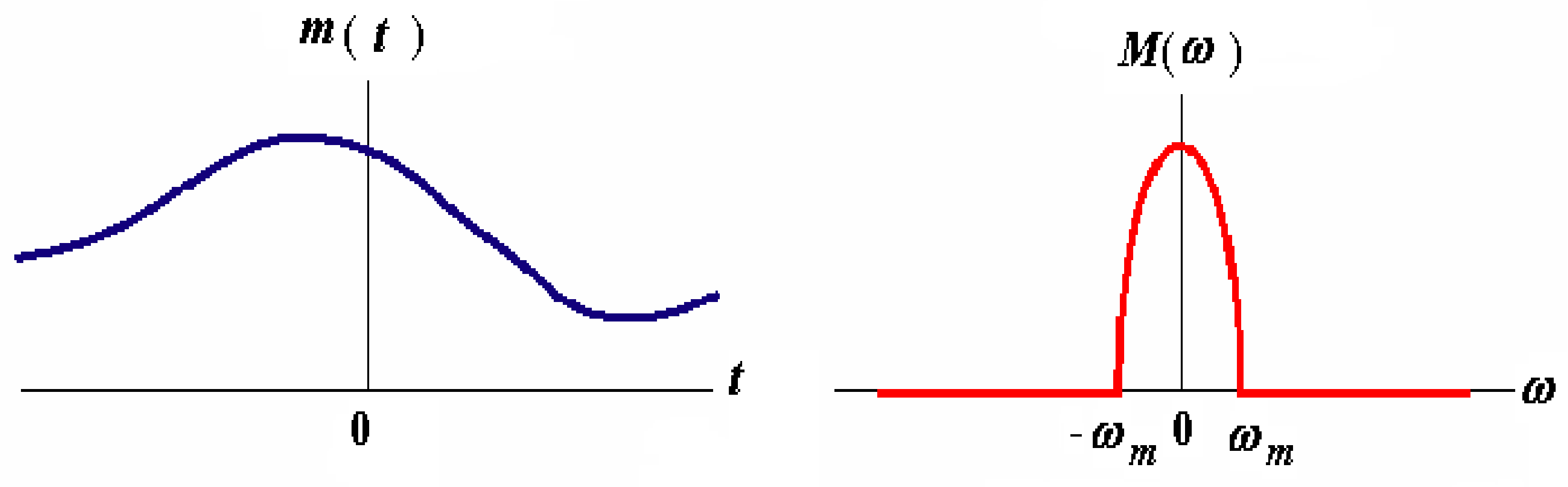
§ 4.2 振幅调制

- 连续时间信号的模拟调制常以正弦波为载波对信号进行调制
- 信号一般可调制在载波(carrier)的振幅、频率(或相位)上
- 被调制的信号$m(t)$一般被视为有限频带的信号
- 信号$m(t)$的频谱记为$M(\omega)$，最高频率设为ω_m



- 载波信号$c(t)$的频率ω_c一般远大于ω_m ($\omega_c >> \omega_m$)

- 调制后的信号一般为一窄带信号
- 任一窄带信号$x(t)$可以表示为低通信号$x_c(t)$和$x_s(t)$的函数：

$$x(t)=x_c(t)\cos\omega_c t+x_s(t)\sin\omega_c t$$

$$=\sqrt{x_c^2(t)+x_s^2(t)}\left[\frac{x_c(t)}{\sqrt{x_c^2(t)+x_s^2(t)}}\cos\omega_c t\right.$$

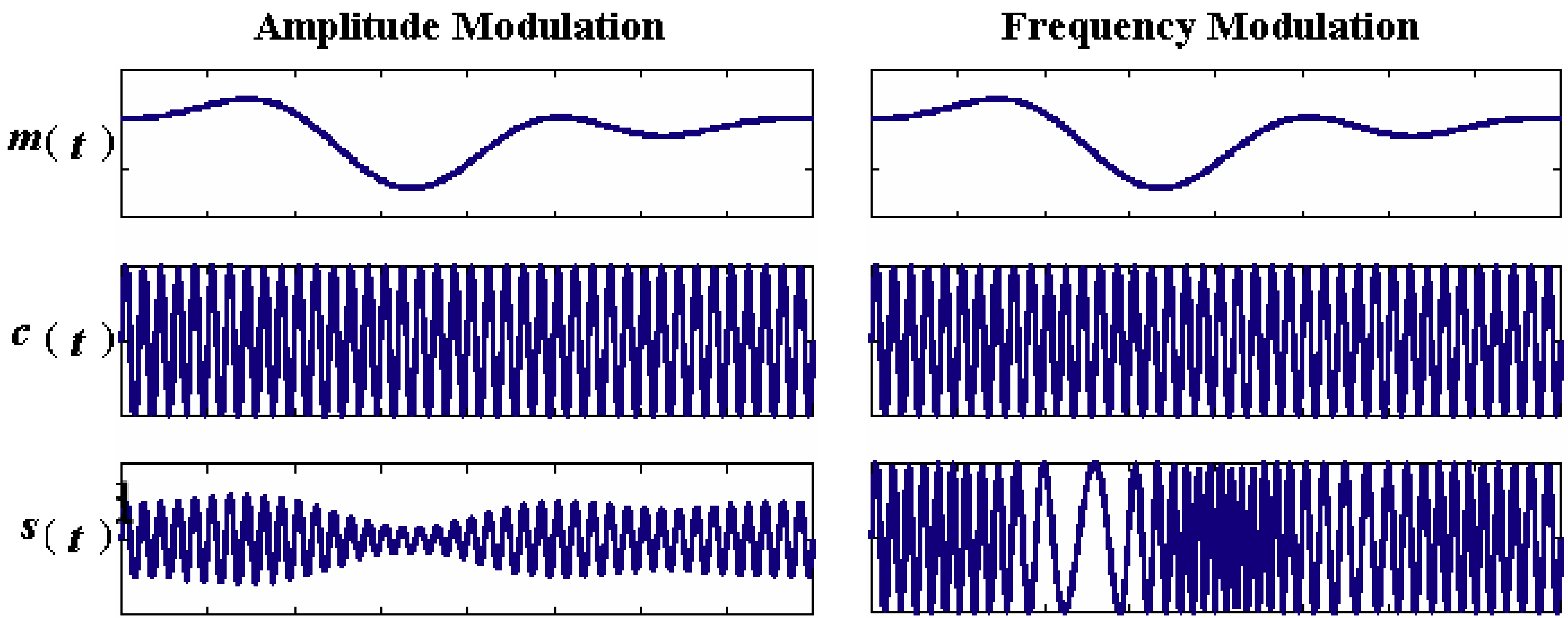
$$\left.+\frac{x_s(t)}{\sqrt{x_c^2(t)+x_s^2(t)}}\sin\omega_c t\right]$$

$$=\alpha(t)\cos[\omega_c t+\varphi(t)]$$

其中 $\alpha(t)=\sqrt{x_c^2(t)+x_s^2(t)},\quad \varphi(t)=-\tan^{-1}\dfrac{x_s(t)}{x_c(t)}$

- **两类调制方式**
  - **振幅调制：信号*m*(*t*)调制在α(t)上，ϕ(*t*)为常数**
  - **角调制(频率调制、相位调制)：**信号***m*(*t*)**调制在***ϕ*(*t*)**上，*α*(*t*)**为常数

$$x(t) = \underbrace{\alpha(t)}_{\text{AM}} \cos\left(\omega_c t + \underbrace{\phi(t)}_{\text{PM or FM}} \right)$$

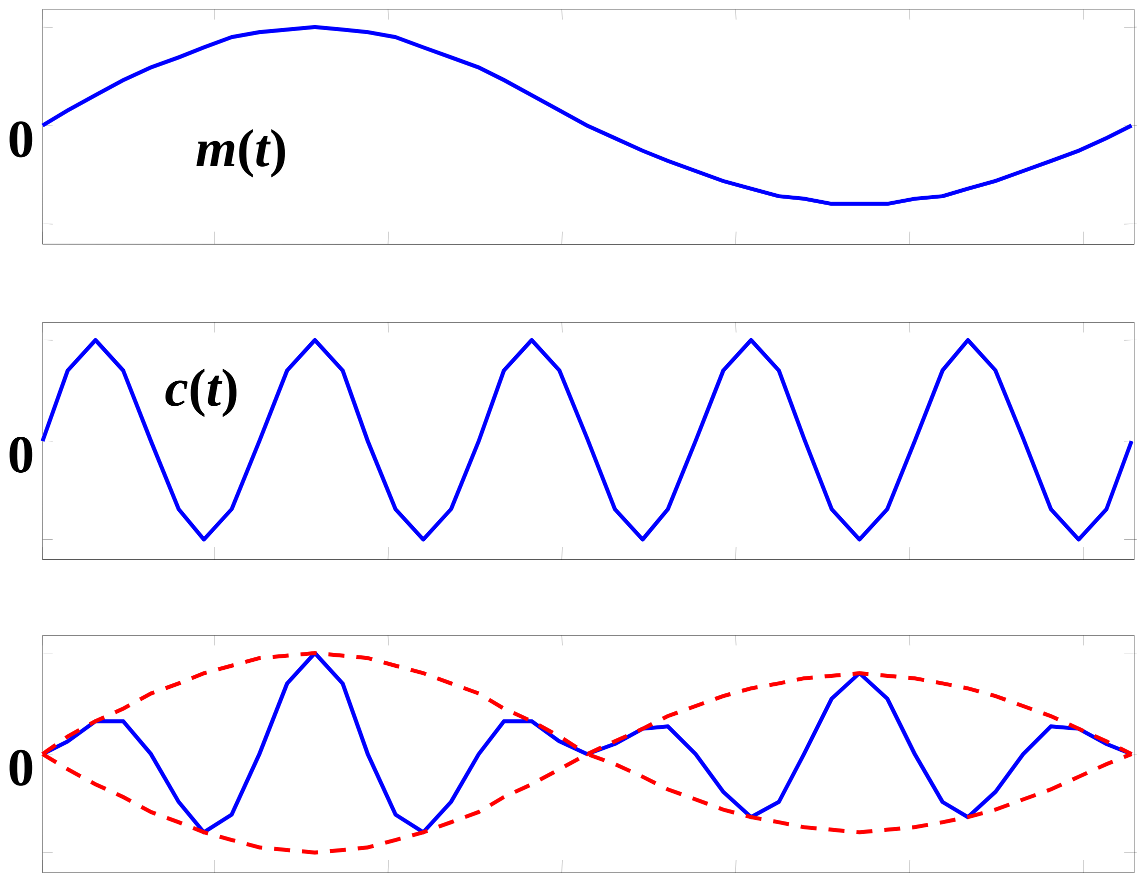


一、双边带(DSB)调制

1、DSB调制的定义

- **DSB调制：将被调制信号*m*(*t*)和载波信号*c*(*t*)相乘**

$$s(t) = m(t) \times c(t) = m(t)\cos\omega_c t$$



- **DSB调制信号*s*(*t*)的包络与被调信号*m*(*t*)的绝对值成正比**

2、**DSB**调制信号的频谱和带宽

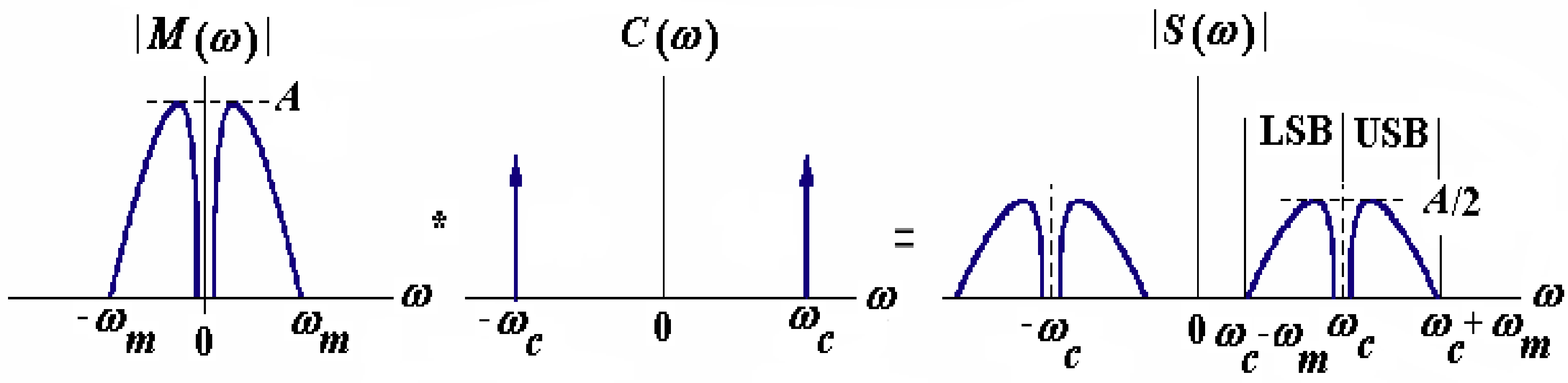
$$s(t) = m(t)\cos\omega_c t \quad \Rightarrow$$

$$S(\omega) = \frac{1}{2\pi}\{M(\omega) * [\mathrm{F}(\cos\omega_c t)]\}$$

$$= \frac{1}{2\pi}\{M(\omega) * \pi[\delta(\omega+\omega_c) + \delta(\omega-\omega_c)]\}$$

$$= \frac{1}{2}[M(\omega) * \delta(\omega+\omega_c)] + \frac{1}{2}[M(\omega) * \delta(\omega-\omega_c)]$$

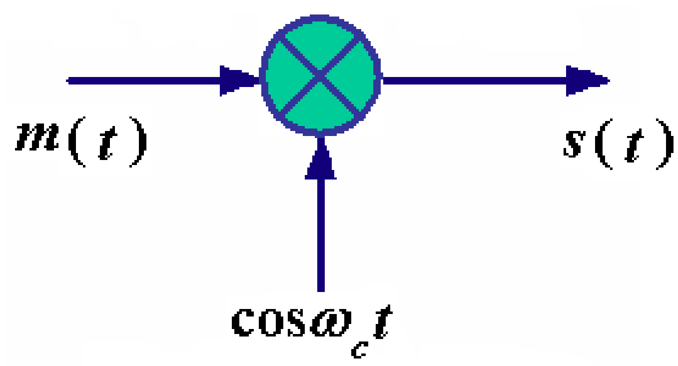
$$= \frac{1}{2}M(\omega+\omega_c) + \frac{1}{2}M(\omega-\omega_c)$$



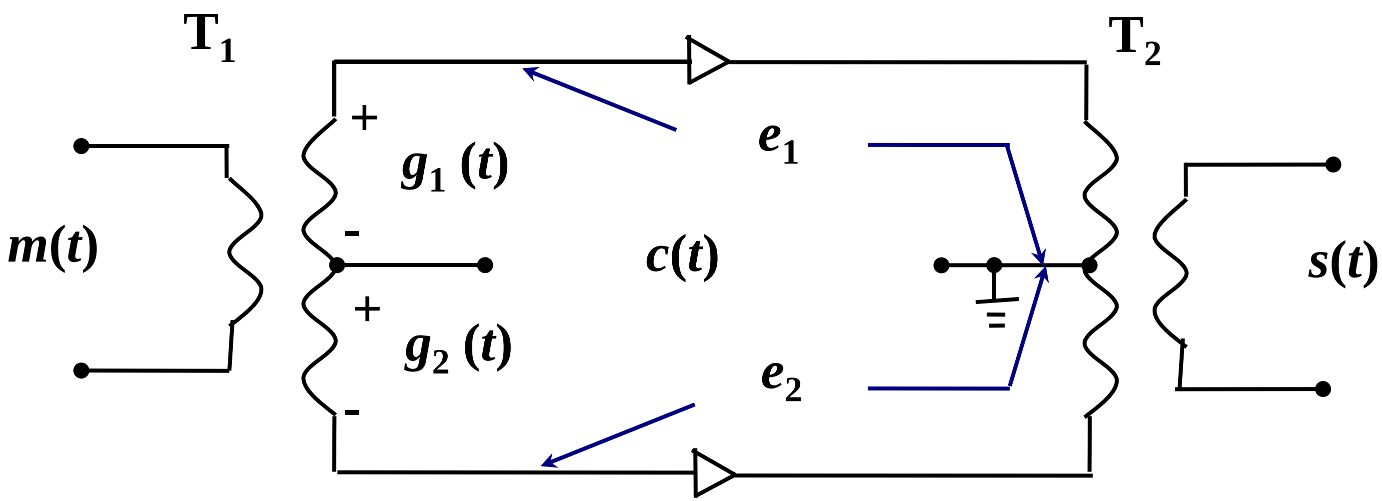
- **DSB调制信号包含两个边带：**
  - **位于$|\omega|>\omega_c$的部分称为上边带(Upper Side Band, USB)**
  - **位于$|\omega|<\omega_c$的部分称为下边带(Lower Side Band, LSB)**
- **DSB调制信号的上下边带对称**
- **DSB调制信号的带宽为$2\omega_m$**
- **DSB调制信号没有载频分量，严格来说称为载波抑制双边带信号(DSB-SC)**

