Transducers

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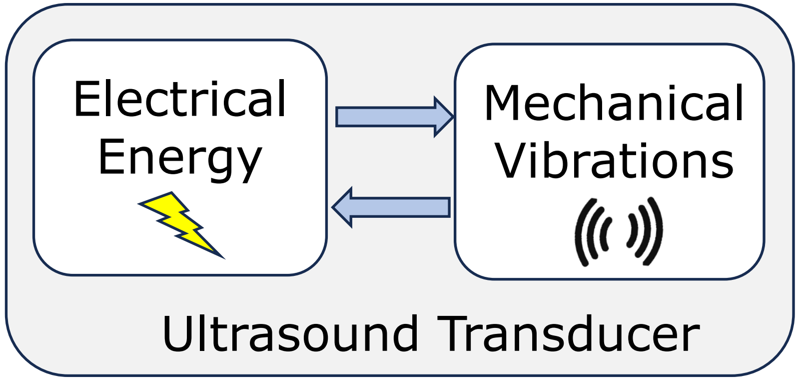
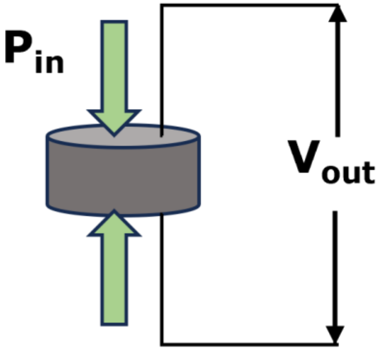
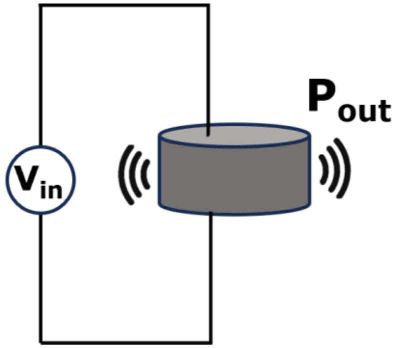
Ultrasound transducers



- The electromechanical conversion based on the piezoelectric/inverse piezoelectric effect



Piezoelectric effect



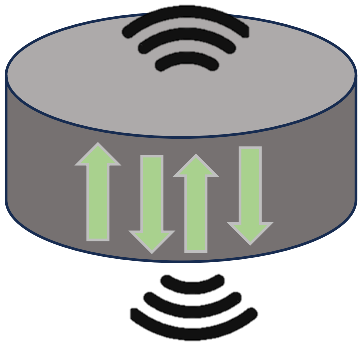
Inverse piezoelectric effect

- Examples: Quartz (natural piezoelectric material), Lead Zirconium Titanate (PZT), PVDF

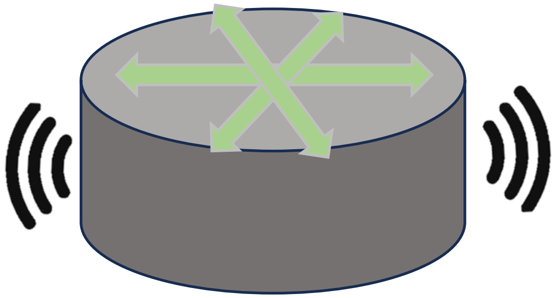
Resonance modes

- Piezoelectric materials are capacitive in nature, and they exhibit resonance at certain frequencies

- Resonance can be **Thickness mode**, or **Radial mode**



Thickness mode resonance



Radial mode resonance

$$Thickness\ mode\ resonant\ frequency = \frac{c_{crystal}}{2 \times thickness}$$

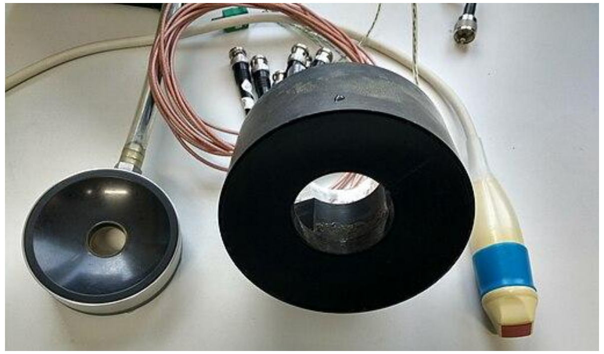
$c_{crystal}$ → speed of sound through the crystal

