EE140 Introduction to Communication Systems

Lecture 6

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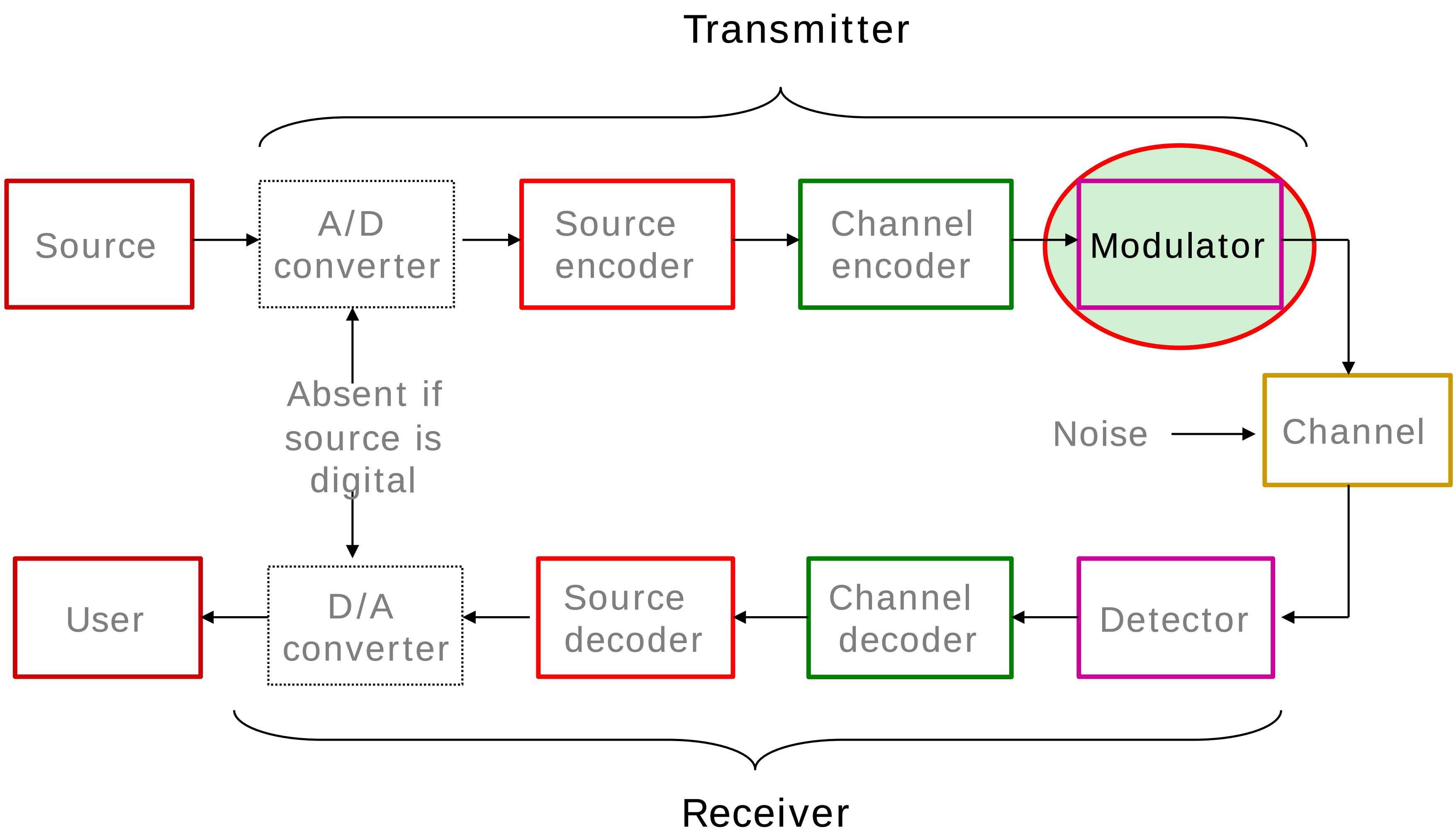
ShanghaiTech University, Fall 2022

Architecture of a (Digital) Communication System



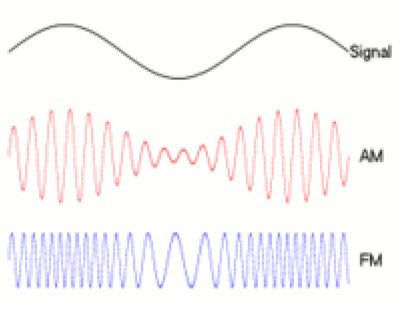
Examples of Analog Modulation

Telephony,
Analog TV, radio
broadcasting

Modulation

- What is modulation?
  - Transform a message into another signal to facilitate transmission over a communication channel
    - Generate a carrier signal at the transmitter
    - Modify some characteristics of the carrier with the information to be transmitted
    - Detect the modifications at the receiver

- Why modulation?
  - Frequency translation
  - Frequency-division multiplexing
  - Noise performance improvement



Modulation

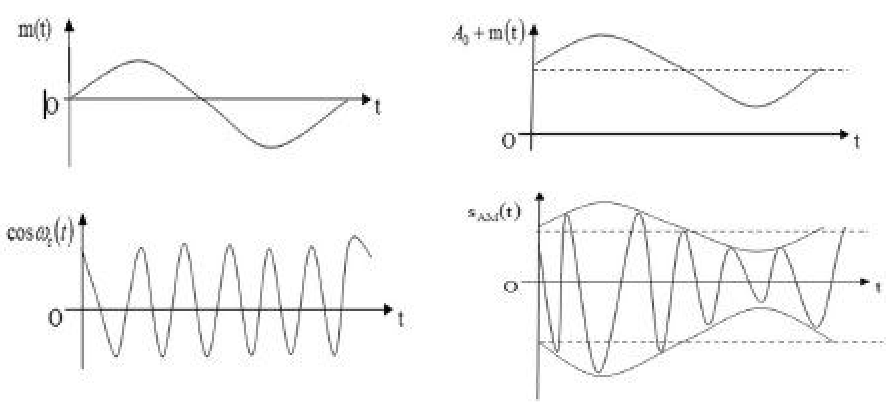
Analog Continuous-Wave Modulation

- Characteristics that can be modified in the carrier

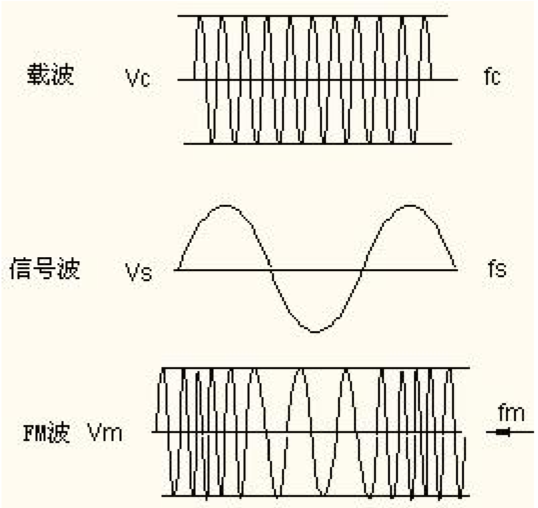
$$C(t) = A(t)\cos(2\pi f(t)t + \theta(t))$$

  - Amplitude $\Rightarrow$ Amplitude modulation
  - Frequency
  - Phase

  $\left.\begin{array}{l}\text{Frequency}\\\text{Phase}\end{array}\right\} \Rightarrow$ Angle modulation



AM



PM

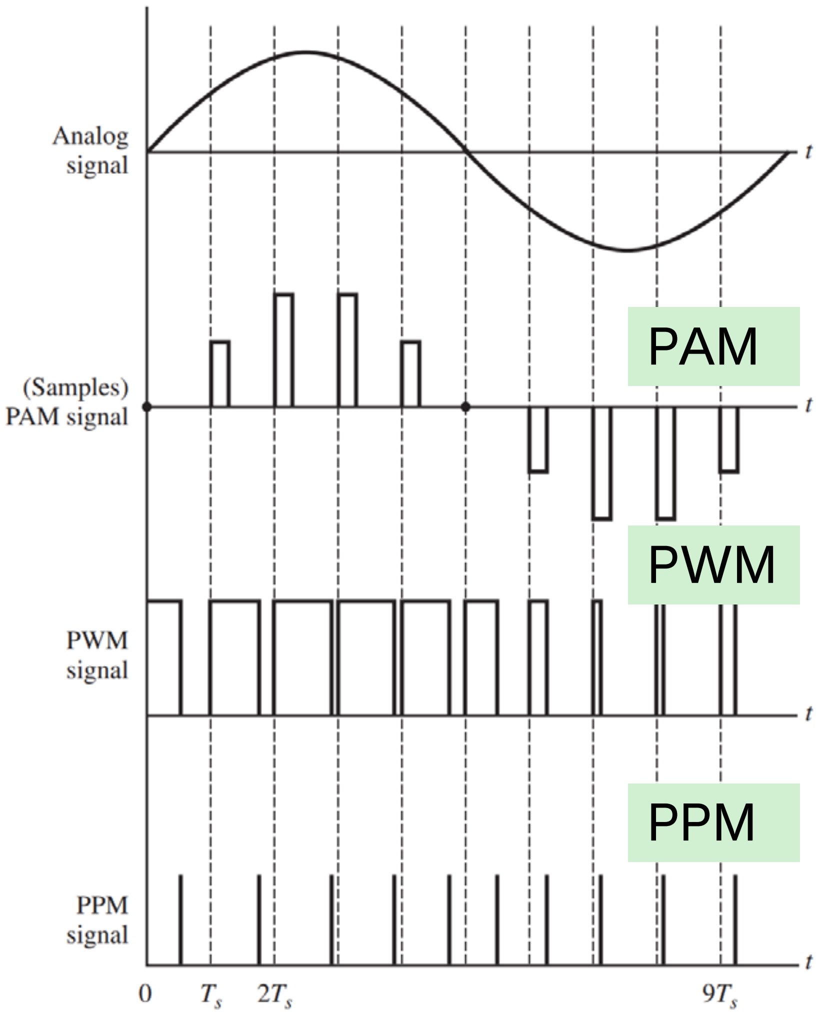
Analog Pulse Modulation

- Characteristics that can be modified in the carrier

$$C(t) = \sum_n \Pi\left(\frac{t - nT_S + \frac{1}{2}\tau}{\tau}\right)$$

  - Amplitude ⇨ Amplitude modulation
  - Width
  - Position

  Width, Position ⇨ Angle Modulation



Outline

Continuous-wave modulation: amplitude modulation

⇓

Pulse modulation: amplitude modulation

Linear Modulation

⇓

Continuous-wave modulation: angle modulation

⇓

Pulse modulation: angle modulation

Non-linear Modulation

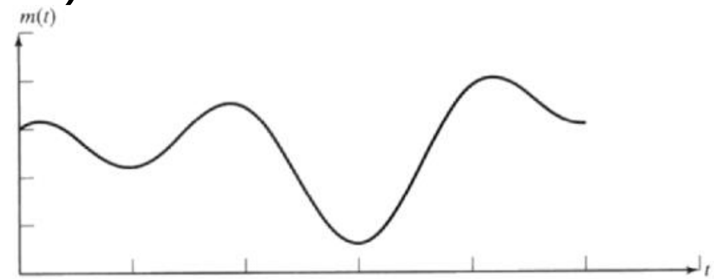
Contents

- Analog Modulation
  - Continuous-Wave Amplitude Modulation
    - DSB
    - SSB
    - VSB
  - Pulse Amplitude Modulation
  - Angle Modulation (phase/frequency)

