"Ultrasound Medical Equipment: Physics, Electronics and Evolution from 2D to 4D Imaging Systems"

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Technology R&D

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Contents

Acnoledgements

I thank Daniele Ronchi for the preparation of this material in occasion of the TOM 2009

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The Importance of Ultrasound Imaging

- Non-invasive diagnostic method
- No ionizing radiation (vs. X-ray imaging)
- Fast and no recovery time between patients (vs. MRI)
- Real time imaging
- The machine can stay in a normal room (vs. MRI)
- Portable systems
- Low cost with respect to the other imaging methods
- Wider diffusion: every doctor can buy an ultrasound scanner

- Drawback: lower resolution with respect to MRI, TAC, PET
- Main advantage: preventive screening

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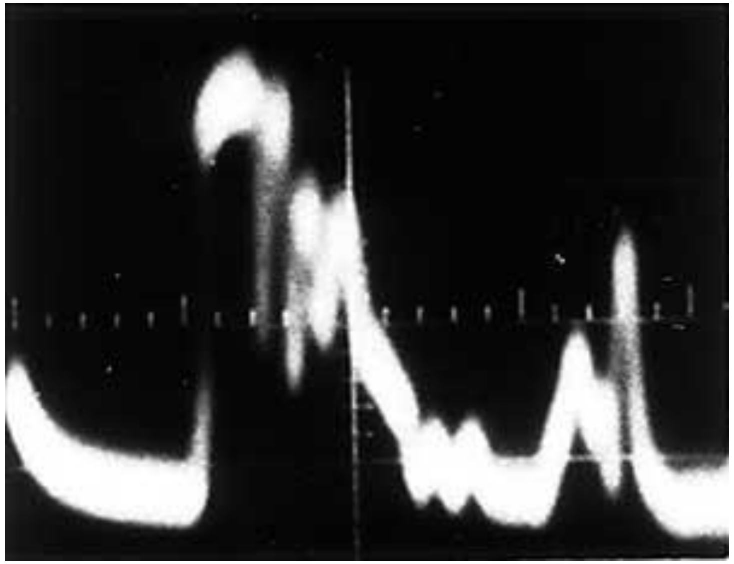
Ultrasound History 1



- Early '50, A-mode (Amplitude) imaging:
  - Oscilloscope-like image
  - X-axis is time (=depth)
  - Y-axis is voltage (= pressure intensity)
  - One direction fixed, the doctor has to move the probe

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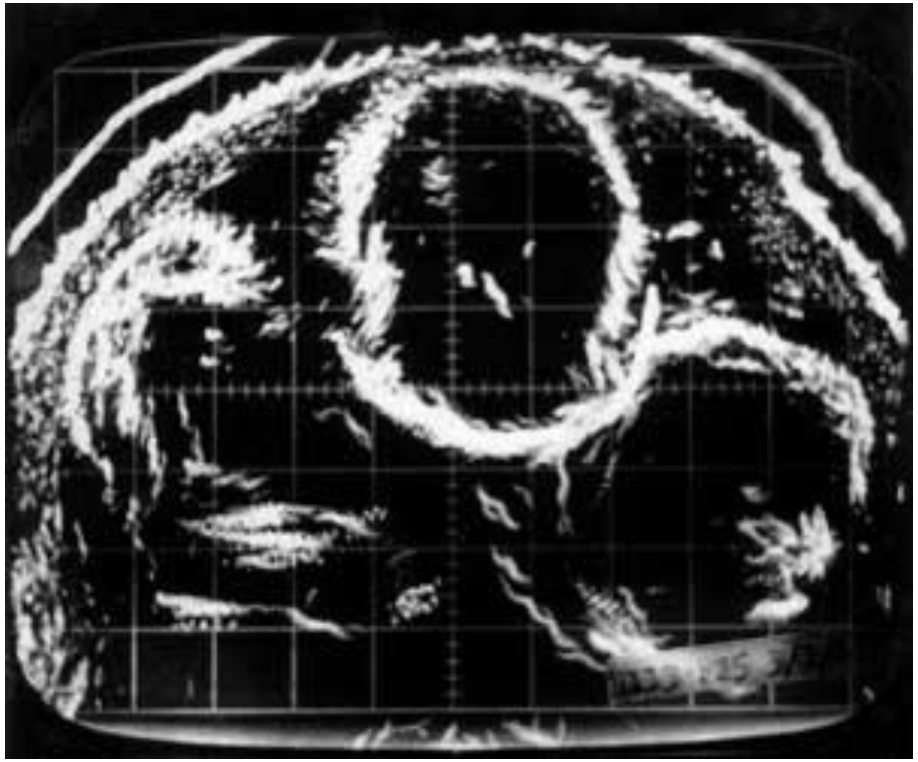
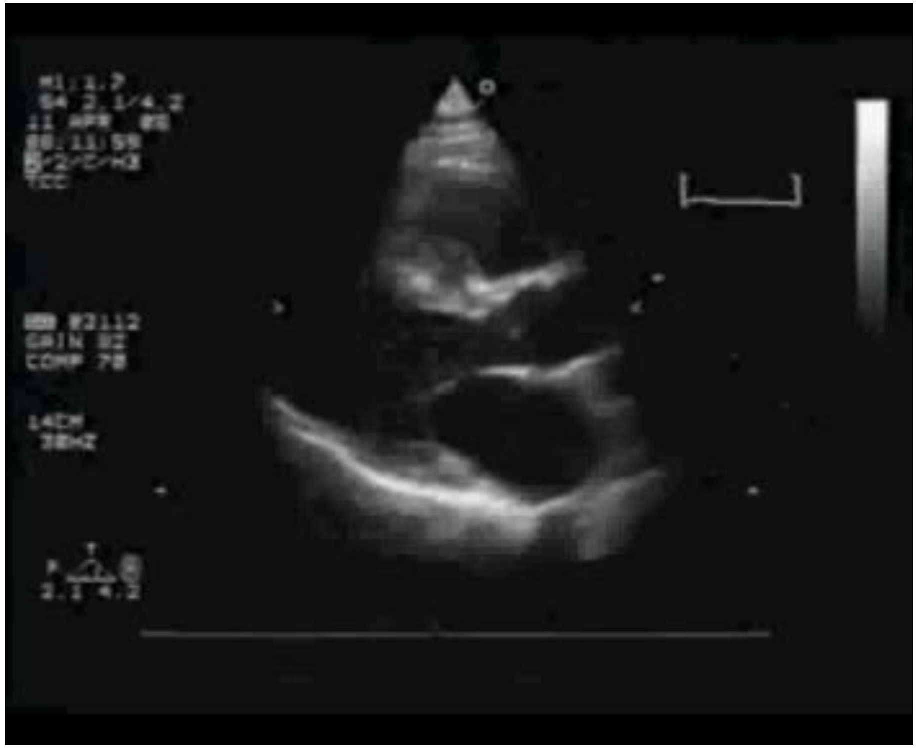
Ultrasound History 2



- Late '50s, B-mode (Brightness) static imaging :
  - A plane of the patient's body is scanned by a mechanical motion
  - Possibility to recognize body structures
  - Y-axis is depth
  - Only black and white images available

Ultrasound History 3



- '60s, real time B-mode imaging:
  - The picture is refreshed often, as in a TV screen
  - Transducers in a linear array
  - Electronic beam steering
  - Grey-scale images available
  - The fast scan allows to see the heart beating

Ultrasound History 4

- 2000, 3D ultrasound imaging:
  - Mechanical steering of the 2D beam in the vertical direction
  - In case of manual steering, accelerometers to reconstruct the scan plane orientation.
  - Image processing to get a 3D static picture
  - Only suitable for not fast moving structures like a fetus

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Physics Background

- Ultrasound Imaging History
- Physics Background
  - Acoustics
  - Phased Arrays
- The Ultrasound Scanner
  - General Description
  - Specifications for Electronics
- The Benefits of Integration for Ultrasound Imaging
  - Handling Thousands of Channels
  - High Voltage Transmission Circuits
  - Low Voltage Reception Circuits
- Examples of Commercial Products

Definition

- Ultrasound means acoustic waves with frequencies greater than 20KHz that is the limit of the human ear.
- For human tissue imaging the frequency range used is from 1MHz to 20MHz. The frequency choice depends on the target and the resolution needed.
- The sound speed is supposed constant and equals 1540m/s, even if it can change depending on the tissue density.

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Attenuation

- A longitudinal pressure wave propagating into the human body decreases exponentially with the law: $$p(z) = p(z=0)\, e^{-\alpha z}$$

  where z is the wave propagation direction.

- The attenuation coefficient α is strongly dependent on the frequency since $\alpha \cong 1$ dB/(MHz*cm) for the human body in a round trip path (from transmission to reception).

- The attenuation coefficient depends on the medium where the wave travels, but usually it is considered constant.

- This implies that the attenuation has to be compensated in the receiver electronics.

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Resolution

- Since the acoustic wave propagates in a volume, we can define:
  - Axial resolution.
    - It is the smallest detail that can be seen in the direction of propagation and depends strongly on the frequency.
    - Since the sound speed c is nearly constant in the soft tissue the wavelength λ is a function of the wave frequency:
      $$\lambda = c/f$$
    - so for a 4MHz wave, the smallest detail that can be seen in the propagation direction is 380 micron.
  - Lateral resolution.
    - It is the smallest detail that can be seen in the direction perpendicular to the propagation axis.
    - Depends on many factors including frequency, the transducer array width, the single transducer dimensions, the capability of focusing the ultrasonic beam.

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Acoustic Impedance

- The acoustic impedance of a medium is a parameter dependent on frequency, density and sound speed.

- In the ultrasound imaging frequency range the acoustic impedance Z is:

$$Z = \rho c$$

  where ρ is the medium density and c the longitudinal wave speed.

