Chapter Outline

Heterodyne Receivers

- ✓ Problem of Image
- ✓ Mixing Spurs
- ✓ Sliding-IF RX

Direct-Conversion Receivers

- ✓ LO Leakage and Offsets
- ✓ Even-Order Nonlinearity
- ✓ I/Q Mismatch

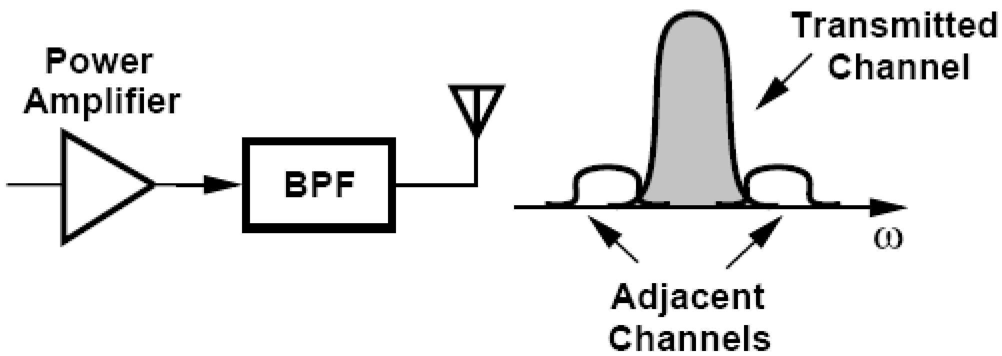
Image-Reject and Low-IF Receivers

- ✓ Hartley and Weaver Receivers
- ✓ Low-IF Receivers
- ✓ Polyphase Filters

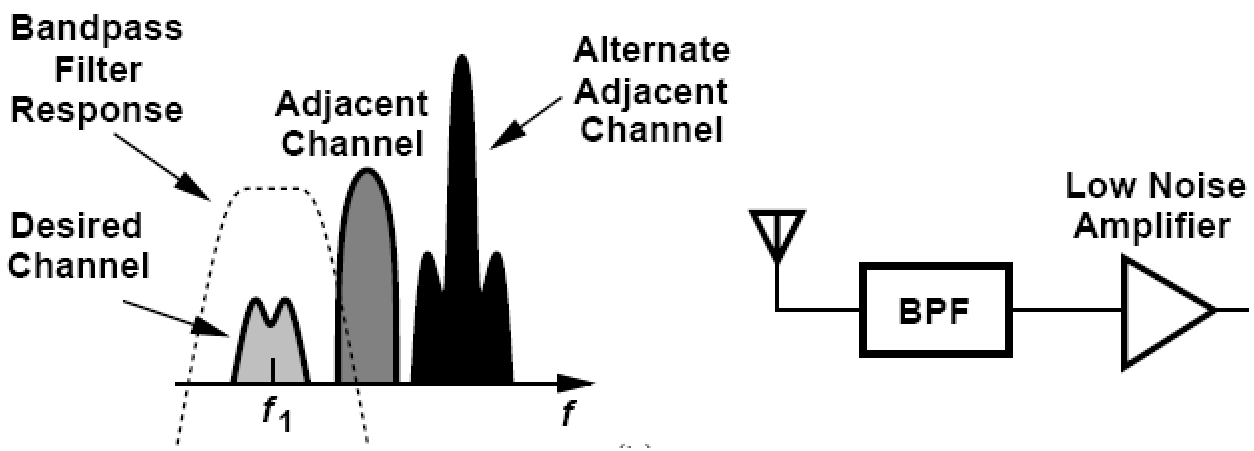
Transmitter Architecture

- ✓ TX Baseband Processing
- ✓ Direct-Conversion TX
- ✓ Heterodyne and Sliding-IF TX

General Considerations: Narrow Channel Bandwidth

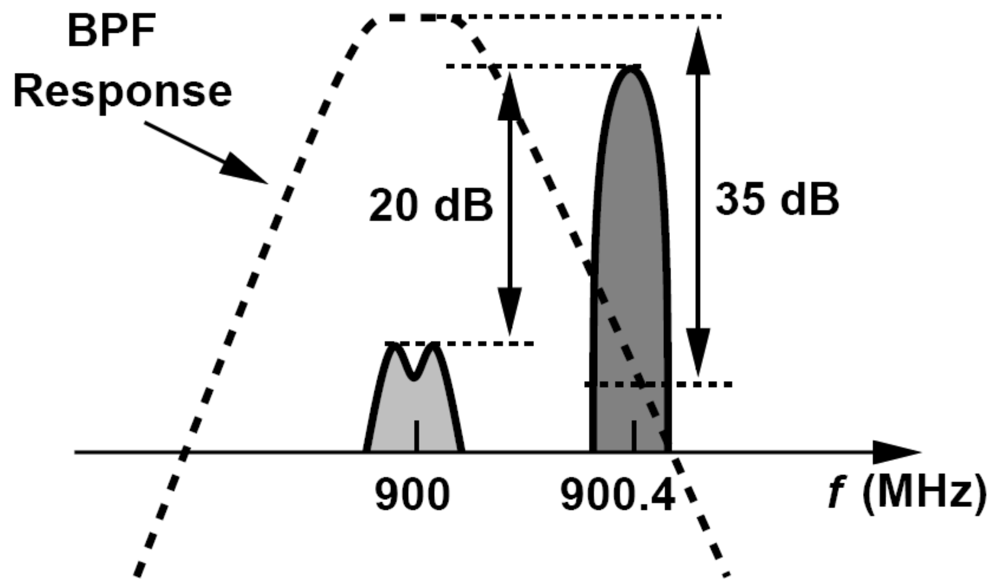


(a)



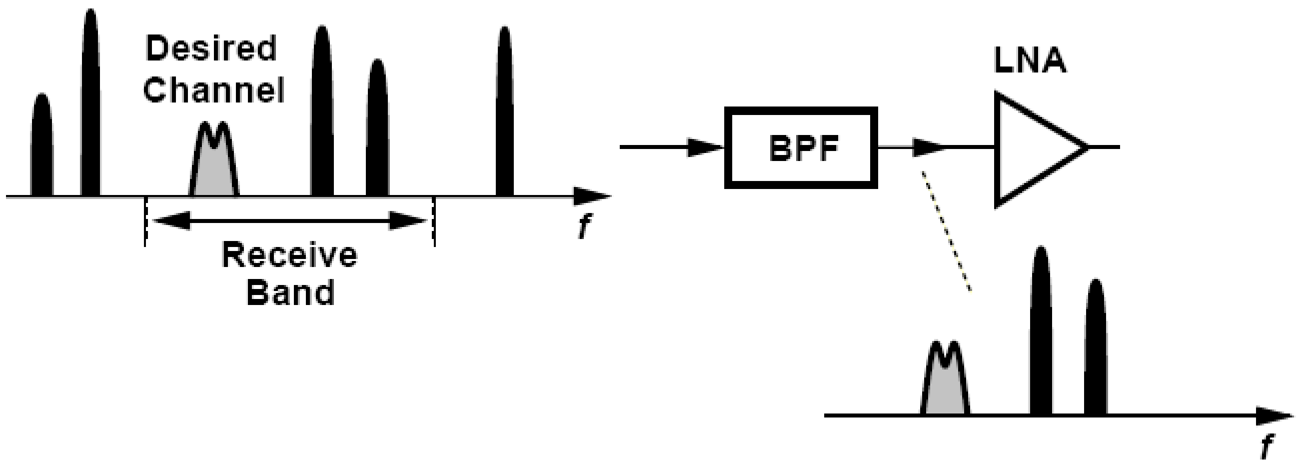
- Narrow channel bandwidth impacts the RF design of the transceiver.

Can We Simply Filter the Interferers to Relax the Receiver Linearity Requirement?



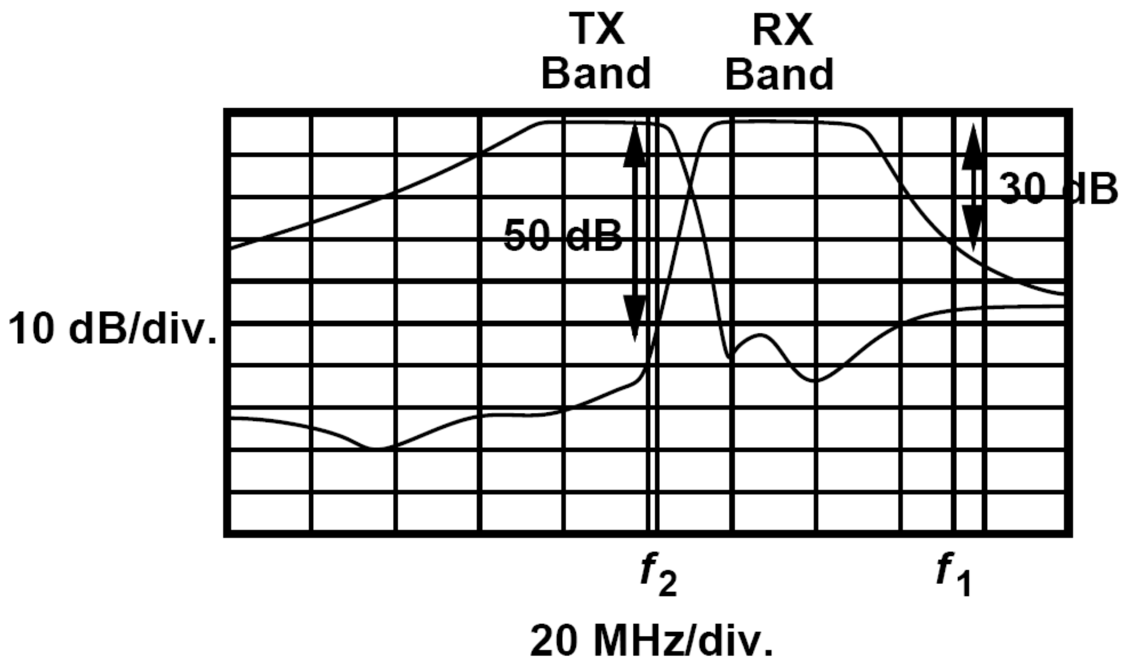
- First, the filter must provide a very high *Q*
- Second, the filter would need a variable, yet precise center frequency