3、DSB信号的调制

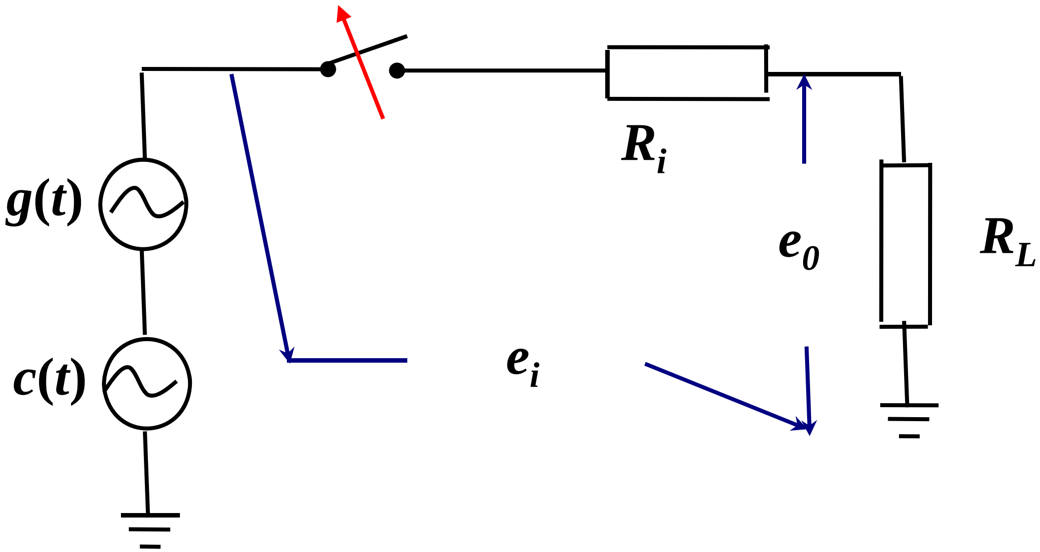
- **被调信号$m(t)$与载波信号$c(t)$相乘**



- **可通过平衡调制器实现**
- **平衡调制器：使两信号相乘，且因对称性平衡掉载波频率项**



- T_1为低频变压器，T_2为高频变压器(且起高频带通滤波作用)
- 二极管导通与否取决于$c(t)$的极性(条件：$c(t)$足够大)
- $c(t)>0$，二极管导通，内阻为R_i (负载设为R_L)
- $c(t)<0$，二极管截止
- 平衡调制器的单边等效电路为：



- 加在二极管上的电压为：

$$e_i(t) = c(t) + g(t) = A\cos\omega_c t + g(t)$$

- **输出电压为：**

$$e_o(t)=\begin{cases}\dfrac{R_L}{R_i+R_L}e_i(t)=Ke_i(t) & A\cos\omega_c t>0\\ 0 & A\cos\omega_c t<0\end{cases}$$

$$=[A\cos\omega_c t+g(t)]P(t)$$

其中*P*(*t*)为周期开关信号：

$$P(t)=\begin{cases}K & -\dfrac{T}{4}+nT<t<\dfrac{T}{4}+nT, \quad T=\dfrac{2\pi}{\omega_c}\\ 0 & \text{else}\end{cases}$$

- ***P*(*t*)可以用傅里叶级数表示：**

$$P(t)=K\left\{\frac{1}{2}+\sum_{n=0}^{\infty}Sa\left[\frac{(2n+1)\pi}{2}\right]\cos(2n+1)\omega_c t\right\}$$

- **平衡调制器上半部分的输出电压为：**

$$e_{o1}(t) = K\left\{\frac{1}{2}[A\cos\omega_c t + g_1(t)] + \frac{2}{\pi}\cos\omega_c t[A\cos\omega_c t + g_1(t)]\right.$$

$$\left. + \phi(t)[A\cos\omega_c t + g_1(t)]\right\} = K\left[\frac{1}{2}A\cos\omega_c t + \frac{1}{2}g_1(t)\right.$$

$$\left. + \frac{2}{\pi}A\cos^2\omega_c t + \frac{2}{\pi}g_1(t)\cos\omega_c t + \phi_1(t) + \phi_2(t)\right]$$

其中 $\phi(t) = \sum_{n=1}^{\infty} Sa\left[\frac{(2n+1)\pi}{2}\right]\cos(2n+1)\omega_c t$

$$\phi_1(t) = A\cos\omega_c t\phi(t) = \sum_{n=1}^{\infty} Sa\left[\frac{(2n+1)\pi}{2}\right]A\cos\omega_c t\cos(2n+1)\omega_c t$$

$$\phi_2(t) = g_1(t) = \sum_{n=1}^{\infty} Sa\left[\frac{(2n+1)\pi}{2}\right]g_1(t)\cos(2n+1)\omega_c t$$

- 对于平衡调制器的下半部分，其输入电压为：

$$e_{i2}(t) = c(t) + g_2(t) = A\cos\omega_c t - g_1(t)$$

- 类似地，其输出电压为：

$$e_{o2}(t) = K\left[\frac{1}{2}A\cos\omega_c t - \frac{1}{2}g_1(t) + \frac{2}{\pi}A\cos^2\omega_c t\right.$$

$$\left. - \frac{2}{\pi}g_1(t)\cos\omega_c t + \phi_1(t) - \phi_2(t)\right]$$

- 变压器T_2的初级输入为：

$$e_{o1}(t) - e_{o2}(t) = K\left[g_1(t) + \frac{4}{\pi}g_1(t)\cos\omega_c t + 2\phi_2(t)\right]$$

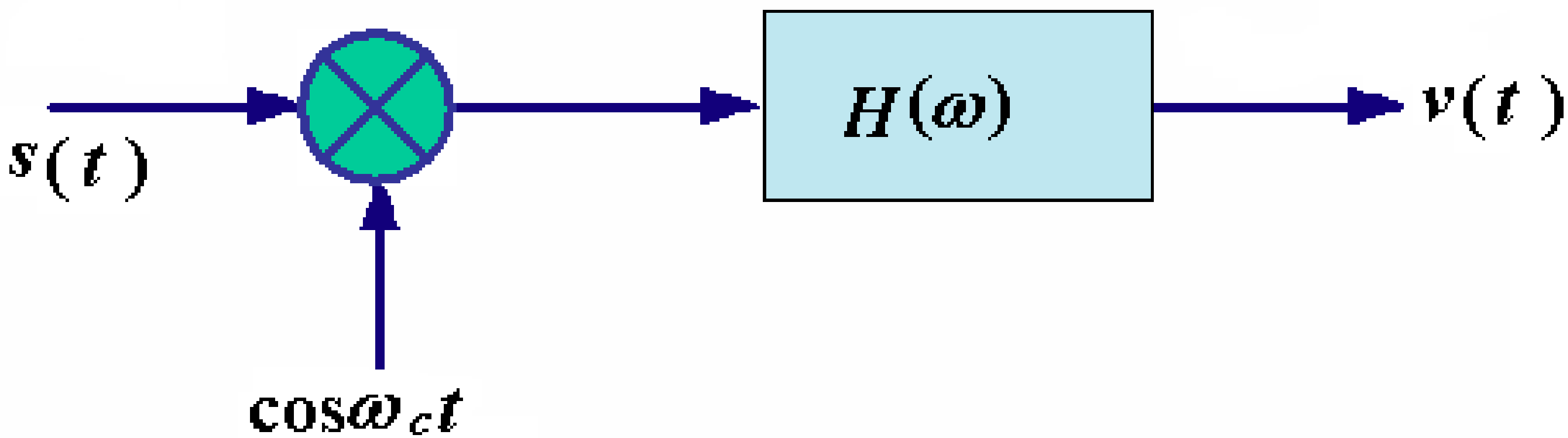
- 变压器T_1的作用： $g_1(t) = m(t)$

- $\phi_2(t)$各分量的频率均远大于ω_c
- 变压器T_2起带通滤波作用，只取出ω_c附近的分量

$$e_o(t) = K \cdot \frac{4}{\pi} m(t)\cos\omega_c t = k \cdot m(t)\cos\omega_c t$$

4、DSB信号的解调

- DSB调制信号的包络与$|m(t)|$成正比，不与$m(t)$成正比
- 不能用包络检波的方法进行解调
- 需用相干解调的方法：本地振荡器产生一个频率和相位与载波一致的信号与接收信号相乘，再用低通滤波取出调制信号



- **设接收的调制信号为：** $s(t) = m(t)\cos(\omega_c t + \theta_c)$
- **本地产生的信号为：** $c_0(t) = \cos(\omega_0 t + \theta_0)$

$$r(t) = s(t)\cos(\omega_0 t + \theta_0) = m(t)\cos(\omega_c t + \theta_c)\cos(\omega_0 t + \theta_0)$$

$$= \frac{1}{2}m(t)\cos[(\omega_c - \omega_0)t + \theta_c - \theta_0] + \frac{1}{2}m(t)\cos[(\omega_c + \omega_0)t + \theta_c + \theta_0]$$

- **若本地产生的信号的频率和相位与载波信号相同：**

$$\omega_c = \omega_0, \quad \theta_c = \theta_0$$

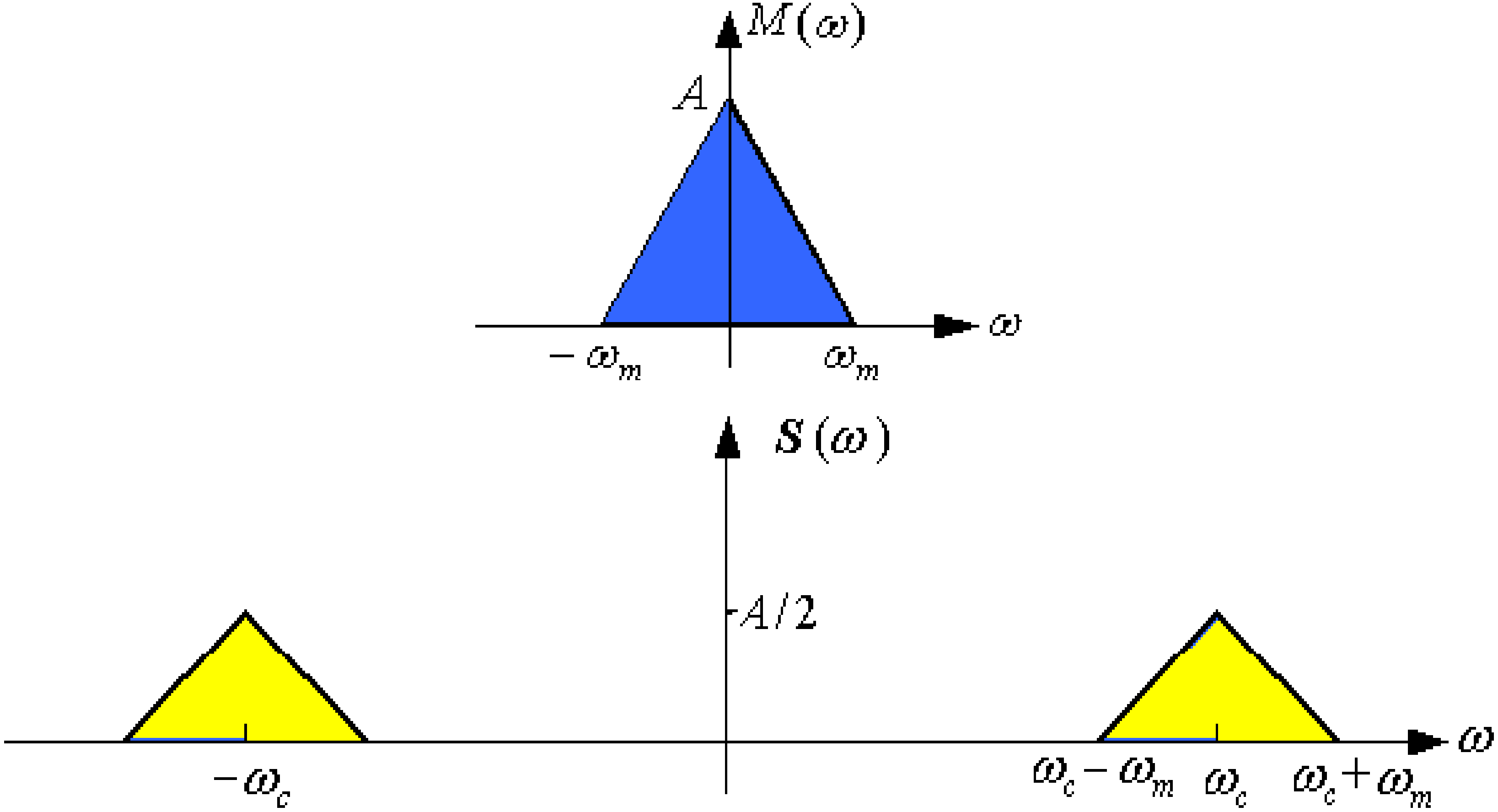
$$\Rightarrow \quad r(t) = \frac{1}{2}m(t) + \frac{1}{2}m(t)\cos(2\omega_c t + 2\theta_c)$$

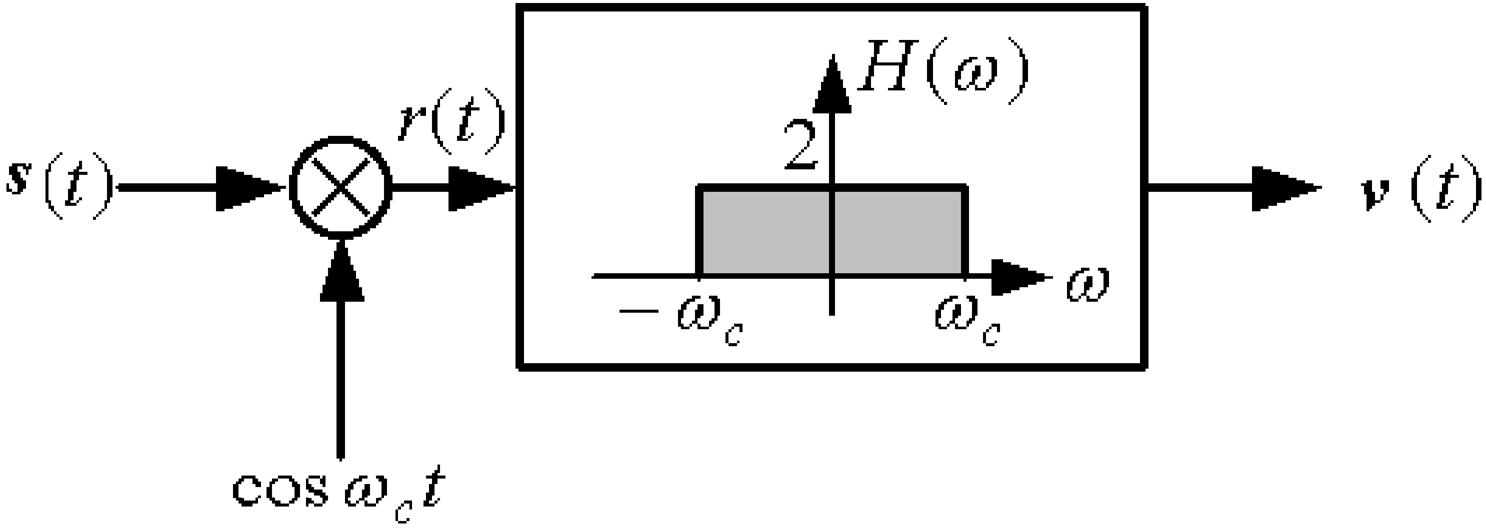
- **经过低通滤波，得到：**

$$v(t) \propto m(t)$$

- **观察一下频谱的变化**

$$s(t) = m(t)\cos\omega_c t \quad \Rightarrow \boxed{S(\omega) = \frac{1}{2}[M(\omega+\omega_c) + M(\omega-\omega_c)]}$$





