Electrical and Computer Engineering

**ELEC 391**
**Electrical Engineering Design Studio II**

# Introduction to Amplitude Modulation

Introduction to project management. Problem definition. Design principles and practices. Implementation techniques including circuit design, software design, solid modeling, PCBs, assembling, and packaging. Testing and evaluation. Effective presentations. [2-0-4]





- During this lecture, the instructor will bring up many points and details not given on these slides. Accordingly, it is expected that the student will annotate these notes during the lecture.
- The lecture only introduces the subject matter. Students must complete the reading assignments and problems if they are to master the material.

# Introduction

- Although many more complicated modulation schemes have been developed during the past century, amplitude modulation is still widely used for broadcast radio, amateur radio, television (video), and aeronautical communications.
- Its chief advantages are simplicity, low cost and bandwidth efficiency.
- Its main disadvantages are susceptibility to noise and interference and, in certain variants, poor power efficiency due to the presence of a large unmodulated carrier.
- Given an operational AM transmitter, how would you determine the bandwidth, modulation index, and efficiency of the signal that it is emitting?  Use a spectrum analyzer, of course!





# Objectives

Upon completion of this briefing, you will be able to:

- Describe and derive the basic principles, advantages, and disadvantages of DSB-SC modulation and demodulation.
- Describe and derive the basic principles, advantages, and disadvantages of DSB-LC modulation and demodulation.
- Describe and derive the basic principles, advantages, and disadvantages of SSB and quadrature multiplexing
- Explain how frequency mixers may be applied in RF systems.
- Describe frequency mixer performance at the system level.
- Be prepared to complete the major project with skill and efficiency.

# 1. Amplitude Modulation

- AM is a form of analog modulation in which the instantaneous amplitude of the modulated signal $x(t)$ is linearly related to the amplitude of the message signal $m(t)$.

- Types:
  - Double Sideband – Suppressed Carrier (DSB-SC)
  - Double Sideband – Large Carrier (DSB-LC) (*used in BCB*)
  - Single Sideband (SSB) (*used in marine and amateur radio*)
    - Upper Sideband (USB)
    - Lower Sideband (LSB )
  - Vestigial Sideband (VSB) (*was used in NTSC television video*)





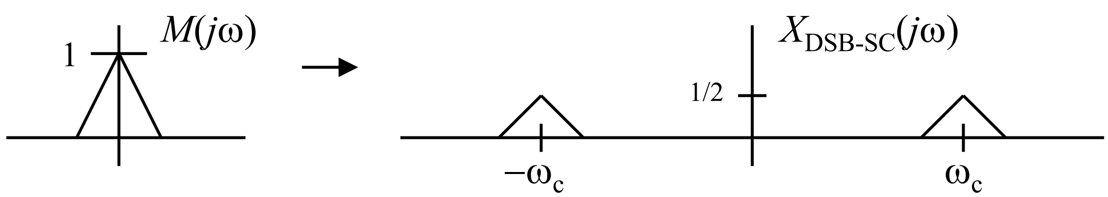
# 2. Double Sideband Modulation – Suppressed Carrier

- If the instantaneous amplitude is proportional to $m(t)$, the result is DSB-SC

$$x_{\text{DSB-SC}}(t) = m(t)\cos(\omega_c t)$$

- Apply the modulation property to show that

$$X_{\text{DSB-SC}}(j\omega) = \tfrac{1}{2}M\left(j(\omega+\omega_c)\right) + \tfrac{1}{2}M\left(j(\omega-\omega_c)\right)$$

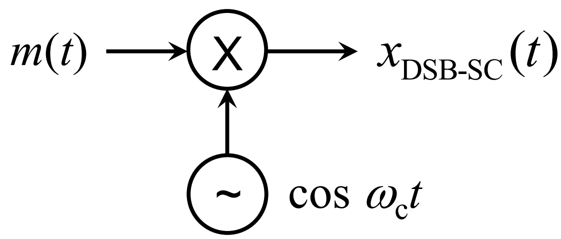



- DSB-SC simply translates the baseband spectrum to the frequency of the carrier signal.

- Note that:
  - the upper and lower sidebands are redundant.
  - the bandwidth of the modulated signal is double that of the message signal.

## Implementation of DSB-SC

- Equation 1 implies the following implementation:



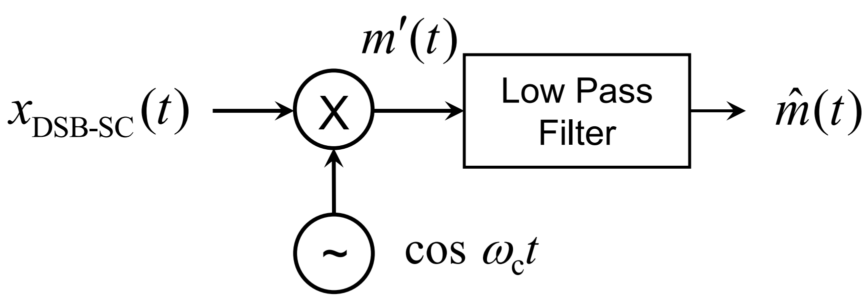

- If $m(t) = \cos \omega_m t,\ \omega_m << \omega_c$, what does $x_{\text{DSB}}(t)$ look like? (An exercise for you!)