Channel Selection and Band Selection



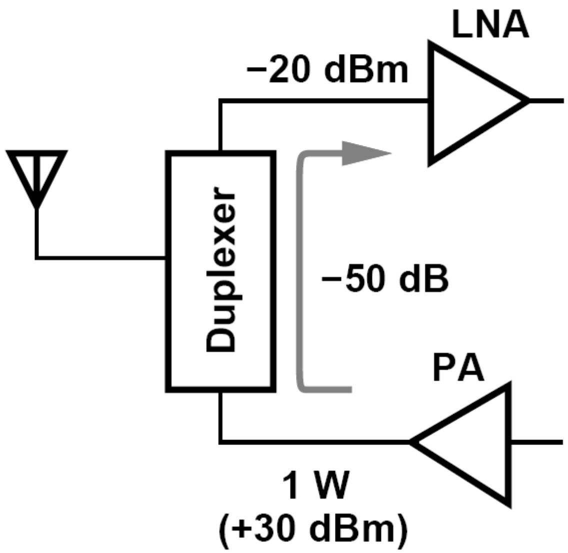
- **All of the stages in the receiver chain that precede channel-selection filtering must be sufficiently linear**
- **Channel selection must be deferred to some other point where center frequency is lower and hence required *Q* is more reasonable**
- **Most receiver front ends do incorporate a "band-select" filter**

Duplexer Characteristics



- The front-end band-select filter suffers from a trade-off between its selectivity and its in-band loss because the edges of the band-pass frequency response can be sharpened only by increasing the order of the filter.
- Front-end loss directly raises the *NF* of the entire receiver

TX-RX Feedthrough



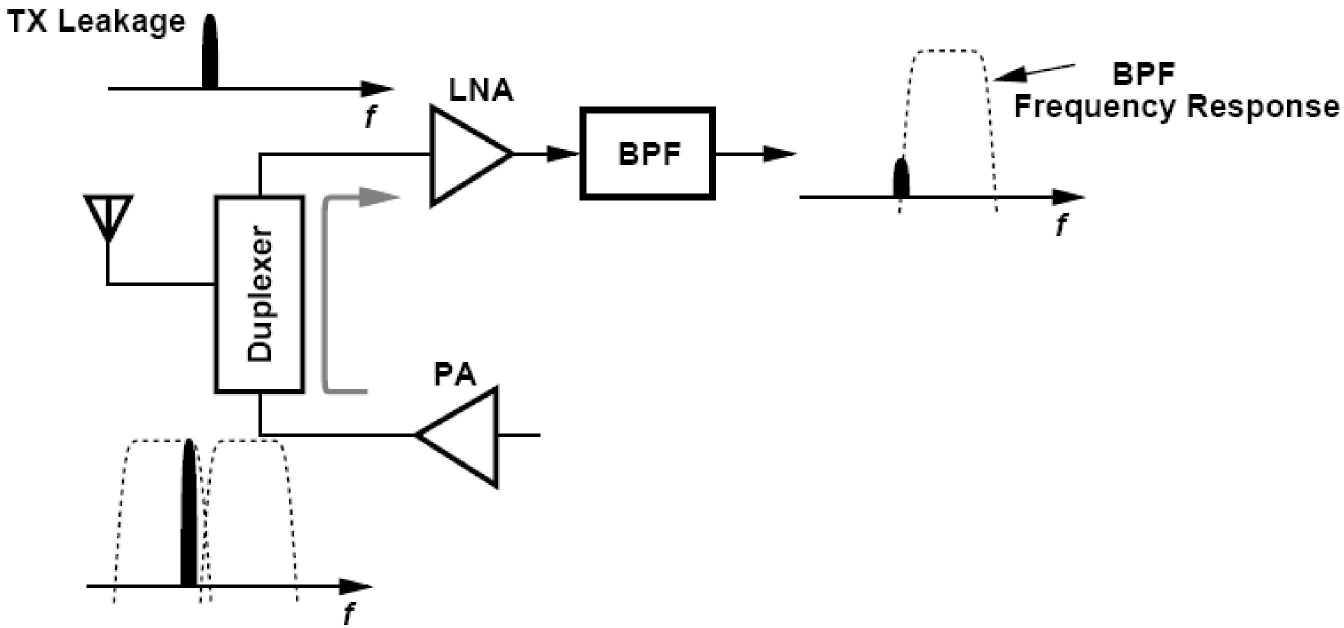
- In full-duplex standards, the TX and the RX operate concurrently.
- With a 1-W TX power, the leakage sensed by LNA can reach -20dBm, dictating a substantially higher RX compression point.

An Example of TX-RX Leakage

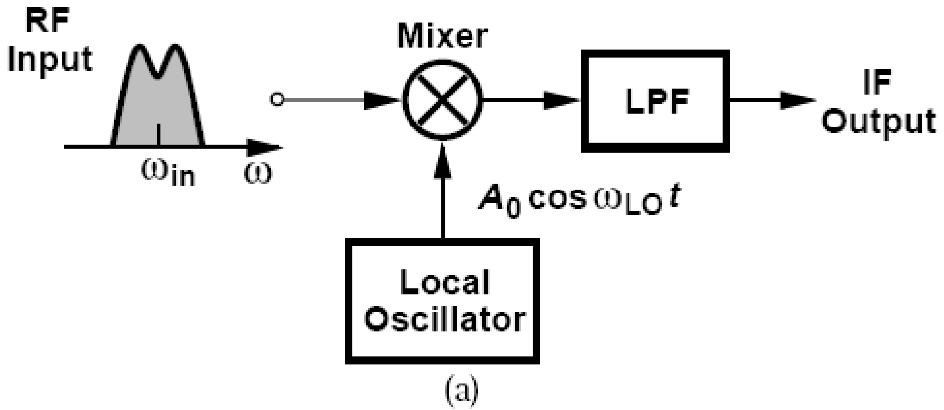
Explain how a band-pass filter following the LNA can alleviate the TX-RX leakage in a CDMA system.

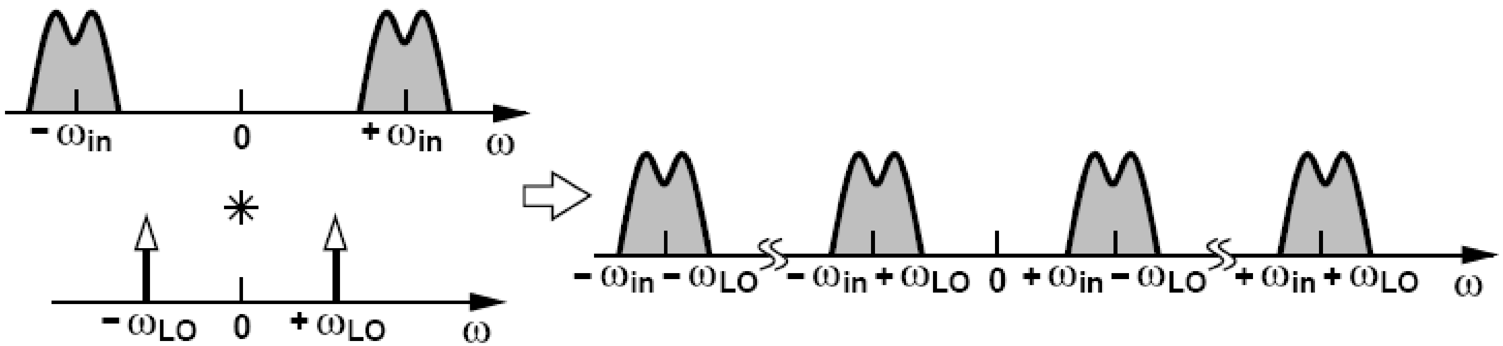
Solution:

As depicted in below, if the BPF provides additional rejection in the TX band, the linearity required of the rest of the RX chain is proportionally relaxed. The LNA compression point, however, must still be sufficiently high.