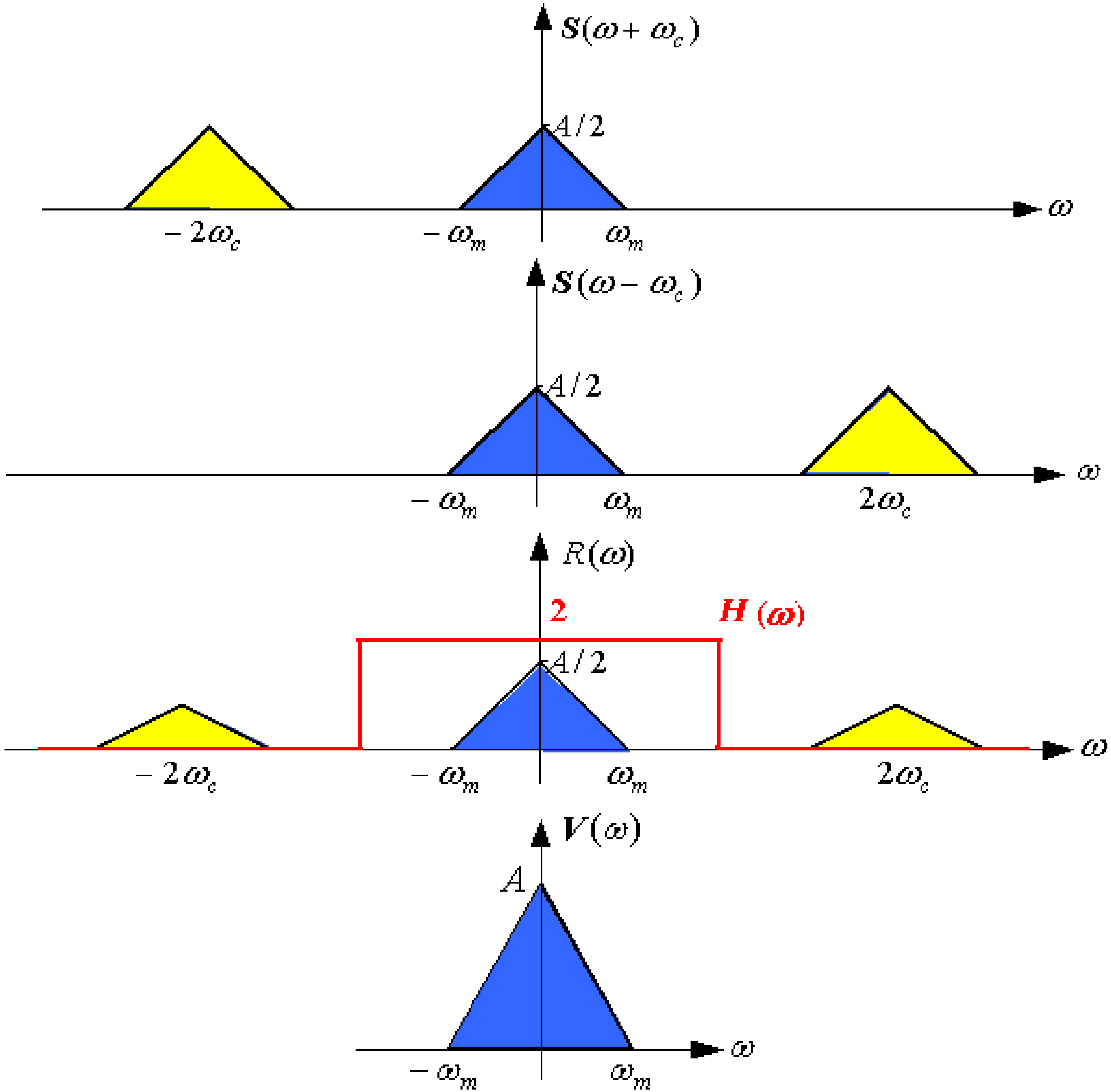
$$r(t) = s(t)\cos\omega_c t = [m(t)\cos\omega_c t]\cos\omega_c t$$

$$R(\omega) = \frac{1}{2\pi}S(\omega) * \pi[\delta(\omega+\omega_c)+\delta(\omega-\omega_c)] = \frac{1}{2}S(\omega+\omega_c)$$

$$+\frac{1}{2}S(\omega-\omega_c) = \frac{1}{4}M(\omega)+\frac{1}{4}M(\omega+2\omega_c)+\frac{1}{4}M(\omega-2\omega_c)$$

$$+\frac{1}{4}M(\omega) = \frac{1}{2}M(\omega)+\frac{1}{4}M(\omega+2\omega_c)+\frac{1}{4}M(\omega-2\omega_c)$$

$$\boxed{\therefore \quad V(\omega) = R(\omega)H(\omega) = M(\omega)}$$



S(ω+ ω_c)
A/2
ω
−2ω_c
−ω_m
ω_m
S(ω− ω_c)
A/2
ω
−ω_m
ω_m
2ω_c
R(ω)
2
H (ω)
A/2
ω
−2ω_c
−ω_m
ω_m
2ω_c
V(ω)
A
ω
−ω_m
ω_m

- 解调中仍可用平衡调制器，只是T_1为高频变压器(传输DSB调制信号)，T_2为低频变压器(且起低通滤波作用)
- 当本地信号和载波存在频率误差和/或相位误差：

$$\Delta\omega = \omega_0 - \omega_c, \quad \Delta\theta = \theta_0 - \theta_c$$

- 解调(相乘、低通滤波)后的信号为：

$$v(t) = m(t)\cos(\Delta\omega t + \Delta\theta)$$

无法准确恢复信号*m*(*t*)

- 相干解调对本地振荡信号的频率和相位有严格要求
- 方法：各种频率稳定系统/DSB信号中传输一定载波分量作为导频，以产生本地振荡信号
- DSB调制不是一种实用的通信制式(带宽、解调)

二、常规双边带调制(Amplitude Modulation, AM)

- **AM是无线电广播所采用的振幅调制方式**

1、AM定义

- **AM：使已调信号*s*(*t*)的包络随被调信号*m*(*t*)变化**

$$s(t) = A[1 + K_m m(t)]c(t) = A[1 + K_m m(t)]\cos\omega_c t$$

其中常数K_m>0称为调幅指数

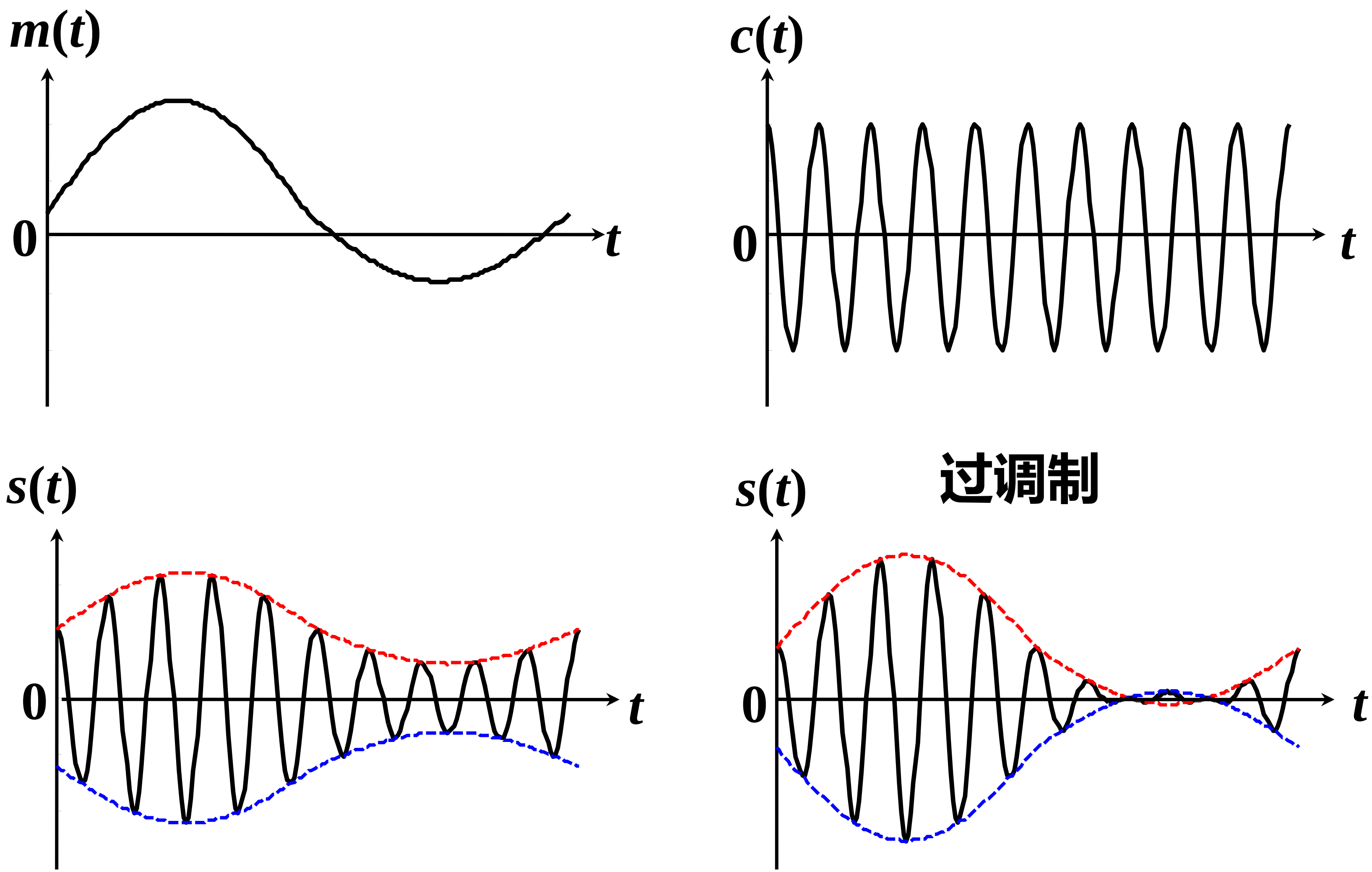
- **为保证已调信号*s*(*t*)的包络随被调信号*m*(*t*)变化，应有：**

$$[1 + K_m m(t)] \geq 0 \quad \rightarrow \quad K_m \left| \left[m(t)_{\min} \middle| m(t) < 0 \right] \right| \leq 1$$

$$\text{if} \quad \left| \left[m(t)_{\min} \middle| m(t) < 0 \right] \right| \geq \left[m(t)_{\max} \middle| m(t) > 0 \right]$$

$$\text{then} \quad K_m \, | m(t) |_{\max} \leq 1$$

- 上述条件不满足，已调信号包络与被调信号不同：**过调制**

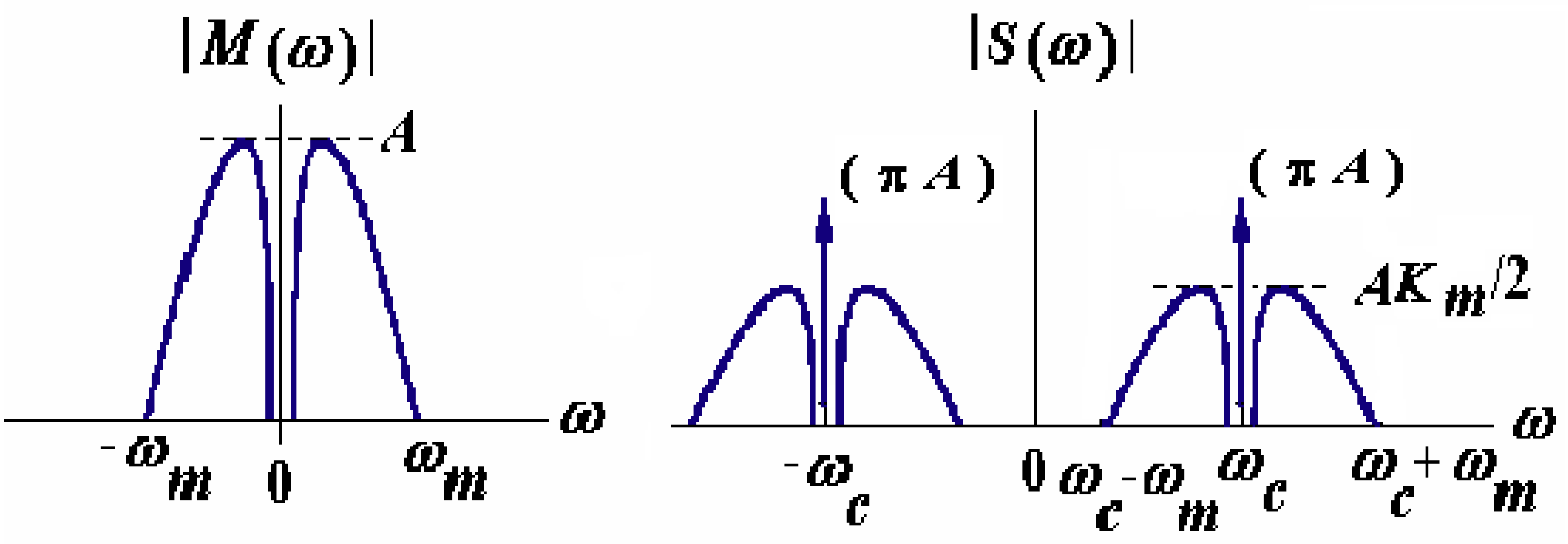


2、AM调制信号的频谱和带宽

$$s(t) = A[1 + K_m m(t)]\cos\omega_c t = A\cos\omega_c t + AK_m m(t)\cos\omega_c t$$

$$\therefore \quad S(\omega) = \pi A\delta(\omega - \omega_c) + \pi A\delta(\omega + \omega_c)$$

$$+ \frac{1}{2}AK_m M(\omega - \omega_c) + \frac{1}{2}AK_m M(\omega + \omega_c)$$



- **AM信号的频谱比DSB信号多一个载波频率项**
- **AM信号的带宽为2ω_m**

3、AM调制信号的功率分配问题

- **AM信号可以写成：**

$$s(t) = A\cos\omega_c t + AK_m m(t)\cos\omega_c t = A\cos\omega_c t + f(t)\cos\omega_c t$$

其中 $AK_m m(t) = f(t)$ **且满足** $A + f(t) \geq 0$

- **AM信号的平均功率(信号平方的时间平均)为：**

$$P = \overline{s^2(t)} = \overline{[A + f(t)]^2 \cos^2\omega_c t}$$

$$= \overline{A^2\cos^2\omega_c t} + \overline{f^2(t)\cos^2\omega_c t} + \overline{2Af(t)\cos^2\omega_c t}$$

- **假设*f*(*t*)没有直流分量：** $\overline{f(t)} = 0$

$$\cos^2\omega_c t = \frac{1}{2} + \frac{1}{2}\cos 2\omega_c t, \quad \overline{\cos 2\omega_c t} = 0$$

$$\therefore \quad P = \frac{1}{2}A^2 + \frac{1}{2}\overline{f^2(t)} = P_c + P_{SB}$$

- **功率利用率η：边带功率P_{SB}与平均功率P之比**

$$\eta = \frac{P_{SB}}{P} = \frac{P_{SB}}{P_c + P_{SB}}$$

- **当被调信号为单频信号时：** $m(t) = A_m \cos \omega_m t$
  - **若实现百分之百的调制：** $K_m A_m = 1$

$$s(t) = A\cos \omega_c t + AK_m m(t)\cos \omega_c t = A\cos \omega_c t + f(t)\cos \omega_c t$$

$$f(t) = AK_m A_m \cos \omega_m t = A\cos \omega_m t$$

$$f(t)\cos \omega_c t = \frac{1}{2}A\cos(\omega_c - \omega_m)t + \frac{1}{2}A\cos(\omega_c + \omega_m)t$$

$$\therefore \quad P_c = \frac{1}{2}A^2, \quad P_{SB} = \frac{1}{2}\left(\frac{1}{2}A\right)^2 + \frac{1}{2}\left(\frac{1}{2}A\right)^2 = \frac{1}{4}A^2$$

$$\Rightarrow \quad \eta = \frac{P_{SB}}{P} = \frac{P_{SB}}{P_c + P_{SB}} = \frac{A^2/4}{A^2/2 + A^2/4} = \frac{1}{3}$$

载波功率占了2/3

- **若调制指数取得很小，如：** $K_m A_m = 1/3$

$$s(t) = A\cos\omega_c t + AK_m m(t)\cos\omega_c t = A\cos\omega_c t + f(t)\cos\omega_c t$$

$$f(t) = AK_m A_m \cos\omega_m t = \frac{1}{3}A\cos\omega_m t$$

$$f(t)\cos\omega_c t = \frac{1}{6}A\cos(\omega_c - \omega_m)t + \frac{1}{6}A\cos(\omega_c + \omega_m)t$$

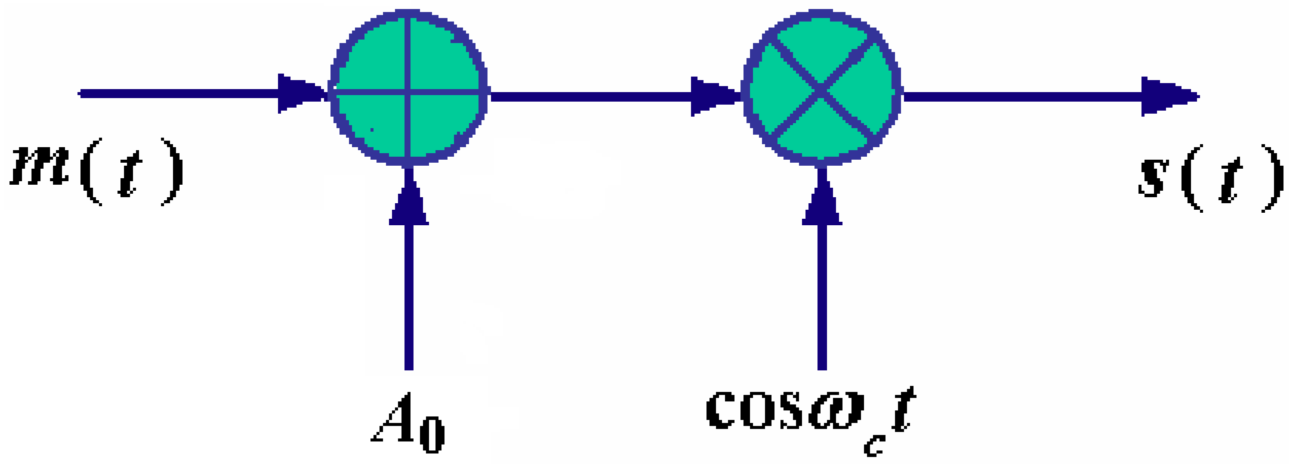
$$\therefore \quad P_c = \frac{1}{2}A^2, \quad P_{SB} = \frac{1}{2}\left(\frac{1}{6}A\right)^2 + \frac{1}{2}\left(\frac{1}{6}A\right)^2 = \frac{1}{36}A^2$$

$$\Rightarrow \quad \eta = \frac{P_{SB}}{P} = \frac{P_{SB}}{P_c + P_{SB}} = \frac{A^2/36}{A^2/2 + A^2/36} \approx 0.053$$

