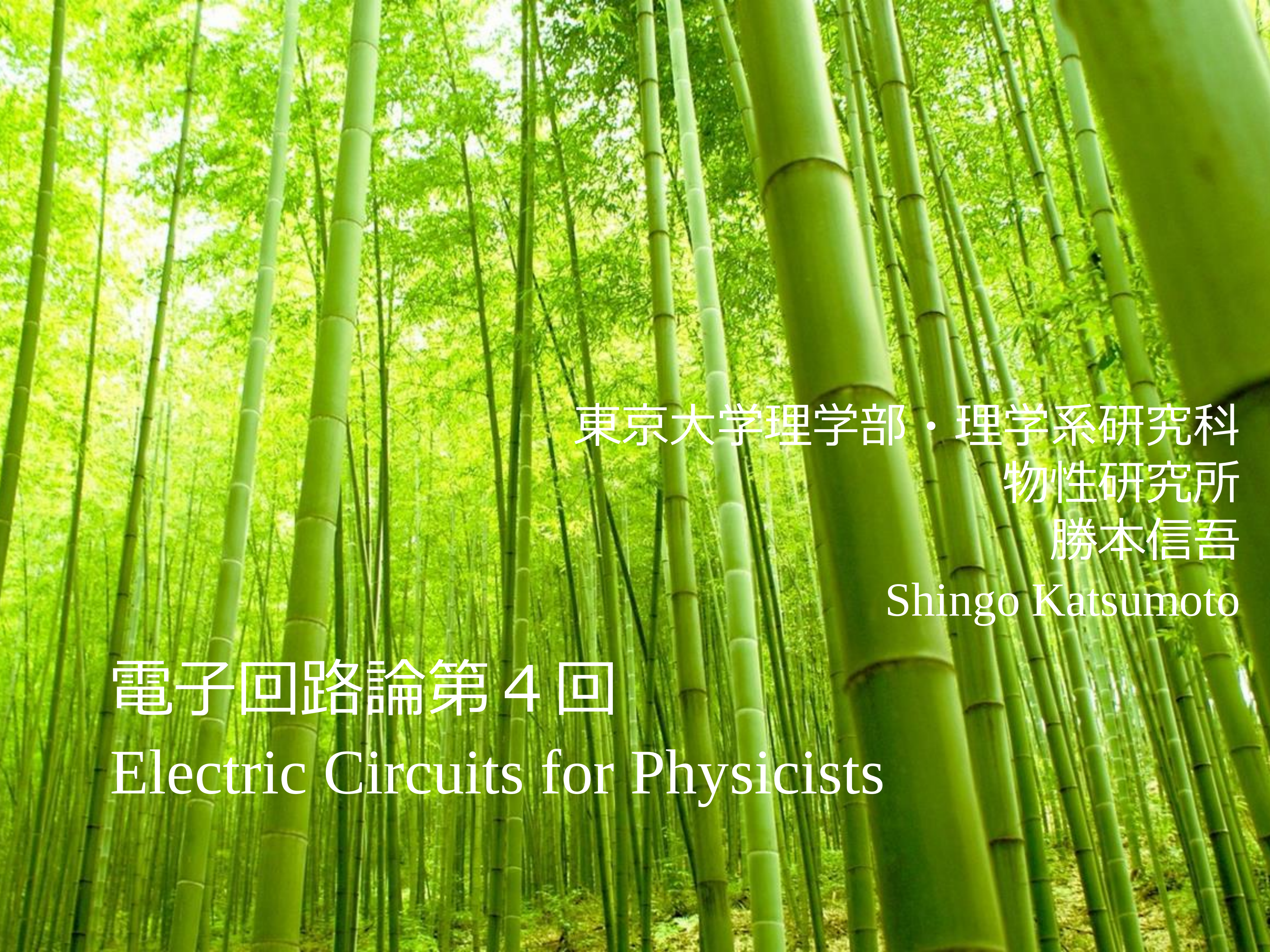

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勝本信吾
Shingo Katsumoto

電子回路論第４回

Electric Circuits for Physicists

Introduction of useful free software

Circuit Simulator

LTSpice (Linear Technology)

・・とはならない

By トランジスタ技術

Circuit Simulator

Download LTSpice from the web site of Linear Technology

What is Spice?

SPICE: Simulation Program with Integrated Circuit Emphasis

A language which describes electronic circuits (corresponding to circuit diagrams).

ex) a CR circuit and a dc power source

```
* 0---R1---1---C1---2---V1---0
R1 0 1 10
C1 1 2 20
V1 2 0 5
.END
```

Graphical user interface: Circuit diagram

Linear Technology
web site

Newest version
LTSpice XVII !!

LT4320	LT4320/LT4320-1 - 理想ダイオード・ブリッジ・コントローラ
LTC3114-1	LTC3114-1 - 出力電流をプログラム可能な40V、1A同期整流式昇降圧DC/DCコンバータ
LTC3355	LTC3355 - SCAPチャージャとバックアップ・レギュレータを内蔵した20V/1A降圧DC/DCシステム
LTC3331	LTC3331 - 環境発電（エナジーハーベスト）バッテリ・チャージャを内蔵したナノパワー昇降圧DC/DCコンバータ
LT8471	LT8471 - 2Aスイッチと同期機能を備えたデュアル・マルチトポロジーDC/DCコンバータ

LT4321 PoE理想ダイオード・ブリッジ・コントローラ - 製品概要ビデオ

Operation example

Design Simulation and Device Models

リニアテクノロジーは高性能なスイッチング·レギュレータやアンプ、データ·コンバータ、フィルターなどを使用した回路を、初めての設計者でも短時間に容易に評価できるよ
ムデザイン·シミュレーション·ツールを提供しています。

- LTspice IV
- LTpowerCAD
- LTpowerPlay
- Amplifier Simulation & Design
- Filter Simulation & Design
- Timing Simulation & Design
- Data Converter Evaluation Software
- Dust Networks Starter Kits

LTSPICE IV

LTspice IV

LTspice IVは高性能なSpice IIIシミュレータと回路図入力、波形ビューワに改善を加え、スイッチング·レギュレータのシミュレーションを容易にするためのモデルを搭載しています。Spiceの改善により、スイッチング·レギュレータのシミュレーションは、通常のSpiceシミュレータ使用時に比べて著しく高速化され、ほとんどのスイッチング·レギュレータにおいて波形表示をほんの数分で行なうことができます。Spiceとリニアテクノロジーのスイッチング·レギュレータの80%に対応するMacro Model、200を超えるオペアンプ用モデルならびに抵抗、トランジスタ、MOSFETモデルをここからダウンロードできます。

- LTspice IV（Windows用）をダウンロード（2014年5月5日更新）
- ·LTspice IV（Mac OS X 10.7+用）をダウンロード
- 関連情報 & ショートカット
- Mac OS X用ショートカット
- スタート·ガイド
- ユーザ·ガイド（ヘルプ·ファイル参照）
- トランスの使用
- デモ回路集
- セミナーの開催予定を見る

LTspiceのツイッターをフォロー

LTspiceに関するビデオを見る

LTPOWERCAD

References

For circuit basics:

“Foundations of Analog and Digital Electronic Circuits”

by A. Agarwal and J. H. Lang (Elsevier, 2005)
1000 printed pages!
Ch.1 The Circuit Abstraction

“Teach Yourself Electricity and Electronics” 3rd Ed.

by Stan Gibilisco (McGraw-Hill, 2002) 748 printed pages

“Schaum’s outlines: Electric Circuits” 6th ed.

by M. Nahvi, J. A. Edminister (McGraw-Hill, 2014) 504pages

For measurement circuits:

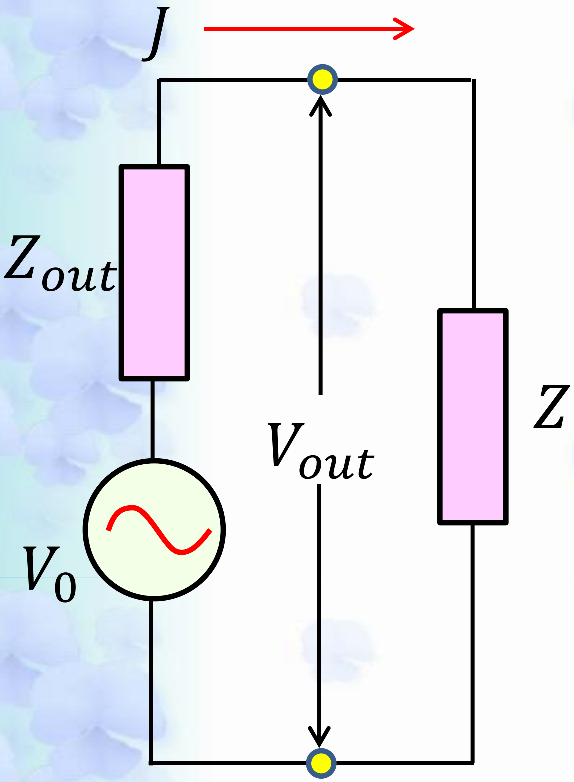
“Electrical and Electronics Measurements”

by G. K. Banerjee (PHI Learning Private, 2012) 835 pages

Outline today

3.2 Two terminal-pair passive circuits
3.2.1 Impedance matching (concept)
3.2.2 Poles and zeros of transfer function and Bode diagram
3.2.3 Image impedance
3.2.4 Impedance matching with terminal-pair circuits
3.2.5 Fidelity and distortion
3.2.6 Filter circuits

Impedance matching



$$V_{\mathrm{out}}(i\omega) = V_0(i\omega) - Z_{\mathrm{out}}(i\omega)J(i\omega)$$

$$P = \mathrm{Re}(V_{\mathrm{out}}^* J) = \mathrm{Re}\left(\frac{Z^* V_0^*}{Z^* + Z_{\mathrm{out}}^*}\frac{V_0}{Z + Z_{\mathrm{out}}}\right)$$

$$= \frac{|V_0|^2}{|Z + Z_{\mathrm{out}}|^2}\mathrm{Re}(Z)$$

Maximum power: $P_{\mathrm{max}} = \dfrac{|V_0|^2}{4\mathrm{Re}(Z_{\mathrm{out}})^2}$

