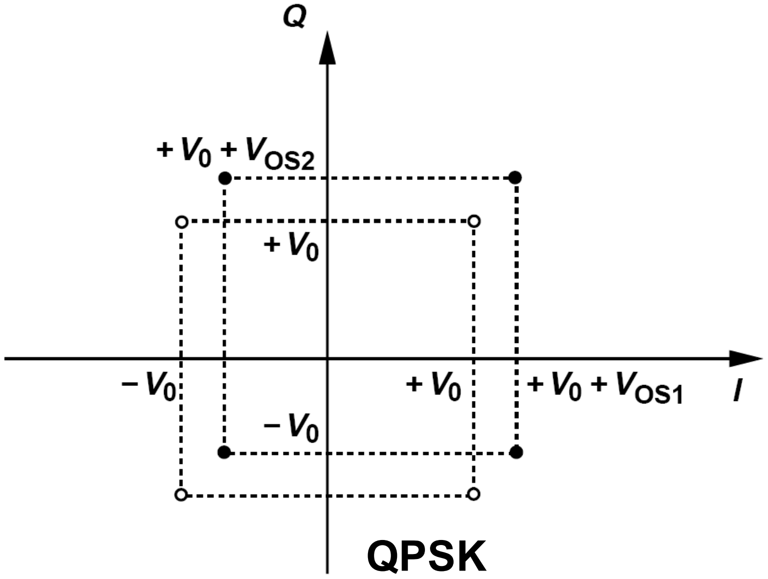
Carrier Leakage & Signal Constellation

DC offsets in the analog BB circuitry and BB port of each Upconversion mixer → upconverter output contains a fraction of the *unmodulated* carrier.

$$V_{out}(t) = [A(t)\cos\phi + V_{OS1}]\cos\omega_c t - [A(t)\sin\phi + V_{OS2}]\sin\omega_c t$$

$$V_{out}(t) = A(t)\cos(\omega_c t + \phi) + V_{OS1}\cos\omega_c t - V_{OS2}\sin\omega_c t$$

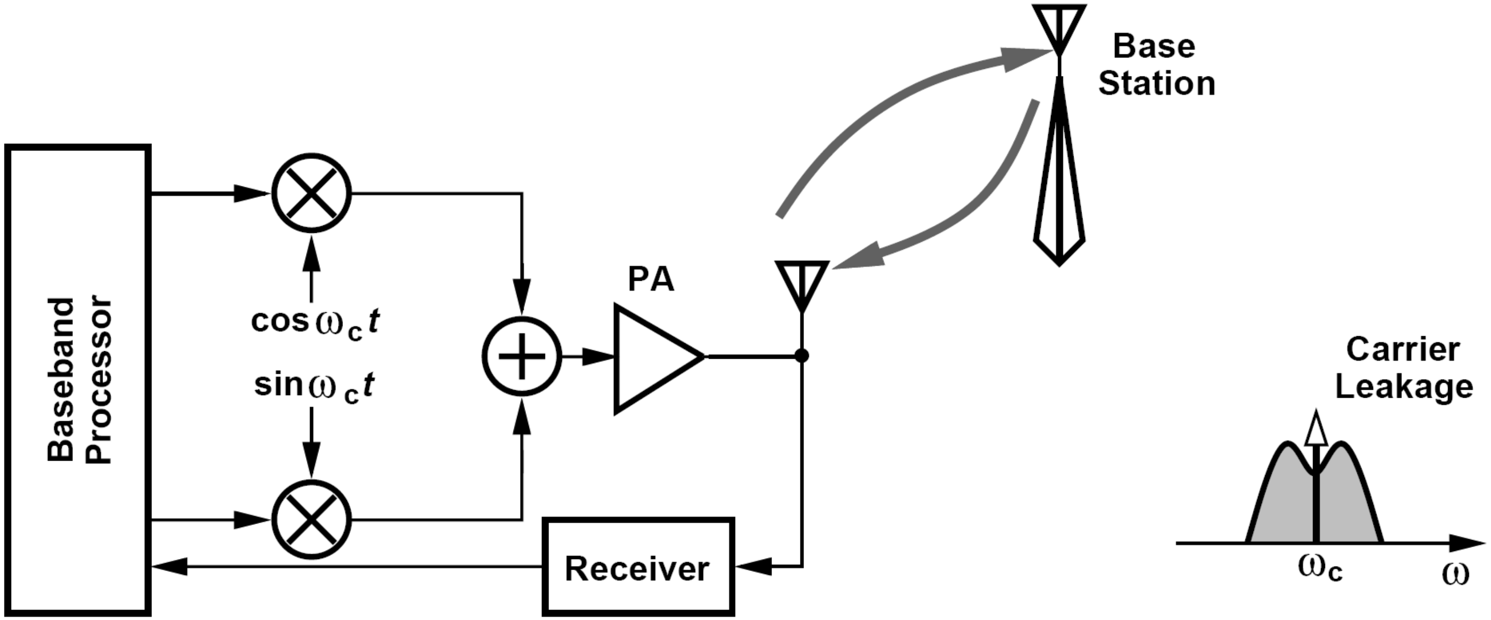
$$\text{Relative Carrier Leakage} = \frac{\sqrt{V_{OS1}^2 + V_{OS2}^2}}{\sqrt{\overline{A^2(t)}}}$$



- **Distorts the signal constellation, raising the EVM @ TX output, and complicates TX power control.**