- The unit is kg/(m^2*sec), or rayl. Here some examples (Mrayl):
  - air 0.0004
  - water 1.48
  - fat 1.38
  - blood 1.61
  - liver 1.65
  - bone 6.00
  - aluminum 17.00

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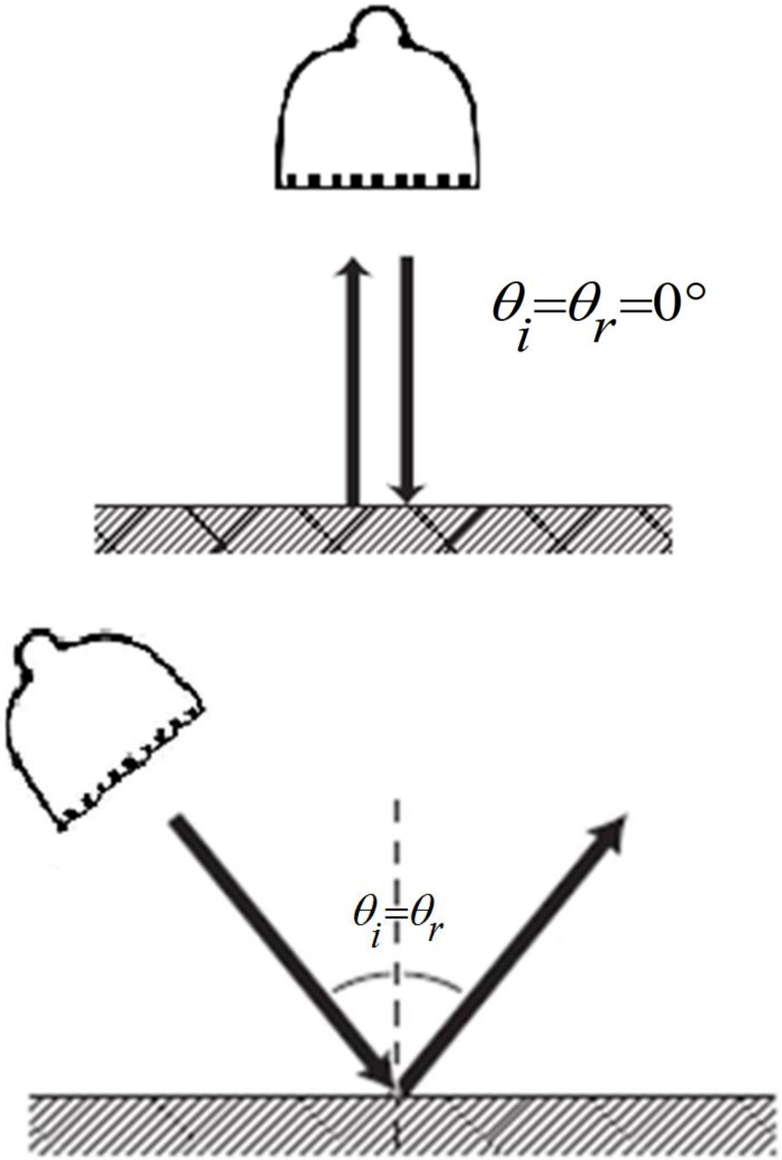
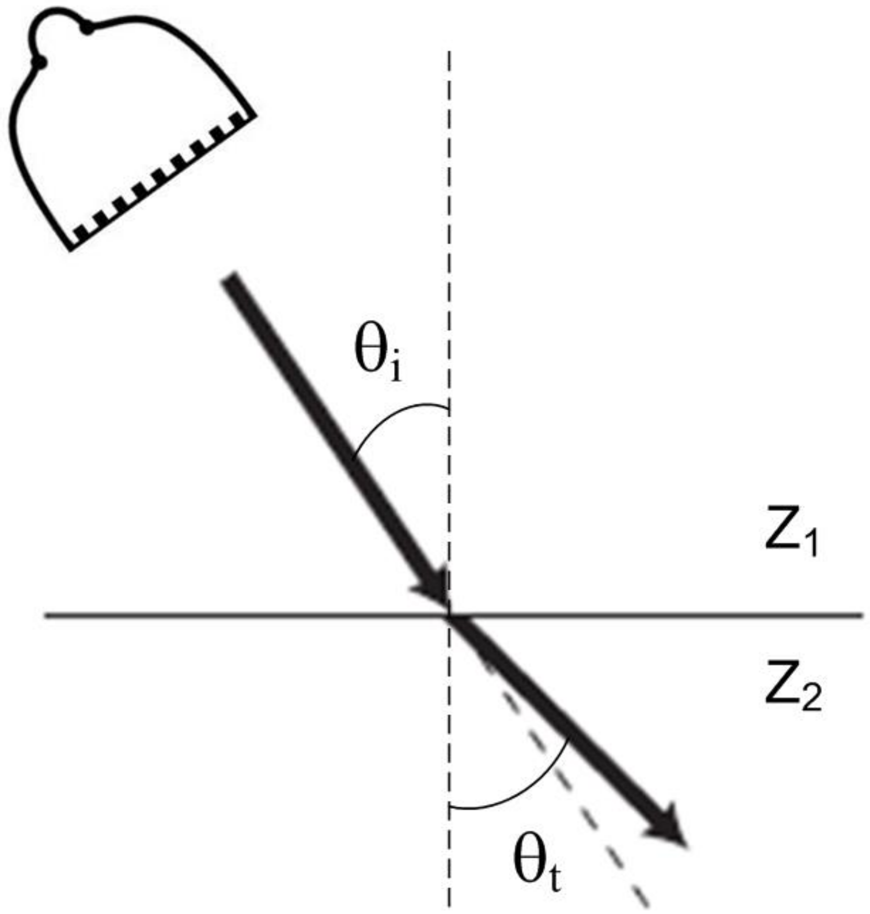
Reflection and Refraction



- When a sound wave reaches the interface between two media with a different acoustic impedance, happens:
  - a reflection back in the medium where the wave is coming; this wave has the same speed as before;
  - a refraction in the second medium so that there is a change in the wave speed.

- This phenomenon is governed, as in optics, by Snell's laws:
  - for reflection $\theta_i = \theta_r$

Reflection and Refraction 2



- Snell's laws:
  - for refraction
    $\sin(\theta_i)/\sin(\theta_t) = c_1/c_2$

- To receive a strong echo from a discontinuity it is necessary that the acoustic wave is perpendicular to the interface.

- In the human body many tissues behave as "scatterers", so that they always reflect part of the incoming energy in the wave direction.

- Bones and air have an acoustic impedance very different from the soft tissue one, so all the acoustic wave is reflected.

- Ultrasound imaging can not see beneath bones or empty cavities.

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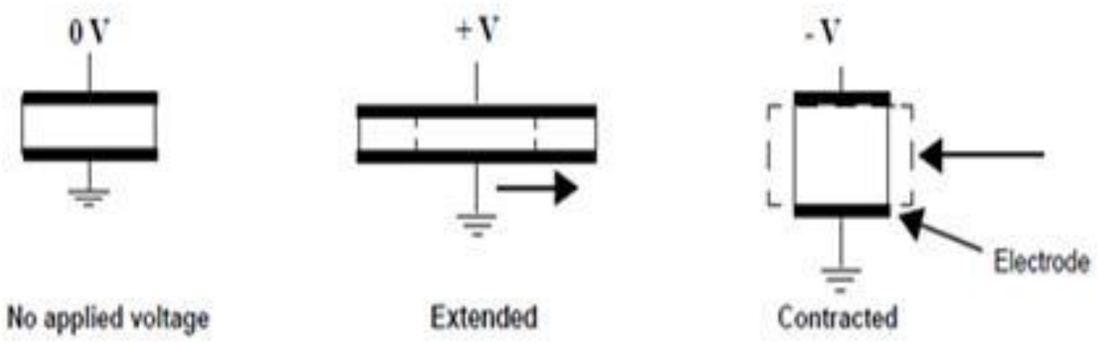
Intensity

- The temporal intensity of an acoustic wave is the average energy carried by the wave in a unit area in a time unit.
- Since an ultrasound machine generates short pulses also the single pulse intensity is very important to avoid damages to the biological tissues.
- Not only the temporal intensity has to be considered, but also the spatial intensity because the beam is focused.
- Biological effects:
  - average intensity too high causes an increase in temperature;
  - peak intensity (temporal and spatial) too high can cause the generation of micro-bubbles (cavitation) and a damage to the cells;
  - this is measured with the Mechanical Index (MI), a parameter proportional to the maximum rarefactional pressure of a longitudinal wave and divided by the ultrasound frequency square root;
  - the maximum MI allowed by the FDA is 1.9, or 1 for fetal imaging.

Piezo-Electric Effect

The effect of applied voltage on piezoelectric materials.



- Piezoelectric materials are able to generate charges when a mechanical stress is applied or, vice-versa, they have a deformation under an electrical stimulus.

- Due to the crystal structure a compression generates an electric field, e.g. in the picture:
  1) no stress applied;
  2) extension in the x-axis, positive voltage on y-axis;
  3) compression in the x-axis, negative voltage on y-axis.

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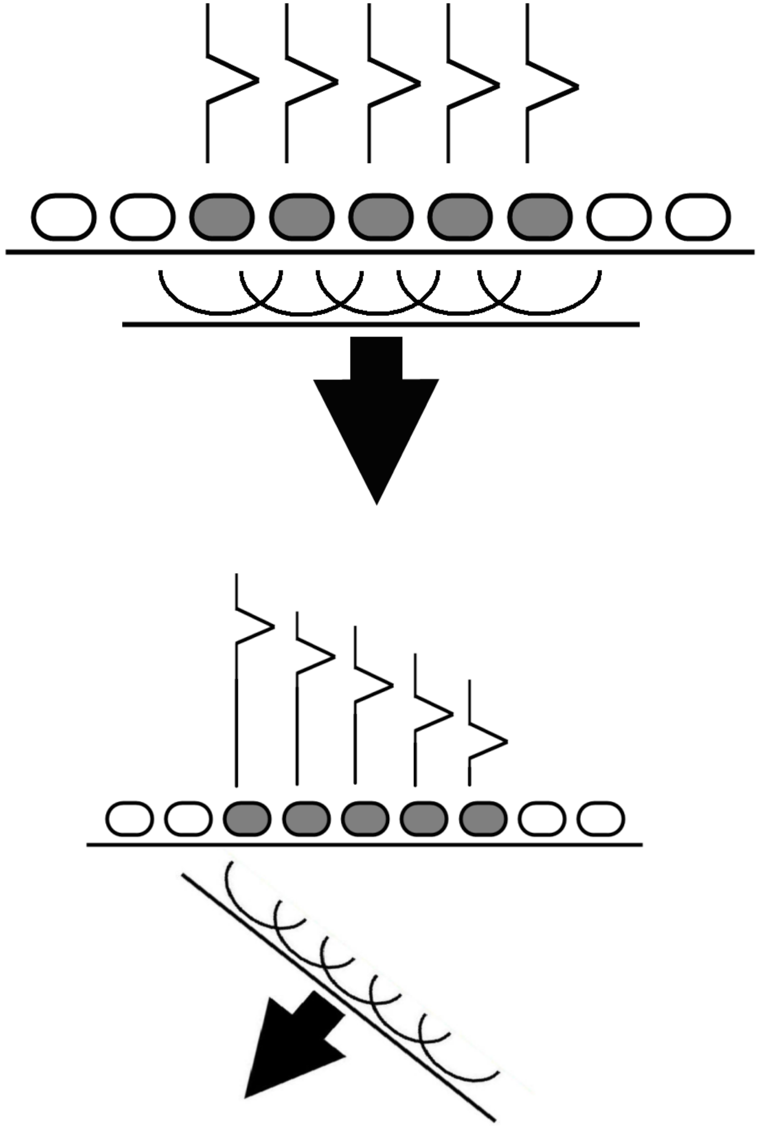
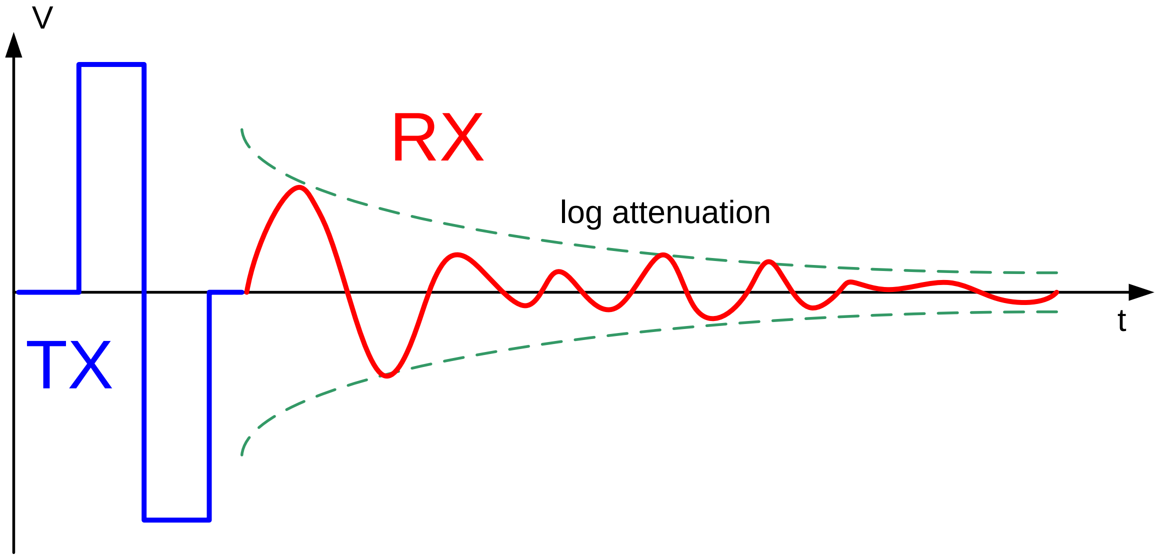
Transducer Array



