Transceiver Architectures (1/2)

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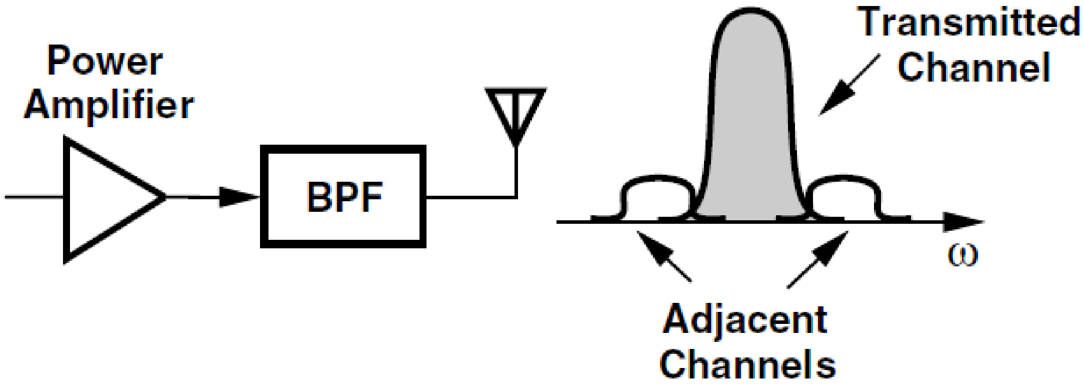
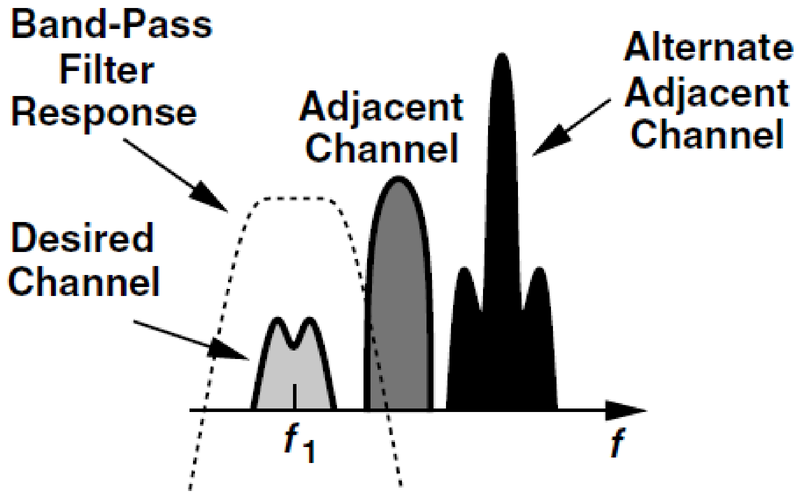
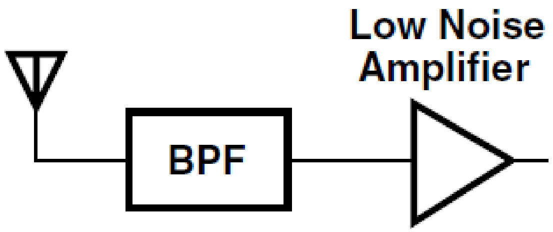
Transmitter/Receiver Front Ends

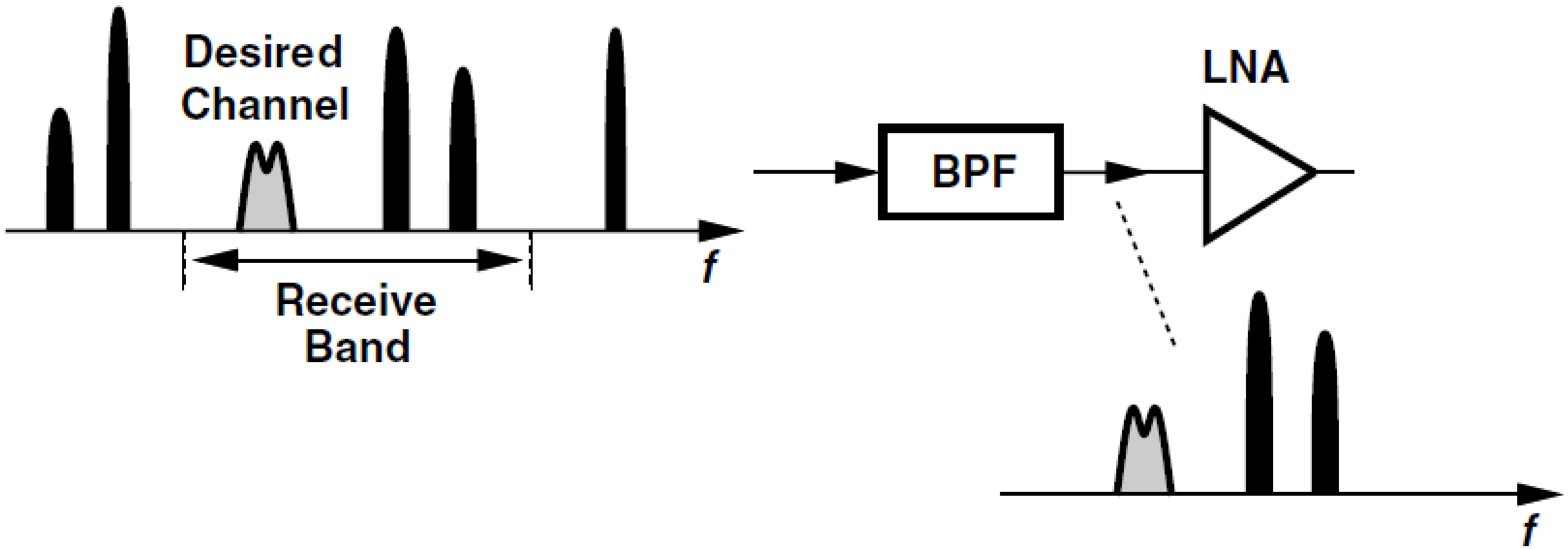






[B. Razavi, RF Microelectronics]

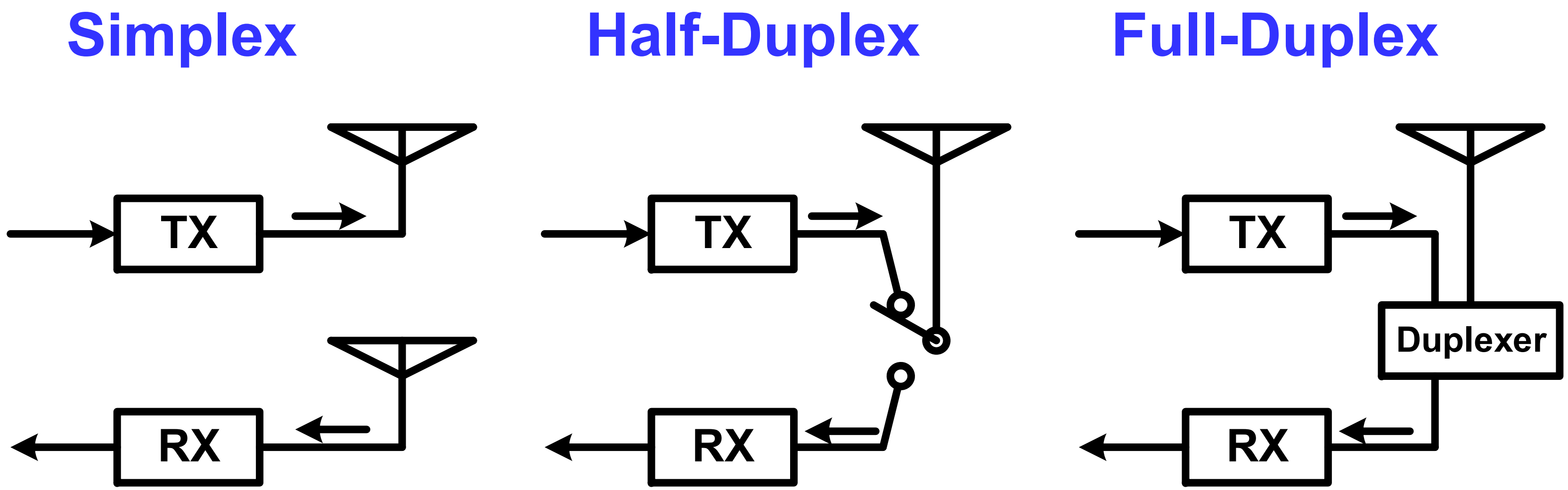
Band-Selection Filtering



❑Most receiver front ends do incorporate a “band-select” filter, which selects the entire receive band and rejects “out-of-band” interferers, thereby suppressing components that may be generated by users that do not belong to the standard of interest.

[B. Razavi, RF Microelectronics]

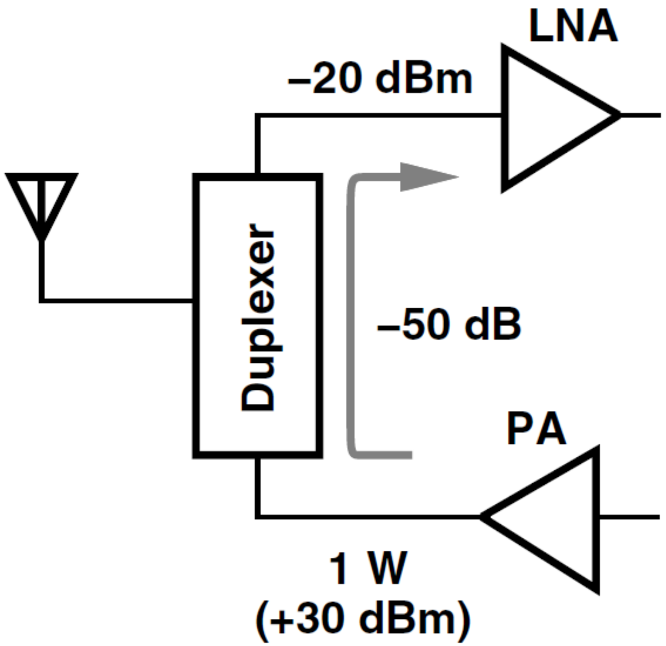
TX-RX Standards

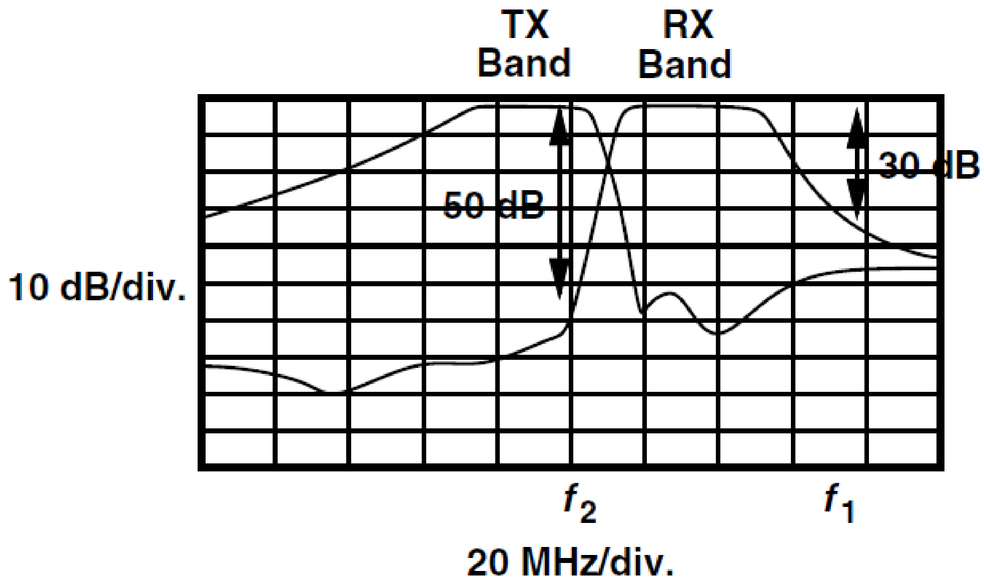


- Simplex: The transceiver can only transmit or receive signals
- Half-Duplex: The transceiver can conduct TX and RX, but not at the same time
- Full-Duplex: TX and RX operate concurrently