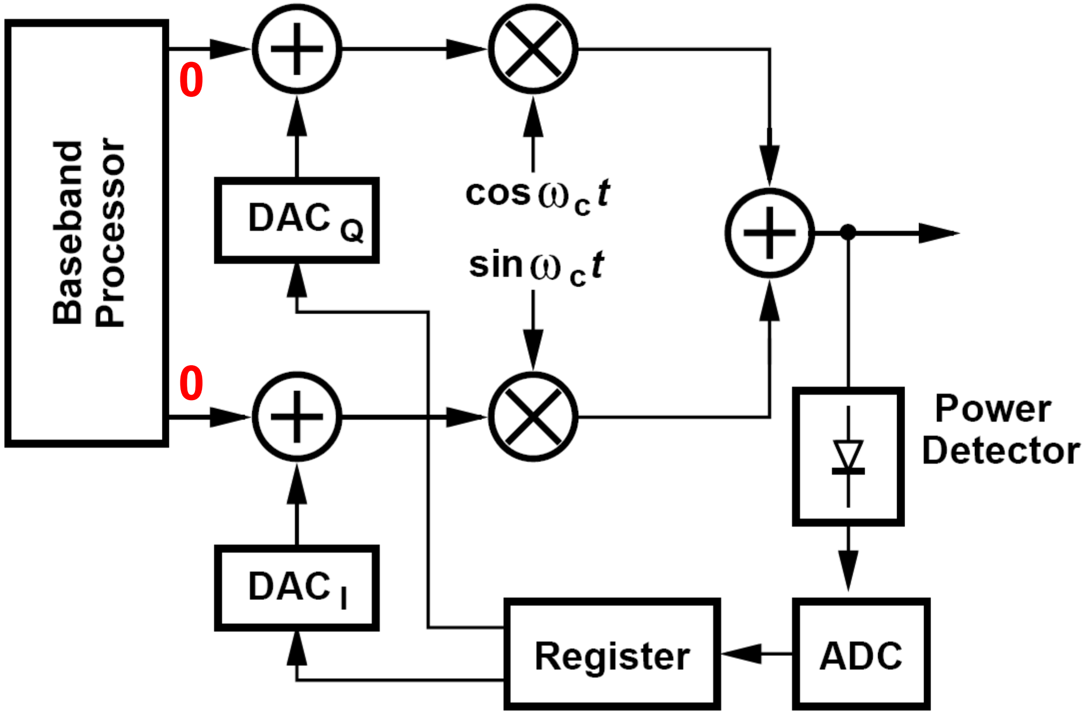
Carrier Leakage & PA Power Control

- **If the output power of the TX must be varied across a wide range by varying the amplitude of the BB signals (& not PA itself), for ex, when CDMA mobiles come closer to the base station to avoid the near-far effect,**



Close proximity of BS-UE → BS requests UE to reduce its transmitted power → carrier leakage power dominates in the TX spectrum, making it difficult to measure the actual signal power.

Carrier Leakage Reduction



- BB processor produces a zero output → detector measures leakage only
- Loop consisting of the TX, the detector, and the DACs drives the leakage toward zero, with the final settings of the DACs stored in the register.
- LMS or exhaustive search calibration

Upconversion of Mixer Non-Linearity

- **Excessive nonlinearity in the BB port can corrupt the signal or raise the adjacent channel power (ACP).**

Consider GMSK signal

$$V_{out}(t) \;=\; A(t)\cos\omega_c t\cos[\phi(t)] - A(t)\sin\omega_c t\sin[\phi(t)]$$

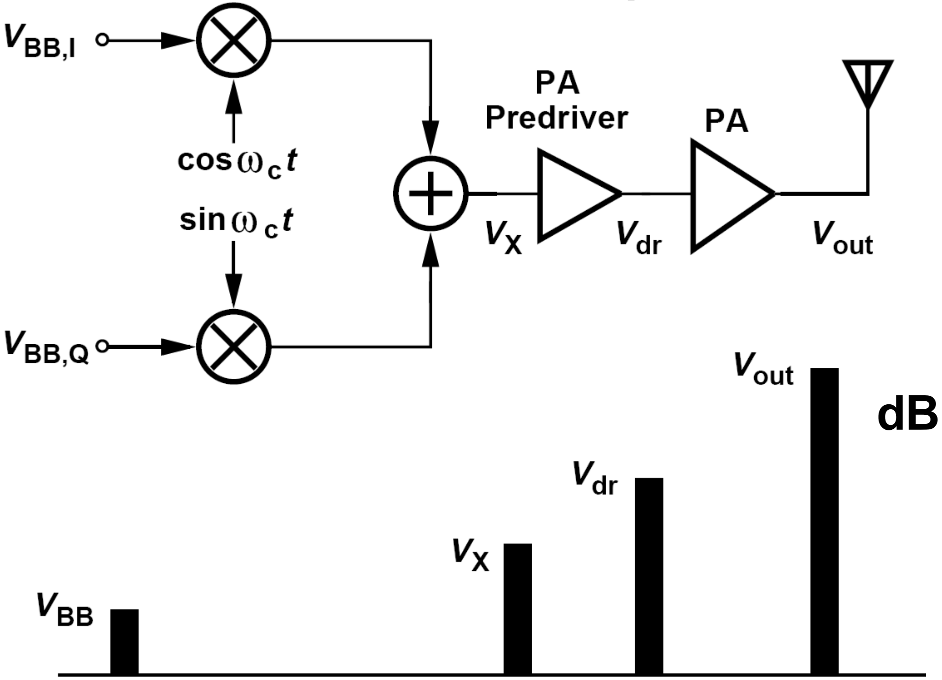
If BB I/Q inputs experience a nonlinearity given by $\alpha_1 x + \alpha_3 x^3$,

$$\begin{aligned} V_{out}(t) &= (\alpha_1 A\cos\phi + \alpha_3 A^3\cos^3\phi)\cos\omega_c t - (\alpha_1 A\sin\phi + \alpha_3 A^3\sin^3\phi)\sin\omega_c t \\ &= \left(\alpha_1 A + \frac{3}{4}\alpha_3 A^3\right)\cos(\omega_c t + \phi) + \frac{\alpha_3 A^3}{4}\cos(\omega_c t - 3\phi). \end{aligned}$$

