High Speed Communication Circuits and Systems
Lecture 10
Mixers

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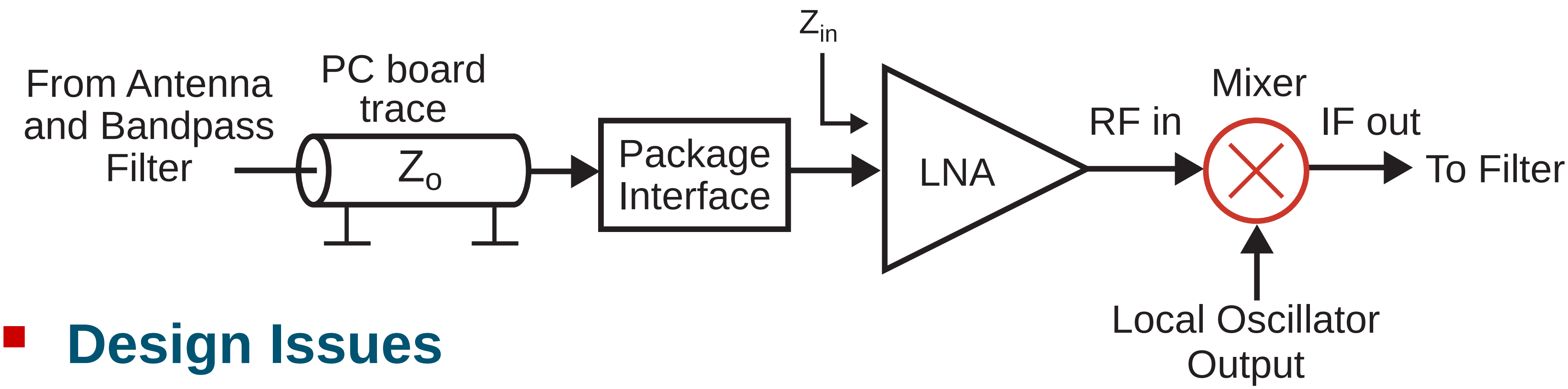
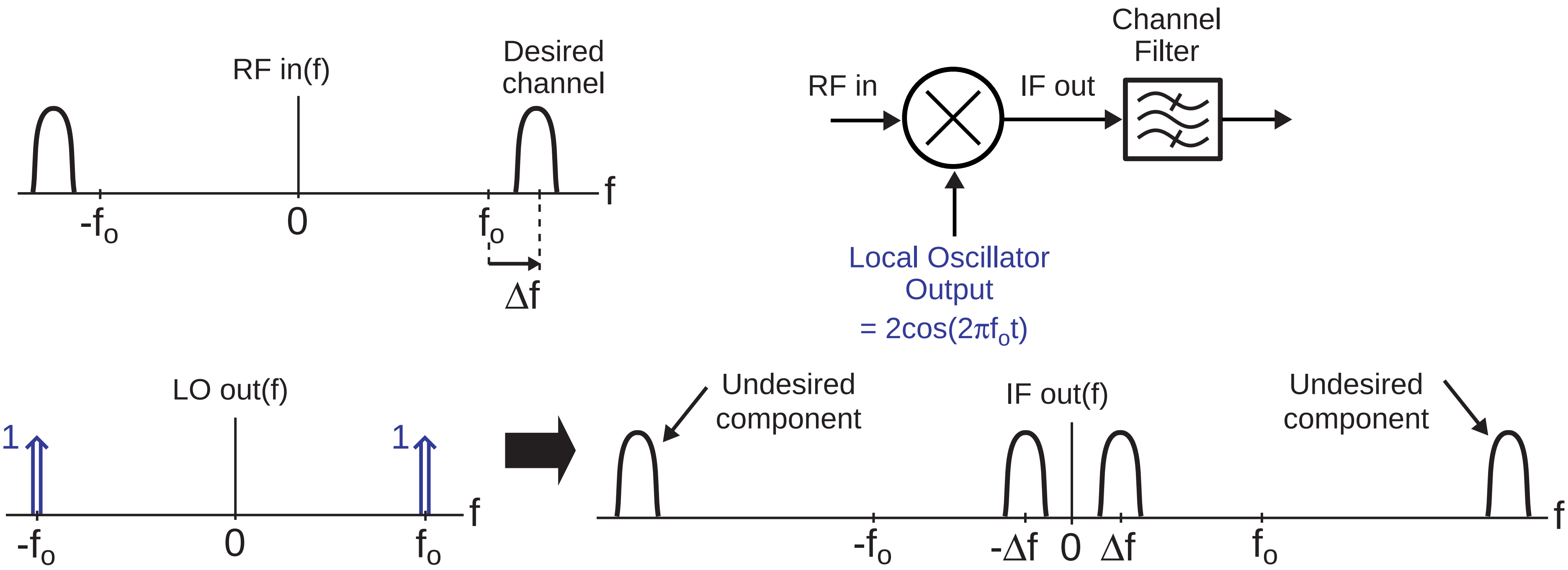
Mixer Design for Wireless Systems



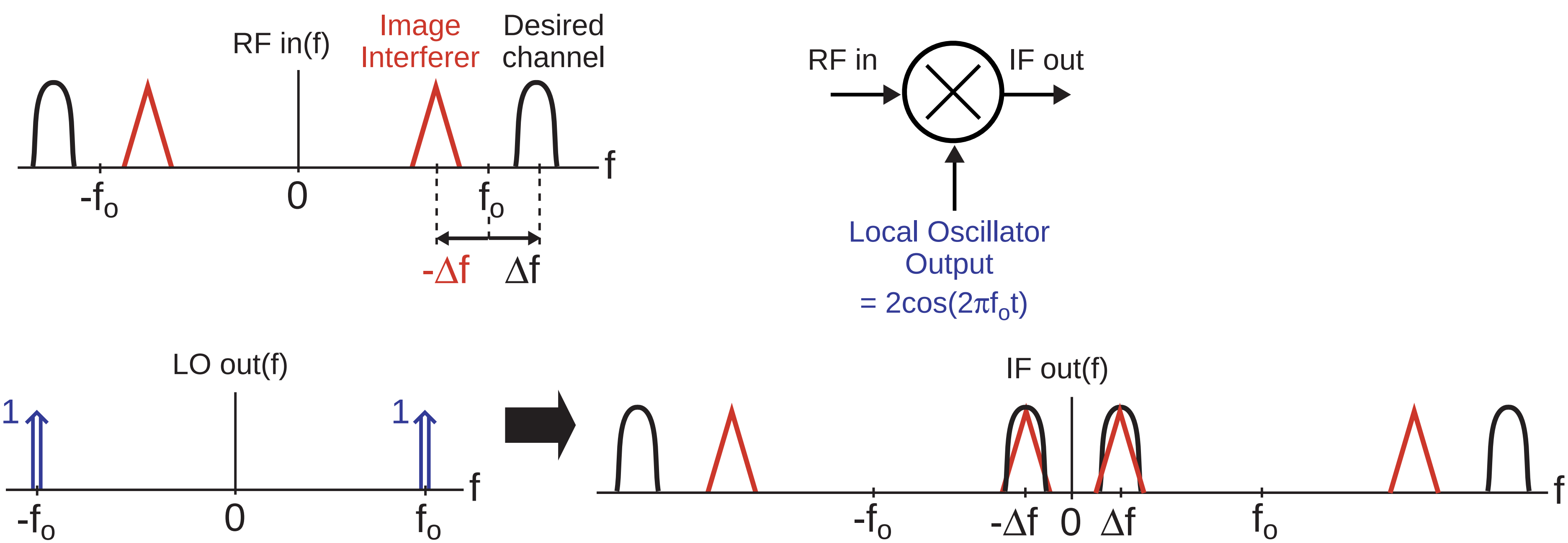
- **Design Issues**
  - **Noise Figure – impacts receiver sensitivity**
  - **Linearity (IIP3) – impacts receiver blocking performance**
  - **Conversion gain – lowers noise impact of following stages**
  - **Power match – want max voltage gain rather than power match for integrated designs**
  - **Power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

Ideal Mixer Behavior



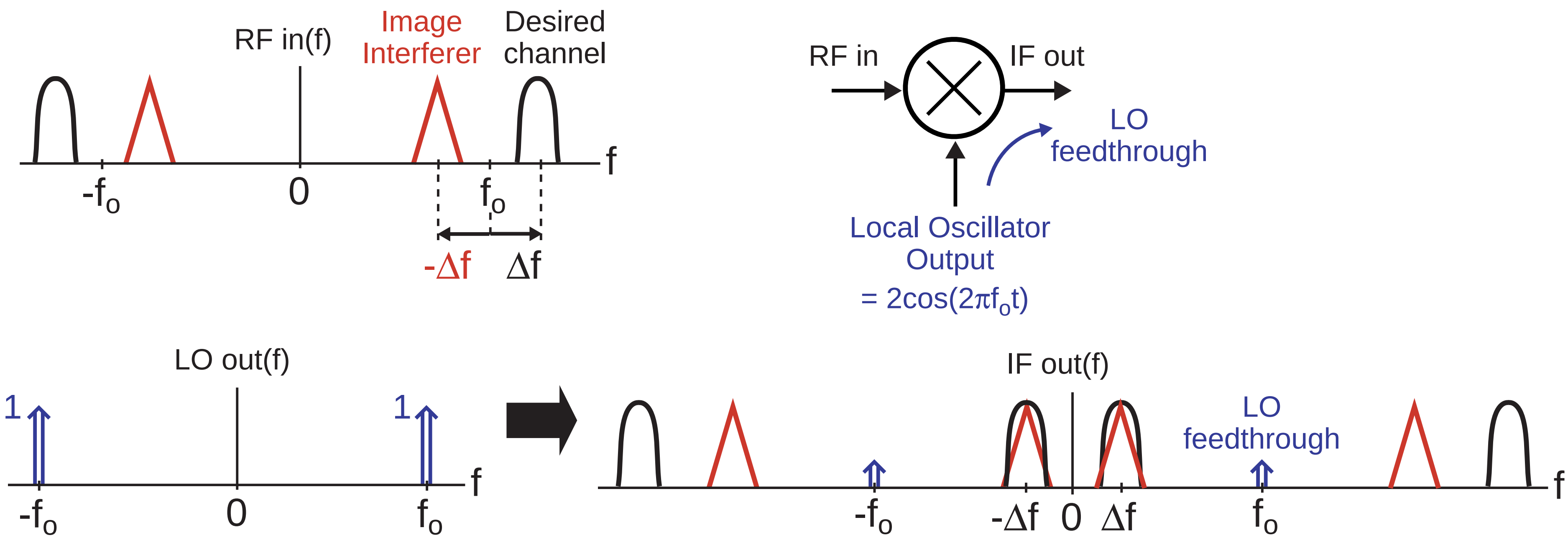
- **RF spectrum converted to a lower IF center frequency**
  - **IF stands for intermediate frequency**
    - If IF frequency is nonzero – heterodyne or low IF receiver
    - If IF frequency is zero – homodyne receiver
- **Use a filter at the IF output to remove undesired high frequency components**

The Issue of Aliasing



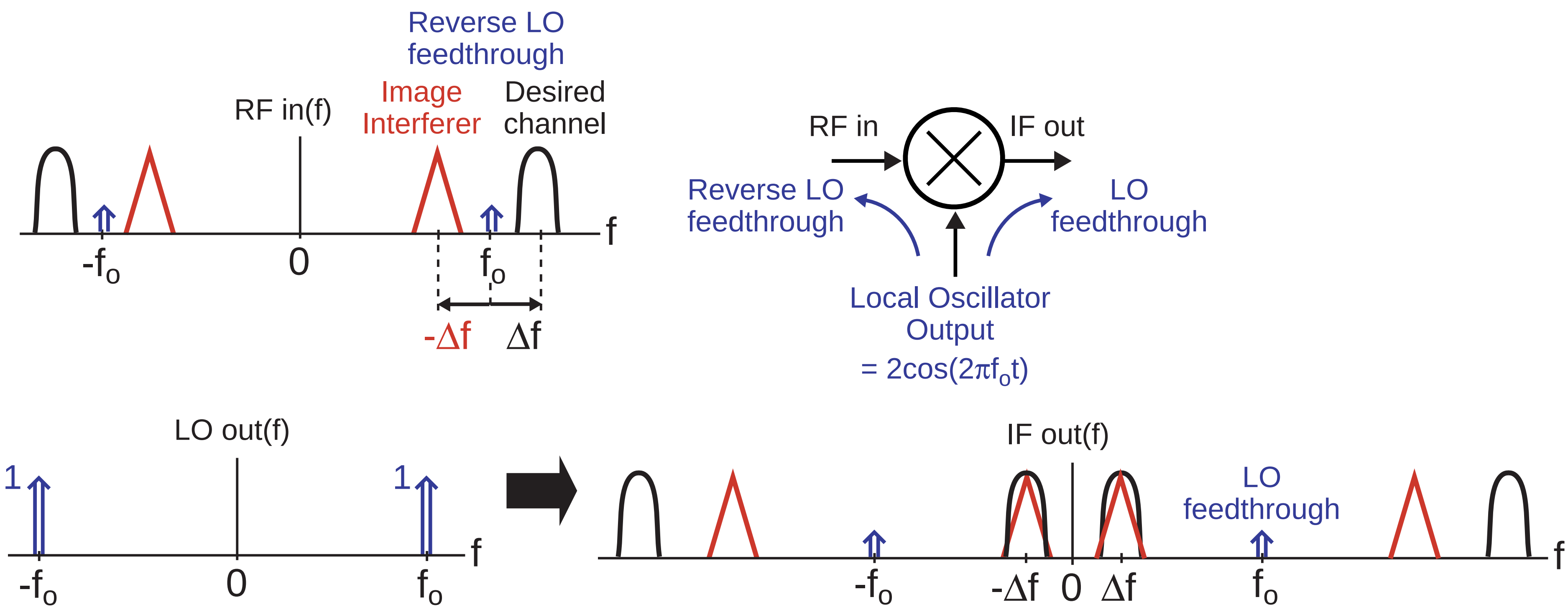
- **When the IF frequency is nonzero, there is an image band for a given desired channel band**
  - **Frequency content in image band will combine with that of the desired channel at the IF output**
  - **The impact of the image interference cannot be removed through filtering at the IF output!**

LO Feedthrough



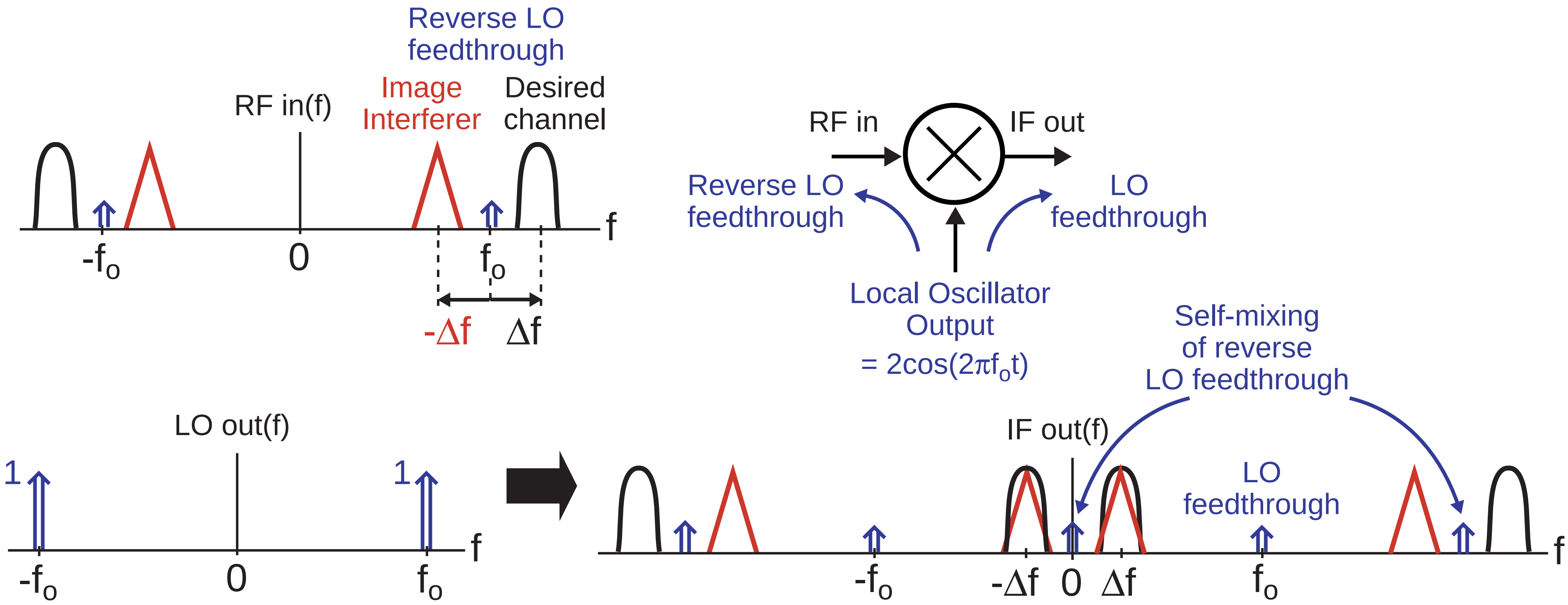
- **LO feedthrough will occur from the LO port to IF output port due to parasitic capacitance, power supply coupling, etc.**
  - **Often significant since LO output much higher than RF signal**
    - If large, can potentially desensitize the receiver due to the extra dynamic range consumed at the IF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

