EE140 Introduction to Communication Systems

Lecture 6

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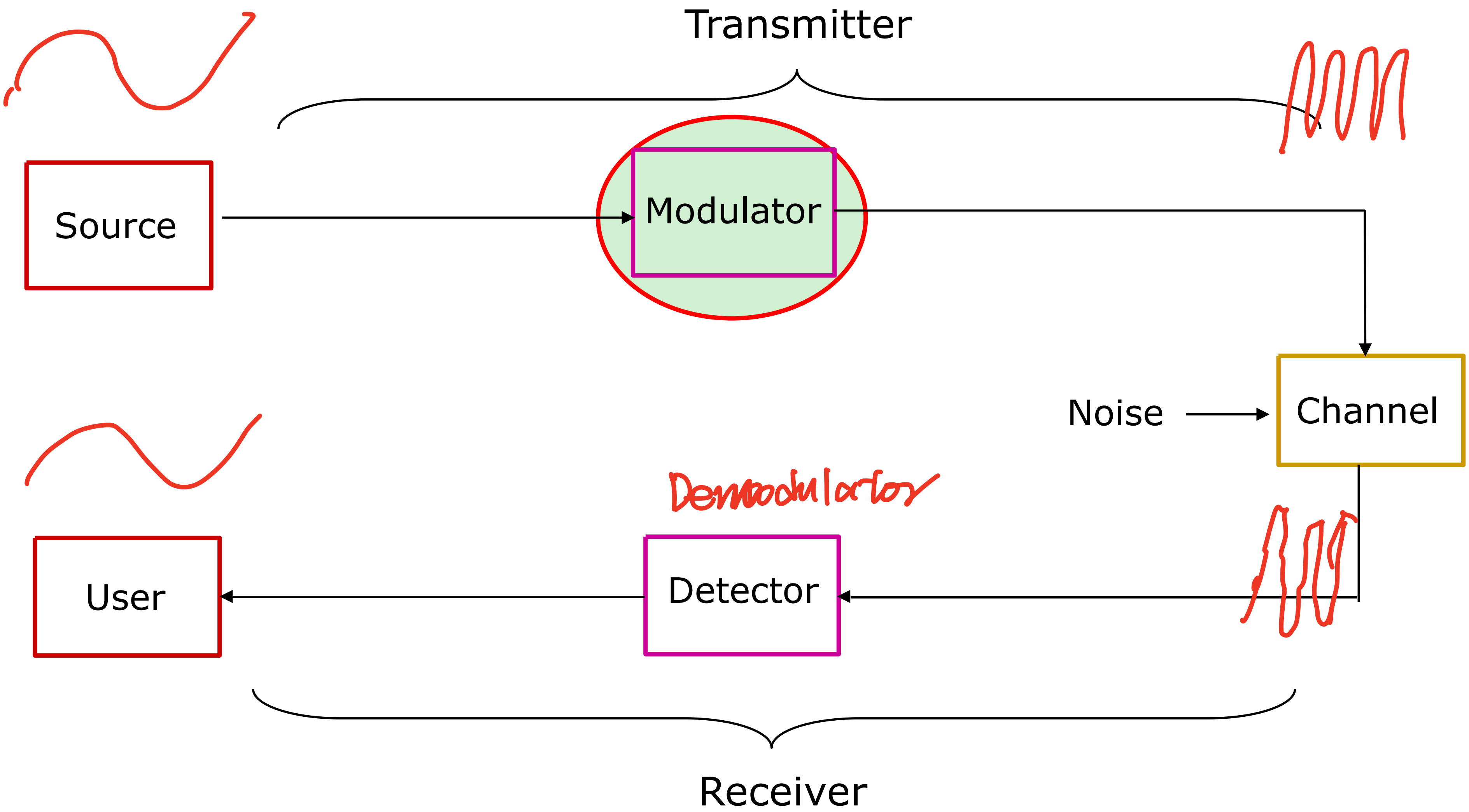
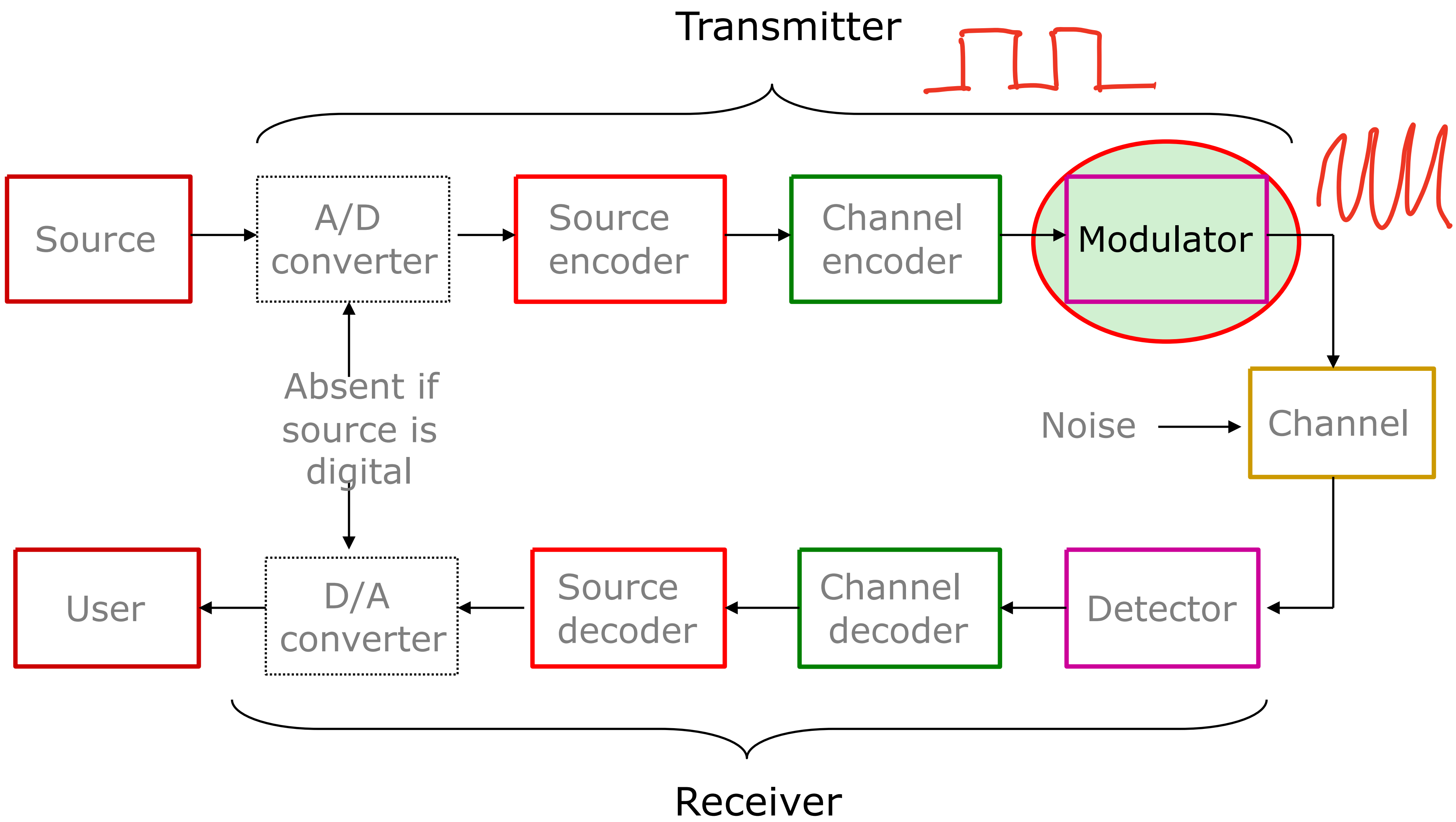
ShanghaiTech University, Fall 2025

Architecture of an Analog Communication System



Architecture of a (Digital) Communication System



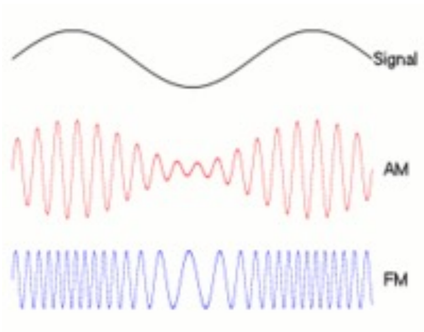
Examples of Analog Modulation

Telephony,
Analog TV, radio
broadcasting

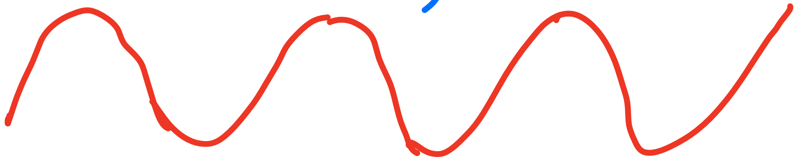
Modulation

- 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



Source $m(t)$

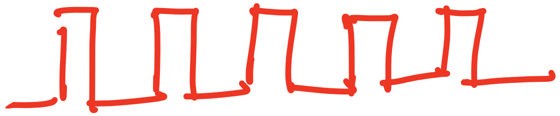


Baseband signal / Modulating signal

Carrier

- Analog continuous wave $c(t)$ sin/cos

- Analog pulse wave



Modulated signal $\underline{x_c(t)}$

Carrier $\underline{\sin/\cos}$

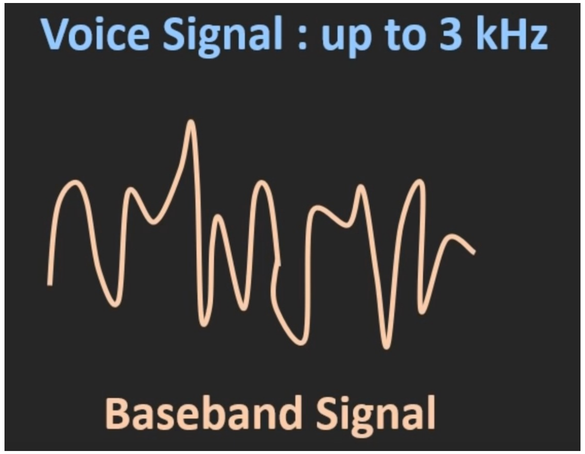
Analog continuous wave Mod.