Impedance matching condition: $Z = Z_{\mathrm{out}}^*$

Zeros and Poles of Transfer Functions

$$W(s) = B\frac{(s-\beta_1)\cdots(s-\beta_m)}{(s-\alpha_1)\cdots(s-\alpha_n)}$$

$\{\alpha_j\}$: Poles

$\{\beta_j\}$: Zeros

Bode diagram

$$\log|W(i\omega)| = \log|B| + \sum_{j=1}^{m}\log|(i\omega-\beta_j)| - \sum_{j=1}^{n}\log|(i\omega-\alpha_j)|,$$

$$\arg(W(i\omega)) = \arg(B) + \sum_{j=1}^{m}\arg(i\omega-\beta_j) - \sum_{j=1}^{n}\arg(i\omega-\alpha_j)$$

$$W(s) = \frac{1}{s+1}$$

$$\frac{d\theta}{d(\log\omega)} = -\frac{e^x}{e^{2x}+1}, \qquad \frac{d^2\theta}{dx^2} = -\frac{e^x(1-e^{2x})}{(e^{2x}+1)^2}$$

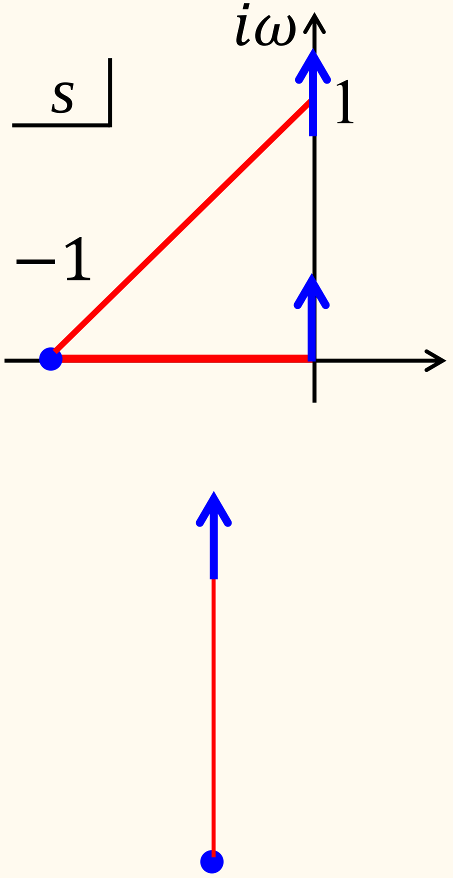
$$\arg[W] = \theta$$

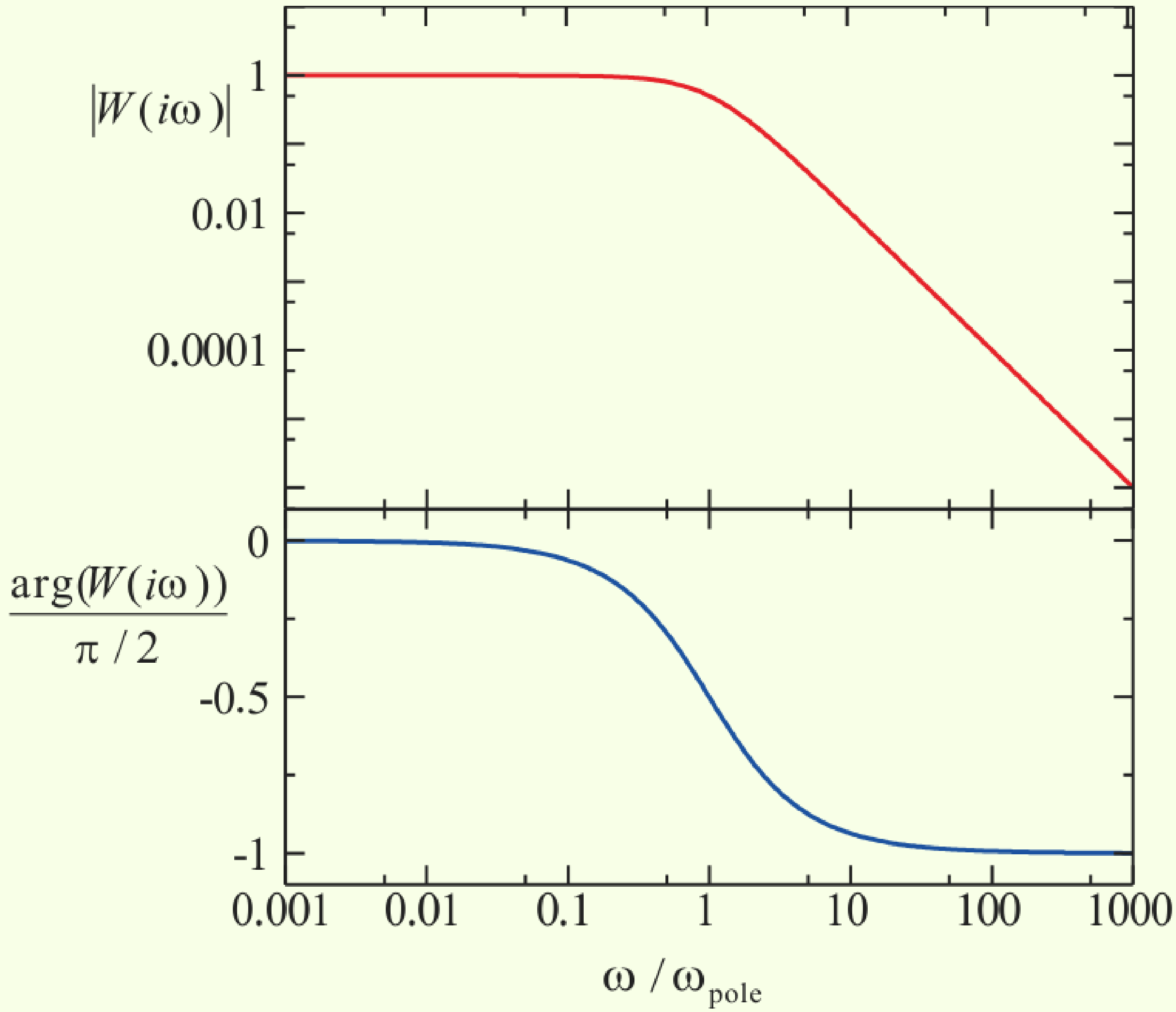
$$\log\omega = x$$

$$\frac{d(\log|W(i\omega)|)}{d(\log\omega)} = -\frac{e^2x}{1+e^{2x}}, \qquad \frac{d^2(\log|W|)}{dx^2} = -\frac{2e^{2x}}{(1+e^{2x})^2}$$

Effect of a Pole on the Real Axis for Bode Diagram

$$W(s) = \frac{1}{s+1}$$



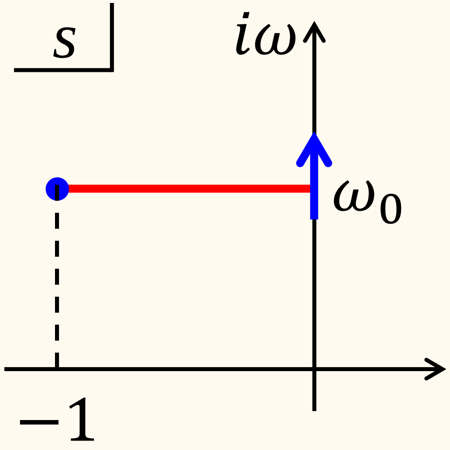


Effect of a Resonance Pole (Finite Imaginary Part)

$$W(s) = \frac{1}{s + 1 - i\omega_0}$$

$(\omega_0 > 0)$

(fake example)



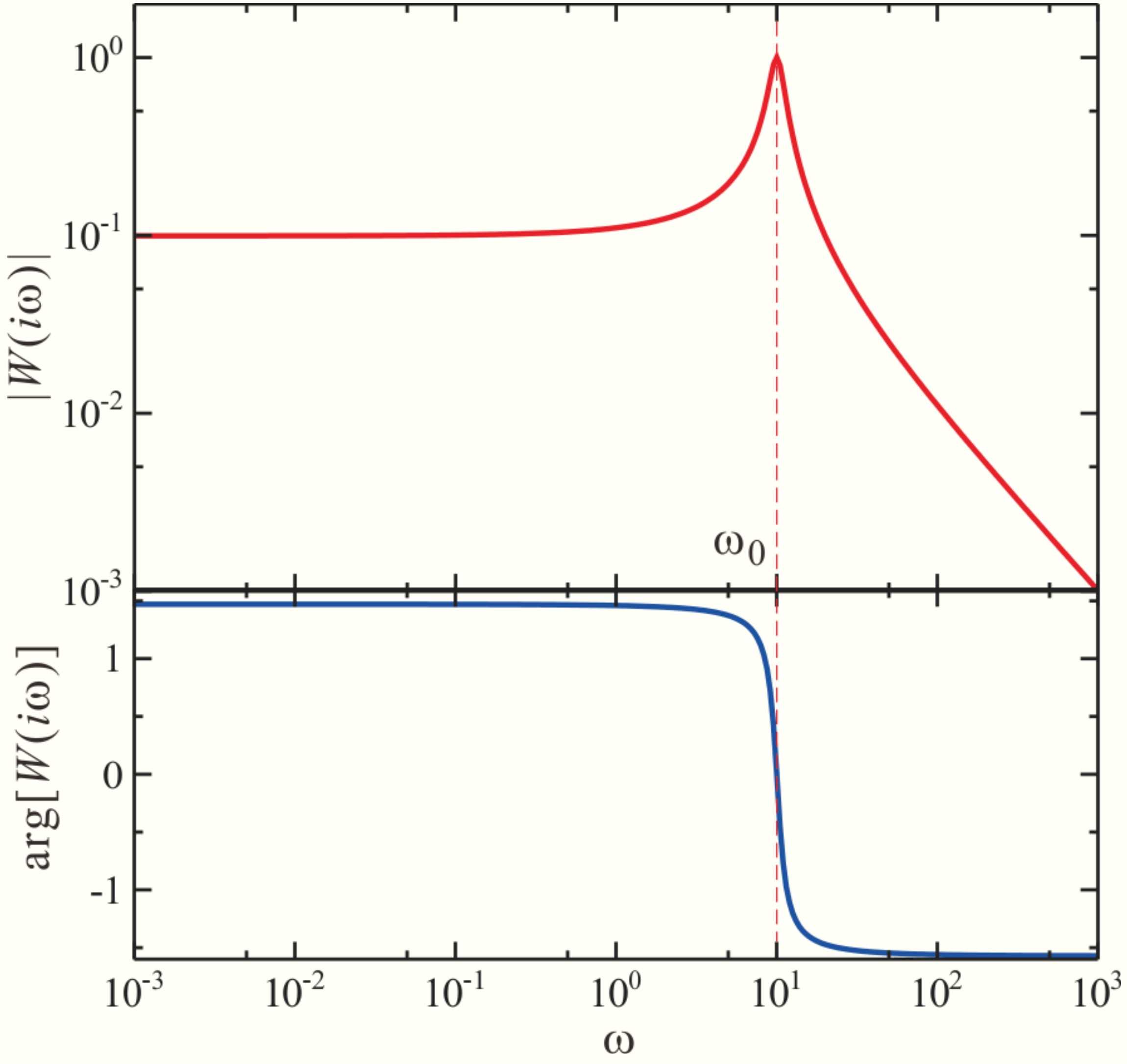
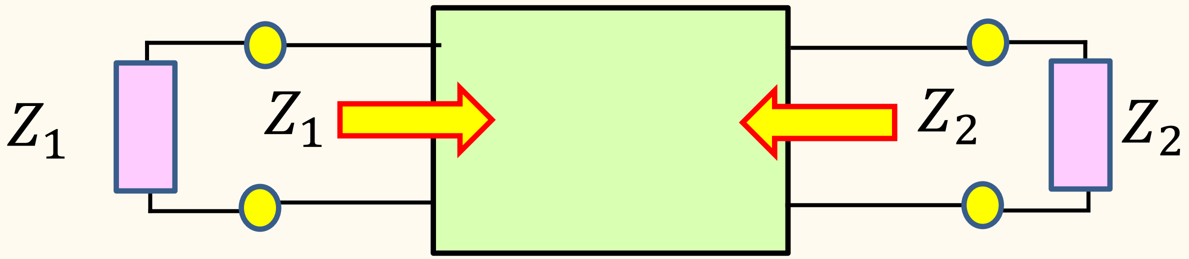
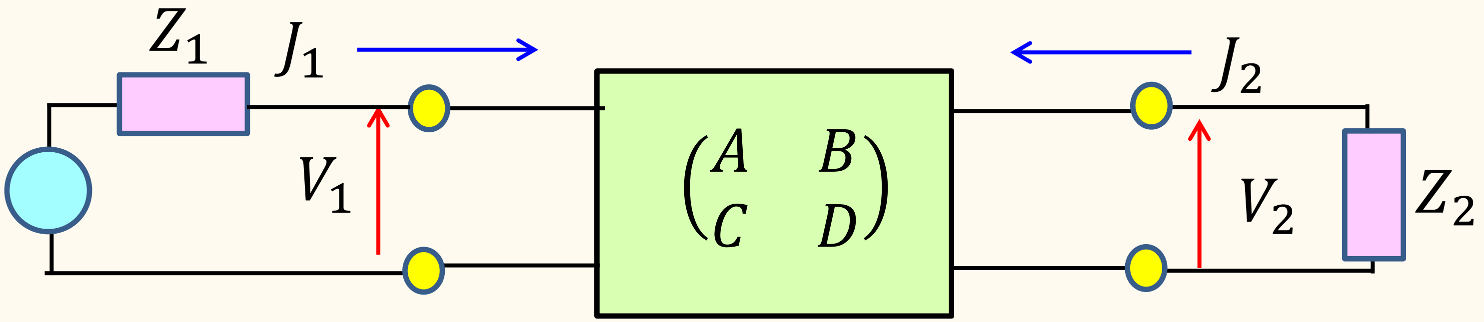


