Mixer Design

- Introduction to mixers
- Mixer metrics
- Mixer topologies
- Mixer performance analysis
- Mixer design issues

What is a mixer

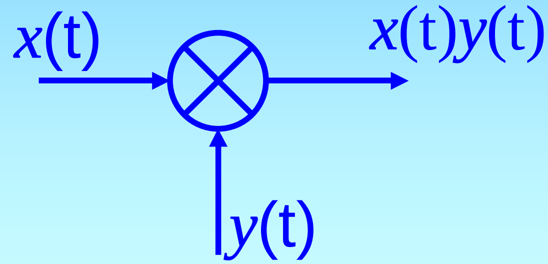
- Frequency translation device
  - Convert RF frequency to a lower IF or base bandfor easy signal processing in receivers
  - Convert base band signal or IF frequency to a higher IF or RF frequency for efficient transmission in transmitters
- Creative use of nonlinearity or time-variance
  - These are usually harmful and unwanted
  - They generates frequencies not present at input
- Used together with appropriate filtering
  - Remove unwanted frequencies

Two operation mechanisms

- Nonlinear transfer function
  - Use device nonlinearities creatively!
  - Intermodulation creates the desired frequency and unwanted frequencies
- Switching or sampling
  - A time-varying process
  - Preferred; fewer spurs
  - Active mixers
  - Passive mixers

An ideal nonlinearity mixer

If $$x(t) = A\cos w_1 t$$
$$y(t) = B\cos w_2 t$$

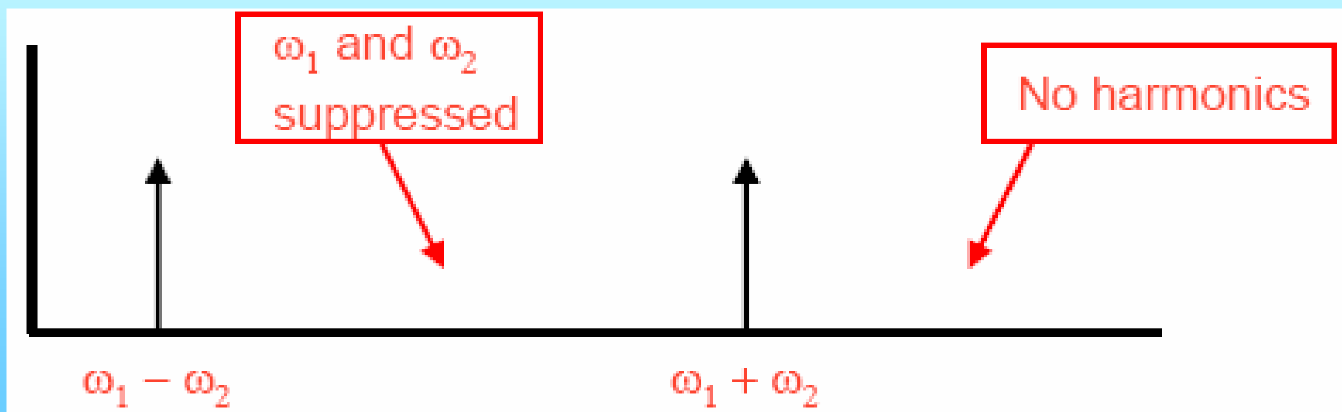


Then the output is

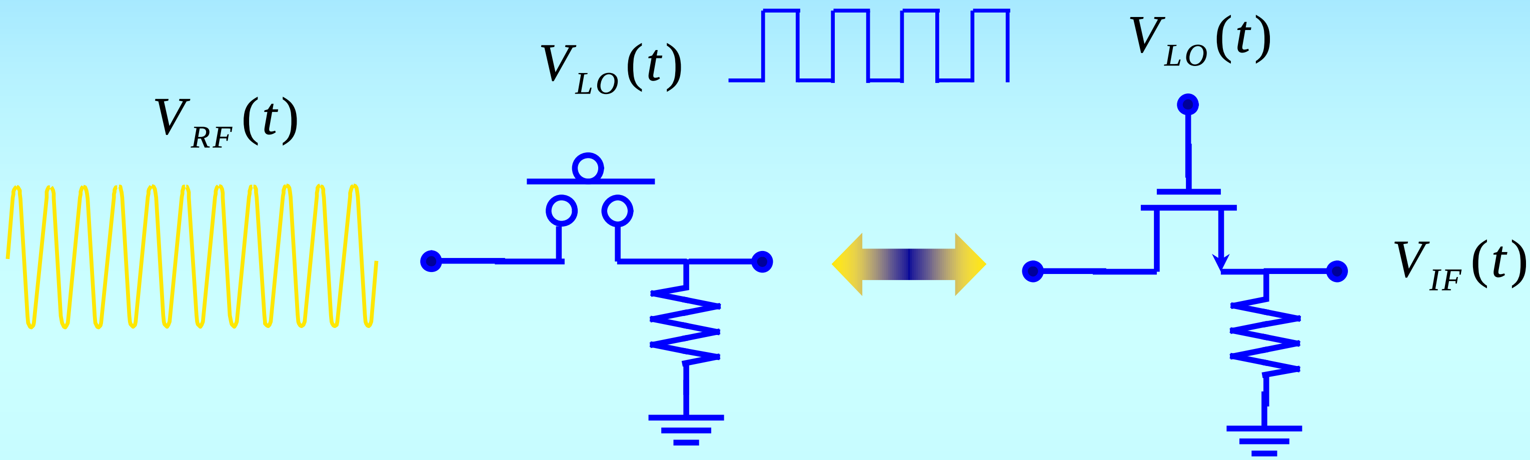
$$A\cos w_1 t \cdot B\cos w_2 t = \frac{AB}{2}\cos(w_1 - w_2)t + \frac{AB}{2}\cos(w_1 + w_2)t$$

down convert

up convert

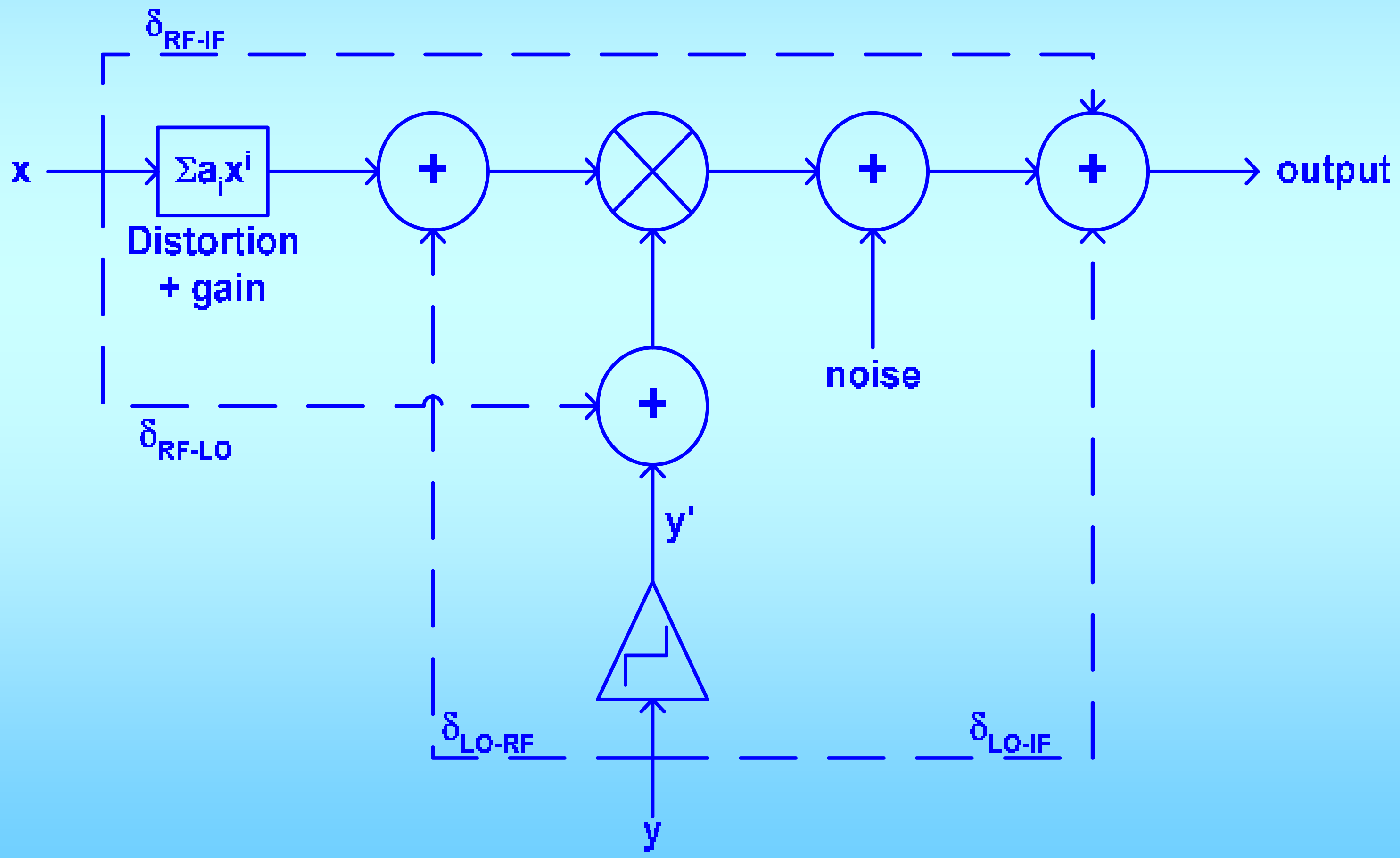


Commutating switch mixer



$$
\begin{aligned}
&V_{RF}(t)\cdot V_{LO}(t)\\
&= A_{RF}\sin(\omega_{RF}t)\times sq(\omega_{LO}t)\\
&= \frac{2}{\pi}A_{RF}\left[\cos(\omega_{RF}-\omega_{LO})t+\frac{1}{3}\cos\left(3(\omega_{RF}-\omega_{LO})t\right)+\mathbf{K}\right]
\end{aligned}
$$

A non-ideal mixer



Mixer Metrics

- Conversion gain – lowers noise impact of following stages
- Noise Figure – impacts receiver sensitivity
- Port isolation – want to minimize interaction between the RF, IF, and LO ports
- Linearity (IIP3) – impacts receiver blocking performance
- Spurious response
- Power match – want max voltage gain rather than power match for integrated designs
- Power – want low power dissipation
- Sensitivity to process/temp variations – need to make it manufacturable in high volume

Conversion Gain

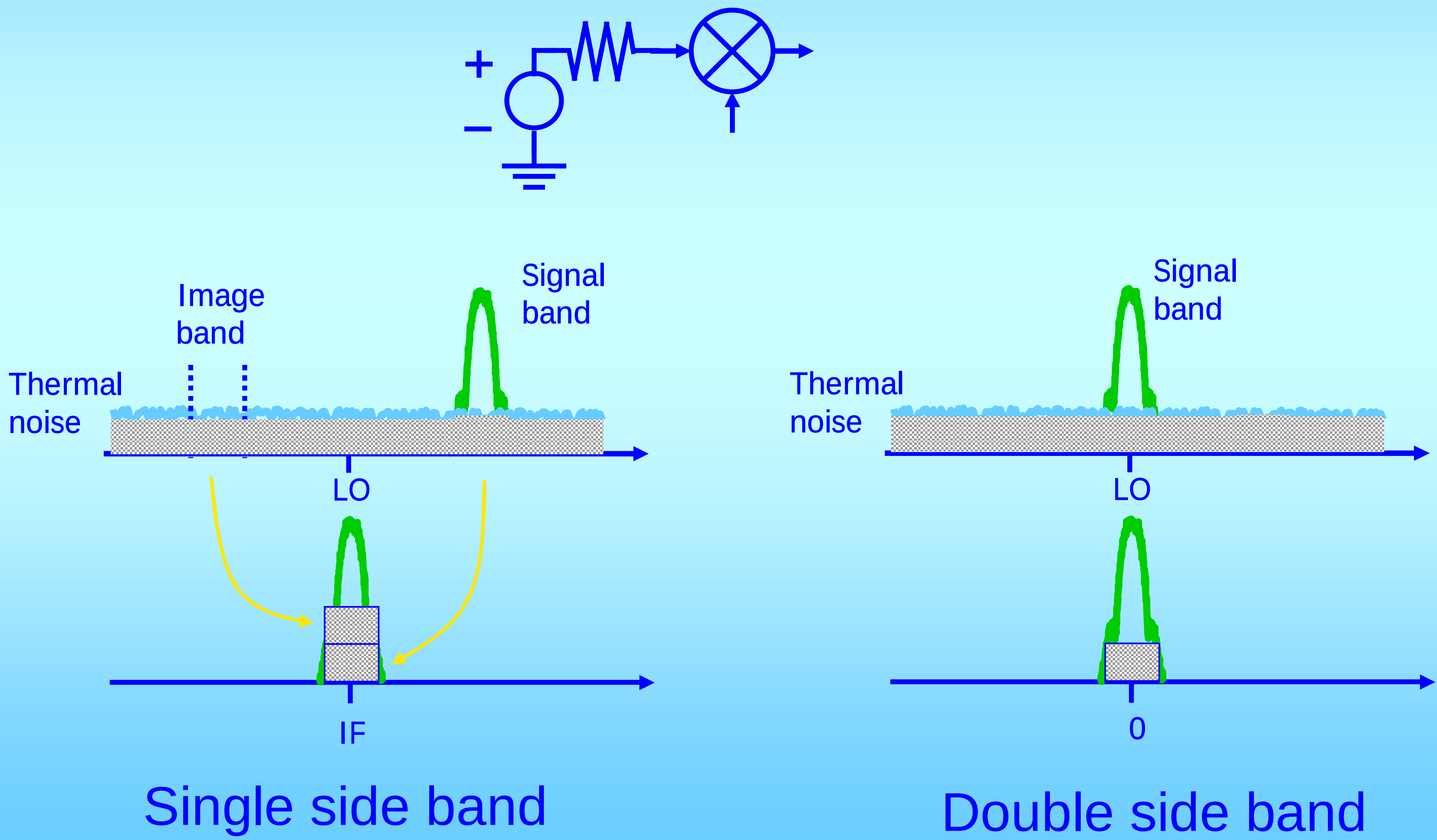
- Conversion gain or loss is the ratio of the desired IF output (voltage or power) to the RF input signal value (voltage or power).

$$\text{Voltage Conversion Gain} = \frac{\text{r.m.s. voltage of the IF signal}}{\text{r.m.s. voltage of the RF signal}}$$