[B. Razavi, RF Microelectronics]

TX-RX Feedthrough

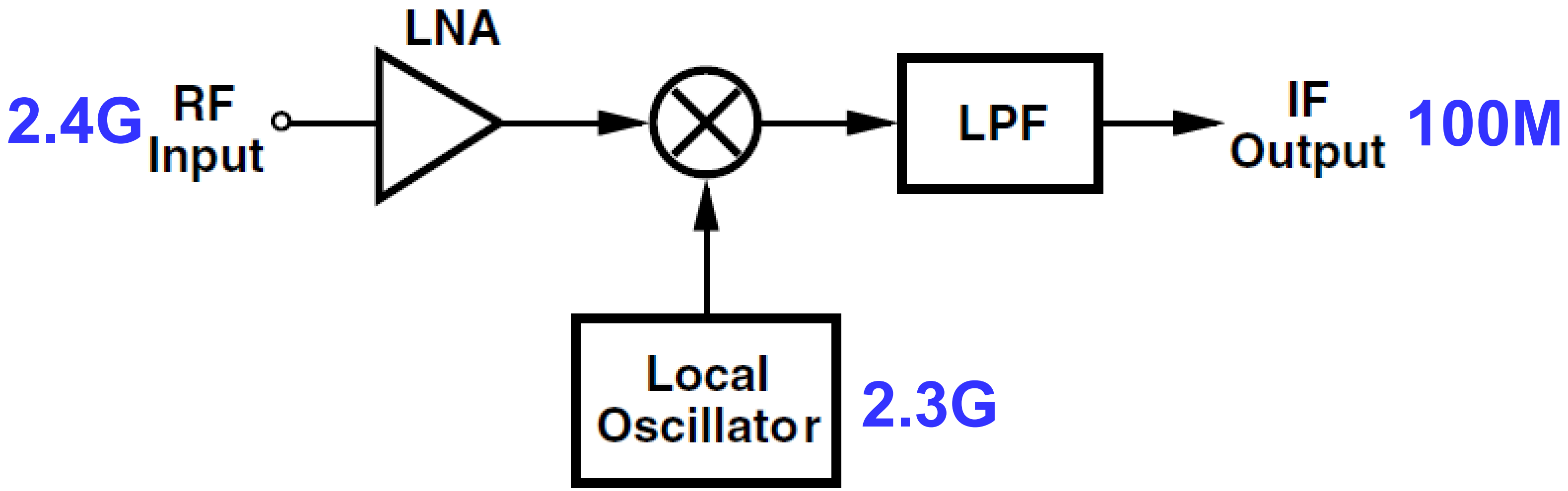


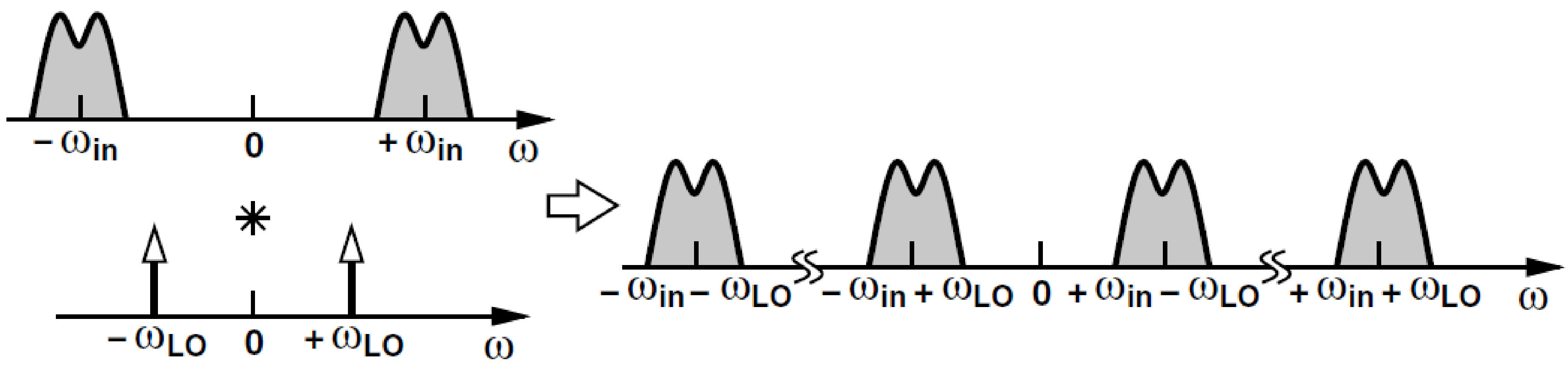


- In full-duplex standards, the TX and RX operate concurrently
- The duplexer helps to reject the TX leakage to the RX
- With a 1-W TX power, the leakage sensed by the RX can reach -20 dBm , dictating a substantially higher RX compression point.

[B. Razavi, RF Microelectronics]

Heterodyne Receiver





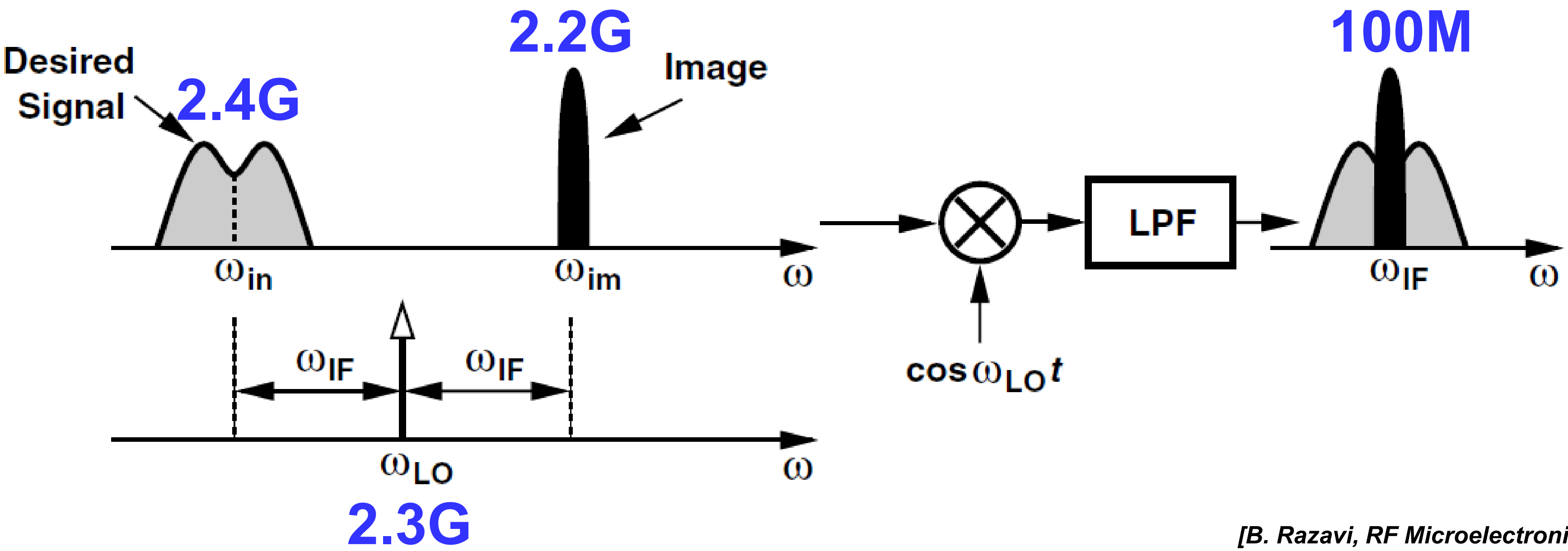
[B. Razavi, RF Microelectronics]

Problem of Image

❑Heterodyne receivers suffer from an effect called the "image."

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

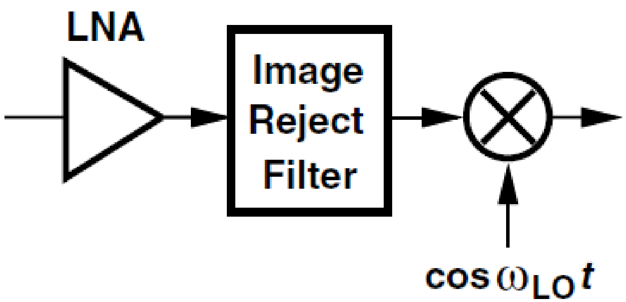
❑whether ω_{in} lies above ω_{LO} or below ω_{LO}, it is translated to the same IF

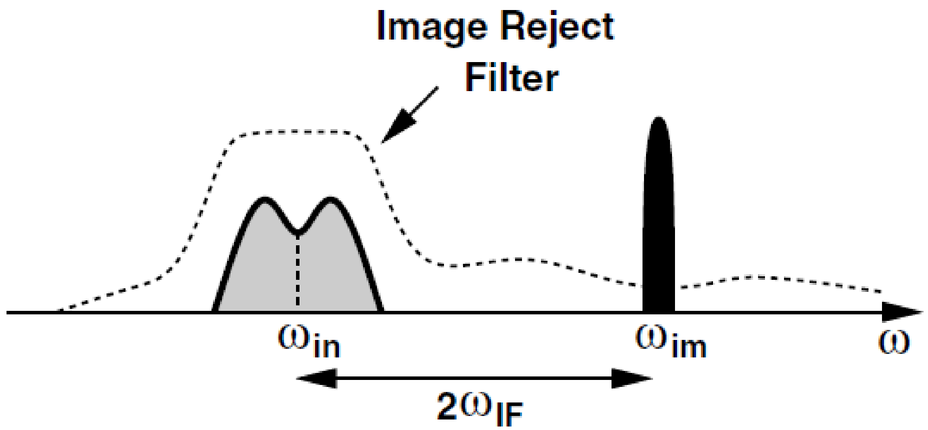


[B. Razavi, RF Microelectronics]

Image Rejection

- The most common approach is to precede the mixer with an "image-reject filter." The filter will be easy to design if $2\omega_{IF}$ is sufficiently large.