- To generate the ultrasound wave it is convenient to use not only a single piezoelectric transducer, but at least an array of transducers.
- Sending the same excitation with no delay to all the transducers results in a constructive interference in the direction perpendicular to the array.
- If the delay between different channels is changed, the beam can be steered in another direction like in electro-magnetic phased arrays.

The Electric Signal



- The electric signal across the transducer is very different from transmission to reception:
  - TX: some high voltage pulses (up to ± 150V) with a 10us total duration;
  - RX: low voltage wave with a 100us÷200us duration before another high voltage pulse depending on the application:
    - each us during rx corresponds to: 1540m/s * 1us / 2 = 0.77mm (the two factor takes into account the two way path).

The figure above is not in scale from tx to rx part.

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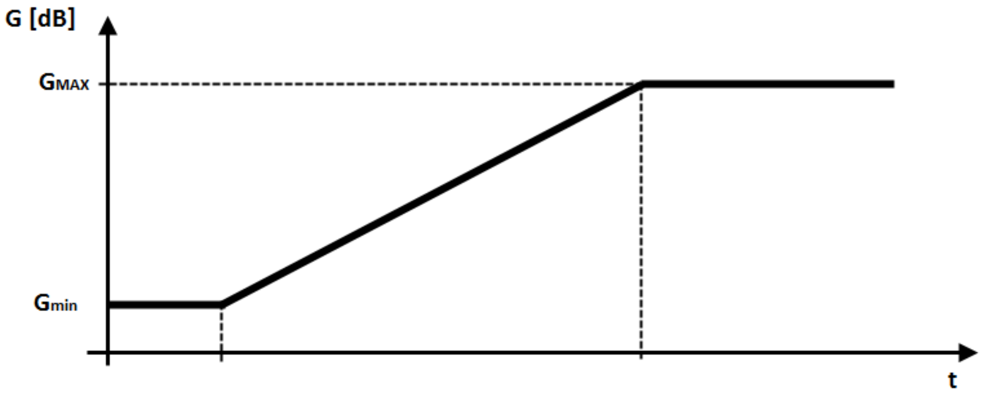
Reception Path – TGC and PGA



- Time Gain Controlled amplifier
  - extends the channel dynamic range;
  - with a 40dB variation increases the ADC input dynamic range to 100dB;
  - the gain variation is **linear in dB** to compensate the human body attenuation;
  - the control can be analog or digital.

- Programmable Gain Amplifier
  - in components available on the market and not dedicated to a particular system it allows to meet the ADC input dynamic range;
  - usually 10÷15dB variation in 3÷5dB steps.

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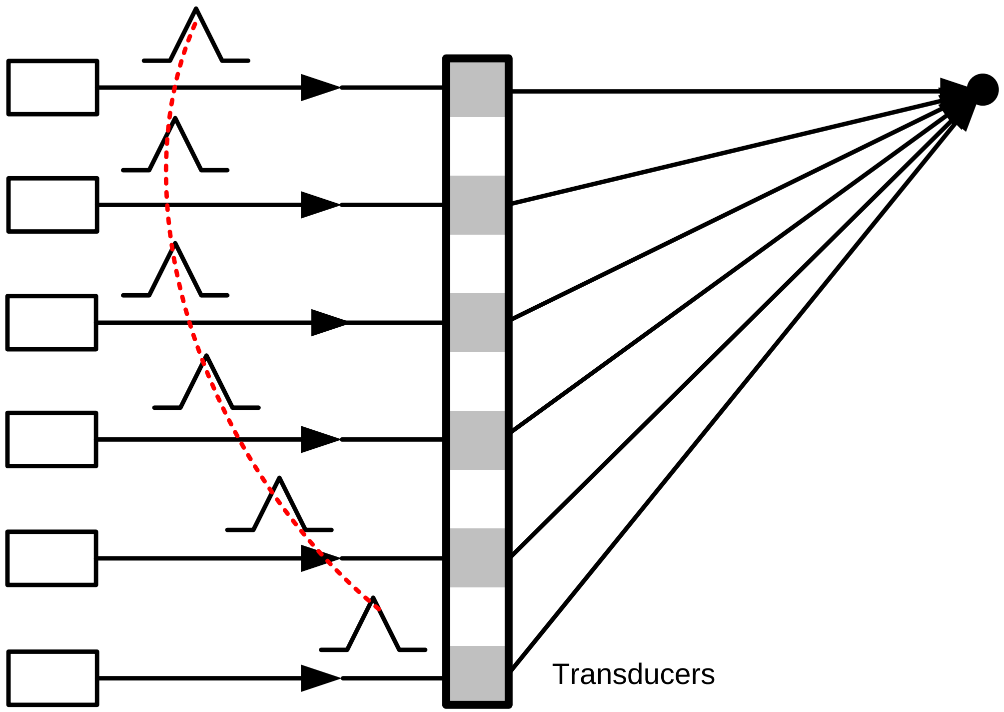
Beamforming TX



- The electronics builds a delay profile to maximize the energy sent in one direction (scan line) or to a point in the volume.
- It is necessary to guarantee an high delay matching between different channels.
- To improve the beam profile some elements can be turned off or can be excited with a lower voltage to apply a sort of “spatial windowing” (also using common windows for temporal analysis like Hamming, Hanning) that is called “apodization”.

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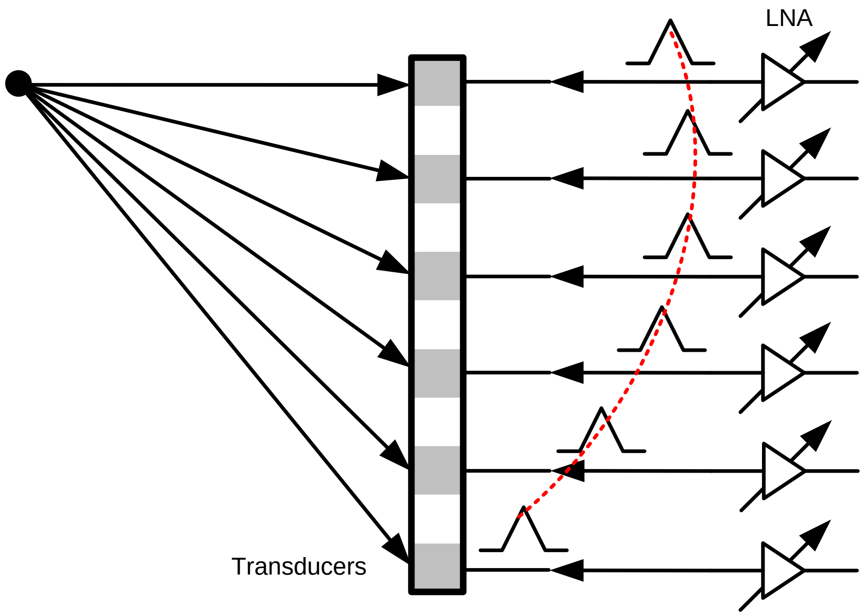
Beamforming RX

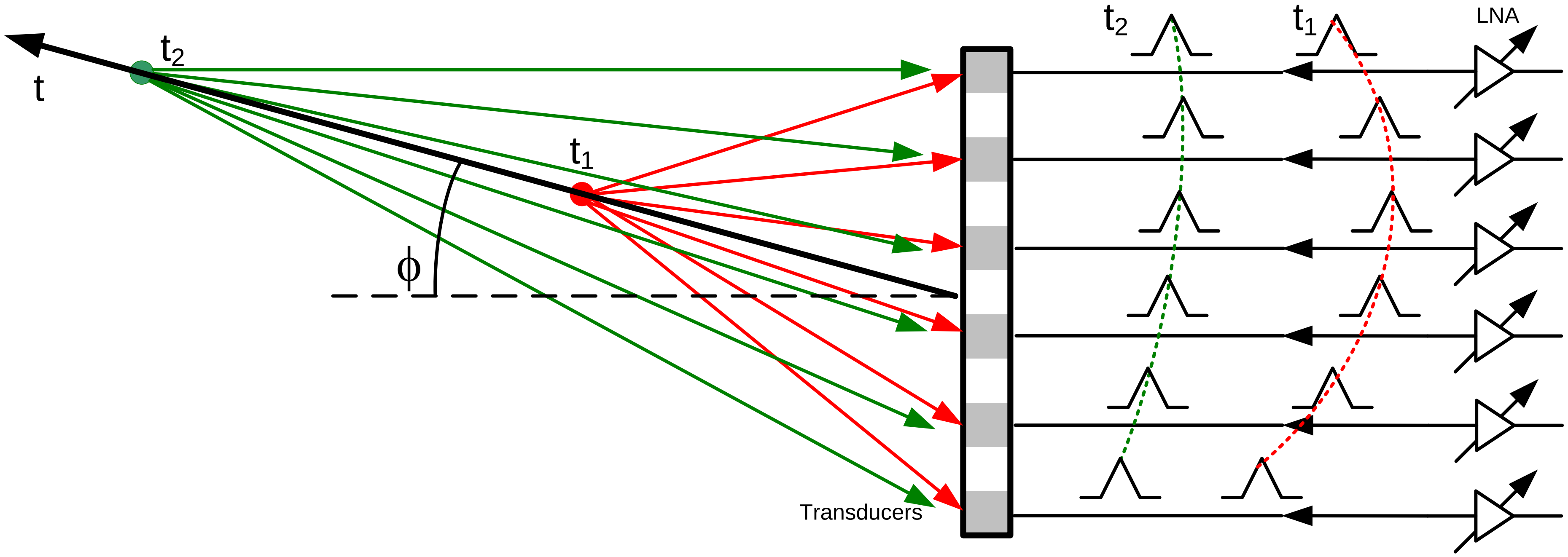


- Also during reception a correct focusing is important to have the best reconstruction of the image.

