数字信号处理

周治国

2015. 11

第五章 数字滤波器

FIR数字滤波器

窗函数设计法

三、窗函数方法：Windowing Method

设计原理：

$$H'_d(e^{j\omega}) = \begin{cases} 1\ , & |\omega| \le \omega_c \\ 0\ , & \omega_c \le |\omega| \le \pi \end{cases}$$

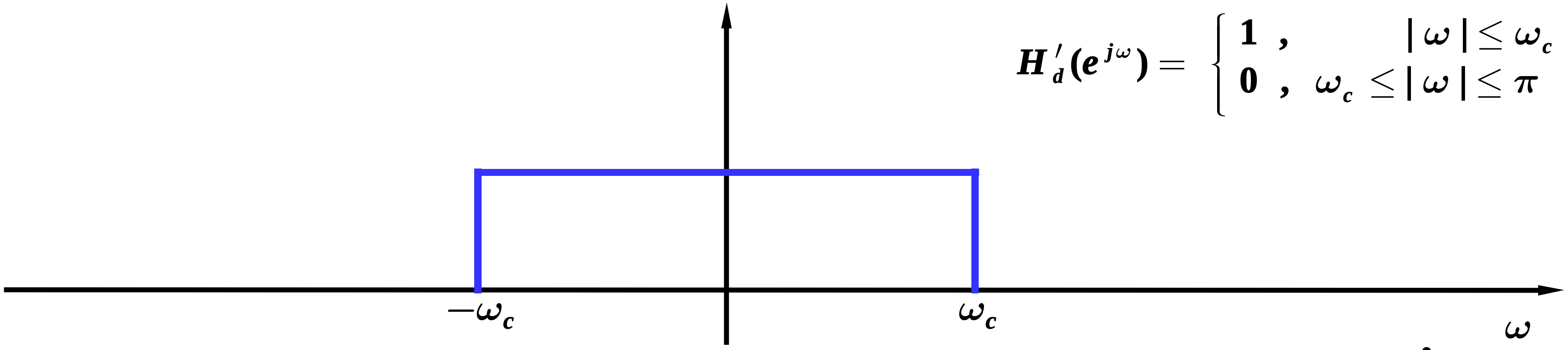
$$h'_d(n) = \frac{1}{2\pi}\int_{-\omega_c}^{\omega_c} e^{j\omega n} d\omega = \frac{\sin \omega_c n}{\pi n}$$

$$H_d(e^{j\omega}) = \begin{cases} e^{-j\frac{N-1}{2}\omega}\ , & |\omega| \le \omega_c \\ 0\ , & \omega_c \le |\omega| \le \pi \end{cases}$$

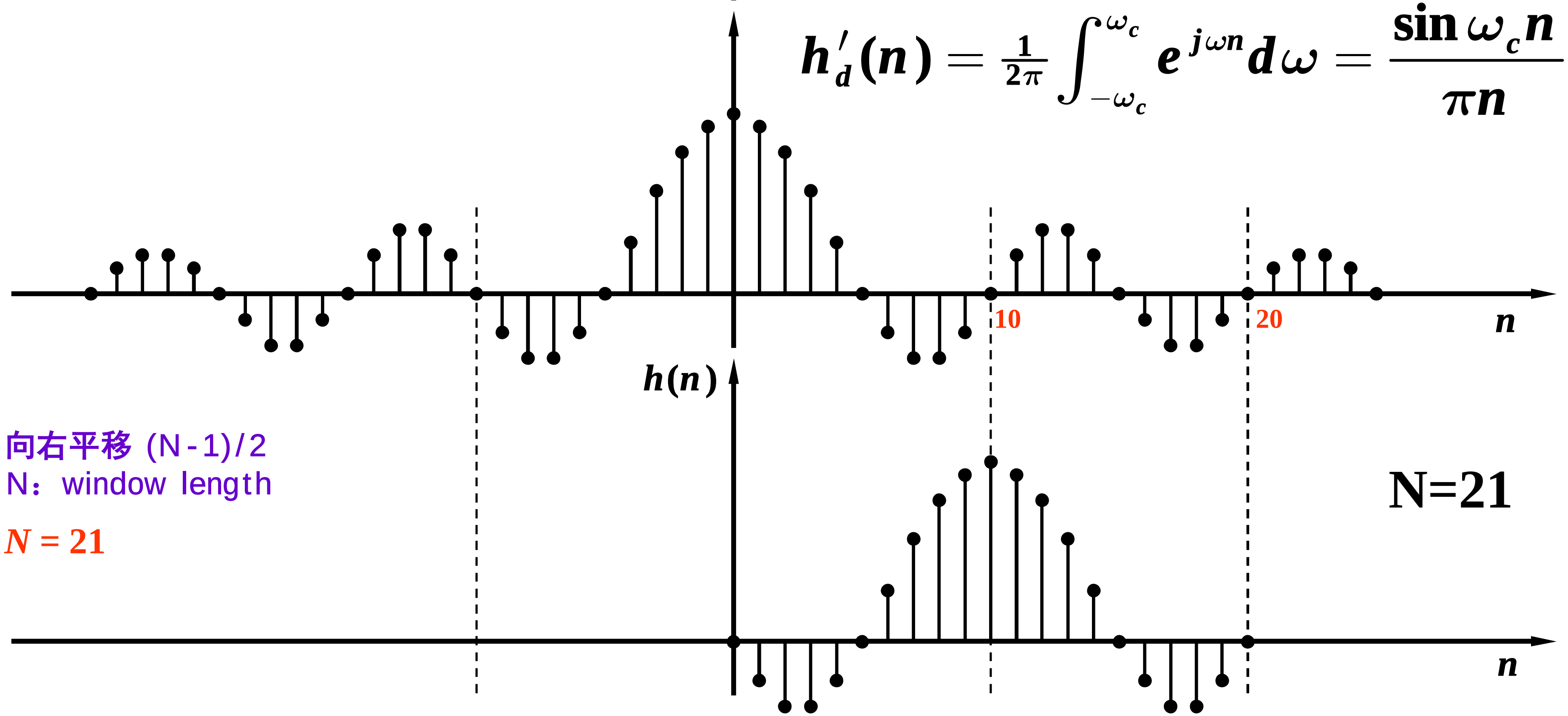
$$h_d(n) = \frac{1}{2\pi}\int_{-\omega_c}^{\omega_c} e^{-j\frac{N-1}{2}\omega} e^{j\omega n} d\omega = \frac{\sin\left[\omega_c\left(n - \frac{N-1}{2}\right)\right]}{\pi\left(n - \frac{N-1}{2}\right)}$$

$$h(n) = h_d(n)R_N(n) = \begin{cases} h_d(n)\ , & 0 \le n \le N-1 \\ 0\ ,\ \text{其他} \end{cases}$$

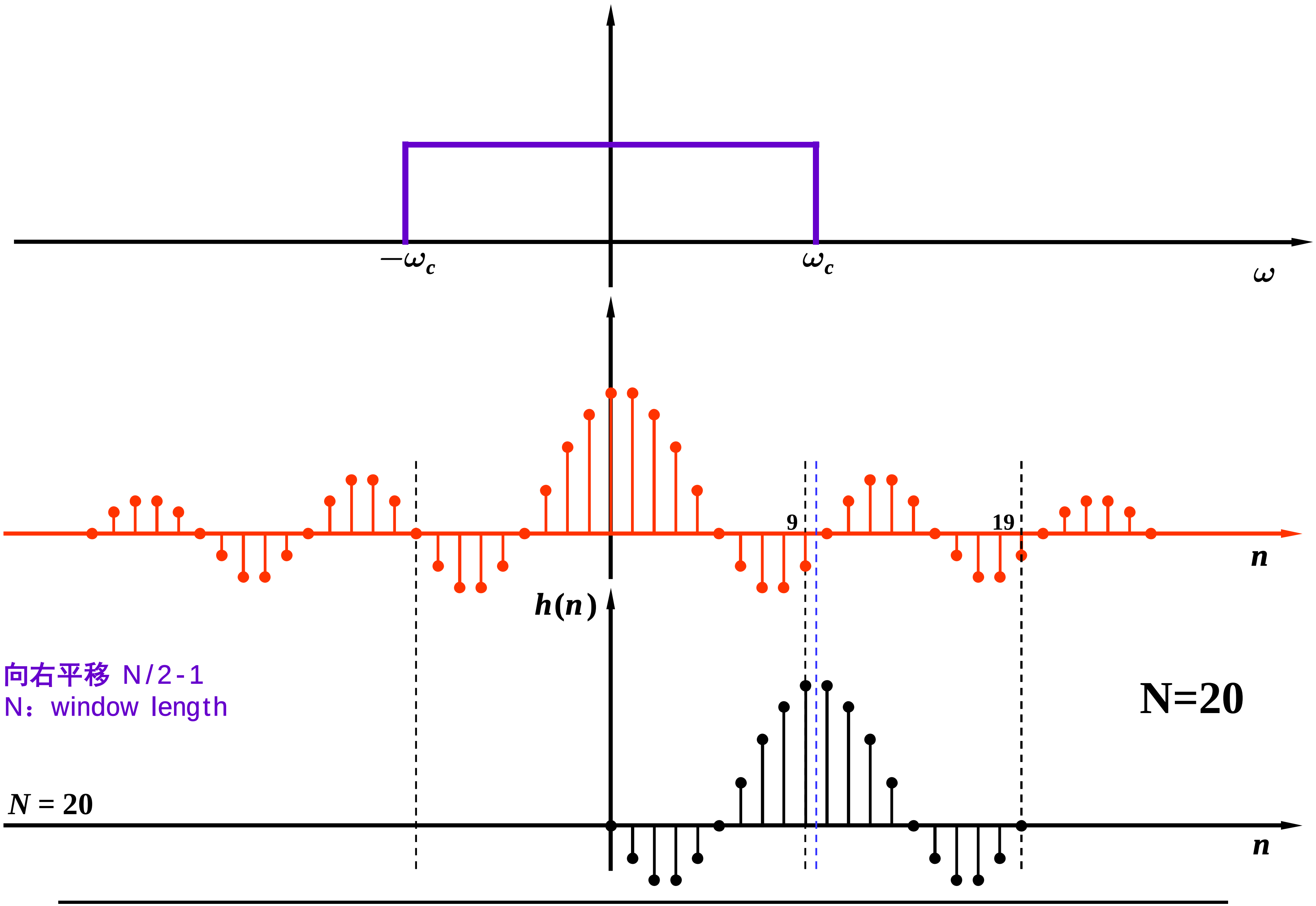
$$H_d'(e^{j\omega}) = \begin{cases} 1\ , & |\omega| \le \omega_c \\ 0\ , & \omega_c \le |\omega| \le \pi \end{cases}$$



$$h_d'(n) = \frac{1}{2\pi}\int_{-\omega_c}^{\omega_c} e^{j\omega n} d\omega = \frac{\sin \omega_c n}{\pi n}$$