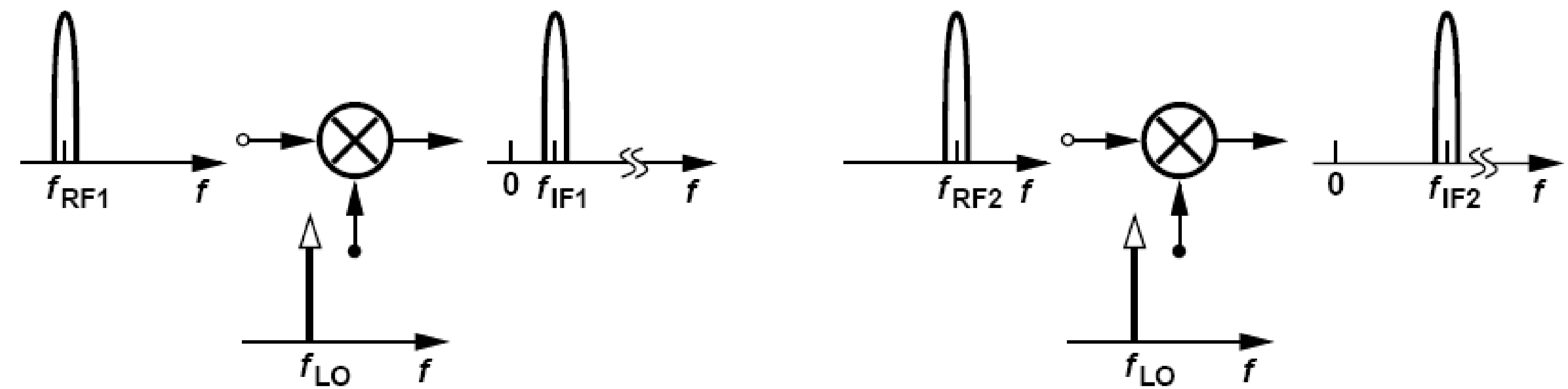
Basic Heterodyne Receivers



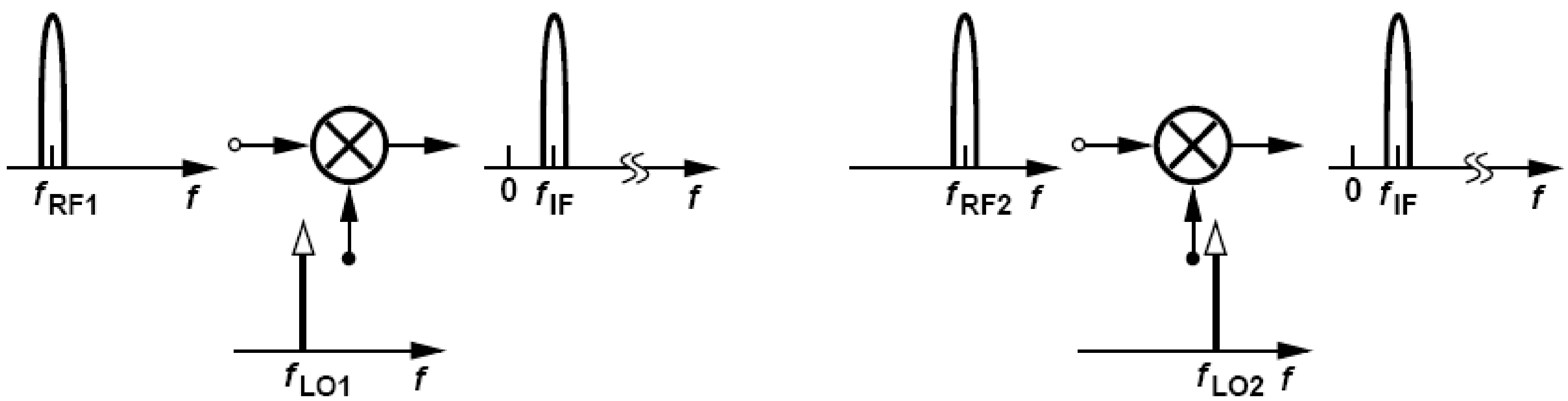


- **“Heterodyne” receivers employ an LO frequency unequal to ω_{in} and hence a nonzero IF**
- **A Mixer performing downconversion.**
- **Due to its high noise, the downconversion mixer is preceded by a low-noise amplifier**

How Does a Heterodyne Receiver Cover a Given Frequency Band?

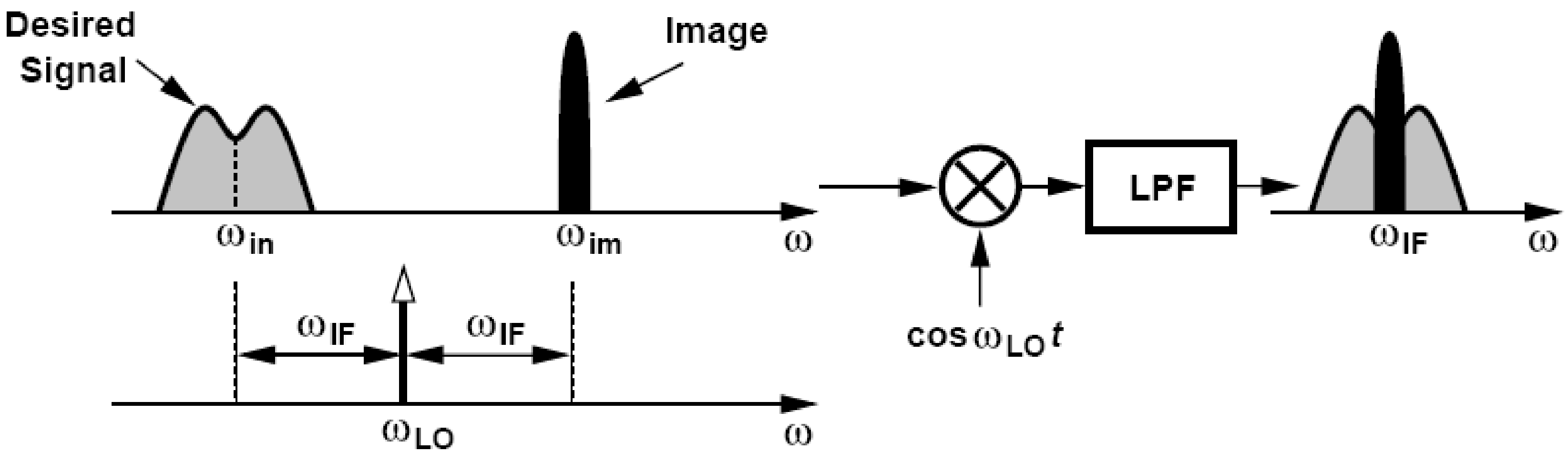


- **Constant LO: each RF channel is downconverted to a different IF channel**



- **Constant IF: LO frequency is variable, all RF channels within the band of interest translated to a single value of IF.**

Basic Heterodyne Receivers: Problem of Image



$$A \cos \omega_{IF} t = A \cos(\omega_{in} - \omega_{LO})t$$
$$= A \cos(\omega_{LO} - \omega_{in})t$$

$$\omega_{im} = \omega_{in} + 2\omega_{IF} = 2\omega_{LO} - \omega_{in}$$

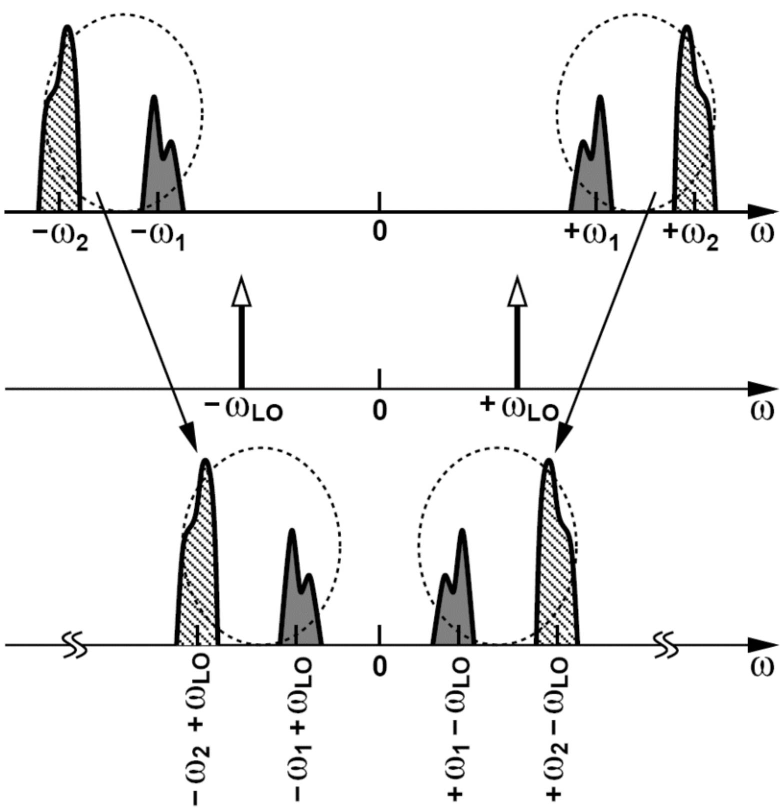
- **Two spectra located symmetrically around ω_{LO} are downconverted to the IF**

An Example of Image (I)

Suppose two channels at ω_1 and ω_2 have been received and $\omega_1 < \omega_2$. Study the downconverted spectrum as the LO frequency varies from below ω_1 to above ω_2.

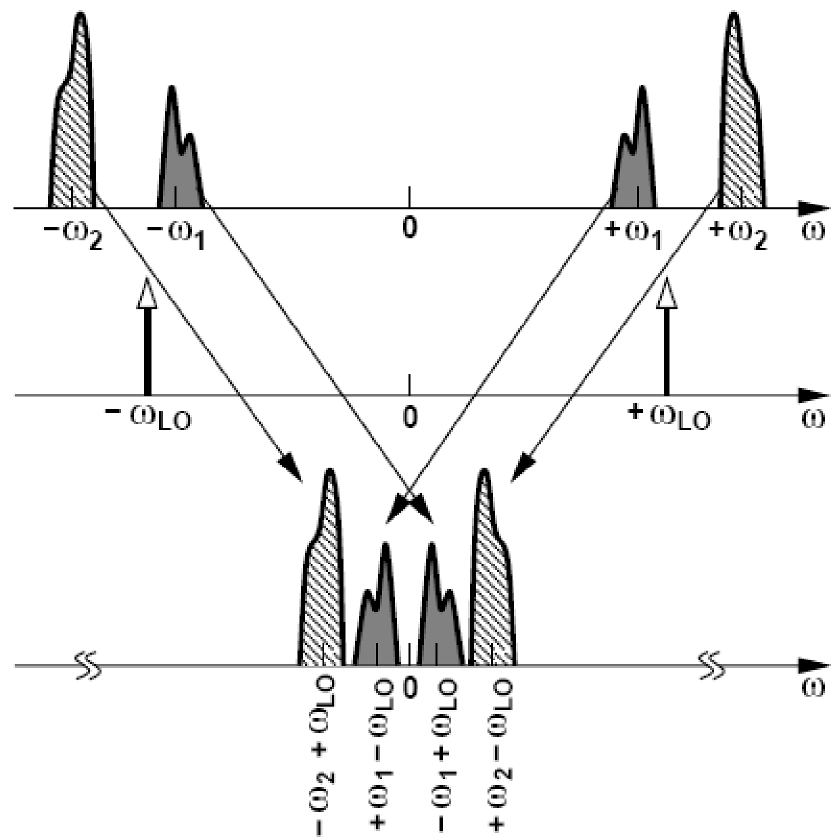
Solution:

$\omega_{LO} < \omega_1$



(a)