Transducers

Various types of Ultrasound transducers:

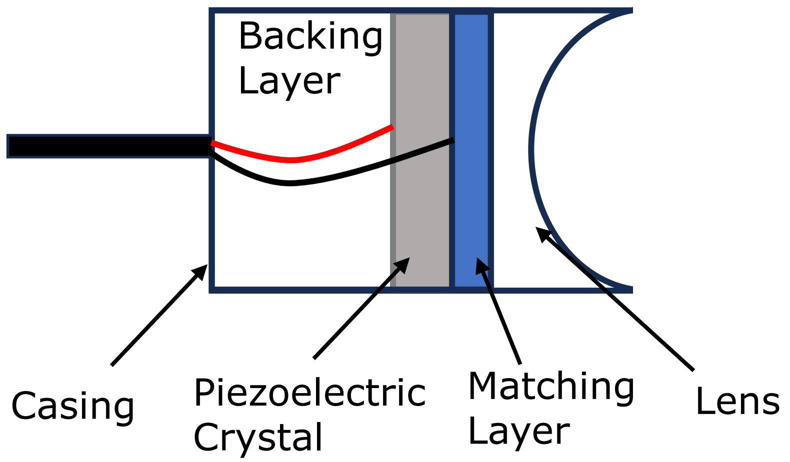
- Single-element transducers
- Linear array transducers
- Curvilinear array transducers
- Phased array transducers

"File:UltrasoundProbe2006a.jpg" by The original uploader was Drickey at English Wikipedia. is licensed under CC BY-SA 2.5.



"HIFU Transducers Compared with Cardiac Imaging Probe" by Chris Adams is licensed under CC BY-SA 4.0.(public domain image)

Single-element transducer



Matching layer: Reduces impedance mismatch between layers and helps in transferring maximum mechanical power.

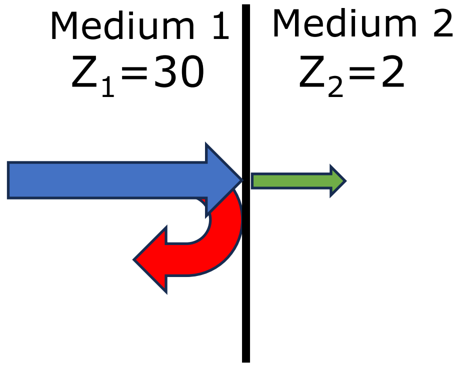
Lens: For focusing the ultrasound waves

Backing Layer: To control ringing in the transducer

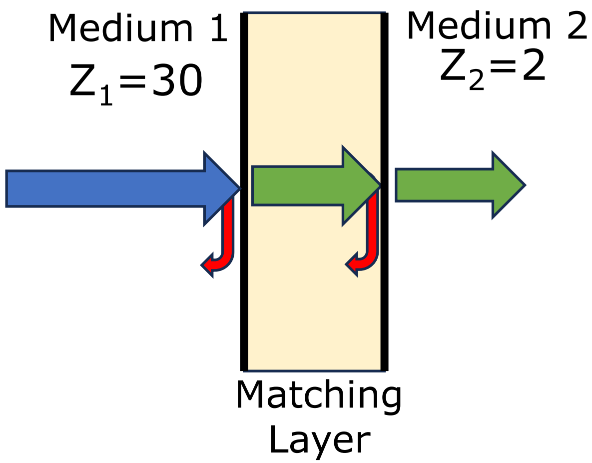
Matching layer

- The acoustic impedance of a PZT is ~30 MRayls, and average acoustic impedance of tissue is ~2 MRayls
- Reflection coefficient at PZT-tissue interface will be large due to impedance mismatch

- A third layer (matching layer) is added in between the two layers for better coupling of acoustic energy



Without matching Layer



With matching Layer

Matching layer

- The impedance of the matching layer is intermediate to the input and output layers
- For perfect matching,

$$Z_{ml} = \sqrt{Z_1 \times Z_2}$$

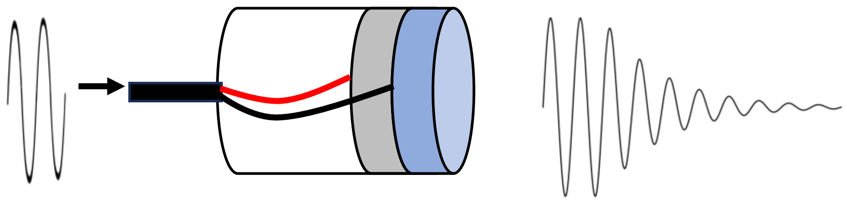
Z_1, and Z_2 are the acoustic impedances of the input and output layers

