EE 508
Lecture 1

Introduction to Course

Catalog Course Description:

E E 5080. Filter Design and Applications. (3-3) Cr. 4. *Prereq: 5010.* Filter design concepts. Approximation and synthesis. Transformations. Continuous-time and discrete time filters. Discrete, active and integrated synthesis techniques.

Instructor: Randy Geiger

contact information:

294-7745

rlgeiger@iastate.edu

course linked at: www.randygeiger.org

Course Coverage

- Filter design process
- Performance Characterization
  - Linearity/Distortion
  - Noise and SNR
  - Sensitivity
  - Dynamic Range
- Approximation Problem
- Synthesis
- Active and passive realizations
- Integrated Applications
  - Discrete-time filters
    - (SC and digital)
  - Continutous-time filters
- PLLs (if time permits)

Major emphasis will be placed on methods for implementing filters on silicon

COURSE INFORMATION

Room:	Lecture -	Coover 1012
	Labs -	Coover 2046
-		
Time:	Lecture -	MWF 9:55 – 10:45
	Laboratory -	Tues 2:10 – 5:00

Lecture Instructor:

Randy Geiger
2133 Coover
Voice: 294-7745
e-mail: rlgeiger@iastate.edu

Office Hours: MWF 11:00 – 11:50

Zoom Link:
https://iastate.zoom.us/j/96012722038?pwd=MAahCE6d4FAK5tJc2BgY1YHlrooyf3.1

Pass Code: 744898

Course Description:
Filter design concepts. Approximation and synthesis. Transformations. Continuous-time and discrete time filters. Discrete, active and integrated synthesis techniques

Course Web Site http:/class.ee.iastate.edu/ee508/

Homework assignments, lecture notes, laboratory assignments, and other course support materials will be posted on this WEB site. Students will be expected to periodically check the WEB site for information about the course.

Required Test:

There is no required text for this course. But extensive course notes will be posted. There are a large number of books that cover portions of the material that will be discussed in this course and some follow. Part of these focus on the concepts of filter design and some of the best are not new. Those that focus more on integrated applications are mostly rather narrow in scope.

Grading: Points will be allocated for several different parts of the course. A letter grade will be assigned based upon the total points accumulated. The points allocated for different parts of the course are as listed below:

2 Exams	100 pts each
Homework	100 pts.total
Lab and Lab Reports	100 pts.total
Design Project	100 pts. total

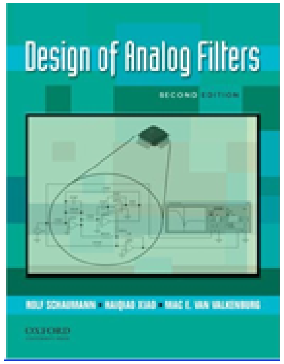
Laboratory:

There will be weekly laboratory experiments. The design project will be the design of an integrated filter structure. Expectations will be to carry the design through post layout simulation.

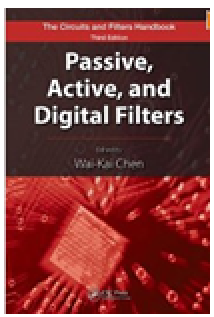
Additional Comments

I encourage you to take advantage of the e-mail system to communicate about any issues that arise in the course. I typically check my e-mail several times a day. Please try to include “EE 5080" in the subject field of any e-mail message that you send so that they stand out from what is often large volumes of routine e-mail messages.

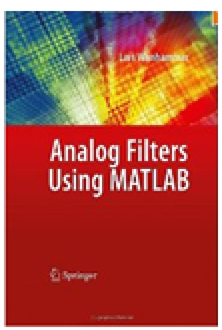
Reference Texts:



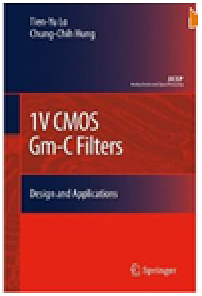
Design of Analog Filters – Second Edition, by Schaumann and Van Valkenburg, Oxford, 2009.



Passive, Active, and Digital Filters, by Wai-Kai Chen, CRC Press, 2009.

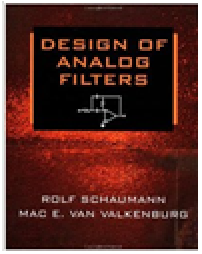


Analog Filters Using MATLAB, by Wanhammar, Springer, 2009.



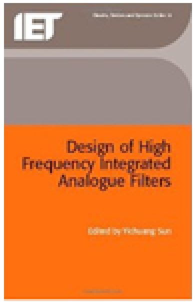
1V CMOS Gm-C Filters, by Lo and Hung, Springer, 2009.

Passivc and Active Filters, Theory and Implementaitons, by Wai-Kai Chen, Wiley, 1986.

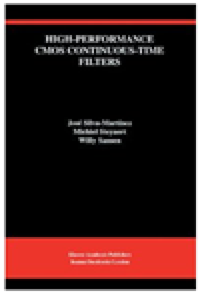


Design of Analog Filters, by Schaumann and Van Valkenburg, Oxford, 2001.