EXAMPLE：截止频率为ω_c的线性相位理想低通滤波器： $h_d(n)$偶对称，奇数点



EXAMPLE：截止频率为ω_c的线性相位理想低通滤波器：$h_d(n)$偶对称，偶数点

矩形窗截断的影响：

$$h(n)=h_d(n)R_N(n)$$

$$W_R(e^{j\omega})\Leftrightarrow R_N(n)$$

$$H(e^{j\omega})=\frac{1}{2\pi}\int_{-\pi}^{\pi}H_d(e^{j\omega})W_R\left[e^{j(\omega-\theta)}\right]d\theta$$

$$\begin{cases} W_R(e^{j\omega})=\dfrac{\sin\left(\dfrac{\omega N}{2}\right)}{\sin\dfrac{\omega}{2}}e^{-j\omega\left(\frac{N-1}{2}\right)}=W_R(\omega)e^{-j\omega\alpha} \\ \alpha=\dfrac{N-1}{2},W_R(\omega)=\dfrac{\sin\left(\dfrac{\omega N}{2}\right)}{\sin\dfrac{\omega}{2}} \end{cases}$$

矩形窗截断的影响：

$$\begin{cases} H_d(e^{j\omega}) = H_d(\omega) e^{-j\omega\alpha} \\ H_d(\omega) = \begin{cases} 1, & |\omega| \le \omega_c \\ 0, & \omega_c \le |\omega| \le \pi \end{cases}, \end{cases}$$

$$\begin{aligned} H(e^{j\omega}) &= \frac{1}{2\pi}\int_{-\pi}^{\pi} H_d(\theta) e^{-j\theta\alpha} W_R(\omega-\theta) e^{j(\omega-\theta)} d\theta \\ &= e^{-j\omega\alpha}\left[\frac{1}{2\pi}\int_{-\pi}^{\pi} H_d(\theta) W_R(\omega-\theta) d\theta\right] \\ &= H(\omega) e^{-j\omega\alpha} \end{aligned}$$

$$H(\omega) = \frac{1}{2\pi}\int_{-\pi}^{\pi} H_d(\theta) W_R(\omega-\theta) d\theta$$

截断效应：吉布斯现象 *用加窗技术减小截断效应*

$$H_d(e^{j\omega}) = \begin{cases} e^{-j\omega\alpha}, & |\omega| \le \omega_c \\ 0, & \omega_c \le |\omega| \le \pi \end{cases} = H_d(\omega)e^{-j\omega\alpha},\ \alpha = \frac{N-1}{2}$$

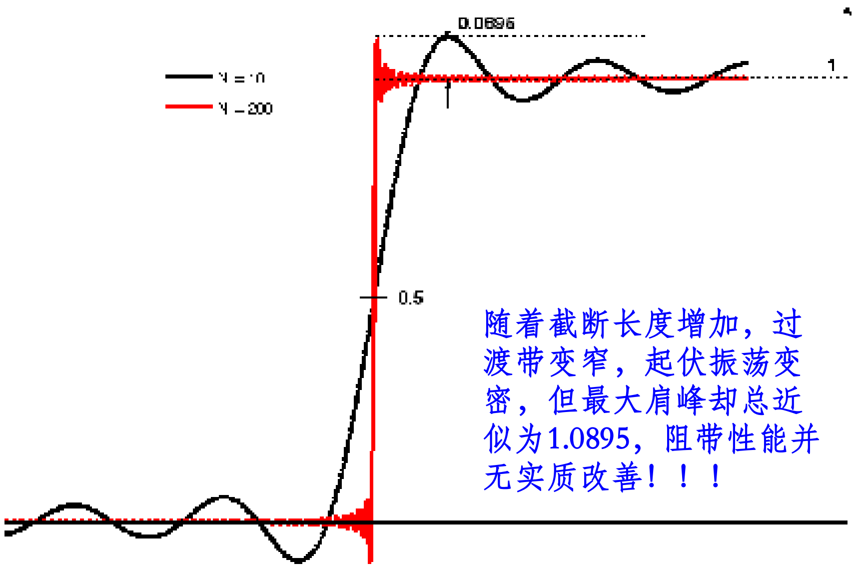
N：窗长

$$H_d(\omega) = \begin{cases} 1, & |\omega| \le \omega_c \\ 0, & \omega_c \le |\omega| \le \pi \end{cases}$$

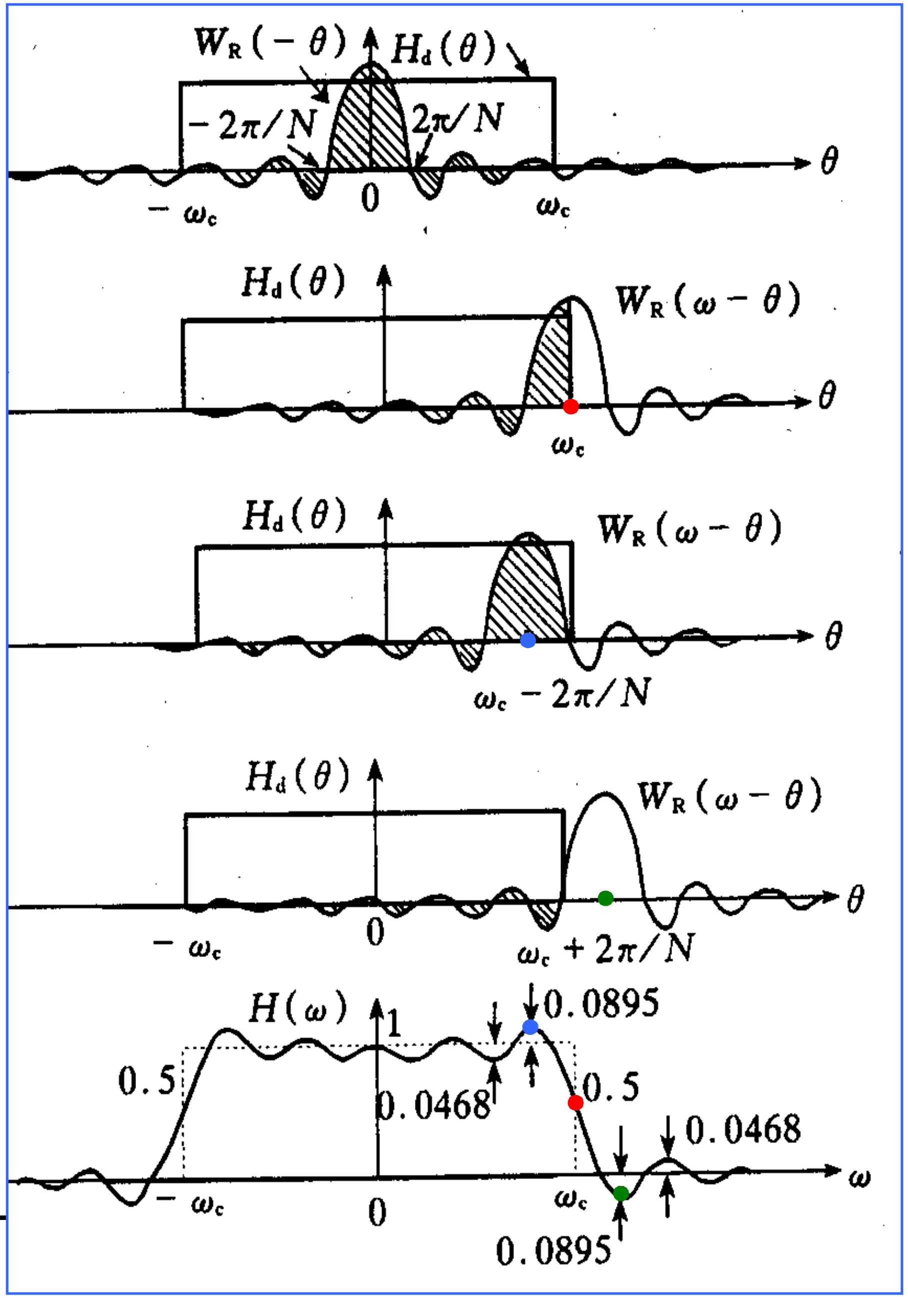
$$W_R(e^{j\omega}) = \frac{\sin(\omega N/2)}{\sin(\omega/2)} e^{-j\omega\alpha} = W_R(\omega)e^{-j\omega\alpha}$$

$$H(e^{j\omega}) = \frac{1}{2\pi}\int_{-\pi}^{\pi} H_d(e^{j\theta}) W_R[e^{j(\omega-\theta)}]d\theta$$

$$= \left[\frac{1}{2\pi}\int_{-\pi}^{\pi} H_d(\theta) W_R(\omega-\theta)d\theta\right] e^{-j\omega\alpha} = H(\omega)e^{-j\omega\alpha}$$



