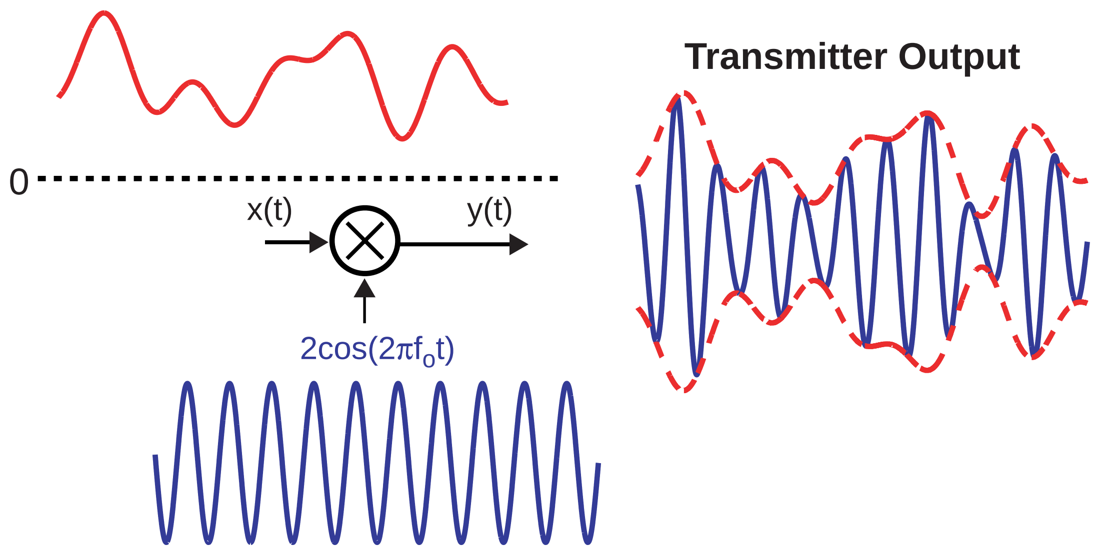
6.776
High Speed Communication Circuits
Lecture 2
Transceiver Architectures

Massachusetts Institute of Technology

February 3, 2005

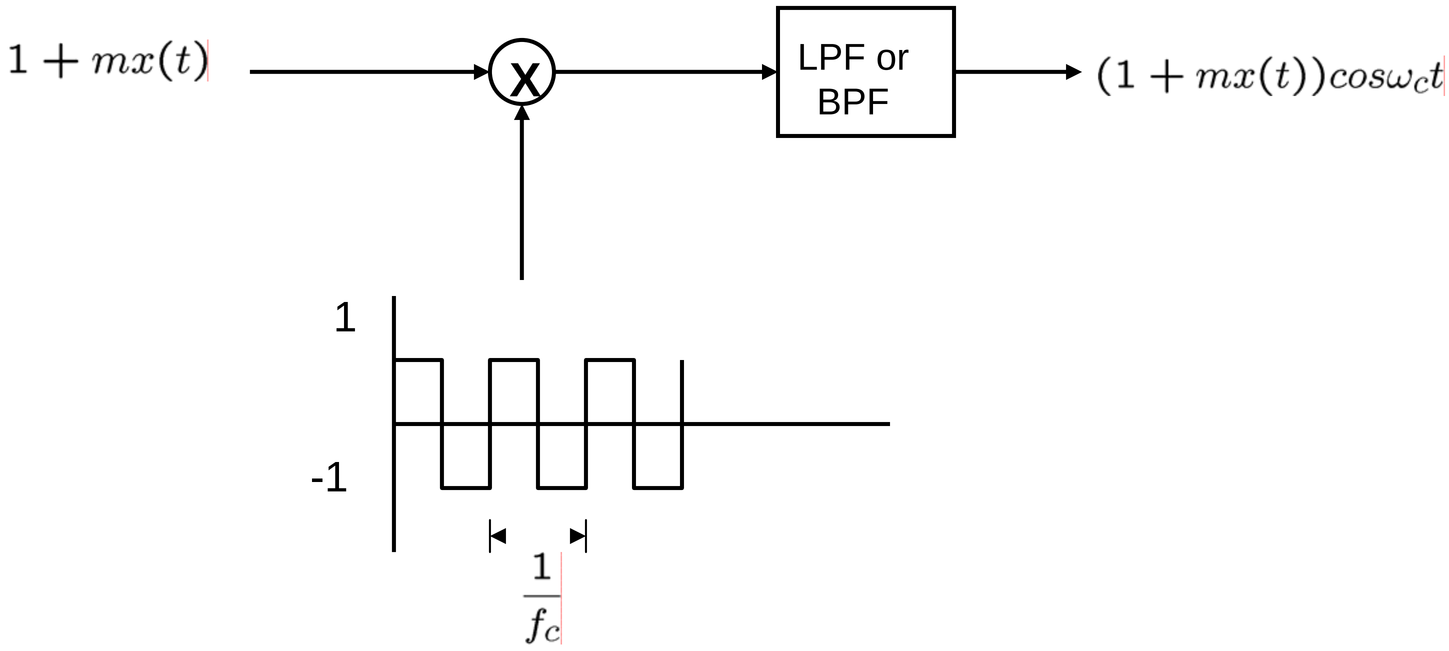
Transceivers for Amplitude Modulation

Amplitude Modulation Review

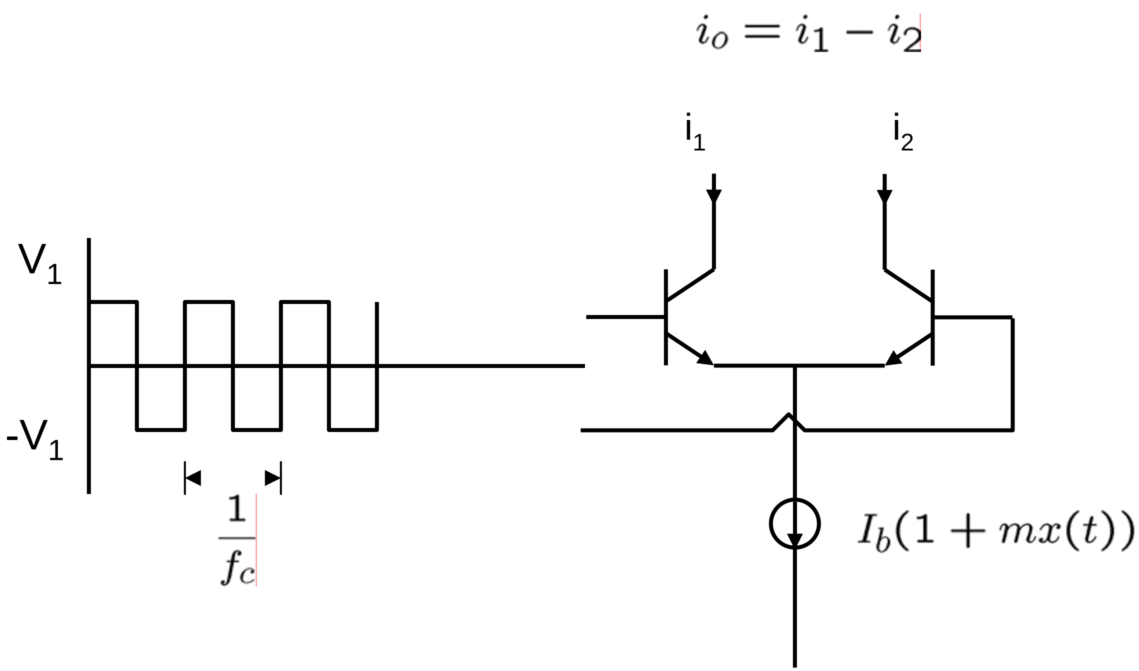


- **Vary the amplitude of a sine wave at carrier frequency f_o according to a baseband modulation signal** $x'(t) = (1 + mx(t))$
- **DC component of baseband modulation signal influences transmit signal and receiver possibilities**
  - **DC value greater than signal amplitude shown above**
    - Allows simple envelope detector for receiver
    - Creates spurious tone at carrier frequency (wasted power)

Amplitude Modulation: Switching Modulator

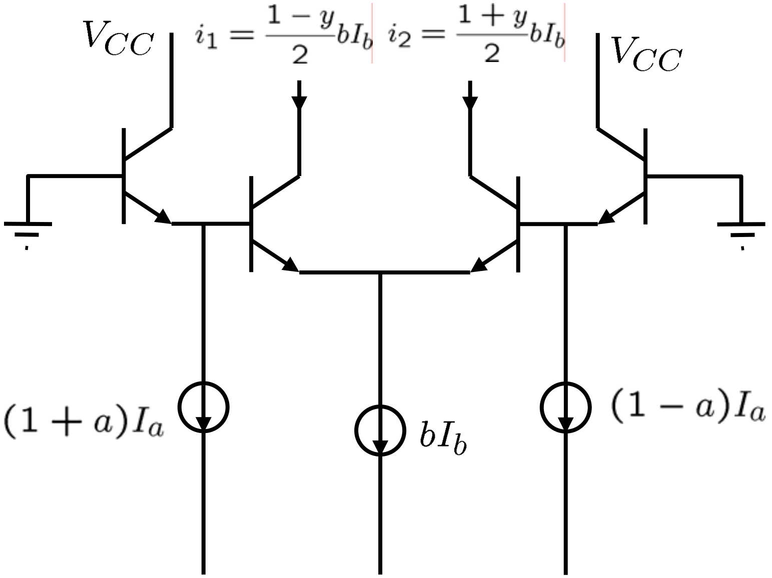


Switching Modulator Example



For full switching $V_1 >> \frac{kT}{q}$

Amplitude Modulation – Gilbert Multiplier



$$(1+a)I_a\frac{1-y}{2}bI_b = (1-a)I_a\frac{1+y}{2}bI_b$$

$$(1+a-y-ay)bI_aI_b = (1-a+y-ay)bI_aI_b$$

$$y = a$$

$$i_o = i_2 - i_1 = ybI_b = abI_b$$

$$b > 0, -1 < a < 1$$

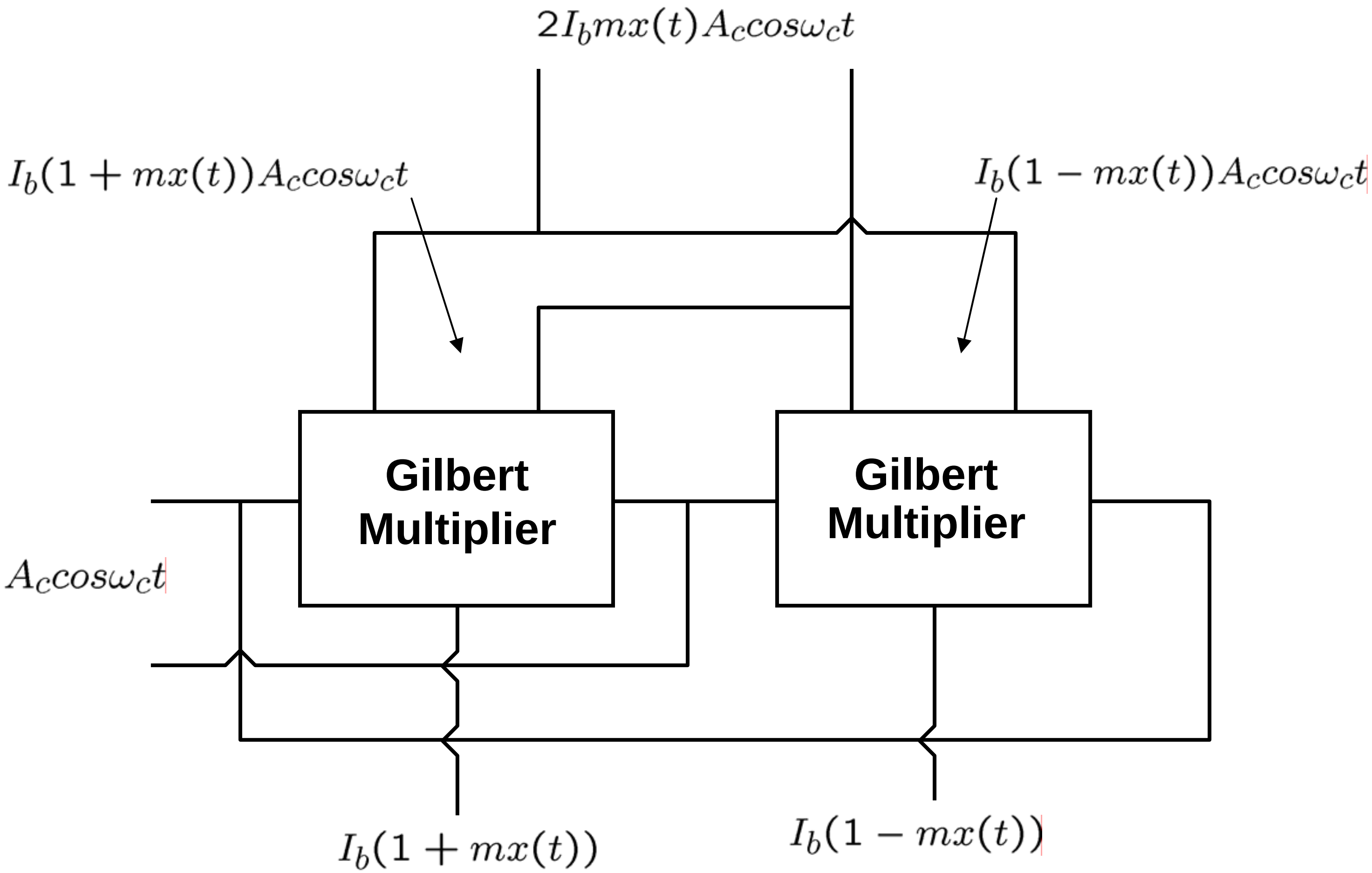
$$a = A_c cos\omega_c t,\ \ b = 1 + mx(t)$$