Image parameters



Z_1 and Z_2 are image impedances



$$\begin{cases} V_1 = AV_2 - BJ_2, \\ J_1 = CV_2 - DJ_2 \end{cases}$$

$$V_2 = -J_2 Z_2$$

$$\begin{cases} Z_1 = \dfrac{V_1}{J_1} = \dfrac{AZ_2 + B}{CZ_2 + D} \\ \\ Z_2 = \dfrac{DZ_1 + B}{CZ_1 + A} \end{cases}$$

Image parameters

$$Z_1 = \sqrt{\frac{AB}{CD}}, \quad Z_2 = \sqrt{\frac{DB}{CA}}$$

$$\frac{V_1}{V_2} = \sqrt{\frac{A}{D}}(\sqrt{AD} + \sqrt{BC}), \quad \frac{J_1}{-J_2} = \sqrt{\frac{D}{A}}(\sqrt{AD} + \sqrt{BC})$$

$$e^\theta \equiv \sqrt{\frac{V_1 J_1}{-V_2 J_2}} = \sqrt{\frac{Z_1}{Z_2} \frac{J_1}{-J_2}} = \sqrt{\frac{Z_2}{Z_1} \frac{V_1}{V_2}} = \sqrt{AD} + \sqrt{BC}$$

θ: Image propagation constant

$$\theta = \alpha + i\beta \ \ (\alpha, \beta \in \mathbb{R})$$

$$\alpha = \frac{1}{2} \ln \left| \frac{V_1 J_1}{V_2 J_2} \right|, \quad \beta = \frac{1}{2} \arg \left[\frac{V_1 J_1}{-V_2 J_2} \right]$$

Image attenuation constant   Image phase shift

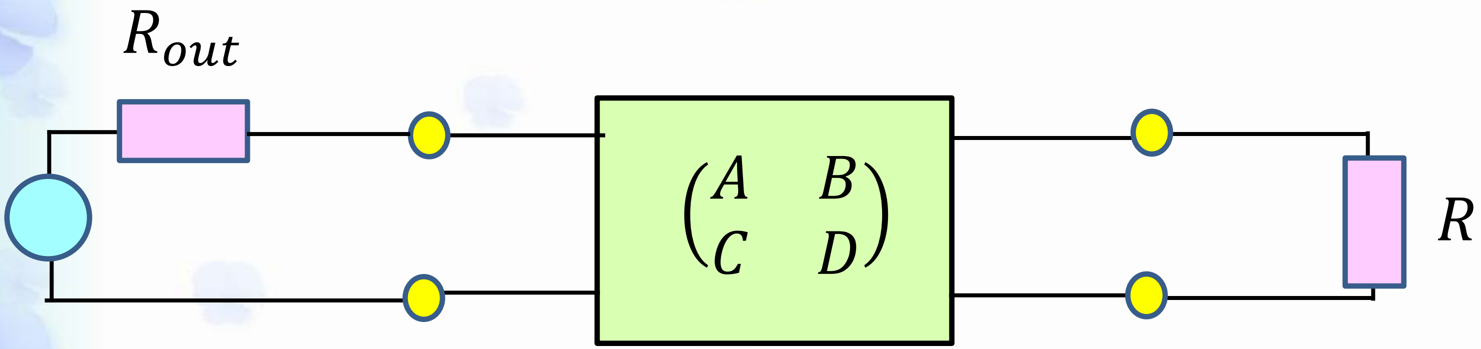
Image parameters

$$A = \sqrt{\frac{Z_1}{Z_2}} \cosh\theta, \quad B = \sqrt{Z_1 Z_2} \sinh\theta,$$

$$C = \frac{1}{\sqrt{Z_1 Z_2}} \sinh\theta, \quad D = \sqrt{\frac{Z_2}{Z_1}} \cosh\theta$$

Z_1, Z_2, θ: Image parameters

Impedance matching with two terminal-pair circuits



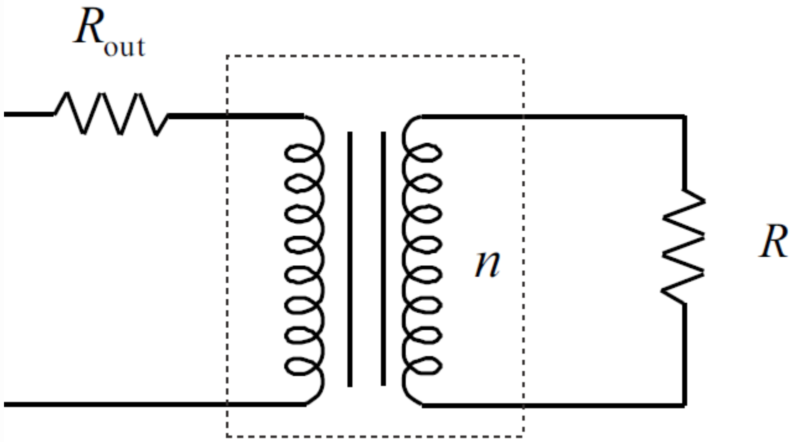
$ABCD \neq 0$ $\quad R_{\text{out}} = \sqrt{\frac{AB}{CD}}, \quad R = \sqrt{\frac{BD}{AC}}$

$A = D = 0$ $\quad R_{\text{out}} = \frac{AR + B}{CR + D}, \quad R = \frac{DR_{\text{out}} + B}{CR_{\text{out}} + A} \rightarrow RR_{\text{out}} = B/C$

$B = C = 0$ $\quad R_{\text{out}}/R = A/D$

Matching transformer

$$n = \sqrt{R/R_{\text{out}}}$$



Fidelity and distortion in wave transformation

Linear response: $w(t) = \mathscr{L}\{u(t)\}$

$$w(t) = A_0 u(t - \tau_0) \qquad \therefore W(i\omega) = A_0 e^{-i\omega\tau_0} U(i\omega)$$

$$\Xi(i\omega) = A_0 e^{-i\omega\tau_0}$$

No distortion condition:

$$|\Xi(i\omega)| = A_0, \ \arg[\Xi(i\omega)] = -\omega\tau_0$$

(1) No filter effect

$$\tau(\omega) = -\frac{d\phi(\omega)}{d\omega} \qquad (\phi(\omega) = \arg[\Xi(i\omega)])$$

(2) No dispersion in group delay

Breaks (1): amplitude distortion, (2): delay distortion

Effect of distortion

Sinusoidal amplitude distortion (amplitude modulation)

$$A(\omega) = a_1 \cos(\tau_1 \omega) + a_0,\ \phi(\omega) = -\tau_0 \omega$$

$$\begin{aligned}
w(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} A(\omega) U(i\omega) e^{i(\omega t + \phi(\omega))} d\omega \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega U(i\omega) \{a_1 \cos(\tau_1 \omega) + a_0\} e^{i\omega(t-\tau_0)} \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega U(i\omega) \left[a_0 + \frac{a_1}{2}(e^{i\tau_1\omega} + e^{-i\tau_1\omega})\right] e^{i\omega(t-\tau_0)} \\
&= a_0 u(t-\tau_0) + \frac{a_1}{2}[u(t-\tau_0+\tau_1) + u(t-\tau_0-\tau_1)]
\end{aligned}$$

