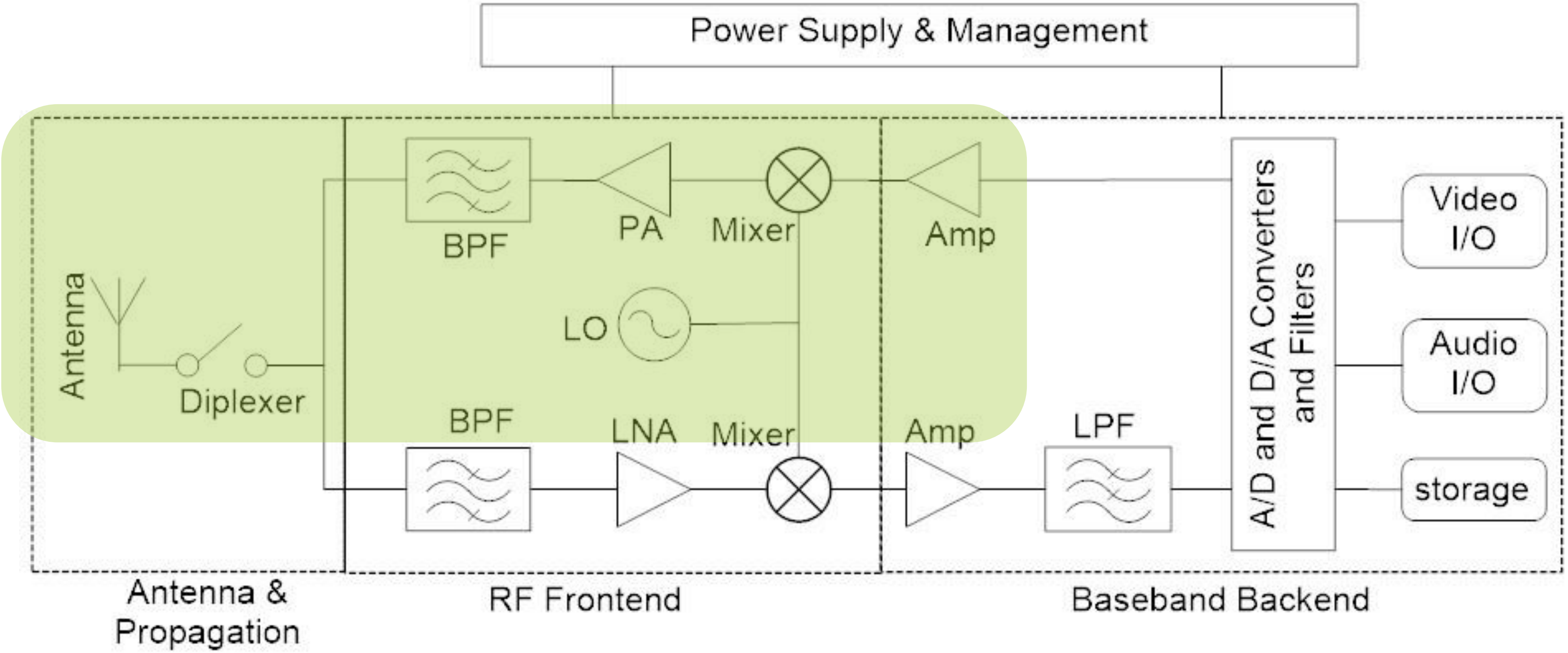
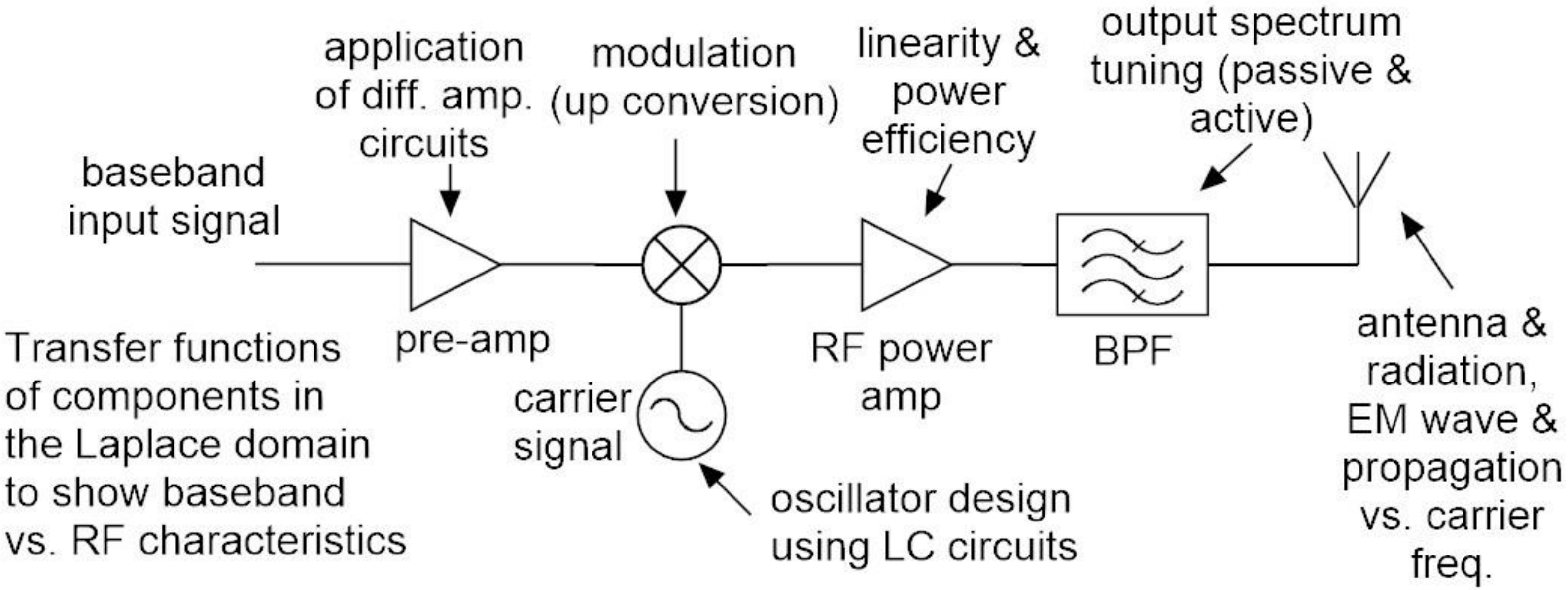
KI4: SIGNAL TRANSMISSION IN A RADIO SYSTEM

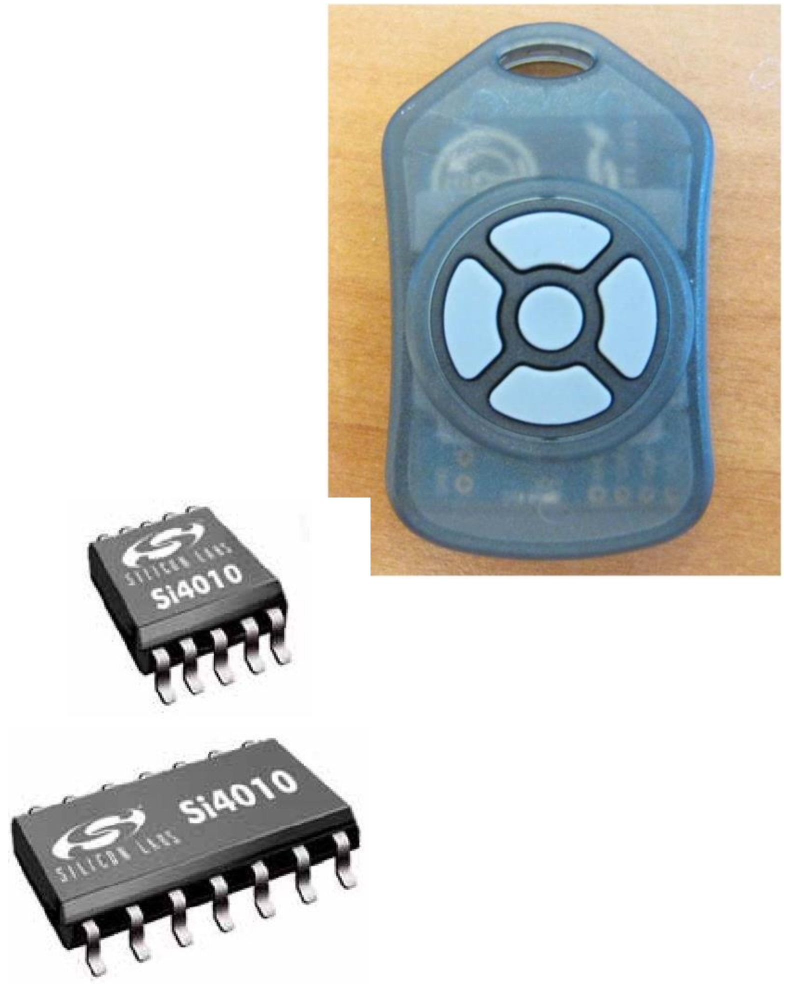


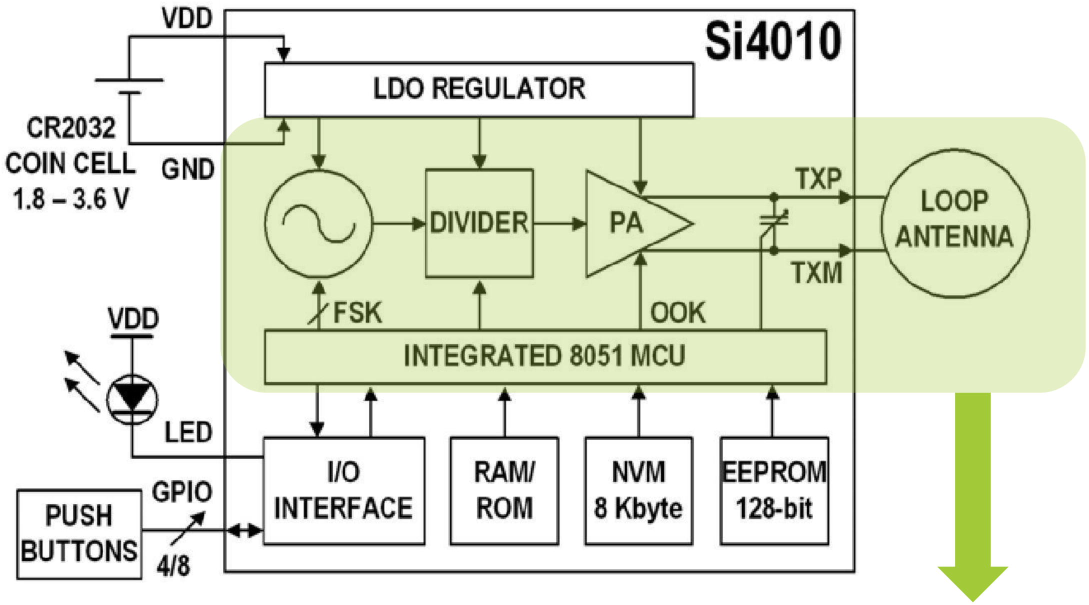
DETAILED TRANSMISSION CHANNEL IN A RADIO SYSTEM

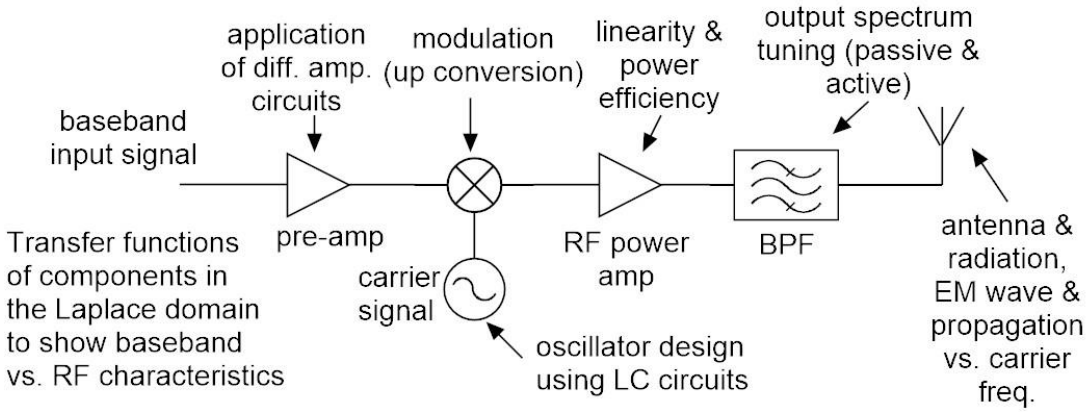


- Pre-amp (332)
- Carrier frequency in radio systems (312)
- Modulation techniques (up conversion) (312)
- CMOS drivers for power amplifiers in radio transmission path (332)
- Band-pass filters (BPF) and their transfer function in the Laplacian domain (312)
- Passive vs. active BPFs (332/312)
- RF power amplifiers and its efficiency illustrated as a CMOS driver plus a BPF (332/342)
- Antennas and radiation in radio systems (342)
- Antenna size as a function of carrier frequency (342)

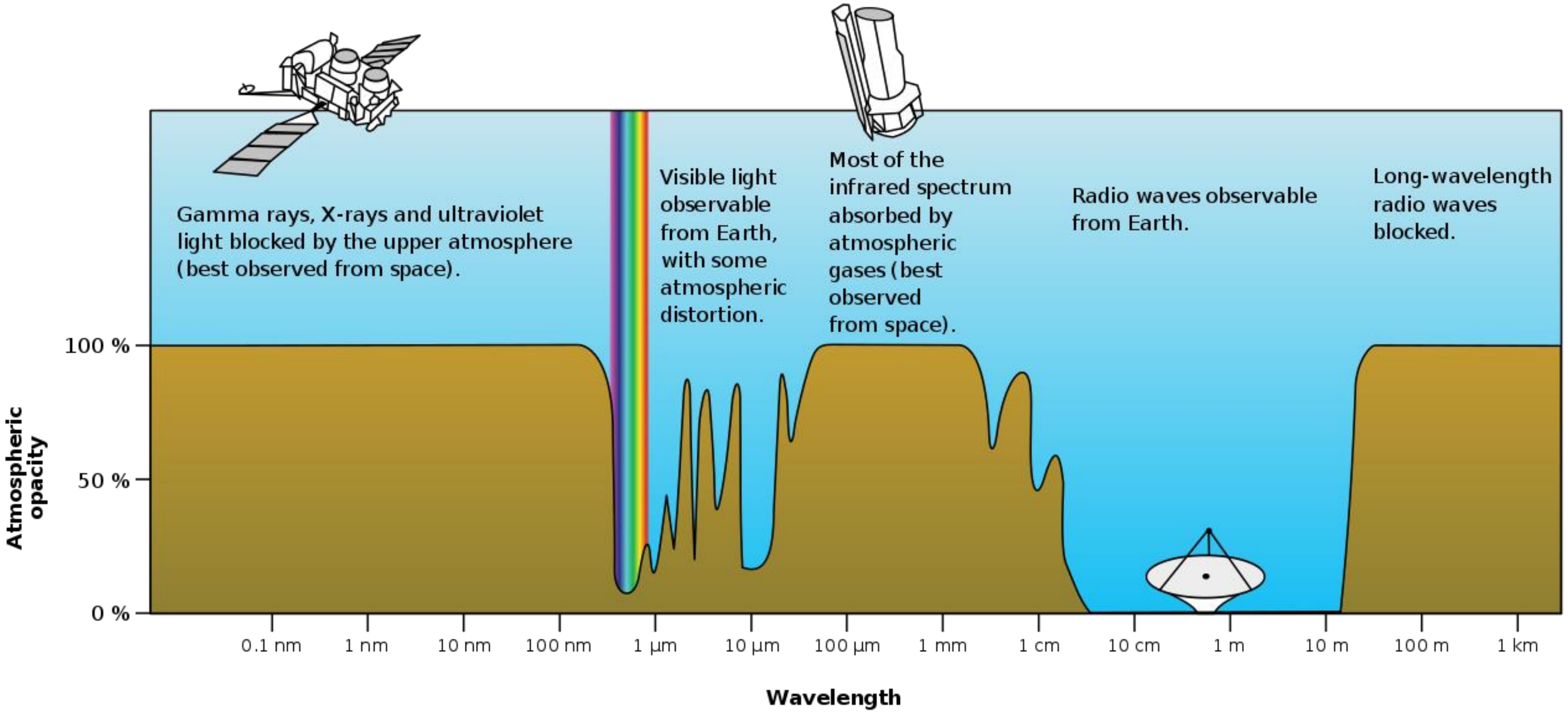
A DEMO SYSTEM – SILICON LAB SINGLE CHIP TRANSMITTER

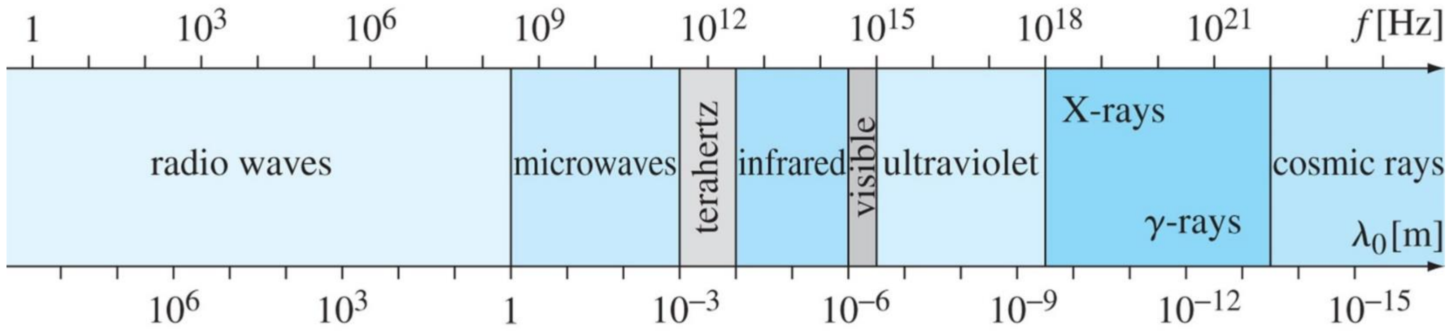






RADIO SPECTRUM ALLOCATION





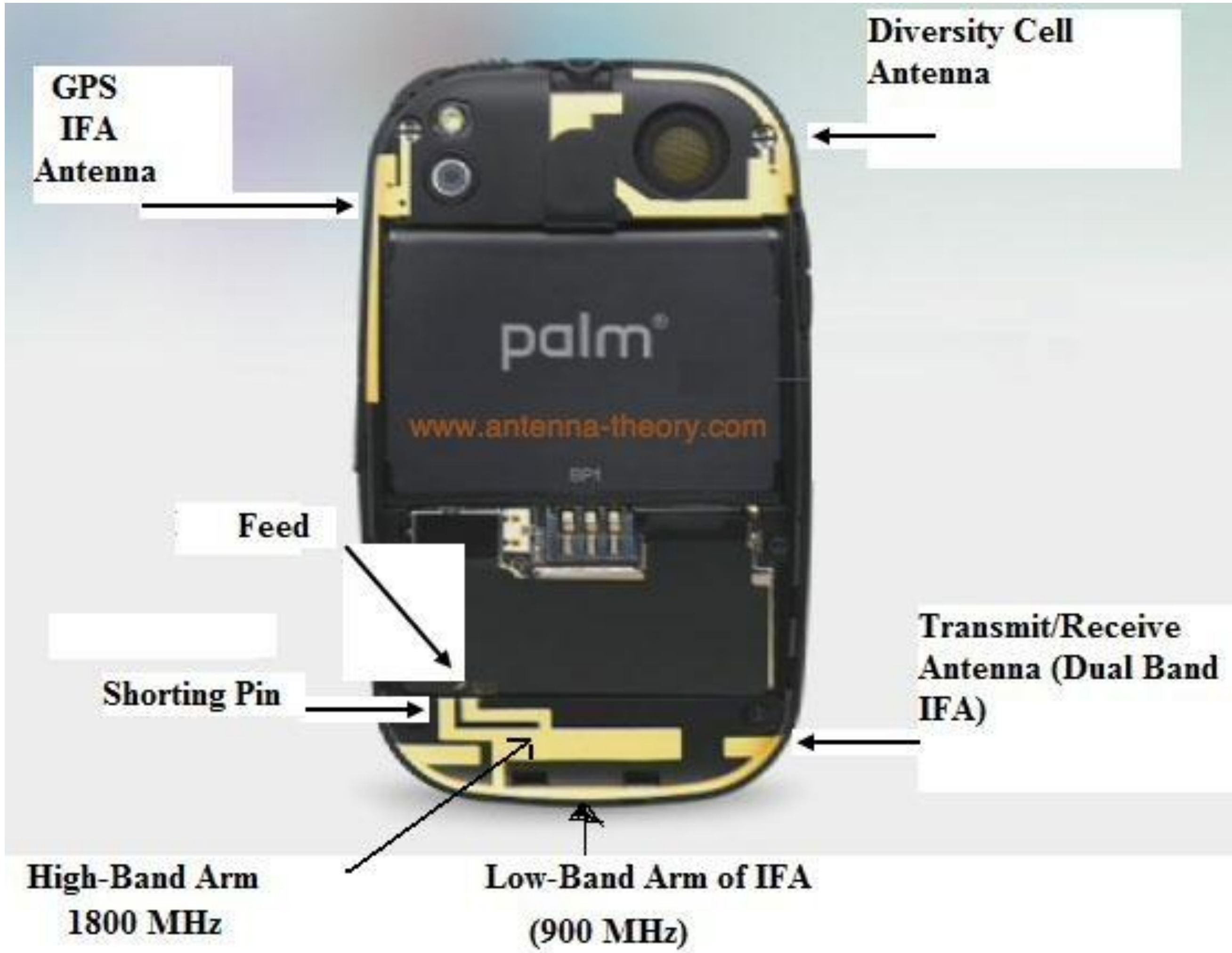
ELECTROMAGNETIC SPECTRUM

Frequency	Free-space wavelength	Band	Selected applications
< 3 Hz	> 100 Mm		Geophysical sensing
3–30 Hz	10–100 Mm	Extremely low frequency (ELF)	Detection of buried metallic objects
30–300 Hz	1–10 Mm	Super low frequency (SLF)	Electric power distribution (50 or 60 Hz), submarine communications, ionospheric sensing
0.3–3 kHz	0.1–1 Mm	Ultra low frequency (ULF)	Telephone, audio systems, geomagnetic sensing
3–30 kHz	10–100 km	Very low frequency (VLF)	Navigation, positioning, ship/submarine comm.
30–300 kHz	1–10 km	Low frequency (LF)	Long-wave broadcasting, radio beacons, navigation
0.3–3 MHz	0.1–1 km	Medium frequency (MF)	AM radio broadcasting (0.535–1.605 MHz)
3–30 MHz	10–100 m	High frequency (HF)	Short-wave broadcasting, amateur radio
30–300 MHz	1–10 m	Very high frequency (VHF) TV channels 2–4 (54–72 MHz) TV channels 5–6 (76–88 MHz) FM radio (88–108 MHz) TV chann. 7–13 (174–216 MHz)	TV broadcasting (all TV channels have a 6-MHz bandwidth), FM radio broadcasting, mobile radio communication, air traffic control, navigation
0.3–3 GHz	0.1–1 m	Ultra high frequency (UHF) TV chann. 14–69 (470–806 MHz) Cellular (824–894 MHz) PCS (1850–1990 MHz) L-band (1–2 GHz) S-band (2–4 GHz)	Radar, TV broadcasting, cellular telephone, personal communication service (PCS), global positioning system – GPS (1.23 and 1.58 GHz), microwave cooking (2.45 GHz), satellite radio
3–30 GHz	1–10 cm	Super high frequency (SHF) C-band (4–8 GHz) X-band (8–12 GHz) K_u-band (12–18 GHz) K-band (18–27 GHz)	Radar, satellite communications, direct TV, wireless communication systems, wireless networks

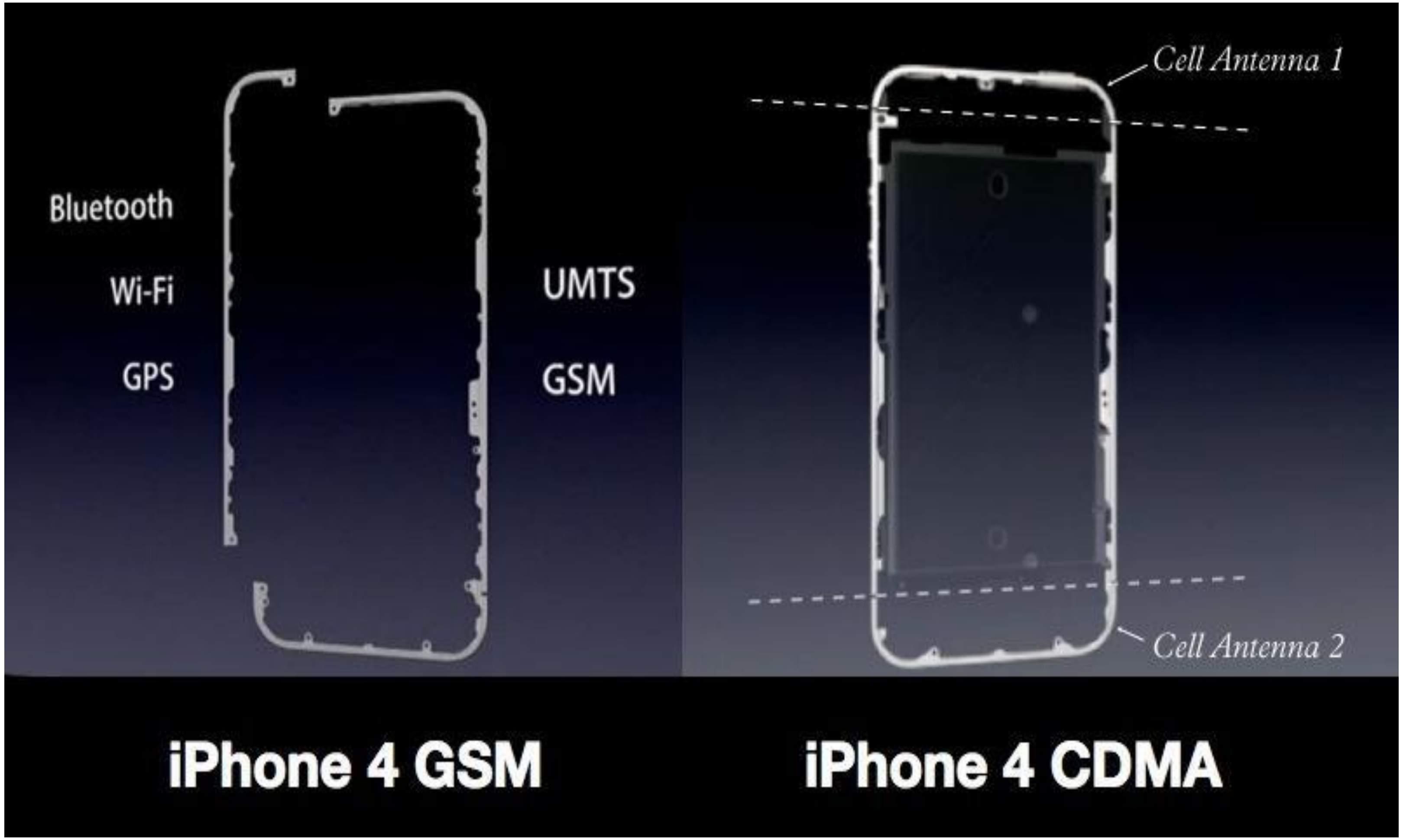
ELECTROMAGNETIC SPECTRUM

30–300 GHz	1–10 mm	Extremely high frequency (EHF) K_a-band (27–40 GHz) V-band (40–75 GHz) W-band (75–110 GHz) Millimeter-wave (110–300 GHz)	Radar, remote sensing, radio astronomy, satellite communications
0.3–3 THz	0.1–1 mm	Submillimeter wave or terahertz	Meteorology, sensors, imaging, astronomy
3–400 THz	0.75–100 μm	Infrared (IR)	IR heating, night vision, optical communications
400–789 THz	380–750 nm	Visible light Red (620–750 nm) Orange (590–620 nm) Yellow (570–590 nm) Green (495–570 nm) Blue (450–495 nm) Violet (380–450 nm)	Vision, optical devices and systems, lasers
10^{15}–10^{18} Hz	0.3–300 nm	Ultraviolet (UV)	UV sterilization, lasers, semiconductor processing
10^{17}–10^{21} Hz	0.3 pm–3 nm	X-rays	Medical diagnostics
10^{19}–10^{22} Hz	0.03–30 pm	γ-rays	Radiation medical therapy, astrophysics
$> 10^{22}$ Hz	< 0.03 pm	Cosmic rays	Astrophysics