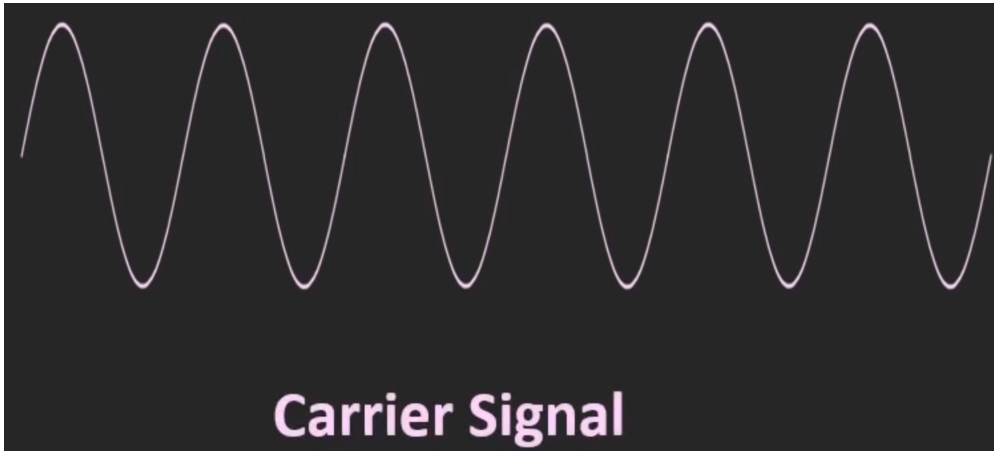
AM FM PM

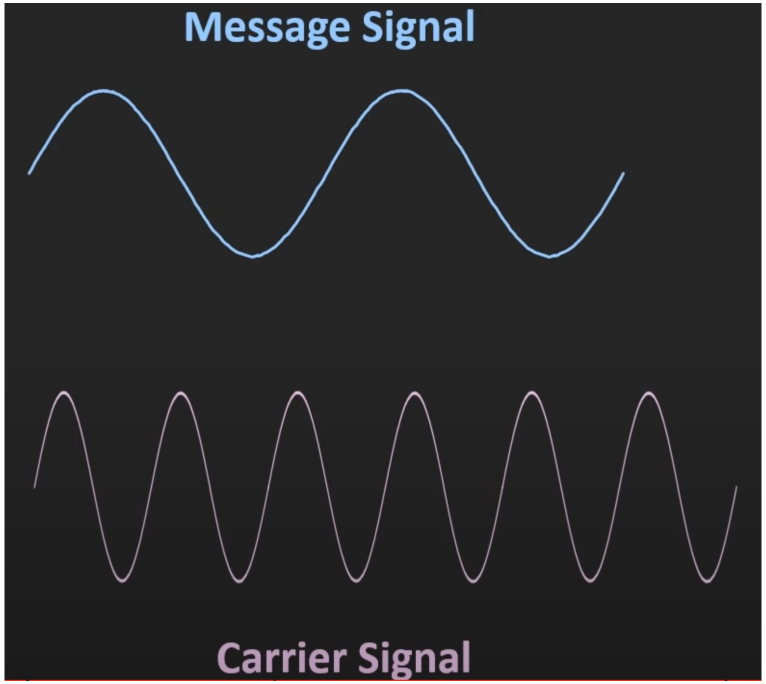
Analog pulse wave Mod

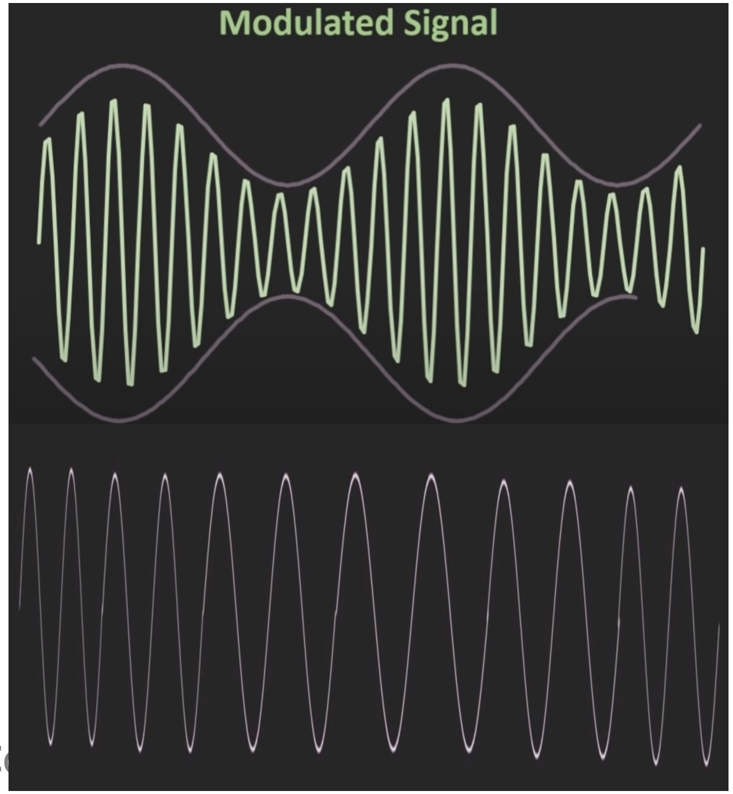
PAM PWM PPM

Modulation


Voice Signal : up to 3 kHz
Baseband Signal

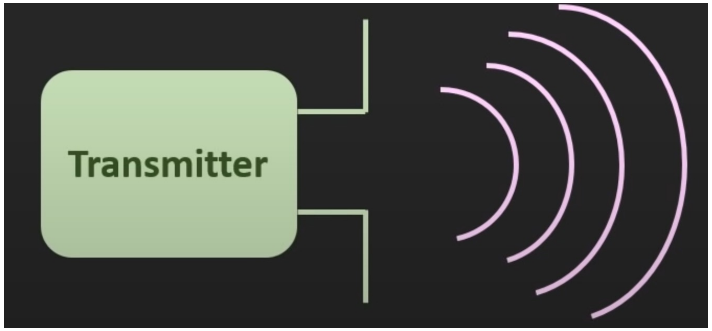

Carrier Signal


Message Signal
Carrier Signal


Modulated Signal

Modulation

1. Reduce antenna size



① $d \propto \lambda$

② FDM

③ reliability

2. Reduce the interference, allow multiplexing of signal

Analog Continuous-Wave Modulation

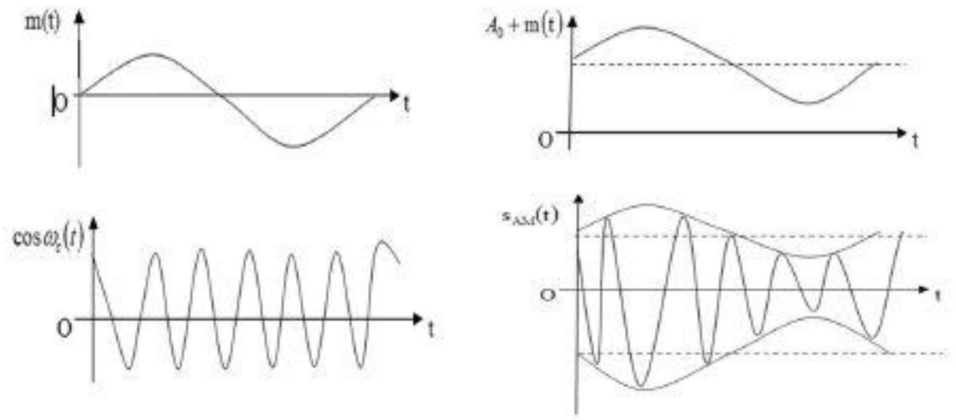
- Characteristics that can be modified in the carrier

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

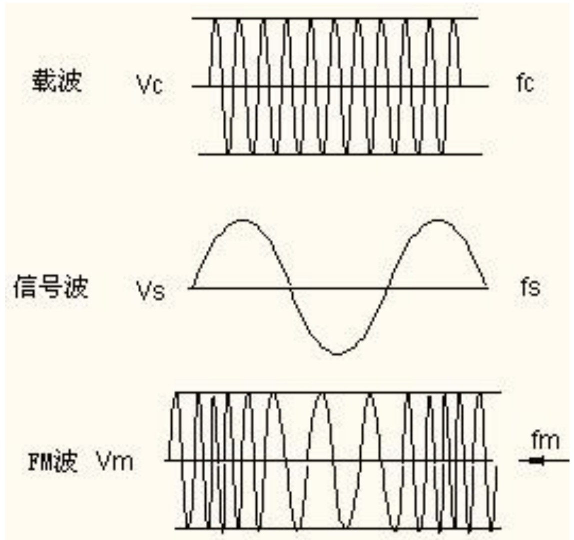
$A(t)$ – Amplitude AM ⇨ Amplitude modulation

$f(t)$ – Frequency FM

$\theta(t)$ – Phase PM ⇨ Angle modulation



AM



FM

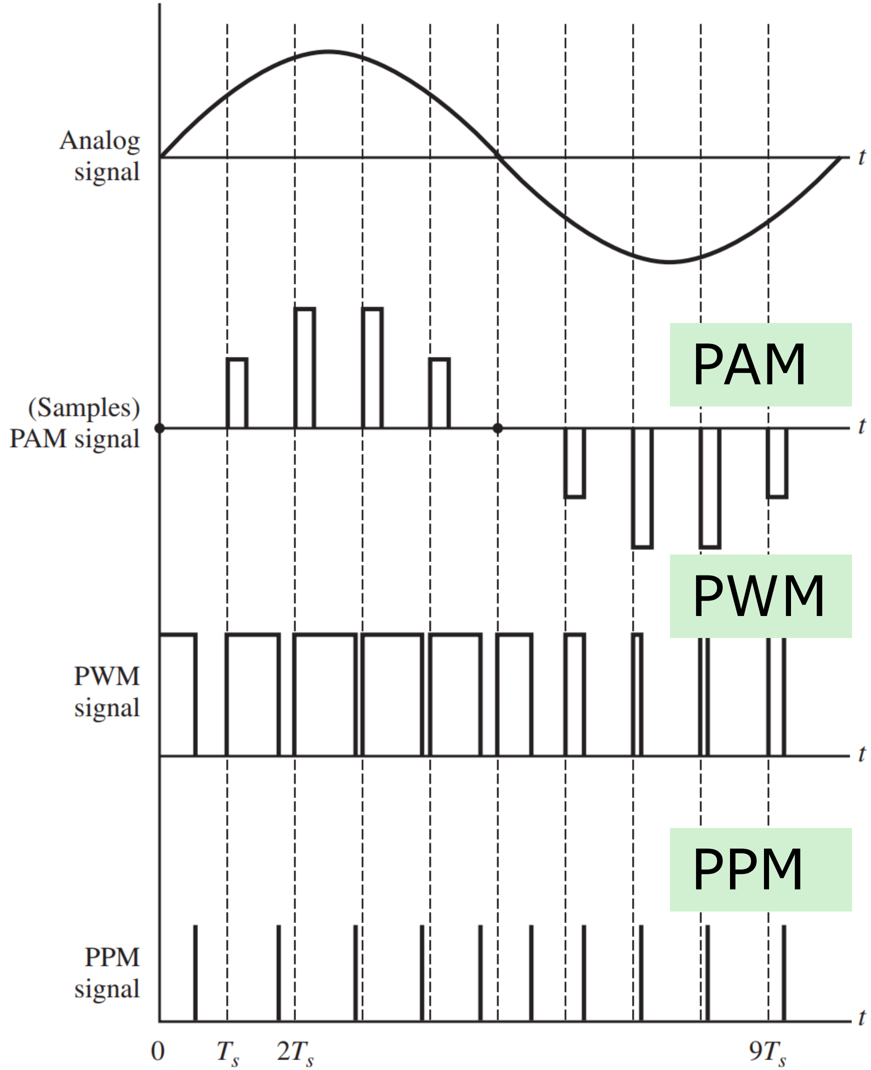
Analog Pulse Modulation

- 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

  } ⇨ 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)

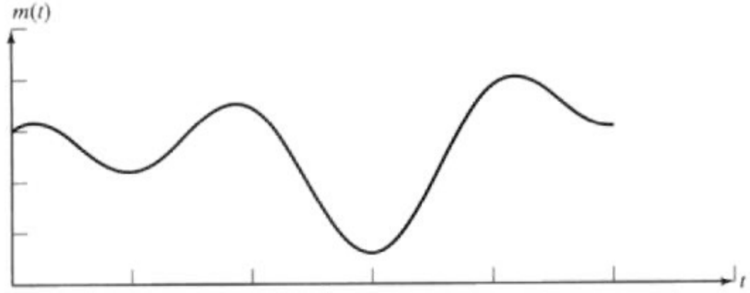
DSB-SC

DSB - LC(AM)

Amplitude Modulation

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

    $m(t)$

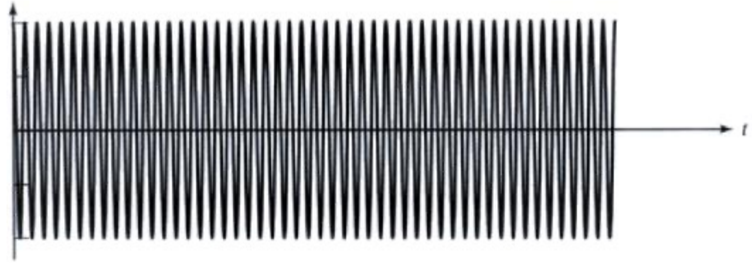


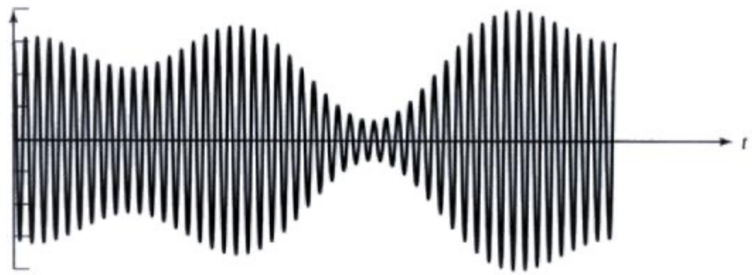
  - Carrier wave

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

  - Modulated wave

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





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

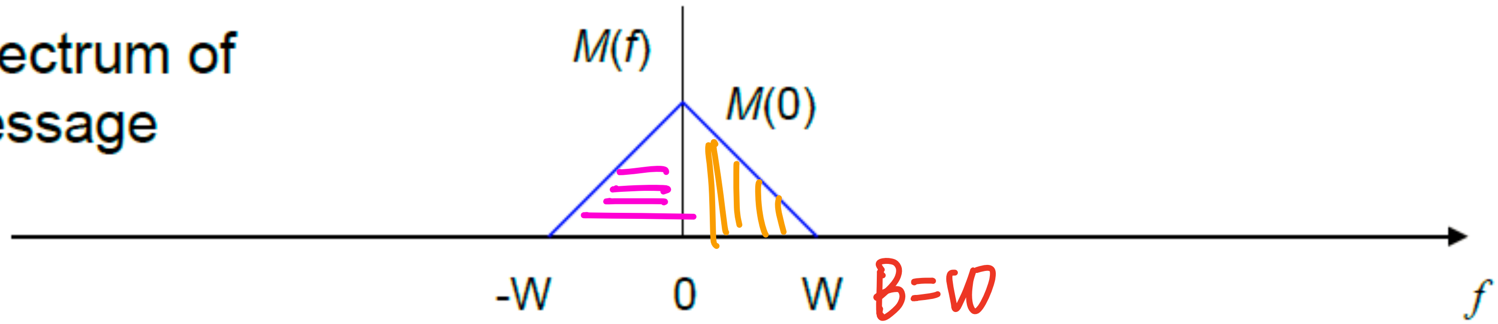
① USB $|f| \geq f_c$
LSB $|f| \leq f_c$
$B = 2W$

② SC, No Carrier

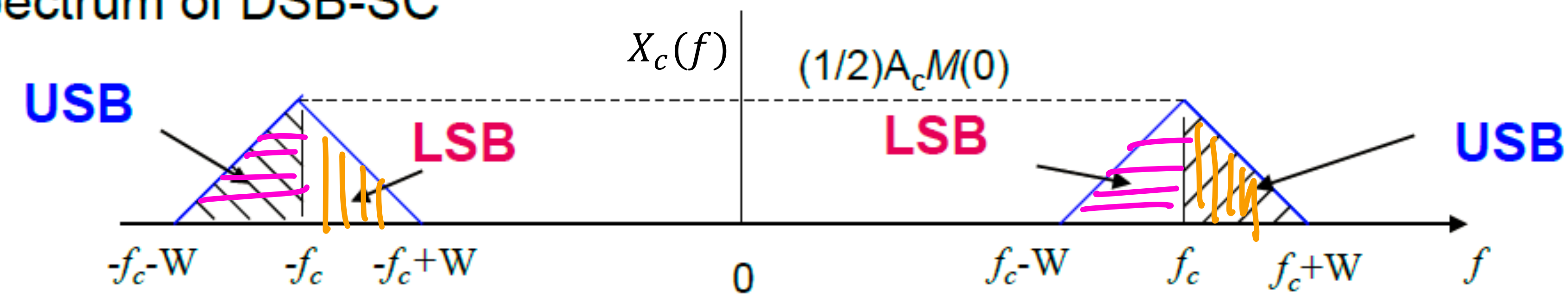
③ Linear Mod
Time: $x_c(t) = m(t)\,c(t)$
Freq:

DSB-SC Spectrum

Spectrum of message



Spectrum of DSB-SC

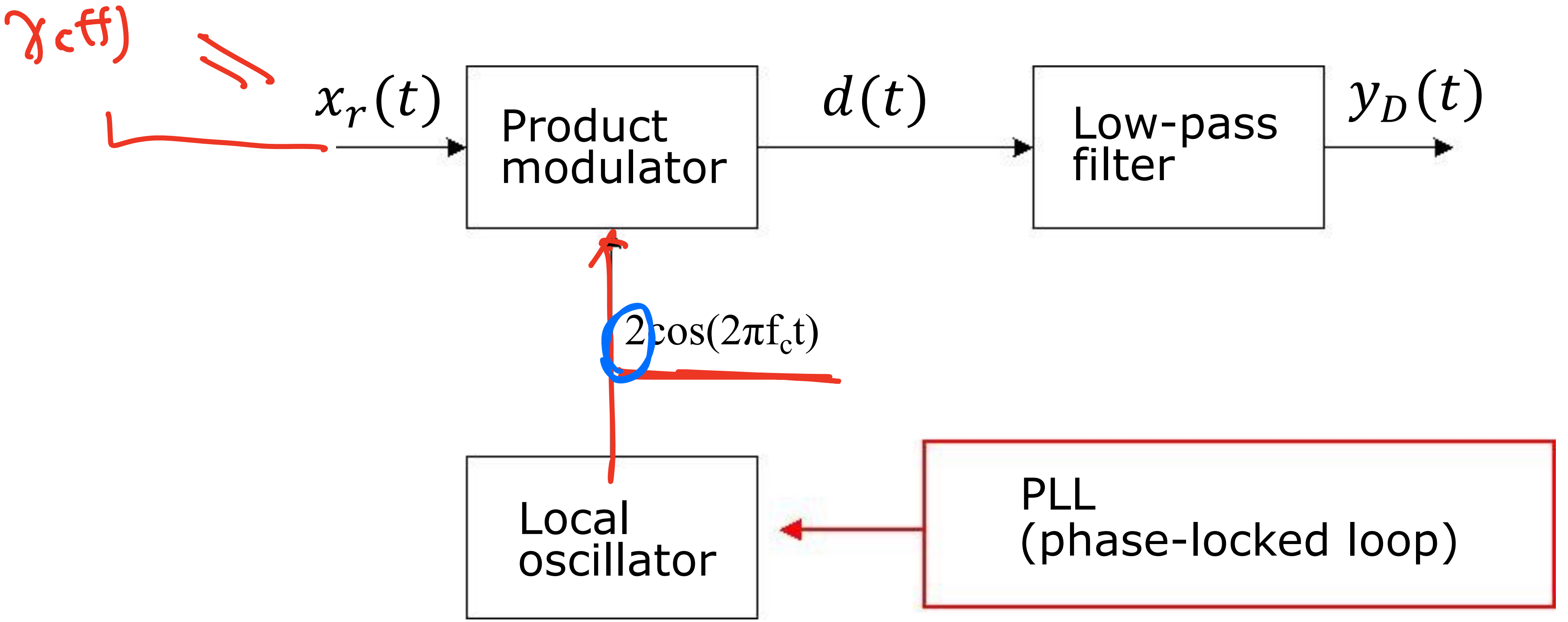


$$X_c(f) = \frac{1}{2} A_c [M(f - f_c) + M(f + f_c)]$$

Demodulation of DSB-SC Signals

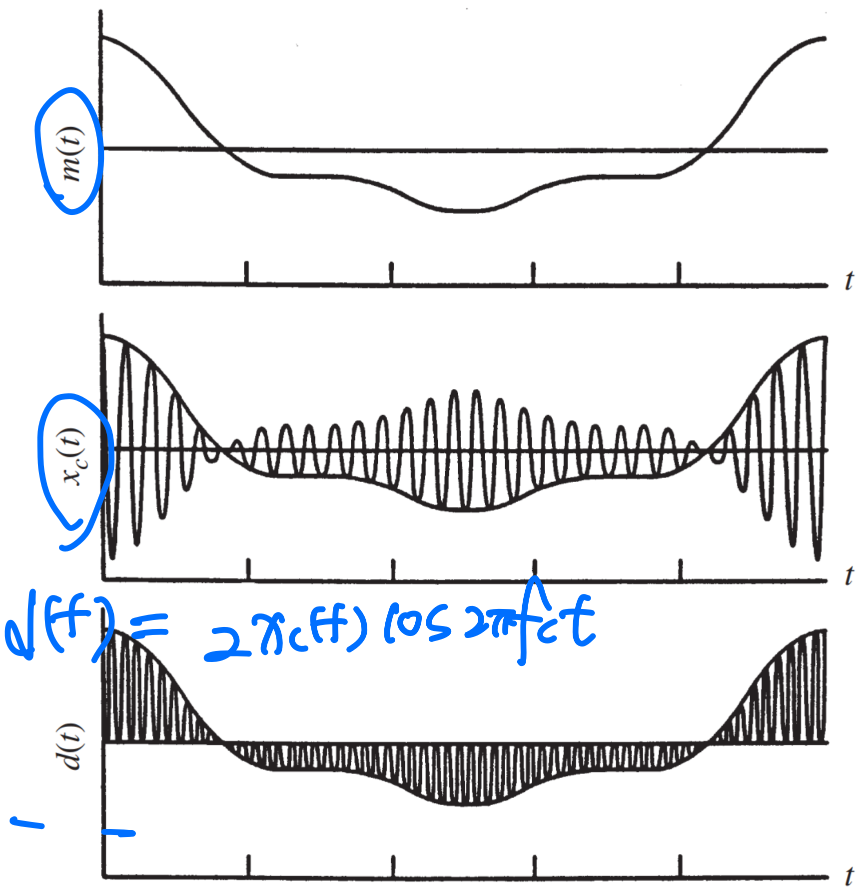
- Phase-coherent demodulation

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

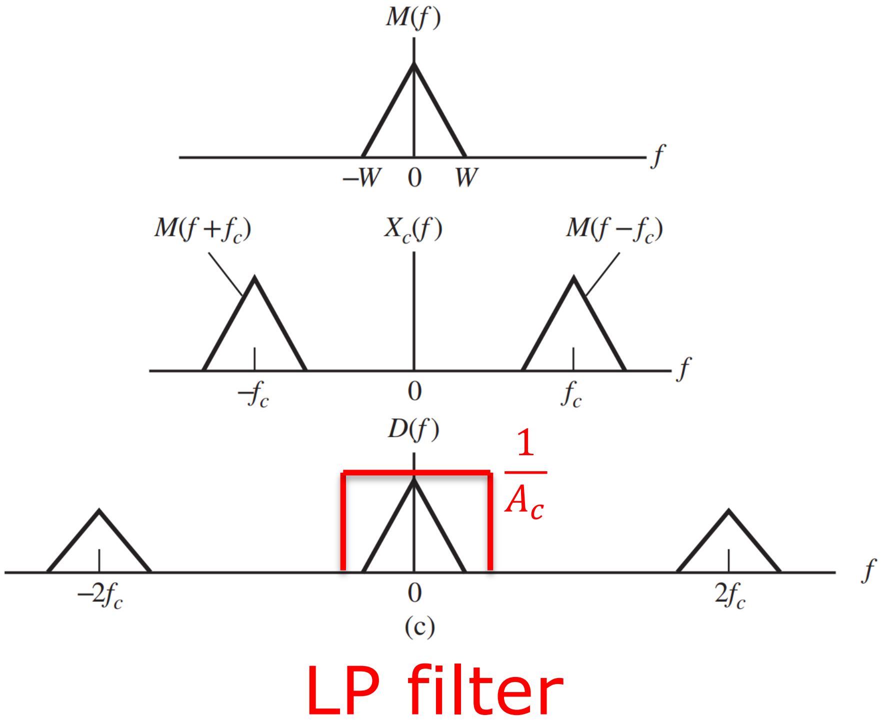


Demodulation of DSB-SC Signals

- DSB-SC demodulation: graphic interpretation



(b)



(c)

Comment on DSB-SC

- Good:
  - 100% power efficient

① Modulation easy

- Bad:
  - High transmission bandwidth: B=2W

⇒ SSB: B=W

  - Demodulation is difficult: Phase Coherent
    - **Phase error**→ serious distortion

$A_c m(t)\cos(2\pi f_c t)$

$$d(t) = x_c(t) 2\cos(2\pi f_c t + \theta(t))$$

$$= A_c \cos\theta(t)\, m(t) + A_c m(t)\cos(4\pi f_c t + \theta(t))$$

$$y_D(t) = m(t)\cos\theta(t)$$

Serious distortion

Time-varying phase error

    - 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

$$x_c(t) = A_c m(t)\cos 2\pi f_c t + A_c \cos 2\pi f_c t = A_c(1+m(t))\cos 2\pi f_c t$$

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

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

① $m_n(t) = \dfrac{m(t)}{|\min m(t)|} \geq -1$

② $a: \ 0 < a \leq 1$

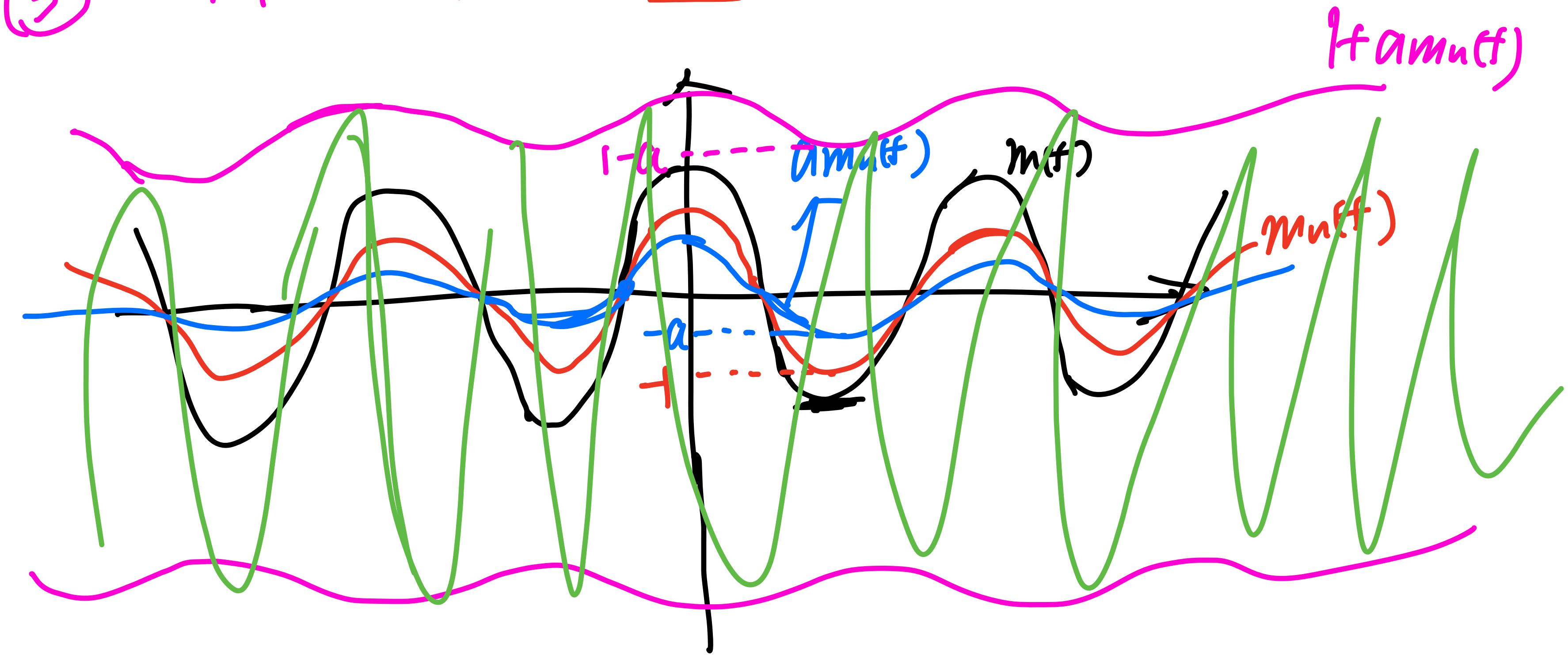
$a\,m_n(t) \geq -a \geq -1$

③ $1 + a\,m_n(t) \geq \underline{1-a} \geq 0$

④ $x_c(t) = A_c(1 + a\,m_n(t))\cos 2\pi f_c t$

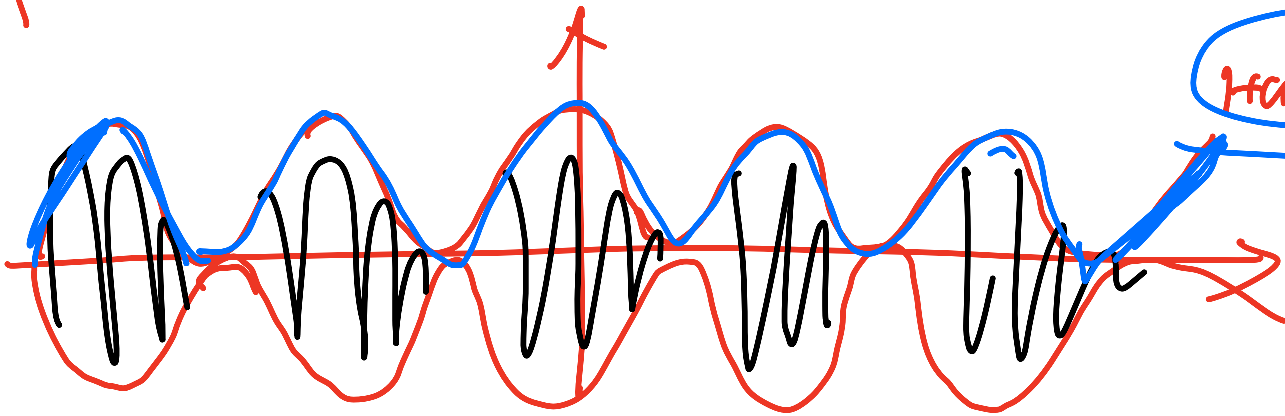
$= \underline{A_c \cos 2\pi f_c t}$

$+ \underline{A_c\, a\, m_n(t) \cos 2\pi f_c t}$



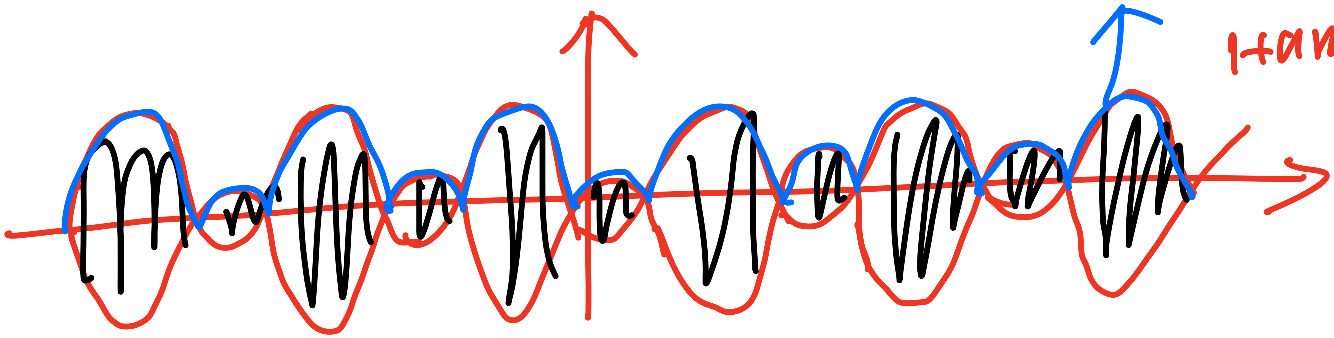
a: Modulation index $\quad 0 < a \le 1 \quad x_c(t) = A_c(1 + a\, m_n(t)) \cos 2\pi f_c t$