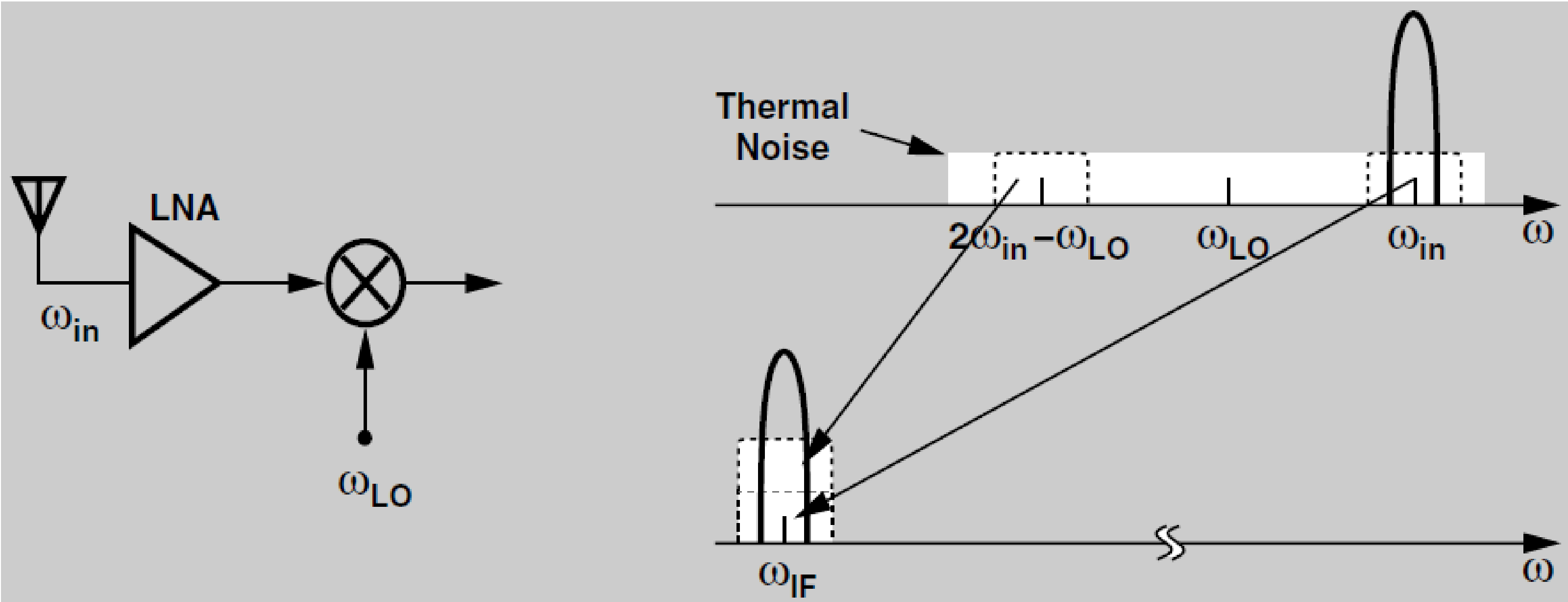




- ω_{IN}=2.4GHz, ω_{LO}=2GHz, ω_{IF}=400MHz → Easy, but power hungry
- ω_{IN}=2.4GHz, ω_{LO}=2.39GHz, ω_{IF}=10MHz → Difficult
- Can the image-reject filter be placed before the LNA?

[B. Razavi, RF Microelectronics]

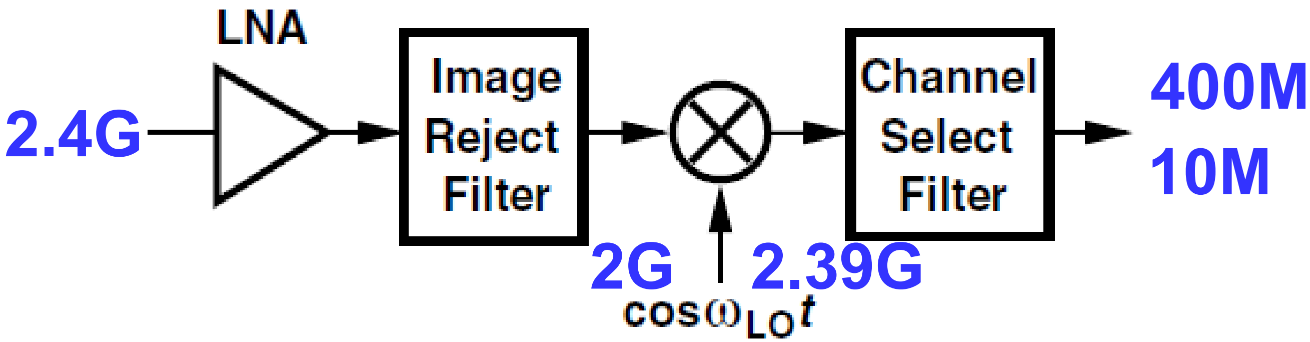
Image Noise



- ❑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.
- ❑An image-reject filter would remove the noise in the image band.

[B. Razavi, RF Microelectronics]

Image Rejection & Channel Selection

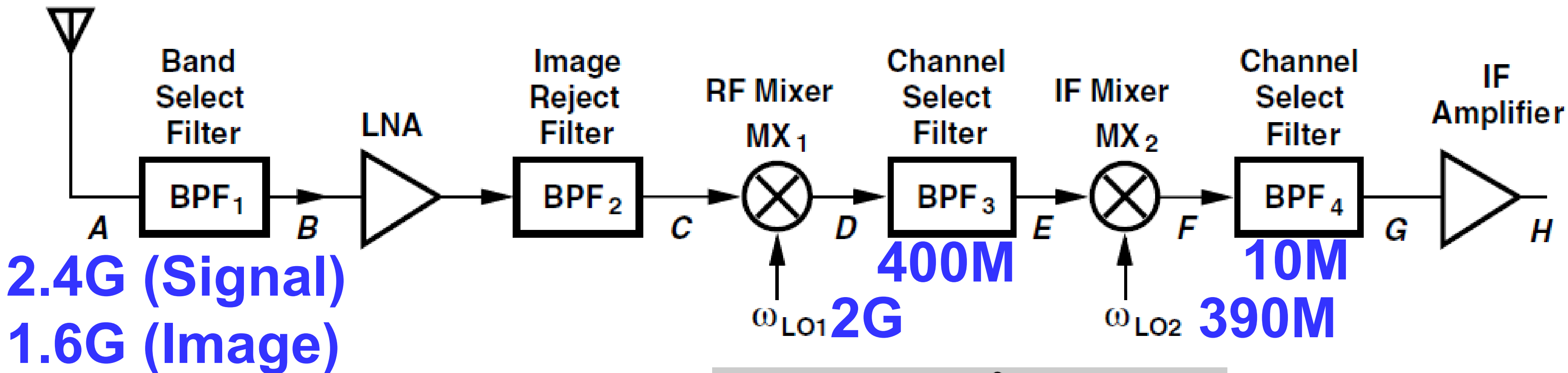


- ω_{IN}=2.4GHz, ω_{LO}=2GHz, ω_{IF}=400MHz
- ω_{IN}=2.4GHz, ω_{LO}=2.39GHz, ω_{IF}=10MHz

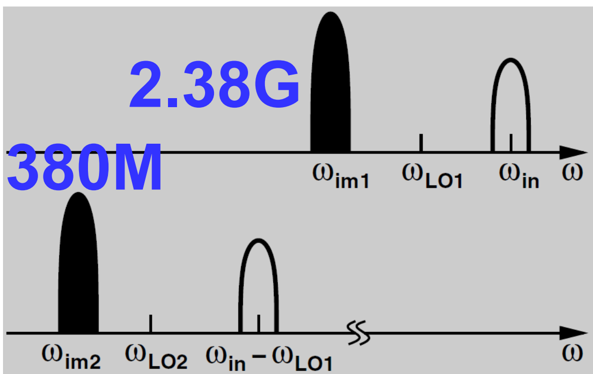
[B. Razavi, RF Microelectronics]

Dual Downconversion

❑The trade-off between image rejection and channel selection proves quite severe, so we can introduce the dual-IF architecture, where each stage is followed by filtering and amplification:



❑Note that the second downconversion may also entail an image called the "secondary image" here



[B. Razavi, RF Microelectronics]

Mixing Spurs

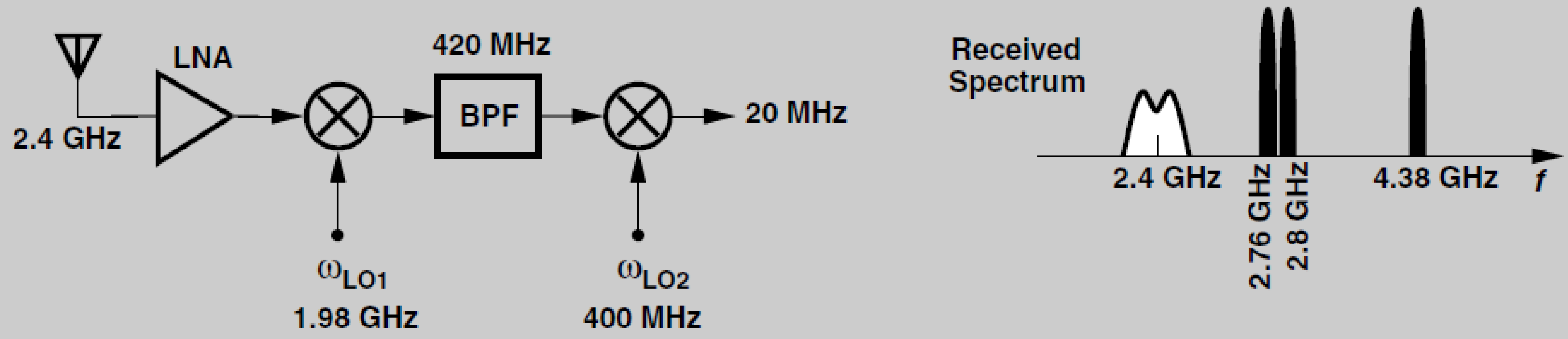
- In real designs, the mixers multiply the RF input by a square-wave LO even if the LO signal applied to the mixer is a sinusoid. We must therefore view mixing as multiplication of the RF input by all harmonics of the LO: $\omega_{in} \pm m\omega_{LO1} \pm n\omega_{LO2}$, where m and n are integers.
- For the desired signal, of course, only $\omega_{in}-\omega_{LO1}-\omega_{LO2}$ is of interest. But if an interferer, ω_{int}, is downconverted to the same IF, it corrupts the signal; this occurs if

$$\omega_{int} \pm m\omega_{LO1} \pm n\omega_{LO2} = \omega_{in} - \omega_{LO1} - \omega_{LO2}$$

- Called "mixing spurs," such interferers require careful attention to the choice of the LO frequencies.

[B. Razavi, RF Microelectronics]

Mixing Spurs

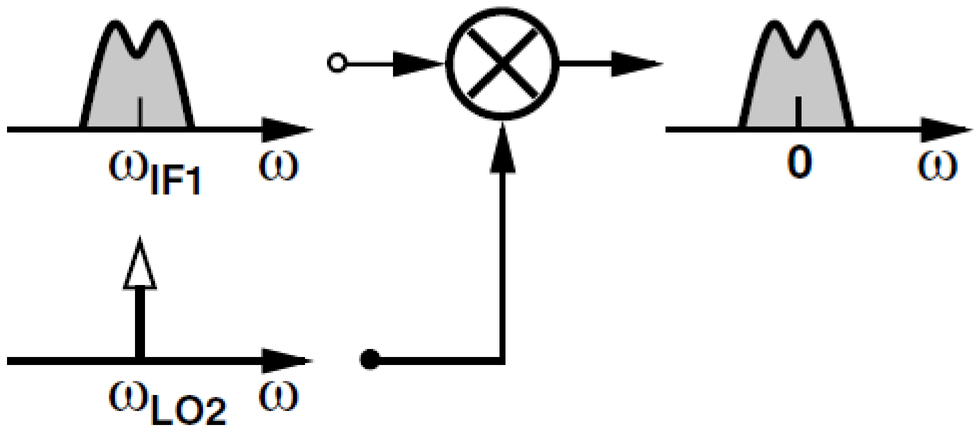


❑Let us consider the second harmonic of LO_2, 800 MHz. If an interferer appears at the first IF at 820MHz or 780 MHz, then it coincides with the desired signal at the second IF. In the RF band, the former corresponds to 820MHz+1980MHz=2.8GHz and the latter arises from 780MHz+1980MHz=2.76GHz. We can also identify the image corresponding to the second harmonic of LO_1 by writing f_{in}-$2f_{LO1}$-f_{LO2}=20MHz and hence f_{in}=4.38GHz.

