Design and optimization of a high performance ultrasound imaging probe through FEM and KLM models

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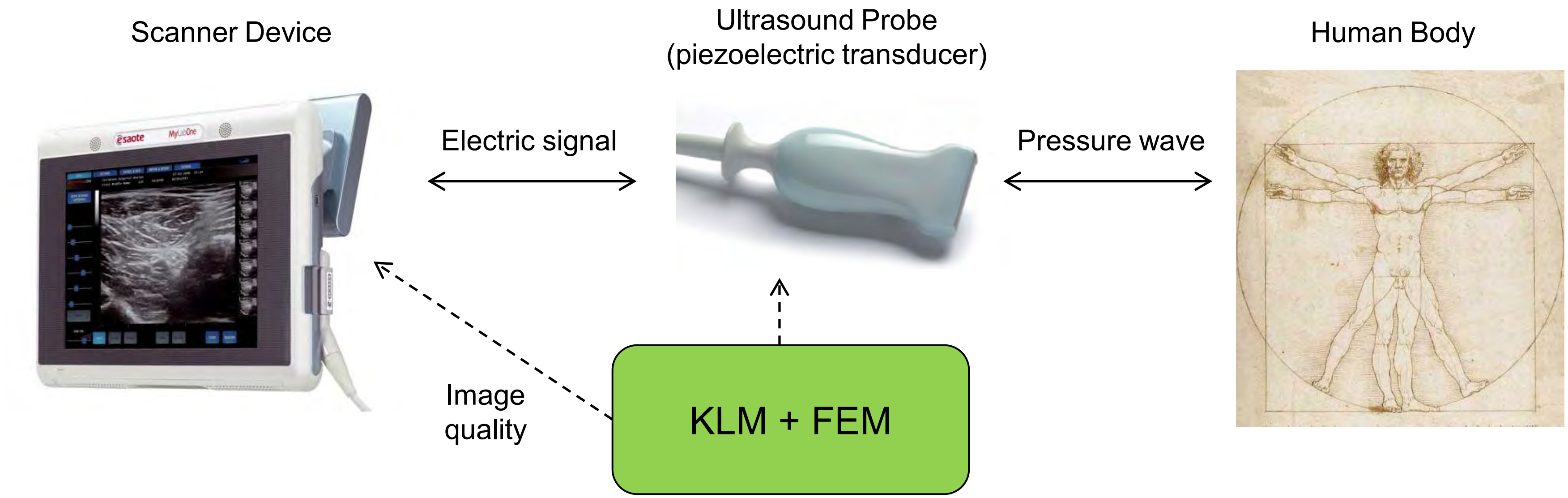
Ultrasound imaging transducer and FEM



- Ultrasound imaging transducers generate a pressure field into the human body
- Differences in acoustic properties of different types of tissue allow the scanner to generate an image
- Quality of the resulting image is strictly related to:
  - technology level of the materials involved in the transducer manufacturing
  - understanding of their interactions
- <u>Simulations greatly help in the study and optimization of transducer electroacoustical performances and image quality improvement</u>

Input specification

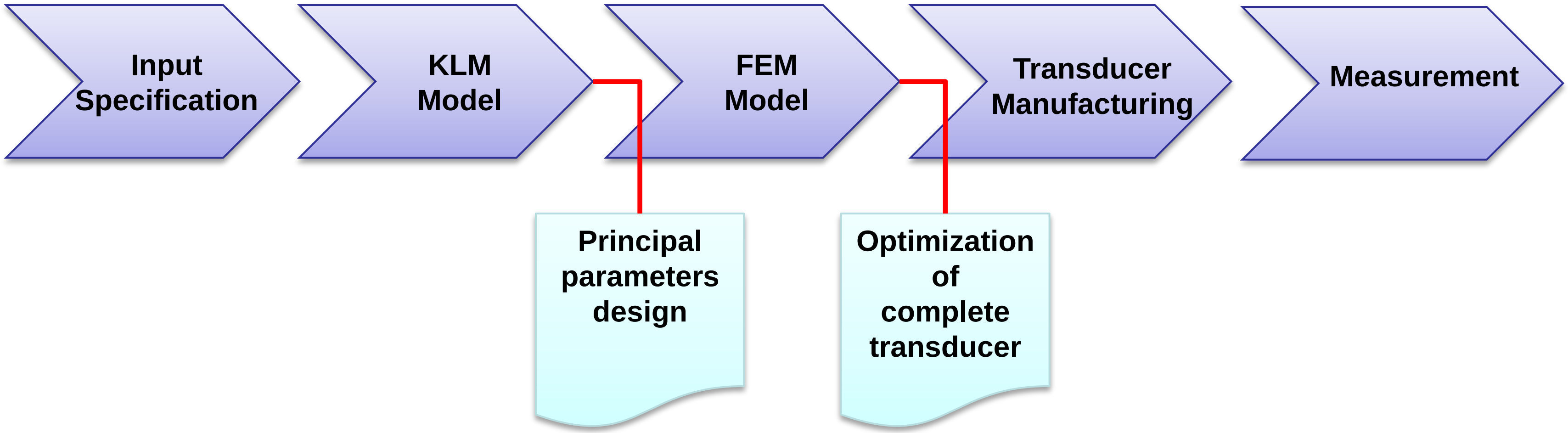
Design an ultrasound linear array imaging probe with:

