Technical University of Lodz
Institute of Electronics

Electronic Circuits

Marcin Kociołek PhD
Medical Electronics Division
Łódź 2018

General info

Lecturer:
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Consultation:
please check my calendar:
http://www.eletel.p.lodz.pl/kociolek/timetable2010.html

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General info

2 ECTS credits - 50 ÷ 60 h. of work
(1 ECTS – 25 ÷ 30 h)
Lecture:
15 h
Laboratory:
15 h
Self work:
20 ÷ 30 (during 15 weeks of semester)

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Final Mark - lecture

1) 7 partial test (10 min) each lecture (first one on 2nd meeting)
   – Each test gives 0÷4 credits
   – Final mark is:
     • >19 4
     • >21 4,5
     • >23 5
   – First test can be repeated
   – A student, who will inform me before 8.00 on test day, about his/her absence on the test, has the right to take this test at other time
   – Additional test time will be scheduled in the last meeting of the semester. At this time a Student will be able to retake the first test and/or take missing test. A student will be able to take maximum of 2 tests

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Final Mark - lecture

2) Pirate test (whole material test) two times during exam session + one time during repetition session. Positive mark for number of received credits > half of total number of credits from the test.

Remarks:
- Tests results will be published on my webpage in 5 work days after the test
- Works will be available for review during my consultation hours only for 5 days after publication of results.

Laboratory:
Mark for the report and work during laboratories.

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Lecture Plan

1. Operational Amplifiers
2. Noise in active circuits
3. Analog multipliers
4. Power amplifiers integrated circuits
5. Band pass amplifiers integrated circuits
6. Active analog filters with continuous and discrete time
7. Phase-locked loop and its applications
8. Detectors of amplitude, frequency and phase
9. Programmable analog circuits and their applications
10. Application specific integrated circuits
11. Digital to analog and analog to digital converters

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Laboratory

Laboratory: 15h (L215, B9)
- Linear distortion
- Nonlinear distortion
- Broadband amplifier
- Power amplifier
- …

Warning !

Slides shown during lectures do not cover all knowledge needed for passing all tests. Knowledge is passed during the lecture.

It is very wise to make notes from the lecture. It is also worth of effort to read publications which covers presented topics.

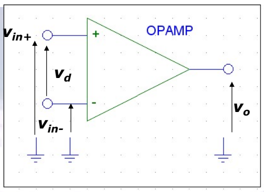
Lecture Plan

1. **Noise in active circuits**
2. Analog multipliers
3. Power amplifiers integrated circuits
4. Band pass amplifiers integrated circuits
5. Active analog filters with continuous and discrete time
6. Phase-locked loop and its applications
7. Detectors of amplitude, frequency and phase
8. Digital to analog and analog to digital converters

Operational Amplifier (OPAMP) circuits

operational amplifier:
- DC amplifier
- High voltage gain
- Symmetrical (differential) input
- Asymmetrical output

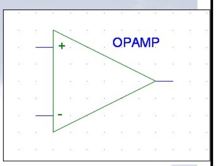
Applications:
- Linear an nonlinear operations
- Usually works with high negative gain

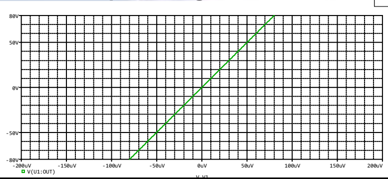


$$v_o = A_{vd}(v_{in+} - v_{in-}) = A_{vd} v_d$$

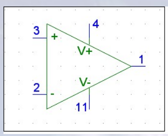
Operational Amplifier (OPAMP) circuits

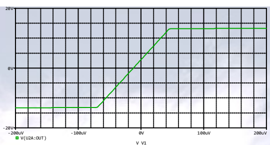
Ideal opamp:
- Infinite input impedance
- Zero output resistance
- Infinite voltage gain
- No limitation of output voltage
- Infinite bandwidth
- **Output voltage unrelated to the sum of input voltages**





Operational Amplifier (OPAMP) circuits





$$v_{out} = A_{vd}(v_{in+} - v_{in-}) + A_{vd}(v_{in+} + v_{in-}) + v_{noise} + V_{offset}$$

$$A_{vd} = \left.\frac{\Delta V_o}{\Delta V_d}\right|_{U_c = const} \qquad A_{vc} = \left.\frac{\Delta V_o}{\Delta V_c}\right|_{U_c = const}$$

$$TC = \frac{A_{vd}}{A_{vc}} \qquad CMRR = 20\log\frac{A_{vd}}{A_{vc}}$$

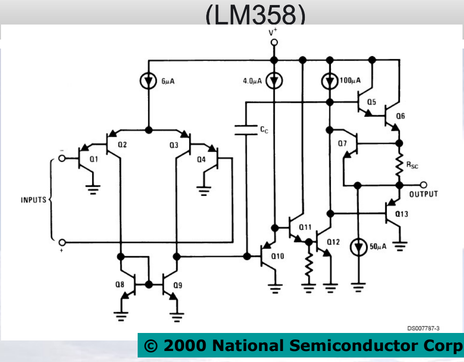
Operational Amplifier (OPAMP) parameters

Name	unit	uA741
Gain ($A_{vd,min}$)	V/mV	25
Common mode rejection ratio (CMRR)	DB	80
Input current I_{IN}	nA	500
Wejściowy prąd niezrównoważenia I_N	nA	200
Wejściowe napięcie niezrównoważenia U_N	mV	6
Współczynnik temperaturowy napięcia niezrównoważenia	μV/°C	30
Współczynnik zmian wejściowego napięcia niezrównoważenia od zmian napięcia zasilania (SVRR)	μV/V	30

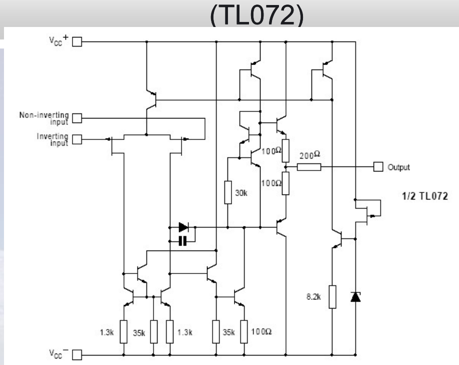
Operational Amplifier (OPAMP) parameters

Name	unit	uA741
Input resistance (R_{ind})	MΩ	2
Output resistnce (R_o)	Ω	75
Bandwidth (f_1 lub f_T)	MHz	1
Slew rate *(SR)*	V/μs	0,6
Maximum input differential voltage (V_{IND})	V	±30
Maximum common input voltage (V_{INC})	V	±15
Supply voltage	V	-15,+15
Power dissipated *(P)*	mW	50
Operation temperature range (t_{min}, t_{max})	°C	0,+70

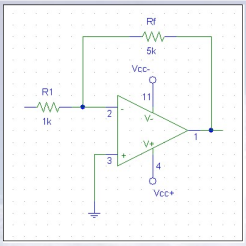
Operational Amplifier (OPAMP) example (LM358)

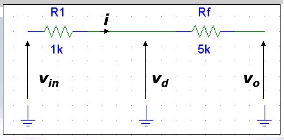


Operational Amplifier (OPAMP) example (TL072)



Inverting amplifier





$$v_{in} - v_o = i(R_1 + R_f)$$

$$v_d = v_i - iR_1$$

$$v_o = -v_d A$$

Inverting amplifier

$$v_o = -v_d A \qquad v_{in} - v_o = i(R_1 + R_f)$$

$$v_d = -v_o \frac{1}{A} \qquad i = (v_{in} - v_o)\frac{1}{R_1 + R_f}$$

$$v_d = v_{in} - iR_1$$

$$-v_o \frac{1}{A} = v_{in} - (v_{in} - v_o)\frac{R_1}{R_1 + R_f}$$

$$-v_o \frac{1}{A} = v_{in} - v_{in}\frac{R_1}{R_1 + R_f} + v_o \frac{R_1}{R_1 + R_f}$$

Inverting amplifier

$$-v_o\frac{1}{A} = v_{in} - v_{in}\frac{R_1}{R_1+R_f} + v_o\frac{R_1}{R_1+R_f}$$

$$-v_o\frac{1}{A} - v_o\frac{R_1}{R_1+R_f} = v_{in} - v_{in}\frac{R_1}{R_1+R_f}$$

$$-v_o\left(\frac{1}{A}+\frac{R_1}{R_1+R_f}\right) = v_{in}\left(1-\frac{R_1}{R_1+R_f}\right)$$

$$\frac{v_o}{v_{in}} = -\frac{1-\dfrac{R_1}{R_1+R_f}}{\dfrac{1}{A}+\dfrac{R_1}{R_1+R_f}}$$

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Inverting amplifier

$$\frac{v_o}{v_{in}} = -\frac{1-\dfrac{R_1}{R_1+R_f}}{\dfrac{1}{A}+\dfrac{R_1}{R_1+R_f}} = -\frac{\dfrac{R_1+R_f-R_1}{R_1+R_f}}{\dfrac{R_1+R_f+AR_1}{A(R_1+R_f)}}$$

$$\frac{v_o}{v_{in}} = -\frac{R_f}{R_1+R_f}\frac{A(R_1+R_f)}{R_1+R_f+AR_1} = \frac{AR_f}{R_1+R_f+AR_1}$$

$$\frac{v_o}{v_{in}} = -\frac{AR_f}{R_1+R_f+AR_1} = -\frac{R_f}{R_1}\frac{AR_1}{R_1+R_f+AR_1}$$

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Inverting amplifier

$$\frac{v_o}{v_{in}} = -\frac{AR_f}{R_1+R_f+AR_1} = -\frac{R_f}{R_1}\frac{AR_1}{R_1+R_f+AR_1}$$

$$\frac{v_o}{v_{in}} = -\frac{R_f}{R_1}\frac{1}{\dfrac{1}{A}+\dfrac{R_f}{AR_1}+1} = -\frac{R_f}{R_1}\frac{1}{\dfrac{R_1+R_f}{AR_1}+1}$$

$$\frac{v_o}{v_{in}} = -\frac{R_f}{R_1}\frac{1}{1+\dfrac{1}{A\beta_v}}$$

$$\beta_v = \frac{R_1}{R_1+R_f}$$

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Inverting amplifier

$$\frac{v_o}{v_{in}} = -\frac{R_f}{R_1}\frac{1}{1+\dfrac{1}{A\beta_v}}$$

$$\beta_v = \frac{R_1}{R_1+R_f}$$

$$A\beta_v > 1000$$

$$A_{vf} = -\frac{R_f}{R_1}$$

$$A_{vf} = -\frac{Z_f}{Z_1}$$

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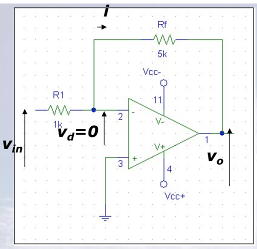
Inverting amplifier



$$v_d = 0$$

$$i_{in-} = 0$$

$$v_{in} = iR_1 \qquad i = \frac{v_{in}}{R_1}$$

$$v_o = -iR_f$$

$$v_o = -v_{in}\frac{R_f}{R_1}$$

$$\frac{v_o}{v_{in}} = -\frac{R_f}{R_1}$$

$$A_{vf} = -\frac{R_f}{R_1}$$

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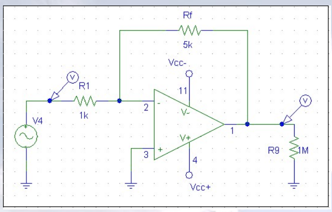
Inverting amplifier



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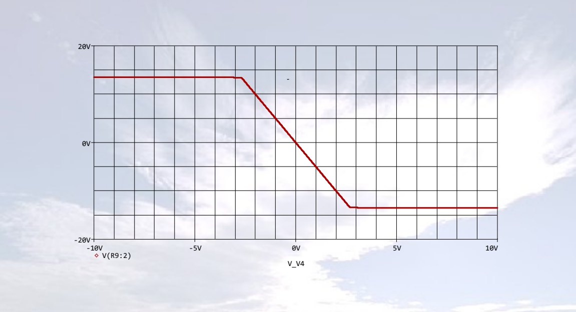
Inverting amplifier
transfer characteristic



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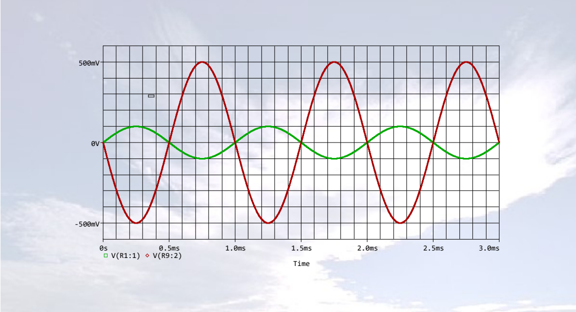
Inverting amplifier
time plots



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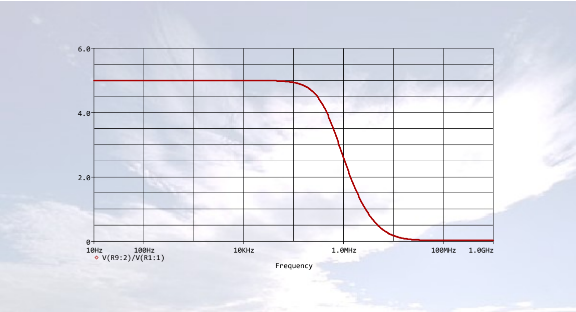
Inverting amplifier
frequency response



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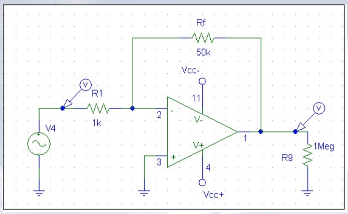
Inverting amplifier
frequency response



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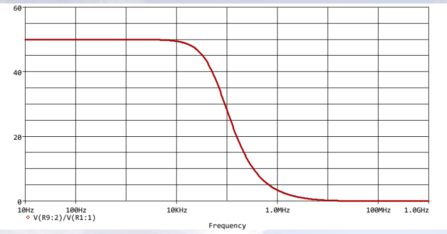
Inverting amplifier
frequency response



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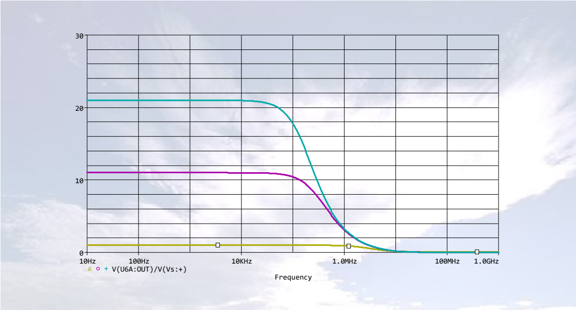
Inverting amplifier
frequency response



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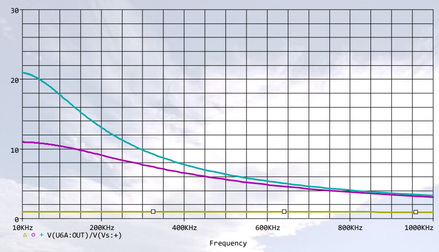
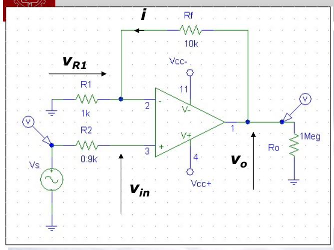
Inverting amplifier frequency response



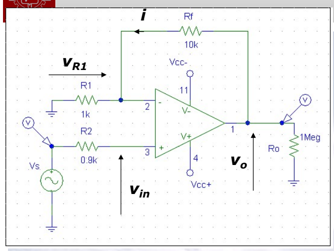
Noninverting amplifier



$$v_d = 0$$

$$i_{in+} = i_{in-} = 0$$

Noninverting amplifier



$$v_d = 0$$

$$i_{in+} = i_{in-} = 0$$

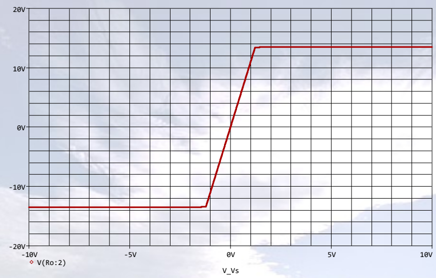
$$v_{in} = iR_1 \qquad i = \frac{v_{in}}{R_1}$$

$$v_o = i(R_f + R_1)$$

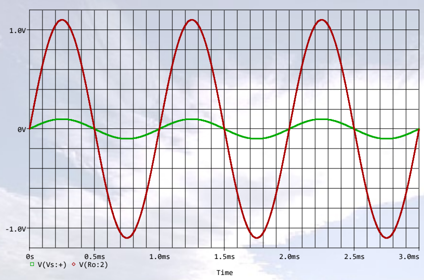
$$v_o = \frac{v_{in}}{R_1}(R_f + R_1)$$

$$A_{vf} = \frac{v_o}{v_{in}} = \frac{R_f}{R_1} + 1$$

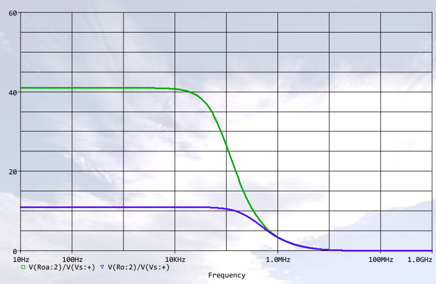
Noninverting amplifier transfer characteristic



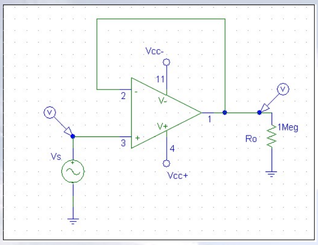
Noninverting amplifier



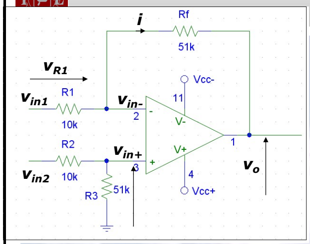
Noninverting amplifier frequency response



Voltage follower



Differential amplifier



$$v_d = 0$$

$$i_{in+} = i_{in-} = 0$$

$$v_{in+} = v_{in2}\frac{R_2}{R_2 + R_3}$$

$$i = (v_{in1} - v_o)\frac{1}{R_1 + R_f}$$

$$v_{in-} = v_{in1} - iR_1$$

$$v_{in-} = v_{in1} - (v_{in1} - v_o)\frac{R_1}{R_1 + R_f}$$

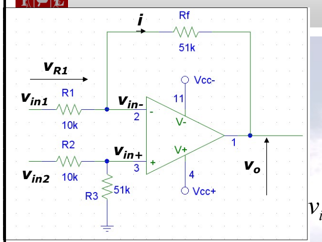
Differential amplifier

$$v_{in-} = v_{in1} - v_{in1}\frac{R_1}{R_1 + R_f} + v_o\frac{R_1}{R_1 + R_f}$$

$$v_{in-} = v_{in1}\left(1 - \frac{R_1}{R_1 + R_f}\right) + v_o\frac{R_1}{R_1 + R_f}$$

$$v_{in-} = v_{in1}\frac{R_f}{R_1 + R_f} + v_o\frac{R_1}{R_1 + R_f}$$

Differential amplifier



$$v_d = 0$$

$$v_{in+} = v_{in-}$$

$$v_{in+} = v_{in2}\frac{R_2}{R_2 + R_3}$$

$$v_{in-} = v_{in1}\frac{R_f}{R_1 + R_f} + v_o\frac{R_1}{R_1 + R_f}$$

$$v_{in2}\frac{R_2}{R_2 + R_3} = v_{in1}\frac{R_f}{R_1 + R_f} + v_o\frac{R_1}{R_1 + R_f}$$

Differential amplifier

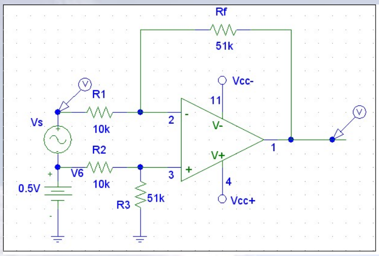
$$v_{in2}\frac{R_2}{R_2 + R_3} = v_{in1}\frac{R_f}{R_1 + R_f} + v_o\frac{R_1}{R_1 + R_f}$$

$$v_o\frac{R_1}{R_1 + R_f} = v_{in2}\frac{R_2}{R_2 + R_3} - v_{in1}\frac{R_f}{R_1 + R_f}$$

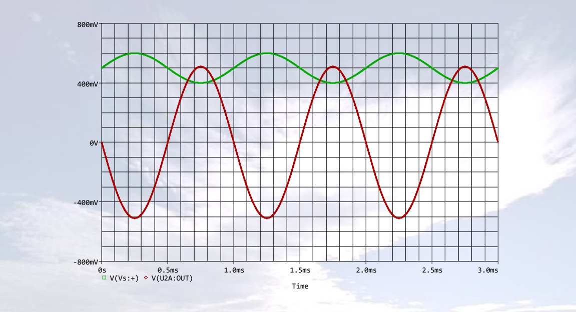
$$\frac{R_1}{R_f} = \frac{R_2}{R_3}$$

$$v_o = \frac{R_f}{R_1}(v_{in2} - v_{in1})$$

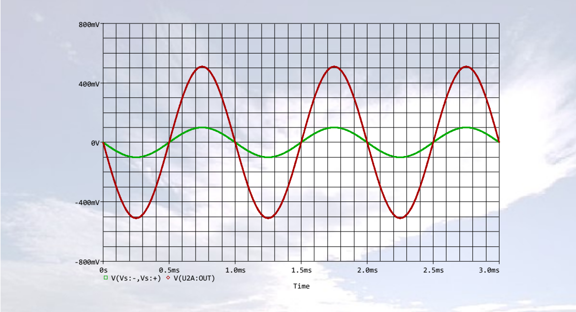
Differential amplifier



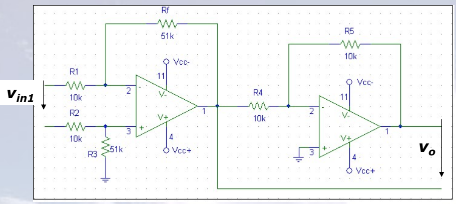
Differential amplifier



Differential amplifier

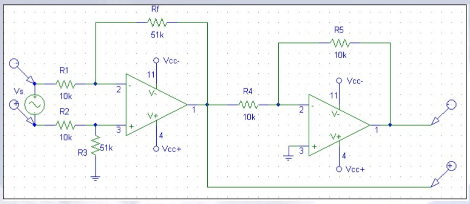


Differential amplifier

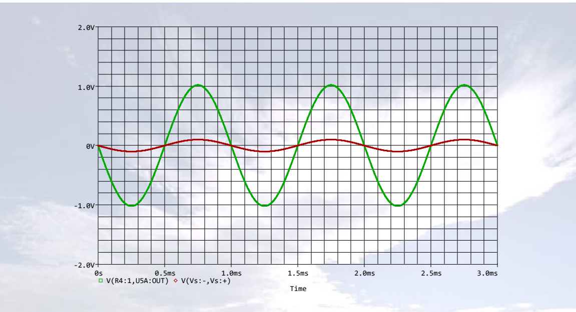


$$v_o = 2\frac{R_f}{R_1}\left(v_{in2} - v_{in1}\right) \qquad v_o = 2\frac{R_f}{R_1}v_{in1}$$

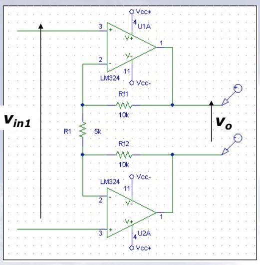
Differential amplifier



Differential amplifier

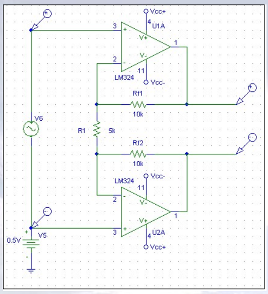


Differential amplifier with very high input resistance

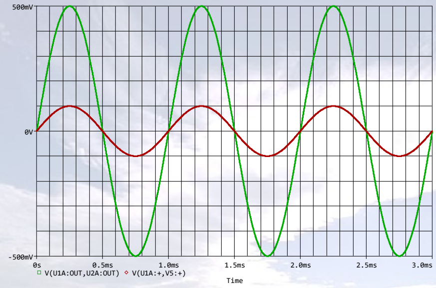


$$v_o = \left(1 + 2\frac{R_f}{R_1}\right)v_{in2}$$

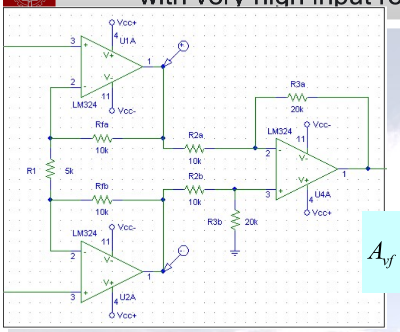
Differential amplifier with very high input resistance



Differential amplifier with very high input resistance

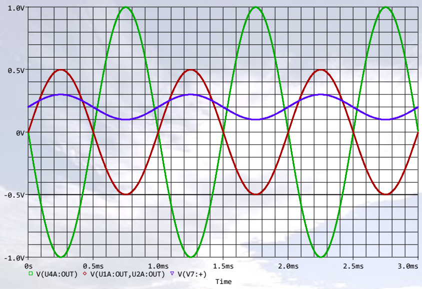


Differential amplifier with very high input resistance

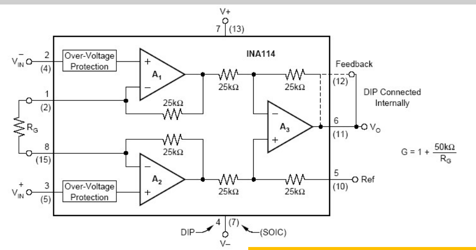


$$A_{vf} = -\left(1 + 2\frac{R_f}{R_1}\right)\frac{R_3}{R_2}$$

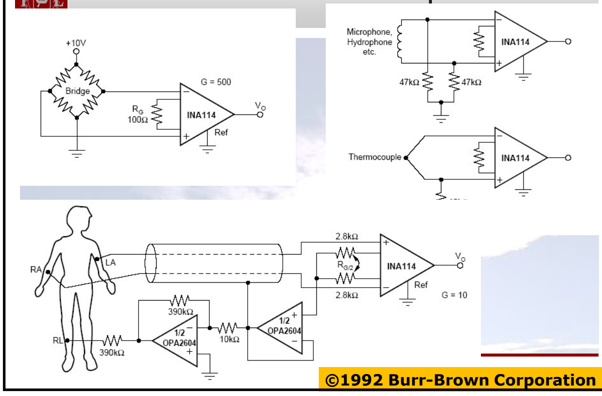
Differential amplifier with very high input resistance



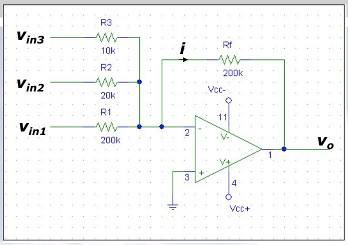
Instrumentation amplifier



Instrumentation amplifier



Summing amplifier

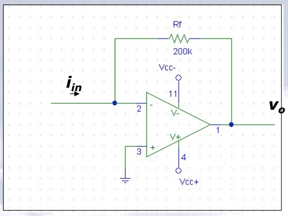


$i = \frac{u_{in1}}{R_1} + \frac{u_{in2}}{R_2} + \frac{u_{in3}}{R_3}$

$u_o = -u_{in1}\frac{R_f}{R_1} - u_{in2}\frac{R_f}{R_2} - u_{in3}\frac{R_f}{R_3}$

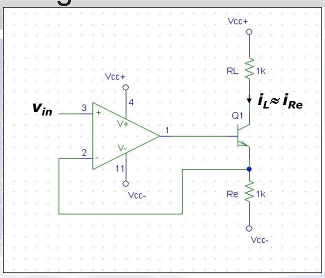
Thanks to the virtual shortcircuit to the ground inputs are separated

Current to voltage transducer



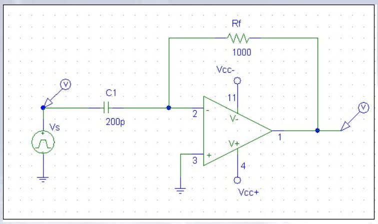
$v_o = -i_{in}R_f$

Voltage to current transducer



$i_L = \frac{v_{in} - V_{cc-}}{R_e}$

Differentiating amplifier

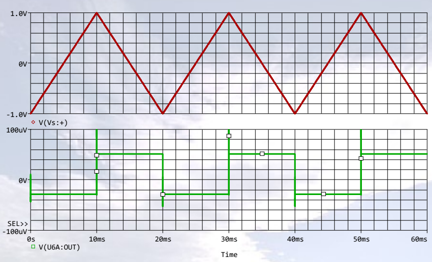


$i(t) = C\frac{\partial v_{in}(t)}{\partial t}$

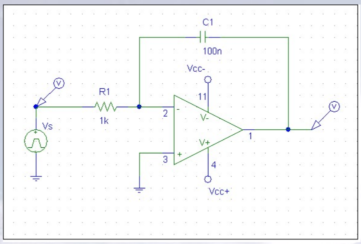
$v_o(t) = -i(t)R_f$

$v_o(t) = -CR_f\frac{\partial v_{in}(t)}{\partial t}$

Differentiating amplifier



Integrating amplifier



$i = \frac{v_{in}}{R_1}$

$i = -C\frac{\partial v_o}{\partial t}$

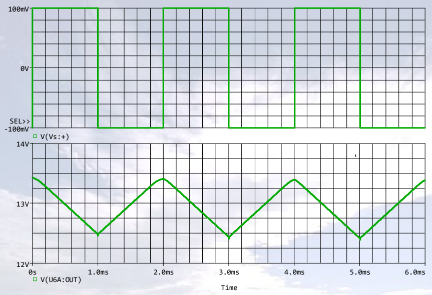
$C\frac{\partial v_o(t)}{\partial t} = -\frac{v_{in}(t)}{R_1}$