- **2nd term also represents a GMSK signal but with 3X modulation index → occupying a larger BW.**
- **For variable-envelope signals, $A^3(t)$ appears in both terms, exacerbating the effect.**

TX Linearity

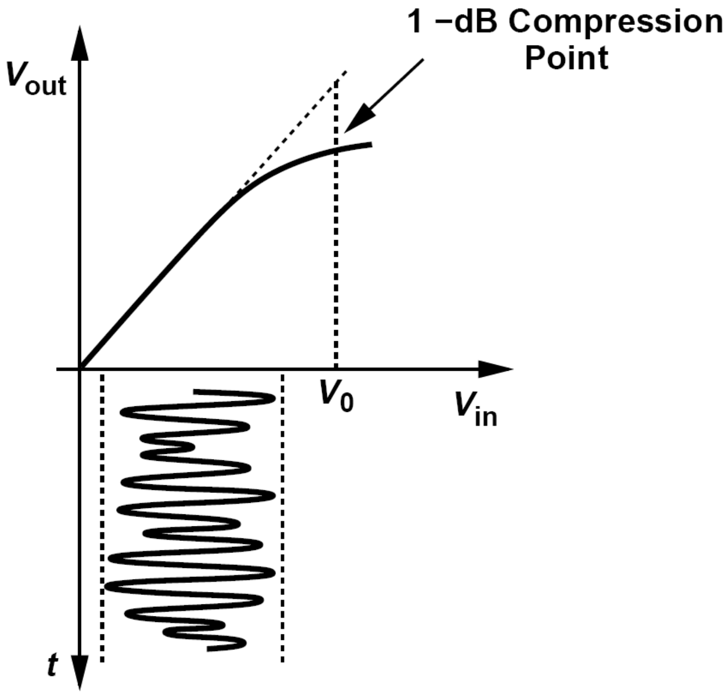
- Distortion of a variable-envelope signal is characterized by the compression that it experiences.
- Largest voltage swing occurs at PA o/p → PA dominates TX compression
- In a good design, preceding stages must remain well below compression as the PA o/p approaches P_{1dB}.



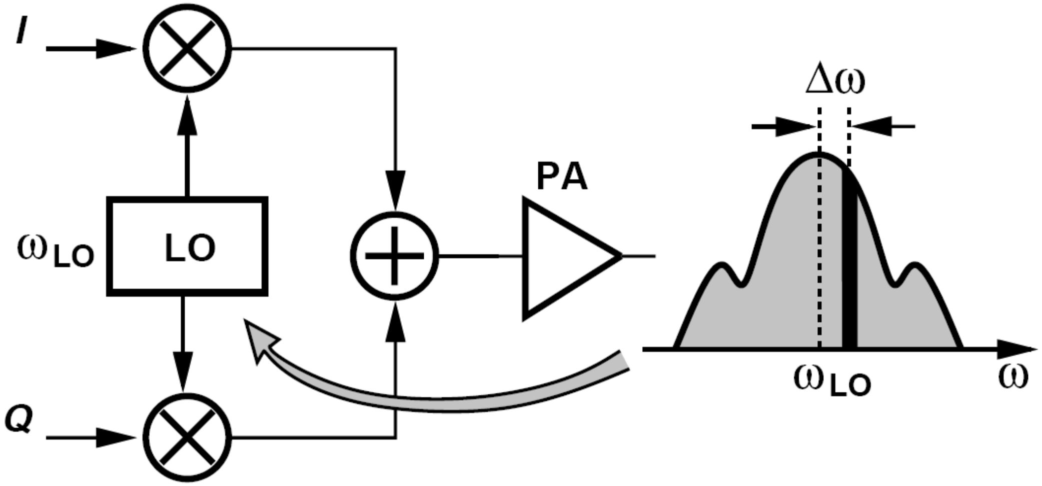
- For linearity, *maximize* the PA gain and *minimize* the output swing of the predriver and the stages preceding it → makes PA design difficult
- Operating at *back-off*: Average power must remain XdB below P_{1dB}.

Back-off Example

- In 802.11a, the average power of the 64-QAM OFDM signal must remain about 8dB below P_{1dB} of a given circuit → circuit must operate at 8-dB back-off.
- If a peak swing of V_0 places the circuit at the 1dB compression point, then the average signal swing must not exceed $V_0/2.51$.