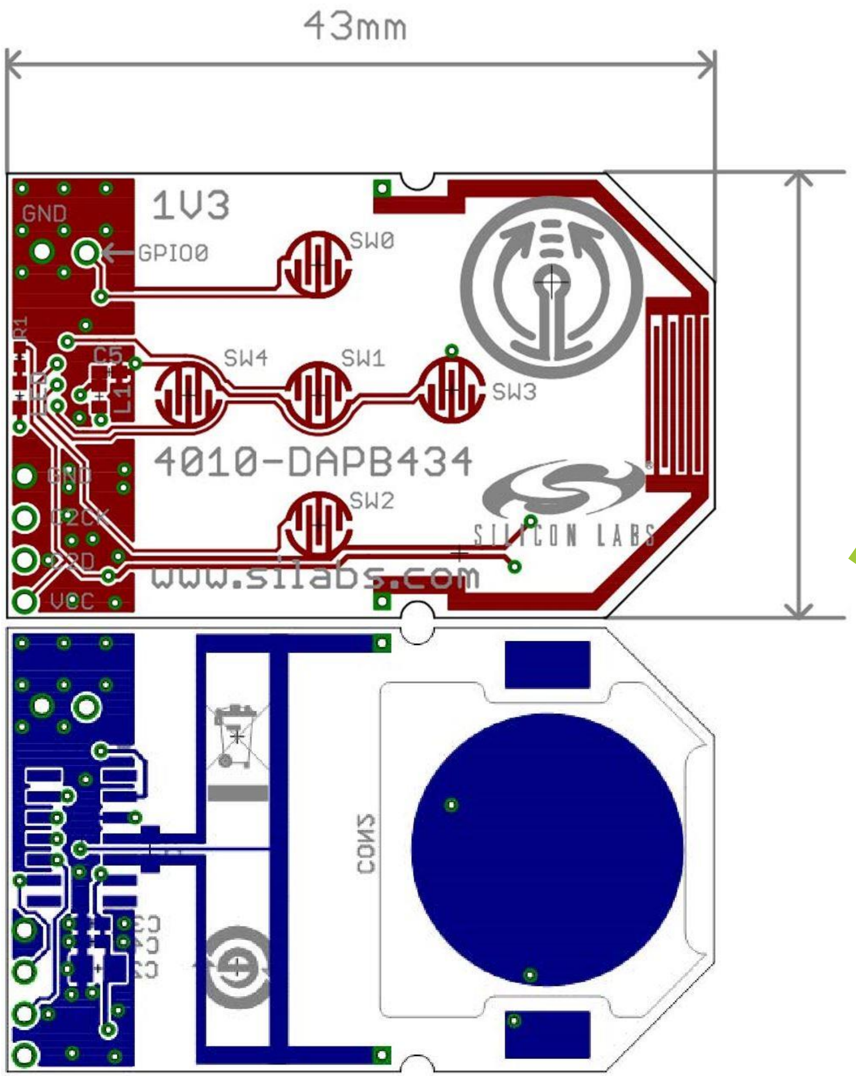
ANTENNA EXAMPLES

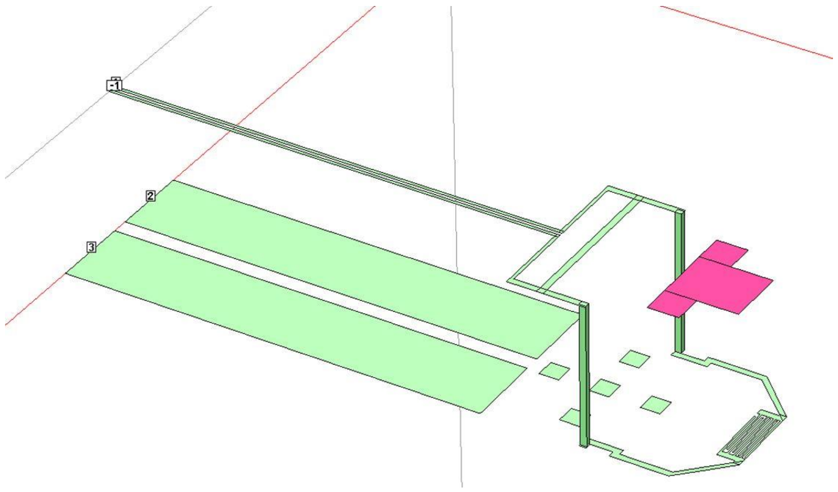


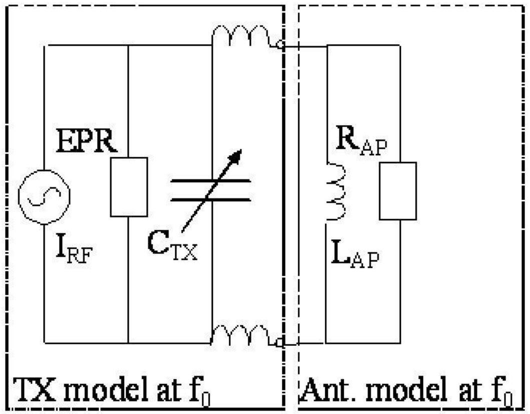
ANTENNA EXAMPLES



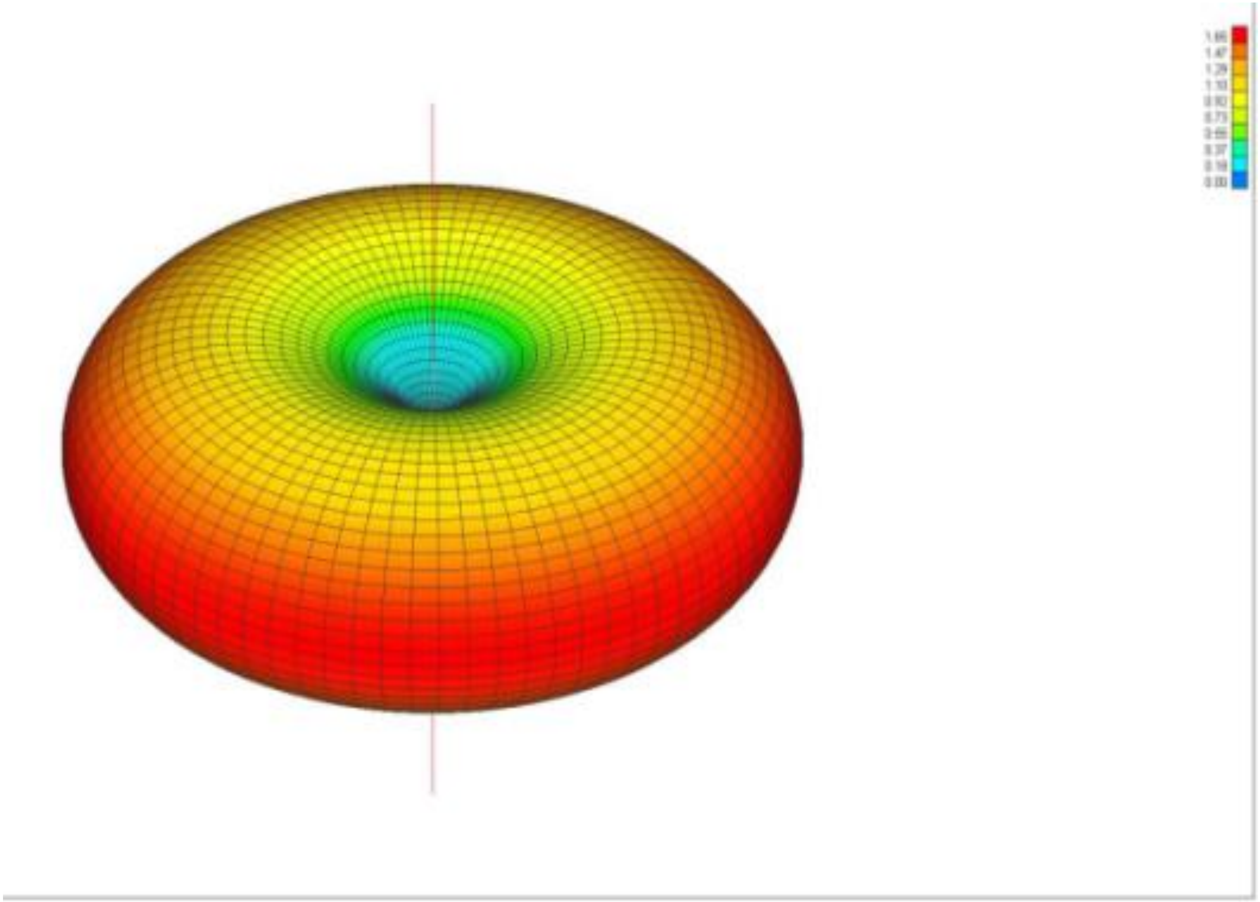
ANTENNA EXAMPLES



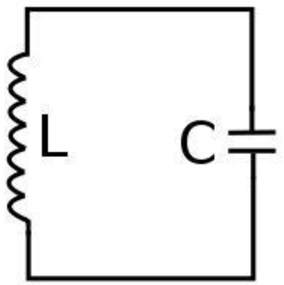




DIPOLE ANTENNA RADIATION PATTERN

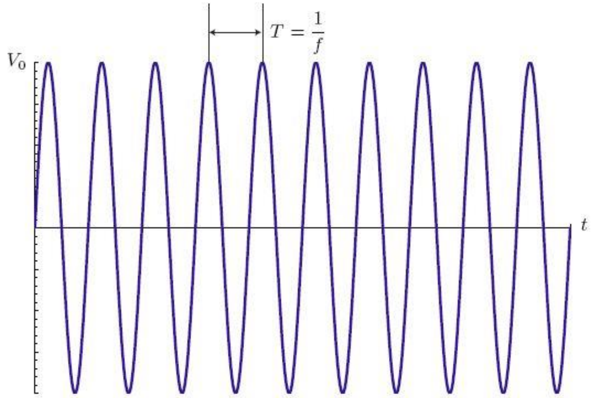


LOCAL OSCILLATOR

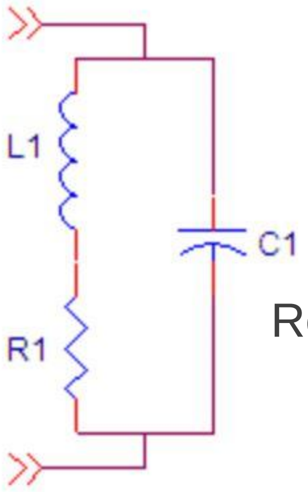


Ideal LC Tank

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

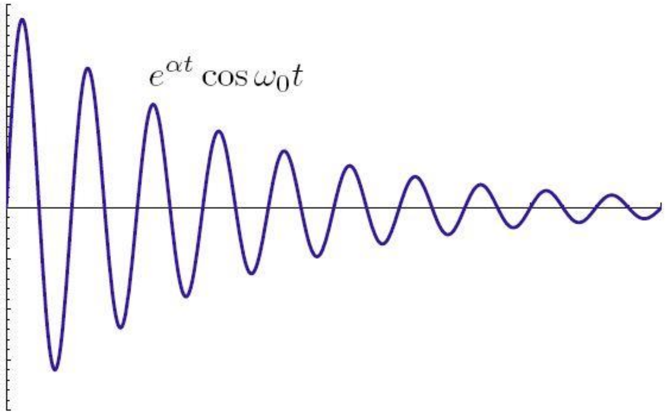


$$Q_L = \frac{\omega_0 L_1}{R_1}$$

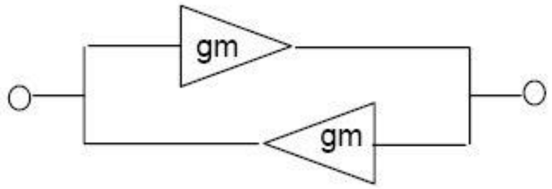


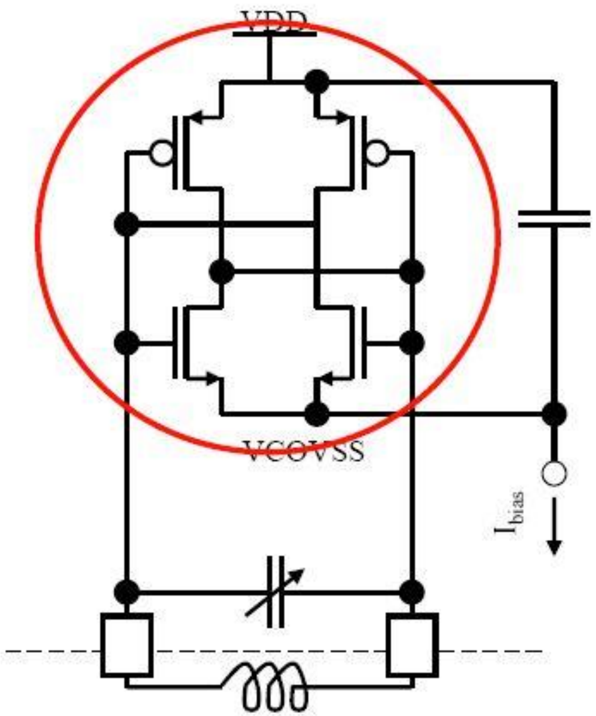
Real LC Tank

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 - \frac{R_1^2 C_1}{L_1}}$$



LOCAL OSCILATOR



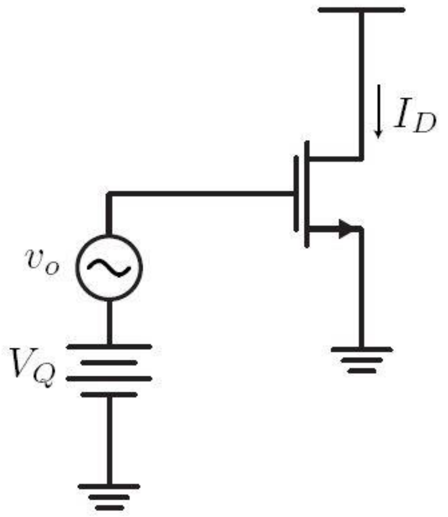


- Tuning is provided by the programmable capacitor
- Tuning range:
  - 902MHz – 928MHz
  - Able to compensate for 5% process variation
  - Able to compensate for 2% inductance variation
- L = 17nH, Q = 30
- Output swing 1Vp-p
- Ibias = 200 – 300uA

MIXER USING SQUARE LAW

$$v_o = V_o \cos(\omega_0 t) \Leftarrow LO\ signal,$$

$$V_o\ is\ set\ not\ to\ put\ the\ FET\ \text{in}\ cutoff$$



$$Square\ Law: I_D = \frac{k'}{2}\frac{W}{L}\left(V_{gs} - V_t\right)^2\left(1 + \lambda V_{ds}\right)$$

$$= \frac{k'}{2}\frac{W}{L}\left(V_Q + V_o \cos\left(\omega_0 t\right) - V_t\right)^2\left(1 + \lambda V_{ds}\right)$$

$$V_Q + V_o \cos\left(\omega_0 t\right) > V_t \Rightarrow V_Q - V_o > V_t\ \ or\ V_o < V_Q - V_t$$

$$Expand\ the\ square\ term:$$

$$\therefore I_D \propto \left(\left(V_Q - V_t\right)^2 + V_o \cos^2\left(\omega_0 t\right) + 2\left(V_Q - V_t\right)V_o \cos\left(\omega_0 t\right)\right)$$

MIXER USING SQUARE LAW

- The DC current from the previous equation:

$$I_{D,DC}=\frac{k'}{2}\frac{W}{L}\left(V_Q-V_t\right)^2\left(1+\lambda V_{ds}\right)$$

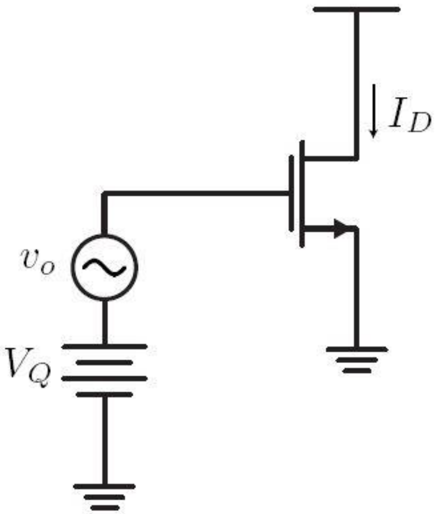
- Further expand the $\cos^2\left(\omega_0 t\right)$ term:

$$\cos^2\left(\omega_0 t\right)=\cos\left(\omega_0 t\right)\cdot\cos\left(\omega_0 t\right)=\frac{1}{2}\left[1+\cos\left(2\omega_0 t\right)\right]$$

$$I_D=\frac{k'}{2}\frac{W}{L}\left(\left(V_Q-V_t\right)^2+V_o\cos^2\left(\omega_0 t\right)+2\left(V_Q-V_t\right)V_o\cos\left(\omega_0 t\right)\right)$$

$$=I_{D,DC}+\frac{k'}{2}\frac{W}{L}\left(V_o^2\cos^2\left(\omega_0 t\right)+2\left(V_Q-V_t\right)V_o\cos\left(\omega_0 t\right)\right)$$

$$=I_{D,DC}+k'\frac{W}{L}\left(\underbrace{\frac{V_o^2}{4}}_{\text{bias point shift}}+\underbrace{\left(V_Q-V_t\right)V_o\cos\left(\omega_0 t\right)}_{\text{LO modulation}}+\underbrace{\frac{V_o^2}{4}\cos\left(2\omega_0 t\right)}_{\text{2nd-order harmonics. ignore}}\right)$$



MIXER USING SQUARE LAW

- MOSFET transconductance under large signal LO input signal:

$$g(t) = \frac{\partial I_D}{\partial V_{gs}} = k'\frac{W}{L}\left(V_{gs} - V_t\right)\left(1 + \lambda V_{ds}\right)$$

- If Vgs follows the LO signal, then Id also follows LO signal.

$$V_{gs}(t) = V_Q + V_o \cos(\omega_0 t)$$

$$\therefore\ g(t) = k'\frac{W}{L}\left(V_Q - V_t + V_o \cos(\omega_0 t)\right)\left(1 + \lambda V_{ds}\right)$$

$$= g_{mQ}\left(1 + \frac{V_o}{V_Q - V_t}\cos(\omega_0 t)\right)\left(1 + \lambda V_{ds}\right)$$

MIXER USING SQUARE LAW

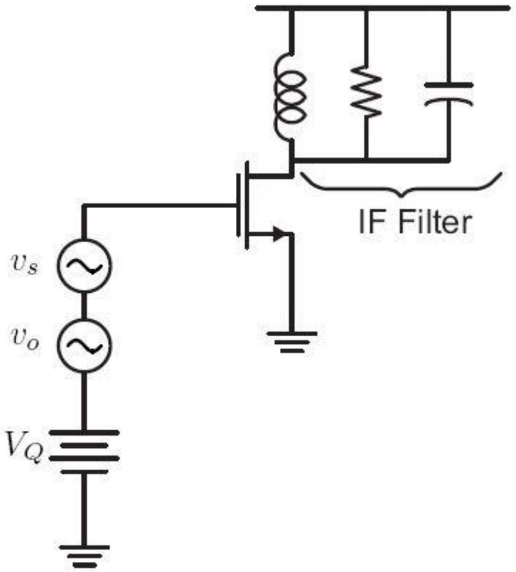
- Add LO and the signal at the input, we have a mixer.

$$i_o(t) = g(t)v_s = g_{mQ}\left(1+\frac{V_o}{V_Q - V_t}\cos(\omega_0 t)\right)\times V_s\cos(\omega_s t)$$

$$i_0(t)_{IF} = \frac{g_{mQ}}{2}\frac{V_o}{V_G - V_t}V_s\cos(\omega_0 \pm \omega_s)t$$

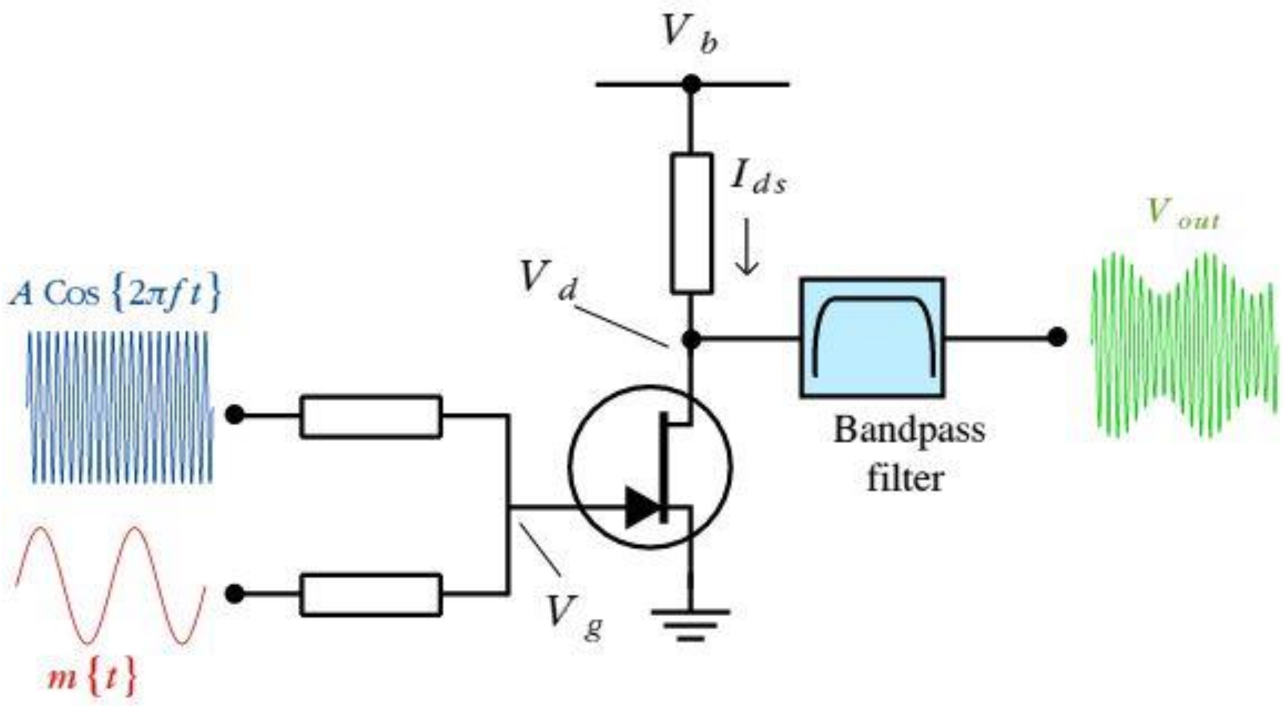
$$g_c(t) = \frac{i_0(t)_{IF}}{V_s} = \frac{g_{mQ}}{2}\frac{V_o}{V_G - V_t}$$

$$= \frac{k'\frac{W}{L}(V_G - V_t)}{2}\frac{V_o}{V_G - V_t} = \frac{k'}{2}\frac{W}{L}V_o$$



- The LC tuning network at the load will only select (i.e. resonate) the desired IF signal and pass it on to the output load. All the other frequencies will be shorted by the tuning network.

MIXER USING SQUARE LAW



MIXER USING SQUARE LAW

- Real modulation using sine function:

$$Fourier\left\{\sin\left(\omega_0 t\right) f\left(t\right)\right\} = \int_{-\infty}^{\infty} f\left(t\right)\left[\frac{e^{j\omega_0 t} - e^{-j\omega_0 t}}{2j}\right] e^{-j\omega t} dt$$

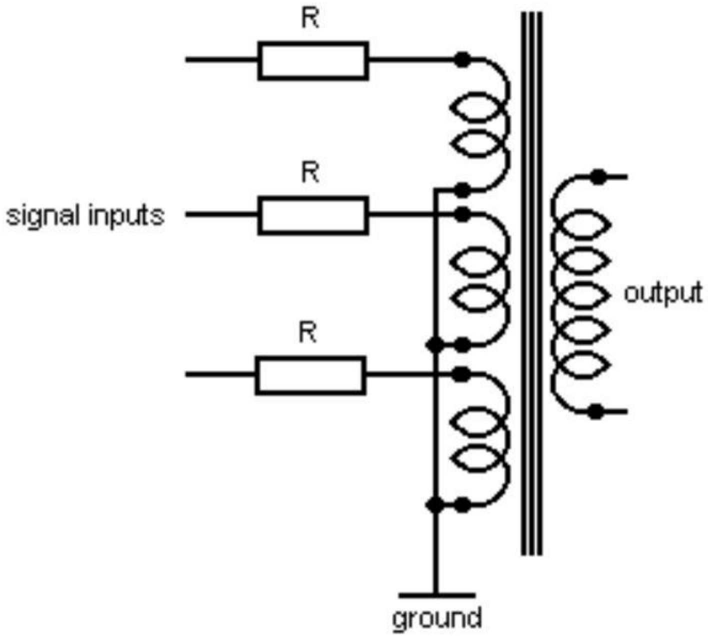
$$= \frac{1}{2j} F\left(\omega - \omega_0\right) - \frac{1}{2j} F\left(\omega + \omega_0\right)$$

$$= \frac{j}{2j^2} F\left(\omega - \omega_0\right) - \frac{j}{2j^2} F\left(\omega + \omega_0\right)$$

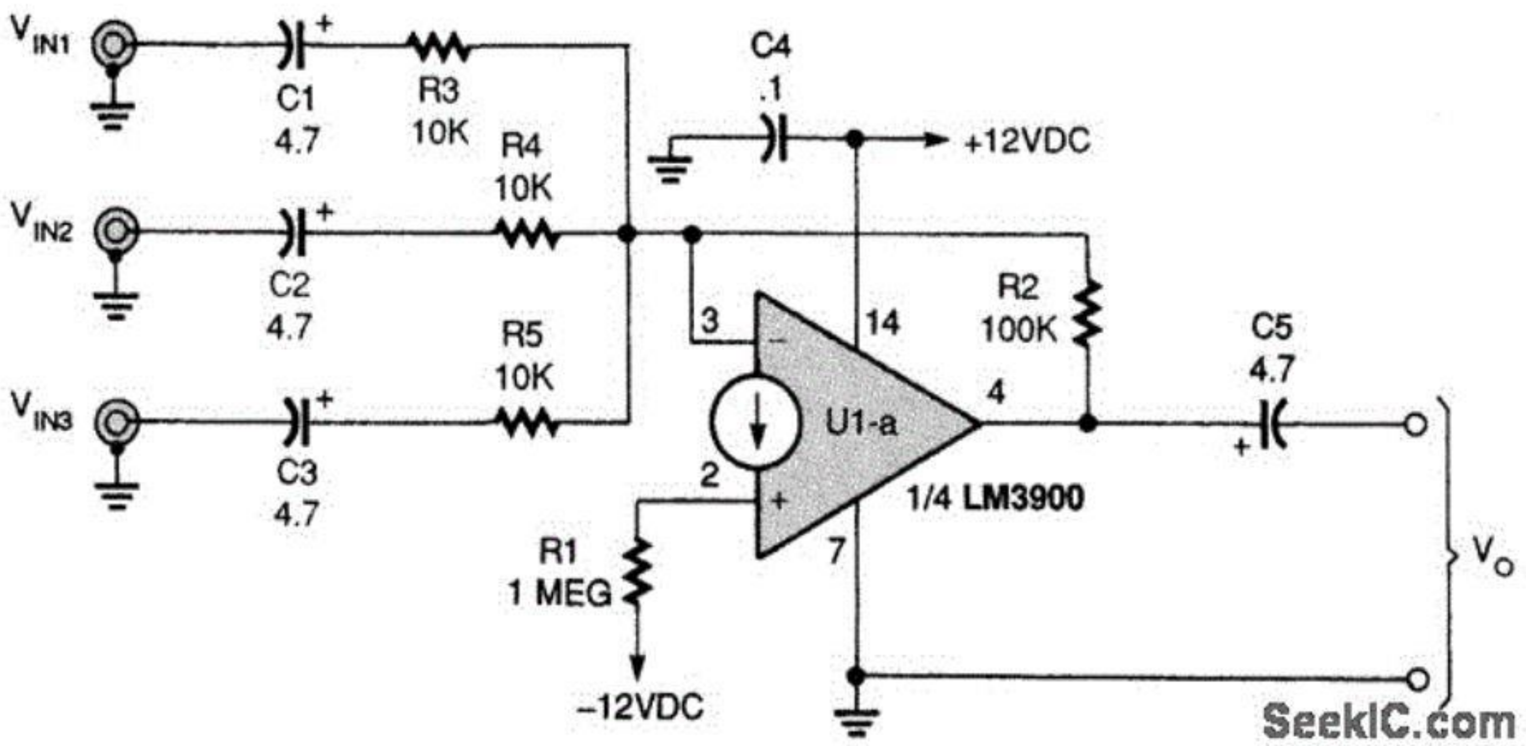
$$= -\frac{j}{2} F\left(\omega - \omega_0\right) + \frac{j}{2} F\left(\omega + \omega_0\right)$$

  – Sine function modulation results in a negative lower band shift and a positive upper band shift