Switched-Capacitor Techniques for High-Accuracy Filter and ADC Design, by Quinn and van Roermund, Springer, 1997.

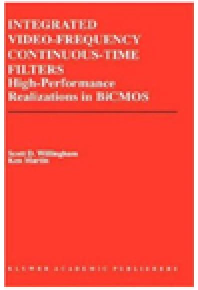


Design of high frequency integrated analogue filters, by Sun, IEE, 2002.

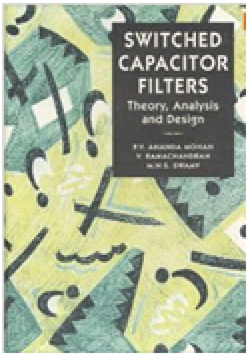


High-Performance CMOS Continuous-Time Filters, by Silva-Martinez, Steyaert, and Sansen, Kluwer, 1993

Introduction to the Design of Transconductor-Capacitor Filters, by Kardontchik, Kluwer, 1992.

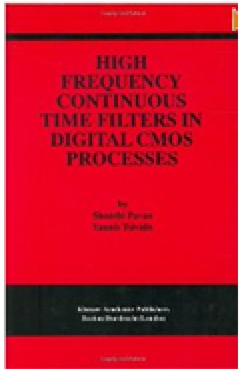


Integrated Video-Frequency Continuous-Time Filters: High-Performance Realizations in BiCMOS, by Willingham and Martin, Kluwer, 1995.

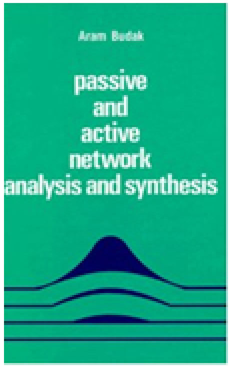


Switched Capacitor Filtrs, Theory, Analysis, and Design, by Mohan, Ramachandran and Swamy, Prentice Hall, 1995.

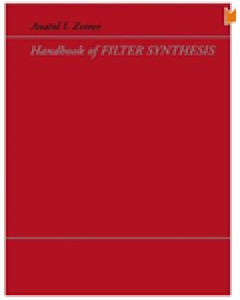
Continuous-Time Active Filter Design, by Deliyannis, Sun, and Fidler, CRC Press, 1998.



High Frequency Continuous-Time Filters in Digital CMOS Processes, by Tsividis and Springer, 2000.



Passive and Active Network Analysis and Synthesis, by Budak, Waveland Press, 1991.



Handbook of Filter Synthesis by Zverev, Wiley, 1967 and 2005.

Digital Filters, Analysis, Design, and Applications, Second Edition, by Antoniou, McGraw Hill, 1993.

Introduction to the Theory and Design of Acitve Filters, by Huelsman and Allen, McGraw Hill, 1980.

MOS Switched-Capacitor and Continuous-Time Integrated Circuits and Systems, by Unbehauen and Cichocki, Springer, 1989.

Filters : The past, the present, and the future

The Past:

- Most filters were analog
- Before around 1970 many used only passive components (amplifying devices were expensive)
- Active filters (using some type of amplifying device) usually without inductors became dominant
- A prime driver to the development of integrated circuits but integration with passives was problematic
- Switched Capacitor techniques proved practical starting in the early ’80s

The Present:

- Switched-capacitor techniques still common
- Some success with integrating R’s and C’s
- Much filtering is done in the digital domain
- Active or passive filters widely used as anti-aliasing front ends to digital systems
- Significant applications at high frequencies in rf circuits
- Filter design expertise often vested in the near-retirement workforce

The Future:

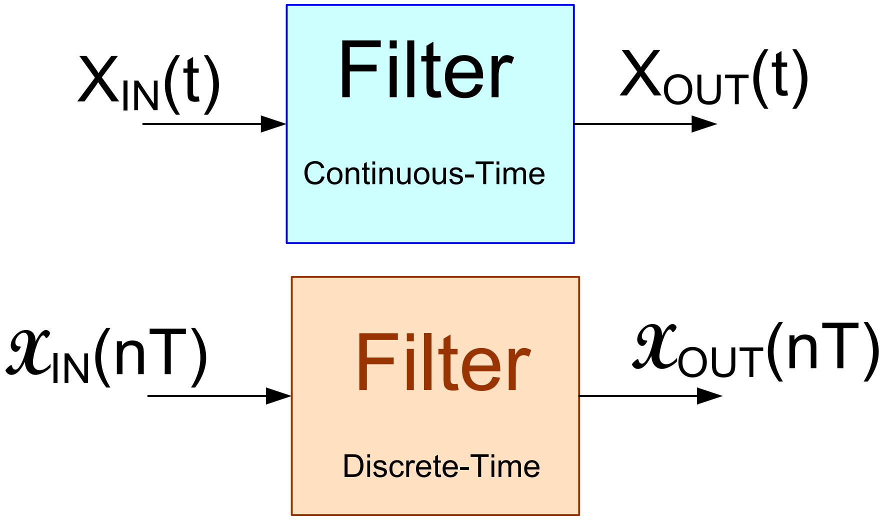
- Applications of continuous-time filters in anti-aliasing applications will remain strong and growth in rf applications
- Discrete time digital filters will continue to be widely used
- Opportunities in hybrid computing systems that combine analog and digital techniques show considerable promise
- Demand for engineers with strong filter design skills should grow

What is a filter?