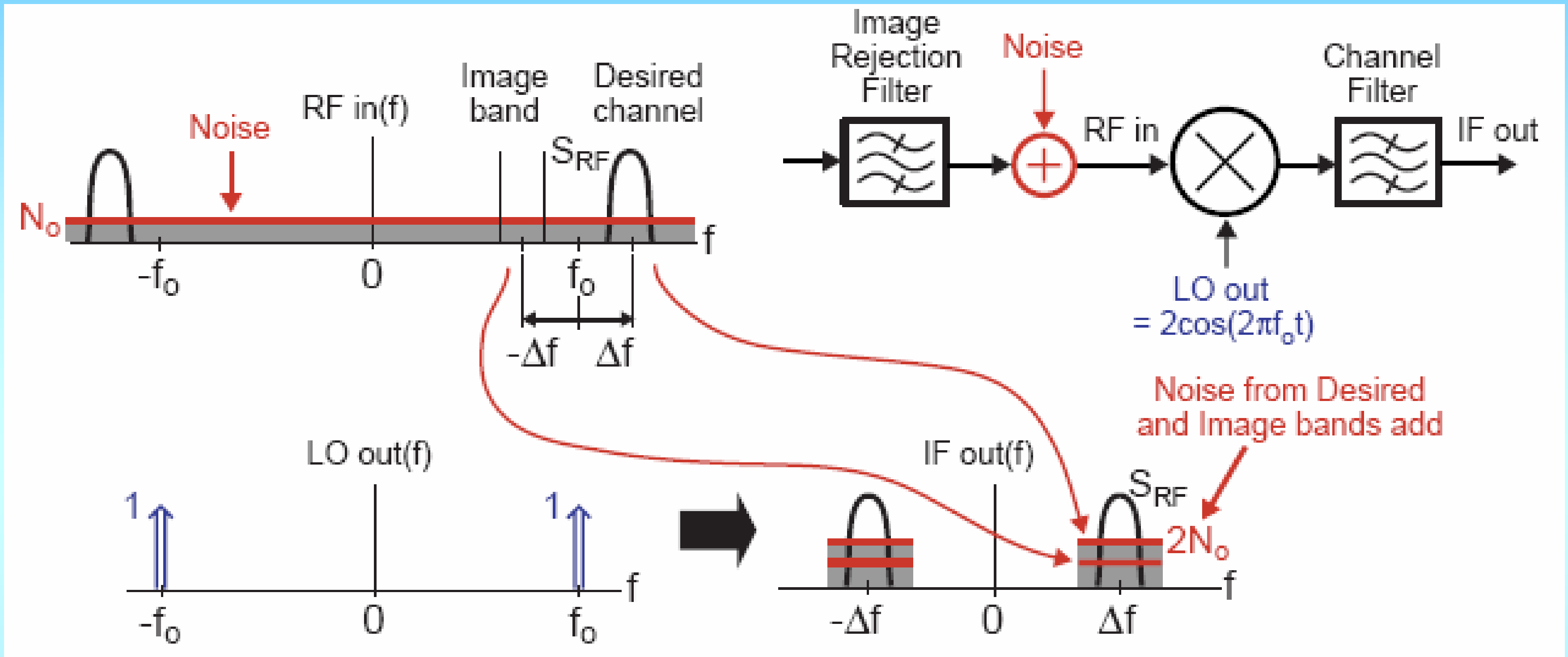
$$\text{Power Conversion Gain} = \frac{\text{IF power delivered to the load}}{\text{Available power from the source}}$$

If the input impedance and the load impedance of the mixer are both equal to the source impedance, then the volltage conversion gain and the power conversion gain of the mixer will be the same.

Noise Figures: SSB vs DSB

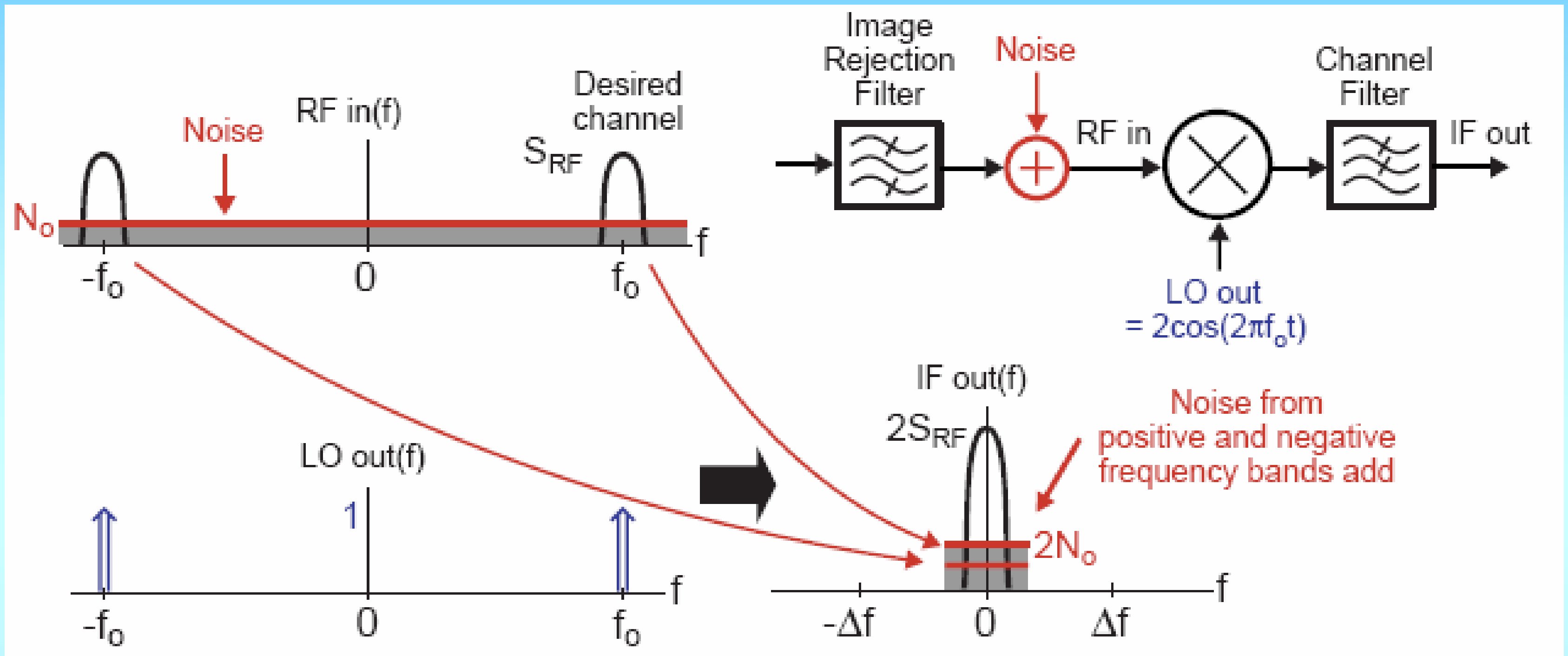


SSB Noise Figure



- Broadband noise from mixer or front end filter will be located in both image and desired bands
- Noise from both image and desired bands will combine in desired channel at IF output
  - Channel filter cannot remove this

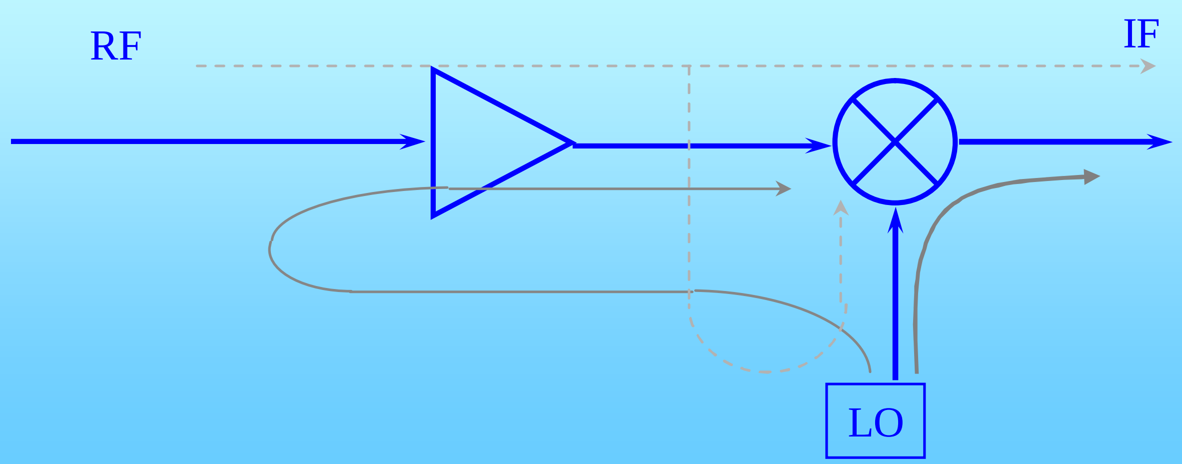
DSB Noise Figure



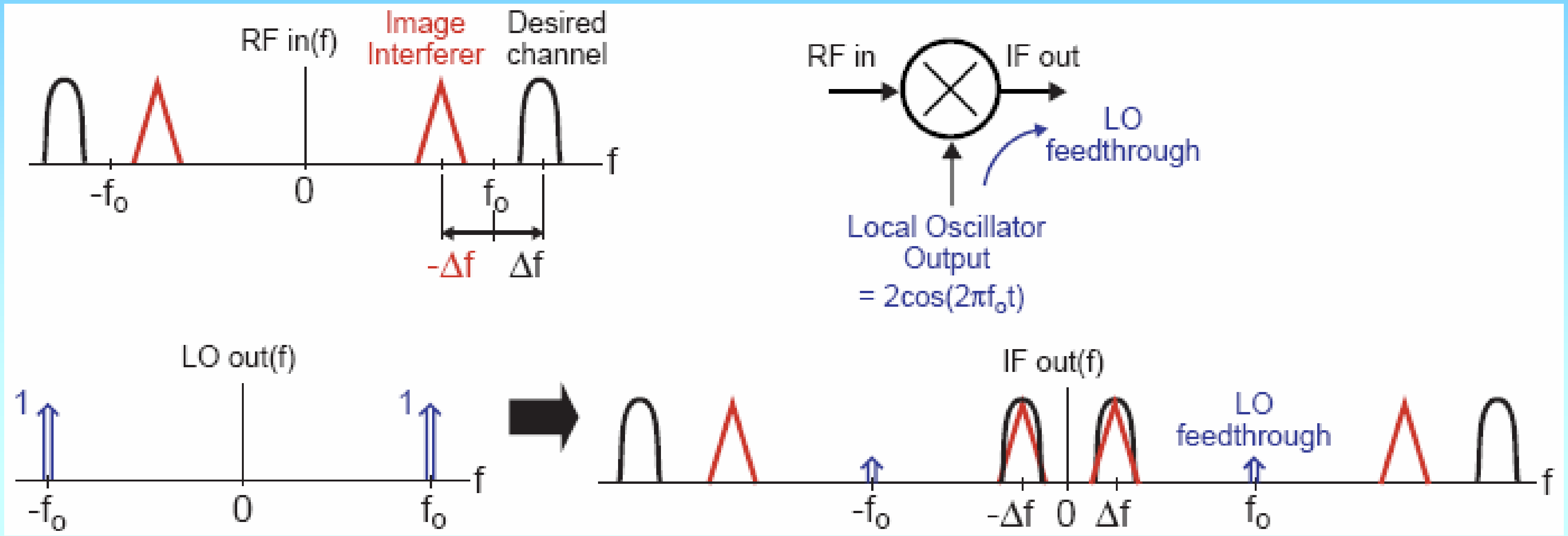
- For zero IF, there is no image band
  - Noise from positive and negative frequencies combine, but the signals combine as well
- DSB noise figure is 3 dB lower than SSB noise figure
  - DSB noise figure often quoted since it sounds better

Port-to-Port Isolations

- Isolation
  - Isolation between RF, LO and IF ports
  - LO/RF and LO/IF isolations are the most important features.
  - Reducing LO leakage to other ports can be solved by filtering.