$$i_o = I_b(1 + mx(t))A_c cos\omega_c t$$

Since b must be positive, the resulting output is AM

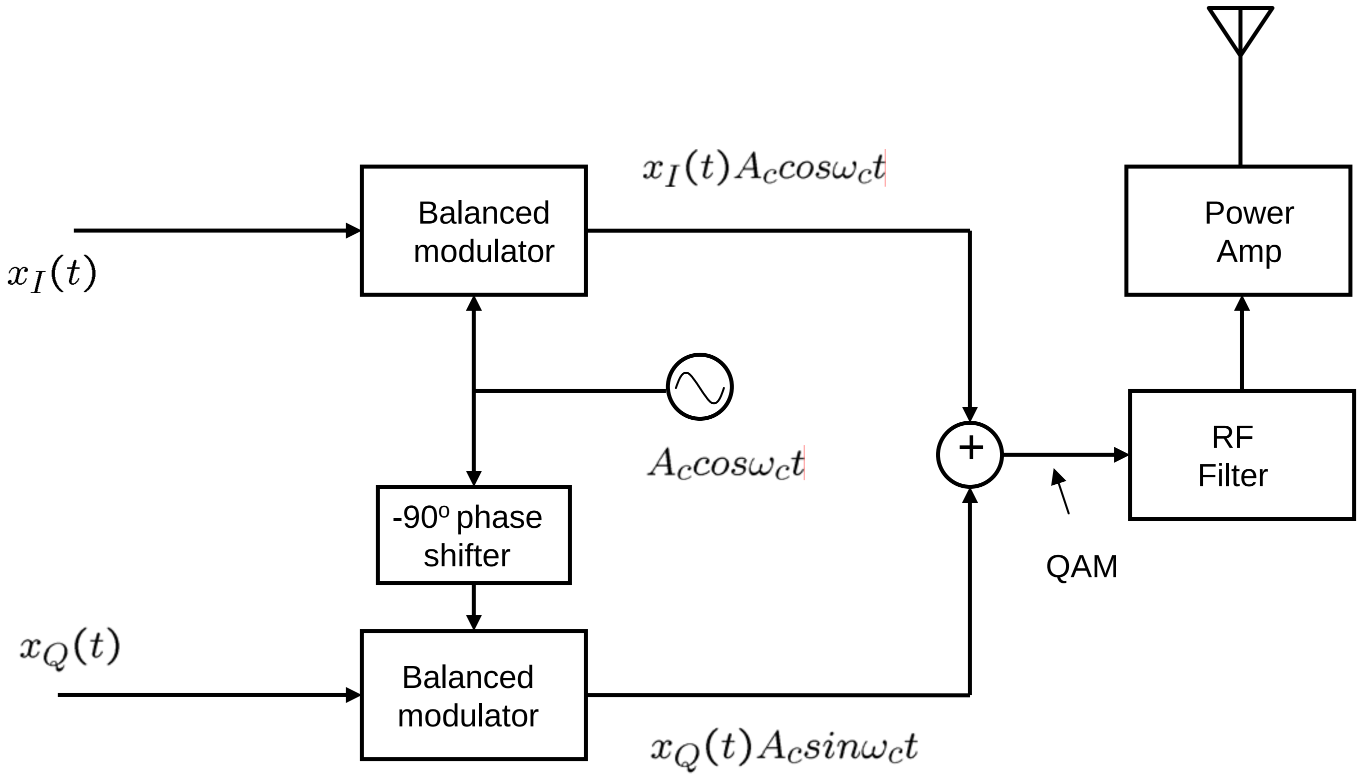
- **Advantage: low harmonics, output filter does not have to be very selective**
- **Disadvantage: higher DC power**

DSB Transmitter: Balanced Modulator



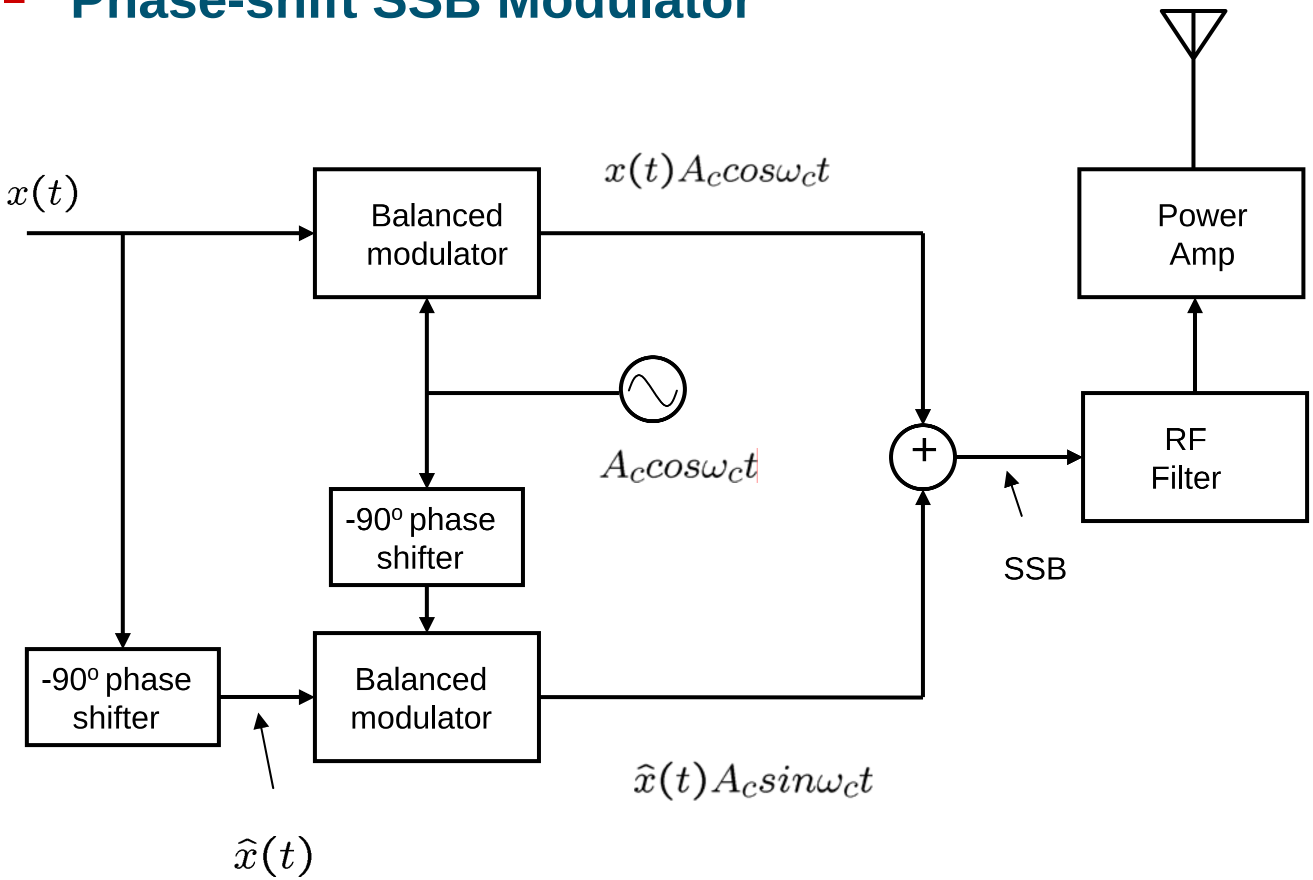
- Carrier component is removed
- Improves modulation linearity (2nd harmonic distortion is cancelled)

QAM Transmitter



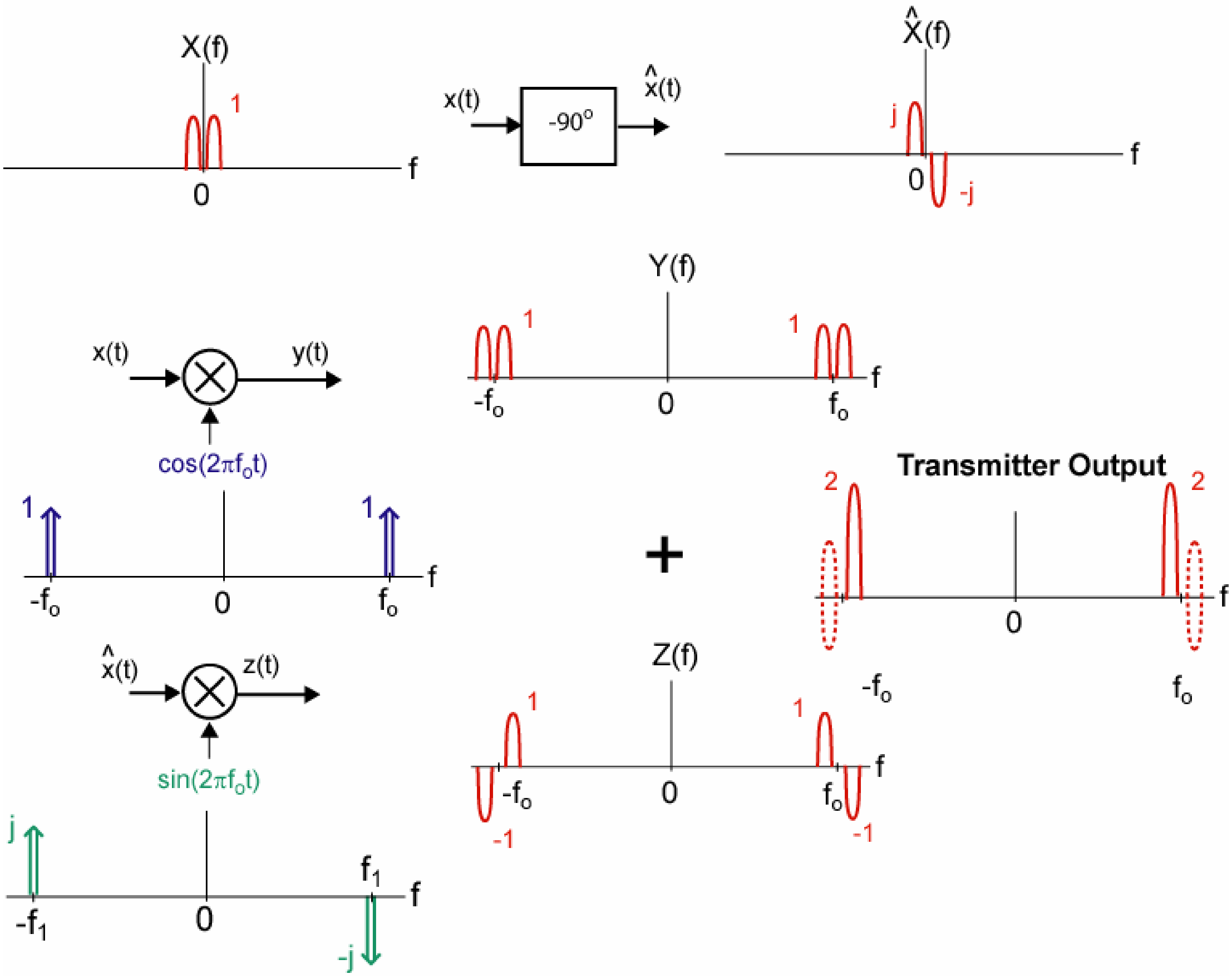
SSB Transmitter I

- **Phase-shift SSB Modulator**



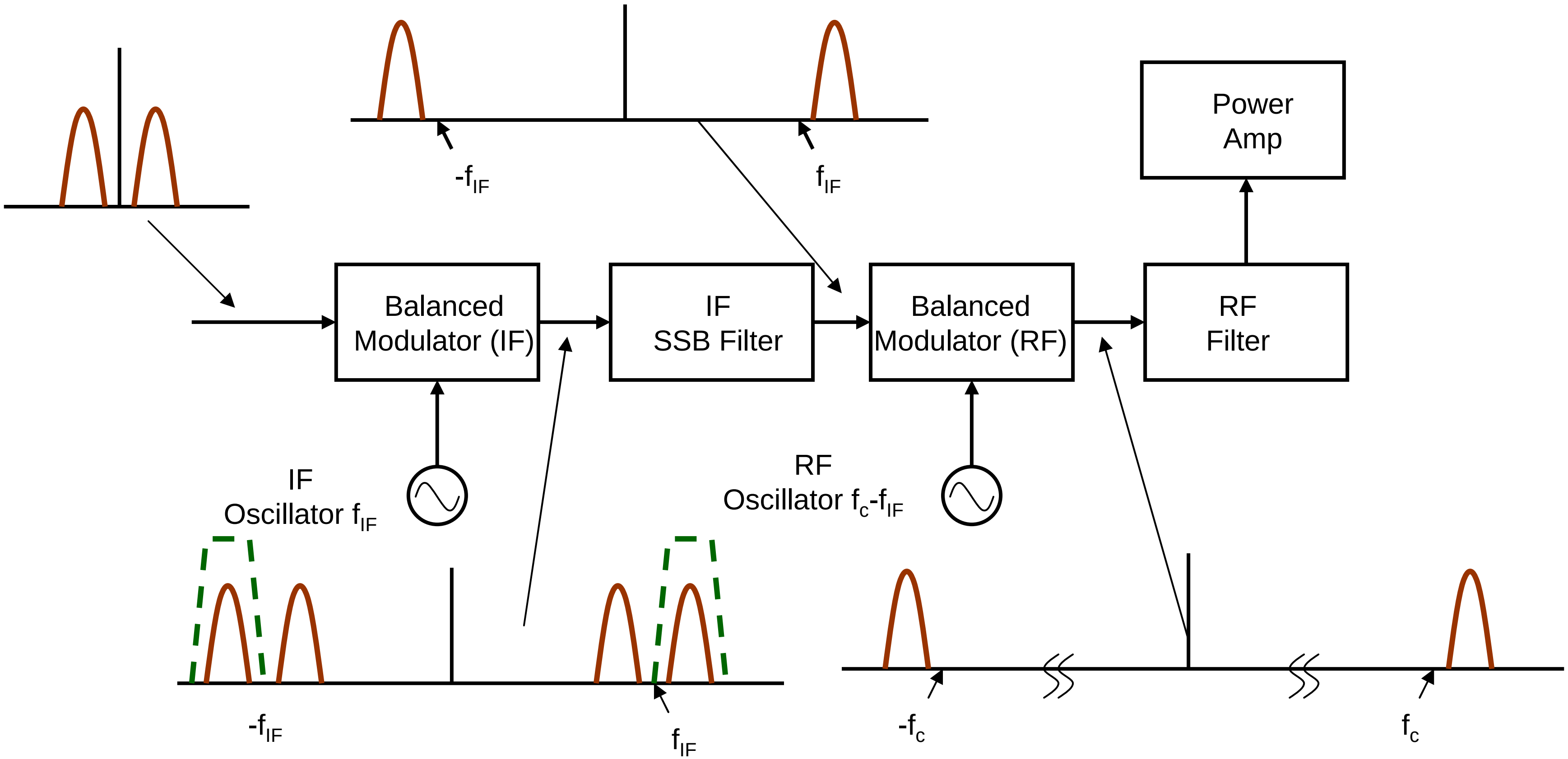
- **Sideband removal depends on phase and amplitude matching**