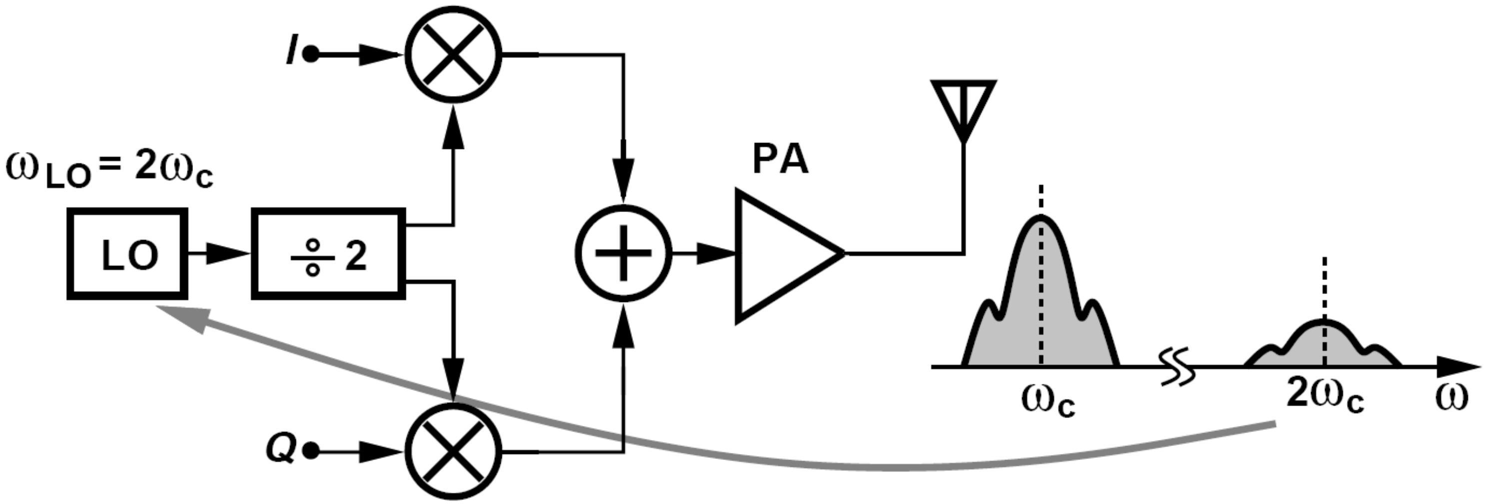


LO Pulling (esp. in Direct Conv. TX)



- PA output exhibits very large swings ($20V_{pp}$ for 1W into 50Ω load)
- Couples to LO through the silicon substrate, package parasitics, and PCB traces, even if PA is off-chip.
- In Direct-conversion TX, PA center frequency $\omega_c = \omega_{LO}$.
- To avoid injection pulling, make the two frequencies different → derive ω_c from ω_{LO} through frequency division or mixing.

Modern Direct-Conversion TX

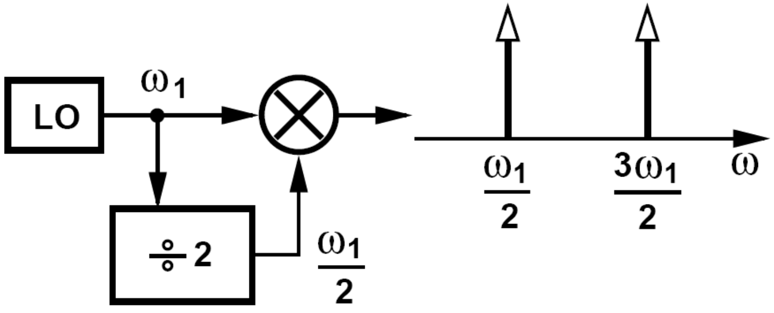


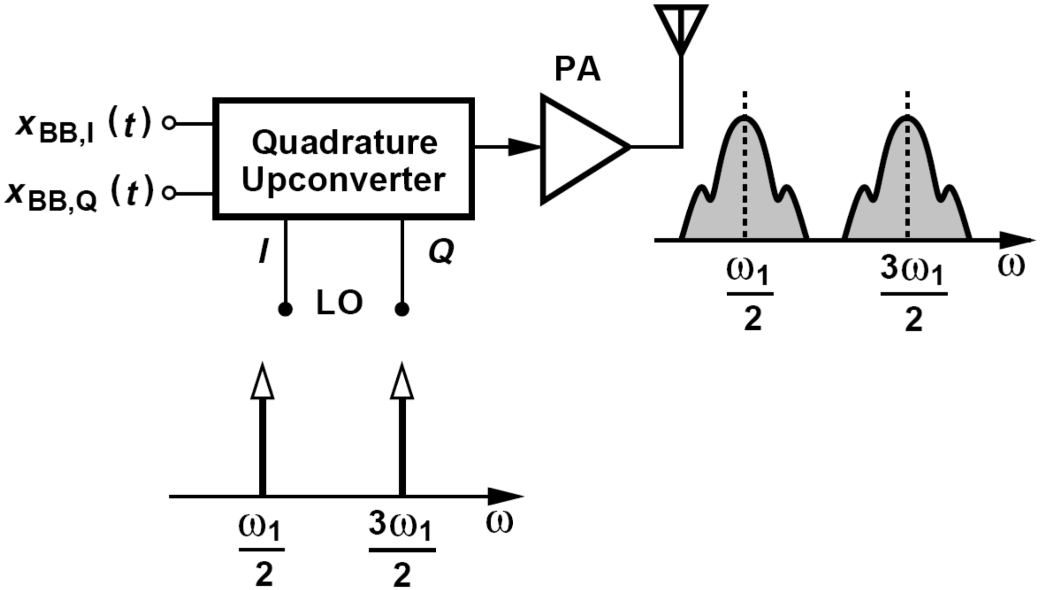
- Popular architecture:

  (1) injection pulling is greatly reduced

  (2) divider readily provides quadrature phases of the carrier
- Divider speed critical, operating at twice of ω_c