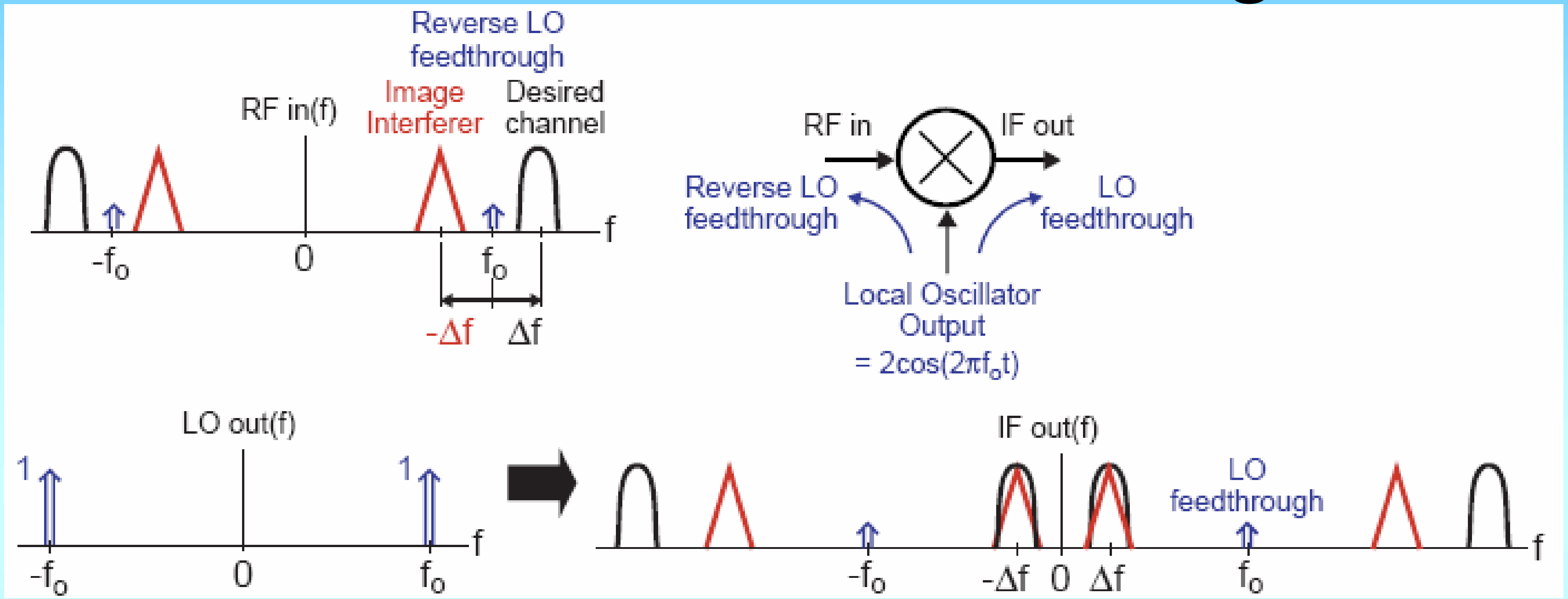


LO Feedthrough



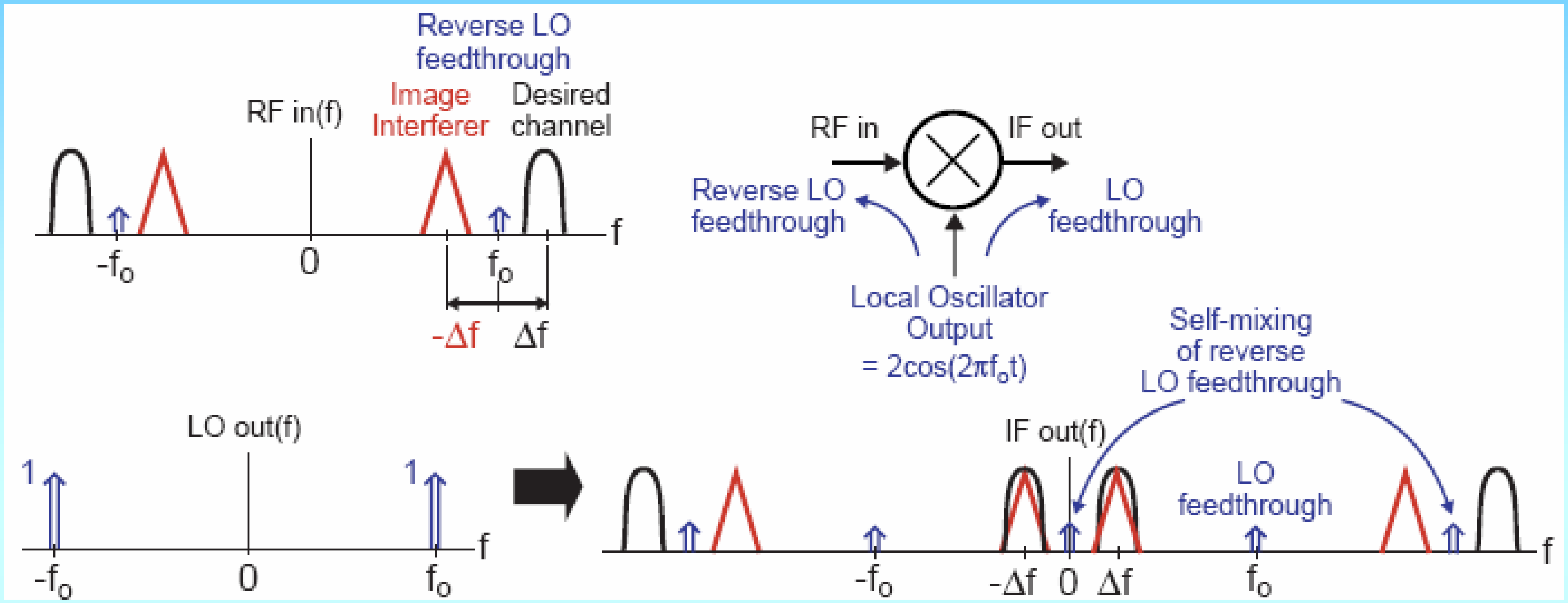
- feedthrough from the LO port to IF output port due to parasitic capacitance, power supply coupling, etc.
- Often significant due to strong LO output signal
  - If large, can potentially desensitize the receiver due to the extra dynamic range consumed at the IF output
  - If small, can generally be removed by filter at IF output

Reverse LO Feedthrough



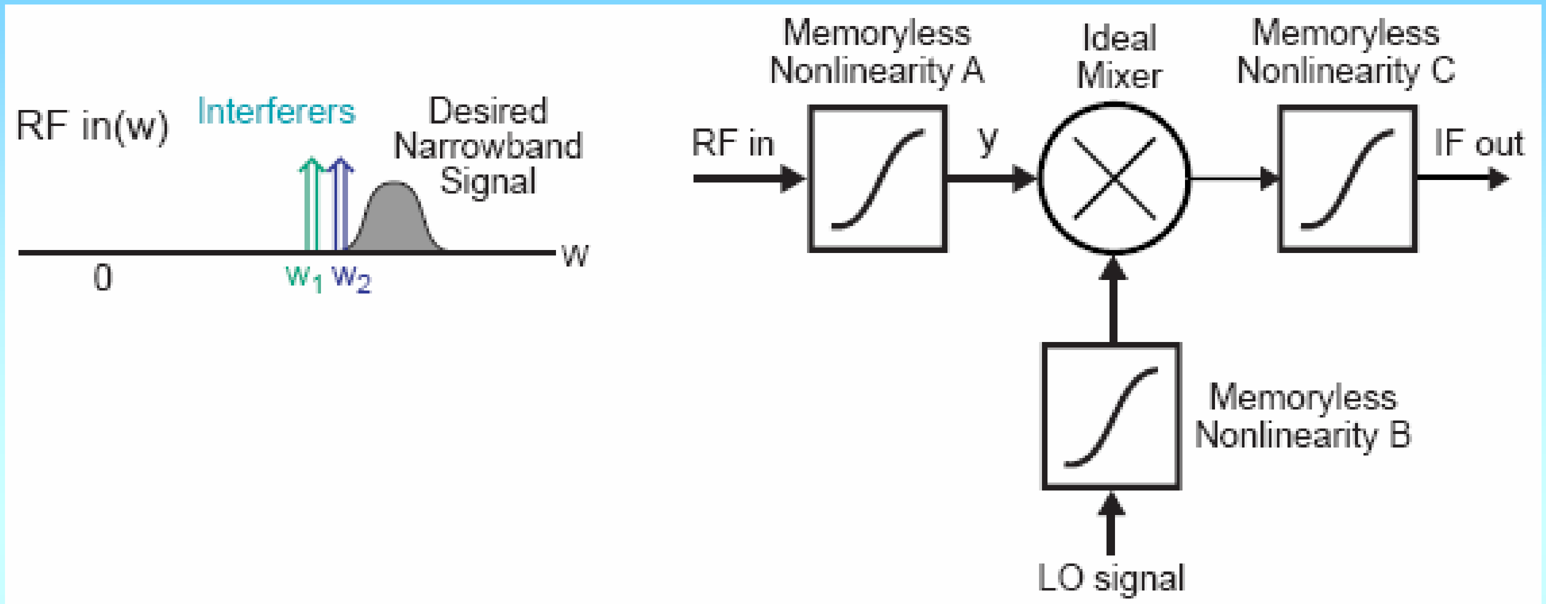
- Reverse feedthrough from the LO port to RF input port due to parasitic capacitance, etc.
  - If large, and LNA doesn't provide adequate isolation, then LO energy can leak out of antenna and violate emission standards for radio
  - Must insure that isolate to antenna is adequate

Self-Mixing of Reverse LO Feedthrough



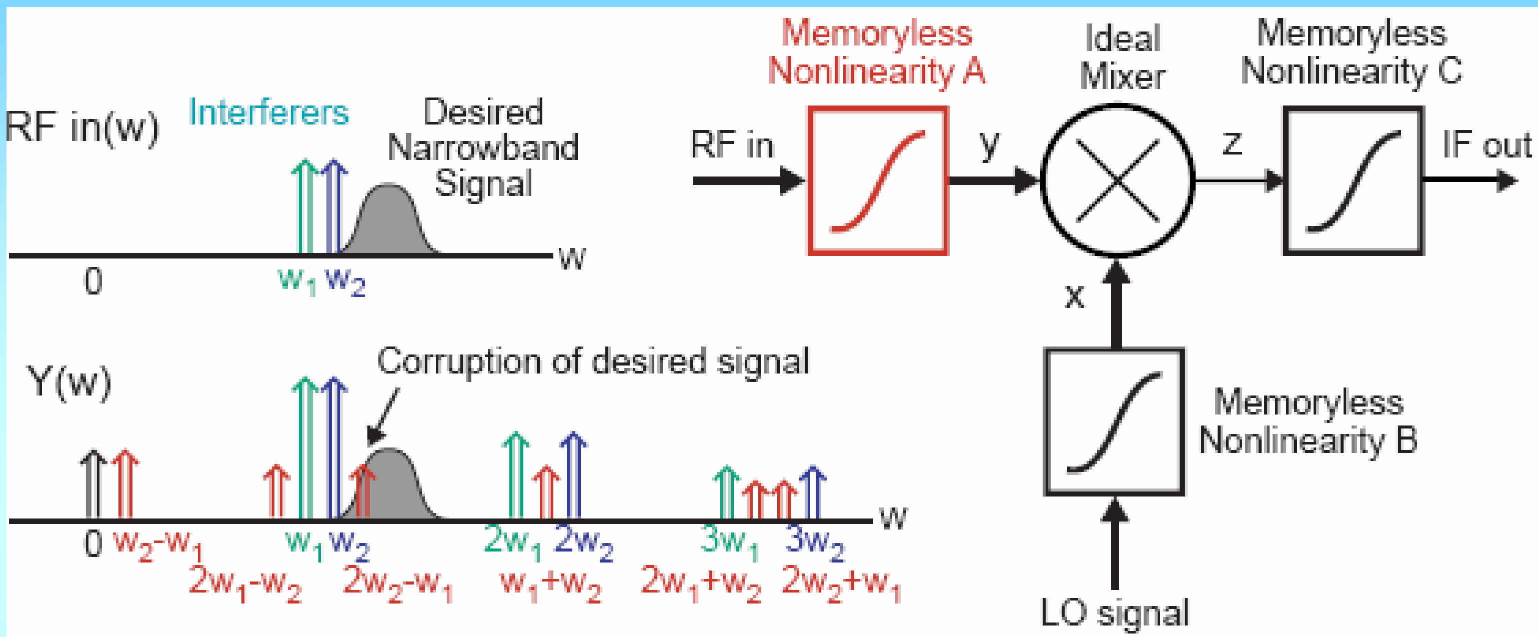
- LO component in the RF input can pass back through the mixer and be modulated by the LO signal
  - DC and 2fo component created at IF output
  - Of no consequence for a heterodyne system, but can cause problems for homodyne systems (i.e., zero IF)

Nonlinearity in Mixers



- Ignoring dynamic effects, three nonlinearities around an ideal mixer
- Nonlinearity A: same impact as LNA nonlinearity
- Nonlinearity B: change the spectrum of LO signal
  - Cause additional mixing that must be analyzed
  - Change conversion gain somewhat
- Nonlinearity C: cause self mixing of IF output

Focus on Nonlinearity in RF Input Path



- Nonlinearity B not detrimental in most cases
  - LO signal often a square wave anyway
- Nonlinearity C avoidable with linear loads
- Nonlinearity A can hamper rejection of interferers
  - Characterize with IIP3 as with LNA designs
  - Use two-tone test to measure (similar to LNA)

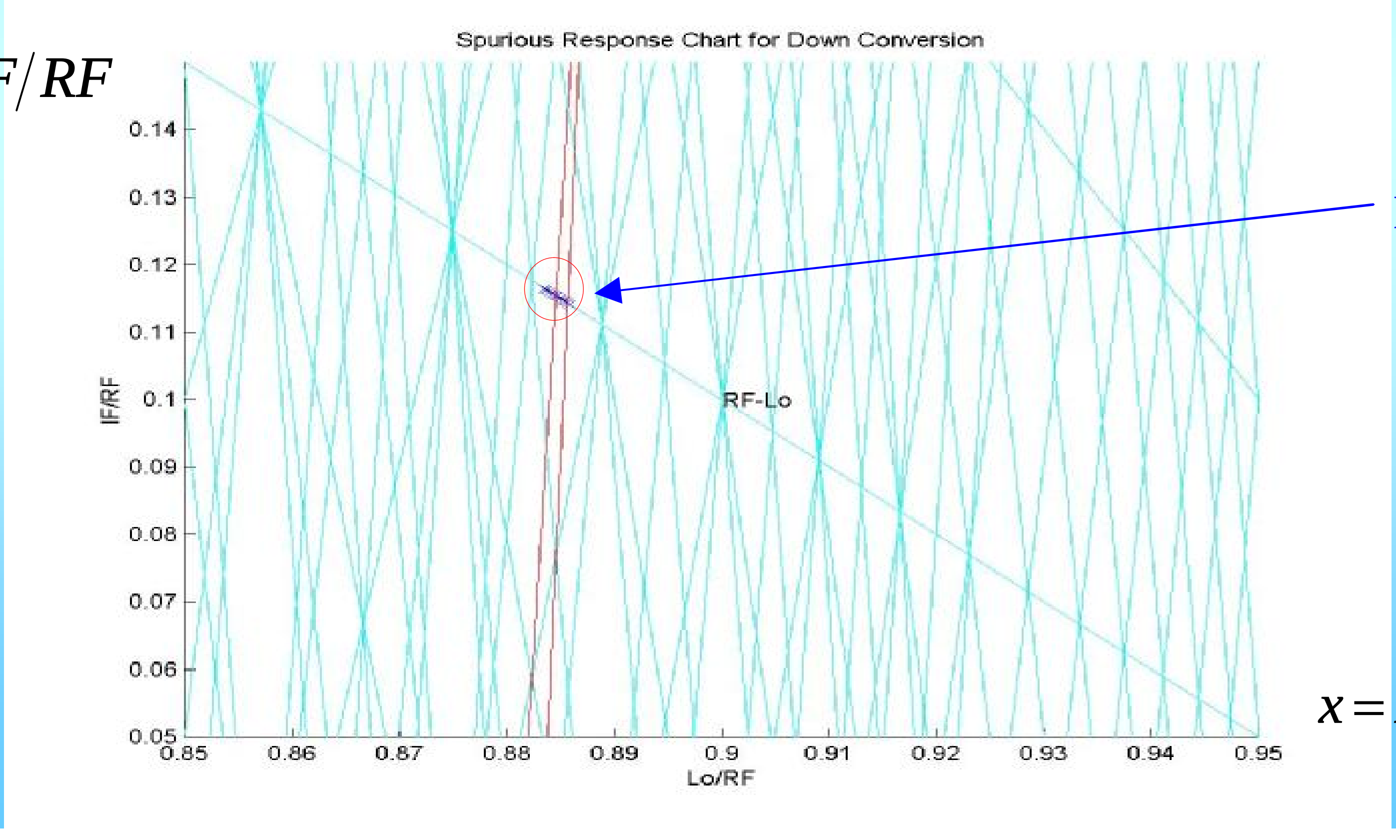
Spurious Response

$$IF = m \cdot RF - n \cdot LO$$

$$\frac{IF}{RF} = -n \cdot \frac{LO}{RF} + m, \quad 0 < \frac{IF}{RF} < \frac{LO}{RF} < 1$$