Conceptual definition:

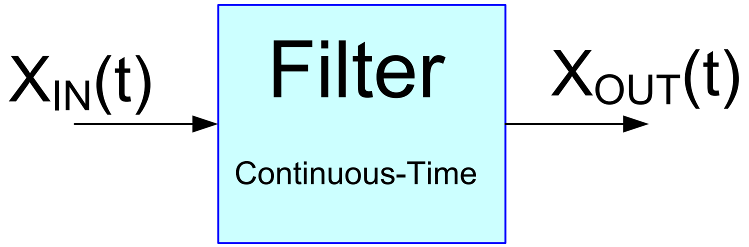
A filter is an amplifier or a system that has a frequency dependent gain

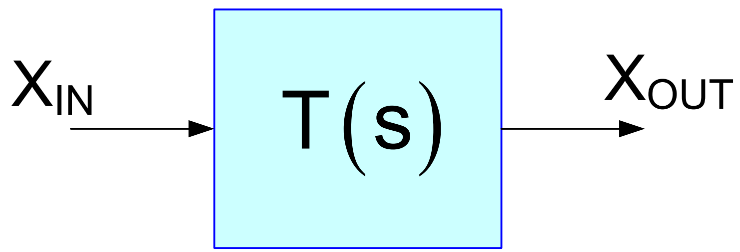
Note:
Implicit assumption is made in this definition that the system is linear. In this course, will restrict focus to filters that are ideally linear



Filters can be continuous-time or discrete-time

Continuous-time filters



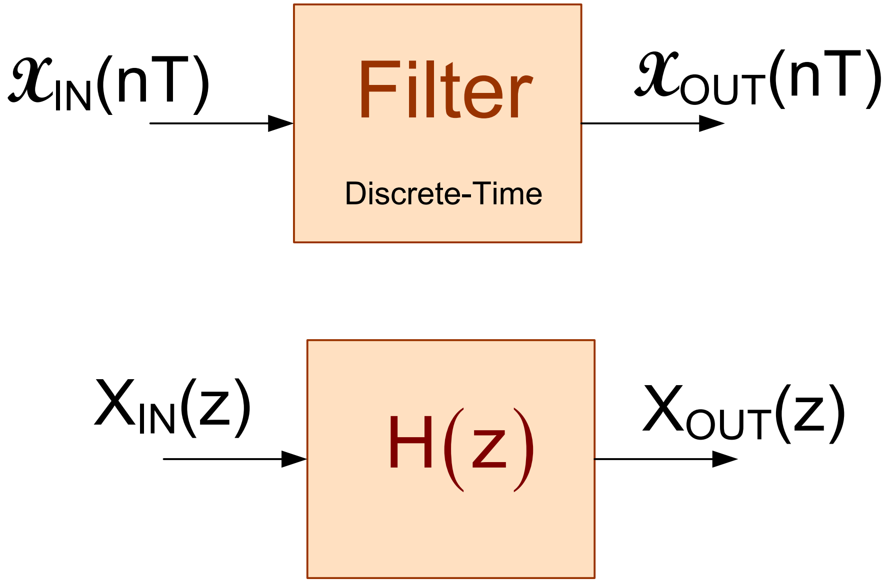


Continuous-time filters are often characterized in the frequency domain

$$T(s) = \frac{X_{OUT}(s)}{X_{IN}(s)}$$

Transfer function characterizes steady-state characteristics of a filter

Discrete-time filters



Discrete-time filters are often characterized in the frequency domain

$$H(z) = \frac{X_{OUT}(z)}{X_{IN}(z)}$$

Transfer function characterizes steady-state characteristics of a filter

Observations:

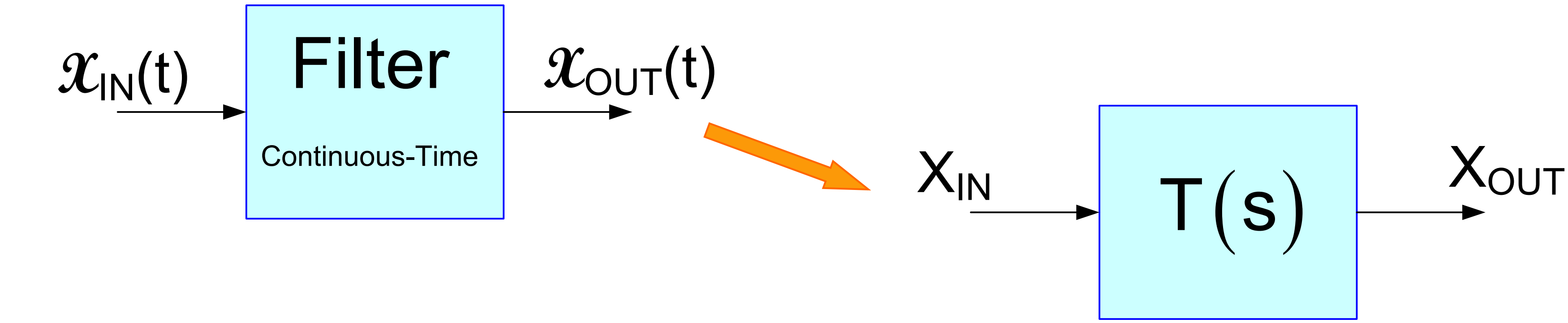
- Some (if not most) filters will exhibit some undesired nonlinearities
- Frequency response characteristics often of most interest in filters but in some filters, other characteristics may be of interest