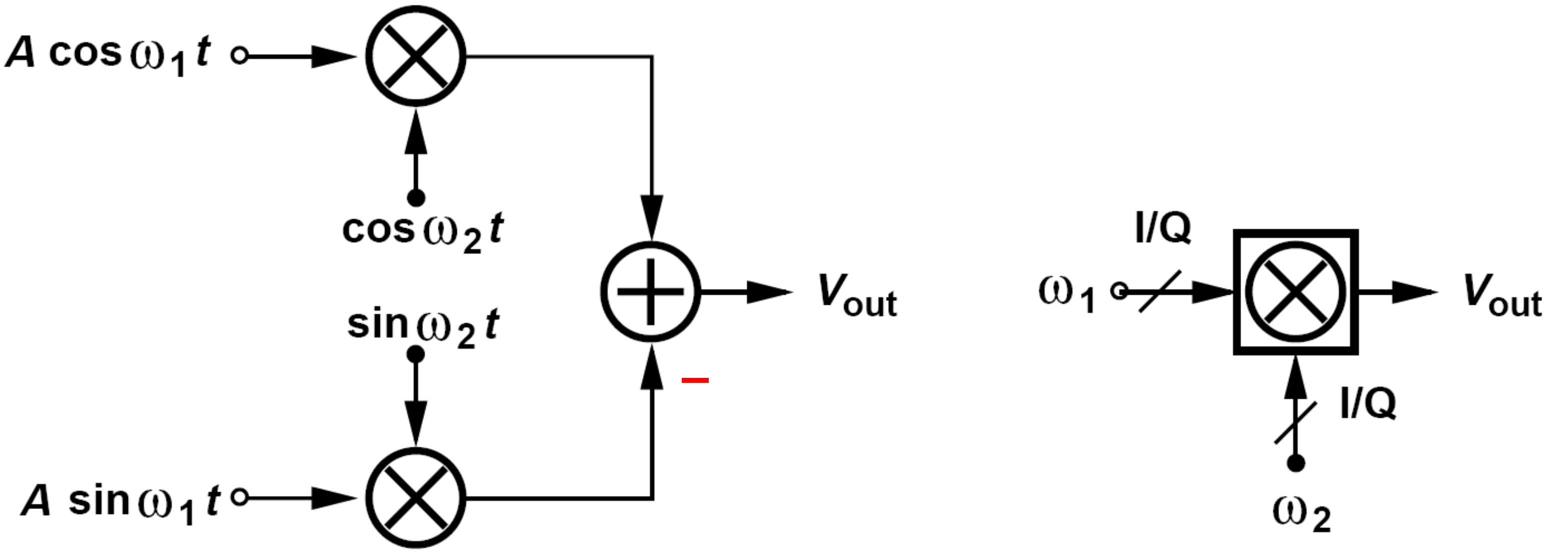
Use Mixing to Derive Frequencies?





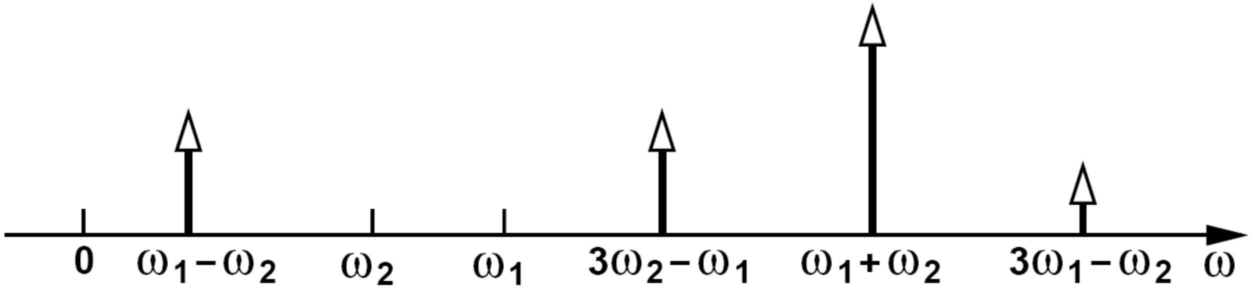
- **Suppress one component to avoid corrupting communication in other channels or bands**
- **Suppression difficult by filtering (only 3X frequency difference) – only 25-30dB**
- **Use single-sideband mixing (SSB mixing) – 30-40dB or even another 25-30dB by SSB followed by 2nd order filtering**