[B. Razavi, RF Microelectronics]

Zero Second IF

- To avoid the secondary image, most modern heterodyne receivers employ a zero second IF. The idea is to place ω_{LO2} at the center of the first IF signal so that the output of the second mixer contains the desired channel with a zero center frequency. In this case, the image is the signal itself, i.e., the left part of the signal spectrum is the image of the right part and vice versa.

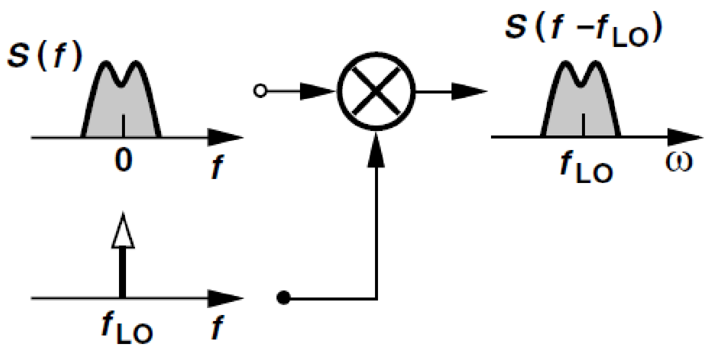


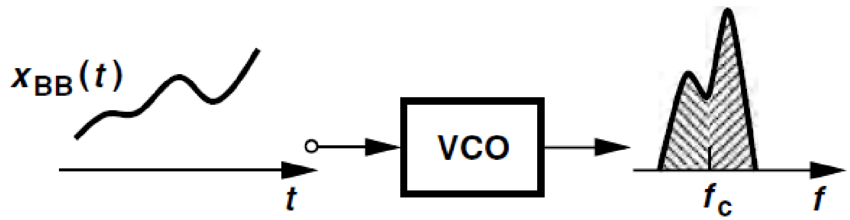
[B. Razavi, RF Microelectronics]

Self Image

❑To understand this effect, we must distinguish between "symmetrically-modulated" and "asymmetrically-modulated" signals.

❑AM signals are symmetric, while PM signals are asymmetric:

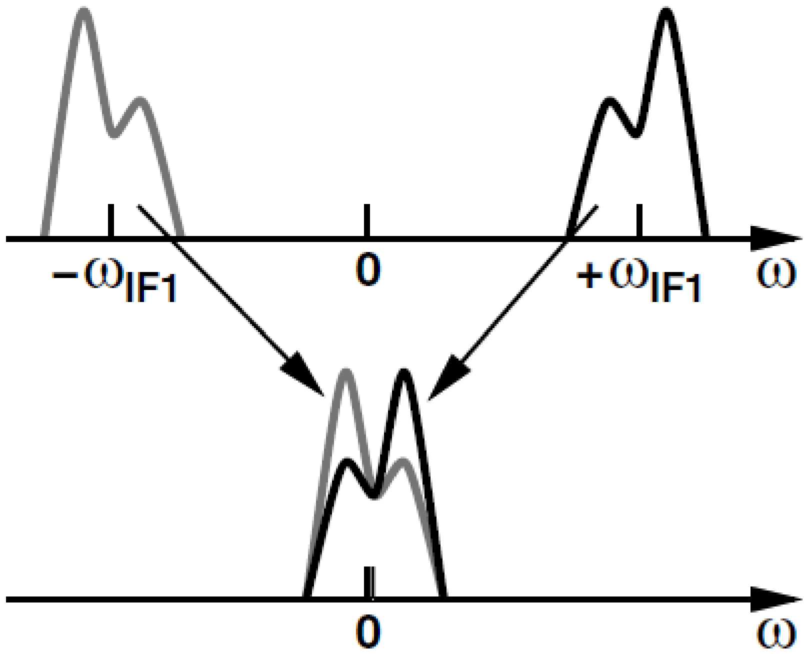




[B. Razavi, RF Microelectronics]

Self Image

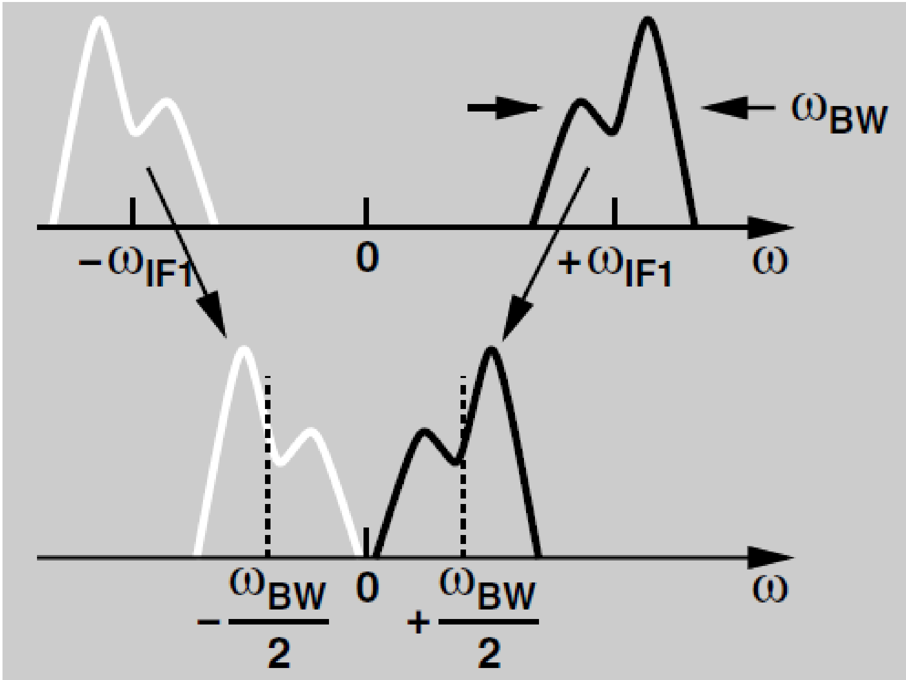
- For an asymmetric signal, downconversion to a zero IF superimposes two copies of the signal, thereby causing corruption if the signal spectrum is asymmetric.



[B. Razavi, RF Microelectronics]

Solution#1: Low IF

❑To avoid self-corruption, the downconverted spectra must not overlap each other. The signal can be downconverted to an IF equal to half of the signal bandwidth.

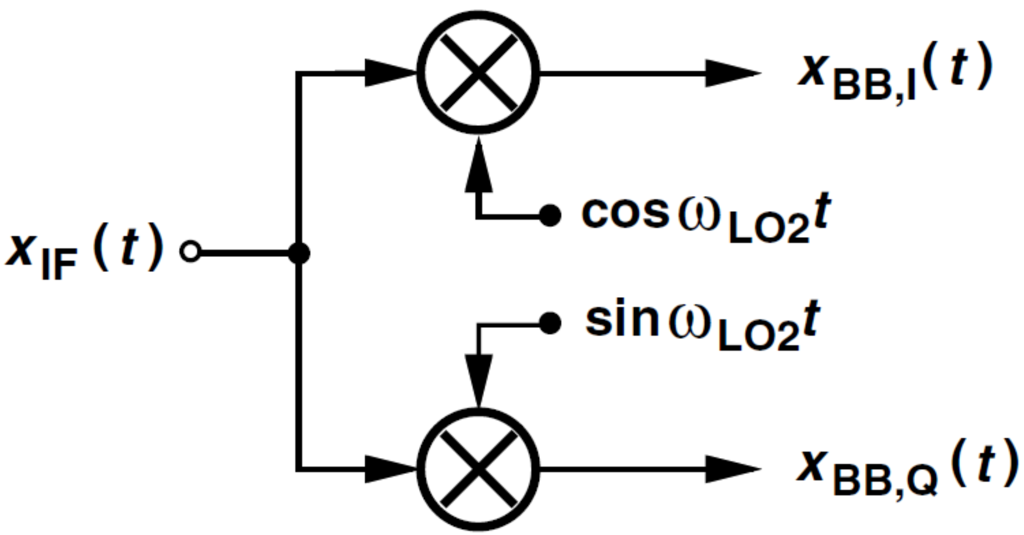


[B. Razavi, RF Microelectronics]

Solution#2: I/Q Conversion

❑To avoid self-corruption in downconversion, we can creat two versions of the downconverted signal that have a phase difference of 90 degrees.

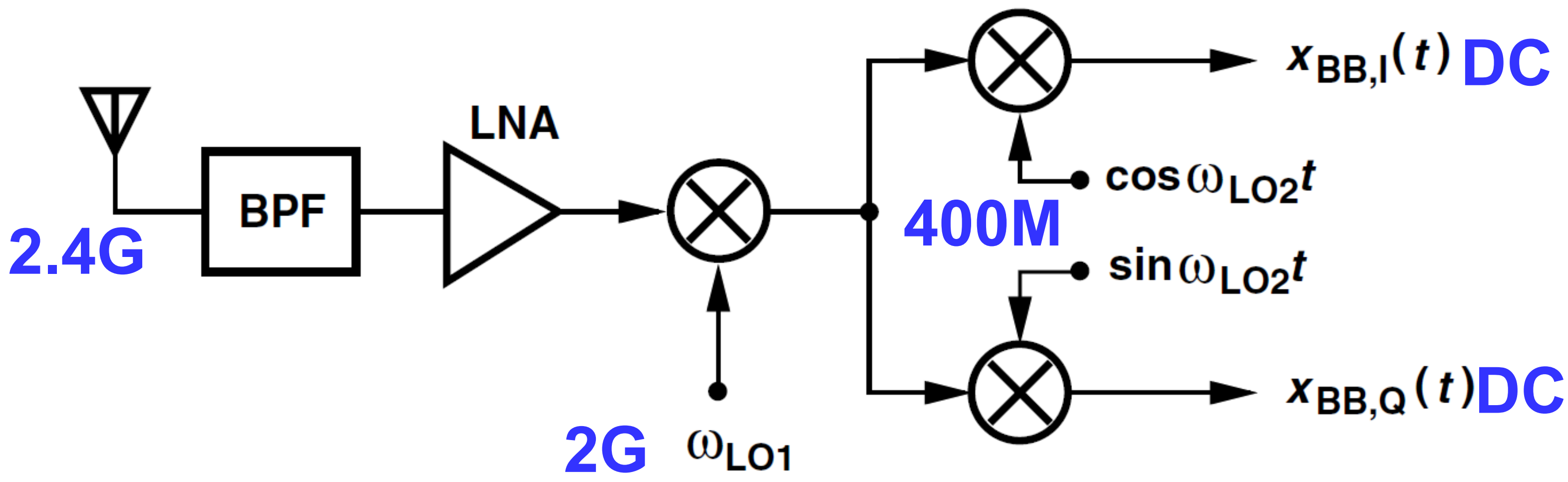
❑"quadrature downconversion" is performed by mixing the RF signal with the quadrature phases of the LO.



❑Though exhibiting identical spectra, the two baseband signals are separated in phase and together can reconstruct the original information.