    Time delay
    Spectral leakage
    Inter-modulation distortion

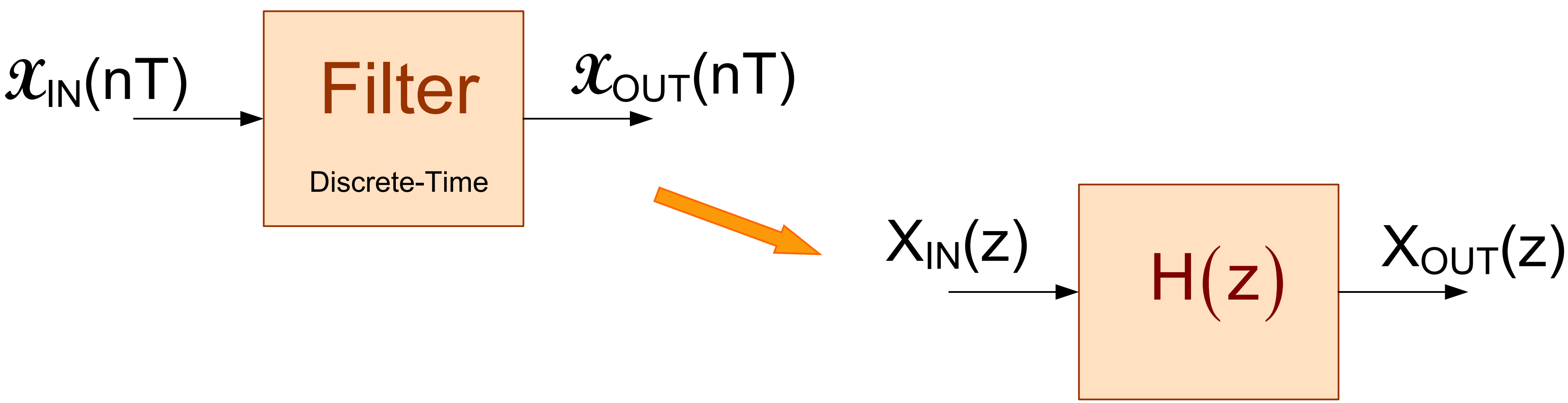
- Some classes of nonlinear circuits that are also termed "filters" and have fundamentally different operational characteristics exist (but are not covered in this course)

    Median Filters
    Log Domain Filters
    …

Most classical filter applications stipulate gain vs f or phase vs f as the desired operating characteristics