Frequency Domain View of Phase-Shift SSB Modulator



SSB Transmitter II

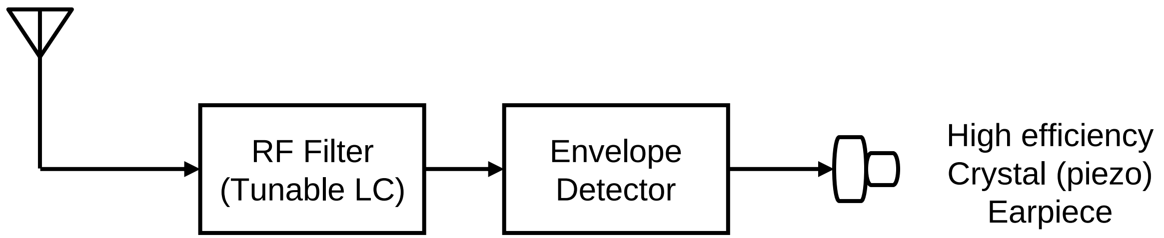
- **Heterodyne SSB Modulator**



Heterodyne Transmitter

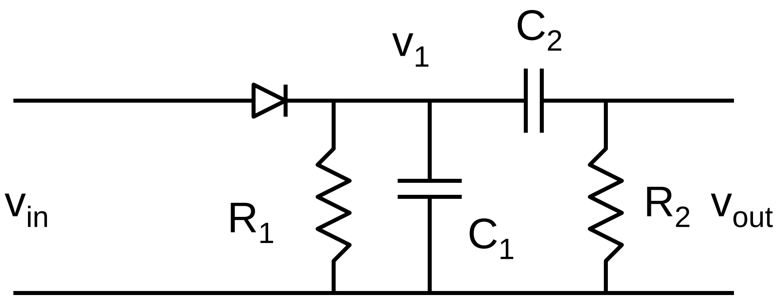
- **Sideband filtering requires high selectivity**
- **Sideband filtering is thus easier at lower IF frequency than at RF freqeuency (for example, at IF frequencies, SAW filters offer very high selectivity, low insertion loss, and low noise figure. They are relatively cheap, too)**
- **Same issues apply to receivers (not just for SSB receiever for that matter). 'Superheterodyne' receivers have been dominant for decades for the same reason.**
- **Requires two oscillators**

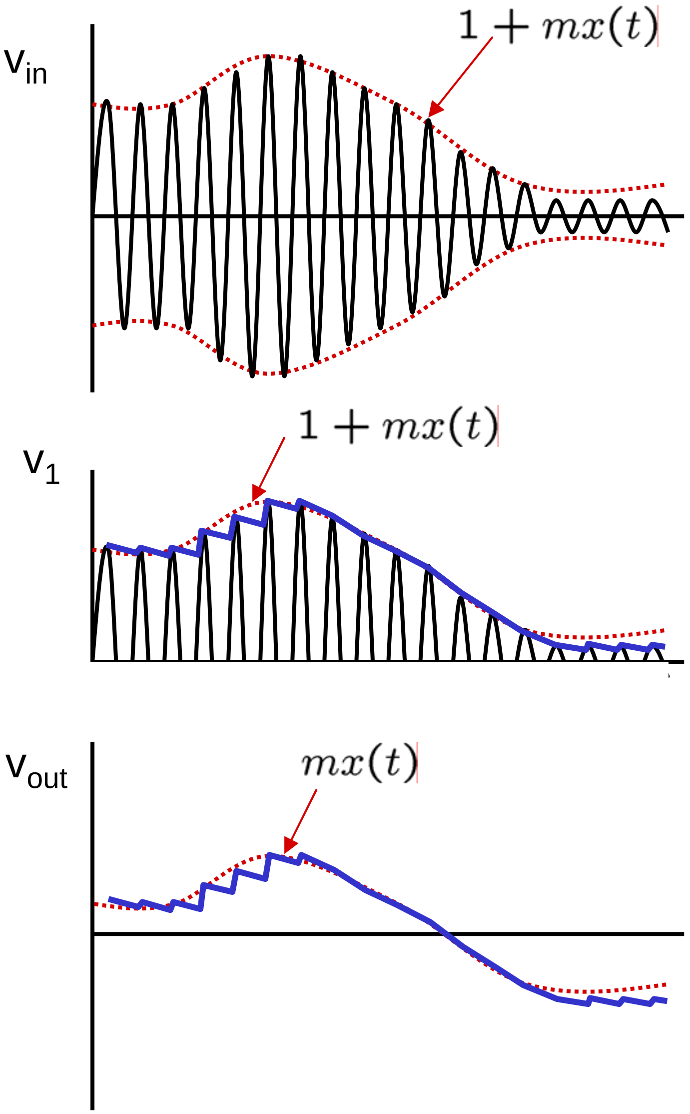
Rudimentary AM Receiver: Envelope Detector



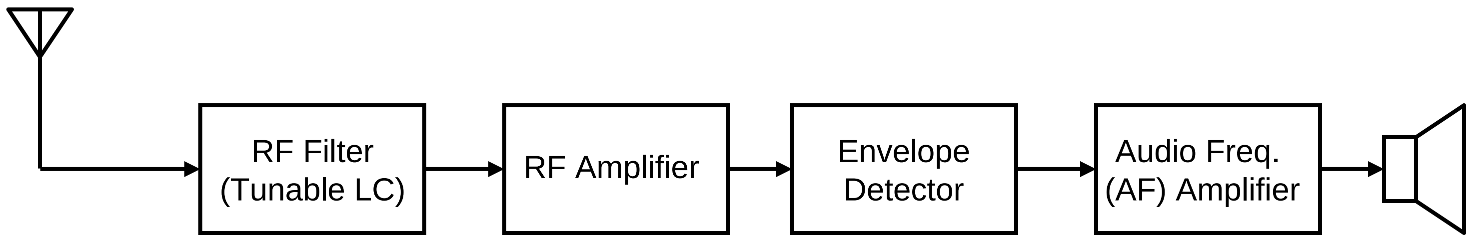
- **Applicable only to standard AM signals (DC shifted baseband)**
- **No active component: very simple and cheap**
- **Low sensitivity: only strong stations can be tuned in**
- **Poor selectivity (single RF filter)**
- **Low baseband output power: can only drive high efficiency crystal earpiece**

Envelope Detector Example



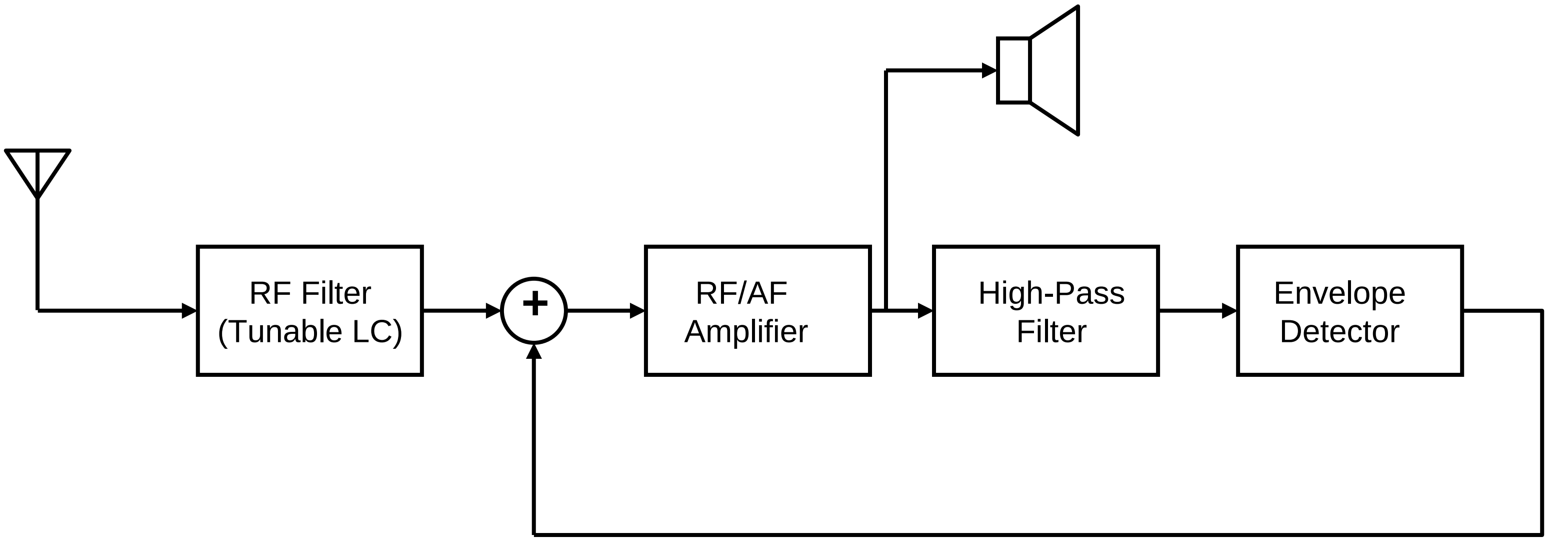


AM Receiver: Amplified Receiver



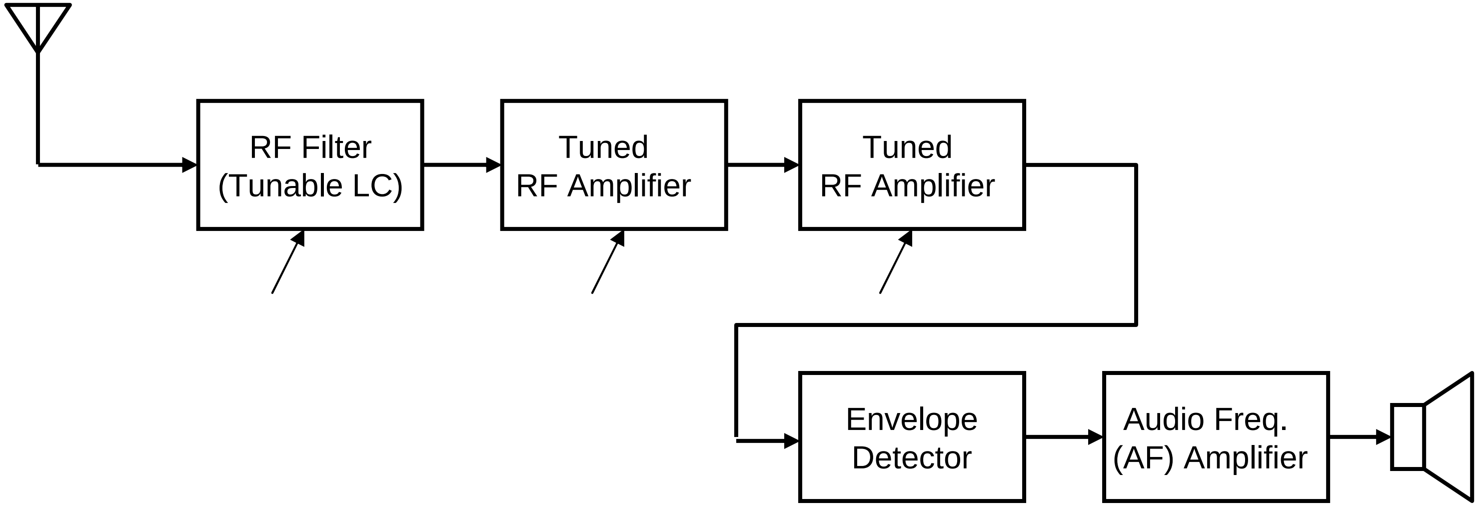
- **Better sensitivity (RF Amp)**
- **Can drive loudspeaker (AF Amp)**
- **RF selectivity is still an issue**
- **Expensive when active devices were very expensive (requires two active devices)**

Reflex Receiver



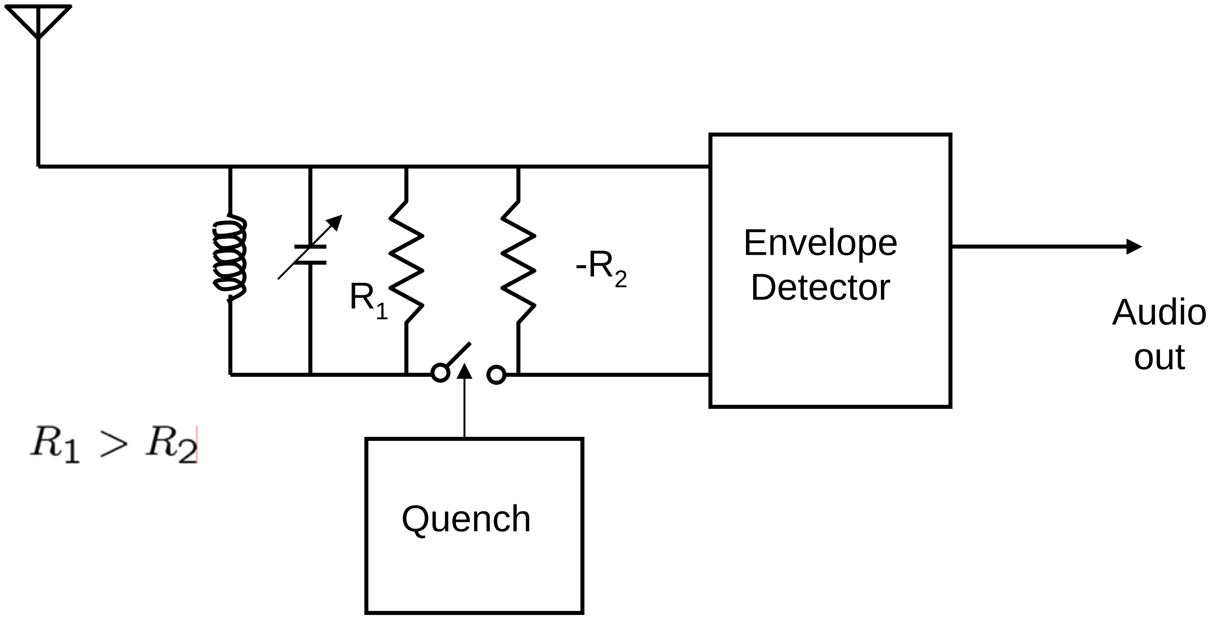
- **Same properties as amplified AM receiver**
- **Single active device amplifies both RF and AF signals**

Multi-Stage RF Amplified Receiver



- **High sensitivity (Multi-stage RF Amp)**
- **High selectivity is a necessity due to high amplification factor: high-Q tuned circuits**
- **Separate tuning of each stage by trial and error (very tedious)**