- Optimum thickness of the matching layer is maintained at $\lambda/4$, or $n\lambda/4$
- Some commonly used materials for matching layer: Alumina-epoxy composite, tungsten-epoxy composite, graphite

Backing layer

- Ultrasound transducers are driven by continuous sinusoids, or short bursts based on application.
- The transducer exhibits ringing behavior at resonance

- For example, if a 2-cycle sine burst is applied to an unbacked transducer, the mechanical oscillation will typically have more than two cycles



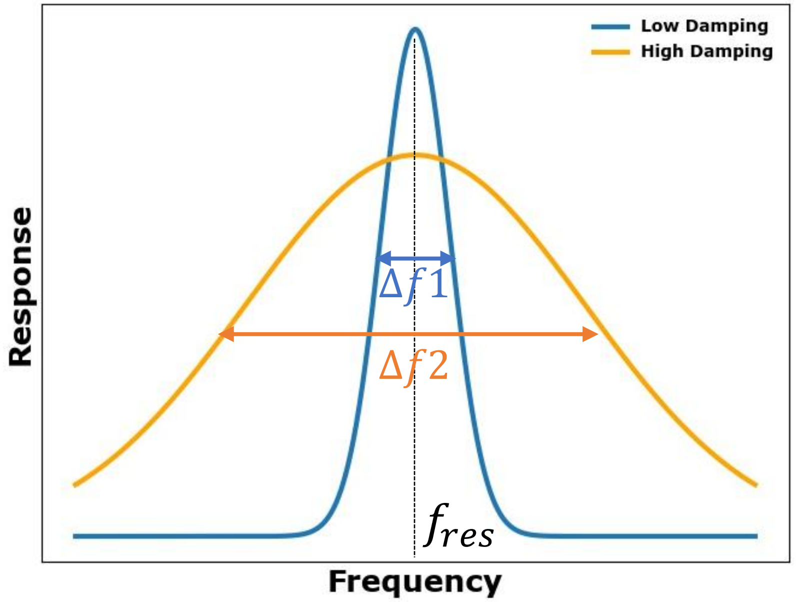
- The extent of ringing can be adjusted by selecting a suitable backing layer.

Backing layer - Damping

For continuous wave applications

- Ringing is acceptable
- No backing/lightly backed transducers
- Transducers have low damping
- Backing material: air

$$Quality\ factor = \frac{f_{res}}{\Delta f}$$

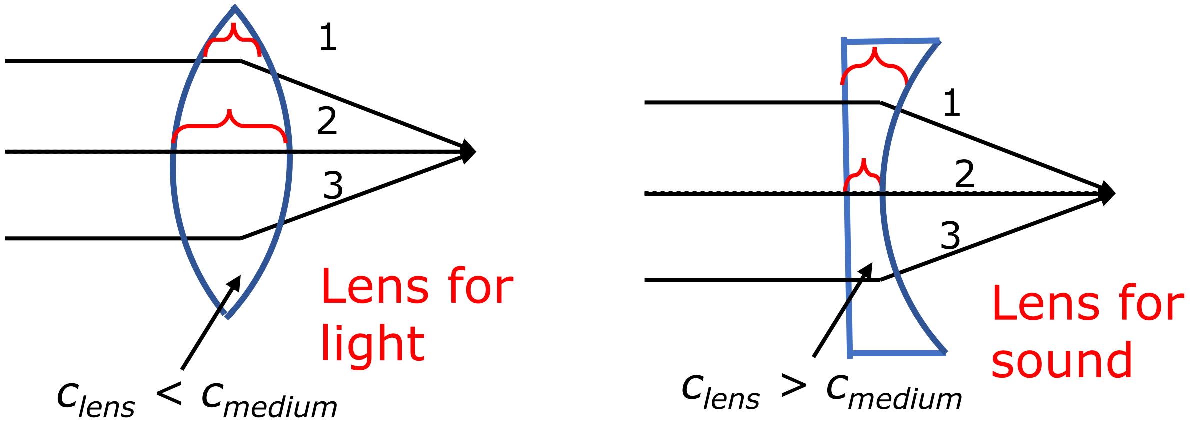


For pulsed wave applications

- Ringing is not preferred
- Heavy backing
- Transducers have high damping
- Backing material: Epoxy/rubber