[B. Razavi, RF Microelectronics]

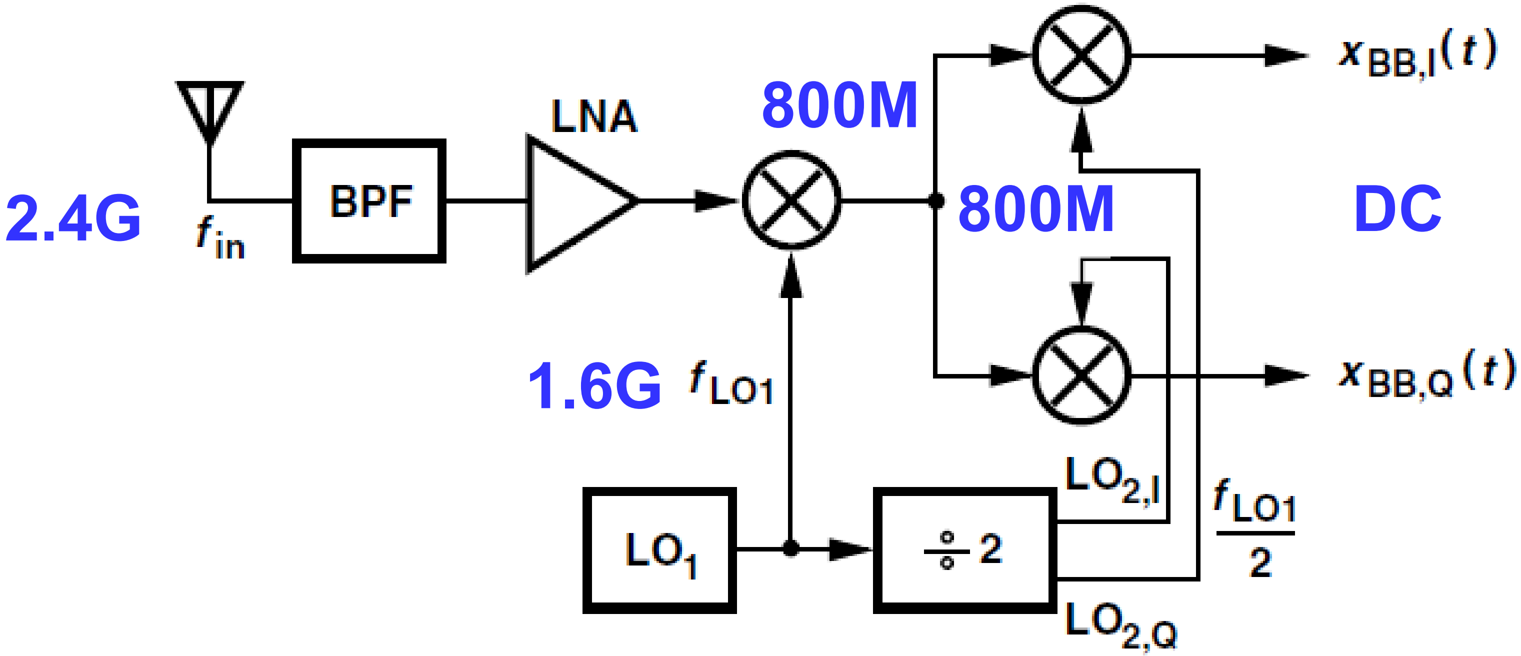
Heterodyne Receiver



- The receiver incorporates a narrow-band LNA design so that the thermal noise of the antenna and the LNA in the image band is heavily suppressed.
- Two LO frequencies are needed.

[B. Razavi, RF Microelectronics]

Slide-IF Heterodyne RX



- ❑Only 1 oscillator/PLL is required, reducing the power consumption.
- ❑Oscillators fabricated on the same chip suffer from unwanted coupling.

[B. Razavi, RF Microelectronics]

Summary of Heterodyne RX

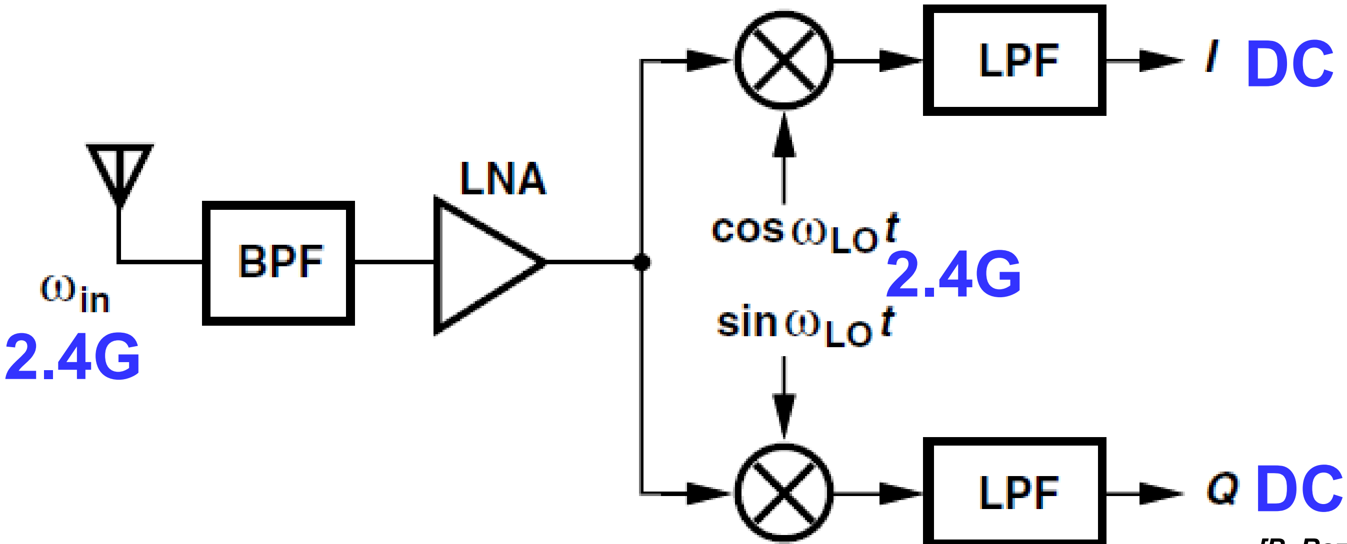
- ❑High performance (widely used in testing instruments) ☺
- ❑High power consumption (high IF) ☹
- ❑RF filter requirement (usually off-chip) ☹
- ❑Problem of Image (image interferer or noise, image filter trades with channel-selection filter) ☹
- ❑Mixing Spurs ☹

[B. Razavi, RF Microelectronics]

Direct-Conversion RX

❑In heterodyne receivers, why the RF signals are not simply translated to DC in the downconversion?

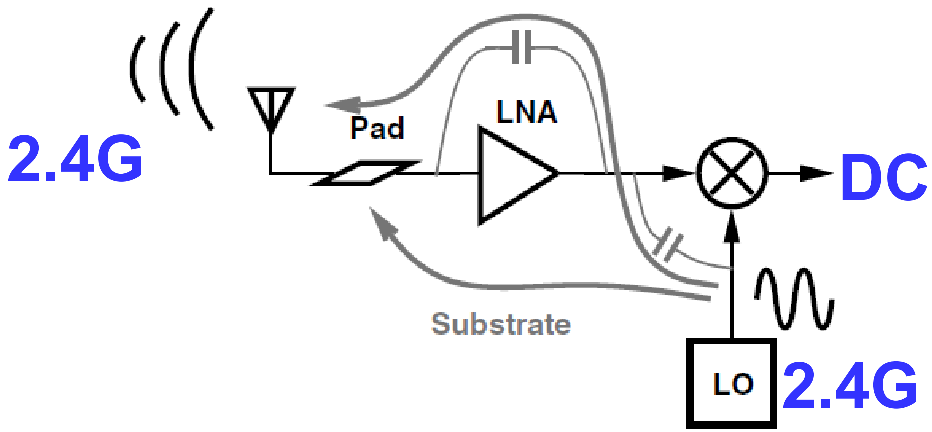
❑Downconversion of an asymmetrically-modulated signal to a zero IF leads to self-corruption unless the baseband signals are separated by their phases



[B. Razavi, RF Microelectronics]

LO Leakage in Direct-Conversion RX

- ❑A direct-conversion receiver emits a fraction of its LO power from its antenna through two paths:
  - ✓ Device capacitances
  - ✓ The substrate to the input pad

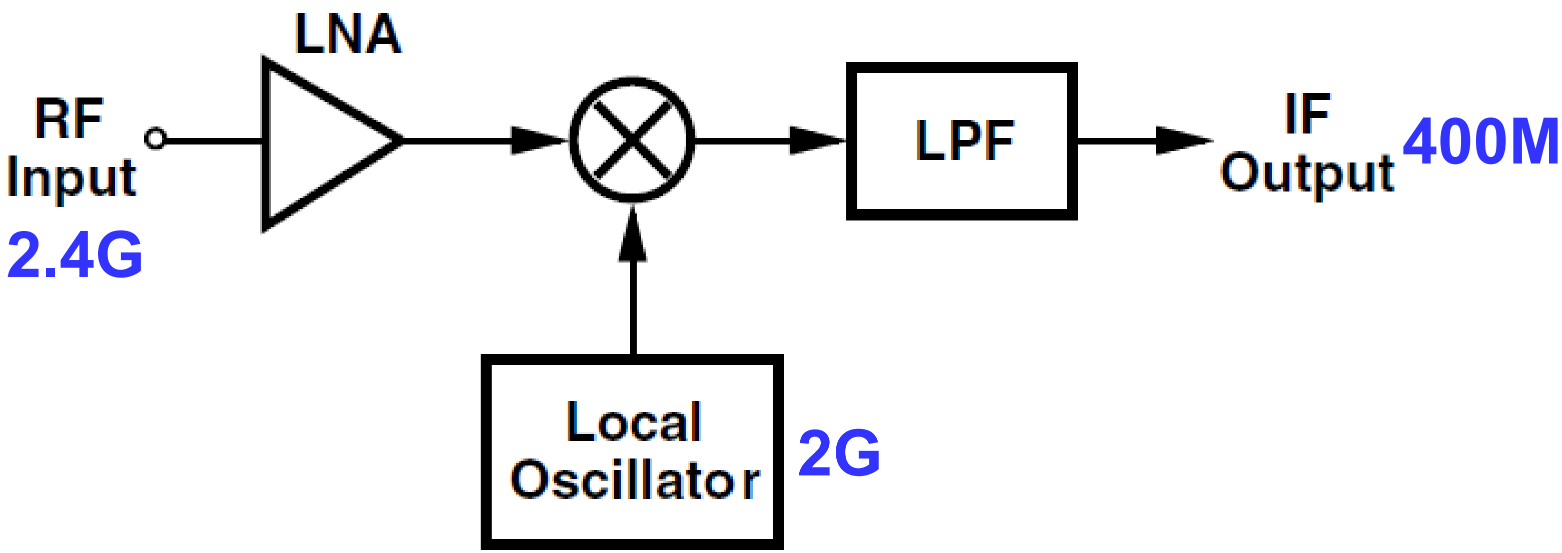


- ❑The LO emission is undesirable because it may desensitize other receivers operating in the same band.