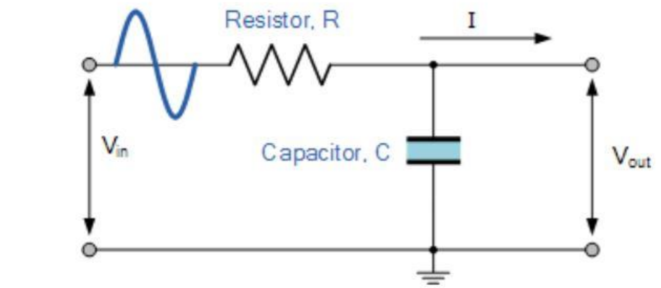
SIGNAL COMBINERS

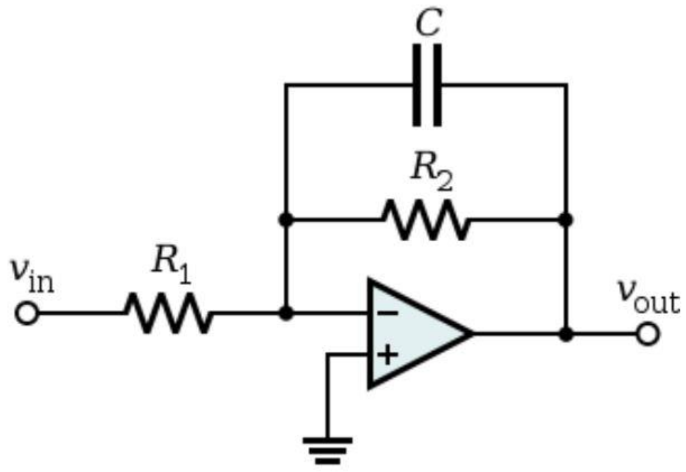


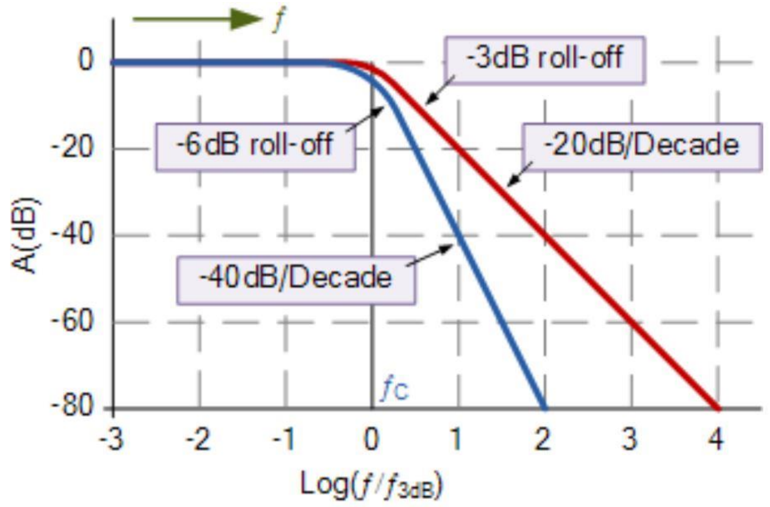
SIGNAL COMBINERS

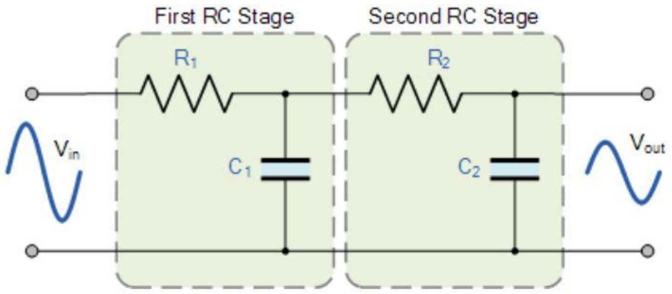


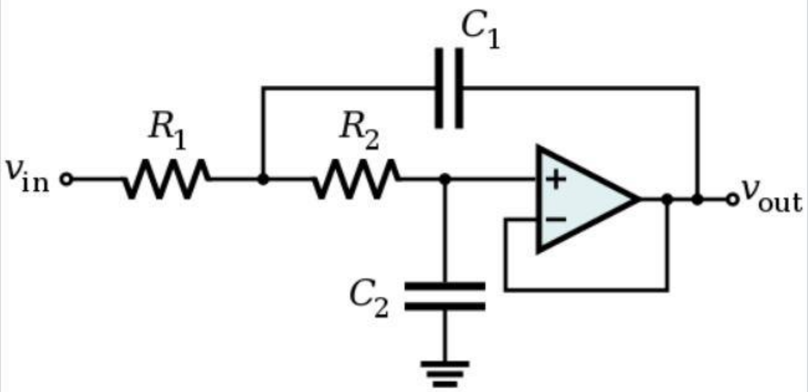
ACTIVE LOW-PASS FILTERS



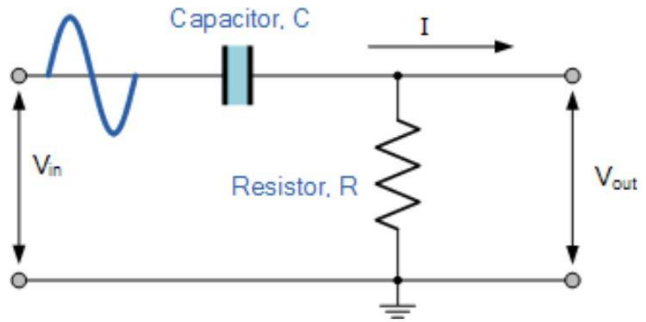


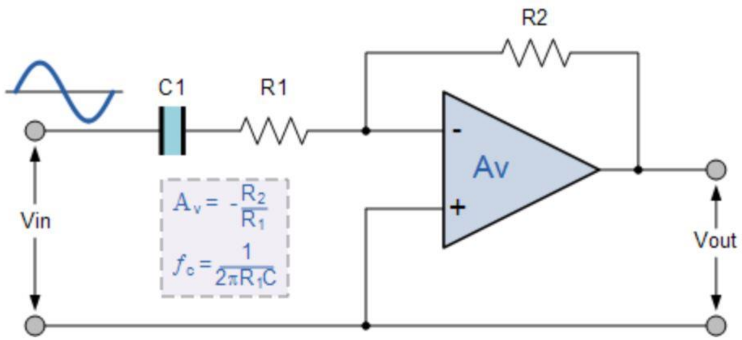


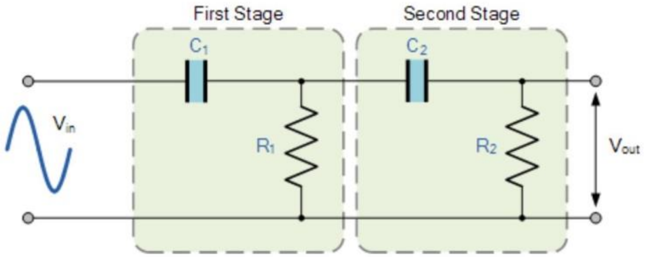


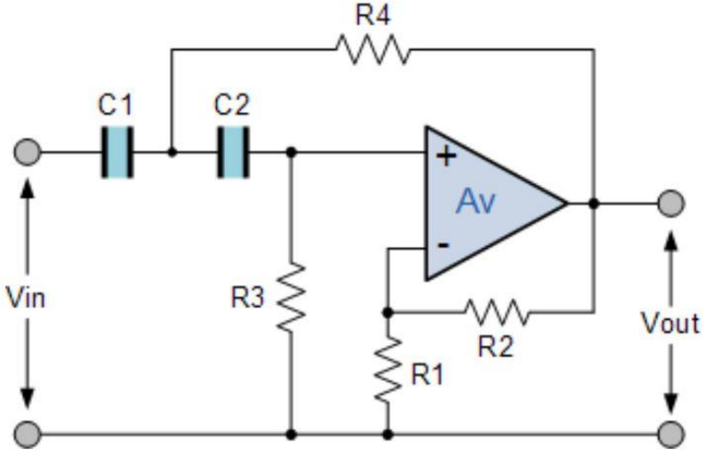


ACTIVE HIGH-PASS FILTERS



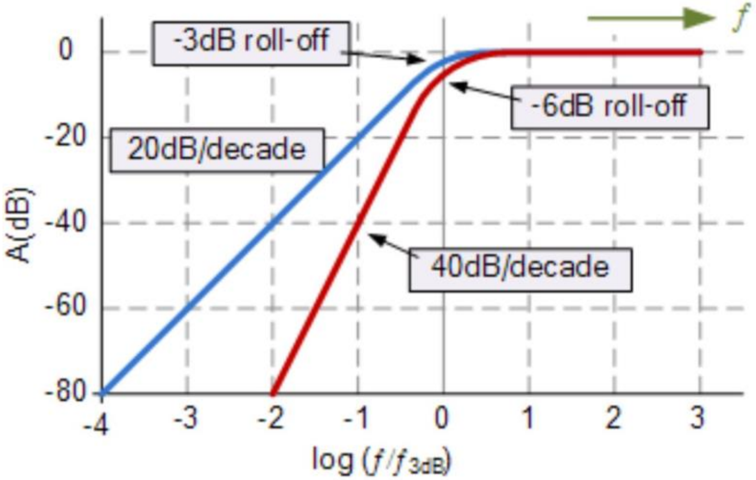




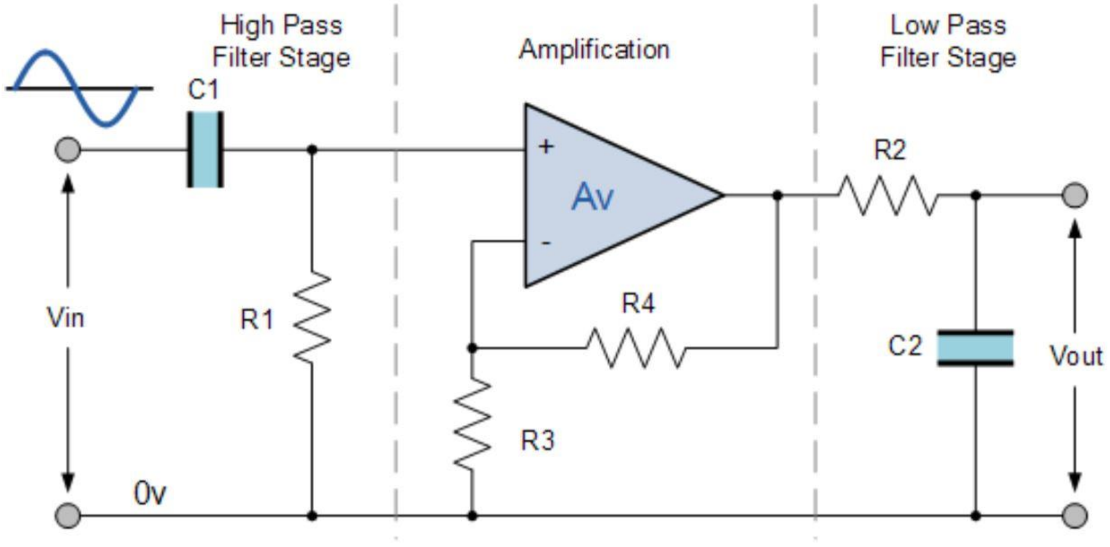


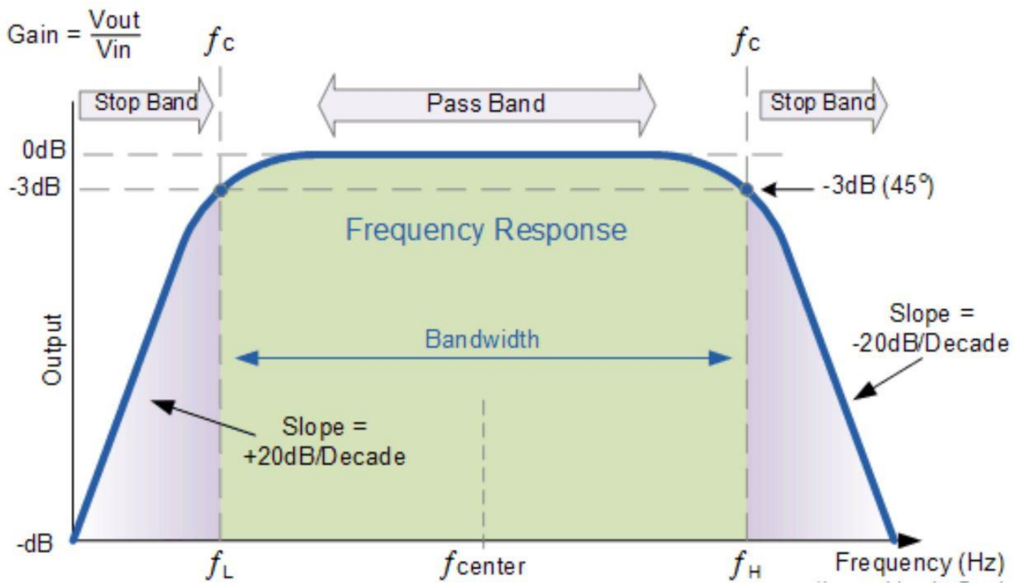
$$Av = 1 + \frac{R_2}{R_1}$$

$$f_C = \frac{1}{2\pi\sqrt{R_3 R_4 C_1 C_2}}$$

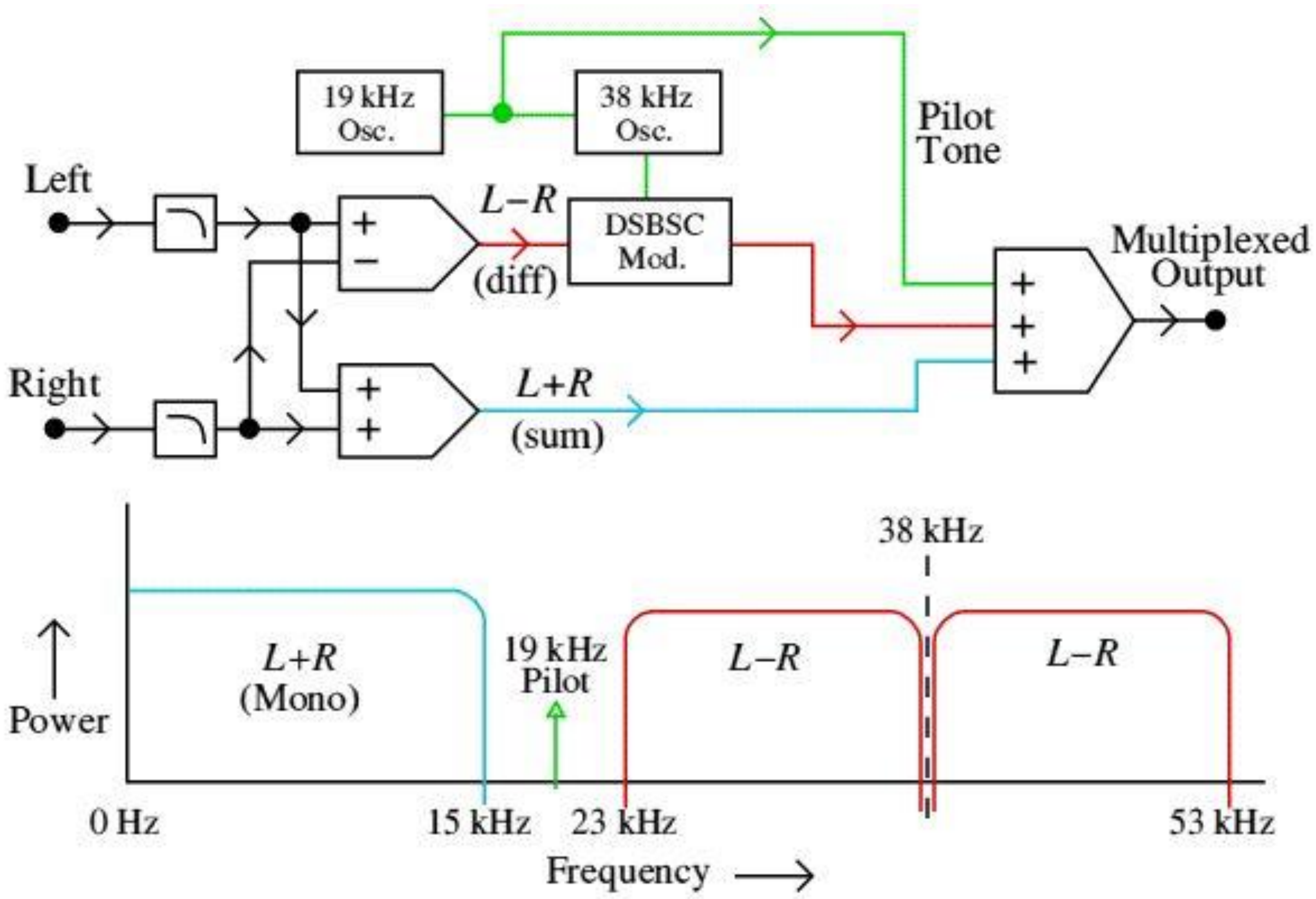


ACTIVE BAND-PASS FILTERS





MONO-CHANNEL VS. STEREO TRANSMISSION

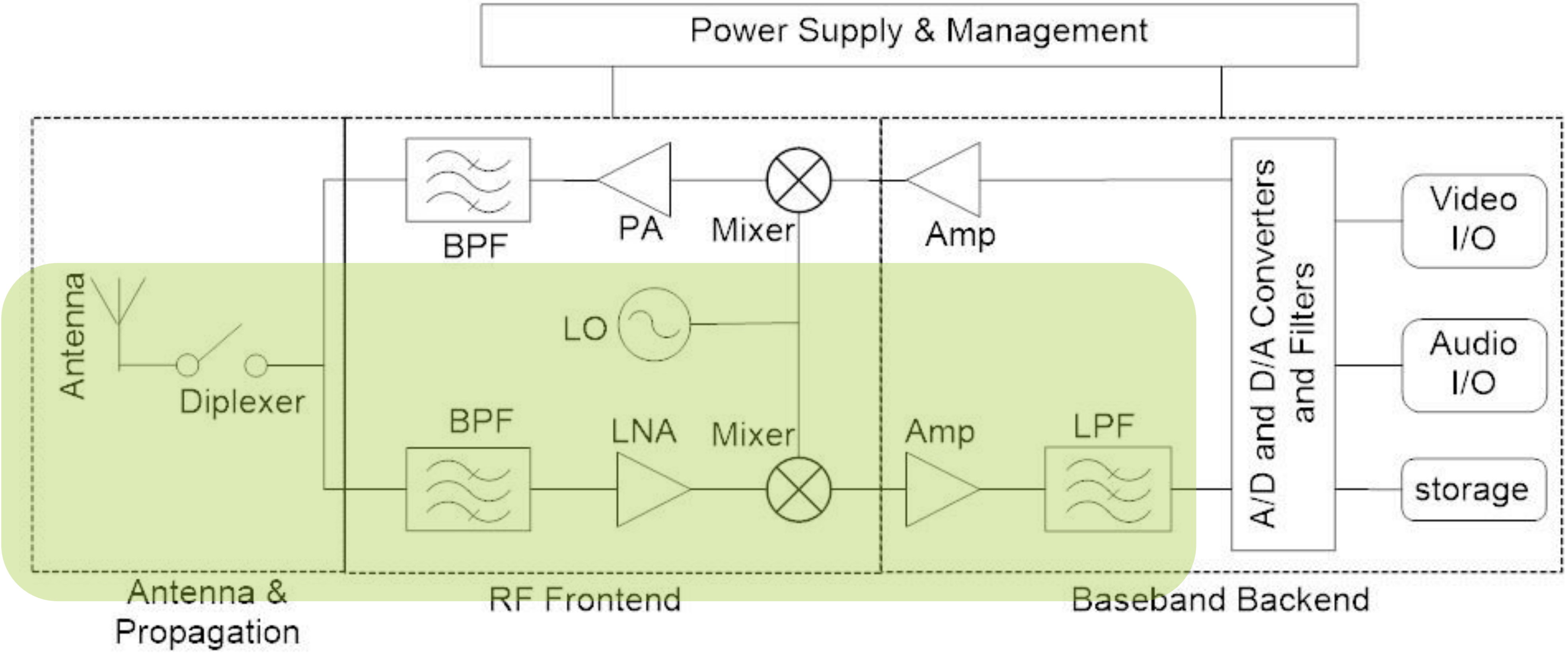


- To recover the stereo signal:

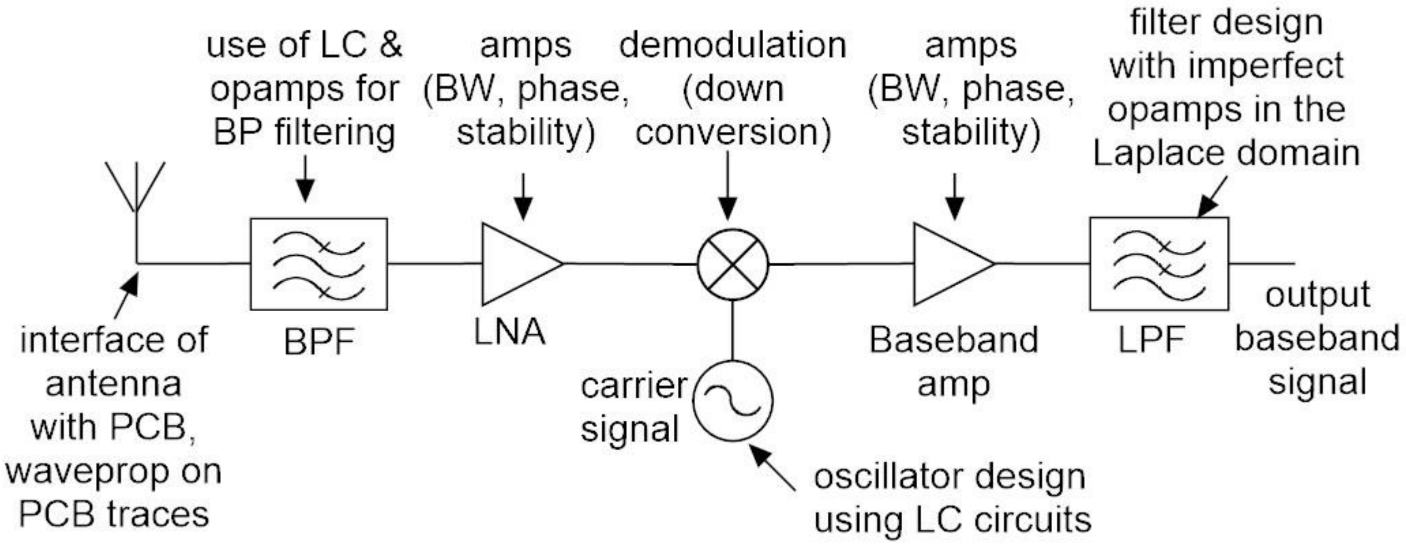
$$L\_channel = \frac{(L+R)+(L-R)}{2}$$

$$R\_channel = \frac{(L+R)-(L-R)}{2}$$

KI5: SIGNAL RECEIVER IN A RADIO SYSTEM

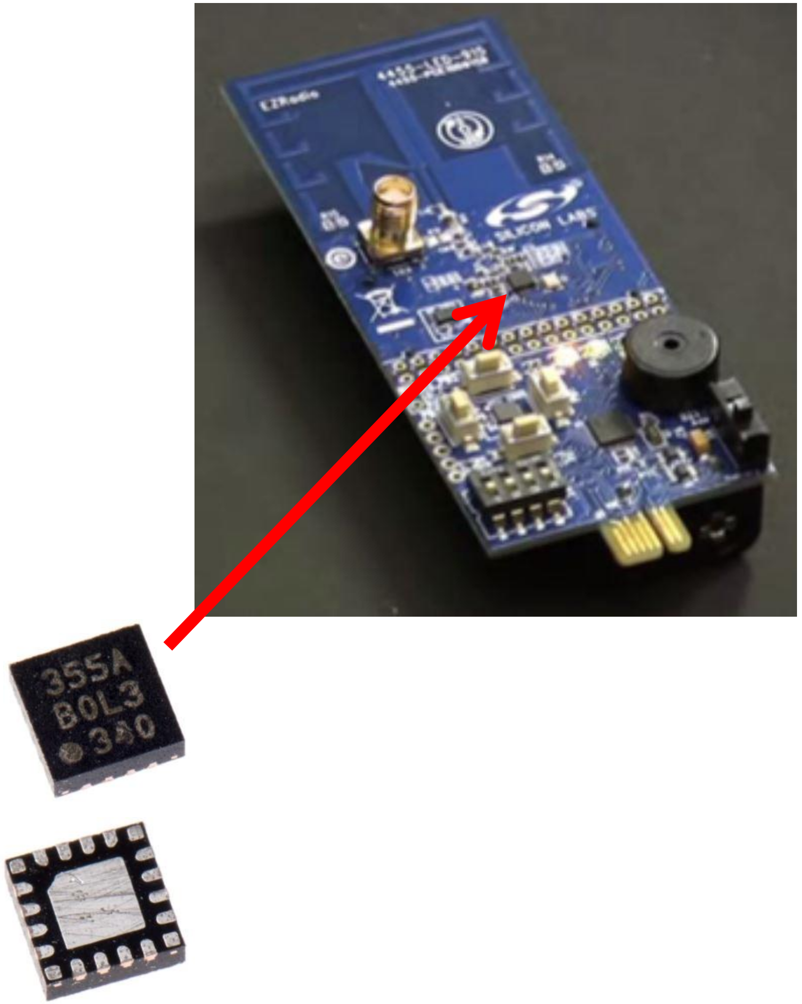


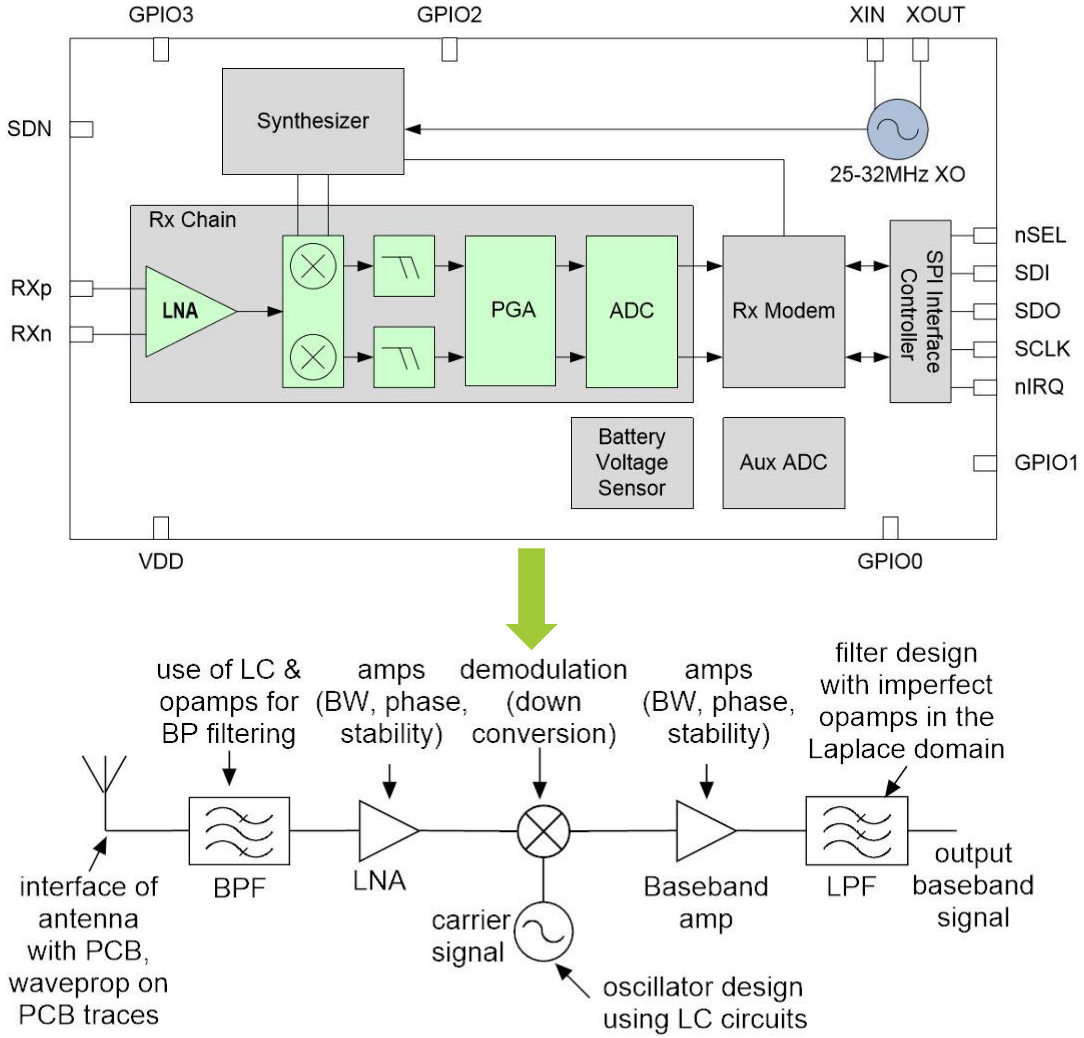
DETAILED RECEIVING CHANNEL IN A RADIO SYSTEM



- Roles of the front-end BPF in radio receiving path (selectivity, signal blocking) (312, 332)
- BPF with LC ladders (312/332)
- Frequency characteristics of amplifiers (312/332)
- Modulation techniques (down conversion) (312)
- Feedback topologies in frequency synthesizers (332)
- Design of baseband LPF/BPF with RC circuits and imperfect amplifiers (312/332)
- Design and characterization of receiver antenna
- Design and characterization of interface between antenna and circuits (matching and transmission line modeling) (342)
- Roles of discrete time signal processing (Z-transform) on future software-defined radio (312)

A DEMO SYSTEM – SILICON LAB SINGLE CHIP RECEIVER





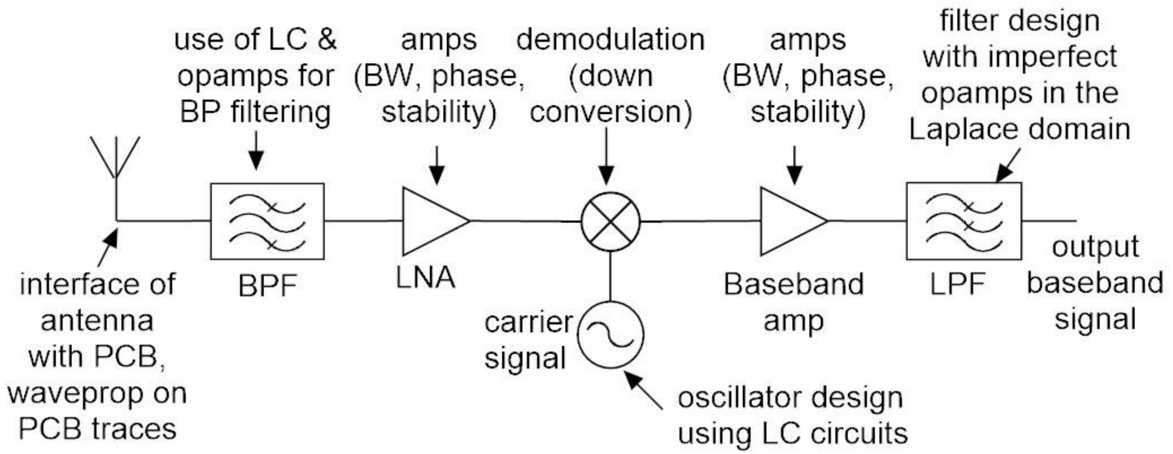
QUESTIONS

1. What signals does the receiver antenna “see”?

2. Assuming the receiver antenna is a dipole antenna for 433MHz signal, what should the dimension of the antenna be?

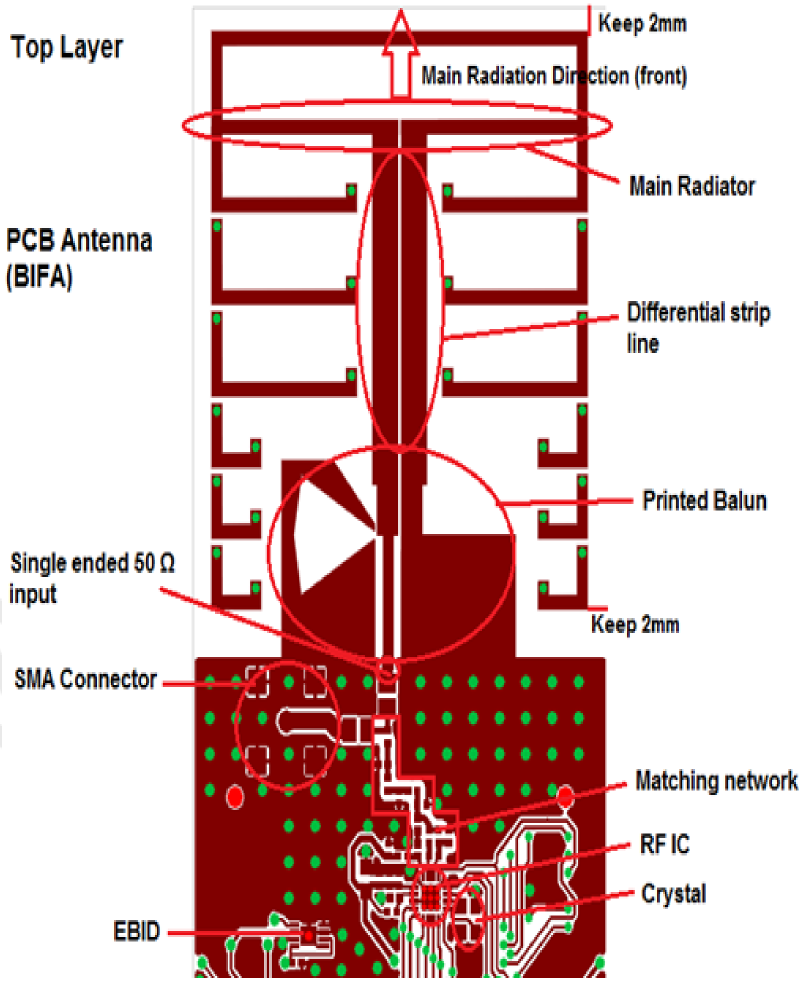
3. What is the purpose of the first BPF?

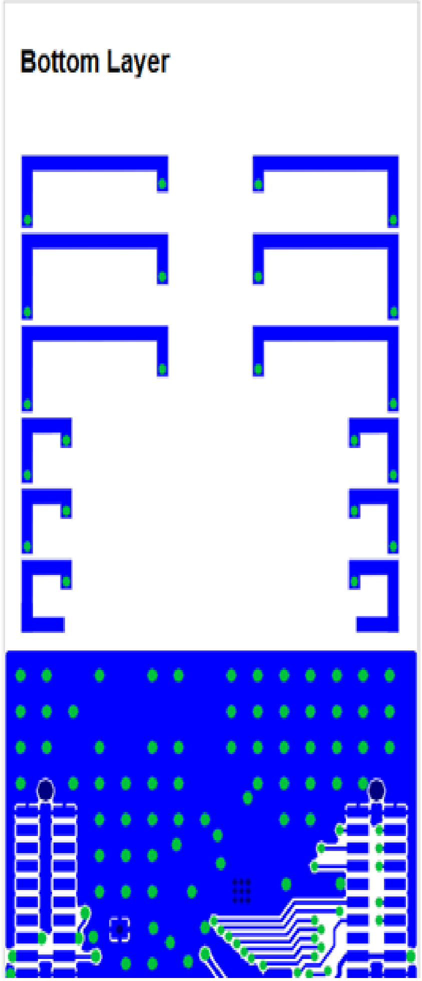
4. How would you build a simple BPF using either passive or active (Op-amps) components?

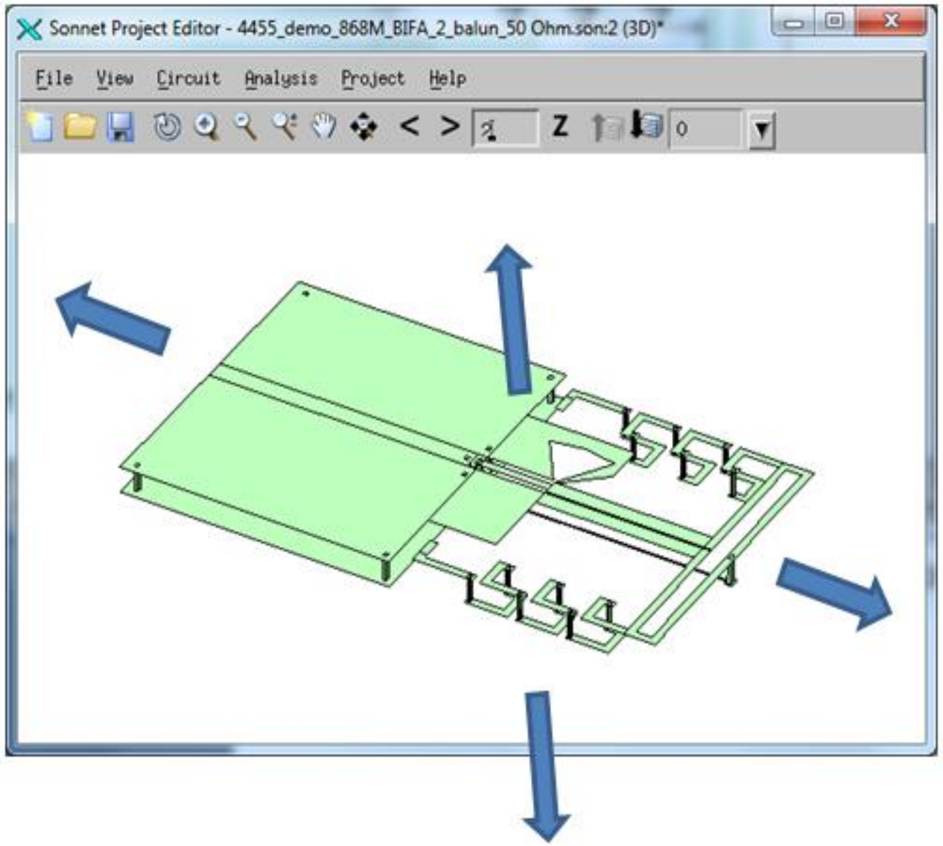


Colorado State University

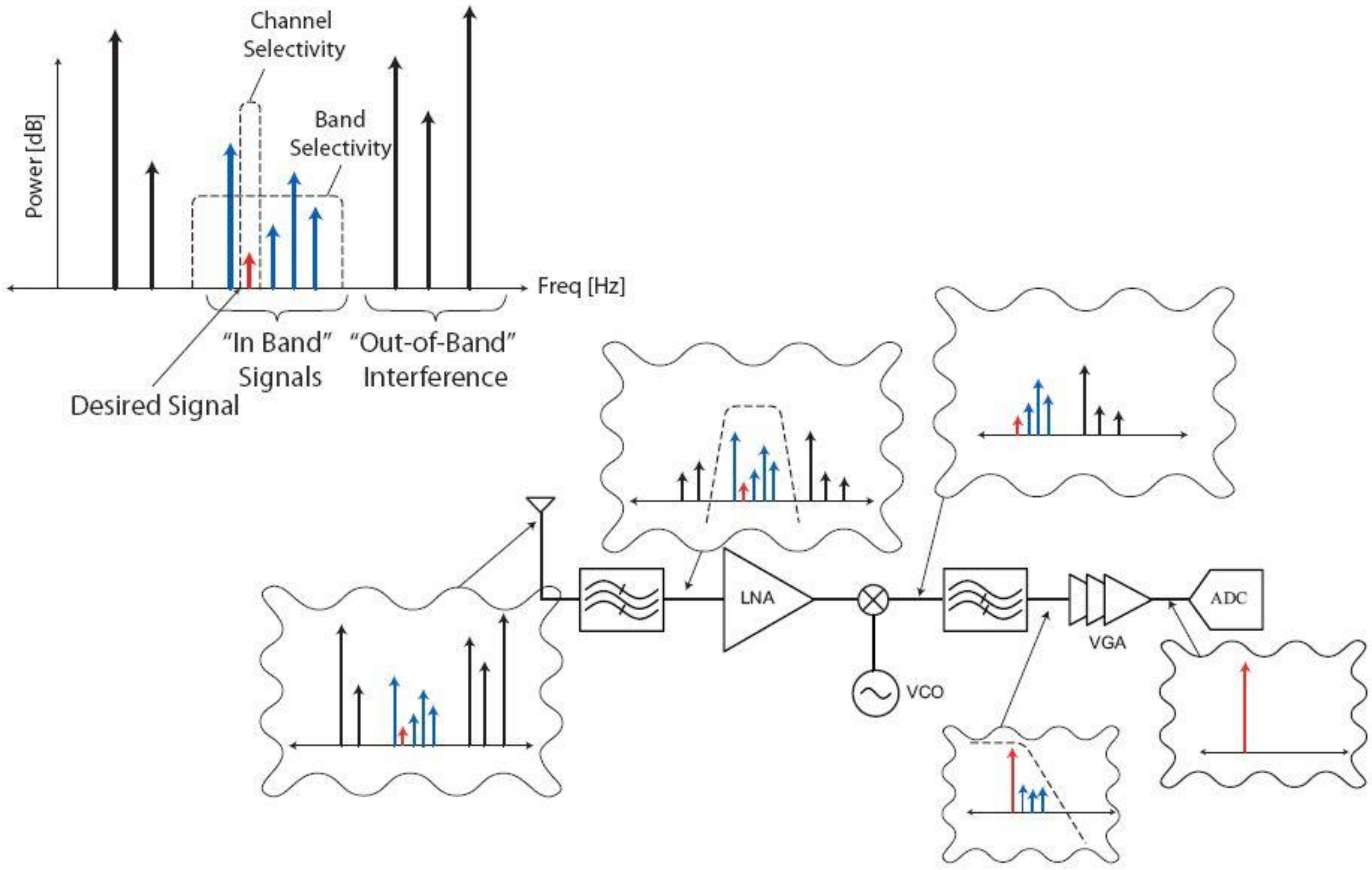
RECEIVING ANTENNA







SIGNAL FLOW IN A GENERIC RECEIVER



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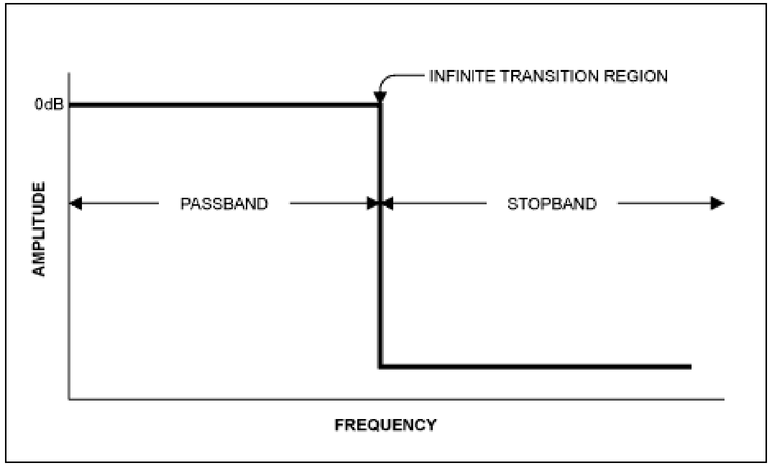
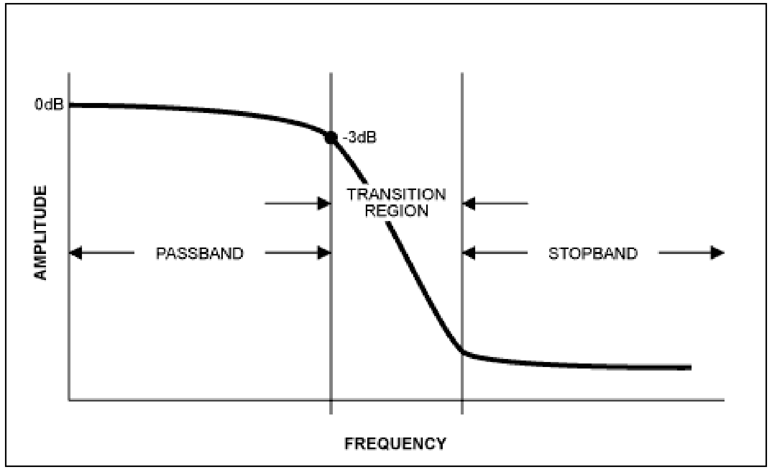
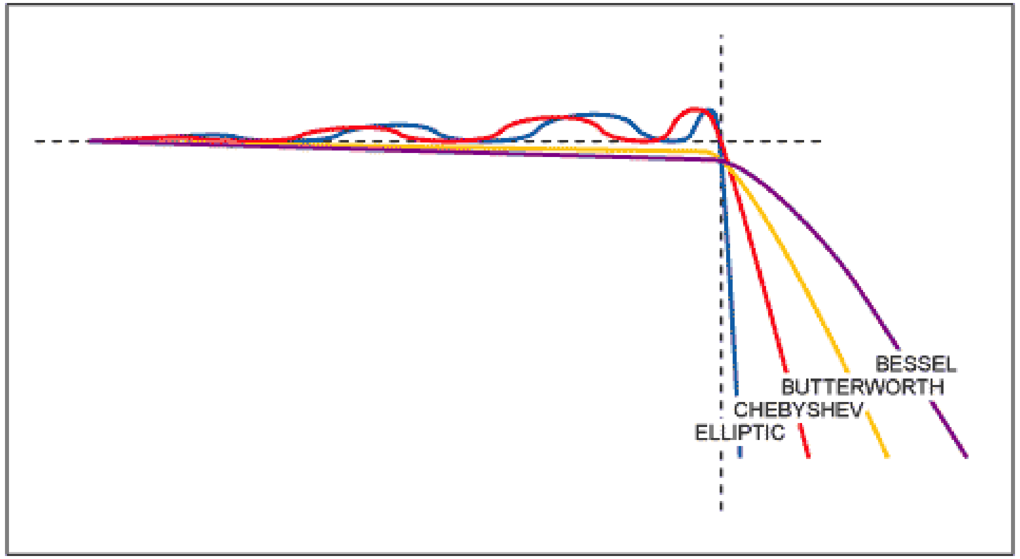
FILTER BASICS