Reverse LO Feedthrough



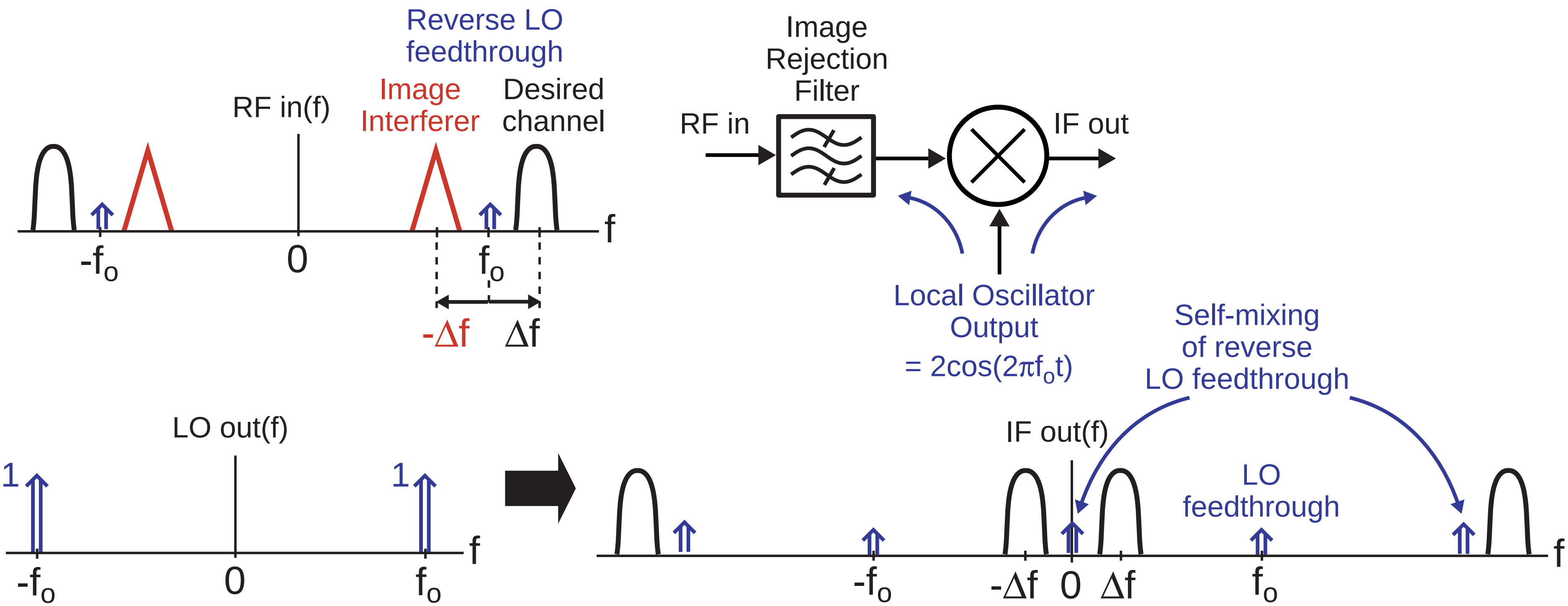
- **Reverse LO feedthrough will occur from the LO port to RF input port due to parasitic capacitance, etc.**
  - **If large, and LNA doesn't provide adequate isolation, then LO energy can leak out of antenna and violate emission standards for radio**
  - **Must insure that isolate to antenna is adequate**

Self-Mixing of Reverse LO Feedthrough



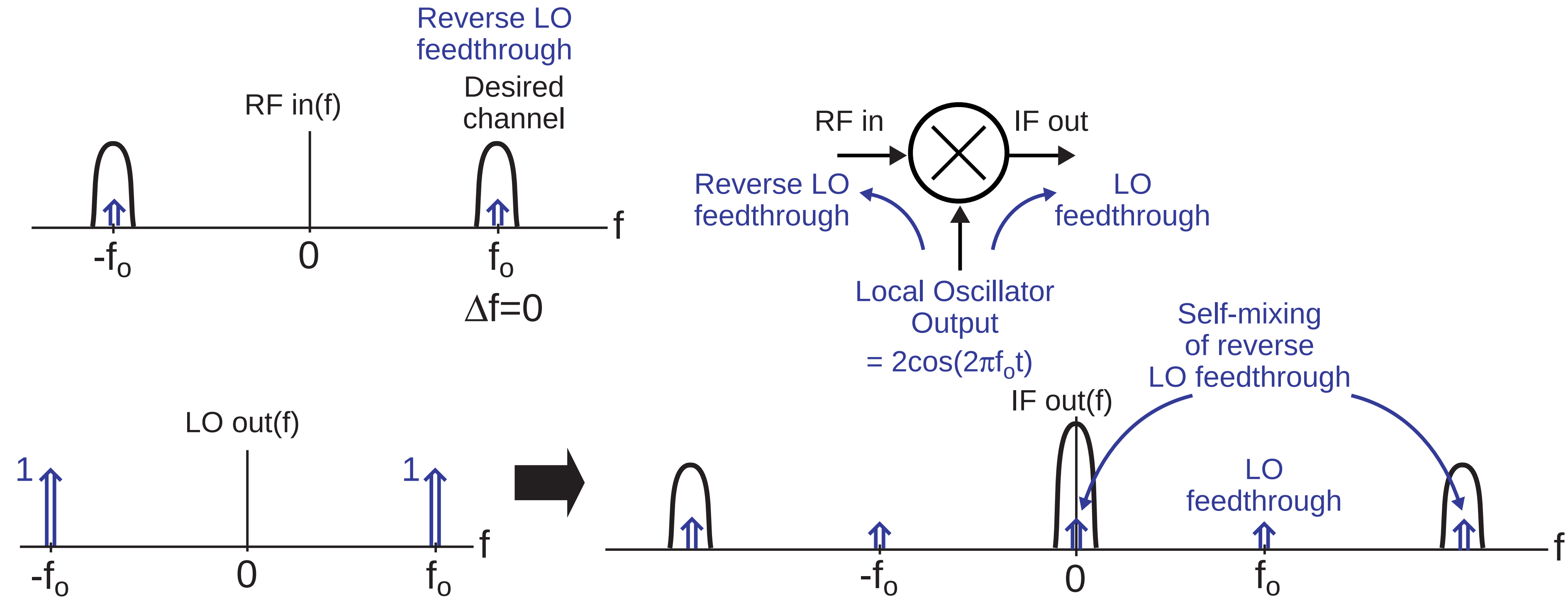
- **LO component in the RF input can pass back through the mixer and be modulated by the LO signal**
  - **DC and $2f_o$ component created at IF output**
  - **Of no consequence for a heterodyne system, but can cause problems for homodyne systems (i.e., zero IF)**

Removal of Image Interference – Solution 1



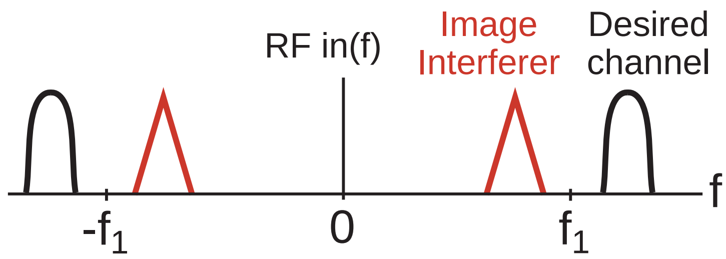
- An image reject filter can be used *before* the mixer to prevent the image content from aliasing into the desired channel at the IF output
- Issue – must have a high IF frequency
  - Filter bandwidth must be large enough to pass all channels
  - Filter Q cannot be arbitrarily large (low IF requires high Q)

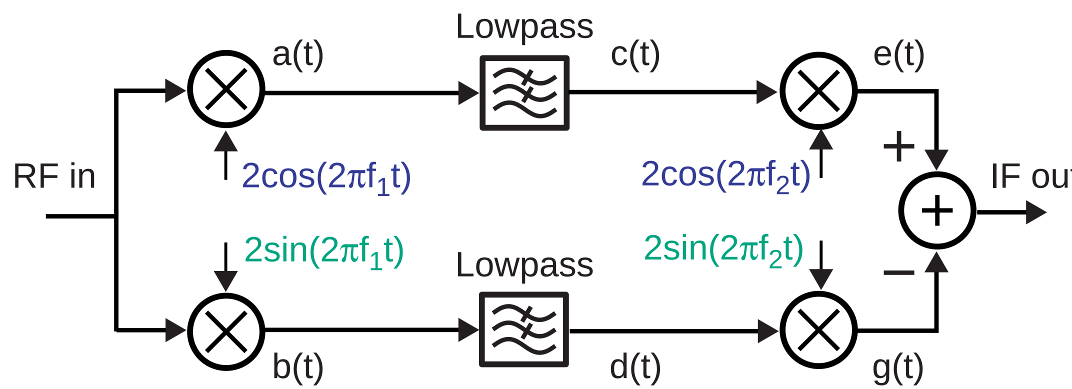
Removal of Image Interference – Solution 2



- Mix directly down to baseband (i.e., homodyne approach)
  - With an IF frequency of zero, there is no image band
- Issues – many!
  - DC term of LO feedthrough can corrupt signal if time-varying
  - DC offsets can swamp out dynamic range at IF output
  - 1/f noise, back radiation through antenna

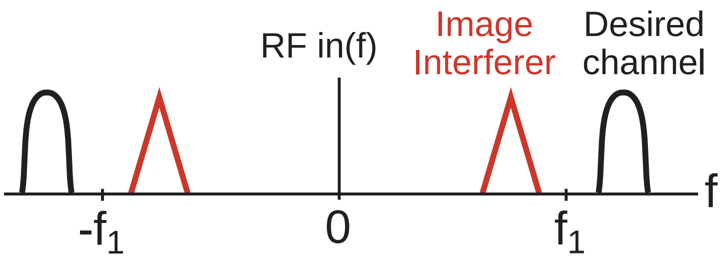
Removal of Image Interference – Solution 3

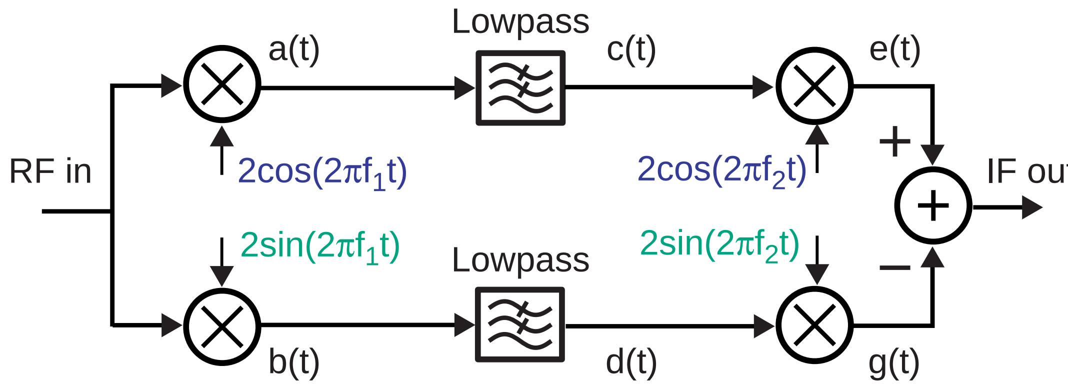




- **Rather than filtering out the image, we can cancel it out using an image rejection mixer**
  - **Advantages**
    - Allows a low IF frequency to be used without requiring a high Q filter
    - Very amenable to integration
  - **Disadvantage**
    - Level of image rejection is determined by mismatch in gain and phase of the top and bottom paths
    - Practical architectures limited to 40-50 dB image rejection

Image Reject Mixer Principles – Step 1





- **Note: we are assuming RF in(f) is purely real right now**

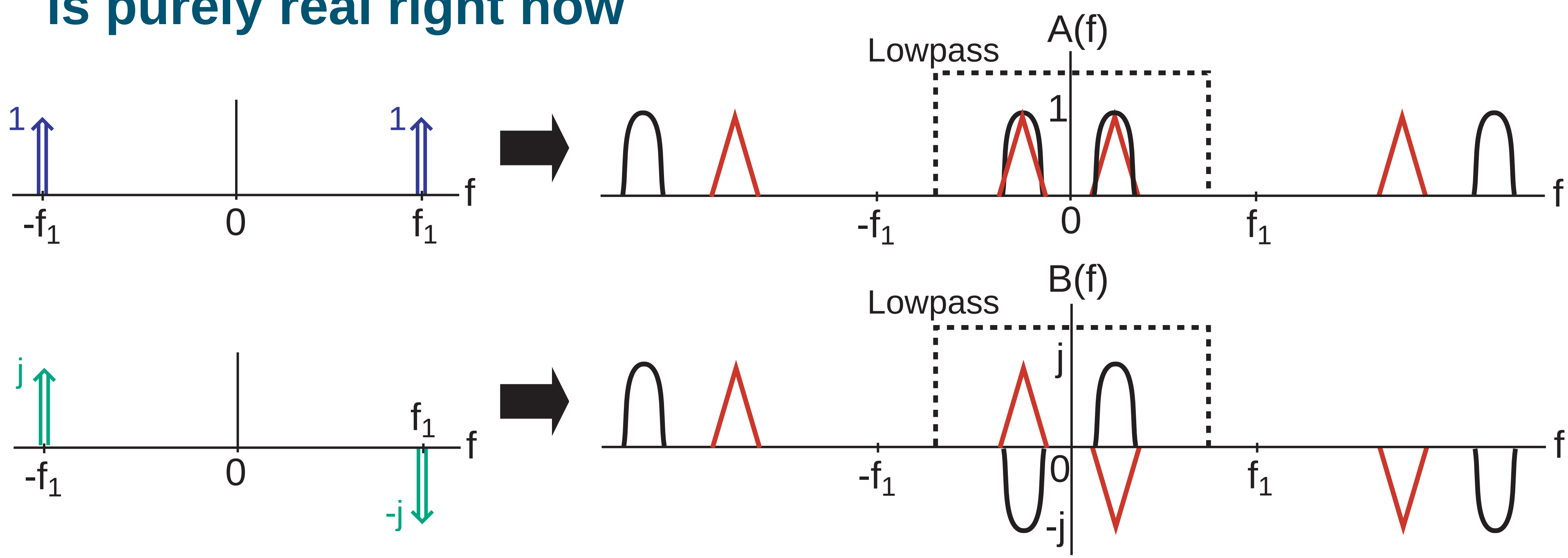
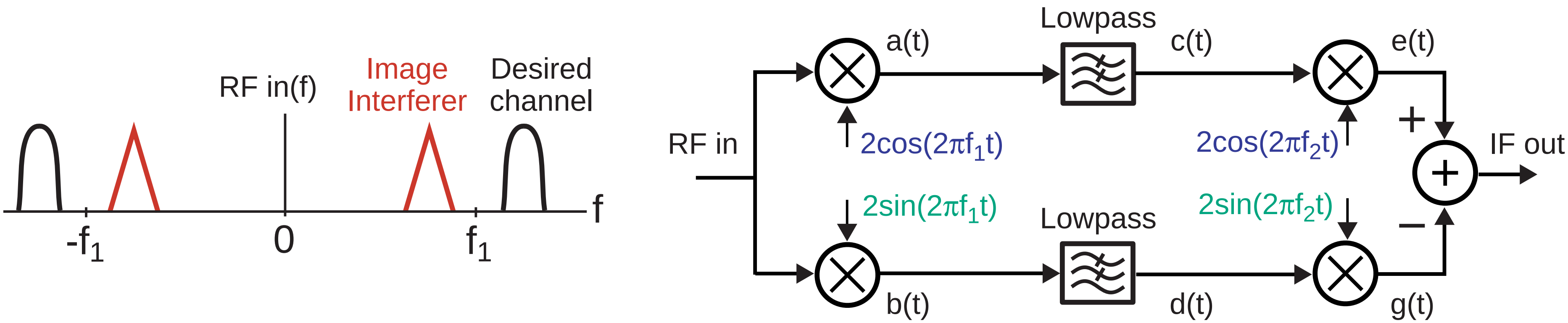


Image Reject Mixer Principles – Step 2



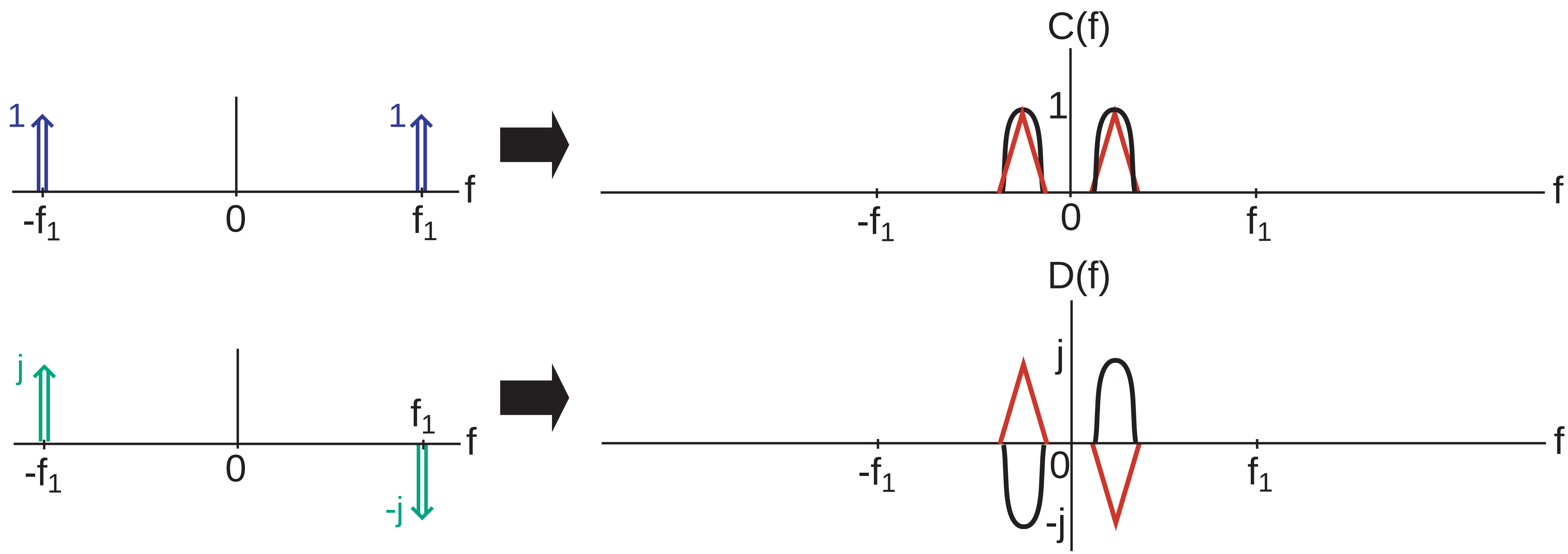


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Image Reject Mixer Principles – Step 3