$\frac{\partial v_o(t)}{\partial t} = -\frac{v_{in}(t)}{CR_1}$

$\frac{\partial v_o(t)}{\partial t} = -\frac{v_{in}(t)}{CR_1}$

$v_o(t) = -\frac{1}{CR_1}\int v_{in}(t)\partial t$

Integrating amplifier



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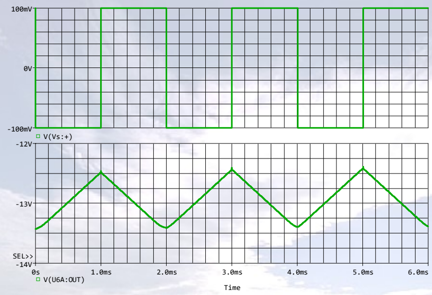
Wzmacniacz całkujący



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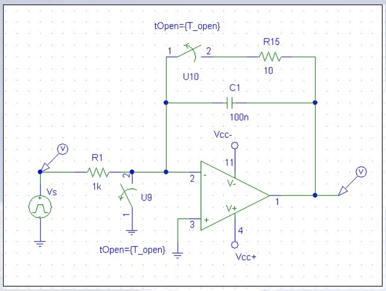
Integrating amplifier



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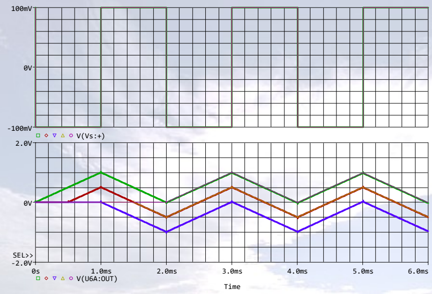
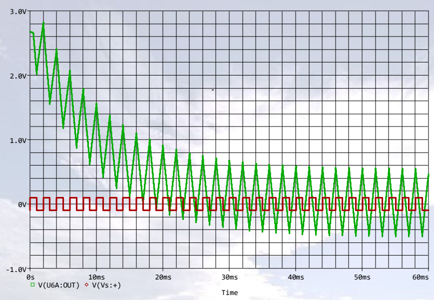
Integrating amplifier



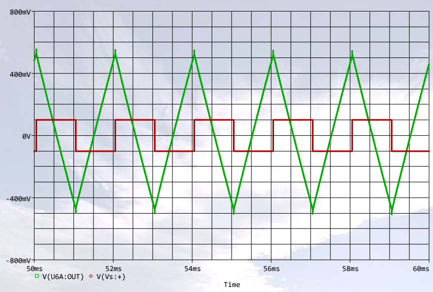
64

Integrating amplifier



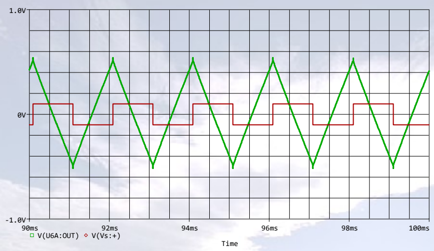
65

Integrating amplifier



66

Integrating amplifier



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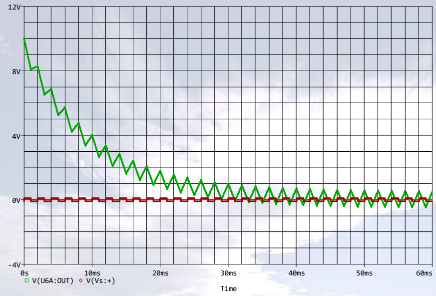
Integrating amplifier



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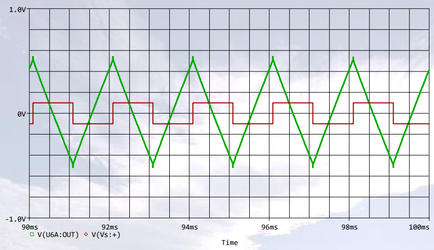
Integrating amplifier



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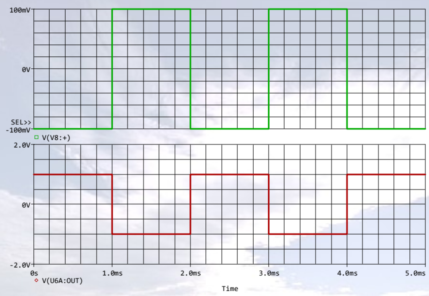
Impulse response



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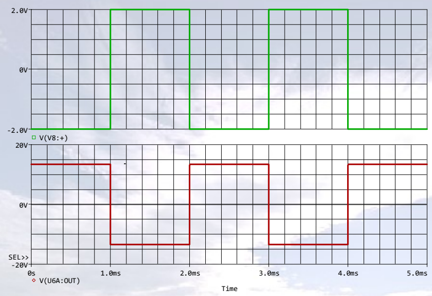
Impulse response



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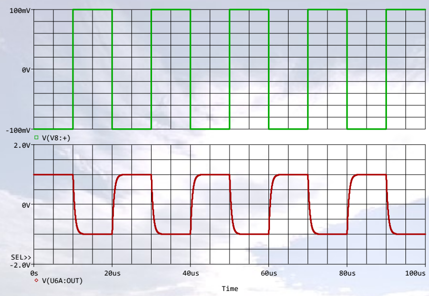
Impulse response



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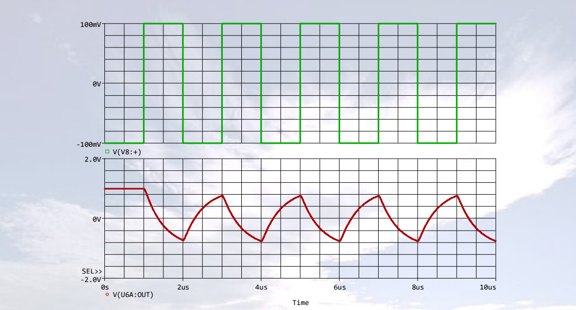
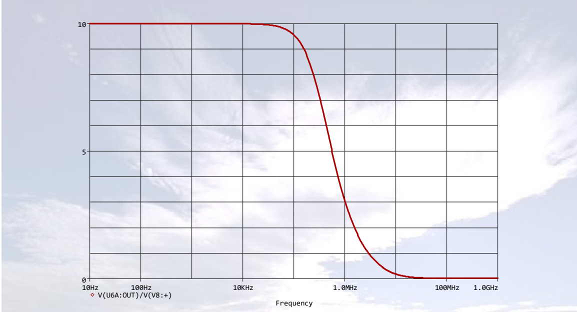
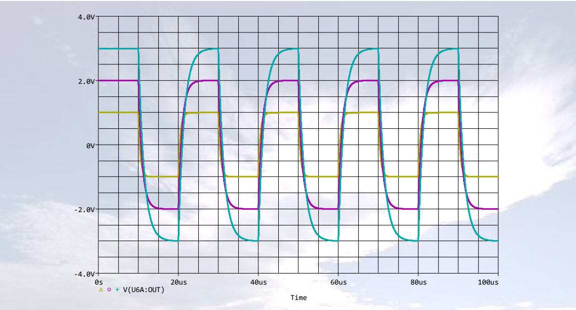
Impulse response



Impulse response

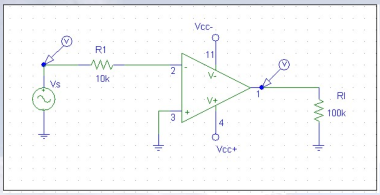


Impulse response

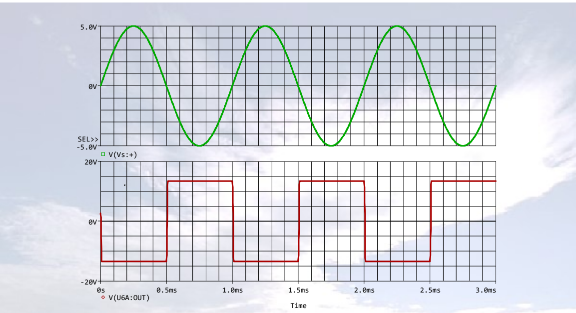


Opamp with open feedback loop-comparator

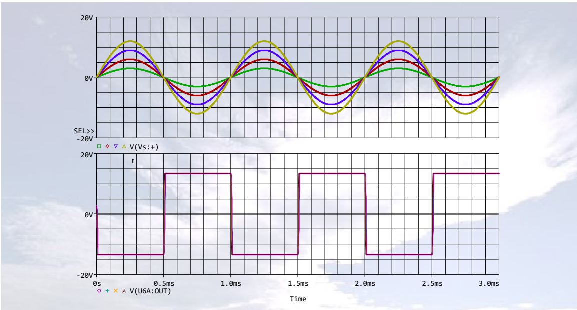
Non regenerative detector of zero crossing



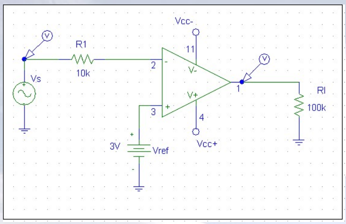
Non regenerative detector of zero crossing



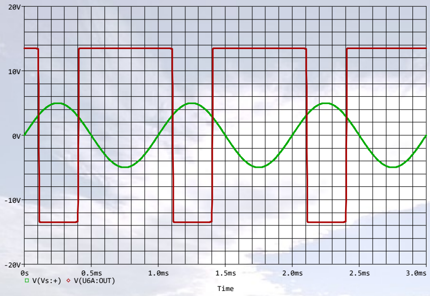
Non regenerative detector of zero crossing



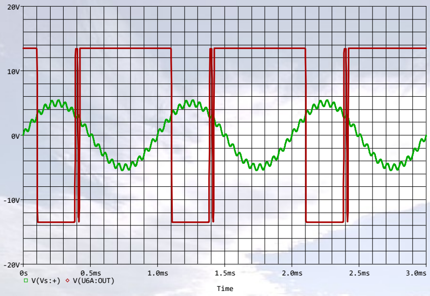
Non regenerative amplitude discriminator



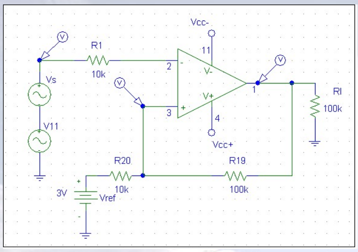
Non regenerative amplitude discriminator



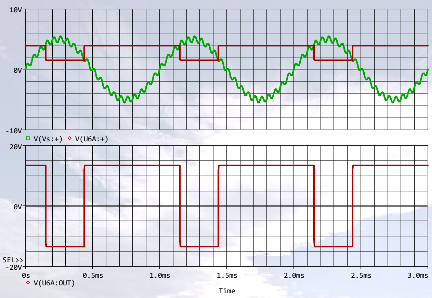
Non regenerative amplitude discriminator



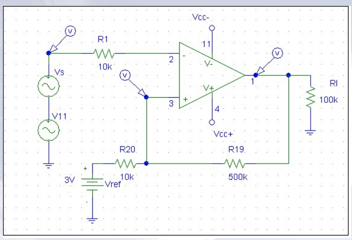
Regenerative amplitude discriminator



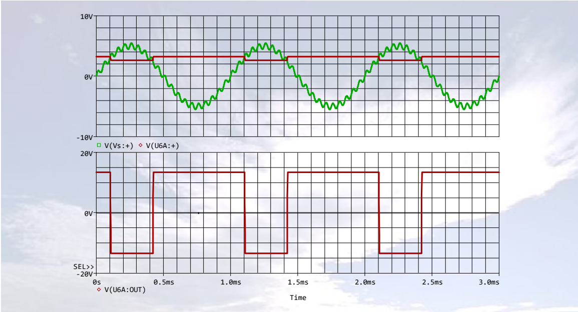
Regenerative amplitude discriminator



Regenerative amplitude discriminator



Regenerative amplitude discriminator



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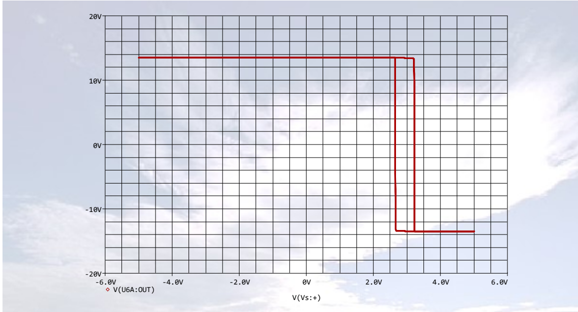
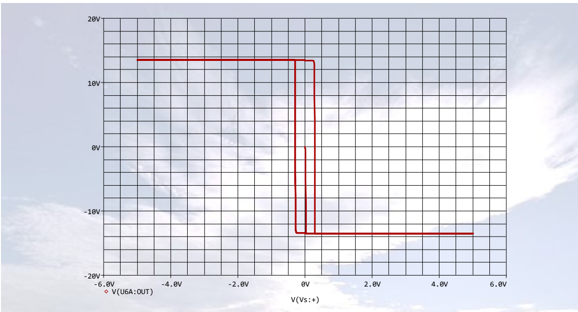
Regenerative amplitude discriminator



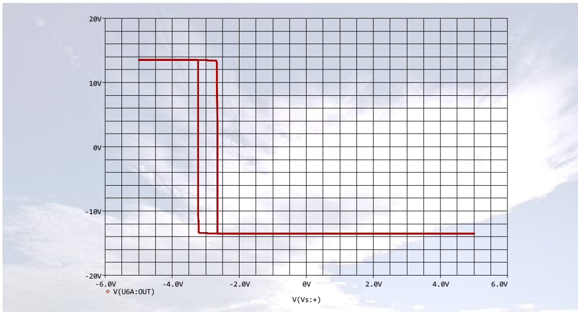
86

Regenerative amplitude discriminator



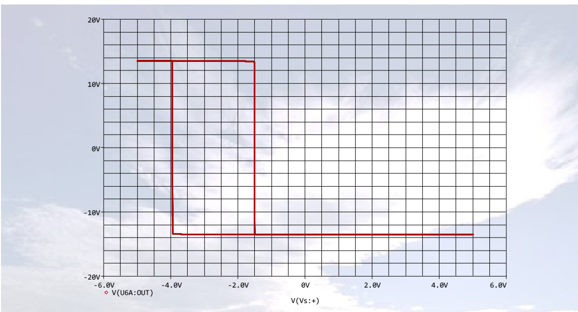
87

Regenerative amplitude discriminator



88

Regenerative amplitude discriminator



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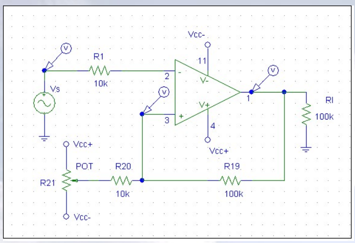
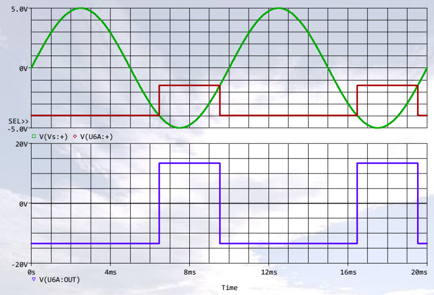
Regenerative amplitude discriminator



90

Regenerative amplitude discriminator



Noise in active circuits

Literature:

Józef Boksa, Analogowe układy elektroniczne, BTC, Warszawa 2007

Waldemar Nawrocki, Krzysztof Arnold, Krzysztof Lange, Układy Elektroniczne, Wydawnictwo Politechniki Poznańskiej, Poznań 1999

Stanisław Kuta, Wykład układy Elektroniczne, szumy w układach elektronicznych, AGH http://student.agh.edu.pl/~mborowka/UE/wyklad/R1.17.ppt

Fabrizio Bonani, Giovanni Ghione, Noise in Semiconductor Devices: Modeling and Simulation Springer (Kindle Edition - 6 Sep 2001)

Noise in active circuits

Noise

Interference

Distortion

Noise in active circuits

Noise:

a random fluctuation in an electrical signal,
a characteristic of all electronic circuits

Interference:

an unwanted external signal causing improper operation of electronic device. e.g. cross-talk, deliberate jamming or other unwanted electromagnetic interference from specific transmitters

Distortion:

unwanted (very often predictable) alteration of signal waveform introduced by electronic device. Distortion is caused by properties of device.

Noise in active circuits

Noise is an unwanted perturbation to a wanted signal; it is called noise as a generalization of the audible noise heard when listening to a weak radio transmission

Noise can block, distort, change or interfere with the meaning of a message in human, animal and electronic communication.

Electronic noise is a random fluctuation in an electrical signal, a characteristic of all electronic circuits.

http://en.wikipedia.org/wiki/Noise_(electronics)
http://en.wikipedia.org/wiki/Noise

Noise in active circuits

Noise Types:

- thermal,
- shot,
- flicker - 1/f,
- burst,
- magnetic,
- ionic,
- avalanche,
- generation recombination,
- …

Thermal Noise

Main source of distortions in electronic circuits.
Johnson–Nyquist noise (sometimes thermal, Johnson or Nyquist noise) is unavoidable, and generated by the random thermal motion of charge carriers (usually electrons), inside an electrical conductor, which happens regardless of any applied voltage.

Predicted by A. Einstein w 1907r
First observed by J. B. Johnson from Bell Labs in 1928
Explained by H Nyquist from Bell Labs

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Thermal Noise

Voltage variance RMS (root mean square) per hertz of bandwidth, is given by:

$$\bar{v} = \sqrt{4k_B T R \Delta f}$$ Johnson-Nyquist equation

where:
- R – resistance [Ω]
- Δf – noise frequency band [Hz],
- k_B – Boltzman's constant = 1,38x10^{-23} [J/K]
- T - temperature [K].

Power of thermal noise

$$P = \frac{\left(\frac{\bar{v}}{2}\right)^2}{R} = k_B T \Delta f$$

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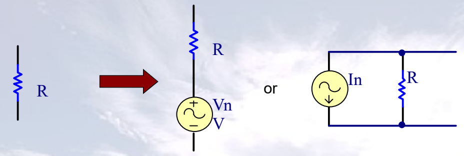
Thermal Noise



Spectral density

$$g_n = \frac{dP}{df} = kT$$

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Thermal Noise

Main properties of thermal noise:
- Present in all resistive elements,
- Caused by thermal excitation of electrons,
- Spectral density is constant in very wide bandwidth (0 -10^{13} Hz),
- Power is proportional to the bandwidth

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Shot noise

Shot noise in electronic devices consists of unavoidable random statistical fluctuations of the electric current through an potential barrier.
Random fluctuations are inherent when current flows through e.g. p-n junction, as the current is a flow of discrete charges (electrons).
Noise is caused by discrete nature of mater.

http://en.wikipedia.org/wiki/Shot_noise

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Shot noise

RMS of current fluctuations is given:

$$I_{sn} = \sqrt{2eI\Delta f}$$ Schottky equation:

where:
- e – elementary charge 1,6x10^{-19} [C],
- I – average current thru device [A],
- Δf – noise bandwidth [Hz]

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Shot noise

Main properties of the shot noise:

- Refers mainly to the p-n junctions,
- Is caused by quantum nature of current,
- Spectrum is equally spaced in frequency,
- Shot noise measurements allow for calculation of element charge

Flicker noise1/f (low frequency noise)

It occurs in almost all electronic devices, and results from a variety of effects, though always related to a direct current

In electronic devices, it is a low-frequency phenomenon, as the higher frequencies are overshadowed by white noise from other sources

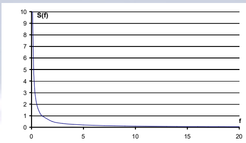
The cause of flicker noise occurrence is not jet explained. 2 hypothesizes:

- Conductivity fluctuations on the junction between 2 different materials in electronic elements (this can explain why such noise exist in various elements)
- Result of few different physical actions among them the dominating is generation and recombination of electric charges in defects of semiconductor crystal structure

Flicker noise1/f (low frequency noise)

Spectral density :

$$S(f) = k\frac{1}{f^{\alpha}}$$



α coefficient is usually close to 1 (range 0,7 – 2).
when :
α= 1 noise is called pink
α= 2 noise is called red

Burst Noise

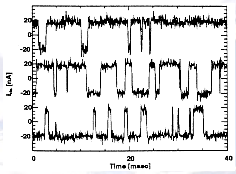
Burst noise consists of sudden step-like transitions between two or more levels

No single source of popcorn noise is theorized to explain all occurrences,

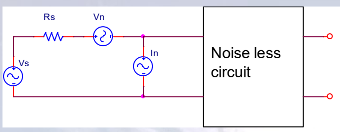
The most commonly invoked cause is the random trapping and release of charge carriers at thin film interfaces or at defect sites in bulk semiconductor crystal.

Properties:

- Impulse time from ms to tens of s
- Frequency < 1Hz
- Amplitude 10 to 100 times higher than amplitude of thermal noise



Noise parameters



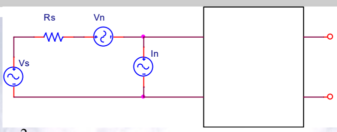
$$SNR = \frac{P_s}{P_n}$$

$$SNR_{out} = SNR_{in}$$ For noiseless circuit

$$SNR_{out} = F \times SNR_{in}$$ For real circuit

where: *F* noise coefficient *F*>1

Noise parameters

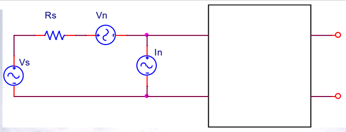


$$V_{n\_total}^2 = V_n^2 + R_s^2 I_n^2 + V_{ns}^2 + 2cV_n I_n R_s$$

where:
$V_{n\text{-}total}$ – total noise voltage taken to the input of circuit
V_{ns} – noise voltage generated by signal source
c – correlation coefficient between V_n and I_n

For *c* = 0: $$V_{n\_total}^2 = V_n^2 + R_s^2 I_n^2 + V_{ns}^2$$

Noise coefficient



$$F = \frac{V_{n\_total}^2}{V_{ns}^2} = \frac{V_n^2 + R_s^2 I_n^2 + V_{ns}^2}{V_{ns}^2}$$

$$F[dB] = 10\log_{10}\frac{V_n^2 + R_s^2 I_n^2 + V_{ns}^2}{V_{ns}^2}$$

Passive elements noises

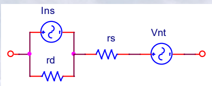
Resistor:
- Thermal noise
- Flicker noise (1/f) caused by flow of the current thru non uniform grainy structure of resistive material

Capacitor
- Very small thermal noise (can be neglected)
- Flicker noise (1/f)
- Capacitance filters out all noise sources connected in parallel to it

Inductor
- Thermal noise
- Barkhausen noise (in iductors with core) caused by magnetic field fluctuations in the core

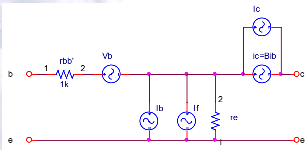
Diode noises

- Thermal noise
- Shot noise



BJT noise

- thermal noise of base region resistance
- shot noise of base current
- shot noise of collector cyrrent
- flicker noise



Noise in integrated circuits

- http://www.national.com/analog/power/ldo#low_noise
- http://www.national.com/ds/LM/LM340.pdf
- http://focus.ti.com/lit/ds/symlink/ina114.pdf

Lecture Plan

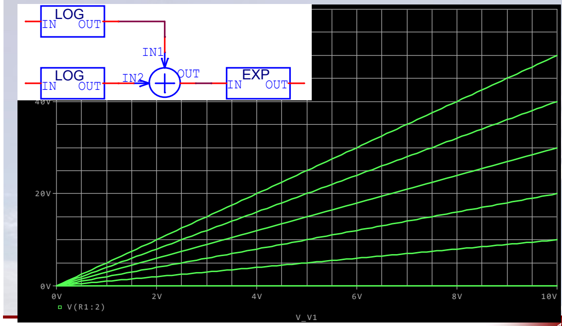
1. Noise in active circuits
2. **Analog multipliers**
3. Power amplifiers integrated circuits
4. Band pass amplifiers integrated circuits
5. Active analog filters with continuous and discrete time
6. Phase-locked loop and its applications
7. Detectors of amplitude, frequency and phase
8. Programmable analog circuits and their applications
9. Application specific integrated circuits
10. Digital to analog and analog to digital converters

Analog multiplier

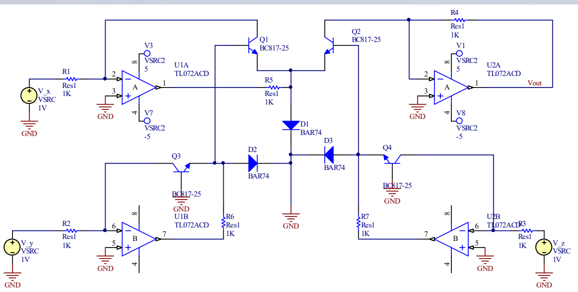
Literature:

U. Tietze, Ch. Shenck, Electronics circuits, design and applications, Springer-Verlag, 2001

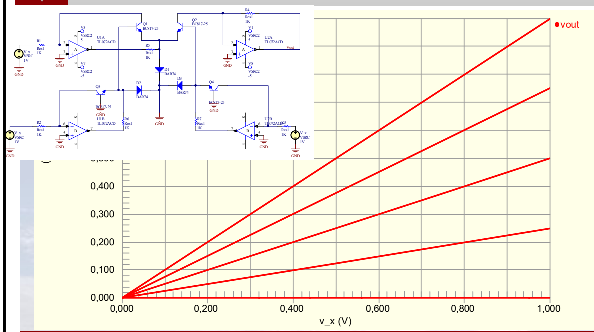
Analog multiplier



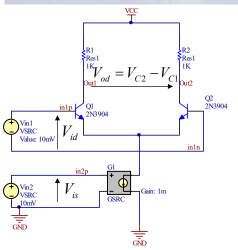
Analog multiplier



Analog multiplier



Analog multiplier (two-quadrant)



$$V_{C1} = V_{CC} - I_{C1}R_1$$

$$V_{od} = R(I_{C1} - I_{C2}) = R\Delta I_C$$

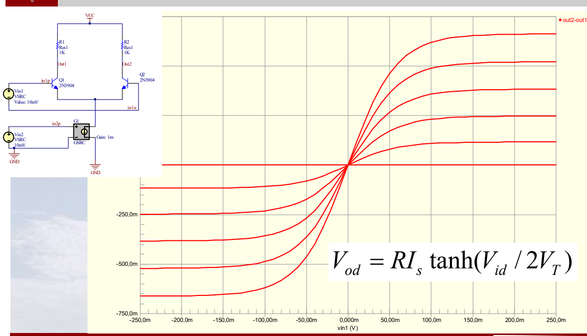
$$i_E = I_{ES}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$

$$I_{C1} = \frac{I_{EE}}{1+\exp(-V_{id}/V_T)}$$

$$I_{C2} = \frac{I_{EE}}{1+\exp(V_{id}/V_T)}$$

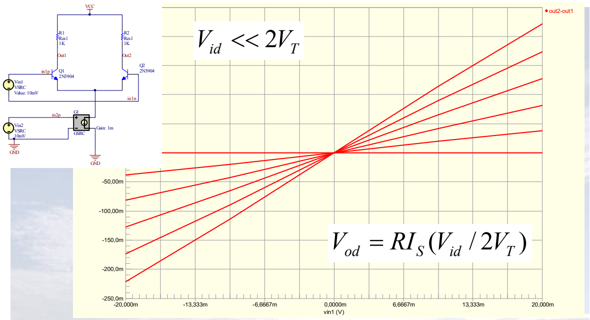
$$V_{od} = RI_s \tanh(V_{id}/2V_T)$$

Analog multiplier (two-quadrant)



$$V_{od} = RI_s \tanh(V_{id}/2V_T)$$

Analog multiplier (two-quadrant)

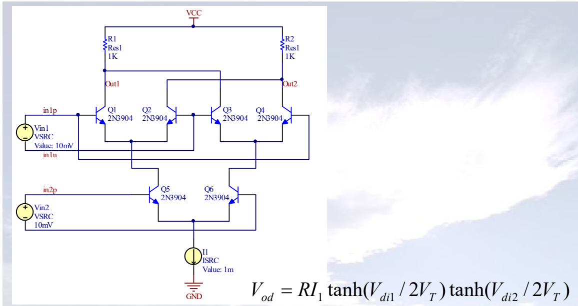


$$V_{id} << 2V_T$$

$$V_{od} = RI_S(V_{id}/2V_T)$$

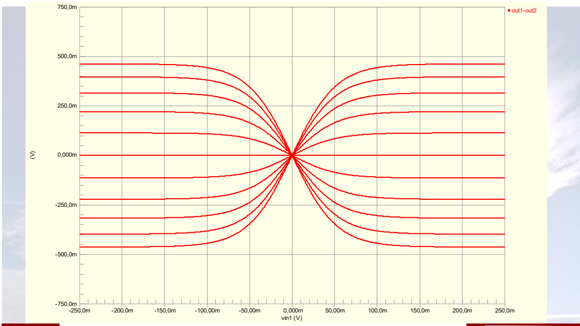
First term of Taylor series

Analog multiplier (four-quadrant) Gilbert cell



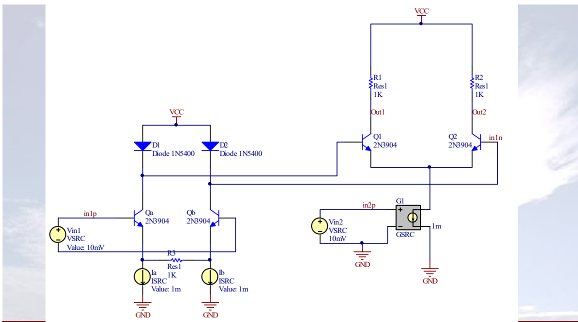
$$V_{od} = RI_1 \tanh(V_{di1}/2V_T)\tanh(V_{di2}/2V_T)$$

Analog multiplier (four-quadrant)