- The signal coming from the point analyzed reaches the transducers with different delays since it has to travel a longer distance.

- So it is necessary a delay compensation to synchronize all the channels.

Dynamic Focusing



- Considering a scan line with an angle ϕ to the array perpendicular, an echo coming from a point near the transducer array at time t_1 generates signals with different relative delays with respect to a point far from the transducers at time t_2.
- To improve the final image quality can be useful to change the delay profile during reception. This is called “Dynamic Focusing”.
- During transmission the Dynamic Focusing is impossible.

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Near Field / Far Field

- It is common to differentiate the zone close to the transducer from the one far from it.

- Near Field:
  - signal with high amplitude
  - necessity to attenuate the signal
  - no noise problem
  - the analog front-end can saturate

- Far field:
  - signal with low amplitude
  - high gain
  - the electronic noise can be a problem
  - the noise figure has to be minimized:

    NF = (total input referred noise)/(transducer noise)

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Doppler Analysis

- If an acoustic wave hits a moving object the returning signal has a shift in frequency Δf depending on the object speed:

$$\Delta f = (f_0 * v_{rel}/c)*\cos(\phi)$$

where:

f_0 is the original frequency

v_{rel} is relative speed between source and receiver, if the source is approaching the receiver the shift is negative

c is the sound speed in the body
ϕ is the acoustic wave angle of incidence.

- This is very useful to measure precisely the blood speed with spectral analysis, but has no imaging capability.

- Maximum sensitivity if the object moves in the direction parallel to the wave propagation (but for imaging – reflection – the best signal is if the structure is perpendicular to the wave direction).

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The Ultrasound Scanner

The Ultrasound Scanner

- An ultrasound scanner is composed of:
  - the probe, it is the part that carries the transducer array and touches the patient’s skin;
  - the console, it is the bigger block containing all the electronics to generate and receive the ultrasound signals, to reconstruct the image and to store the image files;
  - the display, shows the image of the scanned zone;
  - the loudspeaker, gives an hearable information during Doppler analysis.

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The Console

- The console is the main part of the system and is containing:
  - power supply: low voltage, high voltage, digital etc.;
  - a human interface with keyboard, trackball, switches;
  - a computer for all high-level functions like operating system, mass storage devices etc.;
  - high voltage pulsers;
  - beamformers for tx and rx;
  - low noise amplifiers for rx;
  - adjustable delay paths for rx;
  - many A/D converters to digitize the rx waveforms;
  - an image processing unit;
  - a loudspeaker for Doppler analysis;
  - a monitor;
  - a printer.

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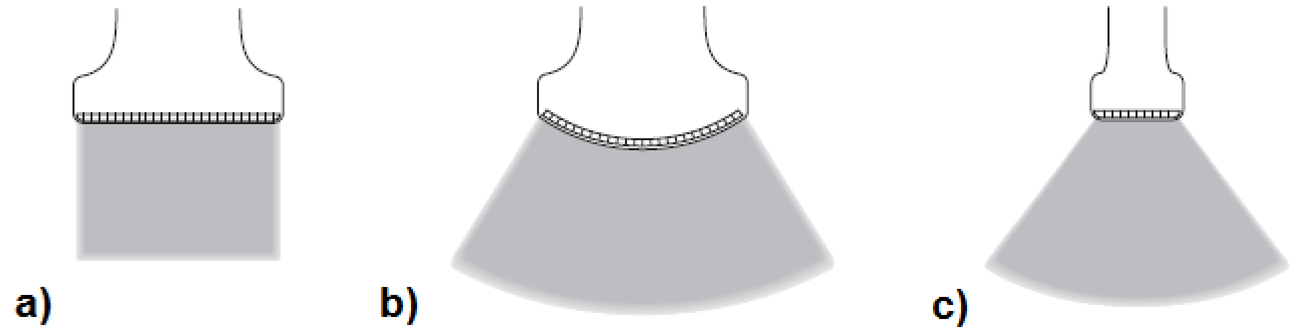
The Probe

- The probe carries the transducer array and all the layers needed to match the transducer acoustic impedance with the human body impedance. An acoustic lens can be mounted in front of the array.

- Normally the array is composed of:
  - 50 ÷ 130 transducers, if each transducer is connected to a coax cable that goes into the console;
  - up to 500 transducers, if there is a multiplexer.

- A 1D array is composed of a line of arrays, but, to improve the beam focusing, 1.5D architectures have been developed where there are 2 or 4 lines of transducers parallel to the main one but smaller in width.

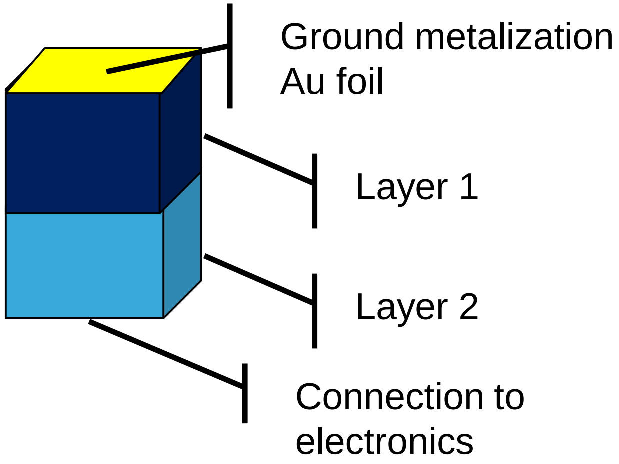
Probe Types

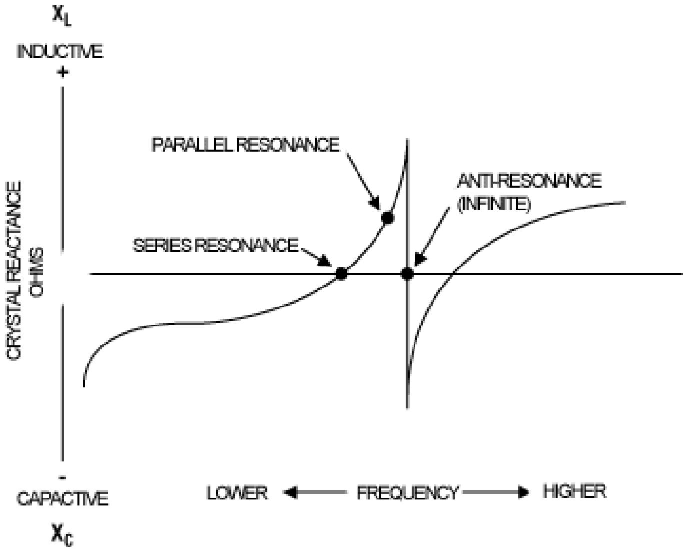


- In the picture some examples of external probes:
  a) linear array;
  b) curved array (gynecological, obstetrical) has a vide view angle;
  c) linear array with electronic beam steering gives a real time visualization.

- Some probes for internal inspections are:
  - TEE, trans-esophageal echocardiogram, for the heart;
  - IVUS, intra-vascular ultrasound.

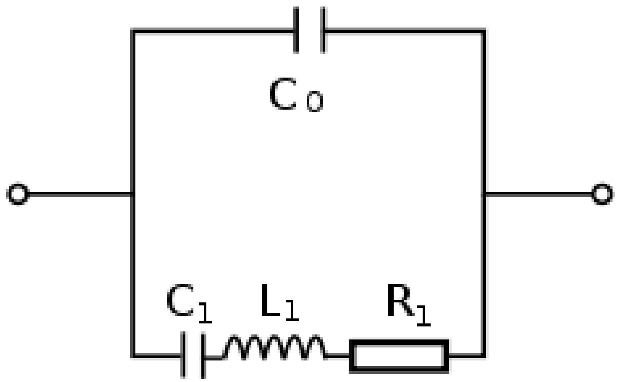
Transducers - Piezoelectric

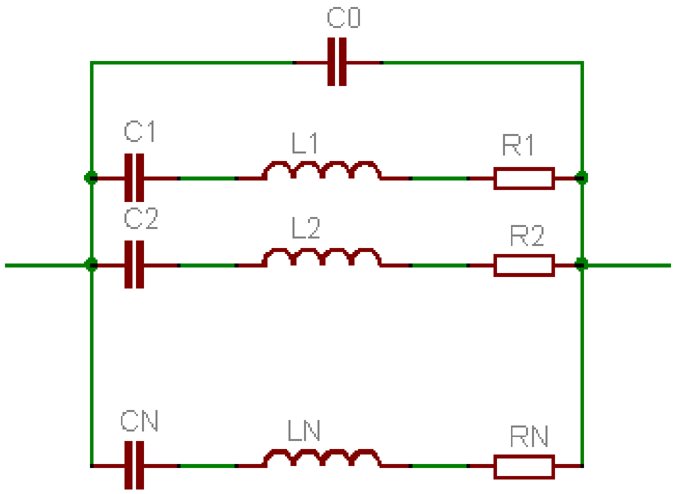




- The most used transducers are piezo-electric. They are made of different ceramic layers to have 3 or 4 resonant frequencies in the 1-10MHz band.
- They show a good linearity and do not require dc biasing during reception.
- For transmission they are actuated with an high voltage waveform (square or staircase).
- Their electrical characteristics are very different, it is difficult to have specifications valid for most cases.
- Pitch from 80 to 400um.

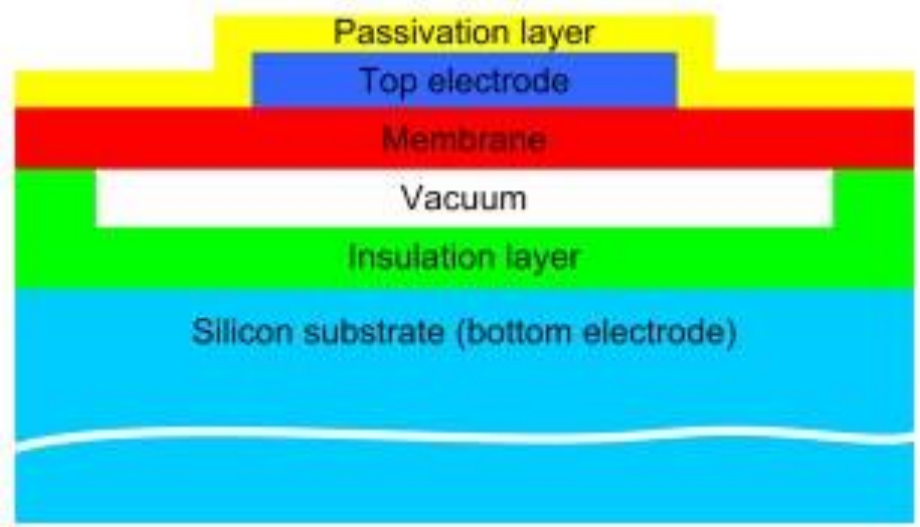
Transducers - Equivalent Circuit





- The equivalent circuit of a piezoelectric transducer with a single resonant frequency is the parallel of a capacitor and an RLC network that models the resonance.
- In case of a multi-layer transducer, each RLC network models a resonant mode.
- Usually a resistor models the acoustic energy flowing into the body.