Amplitude Modulation

- Double-sideband suppressed-carrier AM (DSB-SC)
  - Baseband signal (modulating wave):

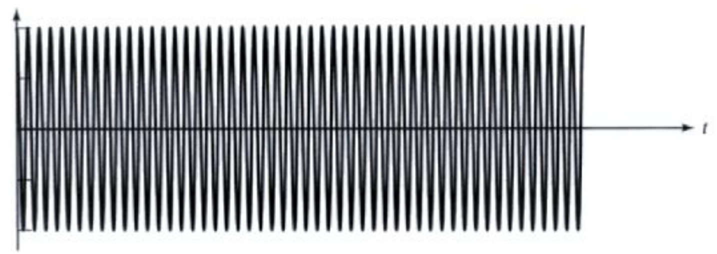
    $m(t)$



  - Carrier wave

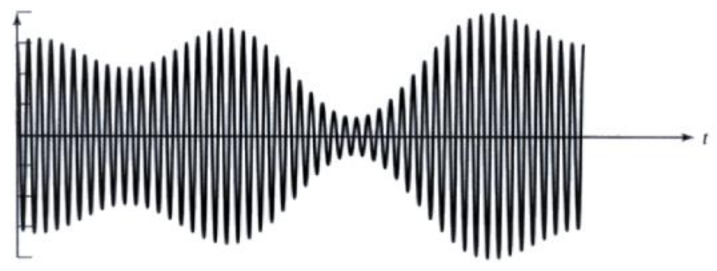
    $C(t) = A_c \cos(2\pi f_c t)$

  - Modulated wave

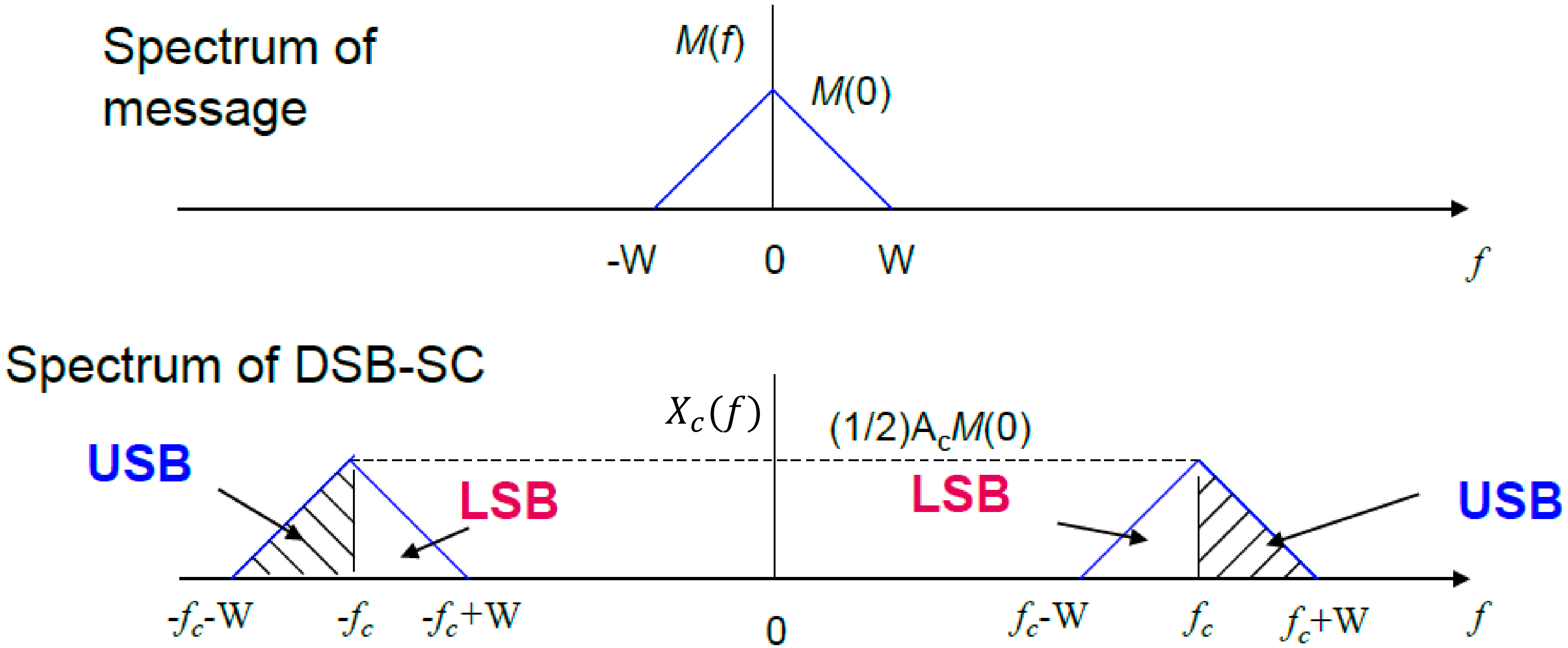


$$\mathrm{x}_c(t) = m(t)C(t)$$
$$= A_c m(t) \cos(2\pi f_c t)$$

$$X_c(f)$$
$$= \frac{1}{2} A_c M(f + f_c) + \frac{1}{2} A_c M(f - f_c)$$



DSB-SC Spectrum

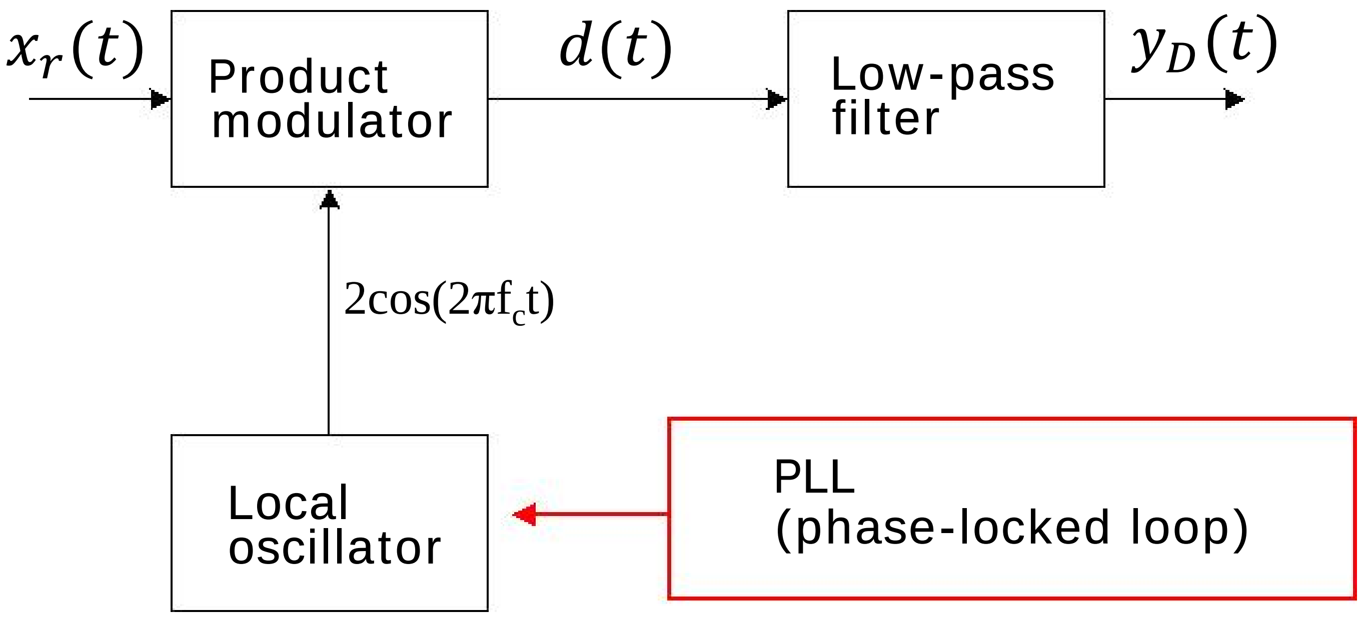


$$X_c(f) = \frac{1}{2}A_c[M(f - f_c) + M(f + f_c)]$$

Demodulation of DSB-SC Signals

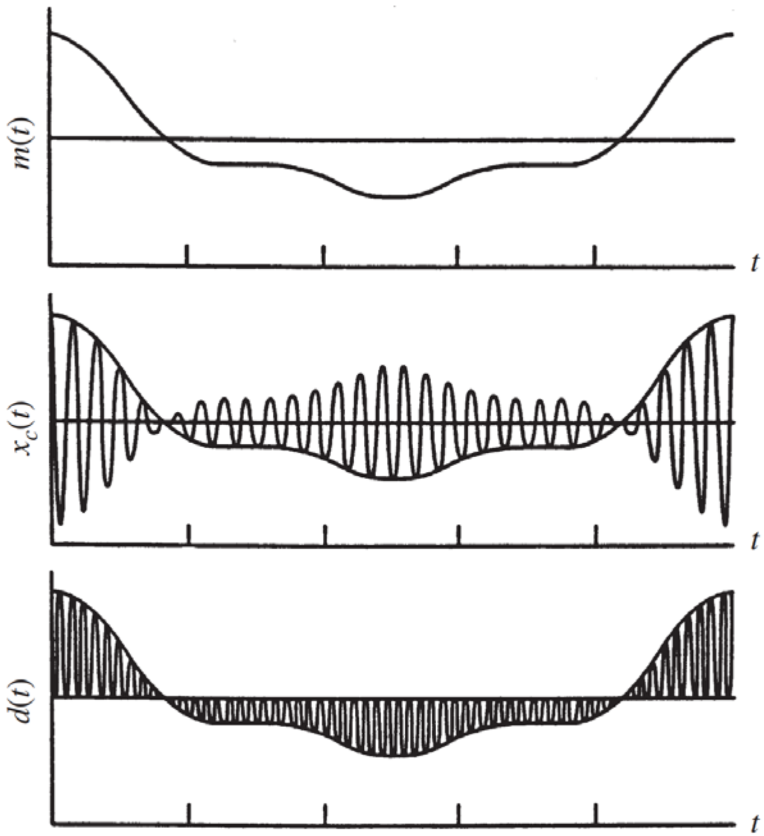
- Phase-coherent demodulation

$$d(t) = x_c(t) 2\cos 2\pi f_c t = A_c m(t) 2\cos^2 2\pi f_c t$$
$$= A_c m(t) + A_c m(t)\ \cos 4\pi f_c t$$