- 144 element array, 0.245 mm pitch
- 5 MHz central frequency
- Wide frequency range: 2 – 11 MHz (@ -20 dB bandwidth)
- Beam "*steering*" capability: greater than 20° from array axis

➢ Mono-dimensional electro-acoustical circuit model (KLM)

➢ COMSOL FEM model

Design procedure


Input Specification

KLM Model

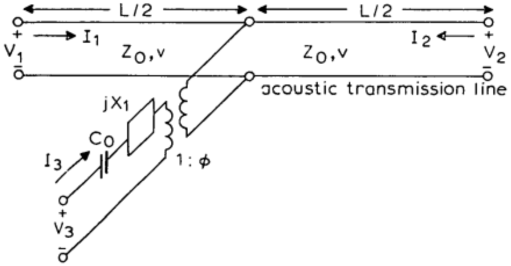
FEM Model

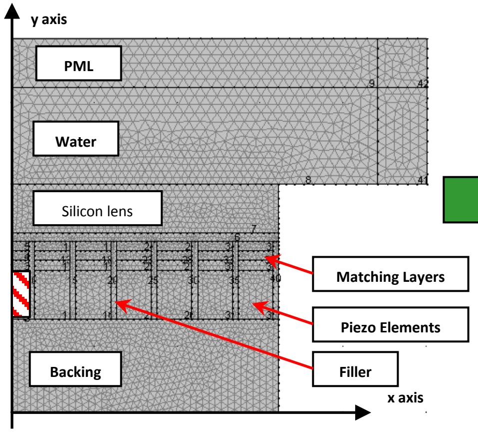
Transducer Manufacturing

Measurement

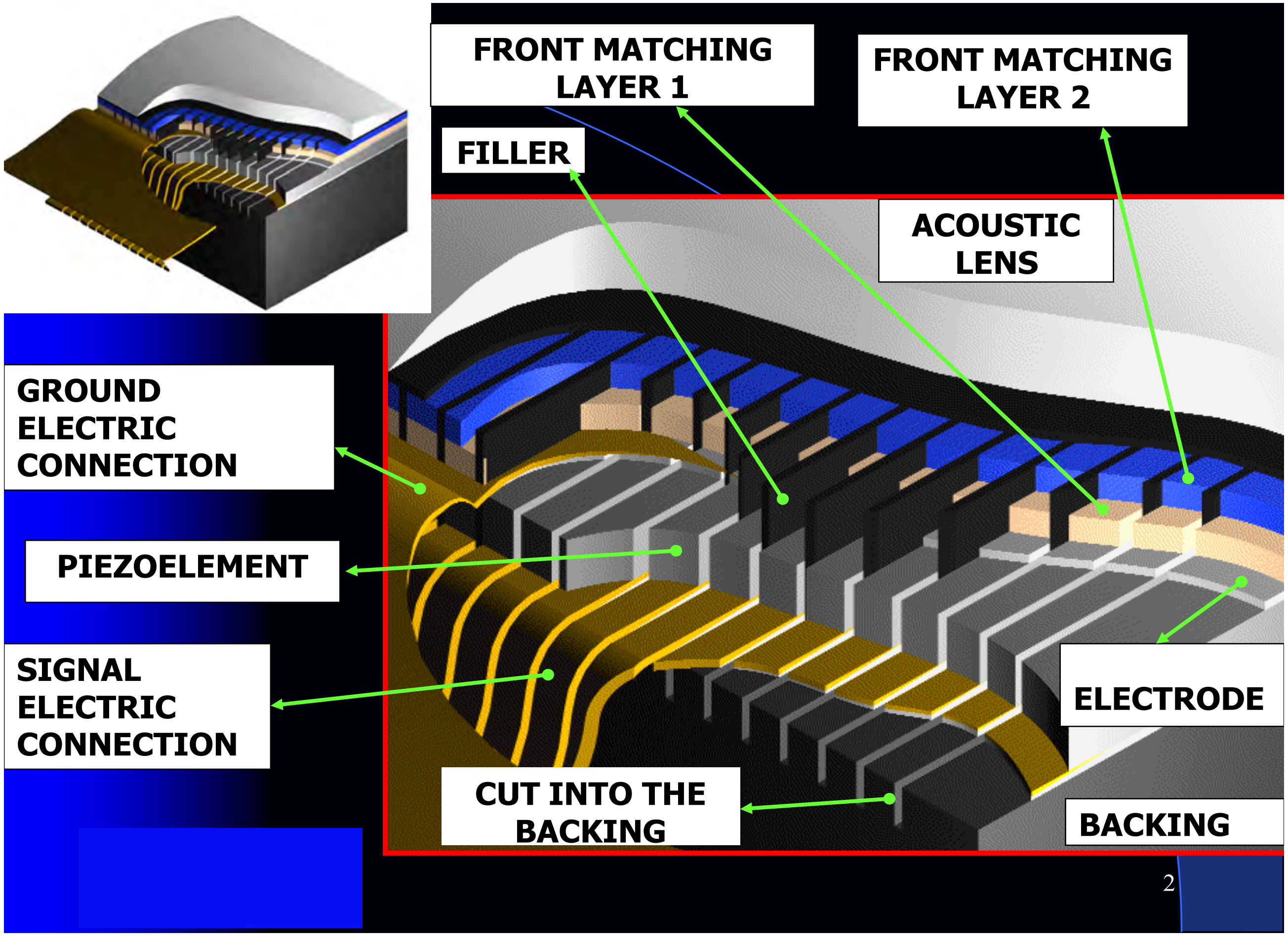
Principal parameters design