$$y = -n \cdot x + m \quad 0 < y < x < 1$$

$y = IF/RF$



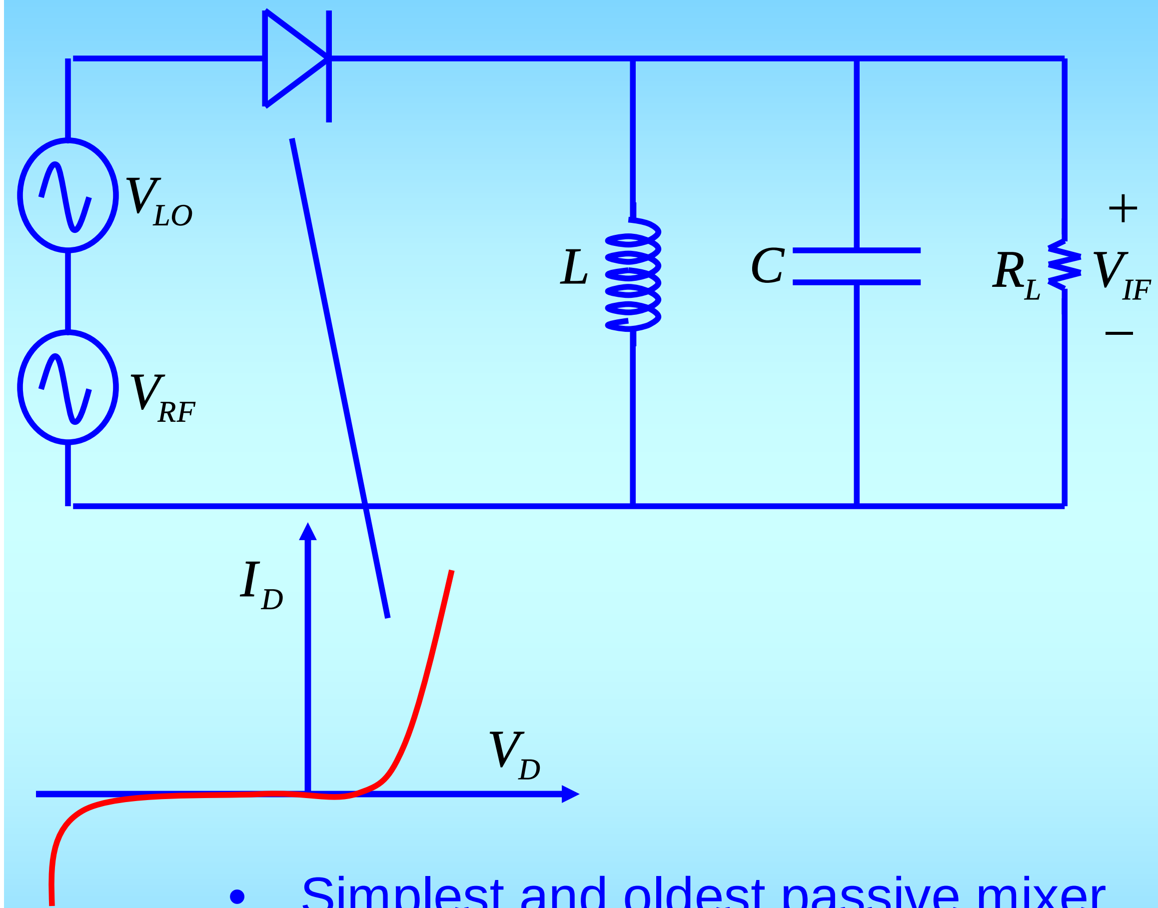
IF Band

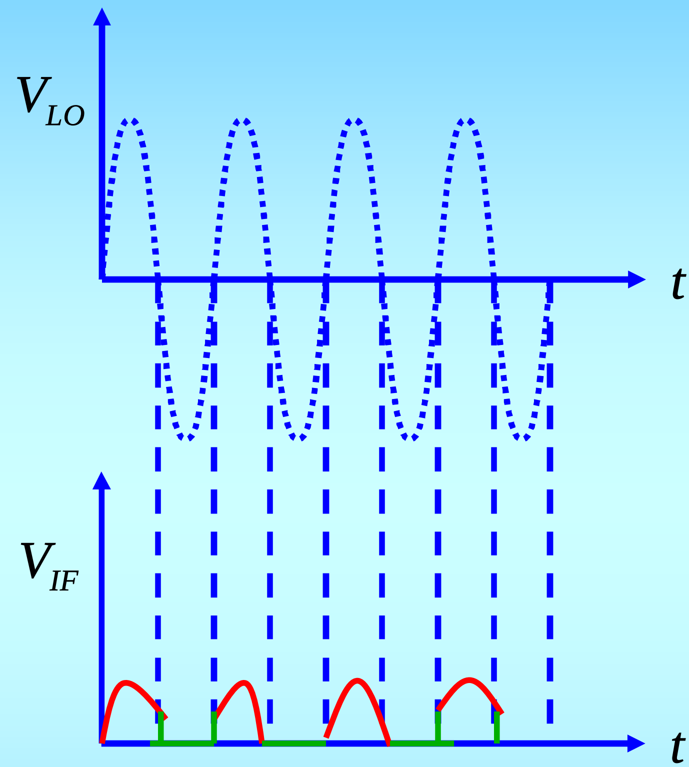
$x = LO/RF$

Mixer topologies

- Discrete implementations:
  - Single-diode and diode-ring mixers
- IC implementations:
  - MOSFET passive mixer
  - Active mixers
  - Gilbert-cell based mixer
  - Square law mixer
  - Sub-sampling mixer
  - Harmonic mixer

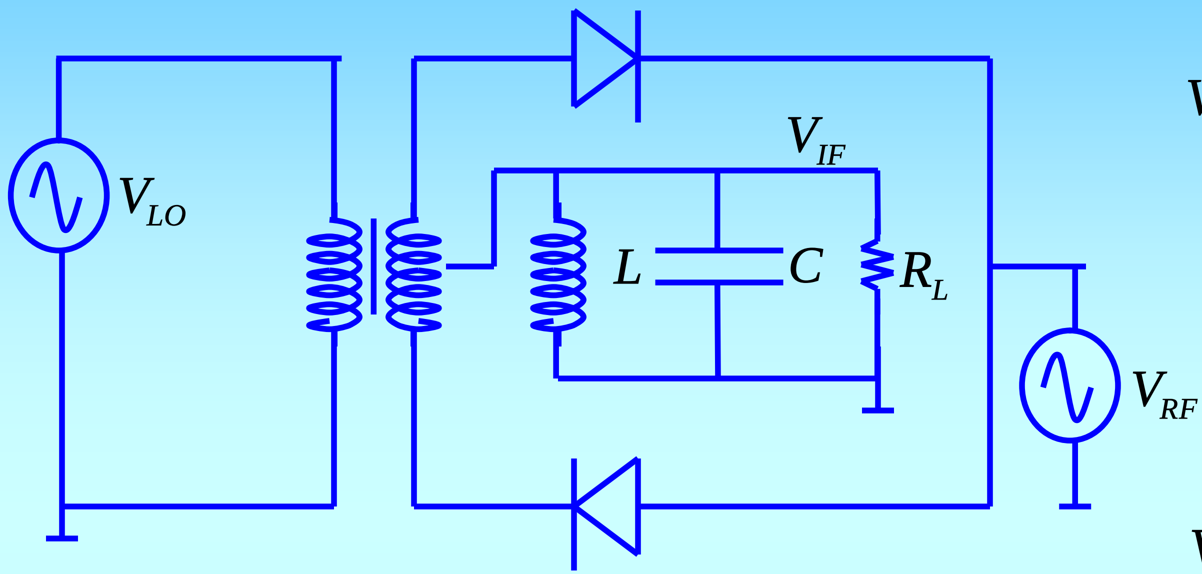
Single-diode passive mixer

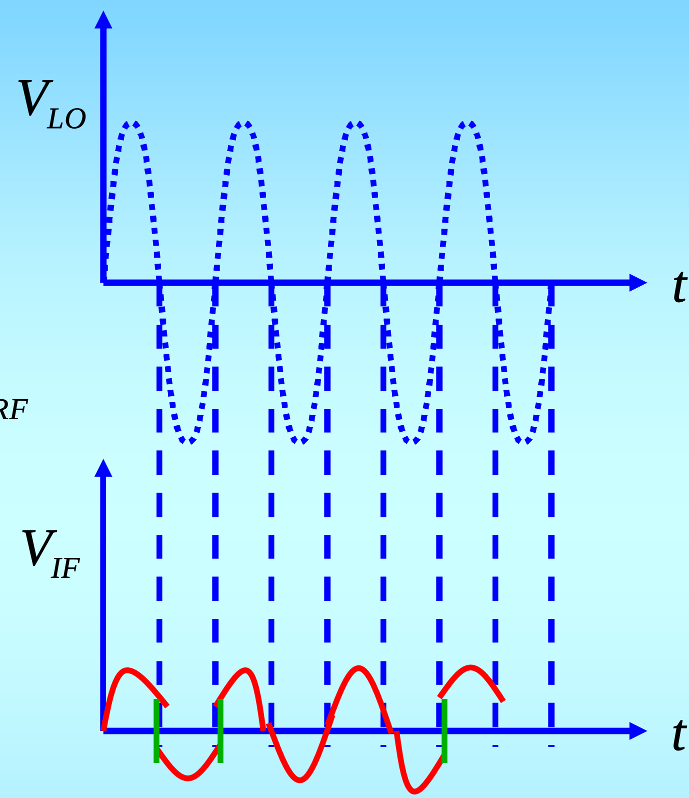




- Simplest and oldest passive mixer
- The output RLC tank tuned to match IF
- Input = sum of RF, LO and DC bias
- No port isolation and no conversion gain.
- Extremely useful at very high frequency (millimeter wave band)

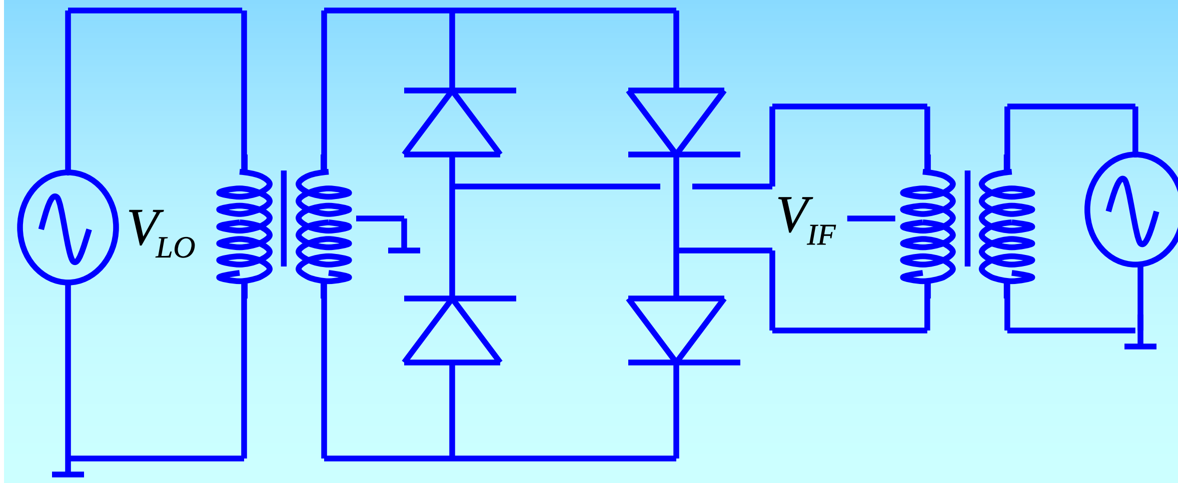
Single-balanced diode mixer

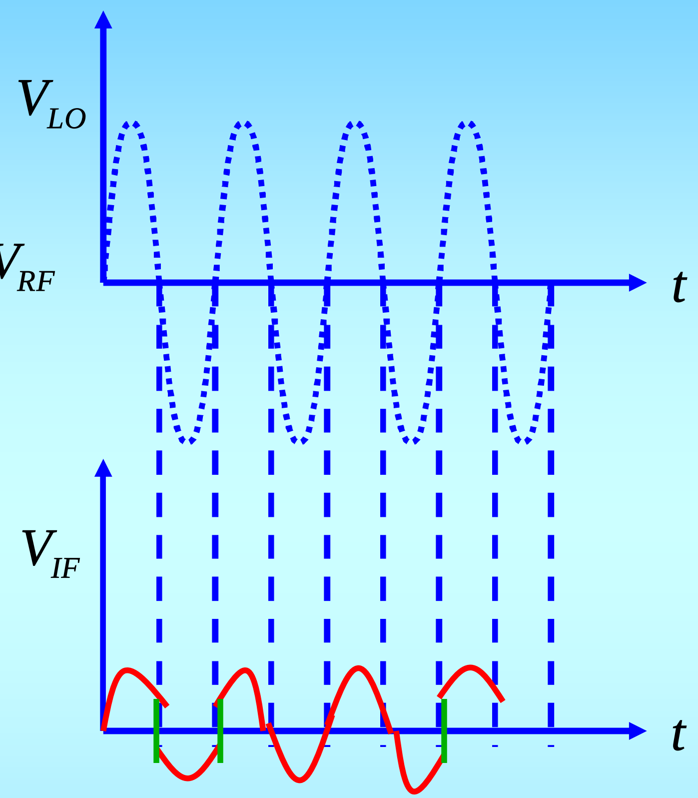




- Poor gain
- Good LO-IF isolation
- Good LO-RF isolation
- Poor RF-IF isolation
- Attractive for very high frequency applications where transistors are slow.