Lens

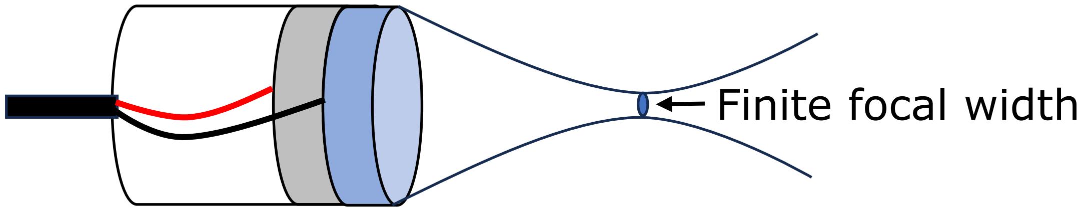
- Lenses are used as the last layer in a transducer to focus ultrasound
- A focused transducer has better lateral resolution and higher focal intensity
- Ultrasound focusing lenses are generally concave in shape, unlike the convex lenses for light

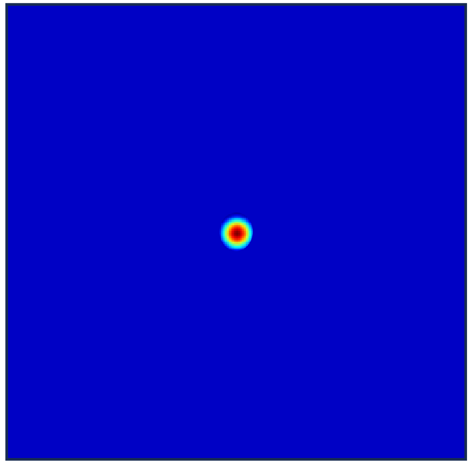


- Waves 1 and 3 travel a larger distance compared to 2 to intersect at the focus
- Hence, these waves travel through the faster lens medium for a longer distance, and hence, the concave shape of the lens

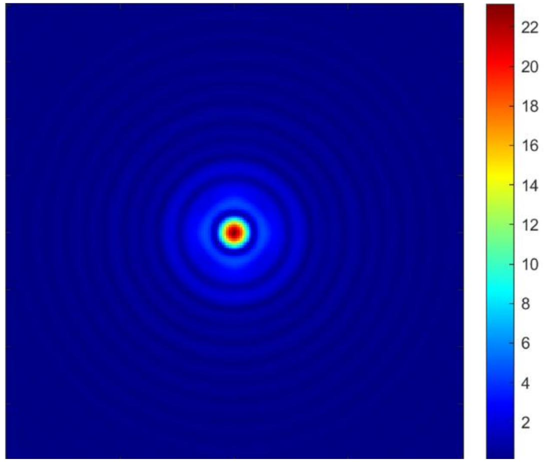
Lens

- Width of beam at focus is directly proportional to the aperture diameter of the transducer
- Focusing on a single point is only applicable if the transducer has infinite aperture
- In practice, the focal width is finite due to the finite length of aperture





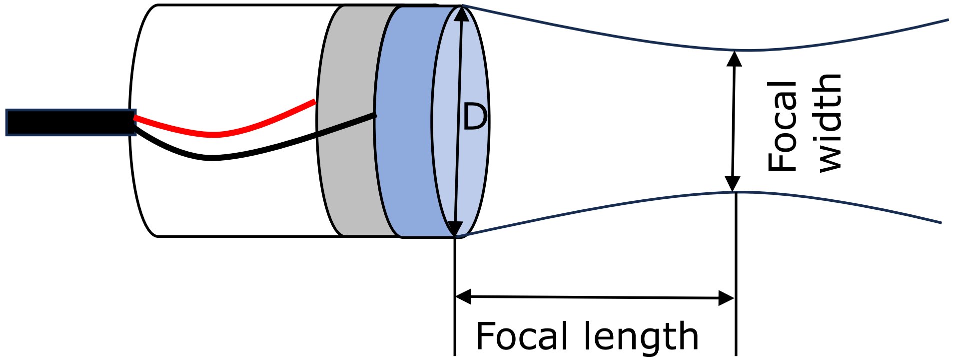
Ideal focusing



Sidelobes in practical focusing

Unfocused transducer

- A transducer without lens/curvature will focus at its natural focus.
- These transducers generally have a larger focal width and focal length, compared to focused transducers