Optimization of complete transducer





Typical linear array probe structure



FRONT MATCHING LAYER 1

FRONT MATCHING LAYER 2

FILLER

ACOUSTIC LENS

GROUND ELECTRIC CONNECTION

PIEZOELEMENT

SIGNAL ELECTRIC CONNECTION

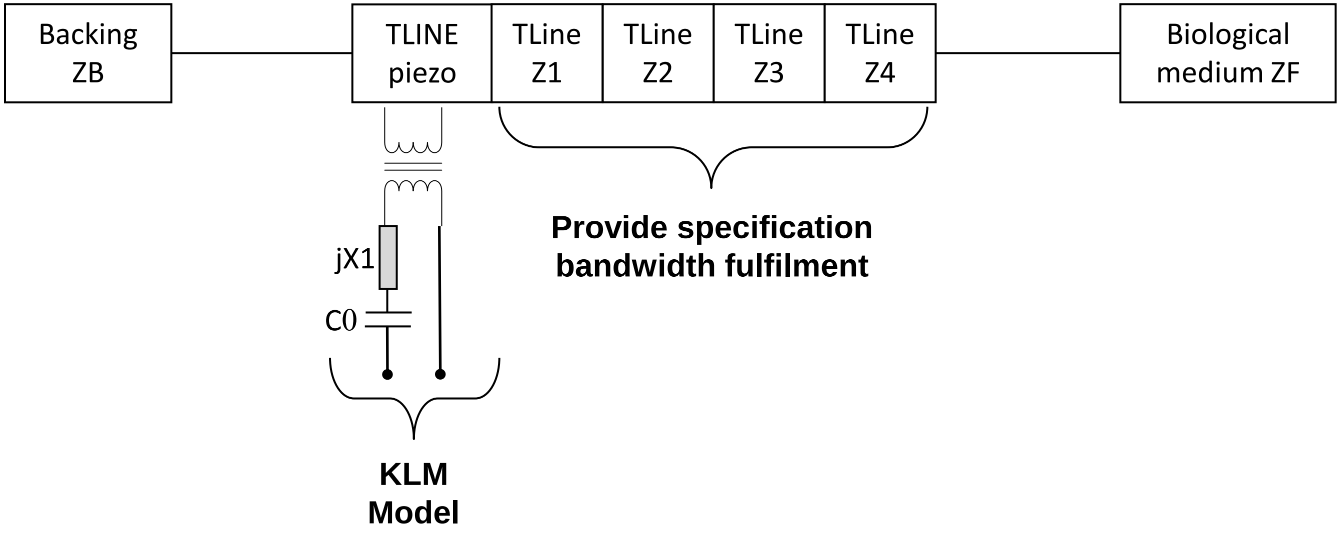
ELECTRODE

CUT INTO THE BACKING

BACKING

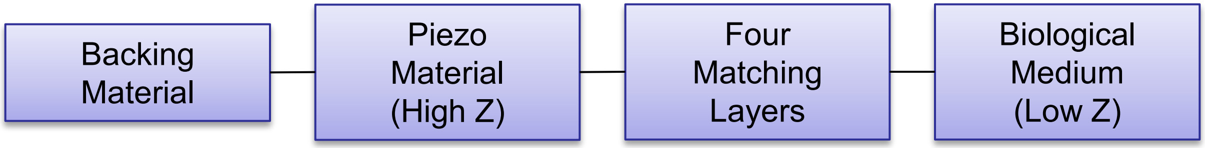
KLM and matching layers model

- Equivalent network of a thickness-mode piezoelectric transducer
- KLM model with transmission line network (Z: acoustical impedance)