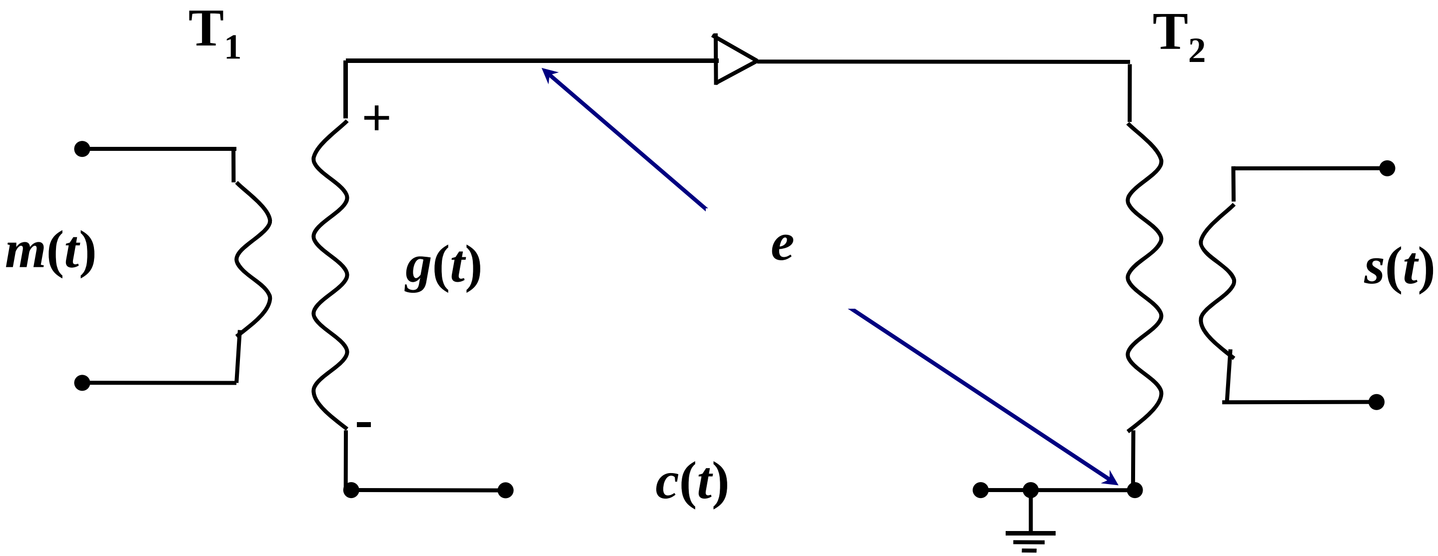
载波功率约占95%

4、AM信号的调制

- **被调信号*m*(*t*)加上一个固定电平，再进行DSB调制**



- 实际上常用非线性器件来调制
- 对DSB调制的平衡调制器只取单边电路：



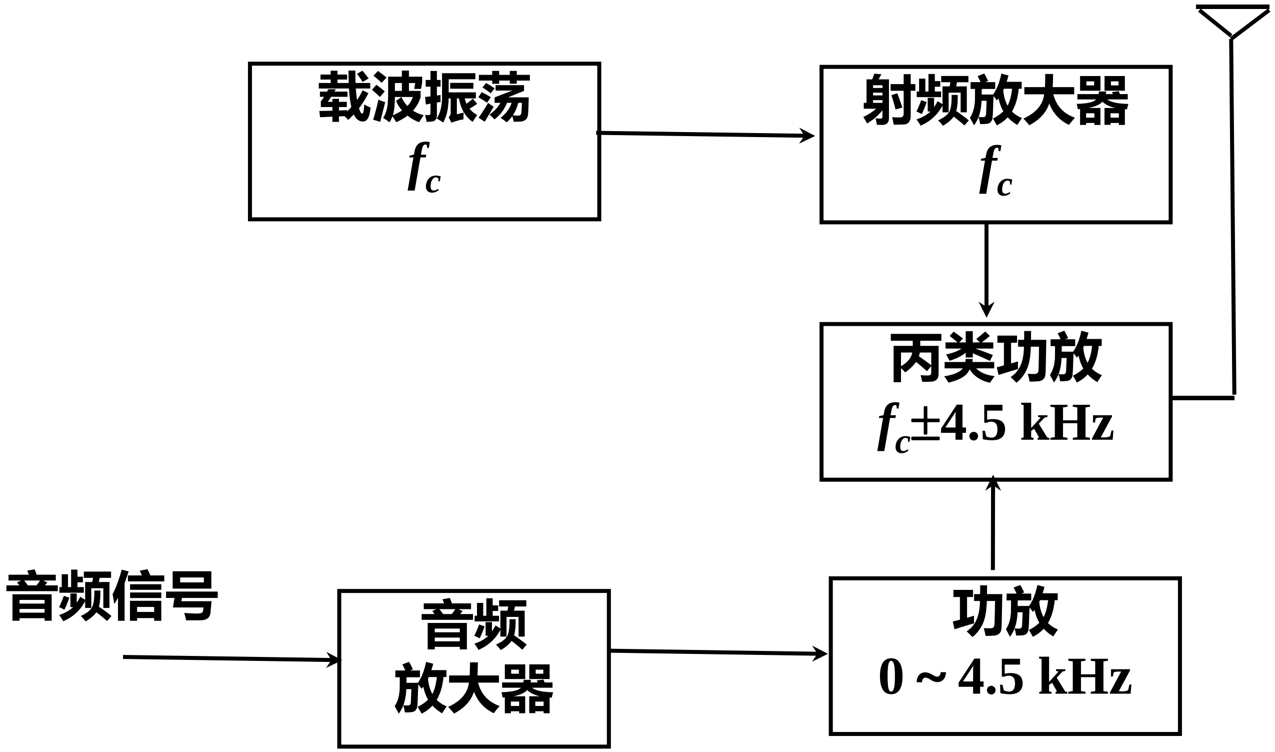
- 前面推导已得出：

$$e(t) = K\left[\frac{1}{2}A\cos\omega_c t + \frac{1}{2}m(t) + \frac{2}{\pi}A\cos^2\omega_c t + \frac{2}{\pi}m(t)\cos\omega_c t + \phi_1(t) + \phi_2(t)\right]$$

- **取出ω_c周围的频率成份(带通滤波器)：**

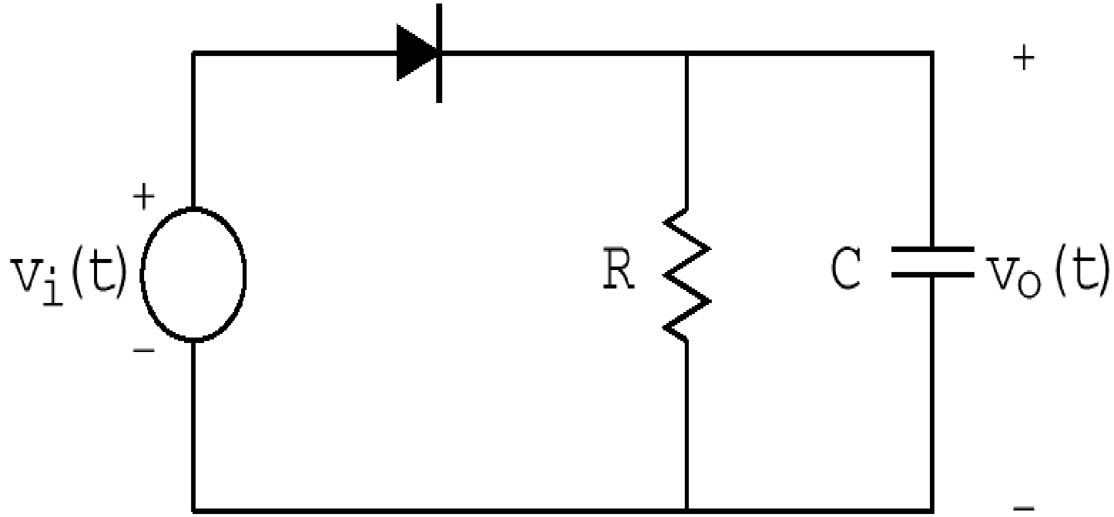
$$s(t)=\frac{1}{2}A\cos\omega_c t+\frac{2}{\pi}m(t)\cos\omega_c t$$

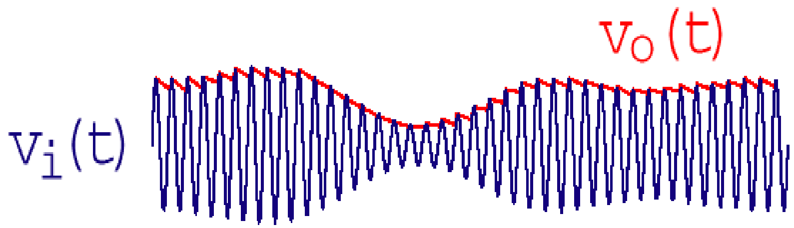
- **广播发射机框图**



5、AM信号的解调

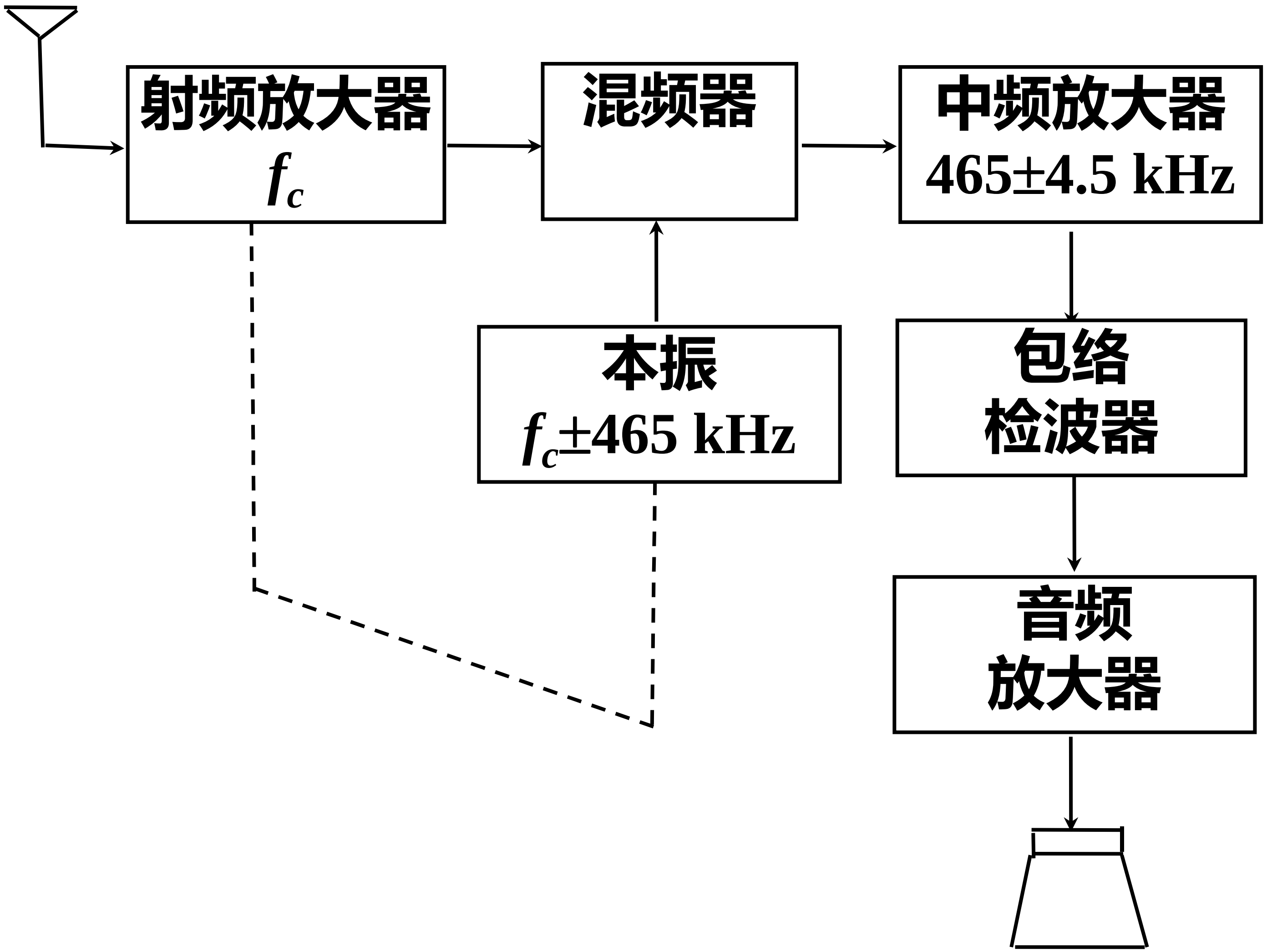
- **通过包络检波器进行解调**





- **RC电路的时间常数应满足：** $\omega_c >> \frac{1}{RC} >> \omega_m$

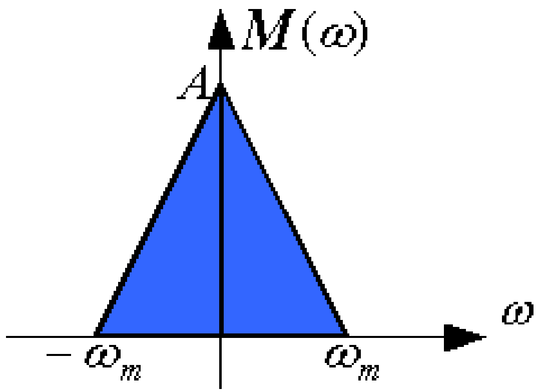
- **AM广播接收机框图**

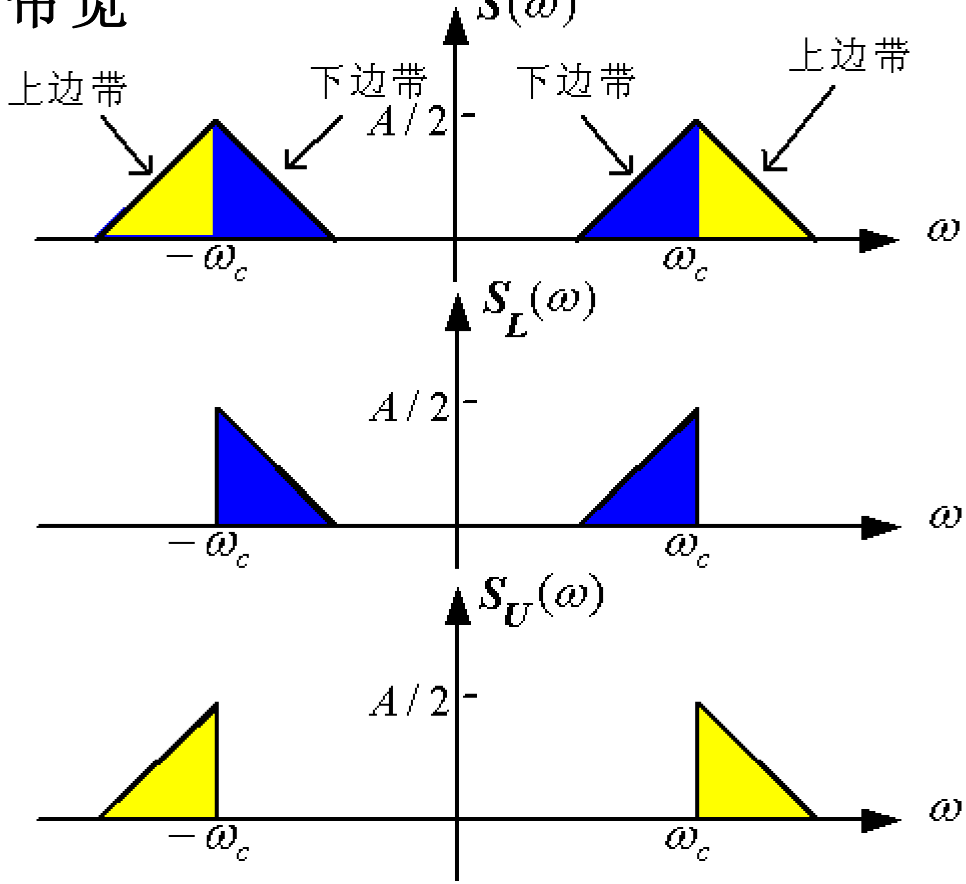


三、单边带(SSB)调制

- **AM和DSB均发射信号的上、下边带**
- **SSB调制：只发送信号的一个边带 → 信号频带宽度减小一半**
- **SSB调制可用于有线长途载波通信和远距短波通信**

1、SSB调制的频谱和带宽





- **设被调信号$m(t)$的频谱为$M(\omega)$，它对ω共轭对称**
- **将$M(\omega)$的$\omega>0$部分记为$M_+(\omega)$，$\omega<0$部分记为$M_-(\omega)$**

$$M(\omega)=\begin{cases} M_+(\omega)=M(\omega)U(\omega) & 0<\omega\le\omega_m \\ M_-(\omega)=M(\omega)U(-\omega) & -\omega_m\le\omega<0 \end{cases}$$

- **上边带调制：**$S_U(\omega)=M_+(\omega-\omega_c)+M_-(\omega+\omega_c)$
- **下边带调制：** $S_L(\omega)=M_-(\omega-\omega_c)+M_+(\omega+\omega_c)$
- **SSB调制信号的频谱带宽为ω_m**