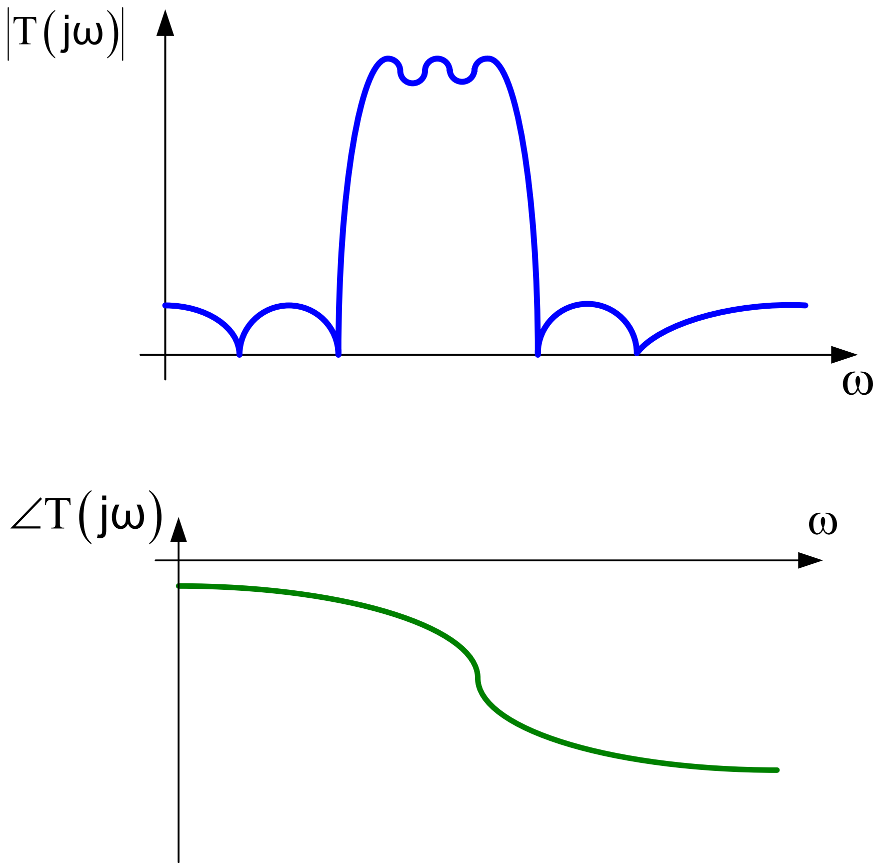


$$T(s) = \frac{X_{OUT}(s)}{X_{IN}(s)}$$



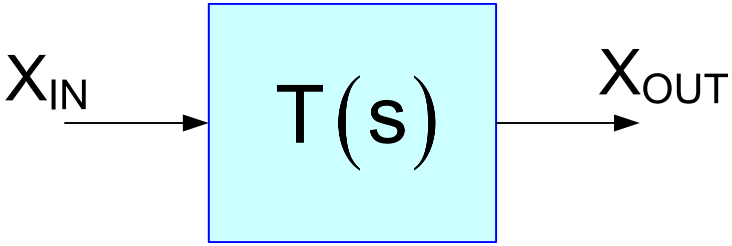
$$H(z) = \frac{X_{OUT}(z)}{X_{IN}(z)}$$

Representation of magnitude and phase characteristics of a filter:



Key properties of filters:

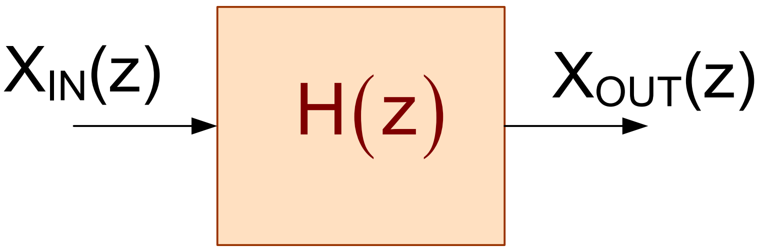
Transfer functions of continuous-time filters with finite number of lumped elements are rational fractions with real coefficients



$$T(s)=\frac{\sum_{i=1}^{m} a_i s^i}{\sum_{i=1}^{n} b_i s^i}=\frac{N(s)}{D(s)}$$

Key properties of filters:

Transfer functions of discrete-time filters with finite number of real additions are rational fractions with real coefficients



$$H(z) = \frac{\sum_{i=1}^{m} a_i z^i}{\sum_{i=1}^{n} b_i z^i} = \frac{N(z)}{D(z)}$$

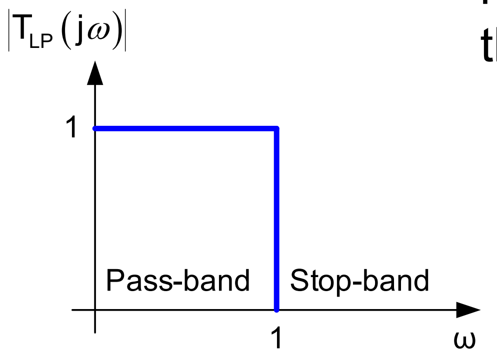
Key properties of filters:

Transfer functions of any realizable filter (finite elements) have no discontinuities in either the magnitude or phase response

Is this property good or bad?

BAD !

Often want filters that will perfectly pass a signal in some frequency range and perfectly block it outside this range



Ideal lowpass filter

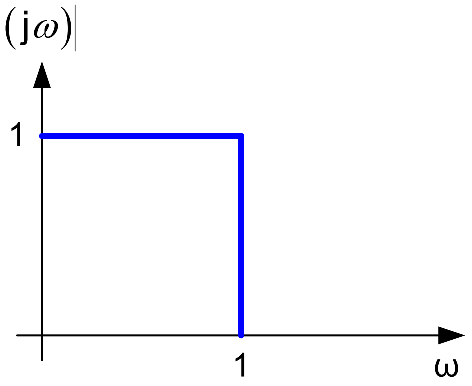
Key properties of filters:

Transfer functions of any realizable filter (finite elements) have no discontinuities in either the magnitude or phase response

Often system designer will “want” overly challenging specifications but really only “need” something somewhat less demanding

Critical that the circuit and system designer agree upon an appropriate relaxed filter requirement so overall system performance is met and design time and circuit cost is acceptable

Observations (based upon lowpass example):



Ideal lowpass filter

The closer the designer comes to realizing the ideal lowpass characteristics, the more complicated and expensive the design becomes