随着截断长度增加，过渡带变窄，起伏振荡变密，但最大肩峰却总近似为1.0895，阻带性能并无实质改善！！！

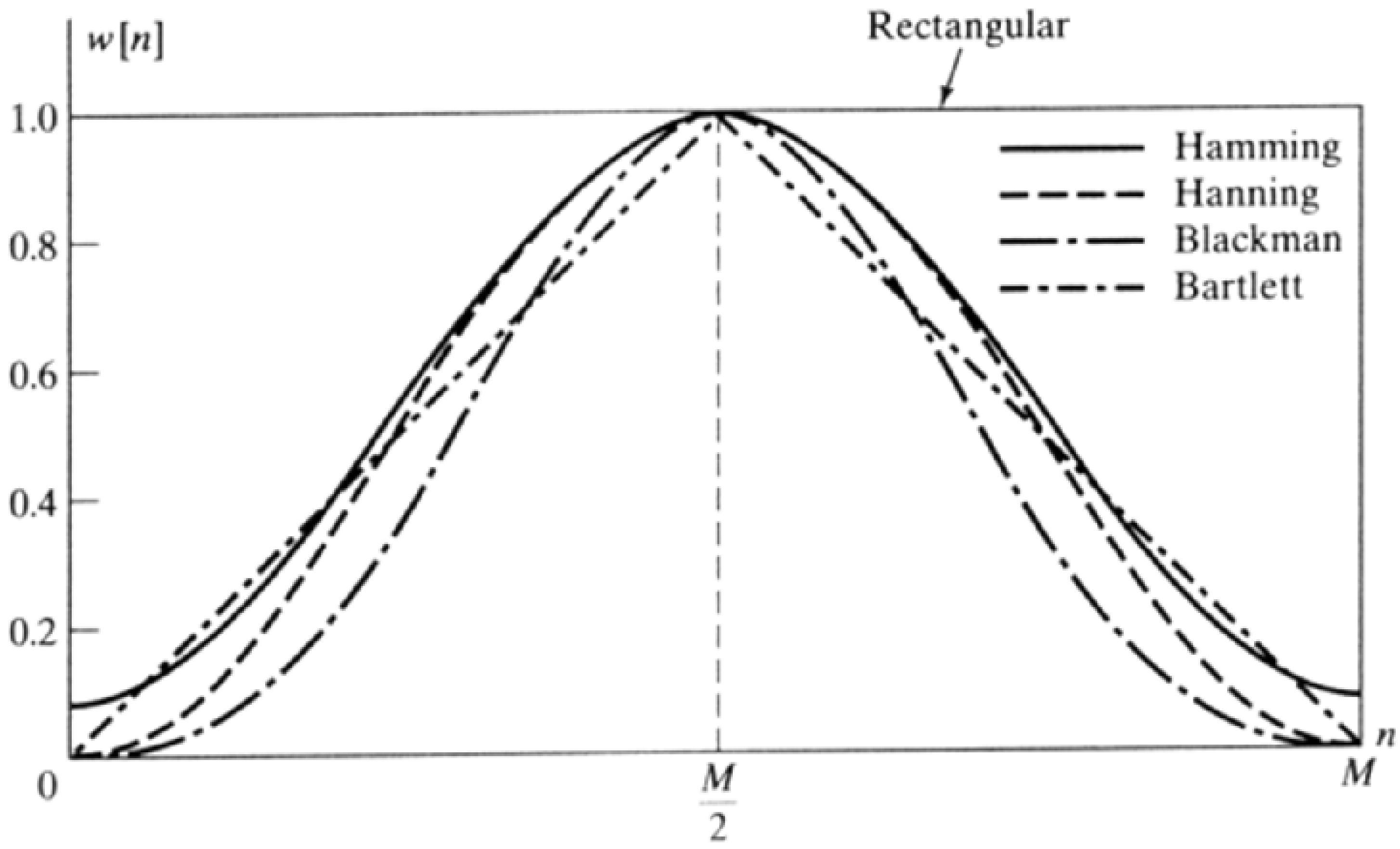


Window Functions for FIR Filter Design

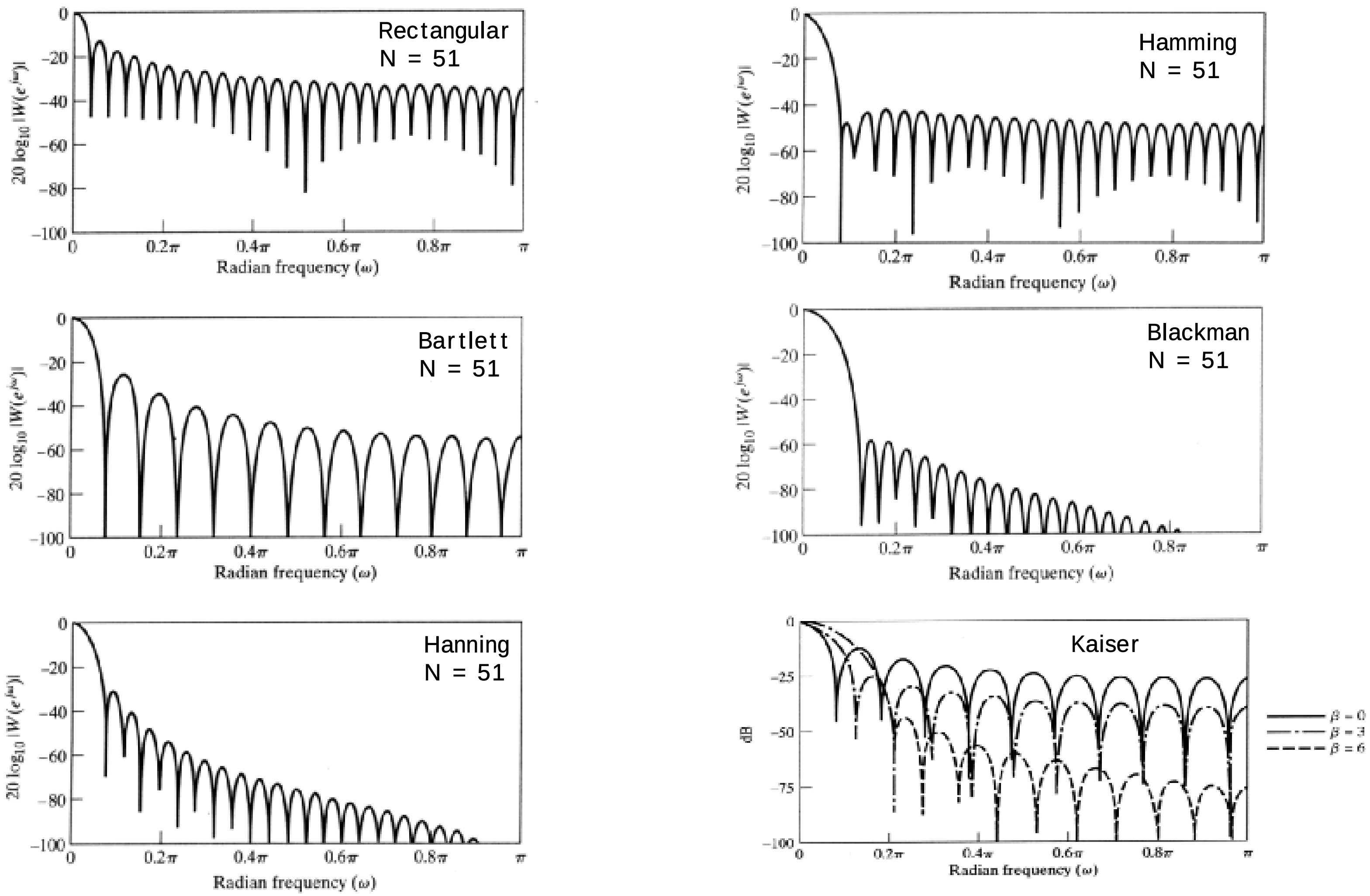
Window Type	Time-Domain Sequence
Rectangular	$w[n] = \begin{cases} 1, & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$
Bartlett (Triangular)	$w[n] = \begin{cases} 2n/M, & 0 \le n \le M/2 \\ 2-2n/M, & M/2 < n \le M \\ 0, & \text{otherwise} \end{cases}$
Hanning	$w[n] = \begin{cases} 0.5 - 0.5\cos(2\pi n/M), & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$
Hamming	$w[n] = \begin{cases} 0.54 - 0.46\cos(2\pi n/M), & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$
Blackman	$w[n] = \begin{cases} 0.42 - 0.5\cos(2\pi n/M) + 0.08\cos(4\pi n/M), & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$
Kaiser	$w[n] = \begin{cases} I_0[\beta(1 - \{(n-\alpha)/\alpha\}^2)^{1/2}]/I_0(\beta), & 0 \le n \le M, \alpha = M/2 \\ 0, & \text{otherwise} \end{cases}$

$I_0(.)$ is zero order modified Bessel function of the first kind, β is window shape parameter. $M = N-1$.

Shape of commonly used window functions.