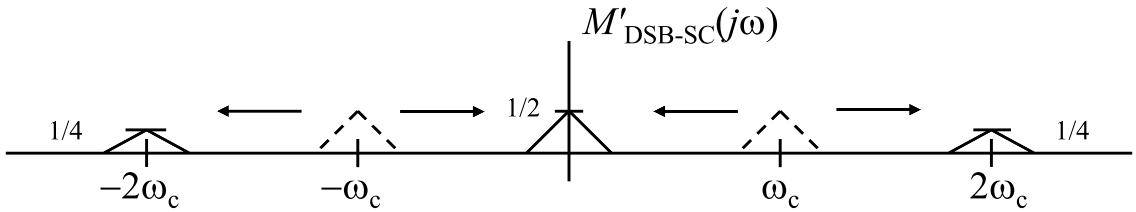
## Demodulation of DSB-SC Signals

- The nature of DSB-SC modulation suggests a strategy for demodulation:




- Questions:
  - What does this process look like in the frequency domain?
  - What should the cut-off frequency of the low pass filter be?
  - What happens if there is a frequency or phase offset between the LOs in the modulator and demodulator?

# Demodulation of DSB-SC Signals - 2




$$m'(t) = m(t)\cos(\omega_c t)\cos(\omega_c t)$$

$$M'(j\omega) = \tfrac{1}{4}M\left(j(\omega+2\omega_c)\right) + \tfrac{1}{2}M(j\omega) + \tfrac{1}{4}M\left(j(\omega-2\omega_c)\right)$$

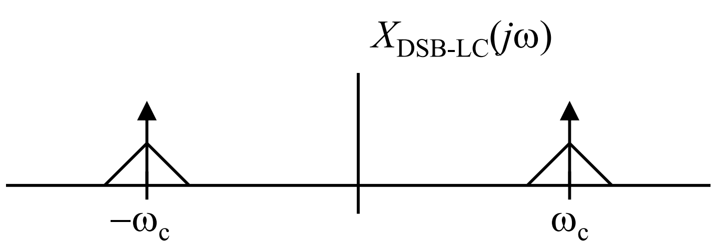
- Given $m'(t)$, can you derive the above expression for $M'(j\omega)$ ?
- What if $m'(t) = m(t)\cos(\omega_c t)\cos(\omega_c t+\phi)$ ?





# 3. Double Sideband Modulation – Large Carrier

- A DSB-LC modulated signal results if a carrier signal is added to a DSB-SC modulated signal.

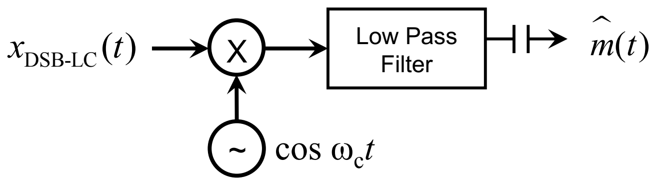



  - What is the advantage of adding a carrier?
  - How large should the carrier be?
  - How can one add a carrier?
  - What are the disadvantages of adding a carrier?

# Demodulation of DSB-LC Signals

- The strategy that we developed for demodulating DSB-SC signals will apply to DSB-LC signals **if** we also apply a DC block at the output.
- It will still suffer from the problems associated with all synchronous demodulators:
  - complexity (and cost)
  - sensitivity to phase and frequency offsets between the LOs in the modulator and demodulator
- DSB-LC offers an alternative: *envelope detection.*