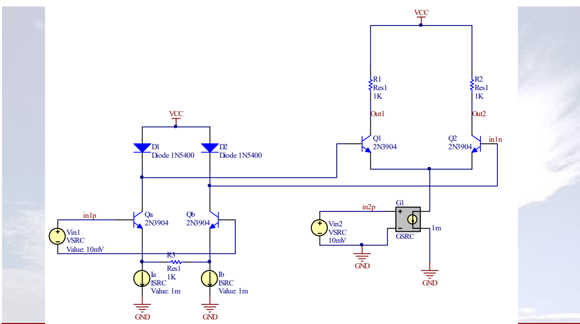


$$V_{od} = RI_1 \tanh(V_{di1}/2V_T)\tanh(V_{di2}/2V_T)$$

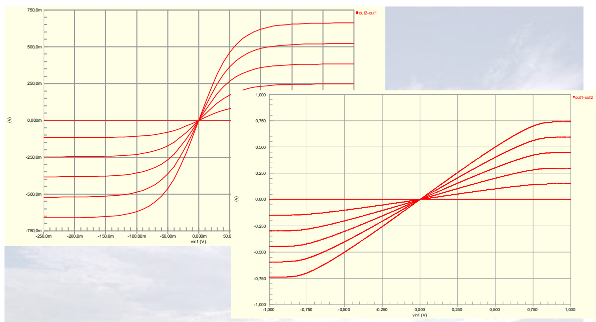
Analog multiplier (two-quadrant) witch linearization



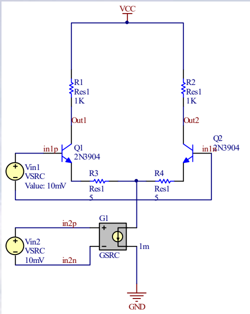
Analog multiplier (two-quadrant) with linearization



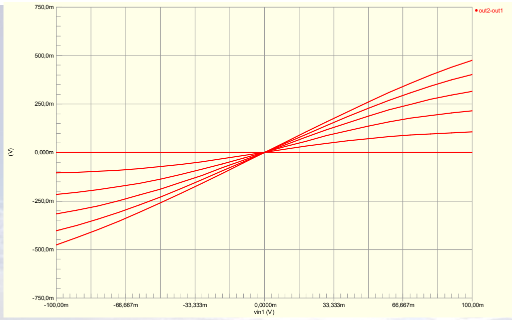
Analog multiplier (two-quadrant) with linearization



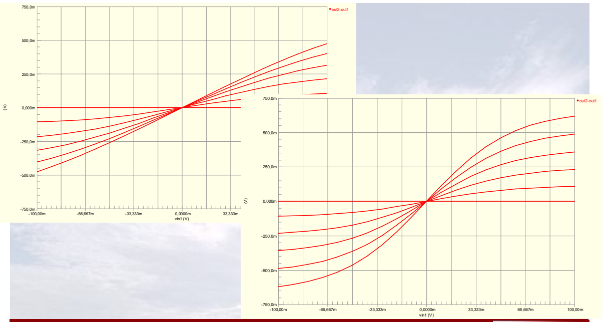
Analog multiplier (two-quadrant) with linearization



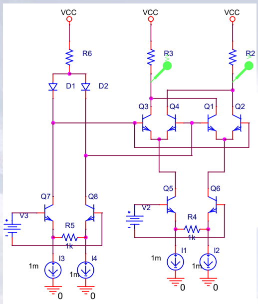
Analog multiplier (two-quadrant) with linearization



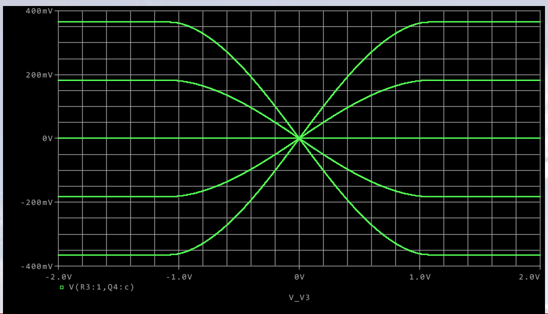
Analog multiplier (two-quadrant) with linearization



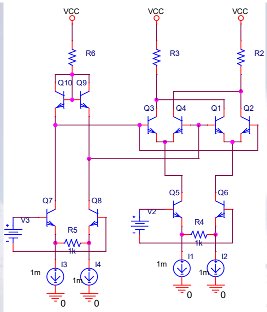
Analog multiplier (four-quadrant) with linearization



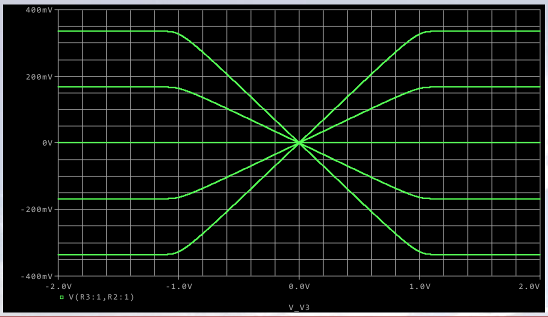
Analog multiplier (four-quadrant) with linearization



Analog multiplier (four-quadrant) with linearization



Układ mnożący różnicowy (cztero ćwiartkowy) z linearyzacją



Analog multiplier application

- Amplitude modulation
- Amplitude detection
- Phase detection
- Frequency detection
- Frequency conversion

Analog multiplier application

- AD532
- ADL5391

Lecture Plan

1. Noise in active circuits
2. **Power amplifiers integrated circuits**
3. Band pass amplifiers integrated circuits
4. Active analog filters with continuous and discrete time
5. Analog multipliers
6. Phase-locked loop and its applications
7. Detectors of amplitude, frequency and phase
8. Programmable analog circuits and their applications
9. Application specific integrated circuits
10. Digital to analog and analog to digital converters

Power amplifiers integrated circuits

Literature:

Józef Boksa, Analogowe układy elektroniczne, BTC, Warszawa 2007

Zbigniew Nosal, Jerzy Baranowski, Układy Analogowe Liniowe, Wydawnictwa Naukowo Techniczne Warszawa 2003

Douglas Self, Audio Power Amplifier Design Handbook, Elsevier 2006

G. Randy Slone, High-Power Audio Amplifier Construction Manual McGraw-Hill 1999

Power amplifiers integrated circuits

1. Main issues
2. Classes of power amplifiers
3. Examples of power amplifiers integrated circuits

Power Amplifier

- an electronic circuit which main purpose is to deliver required power to the load.
- the last amplifier in a transmission chain (the output stage)
- the amplifier stage that typically requires most attention to power efficiency.

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Power Amplifiers

- Power not delivered to the load produces heat.
- Large signal amplitudes make nonlinear distortion
- Small signal models do not apply

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Power amplifier parameters

- Power gain (power dissipated on load to the input power ratio)
- Output power (given in watts by given magnitude of input signal)
- Bandwidth
- Efficiency coefficient (given in percents)
- Total Harmonic Distortion (nonlinear distortion coefficient)

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Power supplies and Efficiency

$P_i + P_s = P_o + P_d$ ⟵ energy conservation law

P_i – input power
P_s – power taken from power supply
P_o – output power
P_d – power dissipated in circuit

$\eta = \frac{P_o}{P_s} \cdot 100\%$ ⟵ efficiency

Why the power efficiency is so important?

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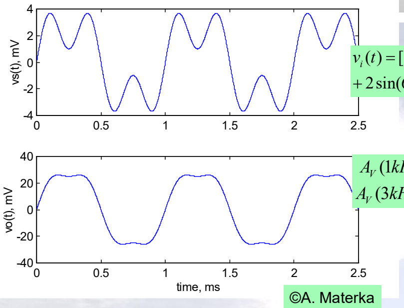
Amplitude distortions



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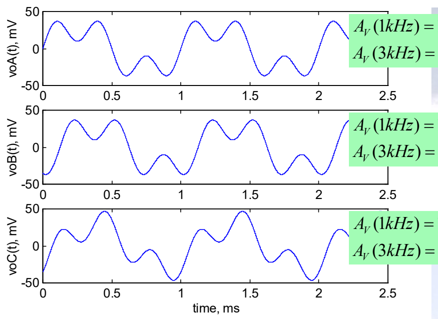
Phase distortions



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Phase distortions

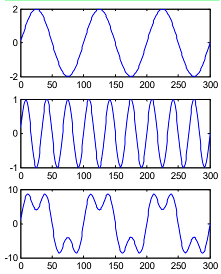
Input signal is the sum of two signals:

1. frequency = 1 kHz; amplitude = 2V
2. frequency = 3 kHz; amplitude = 1V

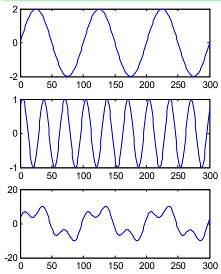
MatLab simulation:
m–file: PhaseDistortion.m
300 samples
Sampling frequency = 100 kHz

Phase distortions

$A_V(1kHz)=4 \quad \angle(1kHz)=0°$
$A_V(3kHz)=4 \quad \angle(3kHz)=0°$

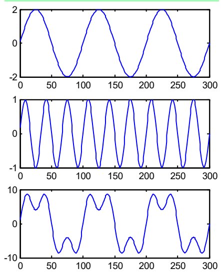


$A_V(1kHz)=4 \quad \angle(1kHz)=0°$
$A_V(3kHz)=4 \quad \angle(3kHz)=45°$

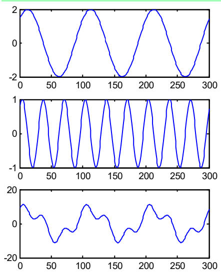


Phase distortions

$A_V(1kHz)=4 \quad \angle(1kHz)=0°$
$A_V(3kHz)=4 \quad \angle(3kHz)=0°$

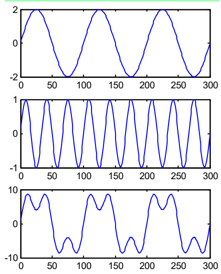


$A_V(1kHz)=4 \quad \angle(1kHz)=45°$
$A_V(3kHz)=4 \quad \angle(3kHz)=45°$

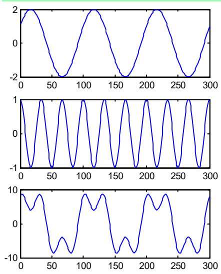


Phase distortions

$A_V(1kHz)=4 \quad \angle(1kHz)=0°$
$A_V(3kHz)=4 \quad \angle(3kHz)=0°$

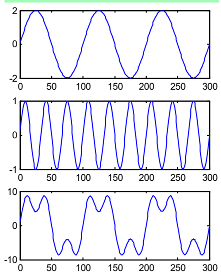


$A_V(1kHz)=4 \quad \angle(1kHz)=30°$
$A_V(3kHz)=4 \quad \angle(3kHz)=90°$

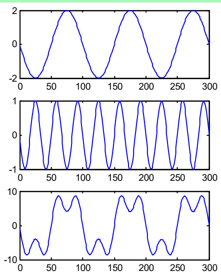


Phase distortions

$A_V(1kHz)=4 \quad \angle(1kHz)=0°$
$A_V(3kHz)=4 \quad \angle(3kHz)=0°$

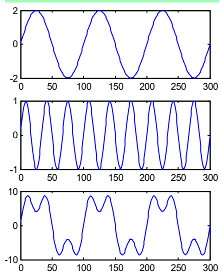


$A_V(1kHz)=4 \quad \angle(1kHz)=180°$
$A_V(3kHz)=4 \quad \angle(3kHz)=180°$

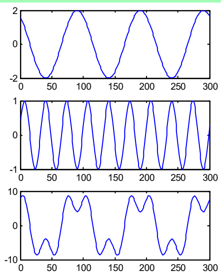


Phase distortions

$A_V(1kHz)=4 \quad \angle(1kHz)=0°$
$A_V(3kHz)=4 \quad \angle(3kHz)=0°$



$A_V(1kHz)=4 \quad \angle(1kHz)=125°$
$A_V(3kHz)=4 \quad \angle(3kHz)=15°$

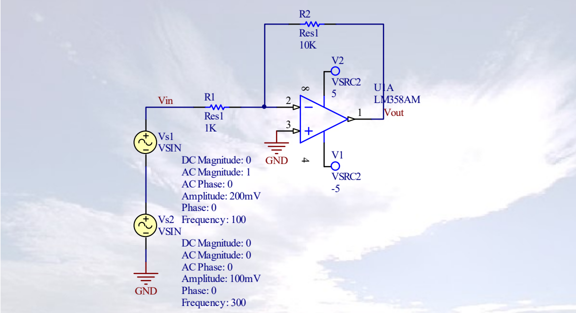


Linear Distortion – Conclusions

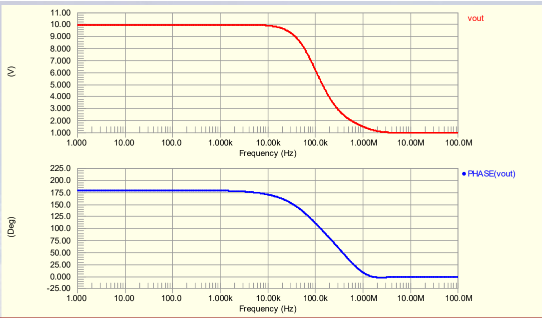
To avoid linear distortion two conditions should be met:

1. Amplitude condition – gain should be constant in the useful band of signal
   A(f) = const dla f $\in (f_L, f_h)$;
2. Phase condition – phase should be equal to 0, equal to 180° or proportional to the frequency in the useful band of signal
   $\varphi(f) = 0°$, $\varphi(f) = 180°$, $\varphi(f) = k*f$ dla f $\in (f_L, f_h)$

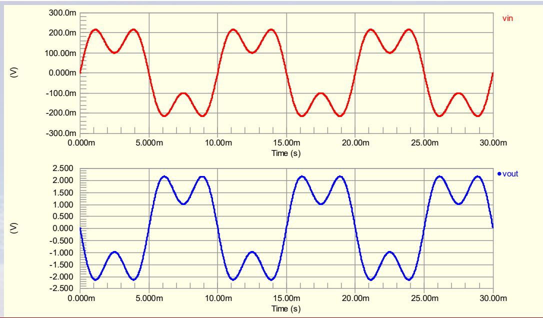
Linear distortions



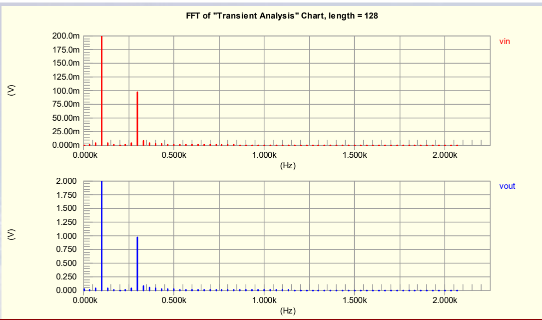
Linear distortions



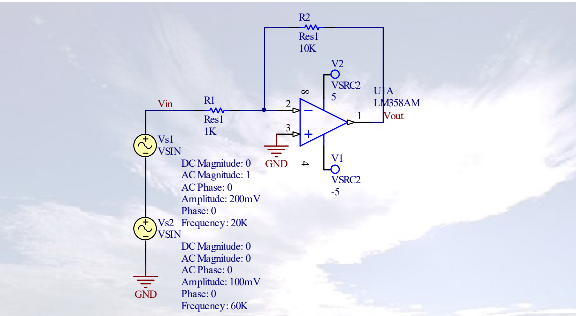
Linear distortions



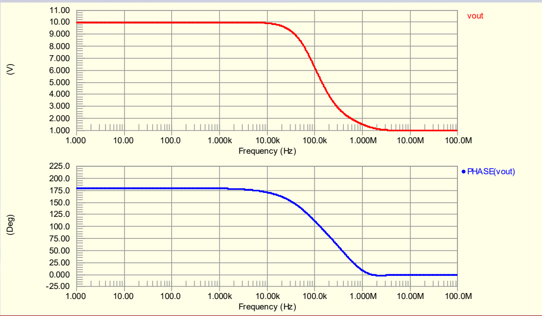
Linear distortions



Linear distortions



Linear distortions



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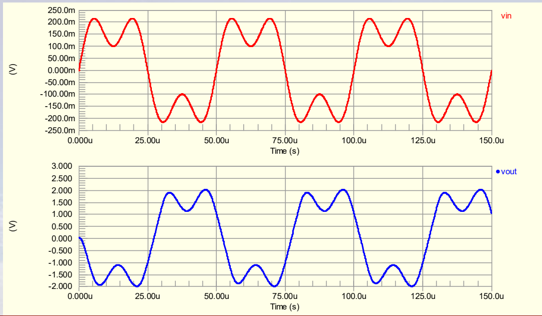
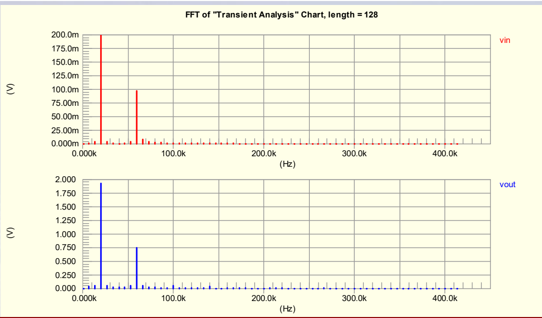
Linear distortions



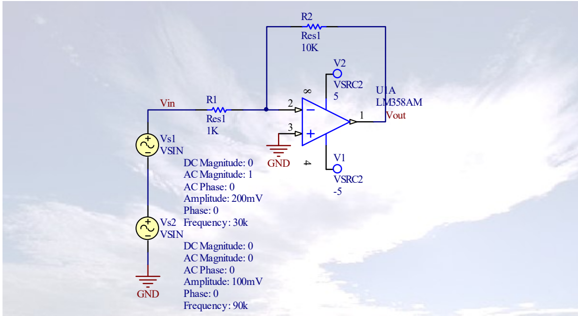
158

Linear distortions



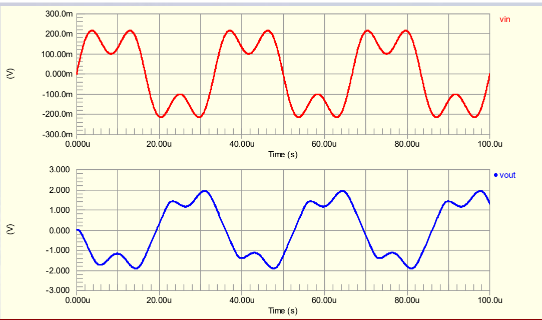
159

Linear distortions



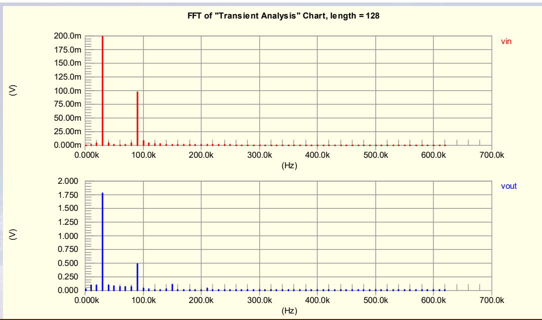
160

Linear distortions



161

Linear distortions



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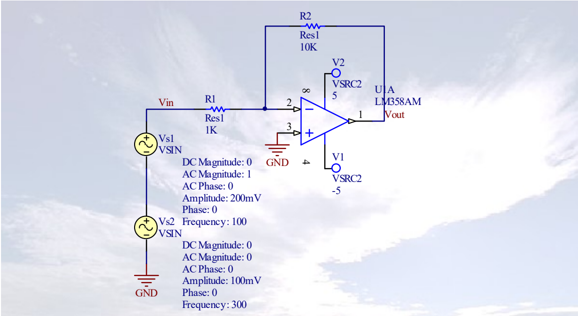
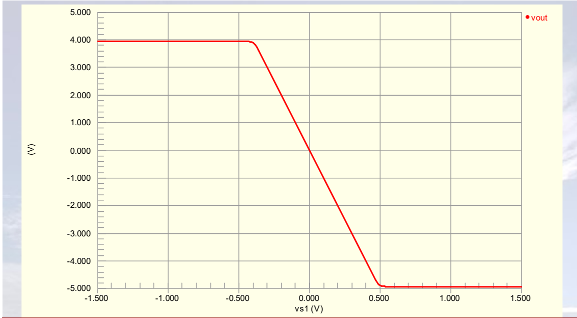
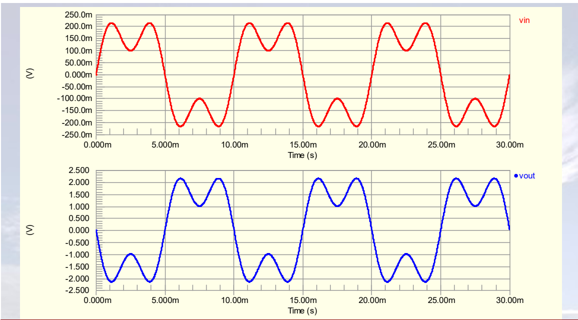
Linear distortions



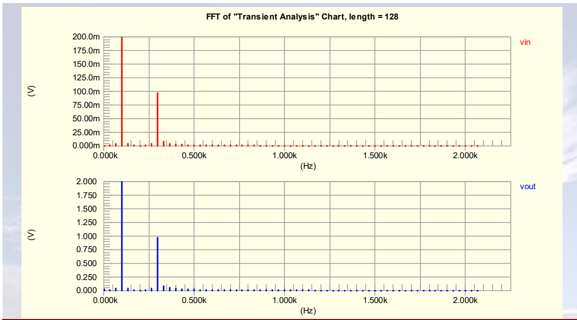
Nonlinear distortions



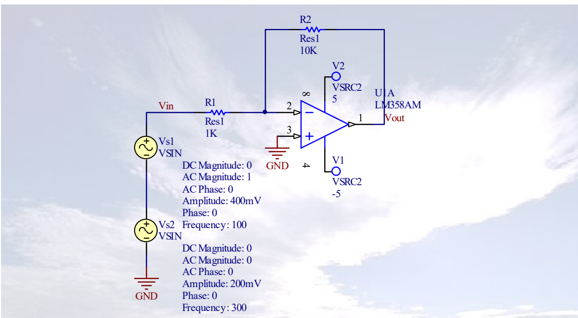
Nonlinear distortions



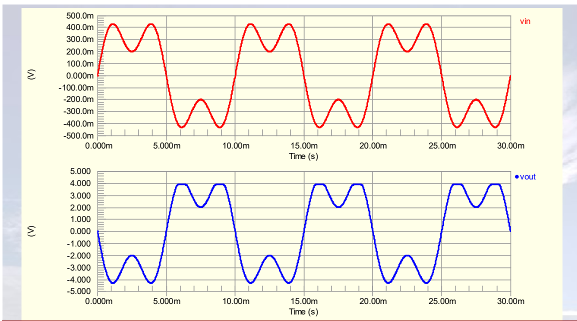
Nonlinear distortions



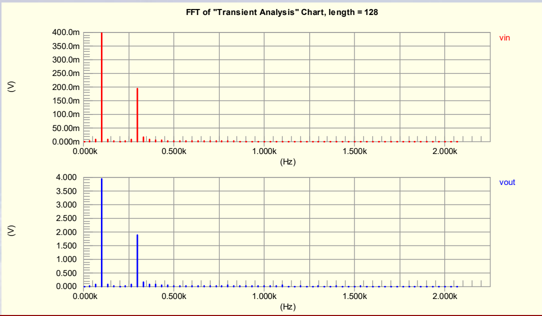
Nonlinear distortions



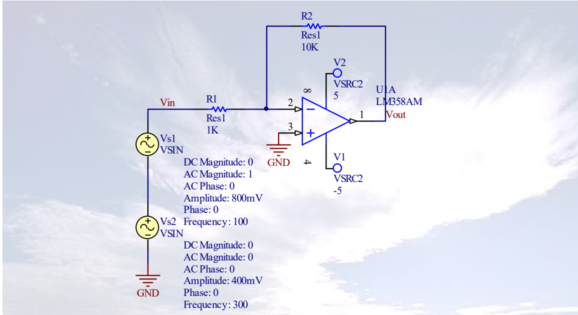
Nonlinear distortions



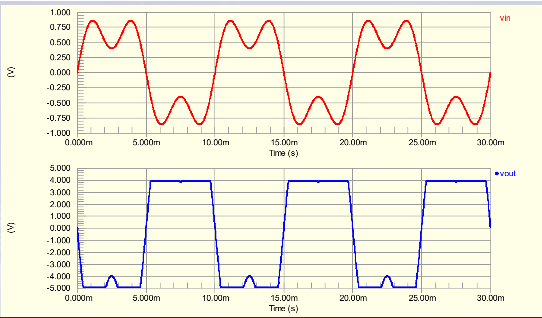
Nonlinear distortions



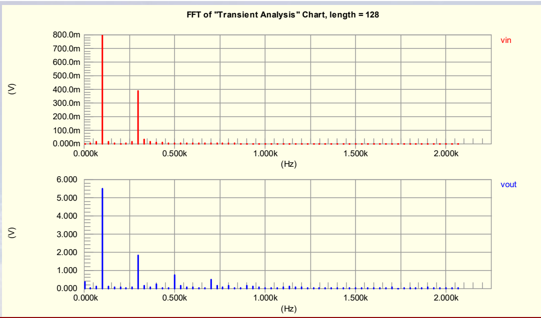
Nonlinear distortions



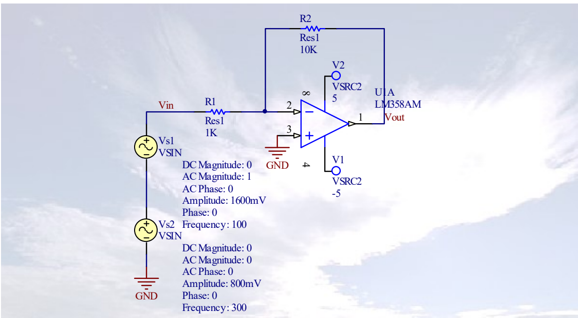
Nonlinear distortions



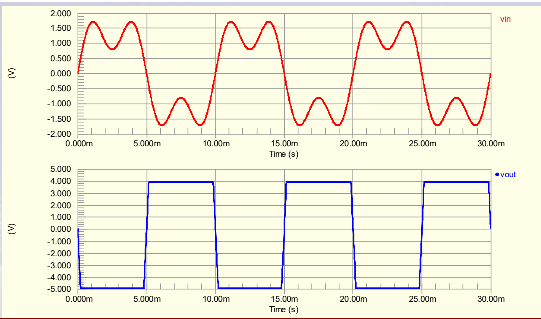
Nonlinear distortions



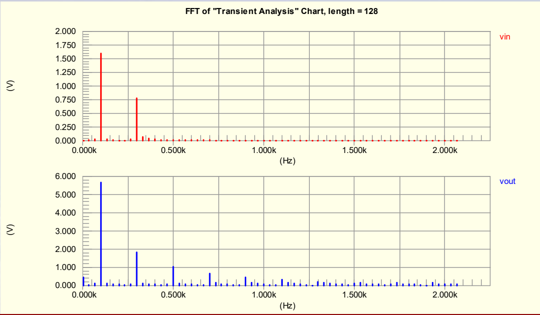
Nonlinear distortions



Nonlinear distortions



Nonlinear distortions



Nonlinear distortions

Nonlinear distortions cause in output signal occurrence of harmonics not present in input signal

Total Harmonic Distortion

Effective value of voltage for higher harmonics to the fundamental ratio measured for sine wave input signal

$$THD = \frac{\sqrt{\sum_{k=2}^{n} V_k^2}}{V_1}$$

where:
V_1 - effective value of voltage for fundamental
V_k - effective value of voltage for k harmonic

$$THD + N = \frac{\sqrt{V_n^2 + \sum_{k=2}^{n} V_k^2}}{V_1}$$

where:
V_n - effective value of voltage for noise

THD in audio systems

- 10% (-20dB) – clearly sensed distortion (improper for audio systems)
- 1% (-40dB) – acceptable distortion level in simple audio systems, can be sensed in hifi for listeners with trained musical hearing
- 0,1% (-60dB) – widely accepted distortion level skipping high end HiFi systems
- 0,01% (-80dB) – distortion level representative for high end HiFi systems, accepted by audiophiles
- 0,001% (-100dB) – distortion level beyond possibilities of audio systems.
- 0,0001% (-120dB) – level comparable with state of art measurement technicues

Decibel notation

Absolute values

$A_{vdB} = 20\log|A_v|\ dB$ Voltage gain

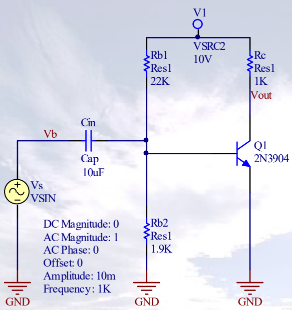
$A_{idB} = 20\log|A_i|\ dB$ Current gain

$G_{dB} = 10\log G\ dB$ Power gain $G = A_v^2 \frac{R_i}{R_L}$

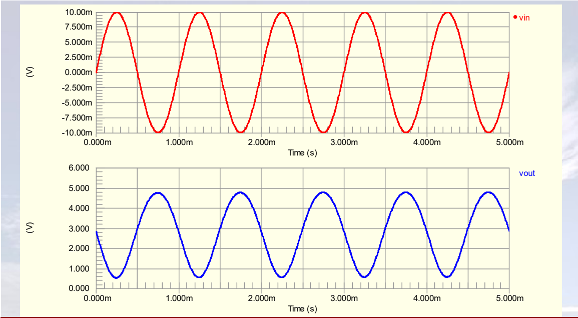
$A_v = 100$	40 dB,	G=100	20 dB,
$A_v = 10$	20 dB,	G=10	10 dB,
$A_v = 1$	0 dB,	G=1	0 dB,
$A_v = 0.1$	-20 dB.	G=0.1	-10 dB.