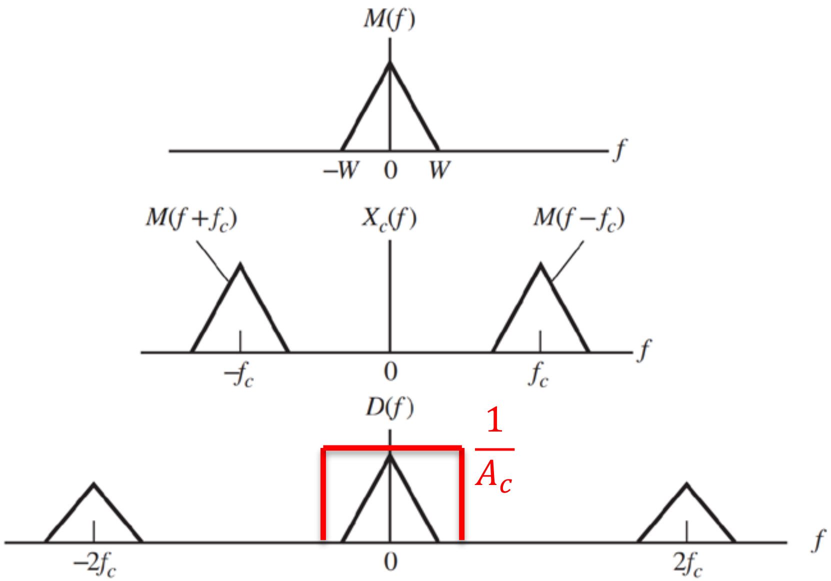


Demodulation of DSB-SC Signals

- DSB-SC demodulation: graphic interpretation



(b)



(c)

LP filter

Comment on DSB-SC

- Good:
  - 100% power efficient
- Bad:
  - High transmission bandwidth: B=2W
  - Demodulation is difficult: Phase Coherent
    - **Phase error**→ serious distortion

Time-varying phase error

$$d(t) = x_c(t) 2\cos(2\pi f_c t + \theta(t))$$
$$= A_c \cos\theta(t)\, m(t) + A_c m(t) \cos(4\pi f_c t + \theta(t))$$
$$y_D(t) = m(t) \cos\theta(t)$$

Serious distortion

    - How to generate phase coherent demodulation carrier
      - Sol 1: Costas phase-locked loop: Complicate the receiver design
      - Sol 2: Transmit the carrier component with the DSB signal, simplify the demodulation design→ Double-sideband, Large-carrier (DSB-LC)

Double-sideband, Large-carrier (DSB-LC)

- DSB-LC signal (conventional AM signal) = DSB-SC signal + a carrier term

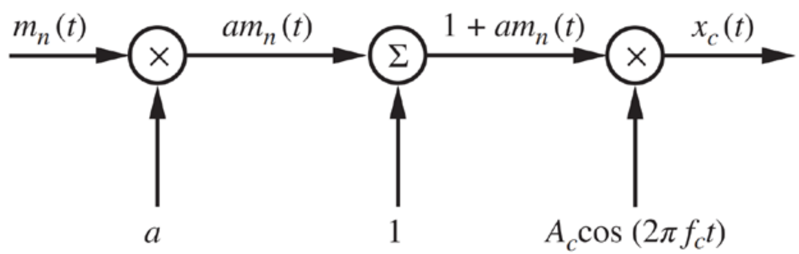
$$x_c(t) = A_c m(t)\cos 2\pi f_c t + A_c \cos 2\pi f_c t$$

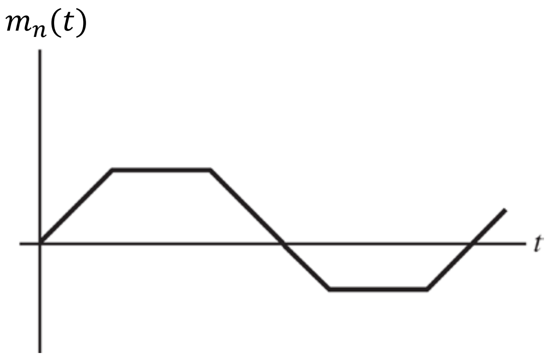
$$x_c(t) = A_c[1 + a m_n(t)]\cos 2\pi f_c t$$

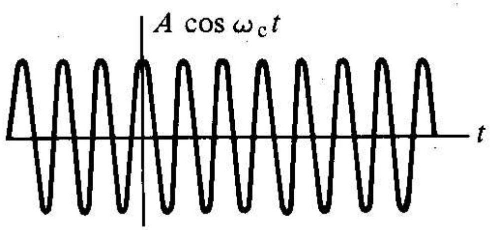
- a: modulation index, $0 < a \leq 1$
- $m_n(t) = \frac{m(t)}{|\min[m(t)]|} \geq -1$
- Envelope of the AM signal $A_c[1 + a m_n(t)]$ is nonnegative for all t

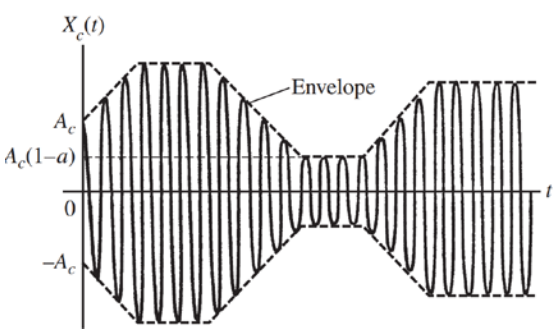
Graphic Interpretation

- DSB-LC signal



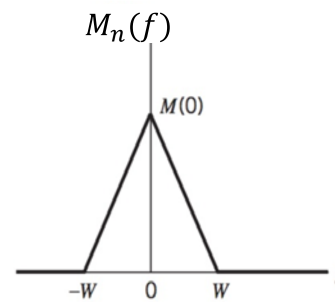


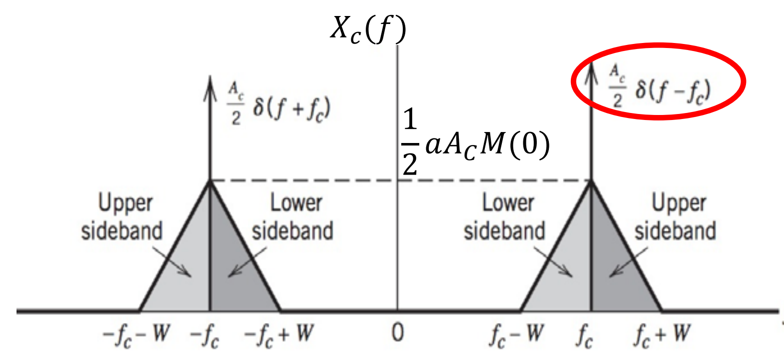




Time domain

Frequency domain

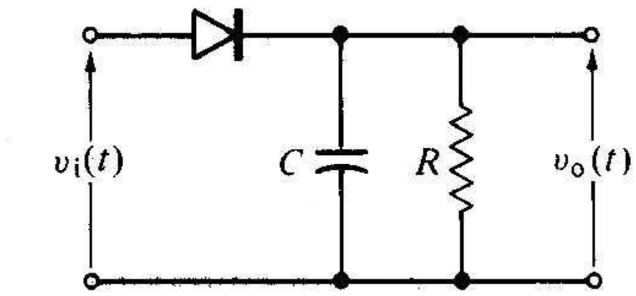




Demodulation of DSB-LC Signals

- Coherent demod: possible, but not easy.
  - Phase and frequency synchronizations are required;
- Noncoherent demod: envelope detection
  - The RC circuit can perform low pass filtering
  - Condition: $1.\ 1 + am_n(t) \geq 0 \Longleftrightarrow 0 < a \leq 1, m_n(t) \geq -1$

    $2.\ f_c \gg W$



The simplicity of envelop detector has made Conventional AM a practical choice for AM-radio broadcasting