*cf.*

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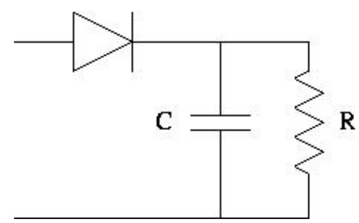
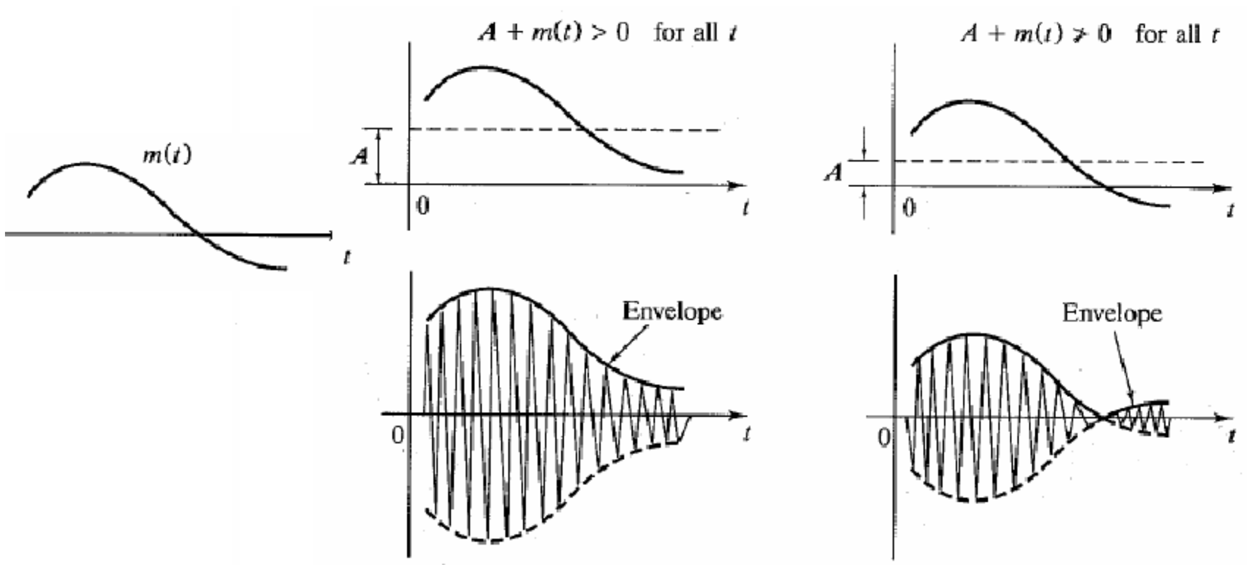




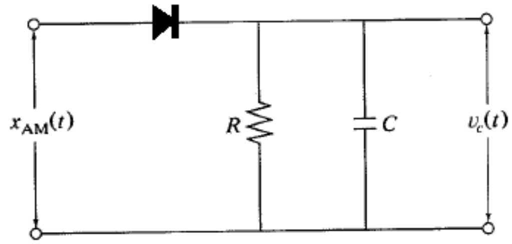


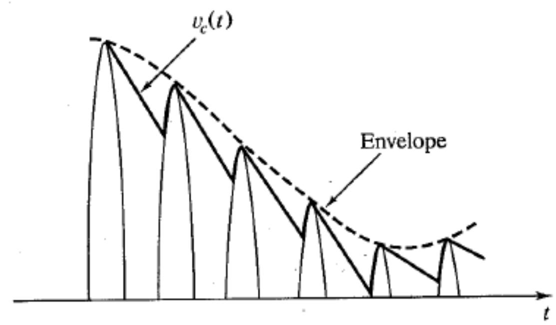

# Envelope Detection

- If $A + m(t) > 0$ or $A \geq \left|\min\{m(t)\}\right|$, the envelope of the modulated signal will follow the shape of the message signal



# Implementation of an Envelope Detector



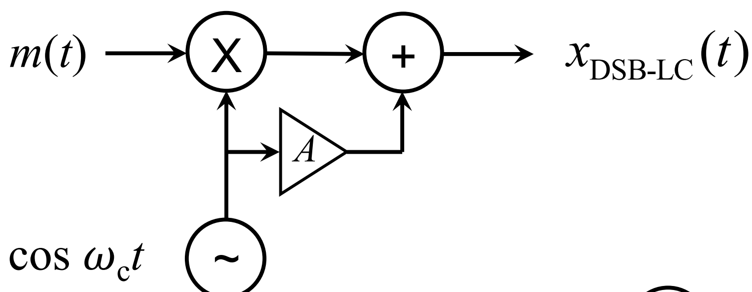

- How should the value of RC be chosen?

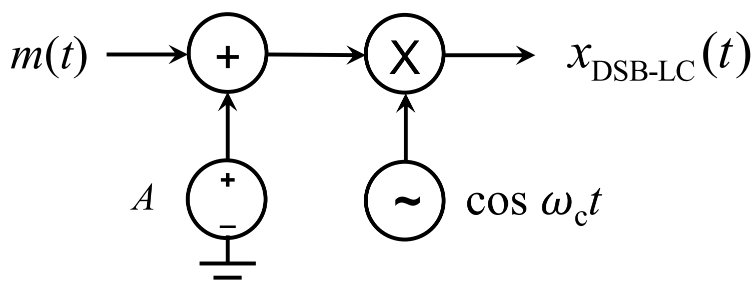




# Implementation of DSB-LC Modulators

- The expression for DSB-LC signals suggests two possible implementations of DSB-LC modulators:




Can you show that these are mathematically equivalent?