$$G_{dB} = A_{vdB} \Leftrightarrow R_L = R_i$$

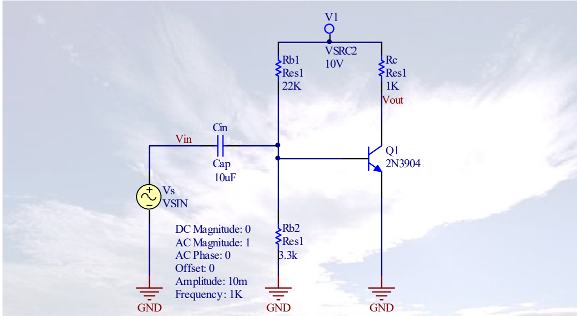
Power Amplifier class A



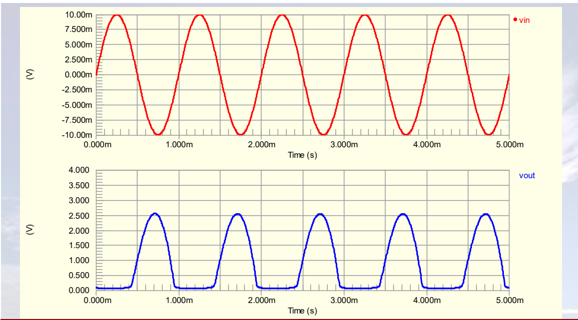
Power Amplifier class A



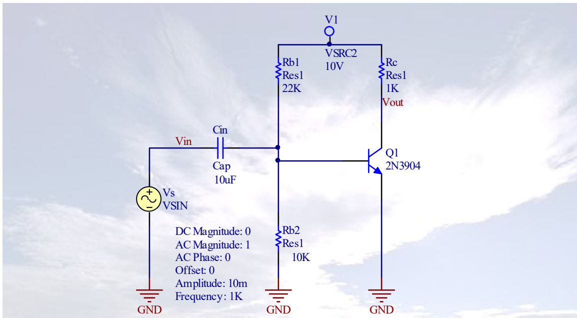
Power Amplifier class B



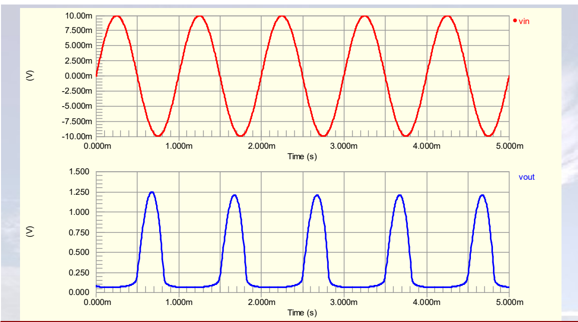
Power Amplifier class B



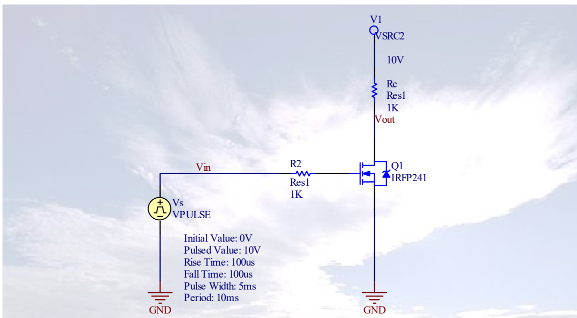
Power Amplifier class C



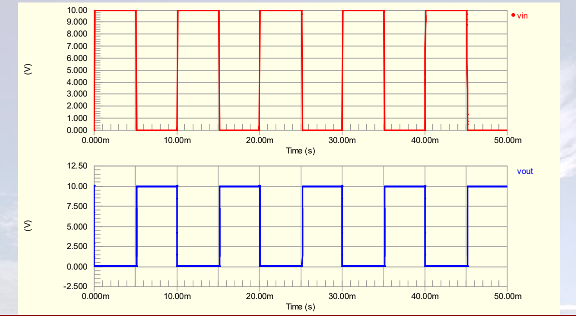
Power Amplifier class C



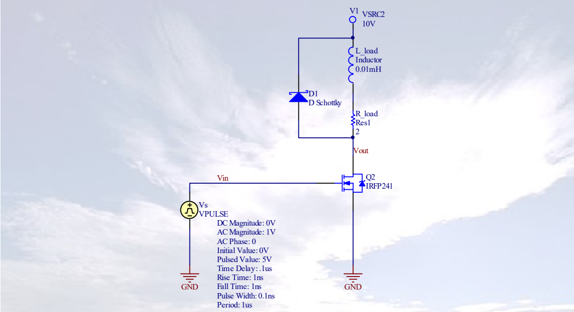
Power Amplifier class D



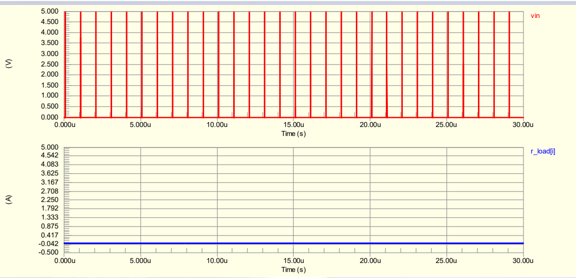
Power Amplifier class D



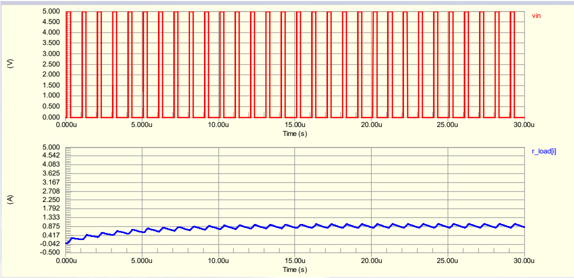
PWM



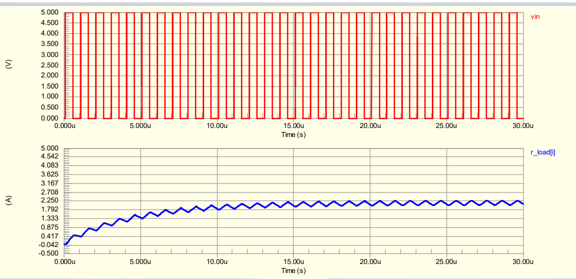
PWM



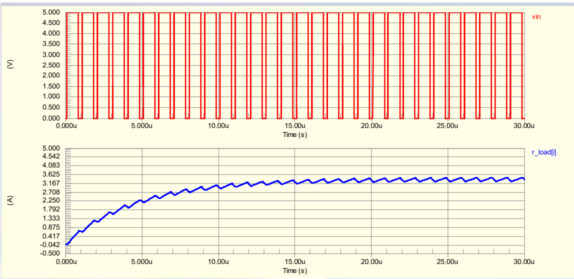
PWM

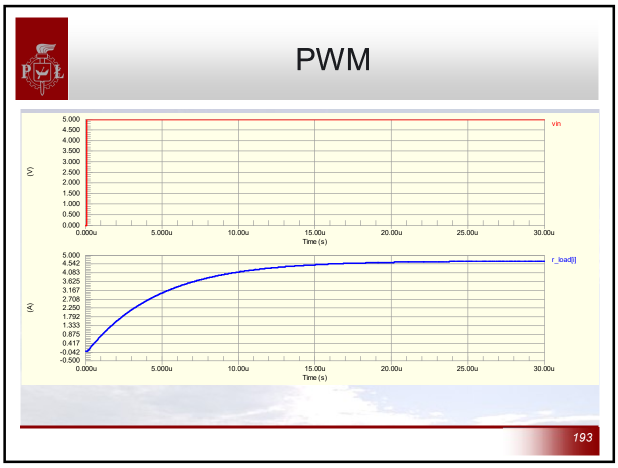


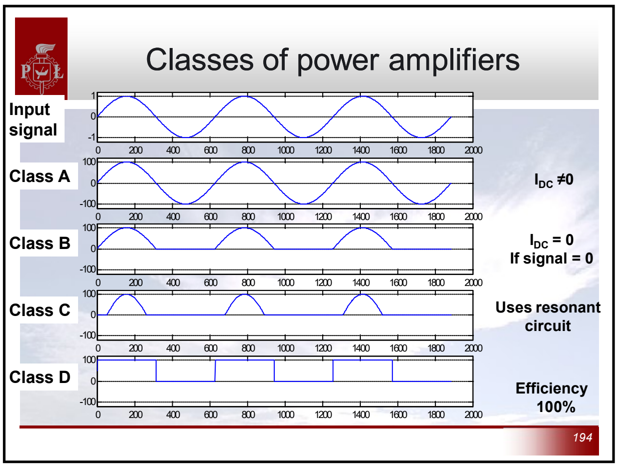
PWM

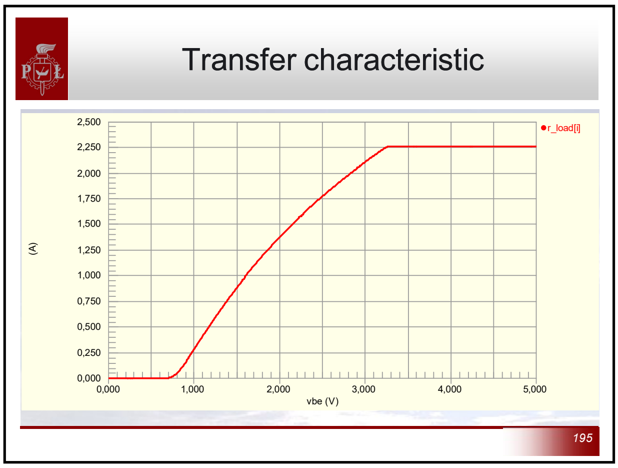


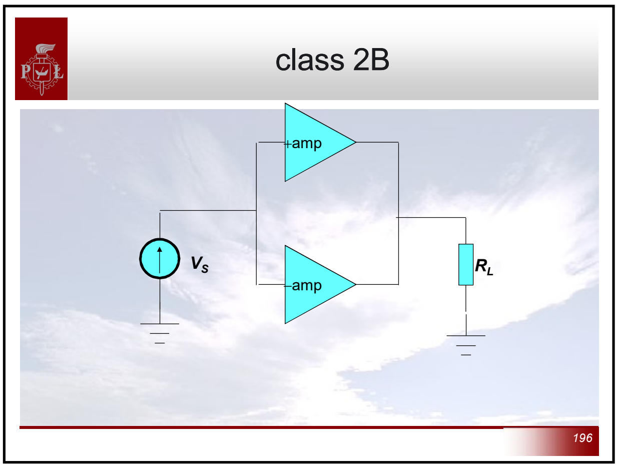
PWM

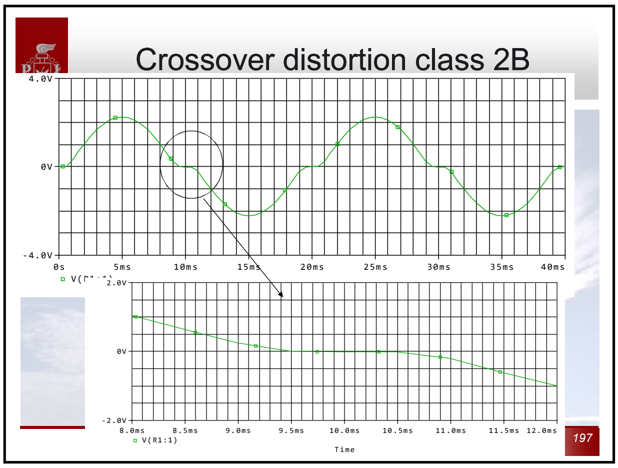


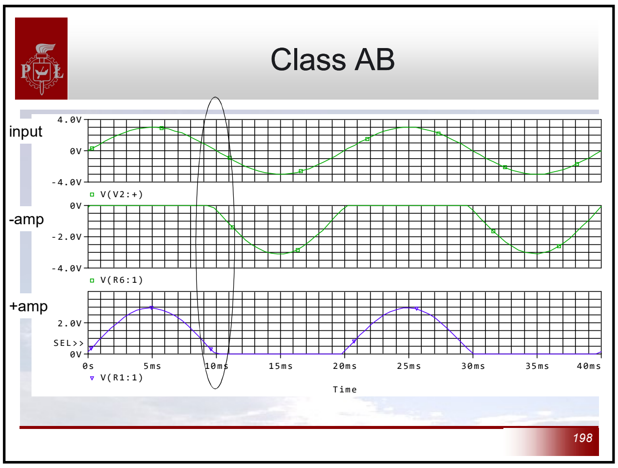

PWM
vin
r_load[i]
Time (s)
193


Classes of power amplifiers
Input signal
Class A
Class B
Class C
Class D
I_DC ≠0
I_DC = 0
If signal = 0
Uses resonant circuit
Efficiency 100%
194

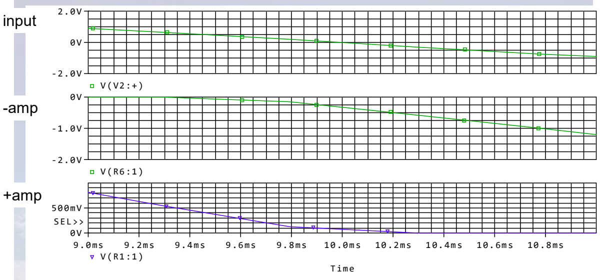

Transfer characteristic
r_load[i]
vbe (V)
195


class 2B
+amp
-amp
V_S
R_L
196

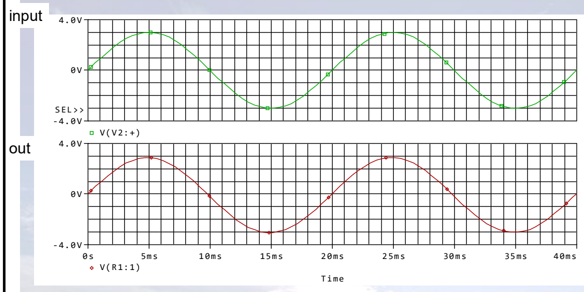

Crossover distortion class 2B
Time
197


Class AB
input
-amp
+amp
V(V2:+)
V(R6:1)
V(R1:1)
Time
198

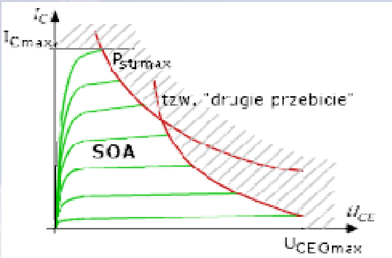
Class AB



Class 2AB



Safe Operation Area



Układy scalone wzmacniaczy mocy.

- LM380 2.5W Audio Power Amplifier
- TDA7052 1 W BTL mono audio amplifier
- LM4780 Overture™ Audio Power Amplifier Series Stereo 60W, Mono 120W Audio Power Amplifier with Mute
- TDA8920B 2 x 100 W class-D power amplifier
- Class D Audio Amplifier Design International amplifier http://www.irf.com/product-info/audio/classdtutorial.pdf

Lecture Plan

1. Noise in active circuits
2. Power amplifiers integrated circuits.
3. **Broadband and impulse amplifiers integrated circuits**
4. Active analog filters with continuous and discrete time
5. Analog multipliers
6. Detectors of amplitude, frequency and phase
7. Phase-locked loop and its applications
8. Programmable analog circuits and their applications.
9. Application specific integrated circuits.
10. Digital integrated circuits.

Broadband and impulse amplifiers integrated circuits

Literature:

Józef Boksa, Analogowe układy elektroniczne, BTC, Warszawa 2007

Waldemar Nawrocki, Krzysztof Arnold, Krzysztof Lange, Układy Elektroniczne, Wydawnictwo Politechniki Poznańskiej, Poznań 1999

Zbigniew Nosal, Jerzy Baranowski, Układy Analogowe Liniowe, Wydawnictwa Naukowo Techniczne Warszawa 2003

Broadband and impulse amplifiers integrated circuits

1. Introduction
2. Relations between frequency characteristic and impulse response of linear circuits
3. Examples of broadband amplifiers integrated circuits

Band pass amplifiers integrated circuits

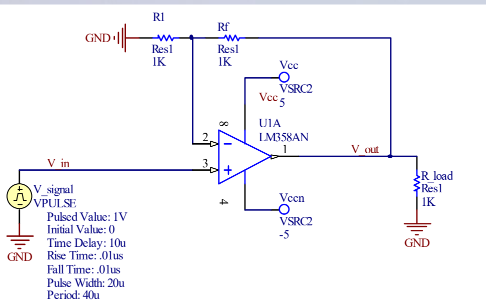
Very large bandwidth $(f_h - f_l) > MHz$

$$\frac{f_h}{f_l} > 10$$

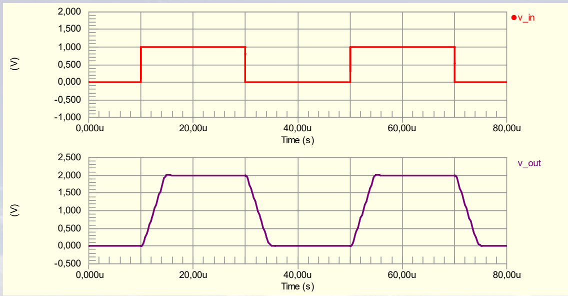
Example of applications:

- CRT TV receivers (30Hz - 6MHz)
- oscilloscopes (DC - few GHz)
- Radar equipment (> 20 GHz)
- Fiber optic telecommunication (100kHz – 25GHz)

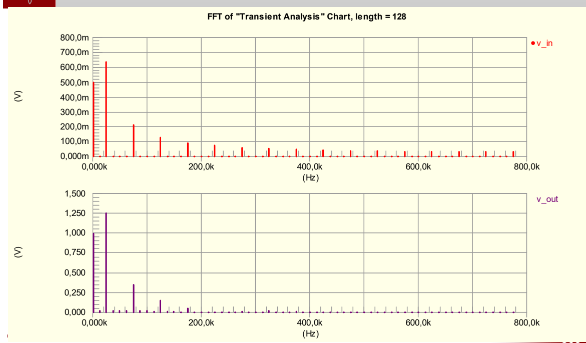
Impulse response of amplifiers



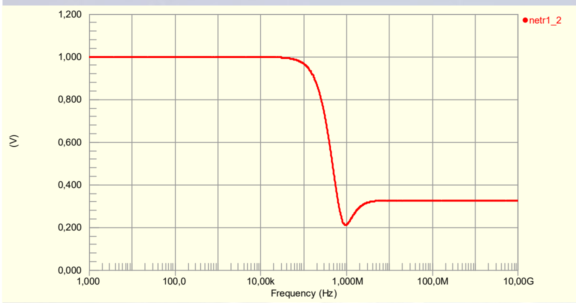
Impulse response of amplifiers

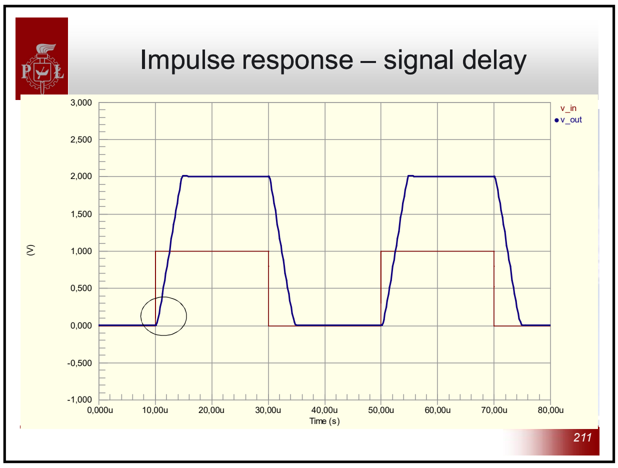


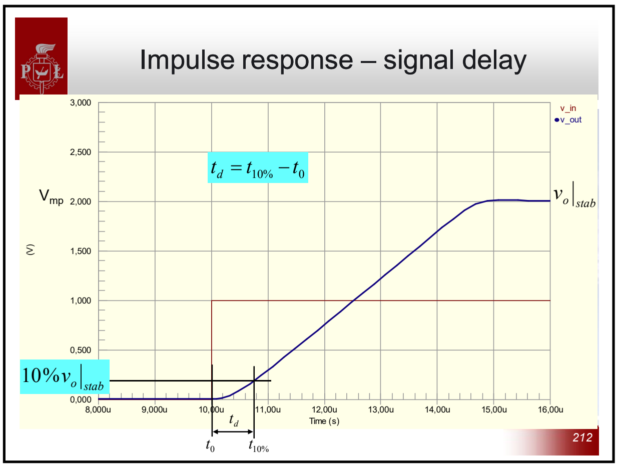
Impulse response of amplifiers

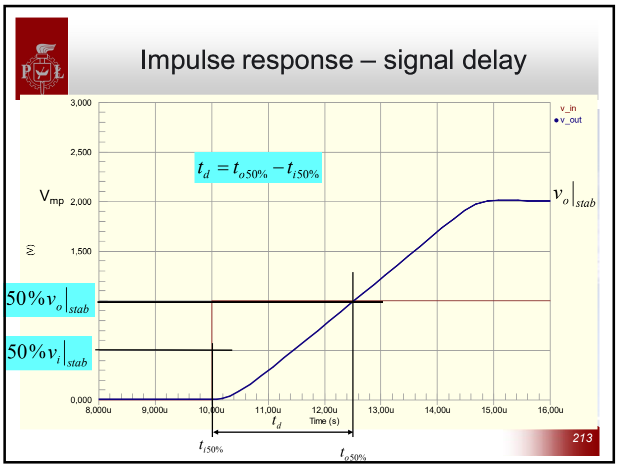


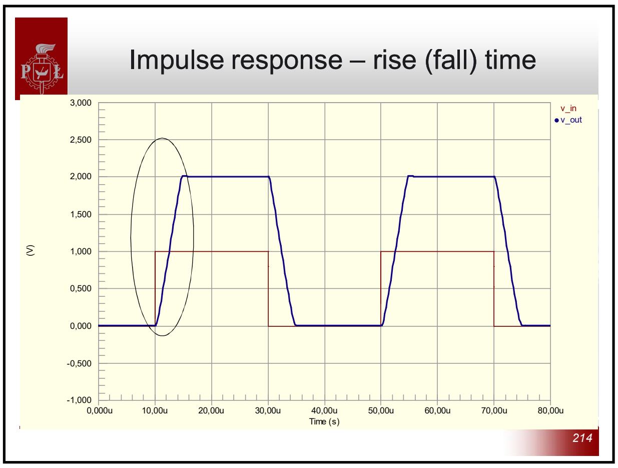
Impulse response of amplifiers

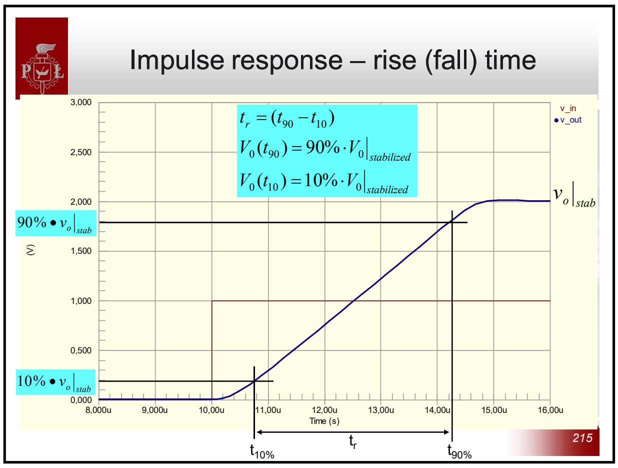


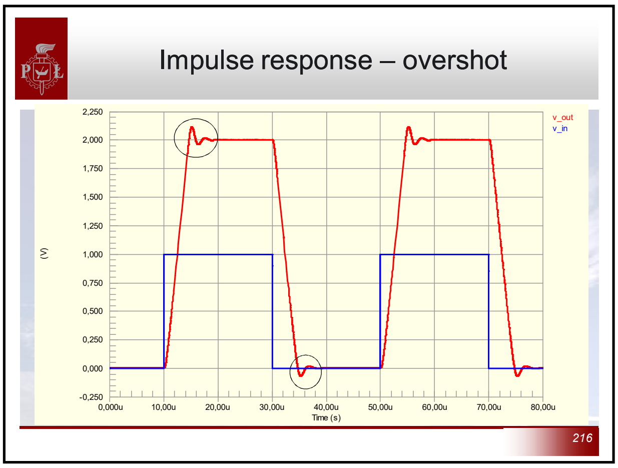

Impulse response – signal delay
v_in
v_out
Time (s)
211


Impulse response – signal delay
$t_d = t_{10\%} - t_0$
V_{mp}
$v_o|_{stab}$
$10\% v_o|_{stab}$
t_d
t_0
$t_{10\%}$
Time (s)
212

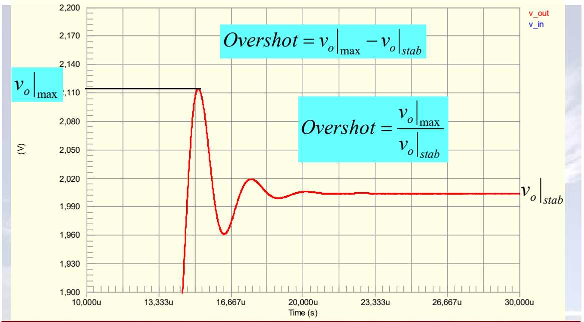

Impulse response – signal delay
$t_d = t_{o50\%} - t_{i50\%}$
V_{mp}
$v_o|_{stab}$
$50\% v_o|_{stab}$
$50\% v_i|_{stab}$
t_d
$t_{i50\%}$
$t_{o50\%}$
Time (s)
213


Impulse response – rise (fall) time
v_in
v_out
Time (s)
214


Impulse response – rise (fall) time
$t_r = (t_{90} - t_{10})$
$V_0(t_{90}) = 90\% \cdot V_0|_{stabilized}$
$V_0(t_{10}) = 10\% \cdot V_0|_{stabilized}$
$v_o|_{stab}$
$90\% \bullet v_o|_{stab}$
$10\% \bullet v_o|_{stab}$
$t_{10\%}$
t_r
$t_{90\%}$
Time (s)
215