Provide specification bandwidth fulfilment

KLM Model

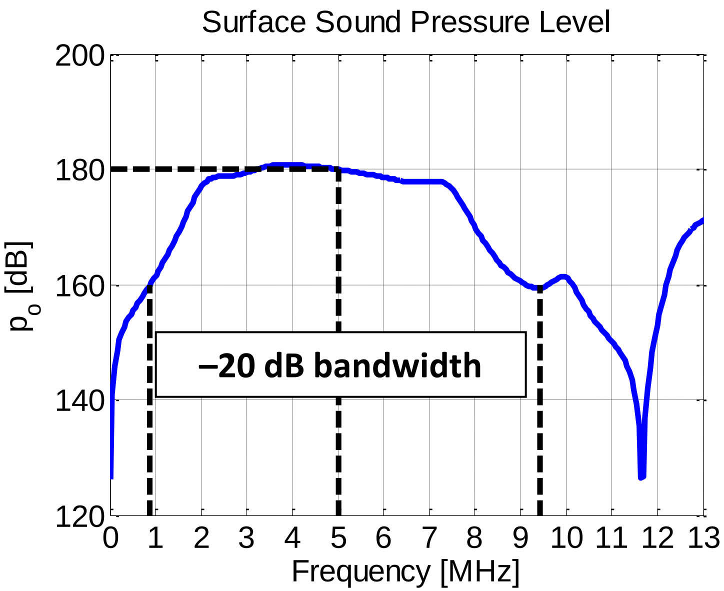


KLM and matching layers design (1)

- Thickness : equal to $\lambda/4$, where λ is the central wavelength calculated in the n–matching layer
- Acoustic Impedance : Binomial or maximally flat response

$$\ln \frac{Z_{n+1}}{Z_n} = 2^{-N} \frac{N!}{(N-n)!\,n!} \ln \frac{ZF}{Z_0}$$

Matching layer:	Sound speed [m/s]	Thickness [wavelength]	Thickness [µm]	Z_n [MRayls]
1st layer	1500	$\lambda/4$	75 µm	18.8
2nd layer	1700	$\lambda/4$	85 µm	9.6
3rd layer	2700	$\lambda/4$	135 µm	3.5
4th layer	1800	$\lambda/4$	90 µm	1.8



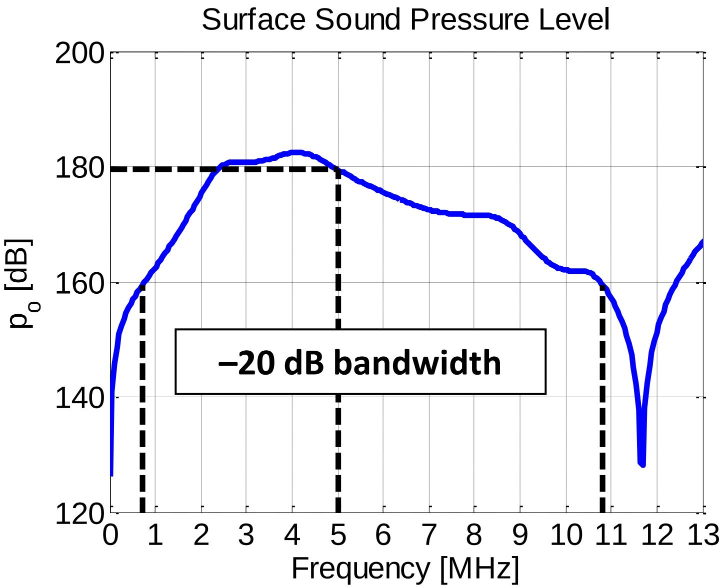
Input bandwidth specification not satisfied

KLM and matching layers design (2)

- Improve the high frequency response without lowering the sound pressure level around the center frequency, through variation of thickness and acoustic impedance of the matching layers

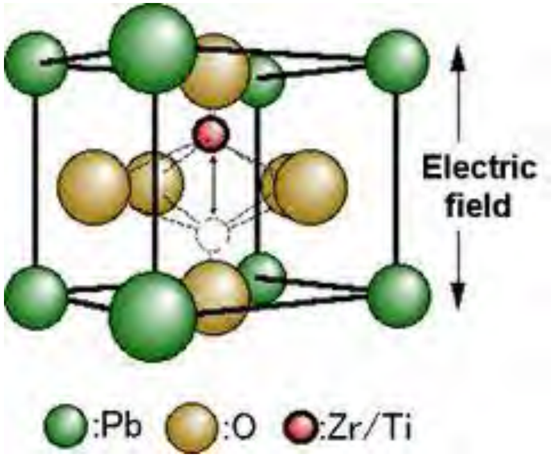
Matching layer:	Sound speed [m/s]	Thickness [wavelength]	Thickness [µm]	Z_n [MRayls]
1st layer	1500	$\lambda/5$	60 µm	8.5
2nd layer	1700	$\lambda/5.67$	60 µm	6.0
3rd layer	2700	$\lambda/9$	60 µm	3.0
4th layer	1800	$\lambda/6$	60 µm	2.0