if $a = 1$



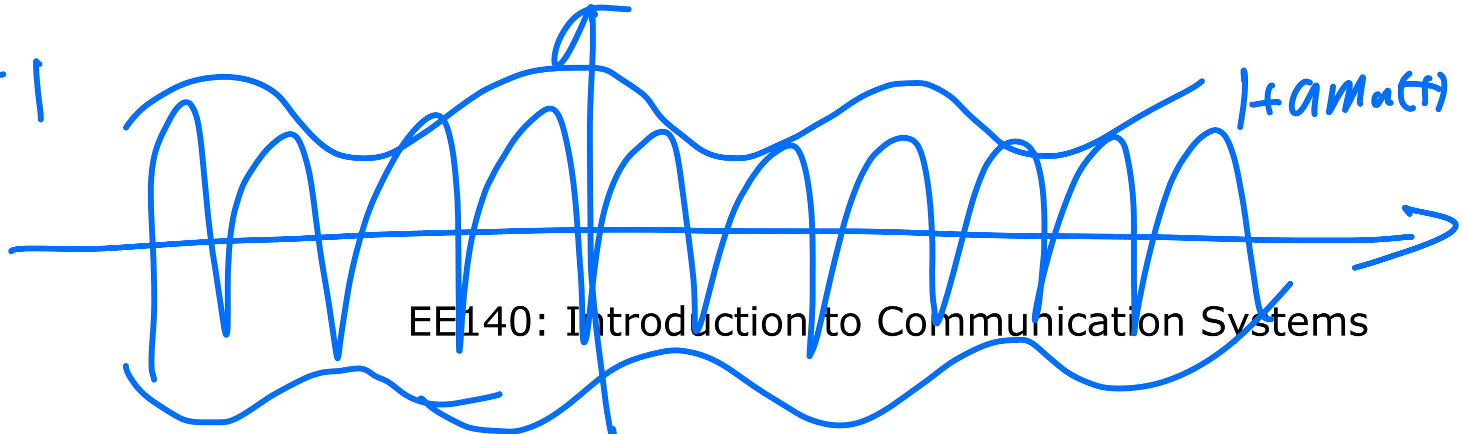
$1 + a\, m_n(t) \ge 0$

if $a > 1$



$1 + a\, m_n(t) < 0$

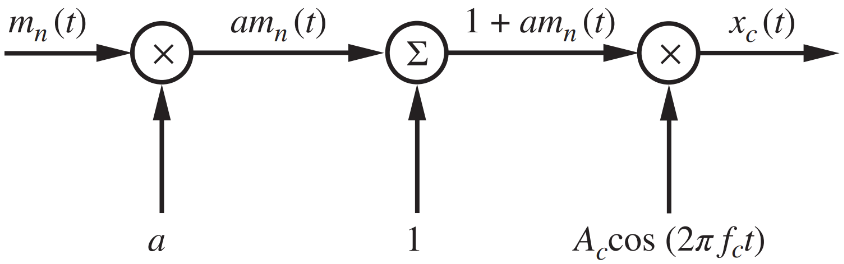
if $a < 1$

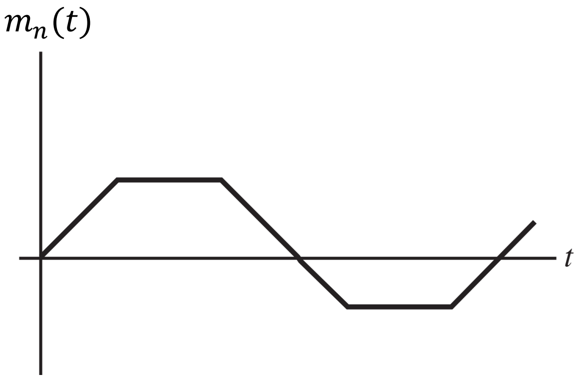


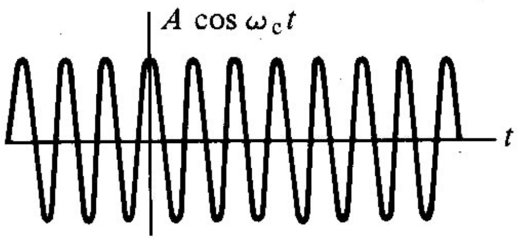
$1 + a\, m_n(t) > 0$

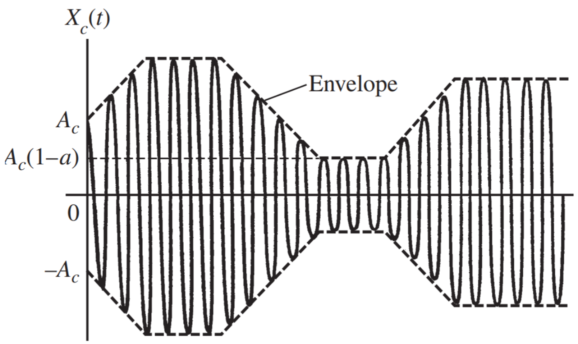
Graphic Interpretation

- DSB-LC signal







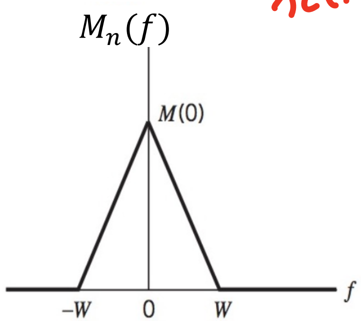


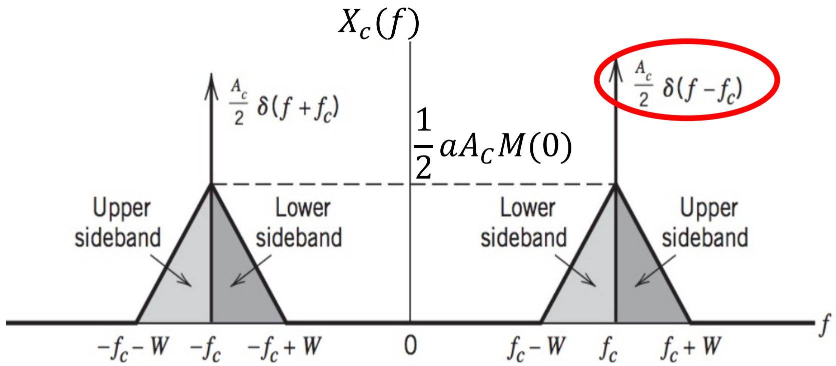
Time domain

Frequency domain

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

$+ A_c a m_n(t) \cos 2\pi f_c t$





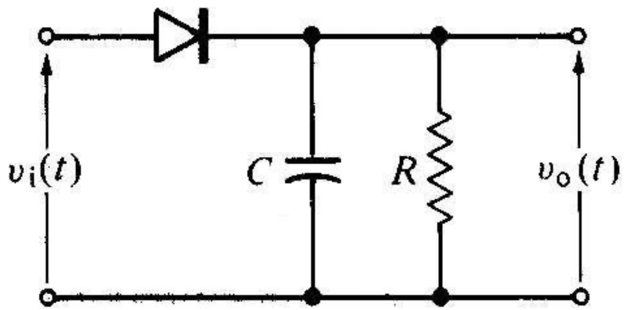
$B = 2W$

$PE < 1$

Demodulation of DSB-LC Signals

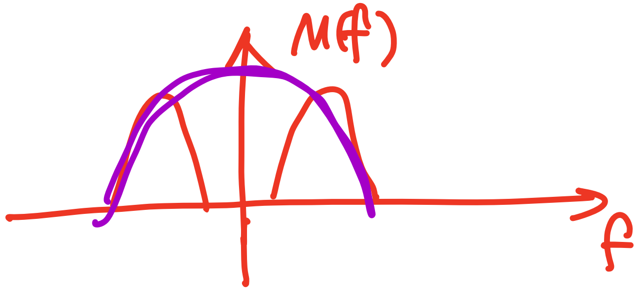
- Coherent demod: possible, but not easy.
  - Phase and frequency synchronizations are required;
- Noncoherent demod: envelope detection
  - The RC circuit can perform low pass filtering
  - Condition: $1.\ 1 + am_n(t) \geq 0 \Longleftrightarrow 0 < a \leq 1, m_n(t) \geq -1$

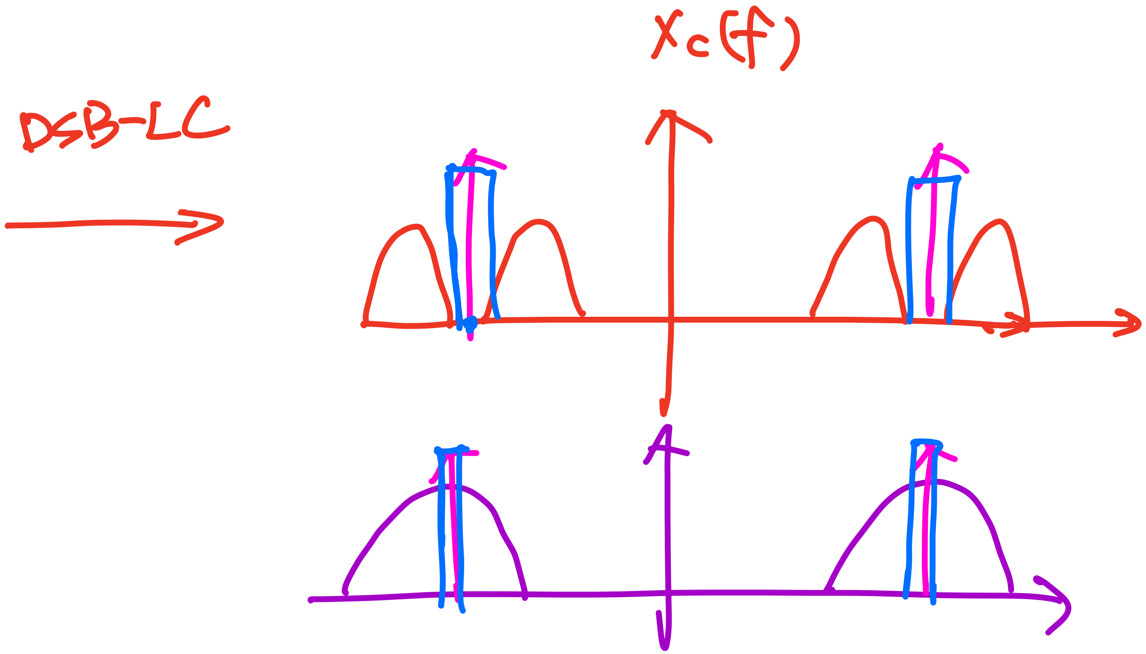
    $2.\ f_c \gg W$



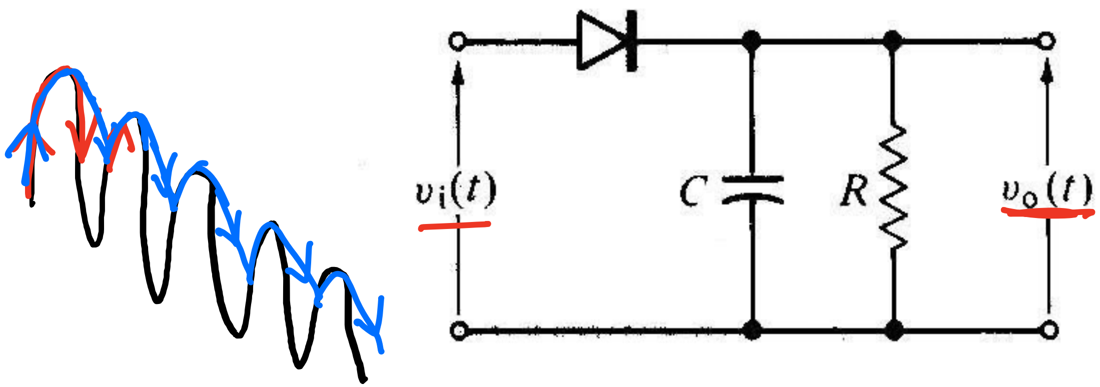
The simplicity of envelop detector has made Conventional AM a practical choice for AM-radio broadcasting

1. Coherent Demodulation



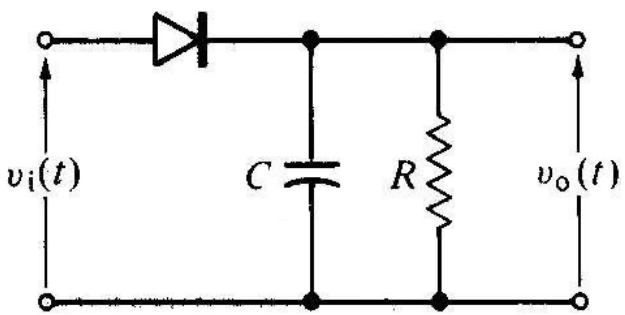


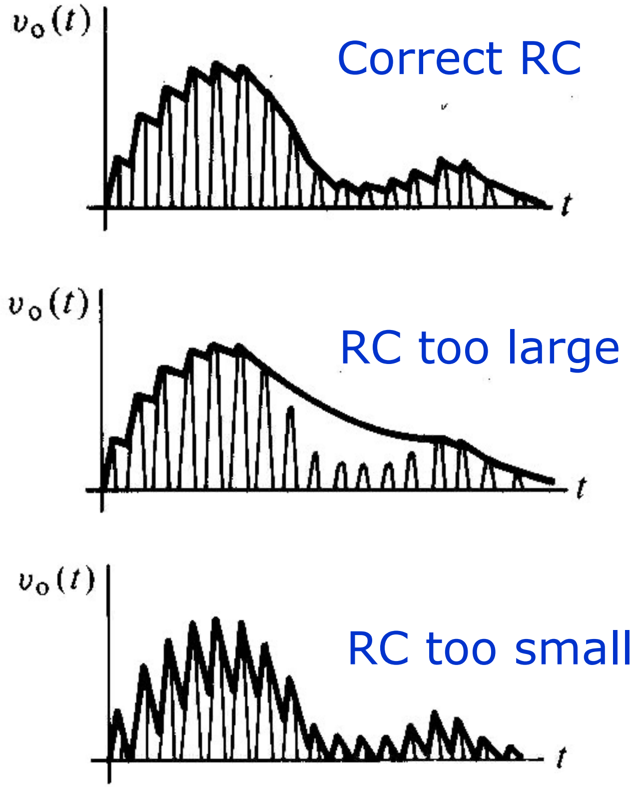
2. Envelope Detection



Demodulation of DSB-LC Signals

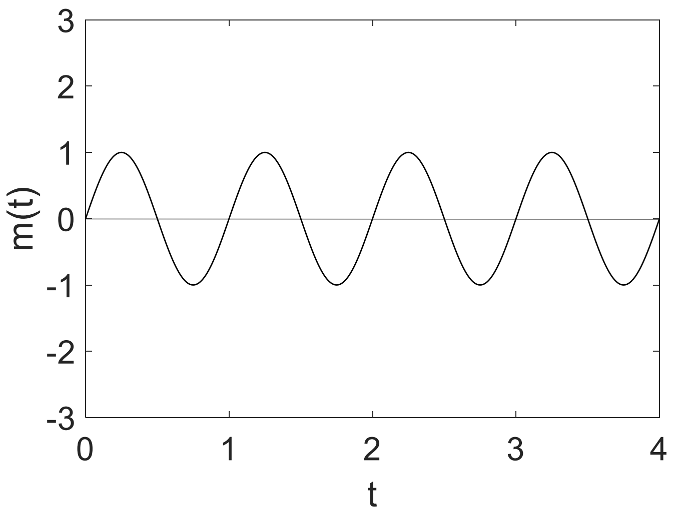
- Coherent demod: possible, but not easy.
  - Phase and frequency synchronizations are required;
- Noncoherent demod: envelope detection
  - The RC circuit can perform low pass filtering
  - Condition: $0 < a \leq 1, m_n(t) \geq -1 \;\&\; f_c \gg W$