Paired echo

Effect of distortion

Sinusoidal group delay distortion

$$A(\omega) = A_0,\ \phi(\omega) = -\tau_0\omega + b_1 \sin(\tau_1\omega)$$

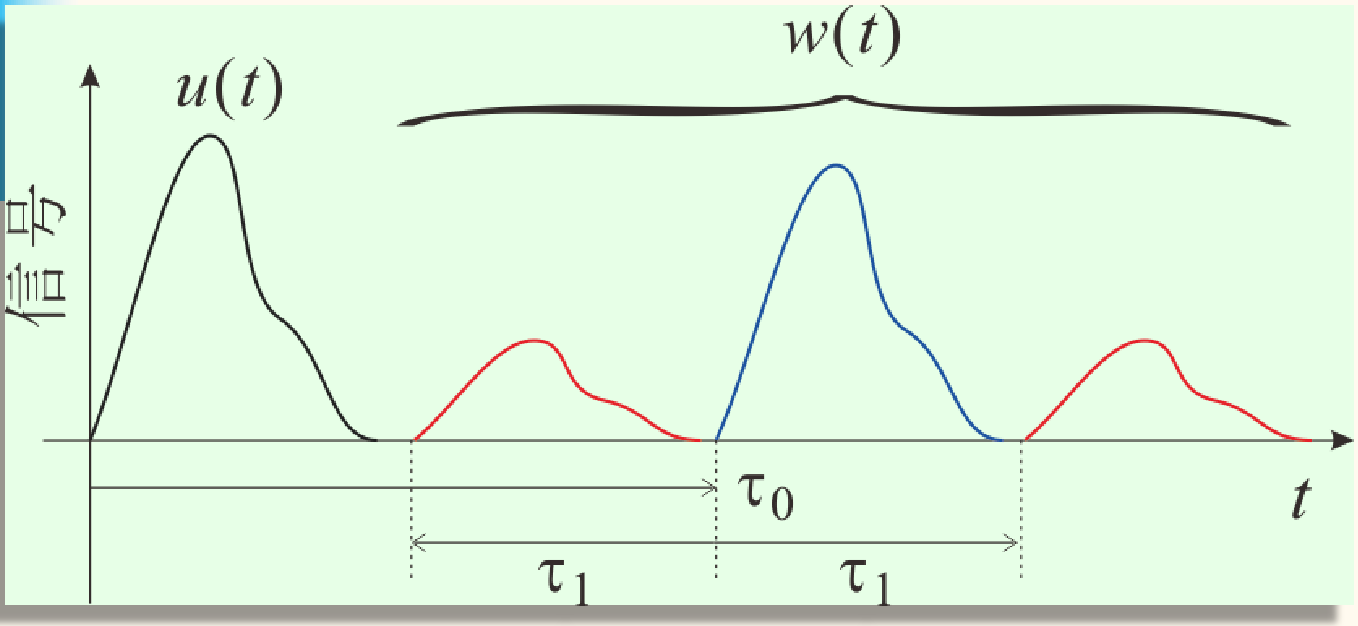
$$\exp[ib_1 \sin(\tau_1\omega)] \approx 1 + \frac{ib_1}{2i}(e^{i\tau_1\omega} - e^{-i\tau_1\omega})$$

$$w(t) = A_0[u(t-\tau_0) + \frac{b_1}{2}\{u(t-\tau_0+\tau_1) - u(t-\tau_0-\tau_1)\}]$$

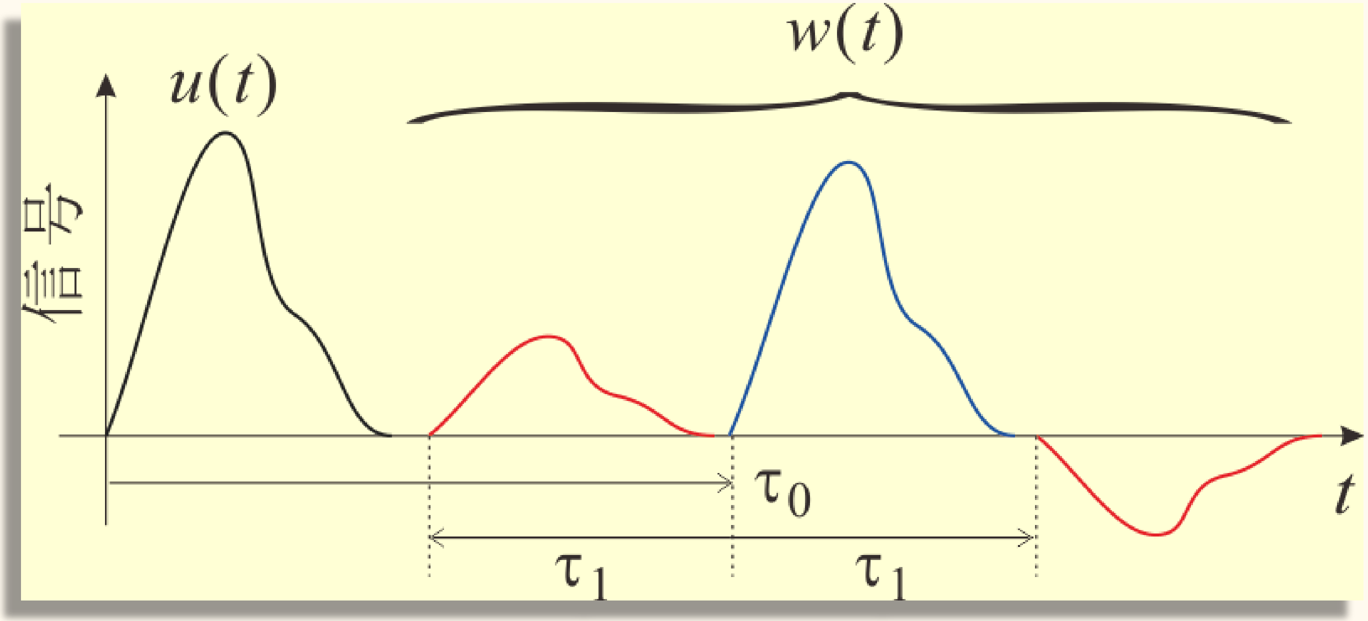
Paired echo

Distortion (paired echo)