[B. Razavi, RF Microelectronics]

LO Leakage in Hyterodyne RX

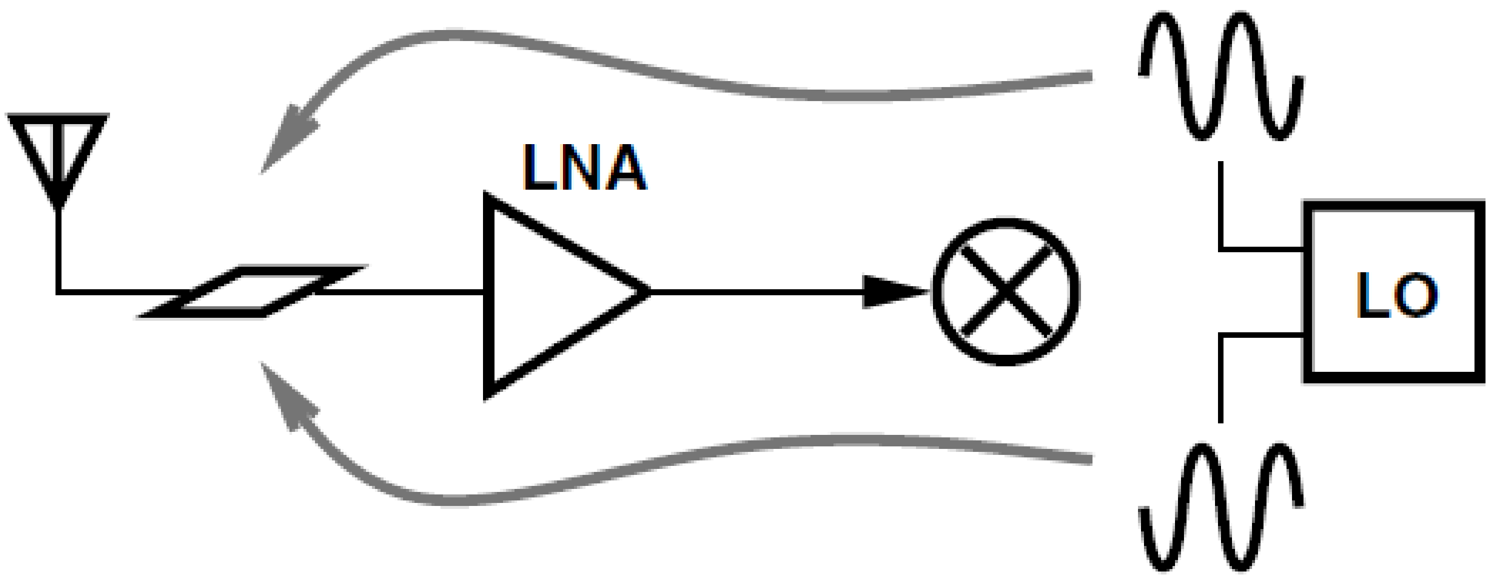
- In heterodyne receivers, the LO frequency falls outside the band, it is suppressed by the front-end band-select filters in both the emitting receiver and the victim receiver.



[B. Razavi, RF Microelectronics]

LO Leakage Cancellation

- LO leakage can be minimized through symmetric layout of the oscillator and the RF signal path.

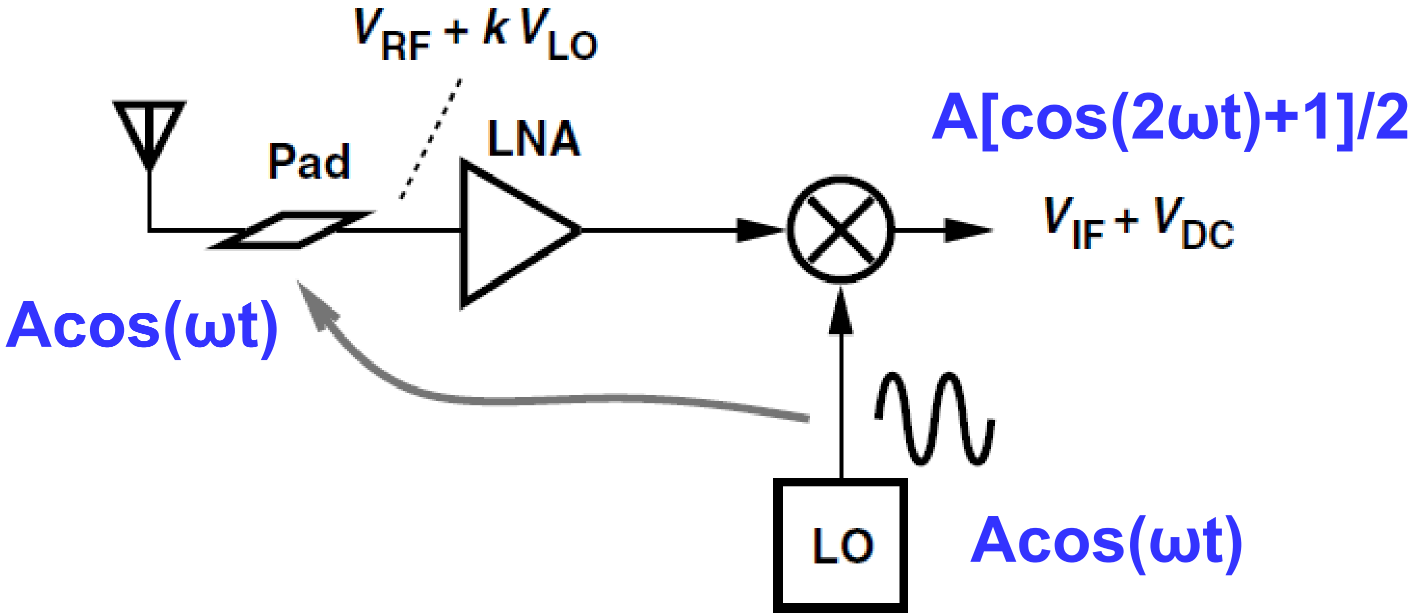


[B. Razavi, RF Microelectronics]

DC Offset

❑The LO leakage phenomenon studied above also gives rise to relatively large dc offsets in the baseband.

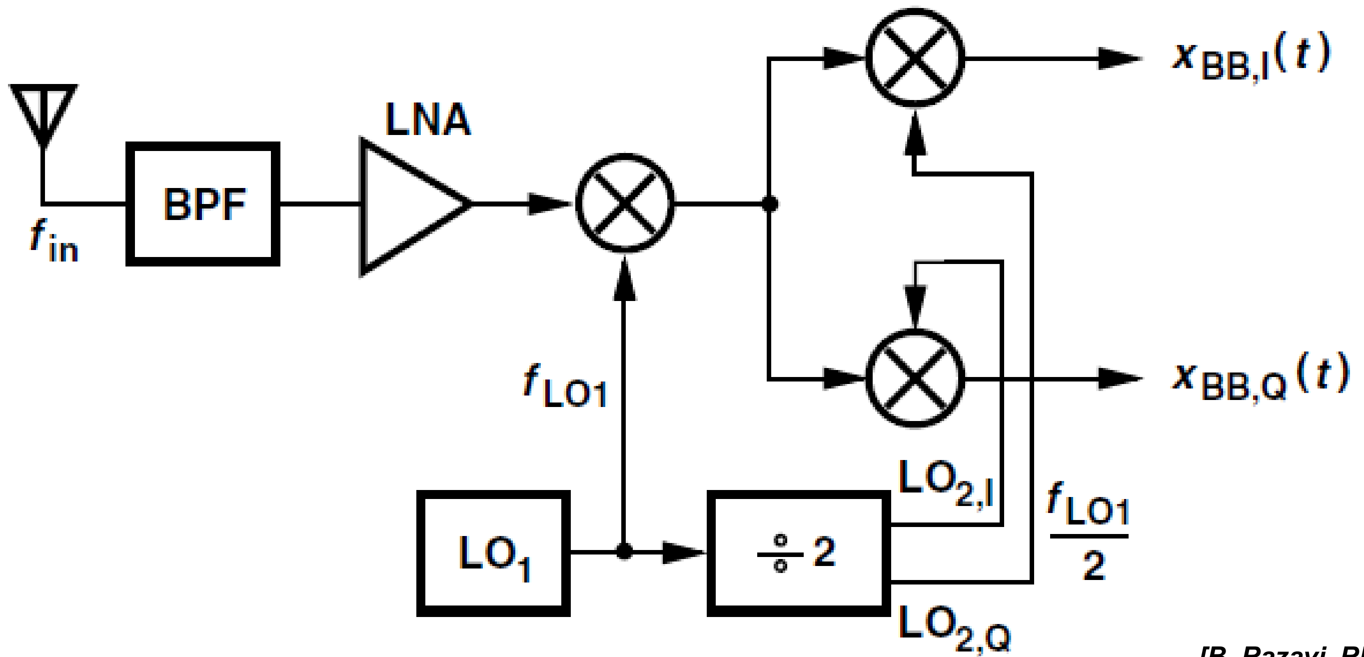
❑This effect produces a DC component in the baseband because multiplying a sinusoid by itself results in a DC term.



[B. Razavi, RF Microelectronics]

DC Offset in Heterodyne RX

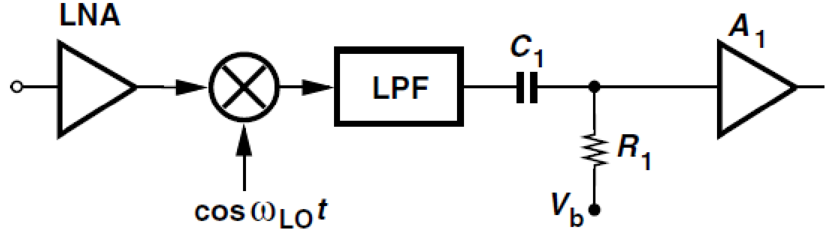
- The leakage of the second LO to the input of the IF mixers produces DC offsets in the baseband.
- Since the second LO frequency is lower, the leakage is smaller than that in direct-conversion receivers.

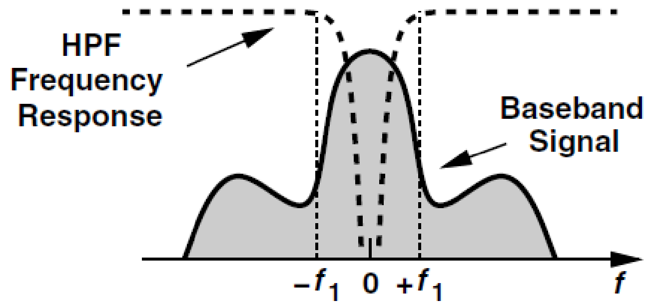


[B. Razavi, RF Microelectronics]

High-Pass Filter

- A high-pass filter can remove a fraction of the signal's spectrum near zero frequency:



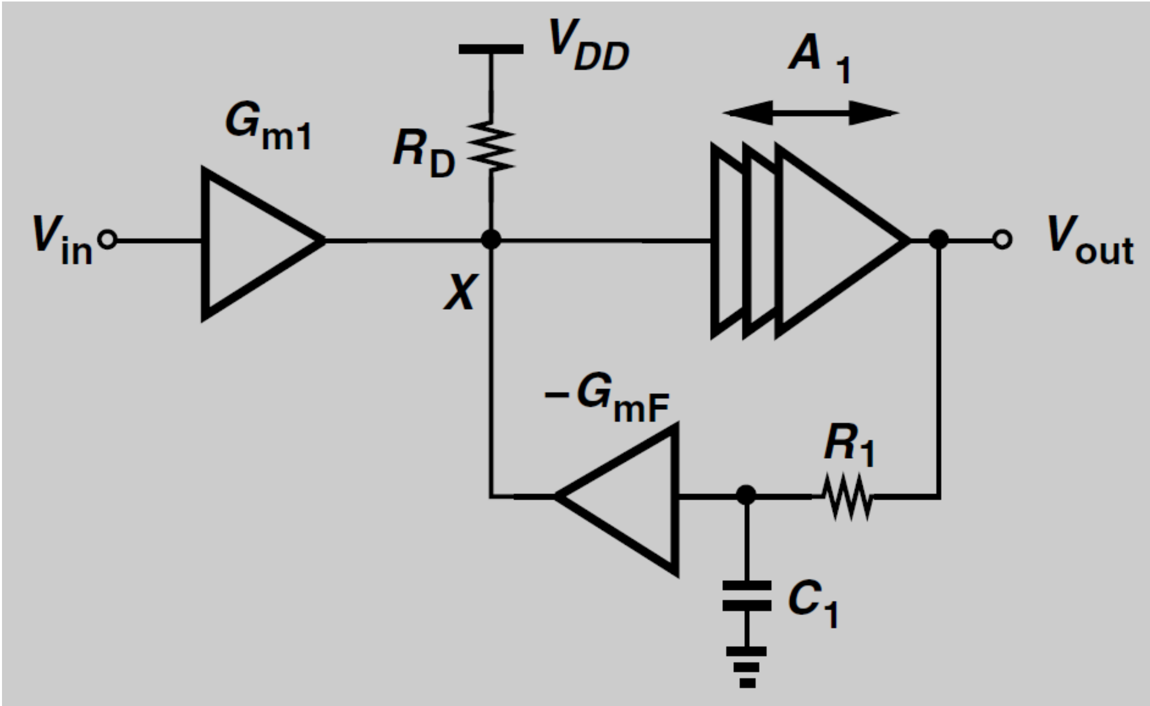


- A fraction of the signal's spectrum near zero frequency is removed, thereby introducing intersymbol interference
- A large capacitor is required for a low/moderate data rate (271 kb/s in GSM necessitates a corner frequency of roughly 20–30 Hz and hence extremely large capacitors and/or resistors)
- Slow response due to the large RC