Input bandwidth specification satisfied



Piezoelectricity in COMSOL

The constitutive equations for a piezoelectric material are (*stress-charge* form):
(the superscripts indicates a zero or constant corresponding field)



$$\begin{cases} \mathbf{T} = \left[\mathbf{c}^{E}\right] \mathbf{S} - \left[\mathbf{e}^{t}\right] \mathbf{E} \\ \mathbf{D} = \left[\mathbf{e}\right] \mathbf{S} + \left[\boldsymbol{\varepsilon}^{S}\right] \mathbf{E} \end{cases}$$

T: stress vector,
c : elasticity matrix,
S : strain vector,
e : piezoelectric matrix,
E : electric field vector,
D : electric displacement vector,
ε **:** dielectric permittivity matrix.

- Elasticity, piezoelectric and dielectric permittivity matrices must be specified to build the model in Comsol
- Manufacturer data are often incomplete and should be checked for the particular operating condition of the piezoelectric material
- Physical insight is the starting point for the model
- Optimization procedure should be used

Electric impedance in COMSOL

The electrical impedance *Z* of a piezoelectric plate can be expressed by the general ohm law:

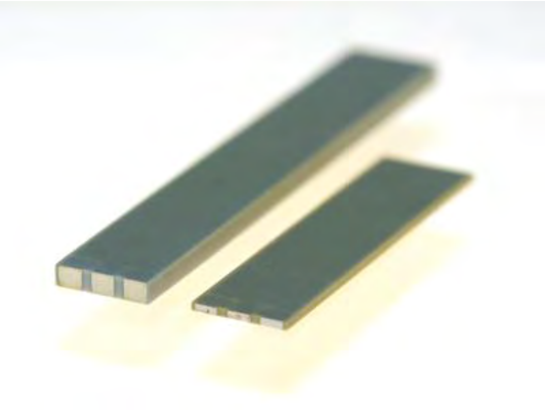
$$Z = \frac{V}{I}$$

V: potential difference voltage across the two plate faces
I: current flowing between plate faces

As regard the electric current flowing in the plate,the following integral holds:

$$I = \int_{plate} j_y(x)dx$$

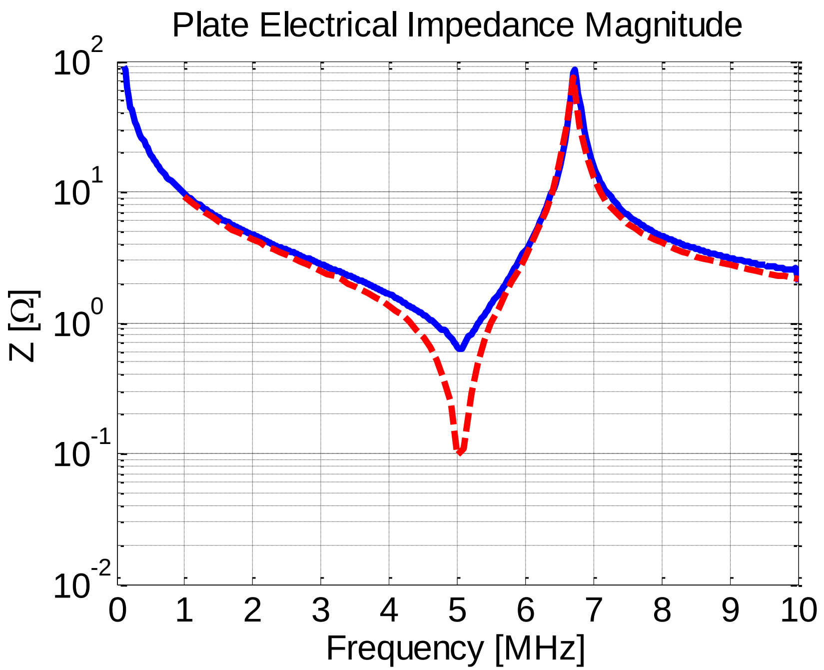
where $\boldsymbol{j_y}$ is the current density component along *y* axis.



This integral has been used in COMSOL as integration variable across the plate surface, in order to use the optimization module with objective function given by the difference of measured and simulated electrical impedance.

Piezoelectric characterization with COMSOL

- Piezoelectric plate alone
- Electrical impedance comparison between measurement (solid) and simulation (dashed)
- Determination of matrices **[c]**, **[e]** and **[ε]** from FEM analysis



Agreement between FEM simulation and measurements are excellent

Acoustics in COMSOL

Pressure waves emitted from the piezoelectric transducer in a biological medium are solution to the wave equation (time domain):

$$\nabla^2 p(r,t) - \frac{1}{c^2}\frac{\partial^2 p(r,t)}{\partial t^2} = 0$$

p is the pressure,
c is the speed of sound in the medium.