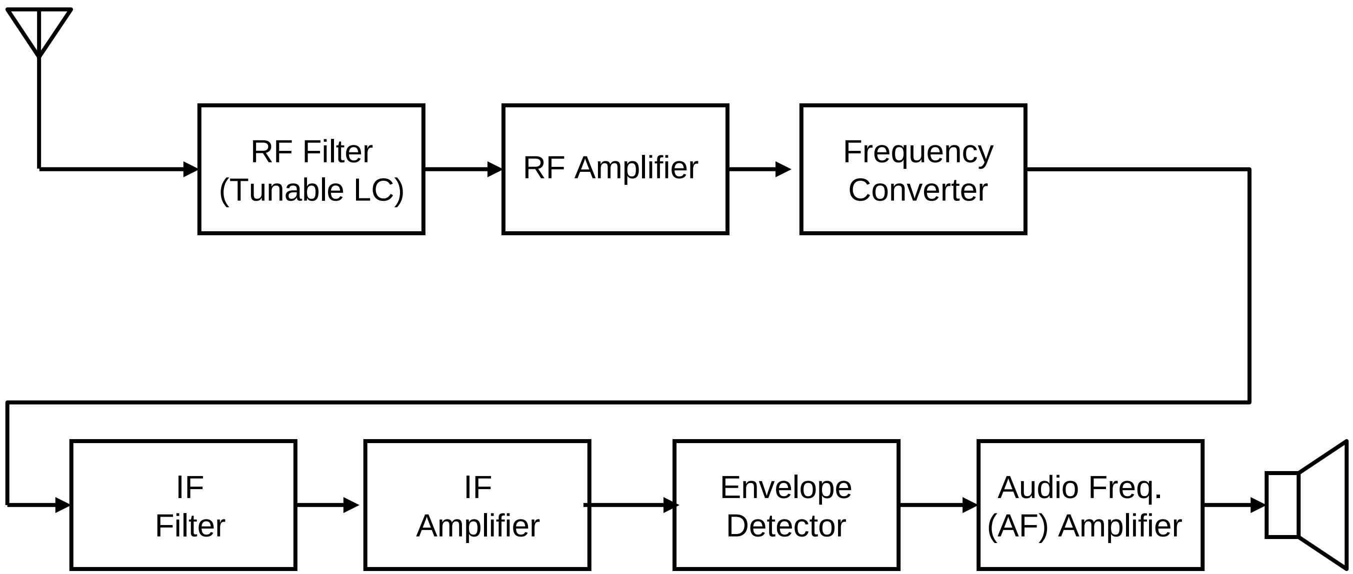
Super-regeneration Receiver



$R_1 > R_2$

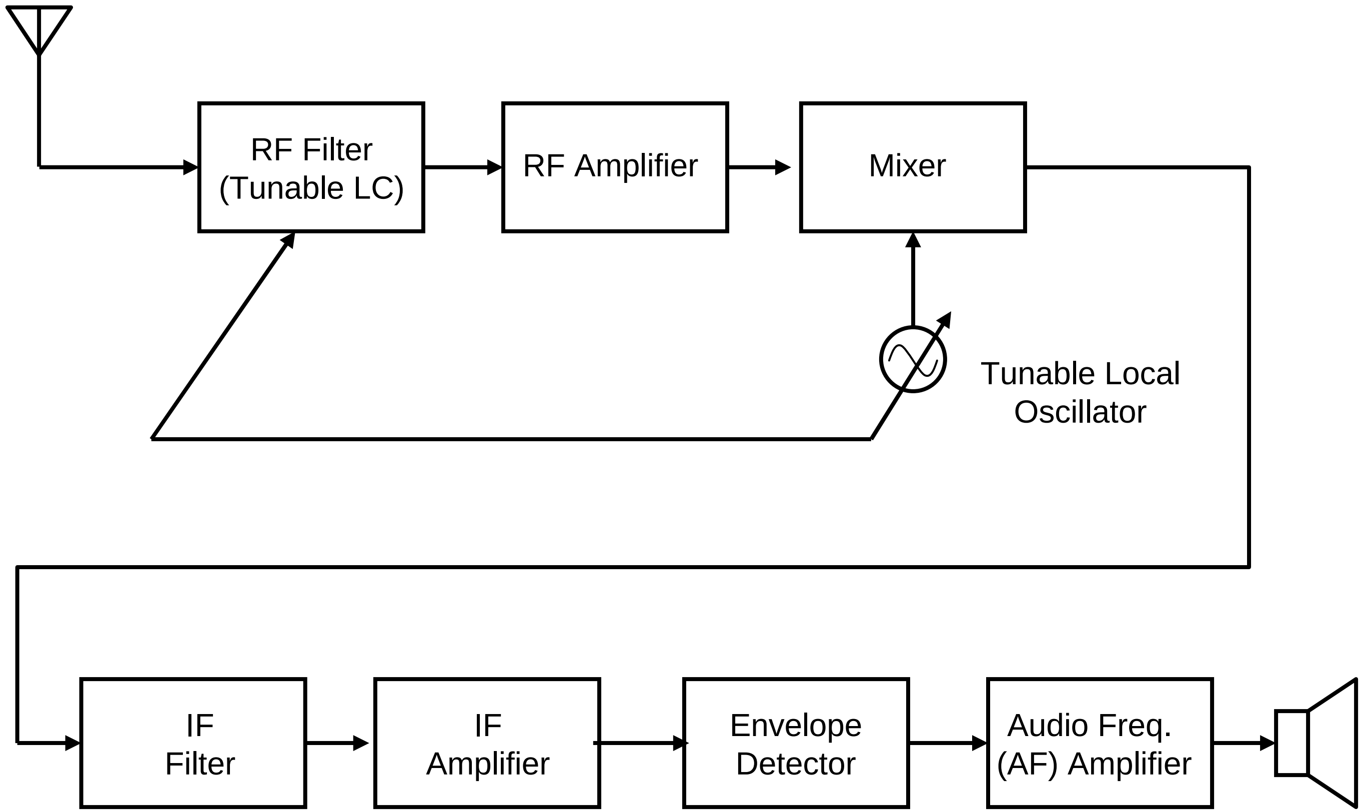
- Quench circuit is either an oscillator (quenching at regular intervals) or amplitude detector (quenches when predetermined amplitude is reached)
- Large effective RF gain can be achieved by a single stage (cheap)
- Generates characteristic hissing due to amplification of thermal noise in the absence of signal

Heterodyne Receiver



- **Frequency converter mixes RF down to lower IF frequency – better selectivity is obtained at the lower frequency IF filter**
- **Excellent selectivity due to the additional IF filtering**
- **Better sensitivity by additional IF amplification**

Superheterodyne Receiver



- **Uses LO frequency higher than carrier, hence 'super' heterodyne**
- **Local oscillator frequency tracks the RF filter frequency by a 'ganged' variable capacitor**

Superheterodyne Receiver Example

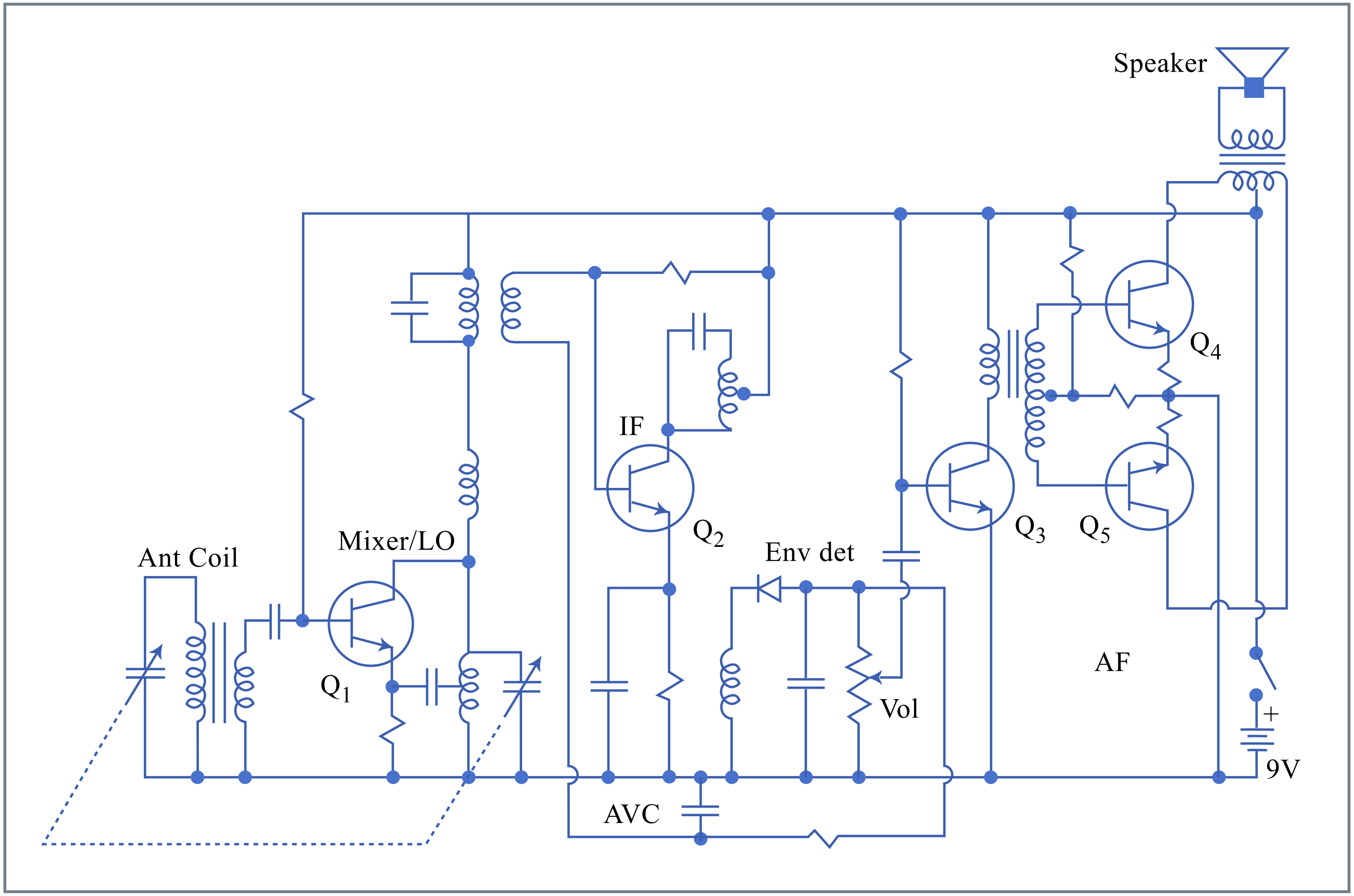


Figure by MIT OCW.

- **Local oscillator frequency tracks the RF filter frequency by a ‘ganged’ variable capacitor**

Superheterodyne Receiver Spectra

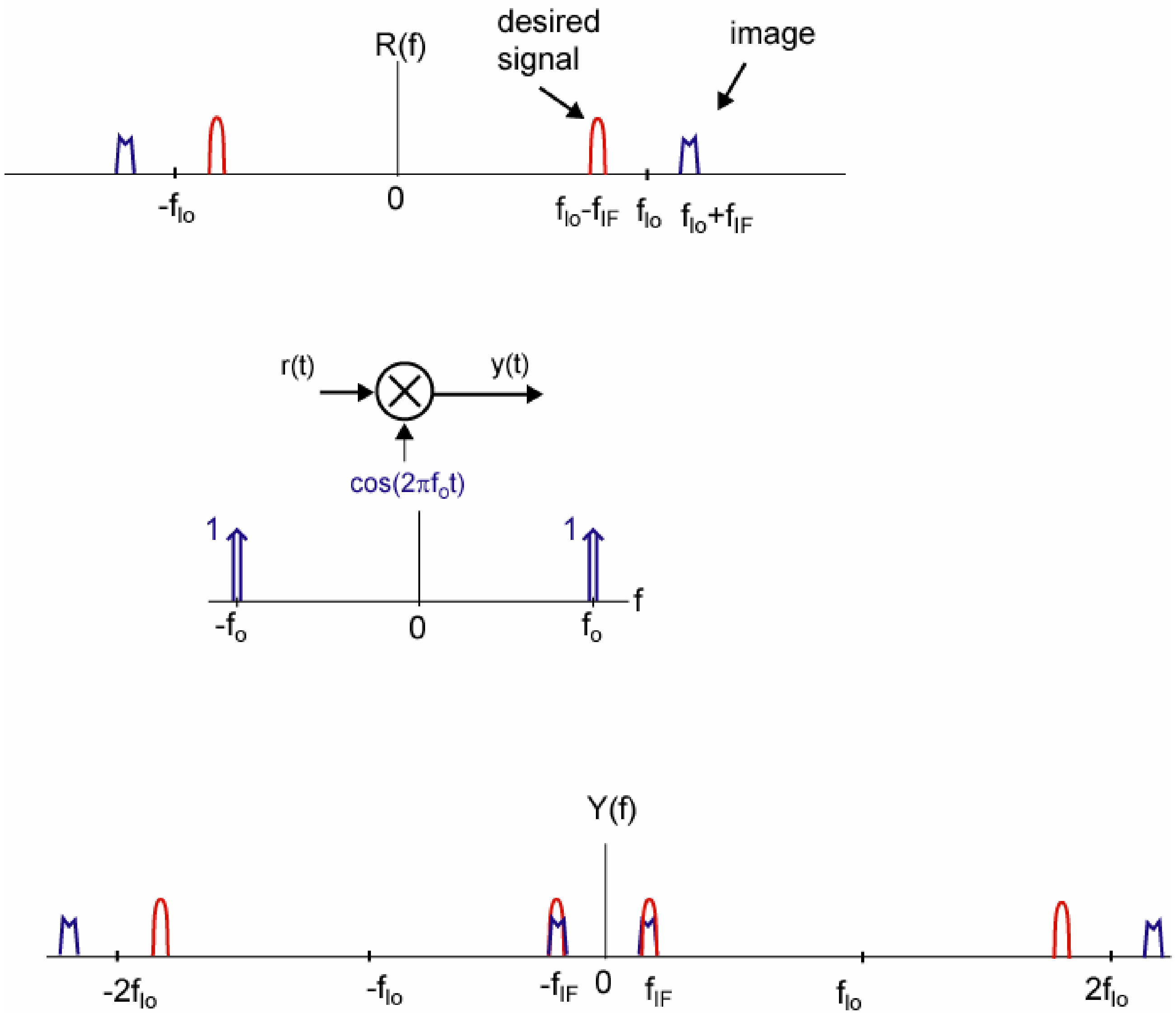
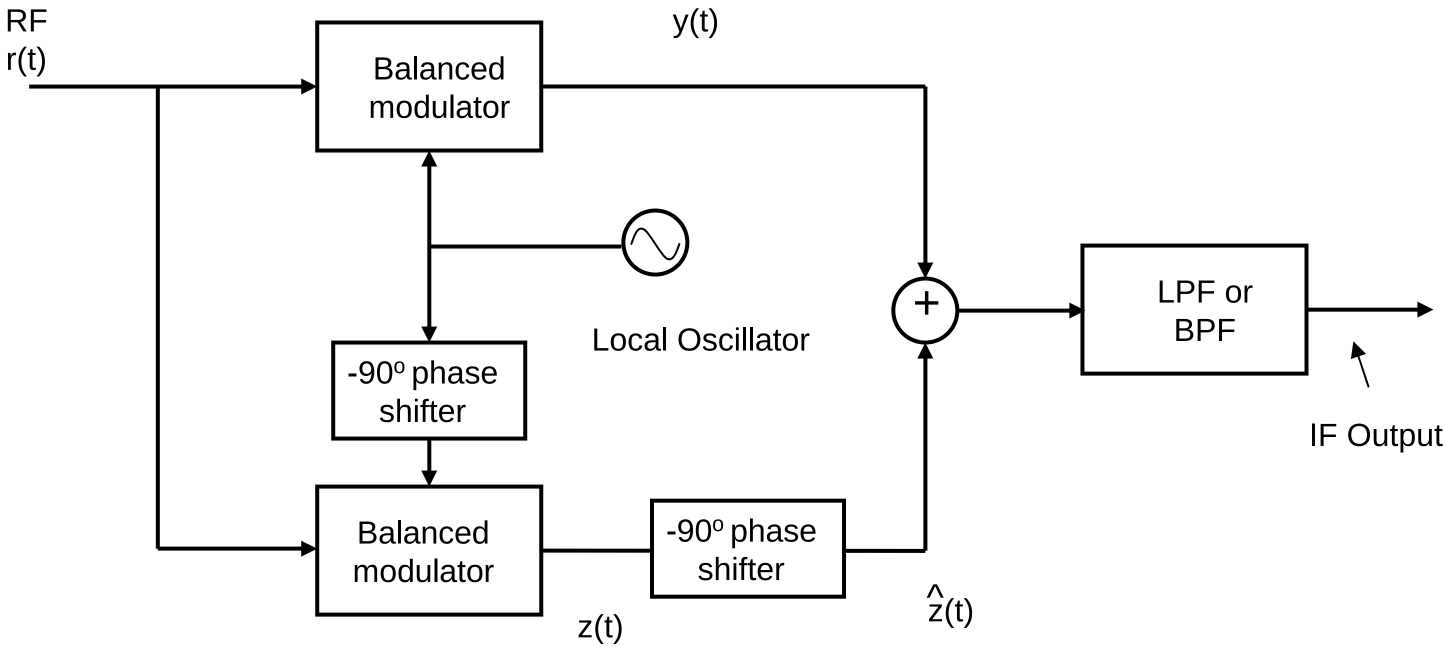