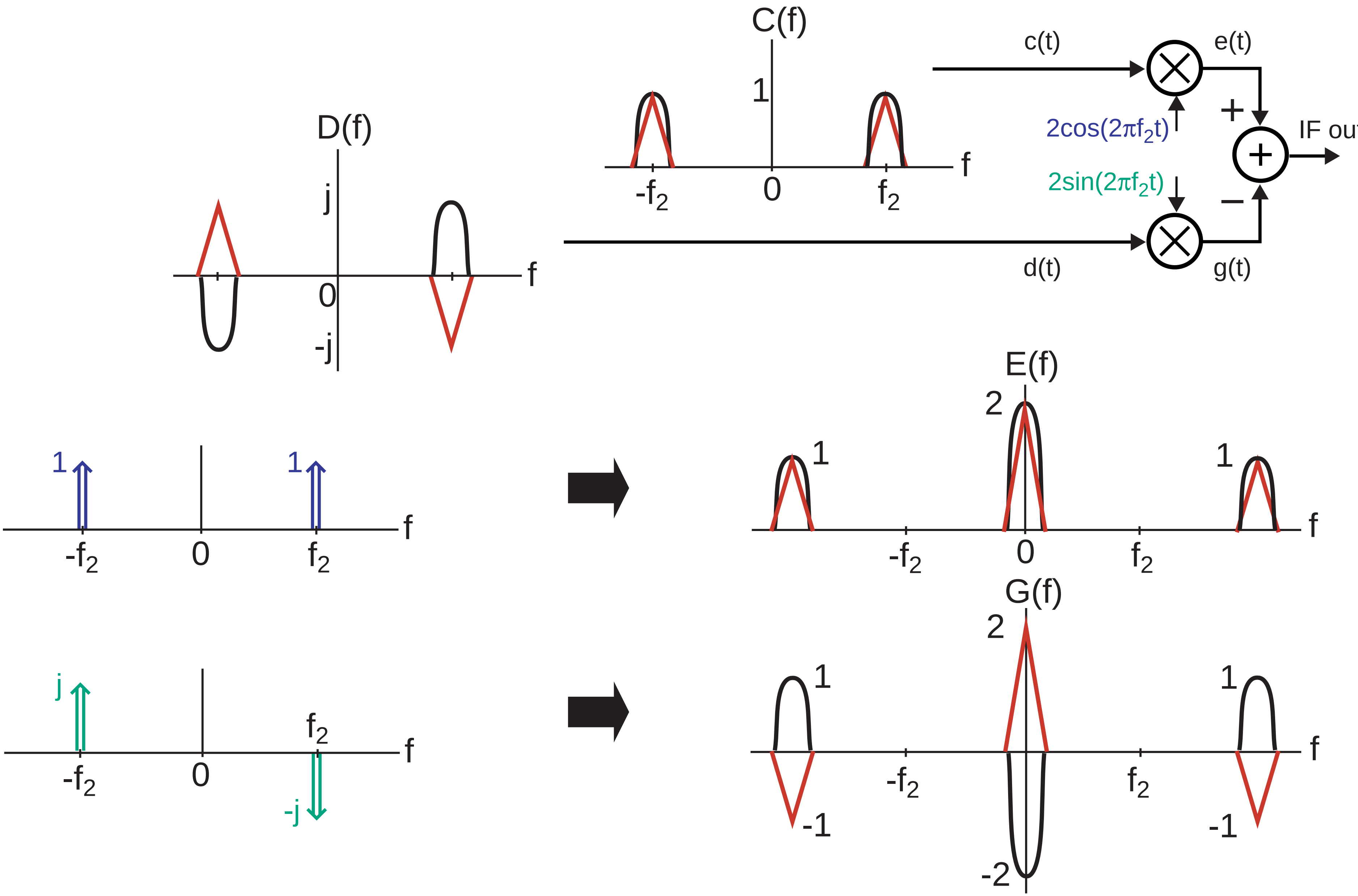


Image Reject Mixer Principles – Step 4

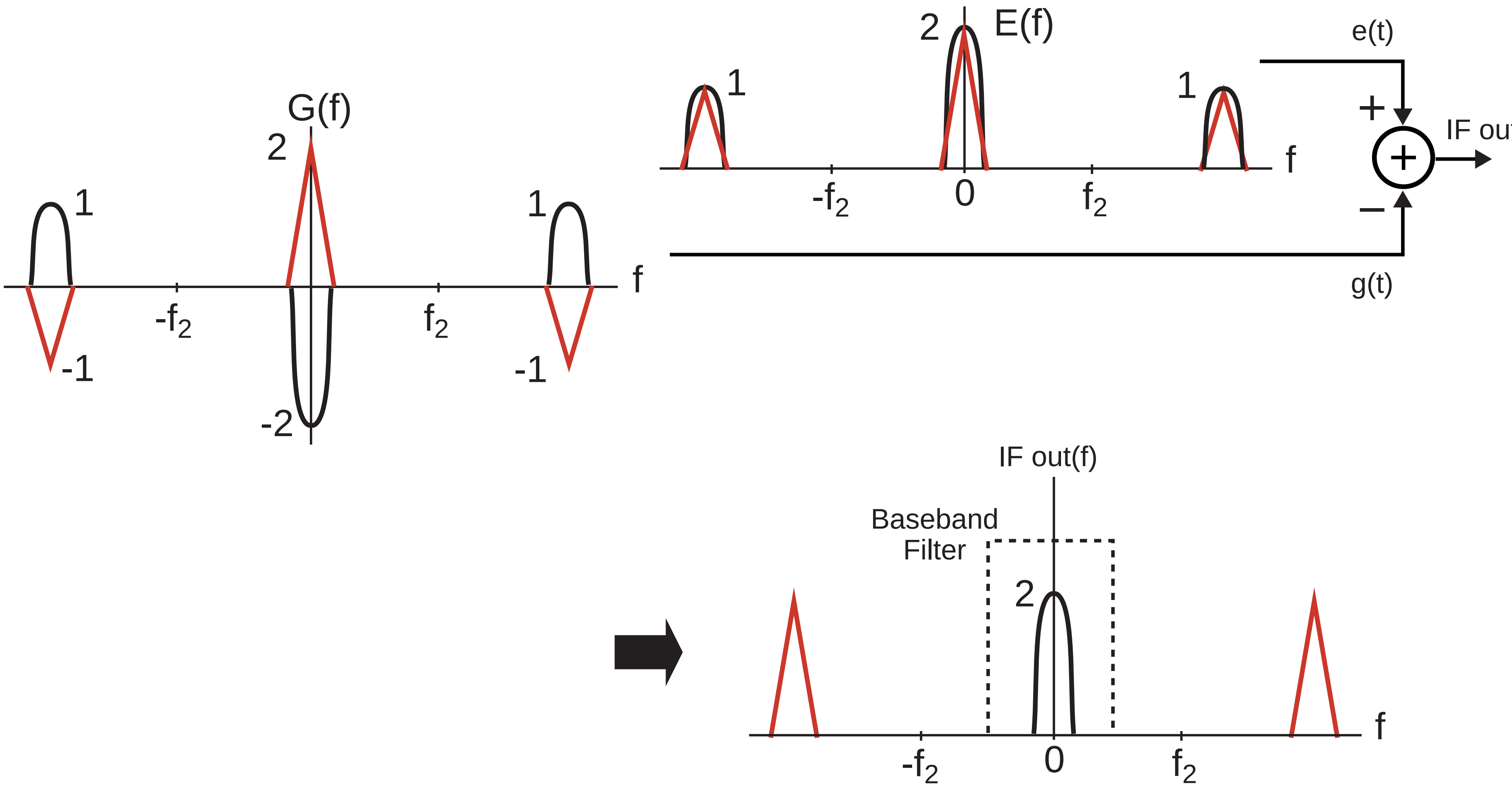
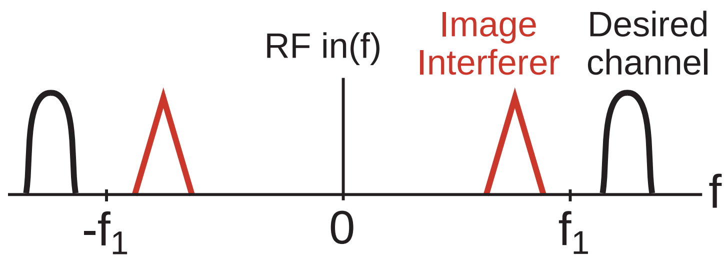
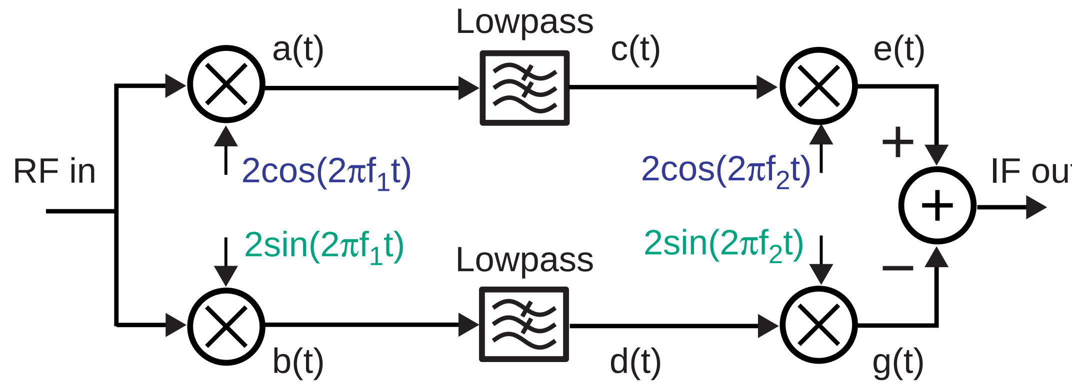
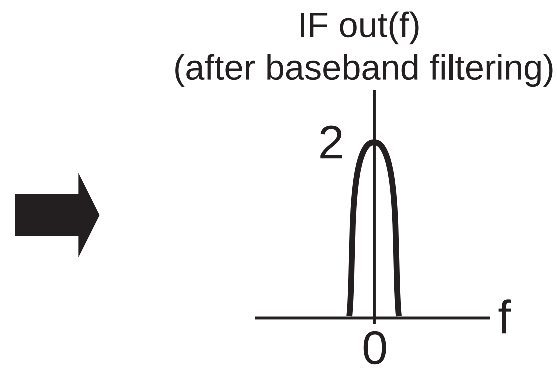


Image Reject Mixer Principles – Implementation Issues

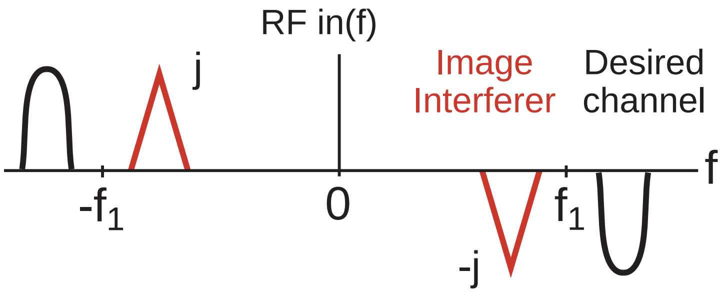


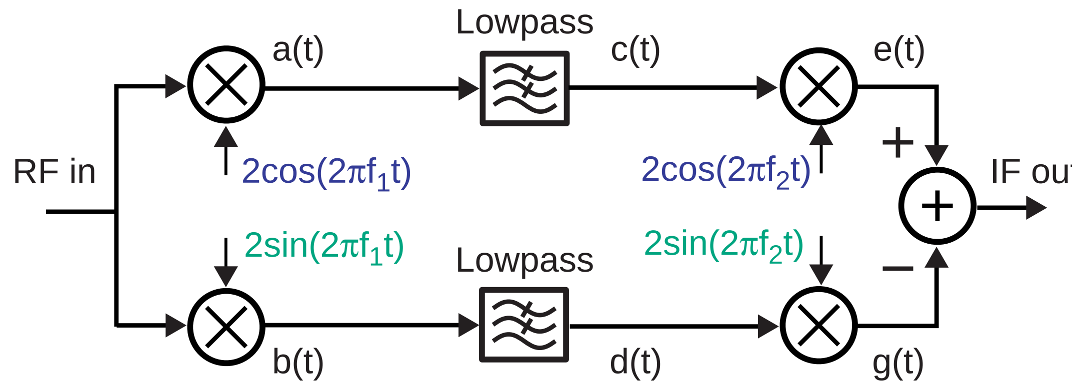


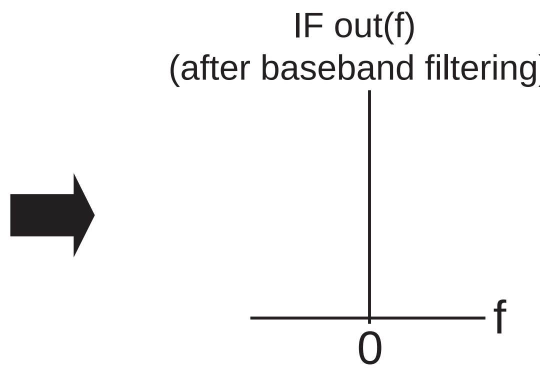


- **For all analog architecture, going to zero IF introduces sensitivity to 1/f noise at IF output**
  - **Can fix this problem by digitizing c(t) and d(t), and then performing final mixing in the digital domain**
- **Can generate accurate quadrature sine wave signals by using a frequency divider**

What if RF in(f) is Purely Imaginary?



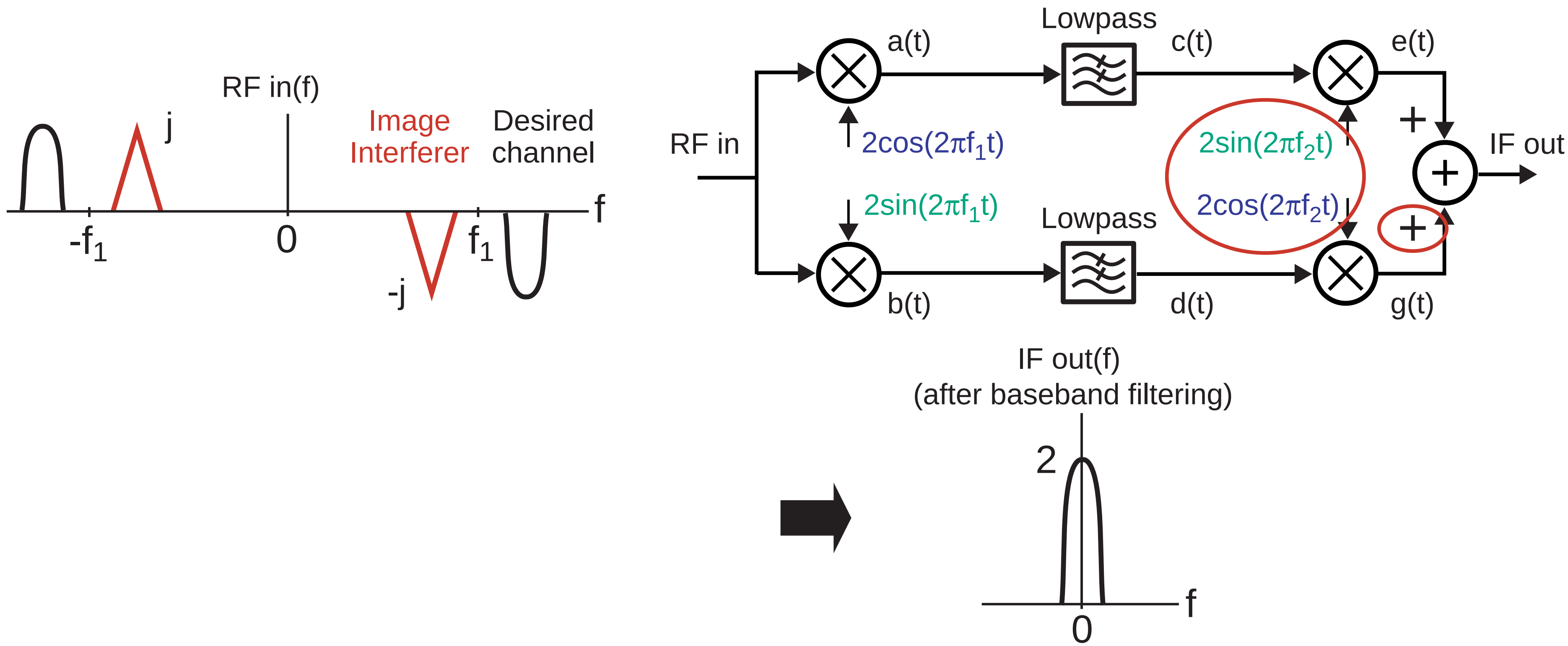




- **Both desired and image signals disappear!**
  - **Architecture is sensitive to the phase of the RF input**