ω_{LO} slightly above ω_1



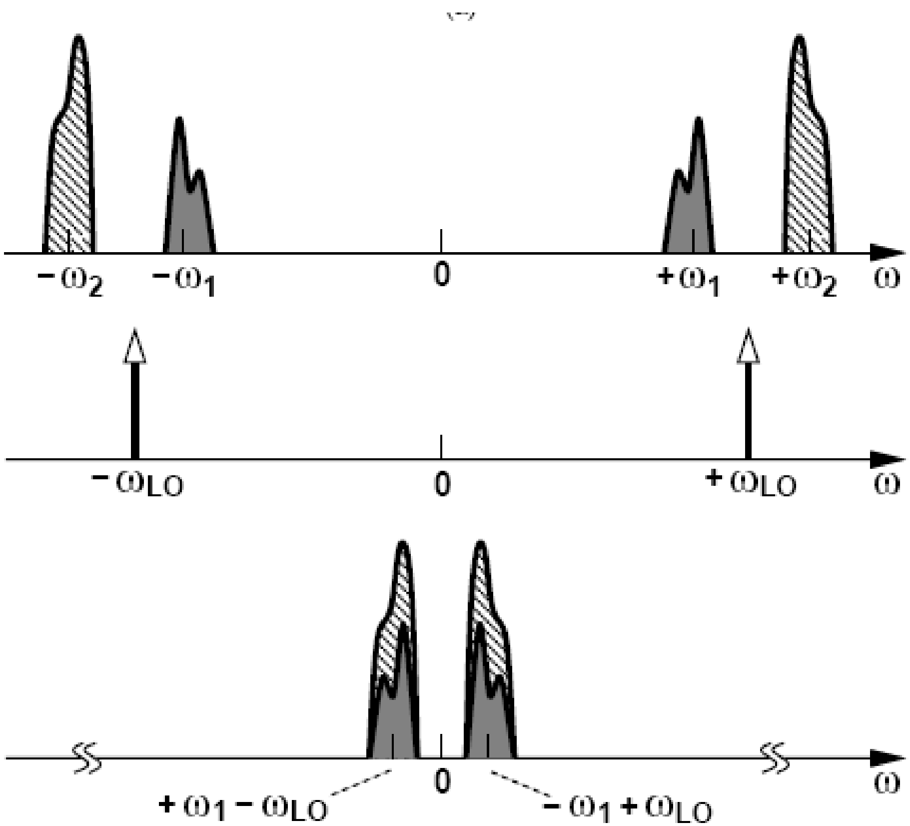
(b)

An Example of Image (Ⅱ)

Suppose two channels at ω_1 and ω_2 have been received and $\omega_1 < \omega_2$. Study the downconverted spectrum as the LO frequency varies from below ω_1 to above ω_2.

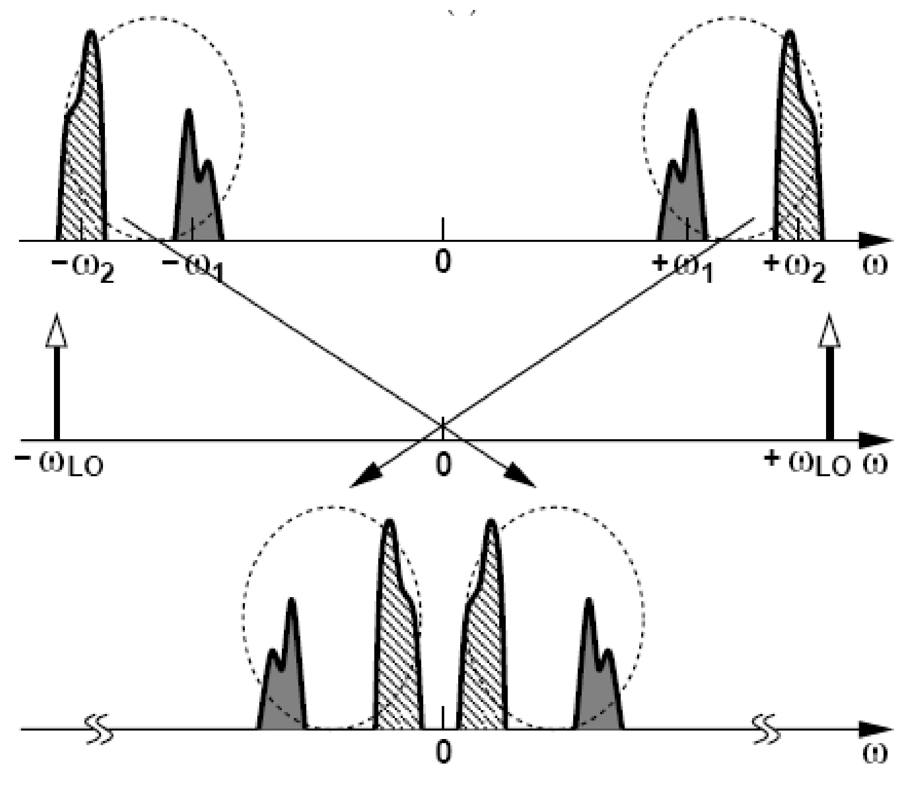
Solution:

ω_{LO} midway between ω_1 and ω_2



(c)

$\omega_{LO} > \omega_2$



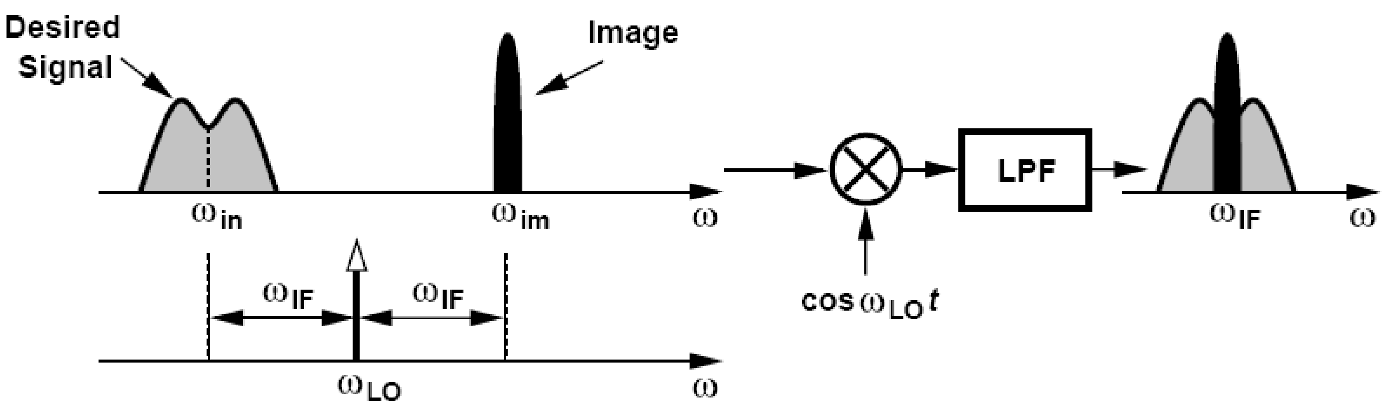
(d)

Another Example of Image

Formulate the downconversion above using expressions for the desired signal and the image.

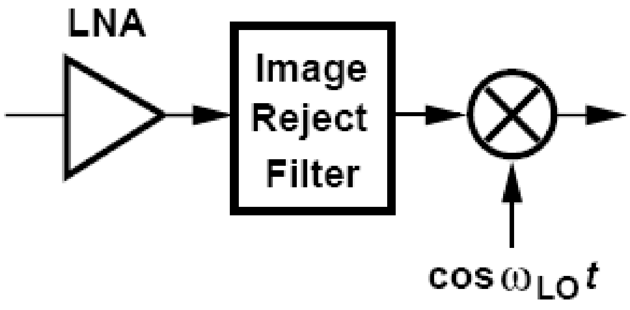
Solution: $A_{in}(t)\cos[\omega_{in}t + \phi_{in}(t)]$ **and** $A_{im}(t)\cos[\omega_{im}t + \phi_{im}(t)]$

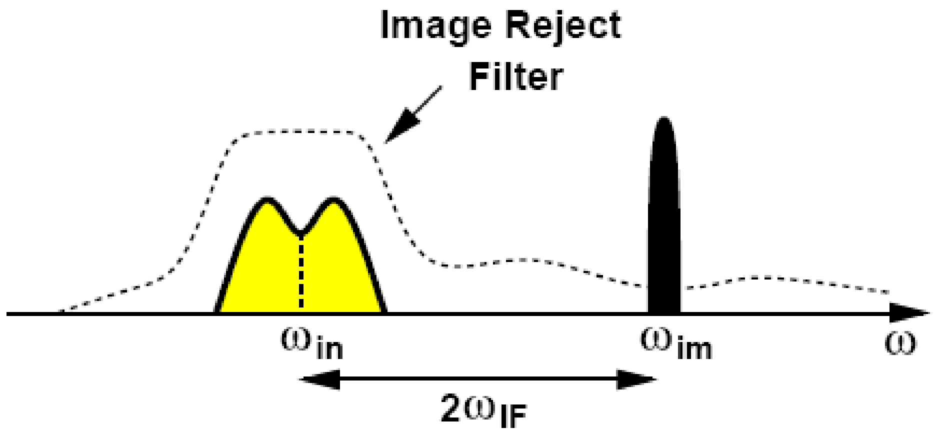
$$\begin{aligned} x_{IF}(t) &= \frac{1}{2}A_{in}(t)A_{LO}\cos[(\omega_{in}+\omega_{LO})t+\phi_{in}(t)] - \frac{1}{2}A_{in}(t)A_{LO}[\cos(\omega_{in}-\omega_{LO})t+\phi_{in}t] \\ &+ \frac{1}{2}A_{im}(t)A_{LO}\cos[(\omega_{im}+\omega_{LO})t+\phi_{im}(t)] \\ &- \frac{1}{2}A_{im}(t)A_{LO}[\cos(\omega_{im}-\omega_{LO})t+\phi_{im}t]. \end{aligned}$$



We observe that the components at $\omega_{in} + \omega_{LO}$ and $\omega_{im} + \omega_{LO}$ are removed by low-pass filtering, and those at $\omega_{in} - \omega_{LO} = -\omega_{IF}$ and $\omega_{im} - \omega_{LO} = +\omega_{IF}$ coincide.