Image Rejection in Superheterodyne Receivers

- **Key Point: image signal at equidistance from f_{lo} converts to the same IF band**
- **The RF filter must remove image! (image reject filter)**
- **Want high IF frequency for easy image rejection**

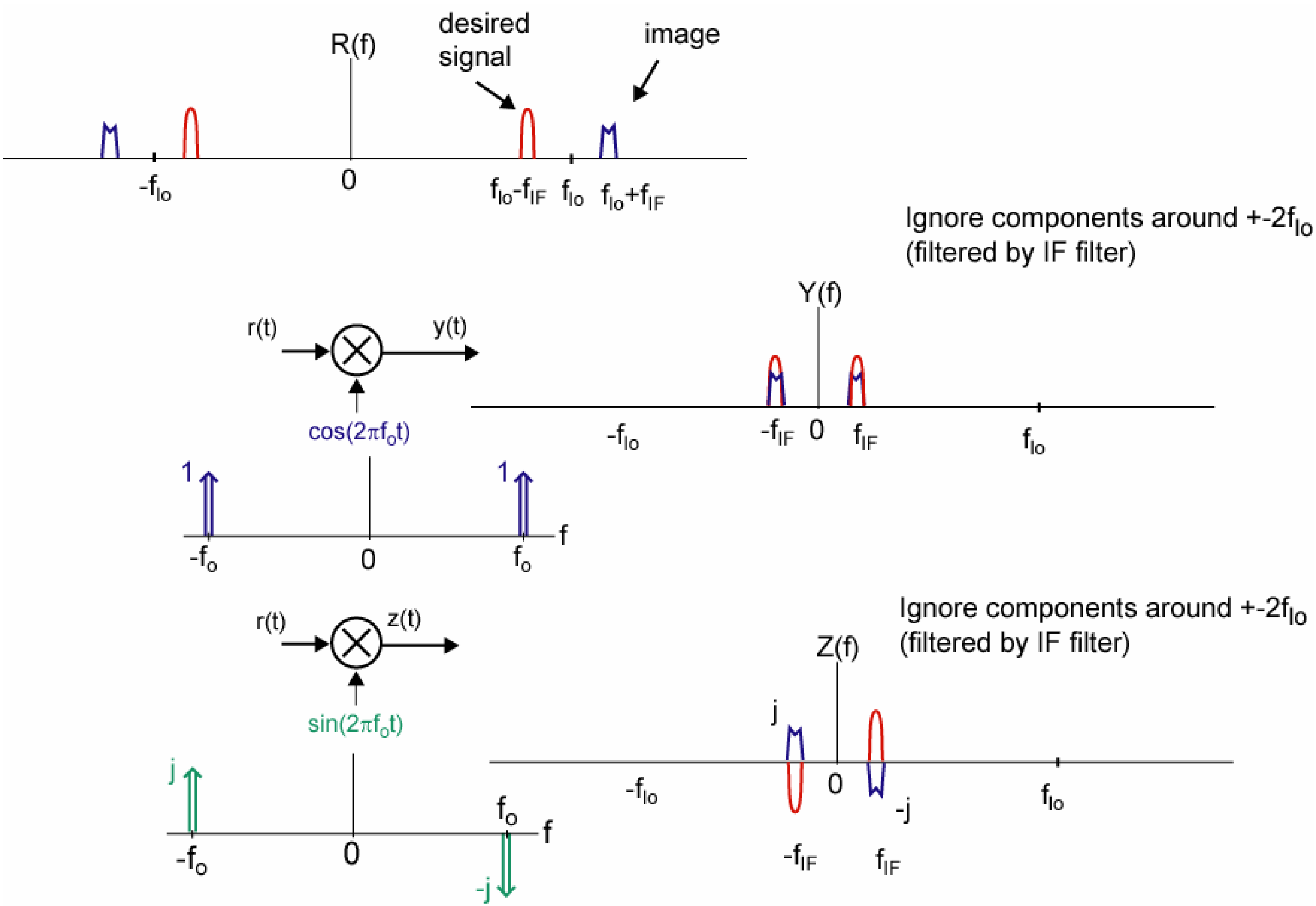
  (the distance between the desired signal and the image is $2f_{IF}$)
- **But, want low IF for easy IF filtering (lower fractional bandwidth**
- **Typically f_{IF} is selected about half the RF band (e.g. AM 500-1700kHz or FM 88-108MHz) as a compromise**
- **The alternative is to employ *image reject* mixer**

Image Reject Mixer

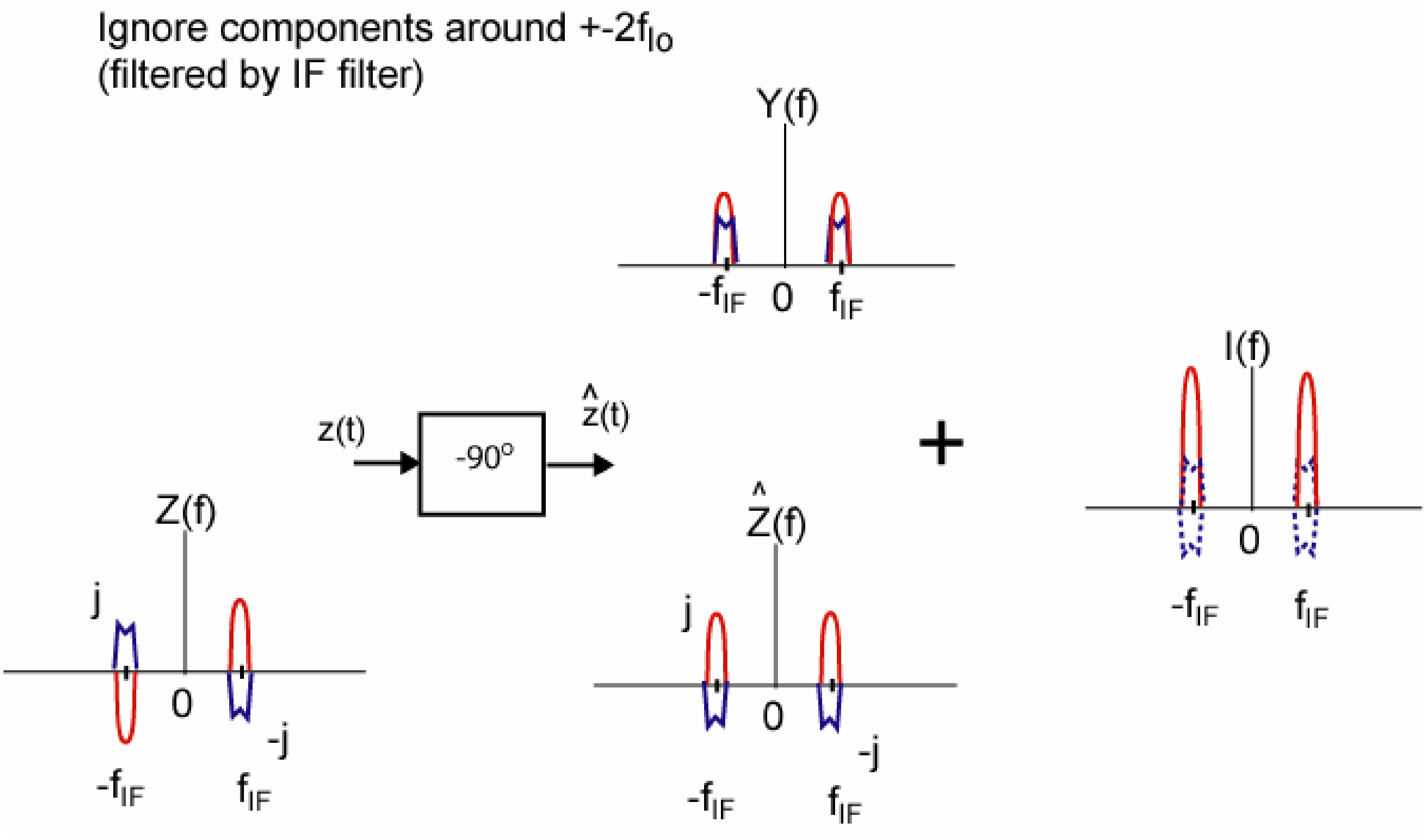


- **Image rejected by similar method to SSB generation**
- **Image rejection limited by amplitude and phase matching of RF and LO paths. 40 dB image suppression is typical**
- **RF filter can reduce the image further if necessary, otherwise the RF image reject filter can be omitted.**

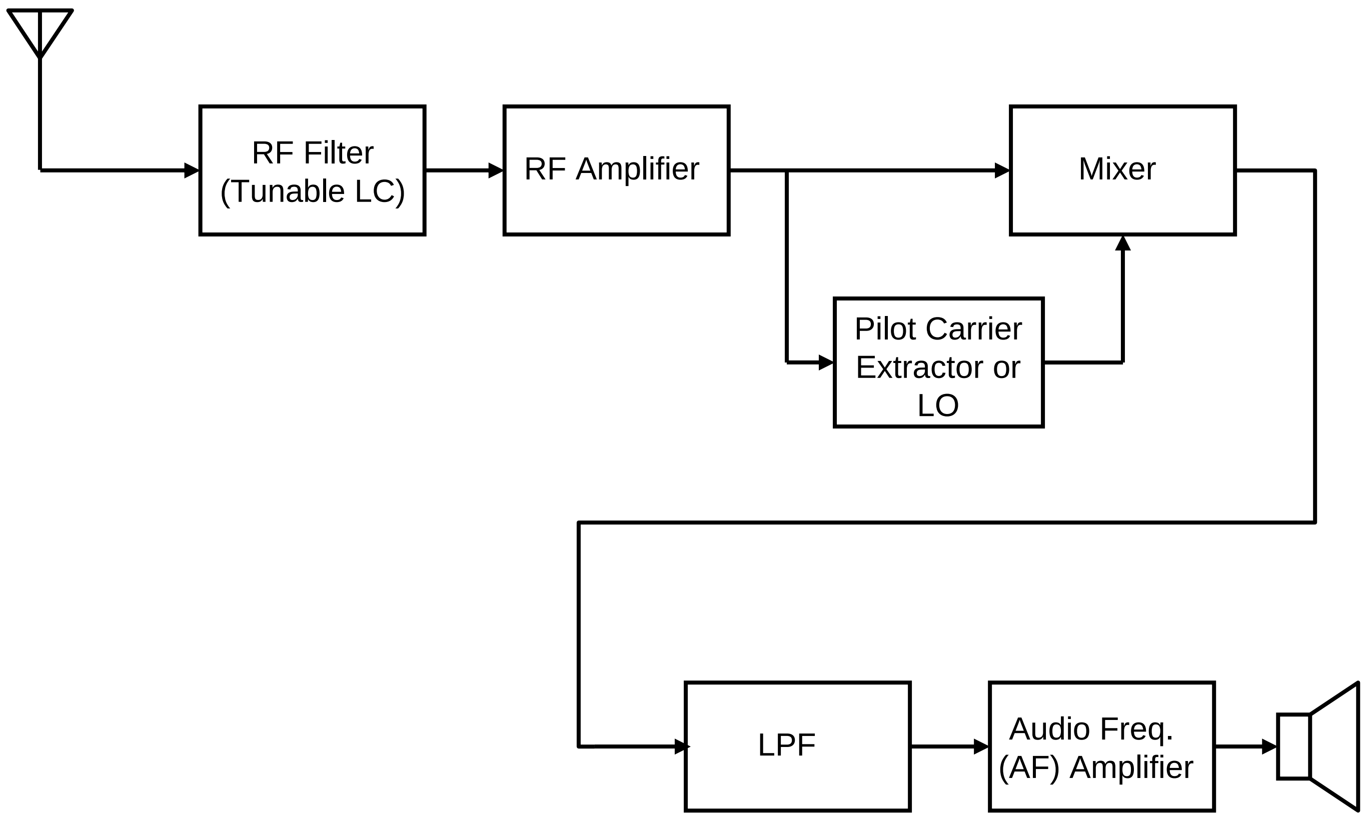
Frequency Domain View of Image Reject Mixer



Frequency Domain View of Image Reject Mixer, Cnt'd



Homodyne Receiver (Coherent Receiver)