Transducers - CMUT



- Recently CMUT (Capacitive Micro machined Ultrasound Transducer) have been developed: they are a silicon membrane capacitively actuated.
- Still no commercial application, but are very interesting because they are built with the silicon technology.
- Wider frequency band.
- Same high voltage waveforms for transmission.
- Necessity of a dc bias during rx to see a variable capacitor.
- No linear response from acoustic input to electrical output.
- With a strong signal, the membrane can touch the lower layer.

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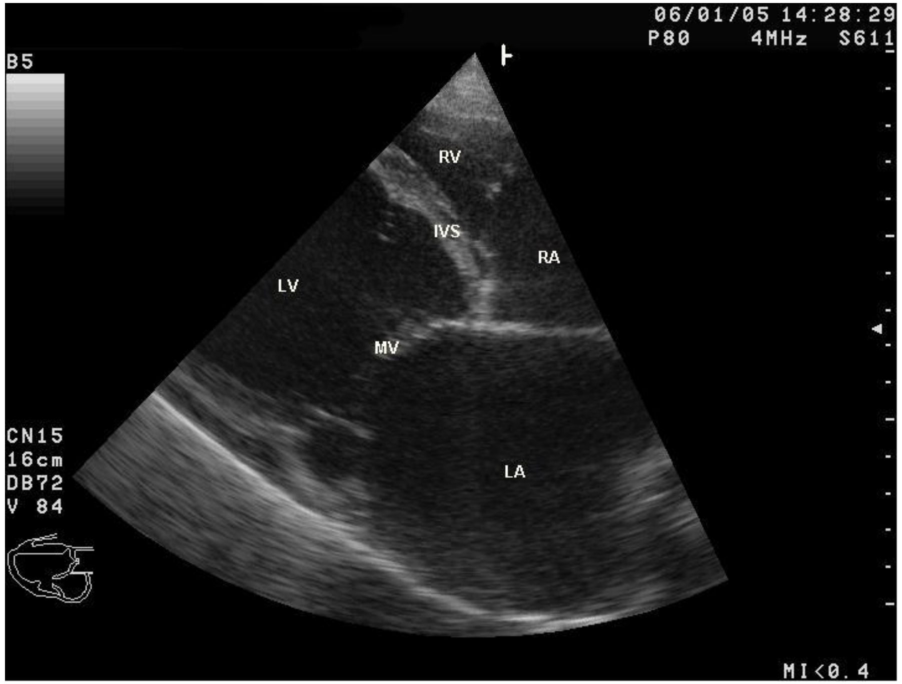
B-Mode



- Highest resolution.
- Highest voltage in transmission.
- Highest electrical and acoustic power.
- Few pulses (2÷5) to avoid biological damage.
- Possibility to use harmonic imaging:
  - reception is tuned to the second harmonic of the transmitted signal;
  - some body structures have a non-linear response to acoustic pressure.
- In the picture an heart detail.

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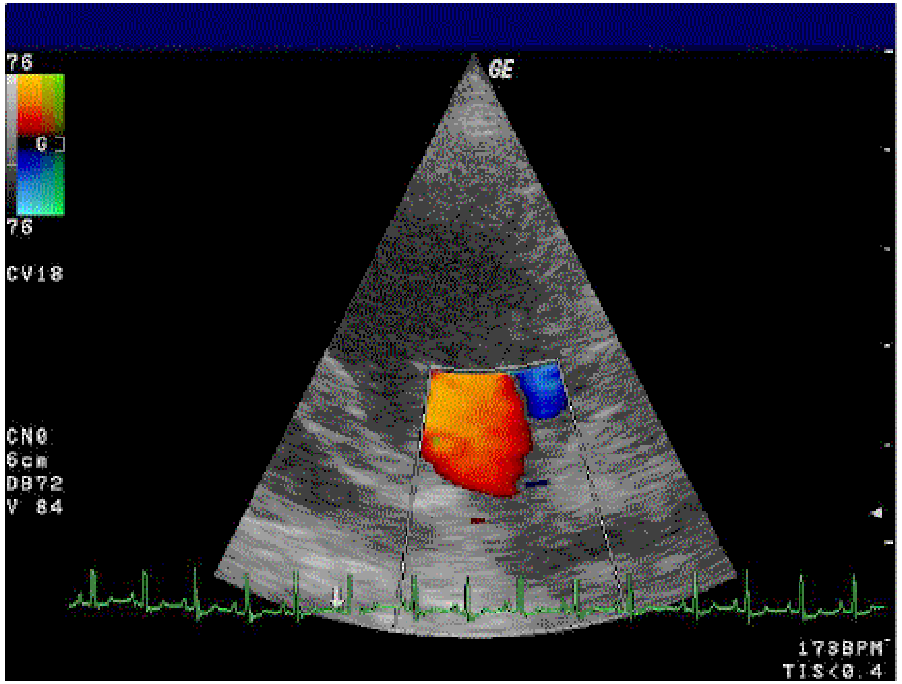
Color Flow



- Blood flow analysis.
- More pulses (5÷15) than B-Mode but lower voltage (70%) to avoid tissue damages.
- The doctor selects an area in the B-Mode scan and the transmitter alternates some B-Mode pulses and some Color Flow pulses.
- The image processing shows different colors for different blood speed in the selected area.
- Imaging mode not based on spectral analysis.

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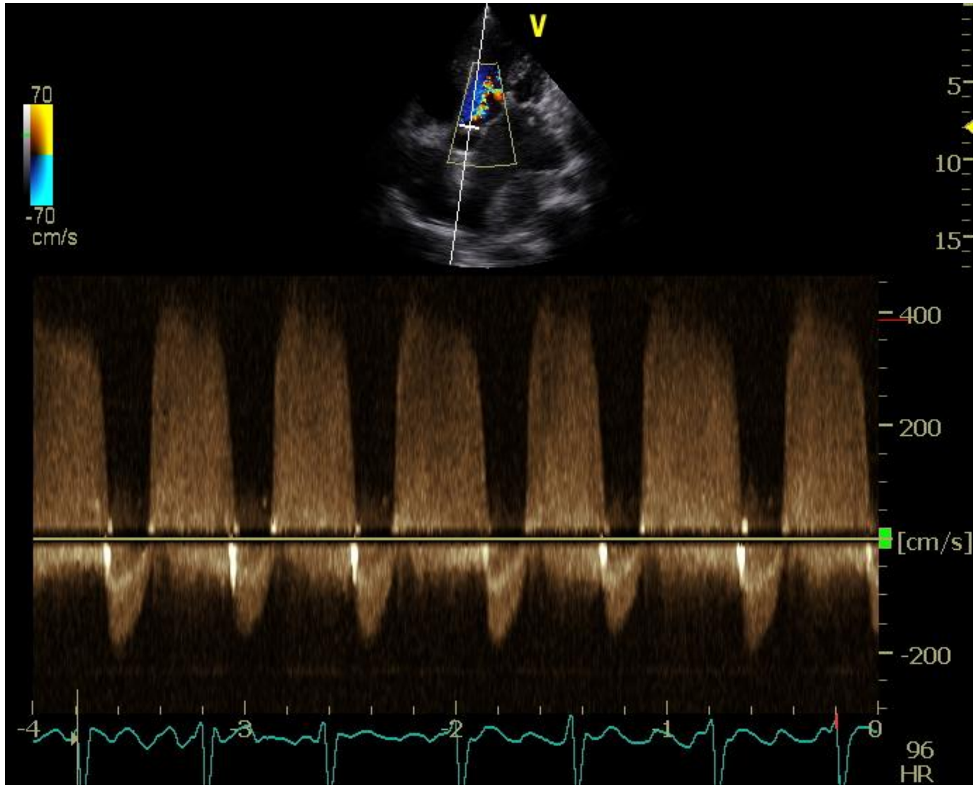
Continuous Wave (CW) - Doppler



- Very different from the previous mode.
- Half transducer array is in transmission mode, the other half in reception.
- The voltage applied is low (<10V) but the waveform is continuous.
- Only a point in the volume is selected and analyzed with an FFT algorithm.
- In the monitor a spectrogram is shown where the brightness is the power, the x axis is time and y axis is blood speed (frequency).
- The loudspeaker is activated to give more information to the doctor (the Doppler frequencies are in the hearable range).

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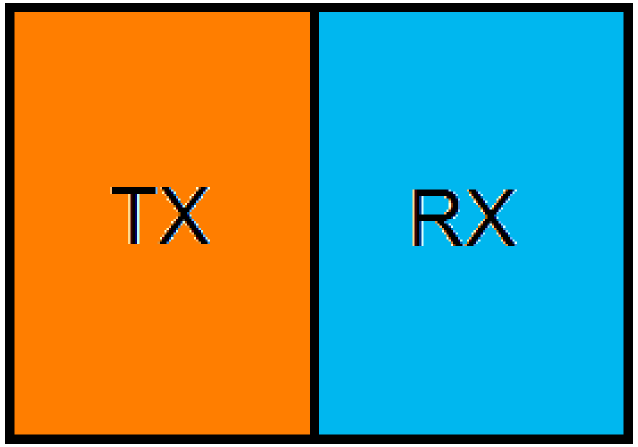
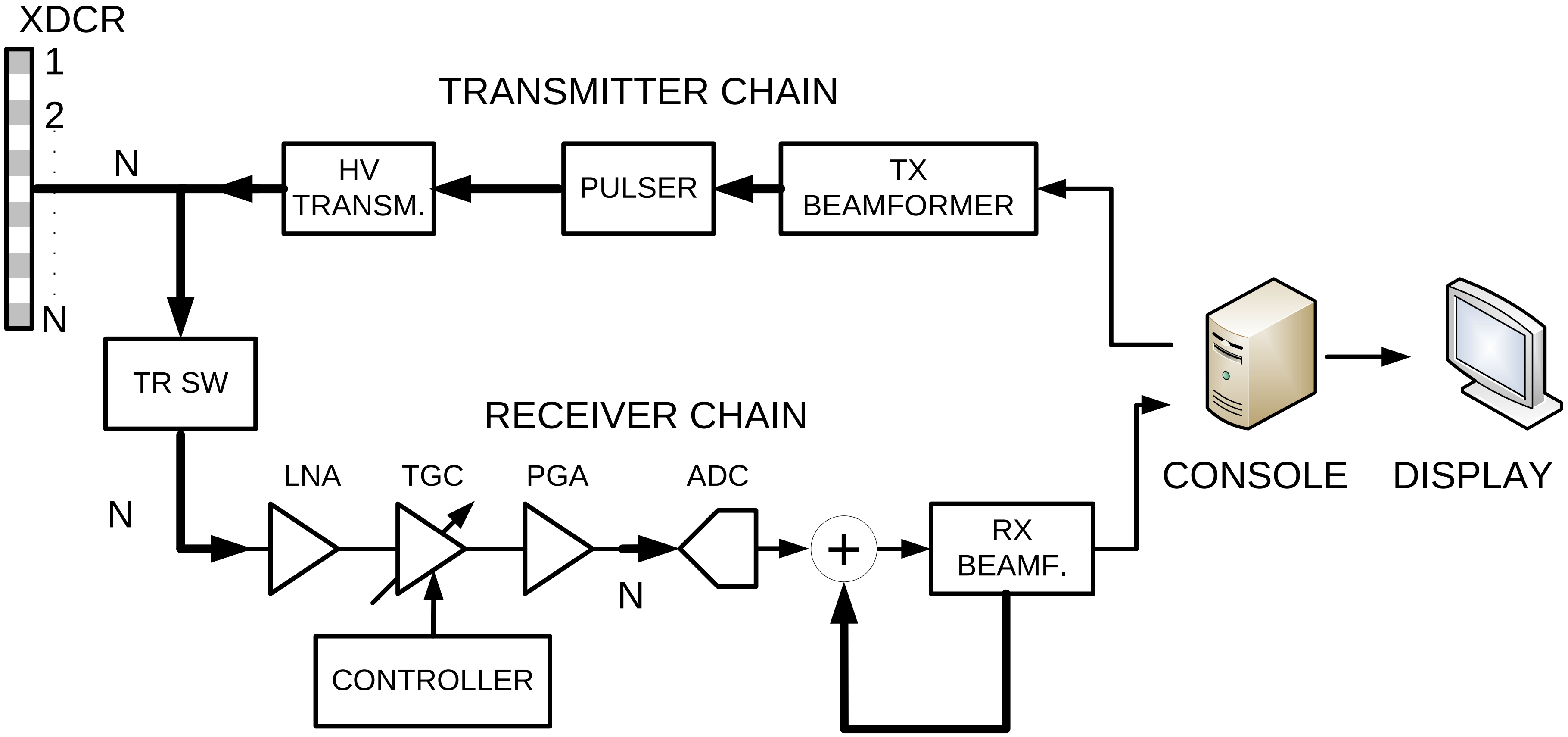
Continuous Wave (CW) 2