2、SSB调制信号的时域表达式

$$\begin{aligned} S_U(\omega)&=M_+(\omega-\omega_c)+M_-(\omega+\omega_c) \\ &=M_+(\omega)*\delta(\omega-\omega_c)+M_-(\omega)*\delta(\omega+\omega_c) \\ &=[M(\omega)U(\omega)]*\delta(\omega-\omega_c)+[M(\omega)U(-\omega)]*\delta(\omega+\omega_c) \end{aligned}$$

$$\because \quad U(\omega) \overset{F}{\longleftrightarrow} \frac{1}{2}\delta(t) - \frac{1}{j2\pi t}$$

$$S_U(\omega) = [M(\omega)U(\omega)] * \delta(\omega - \omega_c) + [M(\omega)U(-\omega)] * \delta(\omega + \omega_c) \Rightarrow$$

$$s_U(t) =$$

$$\left\{ m(t) * \left[\frac{1}{2}\delta(t) - \frac{1}{j2\pi t} \right] \right\} \cdot e^{j\omega_c t} + \left\{ m(t) * \left[\frac{1}{2}\delta(t) + \frac{1}{j2\pi t} \right] \right\} \cdot e^{-j\omega_c t}$$

$$= \frac{1}{2} m(t)[e^{j\omega_c t} + e^{-j\omega_c t}] - \left[m(t) * \frac{1}{j2\pi t} \right] [e^{j\omega_c t} - e^{-j\omega_c t}]$$

$$= m(t)\cos\omega_c t - \left[m(t) * \frac{1}{\pi t} \right] \sin\omega_c t$$

$$= m(t)\cos\omega_c t - \hat{m}(t)\sin\omega_c t$$

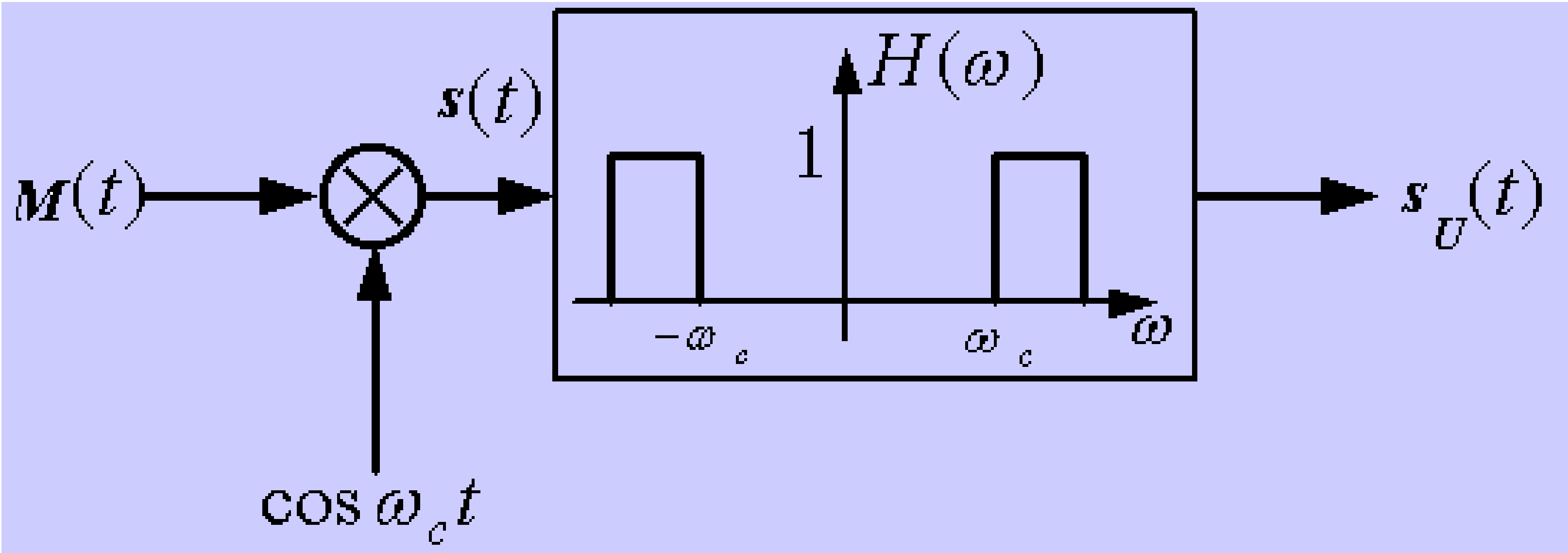
$$m(t) \overset{H}{\longleftrightarrow} \hat{m}(t)$$

- **类似地，对下边带信号，有：**

$$s_L(t) = m(t)\cos\omega_c t + \hat{m}(t)\sin\omega_c t$$

3、SSB的调制方法

方法一：采用带通滤波器



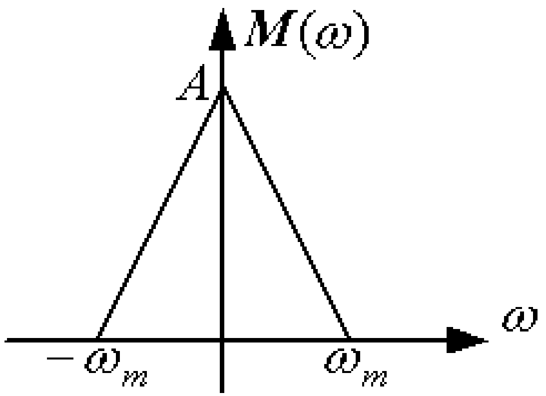
$$H(\omega) = \begin{cases} 1 & \omega_c < |\omega| \le \omega_c + \omega_m \\ 0 & \text{else} \end{cases}$$

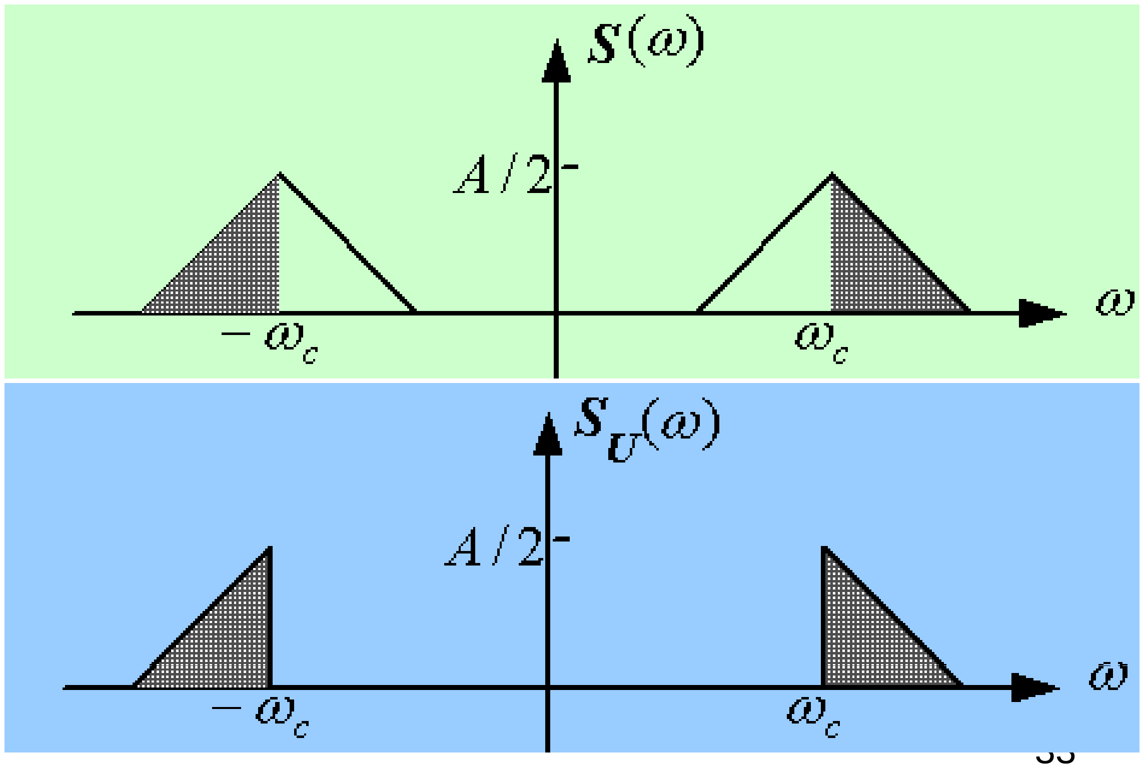
采用带通滤波器实现SSB调制的谱分析

$$s(t) = m(t) \cdot \cos \omega_c t$$

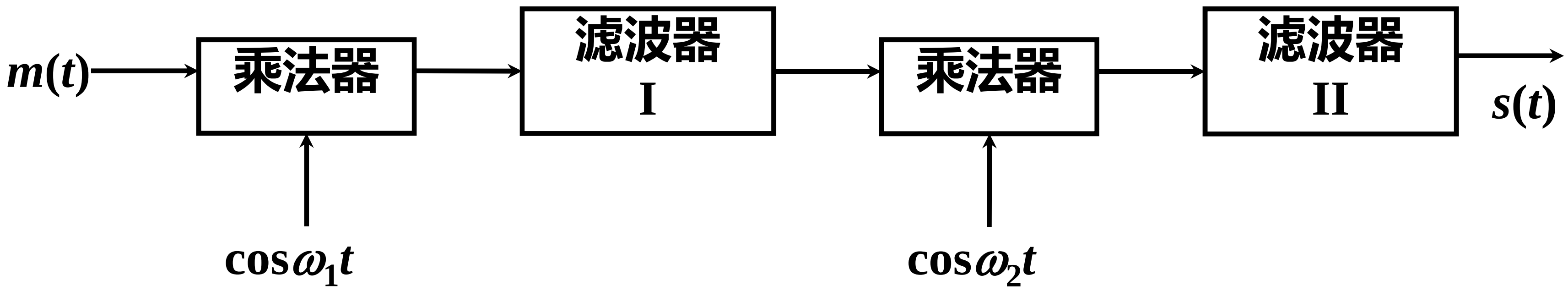
$$\boxed{S(\omega) = \frac{1}{2}[M(\omega+\omega_c) + M(\omega-\omega_c)]}$$

$$\boxed{S_U(\omega) = S(\omega) \cdot H(\omega)}$$

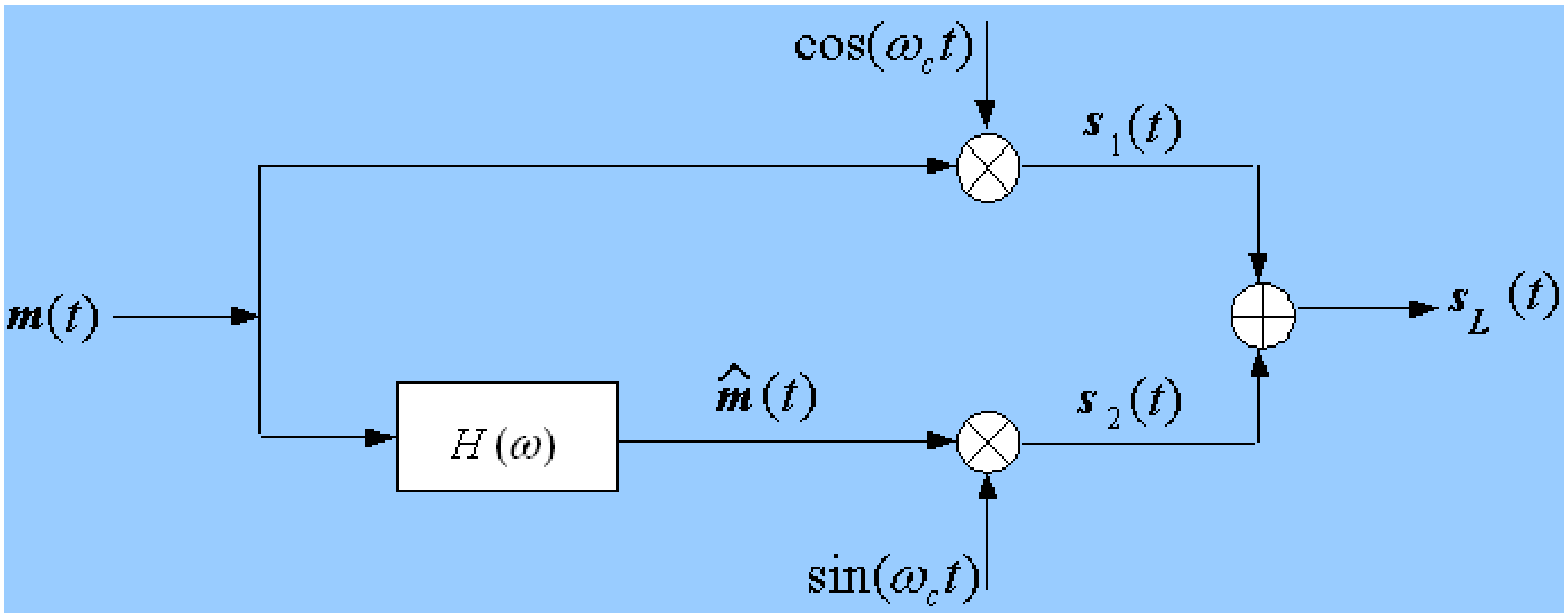




- 带通滤波器法要求$H(\omega)$的截止特性十分陡峭，很难实现
- 实际滤波器存在过渡带，常采用多次频移及多次滤波的方法



方法二：利用希尔伯特(Hilbert)变换



利用希尔伯特变换实现SSB调制的谱分析

$$s_1(t) = m(t)\cos\omega_c t \quad \Rightarrow$$

$$S_1(\omega) = \frac{1}{2}[M(\omega+\omega_c) + M(\omega-\omega_c)]$$

$$M_{\hat{m}}(\omega) = M(\omega)H(\omega) = -jSgn(\omega)M(\omega)$$

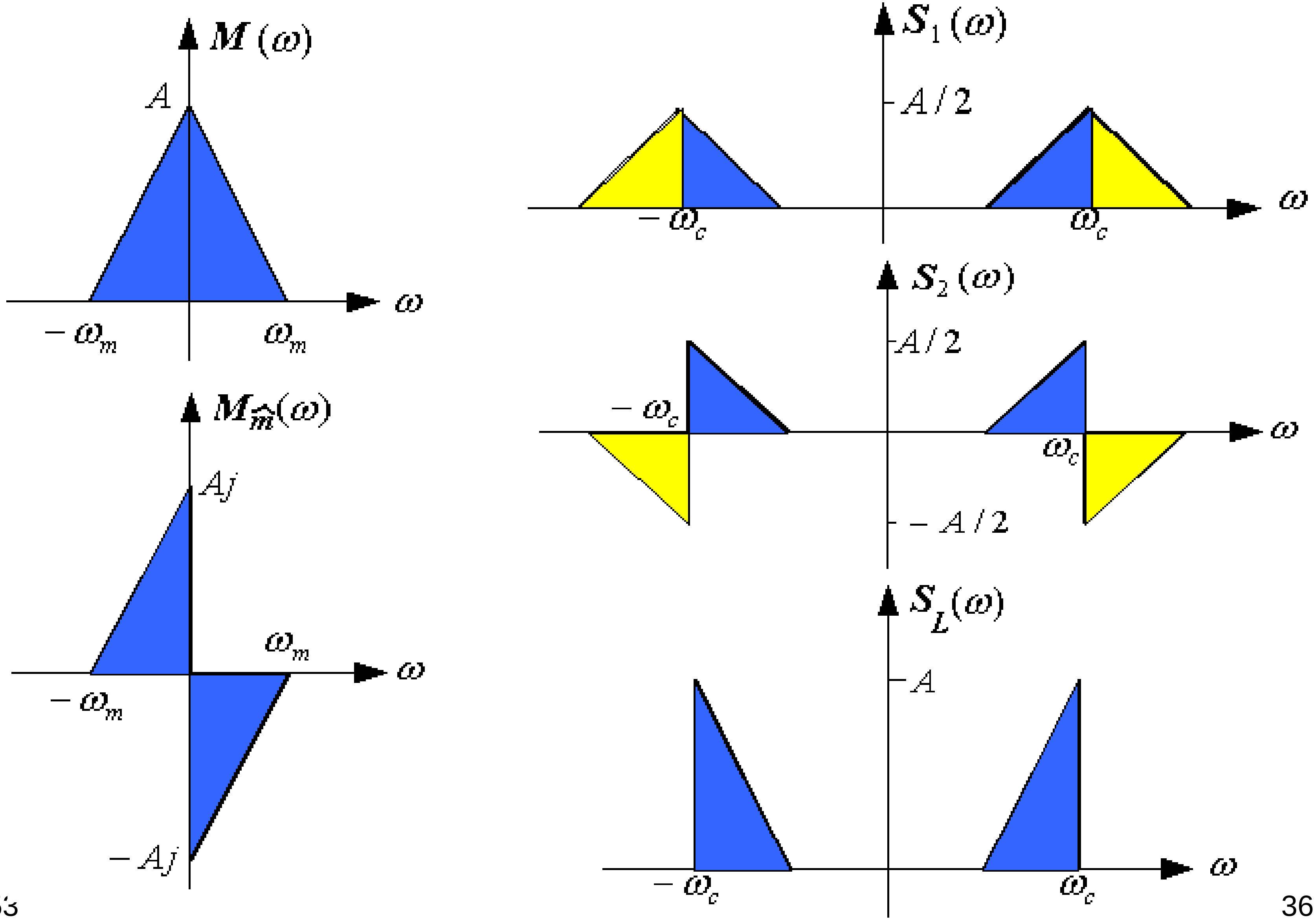
$$S_2(\omega) = \mathrm{F}[\hat{m}(t)\sin\omega_c t] = \frac{1}{2j}[M_{\hat{m}}(\omega-\omega_c) - M_{\hat{m}}(\omega+\omega_c)]$$

$$= \frac{1}{2j}\{-j[Sgn(\omega-\omega_c)M(\omega-\omega_c) - Sgn(\omega+\omega_c)M(\omega+\omega_c)]\}$$

