

# Filters.

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Lecture 04

# Power dissipation

Recall that power dissipated by element is

$$P = VI$$

where  $V$  and  $I$  are real.

Since we use a substitute

$V \cos(\omega t) \rightarrow Ve^{i\omega t}$  and  $I \cos(\omega t) \rightarrow Ie^{i\omega t}$ ,

we need to write

$$P = \operatorname{Re}(V)\operatorname{Re}(I)$$

Recall the Ohm's law

$$V = ZI$$

# Power dissipation by a reactive element

## Theorem

**Average power dissipated by a reactive element (C or L) is 0**

*Lets use as example an inductor.*

$$Z_L = i\omega L = e^{j\frac{\pi}{2}}\omega L, I_L = I_p e^{i\omega t}$$

$$V_L = Z_L I_L = e^{j\frac{\pi}{2}}\omega L I_L = \omega L I_p e^{i(\omega t + \frac{\pi}{2})}$$

$$\text{Re}(I_L) = I_p \cos(\omega t), \text{Re}(V_L) = -\omega I_p L \sin(\omega t)$$

*Thus average power dissipated by the inductor*

$$P = \int_0^T \text{Re}(I_L) \text{Re}(V_L) dt = - \int_0^T I_p \cos(\omega t) \omega I_p L \sin(\omega t) dt$$

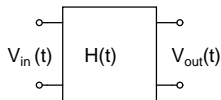
$$P = -\omega I_p^2 L \int_0^T \cos(\omega t) \sin(\omega t) dt = \omega I_p^2 L \int_0^T \frac{1}{2} \sin(2\omega t) dt = 0$$

If function  $f(t)$  goes to zero at  $\pm\infty$  then  $\hat{f}(\omega)$  exists such as

$$f(t) = \int_{-\infty}^{\infty} \hat{f}(\omega) e^{i\omega t} d\omega$$

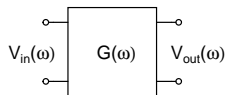
# Transfer function

Time domain



$$V_{out}(t) = \int_{-\infty}^t H(t - \tau) V_{in}(\tau) d\tau$$

Frequency domain



$$V_{out}(\omega) = G(\omega) V_{in}(\omega)$$

Where  $G$  is complex transfer function or gain.

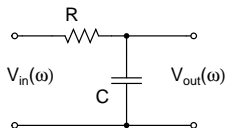
## Definition

$$G(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = |G(\omega)| e^{i\phi(\omega)}$$

Often used values of  $G$  in dB

$$dB = 20 \log_{10}(|G(\omega)|)$$

# Simple example: RC low-pass filter



$$G(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{\frac{1}{i\omega C}}{R + \frac{1}{i\omega C}} = \frac{1}{i\omega RC} \frac{1}{1 + \frac{1}{i\omega RC}} = \frac{1}{1 + i\omega RC}$$

defining  $\omega_{3dB} = \frac{1}{RC}$

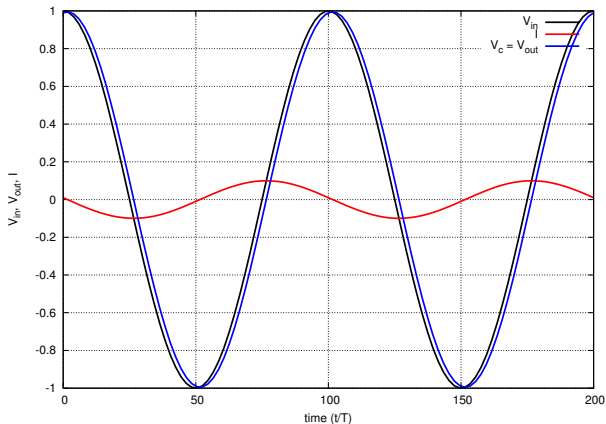
$$G(\omega) = \frac{1}{1 + i\frac{\omega}{\omega_{3dB}}} = \frac{1}{\sqrt{1 + \frac{\omega^2}{\omega_{3dB}^2}}} e^{i\phi}, \phi = \text{atan}\left(-\frac{\omega}{\omega_{3dB}}\right)$$

Note

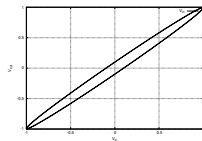
$$|G(\omega = \omega_{3dB})| = 20 \log_{10} \left( \frac{1}{\sqrt{1+1}} \right) = 20 \log_{10} \left( \frac{1}{\sqrt{2}} \right) = -3dB$$