$$Focal\ length = \frac{Aperture\ diameter(D)^2}{4\lambda}$$

(Only for unfocused transducers)

$$Focal\ width = \frac{\lambda \times Focal\ length(d)}{Aperture\ diameter(D)}$$

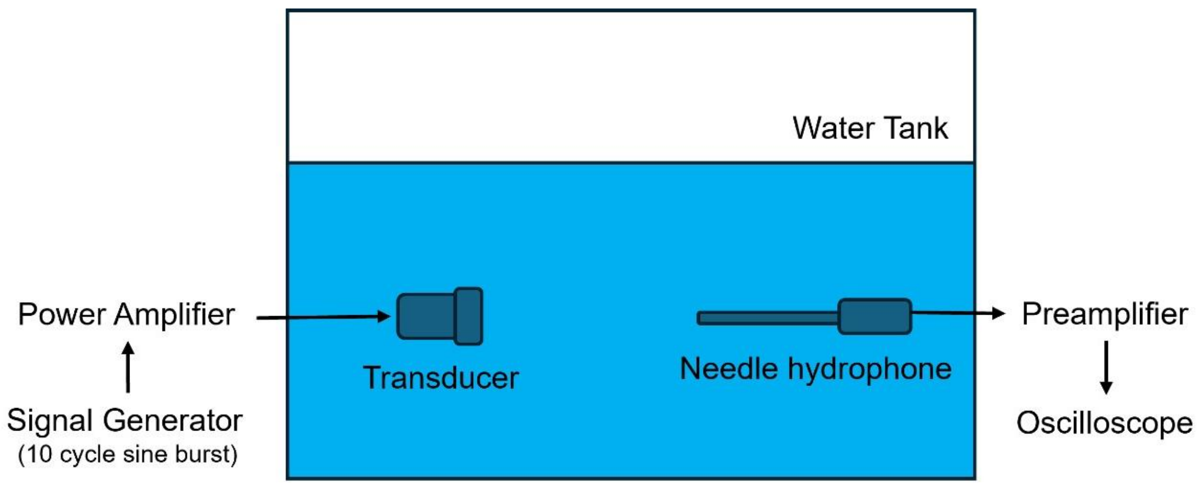
$$f\ number = \frac{Focal\ length(d)}{Aperture\ diameter(D)}$$

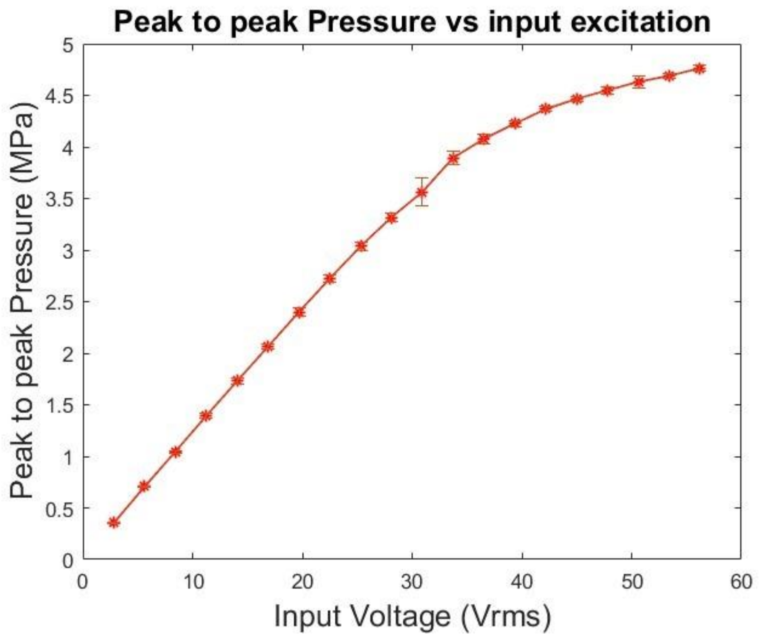
A smaller f-number indicates a tightly focused transducer