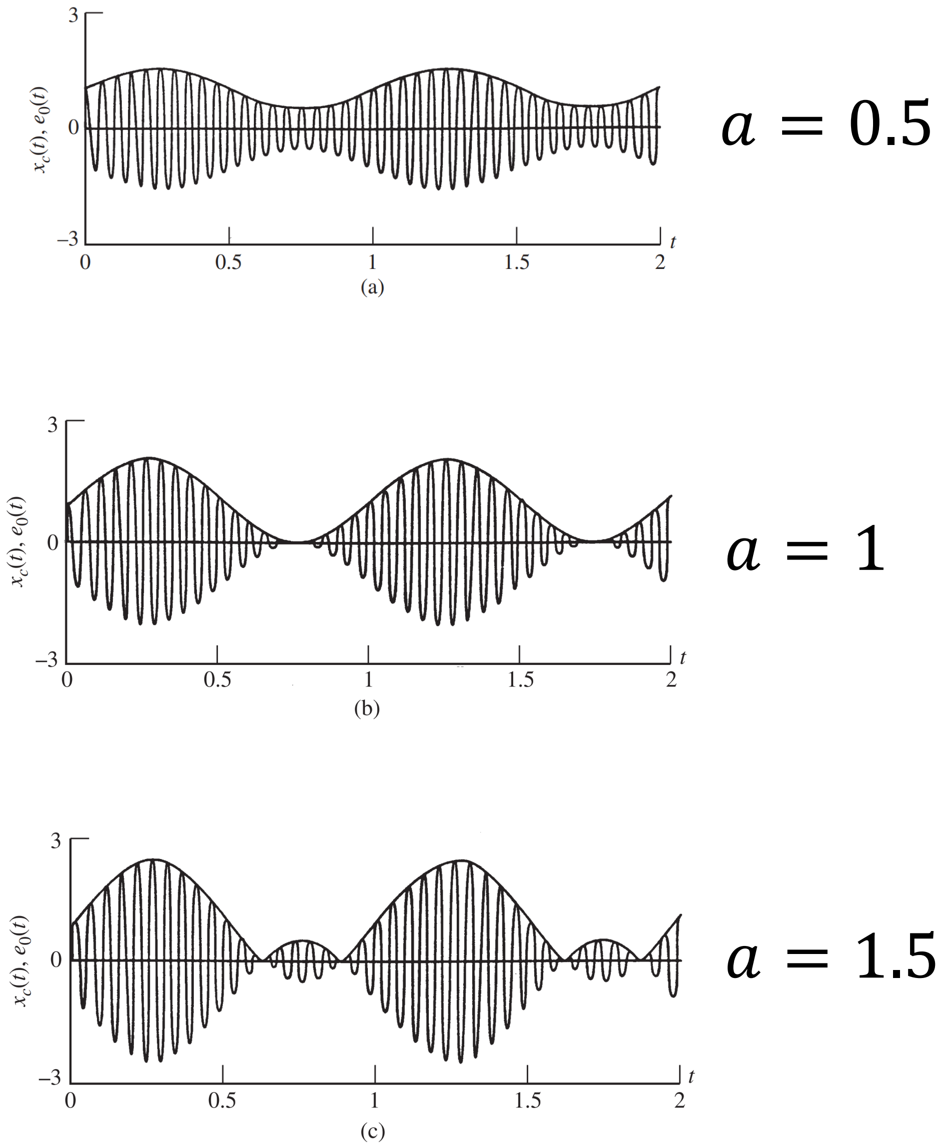


The simplicity of envelop detector has made Conventional AM a practical choice for AM-radio broadcasting

DSB-LC Properties



- 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.



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

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

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

- The transmission efficiency

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

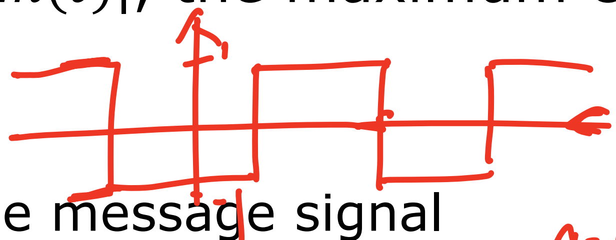
Comments on μ

① $\mu < 1$

② $a \uparrow$ $\mu \uparrow$ $a = 1$ $\mu_{max} = \frac{\langle m_n^2(t)\rangle}{\langle m_n^2(t)\rangle + 1}$

③ $\langle m_n^2(t)\rangle \uparrow$ $\mu \uparrow$

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



$\langle m_n^2(t)\rangle = 1$

$a = 1, \mu = \frac{1}{1+1} = 50\%$

Transmission Efficiency

- The transmission efficiency

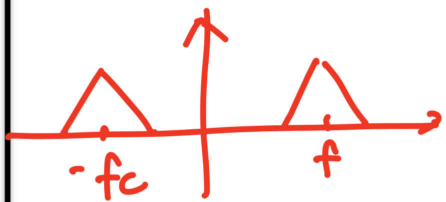
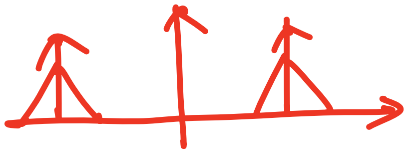
$$\mu = \frac{P_s}{P_t} = \frac{\frac{1}{2}A_c^2 a^2 \langle m_n^2(t) \rangle}{\frac{1}{2}A_c^2 a^2 \langle m_n^2(t) \rangle + \frac{1}{2}A_c^2} = \frac{a^2 \langle m_n^2(t) \rangle}{a^2 \langle m_n^2(t) \rangle + 1}$$

  - If $|\min m(t)| = |\max m(t)|$, the maximum efficiency is 50% for a=1. $m_n(t) = m(t)$ $\mu = \frac{\frac{1}{2}}{\frac{1}{2}+1} = \frac{1}{3}$
  - 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)

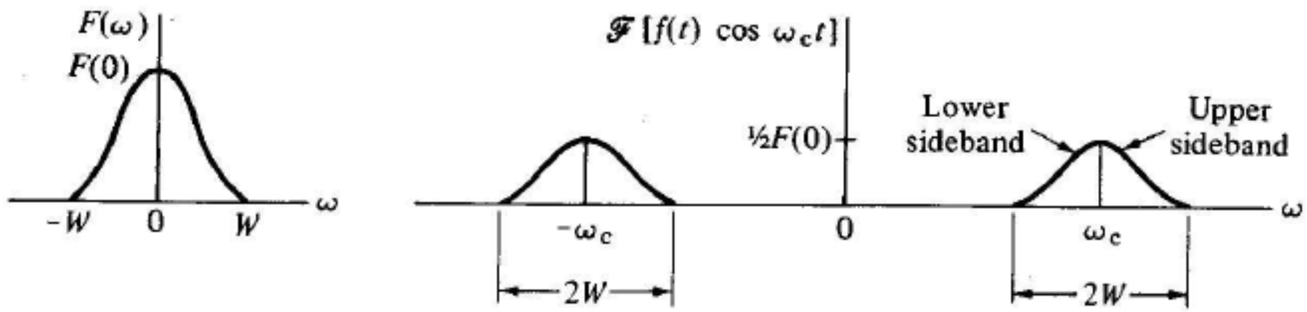
- Good:
  - Demodulation is simple and inexpensive: envelope detection
- Bad:
  - Low power efficiency
  - High transmission bandwidth: B=2W

Mod/ Demod.

AM	Modulation	Demodulation	Bandwidth	Power	Complexity
DSB-SC	$x_c(t) = m(t)c(t)$ 	Coherent Dem. $LP(x_c(t) \cdot c(t))$	$B=2W$	$PE=1$	Simple/complicated
DSB-LC	$x_c(t) = A_c(1+a m_n(t)) \cos 2\pi f_c t$ 	Envelope Det. $(0<a\le 1)$	$B=2W$	$PE=\frac{a^2<m_n^2>}{a^2<m_n^2>+1} < 1$	simple/simple
SSB			$B=W$	$PE=1$	complicated / complicated
VSB			$W<B<2W$	$PE=1$	simple / complicated

Single-sideband (SSB) Modulation

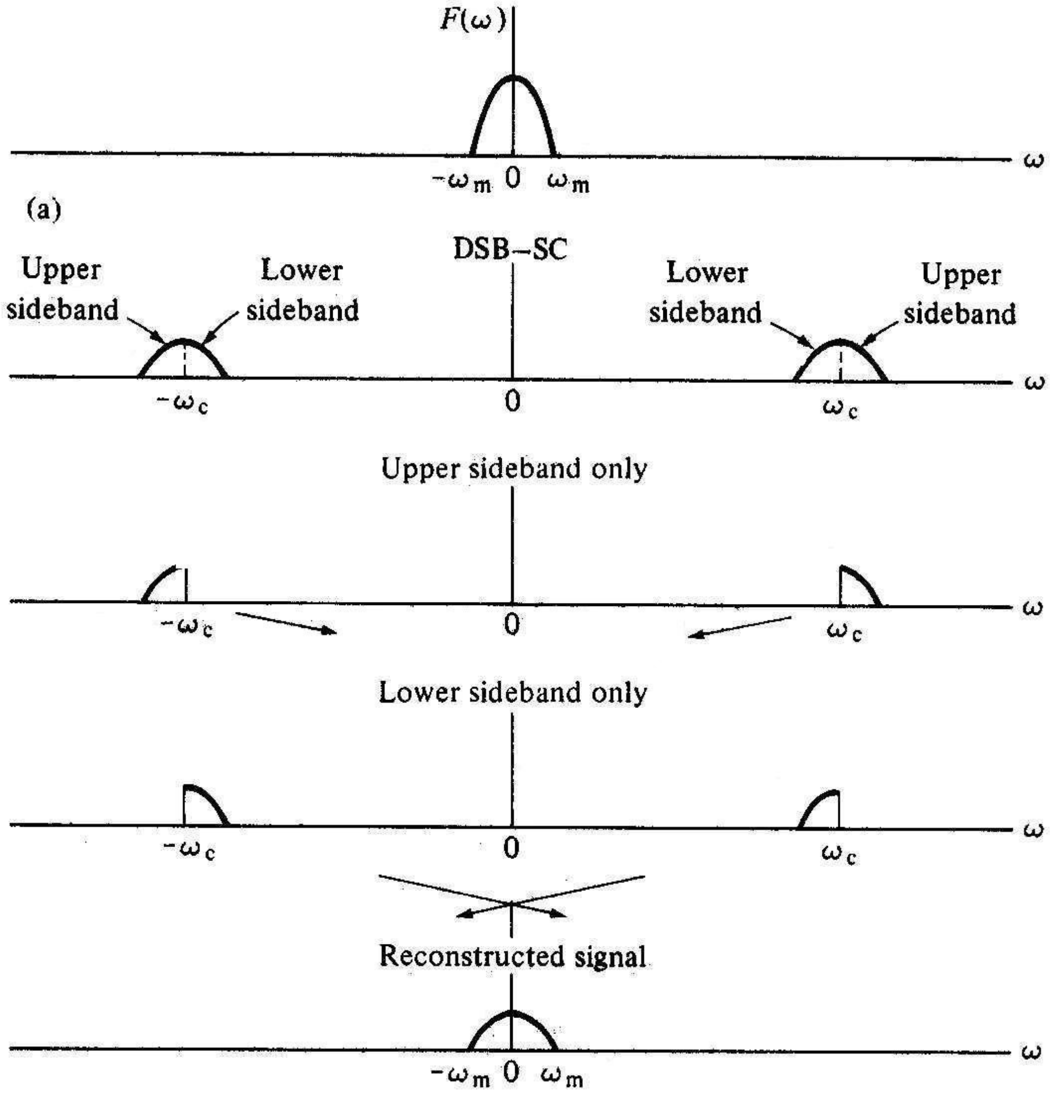
- DSB modulation results in a doubling of the bandwidth of a given signal.



- 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

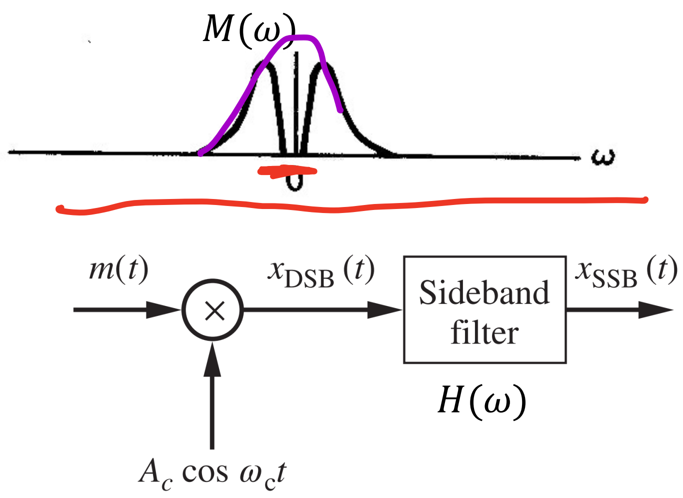
SSB

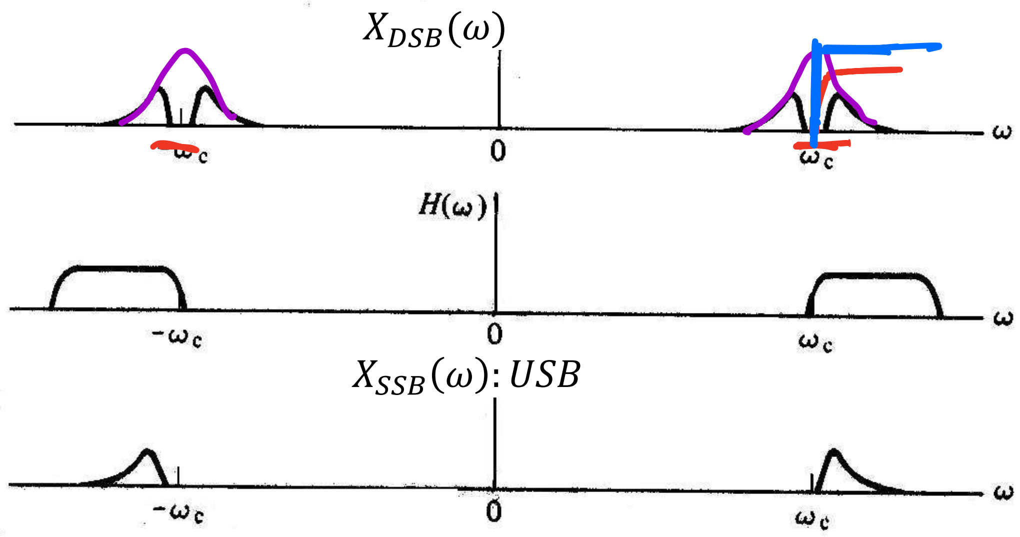
- Advantage: SSB modulation is efficient because it requires no more bandwidth than that of the original signal and only half that of the corresponding DSB signal.



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).