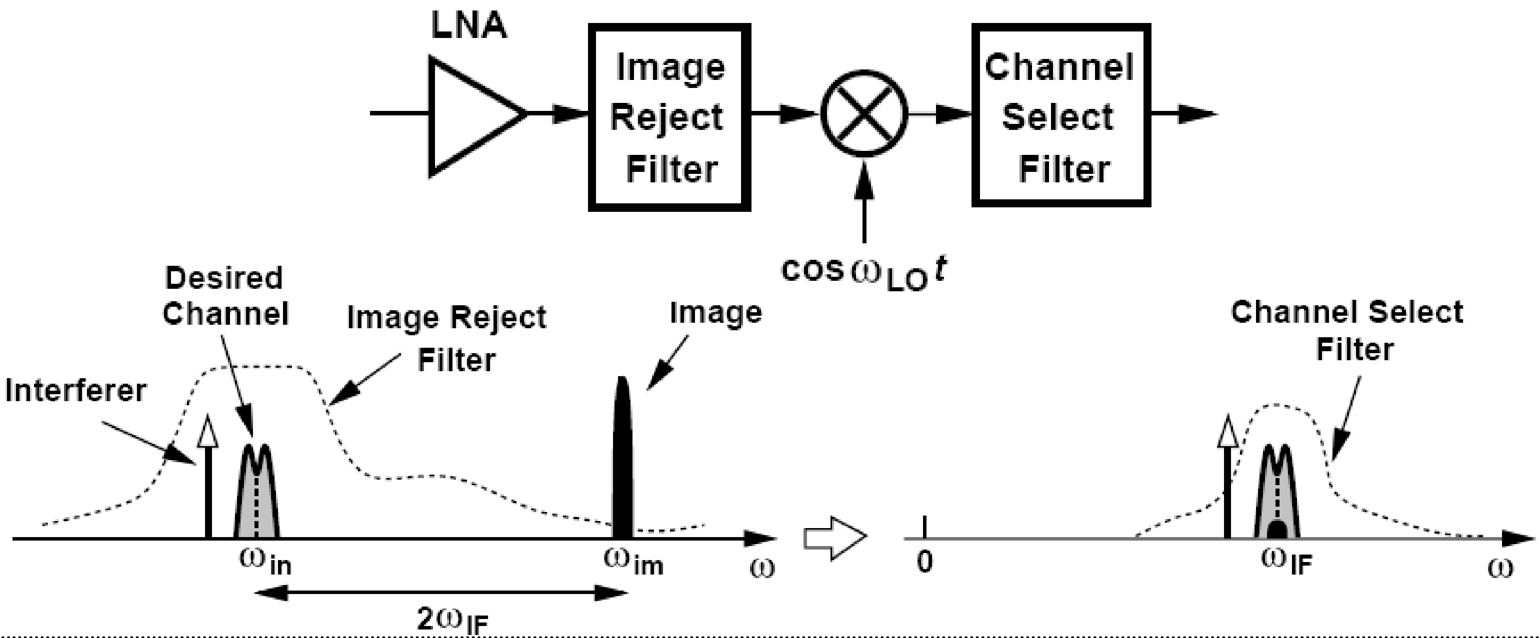
Image Rejection



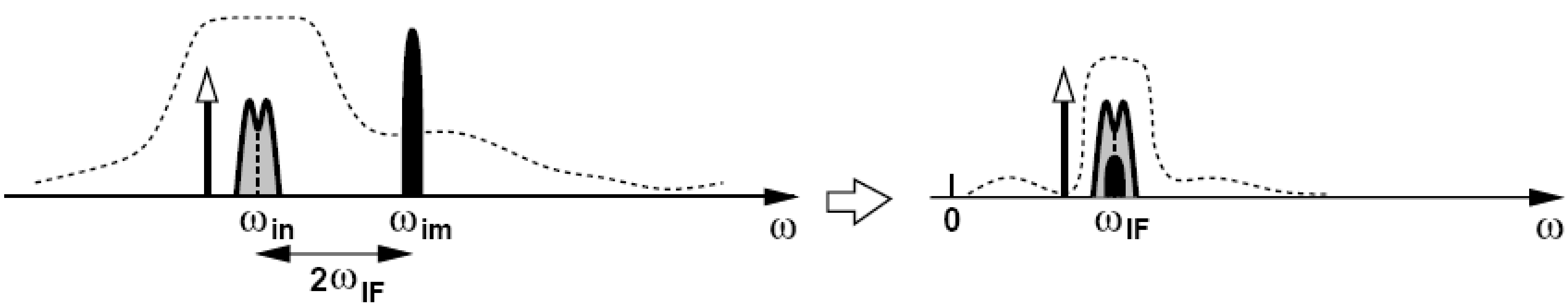


- The most common approach is to precede the mixer with an "image-reject filter"
- A filter with high image rejection typically appears between the LNA and the mixer so that the gain of the LNA lowers the filter's contribution to the receiver noise figure
- The linearity and selectivity required of the image-reject filter have dictated passive, off-chip implementations.

Image Rejection versus Channel Selection



- **A high IF allows substantial rejection of the image.**

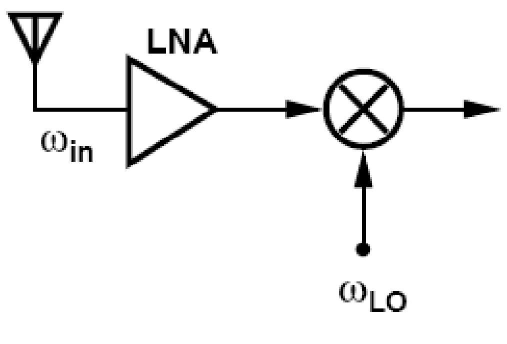


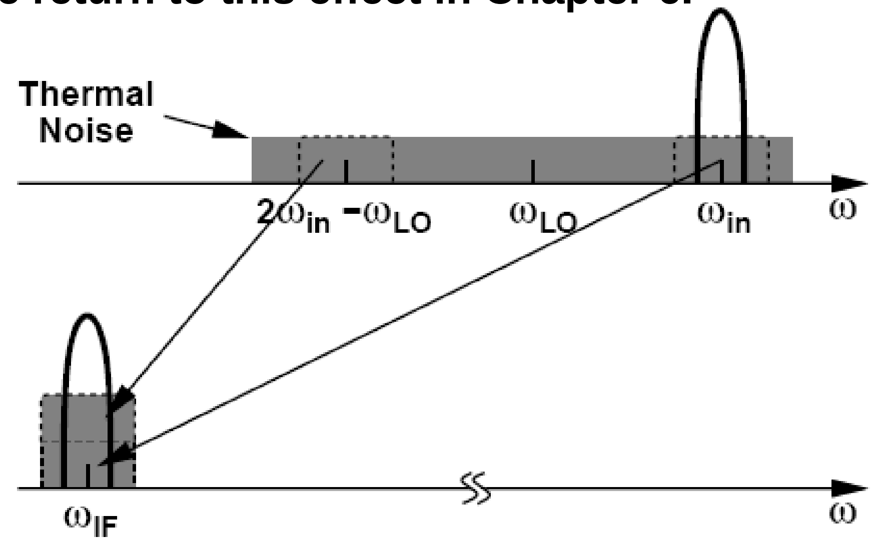
- **A low IF helps with the suppression of in-band interferers.**

An Example of Noise Figure in Receiver

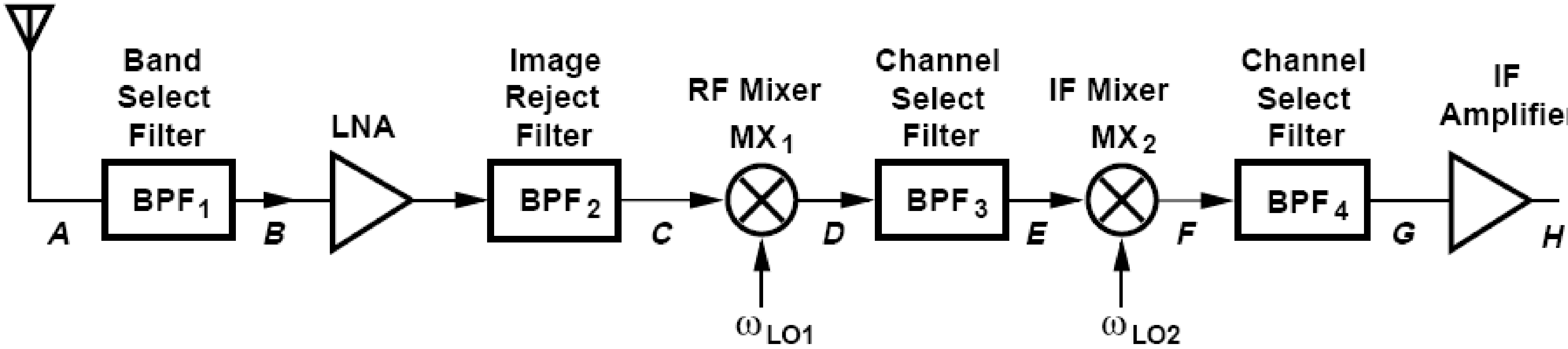
An engineer is to design a receiver for space applications with no concern for interferers. The engineer constructs the heterodyne front end shown in figure below (left), avoiding band-select and image-select filters. Explain why this design suffers from a relatively high noise figure.