# DSB-LC with Single-tone Modulation

- For single - tone modulation,

$$m(t) = a_m \cos \omega_m t.$$

- The modulation index is given by

$$\mu = \frac{|\min\{m(t)\}|}{A} = \frac{a_m}{A}$$

- Thus,

$$m(t) = a_m \cos \omega_m t = \mu A \cos \omega_m t$$

and

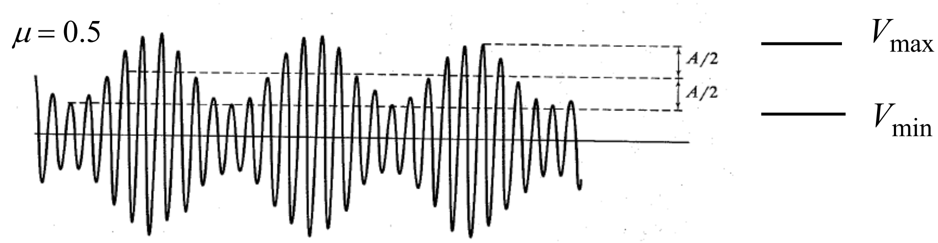
$$\begin{aligned} x_{DSB-LC}(t) &= [A + m(t)] \cos \omega_c t \\ &= A[1 + \mu \cos \omega_m t] \cos \omega_c t \end{aligned}$$



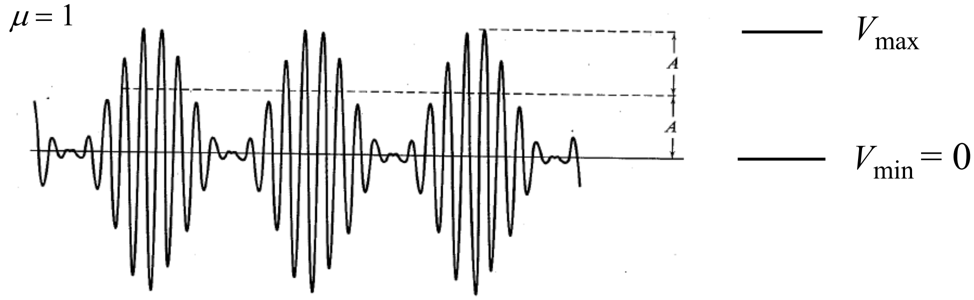


# Modulation Index

- Exercise: Given an AM signal that has been modulated by a single tone (*i.e.,* a cosine signal), and values for $V_{\max}$ and $V_{\min}$, derive an expression for the modulation index $\mu$.




(*a*)




(*b*)

# Efficiency of DSB-LC

- The efficiency of a DSB-LC system is the percentage of the power carried by the sidebands,

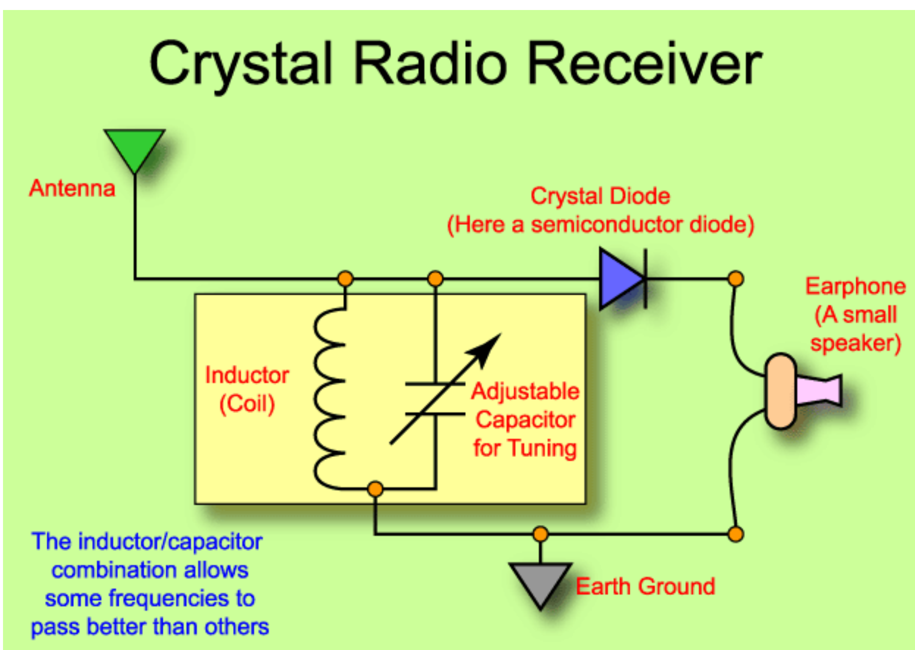
$$\eta = \frac{P_s}{P_t} \times 100\% .$$