Single-Sideband Mixing



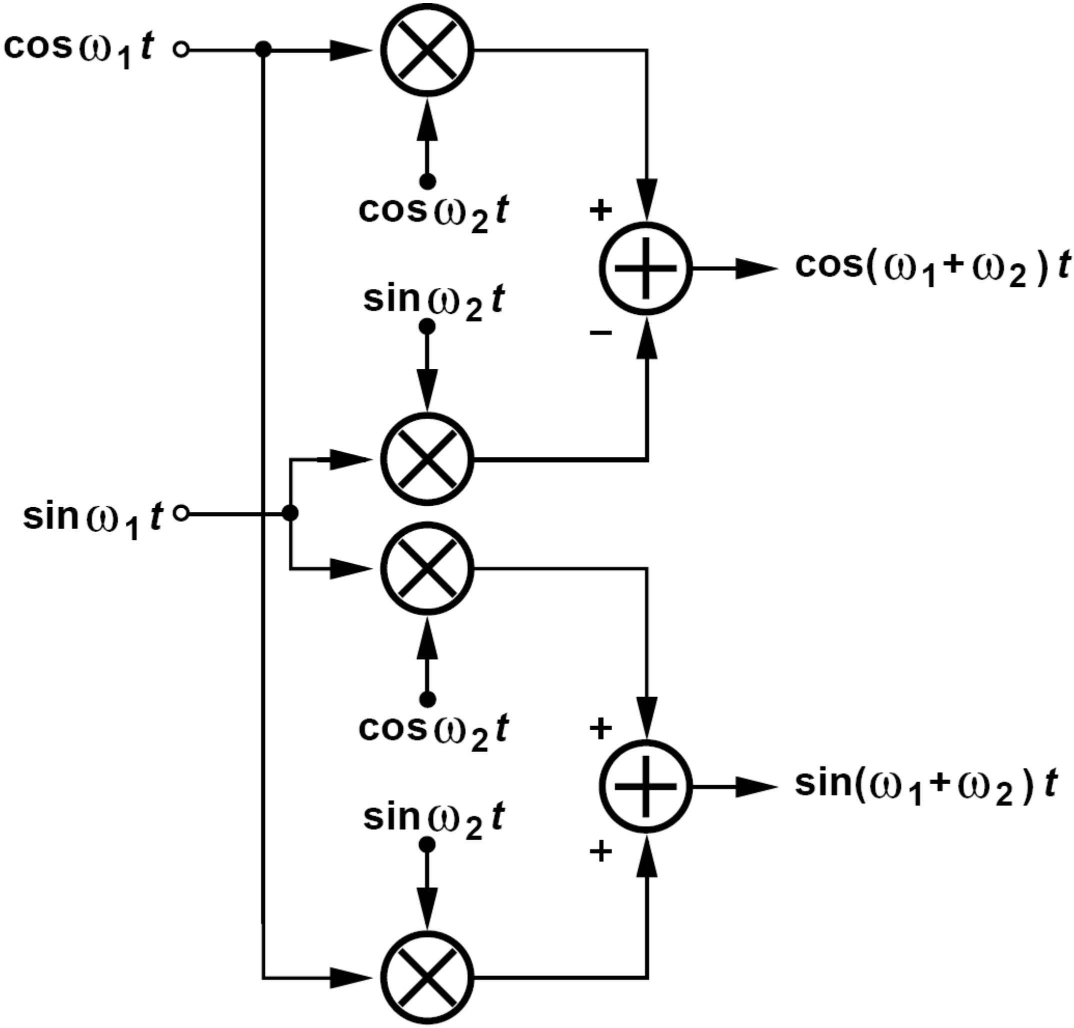
$$\cos\omega_1 t\cos\omega_2 t - \sin\omega_1 t\sin\omega_2 t = \cos(\omega_1+\omega_2)t$$

- Gain and phase mismatches lead to an unwanted sideband
- Harmonics due to nonlinearity on either port result in mixer spurs