- During CW the tx waveform is always present, so the input signal for the receiver has an high amplitude.
- The Doppler signal is close to the carrier, 200Hz÷5KHz, but 60÷70dB lower.
- Two implications:
  - very low jitter transmission, eventually with a dedicated pulser, to keep the fundamental tone very narrow in frequency;
  - different path in reception, usually the same LNA, then a 16 or 18 bit ADC, but in some cases also the LNA can be different.

TX / RX Signal Path



Transmission Path

- The beamformer calculates:
  - the delays between the channels;
  - which channels are off to achieve apodization;
  - what kind of high voltage signal has to be applied.
- The high voltage transmitter can have different architectures:
  - a low voltage pulse generator with correct delays and waveforms that drives the high voltage pulsers connected to the transducers;
  - some high voltage pulse generators with different delays (4÷20) and an high voltage multiplexer to connect the pulse generator to the correct transducer in the array.
- Specs for high voltage components:
  - high current capability, 50÷3000mA depending on the system;
  - low power consumption because the maximum current flows when there is an high voltage applied;
  - voltage capability up to ±150V.

Reception Path – TR switch

- The signal during reception is a low voltage one and has to be processed with normal analog electronics (2.5÷5V).
- But the transducer line is connected to the high voltage pulser, so a protection structure is needed to avoid to destroy the analog path.
- The TR switch is the protection component:
  - open during TX and closed during RX;
  - high voltage technology;
  - low distortion;
  - thermal noise lower than the transducer noise (typically <1nV/sqrt(Hz) for high-end applications);
  - usually in the same die of the high voltage transmitter even if it is part of the reception path.

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Reception Path - LNA

- Low Noise Amplifier
  - 20dB first amplification to the signal to reduce the noise impact of the following stages;
  - signal referred to ground because the second transducer terminal is grounded by construction;
  - low second harmonic distortion (>50dB) to allow harmonic imaging;
  - fast saturation recovery: even if during transmission it is protected by the TR switch, the capacitive coupling and the charge injection when the TR switch closes drive the LNA into saturation;
  - also some highly reflective body structures can cause saturation;
  - each microsecond in saturation corresponds to a 0.77mm image loss;
  - output dynamic range: 60dB;
  - band: from 10 to 60MHz.

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Reception Path – ADC, Beamformer, CW

- ADC
  - 10 ÷ 12 bit resolution;
  - from 20 to 70 M sample/second;
  - increasing the ADC resolution can be decreased the TGC gain variation;
  - in some cases, ΣΔ architectures are used.

- Beamformer
  - the digital samples from all the channels are added together to increase the signal to noise ratio (eg. with 128 channels the SNR increases of sqrt(128) = 21dB);
  - the relative delays are corrected in the digital domain, so can also be achieved the dynamic focusing.

- The CW path is activated with a switch right after the LNA, then arrives to another ADC (16÷18 bit) through I/Q demodulation and different amplification stages.

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The Benefits of Integration

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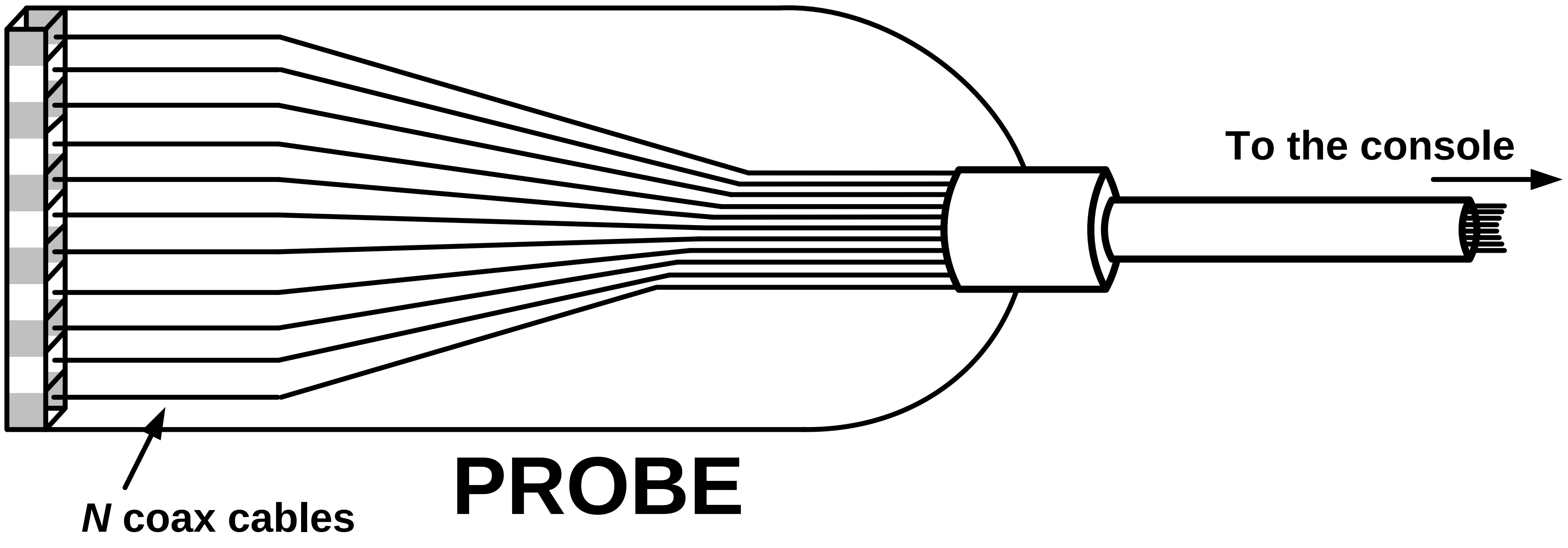
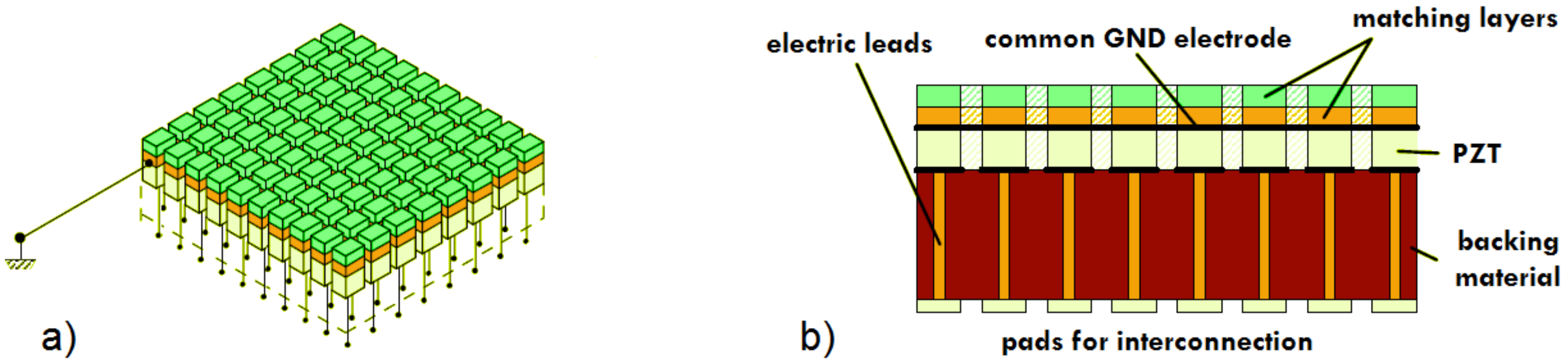
Probe – Linear Array



- This is a simplified scheme for a 1D linear array, where the number of coax cables can go up to nearly 130.
- No electronics inside the probe, all the transducers are directly connected to the console with a 2 meter long cable.

Transducer Matrix



- To achieve a three-dimensional image 2D transducer matrixes have been developed recently.
- Using constructive interference on both axes, the ultrasound beam can be steered in a volume.
- There are thousand of transducers electrically connected together with a ground foil on one side, while the other side goes to the electronics.
- The acoustic performances are improved with matching layers and backing material.