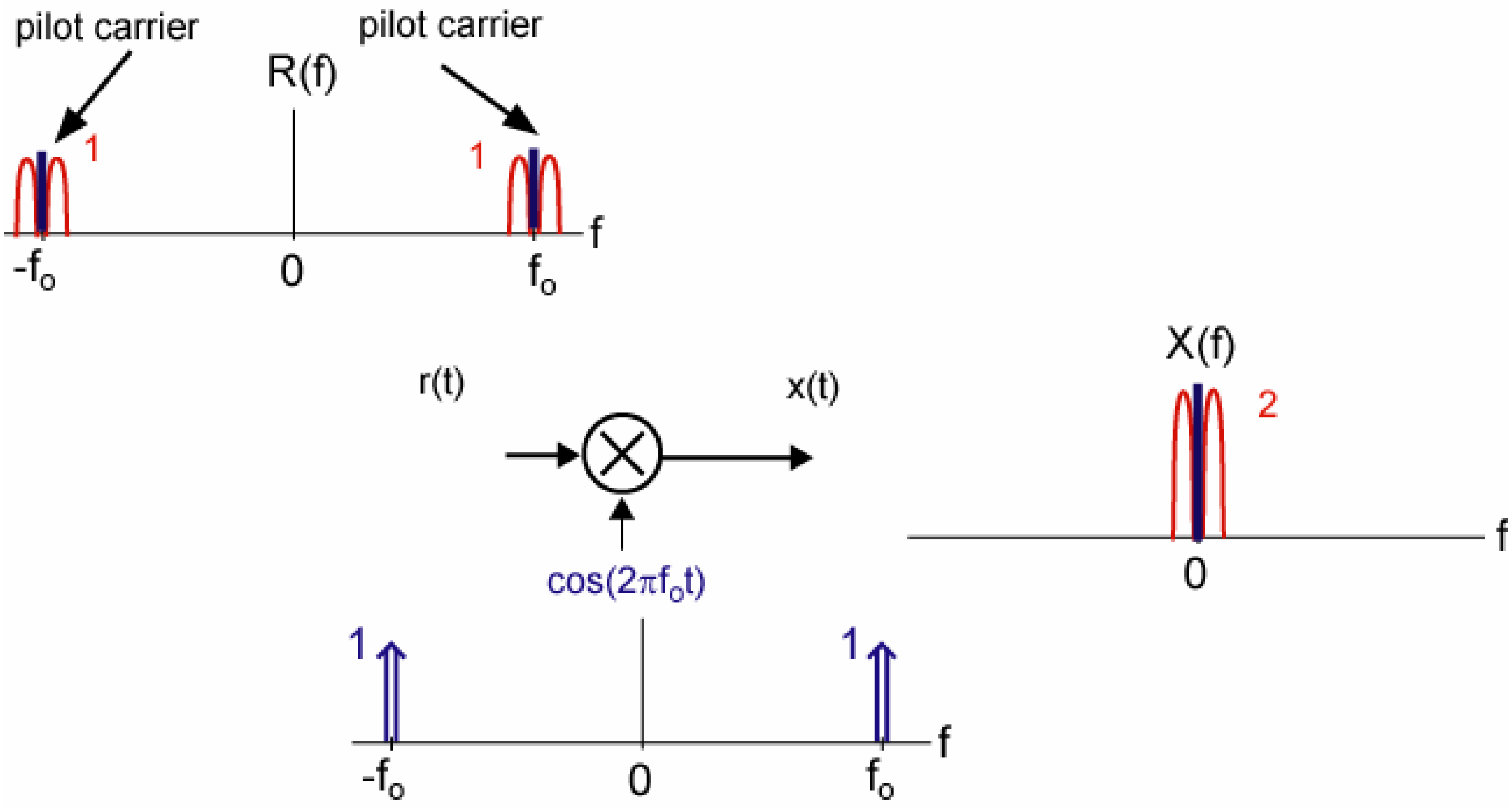


- **Mixes RF signal with the carrier frequency down directly to baseband: no image to reject**

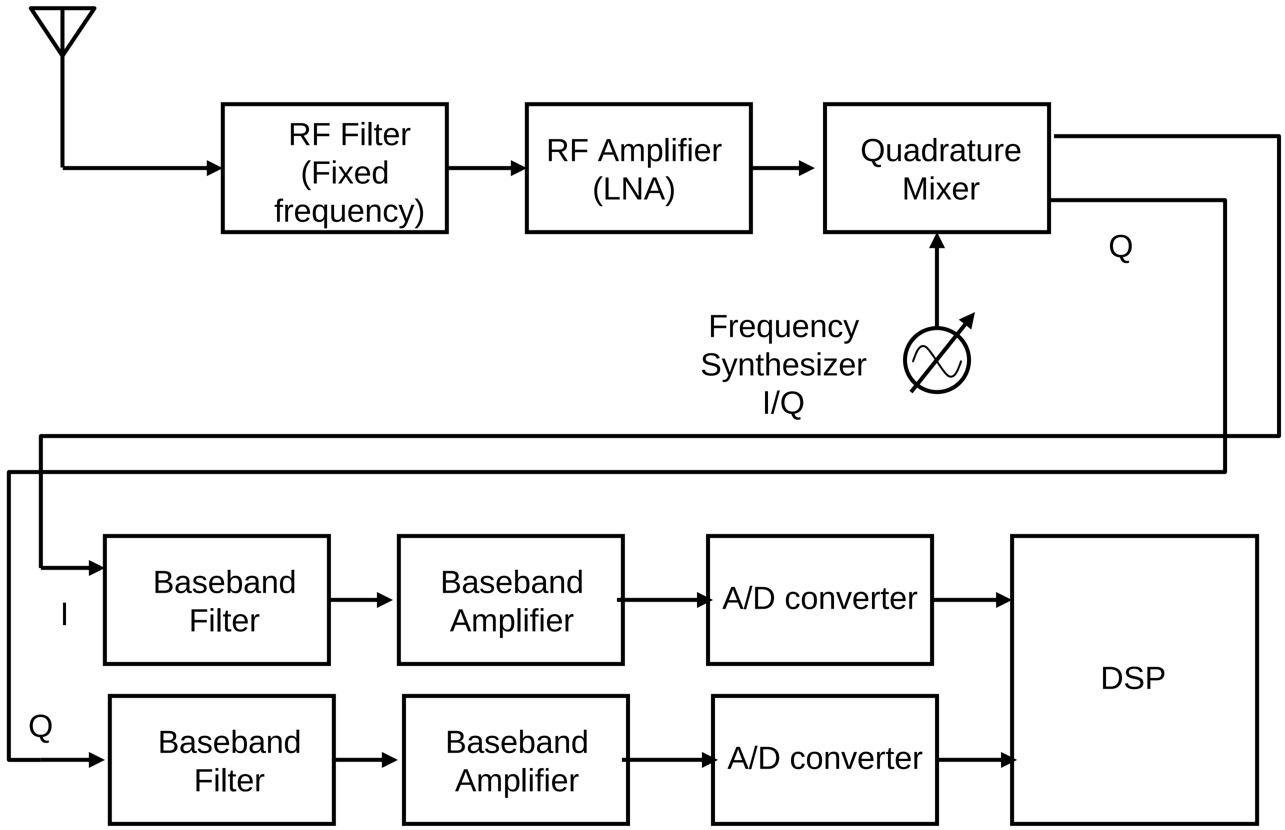
Homodyne Receiver Cont'd

- **No local oscillator if pilot carrier is present – carrier extracted from the transmitted signal (carrier needs to be inserted in DSB or SSB, so not compatible with standard DSB or SSB transmission)**
- **Otherwise, a local oscillator at carrier frequency is needed (see *direct conversion* receiver later)**
- **Carrier extractor can be a narrowband filter, PLL, or an oscillator synchronized by the carrier signal**
- **A form of a direct conversion receiver: same advantages and issues**

Homodyne Receiver Spectra



Direct Conversion (Zero-IF) Receiver



- **Type of a homodyne receiver**
- **Uses coherent detection: a precise local oscillator is required (use frequency synthesizer)**
- **No IF filtering: single-chip integration is possible**

Direct Conversion (Zero-IF) Receiver

- **No IF filtering: single-chip integration is possible**
- **Channel (station) selection in baseband**
- **Since the RF filter is not highly selective, the baseband filter needs to reject interferers: requires much higher dynamic range/SNR and high selectivity in the baseband processing circuit**
- **Channel filtering is typically performed by DSP**
- **No image to reject**
- **Time-varying DC offset due to local oscillator leakage is an important issue**
- **DC offset can be larger than signal and saturate baseband circuits**

Double Conversion Receiver

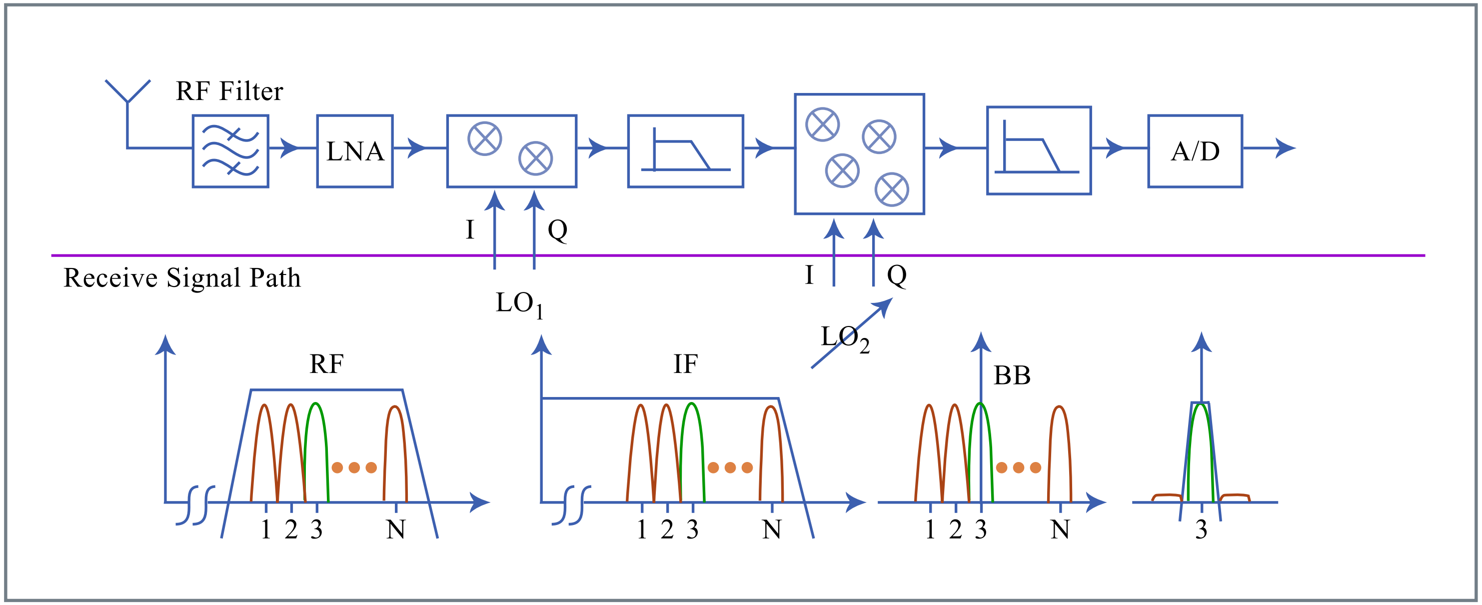


Figure by MIT OCW.

REF: "A 1.9-GHz Wide-Band IF Double Conversion CMOS Receiver for Cordless Telephone Applications,"J C. Rudell, et. al. IEEE J. Solid-State Circuits, Vol. SC-32, Dec. 1997 pp 2071-2088

- I/Q Image rejection provided by 6 mixers
- IF filtering is LPF: single-chip integration is easier
- LO frequency is unequal to carrier – LO leakage is not an issue

Image Rejection in Double Conversion Receiver

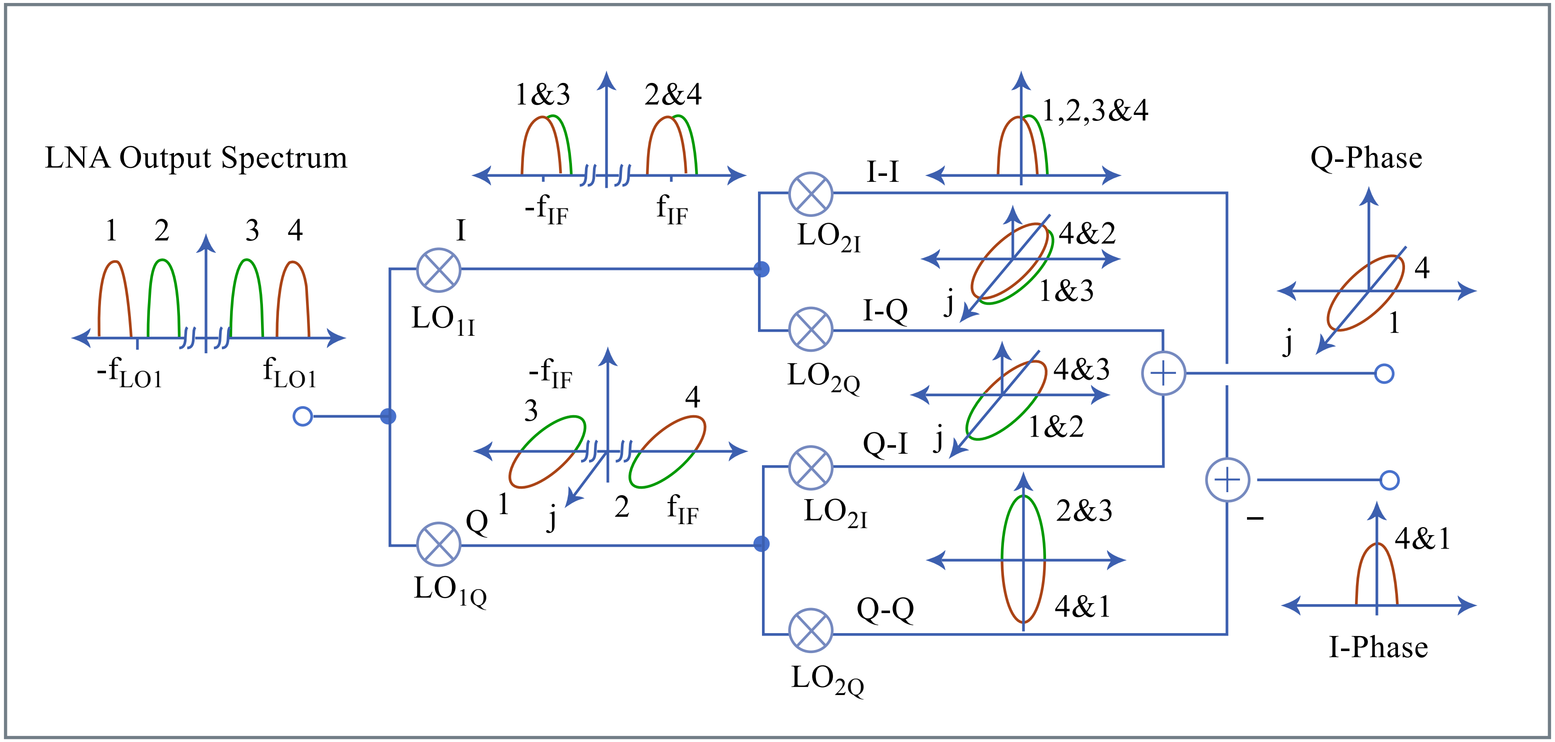
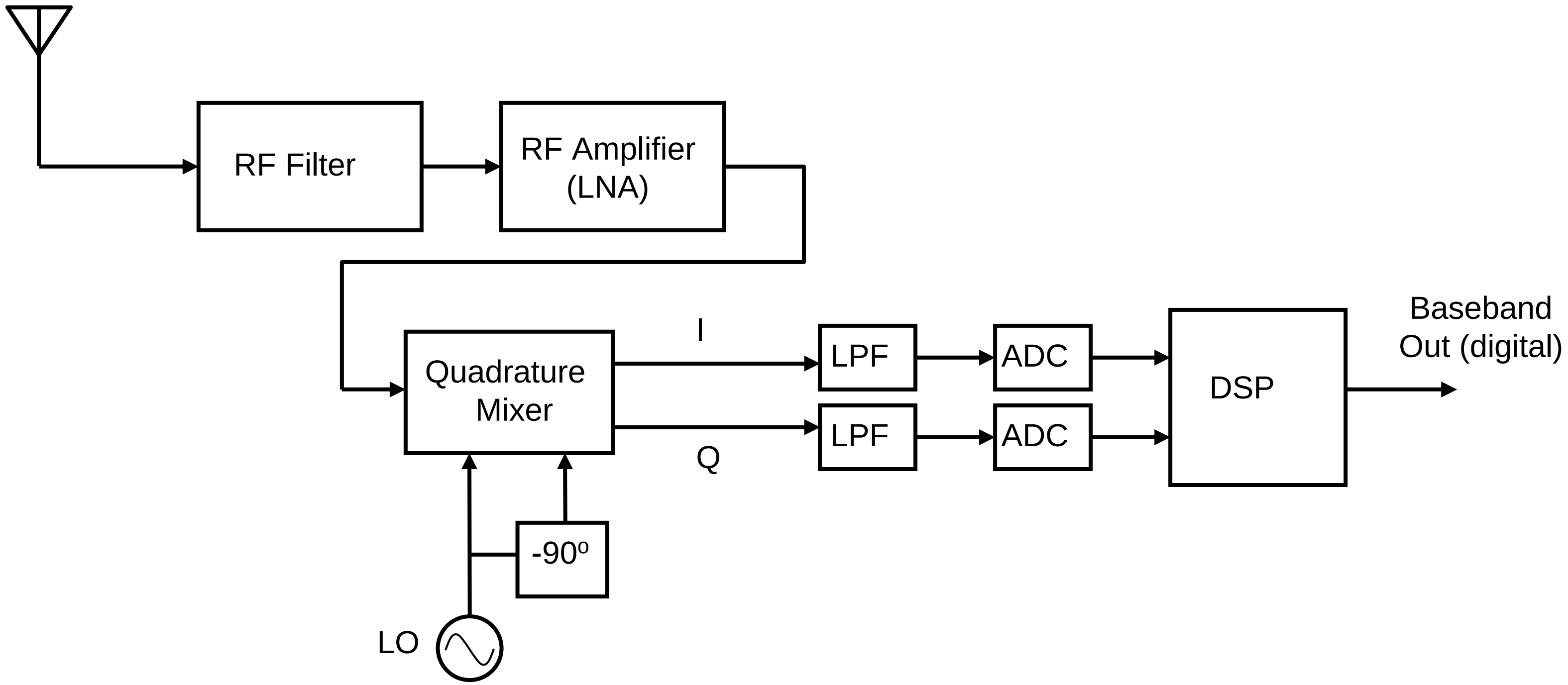