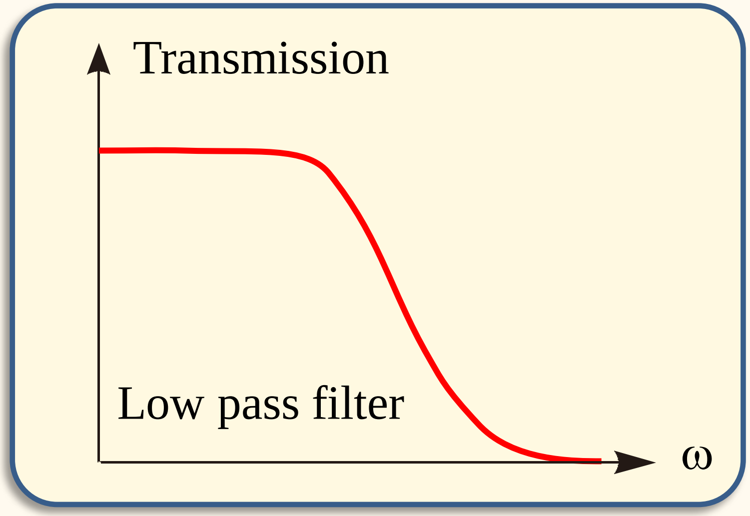
Cosine Amplitude Distortion

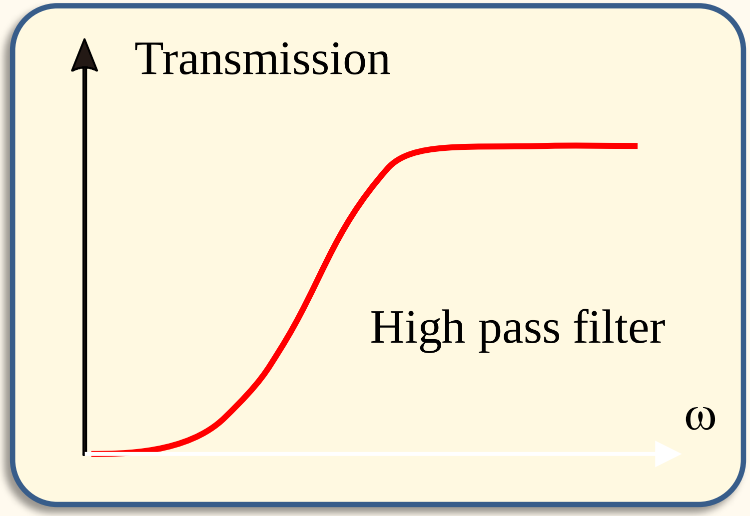


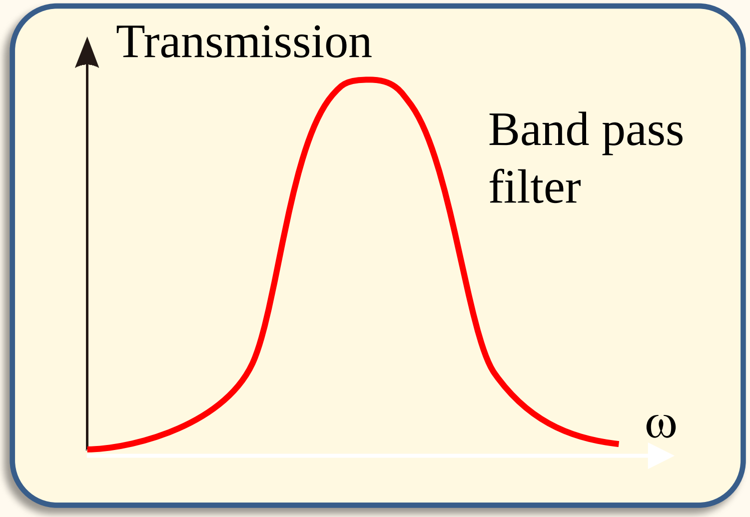
Sine Delay Distortion

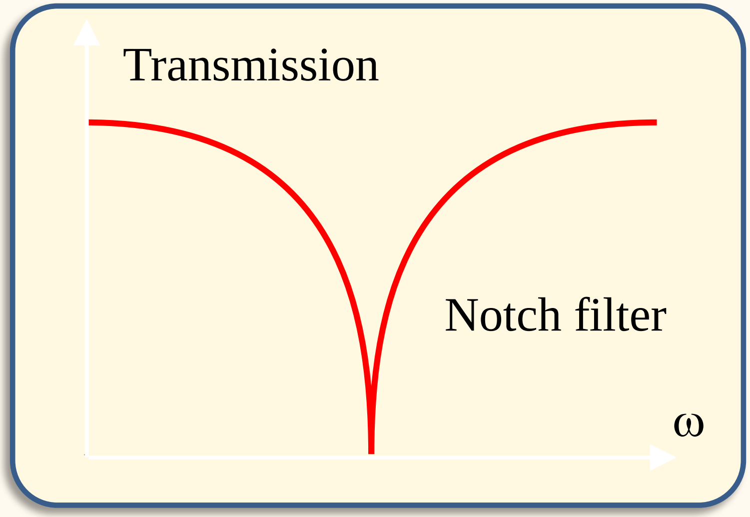


Filter Circuit







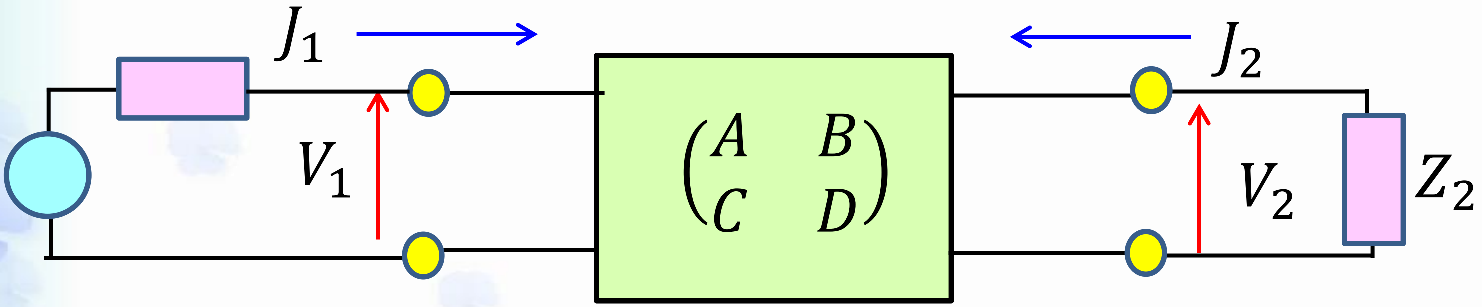


Transmission

Voltage transmission coefficient: $T(i\omega) \equiv \dfrac{V_2(i\omega)}{V_1(i\omega)}$

$$\log T = \log|T| + i\arg T = -\alpha - i\beta$$

attenuation Phase shift

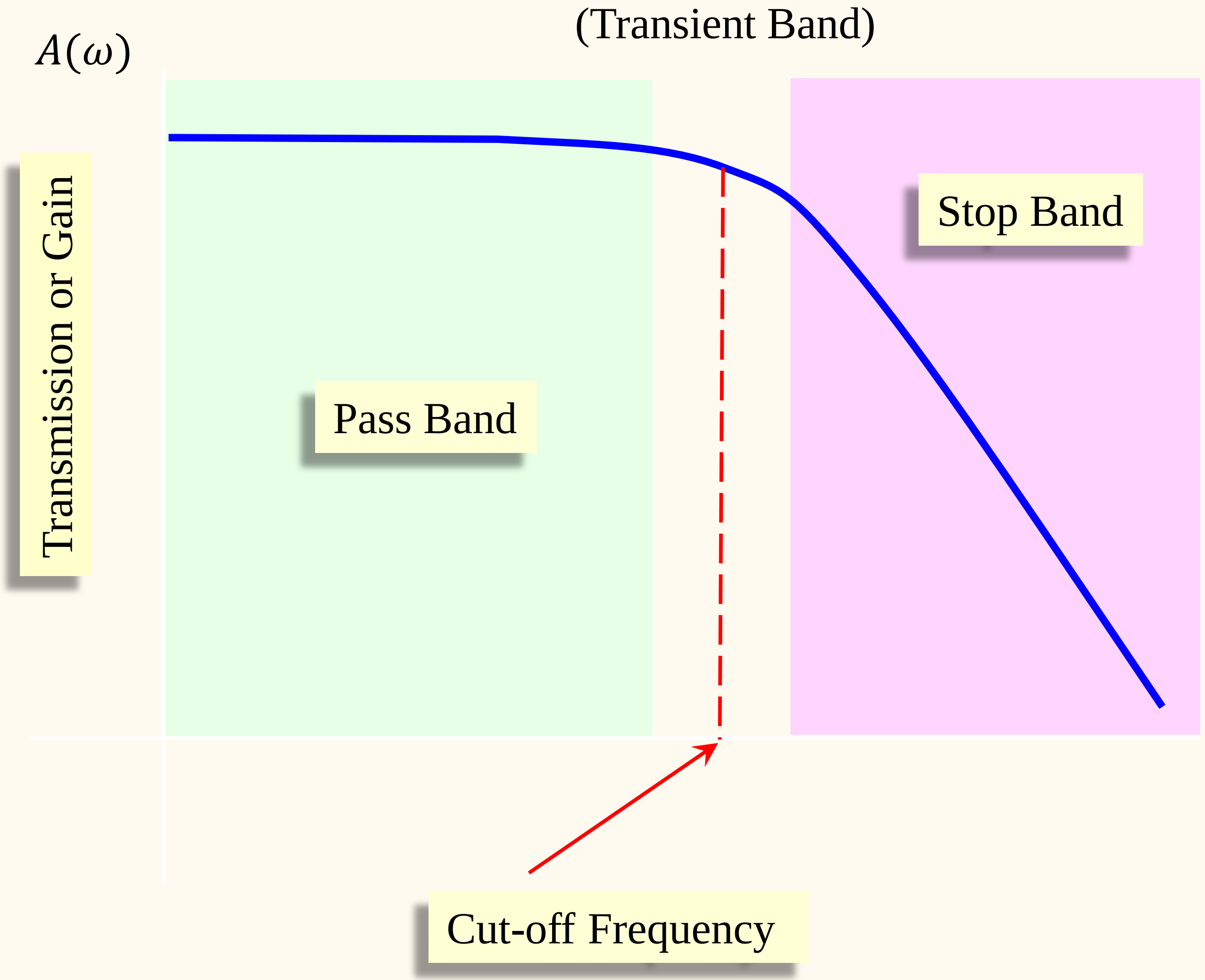


Square root power transmission coefficient

$$S_{\mathrm{B}} \equiv \sqrt{\frac{P_0}{P_2}} = \frac{R_2 A + B + C R_1 R_2 + D R_1}{2\sqrt{R_1 R_2}}$$

Terms for Filters

$$\Xi(i\omega) = A(\omega)e^{i\phi(\omega)}$$


(Transient Band)

$A(\omega)$

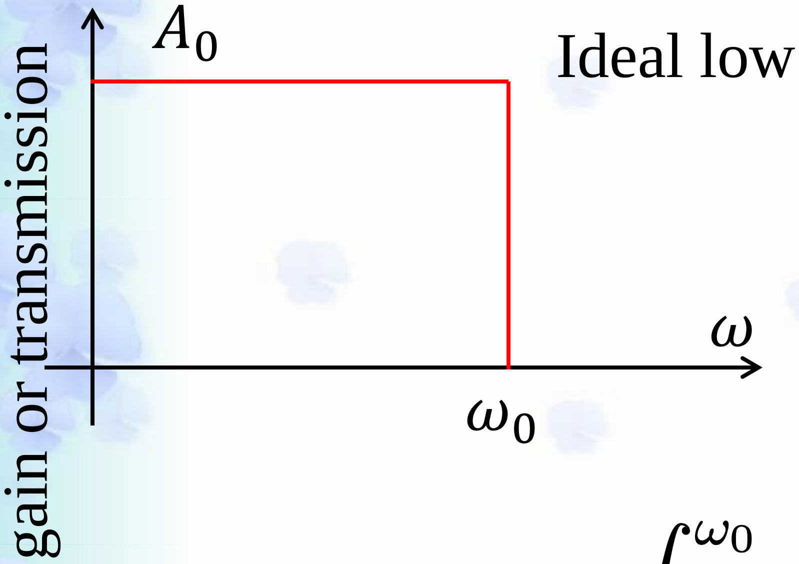
Transmission or Gain

Pass Band

Stop Band

Cut-off Frequency

Ideal filter (not exist)



Ideal low pass filter

$$\Xi(i\omega) = A_0 H(\omega_0 - \omega)$$

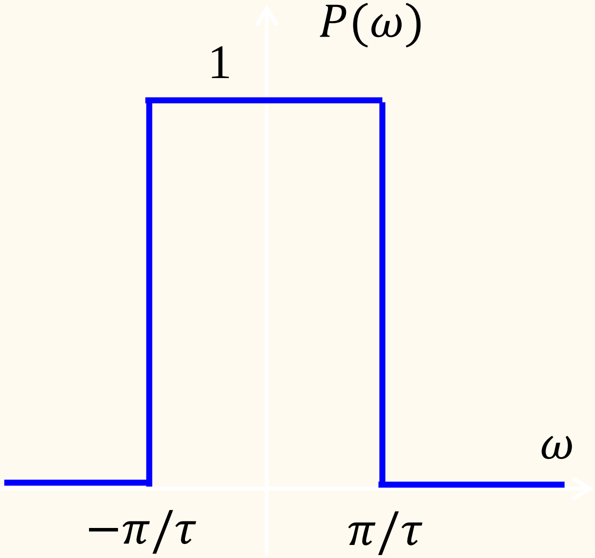
Heaviside function

$$w(t) = \int_{-\omega_0}^{\omega_0} A_0 e^{i\omega t} \frac{d\omega}{2\pi}$$

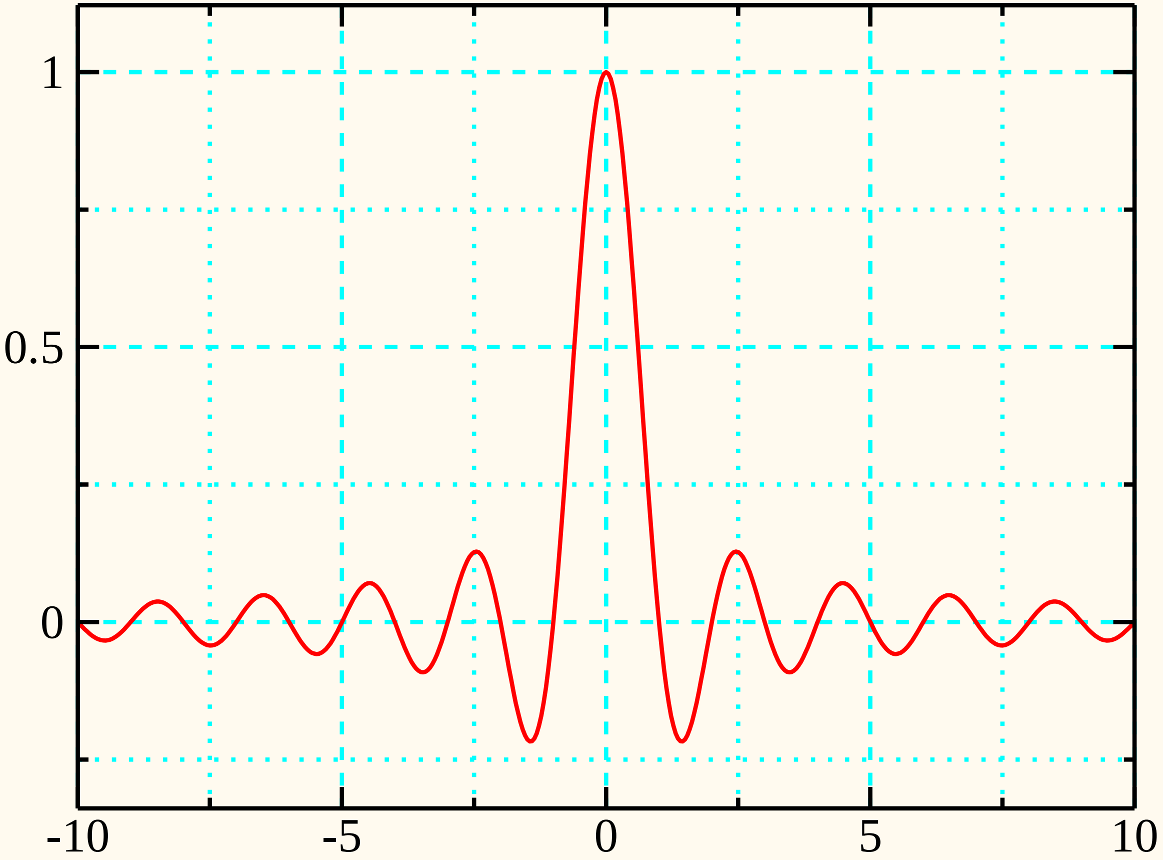
$$= A_0 \int_{-\omega_0}^{\omega_0} \frac{d\omega}{2\pi} \cos \omega t$$