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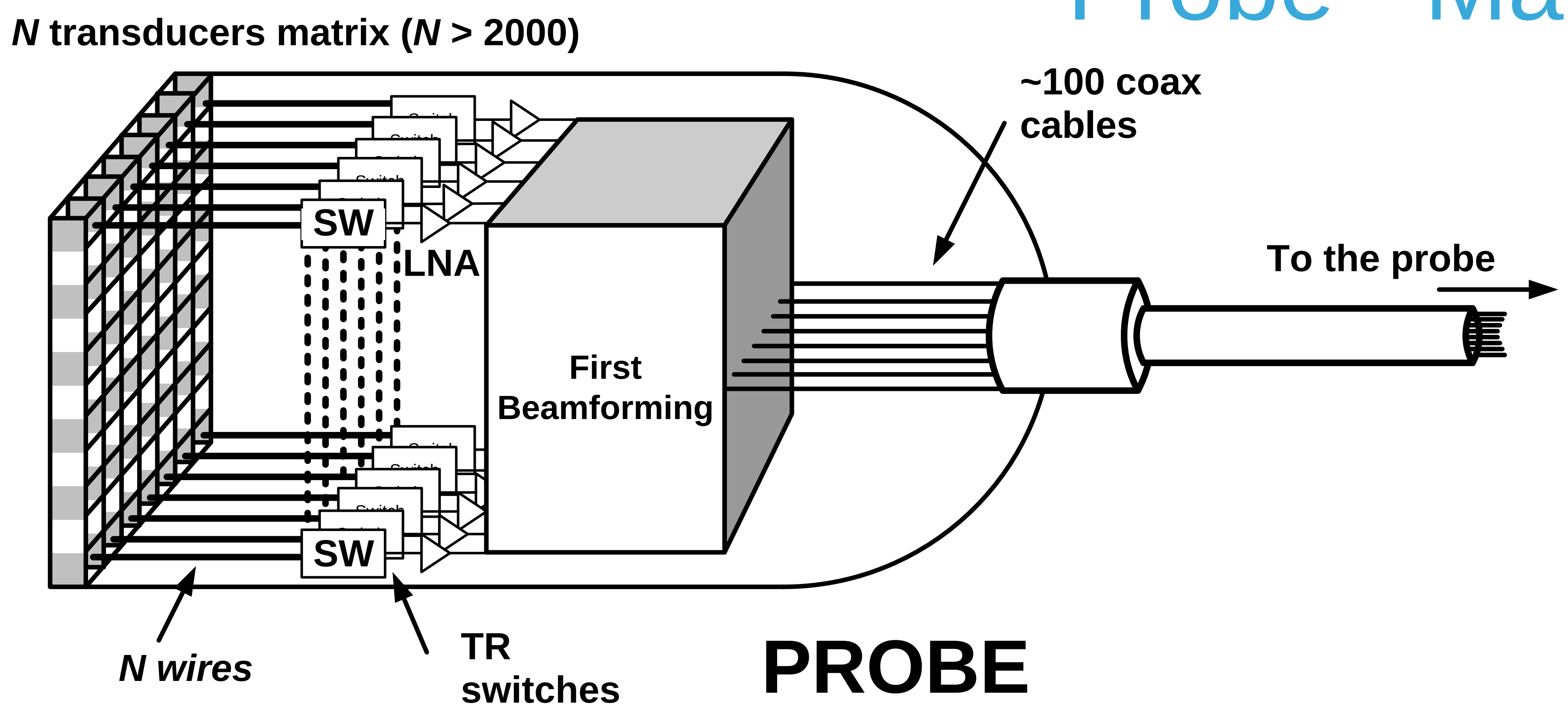
Probe - Matrix



- Put a lot of electronics inside the probe → **INTEGRATION**.
- LNAs and new beamformers are right after the transducers and collect some signals (15-30) with the right delays before sending them to the coax cables connected to the probe.

Problems of Integration

- Since some active circuitry is placed inside the probe two problems arise:
  - asic size, the probe has to be handled easily by the doctor;
  - power dissipation
    - the probe is in direct contact with the patient’s and the doctor’s skin;
    - difficult to have active cooling;
    - maximum allowed power < 10W for external probes, <1W for internal.

- Example for channel power calculation:
  - suppose **4W** available, a 5kHz pulse repetition frequency, 2000 channels and a 3.3V supply;
  - a normal duty cycle is: 5% digital configuration, 5% transmission, 90% reception;
  - suppose negligible the digital configuration contribution and suppose to equally distribute the power between TX and RX phase;
  - for RX means 2W/(0.9*3.3V*2000)=**340uA per channel** to bias the LNA, the TGC and the first beamformer.

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Problems of Integration 2

- Example for channel power calculation:
  - in the TX case assume that the load can be modeled as a **20pF** capacitor to be charged with the scheme: 0V, +50V, -50V, +50V, 0V;
  - assume also that all the energy stored in the capacitor is converted to acoustic energy;
  - from physics is known that to charge a capacitor an energy **$CV^2/2$** is lost in heat;
  - it means that the total energy lost to charge the transducer is $3*20pF*10000V^2/2=0.3uJ$;
  - the power per channel is 0.3uJ/200us = 0.0015W;
  - for all the 2000 channels the **total power is 3W**, more than the initial assumption;
  - the best trade-off has to be found with the system engineer!

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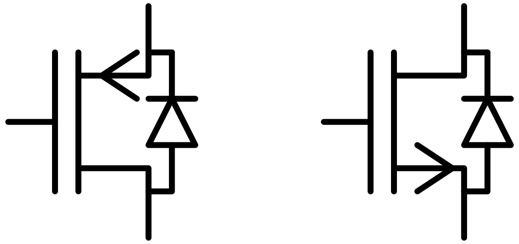
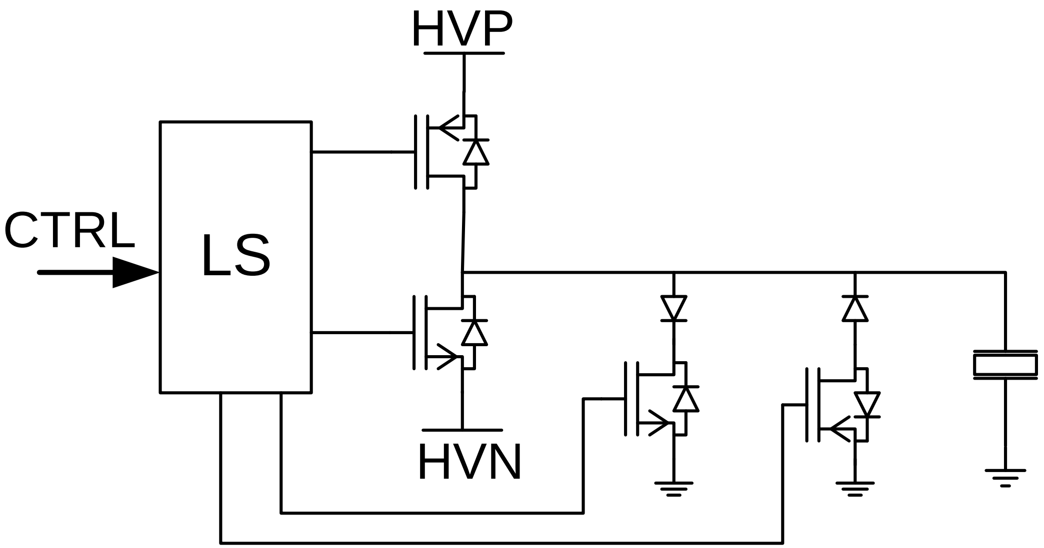
High Voltage Technology

- Diodes: wide low doped regions allow an high voltage reverse bias.
- Vertical D-MOS:
  - discrete components, no integration is possible;
  - the current flows from the top silicon surface to the bottom one;
  - very high voltage and current capability.
- Lateral D-MOS:
  - integrated components;
  - the operation is on the top silicon surface.
- 💣 all the D-MOS have a body-drain diode!
- 💣 the gate oxide is thin, V_{GS} in the logic domain (3.3/5V)!
- V_{DS} and V_{DG} can be high.
- SOI integrated technologies can be useful to reduce the silicon area and to avoid latch-up.



High Voltage Pulser



- In ultrasound application a three level pulser (HVP, HVN, ground) is necessary because the load is capacitive.
- After the last high voltage pulse, the transducer has to be brought to ground before being connected to the receiver.
- Diodes are needed in series to the D-MOS grounded switches because of their body-drain diode.
- The control signal enters a level-shifter (LS) to drive the switches:
  - same delay in the HVP and HVN path to minimize HD2;
  - fast operation to reduce jitter (worse color flow image).
- High side and low side D-MOS have the same current capability to equalize the rise and fall time and reduce HD2 → in the layout the p-channel transistor will be wider.

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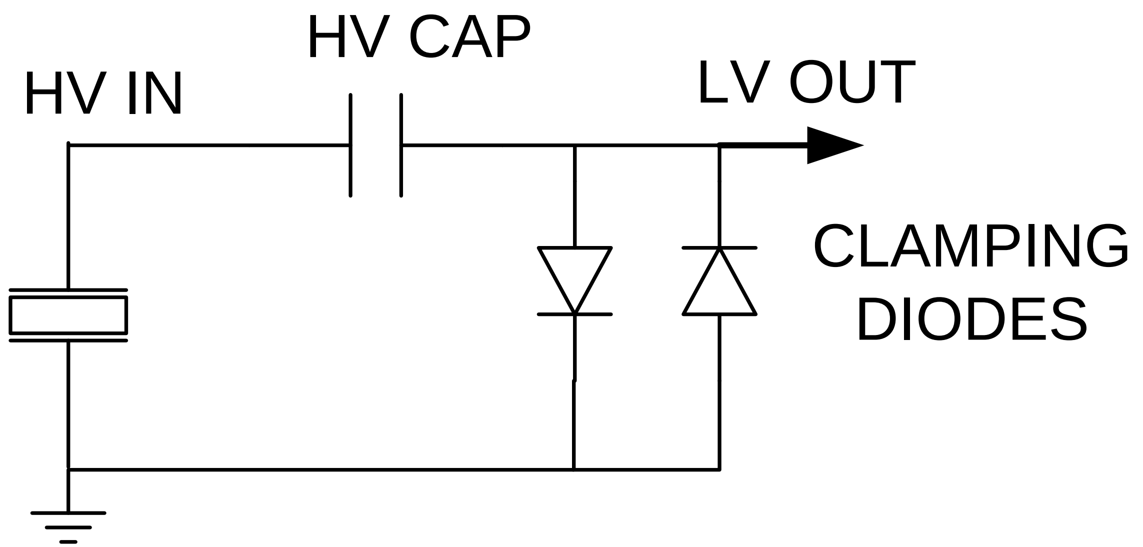
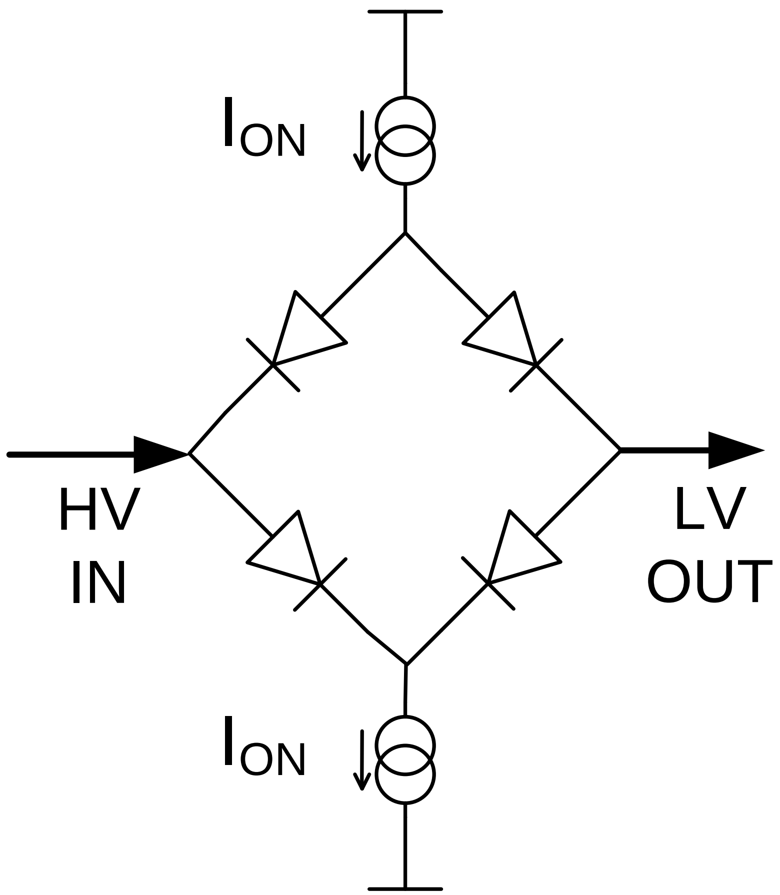
Capacitive TR Switch