- Can you show that

$$\eta = \frac{\mu^2}{2+\mu^2} \times 100\% \qquad ?$$

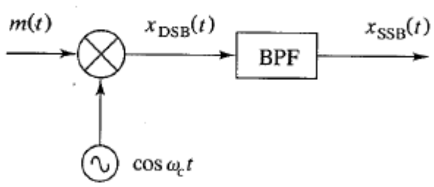


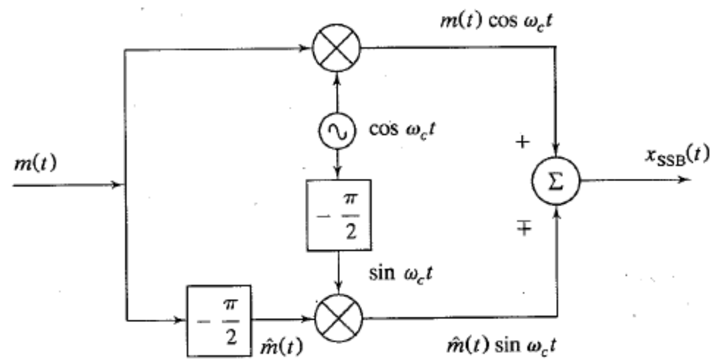




# 4. Single Sideband

- By eliminating one of the redundant sidebands, the bandwidth of a DSB-SC signal can be cut in half.
- The result is called *single sideband* or SSB.
- Removing a sideband is easier said than done!
- Using a bandpass filter is the most obvious approach, but requires extremely sharp (and expensive filters) but other methods (one due to Hartley, another to Weaver) are possible.





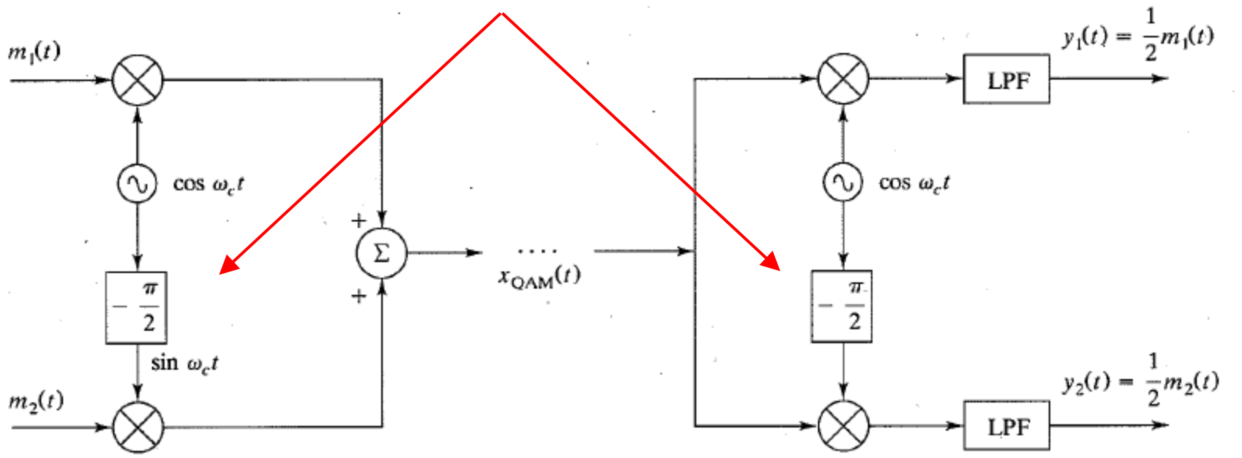



# Demodulation of Single Sideband Signals

- Depending upon which sideband is selected, an SSB signal is described as being USB (upper sideband) or LSB (lower sideband).
- The complexity of the modulator is one limitation of conventional SSB.
- Another is the need for a synchronous demodulator (identical to that used for DSB-SC) to recover the message signal.
- In the 1950's, engineers developed a more complicated form of SSB called *compatible SSB* that can be demodulated using an envelope detector.
- It has not been widely used in practice, however.

# 5. Quadrature Multiplexing

- The orthogonality of sine and cosine signals makes it possible to transmit two signals over the same channel simultaneously.
- This concept is the basis for a digital modulation scheme called quadrature amplitude modulation or QAM.
- What if the phase shift isn't exactly –π/2 rad?