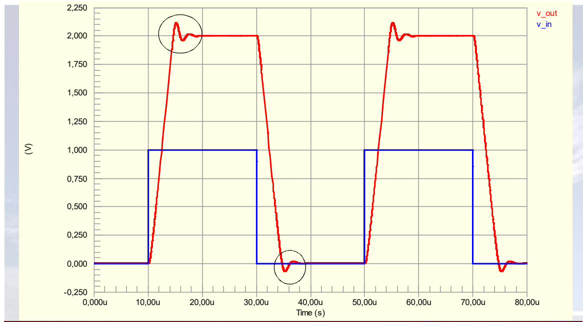

Impulse response – overshoot
v_out
v_in
Time (s)
216

Impulse response – overshot



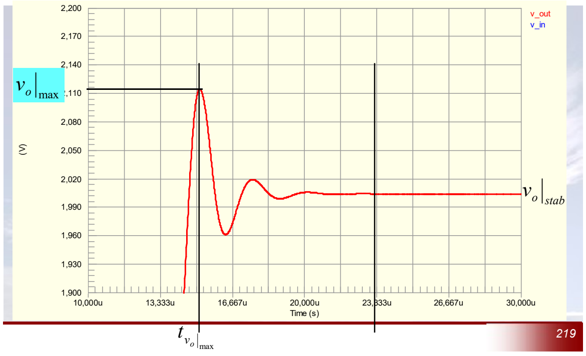
217

Impulse response – ripples



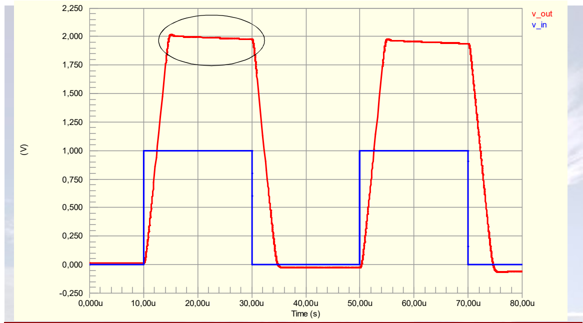
218

Impulse response – ripples



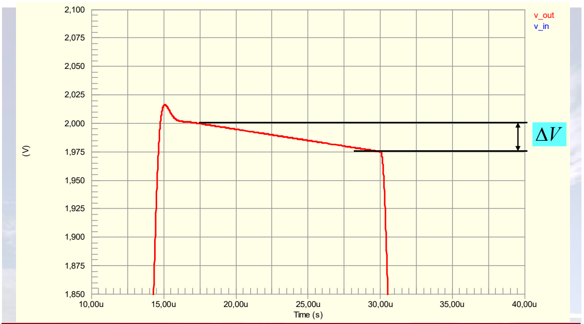
219

Impulse response – tilt



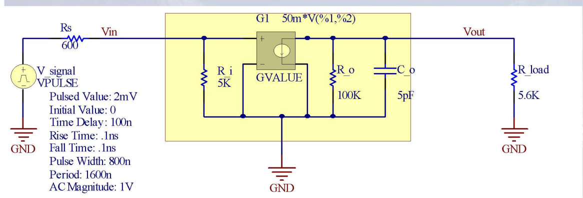
220

Impulse response – tilt



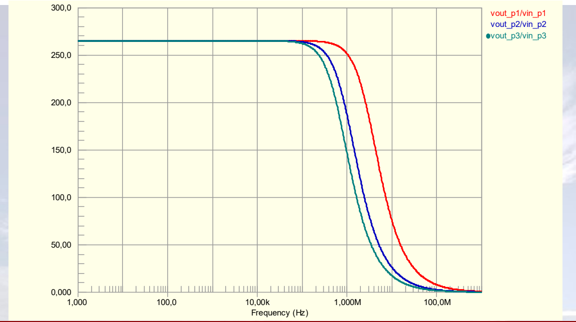
221

Impulse response versus frequency characteristics



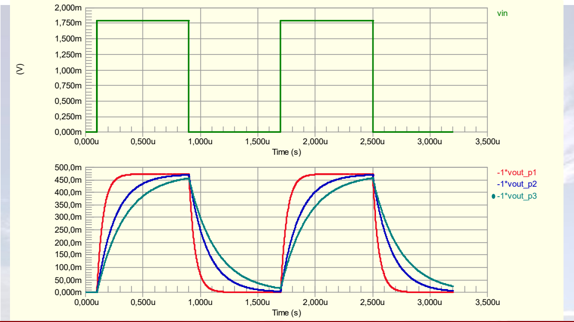
222

Impulse response versus frequency characteristics



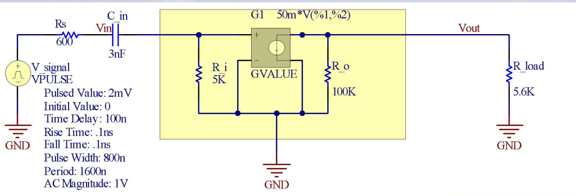
223

Impulse response versus frequency characteristics



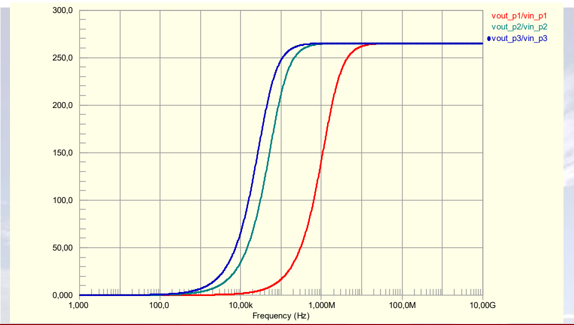
224

Impulse response versus frequency characteristics



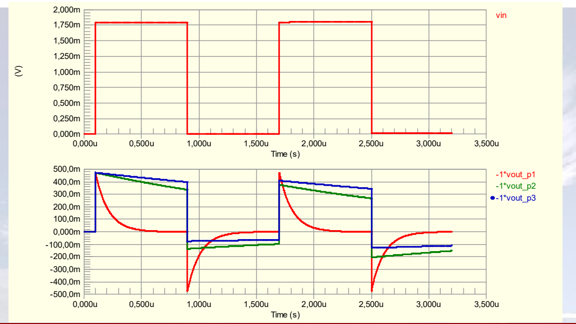
225

Impulse response versus frequency characteristics



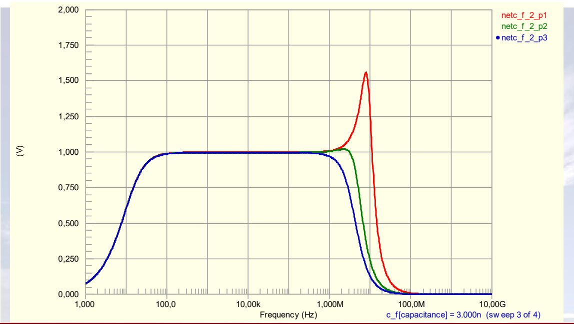
226

Impulse response versus frequency characteristics



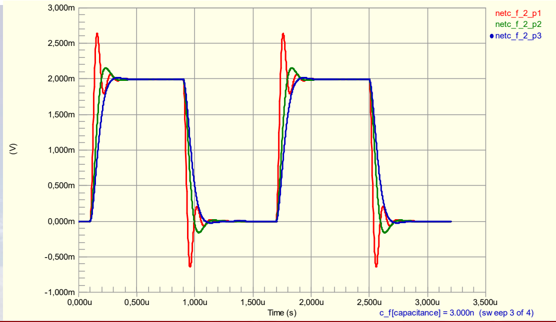
227

Impulse response versus frequency characteristics

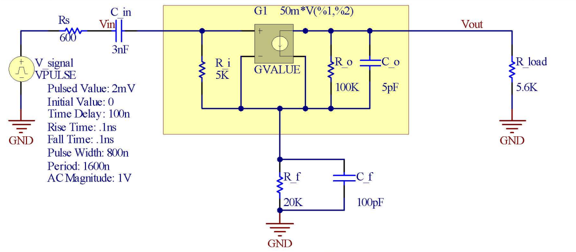


228

Impulse response versus frequency characteristics



Impulse response versus frequency characteristics



Impulse response summary

- Impulse response determine dynamic behavior of an amplifier
- There are 5 types of impulse response distortions:
  - delay
  - mild slope
  - overshoot
  - ripples
  - tilt

Relations between frequency characteristic and impulse response

$$h(t) = L^{-1}\left[\frac{k(s)}{s}\right]$$

Circuit response for unity excitation *1(t)*
Where :
k(s) – circuit transfer function

$$\lim_{t\to\infty} h(t) = \lim_{\omega\to 0} k(j\omega t)$$

Circuit response for spine of the impulse is related to the shape of the frequency characteristics k(jω) for the low frequencies

$$\lim_{t\to 0} h(t) = \lim_{\omega\to\infty} k(j\omega t)$$

Circuit response for edge of the impulse is related to the shape of the frequency characteristics k(jω) for the high frequencies

Relations between frequency characteristic and impulse response

One pole low pass transfer function

$$k(s) = \frac{k_0}{1+\frac{s}{\omega_h}} \qquad h(t) = 1k_0\left(1-e^{-t\omega_h}\right)$$

$$t_r = t_{90\%} - t_{10\%} \qquad t_{90\%} = t\big|_{h(t)=0.9k_0} \qquad t_{10\%} = t\big|_{h(t)=0.1k_0}$$

$$t_r = \frac{2,303}{\omega_h} - \frac{0,105}{\omega_h} = \frac{2,198}{\omega_h} = \frac{2,198}{2\pi f_h} \approx \frac{0,35}{f_h}$$

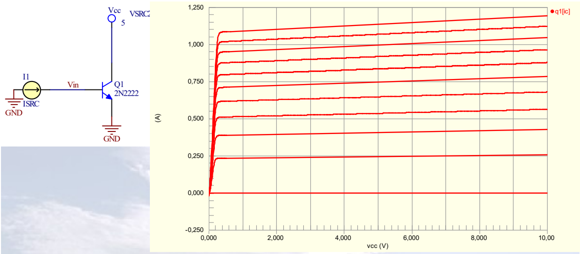
Relations between frequency characteristic and impulse response

One pole high pass transfer function

$$k(s) = \frac{k_0}{1+\frac{\omega_l}{s}} \qquad h(t) = 1k_0 e^{-t\omega_l}$$

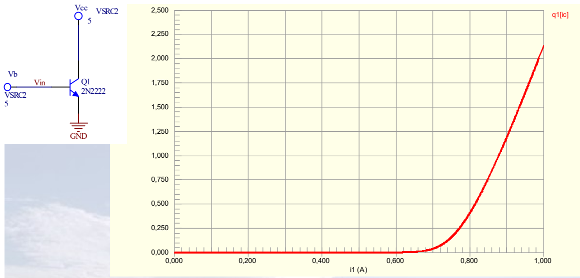
$$\Delta V = \frac{h(0)-h(t)}{h(0)} = \frac{1k_0 - 1k_0 e^{-t\omega_l}}{1k_0} = 1 - e^{-t\omega_l} \approx t\omega_l\Big|_{t<<\frac{1}{\omega_l}}$$

CE amplifier



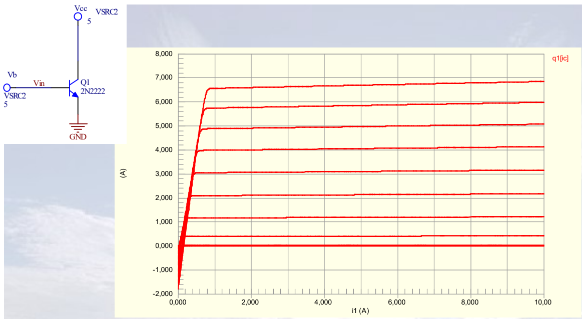
235

CE amplifier



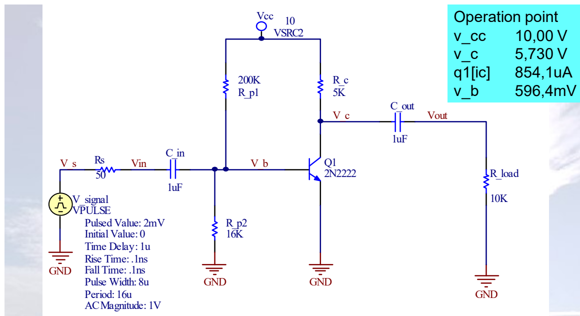
236

CE amplifier



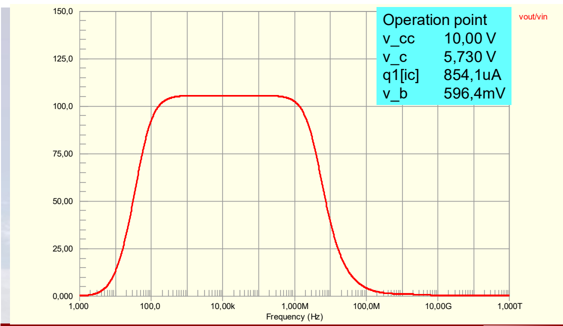
237

CE amplifier



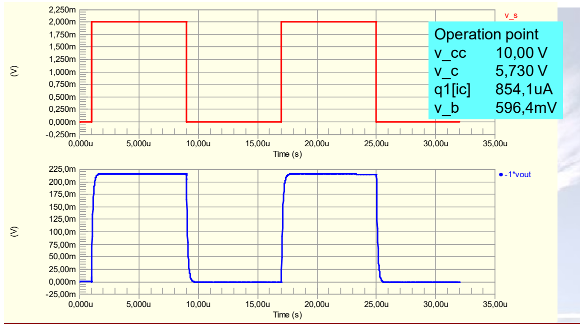
238

CE amplifier



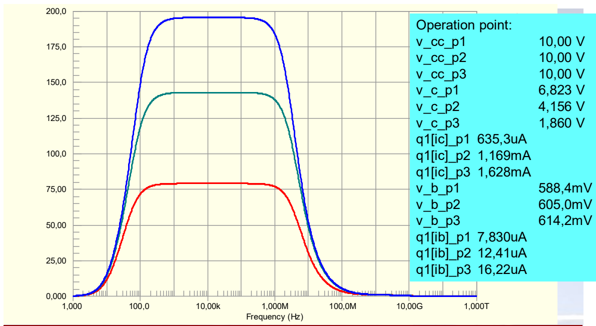
239

CE amplifier



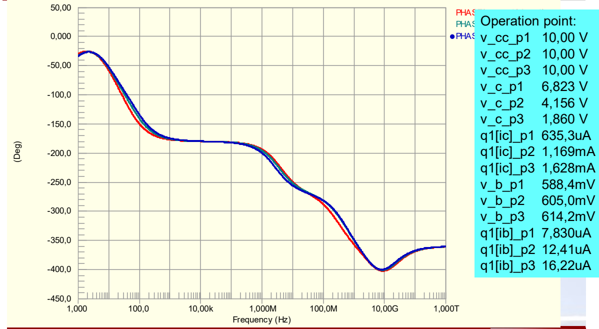
240

CE amplifier modification of the Q point



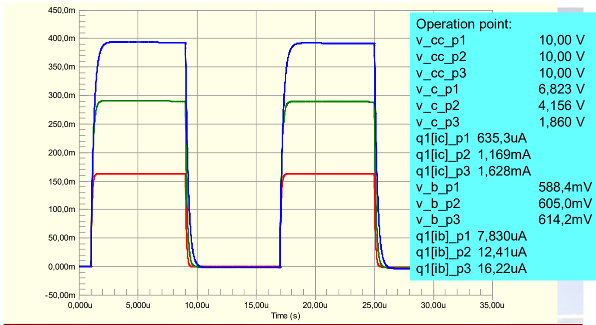
241

CE amplifier modification of the Q point



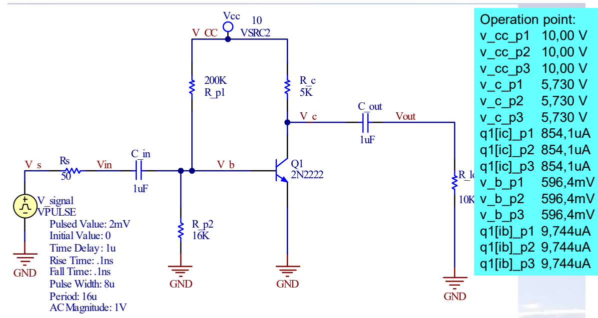
242

CE amplifier modification of the Q point



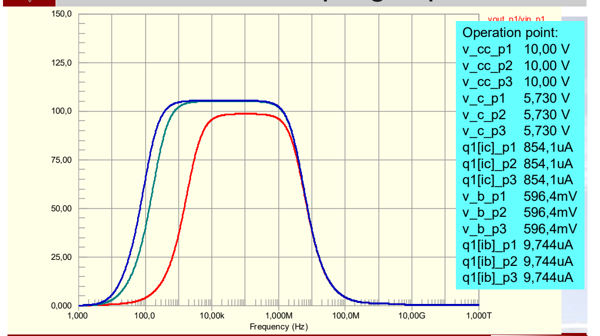
243

CE amplifier modification of coupling capacitances



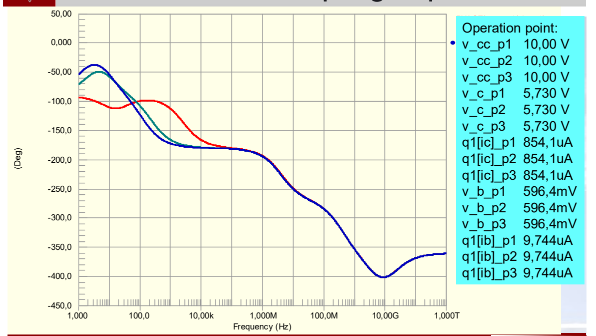
244

CE amplifier modification of coupling capacitances



245

CE amplifier modification of coupling capacitances



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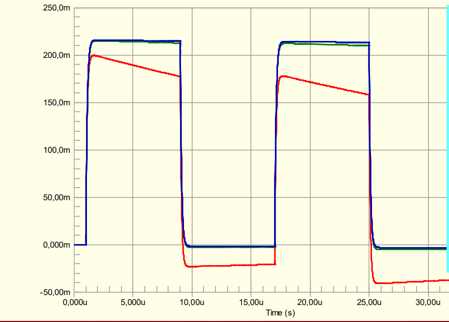
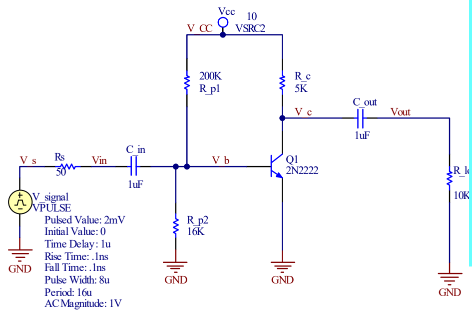
CE amplifier
modification of coupling capacitances



Operation point:
v_cc_p1 10,00 V
v_cc_p2 10,00 V
v_cc_p3 10,00 V
v_c_p1 5,730 V
v_c_p2 5,730 V
v_c_p3 5,730 V
q1[ic]_p1 854,1uA
q1[ic]_p2 854,1uA
q1[ic]_p3 854,1uA
v_b_p1 596,4mV
v_b_p2 596,4mV
v_b_p3 596,4mV
q1[ib]_p1 9,744uA
q1[ib]_p2 9,744uA
q1[ib]_p3 9,744uA

247

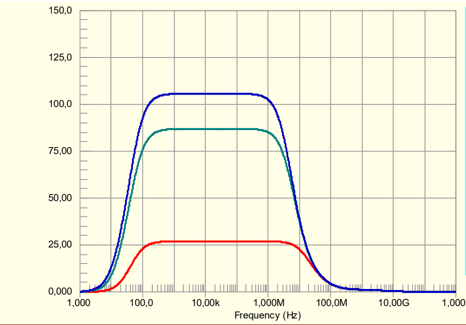
CE amplifier
modification of the load



Operation point:
v_cc_p1 10,00 V
v_cc_p2 10,00 V
v_cc_p3 10,00 V
v_c_p1 5,730 V
v_c_p2 5,730 V
v_c_p3 5,730 V
q1[ic]_p1 854,1uA
q1[ic]_p2 854,1uA
q1[ic]_p3 854,1uA
v_b_p1 596,4mV
v_b_p2 596,4mV
v_b_p3 596,4mV
q1[ib]_p1 9,744uA
q1[ib]_p2 9,744uA
q1[ib]_p3 9,744uA

248

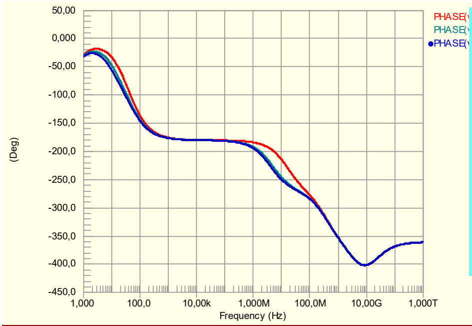
CE amplifier
modification of the load



Operation point:
v_cc_p1 10,00 V
v_cc_p2 10,00 V
v_cc_p3 10,00 V
v_c_p1 5,730 V
v_c_p2 5,730 V
v_c_p3 5,730 V
q1[ic]_p1 854,1uA
q1[ic]_p2 854,1uA
q1[ic]_p3 854,1uA
v_b_p1 596,4mV
v_b_p2 596,4mV
v_b_p3 596,4mV
q1[ib]_p1 9,744uA
q1[ib]_p2 9,744uA
q1[ib]_p3 9,744uA

249

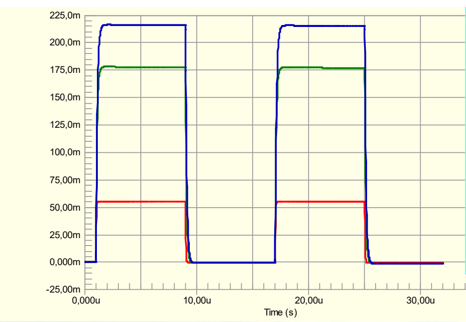
CE amplifier
modification of the load



Operation point:
v_cc_p1 10,00 V
v_cc_p2 10,00 V
v_cc_p3 10,00 V
v_c_p1 5,730 V
v_c_p2 5,730 V
v_c_p3 5,730 V
q1[ic]_p1 854,1uA
q1[ic]_p2 854,1uA
q1[ic]_p3 854,1uA
v_b_p1 596,4mV
v_b_p2 596,4mV
v_b_p3 596,4mV
q1[ib]_p1 9,744uA
q1[ib]_p2 9,744uA
q1[ib]_p3 9,744uA

250

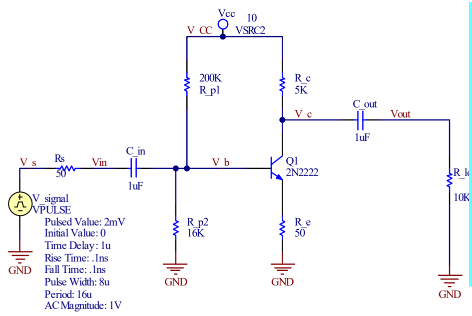
CE amplifier
modification of the load



Operation point:
v_cc_p1 10,00 V
v_cc_p2 10,00 V
v_cc_p3 10,00 V
v_c_p1 5,730 V
v_c_p2 5,730 V
v_c_p3 5,730 V
q1[ic]_p1 854,1uA
q1[ic]_p2 854,1uA
q1[ic]_p3 854,1uA
v_b_p1 596,4mV
v_b_p2 596,4mV
v_b_p3 596,4mV
q1[ib]_p1 9,744uA
q1[ib]_p2 9,744uA
q1[ib]_p3 9,744uA

251

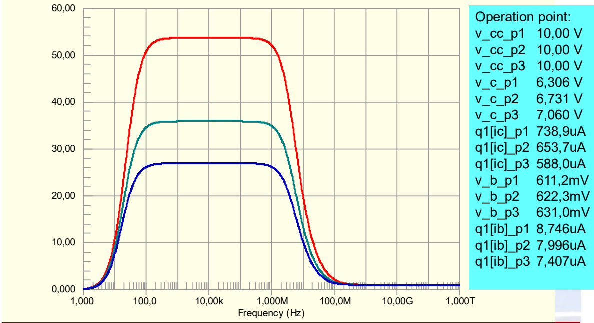
CE amplifier
modification of the feedback



Operation point:
v_cc_p1 10,00 V
v_cc_p2 10,00 V
v_cc_p3 10,00 V
v_c_p1 6,306 V
v_c_p2 6,731 V
v_c_p3 7,060 V
q1[ic]_p1 738,9uA
q1[ic]_p2 653,7uA
q1[ic]_p3 588,0uA
v_b_p1 611,2mV
v_b_p2 622,3mV
v_b_p3 631,0mV
q1[ib]_p1 8,746uA
q1[ib]_p2 7,996uA
q1[ib]_p3 7,407uA

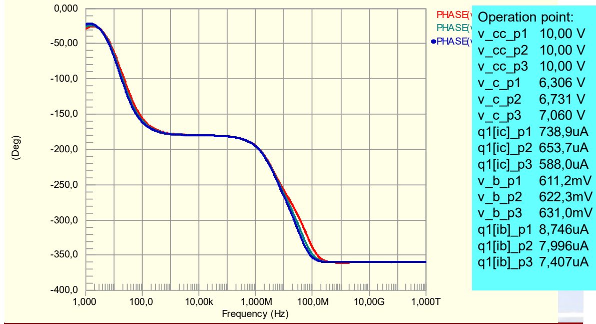
252

CE amplifier modification of the feedback



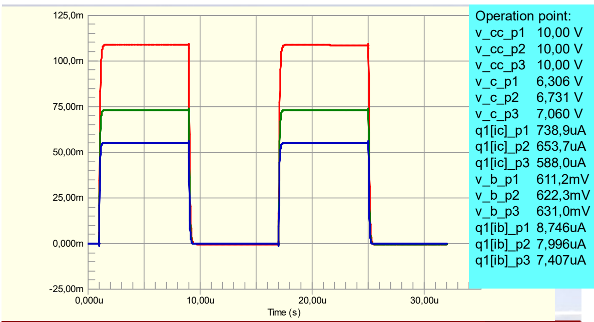
253

CE amplifier modification of the feedback



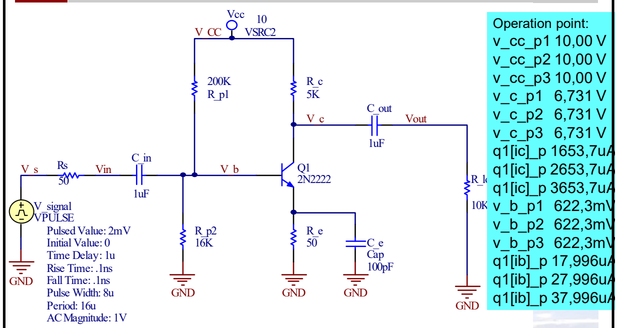
254

CE amplifier modification of the feedback



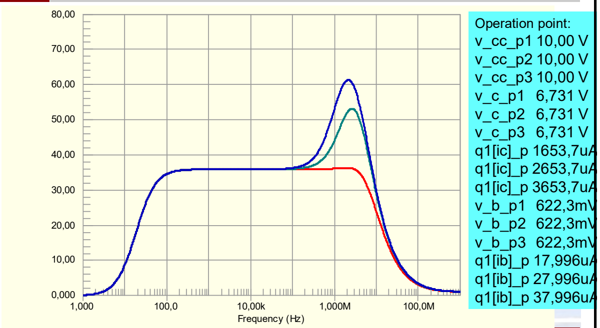
255

CE amplifier modification of the feedback



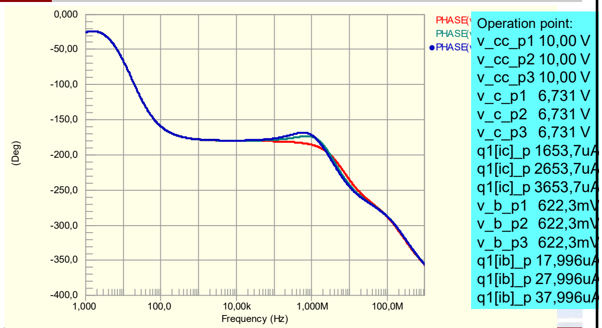
256

CE amplifier modification of the feedback



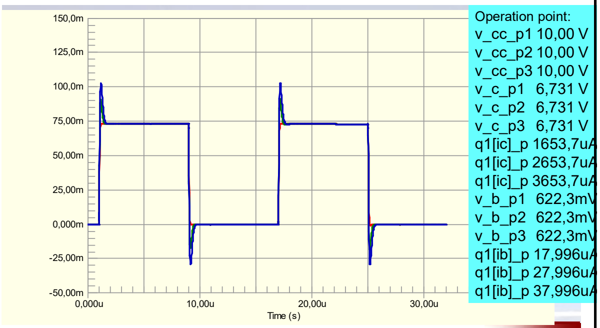
257

CE amplifier modification of the feedback



258

CE amplifier modification of the feedback



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Broad band and impulse amplifier integrated circuits

- LM2904,LM358/LM358A,LM258/ LM258A Dual Operational Amplifier
- AD829 High Speed, Low Noise Video Op
- AD8597/AD8599 Single and Dual, Ultralow Distortion, Ultralow Noise Op Amps
- TL072 TL072A TL072B Low noise JFET dual operational amplifiers

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Lecture Plan

1. Noise in active circuits
2. Power amplifiers integrated circuits.
3. Broadband and impulse amplifiers integrated circuits
4. **Active analog filters with continuous and discrete time**
5. Analog multipliers
6. Detectors of amplitude, frequency and phase
7. Phase-locked loop and its applications
8. Programmable analog circuits and their applications.
9. Application specific integrated circuits.
10. Digital integrated circuits.

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Active analog filters with continuous and discrete time

Literature:

U. Tietze,Ch. Shenck, Electronics circuits, design and applications, Springer-Verlag, 2001

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Active analog filters with continuous and discrete time

1. Passive filters
2. Filter types
3. Active filters of the continuous time
4. Switched capacitance filters
5. DSP filters
6. Examples of integrated circuits with analog filters

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Filter

The piece of electric or electronic circuit responsible for passing or blocking signals with certain band or hawing specified harmonics

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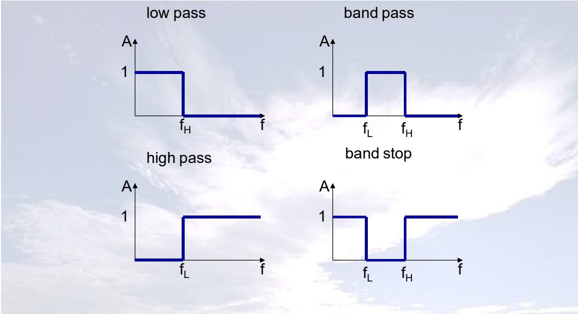
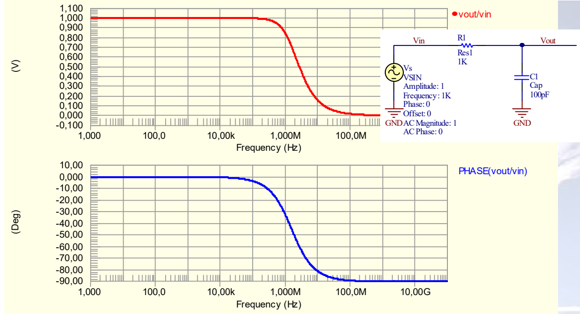
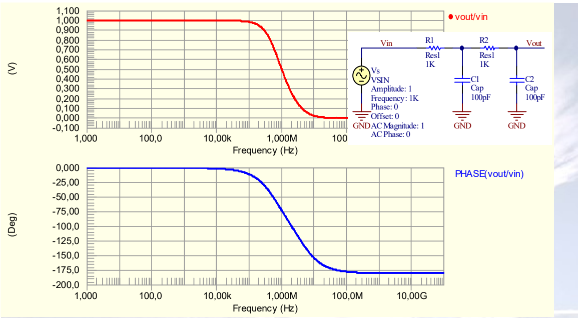
Ideal Filters



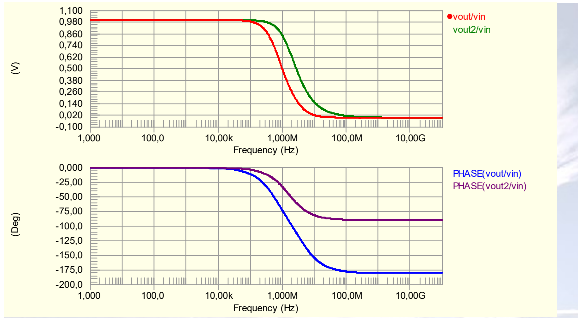
Passive LP filter



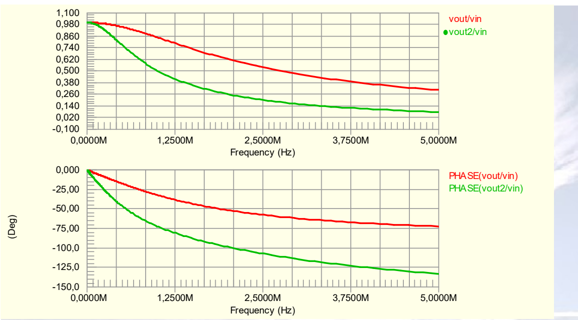
Passive LP filter



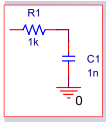
Passive LP filter



Passive LP filter



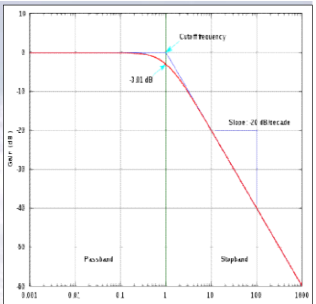
Passive LP filter



$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}$$

$$\omega_c = \frac{1}{\tau} = \frac{1}{RC}$$

$$H(s) = \frac{V_O}{V_I} = K\frac{1}{1+s\tau}$$



Wikipedia
By: Krishnavedala

LP filter applications

- Separation of audio bands for bass, mid-range and tweeter loudspeaker
- Radio transmitters – blocking of harmonics emissions
- Telephonic filters for DSL
- Antyaliasing filters for A/D converters
- Smoothing filters on outputs of D/A converters

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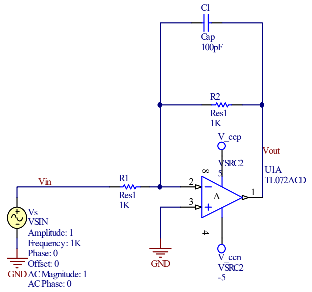
Active LP filter



$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi R_2 C_1}$$

$$\omega_c = \frac{1}{\tau} = \frac{1}{R_2 C_1}$$

$$A_v = -\frac{R_2}{R_1}$$

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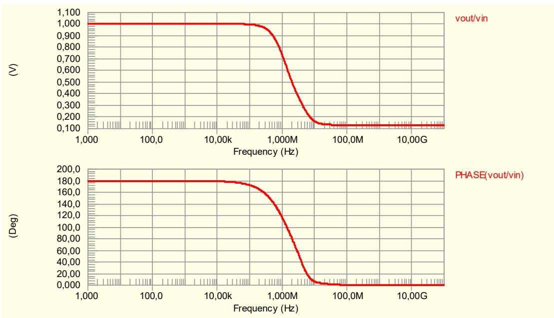
Aktywny filtr LP



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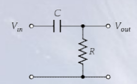
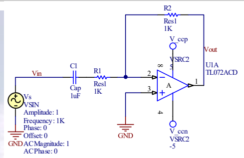
HP filter





$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}$$

$$\omega_c = \frac{1}{\tau} = \frac{1}{RC}$$

$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi R_1 C_1}$$

$$\omega_c = \frac{1}{\tau} = \frac{1}{R_1 C_1}$$

$$A_v = -\frac{R_2}{R_1}$$

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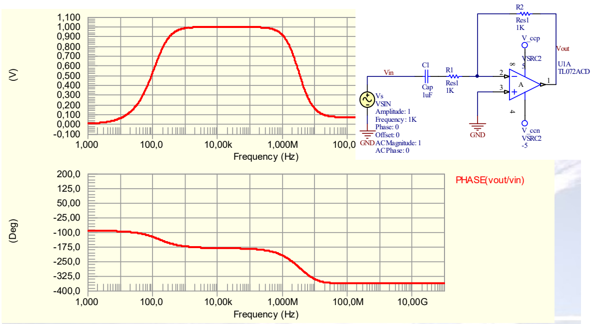
HP filter?