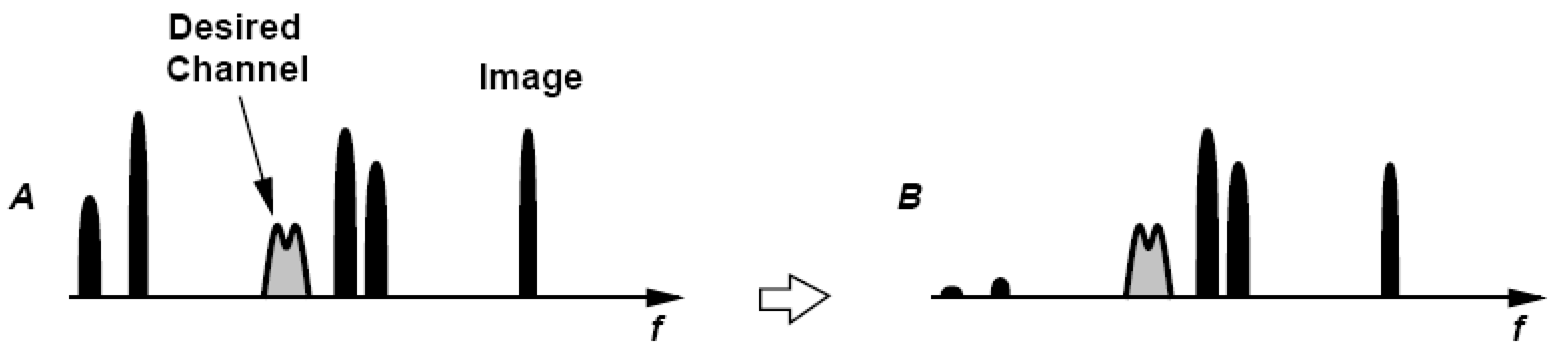
Even in the absence of interferers, the thermal noise produced by the antenna and the LNA in the image band arrives at the input of the mixer. Thus, the desired signal, the thermal noise in the desired channel, and the thermal noise in the image band are downconverted to IF, leading to a higher noise figure for the receiver (unless the LNA has such a limited bandwidth that it suppresses the noise in the image band). An image-reject filter would remove the noise in the image band. We return to this effect in Chapter 6.





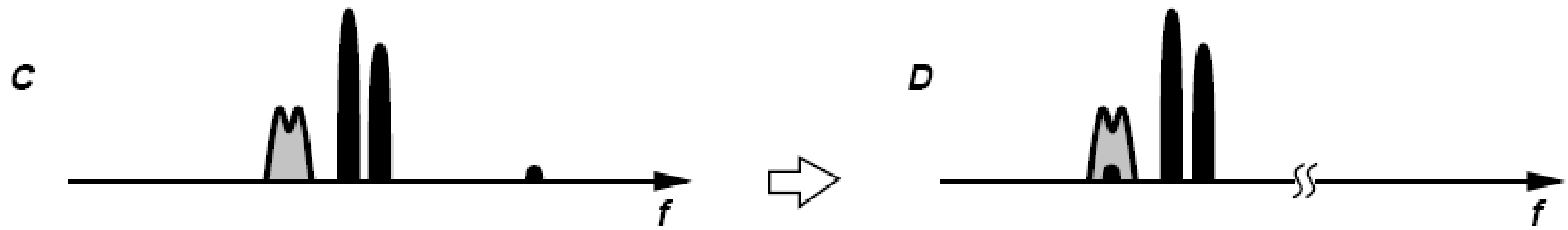
Dual Downconversion (I)



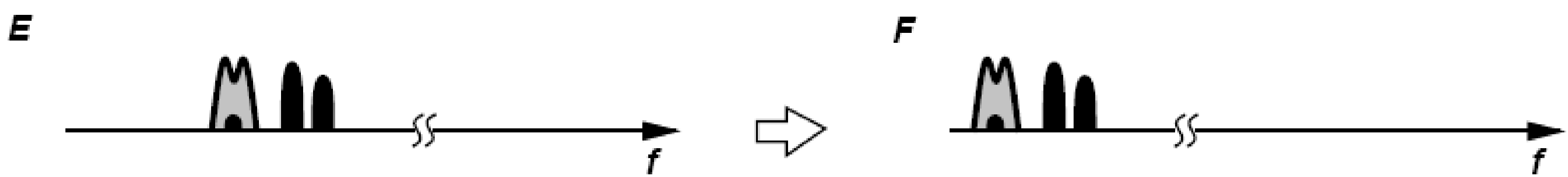


- The front-end filter selects the band while providing some image rejection as well (Point *B*)

Dual Downconversion (Ⅱ)

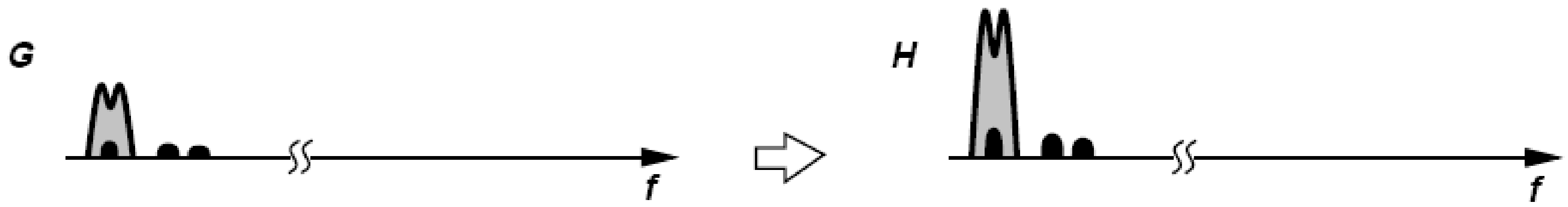


- After amplification and image-reject filtering, spectrum of *C* obtained
- Sufficiently linear mixer translates desired channel and adjacent interferers to first IF (Point *D*)

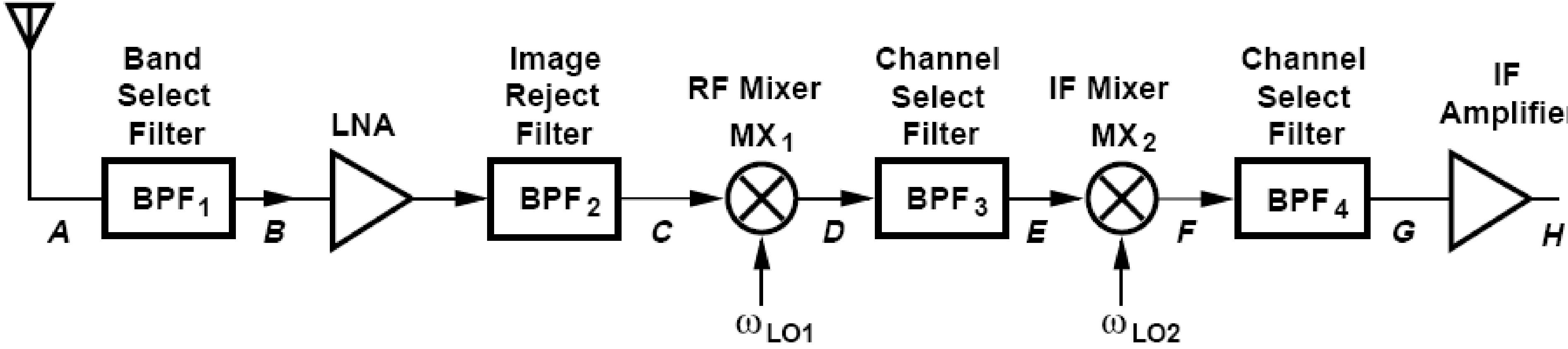


- Partial channel selection BPF_3 permits the use of a second mixer with reasonable linearity. (Point *E*)
- Spectrum is translated to second IF. (Point *F*)

Receiver Architectures



- BPF$_4$ suppresses the interferers to acceptably low levels (Point *G*)
- An optimum design scales both the noise figure and the IP3 of each stage according to the total gain preceding that stage.

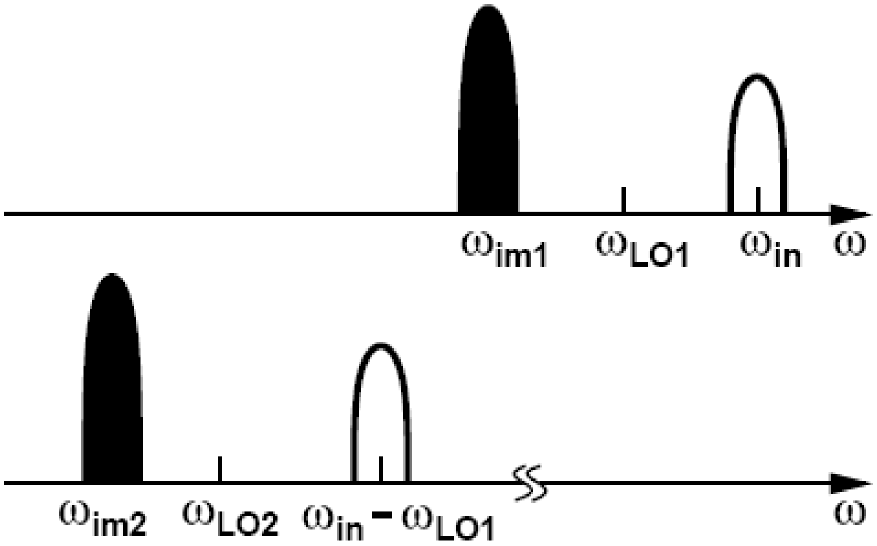


Another Example of Image

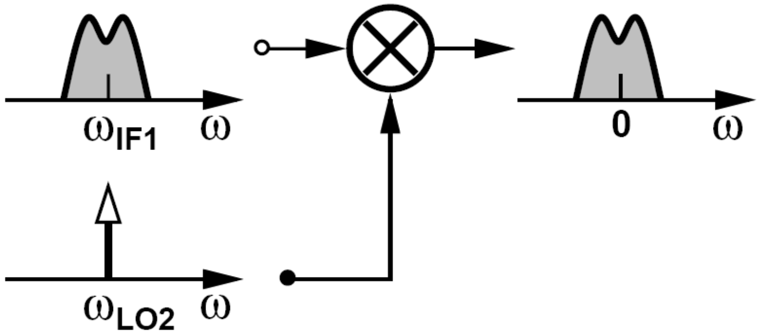
Assuming low-side injection for both downconversion mixers in figure above, determine the image frequencies.

Solution:

As shown below, the first image lies at $2\omega_{LO1} - \omega_{in}$. The second image is located at $2\omega_{LO2} - (\omega_{in} - \omega_{LO1})$.