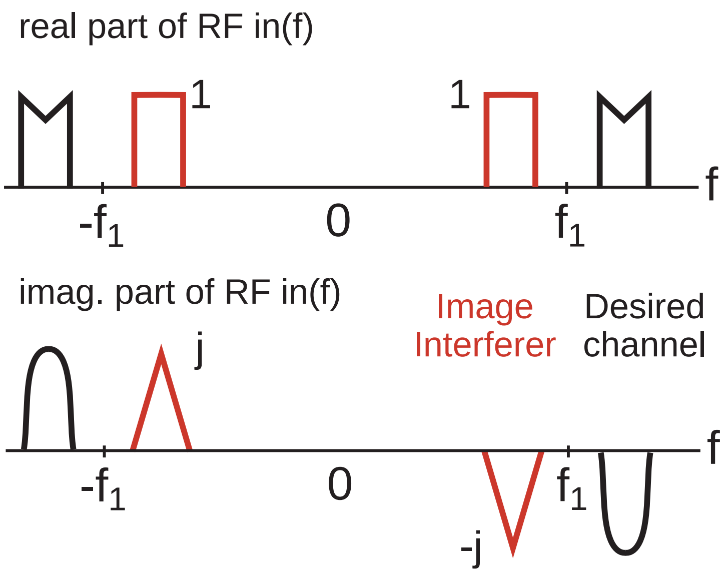
- **Can we modify the architecture to fix this issue?**

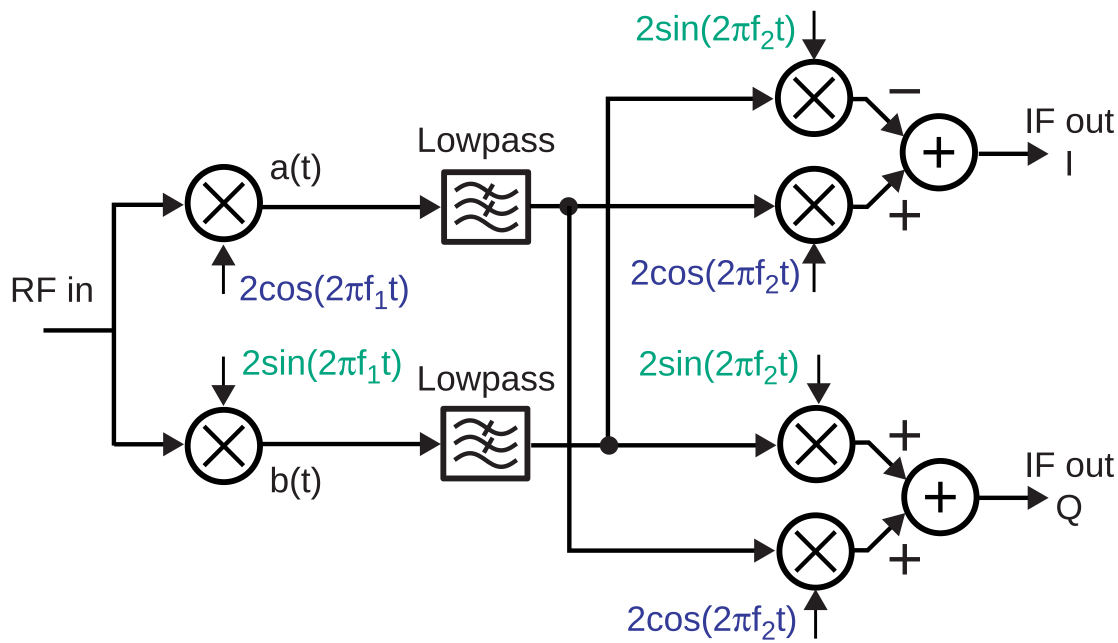
Modification of Mixer Architecture for Imaginary RF in(f)

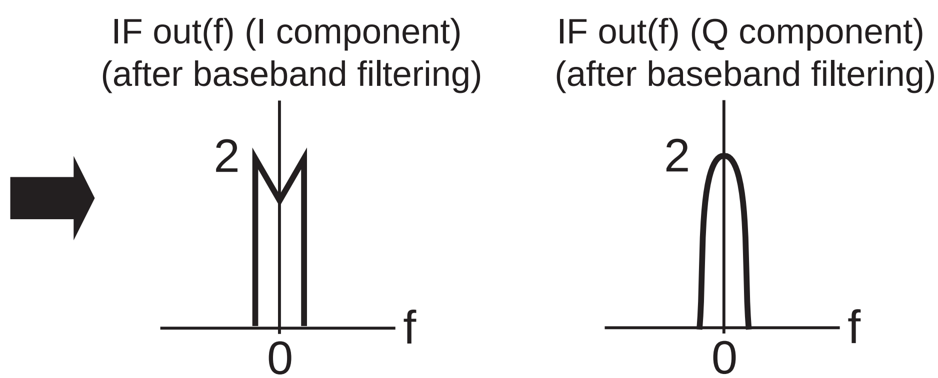


- **Desired channel now appears given two changes**
  - **Sine and cosine demodulators are switched in second half of image rejection mixer**
  - **The two paths are now added rather than subtracted**
- **Issue – architecture now zeros out desired channel when RF in(f) is purely real**

Overall Mixer Architecture – Use I/Q Demodulation

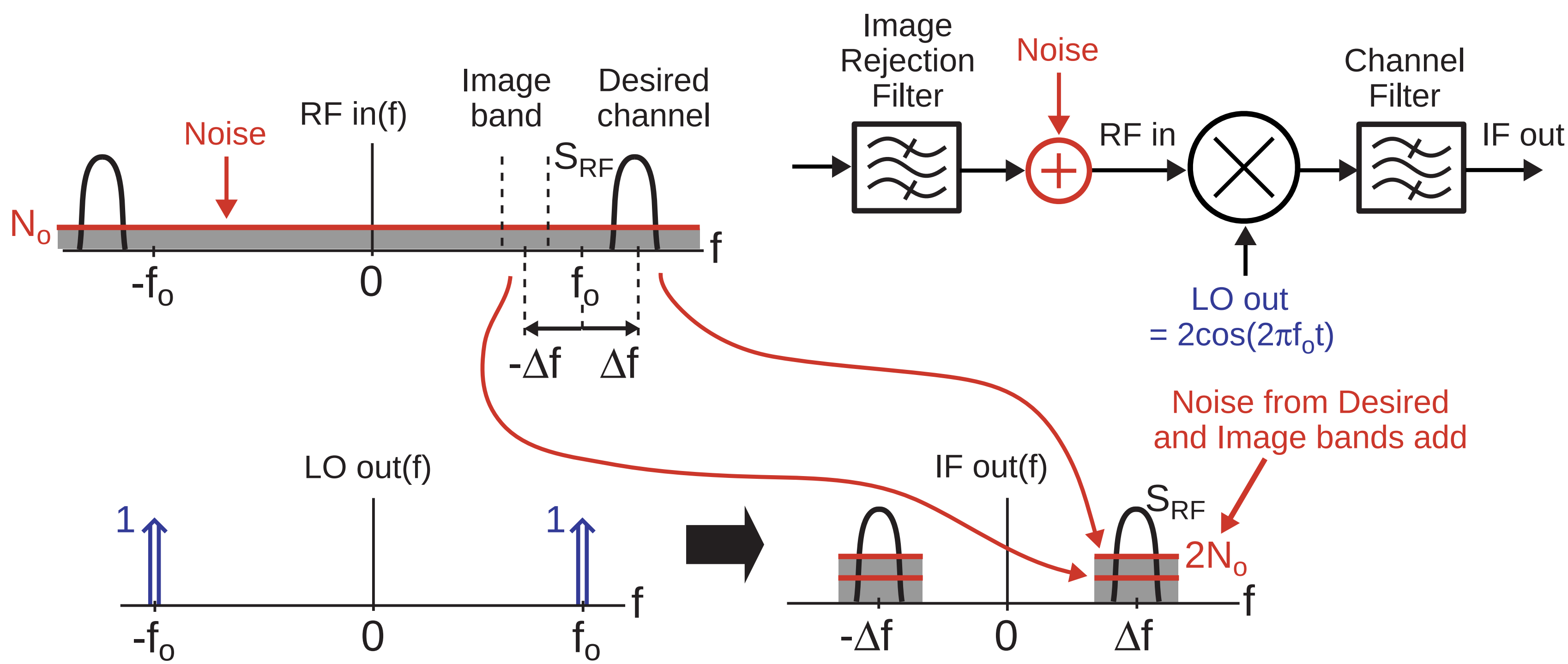






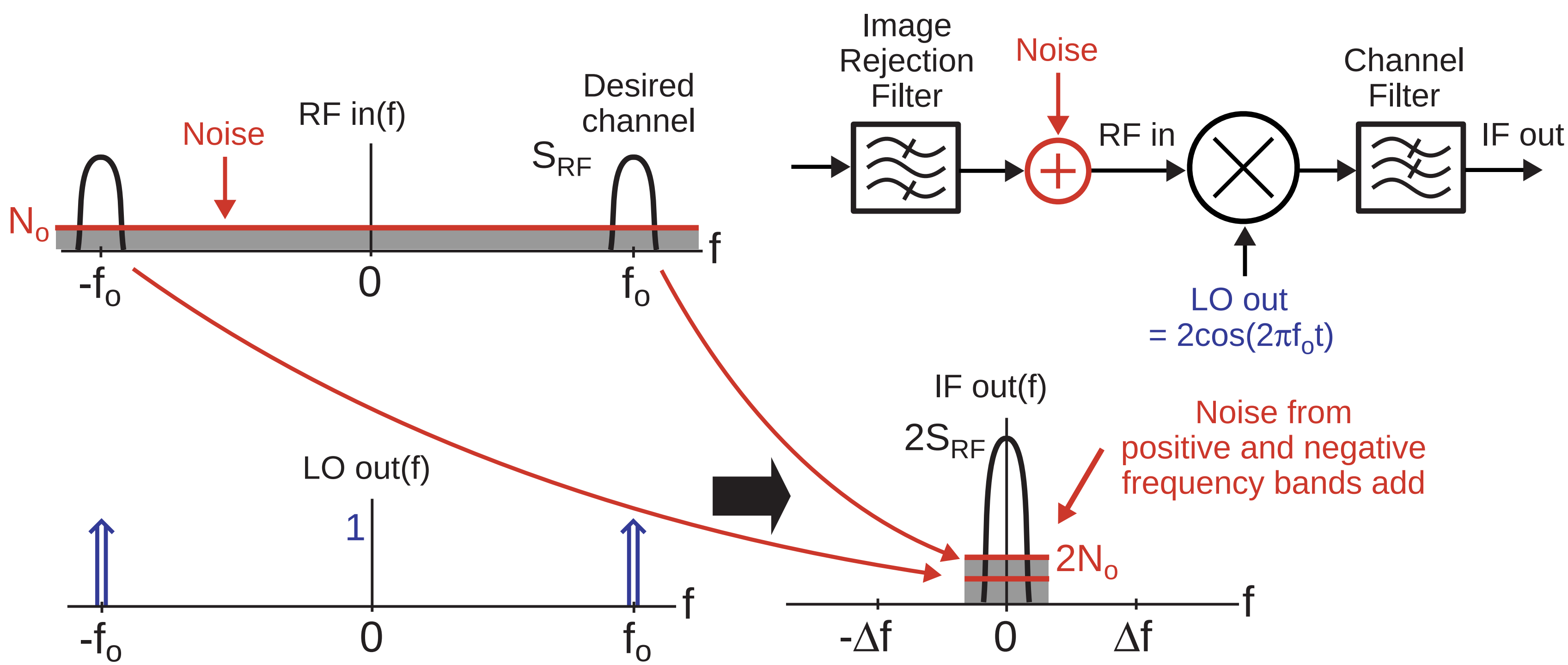
- **Both real and imag. parts of RF input now pass through**

Mixer Single-Sideband (SSB) Noise Figure



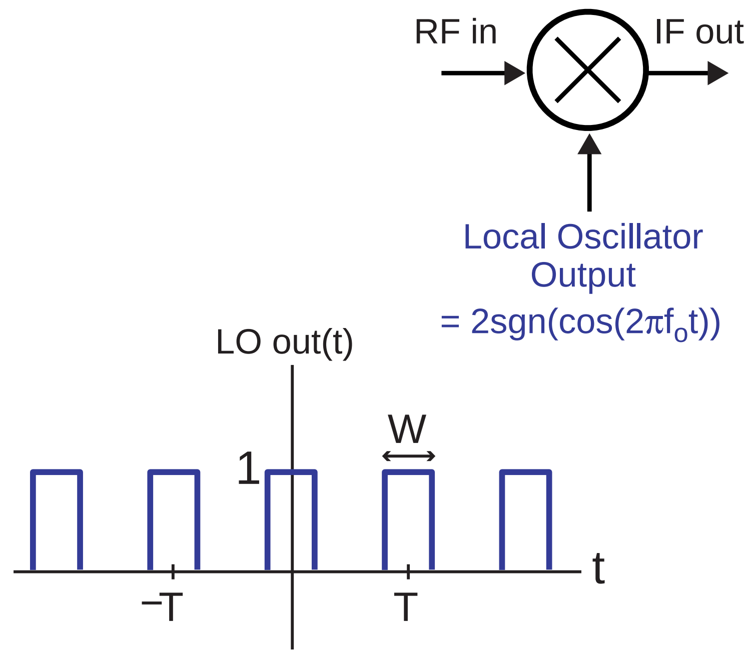
- **Issue – broadband noise from mixer or front end filter will be located in both image and desired bands**
  - **Noise from both image and desired bands will combine in desired channel at IF output**
    - Channel filter cannot remove this
  - **Mixers are inherently noisy!**

Mixer Double-Sideband (DSB) Noise Figure



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

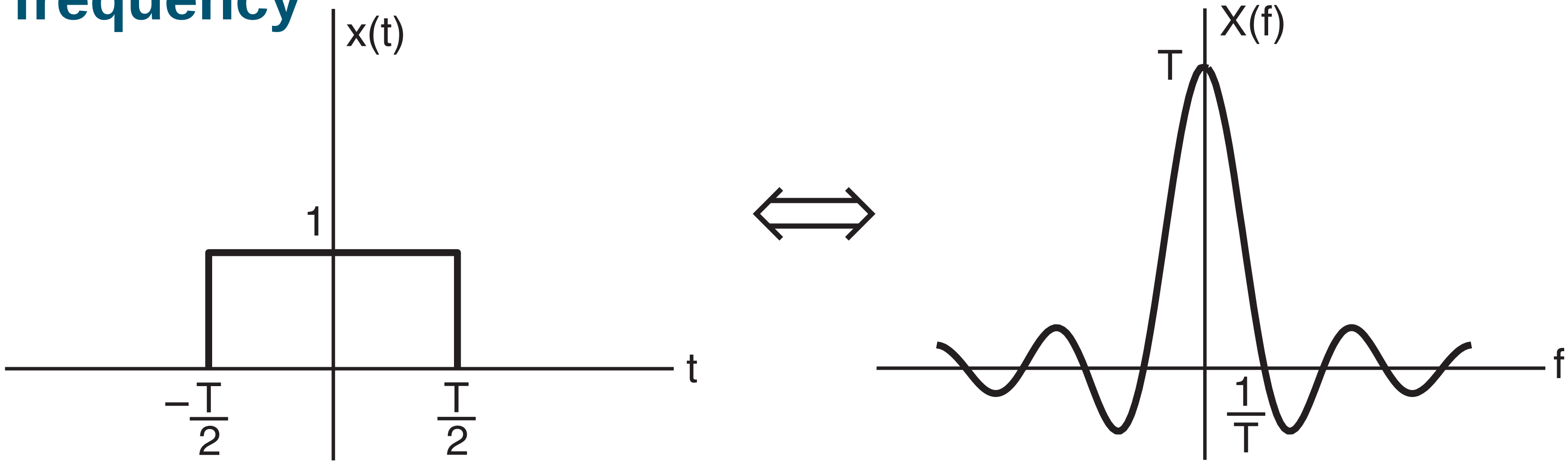
A Practical Issue – Square Wave LO Oscillator Signals