[B. Razavi, RF Microelectronics]

Low-Pass Feedback

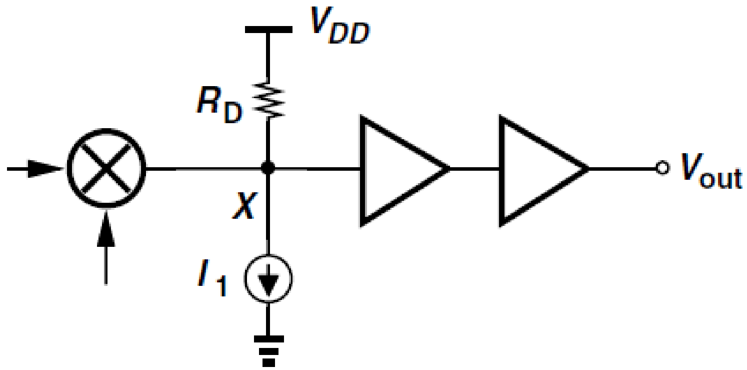
❑A low-pass filter can be set in the feedback path to cancel the DC offset:

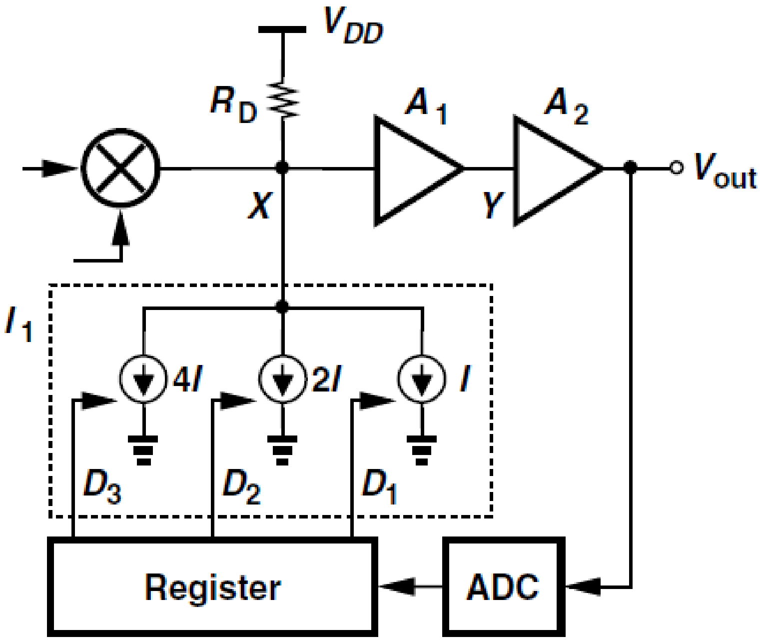


❑This feedback circuit requires greater values for R_1 and C_1 to provide a low f_1

[B. Razavi, RF Microelectronics]

DAC Based Cancellation





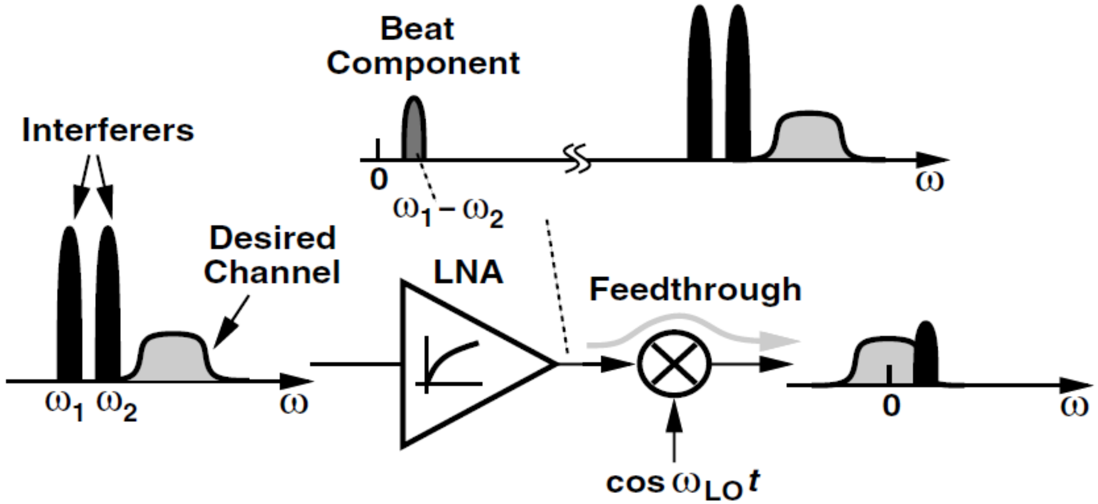
❑A current is drawn from node X to drive the DC content in V_{OUT} to zero.

❑The current is decomposed into units that are turned on or off according to the values stored in the register. These current sources form a DAC.

[B. Razavi, RF Microelectronics]

Even-Order Distortion

❑Direct-conversion receivers are additionally sensitive to even-order nonlinearity in the RF path



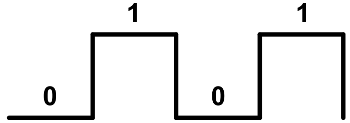
❑The second-order term yields the product of these two interferers and hence a low-frequency "beat" at ω_1-ω_2.

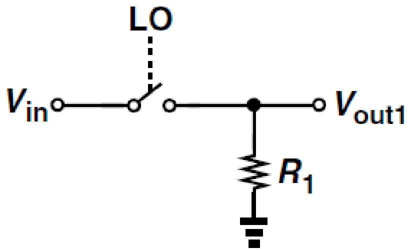
❑A fraction of the low-frequency beat appears in the baseband, thereby corrupting the downconverted signal.

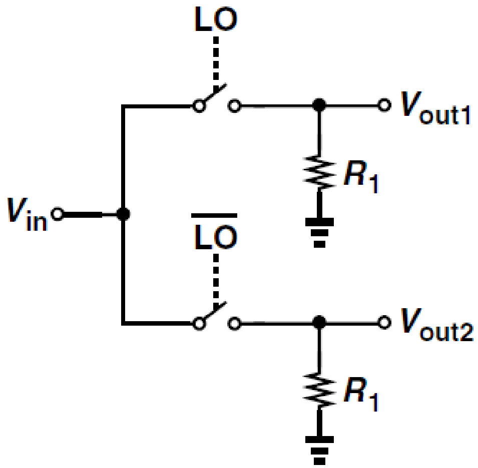
[B. Razavi, RF Microelectronics]

Cancellation by Differential Mixer

❑The DC offset induced by even-order distortion can be cancelled by a mixer with differential output (a square-wave toggling between 0 and 1 with 50% duty cycle):

S(t) 





$$V_{out}(t) = V_{in}(t) \cdot S(t)$$
$$= V_{in}(t)\left[S(t) - \frac{1}{2}\right] + V_{in}(t) \cdot \frac{1}{2}$$

$$V_{out1}(t) = V_{in}(t)S(t)$$
$$V_{out2}(t) = V_{in}(t)[1 - S(t)]$$

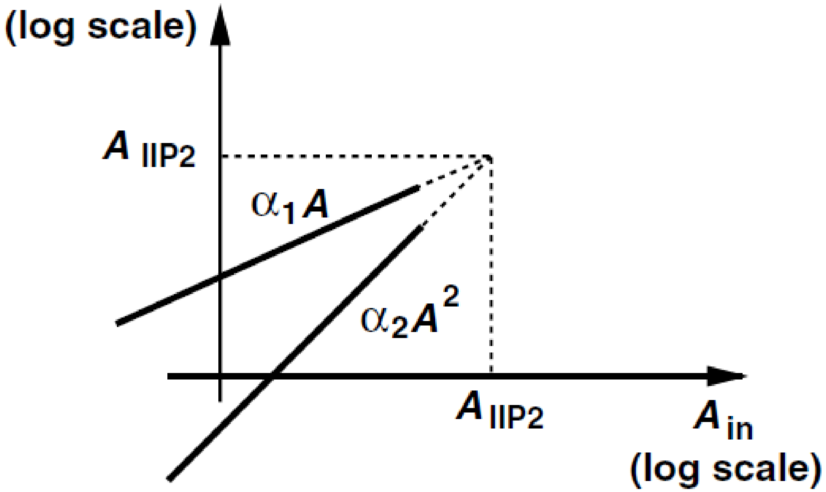
❑If the output is sensed differentially, the RF feedthroughs in $V_{out1}(t)$ and $V_{out2}(t)$ are cancelled while the signal components add. It is this cancellation that is sensitive to asymmetries

[B. Razavi, RF Microelectronics]

Second Intercept Point (IP2)

❑A two-tone test is conducted similar to that for IP3:

$$V_{in}(t) = A\cos\omega_1 t + A\cos\omega_2 t$$



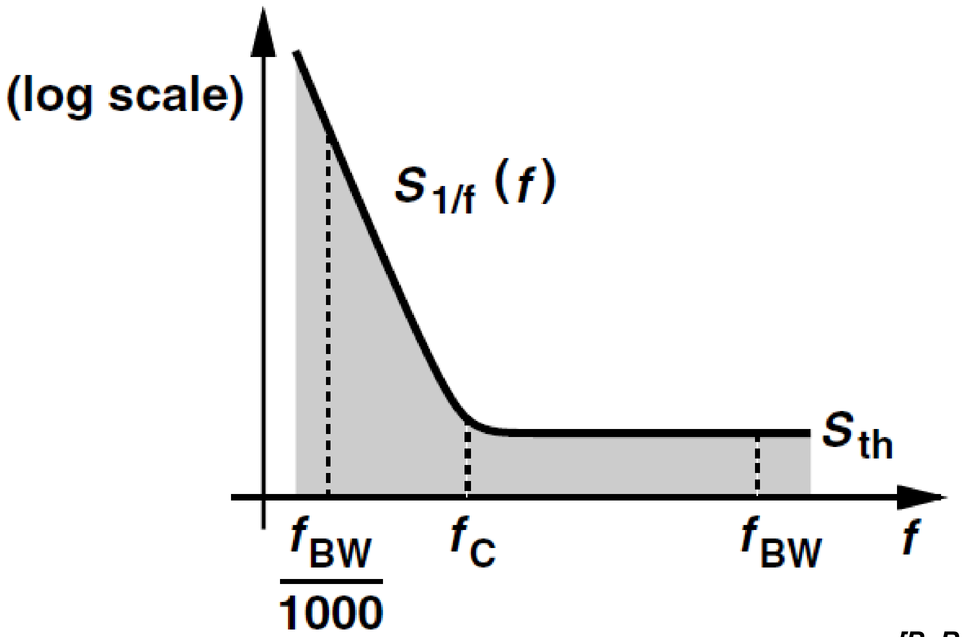
❑The beat amplitude rises with a slope of 2 on a log scale.