Demodulation of DSB-LC Signals

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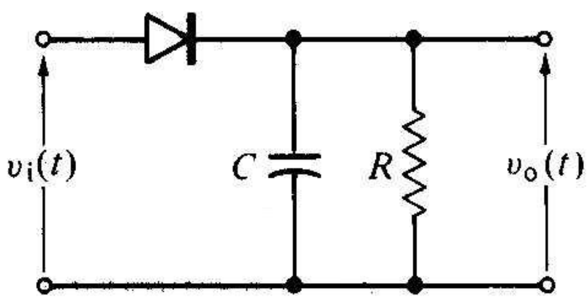
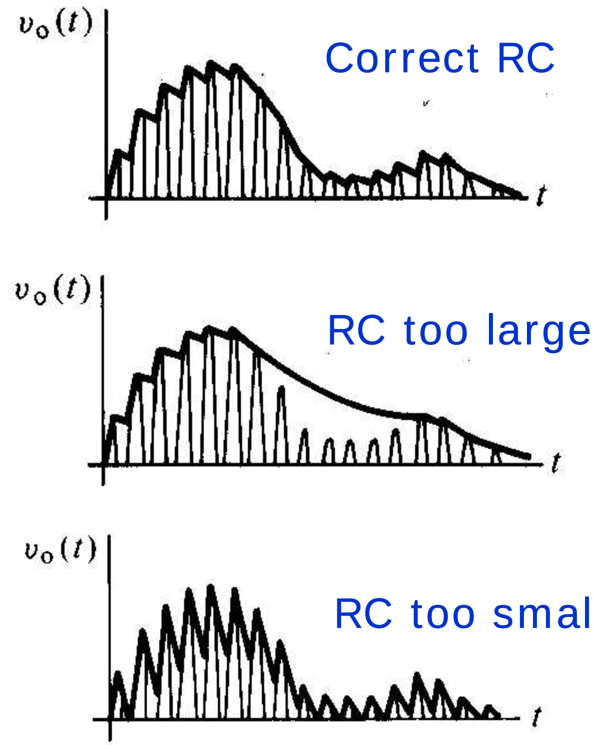
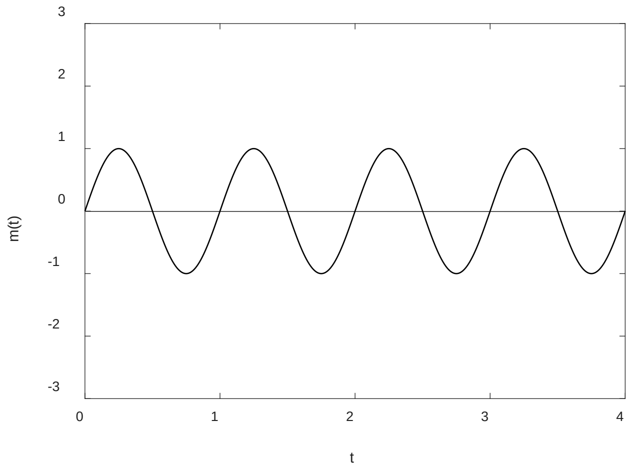
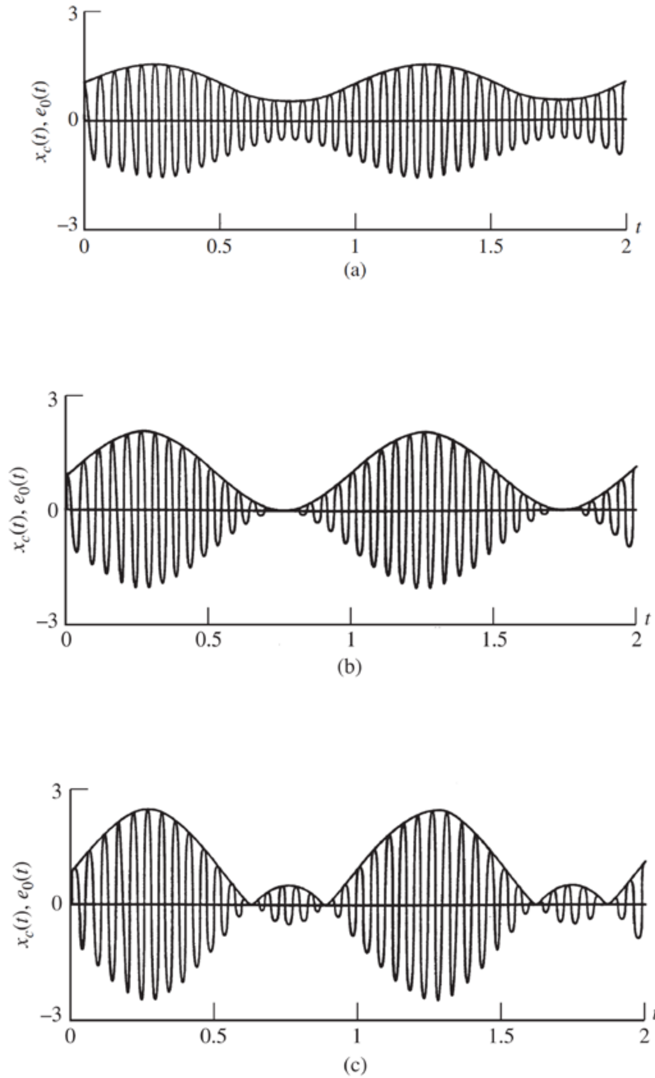




The simplicity of envelop detector has made Conventional AM a practical choice for AM-radio broadcasting

DSB-LC Properties





$a = 0.5$

$a = 1$

$a = 1.5$

- The role played by modulation index a
  - a<1: the envelope is always positive.
  - a=1: minimum value of envelope is zero
  - a>1: envelope detection output is badly distorted.

Transmission Efficiency

- Transmission (modulation,power) efficiency:

$$\begin{aligned}\langle x_c^2(t)\rangle &= \langle A_c^2[1+am_n(t)]^2\cos^2(2\pi f_c t)\ \rangle \\ &= \left\langle \frac{1}{2}A_c^2[1+am_n(t)]^2(1+\cos(4\pi f_c t)\right\rangle \\ &= \left\langle \frac{1}{2}A_c^2[1+am_n(t)]^2\right\rangle \\ &= \frac{1}{2}A_c^2+\frac{1}{2}A_c^2a^2\langle m_n^2(t)\rangle\end{aligned}$$

$m_n(t)$ is slowly varying w.r.t. carrier

$m_n(t)$: zero-average

- The transmission efficiency

$$\mu=\frac{P_s}{P_t}=\frac{\frac{1}{2}A_c^2a^2\langle m_n^2(t)\rangle}{\frac{1}{2}A_c^2a^2\langle m_n^2(t)\rangle+\frac{1}{2}A_c^2}=\frac{a^2\langle m_n^2(t)\rangle}{a^2\langle m_n^2(t)\rangle+1}$$

- If $|\min m(t)|=|\max m(t)|$, the maximum efficiency is 50% for a=1.
  - $\langle m_n(t)\rangle^2\le 1$
  - Square-wave-type message signal

Transmission Efficiency

- The transmission efficiency

$$\mu = \frac{P_s}{P_t} = \frac{\frac{1}{2}A_c^2 a^2 \langle m_n^2(t) \rangle}{\frac{1}{2}A_c^2 a^2 \langle m_n^2(t) \rangle + \frac{1}{2}A_c^2} = \frac{a^2 \langle m_n^2(t) \rangle}{a^2 \langle m_n^2(t) \rangle + 1}$$

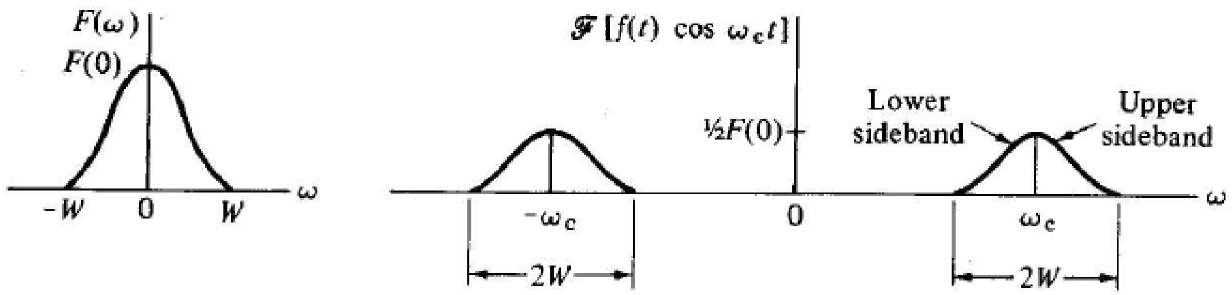
  - If $|\min m(t)| = |\max m(t)|$, the maximum efficiency is 50% for a=1.
  - If $m(t) = cos(2\pi t)$,$\langle m^2(t) \rangle = \frac{1}{2} \rightarrow \ \mu = 33\%$ for a=1.
  - For comparison, the transmission efficiency of a DSB-SC system is 100%.

Comment on DSB-LC (AM)

- Good:
  - Demodulation is simple and inexpensive: envelope detection
- Bad:
  - Low power efficiency
  - High transmission bandwidth: B=2W

Single-sideband (SSB) Modulation

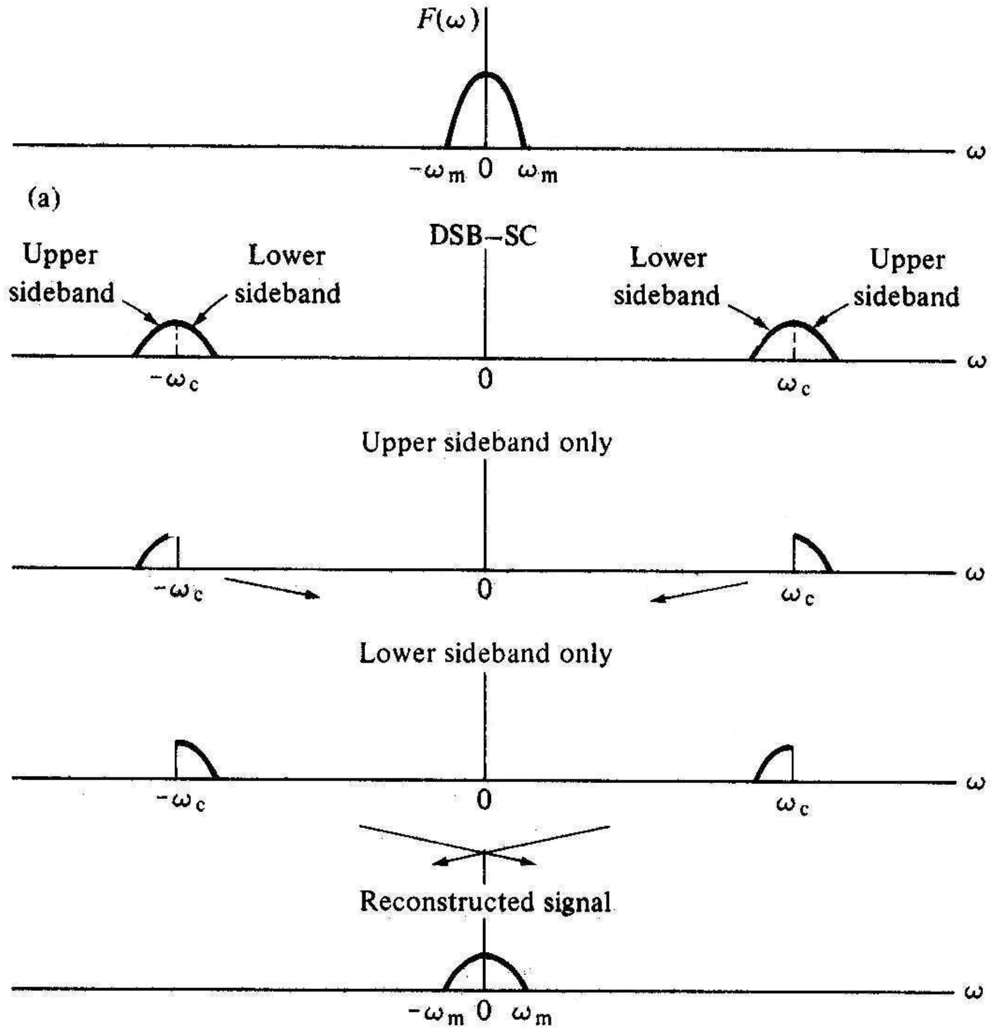
- DSB modulation results in a doubling of the bandwidth of a given signal.