Ideal low-pass filter

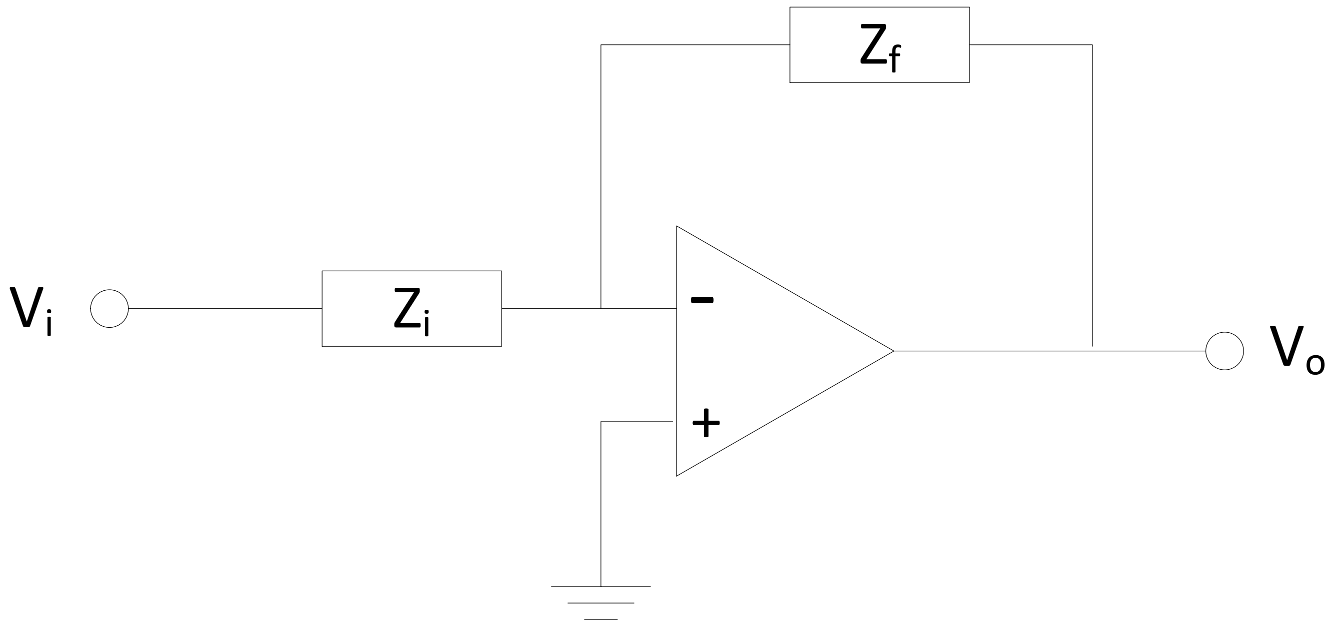


Practical low-pass filter



4 basic filter types

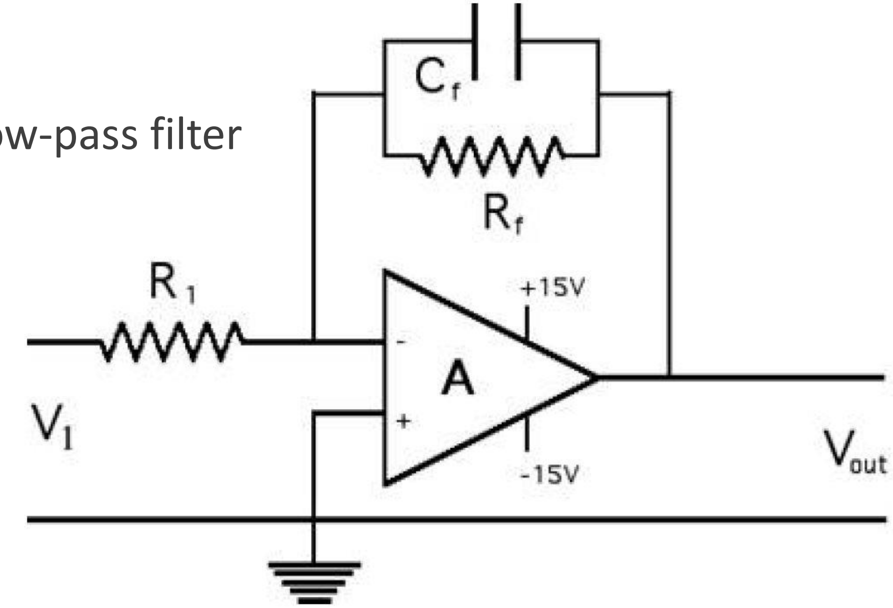
ACTIVE FILTERS



$$H(s) = -\frac{Z_f}{Z_i}$$

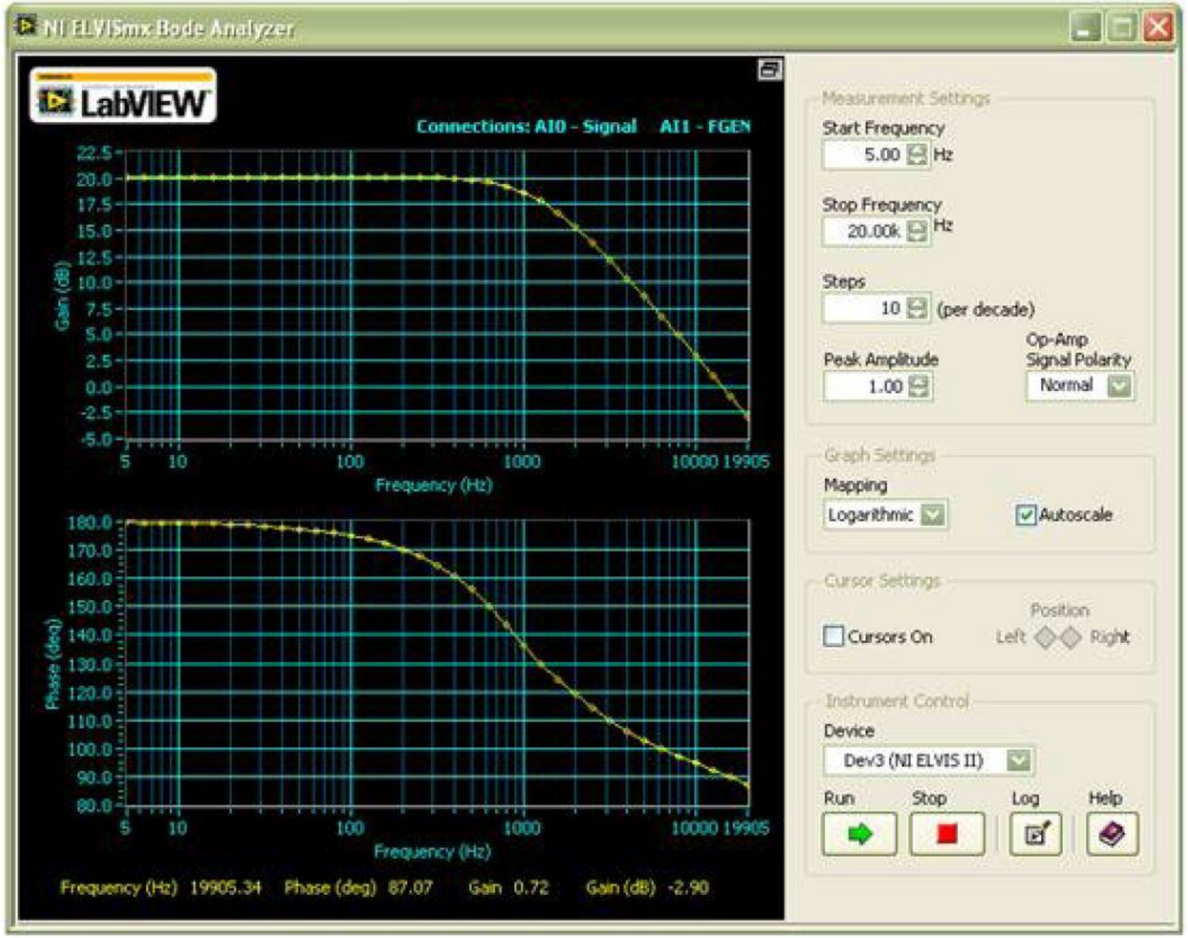
ACTIVE FILTERS

low-pass filter



$$H(s) = -\frac{Z_f}{Z_i} = -\frac{\dfrac{R_f}{1+j\omega R_f C_f}}{R_1} = \frac{-\dfrac{R_f}{R_1}}{1+j\omega R_f C_f}$$

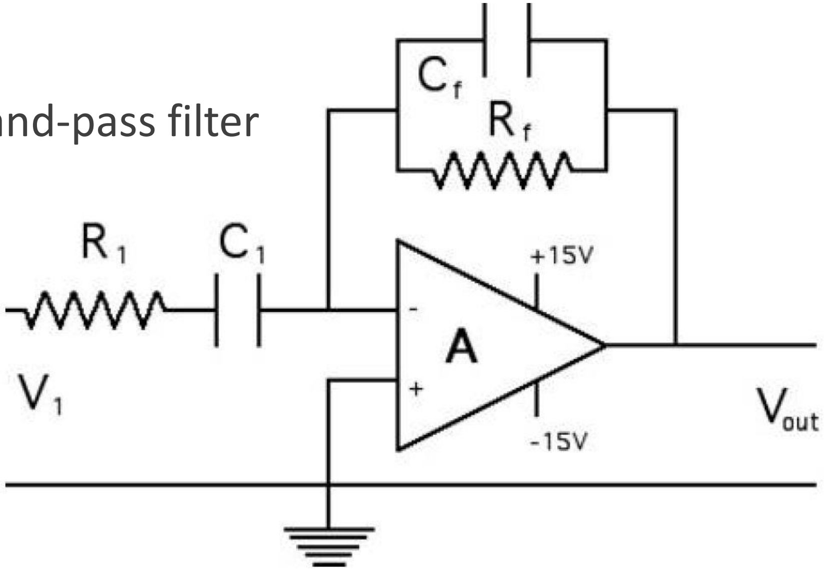
$$p_{filter} = \frac{1}{R_f C_f}$$



Bode plot

ACTIVE FILTERS

band-pass filter



$$H(s) = -\frac{Z_f}{Z_i} = -\frac{\dfrac{R_f}{1+j\omega R_f C_f}}{\dfrac{1+j\omega R_1 C_1}{j\omega C_1}}$$

$$= \frac{-j\omega R_f C_1}{(1+j\omega R_1 C_1)(1+j\omega R_f C_f)}$$

Bode plot

ACTIVE FILTERS

Now, think about the op-amp has a dominant pole at p_{op}, and assume the op-amp has a finite gain and infinite bandwidth

$$H(s) = -\frac{Z_f}{Z_i}\frac{1}{1+\frac{2}{A}} \qquad A \Rightarrow \frac{A}{1+\frac{s}{p_{op}}}$$

$$\frac{1}{1+\frac{2}{A}} = \frac{A}{A+2} = \frac{\frac{A}{1+\frac{s}{p_{op}}}}{\frac{A}{1+\frac{s}{p_{op}}}+2} = \frac{1}{1+\frac{s}{\frac{A}{2}p_{op}}}$$

$$LPF:\ H(s) = -\frac{Z_f}{Z_i}\times\frac{1}{1+\frac{s}{p_{filter}}}\times\frac{1}{1+\frac{s}{\frac{A}{2}p_{op}}}$$

ACTIVE FILTERS

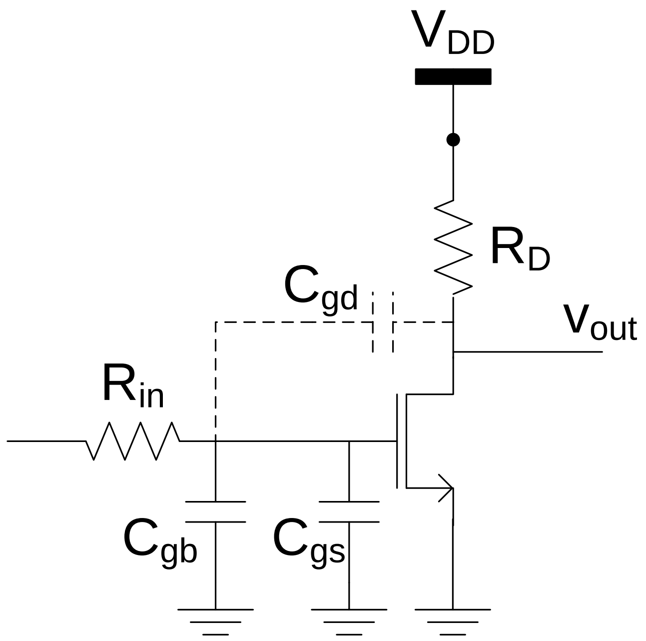
Now, we know we want high DC gain!

$$A_v = g_m R_{out} = \frac{1}{2} g_m r_o = \frac{I_{ds}}{V_{sat}} \frac{1}{\lambda I_{ds}} = \frac{1}{V_{sat}} \times f(L)$$

$$\omega_{p1} = \frac{1}{R_{in} C_{in\_equivalent}} \approx \frac{1}{R_{in} C_{gs}} = \frac{1}{R_{in} \cdot \frac{2}{3} \cdot W \cdot L \cdot C_{ox}}$$

$$g_m = \mu C_{ox} \frac{W}{L} V_{sat} \quad and \quad a_{v0} = g_m R_o$$

$$\therefore \omega_{p1} = \frac{3}{4} \frac{\mu}{L^2} \cdot \frac{r_o}{a_{v0} R_{in}} \cdot V_{sat}$$



Vsat is a crucial parameter for trading off gain, BW, and swing.

ACTIVE FILTERS

Or, you can attack them individually!

$$A_v = g_m R_{out}$$

W/L
Ids

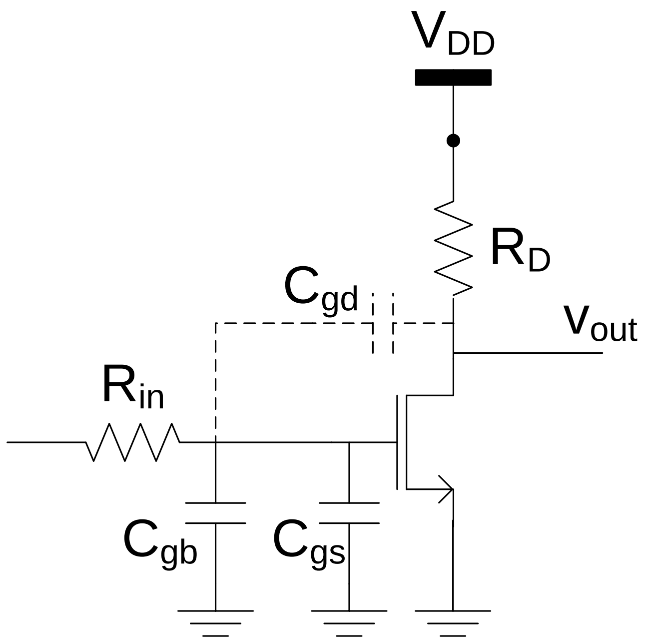
Cascoding
Ids
L

folding

AMPLIFIER DESIGN PLAN

$$I_{ds} = k'\frac{W}{L}\left(V_{gs} - V_t\right)^2 = k'\frac{W}{L}V_{sat}^2$$

$$g_m = 2k'\frac{W}{L}V_{sat} = 2\sqrt{k'\frac{W}{L}I_{ds}} = \frac{2I_{ds}}{V_{sat}}$$



4 design variables (Ids, Vsat, gm, W/L) and 2 equations!

- ***Design for gm and DC gain: Need to pick Vsat and Ids first!***

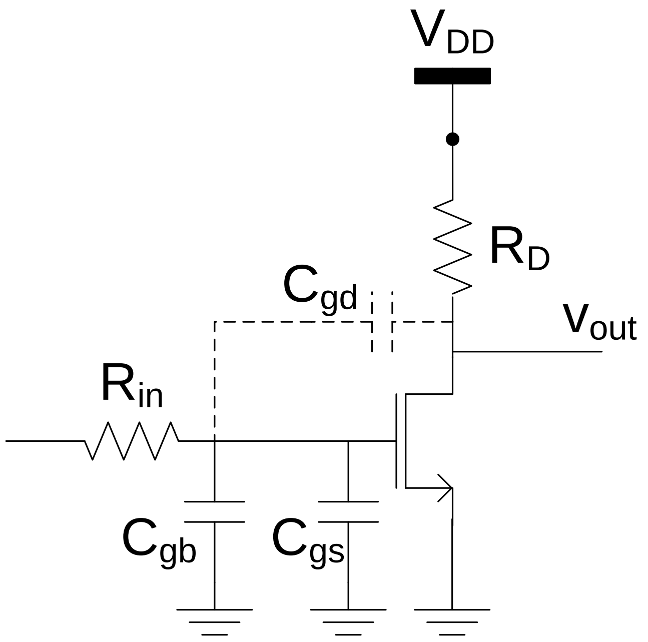
AMPLIFIER DESIGN PLAN

Now, add swing constraint:

$$I_{ds} = k'\frac{W}{L}\left(V_{gs} - V_t\right)^2 = k'\frac{W}{L}V_{sat}^2$$

$$g_m = 2k'\frac{W}{L}V_{sat} = 2\sqrt{k'\frac{W}{L}I_{ds}} = \frac{2I_{ds}}{V_{sat}}$$

$$V_{swing} = V_{dd} - 2V_{sat}$$



5 design variables (Ids, Vsat, gm, W/L, Vswing) and 3 equations!

- ***Design for gm and DC gain: Still need to pick Vsat and Ids first!***

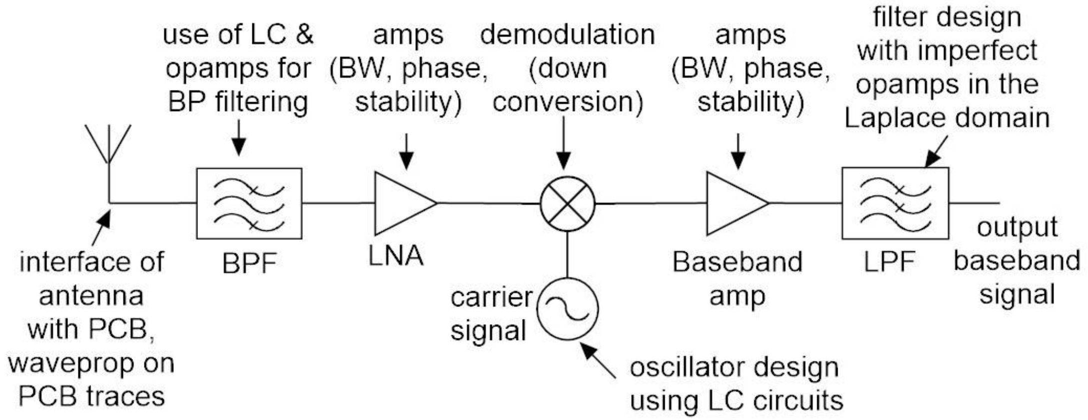
QUESTIONS

5. How does the mixer perform signal down-conversion?

6. Can the same mixer used for up-conversion perform down-conversion?

7. What is the function of the baseband amplifier

8. What is the function of the LPF at the end?



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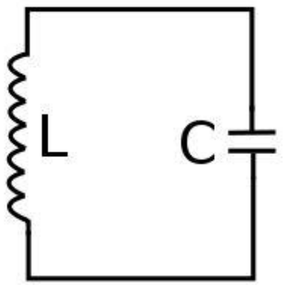
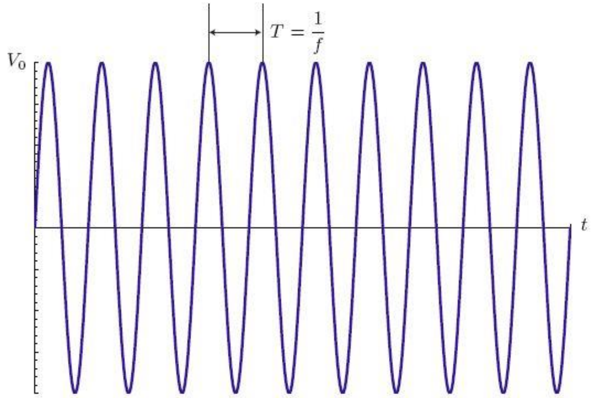
LOCAL OSCILLATOR



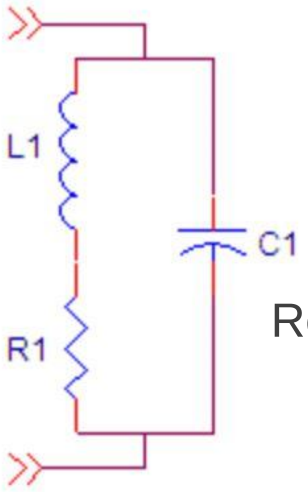
Ideal LC Tank

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

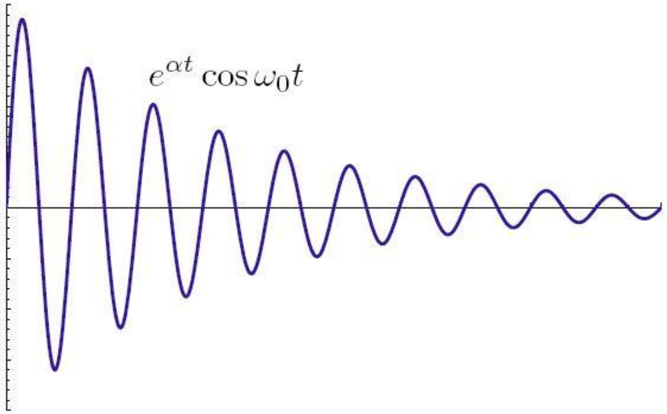


$$Q_L = \frac{\omega_0 L_1}{R_1}$$

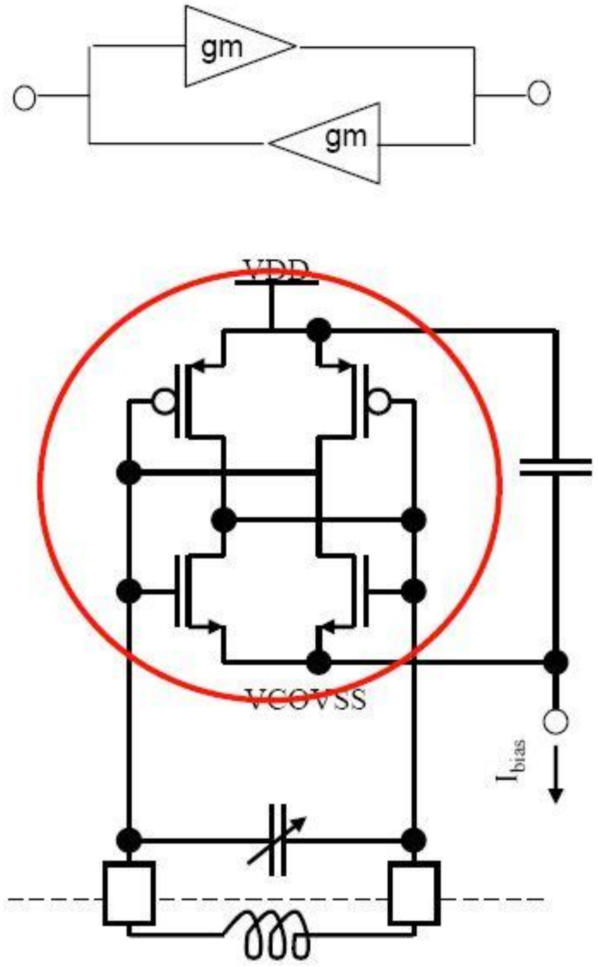
$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 - \frac{R_1^2 C_1}{L_1}}$$



Real LC Tank

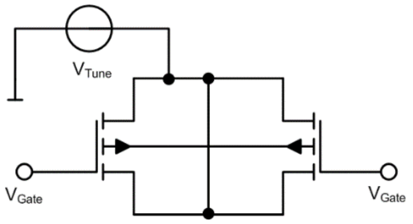


LOCAL OSCILLATOR

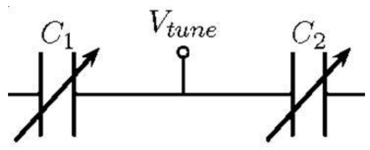


- Tuning is provided by the programmable capacitor
- Tuning range:
  - 902MHz – 928MHz
  - Able to compensate for 5% process variation
  - Able to compensate for 2% inductance variation
- L = 17nH, Q = 30
- Output swing 1Vp-p
- Ibias = 200 – 300uA

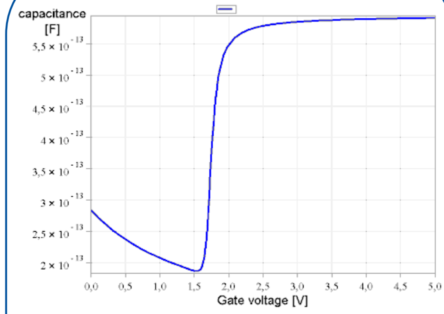
LOCAL OSCILLATOR – USE MOS VARACTOR FOR TUNING



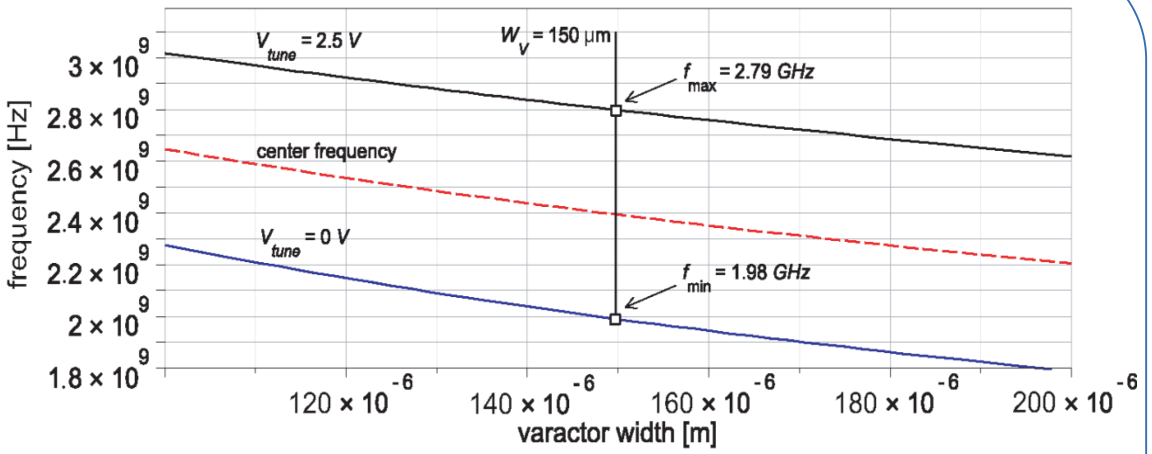
MOS varactor



MOS varactor



CV-characteristic



Tuning range

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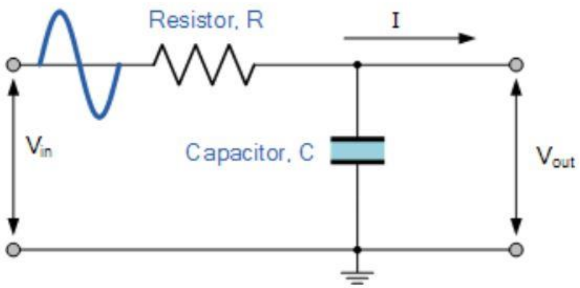
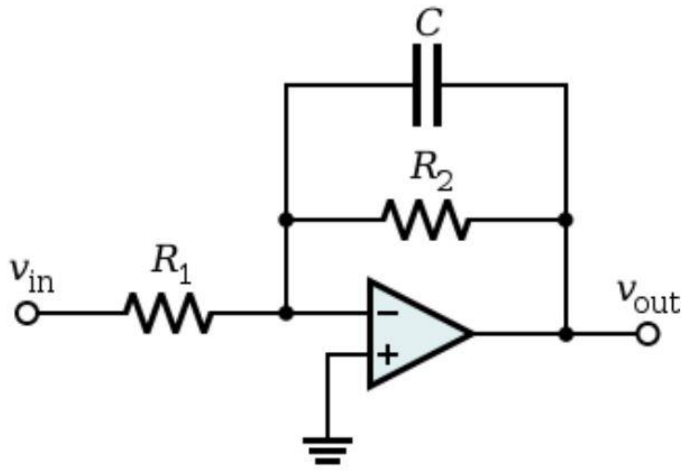
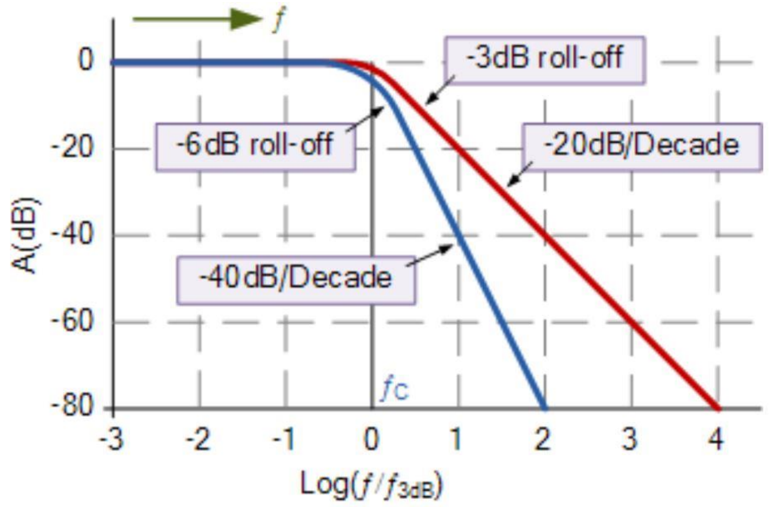
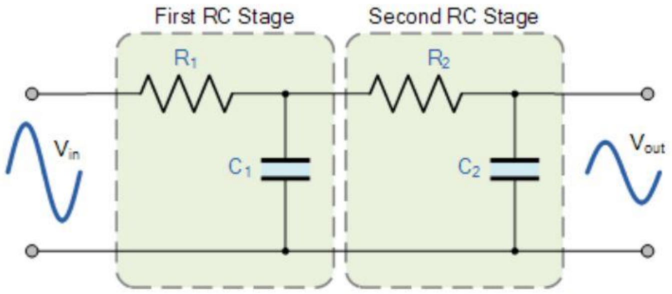
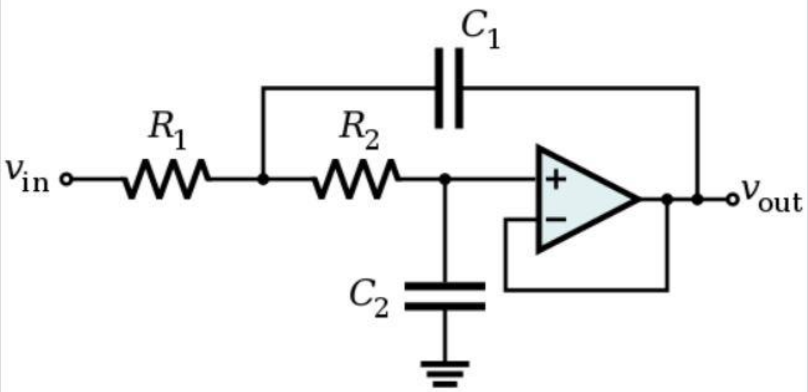
ACTIVE LOW-PASS FILTERS



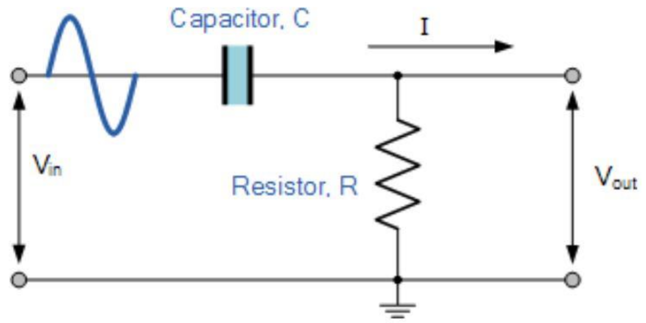


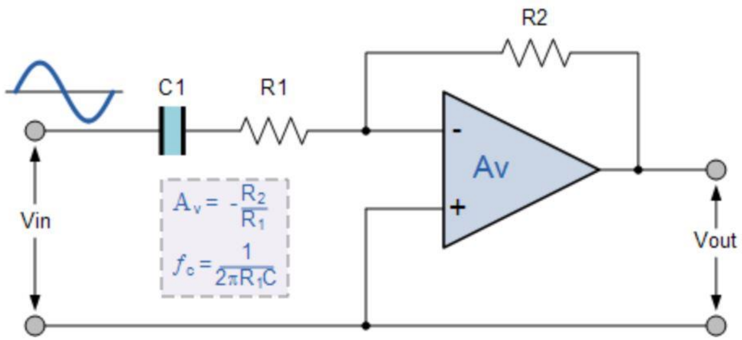


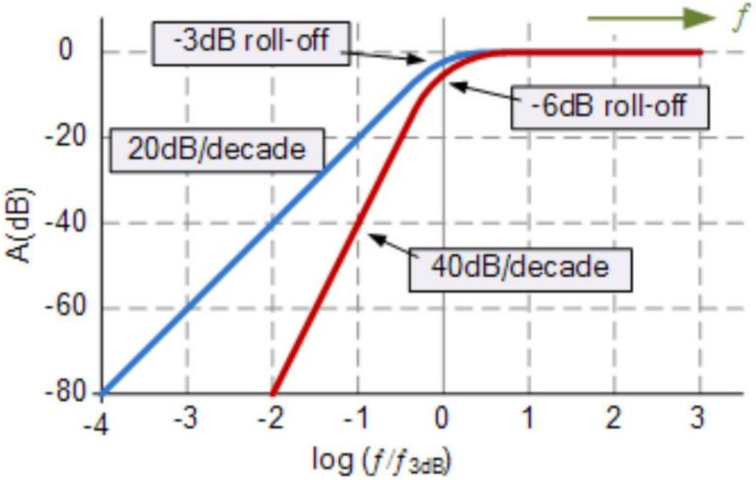


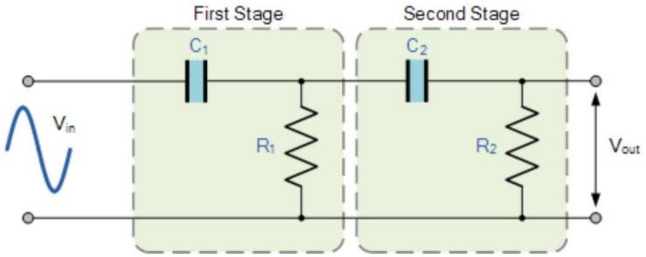


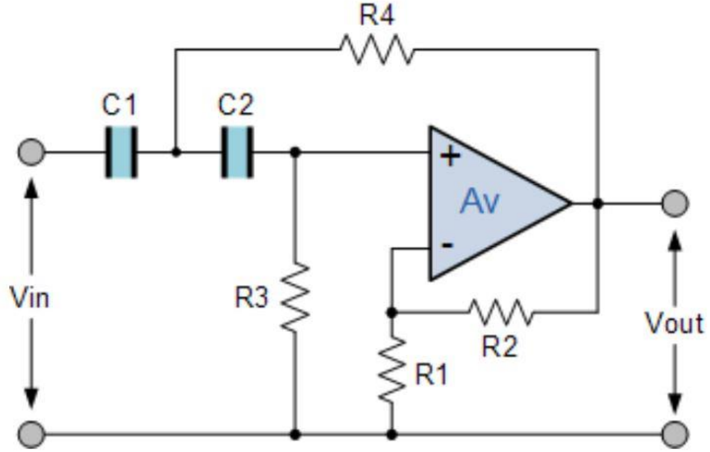
ACTIVE HIGH-PASS FILTERS











$$A_v = 1 + \frac{R_2}{R_1}$$

$$f_C = \frac{1}{2\pi\sqrt{R_3 R_4 C_1 C_2}}$$

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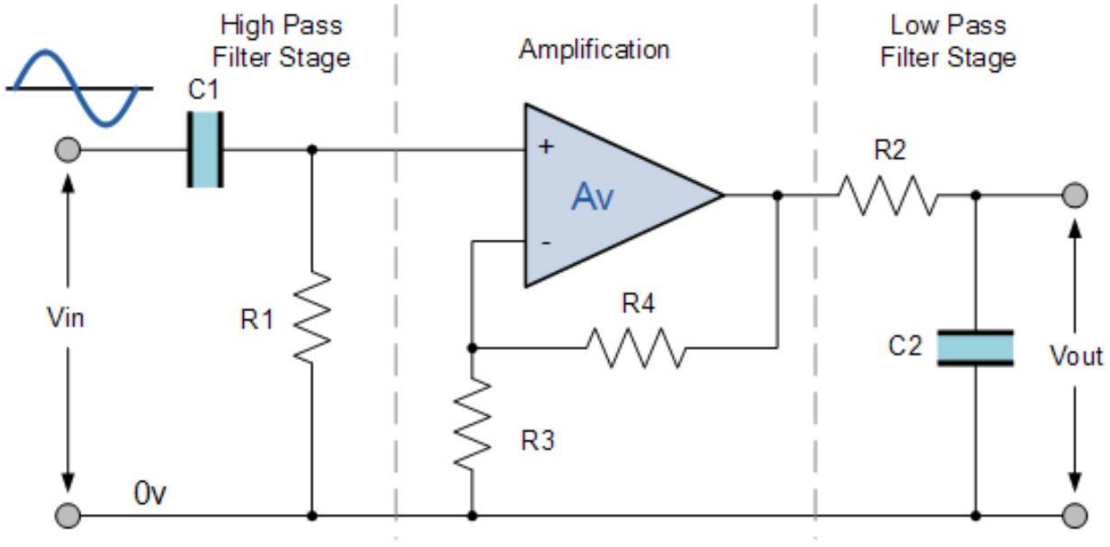
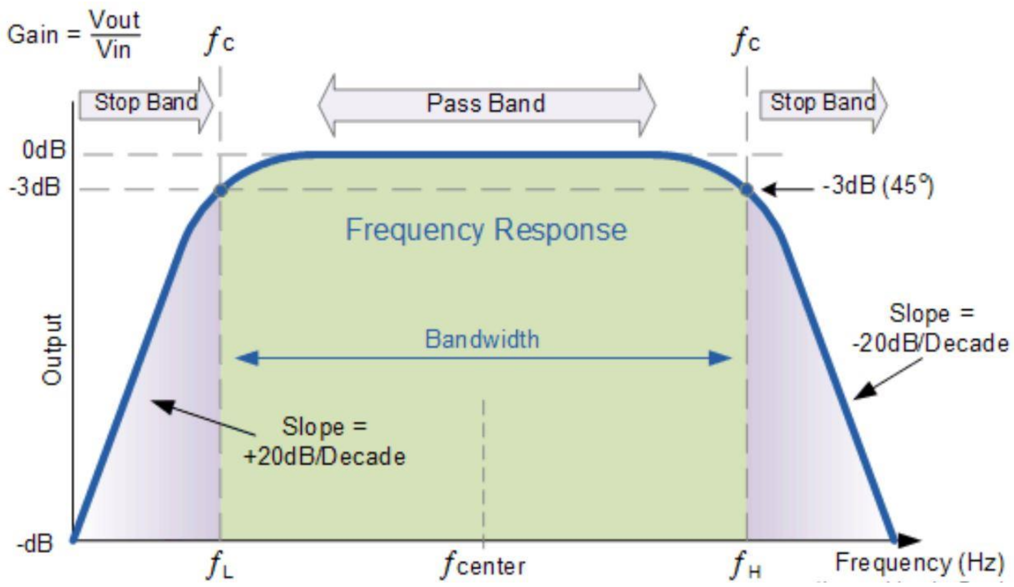
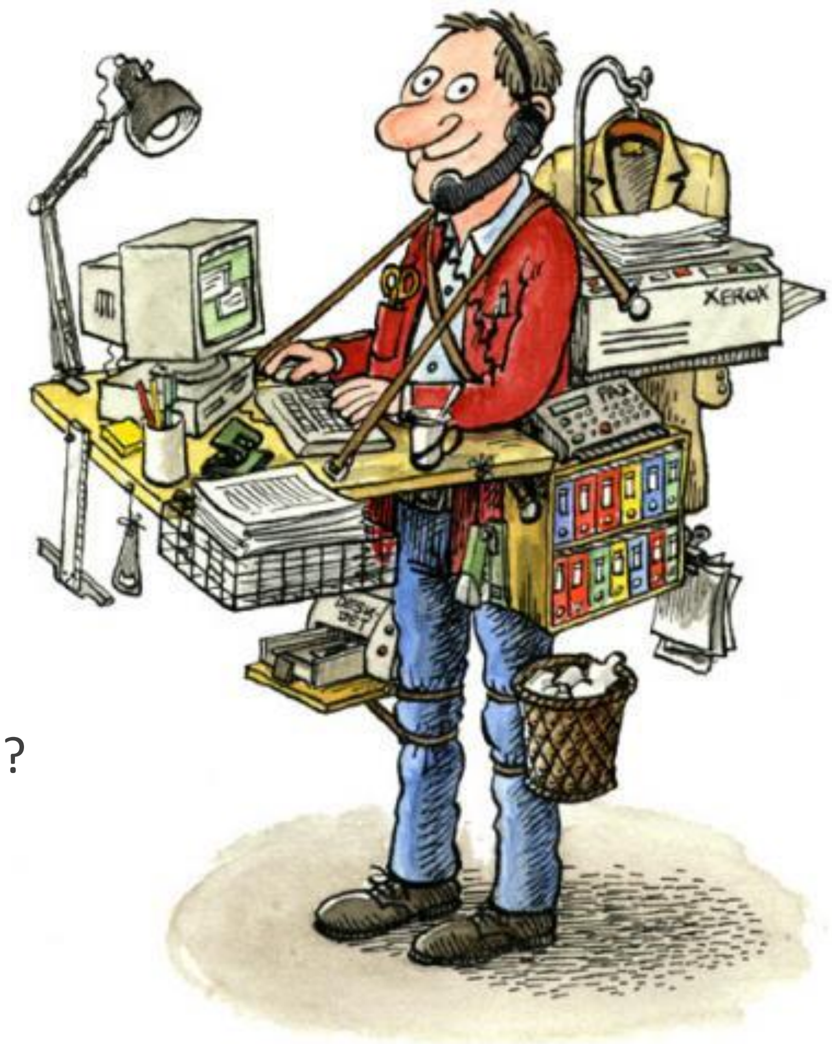
ACTIVE BAND-PASS FILTERS