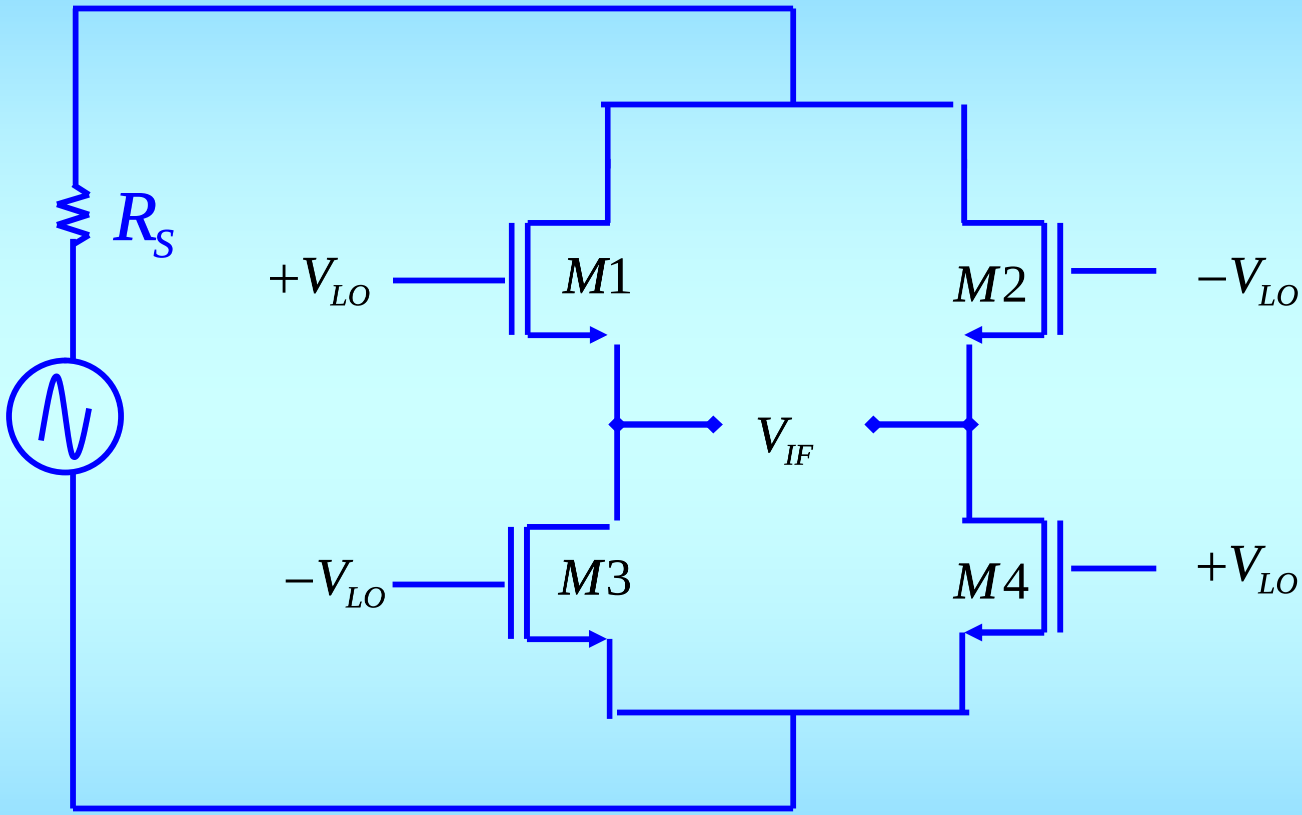
Double-balanced diode mixer





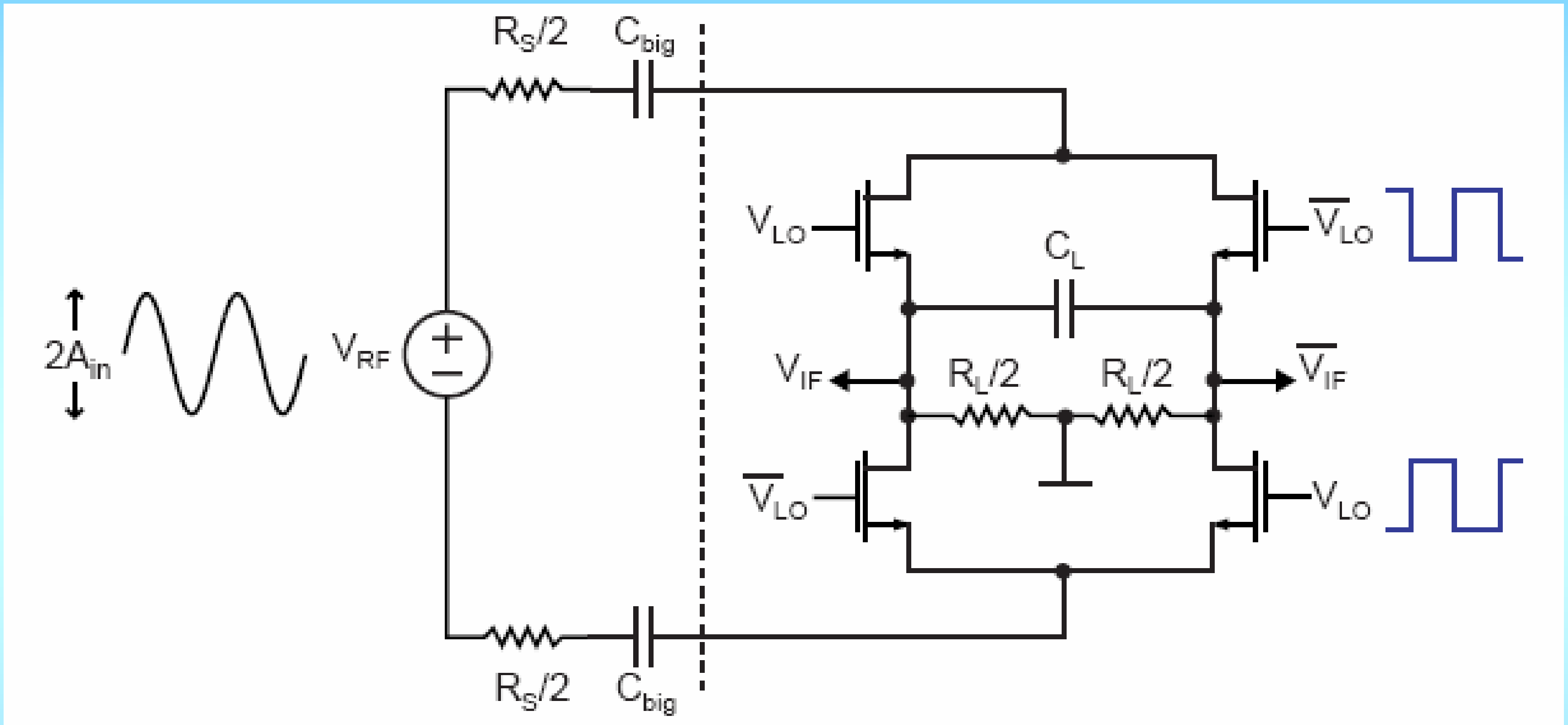
- Poor gain (typically -6dB)
- Good LO-IF LO-RF RF-IF isolation
- Good linearity and dynamic range
- Attractive for very high frequency applications where transistors are slow.

CMOS Passive Mixer



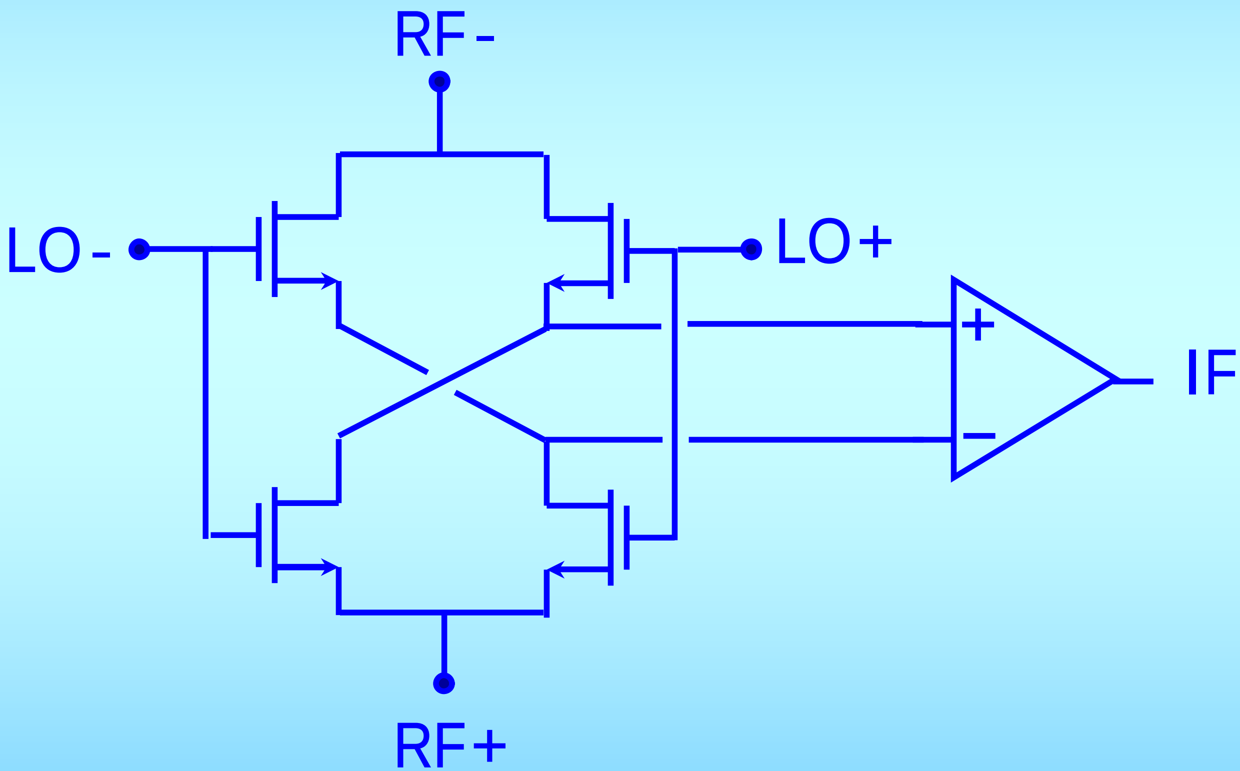
- M1 through M4 act as switches

CMOS Passive Mixer



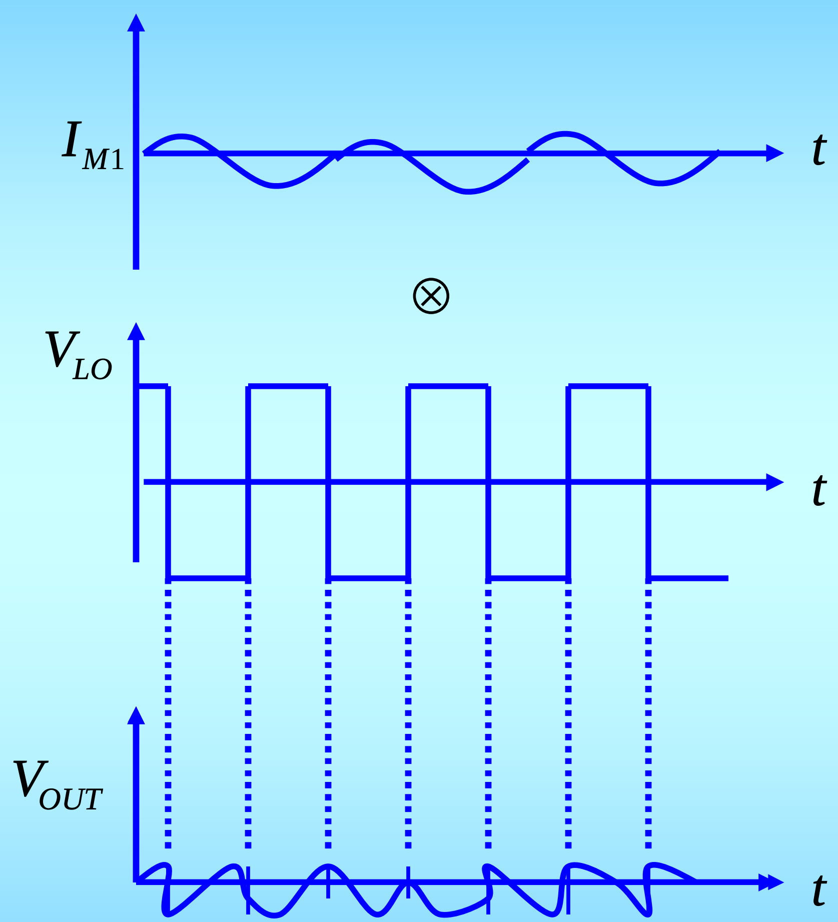
- Use switches to perform the mixing operation
- No bias current required
- Allows low power operation to be achieved