主瓣宽度v.s.副瓣高度


Rectangular
N = 51
Hamming
N = 51
Bartlett
N = 51
Blackman
N = 51
Hanning
N = 51
Kaiser
20 log10 |W(e^jω)|
Radian frequency (ω)
dB
β = 0
β = 3
β = 6

三、窗函数方法：Windowing Method

设计步骤：

(1)给定要求的频率响应函数$H_d(e^{j\omega})$

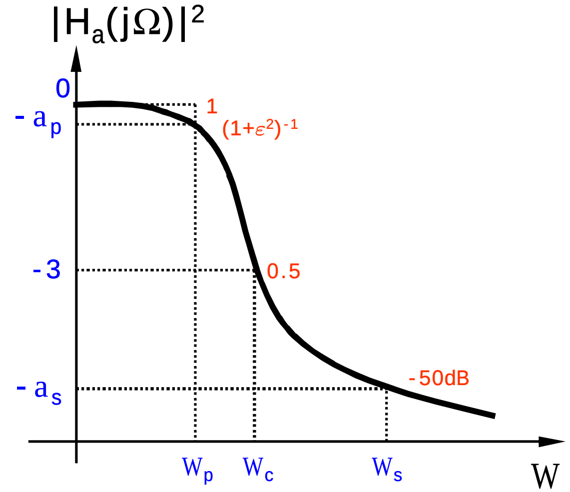
(2)根据$h_d(n)=\frac{1}{2\pi}\int_{-\pi}^{\pi}H_d(e^{j\omega})e^{j\omega n}d\omega$计算$h_d(n)$

(3)根据过渡带及阻带最小衰减要求，选定窗和N

(4)根据$h(n)=h_d(n)R_N(n)$求得$h(n)$

线性相位FIR低通滤波器的设计

例：设计一个线性相位FIR低通滤波器，满足下列条件：抽样频率为15KHz；通带截止频率为1.5KHz；阻带起始频率为3KHz；阻带衰减不小于50dB，幅度特性如右图所示



解：1）确定模拟指标对应的数字频率

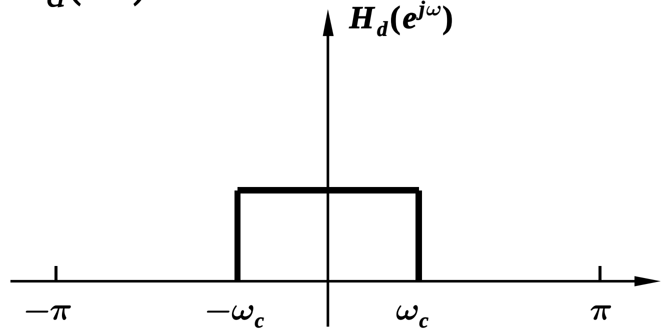
$$\omega_p = 2\pi f_p / F_s = 0.2\pi;\ \omega_s = 2\pi f_s / F_s = 0.4\pi$$

$$\alpha_s = -50\text{dB}$$

2）根据过渡带设定选截止频率ω_c，由此确定$H_d(e^{j\omega})$

$$\omega_c = 2\pi\left[\frac{1}{2}(f_p + f_s)\right] / F_s = 0.3\pi;\ \tau = \frac{N-1}{2}$$

$$H_d(e^{j\omega}) = \begin{cases} e^{-j\omega\tau} & -\omega_c \le \omega \le \omega_c \\ 0 & -\pi \le \omega \le -\omega_c,\ \omega_c \le \omega \le \pi \end{cases}$$

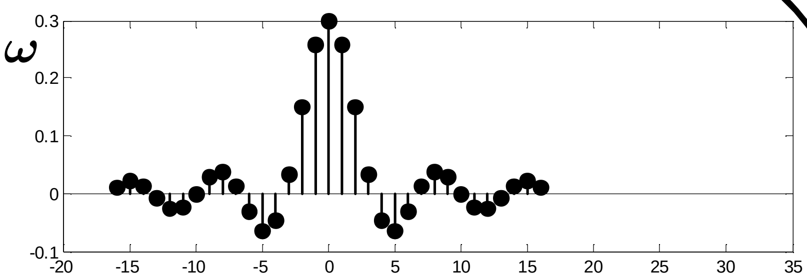


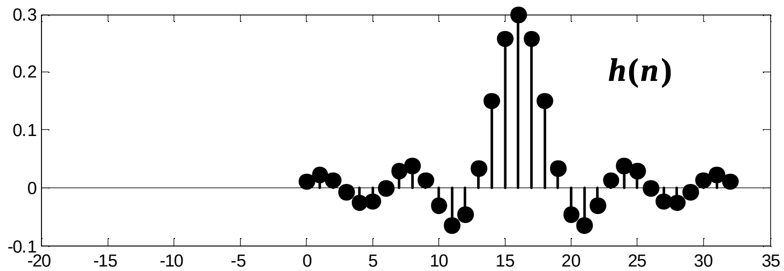
线性相位FIR低通滤波器的设计

$$h_d(n) = \mathrm{IDTFT}\,\{H_d(e^{j\omega})\} = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{-j\omega\tau} e^{j\omega n} d\omega$$

$$= \frac{1}{2\pi}\int_{-\omega_c}^{\omega_c} e^{j\omega(n-\tau)} d\omega$$

$$= \begin{cases} \dfrac{1}{\pi(n-\tau)}\sin[\omega_c(n-\tau)] & n \neq \tau \\ \dfrac{\omega_c}{\pi} & n = \tau \end{cases}$$





3） 求$h_d(n)$

4）据阻带衰减要求选择窗函数：由α_s= 50dB，确定海明窗（-53dB）

$$w(n) = \left[0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right)\right] R_N(n)$$

5）据过渡带宽要求确定窗长N（海明窗：$\Delta\omega = 6.6\pi/N$）

$$\Delta\omega = 2\pi(f_s - f_p) / F_s = 0.2\pi;\ N = A / \Delta\omega = 6.6\pi / 0.2\pi = 33$$