- Each pair of sidebands (i.e. upper or lower) contains the complete information of the original signal.
- The original signal can be recovered again from either the upper or lower pair of sidebands by an appropriate frequency translation. ➔ single-sideband modulation

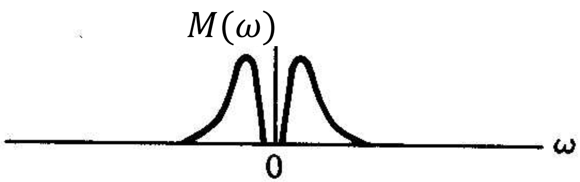
SSB

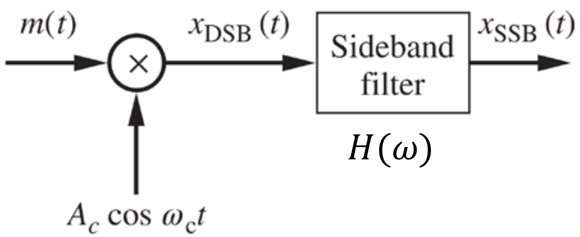
- Advantage: SSB modulation is efficient because it requires no more bandwidth than that of the original signal and only half that of the corresponding DSB signal.

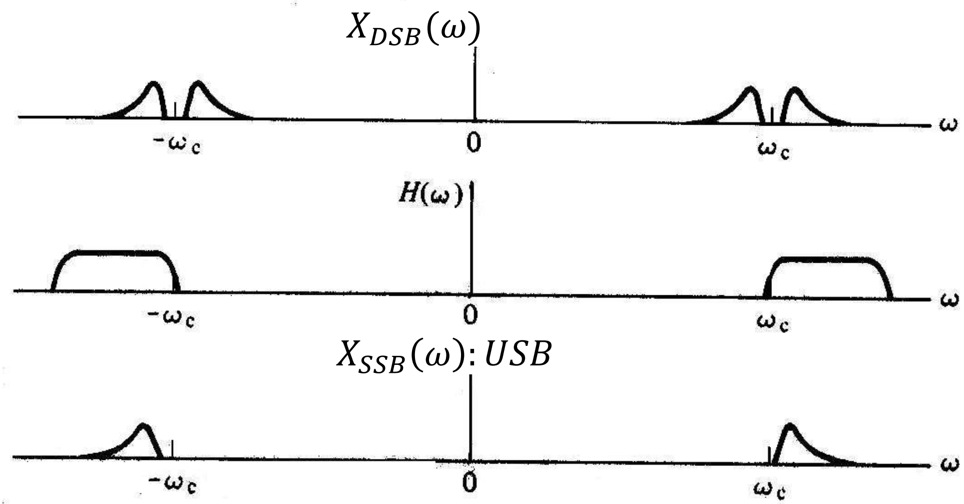


Generation of SSB Signals

- Generation of SSB signals
- Method 1: sideband filtering
  - generate a DSB-SC signal;
  - filter out one pair of sidebands (upper or lower).
- Requirement of method 1:
  - does not contain significant low-frequency components;
  - Ideal filter if low-freq is contained in m(t).





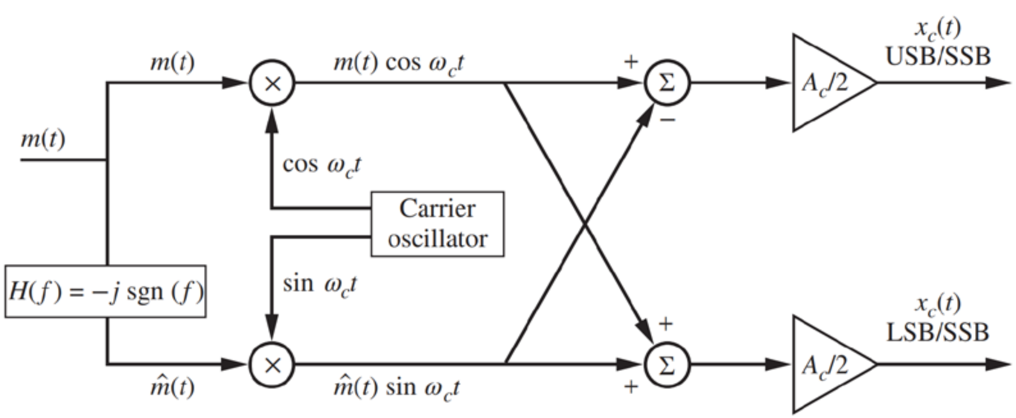


Generation of SSB Signals (Cont'd)

- Method 2: phase-shift
  - generate the quadrature function $\hat{m}(t)$ by shifting the phase of $m(t)$ by 90 degrees at each frequency component.
  - Upper (SSB+) sideband and lower (SSB-) sideband are given by

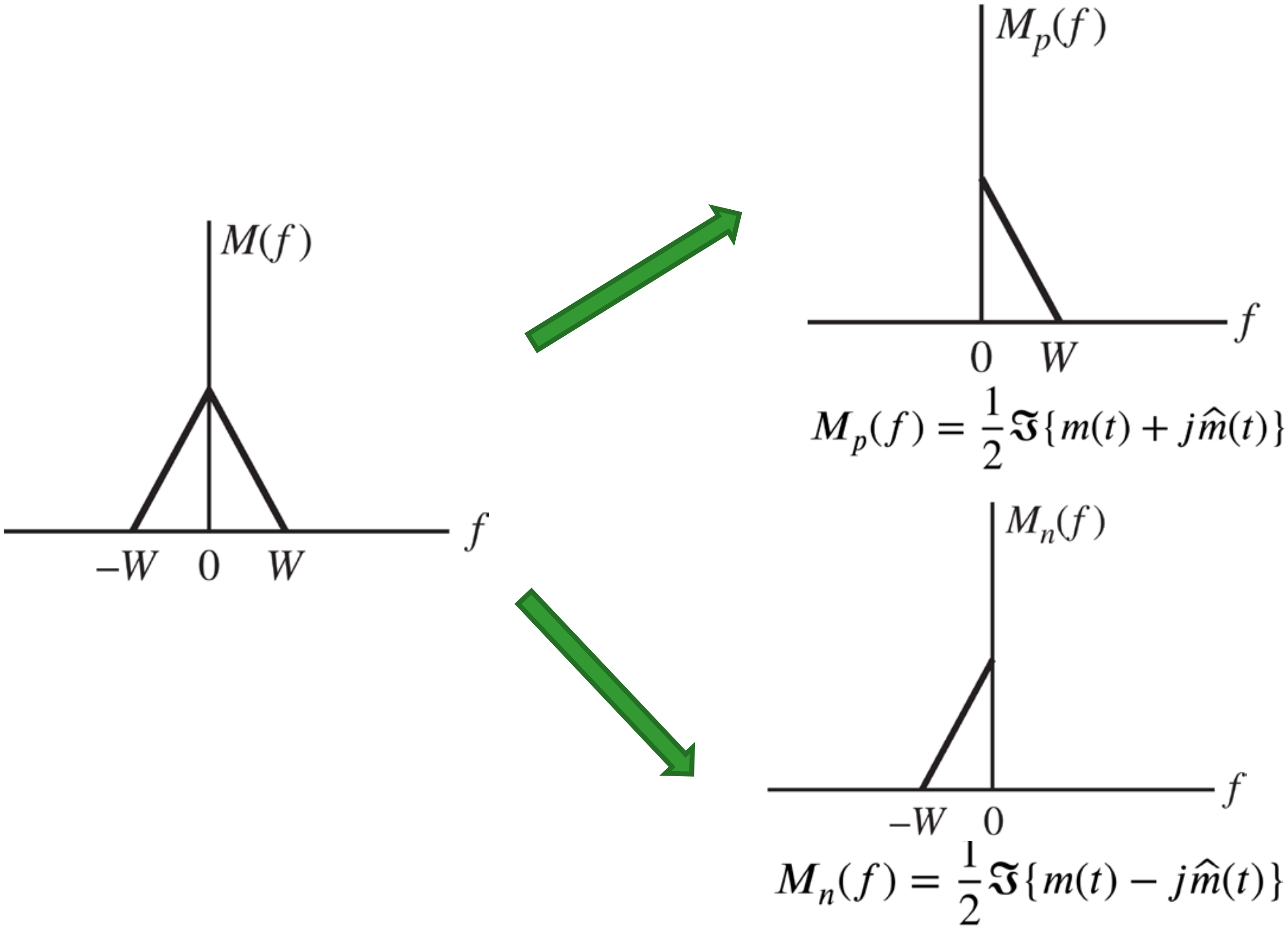
$$x_c(t) = x_{SSB\mp}(t) = \frac{1}{2}A_c m(t)\cos 2\pi f_c\, t \pm \frac{1}{2}A_c \hat{m}(t)\sin 2\pi f_c\, t$$

- Requirement:
  - phase shifted by exactly 90 degrees.
  - Ideal wideband phase shifter



Generation of SSB Signals (Cont'd)