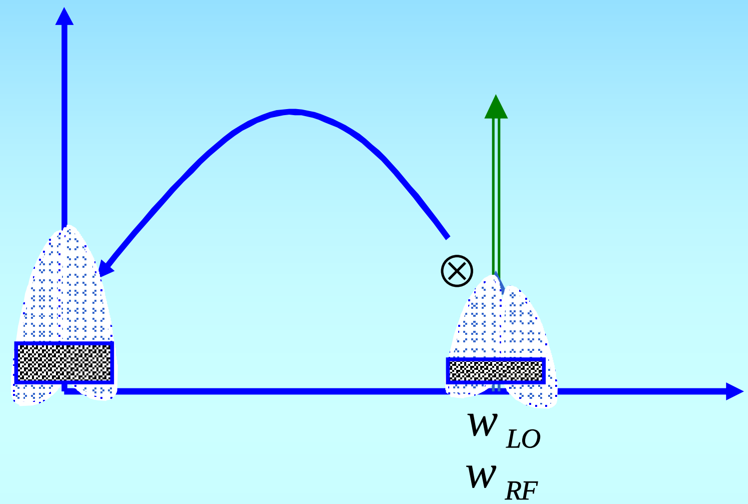
CMOS Passive Mixer



[*] T. Lee

CMOS Passive Mixer



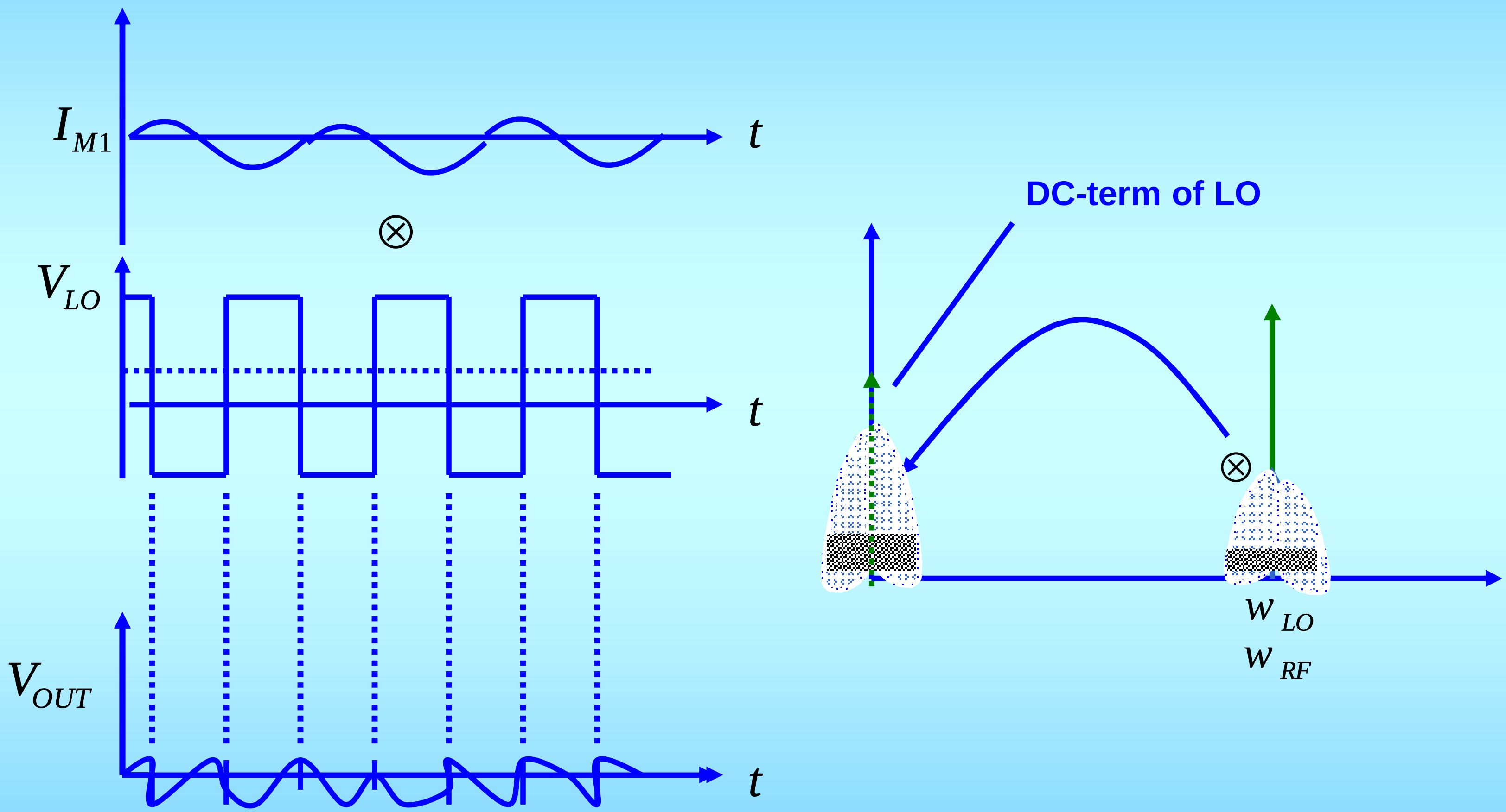


$$G_C = \frac{V_{out}(w_{IF})}{V_{RF}(w_{RF})} = \frac{4}{p}$$

$$V_{out} = V_{RF}.Cos(w_{RF}t) \otimes \left\{ \frac{4}{p} Cos(w_{LO}t) - \frac{4}{3p} Cos(3w_{LO}t) + \frac{4}{5p} Cos(5w_{LO}t) - ... \right\}$$

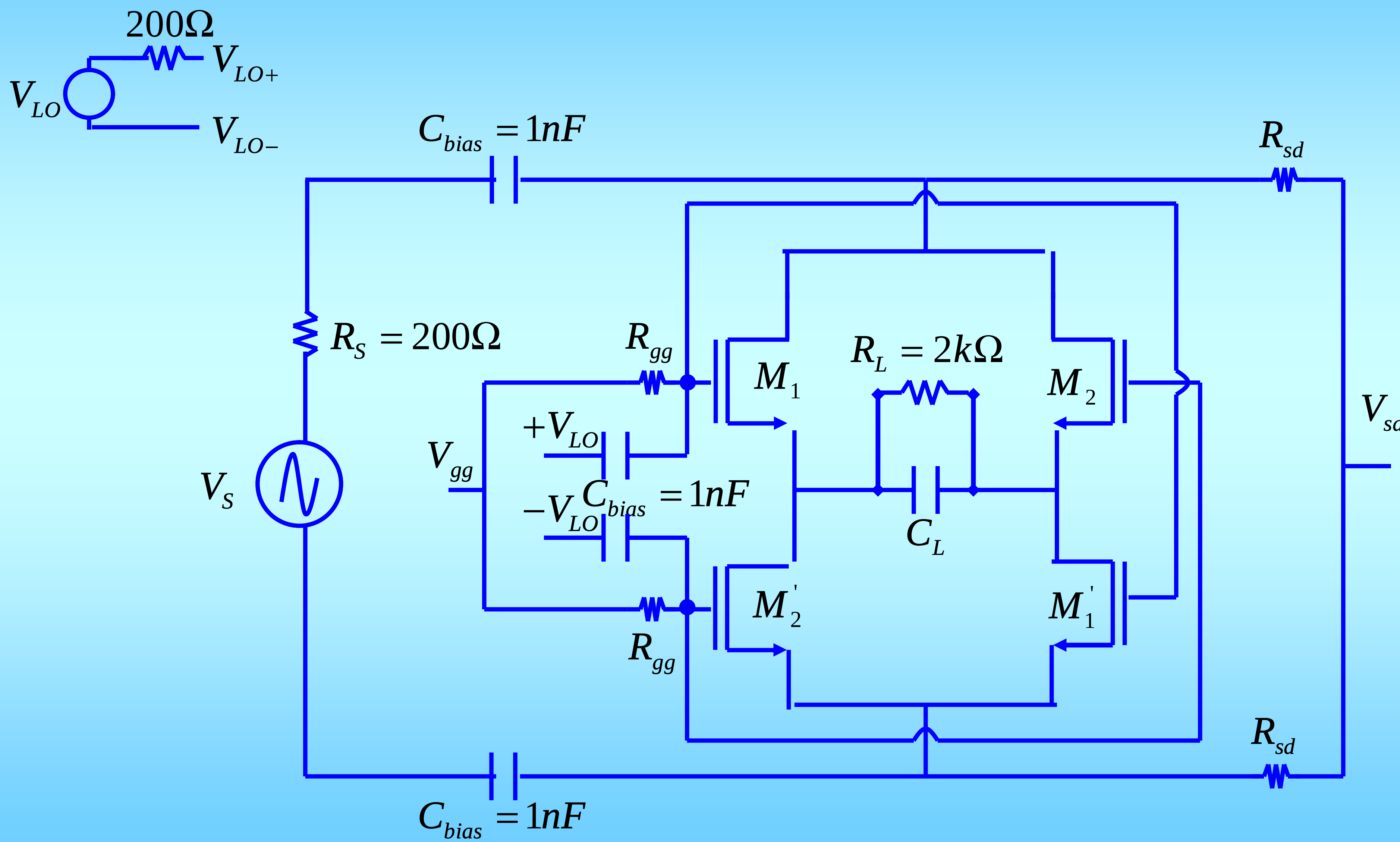
CMOS Passive Mixer

- Non-50% duty cycle of LO results in no DC offsets!!

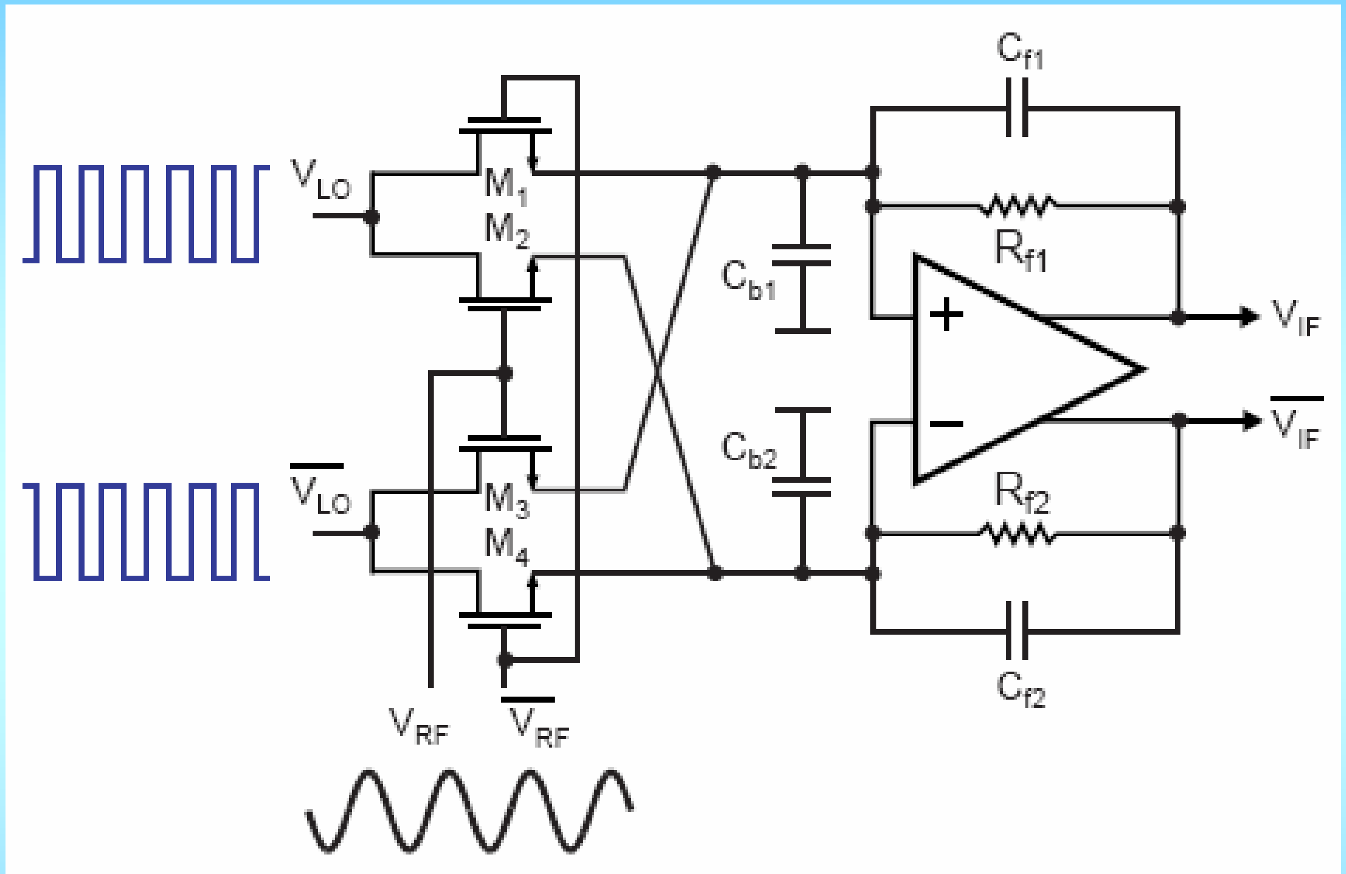


$$V_{out} = V_{RF}.Cos\left(w_{RF}t\right) \otimes \left\{ DC + \frac{4}{p}Cos\left(w_{LO}t\right) - \frac{4}{3p}Cos\left(3w_{LO}t\right) + \frac{4}{5p}Cos\left(5w_{LO}t\right) - ... \right\}$$

CMOS Passive Mixer with Biasing



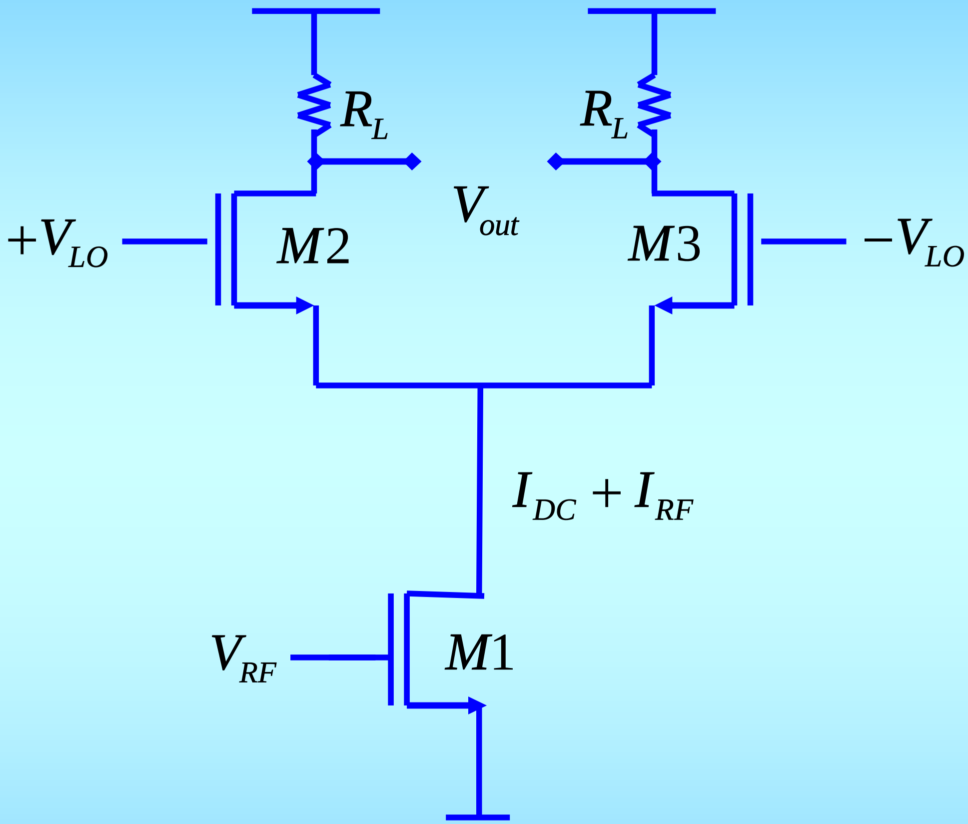
A Highly Linear CMOS Mixer



- Transistors are alternated between the off and triode regions by the LO signal
- RF signal varies resistance of channel when in triode
- Large bias required on RF inputs to achieve triode operation
  - High linearity achieved, but very poor noise figure

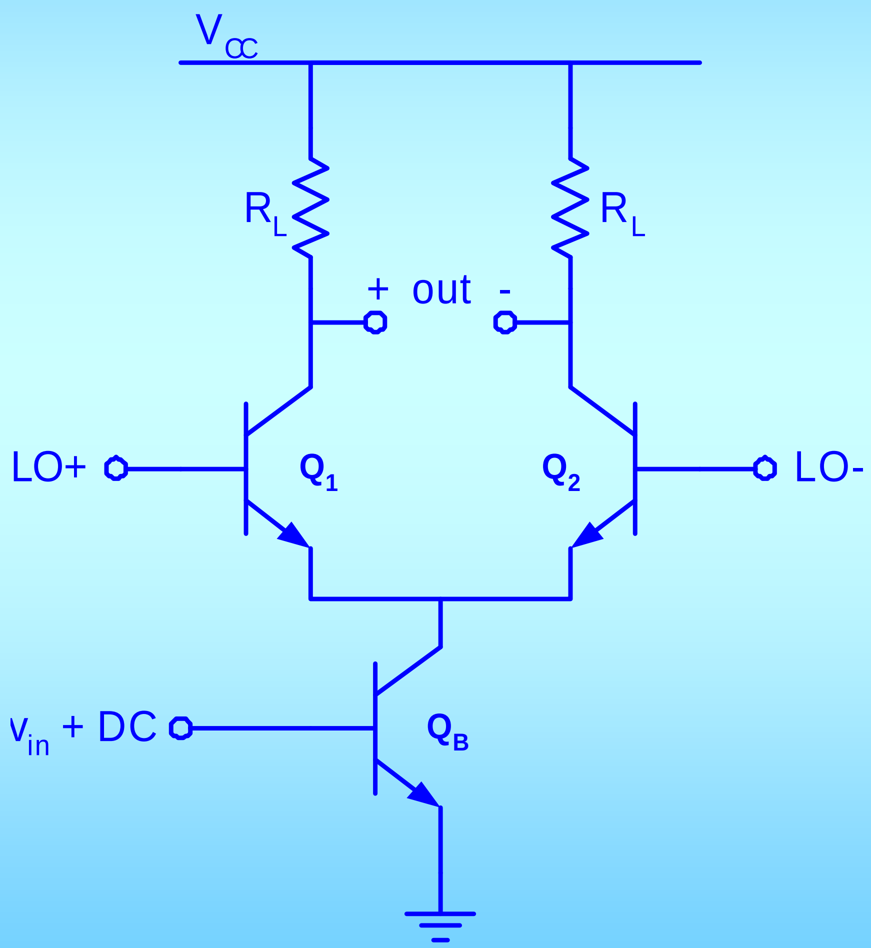
Simple Switching Mixer (Single Balanced Mixer)

- The transistor M1 converts the RF voltage signal to the current signal.
- Transistors M2 and M3 commute the current between the two branches.