线性相位FIR低通滤波器的设计

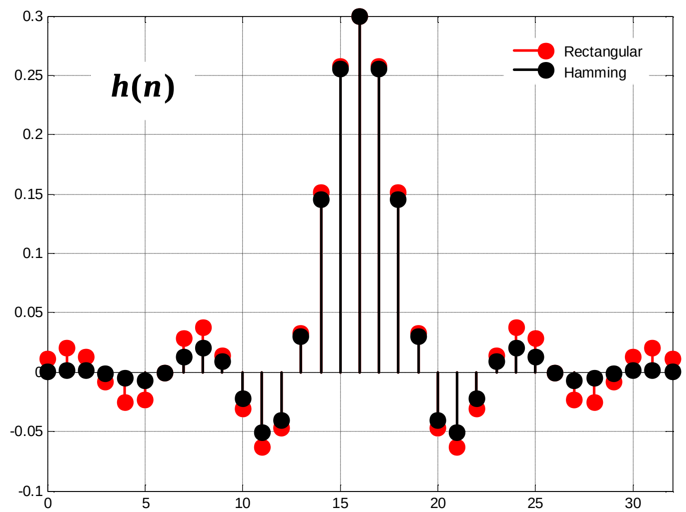
6）确定FIR滤波器的单位抽样响应$h(n)$

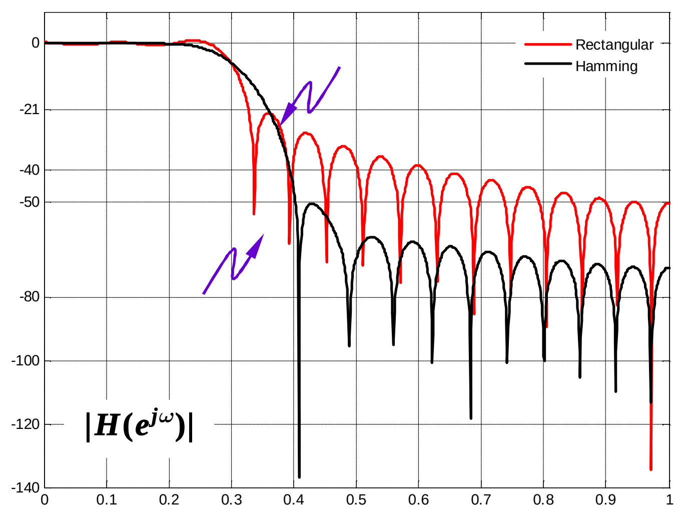
$$\tau=(N-1)/2=16$$

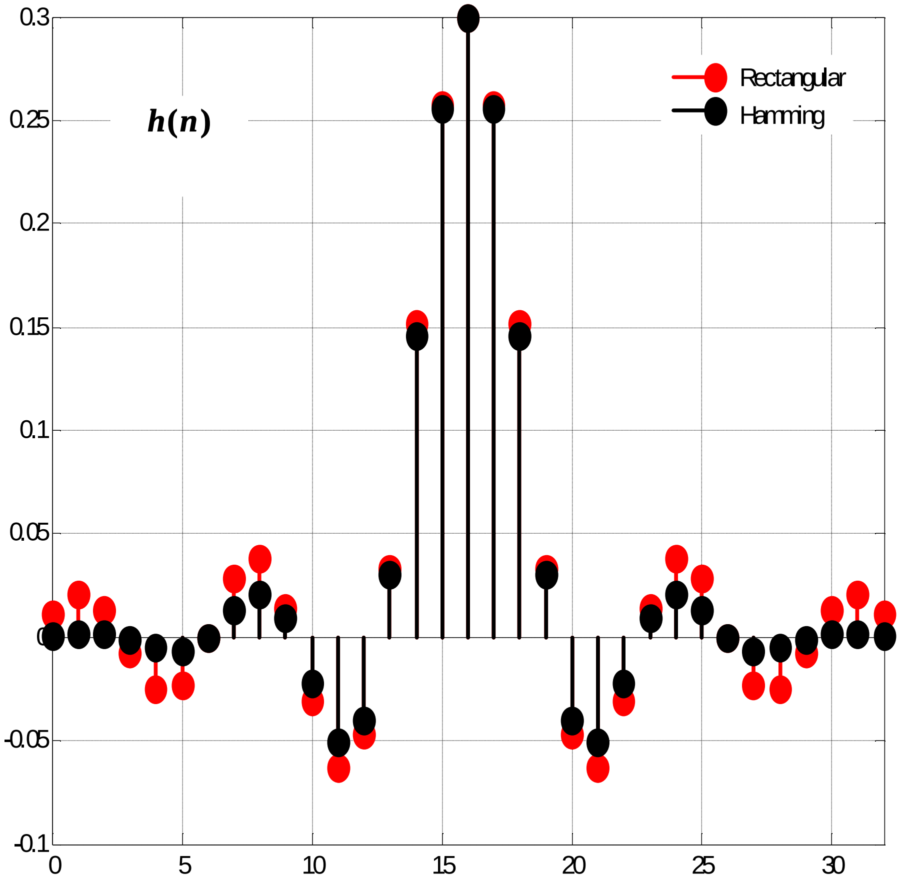
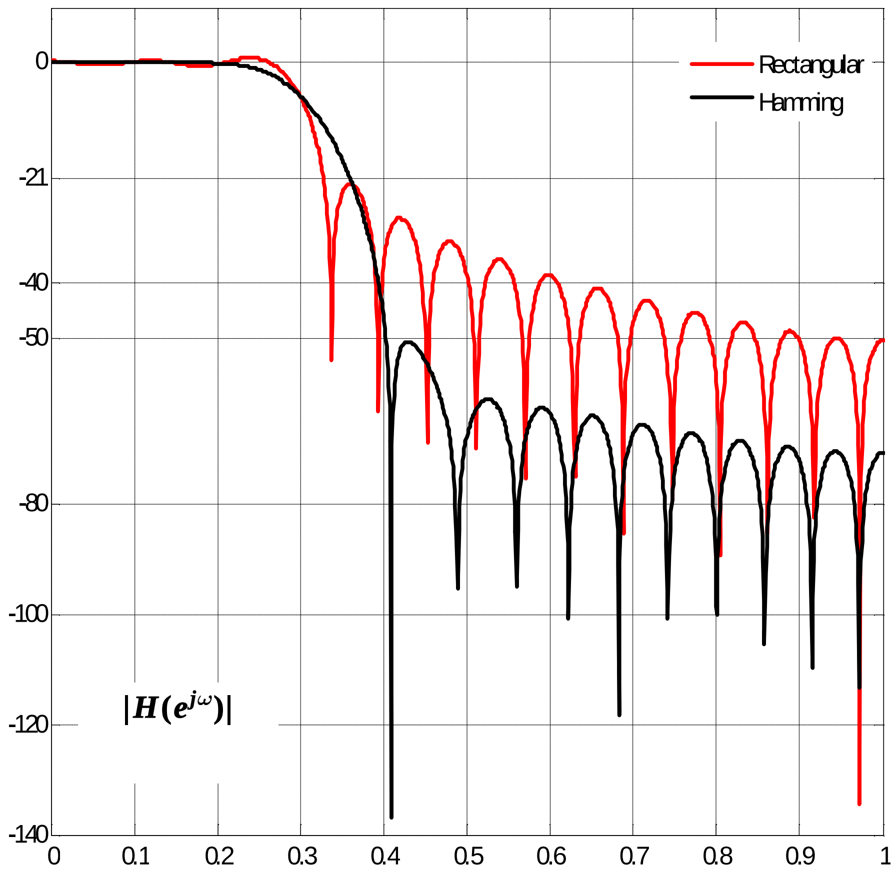
$$h(n)=h_d(n)w(n)$$

$$=\frac{\sin\left[0.3\pi\left(n-16\right)\right]}{\pi\left(n-16\right)}\cdot\left[0.54-0.46\cos\frac{\pi n}{16}\right]R_{33}(n)$$

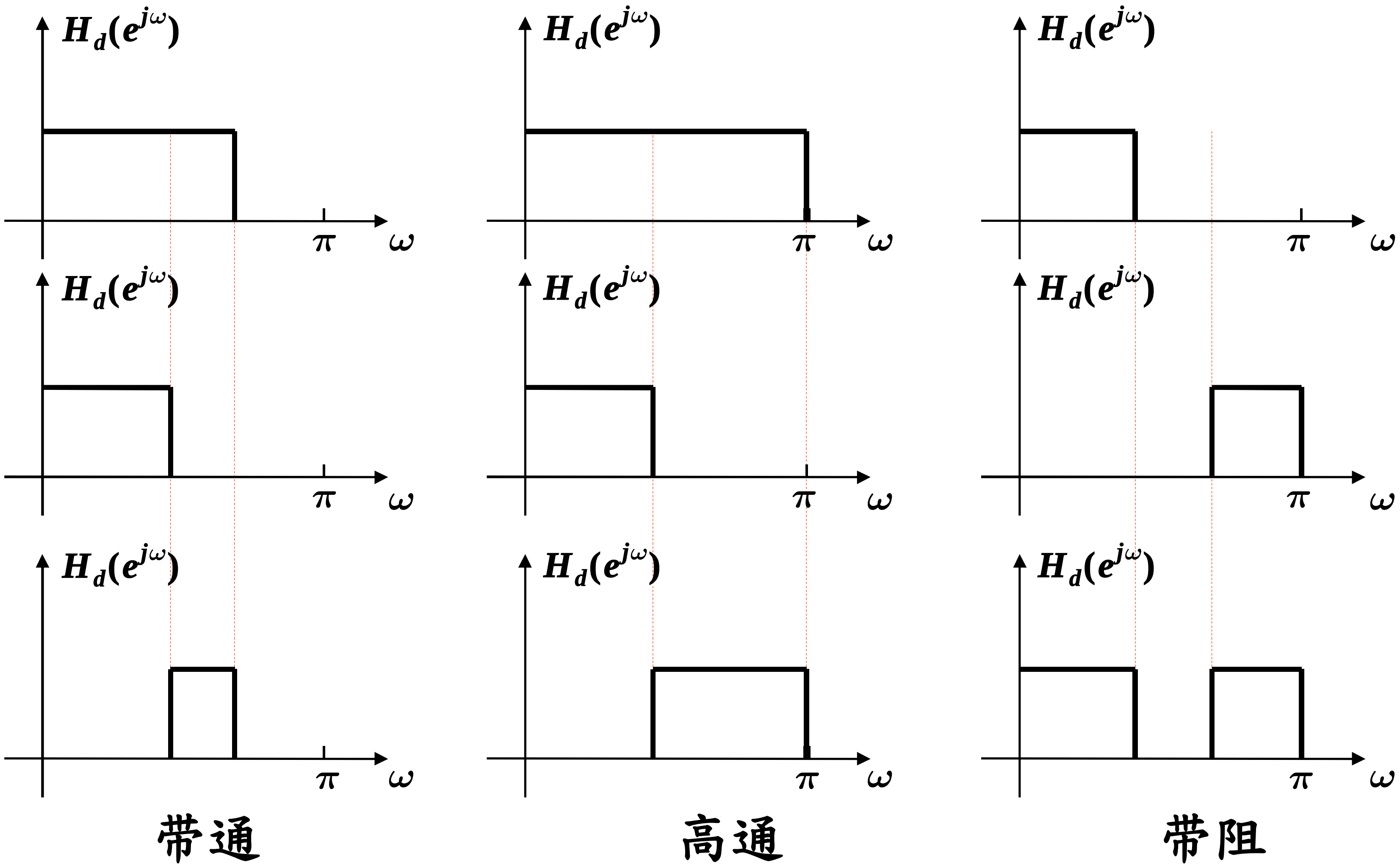
7）求$H(e^{j\omega})$，并检验性能是否满足预定指标。若不满足，则改变N或窗形状重新设计






h(n)
Rectangular
Hamming
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
30

|H(e^{jω})|
Rectangular
Hamming
0
-21
-40
-50
-80
-100
-120
-140
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

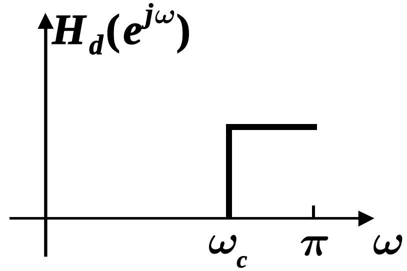
From low pass to band pass, high pass, band stop ...



线性相位FIR高通滤波器的设计公式

— 理想高通的频响：

$$H_d(e^{j\omega}) = \begin{cases} e^{-j\omega\tau} & \omega_c \le |\omega| \le \pi \\ 0 & otherwise \end{cases} \qquad \tau = \frac{N-1}{2}$$



其单位抽样响应：

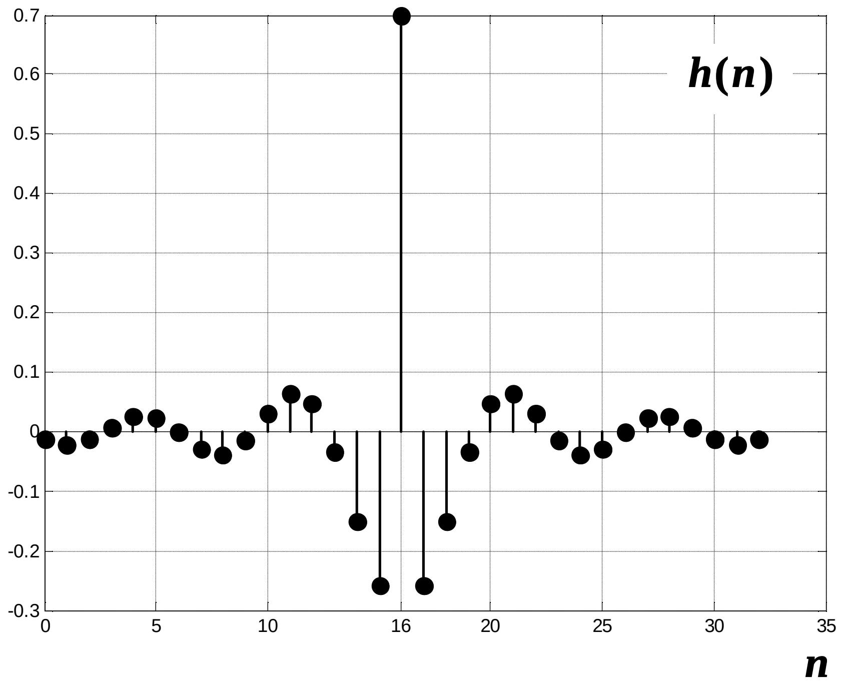
$$h_d(n) = \frac{1}{2\pi}\left[\int_{-\pi}^{-\omega_c} e^{j\omega(n-\tau)} d\omega + \int_{\omega_c}^{\pi} e^{j\omega(n-\tau)} d\omega\right]$$