❑Since the net feedthrough of the beat depends on the mixer and LO asymmetries, the beat amplitude measured in the baseband depends on the device dimensions and the layout.

[B. Razavi, RF Microelectronics]

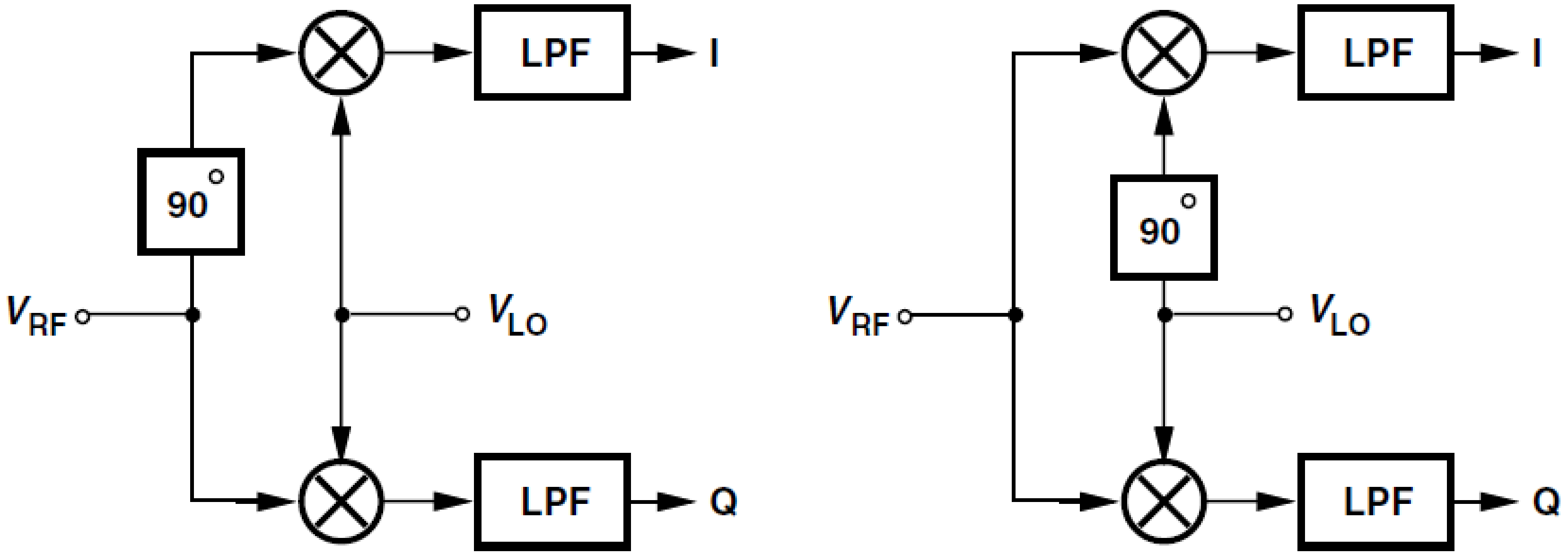
Flicker Noise

❑The downconverted signal in a direct-conversion receiver is still relatively small and hence susceptible to noise in the baseband circuits. Furthermore, since the signal is centered around zero frequency, it can be substantially corrupted by flicker noise.



[B. Razavi, RF Microelectronics]

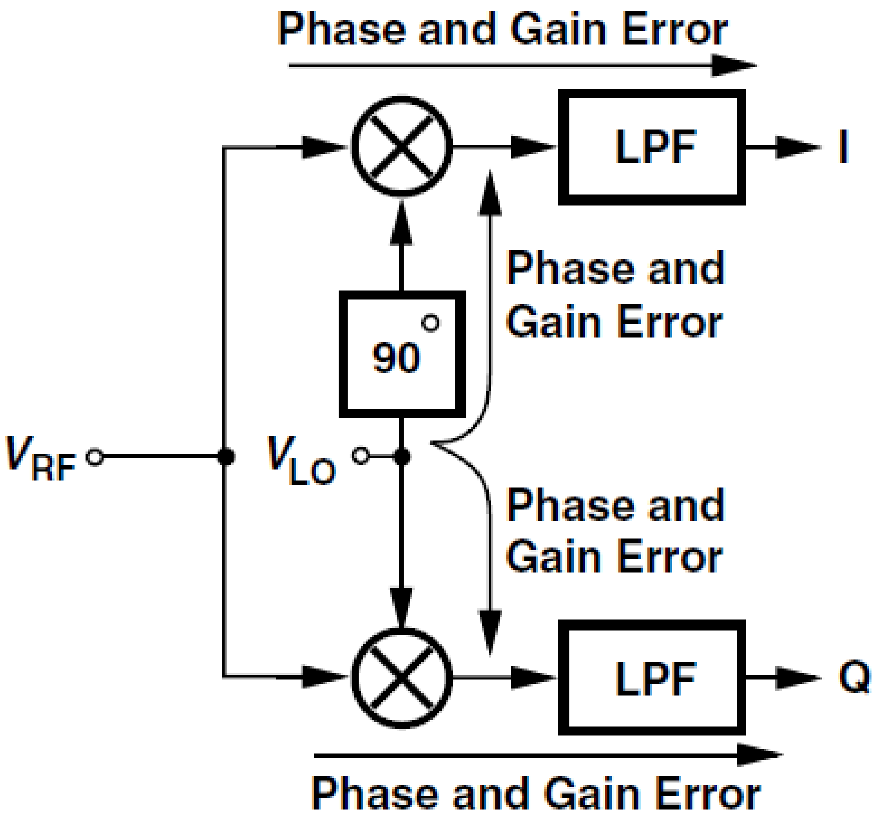
Downconvert



❑**Downconversion of an asymmetrically modulated signal to a zero IF requires separation into quadrature phases. This can be accomplished by shifting either the RF signal or the LO waveform by 90 Degrees. Which one is better?**

[B. Razavi, RF Microelectronics]

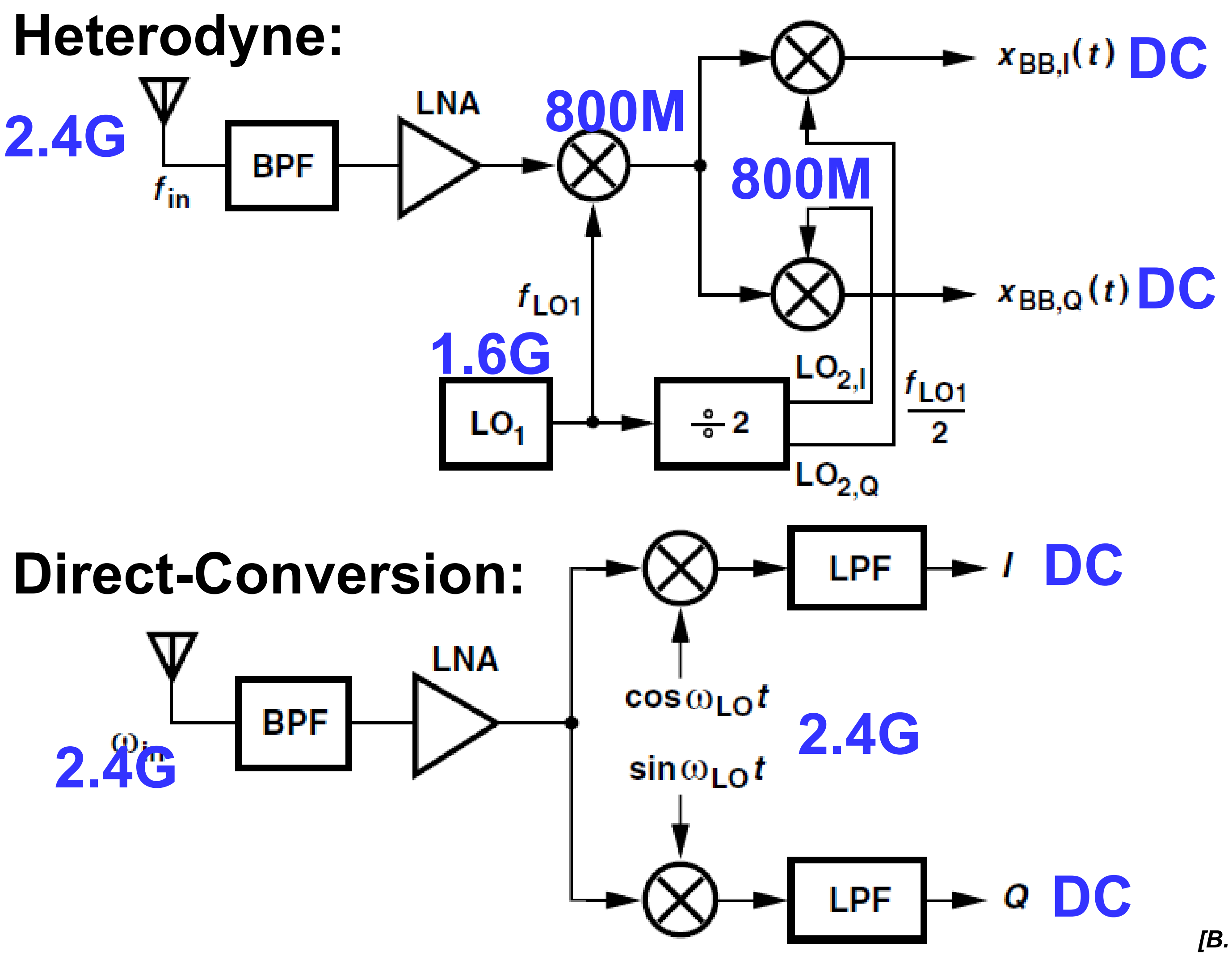
I/Q Mismatch



- **Errors in the 90-degree phase shift circuit and mismatches between the quadrature mixers result in imbalances in the amplitudes and phases of the baseband I and Q outputs.**
- **The baseband stages themselves may also contribute significant gain and phase mismatches.**

[B. Razavi, RF Microelectronics]

Mixing Spurs



[B. Razavi, RF Microelectronics]

Mixing Spurs

- Unlike heterodyne systems, direct-conversion receivers rarely encounter corruption by mixing spurs. This is because, for an input frequency f_1 to fall in the baseband after experiencing mixing with nf_{LO}, we must have $f_1 \approx nf_{LO}$. Since f_{LO} is equal to the desired channel frequency, f_1 lies far from the band of interest and is greatly suppressed by the selectivity of the antenna, the band-select filter, and the LNA.
- The issue of LO harmonics does manifest itself if the receiver is designed for a wide frequency band (greater than two octaves). Examples include TV tuners, "software-defined radios".

[B. Razavi, RF Microelectronics]

Summary of Direct-Conversion RX

❑Low power (IF=DC) ☺

❑No RF filter (low cost) ☺

❑No image interference (but there are image noise and self image issues) ☺

❑Rarely encounter mixing spurs ☺

❑LO leakage ☹

❑DC offset ☹

❑Even-order distortion ☹

❑Flicker noise ☹

❑I/Q mismatch ☹

[B. Razavi, RF Microelectronics]