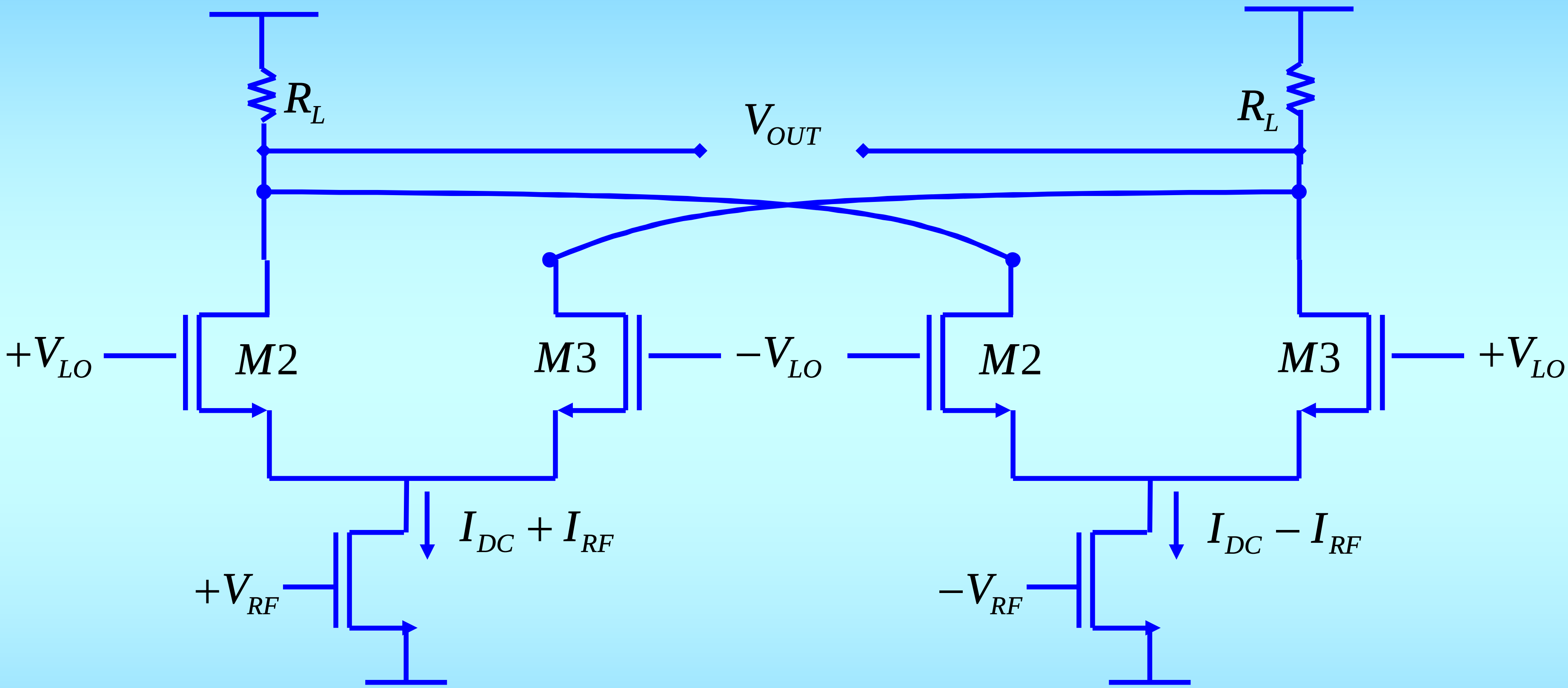
Single balanced active mixer, BJT

- Single-ended input
- Differential LO
- Differential output
- Q_B provides gain for v_{in}
- Q_1 and Q_2 steer the current back and forth at ω_{LO}



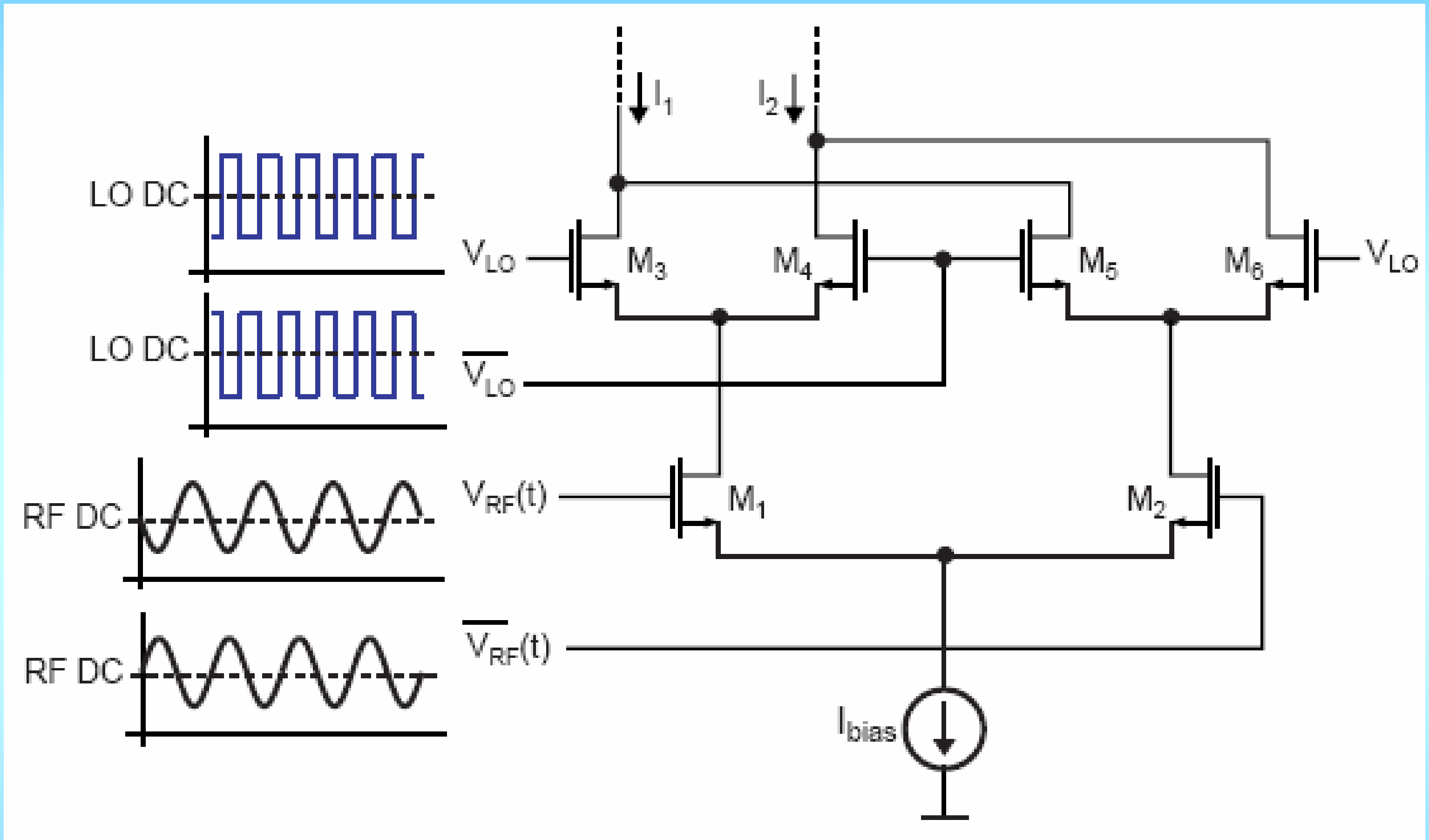
$$v_{out} = \pm g_m v_{in} R_L$$

Double Balanced Mixer



- Strong LO-IF feed suppressed by double balanced mixer.
- All the even harmonics cancelled.
- All the odd harmonics doubled (including the signal).

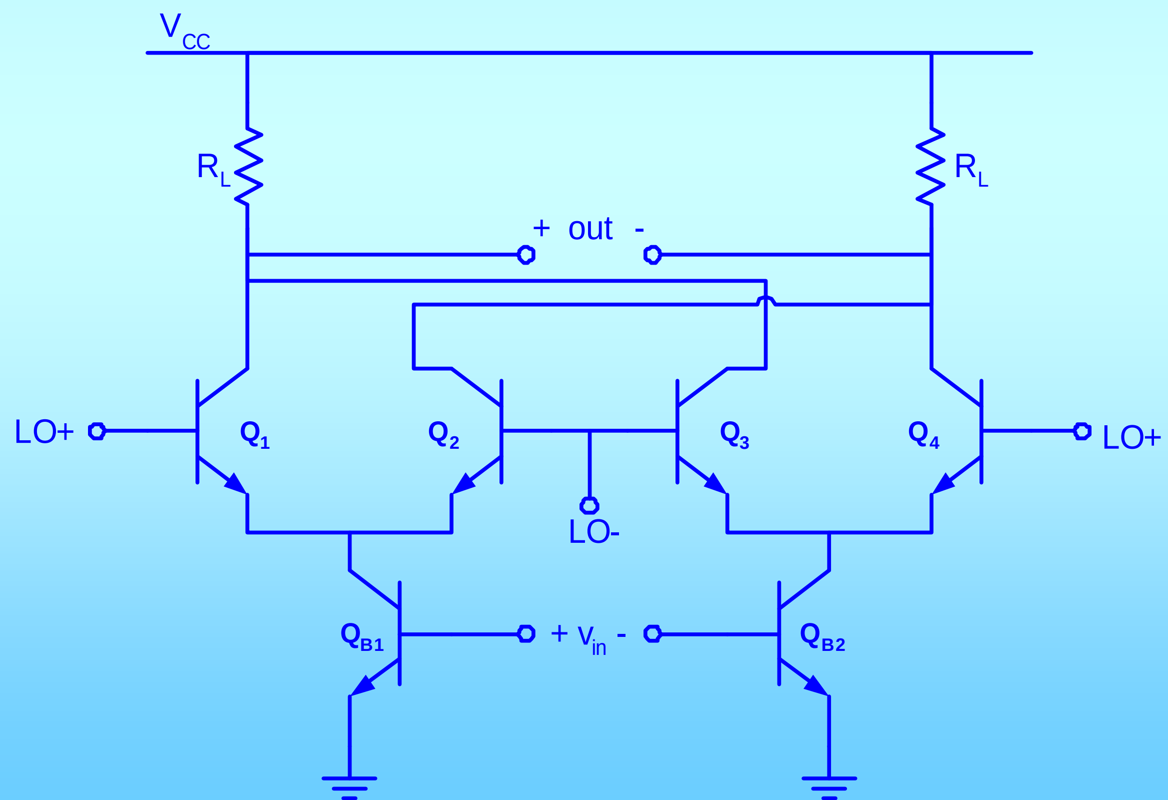
Gilbert Mixer



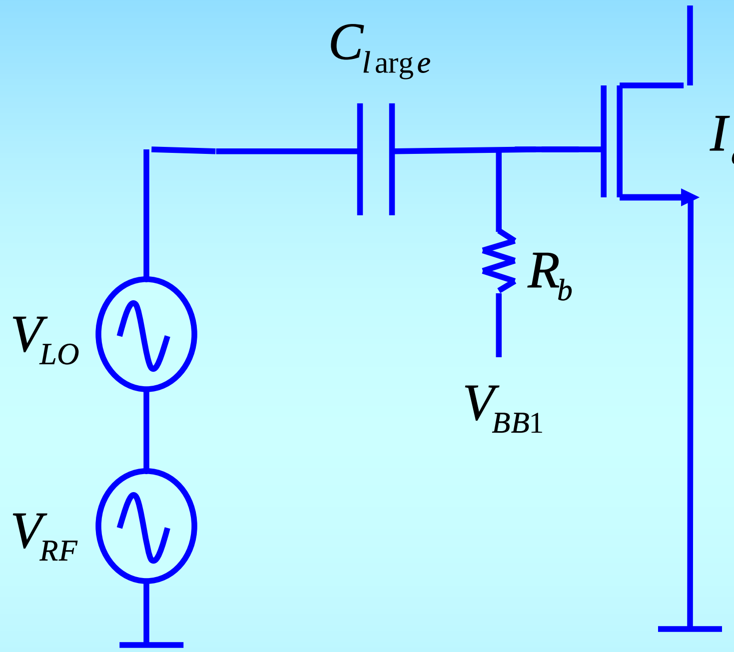
- Use a differential pair to achieve the transconductor implementation
- This is the preferred mixer implementation for most radio systems!