- Method 2: phase-shift

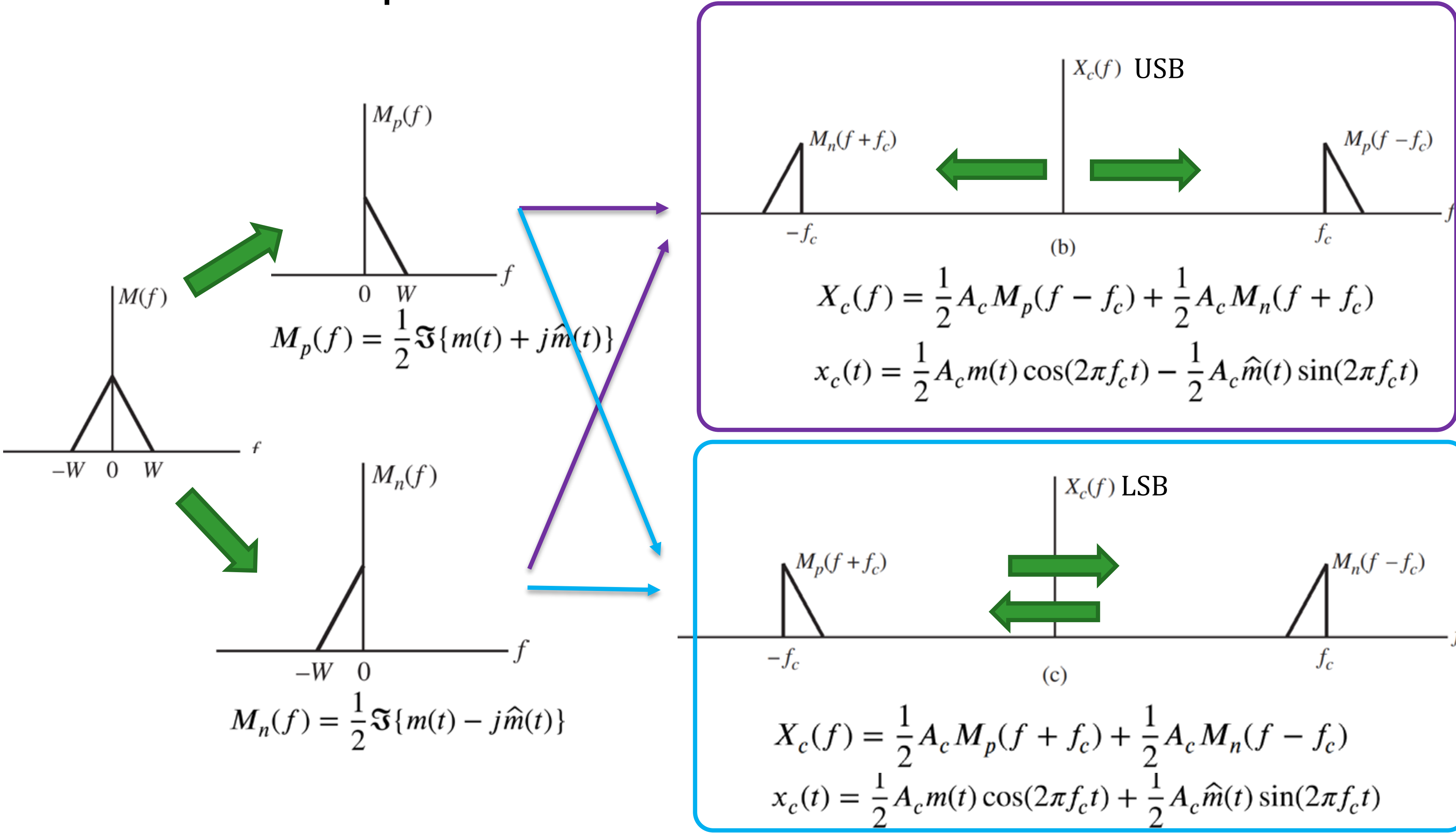


$$M_p(f) = \frac{1}{2}\Im\{m(t) + j\hat{m}(t)\}$$

$$M_n(f) = \frac{1}{2}\Im\{m(t) - j\hat{m}(t)\}$$

Generation of SSB Signals (Cont'd)

- Method 2: phase-shift



$$M_p(f) = \frac{1}{2}\mathfrak{F}\{m(t) + j\hat{m}(t)\}$$

$$M_n(f) = \frac{1}{2}\mathfrak{F}\{m(t) - j\hat{m}(t)\}$$

$$X_c(f) = \frac{1}{2}A_c M_p(f - f_c) + \frac{1}{2}A_c M_n(f + f_c)$$

$$x_c(t) = \frac{1}{2}A_c m(t)\cos(2\pi f_c t) - \frac{1}{2}A_c \hat{m}(t)\sin(2\pi f_c t)$$

$$X_c(f) = \frac{1}{2}A_c M_p(f + f_c) + \frac{1}{2}A_c M_n(f - f_c)$$

$$x_c(t) = \frac{1}{2}A_c m(t)\cos(2\pi f_c t) + \frac{1}{2}A_c \hat{m}(t)\sin(2\pi f_c t)$$

SSB Demodulation

- Synchronous detection
  - Received SSB signal:

$$x_c(t) = \frac{1}{2}A_c m(t)\cos 2\pi f_c\, t \pm \frac{1}{2}A_c \hat{m}(t)\sin 2\pi f_c\, t$$

  - Local generated carrier signal:

$$C(t) = 4\cos[\,2\pi f_c t + \theta(t)]$$

Time-varying phase error

$$x_c(t)C(t) = [\frac{1}{2}A_c m(t)\cos 2\pi f_c\, t \pm \frac{1}{2}A_c \hat{m}(t)\sin 2\pi f_c\, t]4\cos[\,2\pi f_c t + \theta(t)]$$
$$= A_c m(t)\,\{\cos[\,\theta(t)] + \cos[\,4\pi f_c t + \theta(t)]\} \mp A_c \hat{m}(t)\,\{\sin[\,\theta(t)] - \sin[\,4\pi f_c t + \theta]\}$$

  - Through a low-pass filter (LPF), the output is given by:

$$y_D(t) = m(t)\cos\theta(t) \mp \hat{m}(t)\sin\theta(t)$$

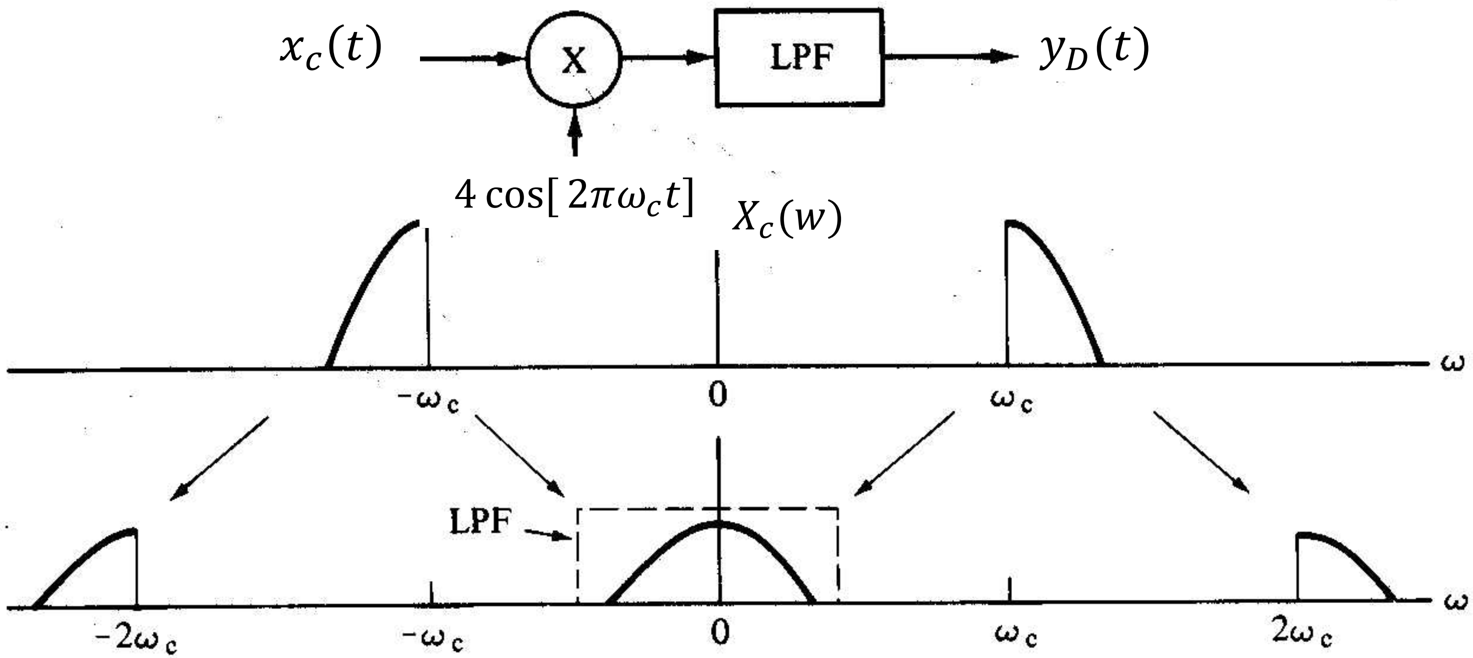
Serious distortion

  - If no error

$$y_D(t) = m(t)$$

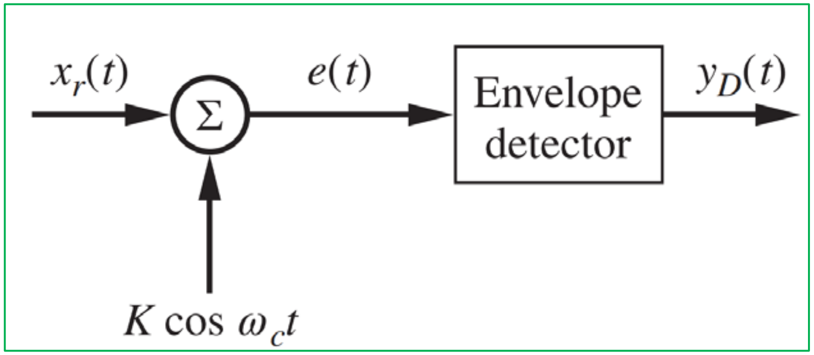
SSB Demodulation (Cont'd)

- Frequency domain graphic interpretation



SSB Demodulation

- Carrier Reinsertion



  - After carrier reinsertion

$$e(t) = \left[\frac{1}{2} A_c m(t) + K\right] \cos 2\pi f_c\, t \pm \frac{1}{2} A_c \widehat{m}(t) \sin 2\pi f_c\, t$$

  - Envelope detection, not straightforward

$$y_D(t) = \sqrt{[\frac{1}{2} A_c m(t) + K]^2 + [\frac{1}{2} A_c \widehat{m}(t)]^2}$$

$$\approx \frac{1}{2} A_c m(t) + K$$

$$[\frac{1}{2} A_c m(t) + K]^2 \gg [\frac{1}{2} A_c \widehat{m}(t)]^2$$

  - Requirement of envelope detection
    - The carrier is much larger than the SSB envelope
    - Phase coherent with original modulation carrier

Comments on SSB

- Good:
  - Save spectrum
  - Save energy
- Bad:
  - Complex implementation (modulation and demodulation)