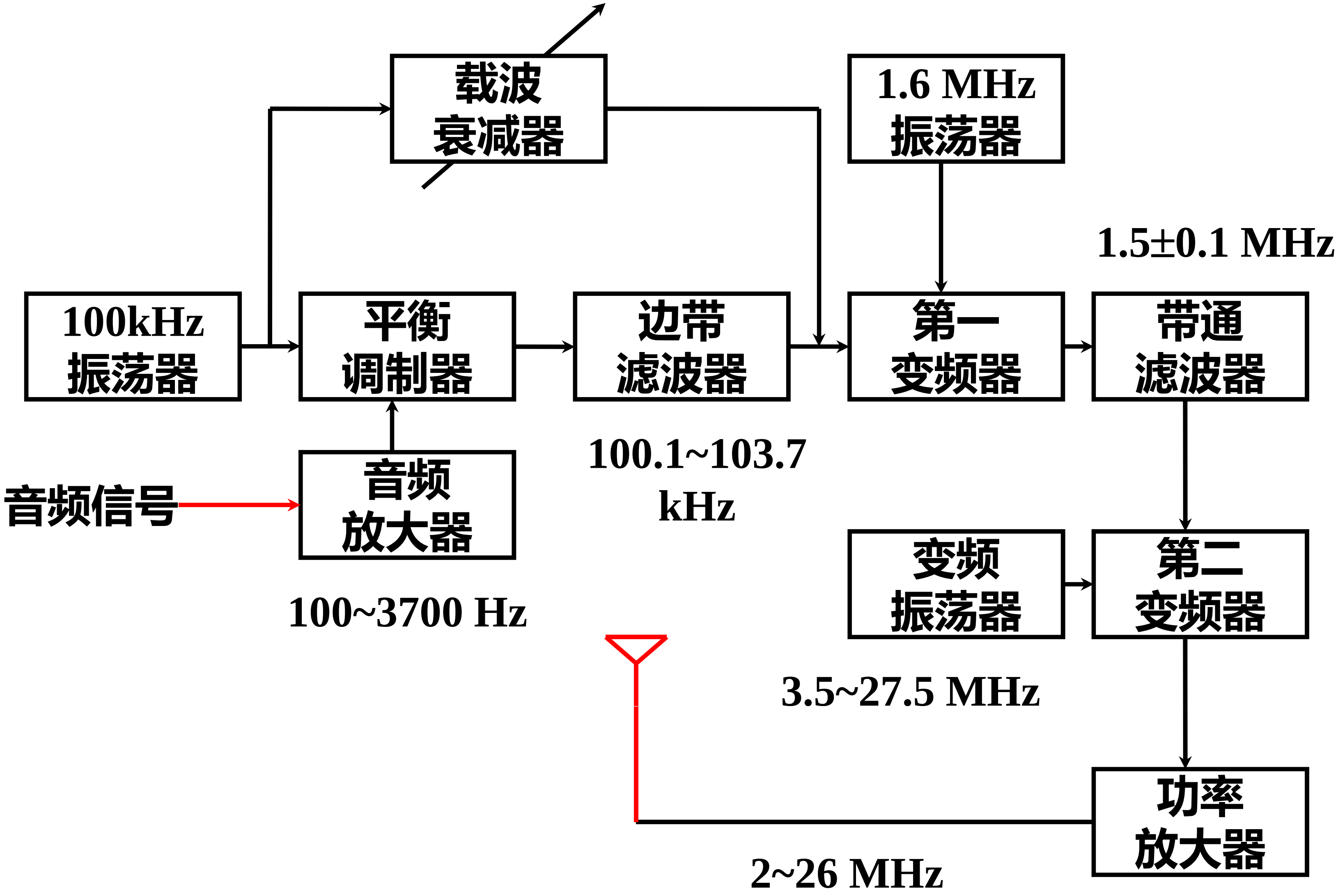
$$= \frac{1}{2}[Sgn(\omega+\omega_c)M(\omega+\omega_c) - Sgn(\omega-\omega_c)M(\omega-\omega_c)]$$

$$\therefore \quad S_1(\omega) + S_2(\omega) = S_L(\omega)$$

利用希尔伯特变换SSB调制的频谱



滤波器法产生SSB信号的发射机框图



4、SSB信号的解调

- **与DSB信号的解调一样，采用相干解调的方法：接收信号与本地相干振荡信号相乘，再用低通滤波取出被调信号**

$$s_{U/L}(t) = m(t)\cos\omega_c t \pm \hat{m}(t)\sin\omega_c t$$

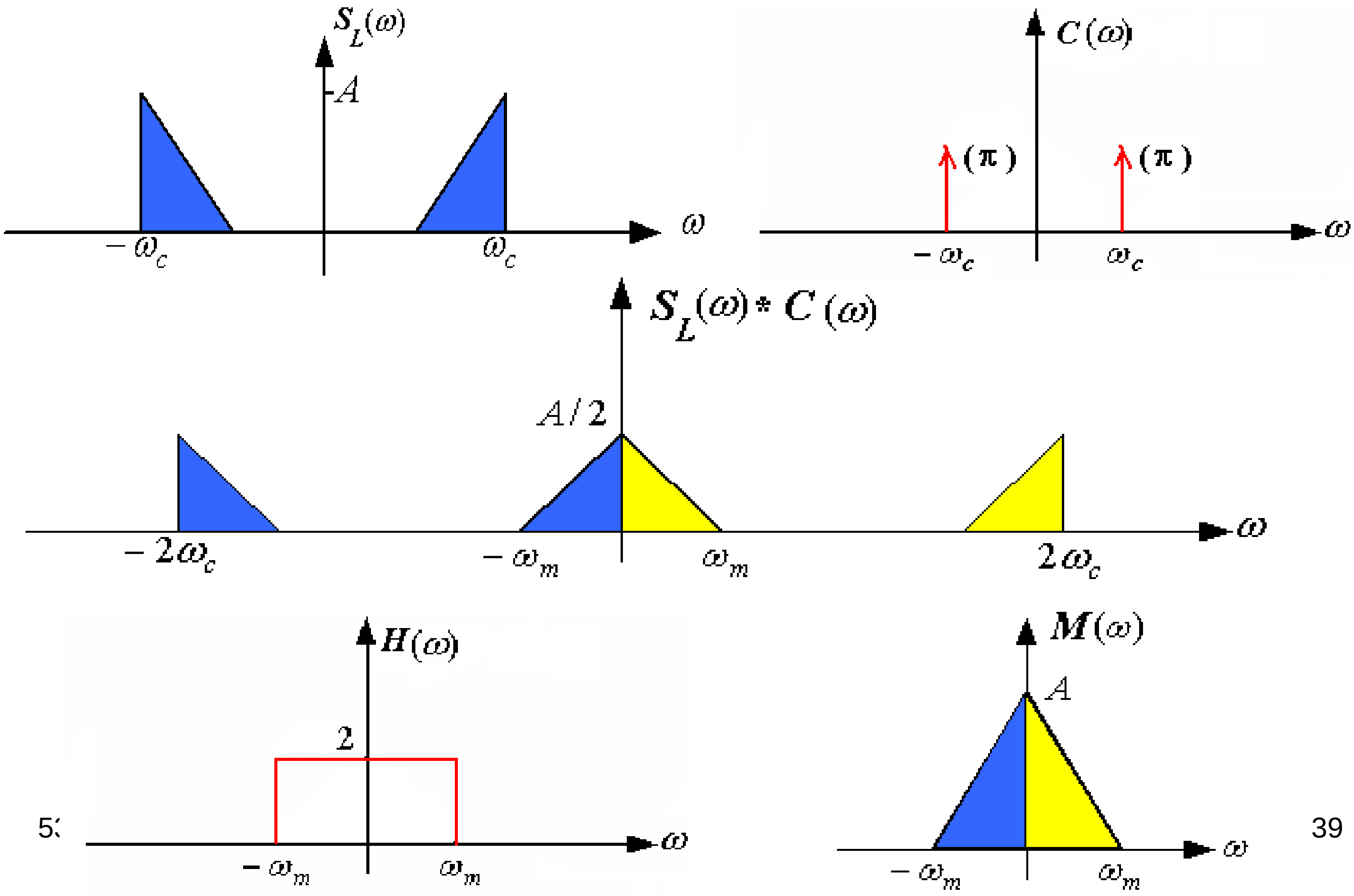
$$s_{U/L}(t)\cos\omega_c t = m(t)\cos^2\omega_c t \pm \hat{m}(t)\sin\omega_c t\cos\omega_c t$$

$$= \frac{1}{2}m(t)(1+\cos 2\omega_c t) \pm \frac{1}{2}\hat{m}(t)\sin 2\omega_c t$$

$$= \frac{1}{2}m(t) + \frac{1}{2}[m(t)\cos 2\omega_c t \pm \hat{m}(t)\sin 2\omega_c t]$$

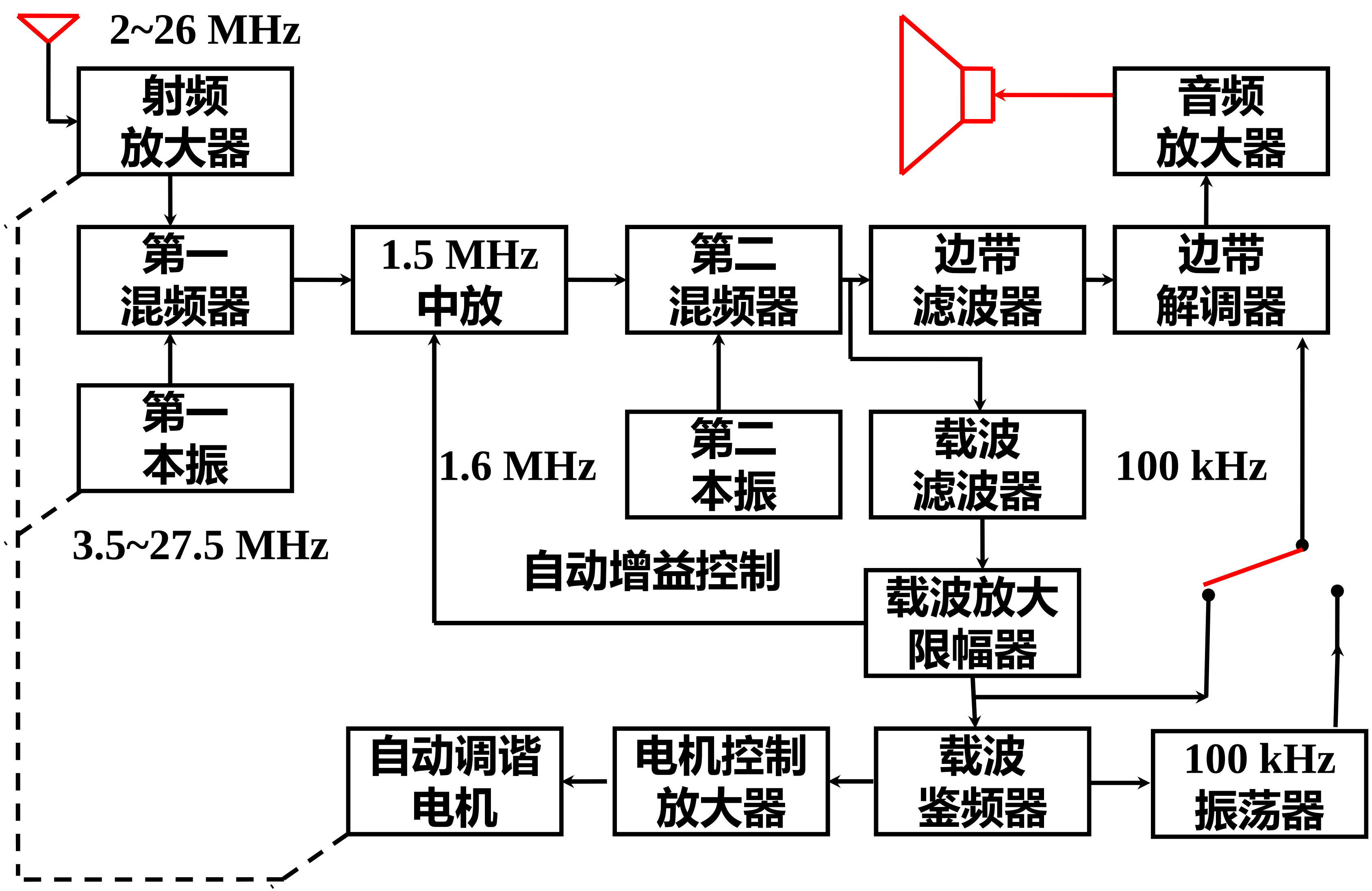
$$\xrightarrow{\text{LPF}} \quad m(t)$$

SSB信号解调的频谱



$S_L(\omega)$
A
ω
$-\omega_c$
ω_c
$C(\omega)$
(π)
(π)
ω
$-\omega_c$
ω_c
$S_L(\omega) * C(\omega)$
$A/2$
ω
$-2\omega_c$
$-\omega_m$
ω_m
$2\omega_c$
$H(\omega)$
2
ω
$-\omega_m$
ω_m
$M(\omega)$
A
ω
$-\omega_m$
ω_m

单边带接收机框图



2~26 MHz
射频
放大器
第一
混频器
第一
本振
3.5~27.5 MHz
1.5 MHz
中放
1.6 MHz
第二
混频器
第二
本振
自动增益控制
边带
滤波器
载波
滤波器
载波放大
限幅器
音频
放大器
边带
解调器
100 kHz
自动调谐
电机
电机控制
放大器
载波
鉴频器
100 kHz
振荡器

- 还可采用**载波重插入**技术：先加入足够大的载波信号，再用包络检波法来解调

$$s_{U/L}(t) = m(t)\cos\omega_c t \pm \hat{m}(t)\sin\omega_c t$$

$$s_{U/L}(t) + A\cos\omega_c t = A\cos\omega_c t + [m(t)\cos\omega_c t \pm \hat{m}(t)\sin\omega_c t]$$

$$= [A + m(t)]\cos\omega_c t \pm \hat{m}(t)\sin\omega_c t$$

插入载波后信号的包络为：

$$e(t) = \sqrt{[A + m(t)]^2 + [\hat{m}(t)]^2}$$

$$\because \quad A >> |m(t)|_{\max},\ A >> |\hat{m}(t)|_{\max}$$

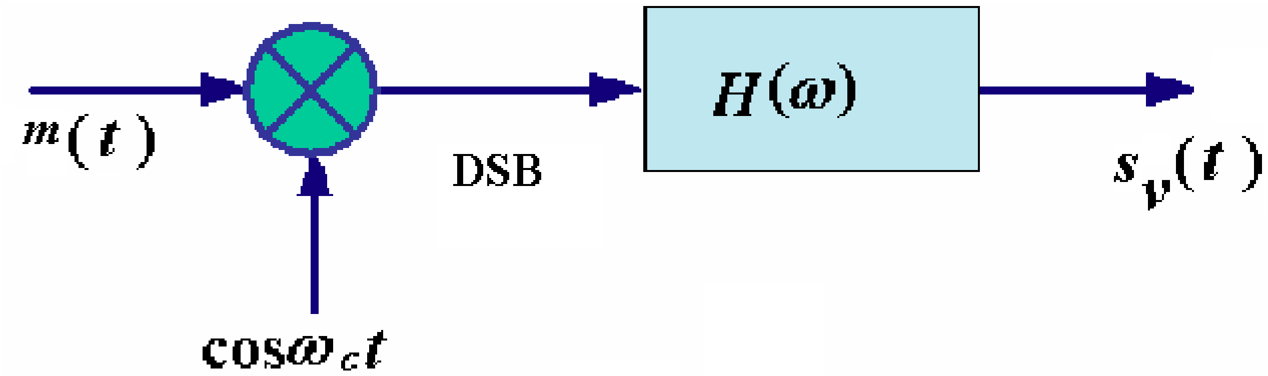
$$e(t) \approx \sqrt{[A + m(t)]^2} = A + m(t)$$