$$= 2A_0 f_0 \frac{\sin \omega_0 t}{\omega_0 t} = 2A_0 f_0 \mathrm{sinc}(2f_0 t)$$

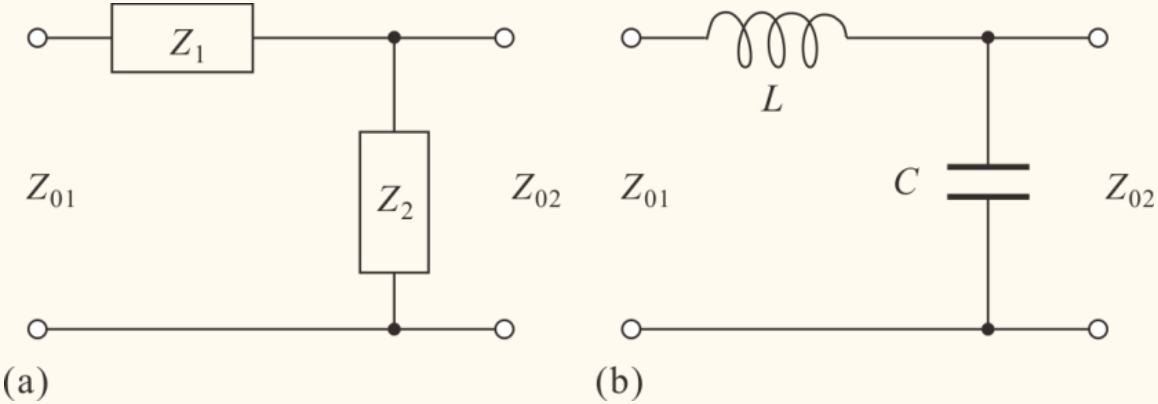
Sinc function



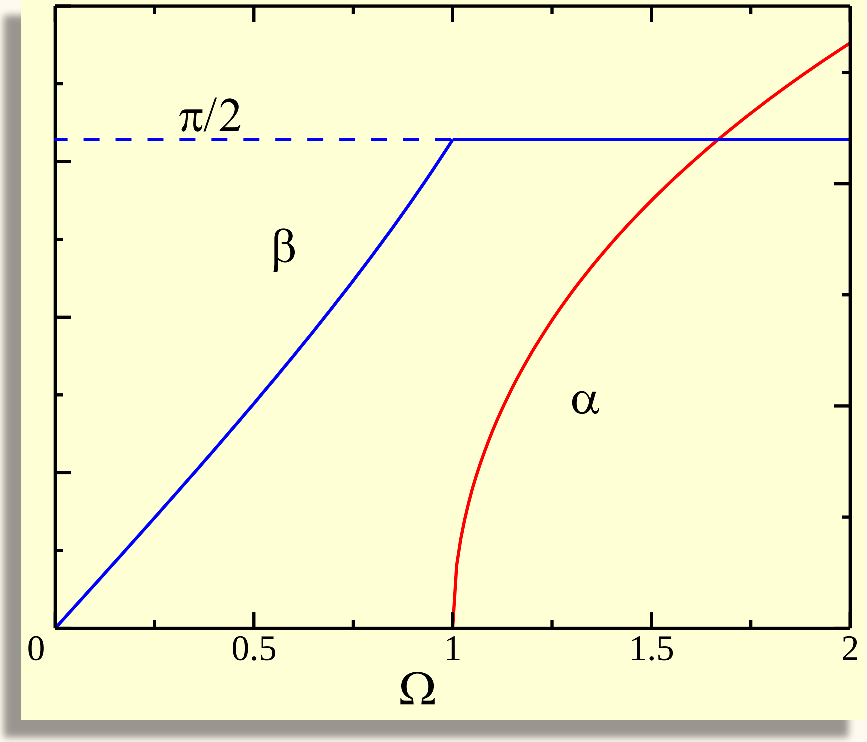
$$\mathrm{sinc}(x) = \frac{\sin \pi x}{\pi x}$$



Constant K type filter



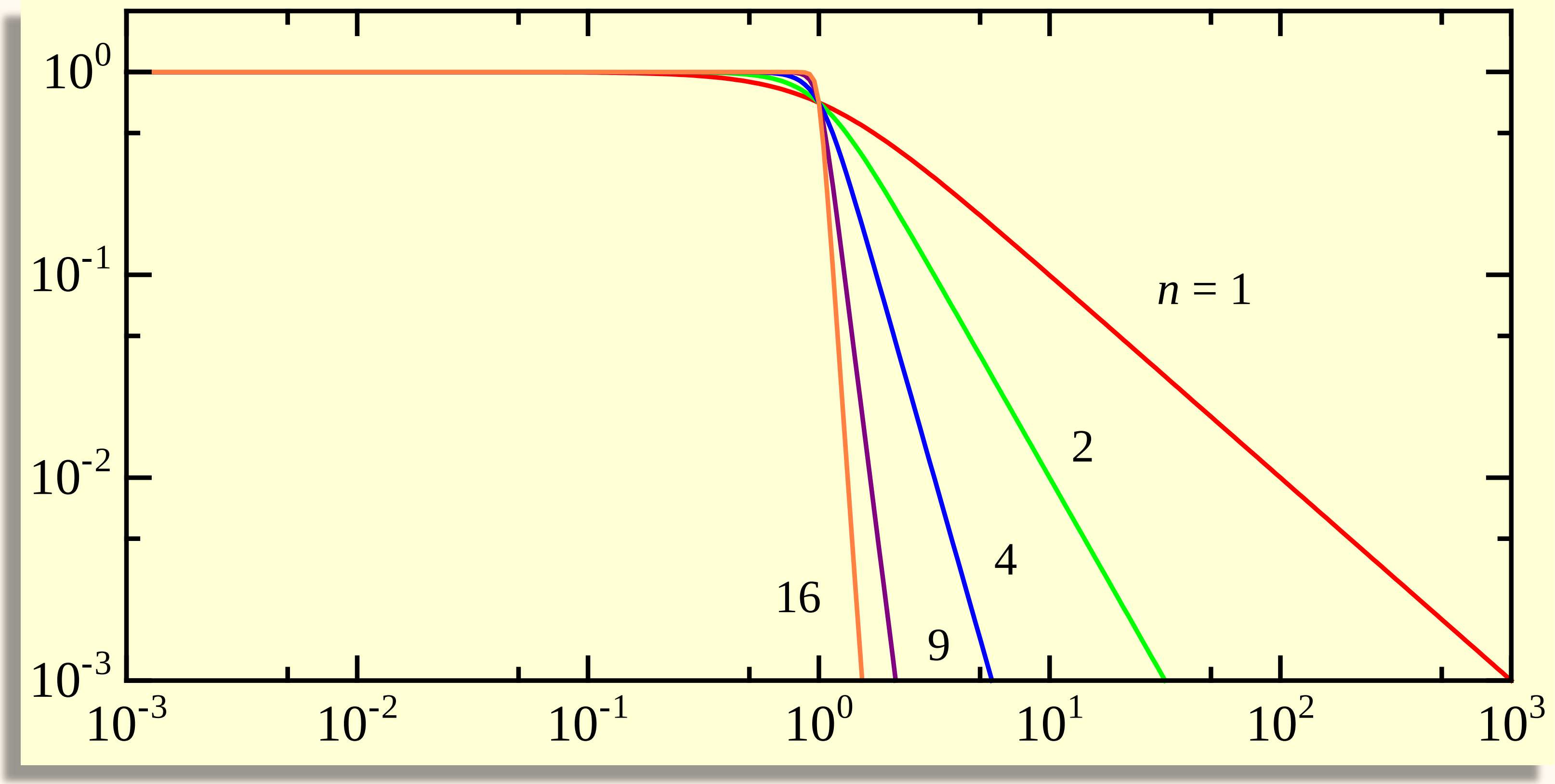
(a) (b)



$$Z_1 Z_2 = R^2 (= K)$$

Butterworth Filter

$$G^2(i\omega/\omega_0) = |H(i\omega)|^2 = \frac{1}{1 + (\omega/\omega_0)^{2n}}$$