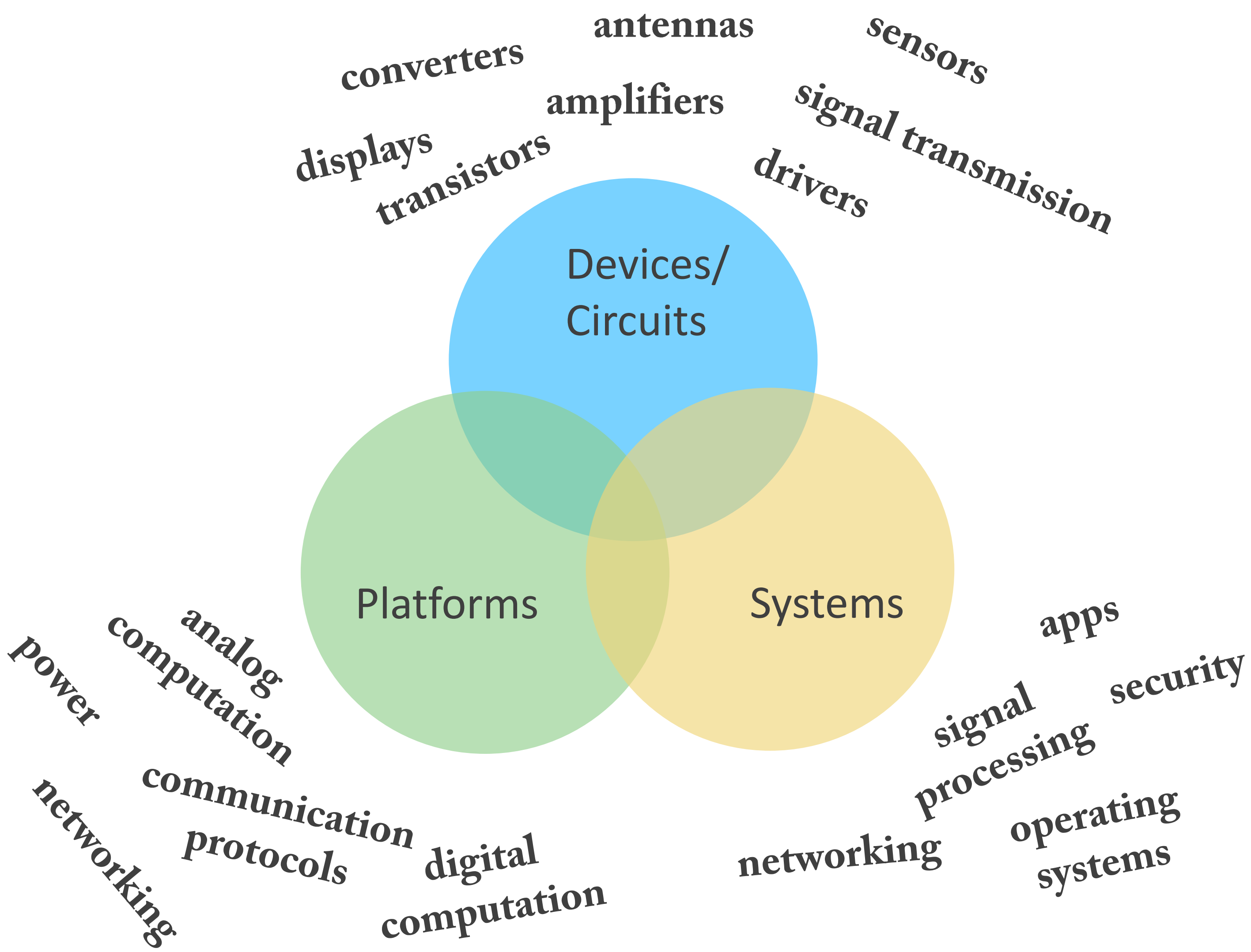


KI6: WRAPPING UP: THE POWER OF SMARTPHONES



Smart office!?

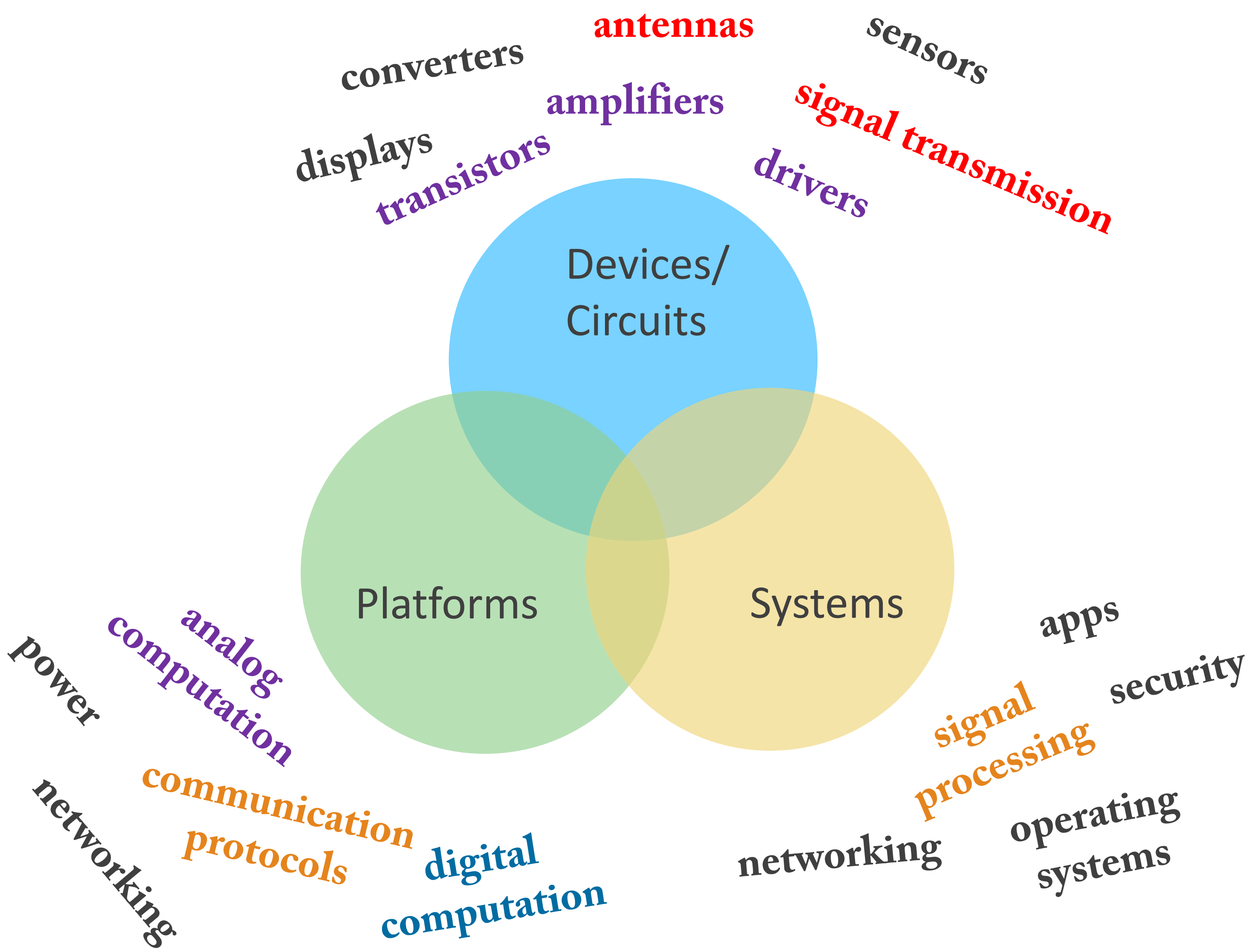
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?



KI6: WHAT ENABLES THE POWER OF SMARTPHONES?

ECE311/312
ECE331/332
ECE341/342

ECE451



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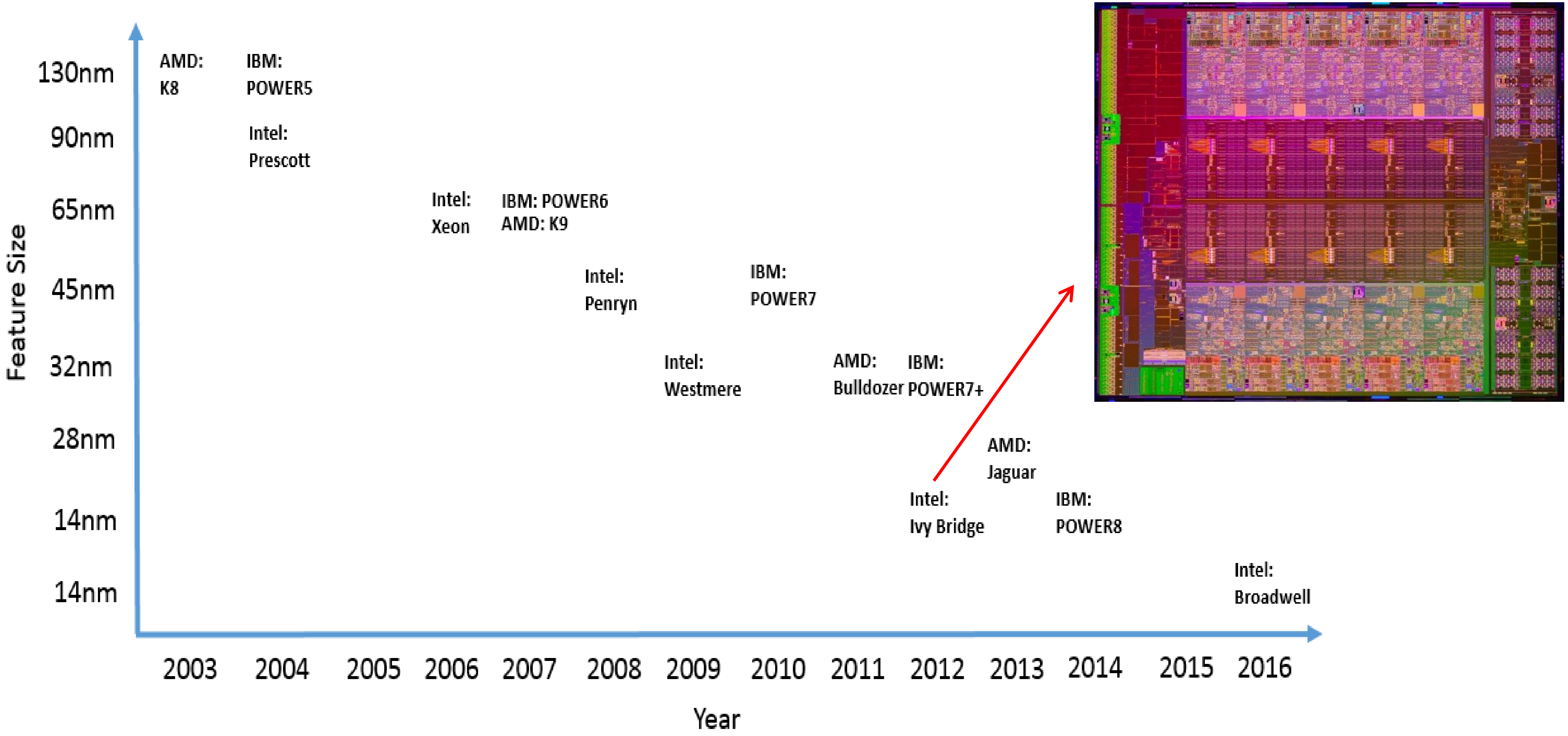
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?

But the advances have been mainly driven by semiconductors and signal processing

KI6: WHAT ENABLES THE POWER OF SMARTPHONES?



Moore’s Law Scaling and Exponential Increase in Functionality

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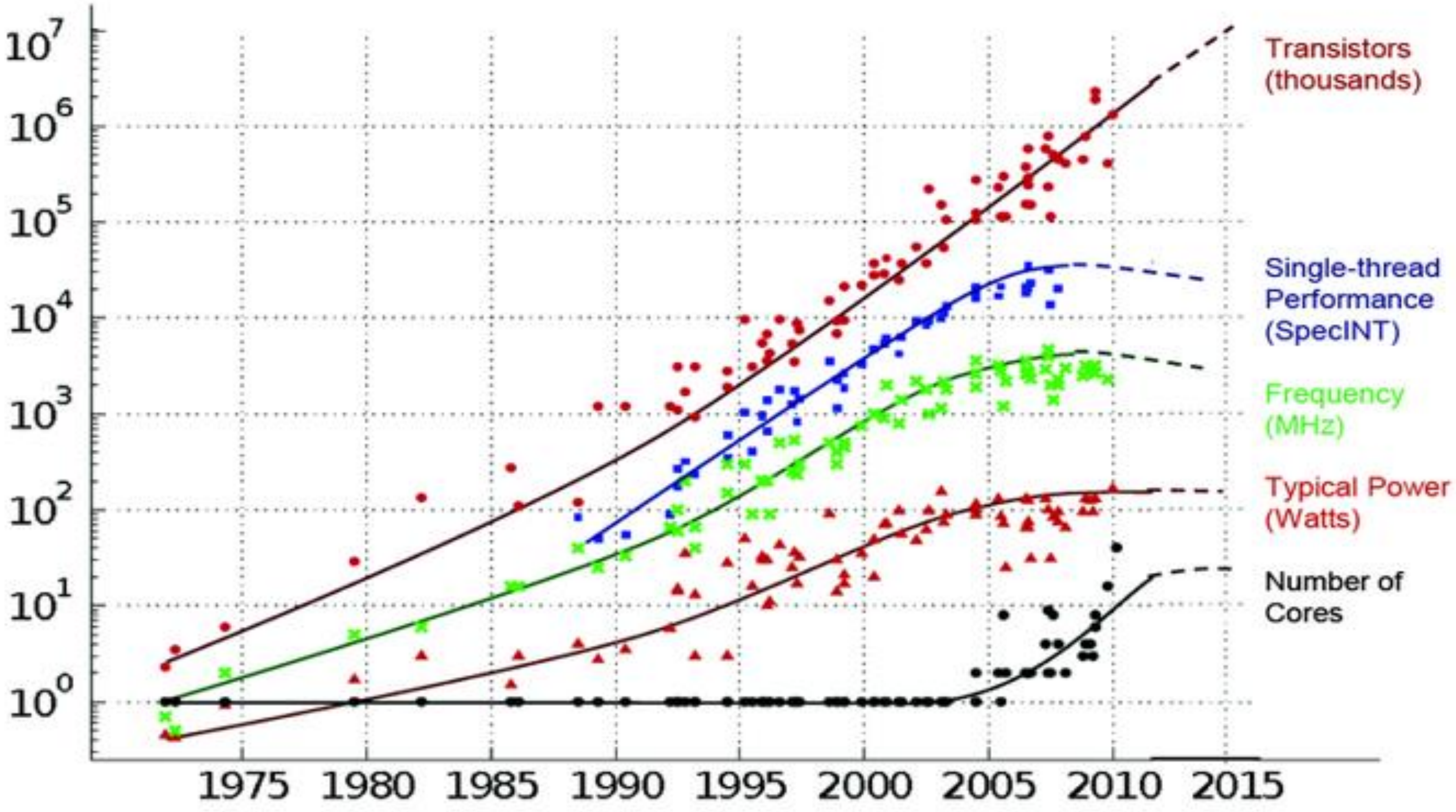
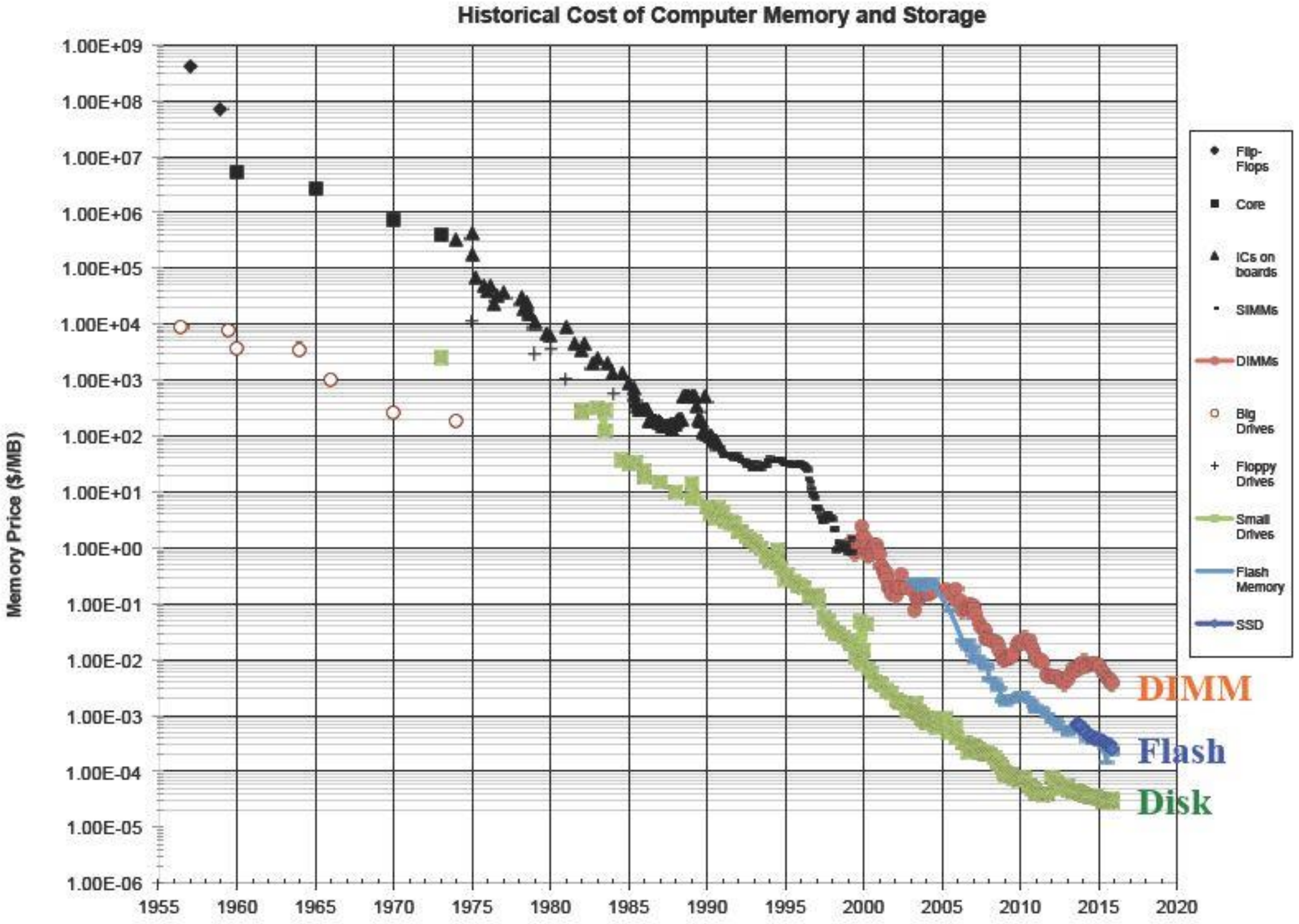
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?



Moore's Law Scaling and Exponential Increase in Functionality

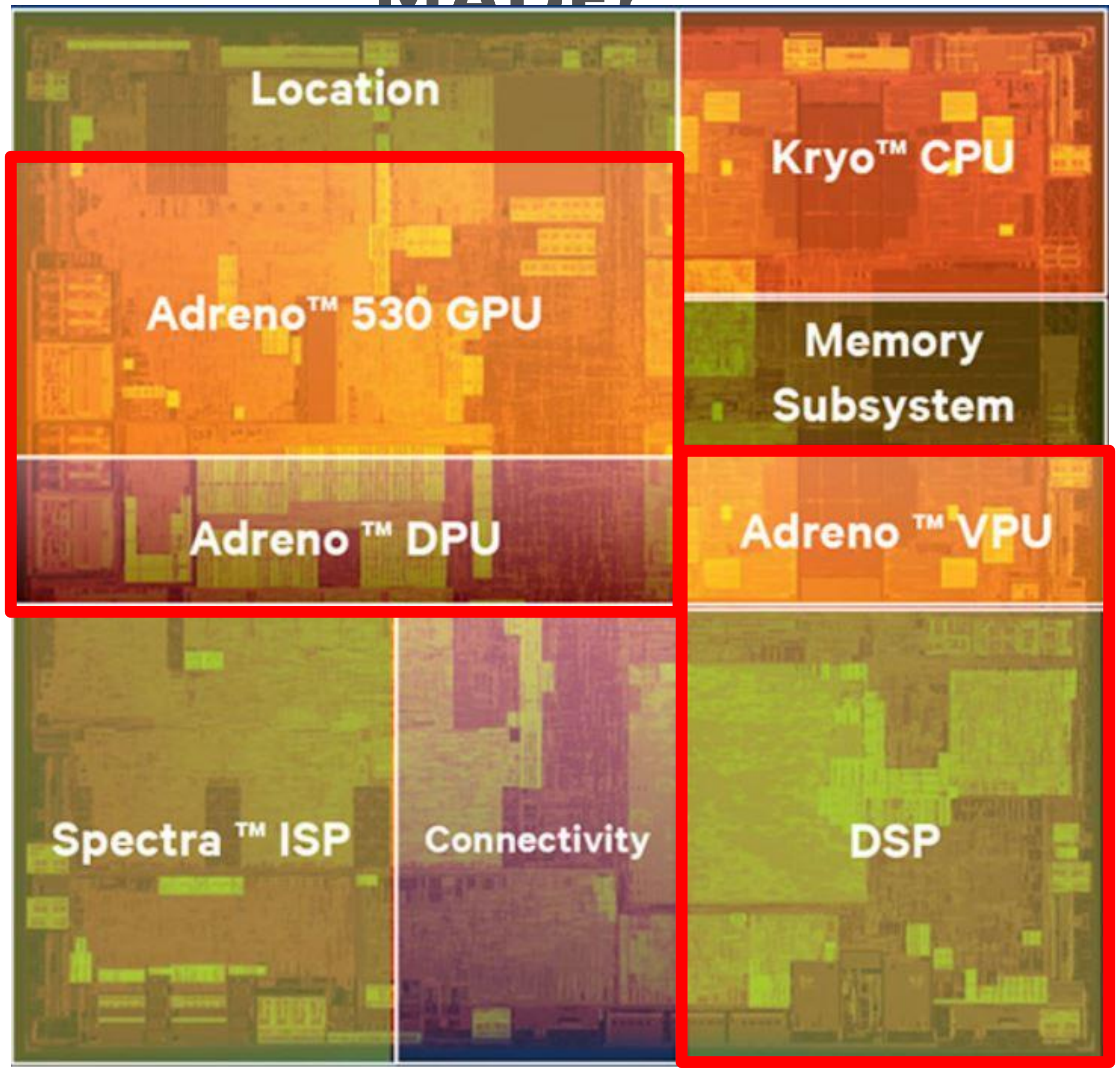
KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

A lot of storage for the exponential amount of garbage we want to keep with us.



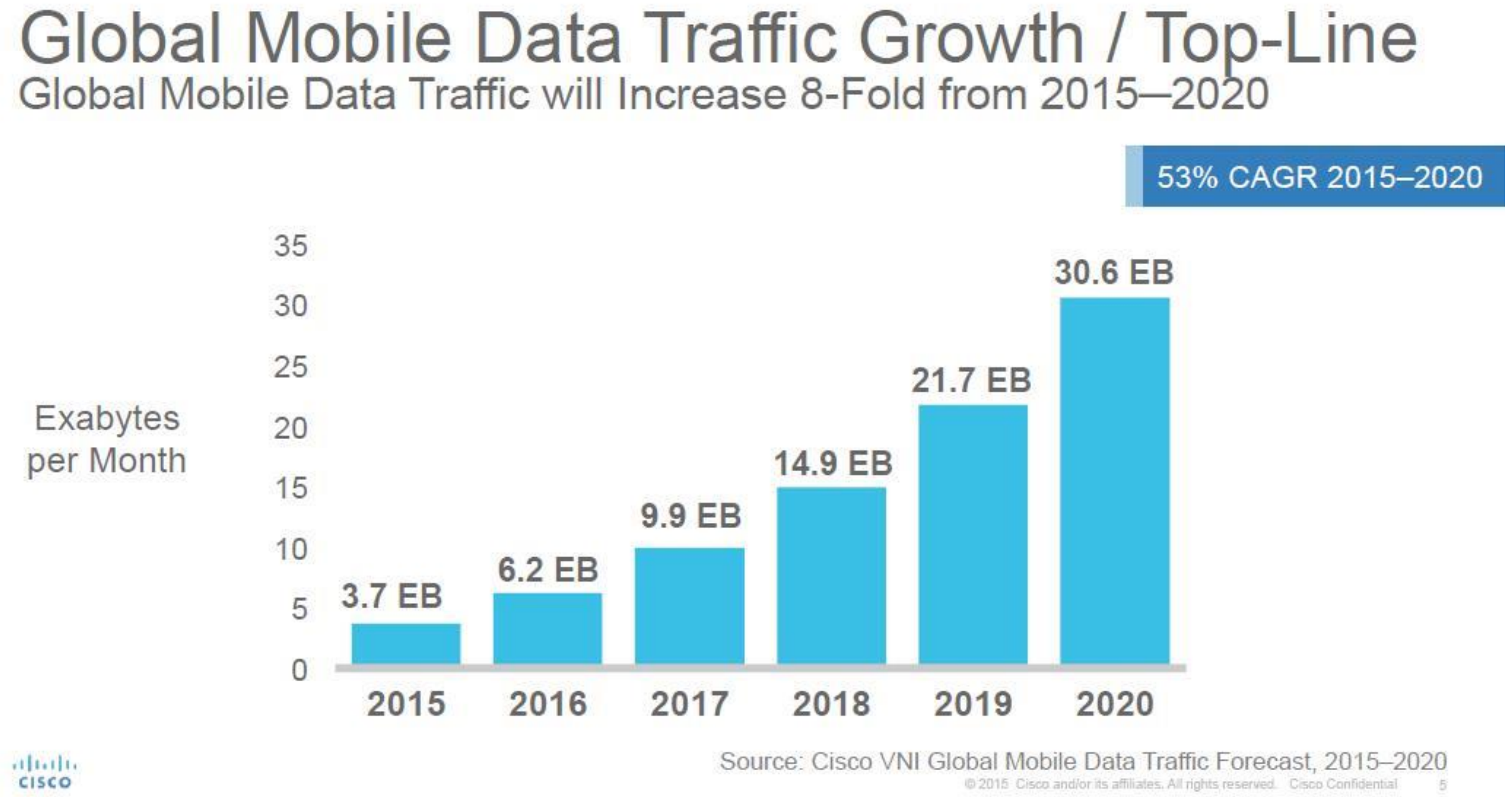
KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

A lot of graphics capabilities



Qualcomm Snapdragon 820 Mobile SOC

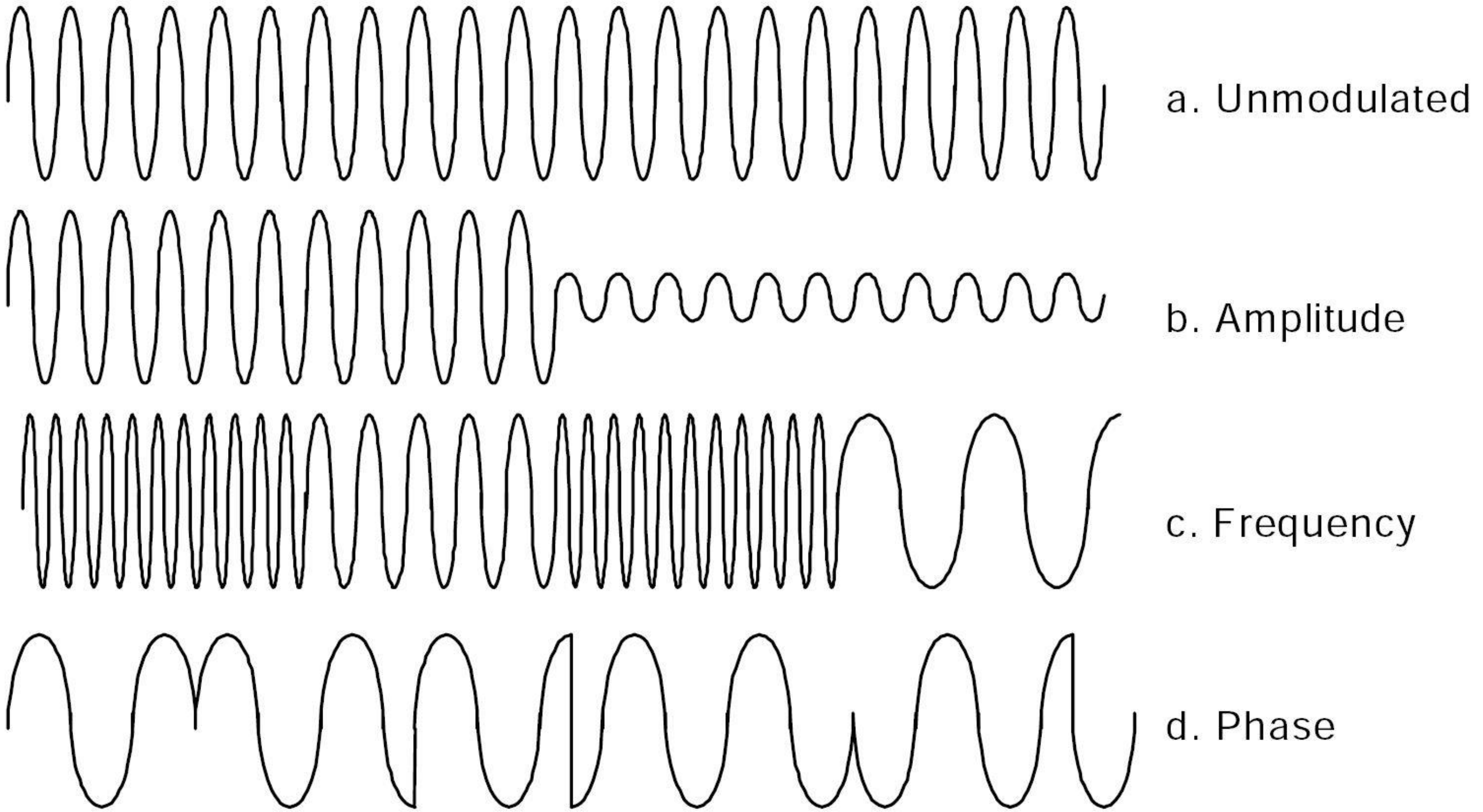
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?