Zero Second IF

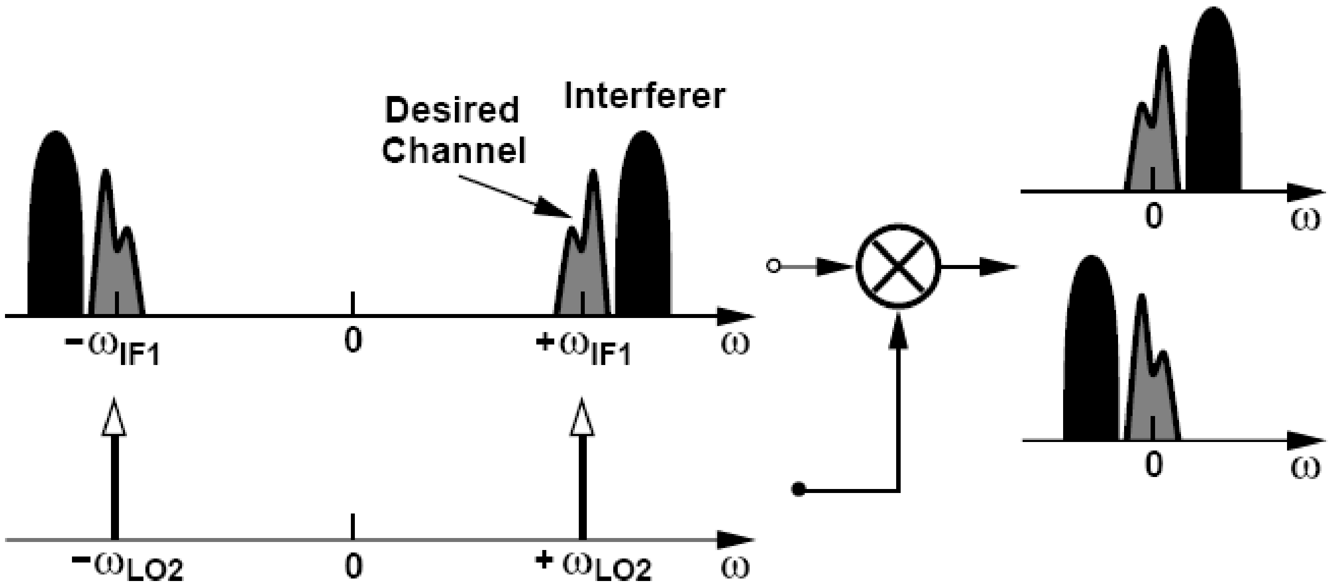


- To avoid secondary image, most modern heterodyne receivers employ a zero second IF.
- In this case, the image is the signal itself. No interferer at other frequencies can be downconverted as an image to a zero center frequency if $\omega_{LO2}=\omega_{IF1}$

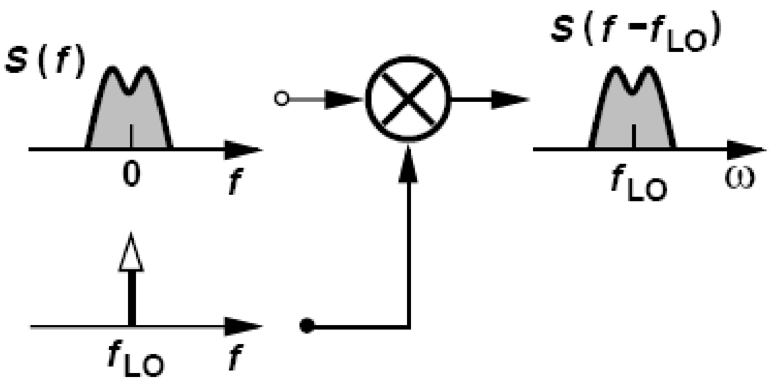
Example of Zero Second IF

Suppose the desired signal in figure above is accompanied by an interferer in the adjacent channel. Plot the spectrum at the second IF if $\omega_{LO2} = \omega_{IF1}$.

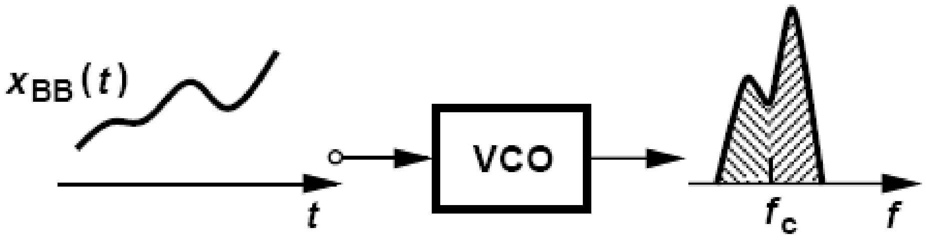
As shown below, the desired channel appears at $\pm\ \omega_{IF1}$ and is accompanied by the interferer. Upon mixing in the time domain, the spectrum at negative frequencies is convolved with the LO impulse at $+\omega_{LO2}$, sliding to a zero center frequency for the desired channel. Similarly, the spectrum at positive frequencies is convolved with the impulse at $-\omega_{LO2}$ and shifted down to zero. The output thus consists of two copies of the desired channel surrounded by the interferer spectrum at both positive and negative frequencies.



Symmetrically-modulated versus Asymmetrically-modulated Signal



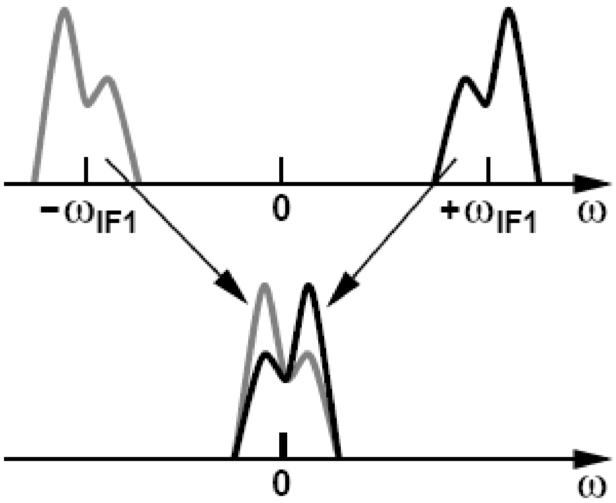
AM signal generation



FM signal generation

- **AM signals are symmetric, FM signals are asymmetric.**
- **Most of today's modulation schemes, e.g., FSK, QPSK, GMSK, and QAM, exhibit asymmetric spectra around carrier frequency.**

Corruption of the Asymmetric Signal Spectrum

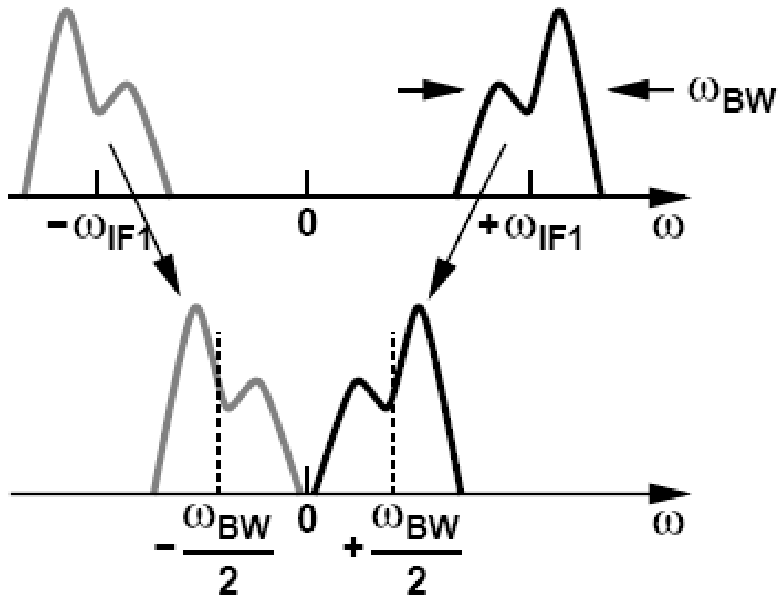


- **Downconversion to a zero IF superimposes two copies of the signal**
- **If the signal spectrum is asymmetric, the original signal spectrum will be corrupted**

An Example of Self-corruption

Downconversion to what minimum intermediate frequency avoids self-corruption of asymmetric signals?

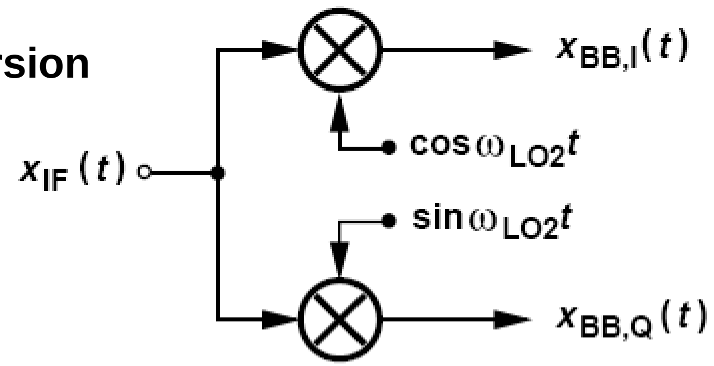
Solution:

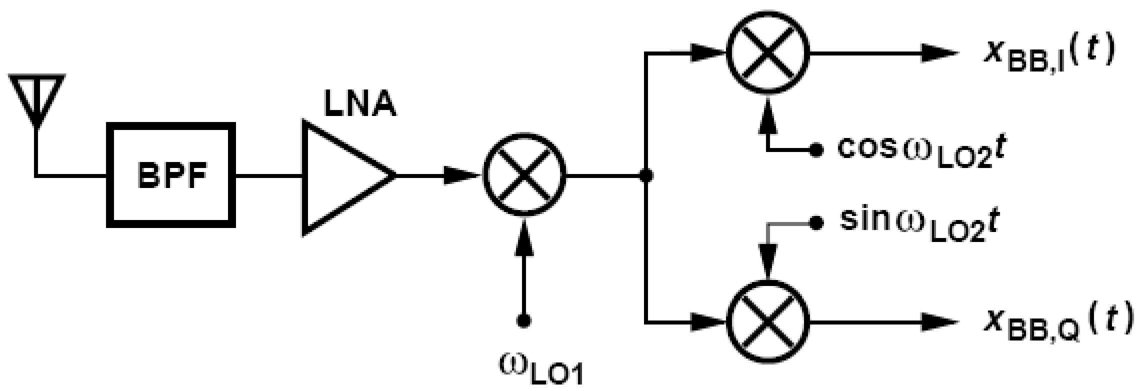


To avoid self-corruption, the downconverted spectra must not overlap each other. Thus, as shown in figure below, the signal can be downconverted to an IF equal to half of the signal bandwidth. Of course, an interferer may now become the image.