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Other filters types

- Band pass
- Band stop
- Notch filter
- Comb filter
- all pass filter

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Filter parameters

- Cutoff frequency usually given for specific attenuation e.g. 3dB.
- Roll-off
- Transition band,
- Ripple
- The order of a filter

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Higher order active filters

Classification based on frequency response:

- Butterworth filter
- Chebyshev filter type I
- Chebyshev filter type II
- Bessel filter
- Elliptic filter
- Optimum "L" filter
- Gaussian filter
- Hourglass filter
- Raised-cosine filter

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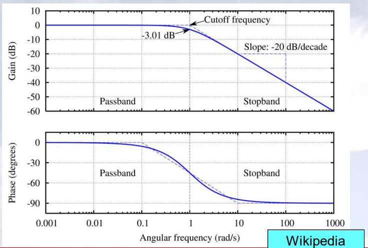
Butterworth filter

maximally flat magnitude filter



Wikipedia
by Omegatron

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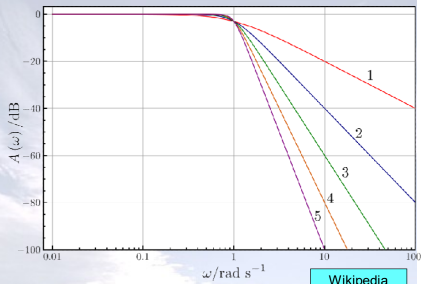
Filtr Butterwortha (Butterworth filter)

$$G^2(\omega) = |H(j\omega)|^2 = \frac{G_0^2}{1+\left(\frac{\omega}{\omega_C}\right)^{2n}}$$



Wikipedia
by Inductiveload

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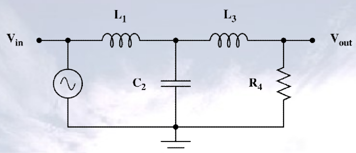
Butterworth filter

$C_2 = 1F$

$R_4 = 1\Omega$

$L_1 = \frac{3}{2}H$

$L_3 = \frac{1}{2}H$



$$H(s) = \frac{V_O}{V_I} = \frac{1}{1+2s+2s^2+s^3}$$

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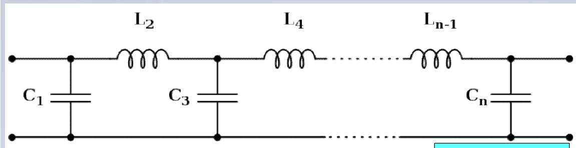
Butterworth filter



Wikipedia
by Alessio Damato

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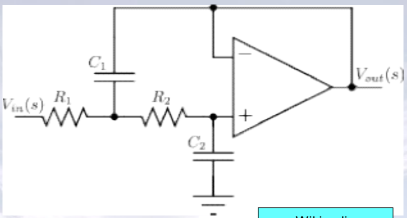
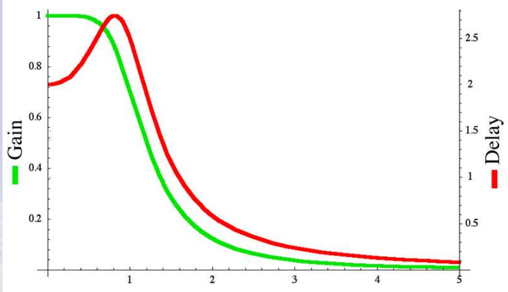
Butterworth filter



Wikipedia
by Guillaume Simard

$$H(s)=\frac{V_O(s)}{V_I(s)}=\frac{1}{1+C_2(R_1+R_2)s+C_1C_2R_1R_2s^2}$$

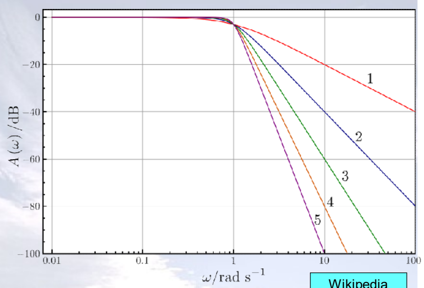
Butterworth filter



Wikipedia
by PAR

Butterworth filter

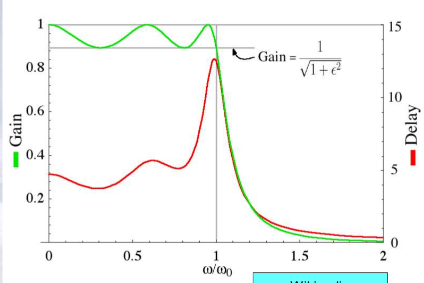
$$G^2(\omega)=|H(j\omega)|^2=\frac{G_0^2}{1+\left(\frac{\omega}{\omega_C}\right)^{2n}}$$



Wikipedia
by Inductiveload

Chebyshev filter type I

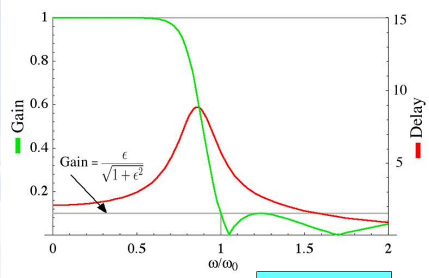
$$G_n(\omega)=|H_n(j\omega)|=\frac{1}{\sqrt{1+\varepsilon^2T_n^2\left(\frac{\omega}{\omega_C}\right)}}$$



Wikipedia
by PAR

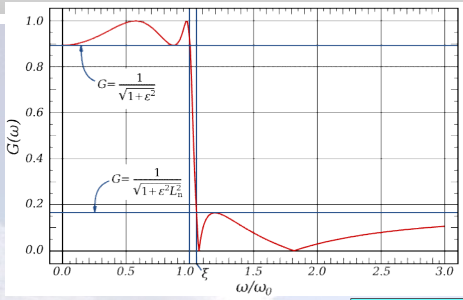
Chebyshev filter type 2

$$G_n(\omega)=|H_n(j\omega)|=\frac{1}{\sqrt{1+\varepsilon^2T_n^2\left(\frac{\omega}{\omega_C}\right)}}$$



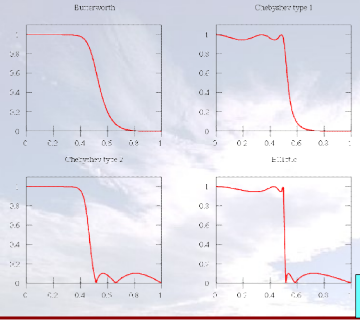
Wikipedia
by PAR

Elliptic filter



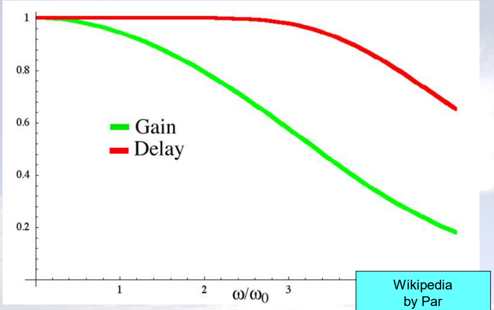
Wikipedia
by Inductiveload

Filter characteristics



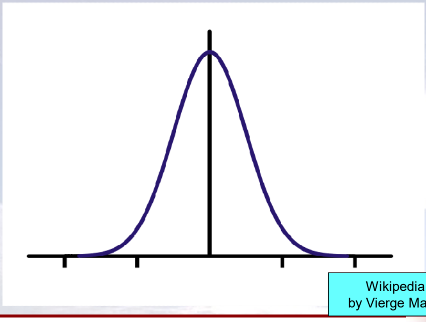
Wikipedia
by Alessio Damato

Bessel filter



Wikipedia
by Par

Gaussian filter



Wikipedia
by Vierge Marie

Active filters of high orders

Classification
- Butterworth filter – no gain ripple in pass band and stop band, slow cutoff
- Chebyshev filter (Type I) – no gain ripple in stop band, moderate cutoff
- Chebyshev filter (Type II) – no gain ripple in pass band, moderate cutoff
- Elliptic filter – gain ripple in pass and stop band, fast cutoff
- Bessel filter – no group delay ripple, no gain ripple in both bands, slow gain cutoff
- Optimum "L" filter
- Gaussian filter – no ripple in response to step function
- Hourglass filter
- Raised-cosine filter

Discrete time filters

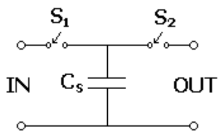
- Switched capacitor
- DSP (Digital Signal Processor)

Switched capacitor

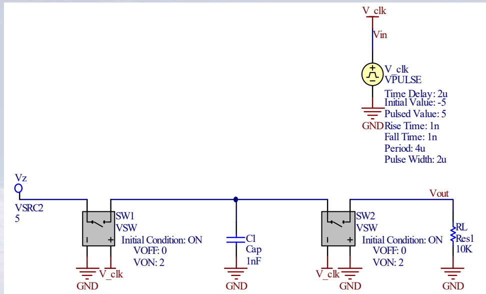
A switched capacitor is an electronic circuit element used for discrete time signal processing. It works by moving charges into and out of capacitors when switches are opened and closed.
Usually, non-overlapping signals are used to control the switches, so that not all switches are closed simultaneously.
Filters implemented with these elements are termed 'switched-capacitor filters'.
Unlike analog filters, which must be constructed with resistors, capacitors (and sometimes inductors) whose values are accurately known, switched capacitor filters depend only on the ratios between capacitances. This makes them much more suitable for use within integrated circuits, where accurately specified resistors and capacitors are not economical to construct

Switched capacitor as a resistor

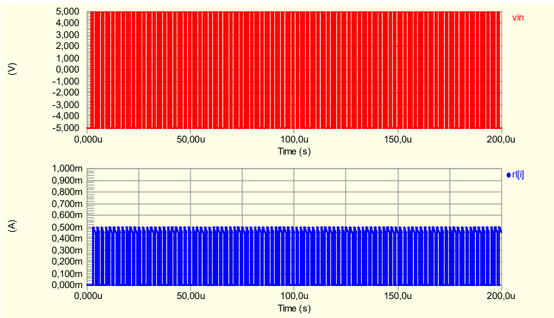
$$q = CV$$
$$q_{In} = C_S V_{In}$$
$$q_{Out} = C_S V_{Out}$$
$$q = q_{Out} - q_{Out} = C_S (V_{Out} - V_{In})$$
$$I = qf$$
$$I = C_S (V_{Out} - V_{In}) f$$
$$V = V_{Out} - V_{In}$$
$$R = \frac{V}{I} = \frac{1}{C_S f}$$



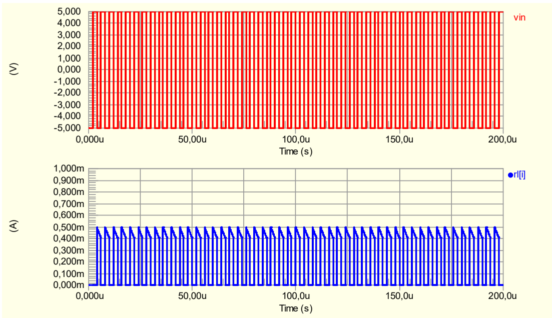
Switched capacitor as a resistor



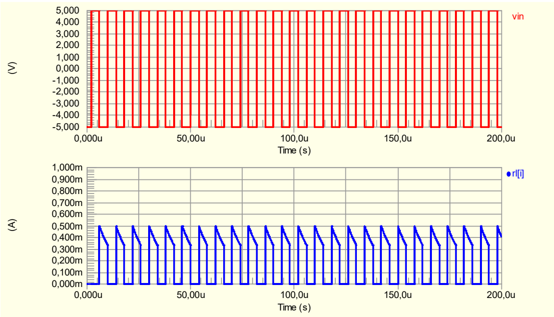
Switched capacitor as a resistor



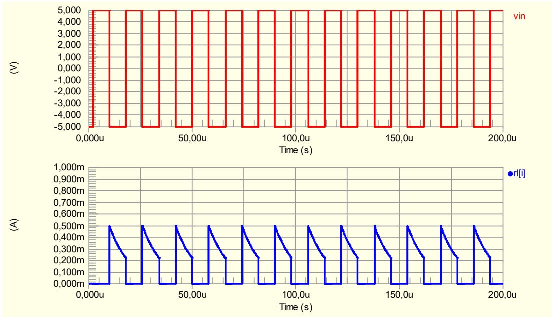
Switched capacitor as a resistor



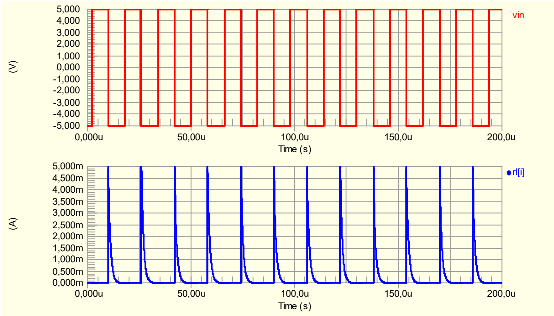
Switched capacitor as a resistor



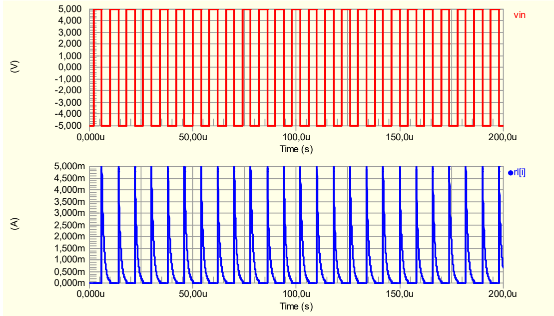
Switched capacitor as a resistor



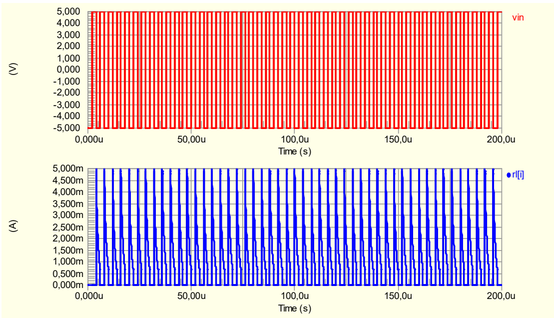
Switched capacitor as a resistor



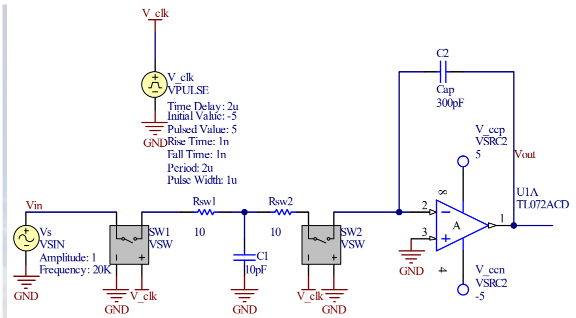
Switched capacitor as a resistor



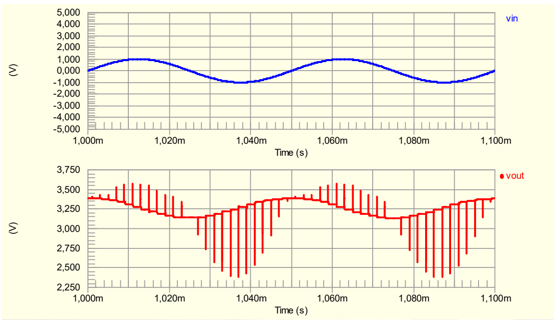
Switched capacitor as a resistor



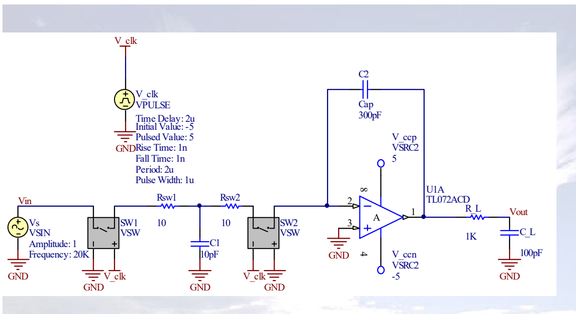
Switched capacitor as an integrator



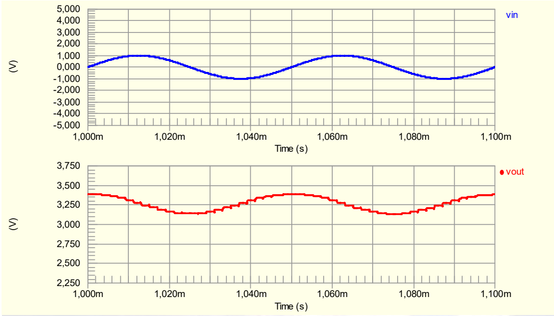
Switched capacitor as an integrator



Switched capacitor as an integrator



Switched capacitor as an integrator



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Analog filters IC

- LTC1062
- LTC1562
- LTC1569-7
- DF1704
- LTC1060
- MAX270
- MAX271
- MAX274
- MAX275
- MAX280
- MAX7480

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Lecture Plan

1. Noise in active circuits
2. Power amplifiers integrated circuits.
3. Broadband and impulse amplifiers integrated circuits
4. Active analog filters with continuous and discrete time
5. **Analog multipliers**
6. Detectors of amplitude, frequency and phase
7. Phase-locked loop and its applications
8. Programmable analog circuits and their applications.
9. Application specific integrated circuits.
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4. Active analog filters with continuous and discrete time
5. Analog multipliers
6. **Detectors of amplitude, frequency and phase**
7. Phase-locked loop and its applications
8. Programmable analog circuits and their applications.
9. Application specific integrated circuits.
10. Digital integrated circuits.

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Detectors of amplitude, frequency and phase

Literature:

U. Tietze,Ch. Shenck, Electronics circuits, design and applications, Springer-Verlag, 2001

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Detectors of amplitude, frequency and phase.

- Modulation
- Radio receiver
- Amplitude detectors
- Frequency detectors
- Phase detectors
- IC implementations

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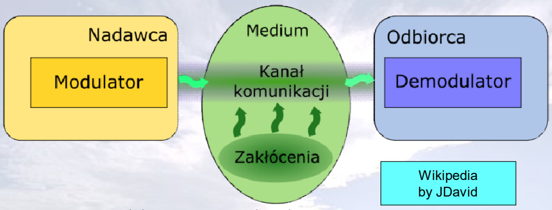
Modulation

signal $v_s(t)$



carier $v_c(t) = V\cos(\omega t)$

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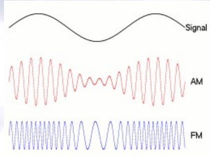
Modulation

Basic modulation types
- amplitude
- frequency
- phase

$c(t) = C\cos(\omega_c t + \varphi_c)$



Wikipedia by Berserkerus

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Amplitude modulation

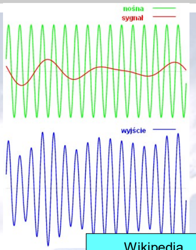
$c(t) = \cos(\omega_c t)$

$m(t) = M\cos(\omega_m t)$

$\omega_m << \omega_c$

$y(t) = [A + m(t)]c(t)$

$y(t) = [A + M\cos(\omega_m t)]\cos(\omega_c t)$



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

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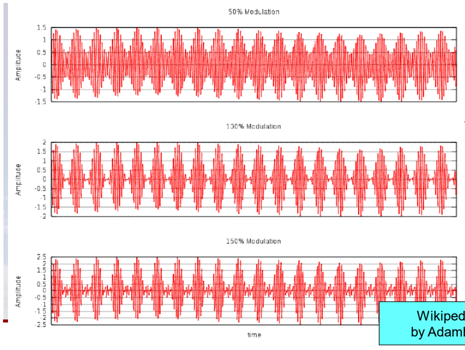
Amplitude modulation



$k = \frac{M}{A}$

$k = \frac{\max(m(t))}{A}$

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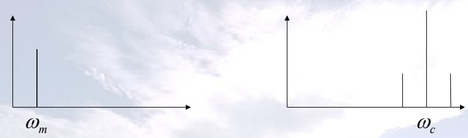
Amplitude modulation

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



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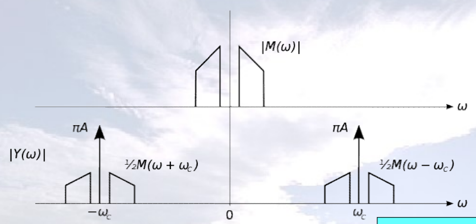
Amplitude modulation

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



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Amplitude modulation

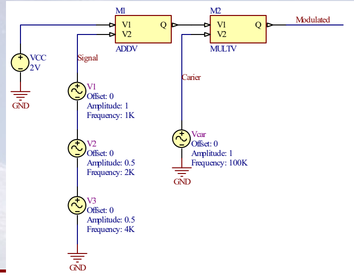
$$y(t) = A\cos(\omega_c t) + \frac{M}{2}\cos((\omega_c + \omega_m)t) + \frac{M}{2}\cos((\omega_c - \omega_m)t)$$

Amplitude modulation

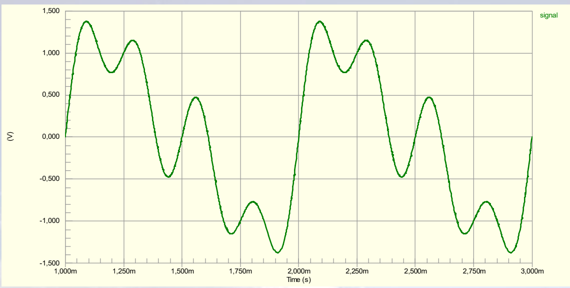
- DSB-LC (AM) Double-Sideband Large Carrier)
- DSB-SC Double-Sideband Suppressed Carrier
- SSB Single-Sideband Modulation
- VSB Vestigial-Sideband Modulation

Amplitude modulation

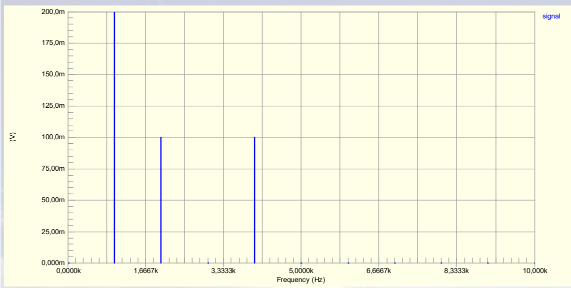
$$y(t) = [A + m(t)]c(t) = [A + M\cos(\omega_m t + \varphi_m)]\cos(\omega_c t)$$



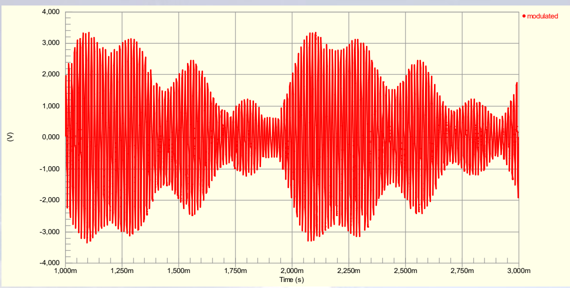
Amplitude modulation



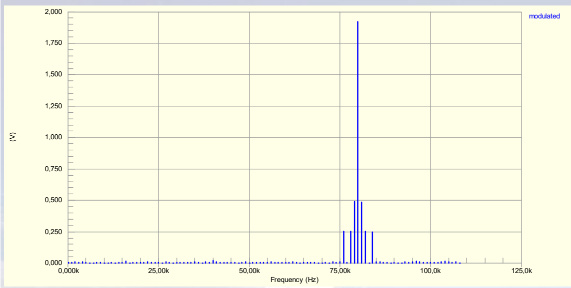
Amplitude modulation



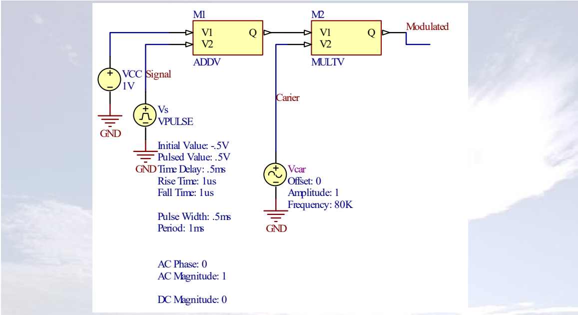
Amplitude modulation



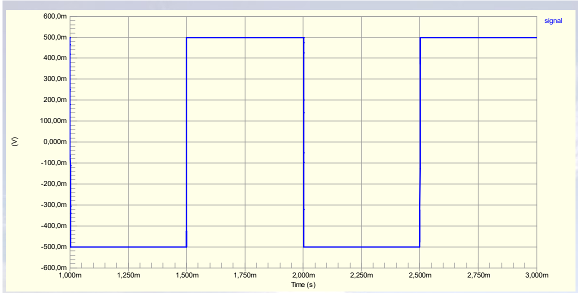
Amplitude modulation



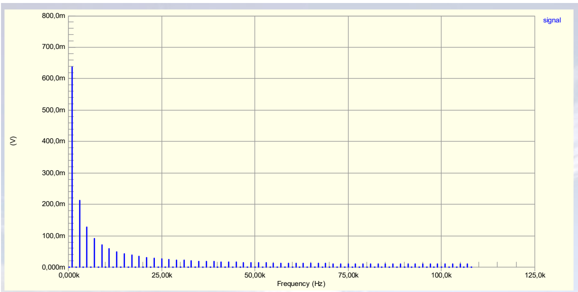
Amplitude modulation



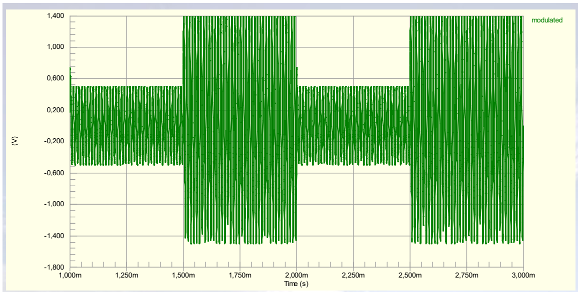
Amplitude modulation



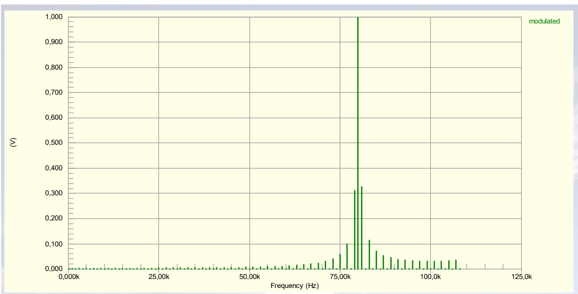
Amplitude modulation



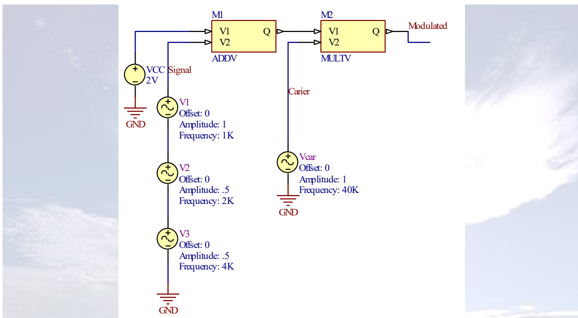
Amplitude modulation



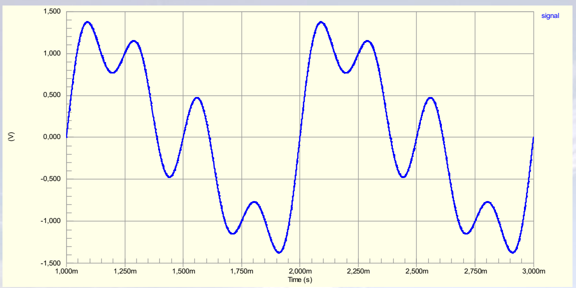
Amplitude modulation



Amplitude modulation



Amplitude modulation



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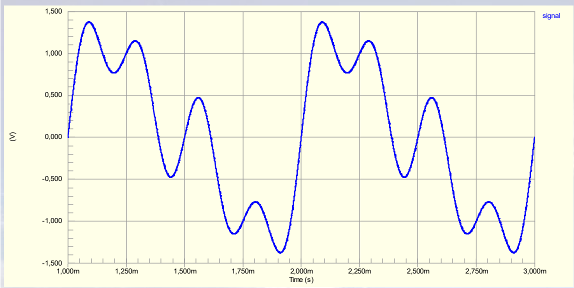
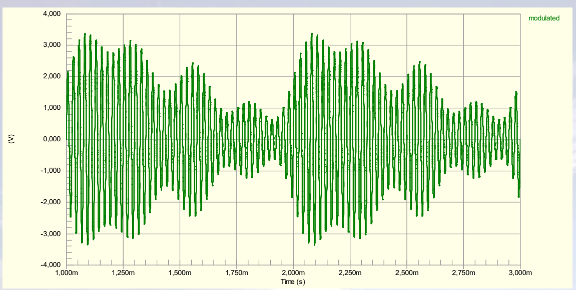
Amplitude modulation