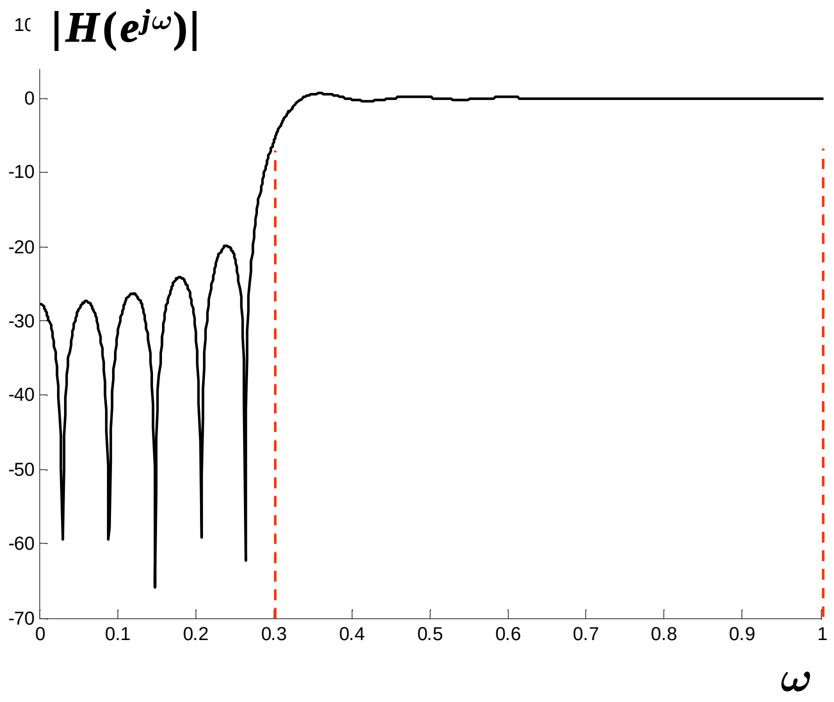
$$= \begin{cases} \dfrac{1}{\pi(n-\tau)}\left\{\sin\left[\pi\left(n-\tau\right)\right] - \sin\left[\omega_c\left(n-\tau\right)\right]\right\} & n \ne \tau \\ \dfrac{1}{\pi}(\pi-\omega_c) & n = \tau \end{cases}$$

$$高通滤波器(\omega_c) = 全通滤波器 - 低通滤波器(\omega_c)$$

线性相位FIR高通滤波器的设计公式

$$\frac{\sin[\pi(n-16)]-\sin[0.3\pi(n-16)]}{\pi(n-16)}$$





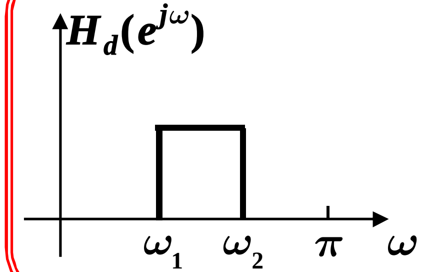
N=33

0.3π

线性相位FIR带通滤波器的设计公式

— 理想带通的频响：

$$H_d(e^{j\omega}) = \begin{cases} e^{-j\omega\tau} & 0 < \omega_1 \le |\omega| \le \omega_2 < \pi \\ 0 & otherwise \end{cases} \qquad \tau = \frac{N-1}{2}$$



其单位抽样响应：

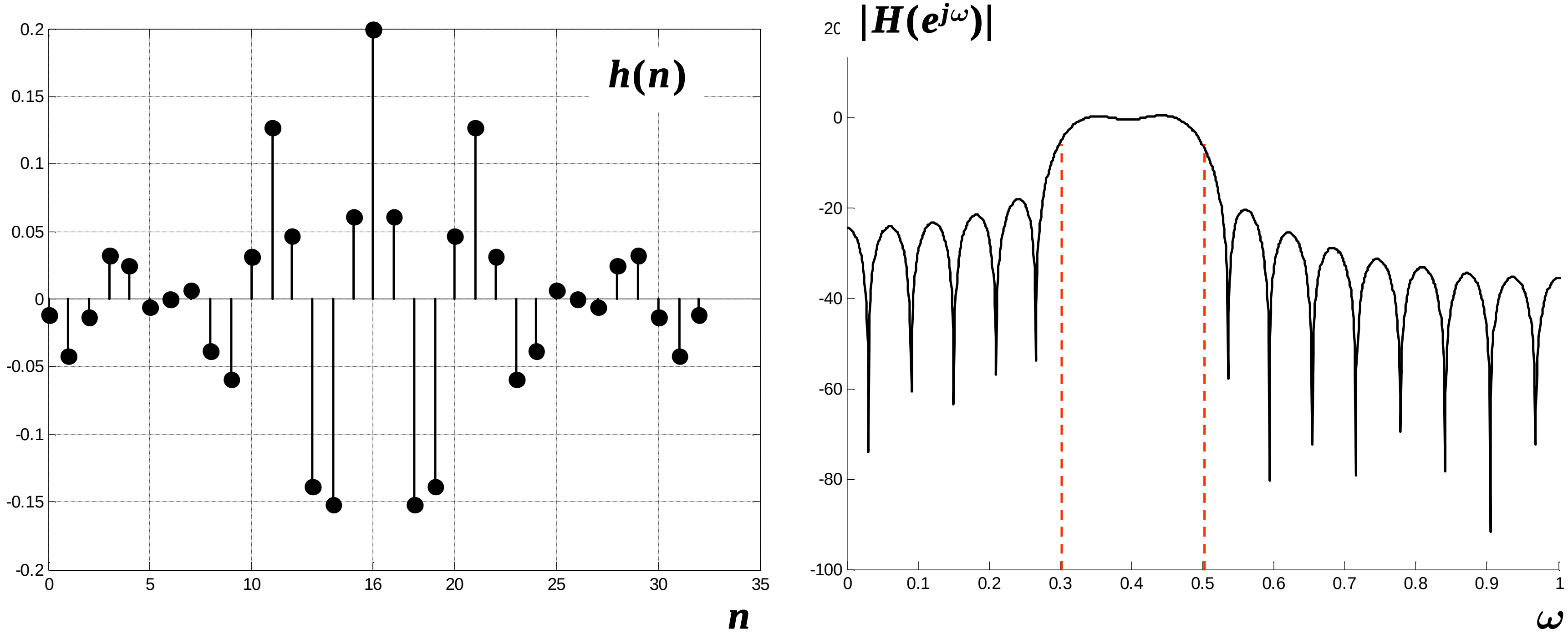
$$h_d(n) = \frac{1}{2\pi}\left[\int_{-\omega_2}^{-\omega_1} e^{j\omega(n-\tau)}d\omega + \int_{\omega_1}^{\omega_2} e^{j\omega(n-\tau)}d\omega\right]$$

$$= \begin{cases} \dfrac{1}{\pi(n-\tau)}\left\{\sin\left[\omega_2(n-\tau)\right] - \sin\left[\omega_1(n-\tau)\right]\right\} & n \ne \tau \\ \dfrac{1}{\pi}(\omega_2 - \omega_1) & n = \tau \end{cases}$$

带通滤波器(ω_1,ω_2) = 低通滤波器(ω_2) − 低通滤波器(ω_1)

线性相位FIR带通滤波器的设计公式

$$\frac{\sin[0.5\pi(n-16)]-\sin[0.3\pi(n-16)]}{\pi(n-16)}$$



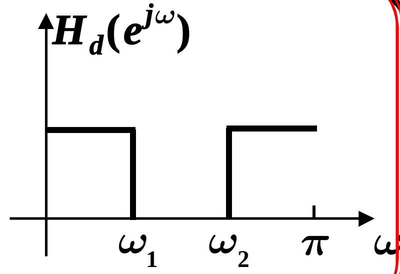
N=33

0.3π, 0.5π

线性相位FIR带阻滤波器的设计公式

— 理想带阻的频响：

$$H_d(e^{j\omega}) = \begin{cases} e^{-j\omega\tau} & 0 \le |\omega| \le \omega_1, \omega_2 \le |\omega| \le \pi \\ 0 & otherwise \end{cases} \quad \tau = \frac{N-1}{2}$$