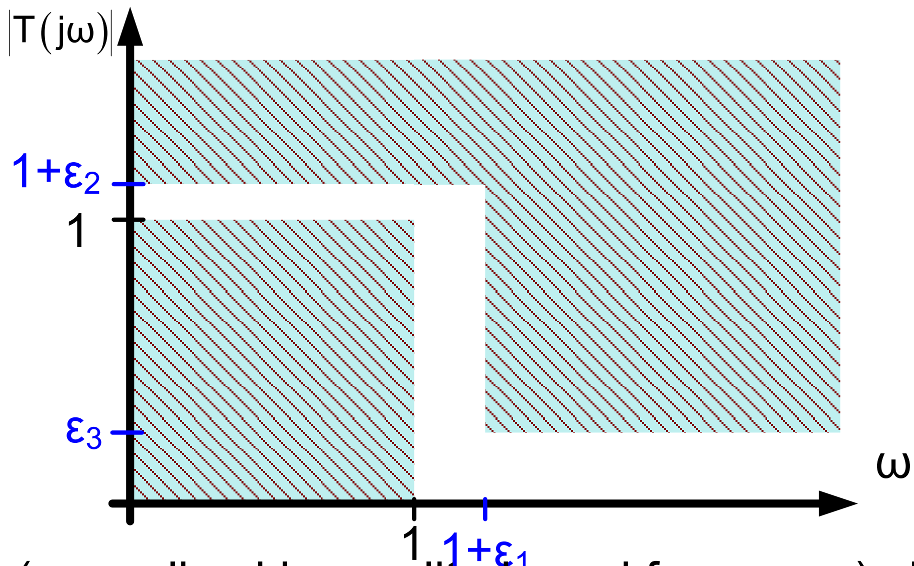
Filter applications often have strict requirements on where major changes in magnitude or phase must occur

Window of transition from “pass-band” to “stop-band” often very narrow

Filter design field has received considerable attention by engineers for about 8 decades

- Passive R,L,C
- Vacuum Tube Op Amp, R,C
- Active Filters (BJTs or Discrete BJT op amps, R,C)
- Active Filters (Integrated op amps, R,C)
- Digital Implementation (ADC,DAC,DSP)
- Integrated Filters (op amps, SC)
- Integrated Filters (op amps, OTAs, Continuous-time and SC)

Filter specifications often given by bounds for acceptable characteristics in frequency domain

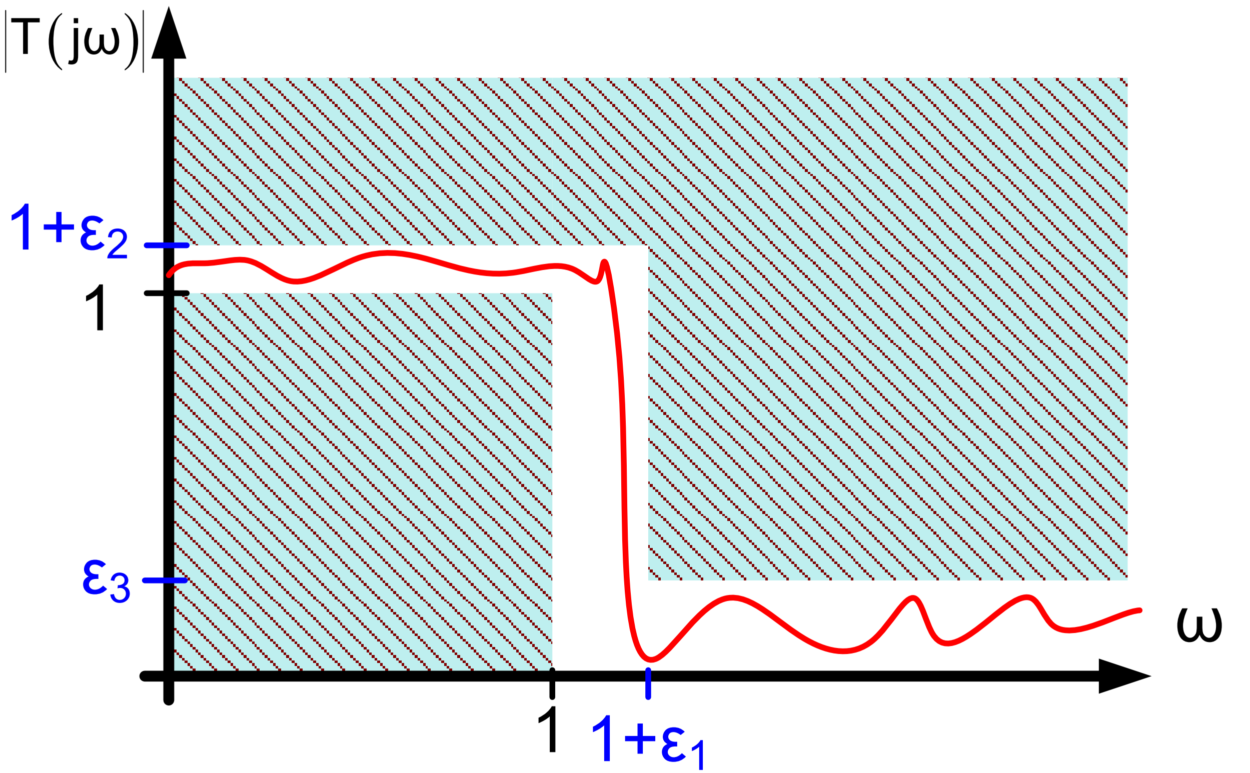


This example (normalized in amplitude and frequency) characterized by the three parameters $\{\varepsilon_1, \varepsilon_2, \varepsilon_3\}$