Figure by MIT OCW.

- Similar to Weaver SSB generator (P.S. #1)
- Image rejection by phase relationship – no passive components
- Image rejection limited by amplitude and phase matching of 6 mixers!

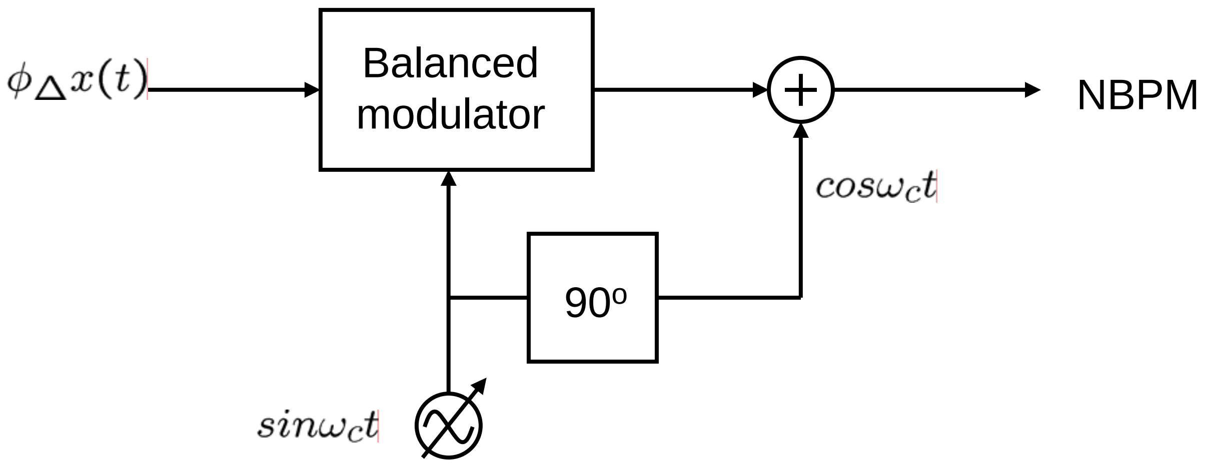
Low-IF Receiver



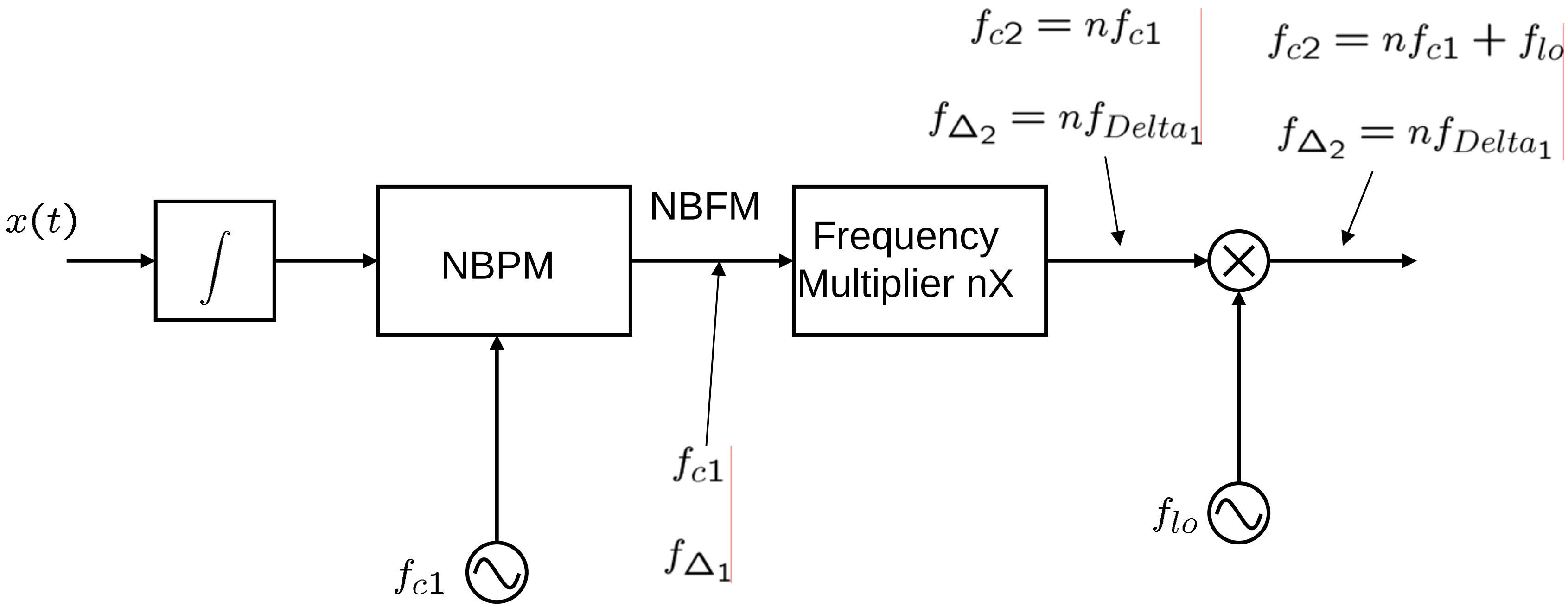
- **Same principle, but image rejected in digital domain: IF frequency can be very low**
- **The IF filter, ADC & DSP operate at low IF frequency: Permits easy single-chip integration**
- **Image rejection still limited by quadrature mixer amplitude & phase matching**

Transceivers for Constant Envelope Modulation

Narrowband Phase Modulator



Indirect Frequency Modulation



- **Frequency multiplier increases the FM bandwidth by nX**

Direct FM: VCO

$v_{in} = Bx(t)$

$f_{out} = f_o + K v_{in}$

- f_o: ‘free running’ frequency of VCO
- Typically, a varactor (voltage-variable capacitor) is used to change oscillation frequency in an oscillator
- Difficult to maintain precise output frequency due to drift in the VCO frequency
- High phase noise

Example of VCO's (Albert Jerng's VCO's)

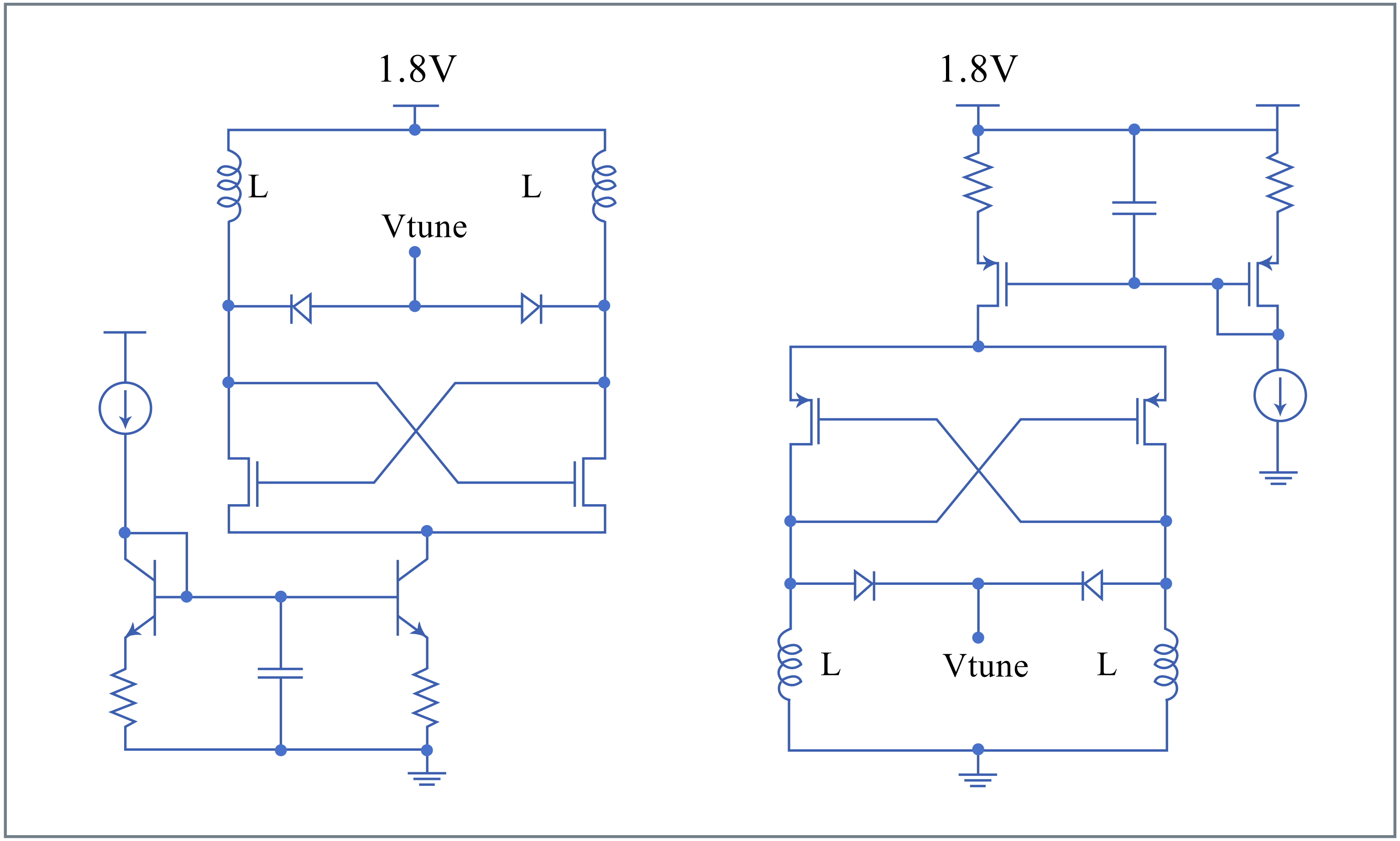
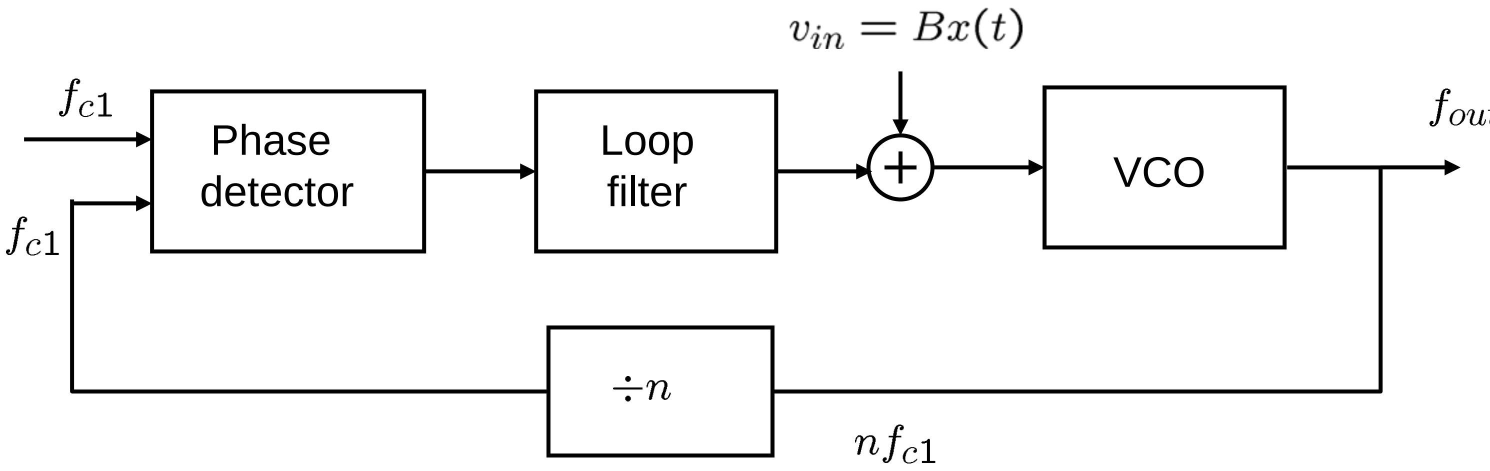


Figure by MIT OCW.