其单位抽样响应：

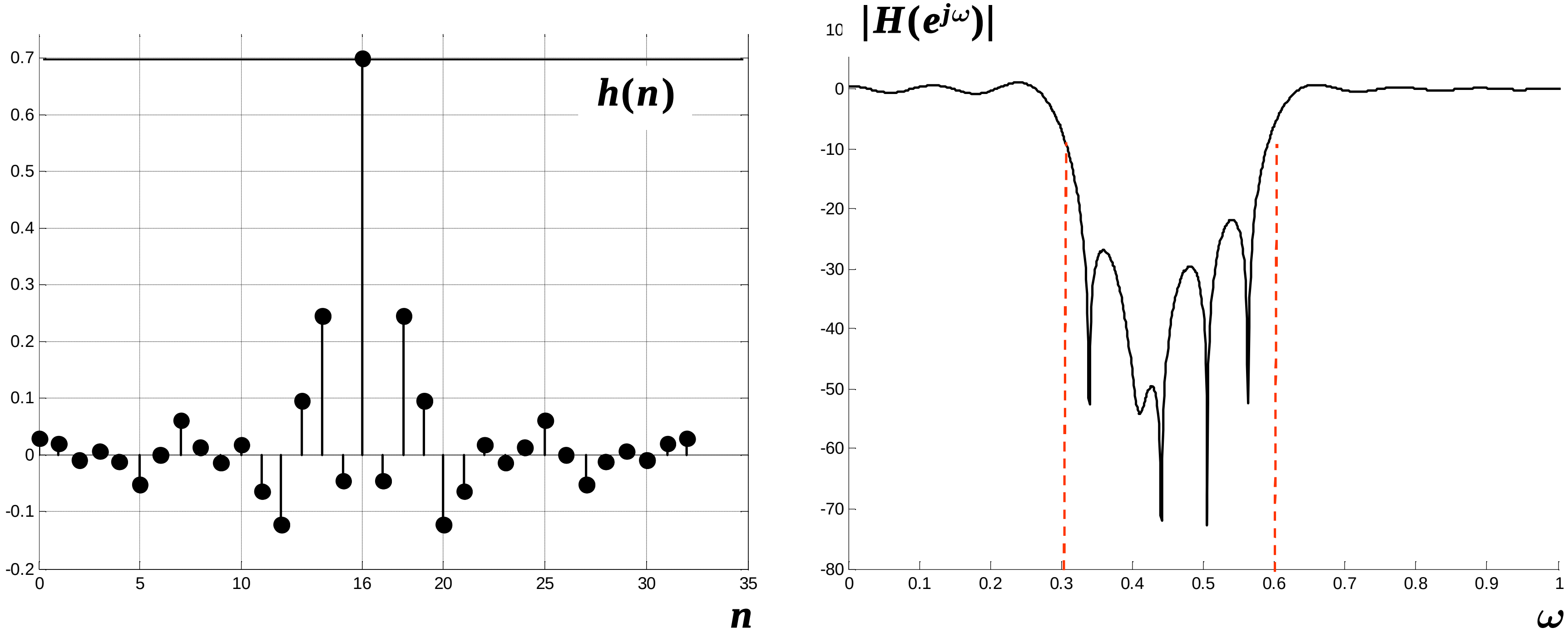
$$h_d(n) = \frac{1}{2\pi}\left[\int_{-\pi}^{-\omega_2} e^{j\omega(n-\tau)}d\omega + \int_{-\omega_1}^{\omega_1} e^{j\omega(n-\tau)}d\omega + \int_{\omega_2}^{\pi} e^{j\omega(n-\tau)}d\omega\right]$$

$$= \begin{cases} \dfrac{1}{\pi(n-\tau)}\left\{\sin[\pi(n-\tau)] + \sin[\omega_1(n-\tau)] - \sin[\omega_2(n-\tau)]\right\} & n \ne \tau \\ \dfrac{1}{\pi}(\pi + \omega_1 - \omega_2) & n = \tau \end{cases}$$

$$带阻滤波器(\omega_1, \omega_2) = 高通滤波器(\omega_2) + 低通滤波器(\omega_1)$$

线性相位FIR带阻滤波器的设计公式

$$\frac{\sin[\pi(n-16)]+\sin[0.3\pi(n-16)]-\sin[0.6\pi(n-16)]}{\pi(n-16)}$$

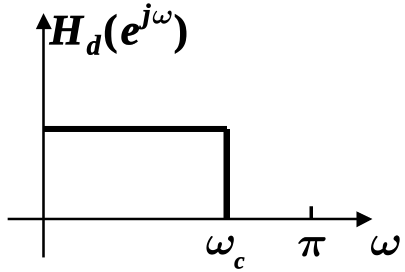


N=33

0.3π, 0.6π

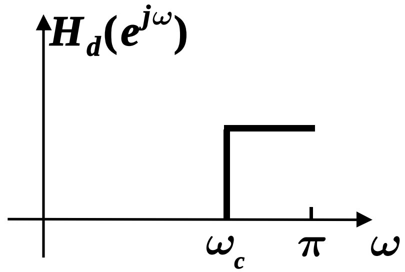
低通滤波器(ω_c)

$$h_d(n)=\begin{cases}\dfrac{1}{\pi(n-\tau)}\sin[\omega_c(n-\tau)] & n\neq\tau\\[2mm] \dfrac{\omega_c}{\pi} & n=\tau\end{cases}$$



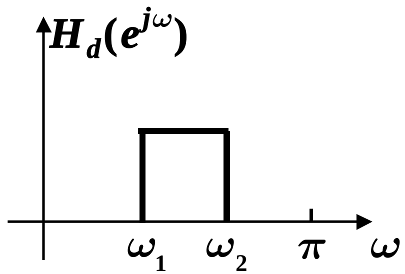
高通滤波器(ω_c) = 全通滤波器 − 低通滤波器(ω_c)

$$h_d(n)=\begin{cases}\dfrac{1}{\pi(n-\tau)}\left\{\sin\left[\pi\left(n-\tau\right)\right]-\sin\left[\omega_c\left(n-\tau\right)\right]\right\} & n\neq\tau\\[2mm] \dfrac{1}{\pi}(\pi-\omega_c) & n=\tau\end{cases}$$



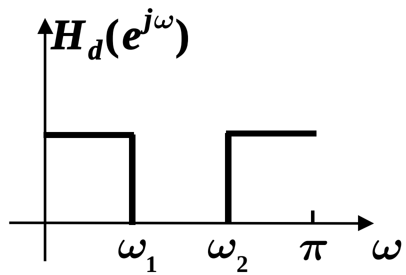
带通滤波器(ω_1,ω_2) = 低通滤波器(ω_2) − 低通滤波器(ω_1)

$$h_d(n)=\begin{cases}\dfrac{1}{\pi\left(n-\tau\right)}\left\{\sin\left[\omega_2\left(n-\tau\right)\right]-\sin\left[\omega_1\left(n-\tau\right)\right]\right\} & n\neq\tau\\[2mm] \dfrac{1}{\pi}\left(\omega_2-\omega_1\right) & n=\tau\end{cases}$$



带阻滤波器(ω_1,ω_2) = 高通滤波器(ω_2) + 低通滤波器(ω_1)

$$h_d(n)=\begin{cases}\dfrac{1}{\pi\left(n-\tau\right)}\left\{\sin\left[\pi\left(n-\tau\right)\right]+\sin\left[\omega_1\left(n-\tau\right)\right]-\sin\left[\omega_2\left(n-\tau\right)\right]\right\} & n\neq\tau\\[2mm] \dfrac{1}{\pi}\left(\pi+\omega_1-\omega_2\right) & n=\tau\end{cases}$$



FIR滤波器设计1—习题集P108

用矩形窗函数方法设计一个FIR线性相位数字低通滤波器，

已知$w_c = 0.5p$, $N = 21$。

(1) 确定单位抽样响应序列$h(n), n = 0, 1, \mathbf{L}, N-1$

(2) 确定滤波器的系统函数$H(z)$

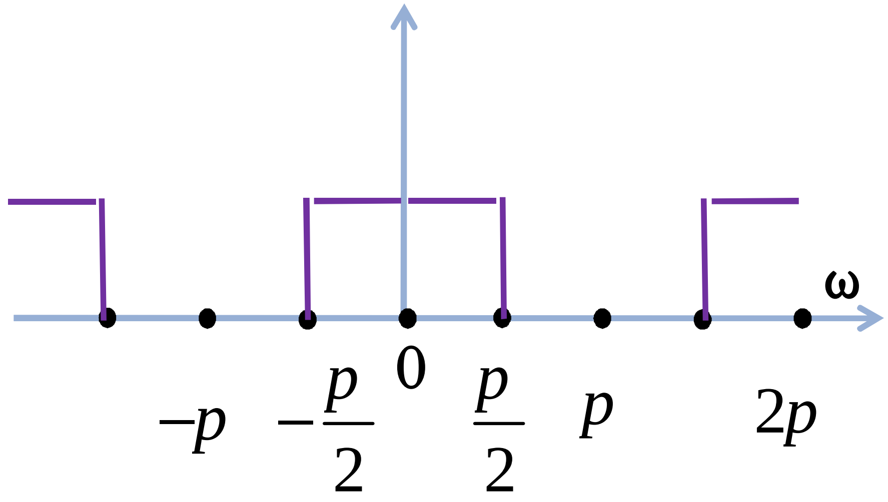
(3) 确定滤波器的频率响应$H(e^{jw})$

(4)给出滤波器的任意一种结构实现形式

理想数字低通滤波器的幅频响应为

$$\left|H_d(e^{jw})\right| = \begin{cases} 1 & -w_c \le |w| \le w_c \\ 0 & w_c < |w| < p \end{cases}$$

解：理想数字低通滤波器的幅频响应为



$$H_d(e^{jw})=\begin{cases} e^{-jwa} & -w_c \le w \le w_c \\ 0 & \text{其他} \end{cases}$$

$$\Rightarrow a=\frac{N-1}{2}=10,\ w_c=\frac{p}{2}$$

$$(1)h_d(n)=\begin{cases} \frac{1}{p(n-t)}\sin[w_c(n-t)] & n\ne t \\ \frac{w_c}{p} & n=t \end{cases}=\begin{cases} \frac{1}{p(n-10)}\sin[\frac{p}{2}(n-t)] & n\ne 10 \\ \frac{1}{2} & n=10 \end{cases}$$

$$h(n)=h_d(n)w(n)=\begin{cases} \frac{1}{p(n-10)}\sin[\frac{p}{2}(n-t)], 0\le n\le 20, n\ne 10 \\ \frac{1}{2}, & n=10 \\ 0, & n\text{为其他} \end{cases}$$

$$h(n)=h_d(n)w(n)=\begin{cases}\dfrac{1}{p(n-10)}\sin[\dfrac{p}{2}(n-t)],0\le n\le 20,n\ne 10\\ \dfrac{1}{2}, & n=10\\ 0, & n\text{为其他}\end{cases}$$

$$h(0)=0;h(1)=\frac{1}{9p}=0.035;$$

$$h(2)=0;h(3)=\frac{-1}{7p}=-0.045;$$

$$h(4)=0;h(5)=\frac{1}{5p}=0.064$$

$$h(6)=0;h(7)=\frac{-1}{3p}=-0.106;$$

$$h(8)=0;h(9)=\frac{1}{p}=0.318;$$

$$h(11)=\frac{1}{p}=0.318;h(12)=0;$$

$$h(13)=\frac{-1}{3p}=-0.106;h(14)=0;$$

$$h(15)=\frac{1}{5p}=0.064;h(16)=0;$$

$$h(17)=\frac{-1}{7p}=-0.045;h(18)=0;$$

$$h(19)=\frac{1}{9p}=0.035;h(20)=0;$$

$$h(10)=\frac{1}{2}$$

$$(2)H(z)=\sum_{n=0}^{N-1}h(n)z^{-n}$$

$$(3)H(e^{jw})=H(z)\big|_{z=e^{jw}}=\sum_{n=0}^{N-1}h(n)e^{-jwn}$$

(4)给出滤波器的任意一种结构实现形式

直接型

FIR滤波器设计2--往年真题

设理想数字高通滤波器的幅频响应为

$$\left|H_d(e^{jw})\right| = \begin{cases} 1 & p/2 \le |w| \le p \\ 0 & |w| < p/2 \end{cases}$$