Vestigial-sideband (VSB) Modulation

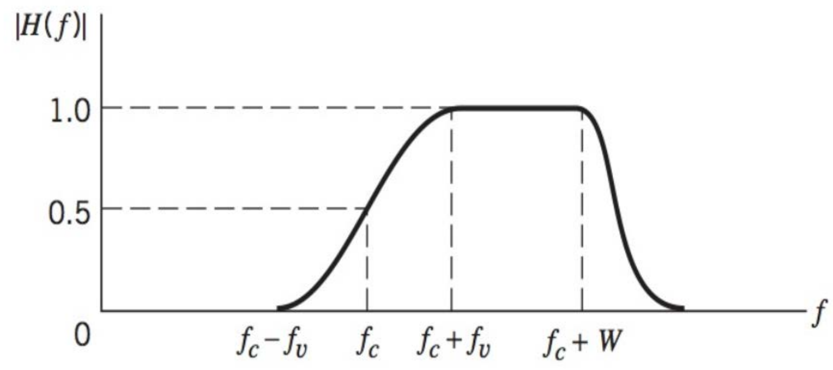
- The generation of SSB signals may be quite difficult when the modulating signal bandwidth is wide or where one cannot disregard the low-frequency components.
- In Vestigial-sideband (VSB) modulation, a portion of one sideband is transmitted.
- VSB is a compromise between SSB and DSB.
- Generation of VSB-SC signals: in frequency domain

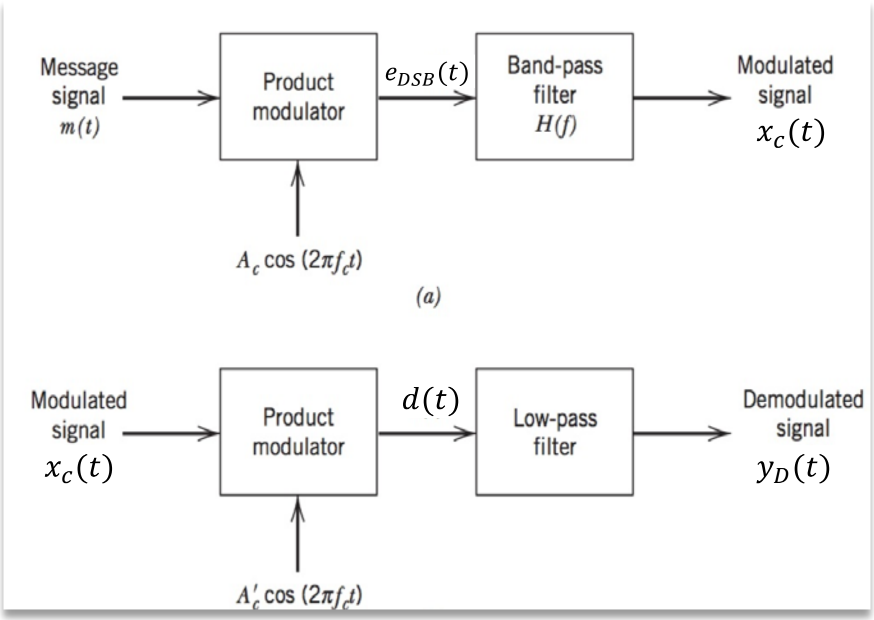
$$X_{VSB-SC}(f) = \frac{A_C}{2}[M(f + f_c) + M(f - f_c)]H(f)$$

  - Where filter $H(f)$ passes some of the lower (or upper) sideband and most of the upper (or lower) sideband.

Vestigial-sideband (VSB) Modulation

- The requirement on the filter
- Consider coherent detection





$$X_c(f) = \frac{A_C}{2}[M(f + f_c) + M(f - f_c)]H(f)$$

$$d(t) = A_c' x_c(t) \cos 2\pi f_c t$$

$$D(f) = \frac{A_c'}{2}[X_c(f + f_c) + X_c(f - f_c)] =$$

$$= \frac{A_C A_c'}{4}\{[H(f - f_c) + H(f + f_c)]M(f)$$

$$+ M(f + 2f_c)H(f + f_c)$$

$$Y_D(f) = \frac{A_C A_c'}{4} M(f)[H(f - f_c) + H(f + f_c)]$$

Vestigial-sideband (VSB) Modulation

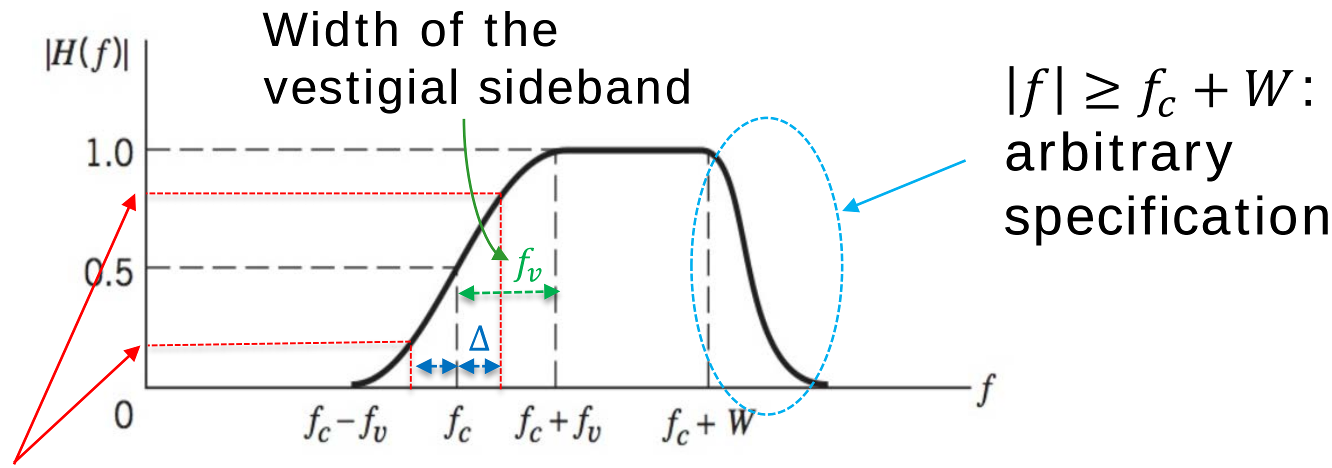
- The requirement on the filter

$$Y_D(f) = \frac{A_C A'_c}{4} M(f)[H(f - f_c) + H(f + f_c)]$$

- Recover the m(t) without distortion

$$H(f - f_c) + H(f + f_c) = 2H(f_c), -W \leq f \leq W$$

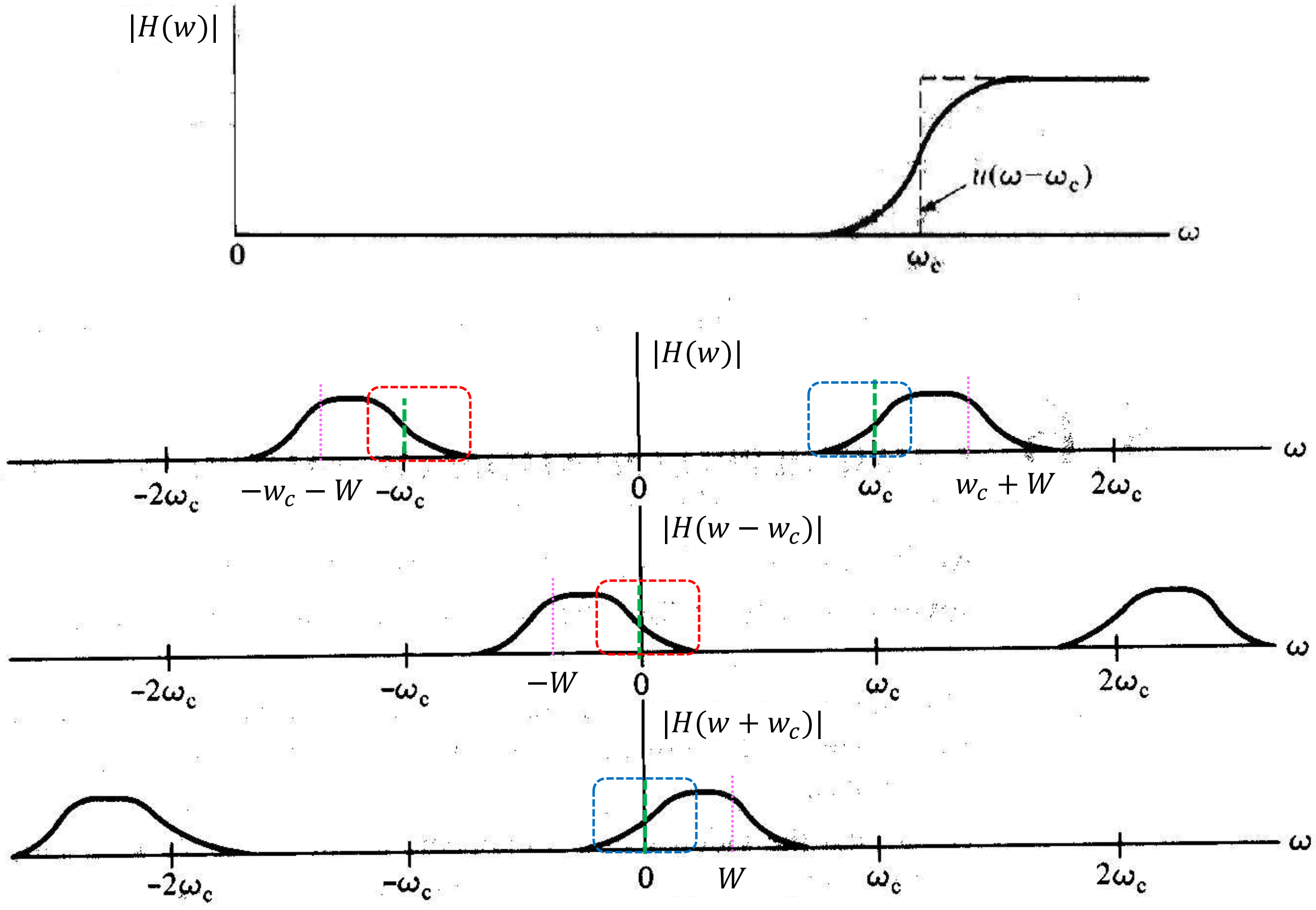
- Cutoff portion of H(f) is odd symmetric around fc.