四、残留边带(VSB)调制

- **滤波器法产生SSB信号要求有陡峭截止特性的边带滤波器，实现相当困难**
- **折衷方法：残留边带调制**

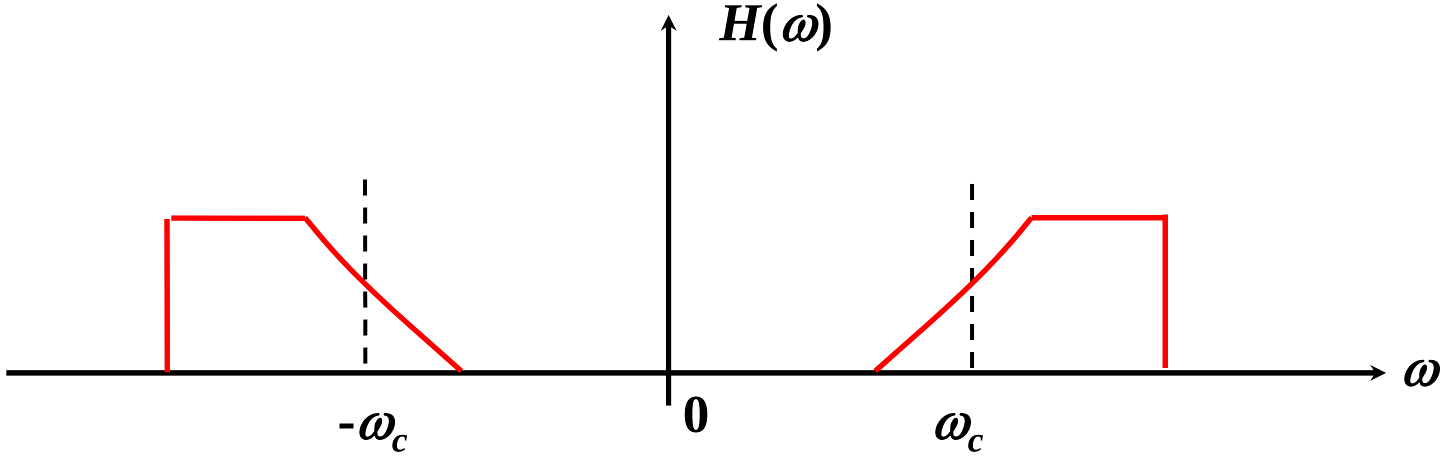
1、VSB的定义和调制方法

- **VSB调制：不像SSB调制那样完全抑制DSB的一个边带，而是使一个边带逐渐截止，另一个边带仍残留一小部分**
- **调制方法：先产生DSB信号，再通过残留边带滤波器，得到VSB信号**

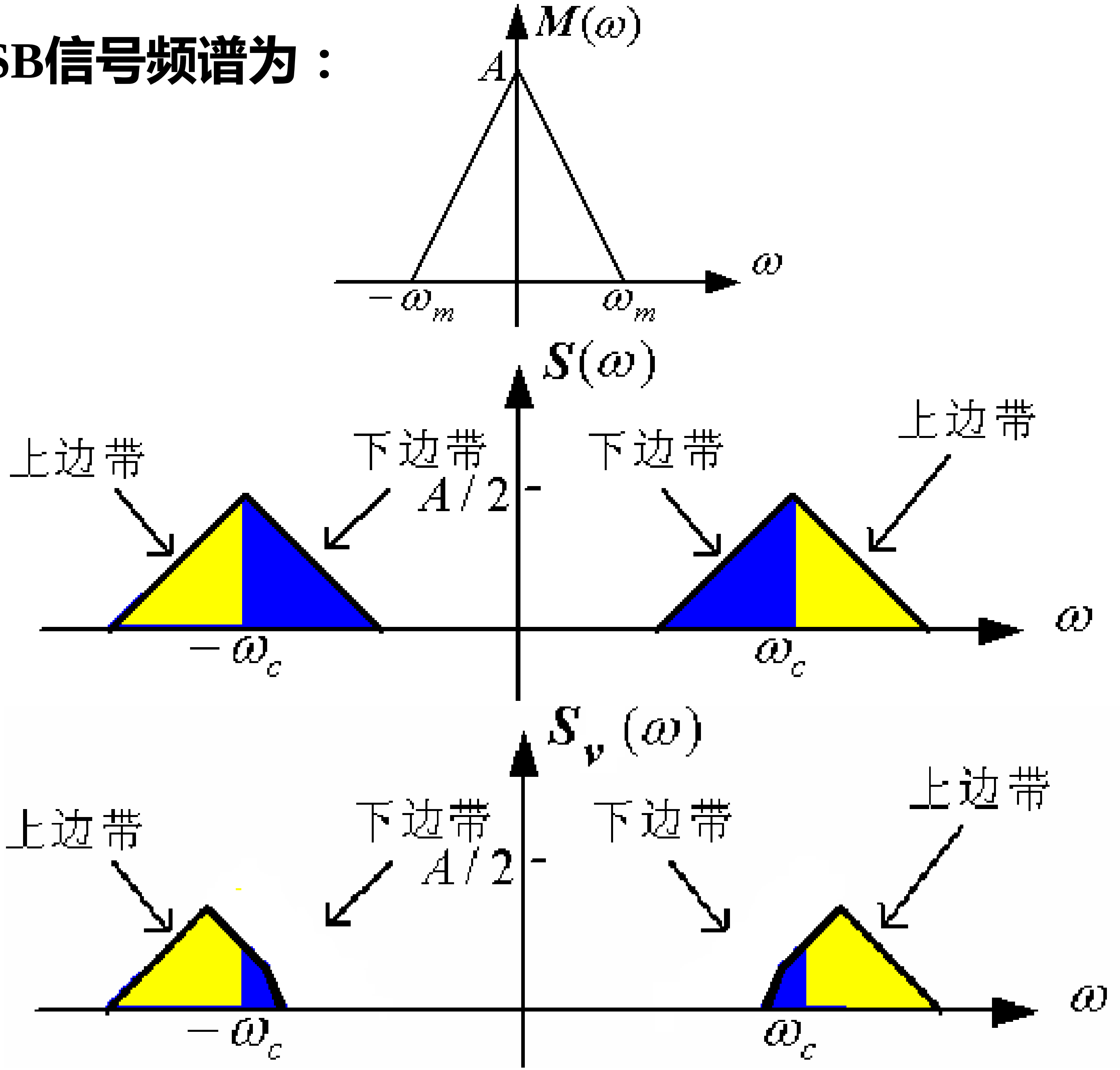


2、VSB信号的频谱和带宽

- **残留下边带时，滤波器传递函数为：**

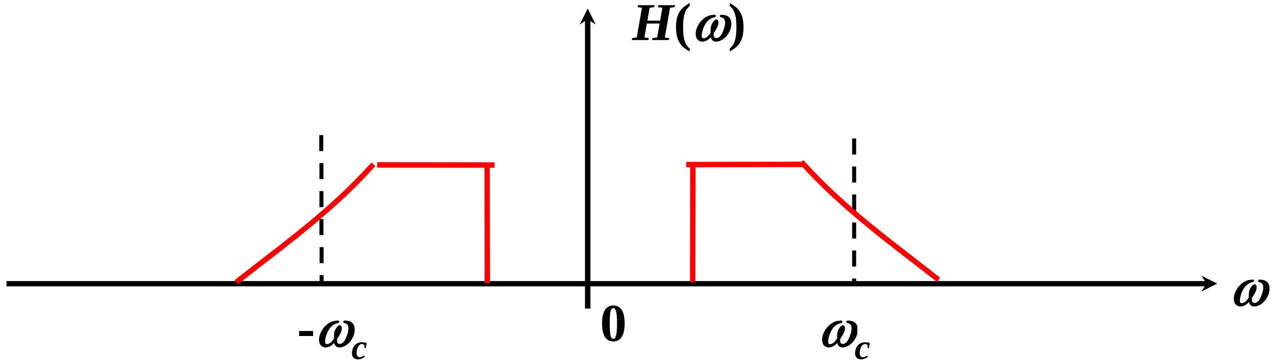


- **VSB信号频谱为：**

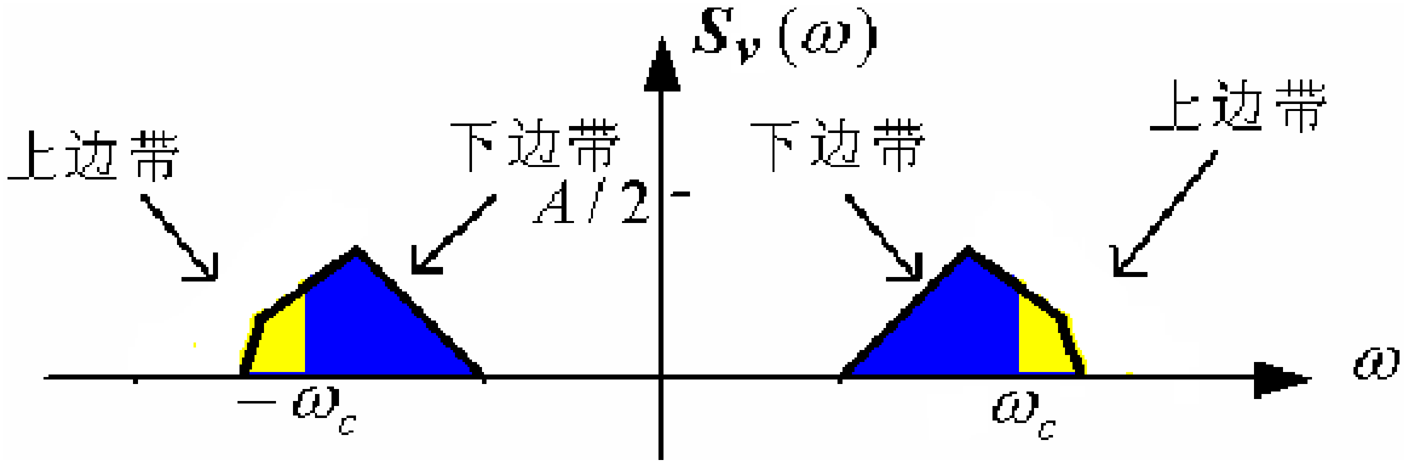


$M(\omega)$
A
ω
$-\omega_m$
ω_m
$S(\omega)$
上边带
下边带
$A/2$
下边带
上边带
ω
$-\omega_c$
ω_c
$S_v(\omega)$
上边带
下边带
$A/2$
下边带
上边带
ω
$-\omega_c$
ω_c

- 残留上边带时，滤波器传递函数为：

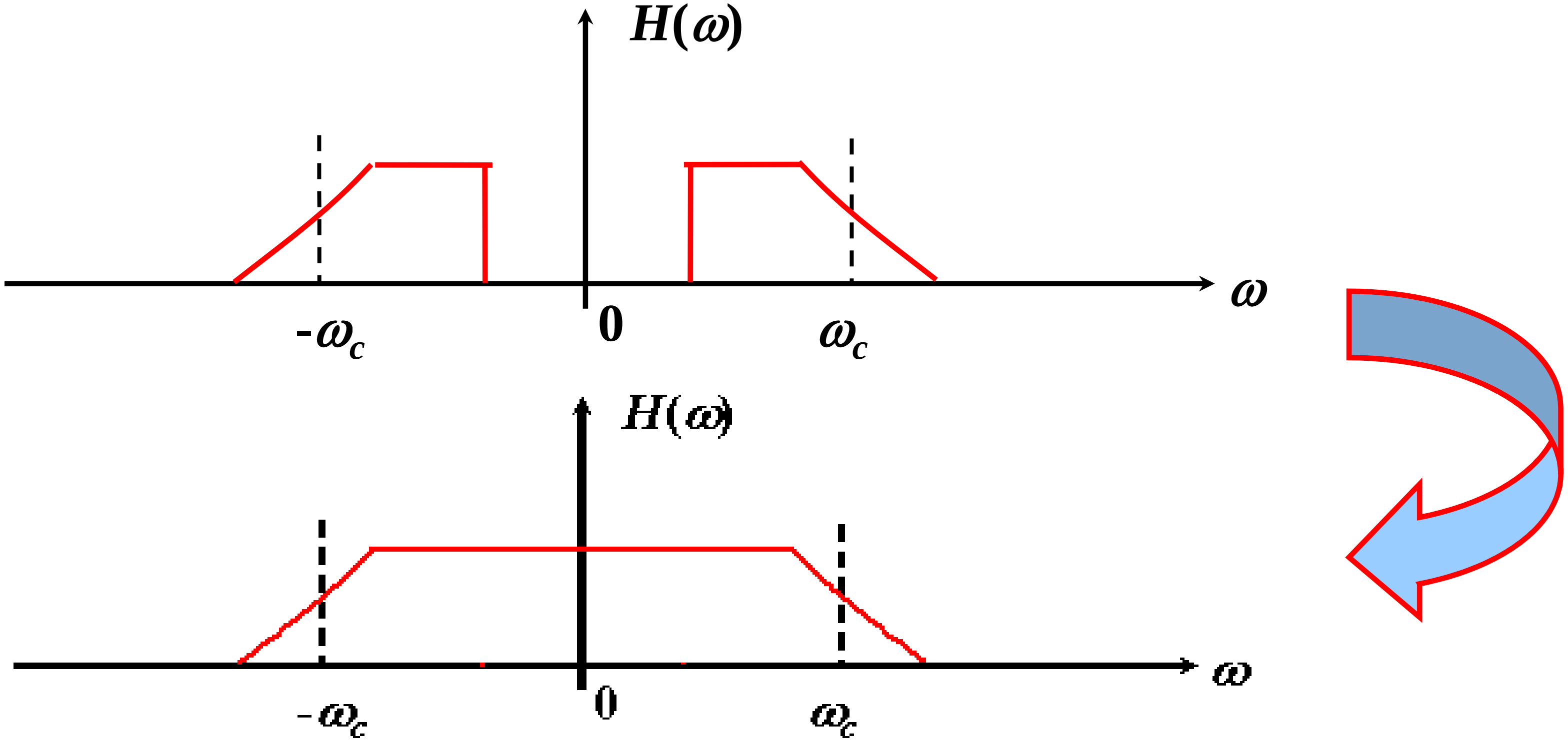


- VSB信号频谱为：



- VSB信号的带宽只比SSB略宽，通常为1.1~1.25ω_m

- **残留上边带时，滤波器传递函数还可以为：**



3、残留边带滤波器$H(\omega)$的特性

$$\because \quad m(t) \overset{F}{\longleftrightarrow} M(\omega) \qquad s_{DSB}(t) = m(t)\cos\omega_c t$$

$$\therefore \quad S_{\mathrm{DSB}}(\omega)=\frac{1}{2}[M(\omega+\omega_c)+M(\omega-\omega_c)]$$

$$\Rightarrow \quad S_{\mathrm{v}}(\omega)=\frac{1}{2}[M(\omega+\omega_c)+M(\omega-\omega_c)]H(\omega)$$

$$e_d(t)=s_v(t)\cos\omega_c t \quad \Rightarrow \quad E_d(\omega)=\frac{1}{2}[S_v(\omega+\omega_c)$$

$$+S_v(\omega-\omega_c)]=\frac{1}{2}\left\{\frac{1}{2}[M(\omega+2\omega_c)+M(\omega)]H(\omega+\omega_c)\right.$$

$$\left.\frac{1}{2}[M(\omega)+M(\omega-2\omega_c)]H(\omega-\omega_c)\right\}$$

- **低通滤波器将滤除$M(\omega+2\omega_c)$和$M(\omega-2\omega_c)$：**

$$e_0(t)\xleftrightarrow{\mathrm{F}}E_0(\omega)=\frac{1}{4}M(\omega)[H(\omega+\omega_c)+H(\omega-\omega_c)]$$