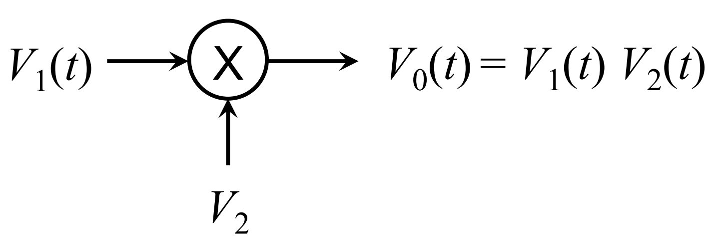







# 6. Frequency Mixers

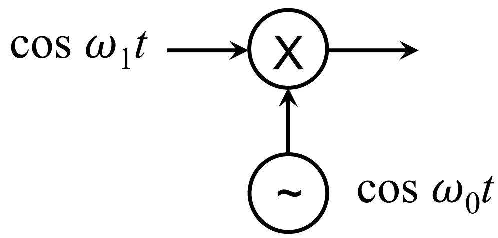
- The ideal mixer is a device that multiplies two time harmonic (or alternating current) input signals:



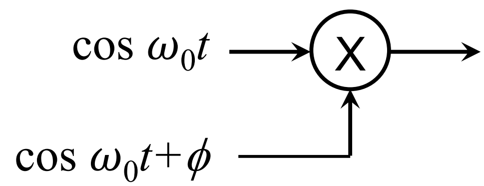

- If the inputs are sinusoids, the ideal mixer output is:

$$
\begin{aligned}
V_0 &= A_1 \cos\omega_1 t \;\; A_2 \cos\omega_2 t \\
&= \frac{A_1 A_2}{2}\left(\cos(\omega_1 - \omega_2)t + \cos(\omega_2 + \omega_1)t\right)
\end{aligned}
$$

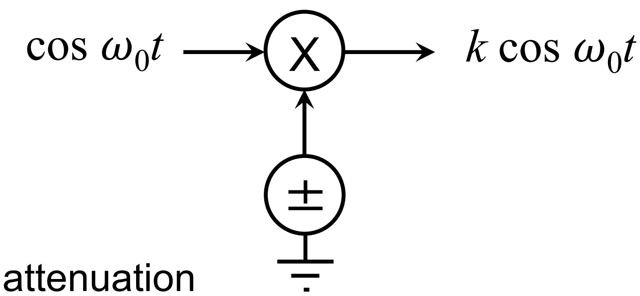
# Applications of Frequency Mixers




Frequency conversion




Phase detection




RF attenuation





# 7. Mixer Types

- In the remainder of this briefing, we consider two aspects of mixers:
  - system-level parameters
  - implementation details

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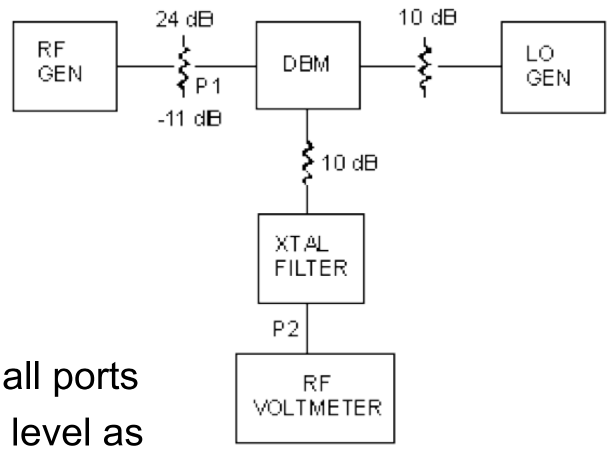
- There are two basic types of passive mixers:
  - single balanced
  - double balanced
- Double balanced mixers generally offer far better performance than single balanced mixers.
- The most obvious difference: double balanced mixers offer high isolation between ports.

# Measuring Mixer Performance

- Conversion Gain is a measure of the efficiency of the mixer in providing frequency translation between the input RF signal and a *single sideband* of the output IF signal.