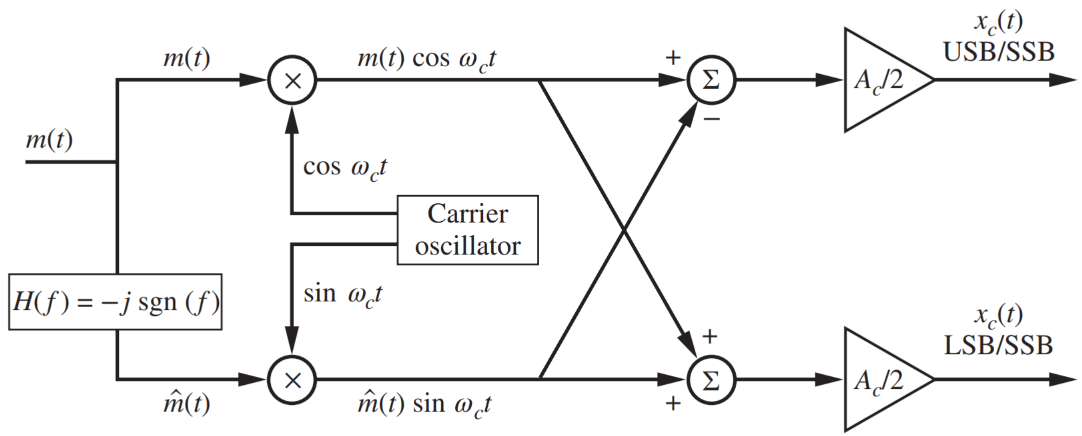


Generation of SSB Signals (Cont'd)

- 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

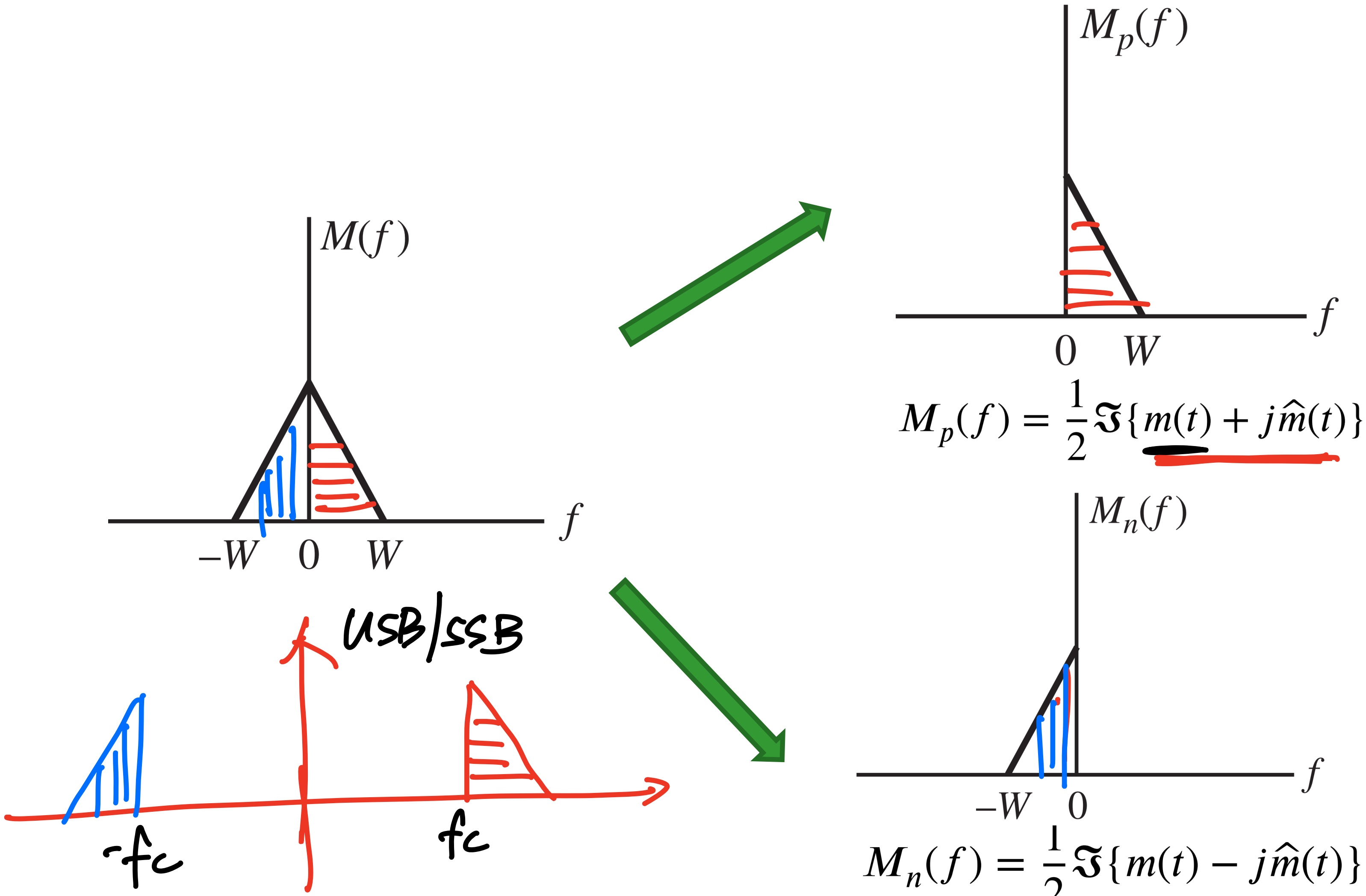
$$x_c(t) = x_{SSB\mp}(t) = \frac{1}{2}A_c m(t)\cos 2\pi f_c\, t \pm \frac{1}{2}A_c\hat{m}(t)\sin 2\pi f_c\, t$$

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



Generation of SSB Signals (Cont'd)

- Method 2: phase-shift



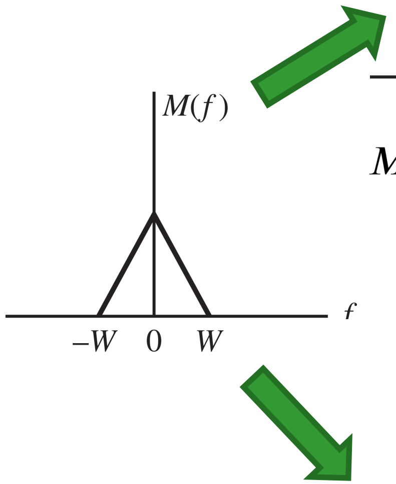
$$M_p(f) = \frac{1}{2}\mathfrak{I}\{m(t) + j\hat{m}(t)\}$$

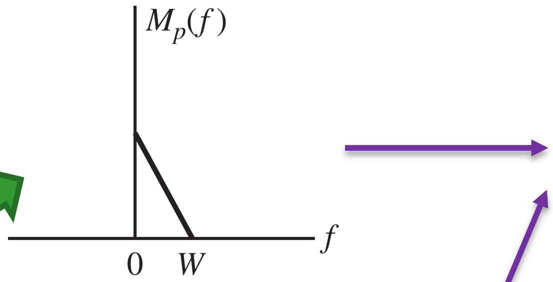
$$M_n(f) = \frac{1}{2}\mathfrak{I}\{m(t) - j\hat{m}(t)\}$$

Generation of SSB Signals (Cont'd)

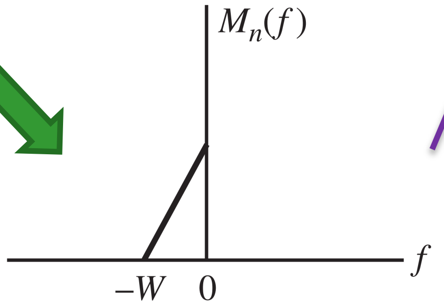
DSB $X_c(f) = \frac{1}{2}A_c M(f-f_c) + \frac{1}{2}A_c M(f+f_c)$

- Method 2: phase-shift

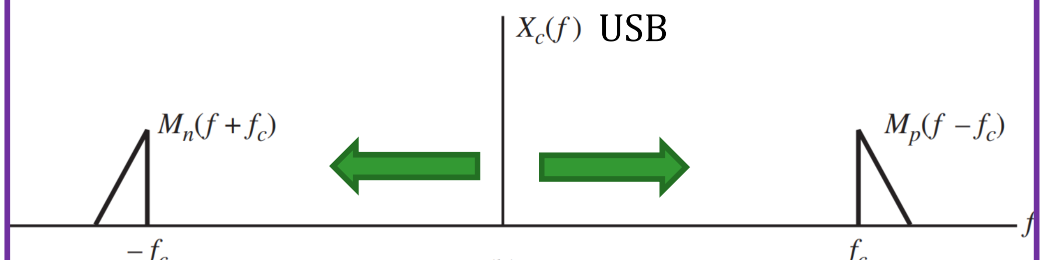




$$M_p(f) = \frac{1}{2}\mathfrak{F}\{m(t) + j\hat{m}(t)\}$$



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



(b)

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

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

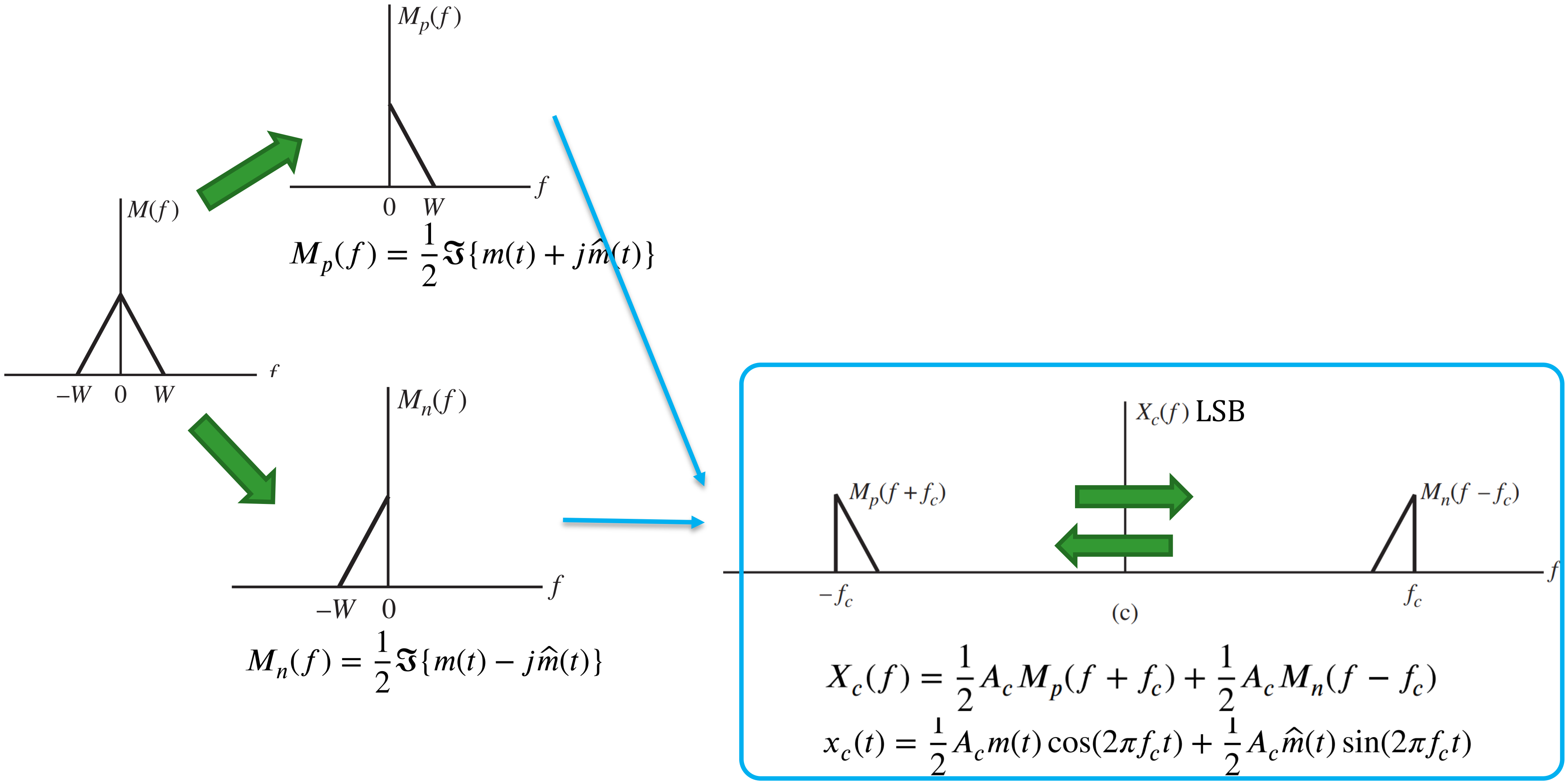
$$x_c(t) = IFT[X_c(f)] = \frac{1}{2}A_c \frac{1}{2}(m(t) + j\hat{m}(t))e^{j2\pi f_c t} + \frac{1}{2}A_c \frac{1}{2}(m(t) - j\hat{m}(t))e^{-j2\pi f_c t}$$

$$= \frac{1}{4}A_c m(t)\left(e^{j2\pi f_c t} + e^{-j2\pi f_c t}\right) + \frac{1}{4}A_c j\hat{m}(t)\left(e^{j2\pi f_c t} - e^{-j2\pi f_c t}\right)$$

$$= \frac{1}{4}A_c m(t)\, 2\cos 2\pi f_c t + \frac{1}{4}A_c j\hat{m}(t)\, 2j\sin 2\pi f_c t$$

Generation of SSB Signals (Cont’d)

- Method 2: phase-shift



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

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

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

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

SSB Demodulation

- Synchronous detection
  - Received SSB signal:

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

  - Local generated carrier signal:

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

Time-varying phase error

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

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

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

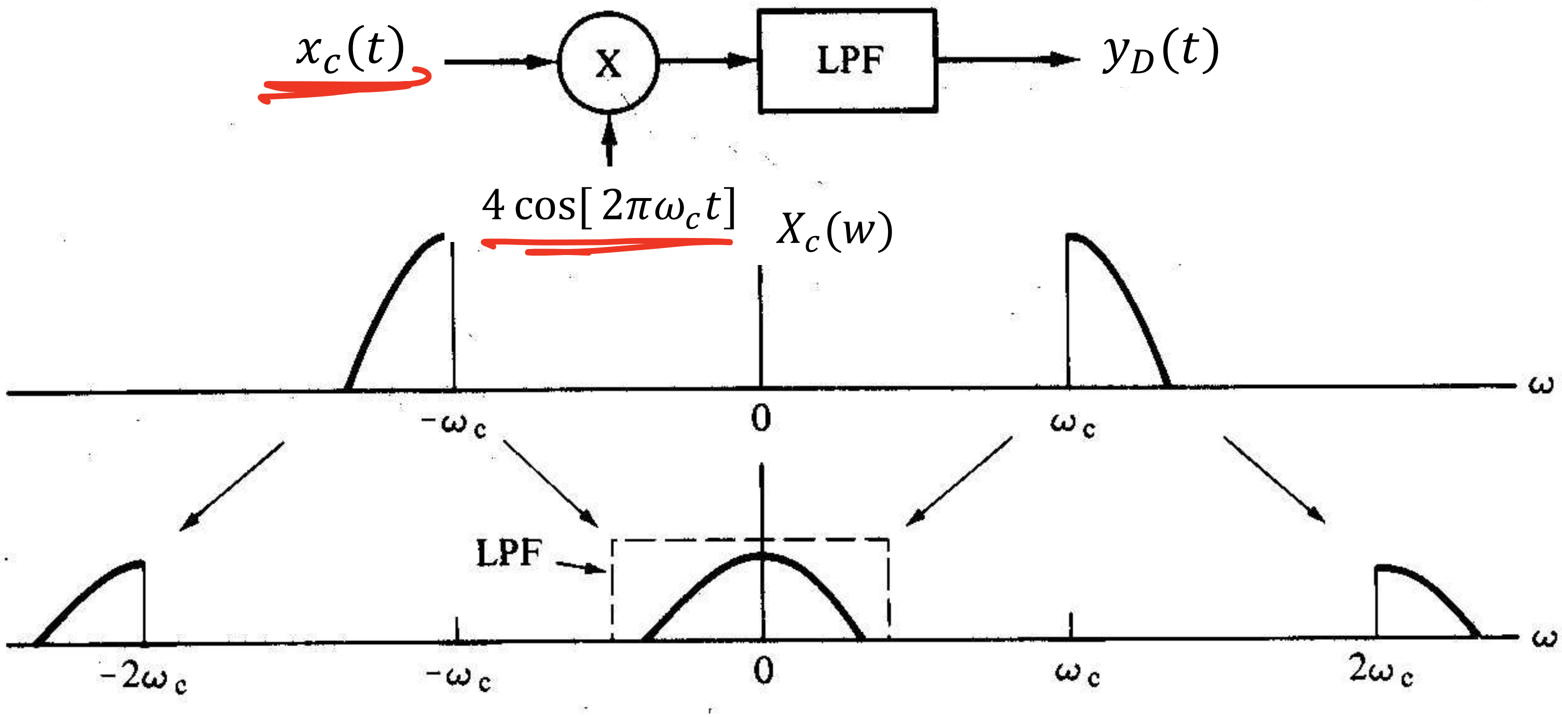
Serious distortion

  - If no error

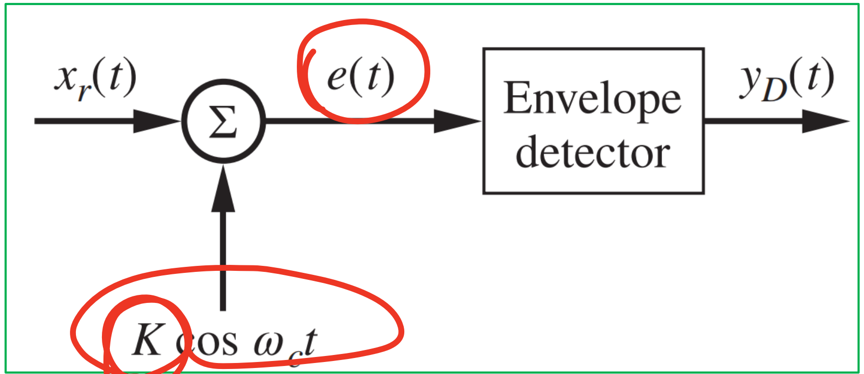
$$\boxed{y_D(t) = m(t)}$$

SSB Demodulation (Cont'd)

- Frequency domain graphic interpretation



SSB Demodulation



- Carrier Reinsertion
  - After carrier reinsertion

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

  - Envelope detection, not straightforward

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

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

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

  - 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

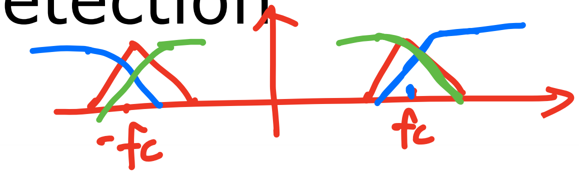
- The generation of SSB signals may be quite difficult when the modulating signal bandwidth is wide or where one cannot disregard the low-frequency components.
- In Vestigial-sideband (VSB) modulation, a portion of one sideband is transmitted.
- VSB is a compromise between SSB and DSB.
- Generation of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

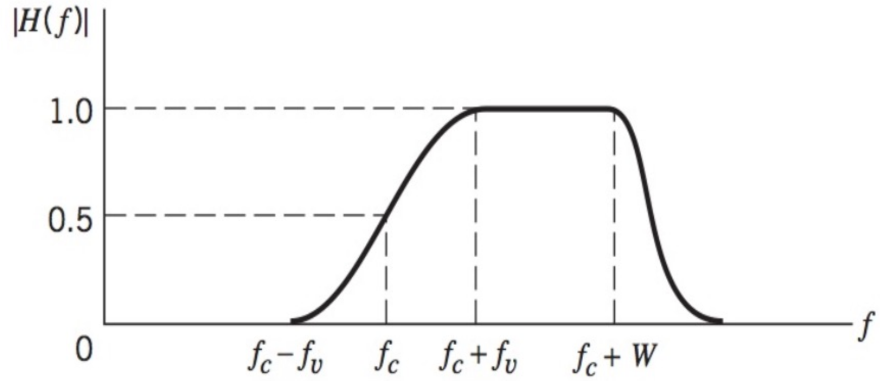
$$X_{VSB-SC}(f) = \frac{A_C}{2}[M(f + f_c) + M(f - f_c)]H(f)$$

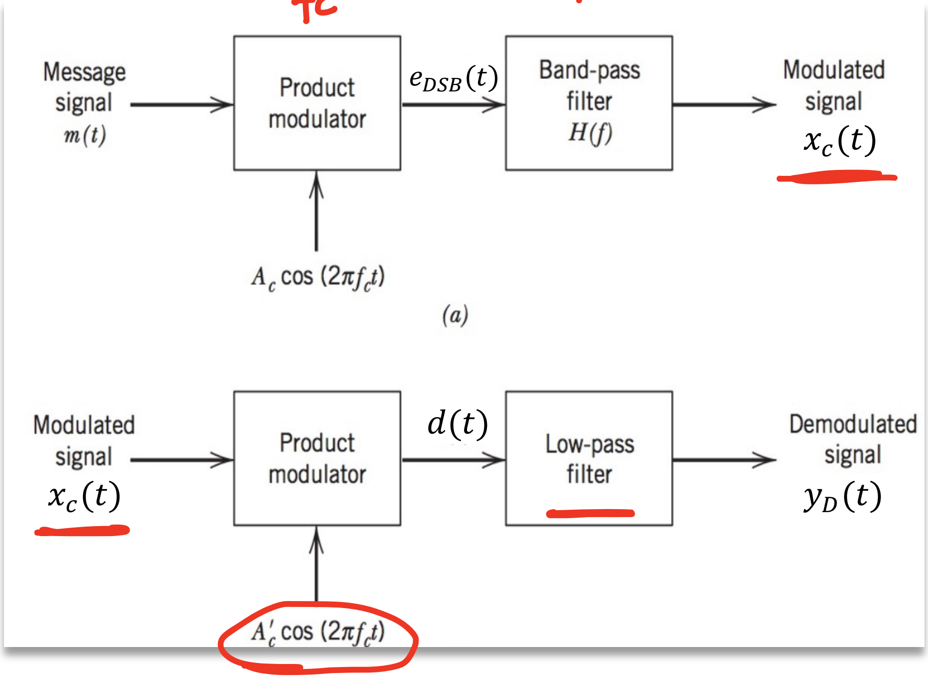
  – Where filter $H(f)$ passes some of the lower (or upper) sideband and most of the upper (or lower) sideband.

Vestigial-sideband (VSB) Modulation

- The requirement on the filter
- Consider coherent detection







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

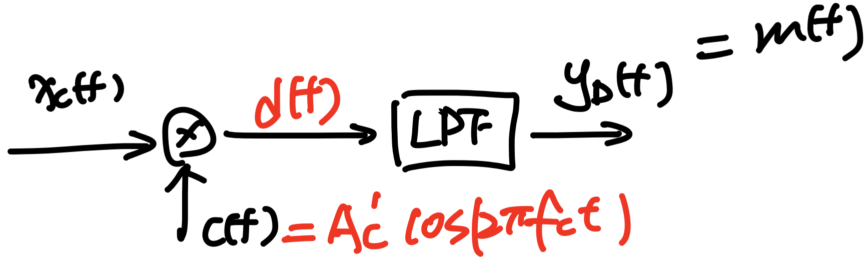
$$d(t) = A'_c x_c(t)\cos 2\pi f_c t$$

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

$$= \frac{A_C A'_c}{4}\{[H(f-f_c) + H(f+f_c)]M(f)$$
$$+ M(f+2f_c)H(f+f_c)$$
$$+ M(f-2f_c)H(f-f_c)\}$$

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

How to design $H(f)$?



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

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

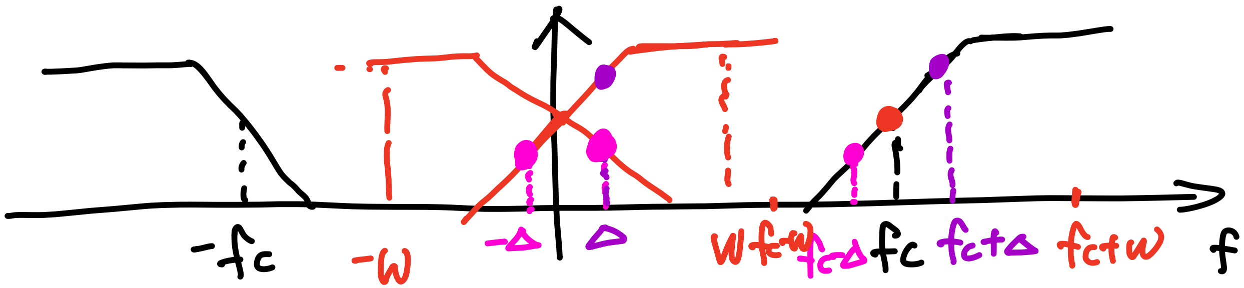
$$D(f) = \frac{A_c'}{2}[X_c(f-f_c)+X_c(f+f_c)]$$

$$= \frac{A_c'}{2}\left[\frac{A_c}{2}[M(f)+M(f-2f_c)]H(f-f_c)+\frac{A_c}{2}[M(f+2f_c)+M(f)]H(f+f_c)\right]$$

$$LPF[D(f)] = \frac{A_cA_c'}{4}[M(f)H(f-f_c)+M(f)H(f+f_c)]$$

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

$$= C, \quad |f|\le W$$



$$\begin{cases} H(f_c+\Delta)+H(f_c-\Delta)=C=2H(f_c) & |\Delta|\le W \\ H(f) \text{ is odd symmetric at } f_c & \boxed{f_c-W\le|f|\le f_c+W} \end{cases}$$

Vestigial-sideband (VSB) Modulation

- The requirement on the filter

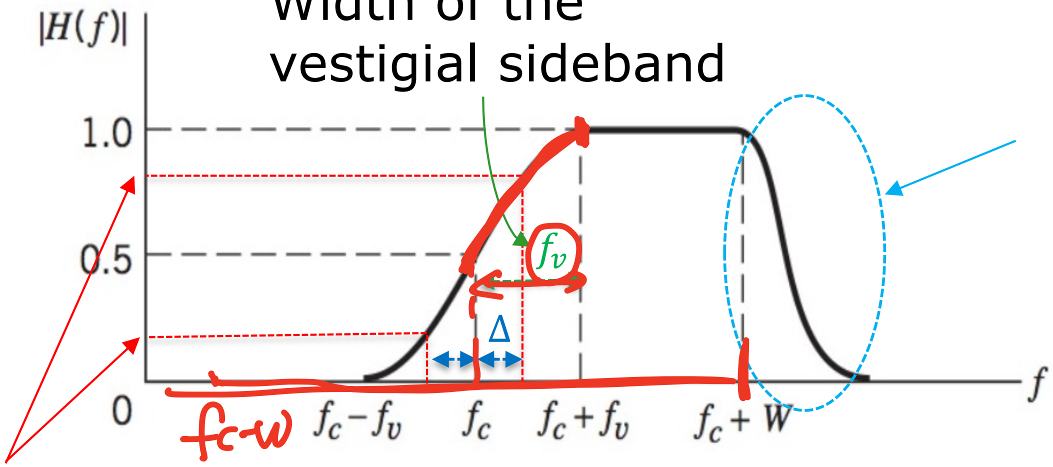
$$Y_D(f) = \frac{A_c A_c'}{4} M(f)[H(f - f_c) + H(f + f_c)]$$

- Recover the m(t) without distortion

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

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

Width of the vestigial sideband

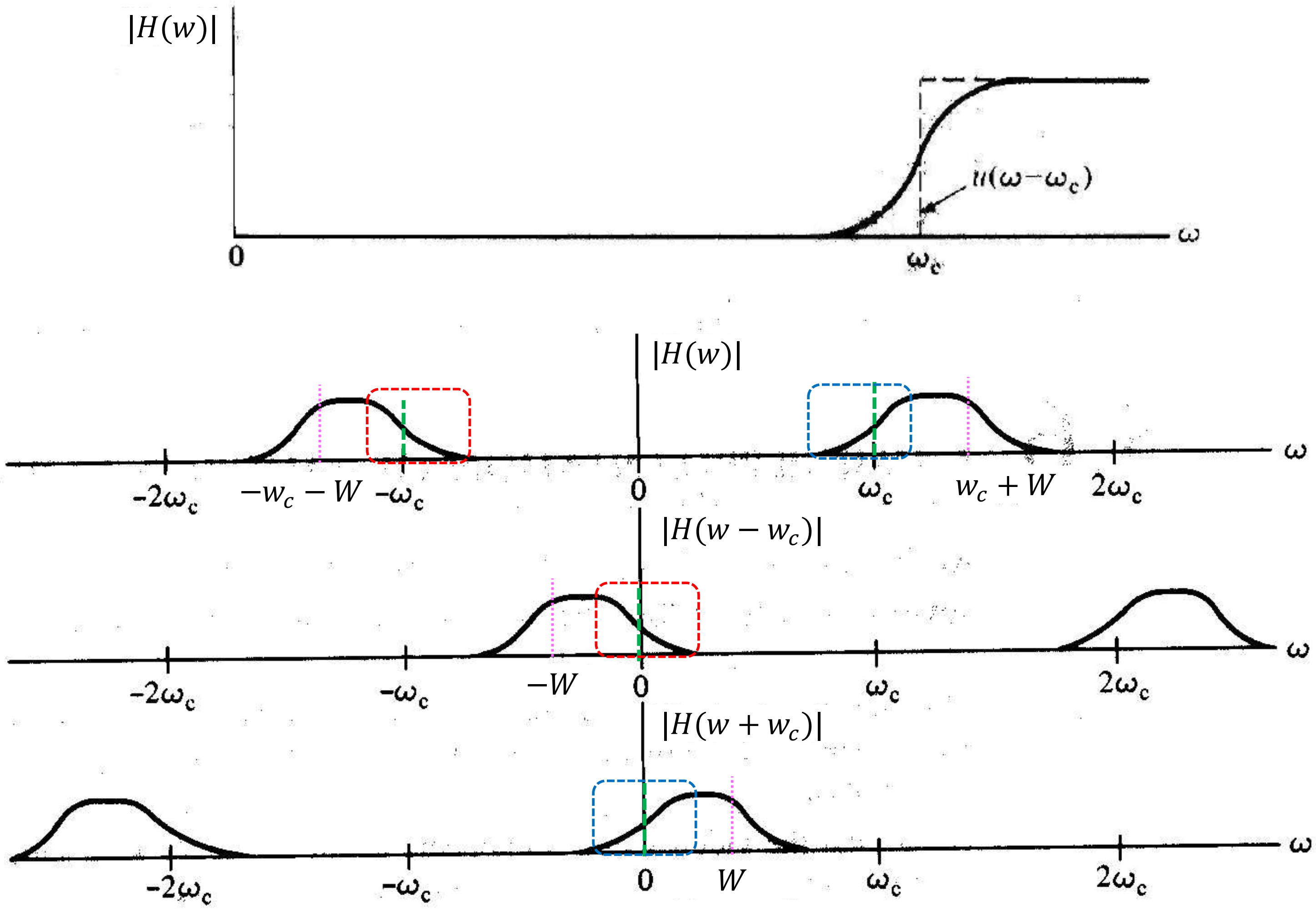


$|f| \ge f_c + W$: arbitrary specification

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

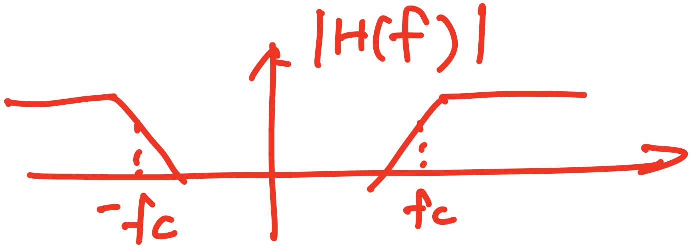
VSB Modulation (Cont'd)