Connectivity and speed

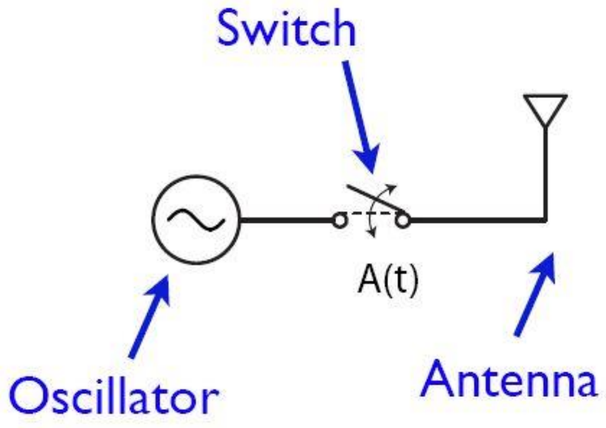
KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

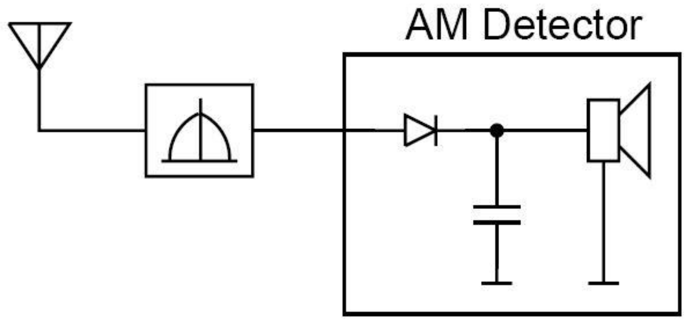
- Increase connectivity through innovations in modulation technology



KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

- AM or FM is simple but is inefficient for frequency spectrum usage

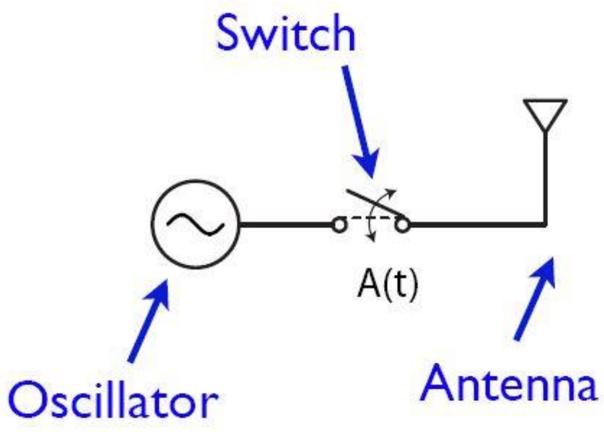


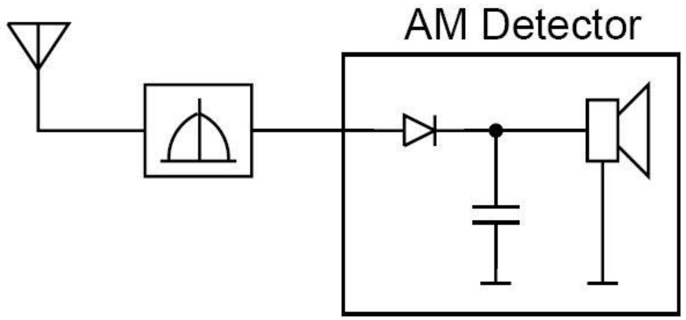


- The oscillator is used to generate carrier signal
- The simplest AM method uses a MOSFET to turn the carrier signal "on" or "off"
- The receiver uses the band-pass filter to tune to the carrier frequency.
- The diode is the simplest way for AM detection.
- If the load is a light (a simple earphone), the receiver doesn't really need power supply as the received signal energy can drive the load directly

KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

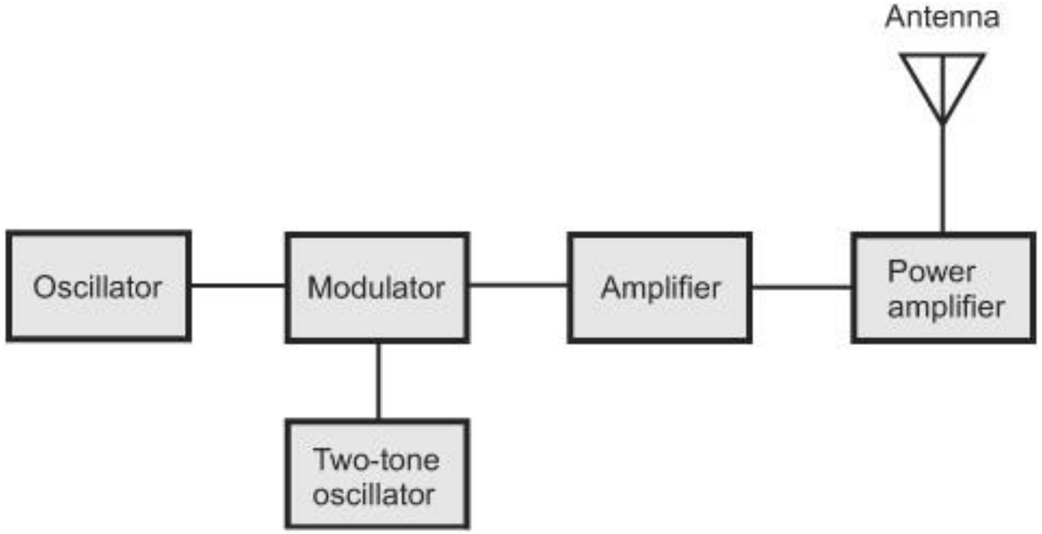
- Limitations of AM:
  - AM signals are more susceptible to noise, especially weather related noise
  - An AM channel only emits one signal channel (can't do stereo)
  - The receiver has poor selectivity, particularly when the carrier frequency is reasonably high.
    - » Hard to control the bandwidth shape (narrow) when the center frequency is increased
  - Starting from the 1920s, the vacuum tubes were used to amplify the received signal to improve receiver sensitivity. However, selectivity is still the major obstacle at the time

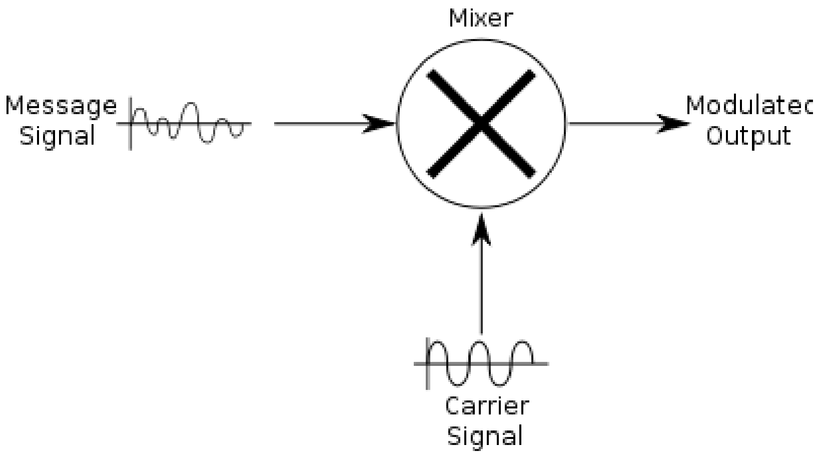




KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

- FM:
  - It doesn't rely on varying amplitudes, it doesn't get as much noise interference
  - An FM channel potentially allow for the source to emit two sub-channels of information simultaneously, allowing for left and right audio channels, perfect for stereo quality, if the carrier frequency is sufficiently high
  - Short transmission distance (< 50 miles)
  - Both AM and FM are analog mode of communication. They are very inefficient in the use of limited frequency spectrum.





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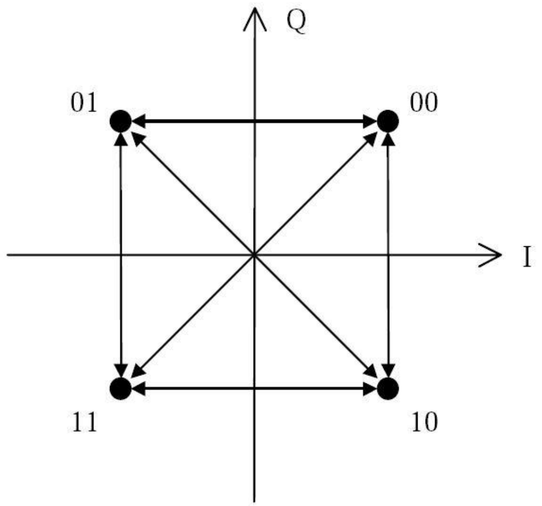
KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

- To improve spectrum efficiency:
  - Modern communication relies on digital signals in the form of symbols.
  - The signal bandwidth for a digital communications channel depends on the symbol rate as opposed to the bit rate.

$$bit\ \ rate = symbol\ \ rate \times bits\ \ per\ \ symbol$$

  - Phase modulation is more suited for digital signal communcation
    - » Binary phase shift keying (BPSK): 1 bit per symbol
    - » Quadrature phase shift keying (QPSK): The four symbols are +45°, +135°, -45°, and -135°.
      - 2 bits per symbol
      - Change in one of the bits ➔ 90 degree shift
      - Change in both bits ➔ 180 degree shift

constellation diagram



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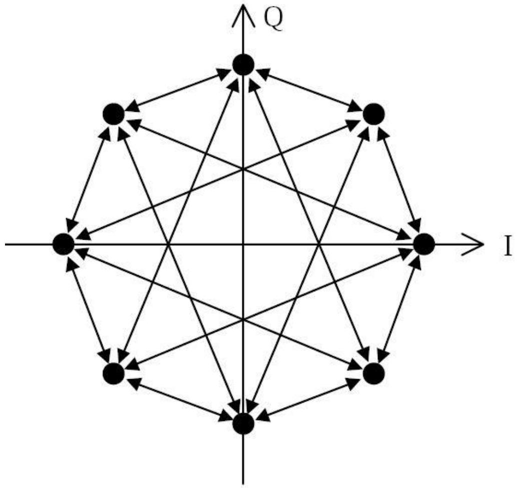
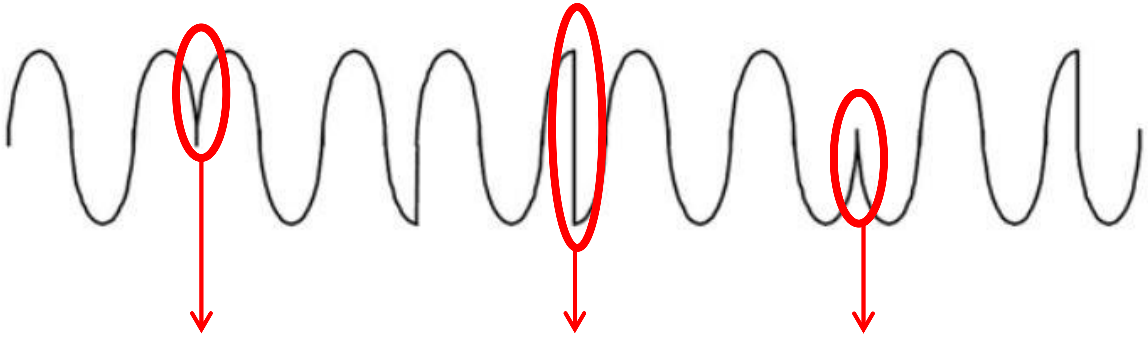
KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

- To improve spectrum efficiency:
  - Phase modulation is more suited for digital signal communication
    - » Differential $\pi/4$ quadrature phase shift keying ($\pi/4$ DQPSK):
      - Allow only $\pm\pi/4$ and $\pm 3\pi/4$ for each bit change
      - Can be viewed as superimposing two QPSK signal constellations offset by 45°
      - To reduce complexity, during each symbol period, a phase angle from one of the QPSK constellations is transmitted. The two constellations are used alternately to transmit every pair of bits. ➔ the output demodulation rate is doubled compared to QPSK ➔ think about pipelining
      - One additional (differential) bit codes which QPSK constellation ➔ giving effective 3bits/symbol



KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

- Problems with the conventional PSK schemes
  - Abrupt changes in carrier signal due to phase change



These abrupt changes cause harmonics extending to infinity

↓

Produce an RF spectrum of considerable bandwidth

↓

Not efficient for limited spectrum usage!

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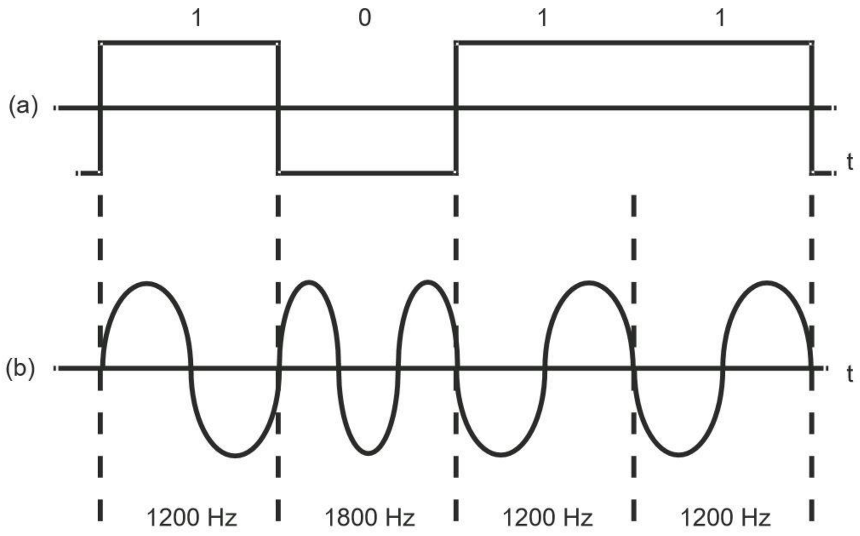
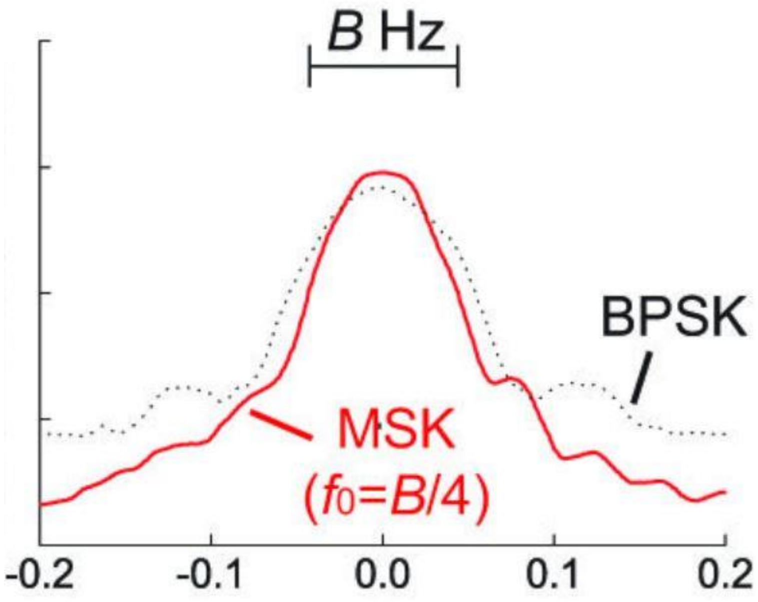
KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

- To improve spectrum efficiency:
  - Minimum shift keying (MSK)
    - » Continuous phase modulation scheme where the modulated carrier contains no phase discontinuities and frequency changes occur at the carrier zero crossings.
    - » The difference between the frequency of a logical zero and a logical one is always equal to half the data rate
      - For example, a 1200 bit per second baseband MSK data signal could be composed of 1200 Hz and 1800 Hz frequencies for a logical one and zero respectively



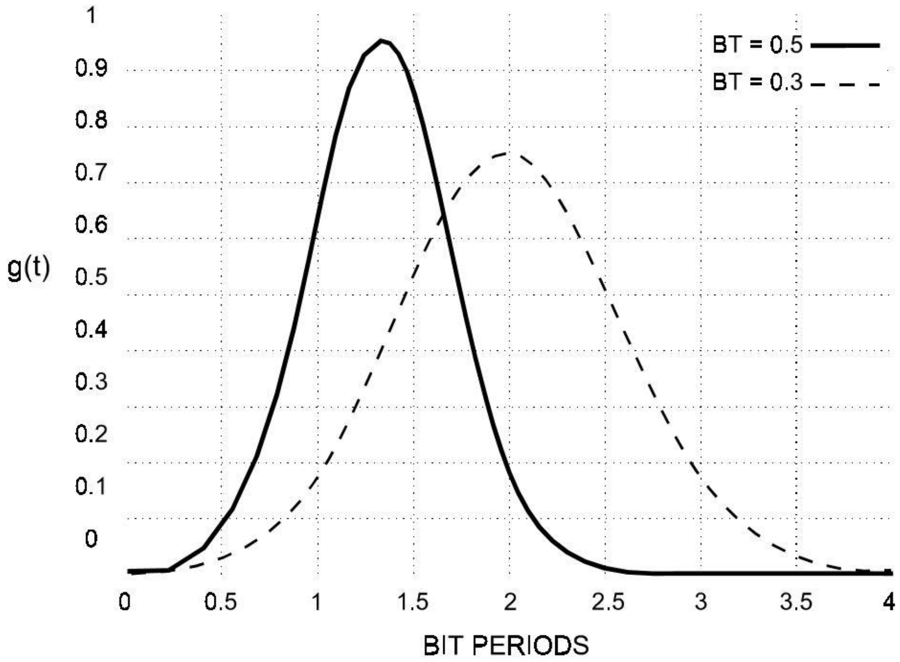
KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

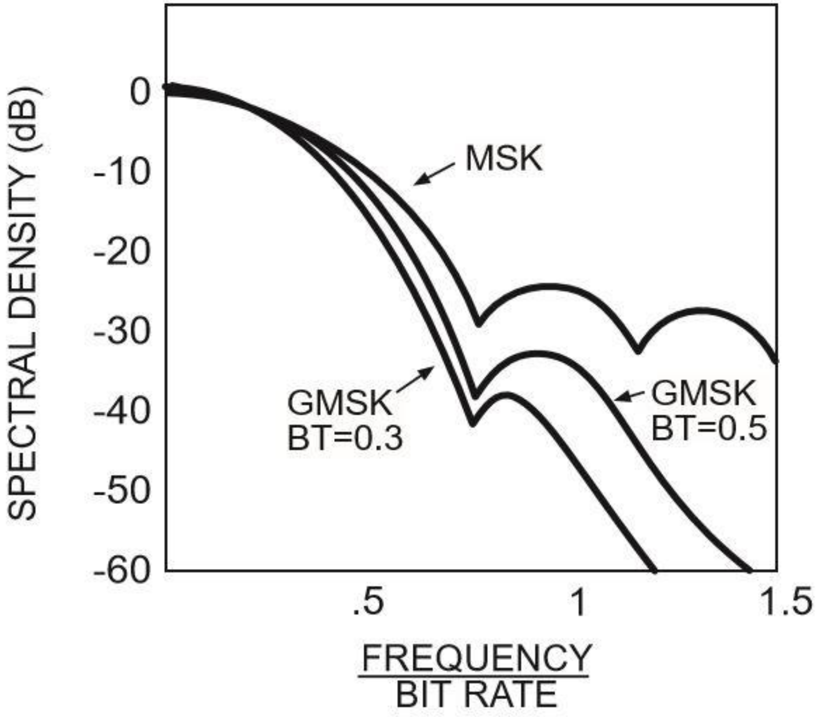
- Problems with MSK:
  - MSK is great for transmitting data where the data rate is relatively low compared to the channel BW
    - » i.e. for high data rates, it still occupy too wide of a BW for the need of current RF applications, even though it is a lot better than BPSK/QPSK.
    - » The spectrum energy outside the required BW mainly comes from the data source, especially when data rates are going up!



KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

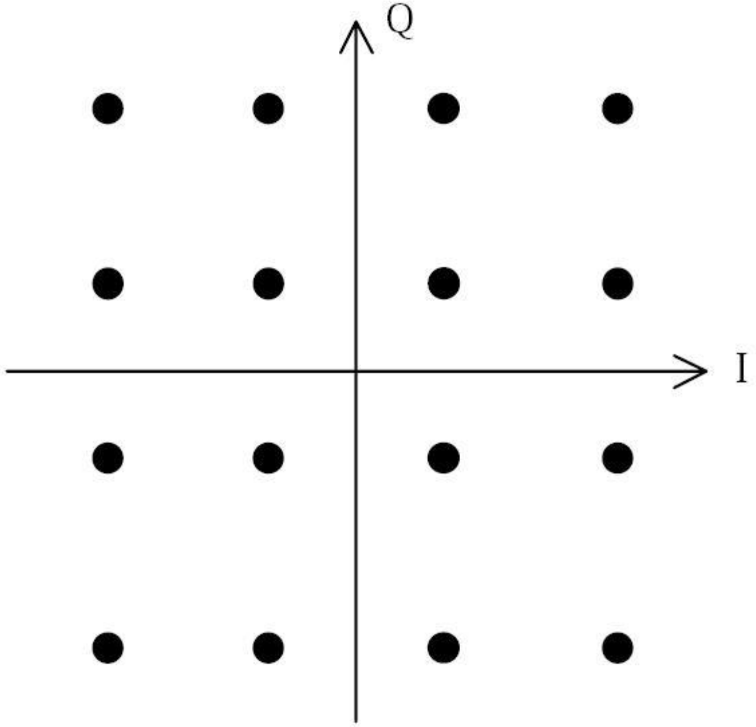
- Gaussian MSK:
  - One solution is to forcefully reduce the spectrum energy outside the defined band (say 200KHz) by using a pre-modulation filter
    - Gaussian filter is a good candidate
    - This leads to GMSK (Gaussian MSK)





KI6: WITH "FREE" TRANSISTORS, WHAT ADVANCES WERE MADE?

- 4G/LTE:
  - Need more performance (data rate) per channel
  - 16 QAM (Quadrature Amplitude Modulation) ➔ 4-bit/symbol ➔ combination of amplitude and phase modulations.

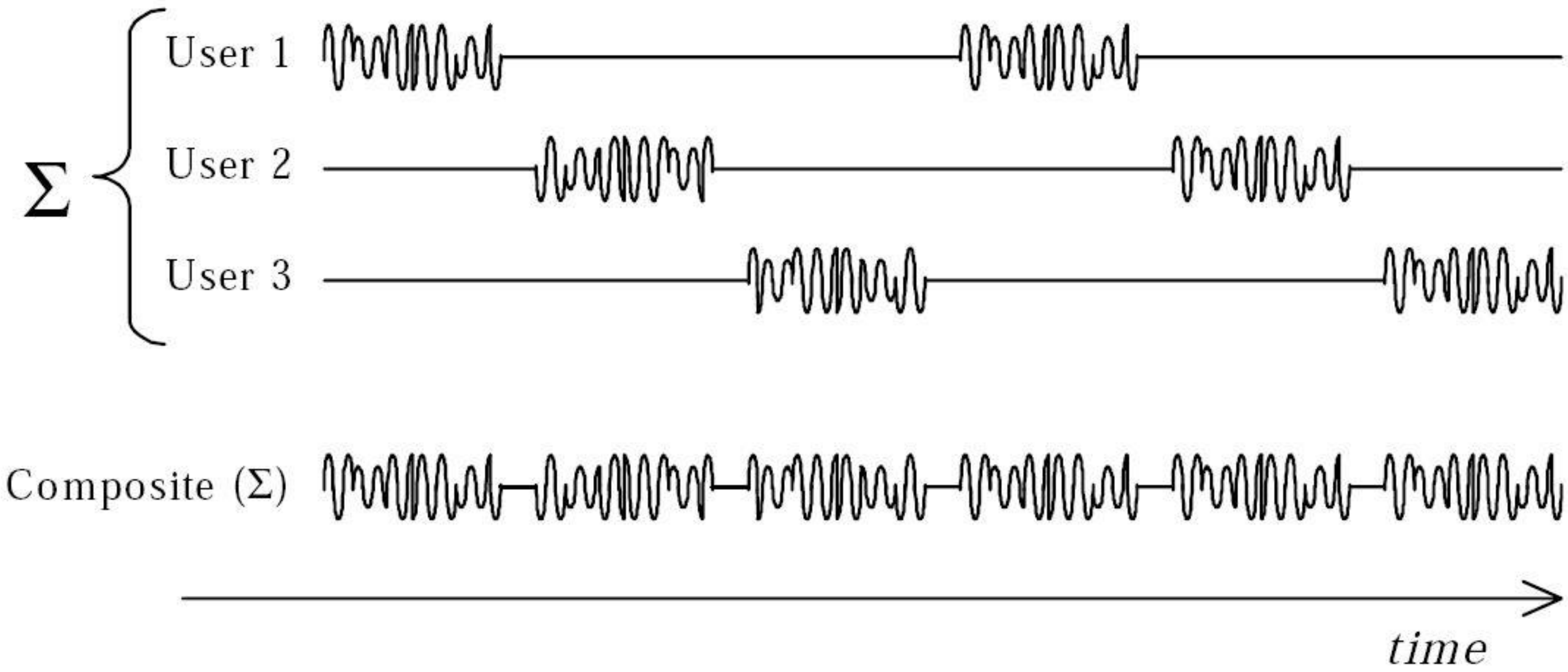


KI6: CELLPHONE COMMUNICATION STANDARD

Parameter	E-GSM900	DCS1800	IS-136	IS-95	PDC
Tx (MHz)	880-915	1710-1785	824-849 1850-1910	824-849	940-956, 1477-1501
Rx (MHz)	925-960	1805-1880	869-894 1930-1990	869-894	810-826, 1429-1453
Access method	TDMA	TDMA	TDMA	CDMA	TDMA
Modulation	GMSK	GMSK	$\pi/4$-DQPSK	QPSK BPSK	$\pi/4$-DQPSK
Carrier spacing (kHz)	200	200	30	1250	25
Duplex	FDD	FDD	FDD	FDD	FDD

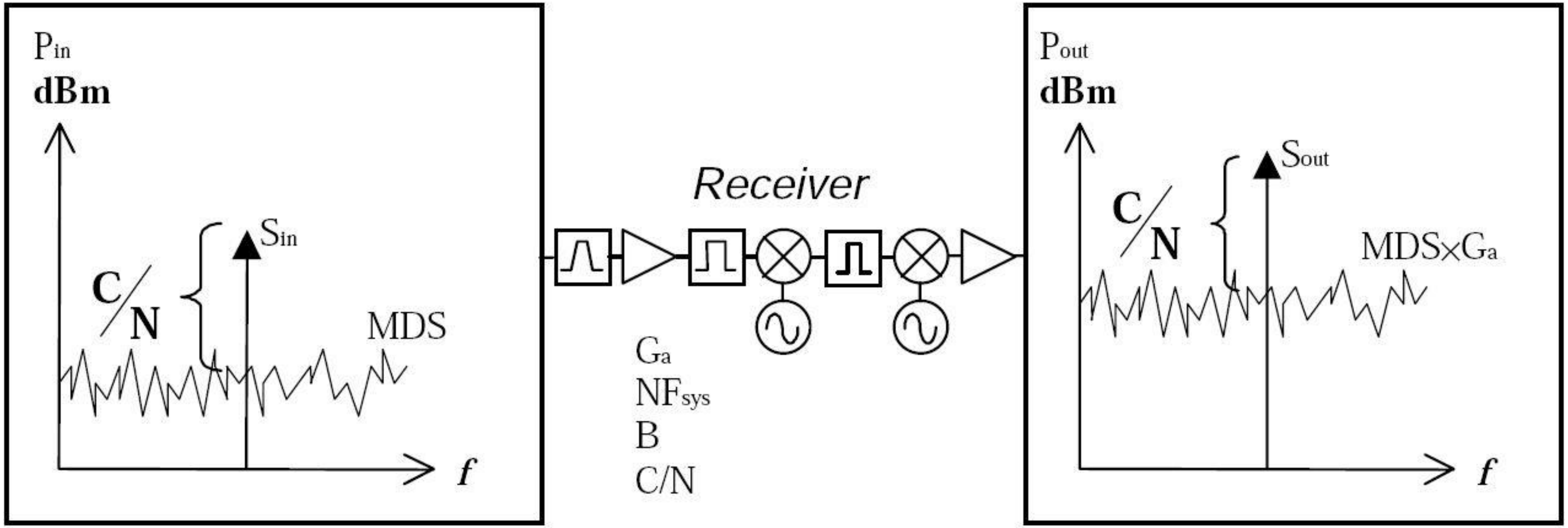
KI6: CELLPHONE COMMUNICATION STANDARD

- TDMA (Time Division Multiple Access) used on GSM phones

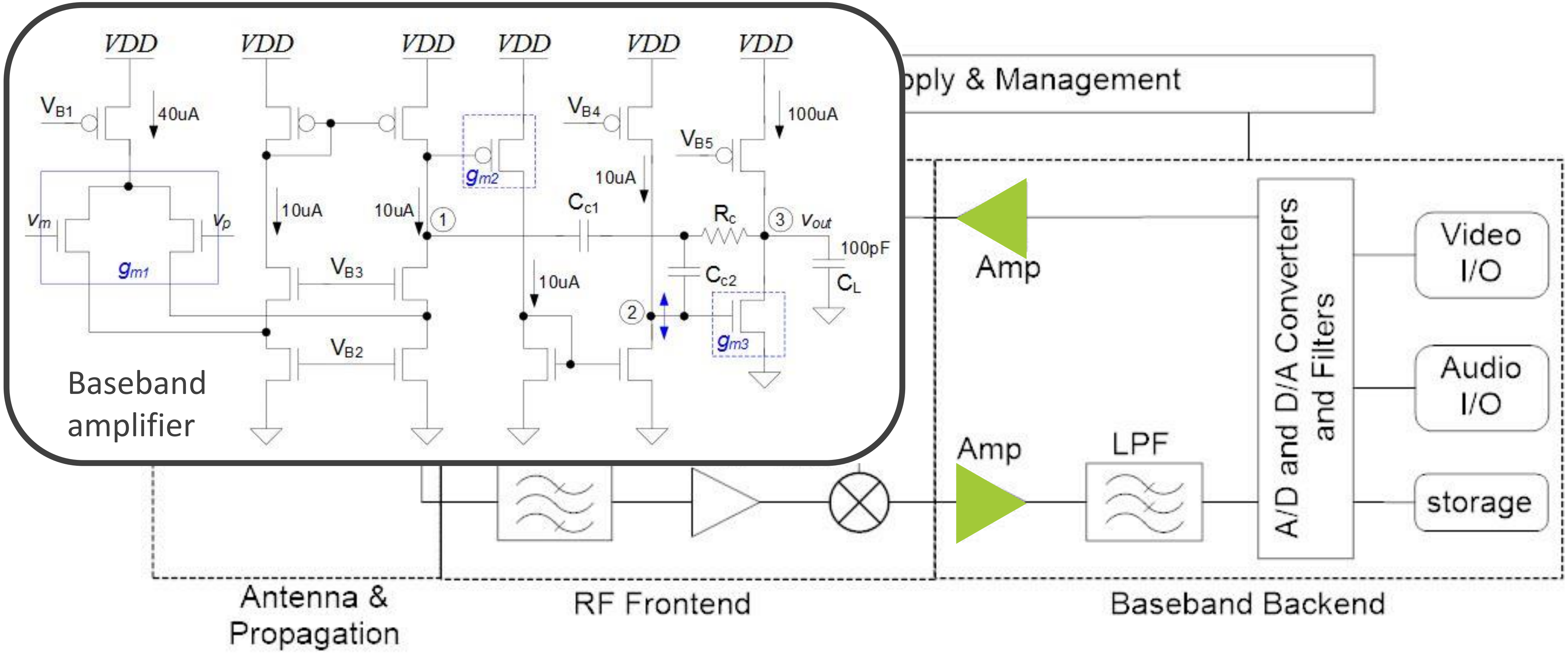


KI6: WHAT ABOUT NOISE?

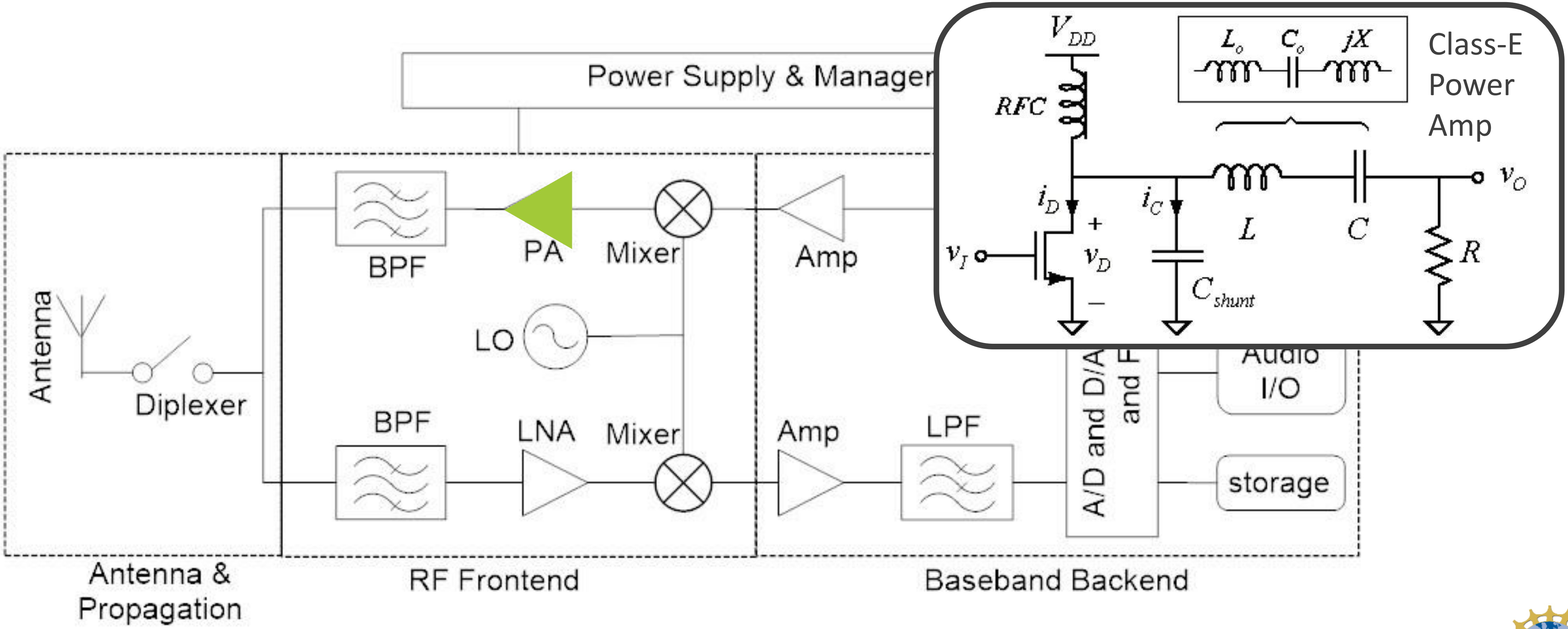
- At the end of the receive, the quality of the signal depends on the noise level
  - Carrier-to-noise ratio decreases through the receiver
  - The minimum detectable signal (MDS) is when C/N ratio reaches zero.



KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?



KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?