$$G_{conv} = \frac{P_{\text{IF, SSB}}}{P_{\text{RF}}}$$




- 50 Ω on all ports
- LO drive level as specified by the vendor

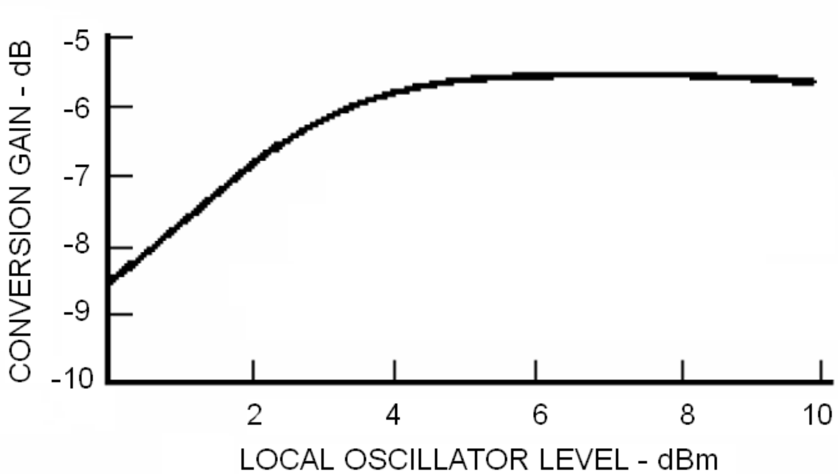
A typical test set up





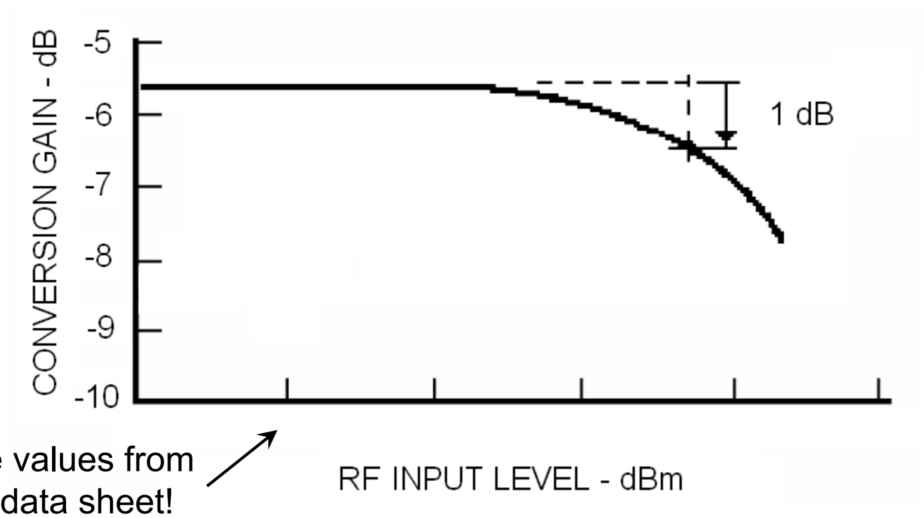
# LO Drive Level

- Conversion gain increases as the LO drive level increases until an optimum level is reached. This is usually specified by the vendor.
- Above this value, conversion gain will begin to drop and the output of the mixer will become distorted.



# Conversion Compression

- Conversion compression is a measure of the maximum RF input signal for which the mixer will provide linear operation.
- The 1 dB compression point is the RF input level at which the conversion gain is 1 dB less than its value at low input levels.

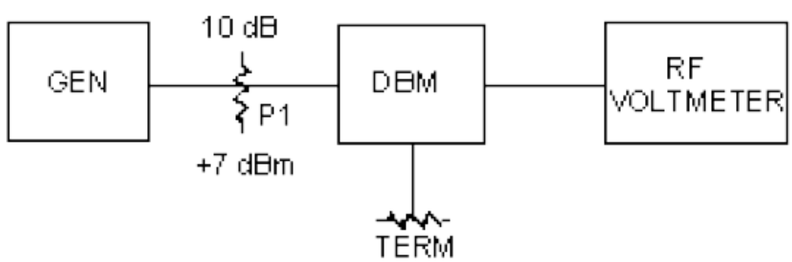



Fill in these values from the mixer data sheet!





# Isolation




- Either LO-RF isolation or LO-IF isolation can be measured.
- Normally, only LO-*x* isolation is specified because the LO drive level is normally >> RF signal level.

# 8. The Double Balanced Mixer as a Phase Detector

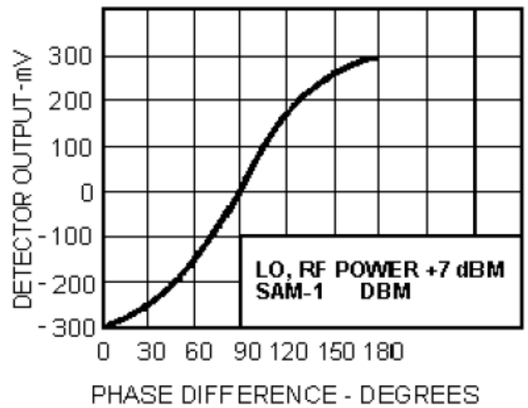
$$A_1 \cos(\omega_0 t) \longrightarrow \otimes \longleftarrow A_2 \cos(\omega_0 t + \varphi)$$

$$\downarrow$$

$$\frac{A_1 A_2}{2} k \cos\varphi + \left( \frac{A_1 A_2}{2} k \cos(2\omega_0 t + \varphi) \right)$$