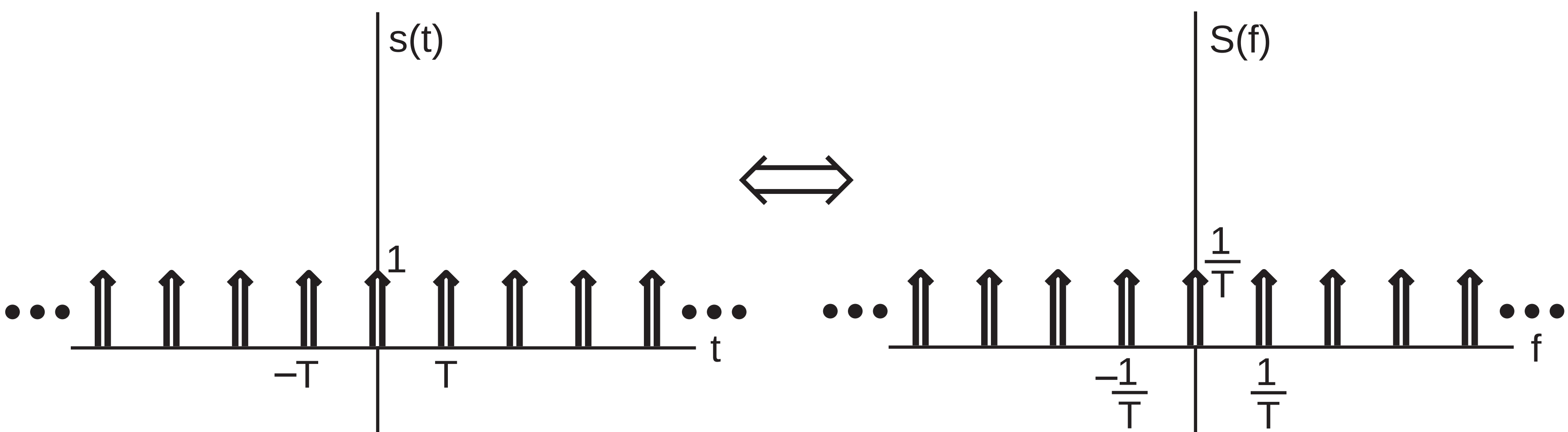
- **Square waves are easier to generate than sine waves**
  - **How do they impact the mixing operation when used as the LO signal?**
  - **We will briefly review Fourier transforms (series) to understand this issue**

Two Important Transform Pairs

- **Transform of a rectangle pulse in time is a sinc function in frequency**

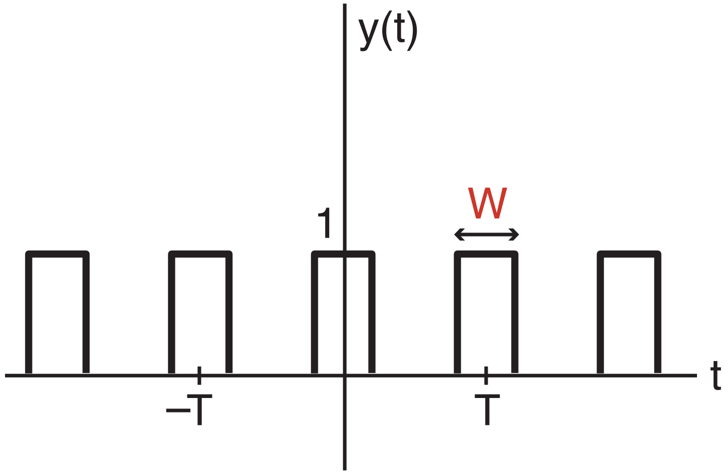


- **Transform of an impulse train in time is an impulse train in frequency**

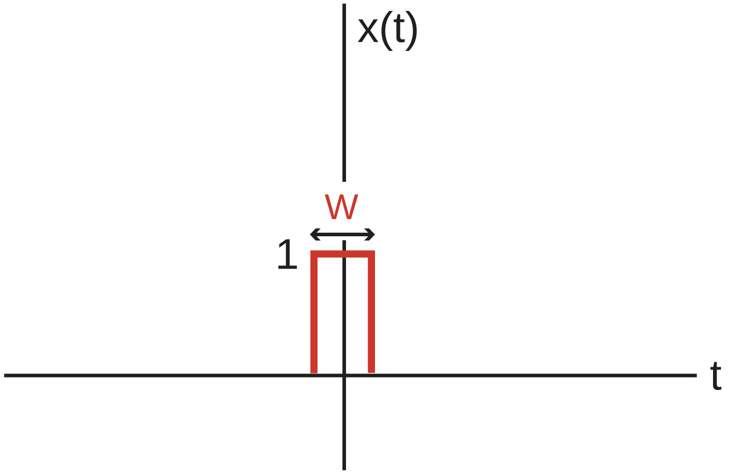


Decomposition of Square Wave to Simplify Analysis

- **Consider now a square wave with duty cycle W/T**



- **Decomposition in time**



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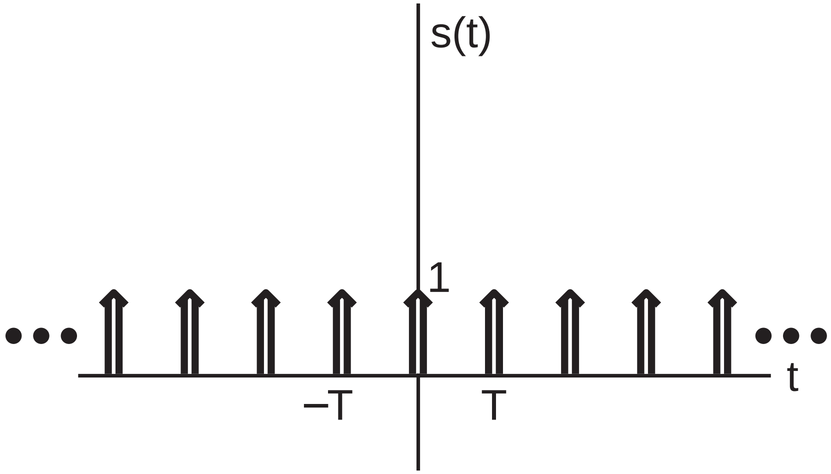
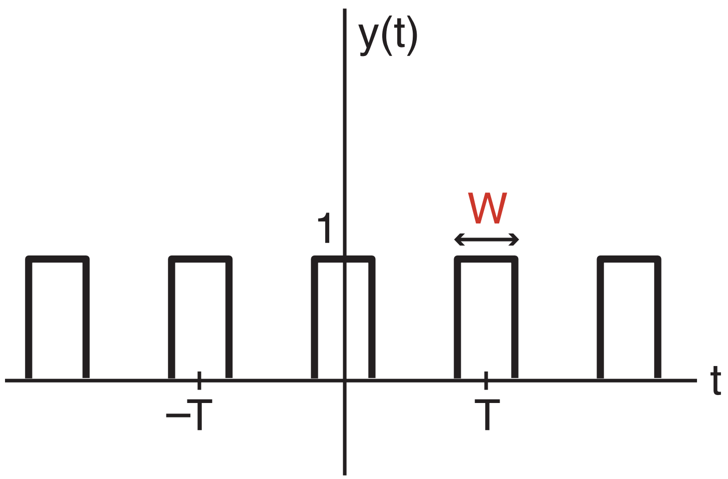
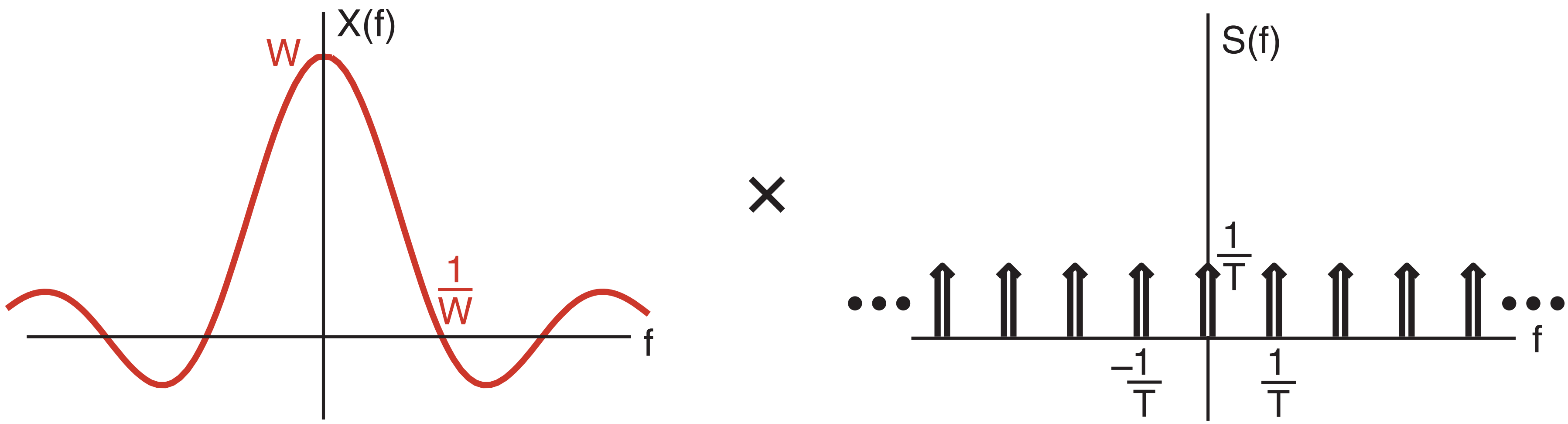


Associated Frequency Transforms

- **Consider now a square wave with duty cycle W/T**

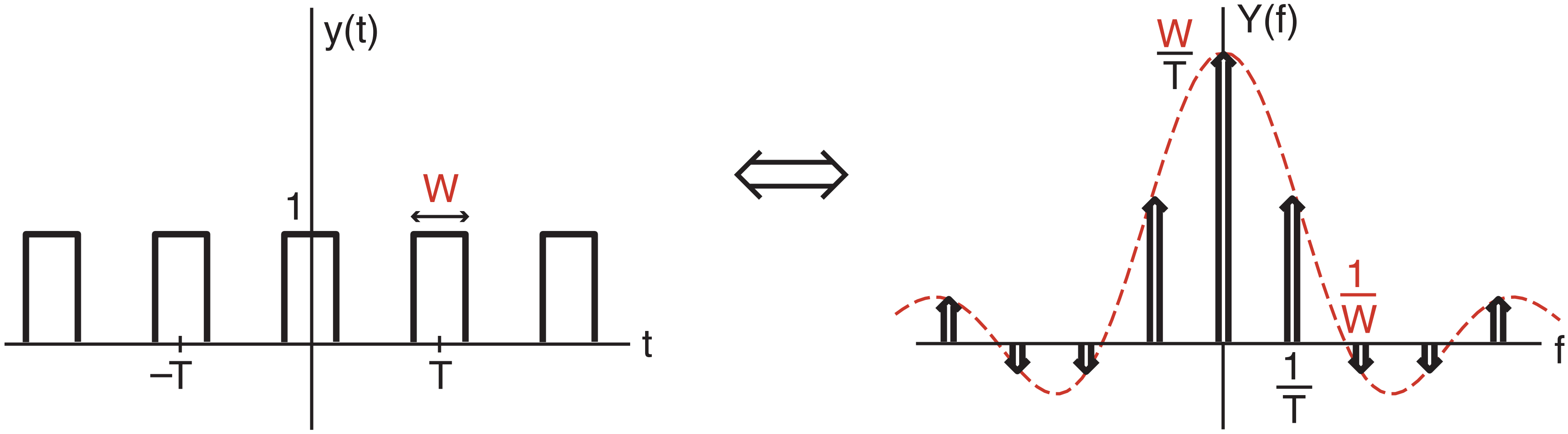


- **Decomposition in frequency**



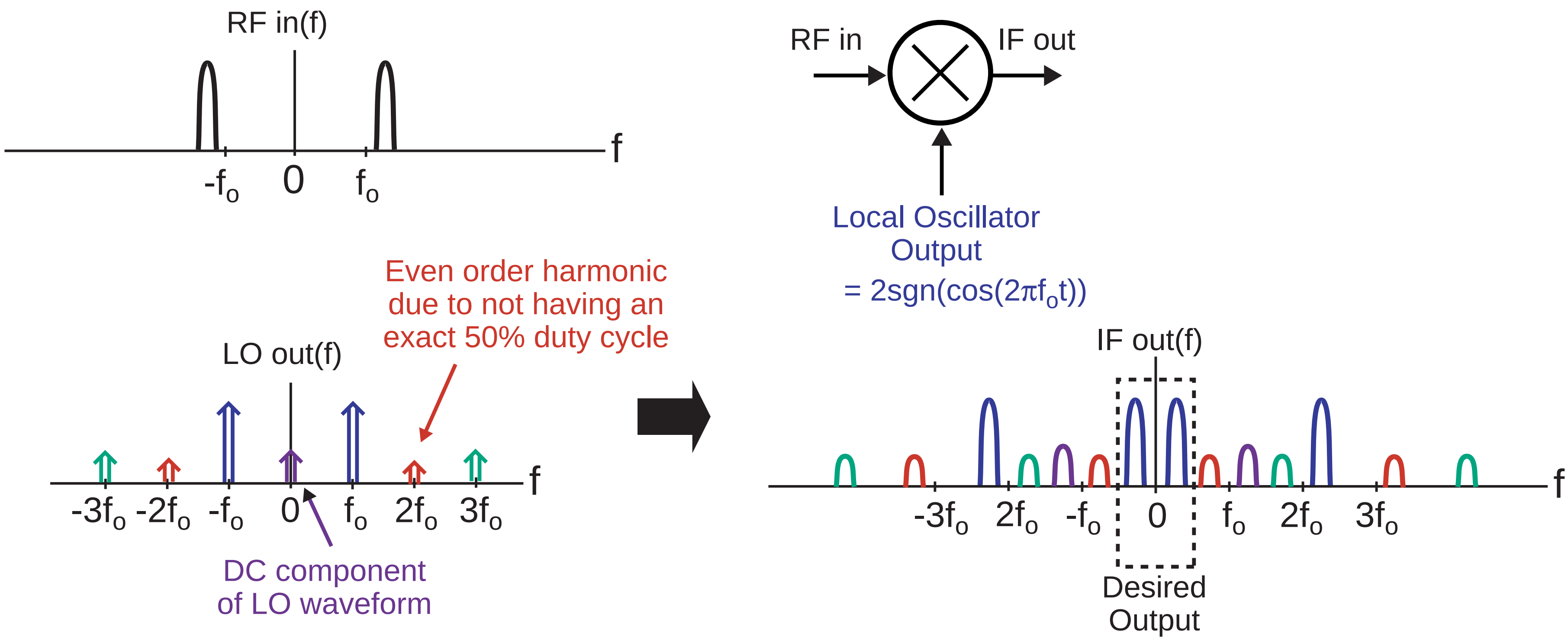
Overall Frequency Transform of a Square Wave

- **Resulting transform relationship**



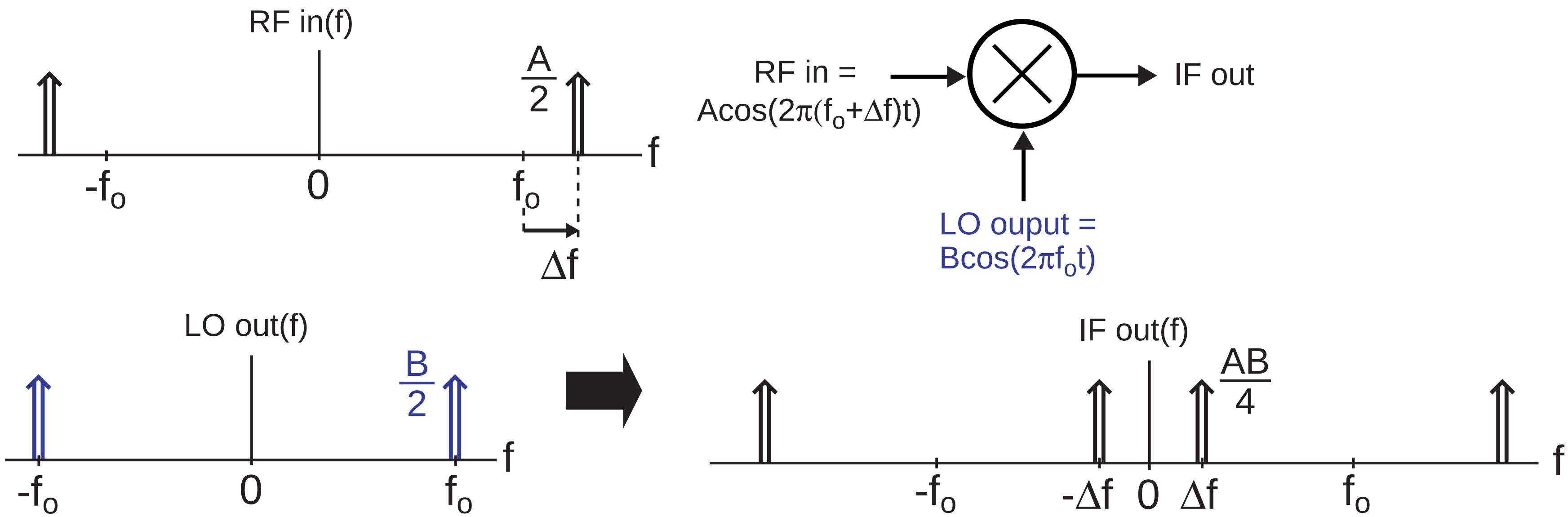
- **Fundamental at frequency 1/T**
  - **Higher harmonics have lower magnitude**
- **If W = T/2 (i.e., 50% duty cycle)**
  - **No even harmonics!**
- **If amplitude varies between 1 and -1 (rather than 1 and 0)**
  - **No DC component**

Analysis of Using Square-Wave for LO Signal



- Each frequency component of LO signal will now mix with the RF input
  - If RF input spectrum sufficiently narrowband with respect to f_o, then no aliasing will occur
- Desired output (mixed by the fundamental component) can be extracted using a filter at the IF output