用矩形窗函数方法设计一个$N=11$时FIR线性相位数字高通滤波器，

(1) 确定单位抽样响应序列$h(n), n=0,1,\text{L}, N-1$

(2) 确定滤波器的系统函数$H(z)$

(3) 确定滤波器的频率响应$H(e^{jw})$

(4)给出滤波器的任意一种结构实现形式

注：四舍五入到小数点后2位

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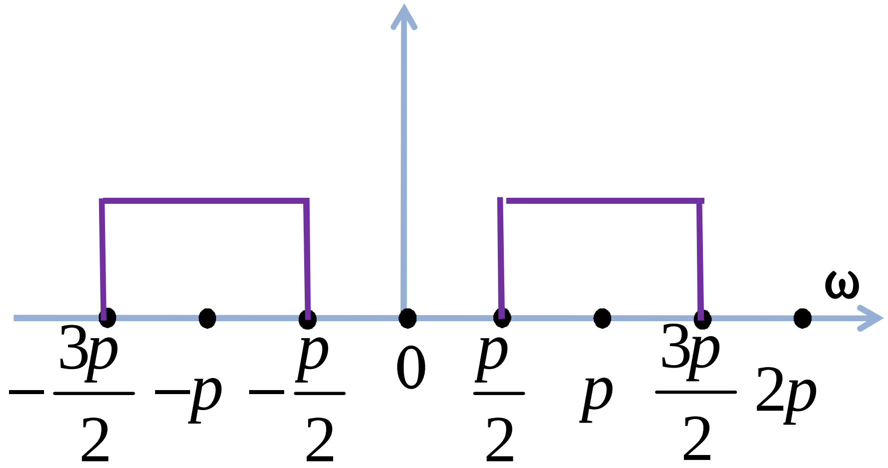
解：理想数字高通滤波器的幅频响为



$$H_d(e^{jw}) = \begin{cases} e^{-jwa} & w_c \le w \le w_c \\ 0 & \text{其他} \end{cases}$$

$$\Rightarrow a = \frac{N-1}{2} = 5,\ \ w_c = \frac{p}{2}$$

$$(1)\left|H_d(e^{jw})\right| = \begin{cases} 1 & p/2 \le |w| \le p \\ 0 & |w| < p/2 \end{cases}$$

$$h_d(n) = \begin{cases} \dfrac{1}{p(n-a)}\left\{\sin\left[p(n-a)\right] - \sin\left[w_c(n-a)\right]\right\} & n \ne a \\ \dfrac{1}{p}(p - w_c) & n = a \end{cases}$$

$$= \begin{cases} \dfrac{1}{p(n-5)}\left\{\sin\left[p(n-5)\right] - \sin\left[\dfrac{p}{2}(n-5)\right]\right\} & n \ne 5 \\ \dfrac{1}{p}(p - \dfrac{p}{2}) & n = 5 \end{cases}$$

$$h_d(n)=\begin{cases}\dfrac{1}{p(n-5)}\left\{\sin\left[p(n-5)\right]-\sin\left[\dfrac{p}{2}(n-5)\right]\right\} & n\neq 5\\ \dfrac{1}{p}(p-\dfrac{p}{2}) & n=5\end{cases}$$

$$h(n)=h_d(n)w(n)=\begin{cases}\dfrac{1}{p(n-5)}\left\{\sin\left[p(n-5)\right]-\sin\left[\dfrac{p}{2}(n-5)\right]\right\}, & 0\le n\le 10, n\neq 5\\ \dfrac{1}{p}(p-\dfrac{p}{2}), & n=5\\ 0, & n\text{为其他}\end{cases}$$

$$h(0)=-\frac{1}{5p}=-0.064;\quad h(1)=0;\quad h(2)=\frac{1}{3p}=0.106;\quad h(3)=0;\quad h(4)=-\frac{1}{p}=-0.318;$$

$$h(5)=\left.\left((-1)^{n-5}\frac{\sin[\frac{p}{2}(n-5)]}{p(n-5)}\right)'\right|_{n=5}=\frac{1}{2};$$

$$h(6)=-\frac{1}{p}=-0.318;\quad h(7)=0;\quad h(8)=\frac{1}{3p}=0.106;\quad h(9)=0;\quad h(10)=-\frac{1}{5p}=-0.064$$

$$(2)H(z)=\sum_{n=0}^{N-1}h(n)z^{-n}$$

$$(3)H(e^{jw})=H(z)\big|_{z=e^{jw}}=\sum_{n=0}^{N-1}h(n)e^{-jwn}$$

(4)给出滤波器的任意一种结构实现形式

直接型

FIR滤波器设计3-1--往年真题

设理想数字带通滤波器的幅频响应为

$$\left|H_d(e^{jw})\right| = \begin{cases} 1 & p/4 \le |w| \le p/2 \\ 0 & p/2 \le |w| \le p, |w| \le p/4 \end{cases}$$

用矩形窗函数方法设计一个$N=9$时FIR线性相位数字带通滤波器，

(1) 确定滤波器单位抽样响应序列$h(n), n=0,1,\mathbf{L},N-1$

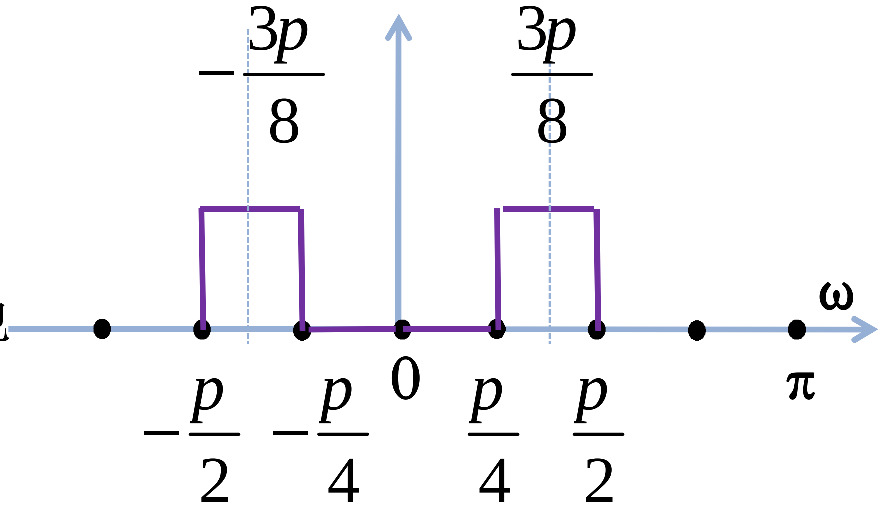
(2) 确定滤波器的系统函数$H(z)$

(3)给出滤波器的任意一种结构实现形式

注：四舍五入到小数点后2位

解：理想数字带通滤波器的幅频响为

$$H_d(e^{jw}) = \begin{cases} e^{-jwa} & -\frac{p}{8} \le w \pm \frac{3p}{8} \le \frac{p}{8} \\ 0 & \text{其他} \end{cases}$$



$$\Rightarrow a = \frac{N-1}{2} = 4,\ w_1 = \frac{p}{4},\ \ w_2 = \frac{p}{2}$$

$$(1) h_d(n) = \begin{cases} \frac{1}{p(n-a)} \{\sin[w_2(n-a)] - \sin[w_1(n-a)]\} & n \ne a \\ \frac{1}{p}(w_2 - w_1) & n = a \end{cases}$$

$$= \begin{cases} \frac{1}{p(n-4)} \left\{\sin\left[\frac{p}{2}(n-4)\right] - \sin\left[\frac{p}{4}(n-4)\right]\right\} & n \ne 4 \\ \frac{1}{4} & n = 4 \end{cases}$$

$$h(n)=h_d(n)w(n)=\begin{cases}\dfrac{1}{p\,(n-4)}\left\{\sin\left[\dfrac{p}{2}(n-4)\right]-\sin\left[\dfrac{p}{4}(n-4)\right]\right\},0\le n\le 8,n\ne 4\\ \dfrac{1}{4},n=4\\ 0,n\text{为其他}\end{cases}$$

$$h(0)=0;h(1)=\frac{1}{-3p}(1-\frac{\sqrt{2}}{2})=-0.03;$$

$$h(2)=\frac{1}{-2p}(-1)=0.16;h(3)=\frac{1}{-p}(-1-\frac{\sqrt{2}}{2})=0.54;$$

$$h(4)=\frac{1}{4};$$

$$h(5)=\frac{1}{p}(1+\frac{\sqrt{2}}{2})=0.54;h(6)=\frac{1}{2p}(1)=0.16;$$

$$h(7)=\frac{1}{3p}(-1+\frac{\sqrt{2}}{2})=-0.03;h(8)=0;$$

$$(2) H(z) = \sum_{n=0}^{N-1} h(n) z^{-n}$$

$$(3) H(e^{jw}) = H(z)\Big|_{z=e^{jw}} = \sum_{n=0}^{N-1} h(n) e^{-jwn}$$

(4)给出滤波器的任意一种结构实现形式

直接型