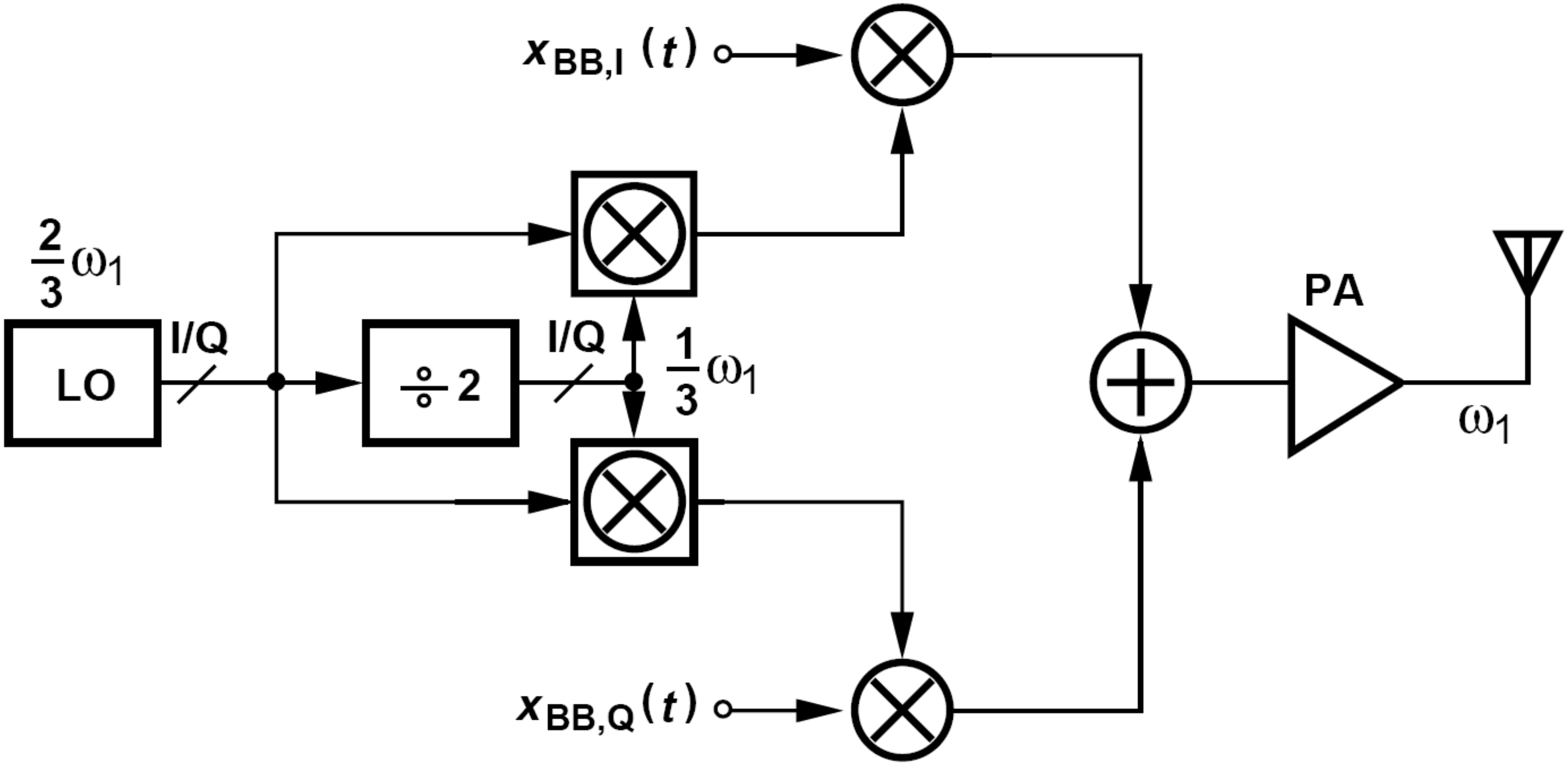


SSB Mixer with Quad Outputs for DCTX

- As $\sin \omega_1 t \cos \omega_2 t + \cos \omega_1 t \sin \omega_2 t = \sin(\omega_1 + \omega_2)t$, duplicate the SSB mixer.



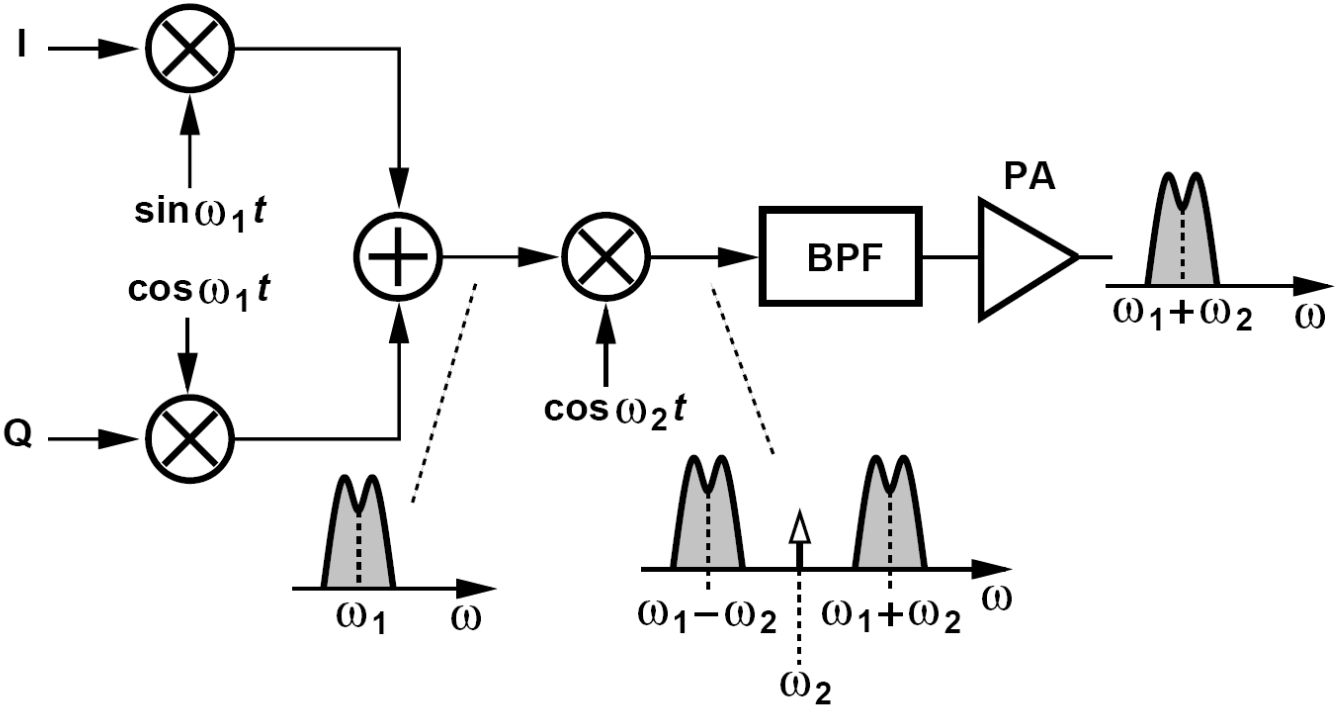
DCTX Using SSB Mixing in LO Path



- Carrier and LO sufficiently different → free from injection pulling.
- Spurs at $5\omega_1/3$ and other harmonic-related frequencies
- LO must provide quadrature phases