332

Amplitude modulation



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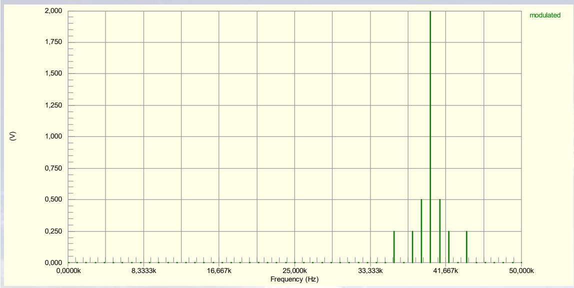
Amplitude modulation



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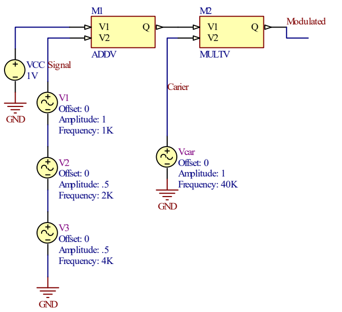
Amplitude modulation



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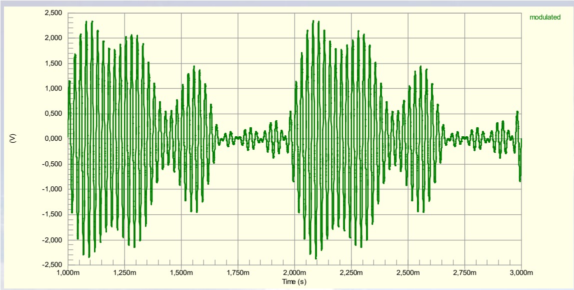
Amplitude modulation



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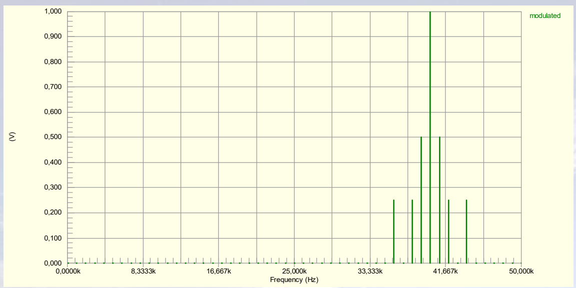
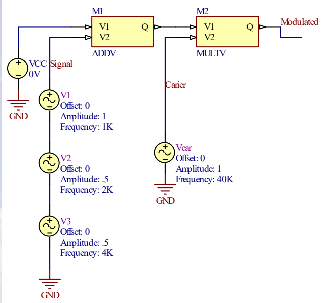
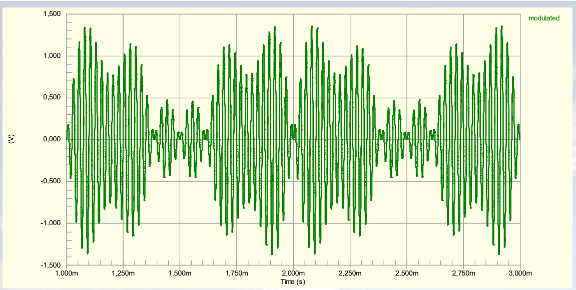
Amplitude modulation



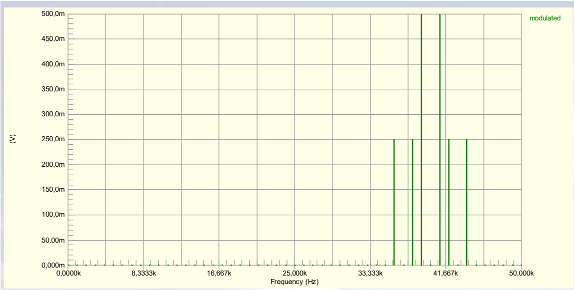
Amplitude modulation



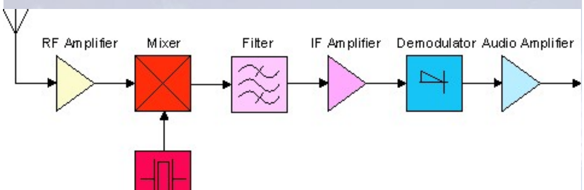
Amplitude modulation



Amplitude modulation

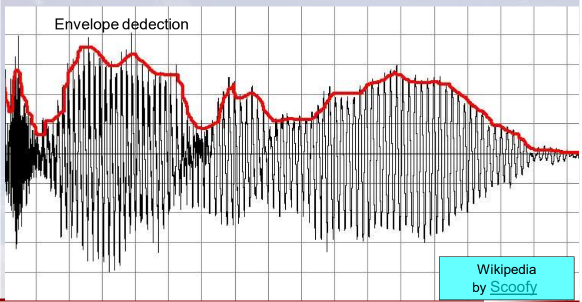


RF receiver



Wikipedia
by Jonnabuz

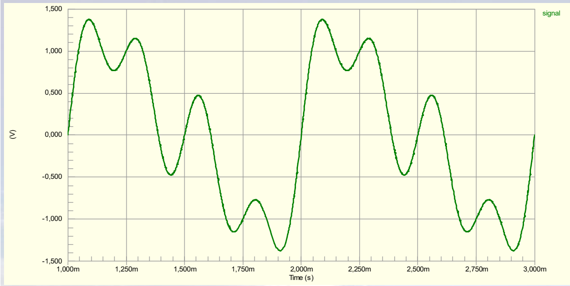
Detection (demodulation) AM signal



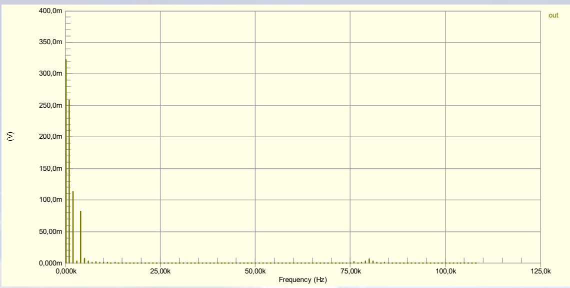
Wikipedia
by Scoofy

Detection (demodulation) AM signal

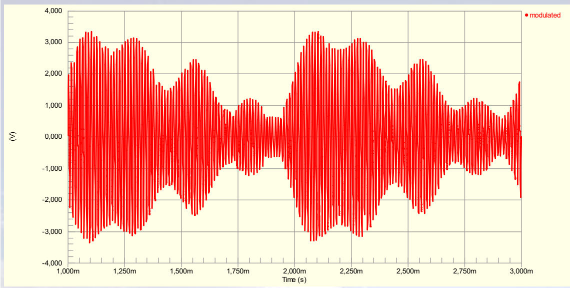
Detekcja (demodulacja) sygnału AM



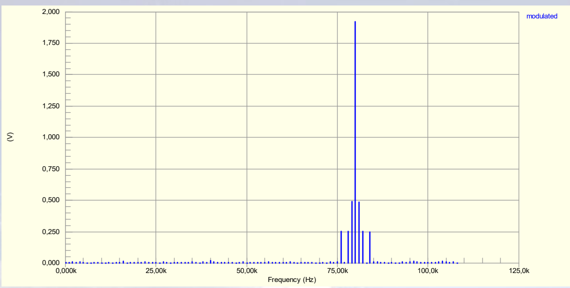
Detection (demodulation) AM signal



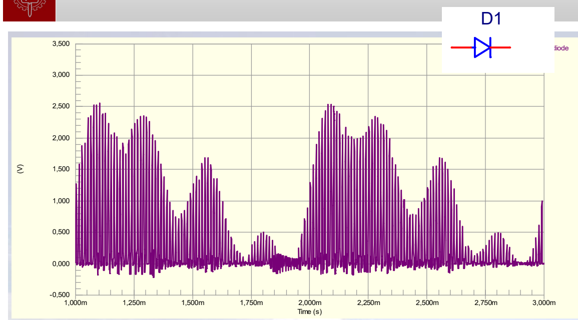
Detection (demodulation) AM signal



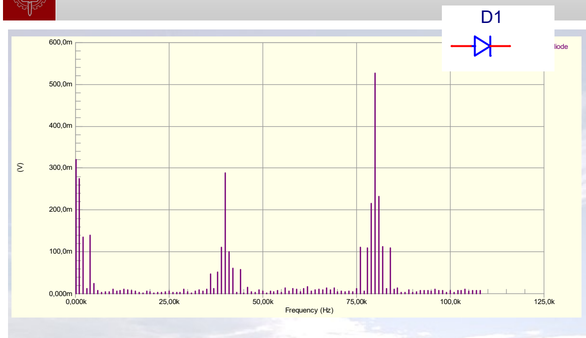
Detection (demodulation) AM signal



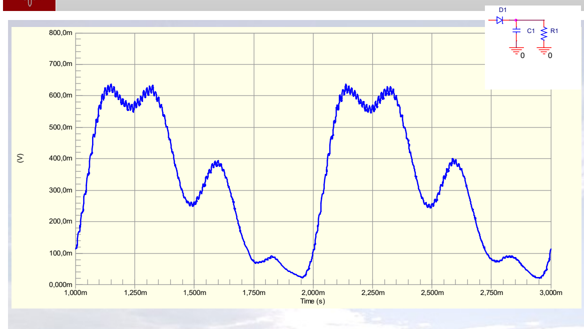
Detection (demodulation) AM signal



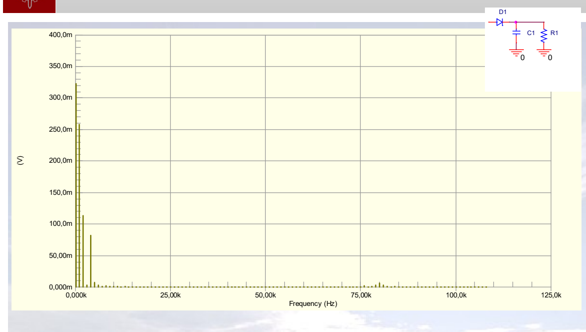
Detection (demodulation) AM signal



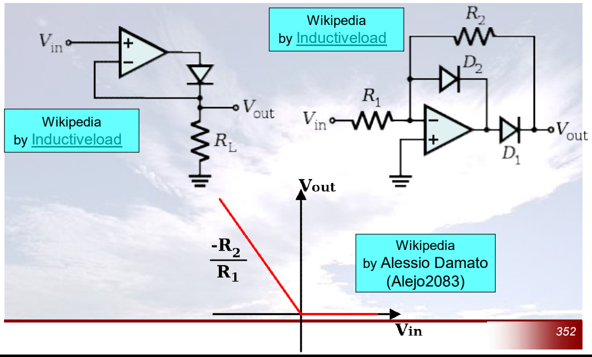
Detection (demodulation) AM signal



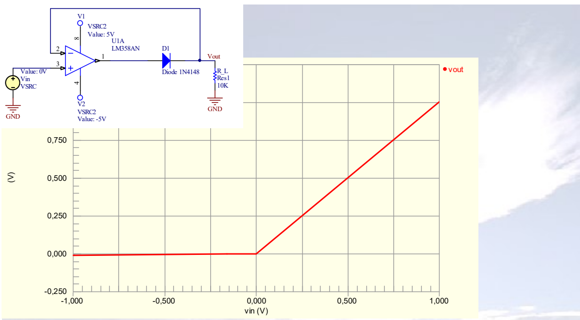
Detection (demodulation) AM signal



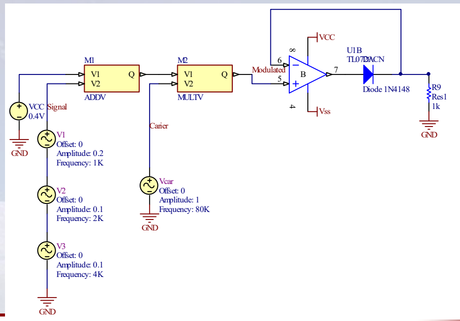
Superdiode



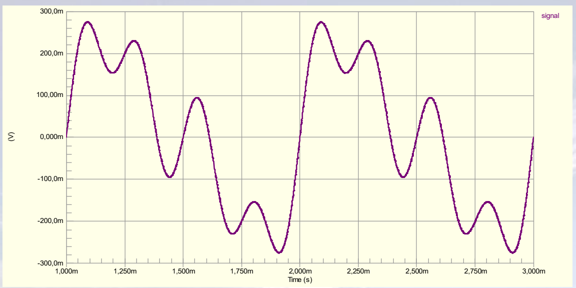
Superdiode



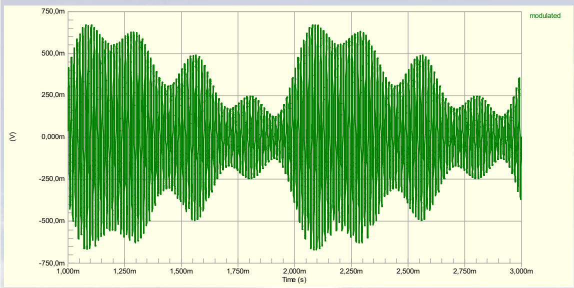
AM detector with superdiode



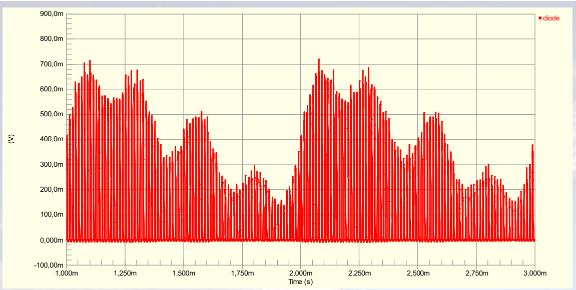
AM detector with superdiode



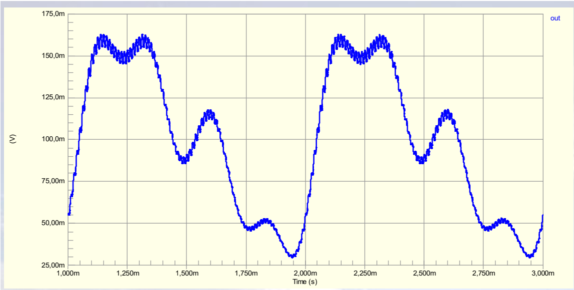
AM detector with superdiode



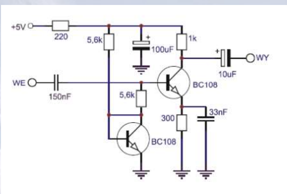
AM detector with superdiode



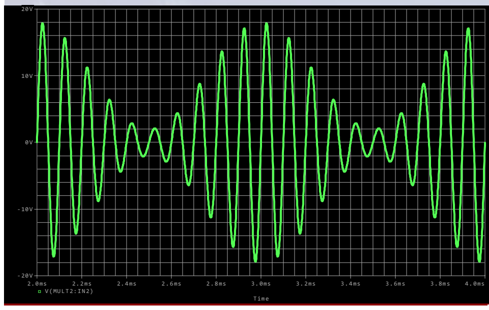
AM detector with superdiode



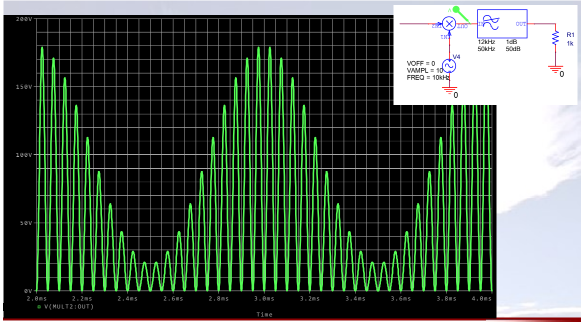
Transistor based demodulator



Detection (demodulation) AM signal



Detection (demodulation) AM signal



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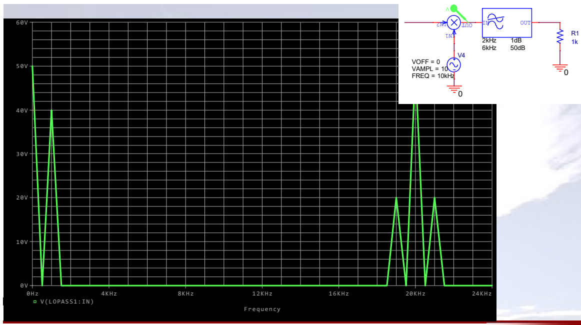
Detection (demodulation) AM signal



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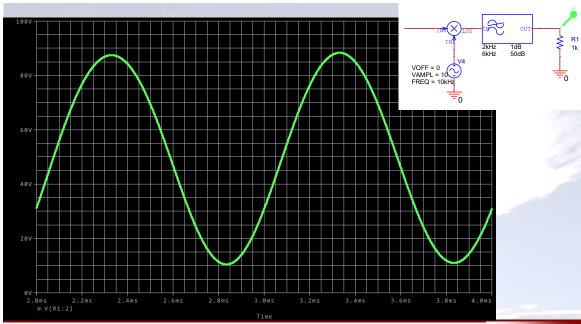
Detection (demodulation) AM signal



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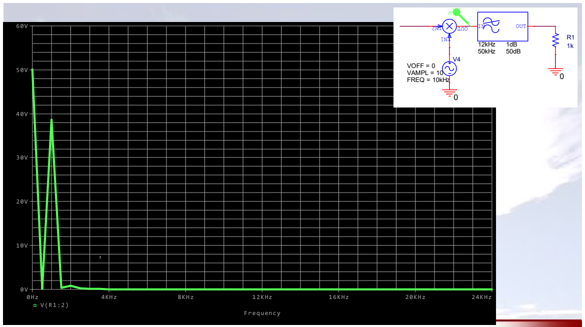
Detection (demodulation) AM signal



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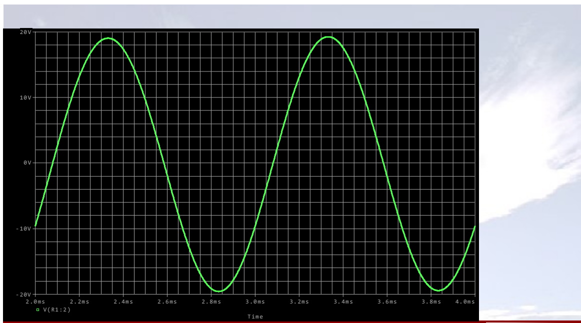
Detection (demodulation) AM signal



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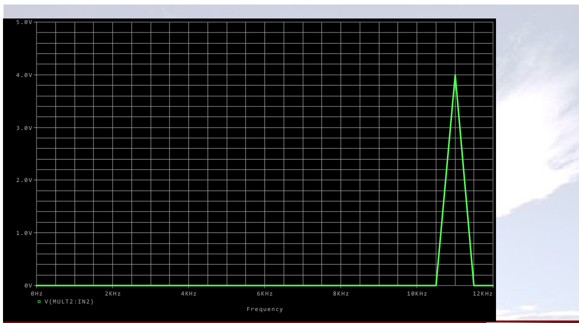
Detection (demodulation) AM signal



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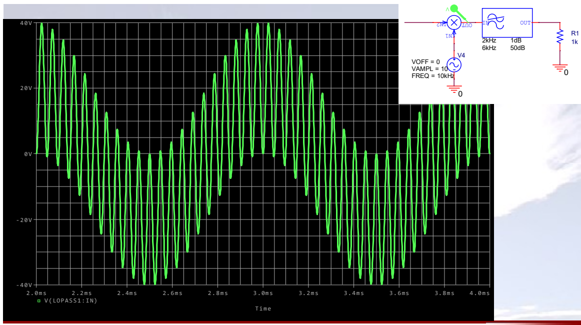
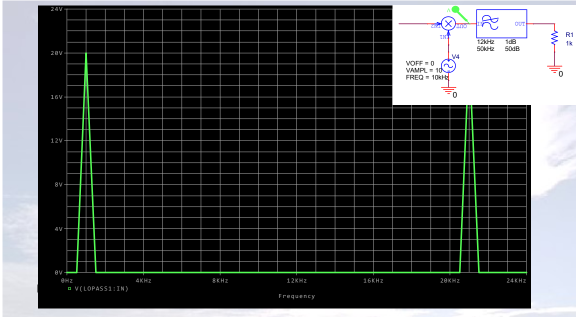
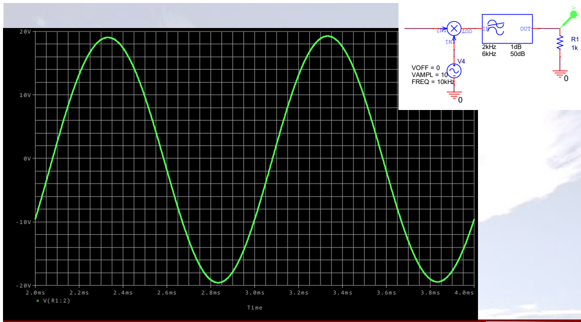
Detection (demodulation) AM signal



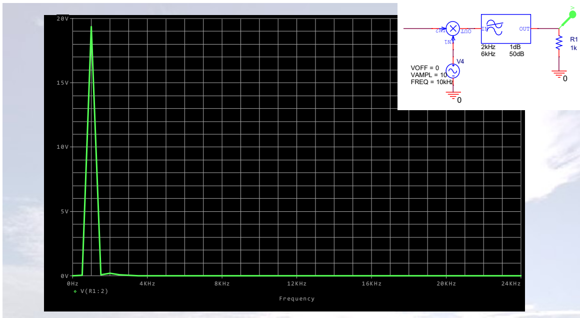
Detection (demodulation) AM signal



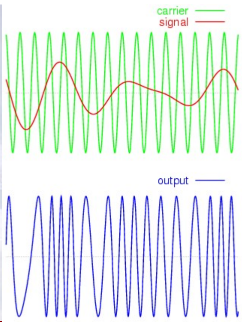
Detection (demodulation) AM signal



Detection (demodulation) AM signal

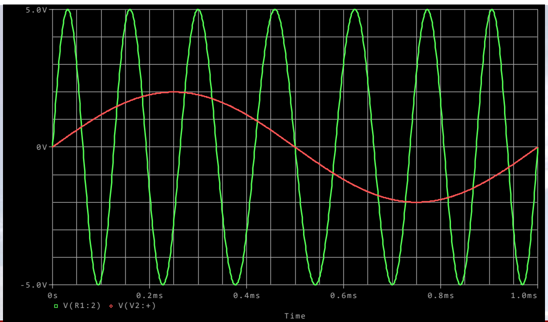


Detection (demodulation) FM signal

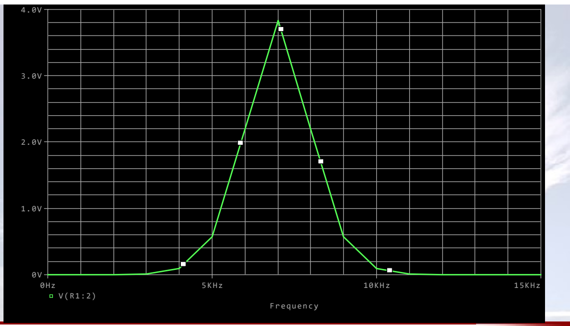


Wikipedia
by Scoofy

FM (carier 7kHz signal 1kHz)



FM (carier 7kHz signal 1kHz)



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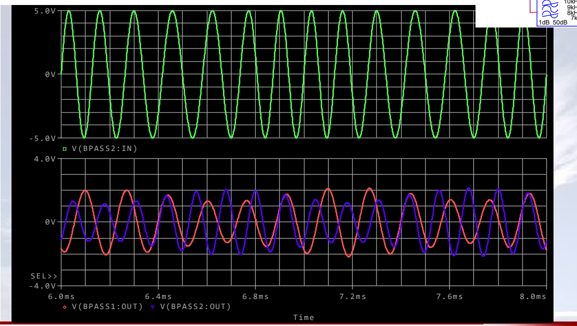
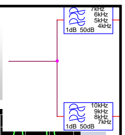
FM Detector (demodulator)

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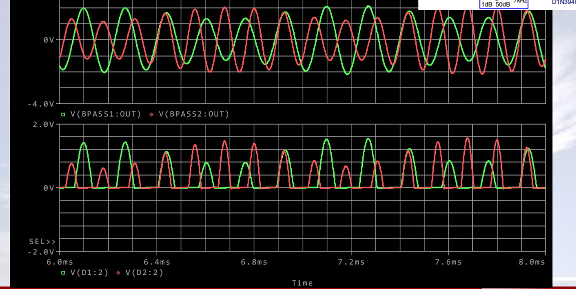
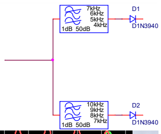
FM Detector

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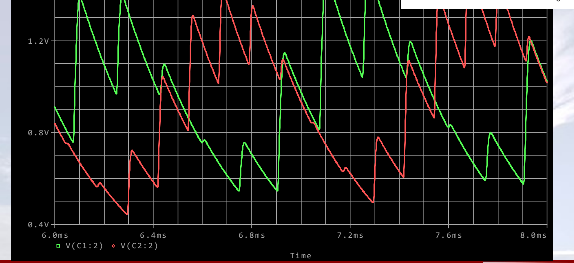
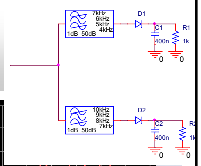
FM Detector

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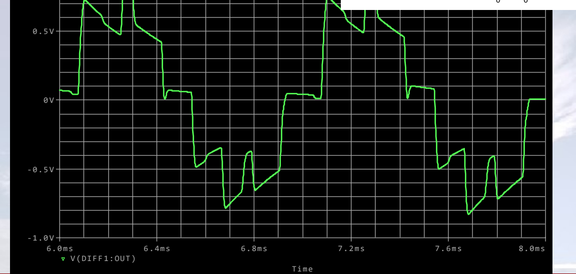
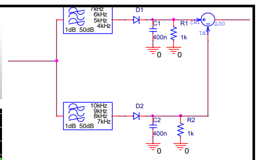
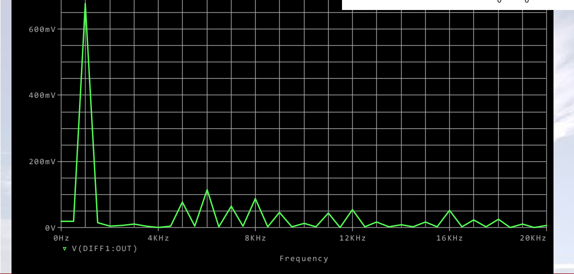
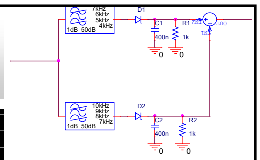
FM Detector