- Frequency domain graphic interpretation

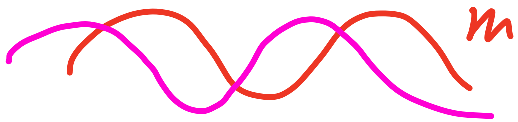


$M(f)[H(f-f_c)+H(f+f_c)]$

Case1: $[H(f-f_c)+H(f+f_c)] = C$



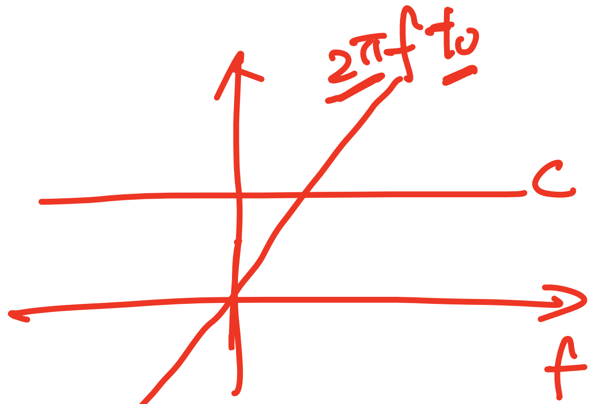
$\angle H(f) = 0$



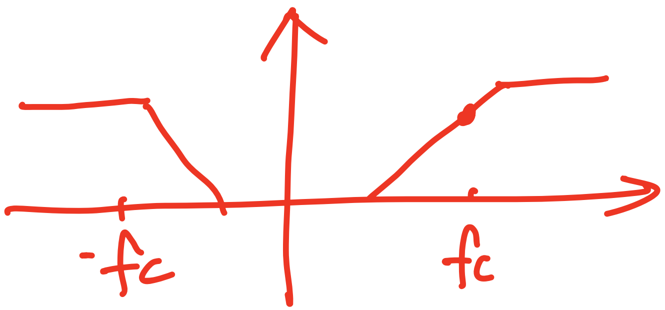
$H(f_c+\Delta) + H(f_c-\Delta) = 2H(f_c), \ |\Delta| \le W$

Case2: $[H(f-f_c)+H(f+f_c)] = Ce^{j2\pi f t_0}$

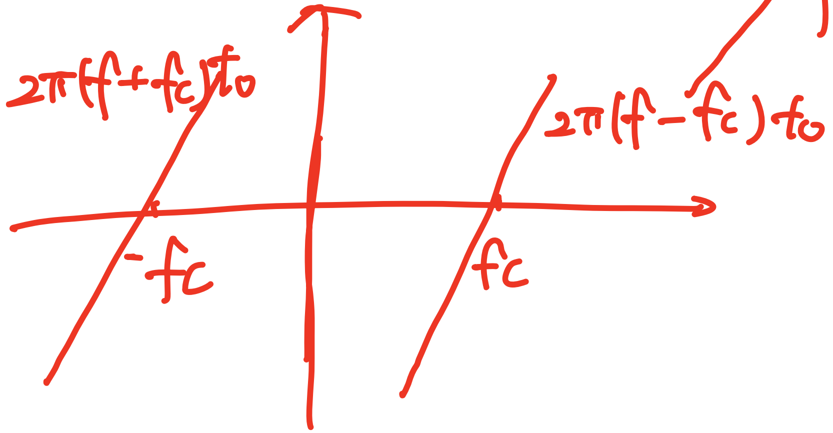
$m(t+t_0)$



$|H(f)|$



$\angle H(f)$



$|H(f_c+\Delta)| + |H(f_c-\Delta)|$

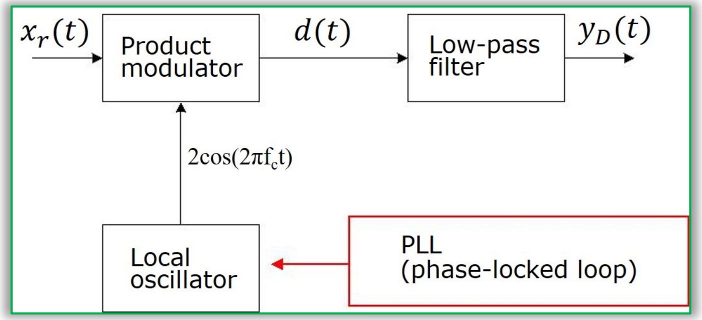
$= C, \ |\Delta| \le W$

Comparison of AM Techniques

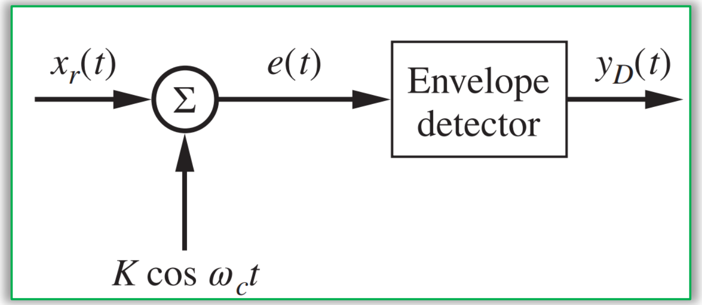
- DSB-SC:
  - more power efficient. Seldom used
- DSB-LC (AM):
  - simple envelop detector
  - Example: AM radio broadcast
- SSB:
  - requires minimum transmitter power and bandwidth. Suitable for point-to-point and over long distances
- VSB:
  - bandwidth requirement between SSB and DSBSC.
  - Example: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

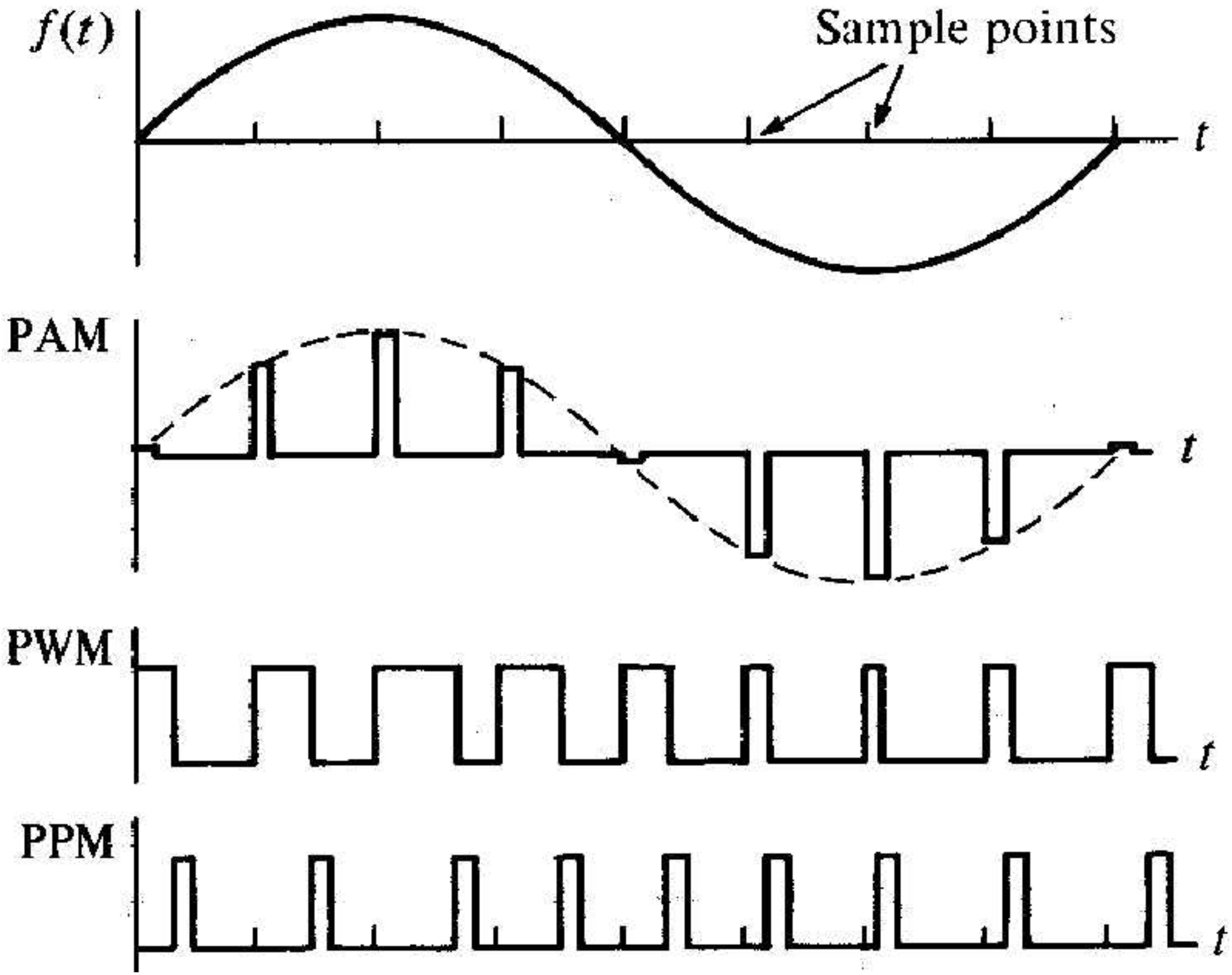
Analog Pulse Modulation

Modulating Signal

Pulse-Amplitude Modulation (PAM)

Pulse-Width Modulation (PWM)

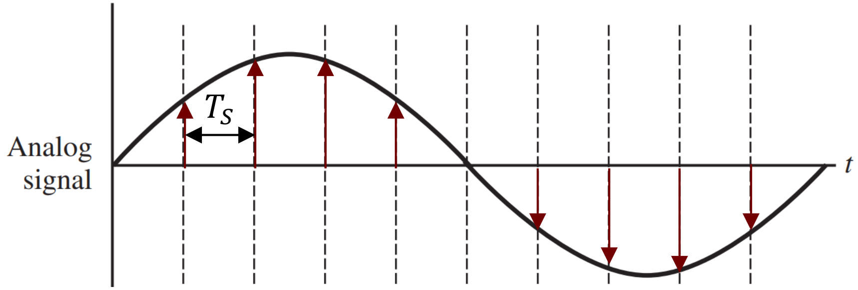
Pulse-Position Modulation (PPM)



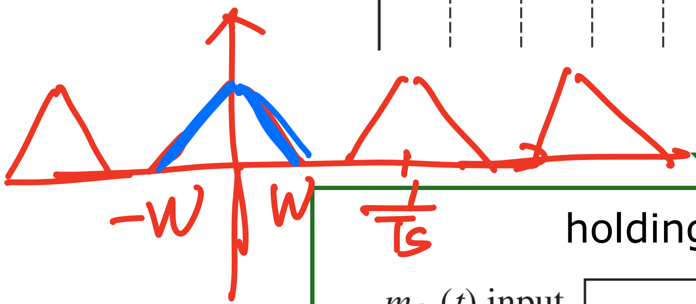
Analog Pulse Modulation (cont'd)

- 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)

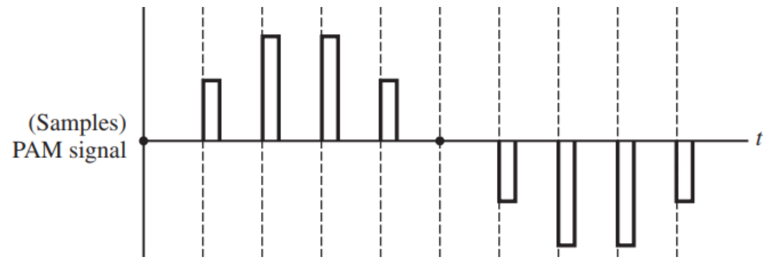


$$m_\delta(t) = \sum_n m(nT_s)\delta(t - nT_s)$$



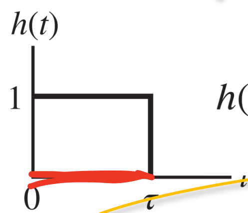
holding circuit

$m_\delta(t)$ input → $h(t)$ → PAM output $m_c(t)$

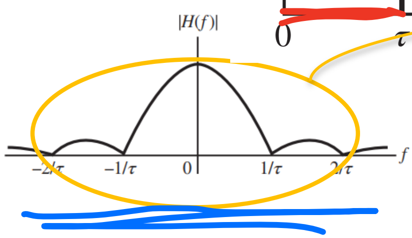


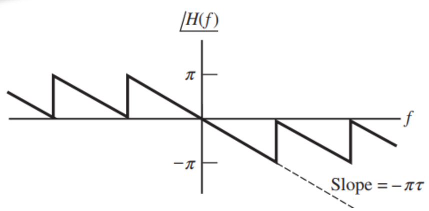
$$m_c(t) = \sum_n m(nT_s)\Pi\left[\frac{(t - nT_s) + \frac{1}{2}\tau}{\tau}\right]$$

PAM



$$h(t) = \Pi\left(\frac{t - \frac{1}{2}\tau}{\tau}\right)$$





$\frac{1}{\tau} << W$

Amplitude distortion

Equalization

$x_c(t)$ → $1/|H(f)|$ → reconstruction → $m(t)$

Thanks for your kind attention!

Questions?