Odd symmetry: $H(f_c + \Delta) + H(f_c - \Delta) = 2H(f_c), |\Delta| \leq f_v$

VSB Modulation (Cont'd)

- Frequency domain graphic interpretation

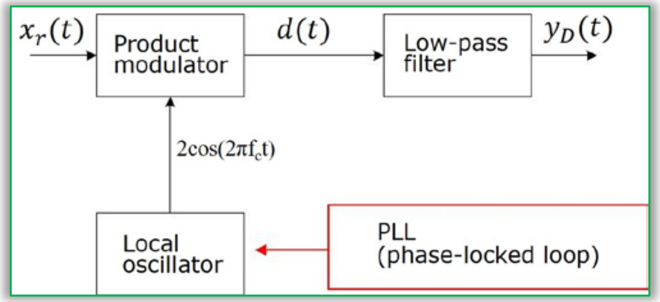


Comparison of AM Techniques

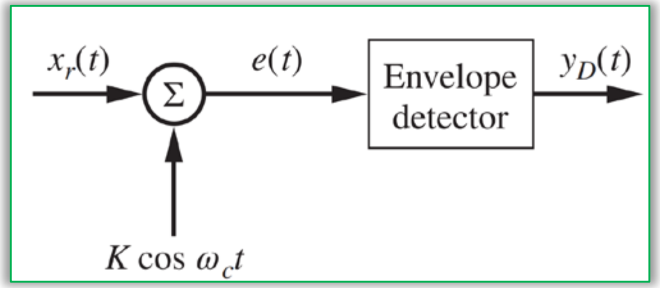
- DSB-SC:
  - more power efficient. Seldom used
- DSB-LC (AM):
  - simple envelop detector
  - Example: AM radio broadcast
- SSB:
  - requires minimum transmitter power and bandwidth. Suitable for point-to-point and over long distances
- VSB:
  - bandwidth requirement between SSB and DSBSC.
  - Example: TV transmission

Comparison of AM Techniques

- Demodulation
  - Coherent Demodulation
    - All linear modulation



  - Envelope Detection
    - DSB-LC(AM)
    - SSB + Carrier reinsertion
    - VSB + Carrier reinsertion



Contents

- Analog Modulation
  - Amplitude modulation
  - Pulse amplitude modulation
  - Angle modulation (phase/frequency)

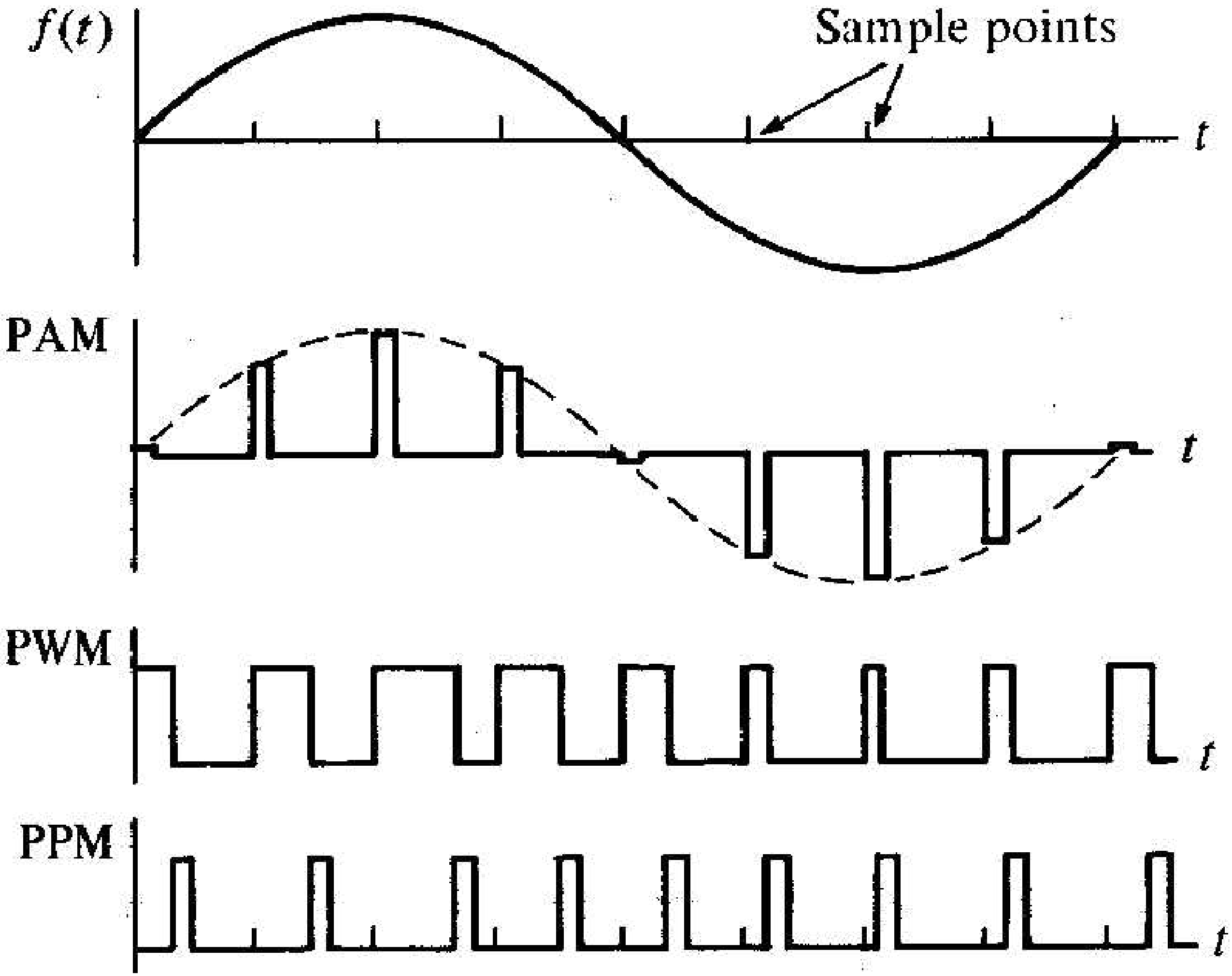
Analog Pulse Modulation

Modulating Signal

Pulse-Amplitude Modulation (PAM)

Pulse-Width Modulation (PWM)

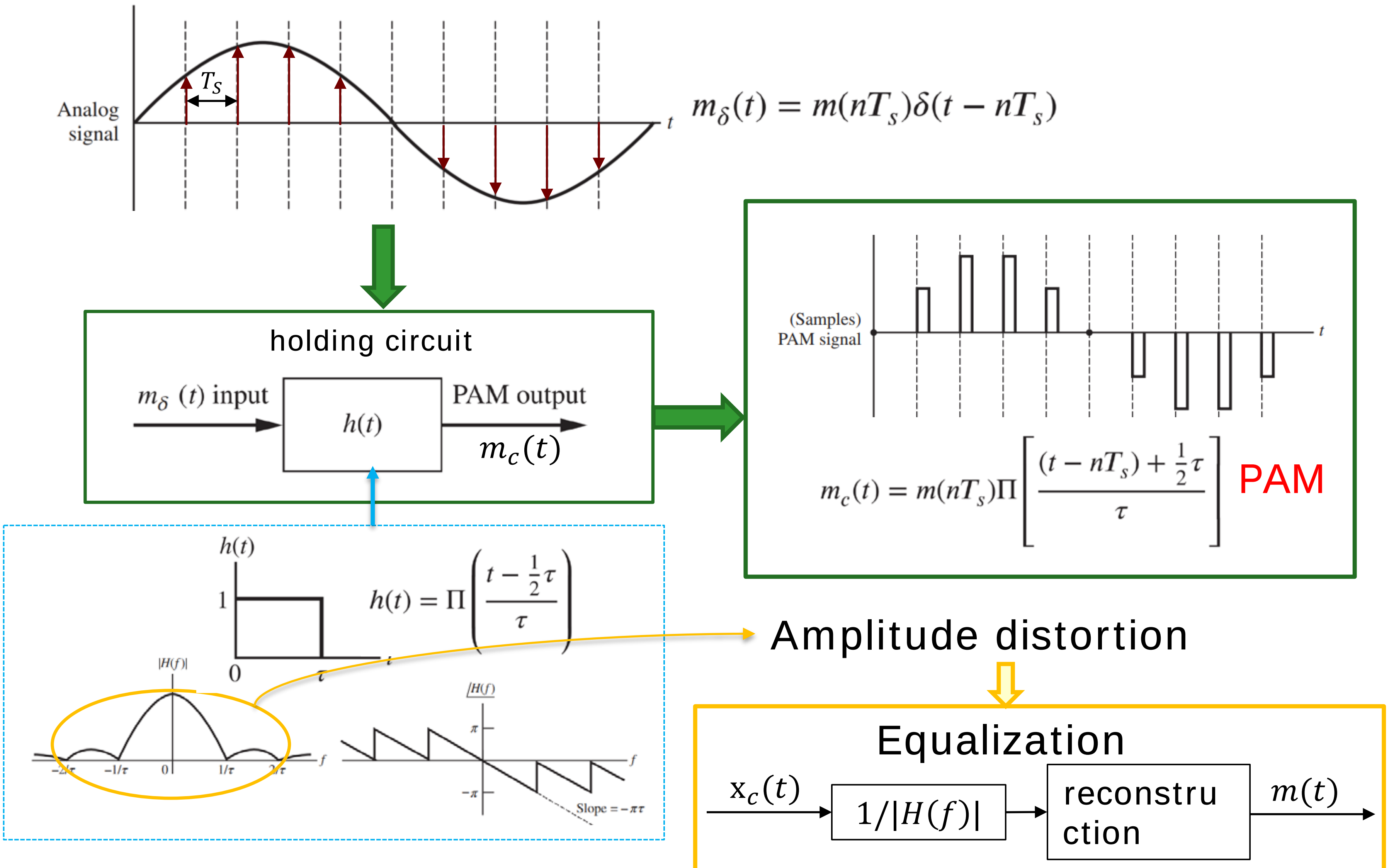
Pulse-Position Modulation (PPM)



Analog Pulse Modulation (cont'd)

- PAM: constant-width, uniformly spaced pulses whose amplitude is proportional to the values of the input at the sampling instants.
- PWM: constant-amplitude pulses whose width is proportional to the values of the input at the sampling instants.
- PPM: constant-width, constant-amplitude pulses whose position is proportional to the values of the input at the sampling instants.

Pulse Amplitude Modulation (PAM)



Thanks for your kind attention!

Questions?