For homogeneous media and plate geometry, we have the (*Helmholtz-Kirchhoff*) far field pressure integral (neglecting the oscillating phase factor):

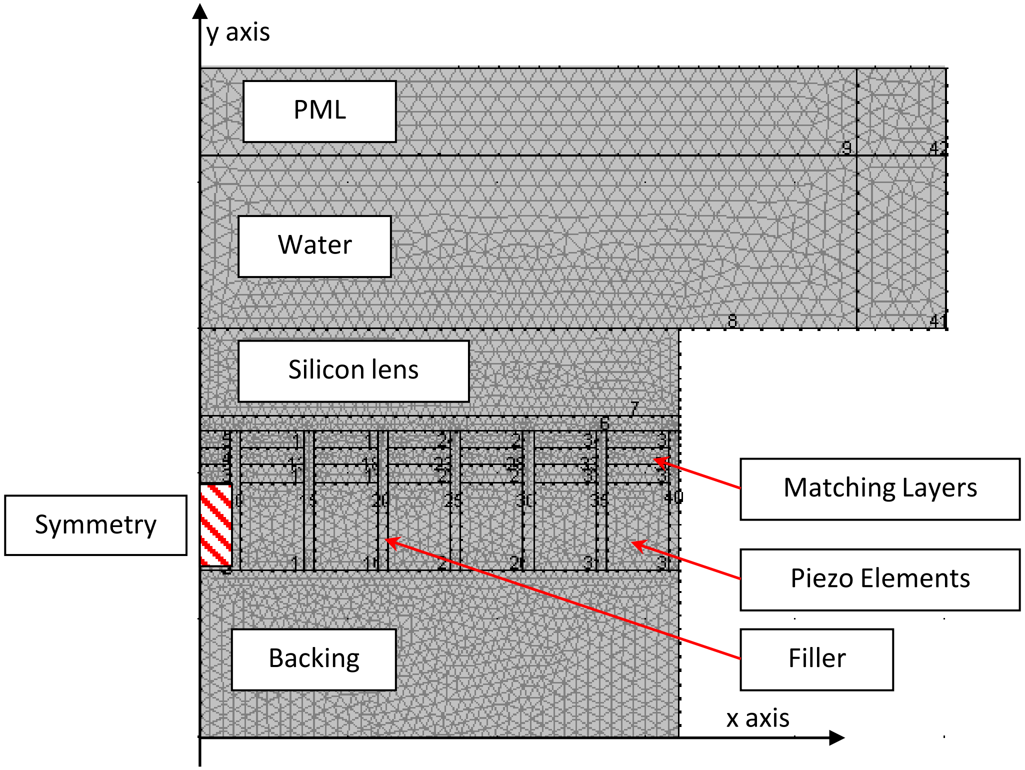
$$p_{far}(X,Y) = \frac{1-j}{4\sqrt{\pi k}} \int_{y=0} 2\cos\left(\frac{kxX}{\sqrt{X^2+Y^2}}\right) \cdot \left(\frac{dp}{dy}(x,0) - jkp(x,0)\frac{Y}{\sqrt{X^2+Y^2}}\right) dx$$

Where k is the wave number, X,Y is the position of observation point and x,y is the position on surface S $(y=0)$ of the plate.

Far field pressure calculation allows the reduction of the acoustic domain to a thin layer in front of the piezoelectric transducer, surrounded by PML (Perfectly Matched Layers). This turns into a tremendous cut of the computation time .