# RC low-pass filter at $\omega = .1/RC$

## Signal vs time

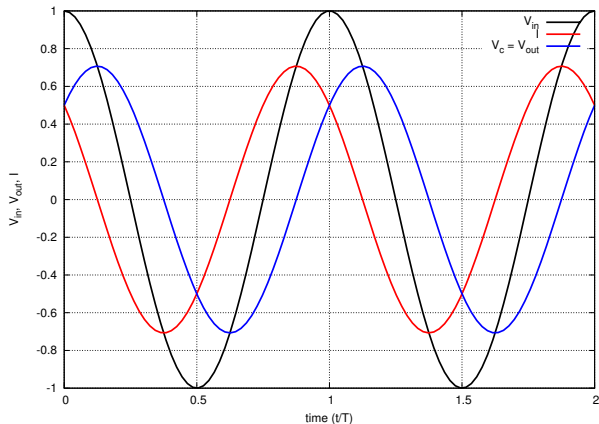


## Lissajous plot

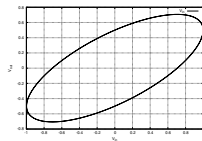


# RC low-pass filter at $\omega = 1/RC$

## Signal vs time



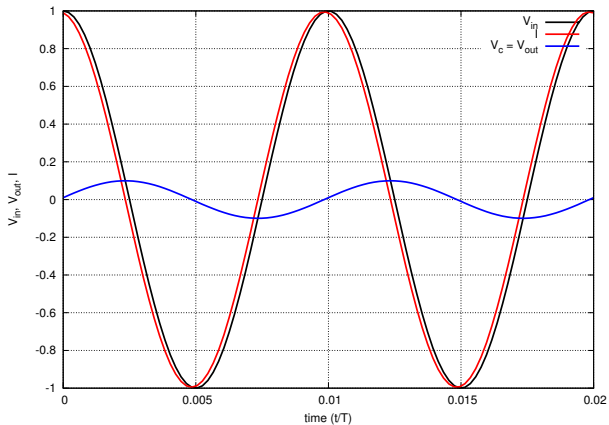
## Lissajous plot



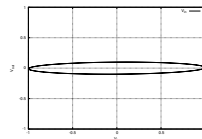


# RC low-pass filter at $\omega = 10/RC$

## Signal vs time



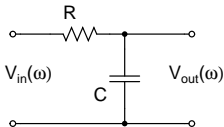
## Lissajous plot



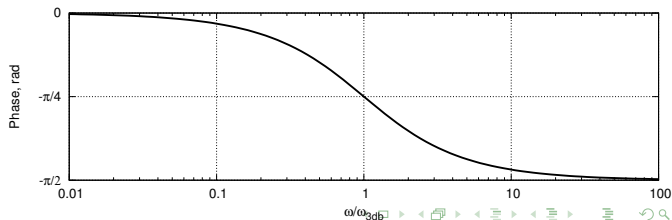
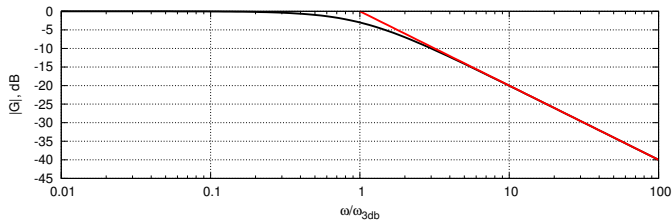
# Bode plots

## Definition

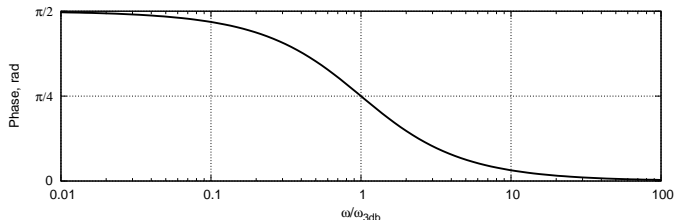
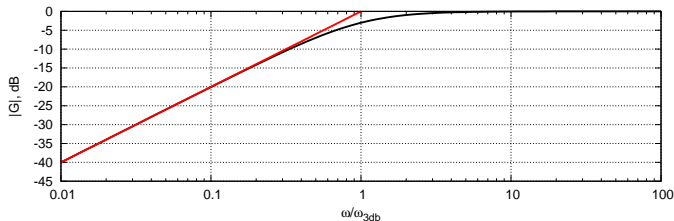
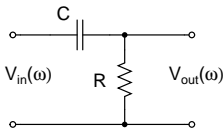
Bode plot: plots of magnitude and phase of the transfer function, where  $|G|$  is often plotted in dB



$$G(\omega) = \frac{1}{1 + j\frac{\omega}{\omega_{3dB}}}$$



# RC high-pass filter

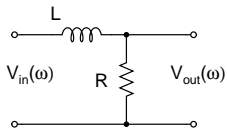


$$G(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{R}{R + \frac{1}{i\omega C}} = \frac{i\omega RC}{1 + i\omega RC} = \frac{i \frac{\omega}{\omega_{3dB}}}{1 + i \frac{\omega}{\omega_{3dB}}}$$