- **若要求VSB信号解调无失真** $E_0(\omega) = k\,M(\omega)$

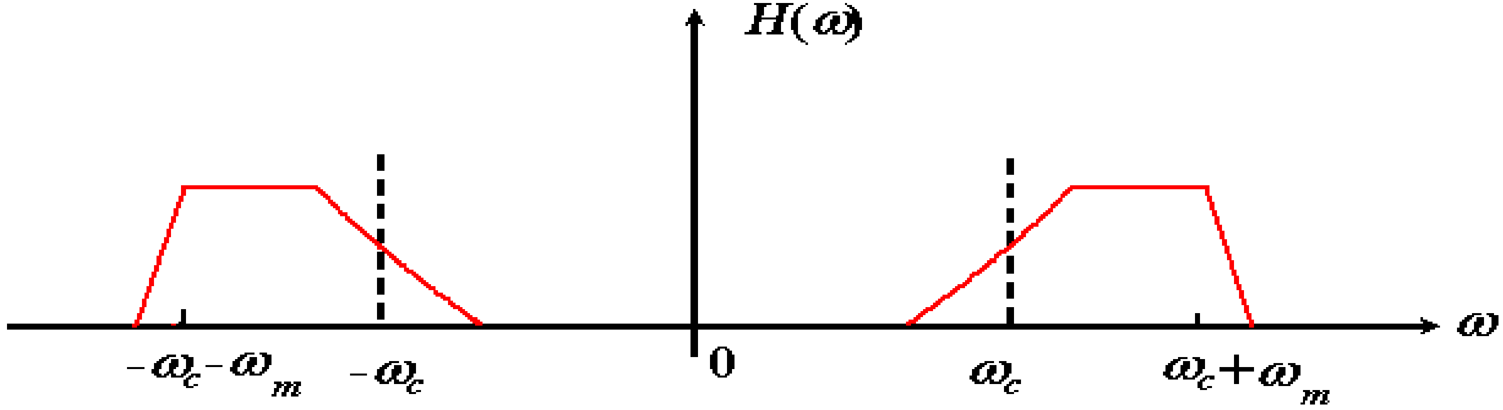
  残留边带滤波器的传递函数应满足：

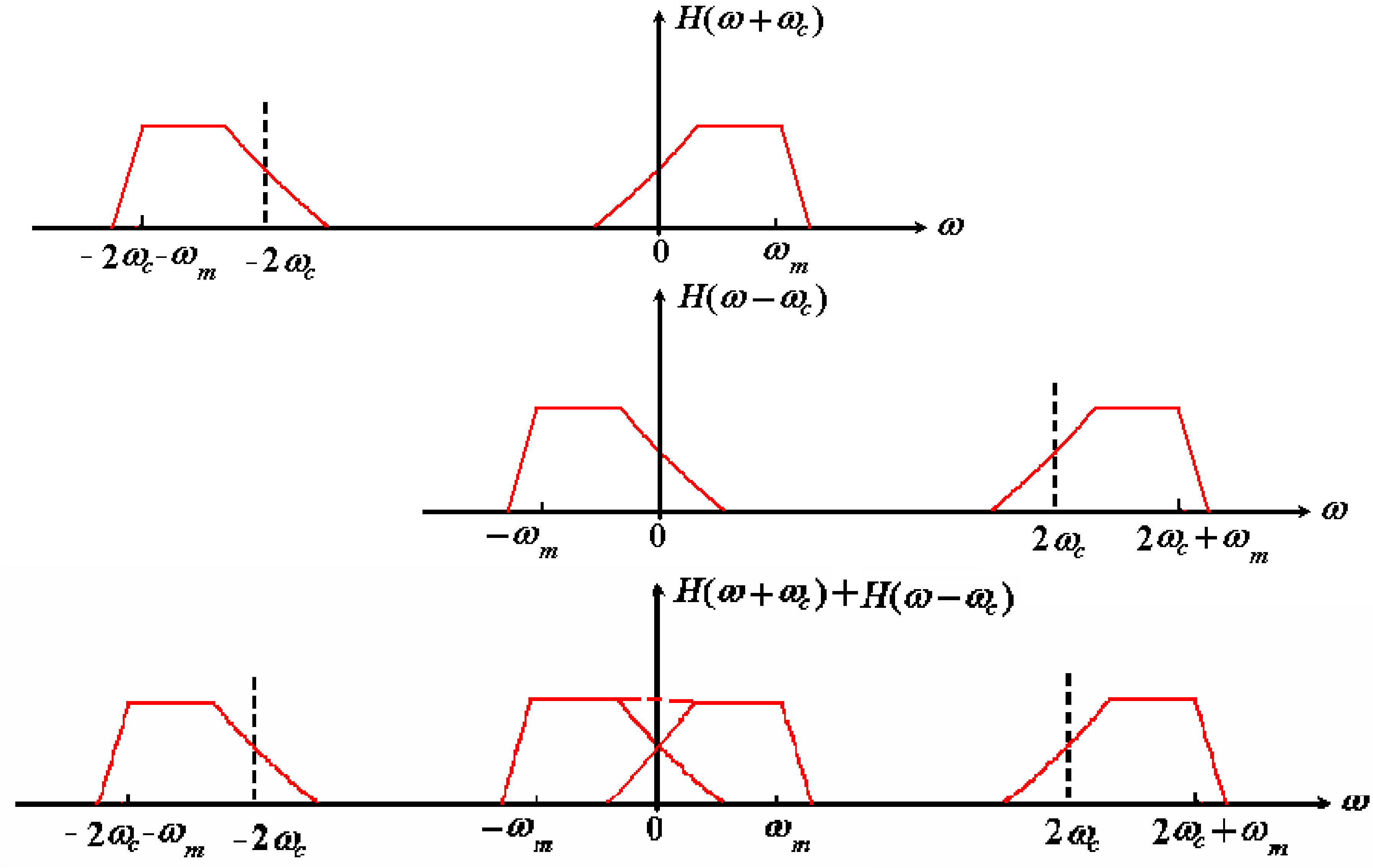
$$H(\omega+\omega_c)+H(\omega-\omega_c)=k \quad (\text{const.})$$

$$\because \quad M(\omega)=0, \quad |\omega|>\omega_m$$

$$\therefore \quad H(\omega+\omega_c)+H(\omega-\omega_c)=k \quad |\omega|\le\omega_m$$

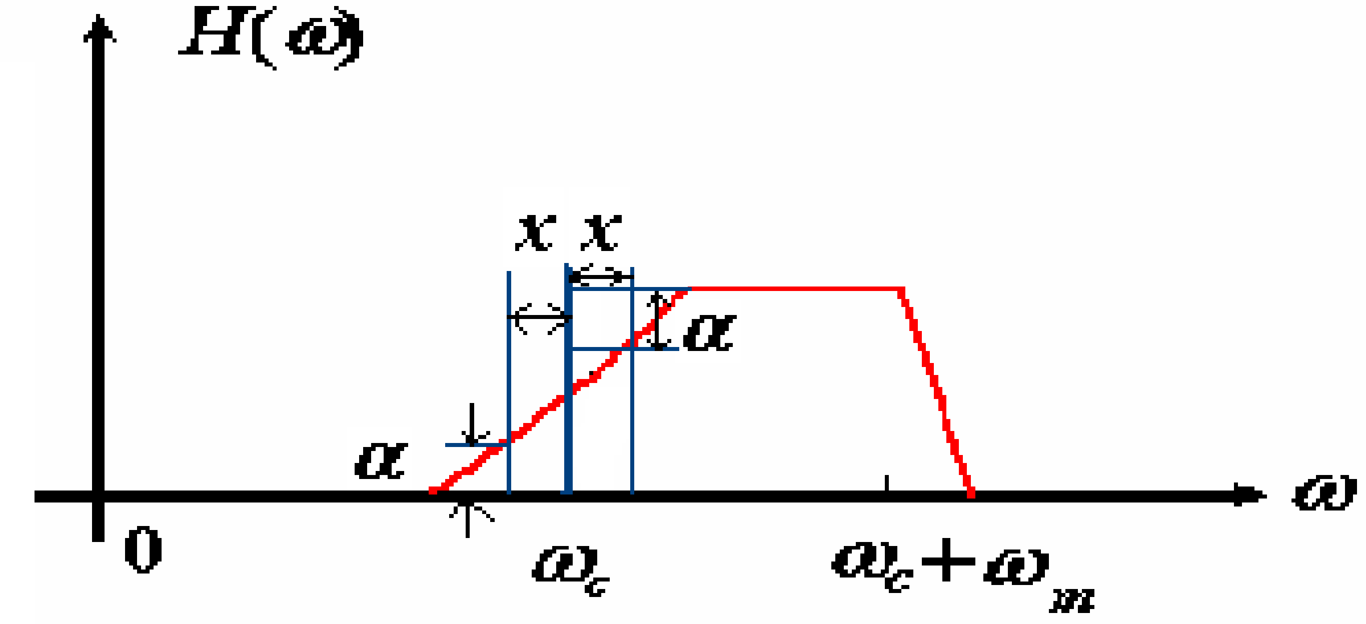
- **以残留下边带为例：**





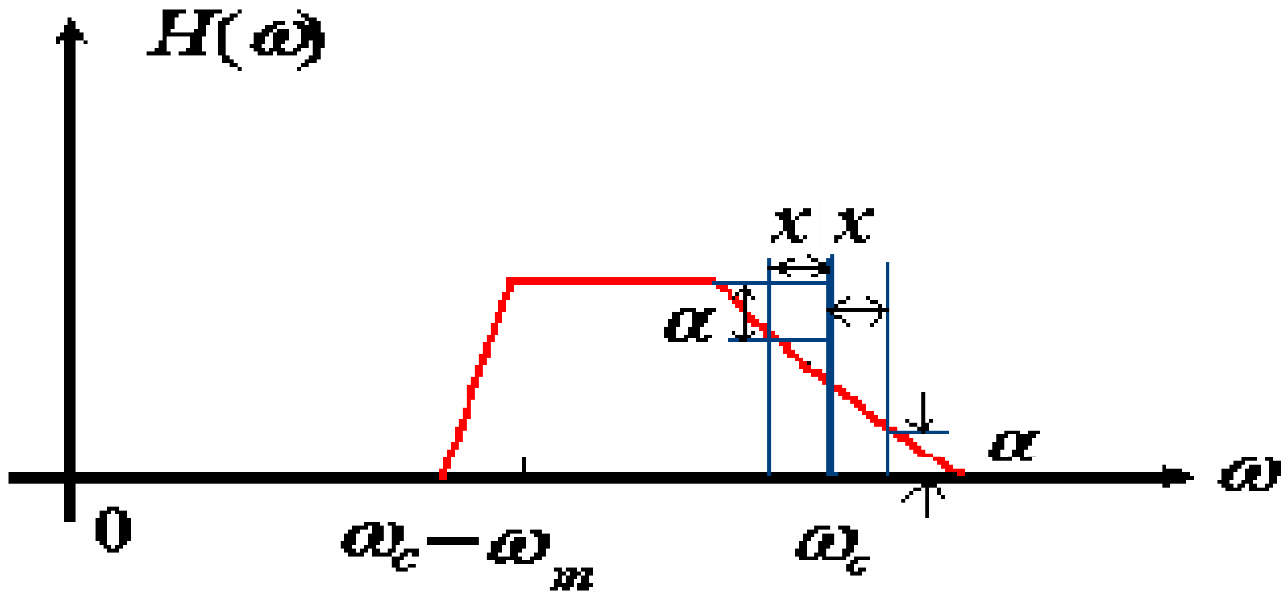
需满足$H(\omega+\omega_c)$和$H(\omega-\omega_c)$之和在$|\omega|<\omega_m$内为常数的条件

- 条件：滤波器的截止特性关于载频具有互补的对称性

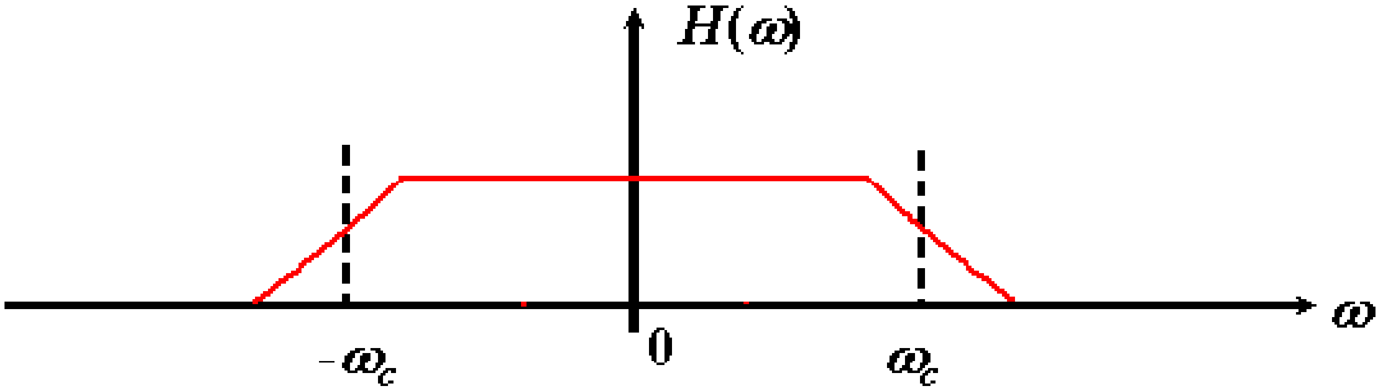


- 满足互补对称特性的滤波器传递函数的形状很多
- 其中应用最多的为直线滚降和余弦滚降

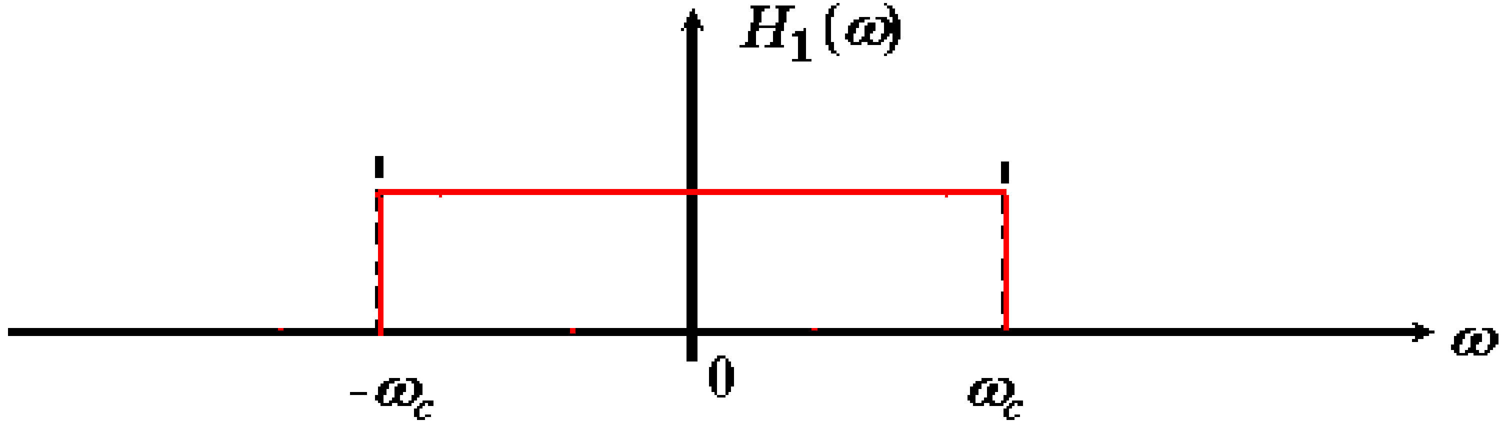
  - 对于上边带残留的情况，类似有：

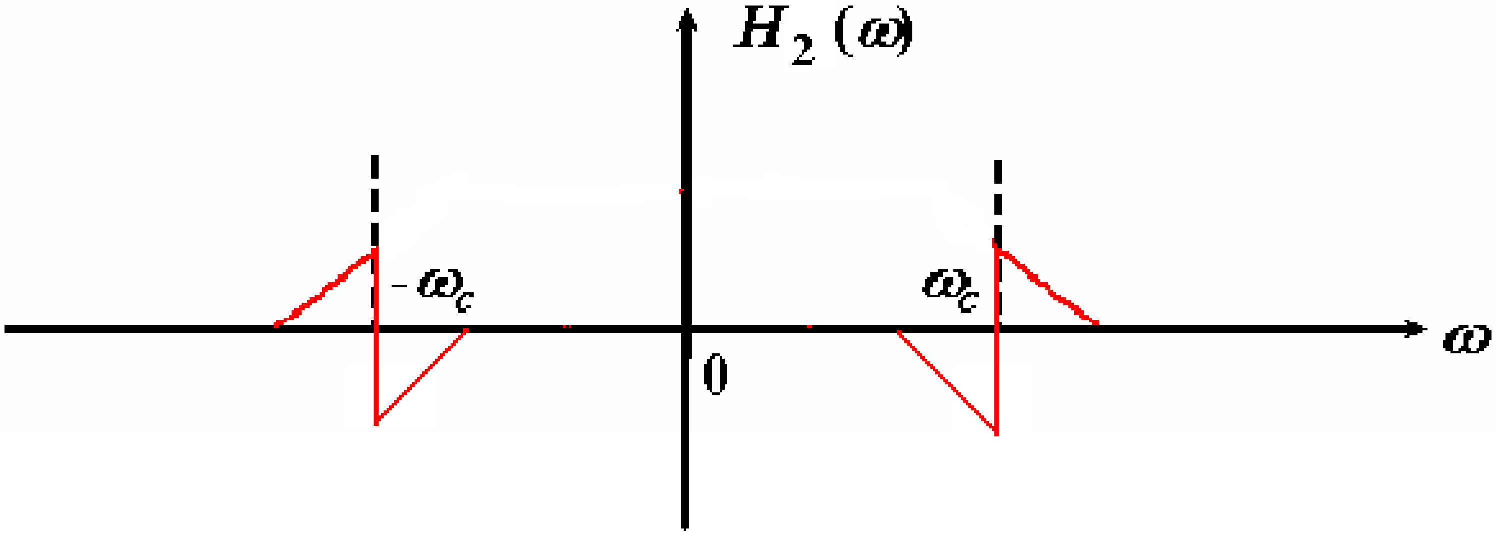


- **对于上边带残留的情况，当残留边带滤波器取为：**



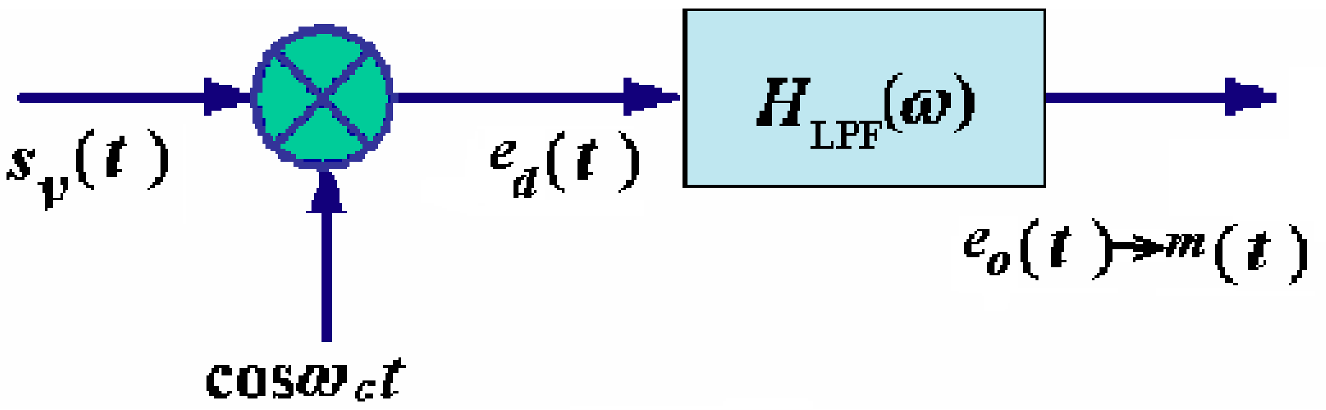
$$\rightarrow \quad H(\omega) = H_1(\omega) + H_2(\omega)$$





4、VSB信号的解调

- 只有残留滤波器截止特性满足上述条件，可用相干解调



- 还可采用加入足够大的载波信号，再用包络检波法来解调

- SSB信号可视为VSB信号的特例(残留边带为0)

53