Voltage Conversion Gain



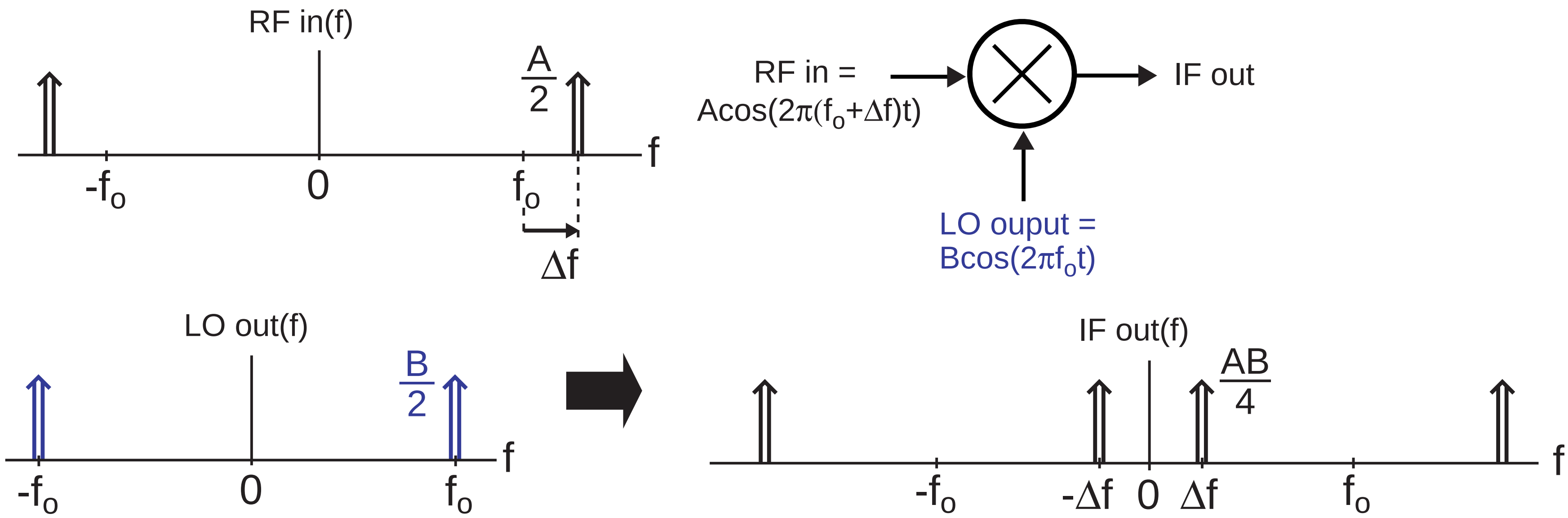
- **Defined as voltage ratio of desired IF value to RF input**
- **Example: for an ideal mixer with RF input = Asin(2π(f_o + Δ f)t) and sine wave LO signal = Bcos(2πf_ot)**

$$IF\ out(t) = \frac{AB}{2}\left(\cos(2\pi(\Delta f)t) + \cos(2\pi(2f_o + \Delta f)t)\right)$$

$$\Rightarrow \text{ Voltage Conversion Gain } = \frac{AB/2}{A} = \frac{B}{2}$$

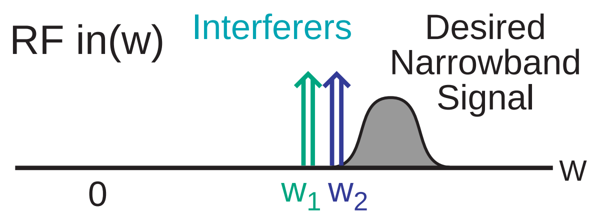
- **For practical mixers, value depends on mixer topology and LO signal (i.e., sine or square wave)**

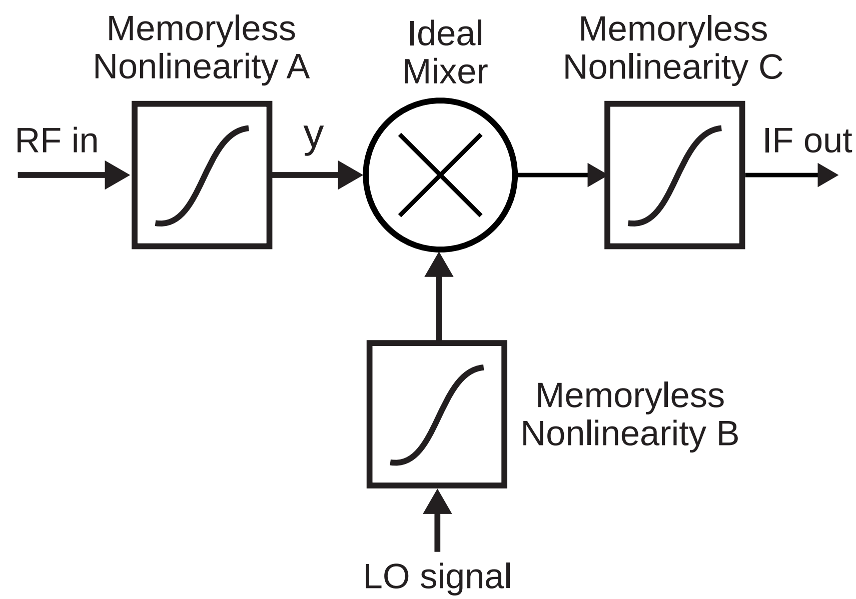
Impact of High Voltage Conversion Gain



- **Benefit of high voltage gain**
  - **The noise of later stages will have less of an impact**
- **Issues with high voltage gain**
  - **May be accompanied by higher noise figure than could be achieved with lower voltage gain**
  - **May be accompanied by nonlinearities that limit interference rejection (i.e., passive mixers can generally be made more linear than active ones)**

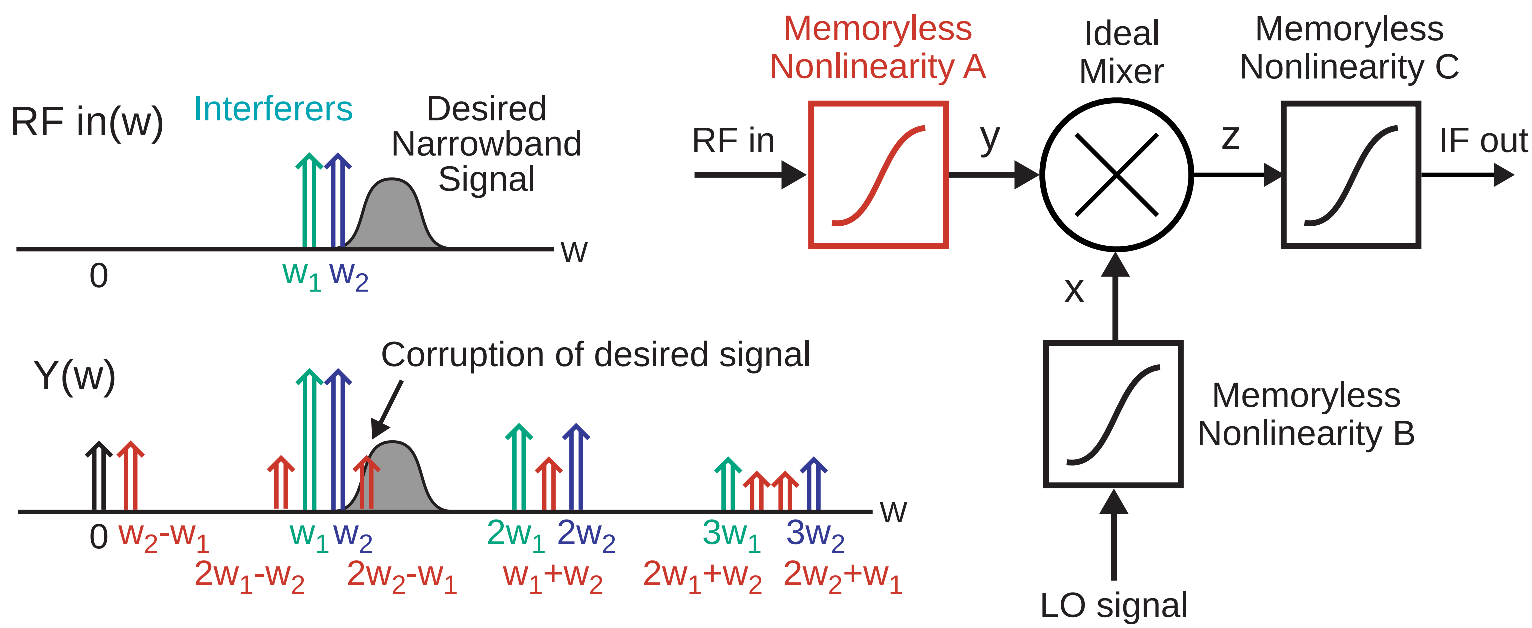
Impact of Nonlinearity in Mixers





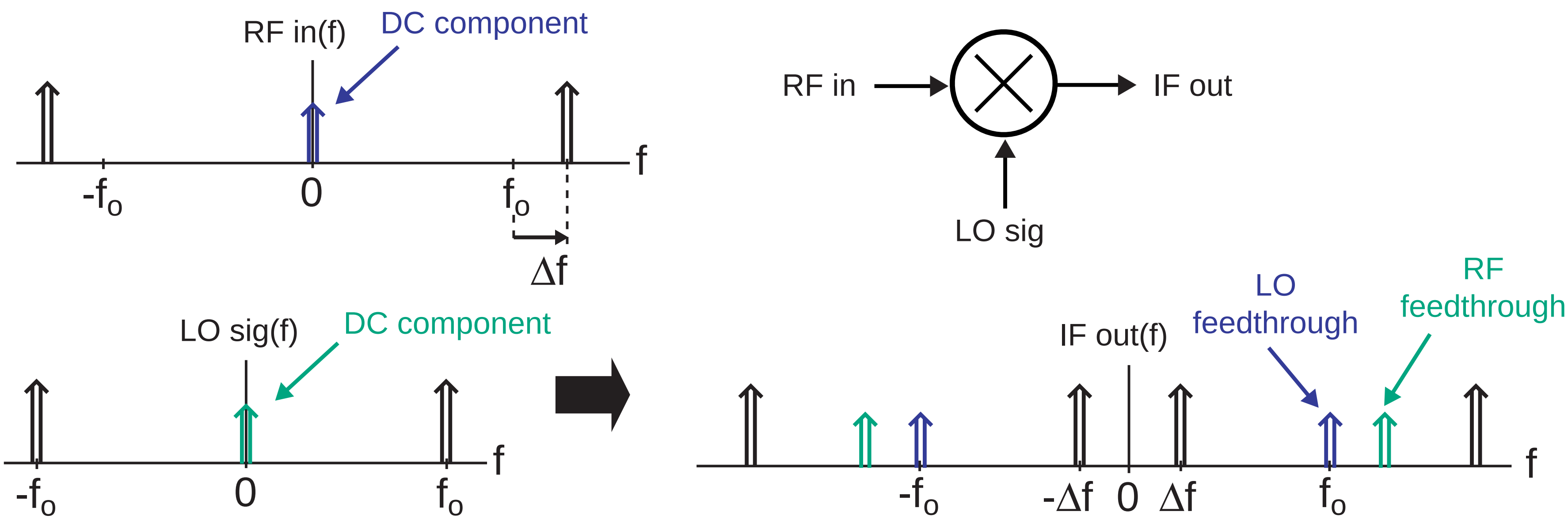
- **Ignoring dynamic effects, we can model mixer as nonlinearities around an ideal mixer**
  - **Nonlinearity A will have the same impact as LNA nonlinearity (measured with IIP3)**
  - **Nonlinearity B will change the spectrum of the LO signal**
    - Causes additional mixing that must be analyzed
    - Changes conversion gain somewhat
  - **Nonlinearity C will cause self mixing of IF output**

Primary Focus is Typically Nonlinearity in RF Input Path



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

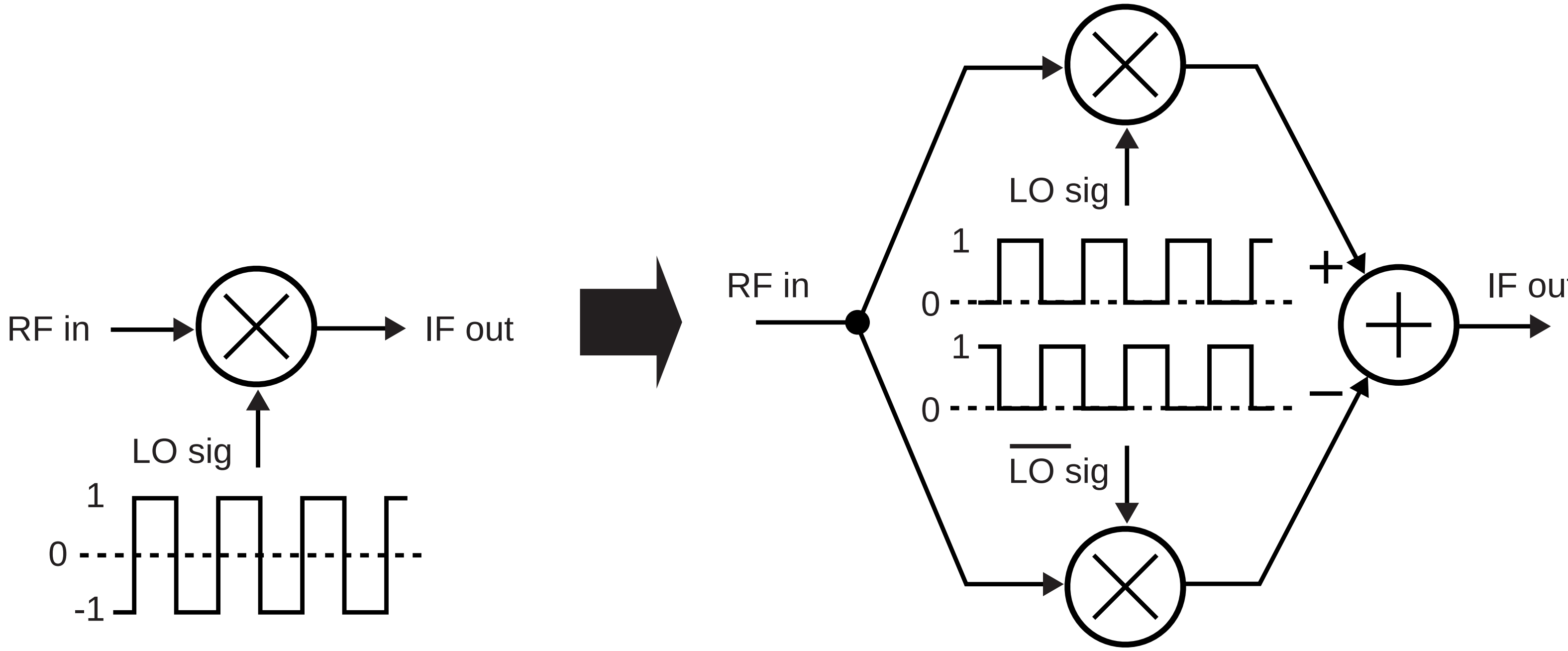
The Issue of Balance in Mixers



- **A balanced signal is defined to have a zero DC component**
- **Mixers have two signals of concern with respect to this issue – LO and RF signals**
  - **Unbalanced RF input causes LO feedthrough**
  - **Unbalanced LO signal causes RF feedthrough**
- **Issue – transistors require a DC offset**

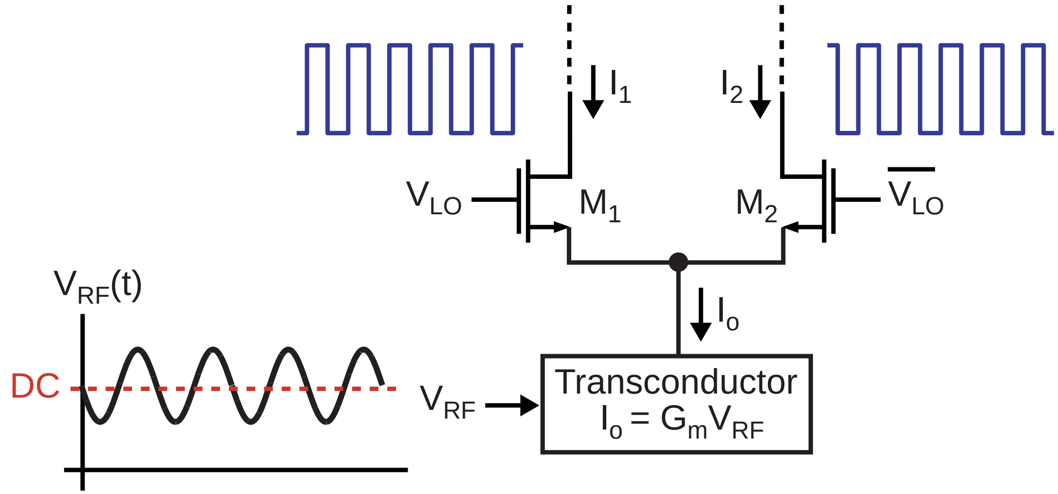
Achieving a Balanced LO Signal with DC Biasing

- **Combine two mixer paths with LO signal 180 degrees out of phase between the paths**