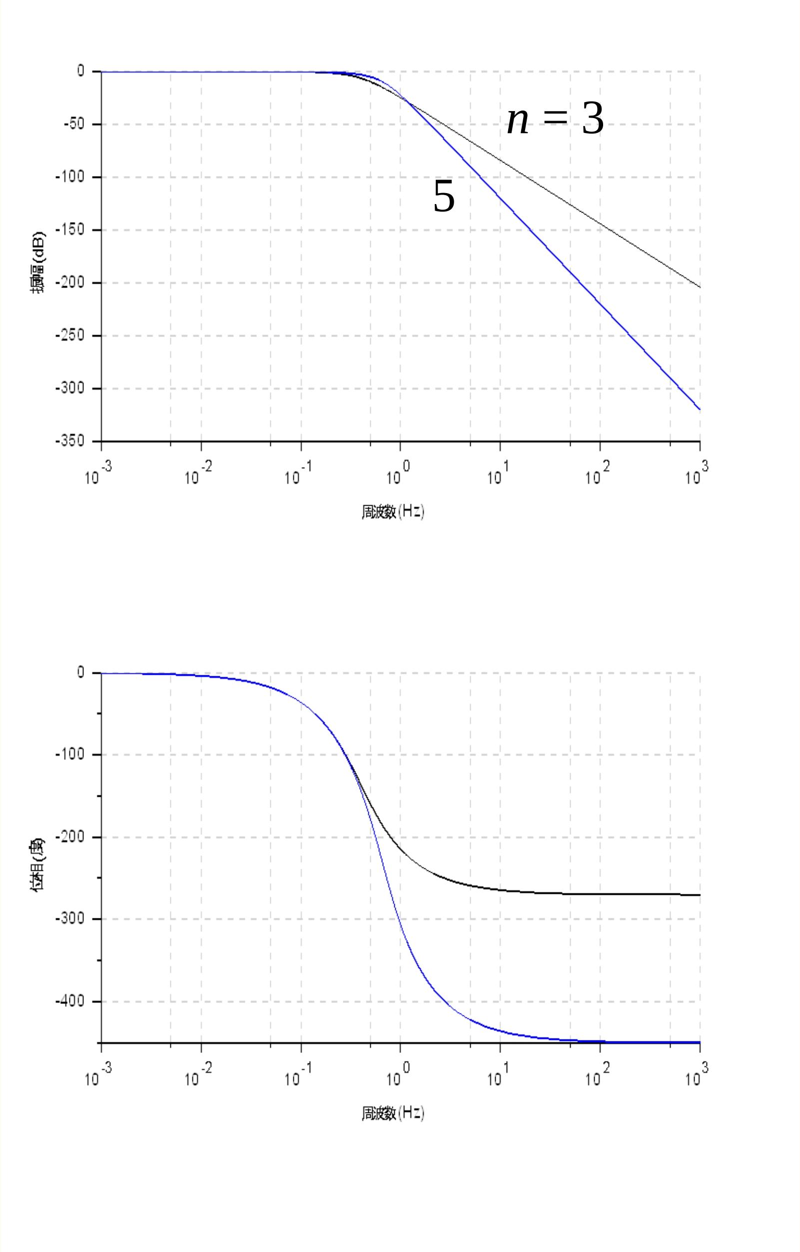
Bessel Filter

Inverse Bessel Polynomial

$$B_0 = 1, \quad B_1(s) = s + 1$$

$$B_n(s) = (2n-1)B_{n-1}(s) + B_{n-2}(s)s^2$$

$$\Xi(s) = \frac{B_n(0)}{B_n(s)}$$

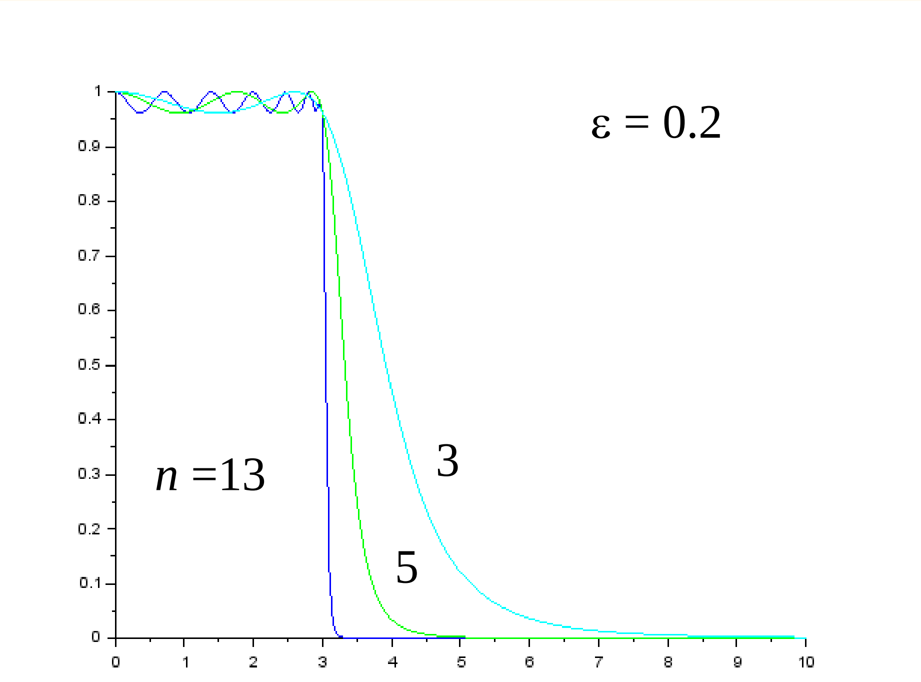


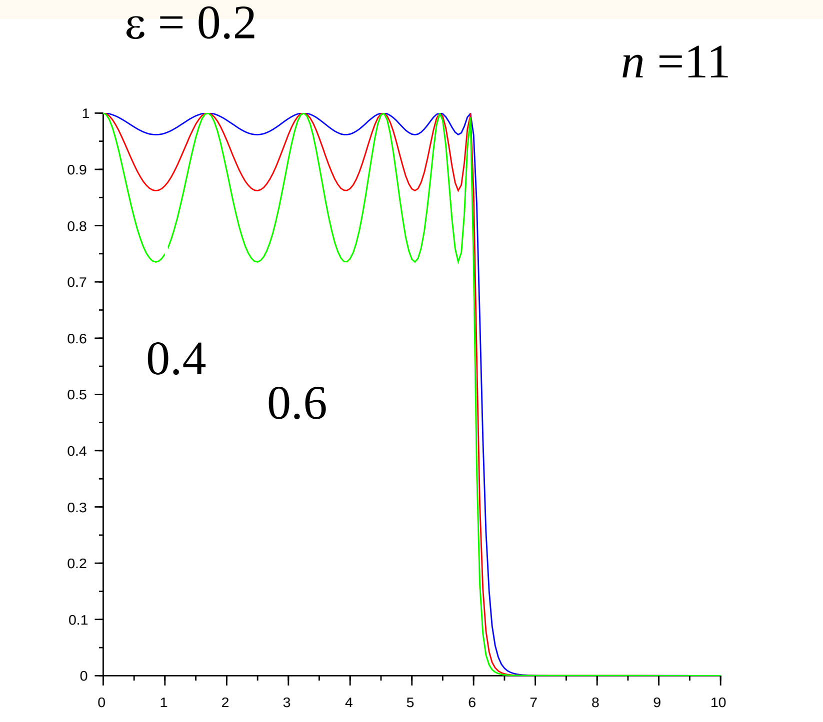
Chebyshev Filter

$$G_n(i\Omega) = |H_n(i\Omega)| = \frac{1}{\sqrt{1+\epsilon^2 T_n^2(\Omega)}}$$

ε: Ripple coefficeint

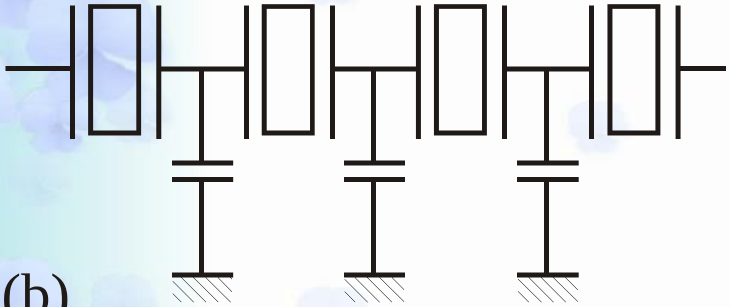
T_n: n-th order Chebyshev polynomial



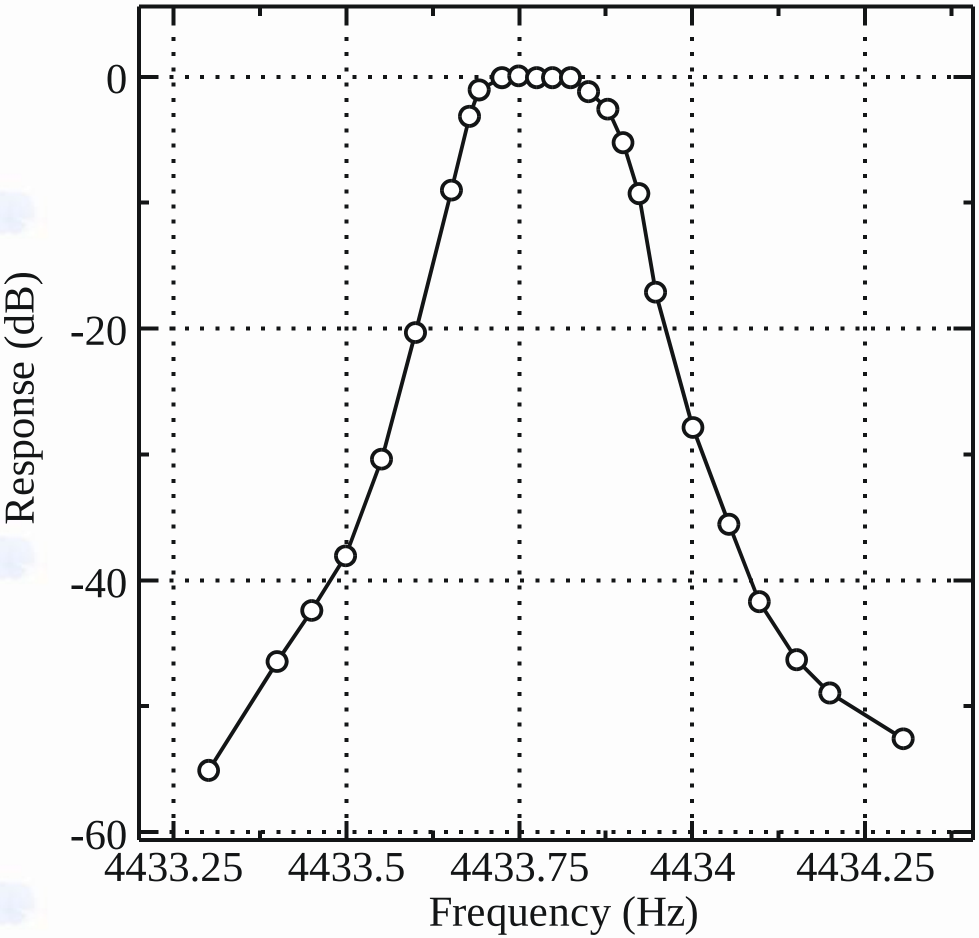


Quartz crystal filter

(a)



(b)



(c)