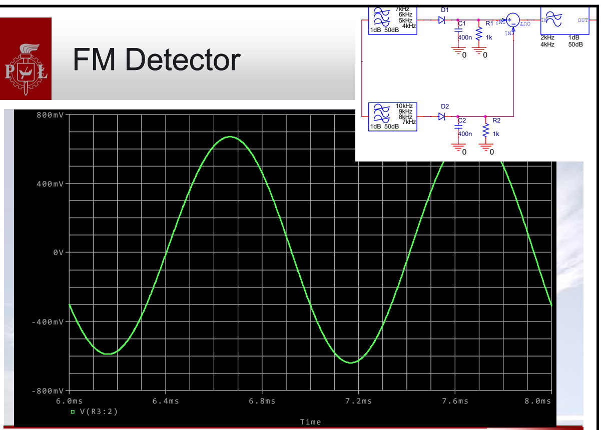
377

FM Detector

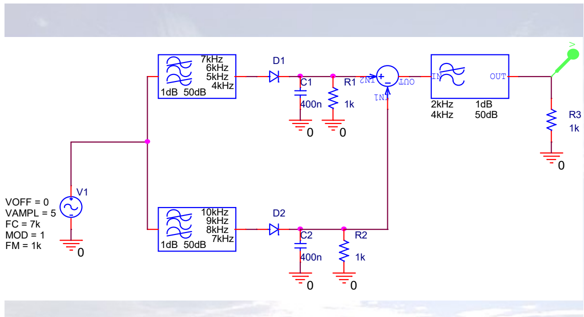



378

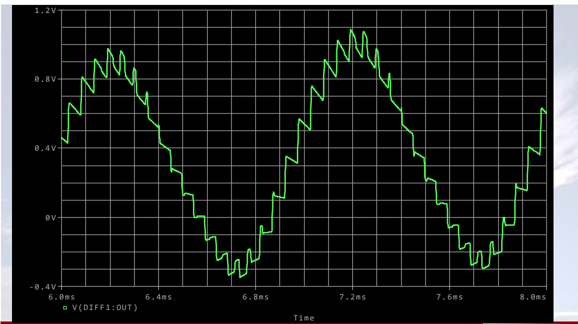
FM Detector



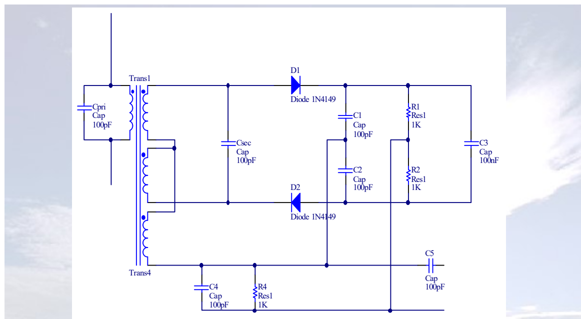
Balanced Slope Detector



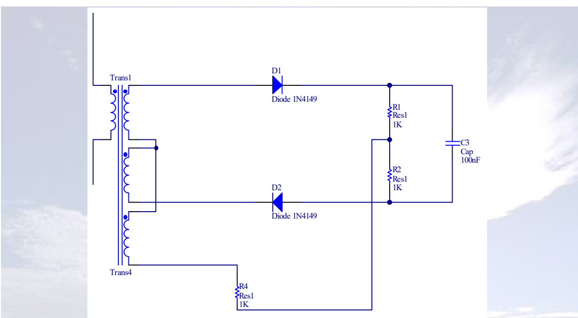
FM Detector



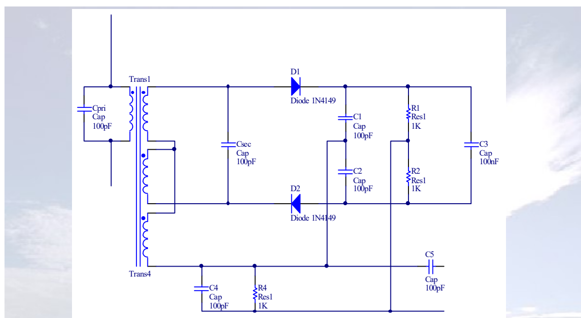
Ratio Detector



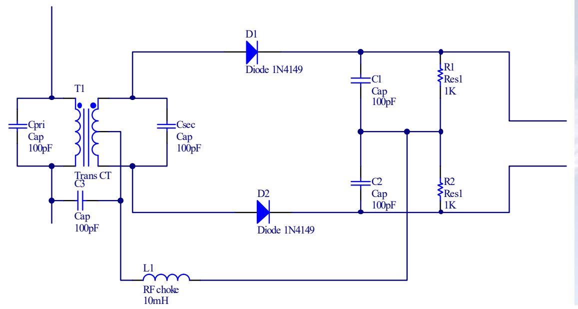
Ratio Detector



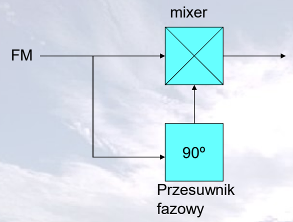
Ratio Detector



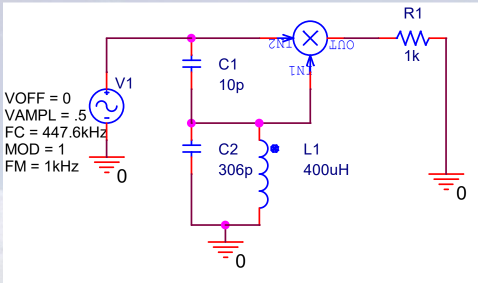
Foster-Seeley detector



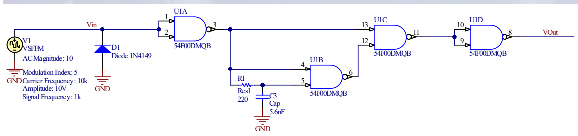
Quadrature FM detector



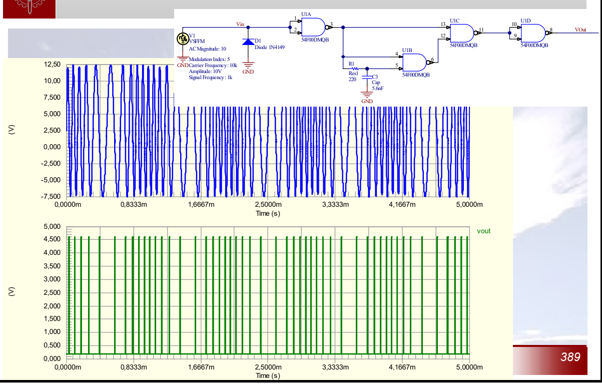
Quadrature FM detector



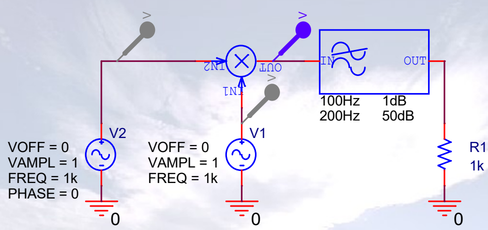
Impulse counting FM demodulator



Impulse counting FM demodulator



Phase detector



Multiplication of two sine waves

$\sin(2\pi f_1 t+\varphi_1)$ $\sin(2\pi f_2 t+\varphi_2)$

$\sin(\omega_1 t+\varphi_1)$ $\sin(\omega_2 t+\varphi_2)$

$\sin(\alpha)\sin(\beta)=\frac{1}{2}\cos(\alpha-\beta)-\frac{1}{2}\cos(\alpha+\beta)$

$\cos(\alpha)=\sin(\alpha+90°)=\sin\left(\alpha+\frac{\pi}{2}\right)$

$-\sin(\alpha)=\sin(\alpha+\pi)$

$$\sin(\omega_1 t+\varphi_1)\sin(\omega_2 t+\varphi_2)=$$
$$=\frac{1}{2}\cos(\omega_1 t-\omega_2 t+\varphi_1-\varphi_2)-\frac{1}{2}\cos(\omega_1 t+\omega_2 t+\varphi_1+\varphi_2)=$$
$$=\frac{1}{2}\sin\left(\omega_1 t-\omega_2 t+\varphi_1-\varphi_2+\frac{\pi}{2}\right)-\frac{1}{2}\sin\left(\omega_1 t+\omega_2 t+\varphi_1+\varphi_2+\frac{\pi}{2}\right)=$$
$$=\frac{1}{2}\sin\left(\omega_1 t-\omega_2 t+\varphi_1-\varphi_2+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(\omega_1 t+\omega_2 t+\varphi_1+\varphi_2-\frac{\pi}{2}\right)$$

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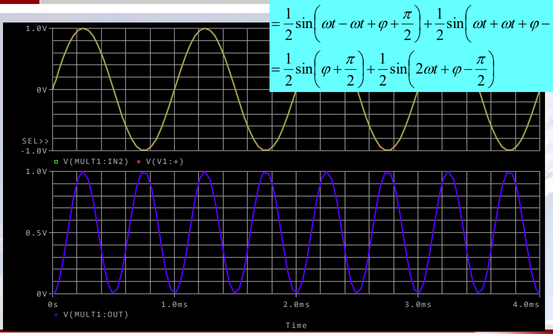
Phase detector

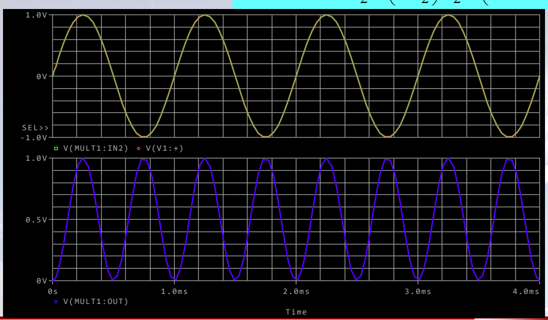
$$\sin(\omega t)\sin(\omega t+\varphi)=$$
$$=\frac{1}{2}\sin\left(\omega t-\omega t+\varphi+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(\omega t+\omega t+\varphi-\frac{\pi}{2}\right)=$$
$$=\frac{1}{2}\sin\left(\varphi+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(2\omega t+\varphi-\frac{\pi}{2}\right)$$



392

Phase detector

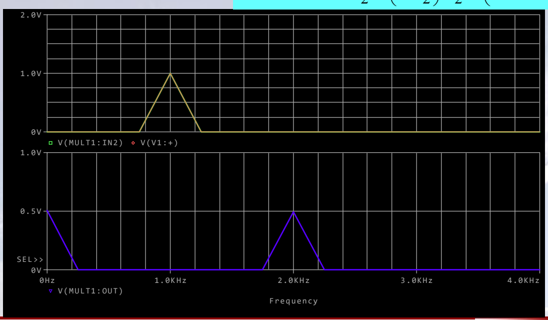
$$\sin(\omega t)\sin(\omega t+\varphi)=\frac{1}{2}\sin\left(\varphi+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(2\omega t+\varphi-\frac{\pi}{2}\right)$$



393

Phase detector

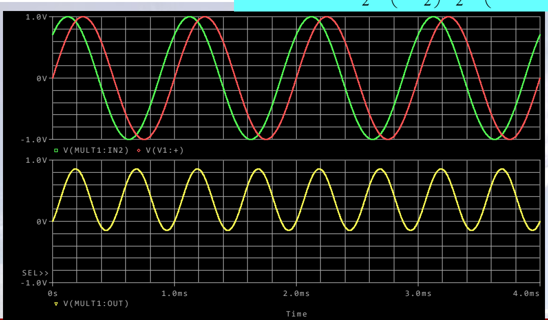
$$\sin(\omega t)\sin(\omega t+\varphi)=\frac{1}{2}\sin\left(\varphi+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(2\omega t+\varphi-\frac{\pi}{2}\right)$$



394

Phase detector

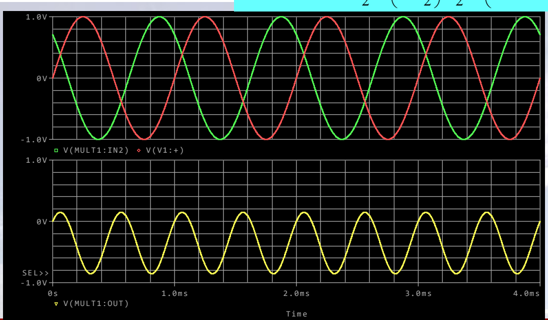
$$\sin(\omega t)\sin(\omega t+\varphi)=\frac{1}{2}\sin\left(\varphi+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(2\omega t+\varphi-\frac{\pi}{2}\right)$$



395

Phase detector

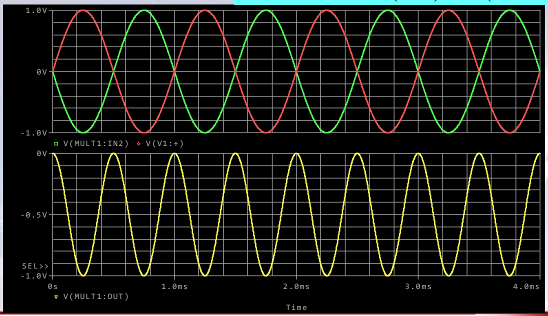
$$\sin(\omega t)\sin(\omega t+\varphi)=\frac{1}{2}\sin\left(\varphi+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(2\omega t+\varphi-\frac{\pi}{2}\right)$$



396

Phase detector

$$\sin(\omega t)\sin(\omega t+\varphi)=\frac{1}{2}\sin\left(\varphi+\frac{\pi}{2}\right)+\frac{1}{2}\sin\left(2\omega t+\varphi-\frac{\pi}{2}\right)$$



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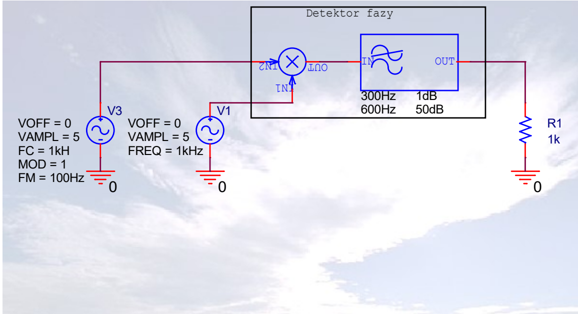
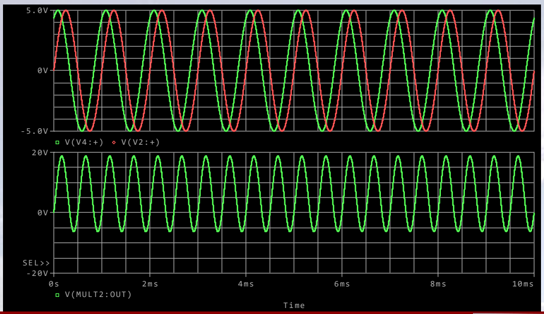
Phase detection



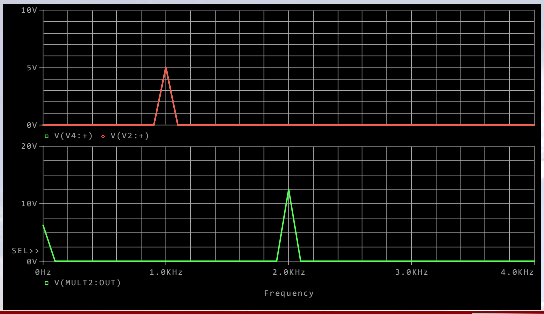
398

Phase detection



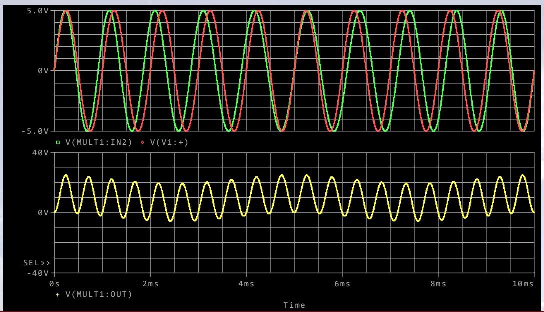
399

Phase detection



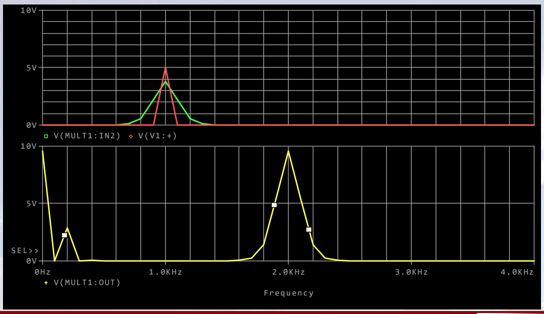
400

Phase detection



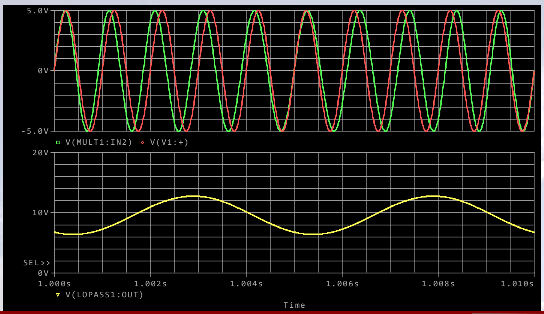
401

Phase detection



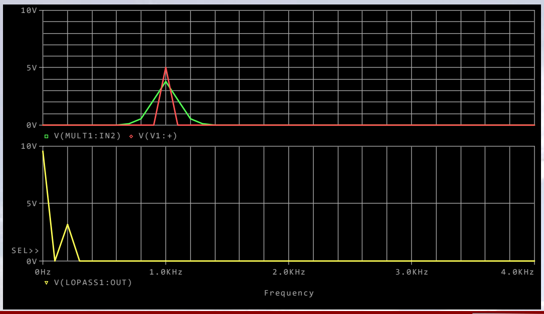
402

Phase detection



403

Phase detection



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Lecture Plan

1. Noise in active circuits
2. Power amplifiers integrated circuits.
3. Broadband and impulse amplifiers integrated circuits
4. Active analog filters with continuous and discrete time
5. Analog multipliers
6. Detectors of amplitude, frequency and phase
7. **Phase-locked loop and its applications**
8. Programmable analog circuits and their applications.
9. Application specific integrated circuits.
10. Digital integrated circuits.

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Detectors of amplitude, frequency and phase

Literature:

U. Tietze,Ch. Shenck, Electronics circuits, design and applications, Springer-Verlag, 2001

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Phase-locked loop (PLL)

PLL is a control system that generates a signal that has a fixed relation to the phase of a "reference" signal.

A PLL circuit responds to both the frequency and the phase of the input signals, automatically raising or lowering the frequency of a controlled oscillator until it is matched to the reference in both frequency and phase.

PLL is an example of a control system using negative feedback.

Wikipedia

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Phase-locked loop (PLL)

Wikipedia
by Alessio Damato
(Alejo2083)

Applications:
- radio, telecommunications,
- computers
- other electronic applications.

Tasks:
- generation of stable frequencies,
- recovering signals from a noisy communication channel,
- distribution of clock timing pulses in digital logic designs such as microprocessors.

Since a single integrated circuit can provide a complete phase-locked-loop building block, the technique is widely used in modern electronic devices, with output frequencies from a fraction of a cycle per second up to many gigahertz.

Wikipedia

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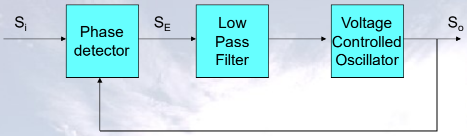
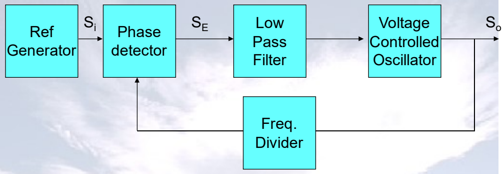
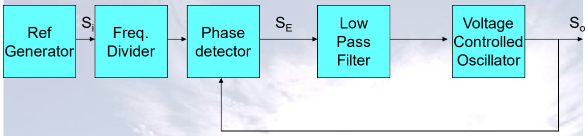
PLL schematics



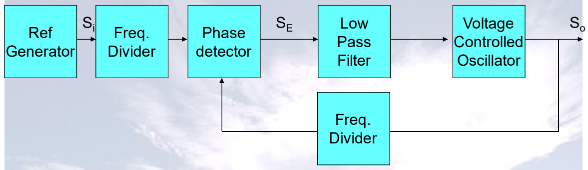
PLL



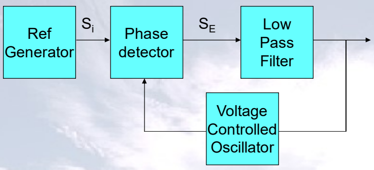
PLL



PLL



PLL as FM demodulator



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8. **Programmable analog circuits and their applications**.
9. Application specific integrated circuits.
10. Digital integrated circuits.

Programmable analog circuits and their applications

Literature:

U. Tietze,Ch. Shenck, Electronics circuits, design and applications, Springer-Verlag, 2001

Lecture Plan

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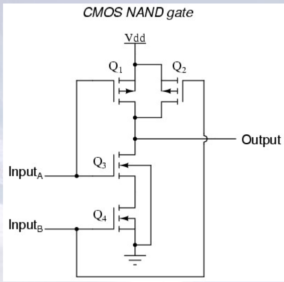
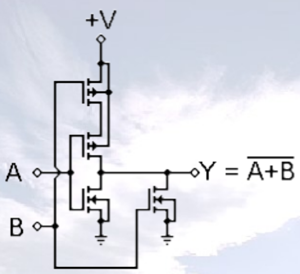
Digital programmable ICs Application specific integrated circuits.

Literature:

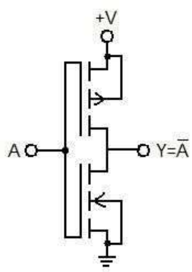
Digital programmable ICs Application specific integrated circuits.



Digital programmable ICs Application specific integrated circuits.



Digital programmable ICs Application specific integrated circuits.

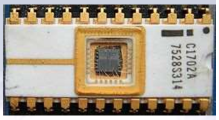


Scheme of not gate in CMOS technology with the use of two MOSFET transistors: one N-channel with its source grounded, and one P-channel with its source connected to +V.

Digital programmable ICs

Read only memory (ROM)

- Programmable read-only memory (PROM)
- EPROM
- EEPROM
- Flash memory
- FeRAM
- MRAM
- PRAM



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PROM as PLD

Address lines - inputs (m)

Data lines – outputs (n)

2^m values stored, 2^n functions avaiable,

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Digital programmable ICs

- Motorola XC157 (1969) 12 gates 30 I/O mask programmable
- General Electric Company (1971) UV PROM PLD.

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Digital programmable ICs

- Programmable read-only memory (PROM)
- Programmable logic devices (PLD)
- Generic array logic (GAL)
- Complex programmable logic device (CPLD)
- Field-programmable gate array (FPGA)

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Application-specific integrated circuit

5,000 to over 100 million gates.

Modern ASICs often include:

- 32-bit processors,
- memory blocks including ROM, RAM, EEPROM, Flash

Designers of digital ASICs use a hardware description language (HDL), such as Verilog or VHDL, to describe the functionality of ASICs.

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Application-specific integrated circuit

- Standard cell design
- Gate array design
- Full-custom design
- Structured design
- Cell libraries, IP-based design, hard and soft macros

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IDM ASIC suppliers

- Avago Technologies
- Elmos Semiconductor
- Cavium Networks
- Fujitsu
- Freescale
- HITACHI
- IBM
- Infineon Technologies
- LSI Corporation
- Marvell Semiconductors
- NEC
- NXP Semiconductors
- ON Semiconductor
- Renesas
- Samsung
- STMicroelectronics
- Texas Instruments
- Toshiba
- TSMC

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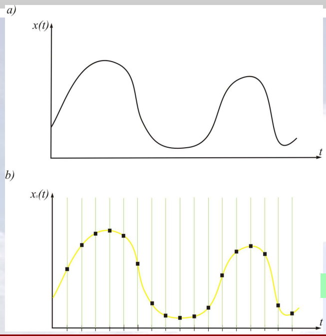
10. **Digital to analog and analog to digital converters**

Analog and Discrete Signals

Analog signal - continuous function of time

Discrete signal - defined at discrete instants of time t_0, t_1, t_2, … such that $t_i - t_{i-1} = \Delta t$ where Δt is the sampling interval

Sampling of an analog signal



©D. Mlynarski

Discrete Signals

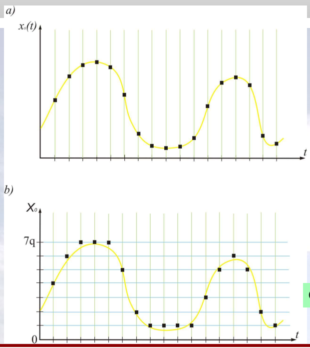
Shannon-Kotelnikov theorem:

An analog signal $x(t)$ can be perfectly reconstructed from its discrete version provided that:

1. $x(t)$ is band-limited, ie. $X(f)=0$, for $f \leq f_h$
2. the sampling frequency $f_s = 1/\Delta t$ is at least equal to $2f_h$

Discrete signal is still an analog signal, but it is not a continuous function of time.

Quantization of an discrete signal



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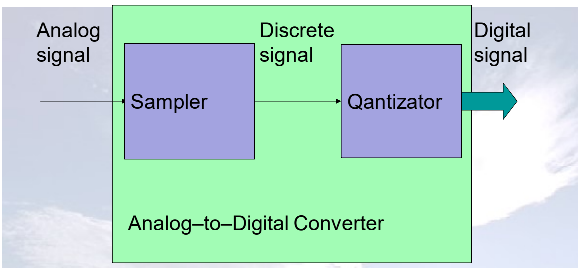
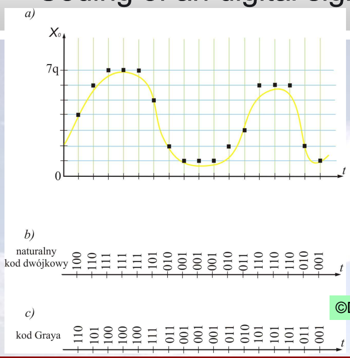
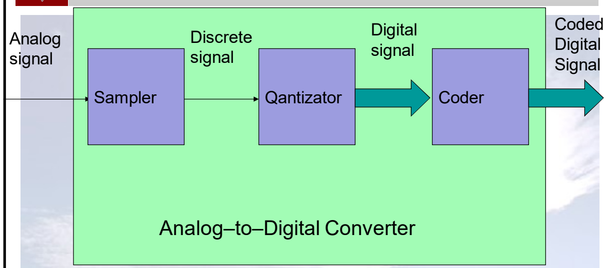
Digital signals



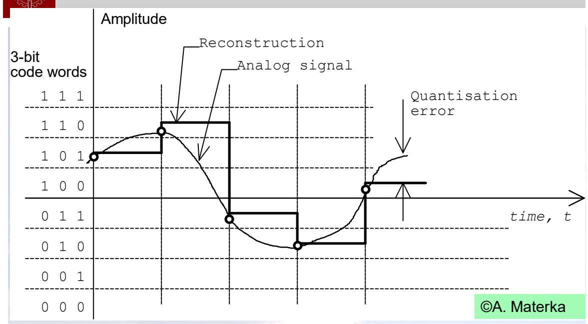
Coding of an digital signal



Analog to digital conversion



Analog signal reconstruction



Digital signals

Number of amplitude zones (quantization levels)

$$N = 2^k$$

k=8 -> N = 256
k=16 -> N = 65536
k=24 -> N = 16 777 216

10-bit - instrumentation,
16-bit - Compact Disc technology
24-bit - color image processing (3 x 8 bit, or 8 bits per color)

Advantages of digital signal processing

coming through the use of digital electronics

- flexibility (digital circuits are programmable),
- smaller tolerances on components,
- lower sensitivity to external (eg. temperature) and internal (eg. ageing and drift) effects,
- accuracy can be controlled by selecting the word length,
- circuits are reproducible (no trimming or tuning during manufacture),
- no accumulation of drift and noise -> unlimited number of successive operations,
- easier to manufacture in IC technology (no large L or C).

Advantages of digital signal processing

related to limitations of analog electronics

- “ideal memory” to store signals for an infinite time -> very low frequency signals can be processed with no need for large Cs and Ls
- linear phase filters - not available in analog electronics,
- circuits for exact compensation of two effects,
- adaptive systems,
- precise signal transforms,
- processing of 2D signals.

Main disadvantages of digital signal processing

- more supply power required (passive digital circuits do not yet exist),
- low-frequency applications,
- when used in analog environment, often complex AD and DA converters are required
- difficulties with AD and DA conversion of very weak and very strong signals -> analog pre- and post-amplifiers required,
- the same information (eg. music signal) requires larger bandwidth as a digital signal than it does as the analog one.

ADC

- http://ww1.microchip.com/downloads/en/devicedoc/21841a.pdf
- http://www.maxim-ic.com/app-notes/index.mvp/id/641/CMP/ELK-11
- http://www.analog.com/library/analogDialogue/archives/39-06/architecture.html
- http://www.beis.de/Elektronik/DeltaSigma/DeltaSigma.html
- http://en.wikipedia.org/wiki/Analog-to-digital_converter
- http://www.maxim-ic.com/app-notes/index.mvp/id/1870
- Data sheets: AD7714, MCP3008, MAX104

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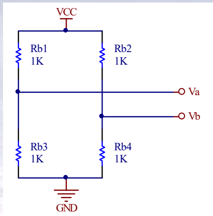
Bridge sensor e.g. load cell



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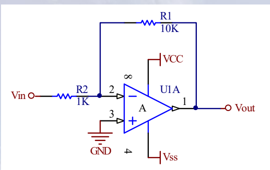
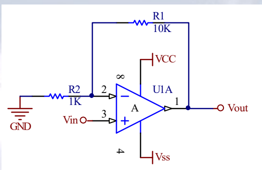
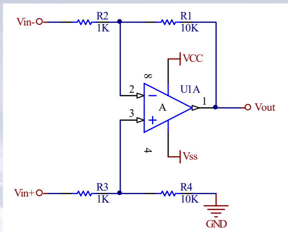
Amplifiers





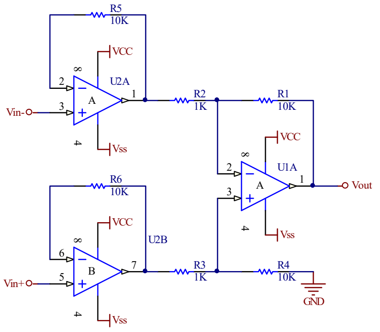
443

Differential amplifier

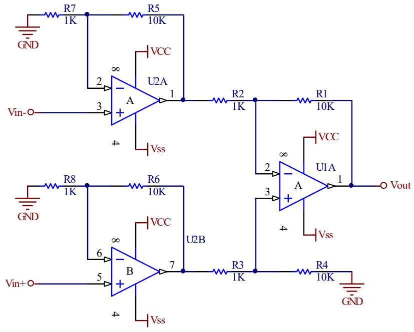


444

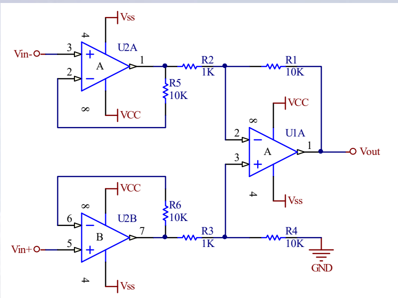
Buffered differential amplifier



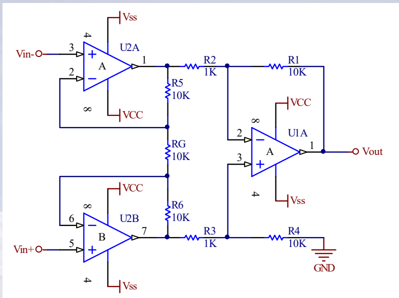
Buffered differential amplifier



Buffered differential amplifier



Instrumentation amplifier



Instrumentation amplifier

- INA114
- INA128
- AD8422
- LT1167