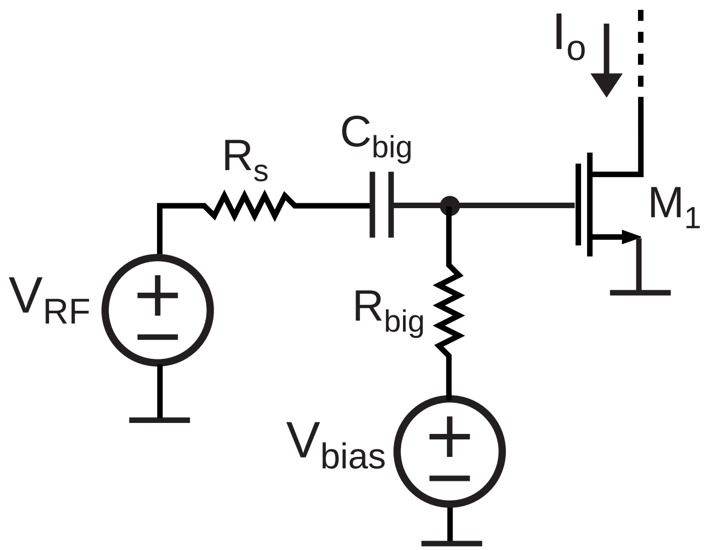
  - **DC component is cancelled**

Single-Balanced Mixer



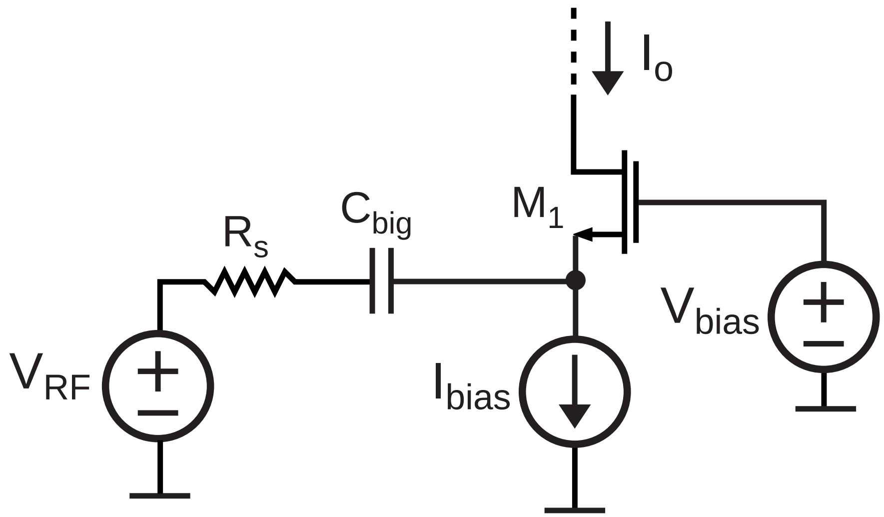
- Works by converting RF input voltage to a current, then switching current between each side of differential pair
- Achieves LO balance using technique on previous slide
  - Subtraction between paths is inherent to differential output
- LO swing should be no larger than needed to fully turn on and off differential pair
  - Square wave is best to minimize noise from M_1 and M_2
- Transconductor designed for high linearity

Transconductor Implementation 1



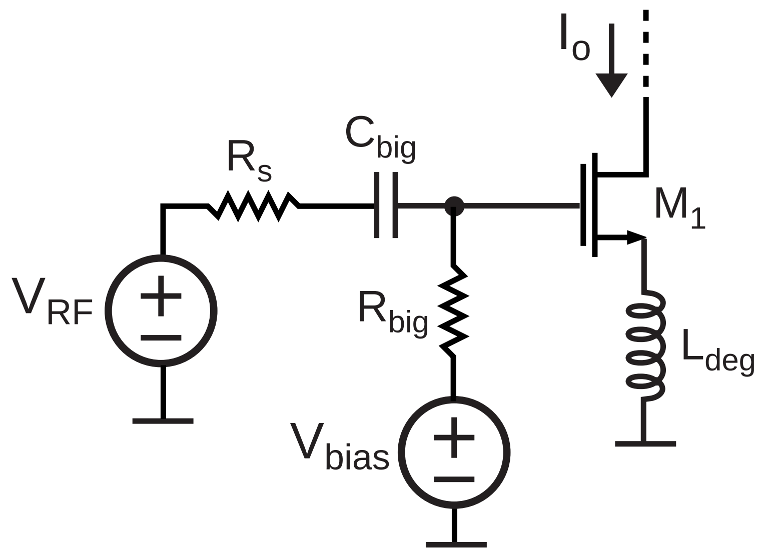
- **Apply RF signal to input of common source amp**
  - **Transistor assumed to be in saturation**
  - **Transconductance value is the same as that of the transistor**
- **High V_{bias} places device in velocity saturation**
  - **Allows high linearity to be achieved**

Transconductor Implementation 2



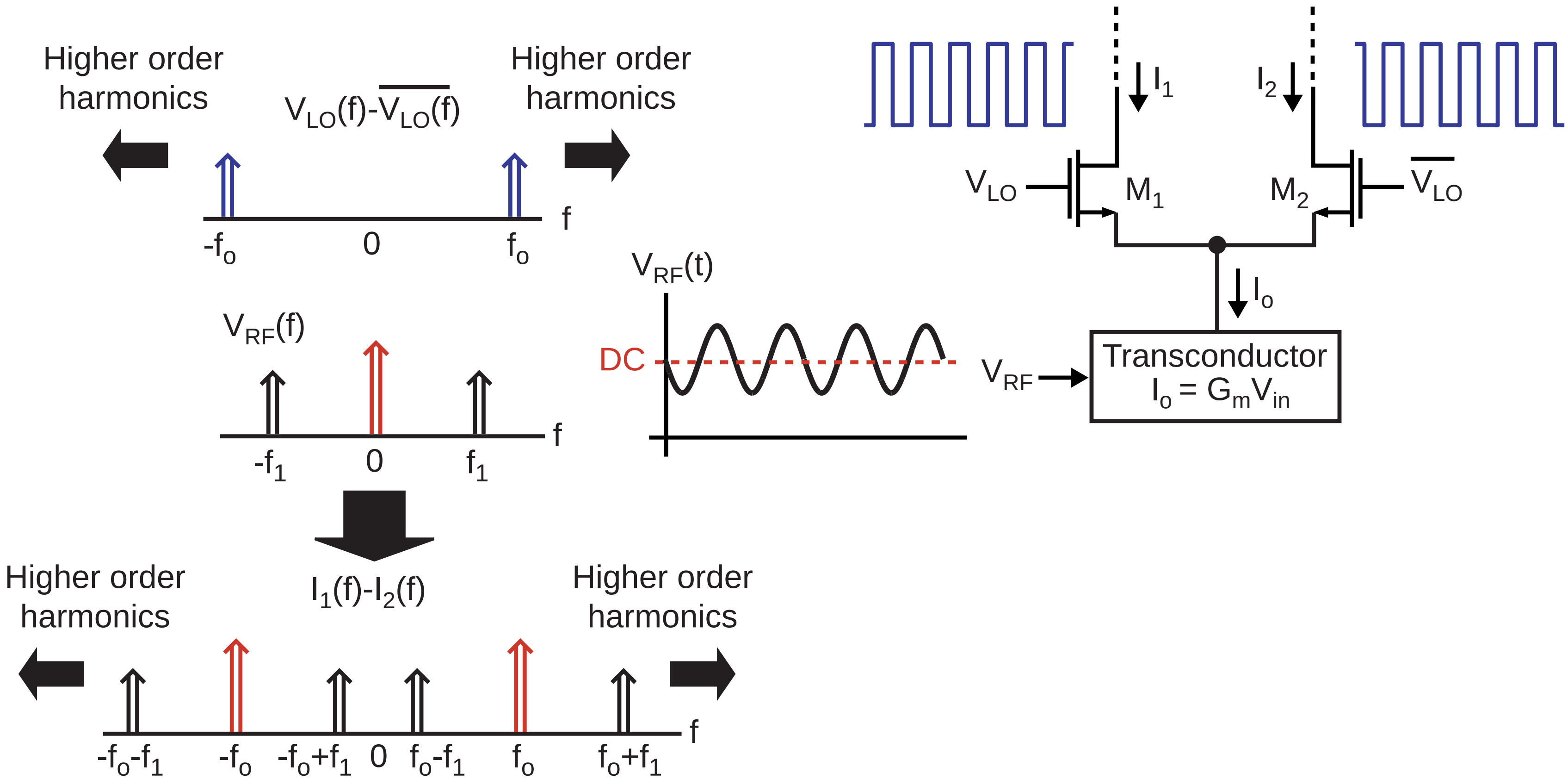
- Apply RF signal to a common gate amplifier
- Transconductance value set by inverse of series combination of R_s and $1/g_m$ of transistor
  - Amplifier is effectively degenerated to achieve higher linearity
- I_{bias} can be set for large current density through device to achieve higher linearity (velocity saturation)

Transconductor Implementation 3



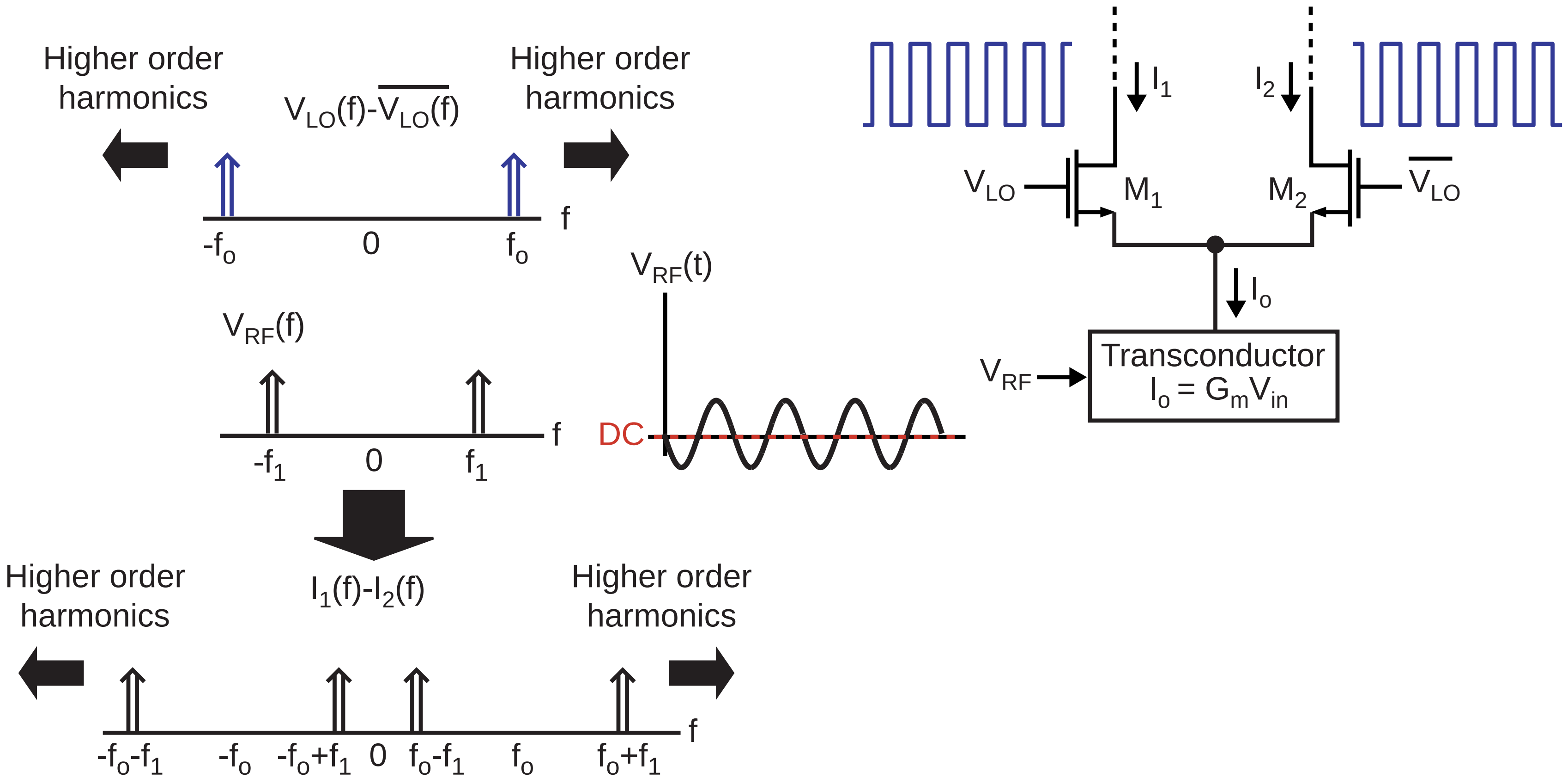
- **Add degeneration to common source amplifier**
  - **Inductor better than resistor**
    - No DC voltage drop
    - Increased impedance at high frequencies helps filter out undesired high frequency components
  - **Don't generally resonate inductor with C_{gs}**
    - Power match usually not required for IC implementation due to proximity of LNA and mixer

LO Feedthrough in Single-Balanced Mixers



- **DC component of RF input causes very large LO feedthrough**
  - **Can be removed by filtering, but can also be removed by achieving a zero DC value for RF input**

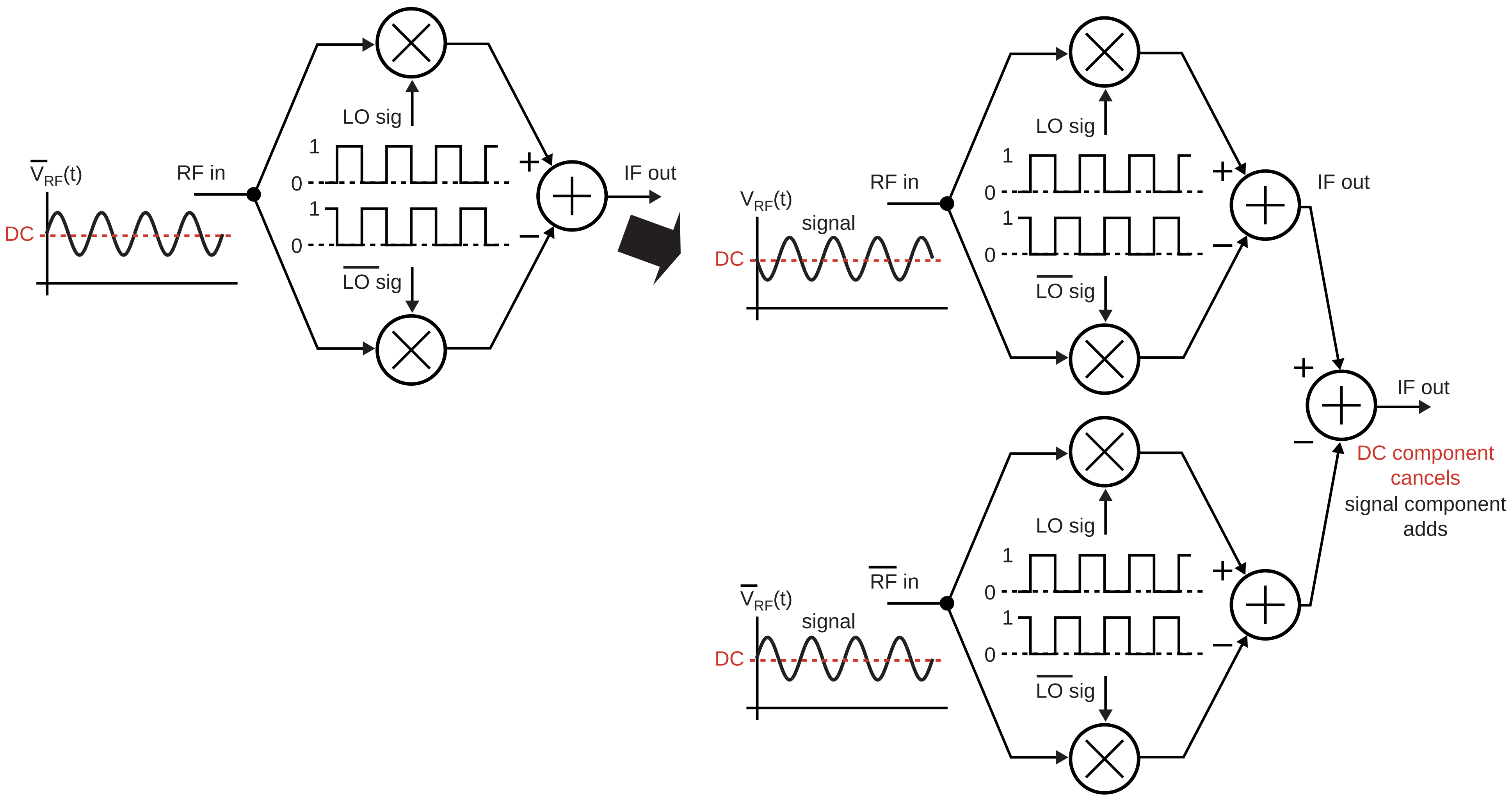
Double-Balanced Mixer



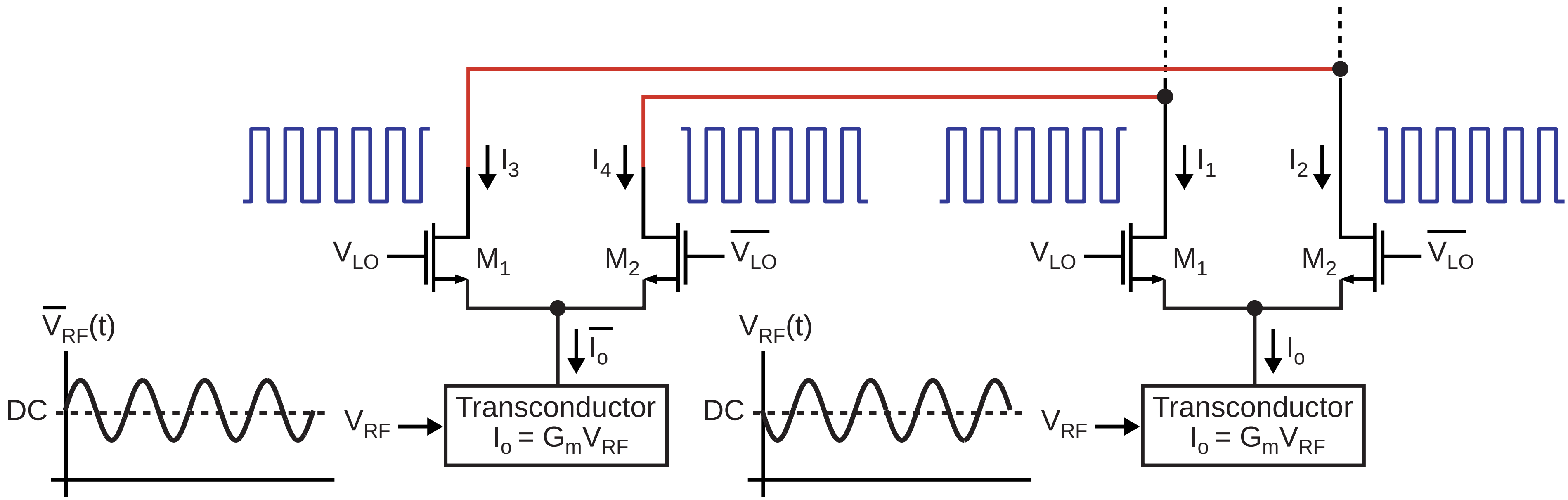
- **DC values of LO and RF signals are zero (balanced)**
- **LO feedthrough dramatically reduced!**
- **But, practical transconductor needs bias current**