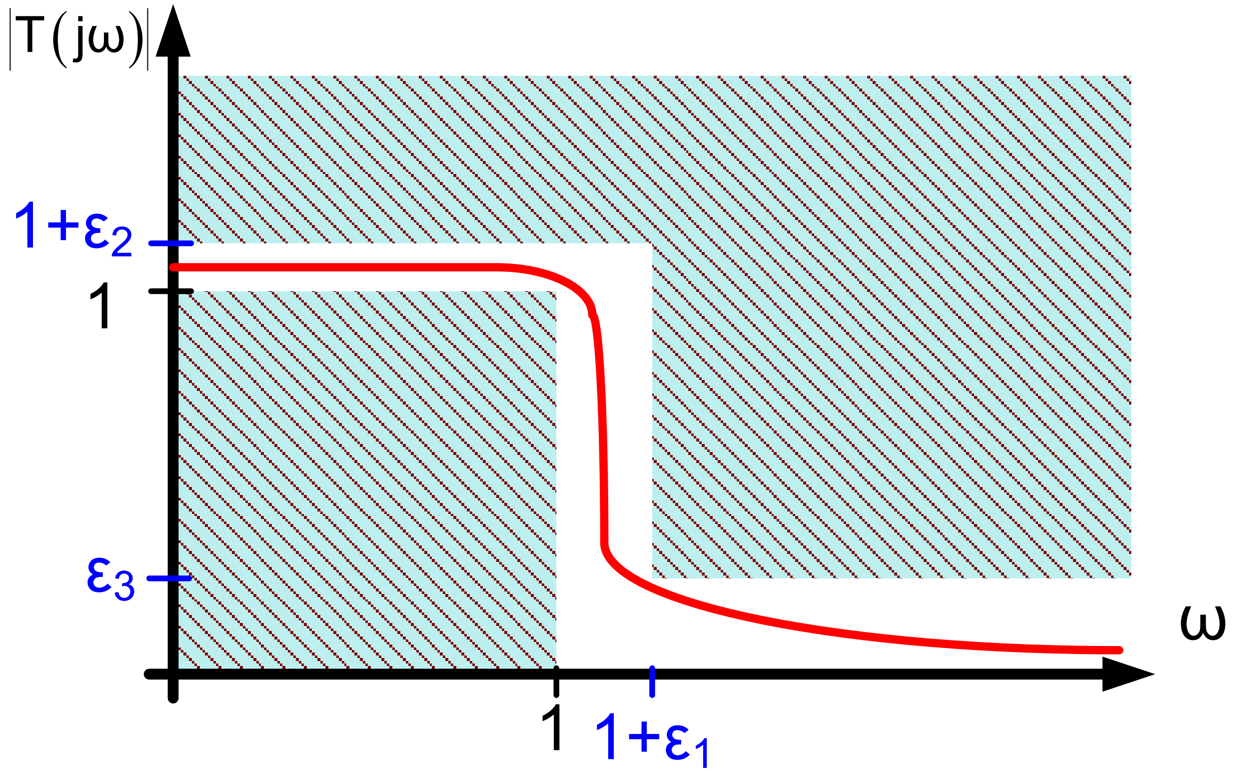
Any circuit that has a transfer function that does not enter the forbidden region is an acceptable solution from a performance viewpoint

Filter design must provide margins for component tolerance, temperature dependence, and aging

Any circuit that has a transfer function that does not enter the forbidden region is an acceptable solution from a performance viewpoint



Any circuit that has a transfer function that does not enter the forbidden region is an acceptable solution from a performance viewpoint



- Minor changes in specifications can have significant impact on cost and effort for implementing a filter

- Work closely with the filter user (customer) to determine what filter specifications are really needed

- This will become increasingly important as many (most) system designers in the future will have weak background in filter issues

Characteristics of Filters that are of Interest

- How closely measured response agrees with desired response
- Cost of implementation
- Sensitivity to components/parameters
- Physical size
- Sensitivity to environmental parameters
- Power dissipation
- Nonlinear distortion
- Intermodulation distortion
- Signal swing
- SNR
- Dynamic Range