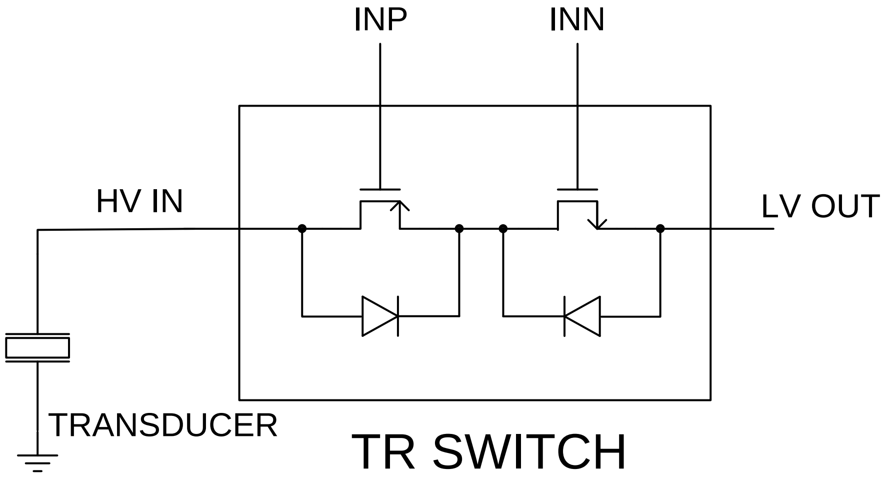
- A very simple way to protect the LNA input, without the need of any control circuit, is to use an high voltage capacitor.
- The fast high voltage edges are able to pass the capacitor but they are clamped by the diodes connected to ground.
- During reception the signal never turns on the diodes so it can go directly to the LNA.
- This solution is very hard to be used in an integrated circuit because of the high voltage capacitor large area.

Diode Bridge TR switch



- The diode bridge with high voltage diodes is a simple and widely used circuit to protect the LNA from the pulser high voltages.
- When the switch is on, a current is flowing through the diodes so that there is a low impedance path between the input and output nodes.
- When the switch is off, no current is flowing, so, as soon as the input signal goes high or low, two diodes become reverse biased and the LNA is protected.
- To have a low impedance, low noise switch, the current level can be too high for an integrated solution.

D-MOS TR Switch



- A Pch/Nch D-MOS TR switch is more suitable for integrated circuits to be placed inside the probe because it does not require a dc bias current.
- The driving signals are more complex than the diode scheme:
  - the Nch has no problem because the source is connected to a low voltage node;
  - the Pch source can go to a high voltage because of the body-drain diode.
- The worst problem are the parasitic capacitors in the signal path:
  - gate-source, gate-drain capacitances;
  - body-drain diode junction capacitance.

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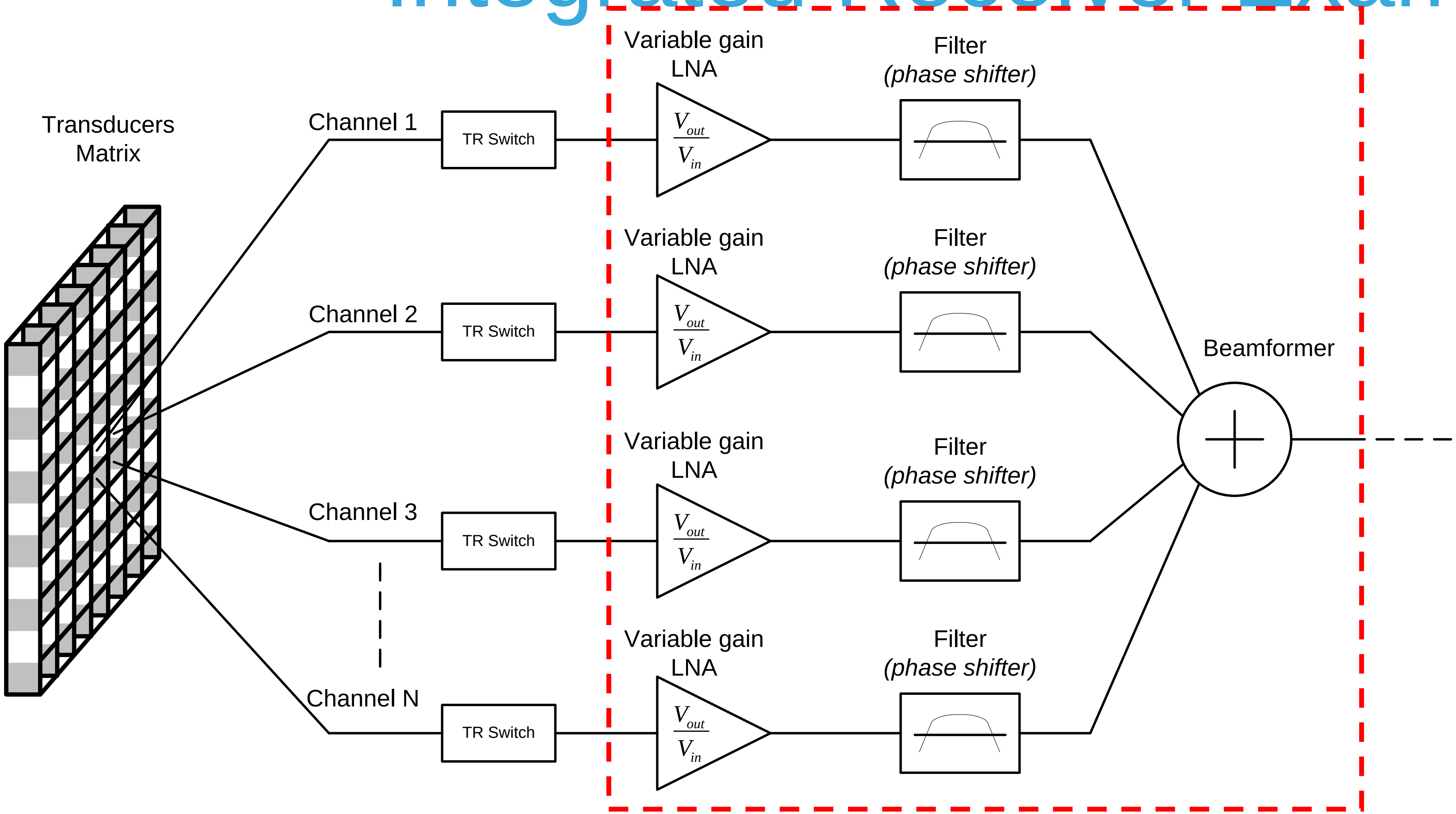
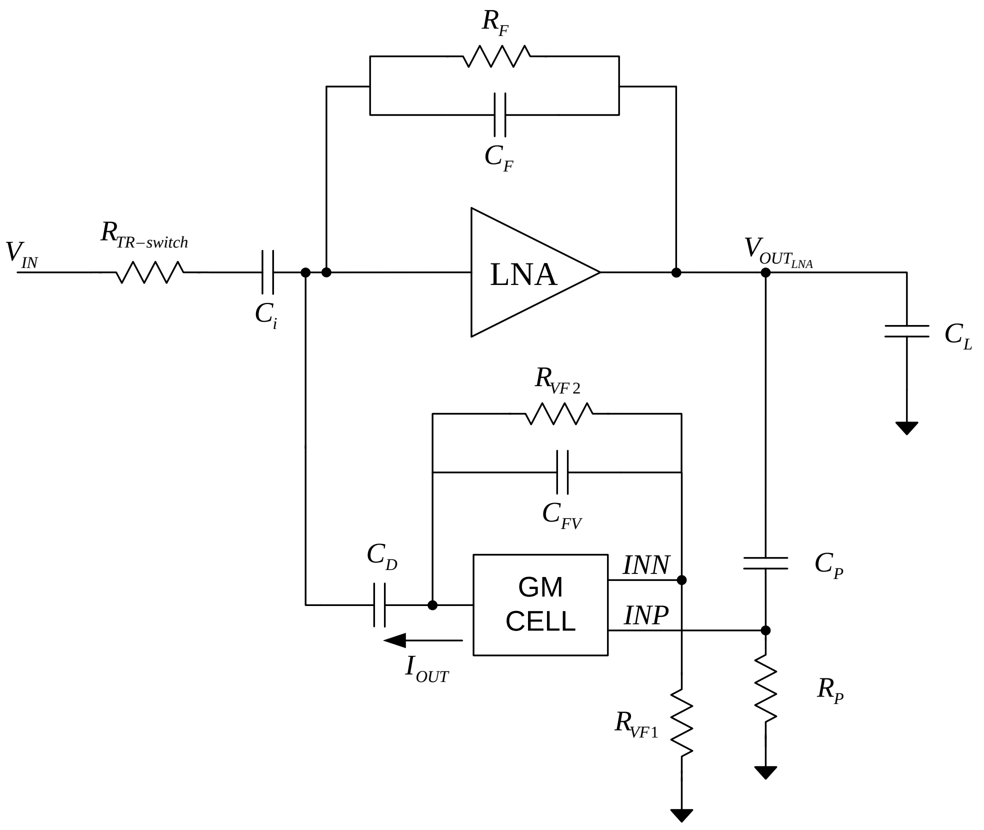
Integrated Receiver Example



- All these components (excluding the TR Switch) have to be integrated in the same die, with tight power constraints.

Variable Gain with GM Cell



- The gain variation is part of the LNA.
- The GM Cell is active only in the first 50us of reception, then it is turned off → no power dissipation.
- The GM Cell subtracts the signal from the input and avoids the LNA saturation in the near field.
- Results from the paper:
  - 26dB maximum gain
  - 12dB gain variation
  - 550uW power consumption
  - 250uW power increase when the TGC has maximum effect

T.Halvorsrød et. al. “A Low-Power Method Adding Continuous Variable Gain to Amplifiers”

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Thank You

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