Achieving a Balanced RF Signal with Biasing

- Use the same trick as with LO balancing

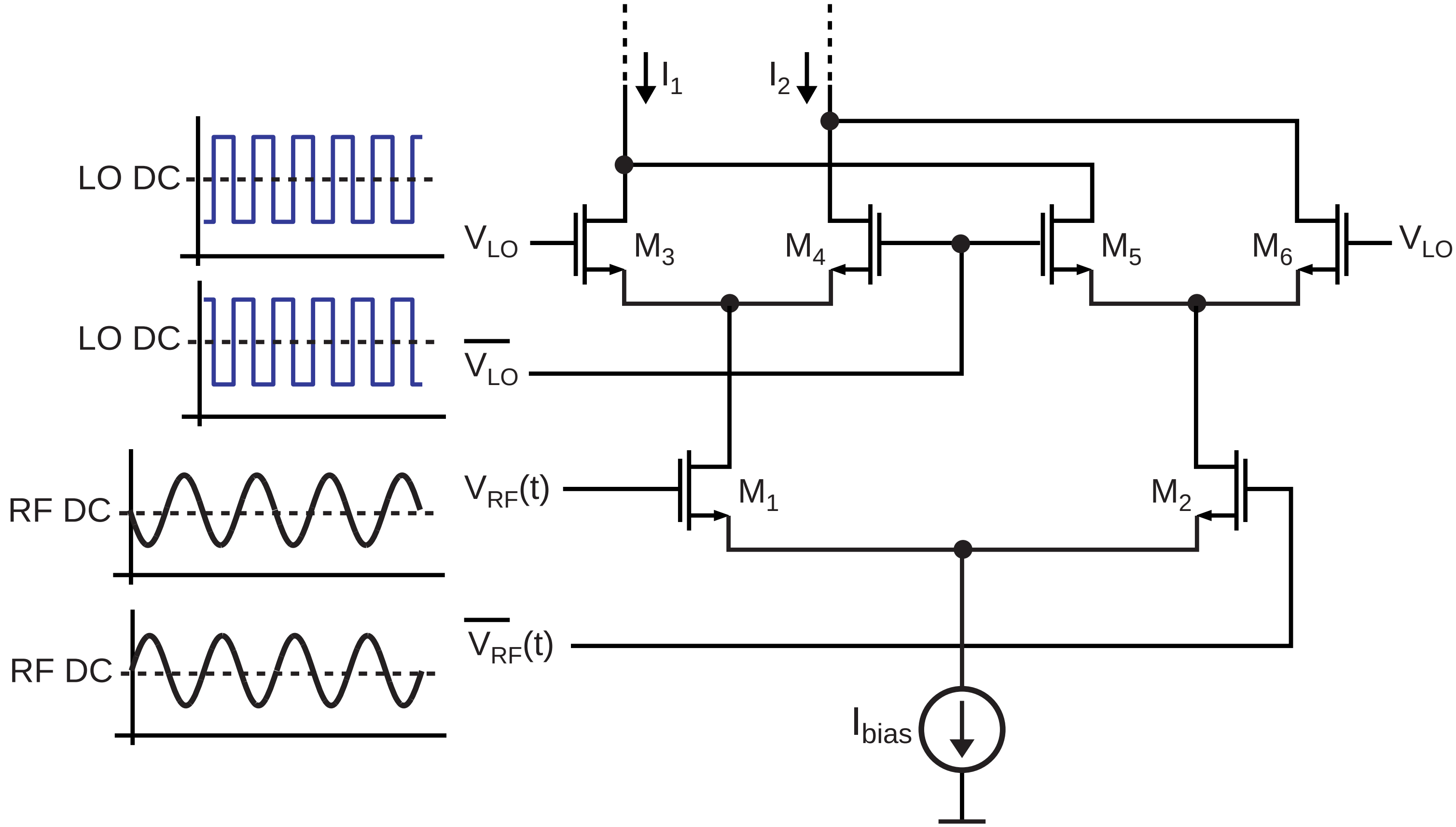


Double-Balanced Mixer Implementation



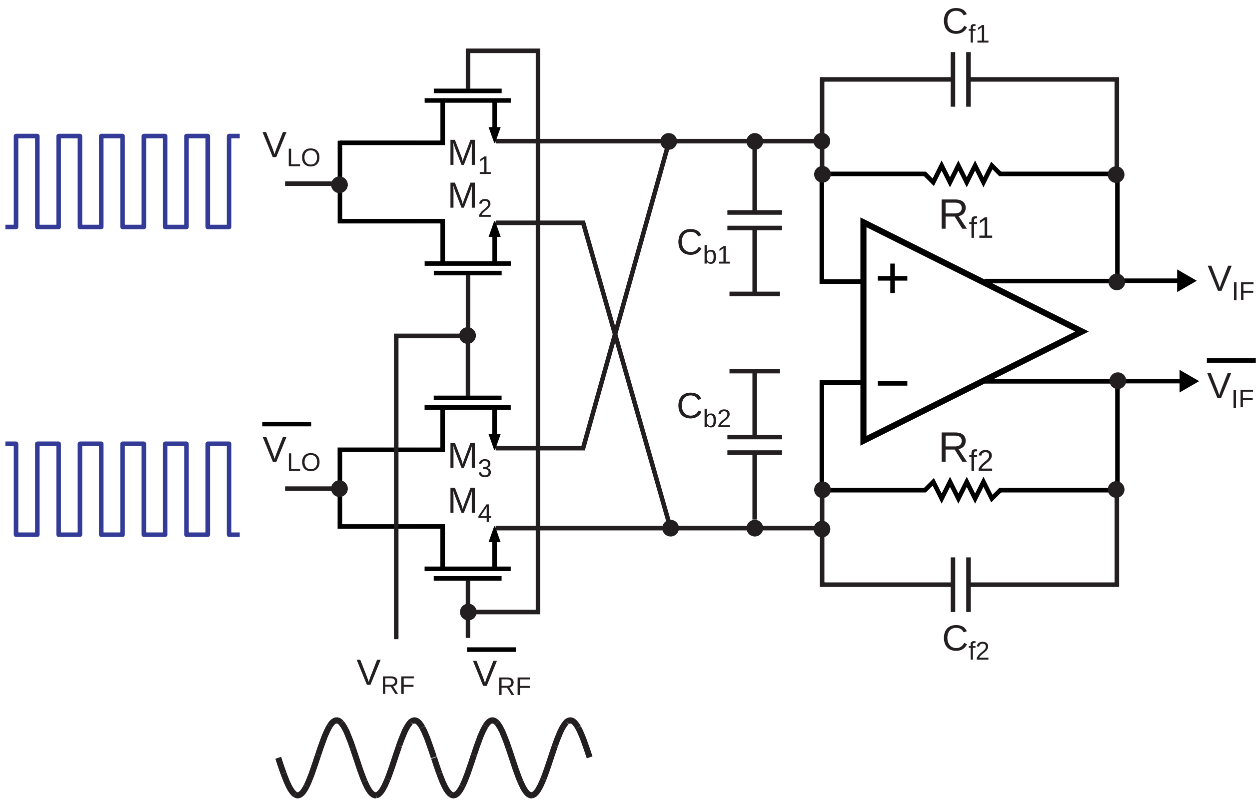
- **Applies technique from previous slide**
  - **Subtraction at the output achieved by cross-coupling the output current of each stage**

Gilbert Mixer



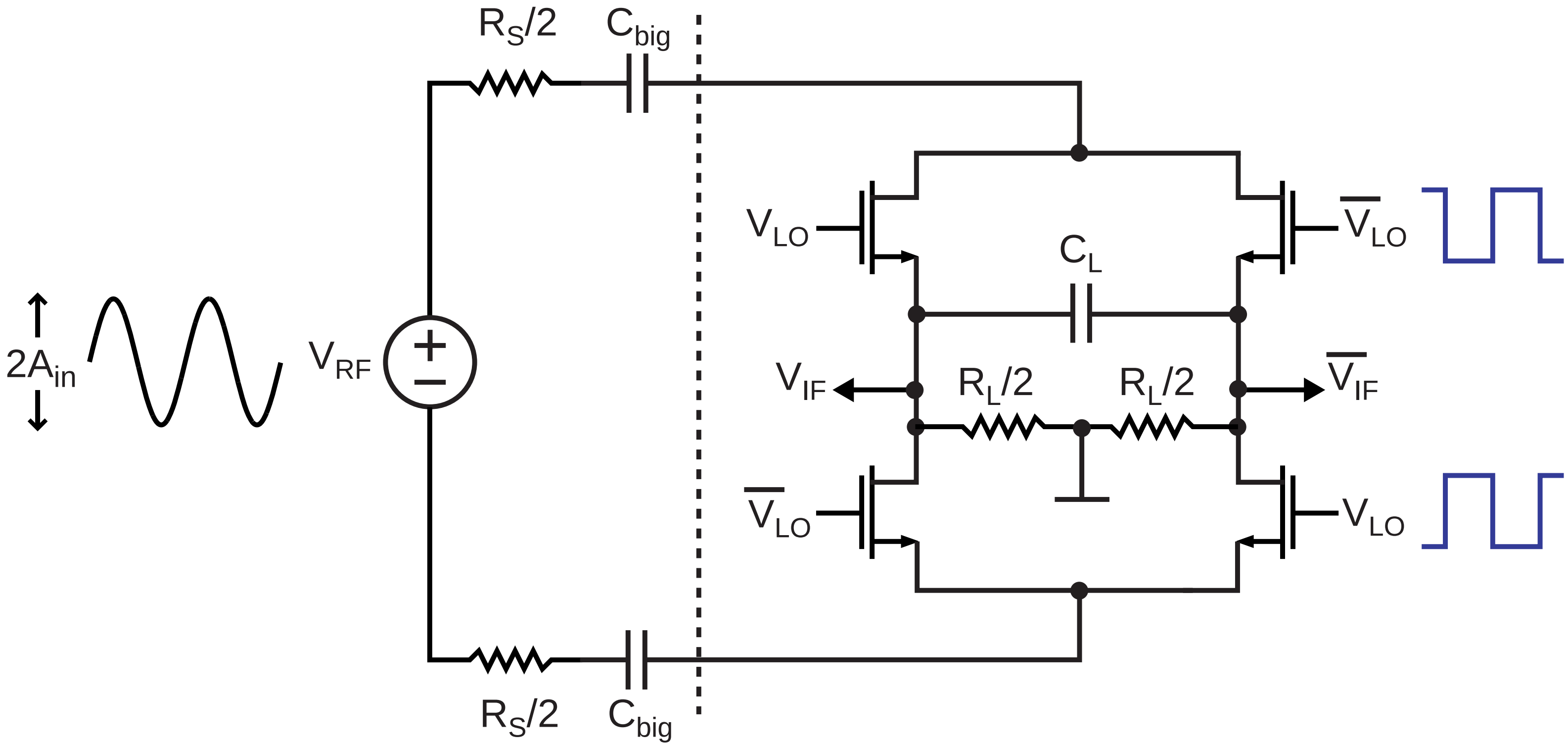
- **Use a differential pair to achieve the transconductor implementation**
- **This is the preferred mixer implementation for most radio systems!**

A Highly Linear CMOS Mixer



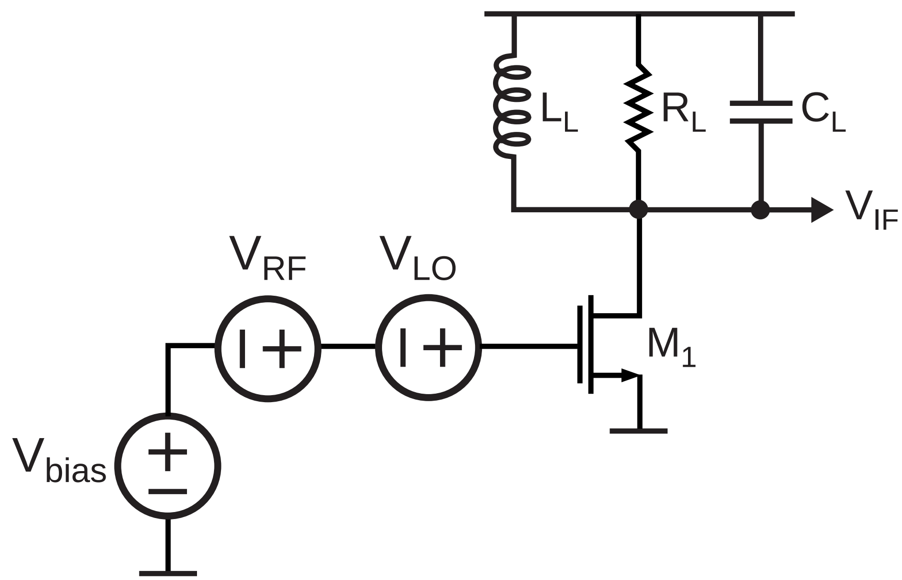
- **Transistors are alternated between the off and triode regions by the LO signal**
  - **RF signal varies resistance of channel when in triode**
  - **Large bias required on RF inputs to achieve triode operation**
- **High linearity achieved, but very poor noise figure**

Passive Mixers



- **We can avoid the transconductor and simply use switches to perform the mixing operation**
  - **No bias current required allows low power operation to be achieved**
- **You can learn more about it in Homework 4!**

Square-Law Mixer

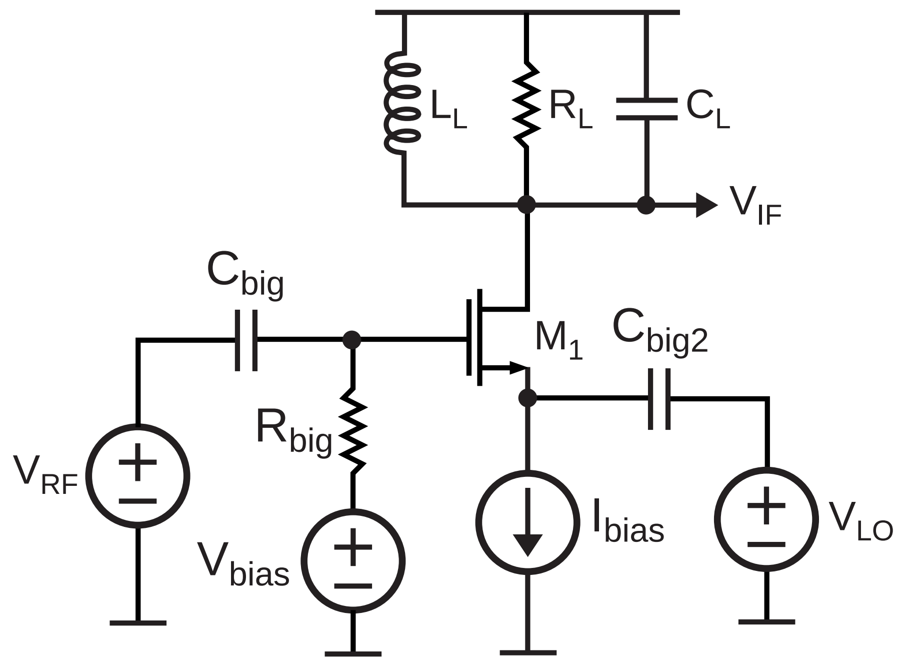


- **Achieves mixing through nonlinearity of MOS device**
  - **Ideally square law, which leads to a multiplication term**

$$(V_{RF} + V_{LO})^2 = V_{RF}^2 + 2V_{RF}V_{LO} + V_{LO}^2$$

  - **Undesired components must be filtered out**
- **Need a long channel device to get square law behavior**
- **Issue – no isolation between LO and RF ports**

Alternative Implementation of Square Law Mixer



- **Drives LO and RF inputs on separate parts of the transistor**
  - **Allows some isolation between LO and RF signals**
- **Issue - poorer performance compared to multiplication-based mixers**
  - **Lots of undesired spectral components**
  - **Poorer isolation between LO and RF ports**