- we must remove the second harmonic term with a LPF

Is there anything unusual about this plot? →








# Parameters of a Phase Detector

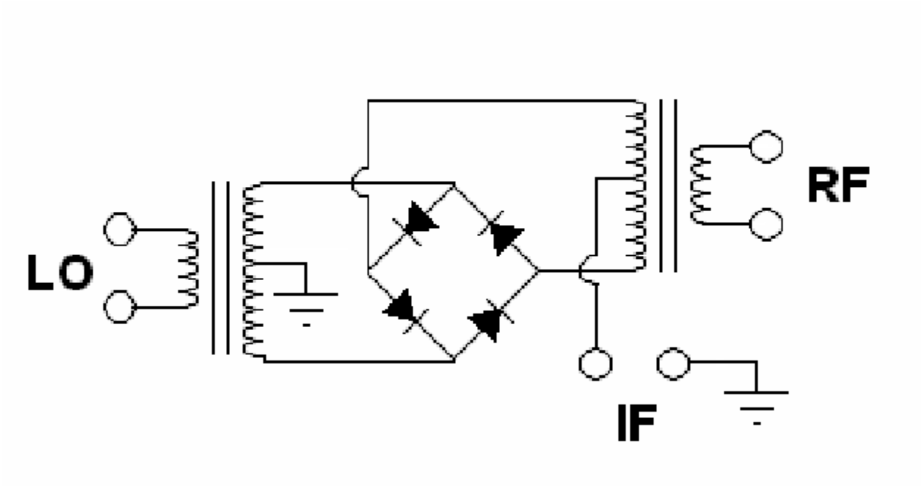
$$\text{Figure of Merit } (M) = \frac{\text{maximum DC voltage at the IF port (mV)}}{\text{RF drive power (dBm)}}$$

- For the SAM-1 on the previous slide

  $M$ = 300 mV/4 dBm = 43

- Not bad for a DBM, but a ‘good” phase detector might have a figure-of-merit of > 100
- Other parameters of interest:
  - DC Offset – the voltage present when: (1) only one signal is present or (2) the two RF signals are in quadrature
  - Frequency Range –such that $M > 0.75\ M_{\text{max}}$
  - Scale Factor – Phase detector output (mV/deg)

# Inside a Double-Balanced Mixer

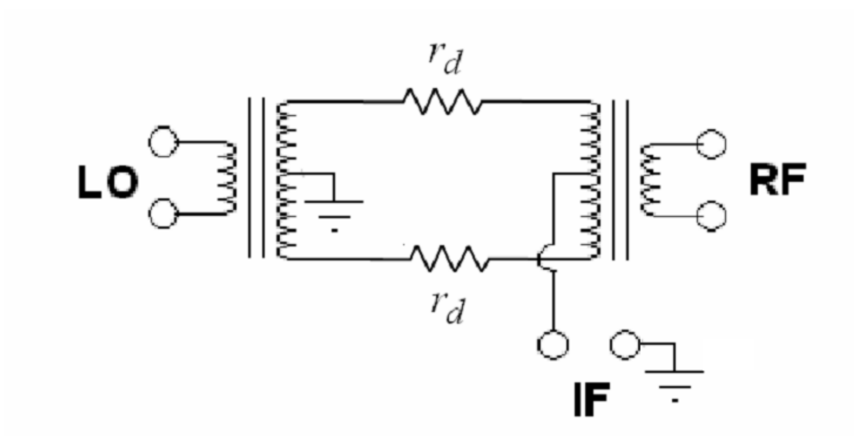



- Where there is no IF signal, isolation between the LO and RF ports is very high.
- If a DC voltage is applied to the IF port, two of the diodes in the ring will start to conduct.





# Applying a DC voltage to the IF port




- Suppose we apply a DC voltage to the IF port
- As $I_{IF}$ increases, $r_d$ will drop and port isolation will drop
- If $I_{IF}$ reverses polarity, the phase of the RF output will shift by 180 degrees. (Why?)

- Here, the insertion gain is (approximately) proportional to the DC drive current while the phase (0 or 180 deg) depends upon the polarity of the drive signal.
- This behaviour suggests that a double-balanced mixer could be used as
  - an RF switch
  - an RF attenuator
  - a BPSK modulator
- Analysis of a four-diode switching mixer as an RF multiplier is a little more complex – a topic best left to fourth year or graduate courses in RF Electronics.





# Summary and Conclusions

- Many types of Amplitude Modulation have been devised: DSB-SC, DSB-LC, SSB, and VSB
- The design engineer must trade off simplicity and cost against the need to improve efficiency and reduce bandwidth.
- Frequency mixers are extremely versatile components that can be used as amplitude modulators, phase detectors, RF attenuators, digital modulators.
- In ELEC 411, you'll find that they're also a key component in superheterodyne receivers.
- Double-balanced mixer offer much better performance than singe-balanced mixers.
- Care must be taken to ensure that the RF and LO drive levels fall in the range appropriate for the mixer being used.