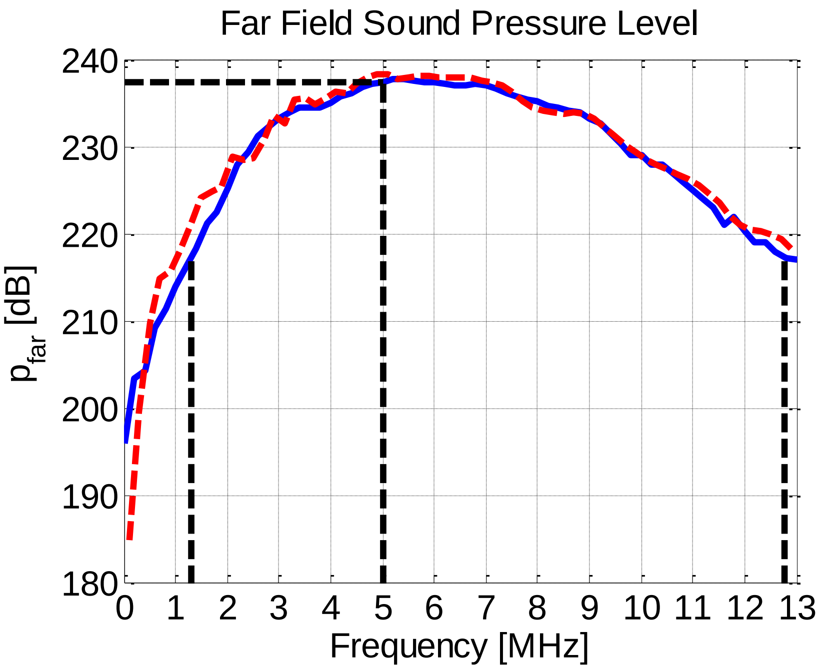
FEM Model in COMSOL

- Transducer COMSOL 2D FEM.
- Red striped block: active piezoelectric element
- Acoustic domain reduced to a small region surrounded by Perfectly Matched Layer (PML), which simulate the zero reflection condition.



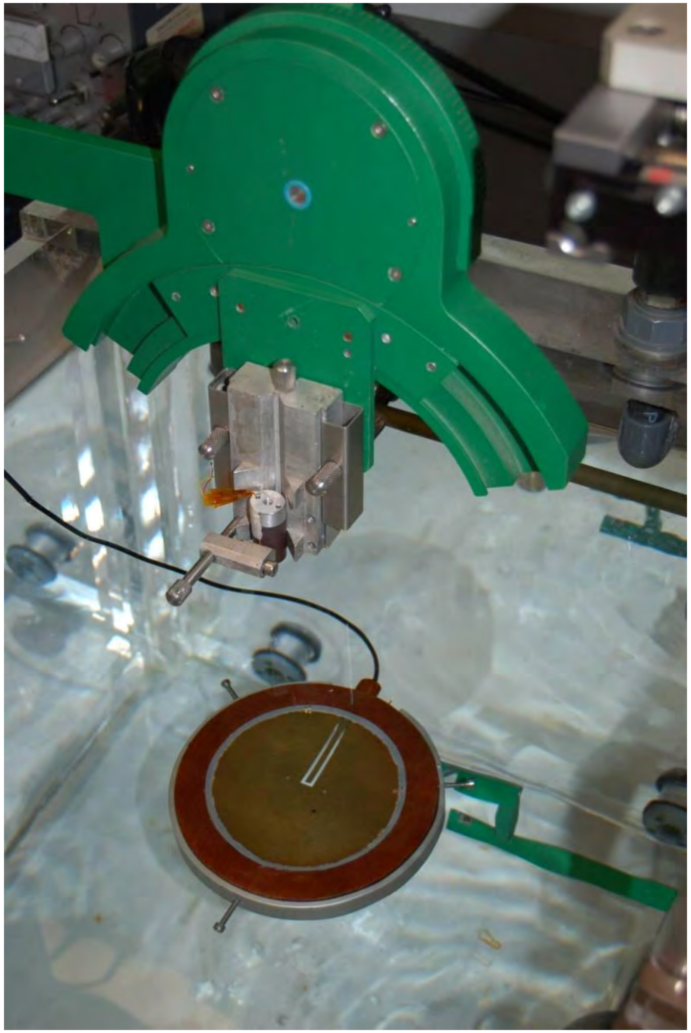
Results: Far field pressure level

- Far field sound pressure level (dB) at a distance of 60 mm from the transducer surface: measured (solid) and simulated (dotted).



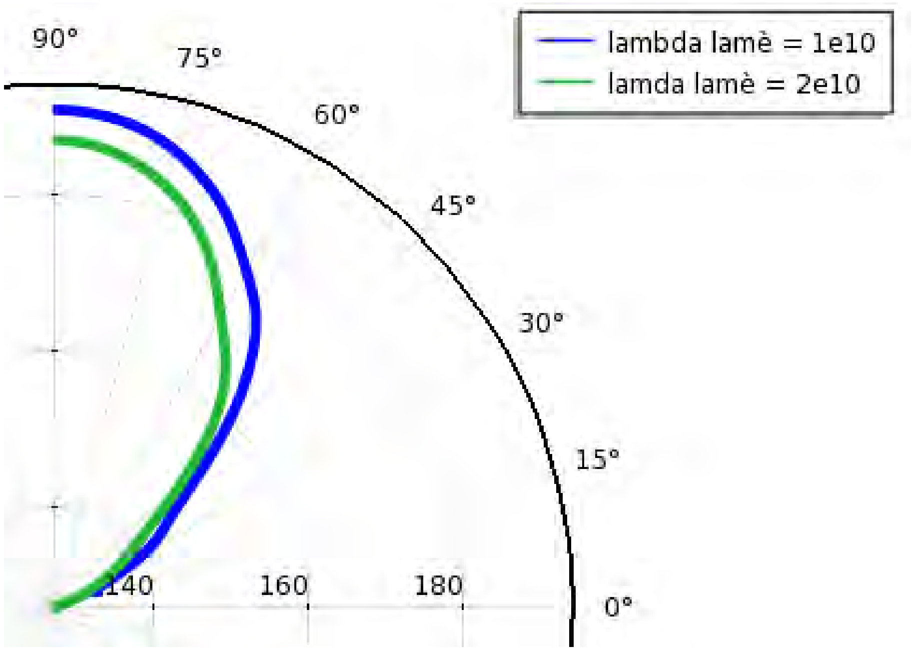
Agreement between FEM simulation and measurements are very good