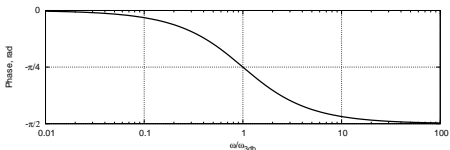
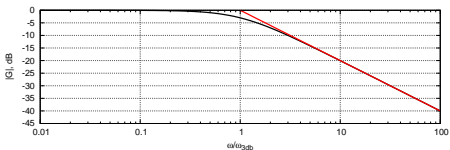
with  $\omega_{3dB} = \frac{1}{RC}$

# RL filters

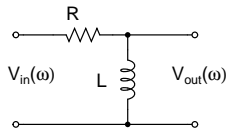
## RL low-pass filter



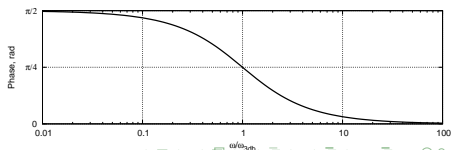
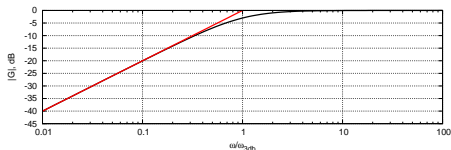
$$G(\omega) = \frac{R}{R + i\omega L}, \omega_{3dB} = \frac{R}{L}$$



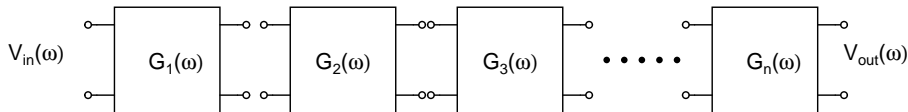
## RL high-pass filter



$$G(\omega) = \frac{i\omega L}{R + i\omega L}$$



# Filters chain

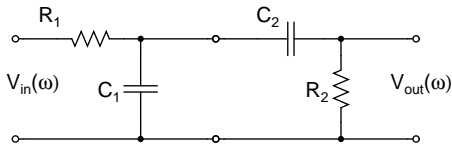


Technically next stage loads the previous and it is quite hard to calculate total transfer function.

However if we use rule of 10 to avoid overloading the previous filter. Every next stage resistor  $R_{i+1} > 10R_i$  we can approximate

$$G_t(\omega) \approx G_1(\omega)G_2(\omega)G_3(\omega) \cdots G_n(\omega)$$

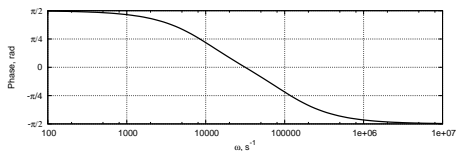
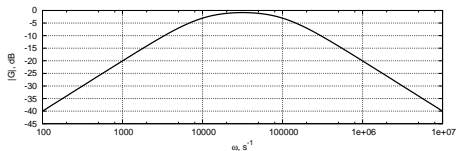
# Example band pass filter



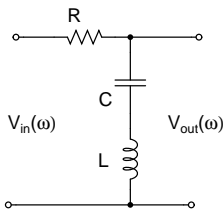
$$G_t(\omega) \approx G_1(\omega)G_2(\omega)$$

$$G_t(\omega) \approx \frac{1}{1 + i\frac{\omega}{\omega_{13dB}}} \frac{i\frac{\omega}{\omega_{23dB}}}{1 + i\frac{\omega}{\omega_{23dB}}}$$

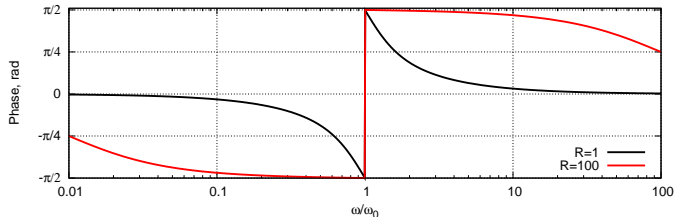
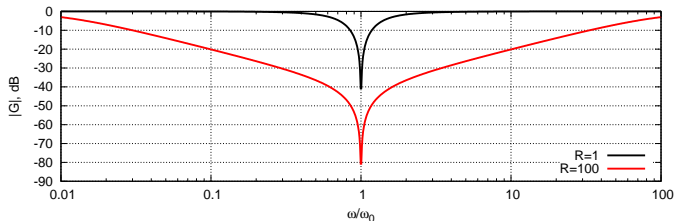
For  $R_1 = 1\text{k}\Omega$ ,  $R_2 = 100\text{k}\Omega$ ,  
 $C_1 = C_2 = .01\mu\text{F}$



# Notch filter - Band stop filter



$$\omega_0 = \frac{1}{\sqrt{LC}}$$



It is impossible to make band stop filter with  $G \approx 1$  with only R,C or R,L elements. R, L, and C combo is required.