How can downconversion to a zero IF avoid self-corruption?

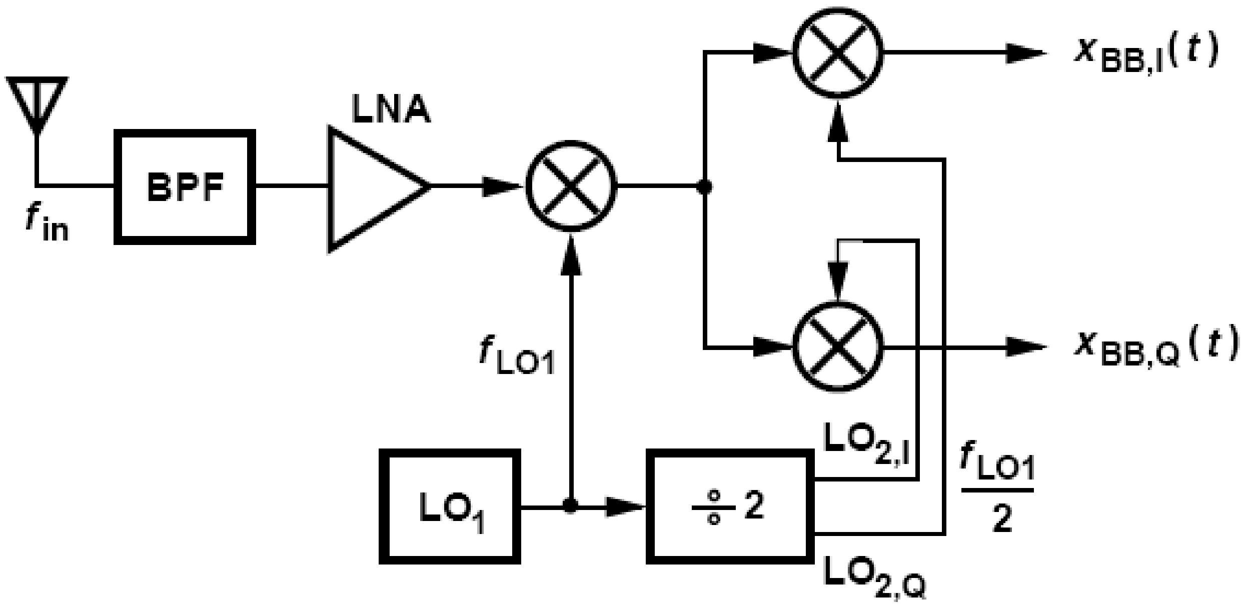
Quadrature downconversion





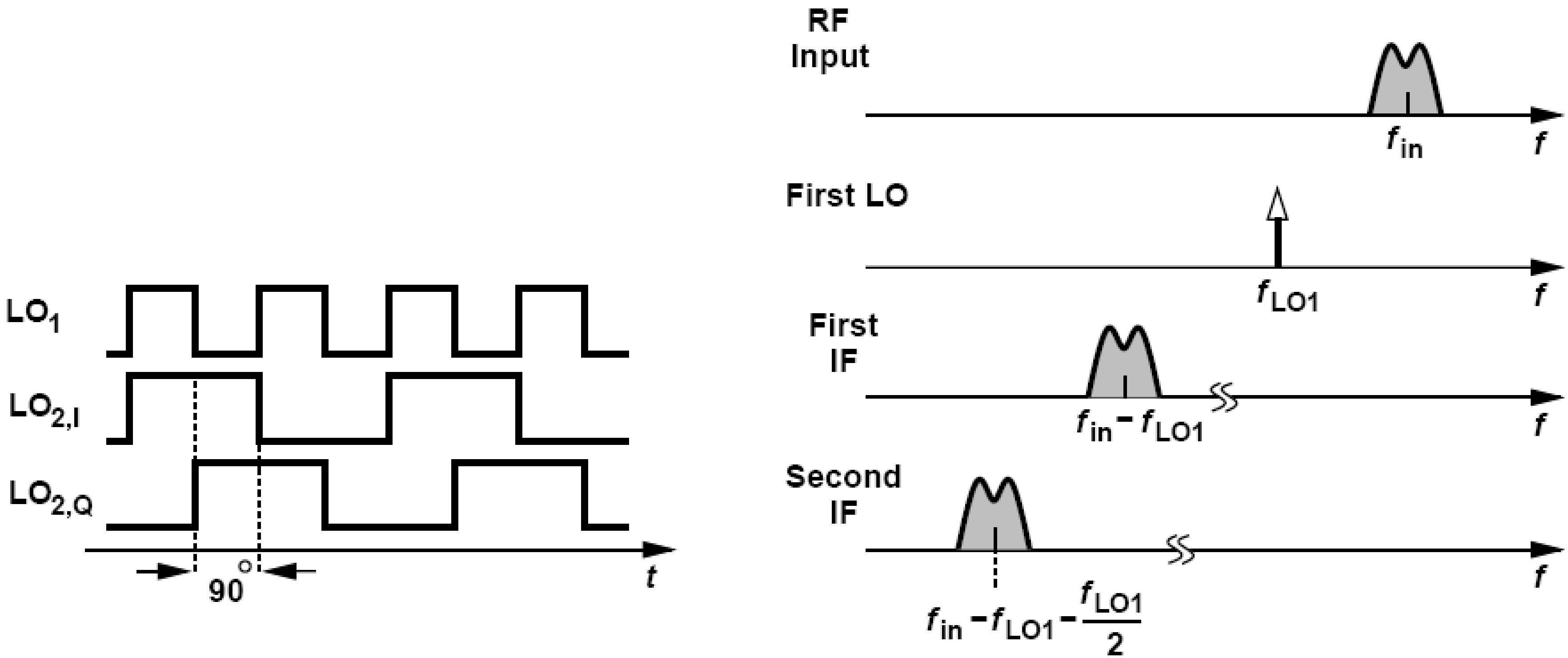
- **By creating two versions of the downconverted signal that have a phase difference of 90°**

Sliding-IF Receivers



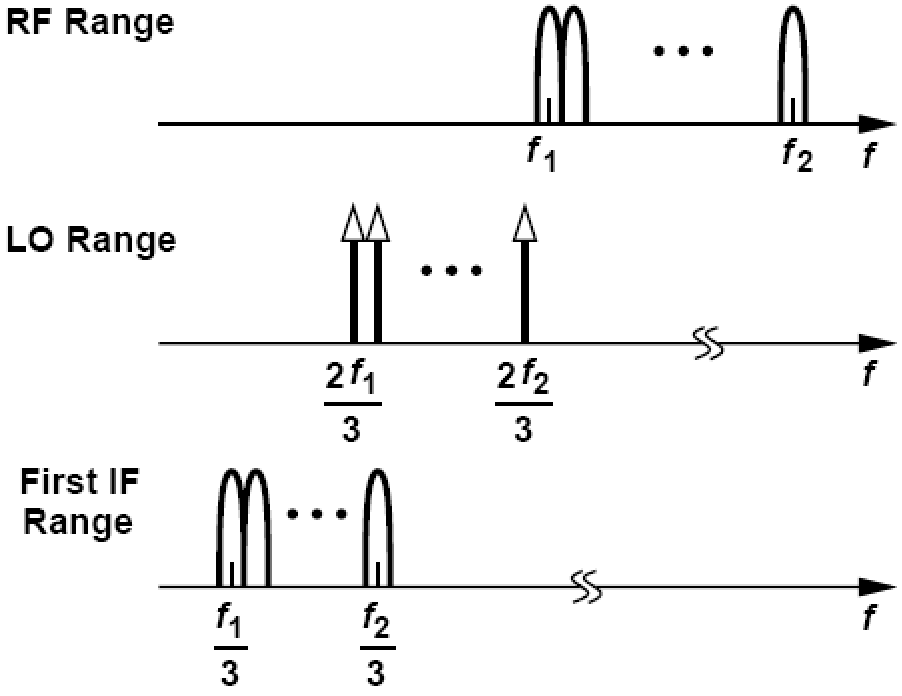
- Modern heterodyne receivers employ only one oscillator
- The second LO frequency is therefore derived from the first by "frequency division"

Sliding-IF Receivers: Divide-by-2 Circuit



- Such divide-by-2 topology can produce quadrature output
- The second LO waveforms at a frequency of $f_{LO1}/2$

Interesting Properties of Sliding-IF Receivers



$$f_{LO1} + \frac{1}{2} f_{LO1} = f_{in}$$
$$f_{LO1} = \frac{2}{3} f_{in}$$
$$f_{IF1} = f_{in} - f_{LO} = \frac{1}{3} f_{in}.$$

Fractional bandwidth:

IF $$\mathrm{BW}_{IF,frac} = \frac{\frac{1}{3}f_2 - \frac{1}{3}f_1}{(\frac{1}{3}f_2 + \frac{1}{3}f_1)/2}$$

RF input $$\mathrm{BW}_{RF,frac} = \frac{f_2 - f_1}{(f_2 + f_1)/2}$$

Sliding-IF Receivers with Divide Ratio of 4

- May incorporate greater divide ratios, e.g., 4

$$f_{LO1} + \frac{1}{4} f_{LO1} = f_{in}$$

$$f_{LO1} = \frac{4}{5} f_{in}.$$

- Second LO f_{in}/5, slightly lower, desirable because generation of LO quadrature phases at lower frequencies incurs smaller mismatches
- Reduces the frequency difference between the image and the signal, difficult to reject image.