Double balanced mixer, BJT

- Basically two SB mixers
  - One gets $+v_{in}/2$, the other gets $–v_{in}/2$



Mixers based on MOS square law



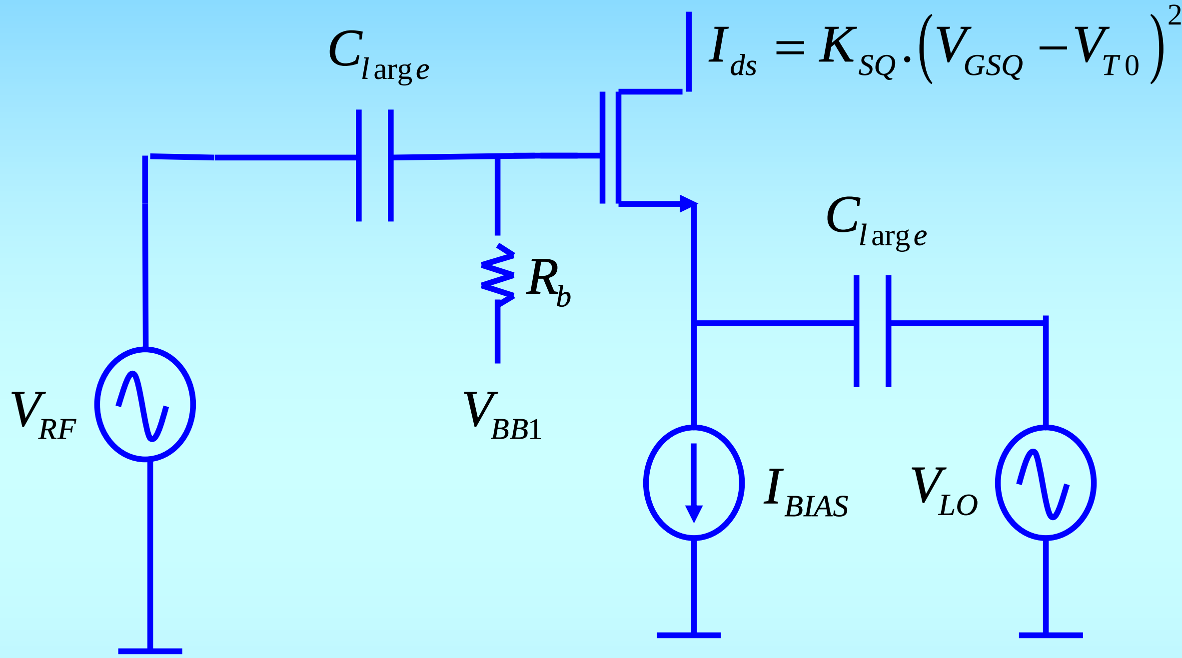
$$I_{ds} = K_{SQ}.\left(V_{GSQ} - V_{T0}\right)^2$$

$$I_{ds} = K_{SQ}.\left(V_{bias} + V_{RF} + V_{LO} - V_{T0}\right)^2$$
$$= K_{SQ}.\left\{\left(V_{bias} - V_{T0}\right)^2 + \left(V_{RF} + V_{LO}\right)^2 + 2\left(V_{bias} - V_{T0}\right).\left(V_{RF} + V_{LO}\right)\right\}$$

$(V_{RF} + V_{LO})^2$ gives rise to

$\cos(w_{RF} - w_{LO})t$ and $\cos(w_{RF} - w_{LO})t$

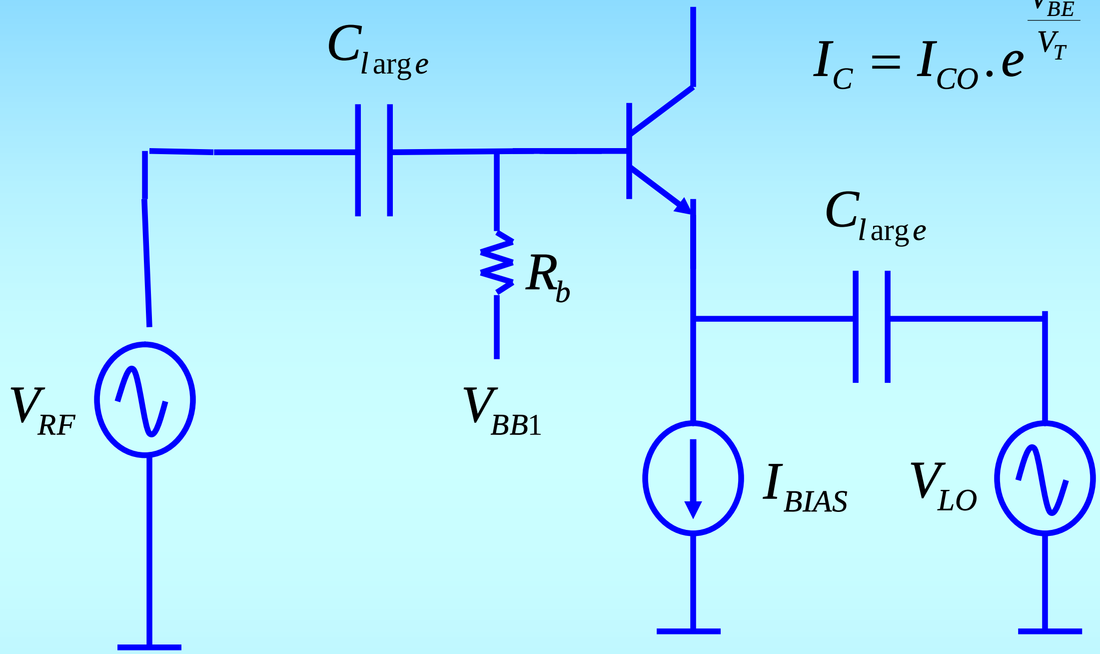
Practical Square Law Mixers



The conversion gain can be shown to be

$$K_{sq}V_{LO} = \frac{mC_{ox}W}{2L}V_{LO}$$

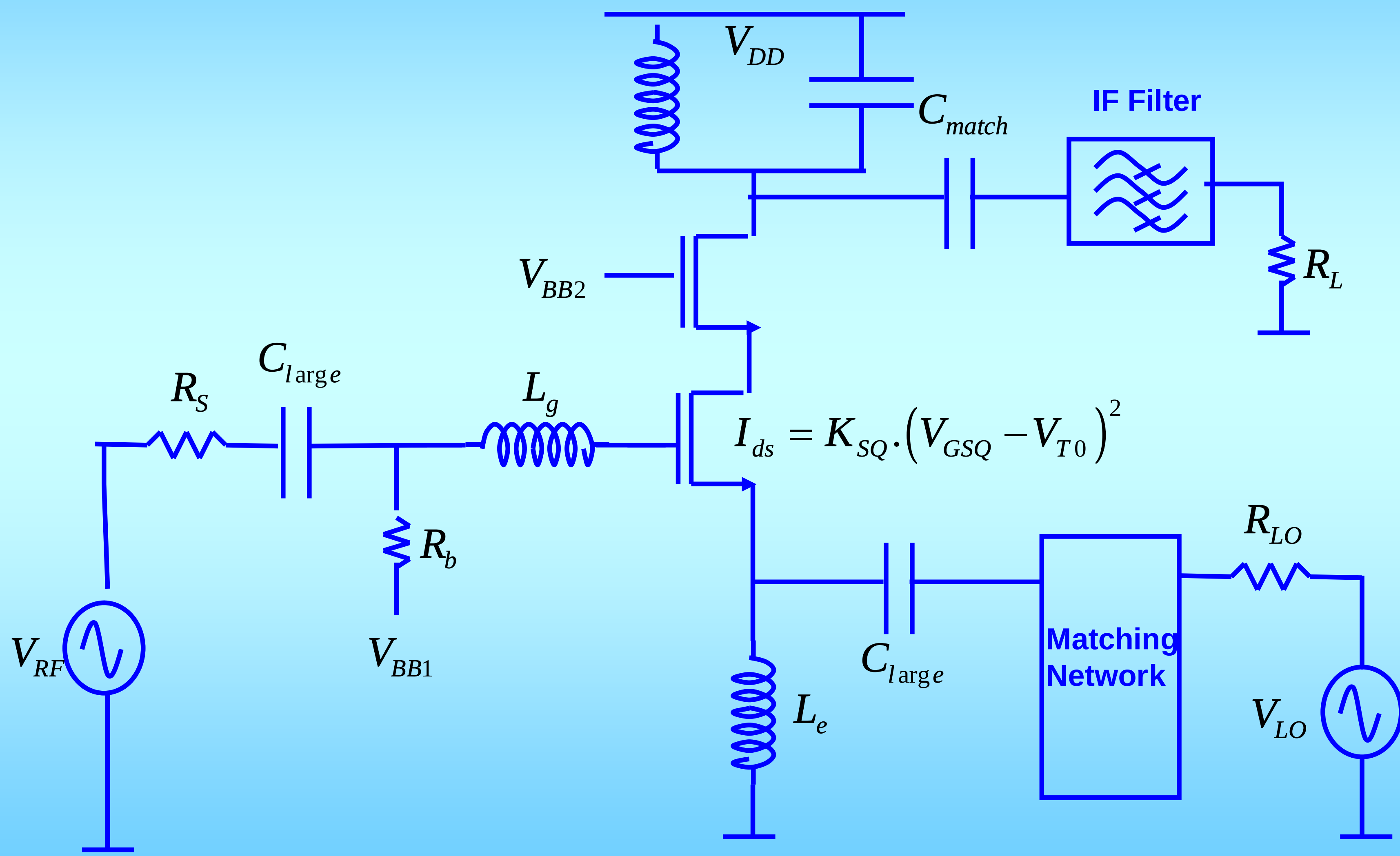
Practical Bipolar Mixer



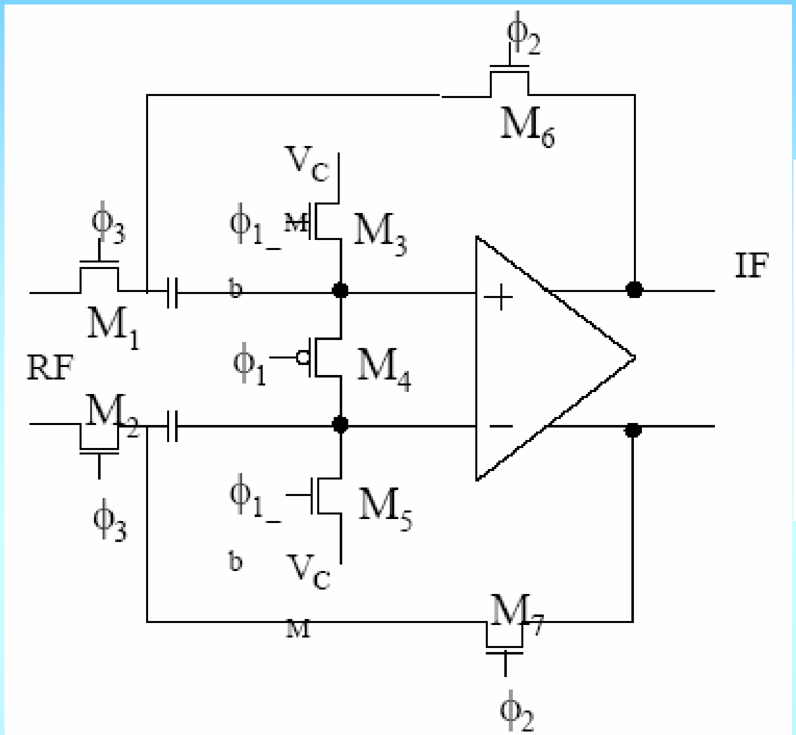
$$I_C = I_{CO}.e^{\frac{V_{BE}}{V_T}}$$

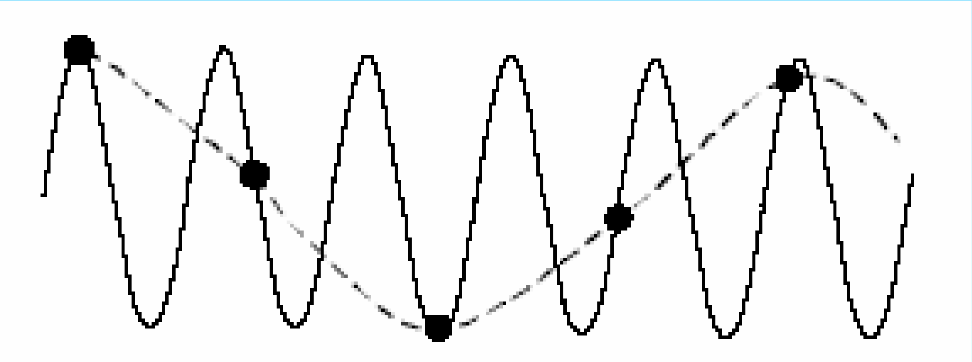
The conversion gain can be shown to be $\dfrac{I_{CQ}}{v_T^2}V_{LO}$

MOSFET Mixer (with impedance matching)



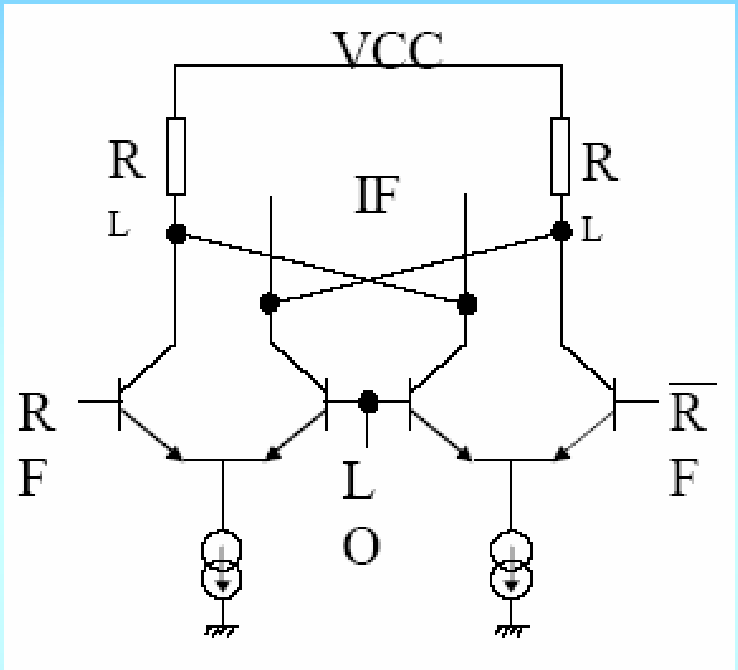
Sub-sampling Mixer





- Properly designed track-and-hold circuit works as sub-sampling mixer.
- The sampling clock's jitter must be very small
- Noise folding leads to large mixer noise figure.
- High linearity

Harmonic Mixer



- Emitter-coupled BJTs work as two limiters.
- Odd symmetry suppress even order distortion eg LO selfmixing.
- Small RF signal modulates zero crossing of large LO signal.
- Output rectangular wave in PWM
- LPF demodulate the PWM

- Harmonic mixer has low self-mixing DC offset, very attractive for direct conversion application.
- The RF single will mix with the second harmonic of the LO. So the LO can run at half rate, which makes VCO design easier.
- Because of the harmonic mixing, conversion gain is usually small