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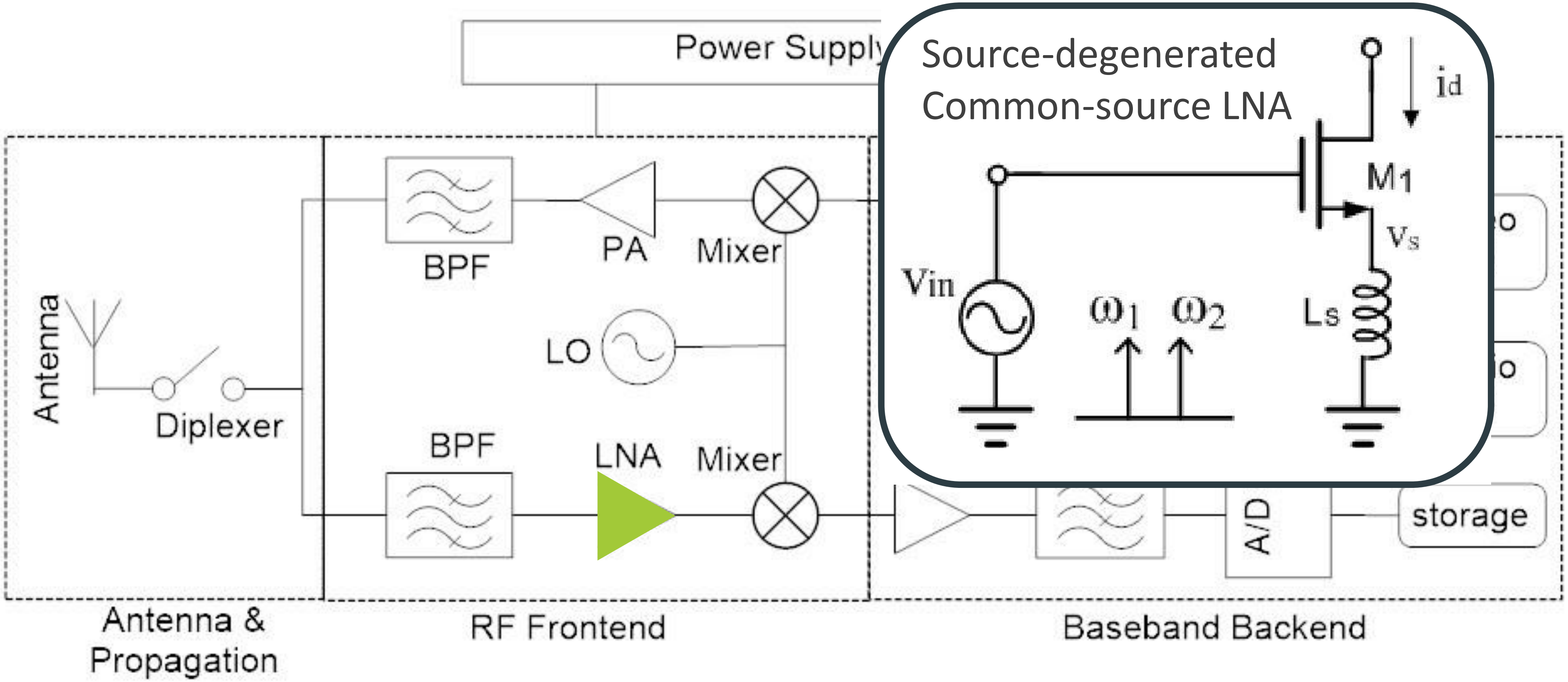
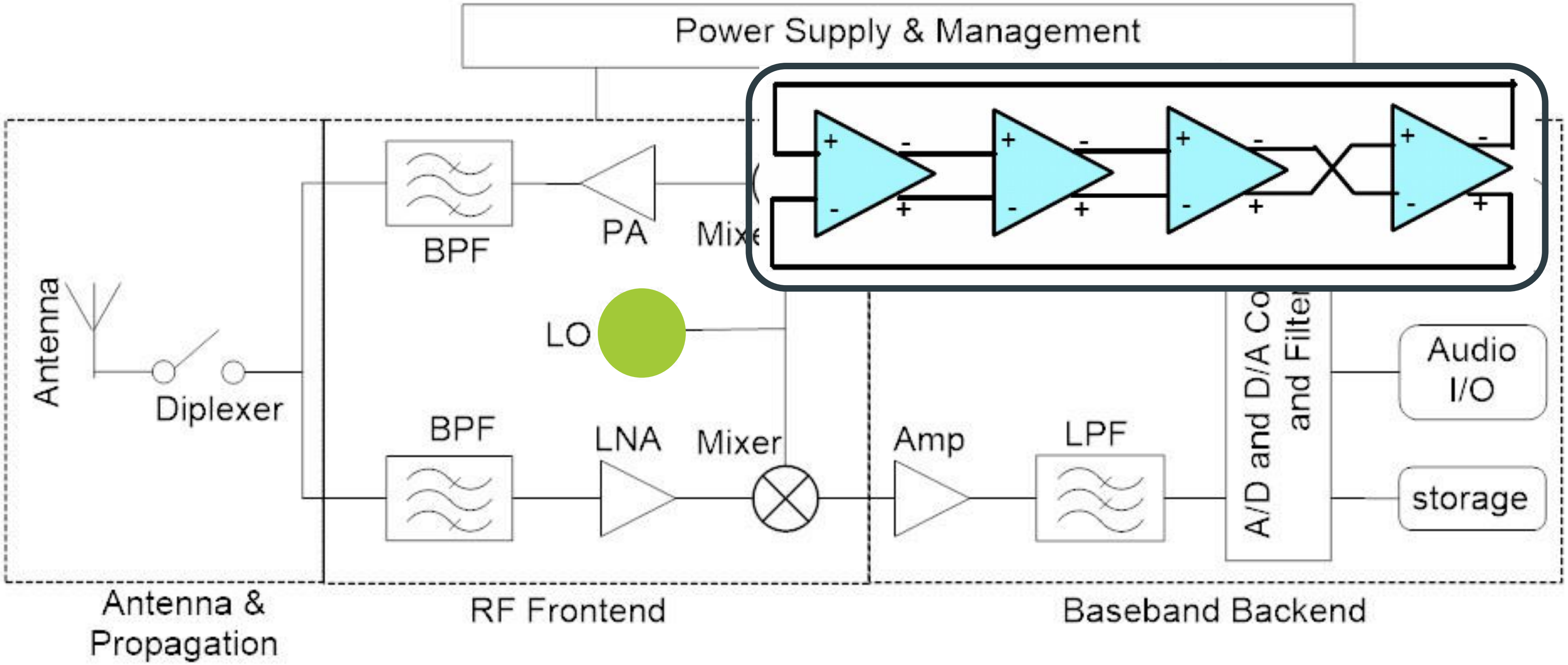
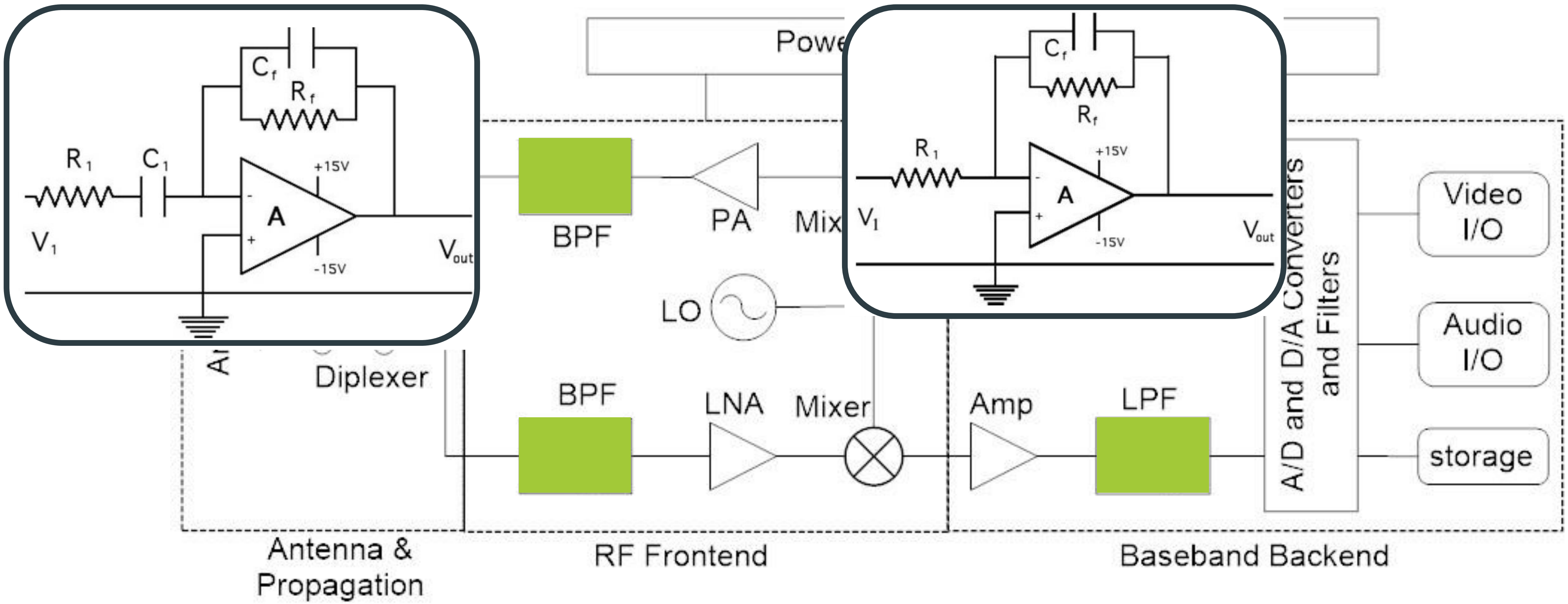
KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?



KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?



KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?



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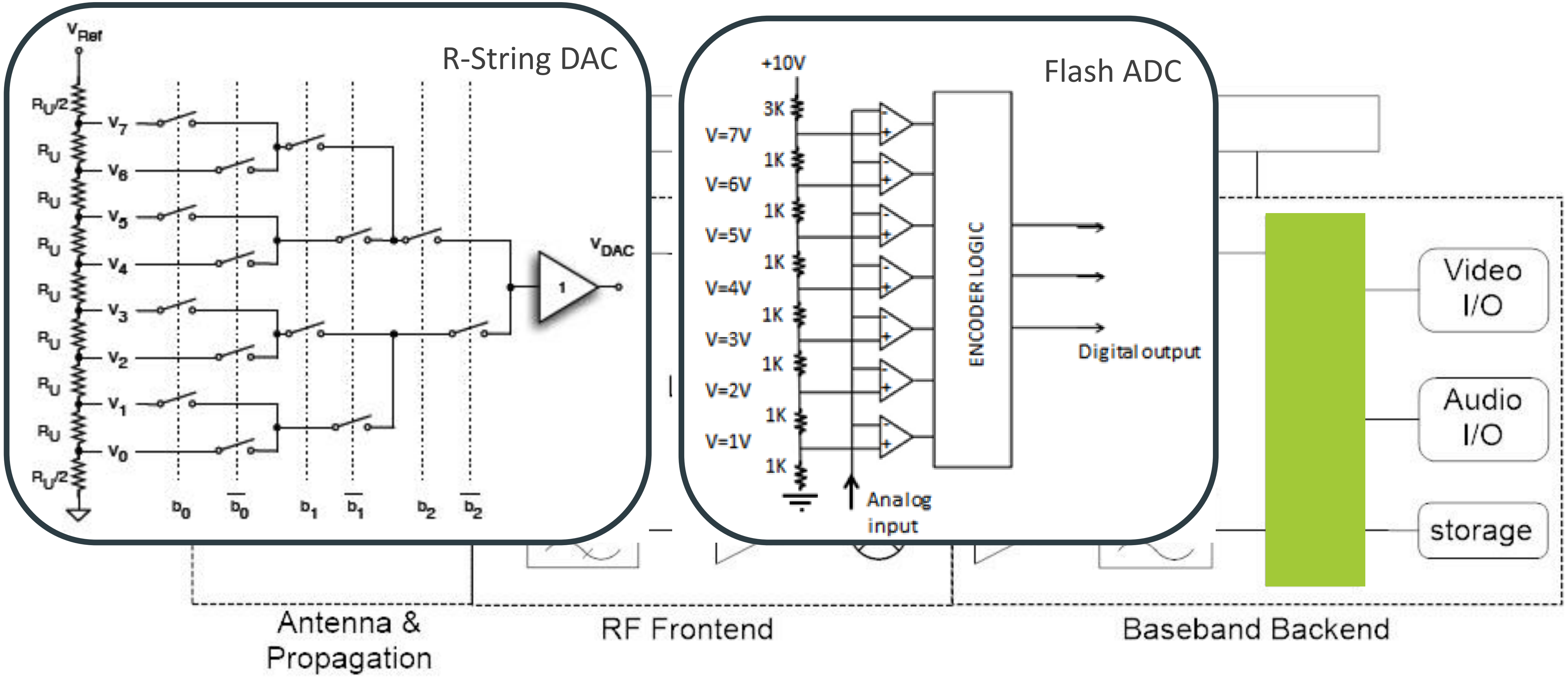
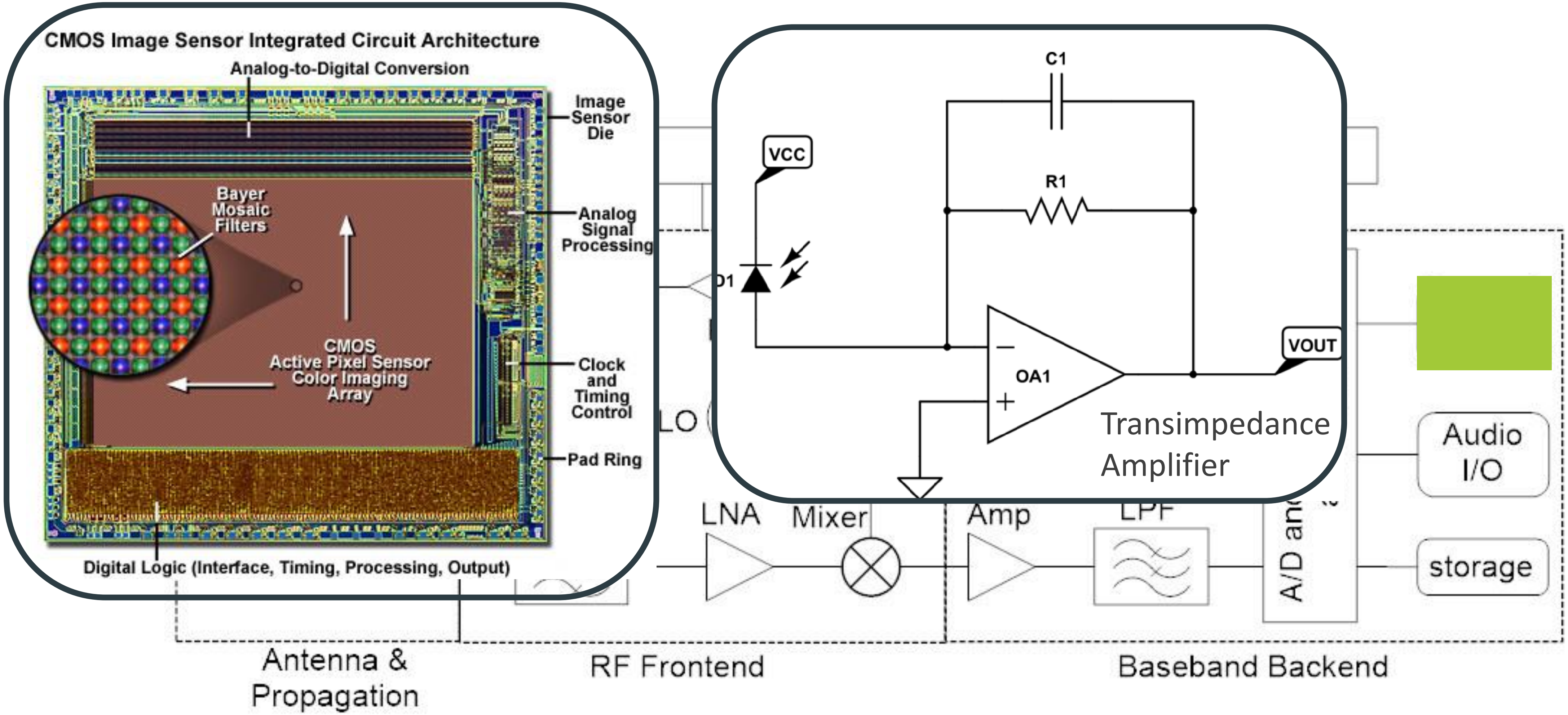
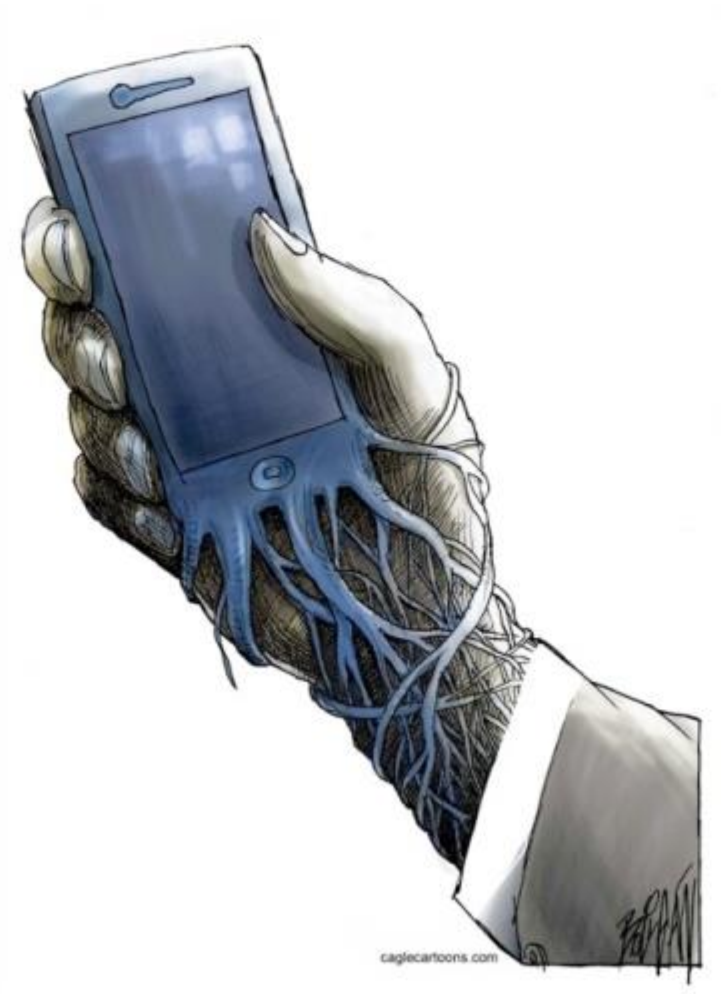
KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?



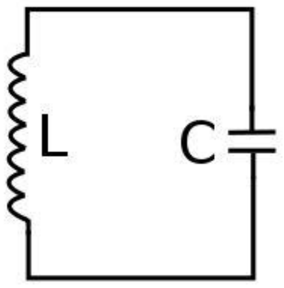
KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?



KI6: FUTURE OF SMARTPHONE?



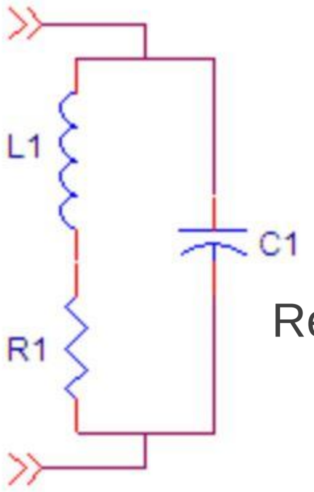
LOCAL OSCILLATOR



Ideal LC Tank

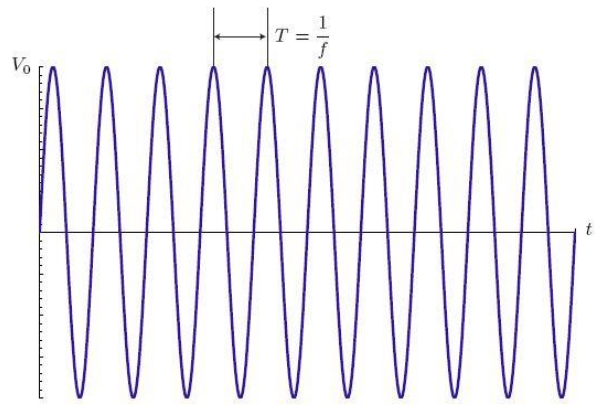
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

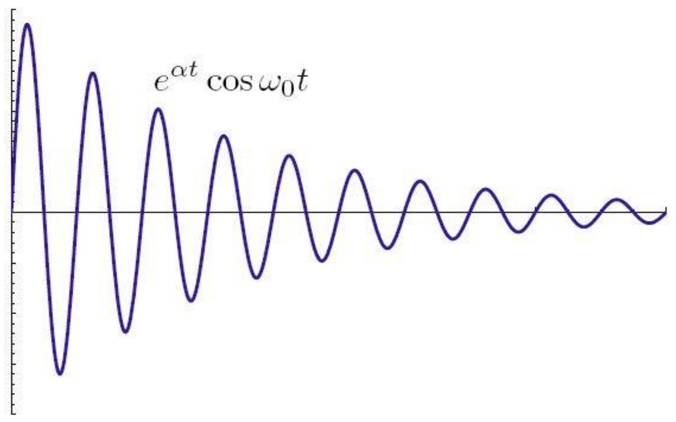
$$Q_L = \frac{\omega_0 L_1}{R_1}$$



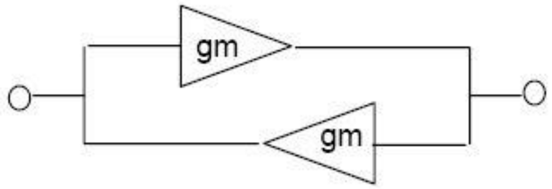
Real LC Tank

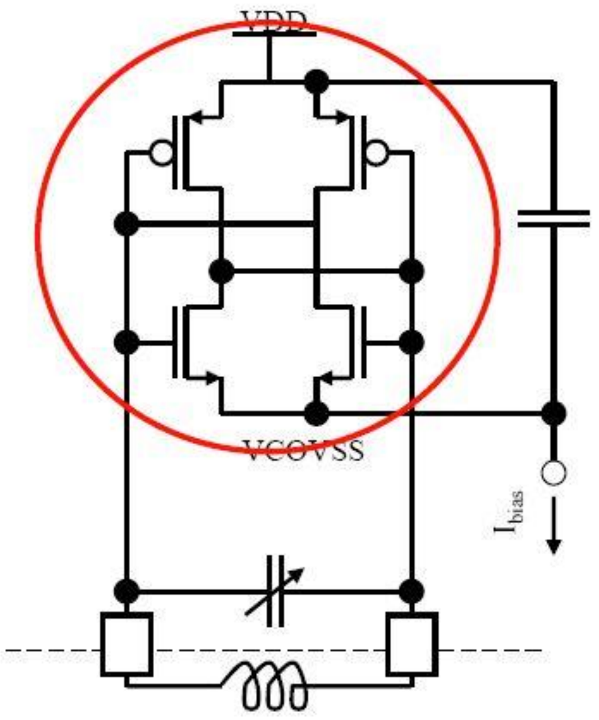
$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 - \frac{R_1^2 C_1}{L_1}}$$





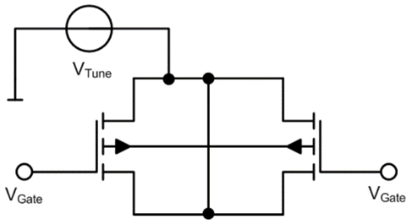
LOCAL OSCILLATOR



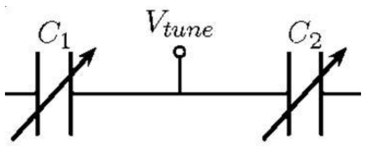


- Tuning is provided by the programmable capacitor
- Tuning range:
  - 902MHz – 928MHz
  - Able to compensate for 5% process variation
  - Able to compensate for 2% inductance variation
- L = 17nH, Q = 30
- Output swing 1Vp-p
- Ibias = 200 – 300uA

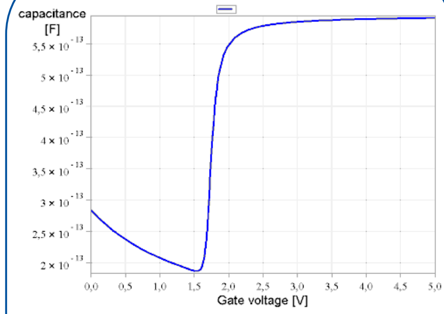
LOCAL OSCILLATOR – USE MOS VARACTOR FOR TUNING



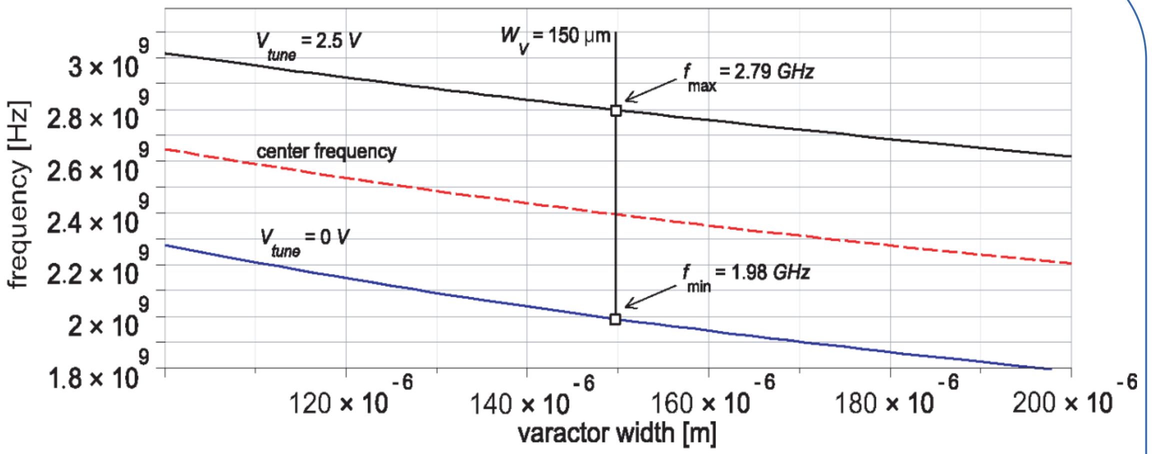
MOS varactor



MOS varactor



CV-characteristic



Tuning range

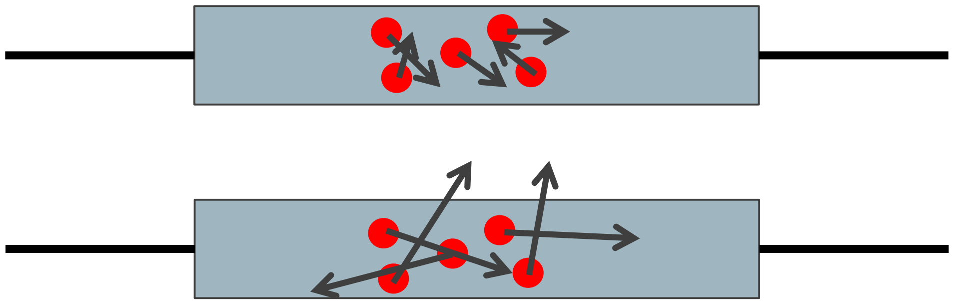
NOISE

- Thermal noise
- Shot noise
- Noise 1/f
- Burst noise
- Transit time noise

Thermal noise

Produced by current fluctuations due to thermal energy in electrons. It is reduced by cooling the circuit even down to LN temperatures

$$v_{rms} = \sqrt{4\, k_B\, T\, R\, \Delta f}$$



https://en.wikipedia.org/wiki/Noise_(electronics)

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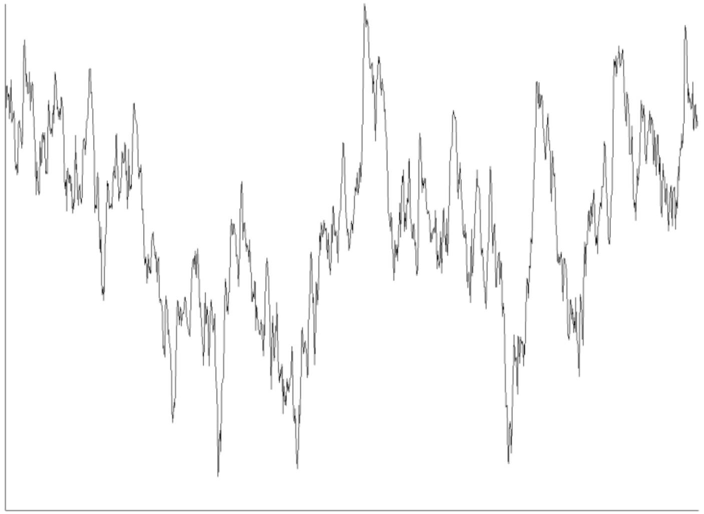
NOISE

Shot noise

Occurs when electrons have to flow across a barrier (diode). Electrons arrive individually and provoke a random fluctuation in the current.
The rms value of the shot noise is given by the Schottky formula $i_n = \sqrt{i\ I\ q\ \Delta f}$

1/f noise

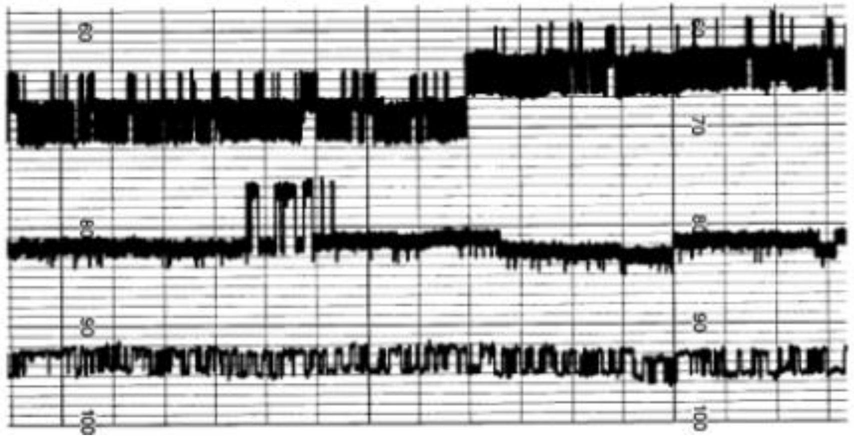
It occurs in almost all electronic devices. It is the consequence of a variety of phenomena like impurities in a conductive channel, or recombination in a transistor due to base current. This kind of noise is typically overshadow in electronic devices at high frequencies. The distribution is approximately Gaussian



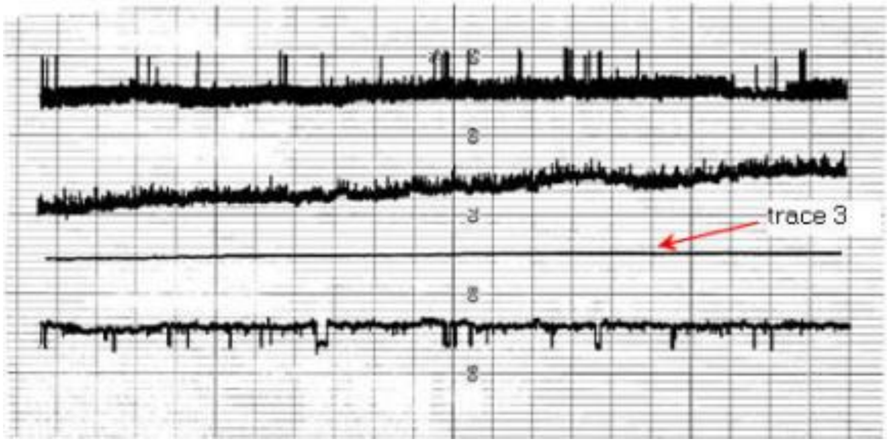
BURST OR “POPCORN” NOISE

Burst or “popcorn” noise

Step-like transitions between two or more discrete voltage or current levels, as high as several hundred of microvolts. It is produced by periodic trapping of carriers in impurities or in defect interfaces in the bulk. These defects can be provoked by manufacturing processes as ion implantation. Whether or not popcorn noise is a real problem, depends on your application, but when you work with small signals and low frequencies (or even DC), it is often a practical issue.



Three OpAmps from the same kind



Three precision thin film resistors plus a reference grade resistor

http://www.advsolned.com/example_popcorn_noise.html

TRANSIT-TIME NOISE

When the time taken by electrons to travel from emitter to collector is comparable to the period of the signal. It is important at high frequencies and dominates over other terms

http://www.advsolned.com/example_popcorn_noise.html

COUPLED NOISE

This is noise captured in the electronic circuits by inductive or capacitive coupling. The sources are various:

- Crosstalk: signal in one channel leaks onto the signal in other channel
- Static noise: produced by atmospheric or natural disturbances like lightning
- Industrial noise: automobiles, ignition of electric motors, HV wires…
- Solar noise: generated in the solar corona. These electrical disturbances generated in the Sun reaches the Earth as random EM signals
- Cosmic noise: produced by stars. It is smaller than the solar noise (because the distance) but collectively (high number) can have apretiable effects

REDUCTION OF EM NOISE INFLUENCE

When building a circuit we want to avoid noises to have the true output of our circuit. Different techniques and strategies can be used to reduce the noise influence in the circuits

- Faraday cage: it is an enclosure that shields the circuit from external EM noise. A Faraday cage is a grounded conductive enclosure
- Avoid ground loops: ground loops generate a voltage difference between two ground nodes. Bring all ground wires to the same potential in a ground bus.
- Wiring: using coaxial cables can reduce noise influence (the mesh acts as a Faraday cage). Also twisted pairs decreases the loop sizes randomizing the noise picking and reducing the overall noise signal
- Filtering

NOISE: FARADAY CAGES

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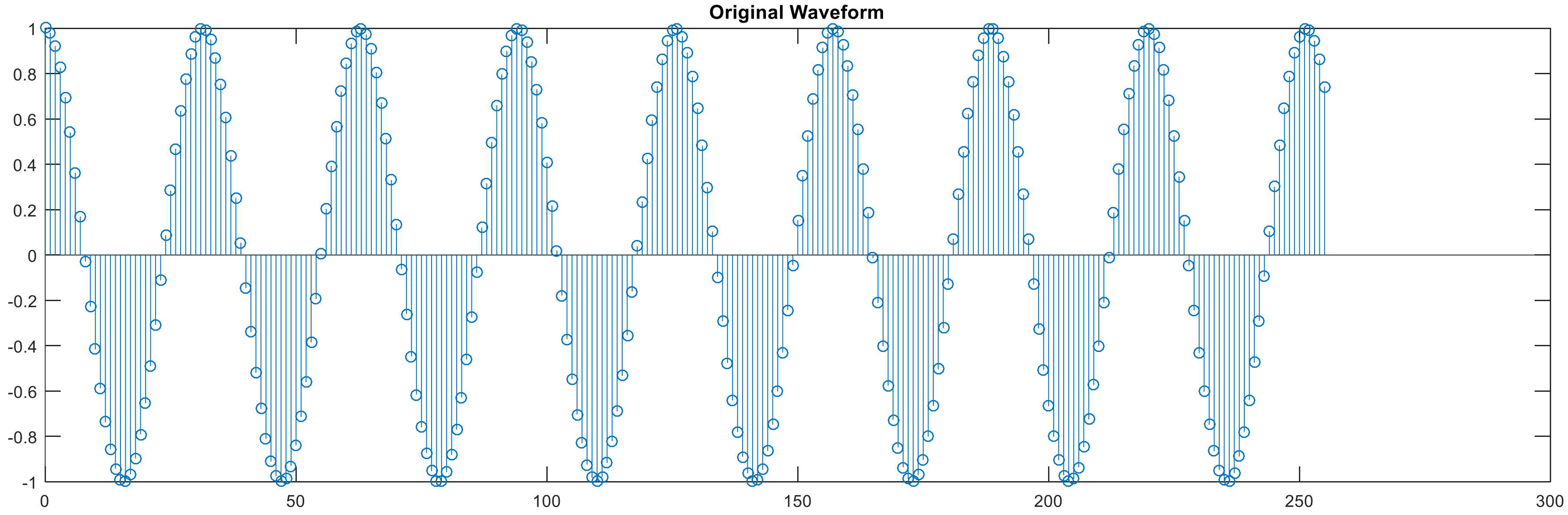
FFTS AND WINDOWING - TIME DOMAIN WAVEFORMS

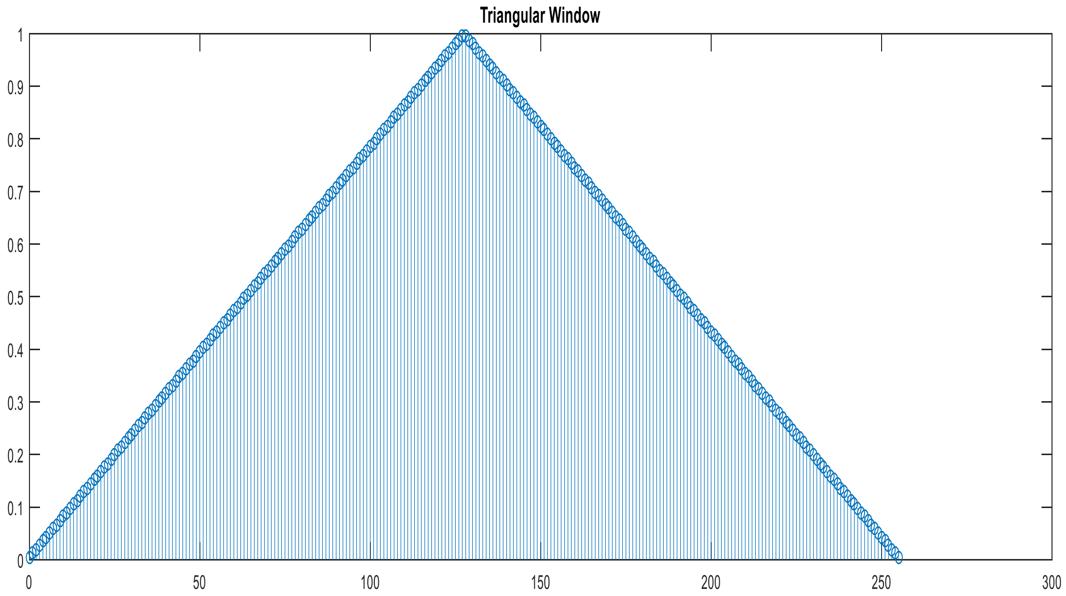
```
>> clear
>> t = [0:255];
>> om = 0.2;
>> y =cos(om*t);
>> stem(t,y)
>> title('Original Waveform')
```