Far field pressure measurement set-up



Results: Directivity

- Single element study: directivity determines focusing and beam steering capability
- Directivity simulation vs. silicon rubber lens material elasticity

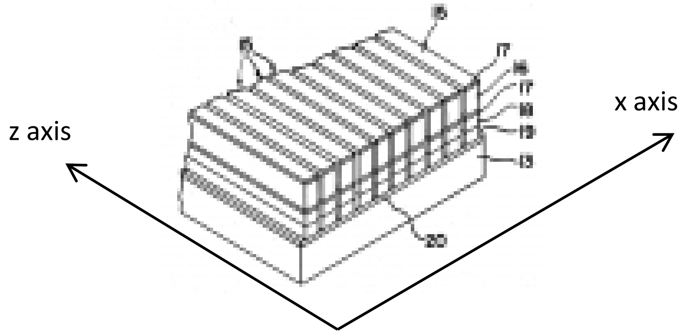


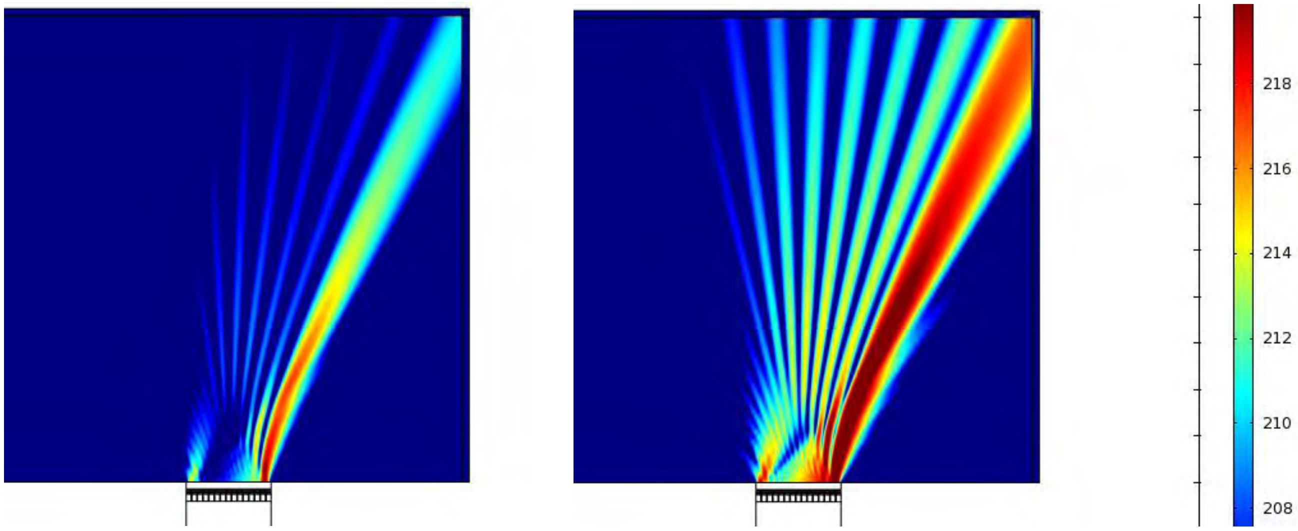
The decrease of probe lens hyperelasticity leads to a larger radiation lobe

Results: Beam stearing capability

- Delay function over x axis

$$\Delta T(x_n) = \frac{2\pi f}{v}\left(y_c - \sqrt{F^2 - (x_n - x_c)^2}\right)$$





Sound pressure level maps: θ = 25° steered beam, F = 20 mm, freq. = 5 MHz, 12 active elements.
Left: Standard silicon lens, Lamè λ = 2 10^{10}. Right: Lower hyperelasticity lens, Lamè λ = 1 10^{10}

Conclusions

Both a mono dimensional electro-acoustical KLM and a 2D FEM model have been used to design an ultrasound linear imaging probe:

- KLM has been used to design the probe matching layer's stack
- FEM has been used for the complete modeling of the probe

Final results for the far field pressure level show a good agreement between measured and simulated performances, thus validating the modeling procedure for the probe

Directivity and "*beam steering*" simulations prove that FEM can greatly help in understanding how probe performances could be improved. For example, it was possible to relate the mechanical properties of the acoustical lens of the probe to its steering capability.

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