Heterodyne TX

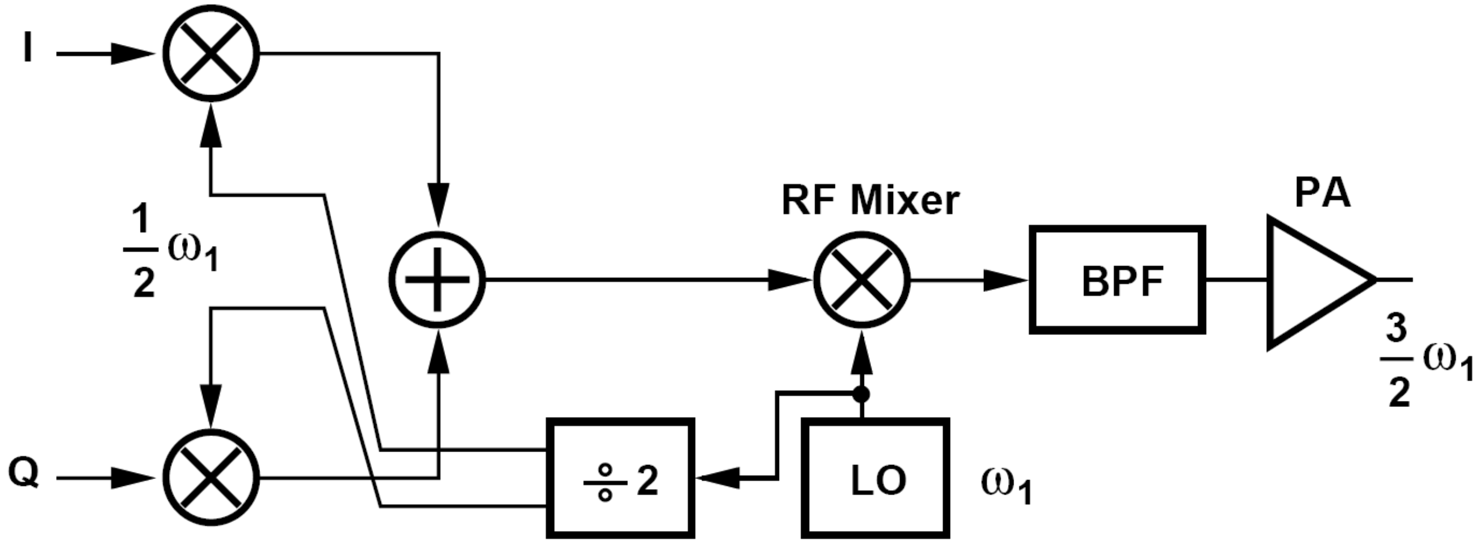
2-step signal upconversion → LO frequency far from the PA output spectrum



- *I/Q* upconversion occurs at a significantly lower frequency than the carrier, exhibiting smaller gain and phase mismatches.
- Two LO, BPF needed.
- Spurs from harmonics of LO1 and LO2.

Sliding-IF TX

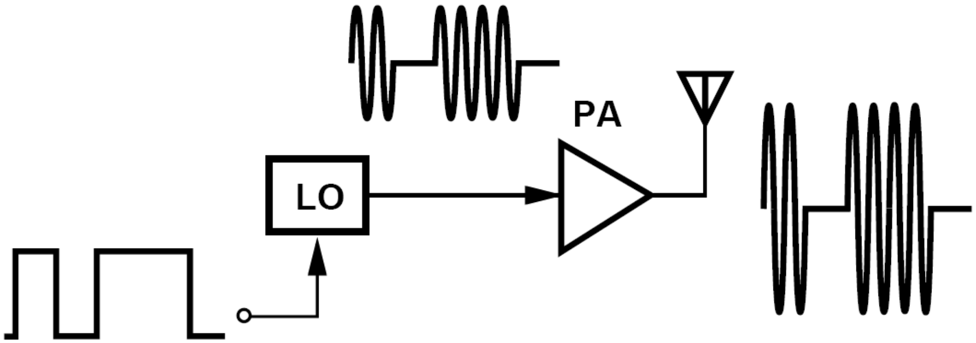
Derive the required LO1 phases from LO2

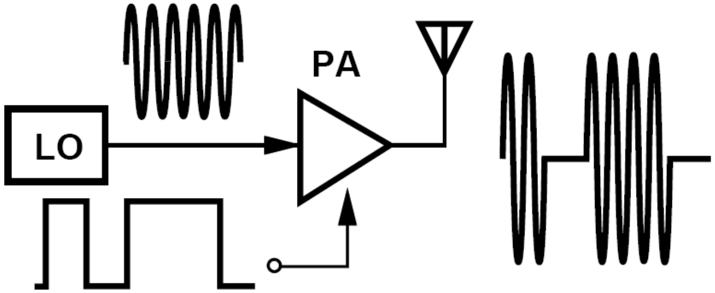


- **Mixing spurs limit usage of heterodyne TX to modulation schemes with moderate SNR (10–12dB) (e.g., QPSK) or systems with a moderate BER (10^{-2})**

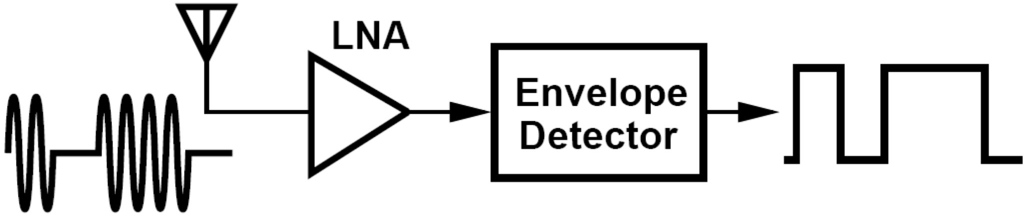
OOK Transceivers: Low-power

- “On-off keying” (OOK) modulation is a special case of ASK where the carrier amplitude is switched between zero and maximum.





- LO is directly turned ON/OFF by the binary BB data → If the LO swings are large enough, the PA also experiences relatively complete switching and delivers an OOK waveform to the antenna. LO cannot be easily controlled by a PLL.
- PA directly turned ON/OFF by the binary BB data



An LNA followed by an envelope detector can recover the binary data.