NMOS VCO

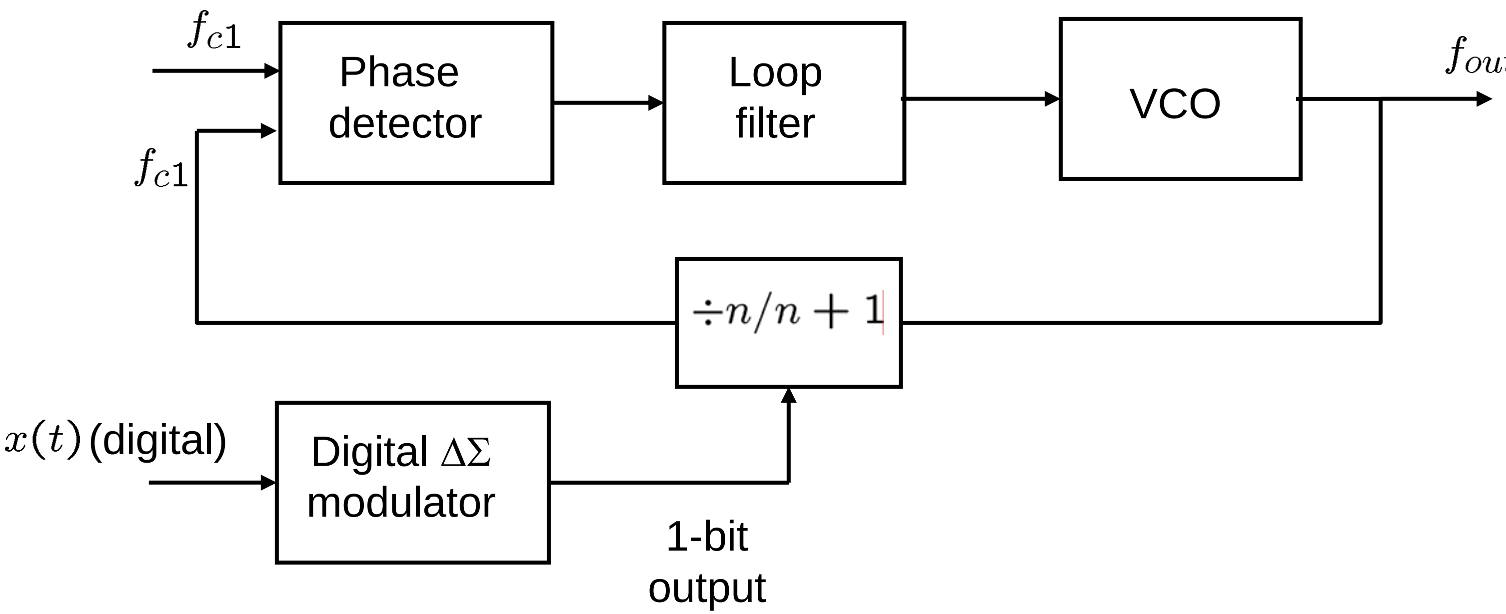
PMOS VCO

PLL-Based Frequency Modulation



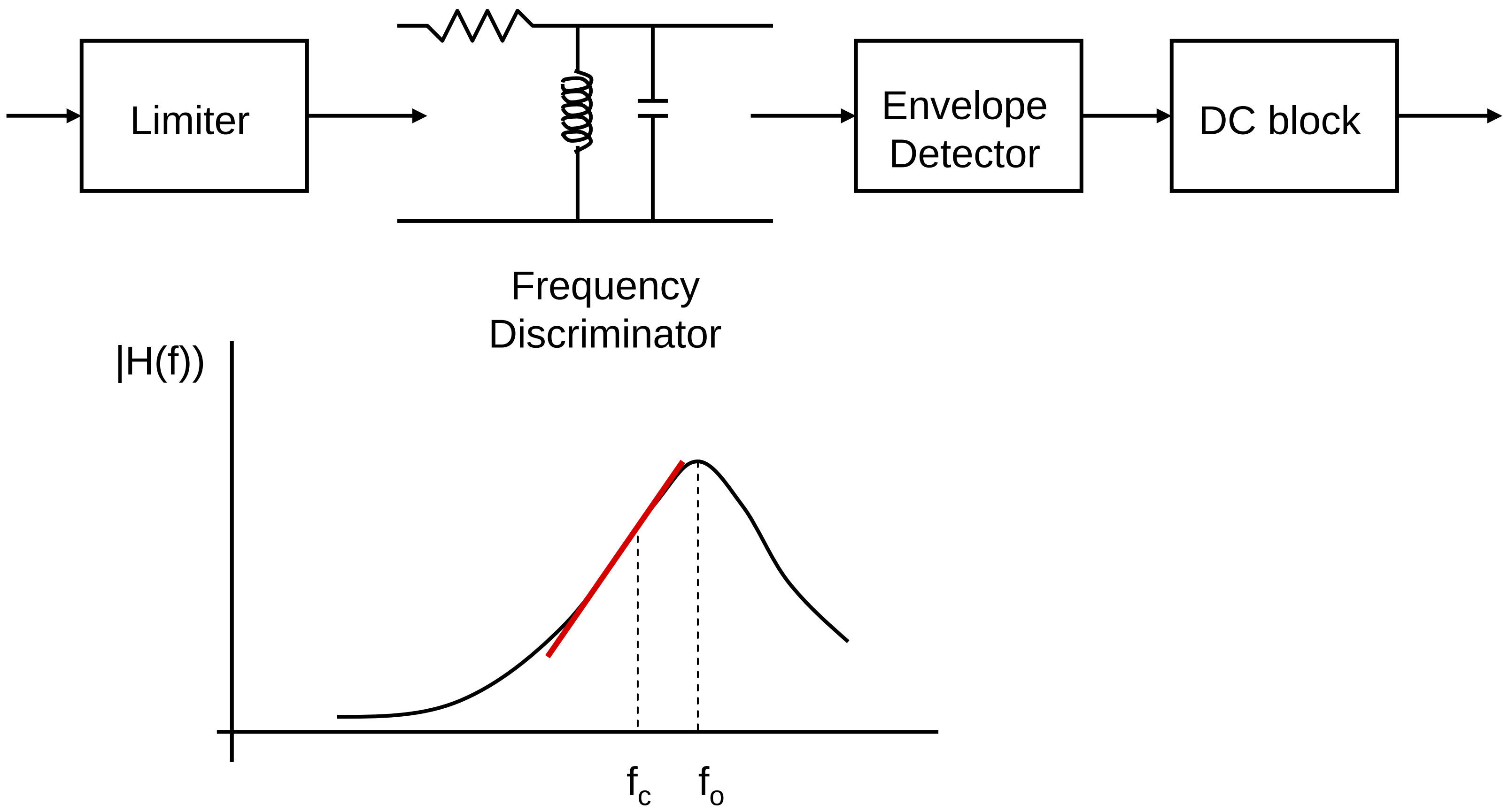
- The loop bandwidth must be lower than the lowest signal frequency
- The center frequency is precisely maintained by the crystal reference f_{c1}

Digital Frequency Modulation Using Fractional-N Synthesizer



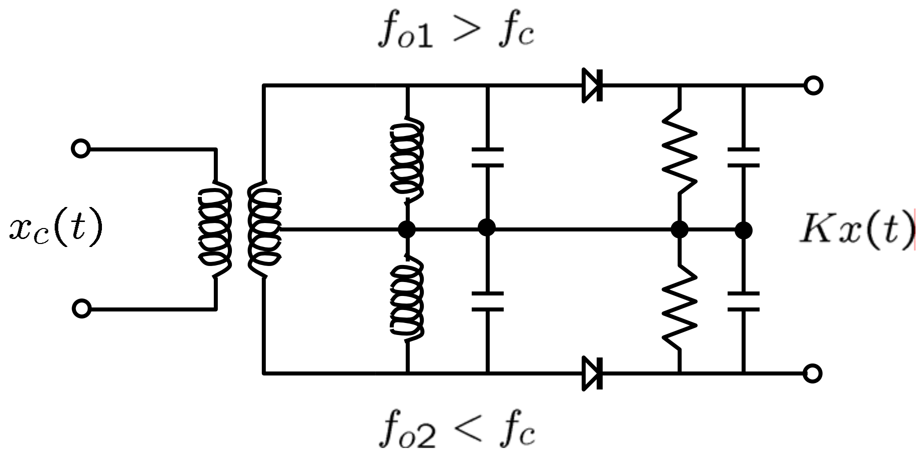
- **Modulo n/n+1 divider is duty-cycle modulated by the signal**
- **Input signal is $\Delta\Sigma$ modulated to push quantization noise out of loop bandwidth**

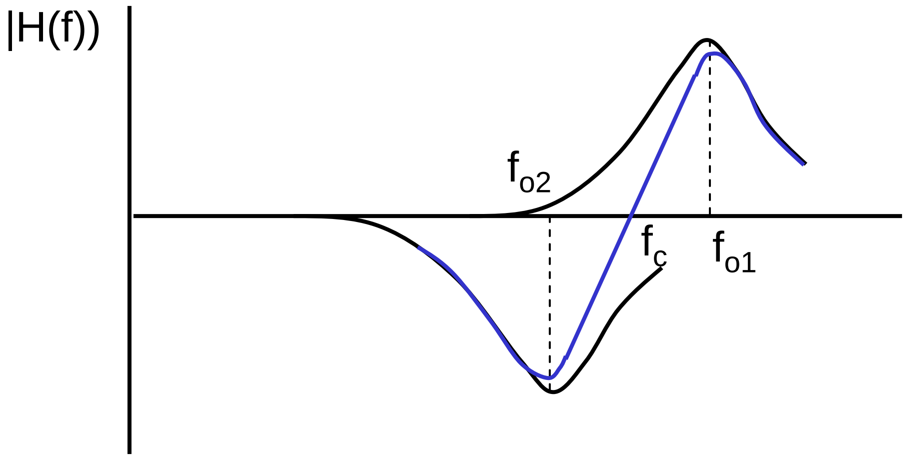
FM Demodulation: Frequency Discriminator



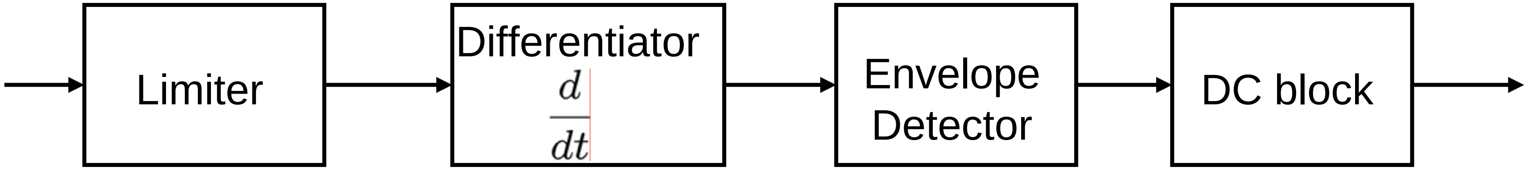
- **Linear f-v range is small: use balanced (differential) discriminator**

Balanced Frequency Discriminator





FM Demodulation by FM-to-AM Conversion

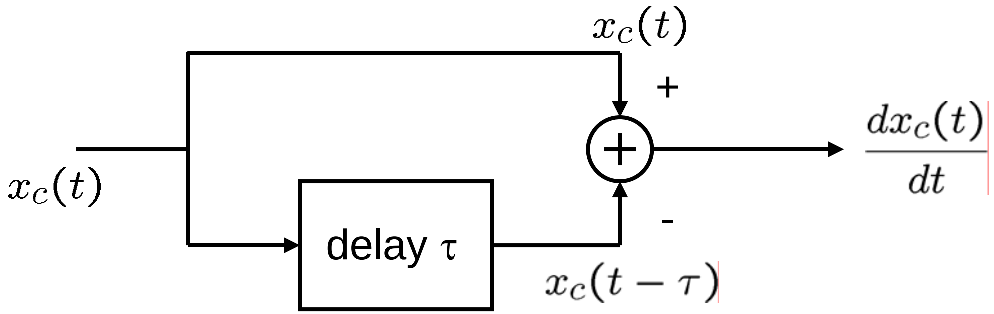


- **Differentiator converts FM signal to AM**
- **Spurious AM must be suppressed by the limiter**

FM Demodulator Example: Delay-Line

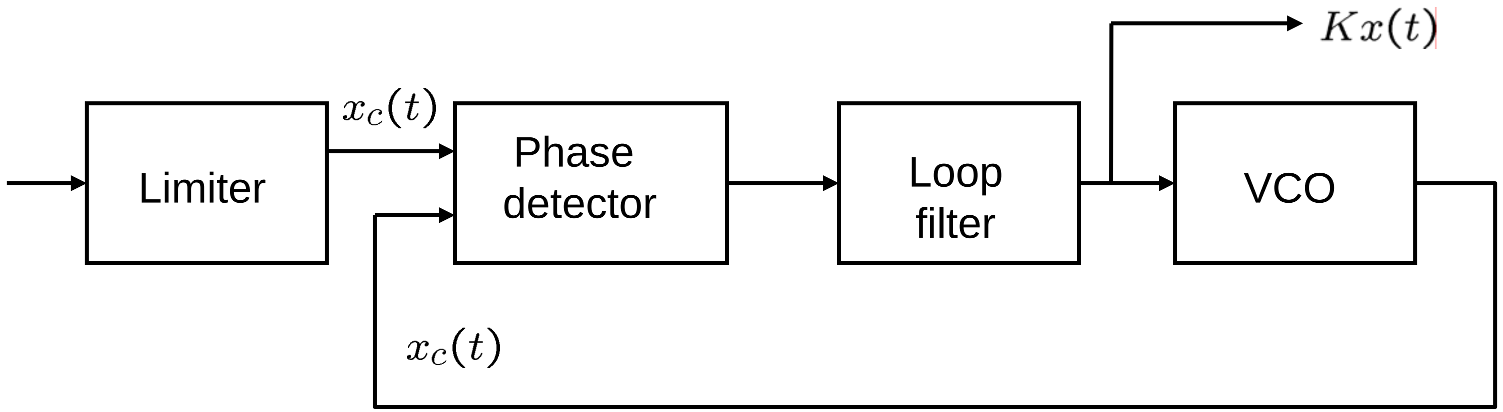
$$\frac{dv(t)}{dt} = lim \frac{1}{\epsilon}[v(t) - v(t-\epsilon)]$$

$$\frac{dx_c(t)}{dt} \approx \frac{1}{\tau}[x_c(t) - x_c(t-\tau)]$$



- **Differentiator is implemented by a transmission line delay**

FM Demodulator Using Phase-Locked Loop



- VCO input voltage is used as output
- VCO is in feedback loop: input output characteristic is the inverse of VCO function (thus f-to-v conversion).