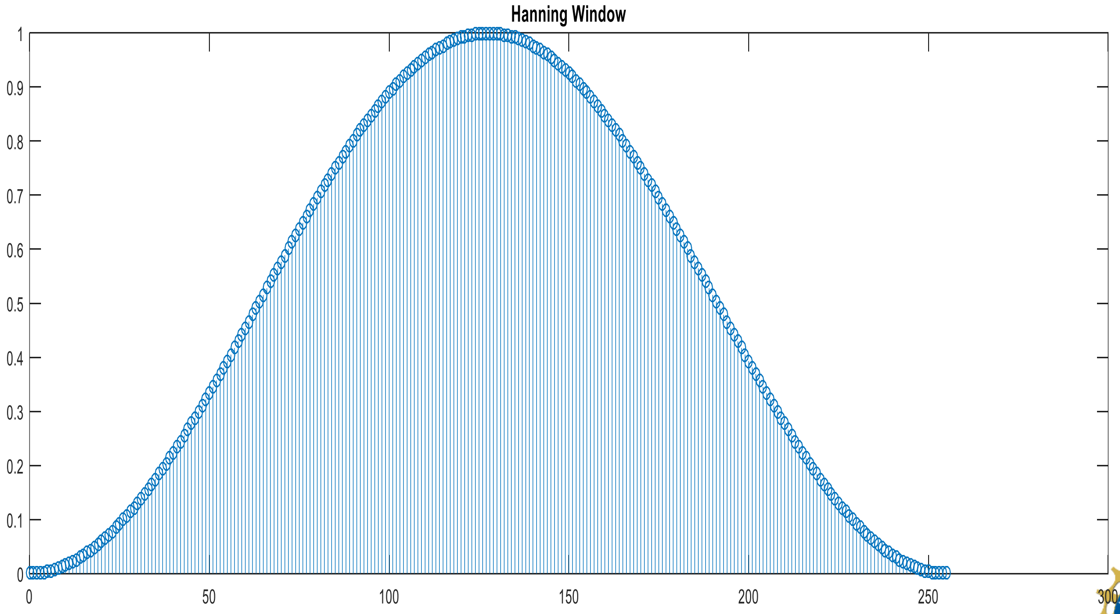


WINDOW FUNCTIONS

```
>> win1 = window(@triang,256).';
>> stem(t,win1)
>> title('Triangular Window')
```

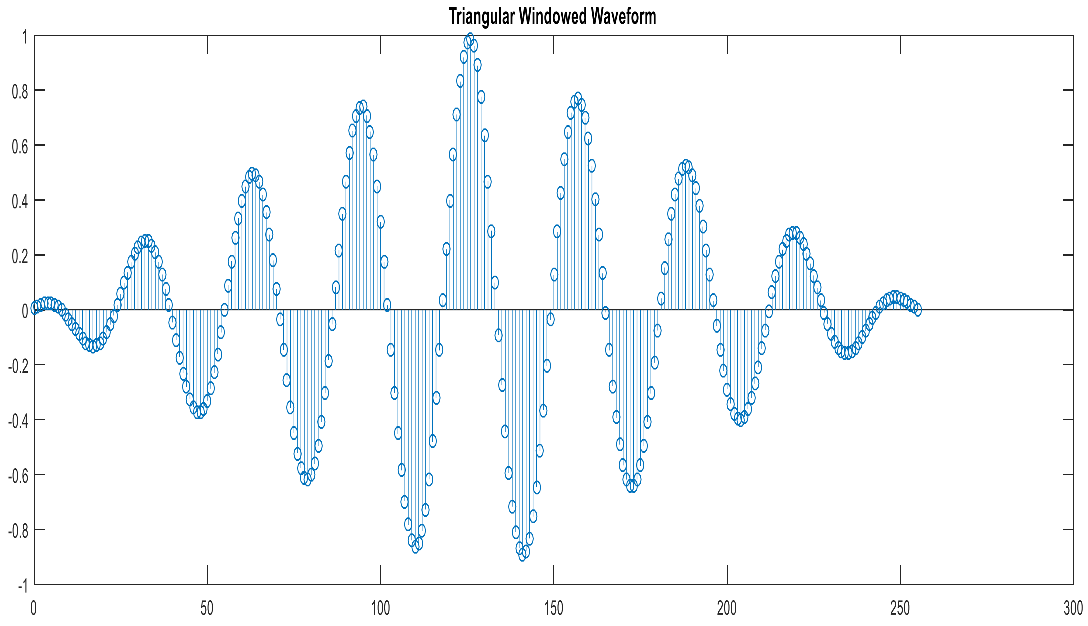
```
>> win2 = hann(256).';
>> stem(t,win2)
>> title('Hanning Window')
```



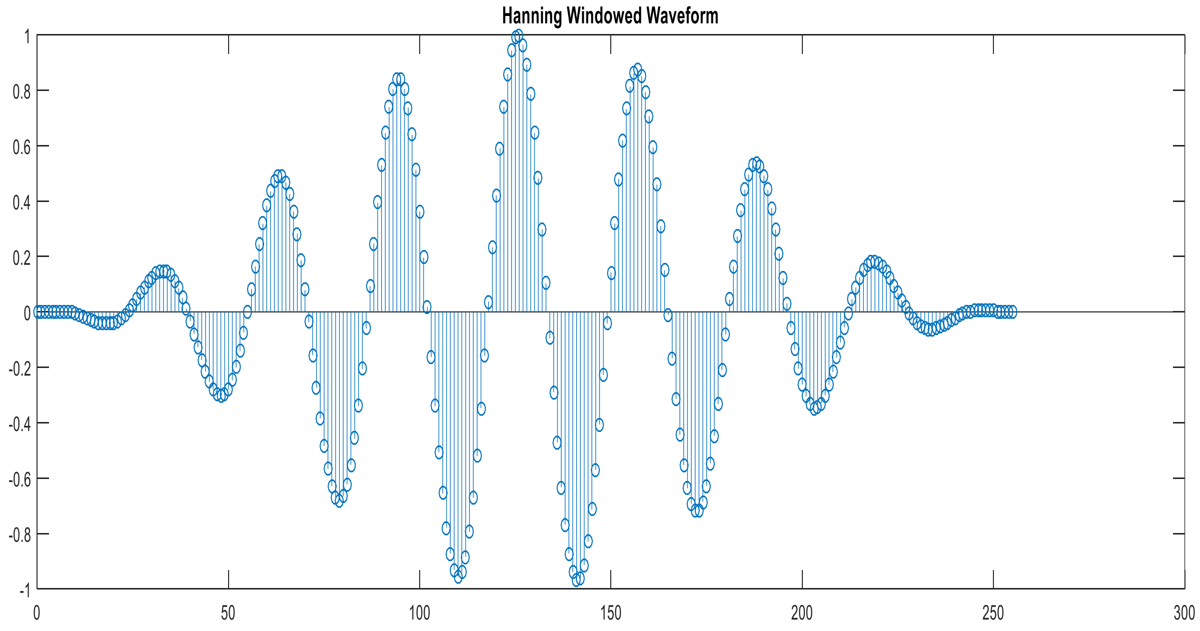


WINDOWED WAVEFORMS

```
>> stem(t,y.*win1)
>> title('Triangular Windowed Waveform')
```




```
>> stem(t,y.*win2)
>> title('Hanning Windowed Waveform')
```



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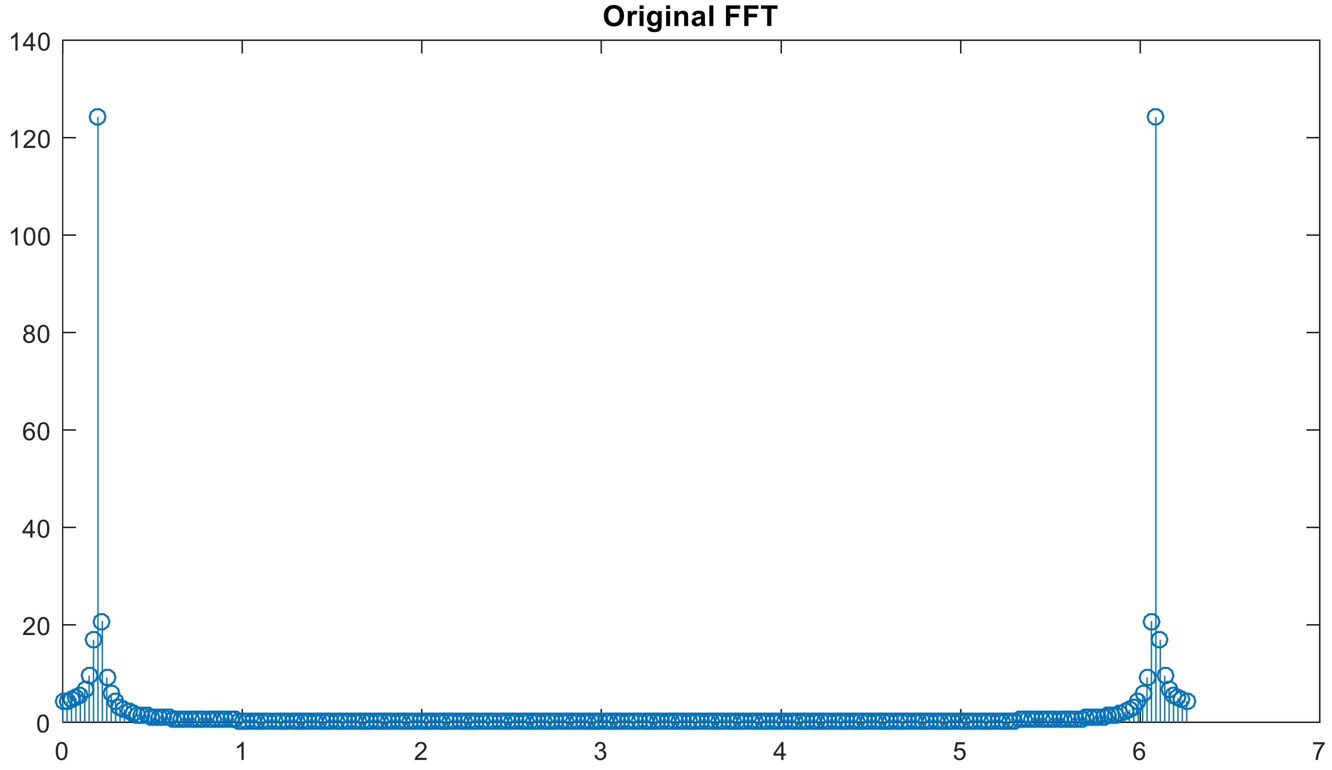
FFT AND WINDOWING

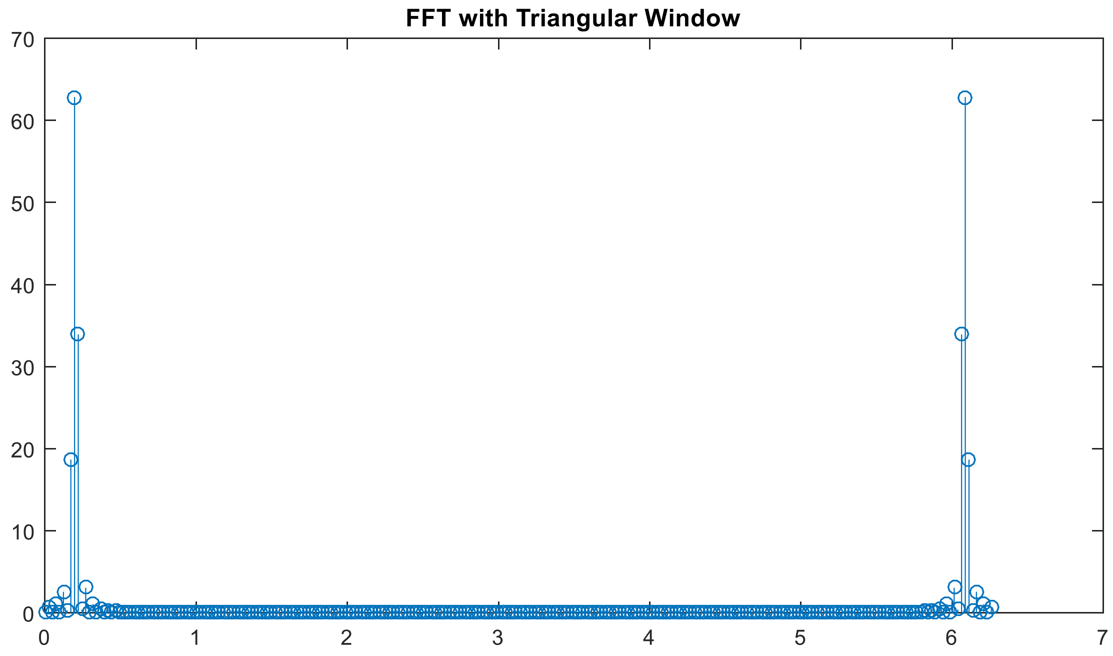
```
>> k = [0:255];
>> omg = 2*pi*k/256;
>> stem(omg,abs(fft(y)))
>> title('Original FFT')
```

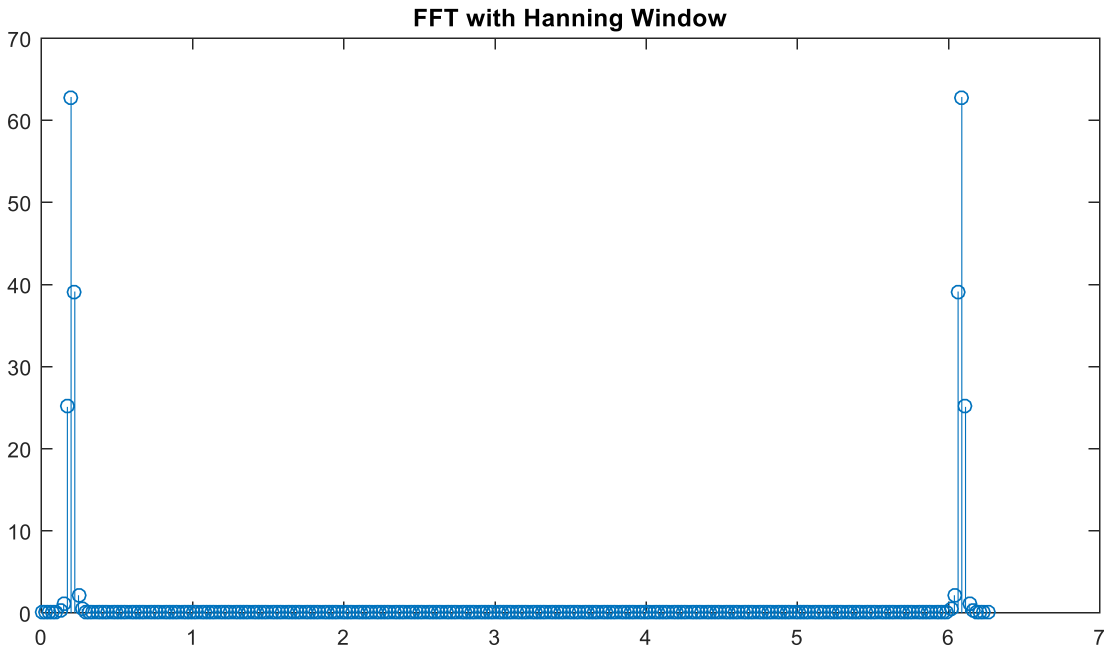


FFT AND WINDOWING

```
>> stem(omg,abs(fft(y.*win1)))
>> title('FFT with Triangular Window')
```

```
>> stem(omg,abs(fft(y.*win2)))
>> title('FFT with Hanning Window')
```

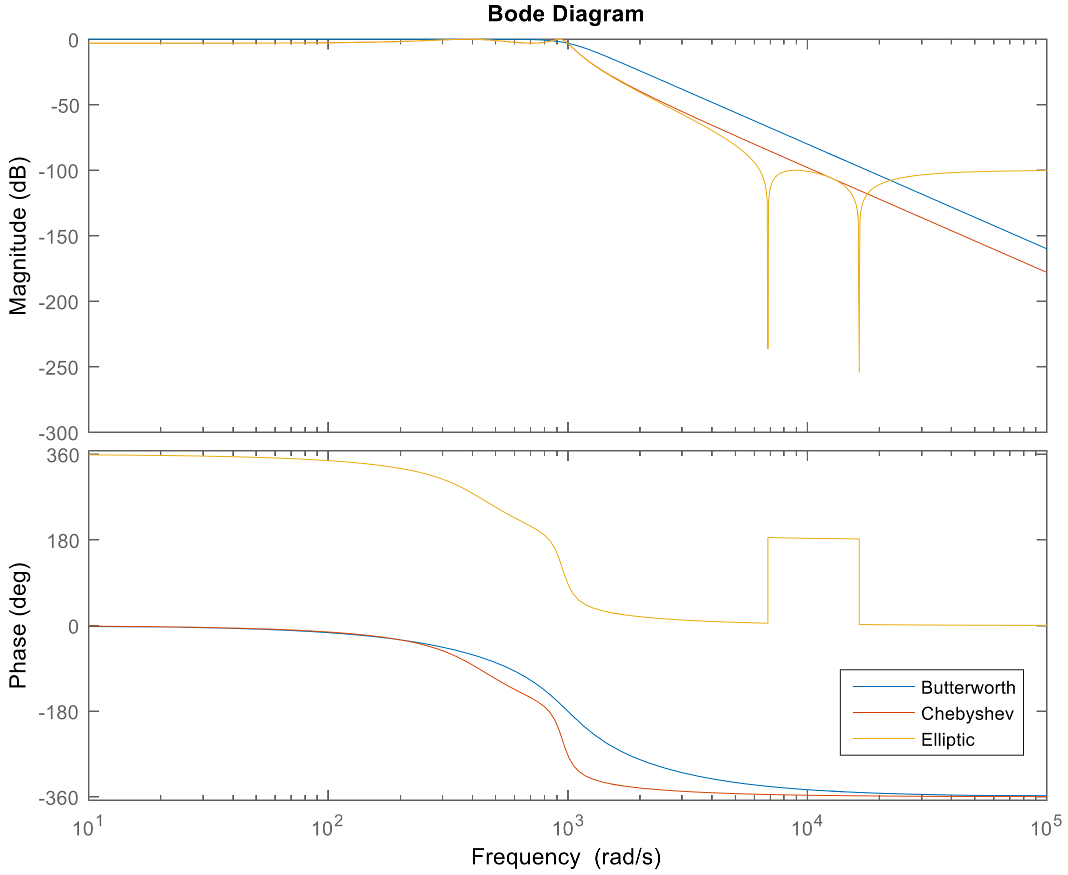


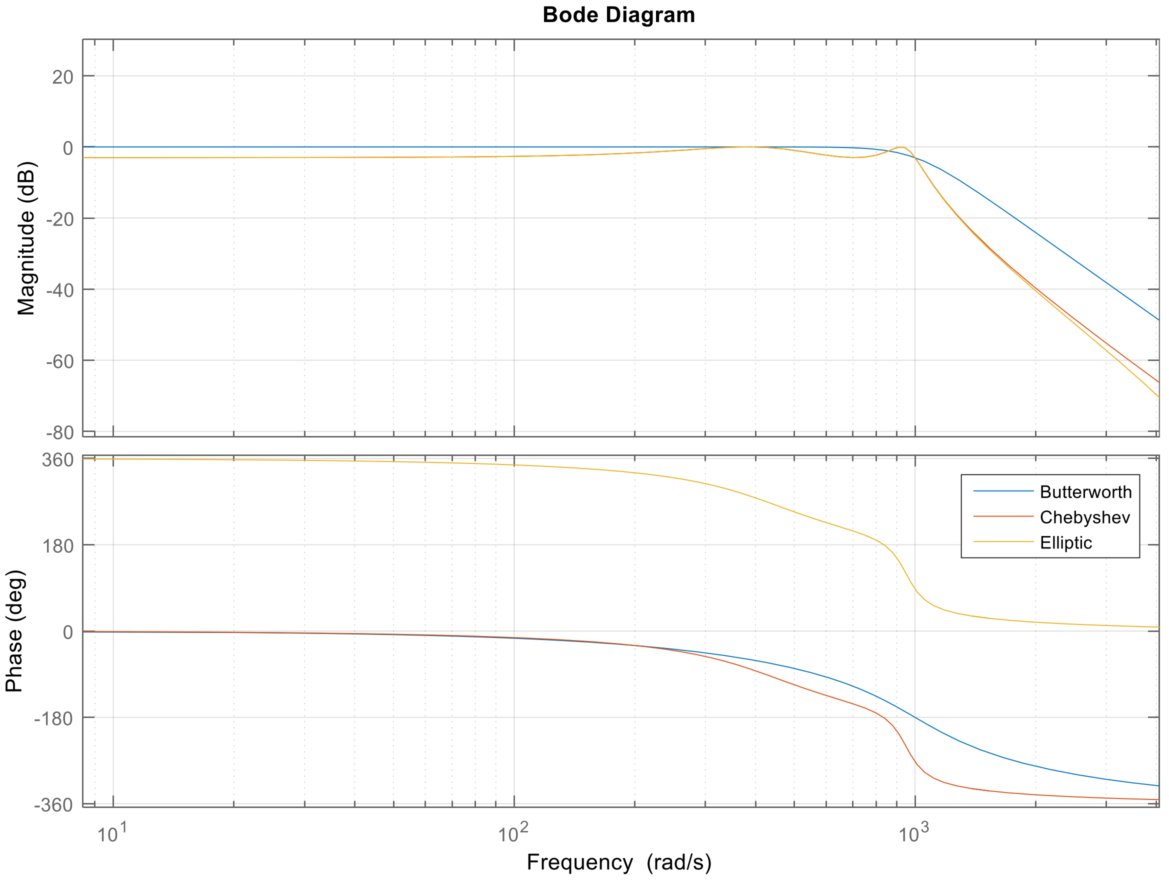


COMPARISON BETWEEN FILTERS

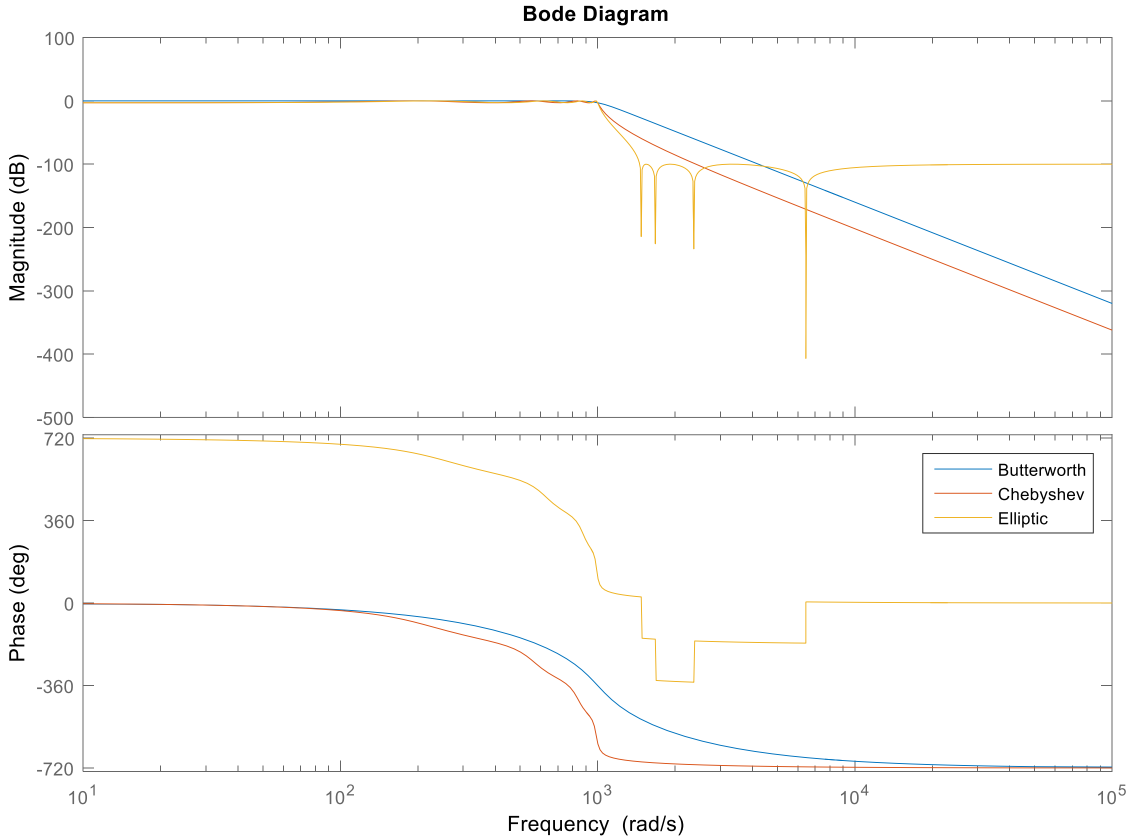
```
ord = 4;

[zb,pb,kb] = butter(ord,1000,'s');
[zc,pc,kc] = cheby1(ord,3,1000,'s');
[ze,pe,ke] = ellip(ord,3,100,1000,'s');

filtb = zpk(zb,pb,kb);
filtc = zpk(zc,pc,kc);
filte = zpk(ze,pe,ke);

bode(filtb,filtc,filte)
legend('Butterworth','Chebyshev','Ellipti
c')
```

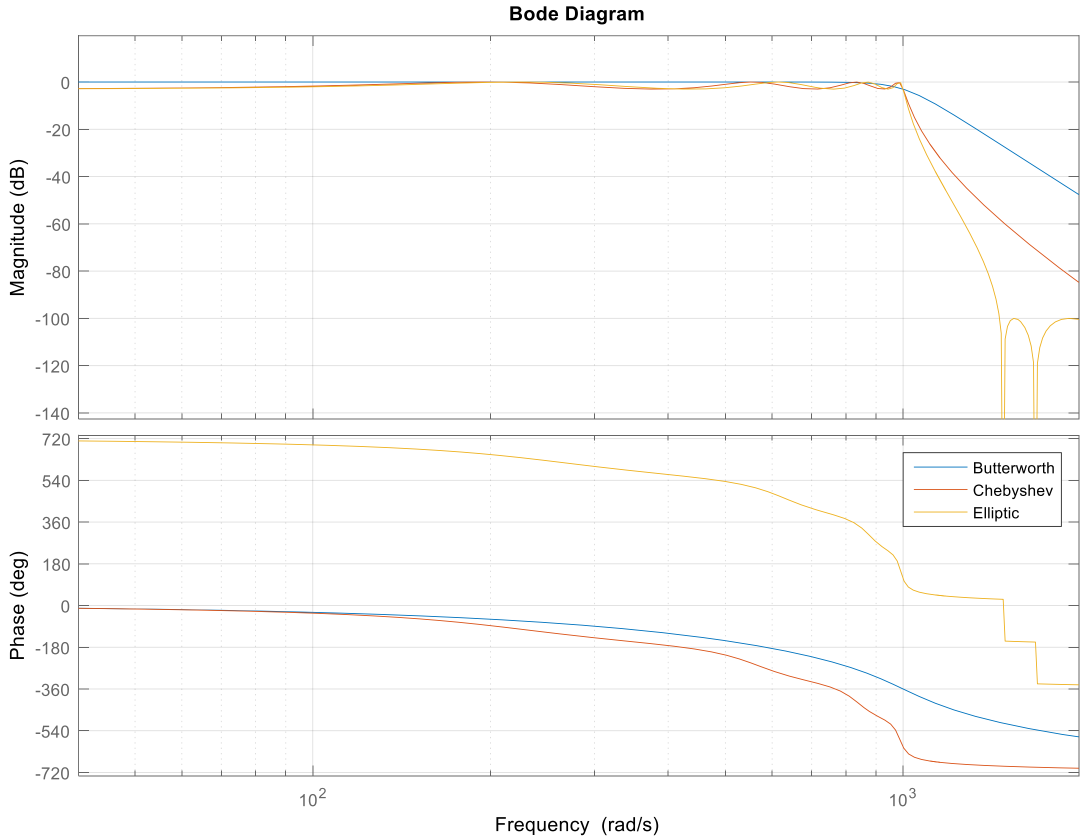
4TH ORDER FILTERS





8TH ORDER FILTERS

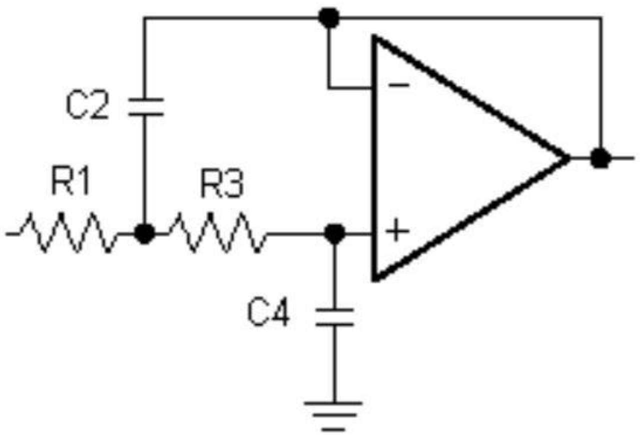




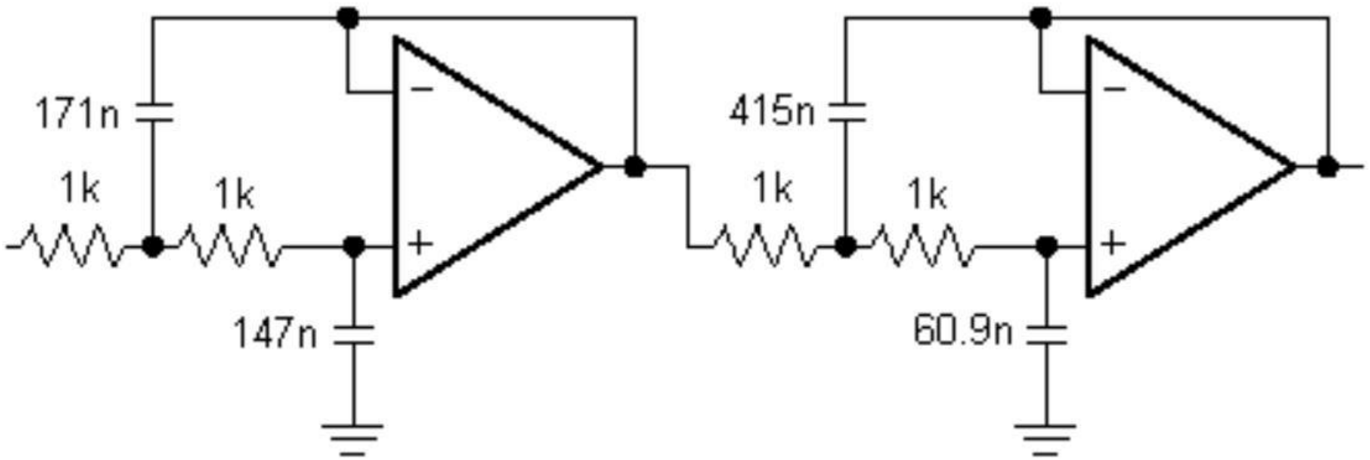
FILTER COMPLEXITY – 4^{TH} ORDER

```
>> filtb
filtb =
                  1e+12
  ------------------------------------------
  (s^2 + 1848s + 1e06) (s^2 + 765.4s + 1e06)
Continuous-time zero/pole/gain model.

>> tf(filtb)
ans =
                      1e12
  ------------------------------------------------
  s^4 + 2613 s^3 + 3.414e06 s^2 + 2.613e09 s + 1e12
Continuous-time transfer function.
>> filte

filte =
       1e-05 (s^2 + 4.687e07) (s^2 + 2.707e08)
  --------------------------------------------------
  (s^2 + 412.7s + 1.982e05) (s^2 + 168.5s + 9.044e05)
Continuous-time zero/pole/gain model.

>> tf(filte)

ans =
  1e-05 s^4 + 1.783e-19 s^3 + 3176 s^2 + 1.356e-10 s + 1.269e11
  ------------------------------------------------------------
     s^4 + 581.3 s^3 + 1.172e06 s^2 + 4.067e08 s + 1.792e11
Continuous-time transfer function.
```

FILTER COMPLEXITY – 4TH ORDER



2nd order Butterworth LPF



4nd order Butterworth LPF

FILTER COMPLEXITY – 4^{TH} ORDER

```
>> filtb
filtb =
                                        1e+24
  ---------------------------------------------------------------------------------
  (s^2 + 1962s + 1e06) (s^2 + 1663s + 1e06) (s^2 + 1111s + 1e06) (s^2 + 390.2s + 1e06)
Continuous-time zero/pole/gain model.

>> tf(filtb)
ans =
                                                    1e24
  -----------------------------------------------------------------------------------------------------------
  s^8 + 5126 s^7 + 1.314e07 s^6 + 2.185e10 s^5 + 2.569e13 s^4 + 2.185e16 s^3 + 1.314e19 s^2 + 5.126e21 s + 1e24
Continuous-time transfer function.

>> filte
filte =
    1e-05 (s^2 + 2.183e06) (s^2 - 6.821e-13s + 2.808e06) (s^2 + 6.821e-13s + 5.595e06) (s^2 + 4.158e07)
  ----------------------------------------------------------------------------------------------------
  (s^2 + 248.5s + 6.769e04) (s^2 + 183.9s + 3.948e05) (s^2 + 101.8s + 7.679e05) (s^2 + 31.38s + 9.815e05)
Continuous-time zero/pole/gain model.
>> tf(filte)

ans =
  1e-05 s^8 - 1.954e-19 s^7 + 521.7 s^6 - 4.348e-11 s^5 + 4.742e09 s^4 - 0.001027 s^3 + 1.45e16 s^2 - 2084 s + 1.426e22
  ---------------------------------------------------------------------------------------------------------------------
    s^8 + 565.5 s^7 + 2.318e06 s^6 + 1.06e09 s^5 + 1.739e12 s^4 + 5.862e14 s^3 + 4.436e17 s^2 + 8.663e19 s + 2.014e22
Continuous-time transfer function.
```

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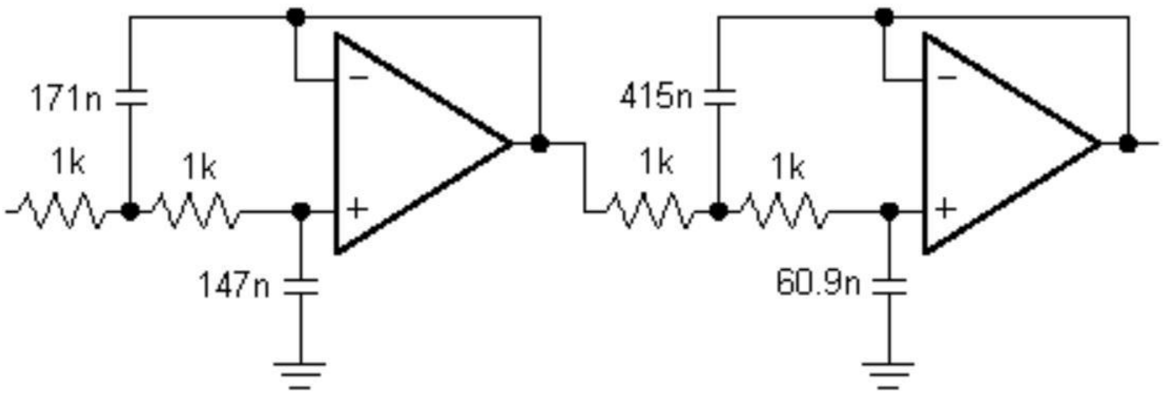
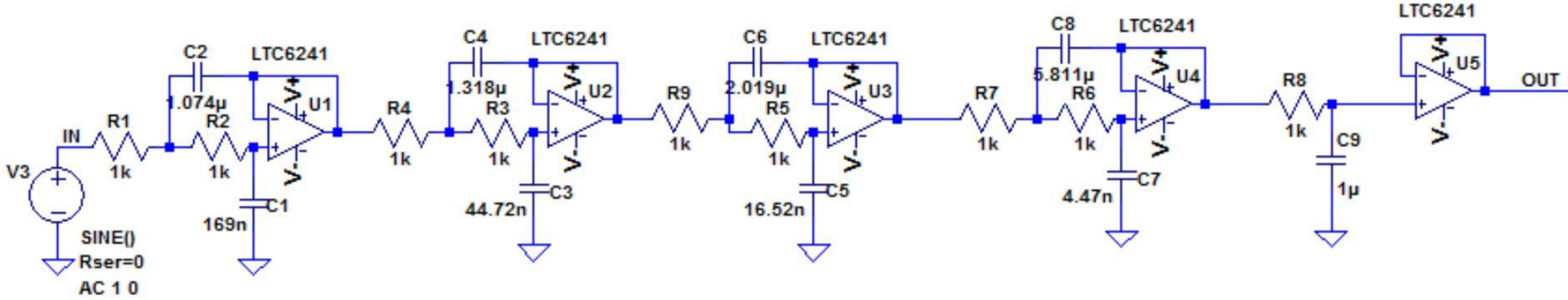
FILTER COMPLEXITY – 8TH ORDER



4nd order Butterworth LPF



8nd order Butterworth LPF

Colorado State University