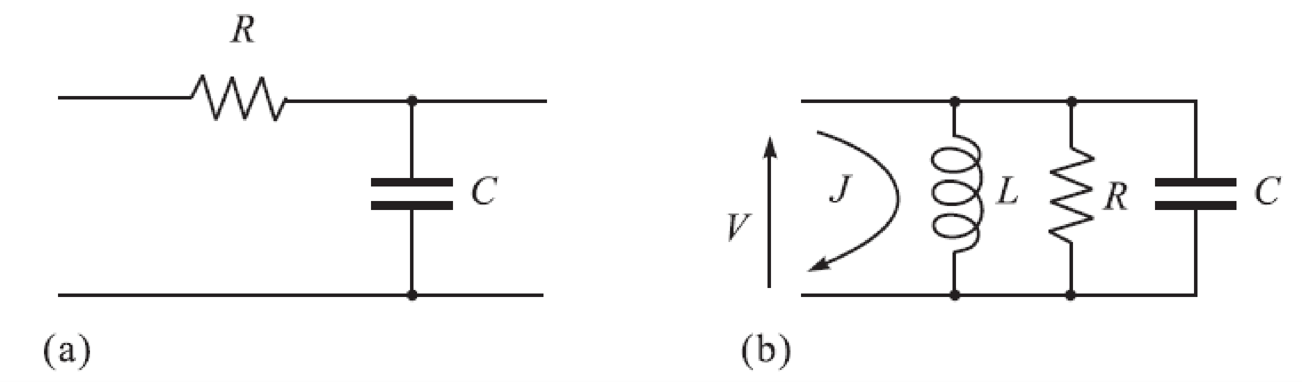
Packaged filters

Web selection page

http://www.minicircuits.com/products/Filters.shtml

Mini-Circuits
Band Pass
19.2 – 23.6MHz 50Ohm

Classification with the number of energy storages



(a) Single energy storage

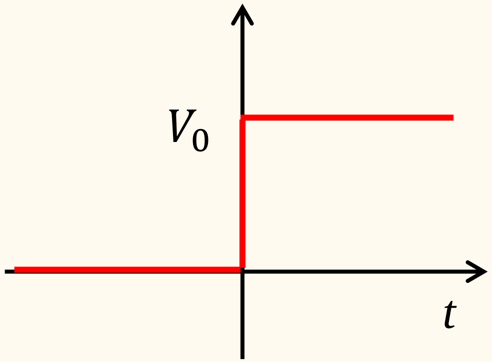
$$\Xi(s) = \frac{1}{1 + s/s_0}$$

(b) Double energy storage

$$\Xi(s) = \frac{1}{b + s + as^{-1}}$$

過渡応答 (Transient Response)

$$w(t) = \int_{-\infty}^{\infty} \Xi(i\omega) U(i\omega) e^{i\omega t} \frac{d\omega}{2\pi}$$

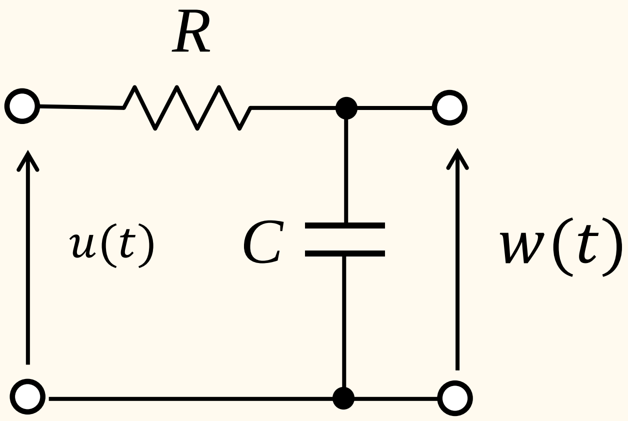


Heaviside

$$H(t) = \begin{cases} 0 & t < 0, \\ 1/2 & t = 0, \\ 1 & t > 0 \end{cases}$$

$$\mathcal{F}\{H(t)\} = \frac{1}{i\omega} + \pi\delta(\omega)$$

Simple application

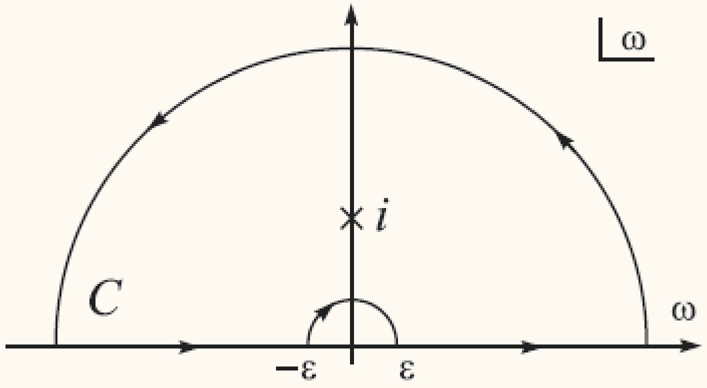


$$V = V_0 \left[1 - \exp\left(-\frac{t}{CR}\right)\right]$$

$$g(t) = \int_{-\infty}^{\infty} \frac{1}{1+i\omega}\left[\frac{1}{i\omega} + \pi\delta(\omega)\right] e^{i\omega t}\frac{d\omega}{2\pi}$$

$$= \int_{-\infty}^{\infty} \frac{e^{i\omega t}}{(i-\omega)\omega}\frac{d\omega}{2\pi} + \frac{1}{2}$$

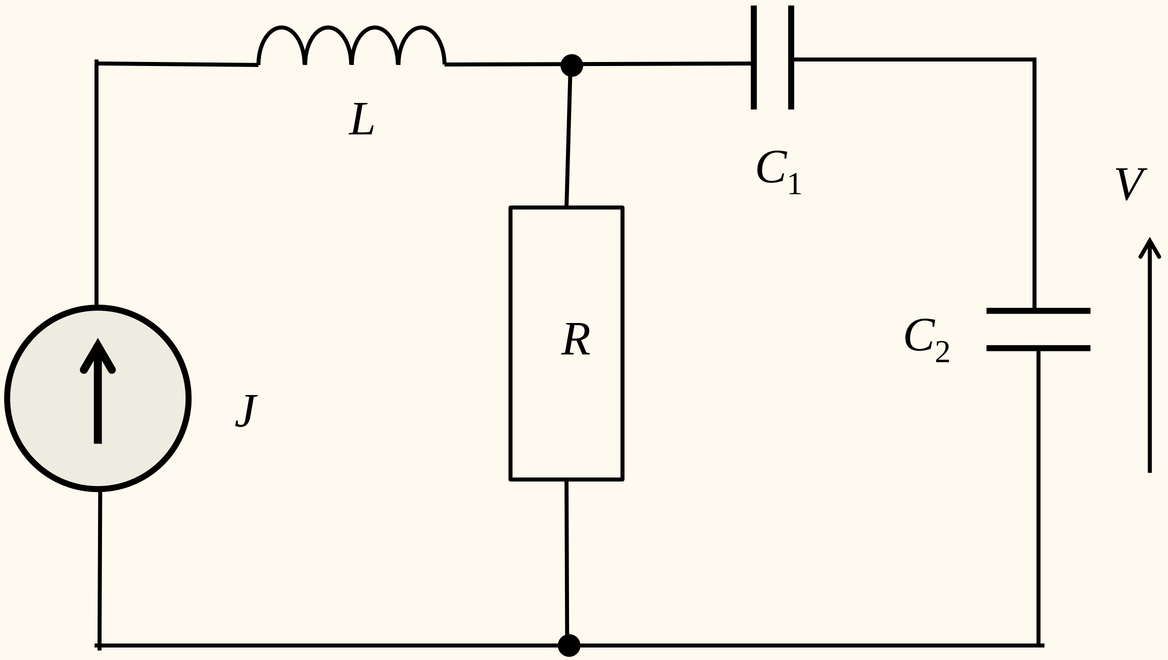
$$-2\pi i \frac{e^{-t}}{2\pi i} - \lim_{\epsilon\to 0}\left[\int_{\pi}^{0} \frac{e^{i\epsilon e^{i\theta} t}}{\epsilon e^{i\theta}(\epsilon e^{i\theta} - i)} \frac{i\epsilon e^{i\theta} d\theta}{2\pi}\right] = -e^{-t} - \frac{1}{2}$$



$$g(t) = -e^{-t}$$

Exercise B-1

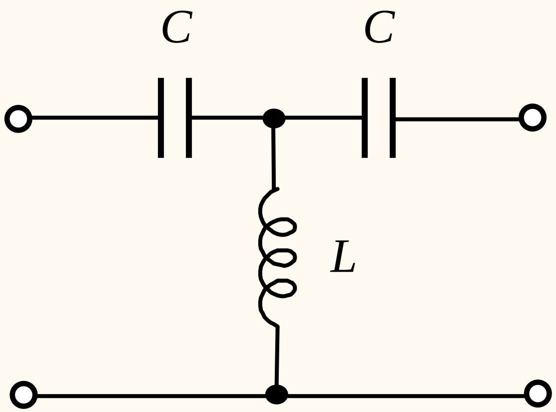
Calculate the voltage V over capacitor C_2 by using Norton theorem.



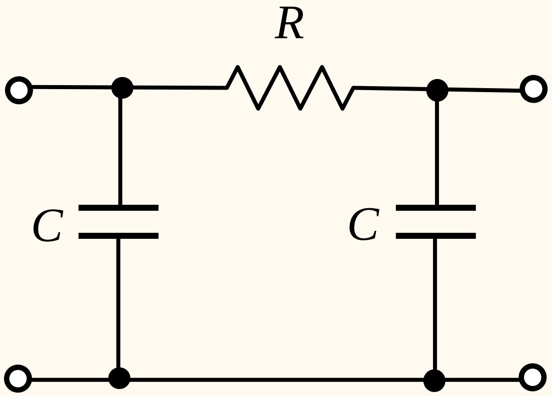
Exercise B-2

Obtain F-matrices for the circuits below.

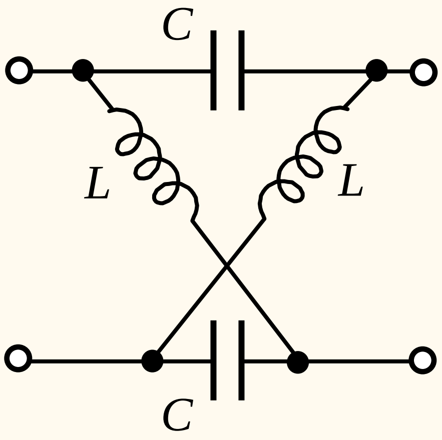
(a)



(b)



(c)



Exercise B-3

The switch below is turned on at $t = 0$.
Obtain the time evolution of voltage v henceforth.