Course Coverage

- Filter design process
- Performance Characterization
  - Linearity/Distortion
  - Noise and SNR
  - Sensitivity
  - Dynamic Range
- Approximation Problem
- Synthesis
- Active and passive realizations
- Integrated Applications
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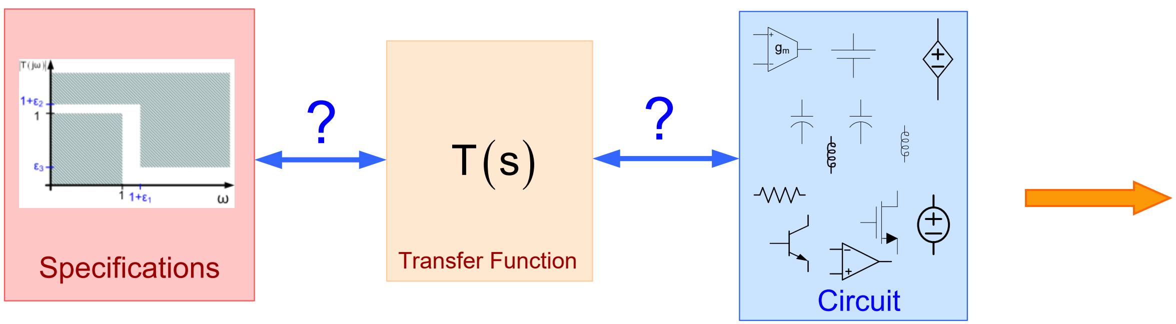
- PLLs (if time permits)

Major emphasis will be placed on methods for implementing filters on silicon

Filter Design Process



Filter Design Strategy: Use the transfer function as an intermediate step between the Specifications and Circuit Implementation

Establish Specifications

- possibly $T_D(s)$ or $H_D(z)$
- magnitude and phase characteristics or restrictions
- time domain requirements

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Approximation

- obtain acceptable transfer functions $T_A(s)$ or $H_A(z)$
- possibly acceptable realizable time-domain responses

↓

Synthesis

- build circuit or implement algorithm that has response close to $T_A(s)$ or $H_A(z)$
- actually realize $T_R(s)$ or $H_R(z)$

↓

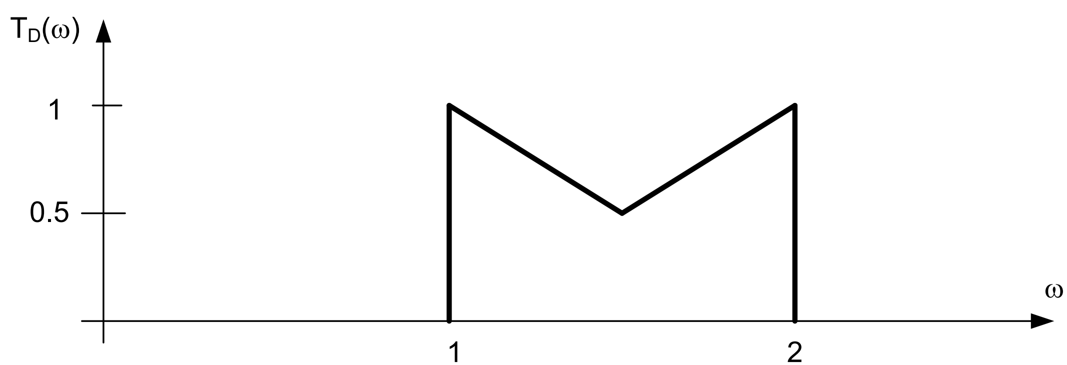
Filter

EE 5080
HW 1
Fall 2024

Short Assignment – due Friday of this week

The seemingly simple problem of obtaining a rational fraction that approximates a desired transfer function can become quite involved and, with the exception of a few standard approximations, there is still often no known technique for obtaining a transfer function. In this assignment, you will be asked to use whatever techniques you have available to obtain a transfer function that approximates a given magnitude response. A metric defined below will be used to assess how good your approximation is for this assignment.

Consider the desired "M" transfer function shown below where the frequency axis is linear.



Mathematically, the desired transfer function magnitude is characterized by the function

$$T_D(\omega) = \begin{cases} 0 & 0 \le \omega \le 1 \\ 2-\omega & 1 < \omega \le 1.5 \\ \omega - 1 & 1.5 < \omega \le 2 \\ 0 & \omega > 2 \end{cases}$$

Obtain a rational fraction approximation, T(s), to this transfer function magnitude. Your approximation is constrained to $m + n \le 6$ where m is the degree of the numerator polynomial and n is the degree of the denominator polynomial. That is

$$\mathbf{T(s)} = \frac{\sum_{i=1}^{m} a_i s^i}{\sum_{i=1}^{n} b_i s^i}$$

The "goodness" of your approximation should be assessed by the L_2 norm defined by

$$\varepsilon = \int_{\omega=0}^{4} \left\| T(j\omega) \right| - T_D(\omega) \Big|^2 \, d\omega$$

You should include your approximation T(s), a plot of the magnitude of your transfer function along with that of $T_D(\omega)$ with a linear frequency axis for $0 < \omega < 5$, the value you obtain for ε, and a brief description of how you obtained your approximation.

Keep track of your time and spend at most 3 hours on this assignment. The major purpose of this assignment is to establish an appreciation for the approximation problem.

Stay Safe and Stay Healthy !

End of Lecture 1