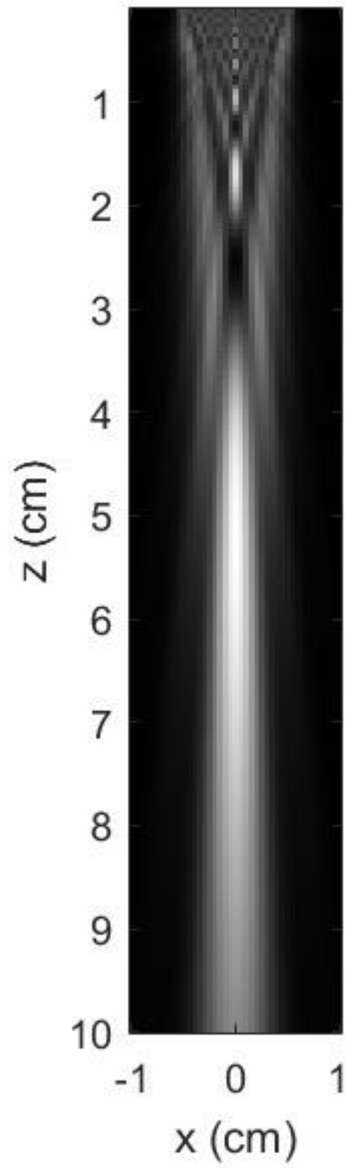
Transducer characterization

- Fabricated transducers are characterized to ensure reliable parameter values
- The axial and lateral pressure and intensity profiles and the pressure outputs
- A pre-calibrated transducer with a small aperture (hydrophone) is used

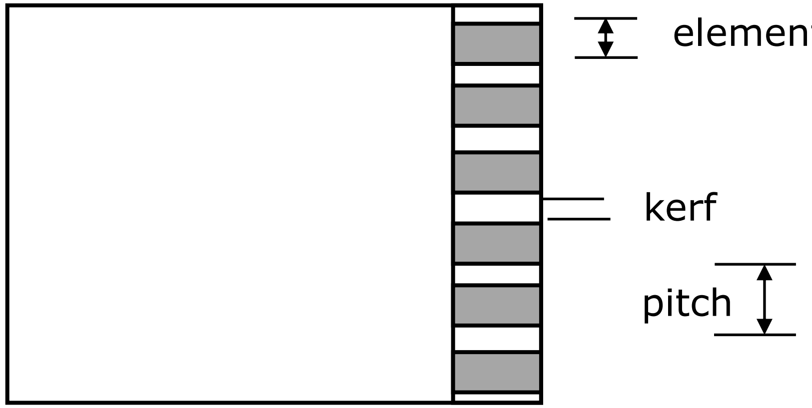
- The hydrophone is moved using manual or motorized linear stages to map the entire beam

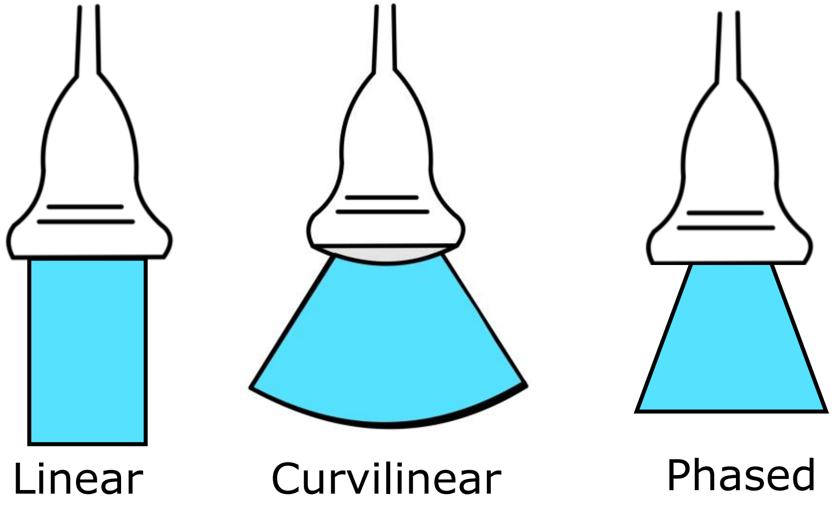






Transducer arrays





- Transducer arrays have multiple single-element crystals and can be electronically scanned to obtain B-mode images

<u>For linear arrays</u>

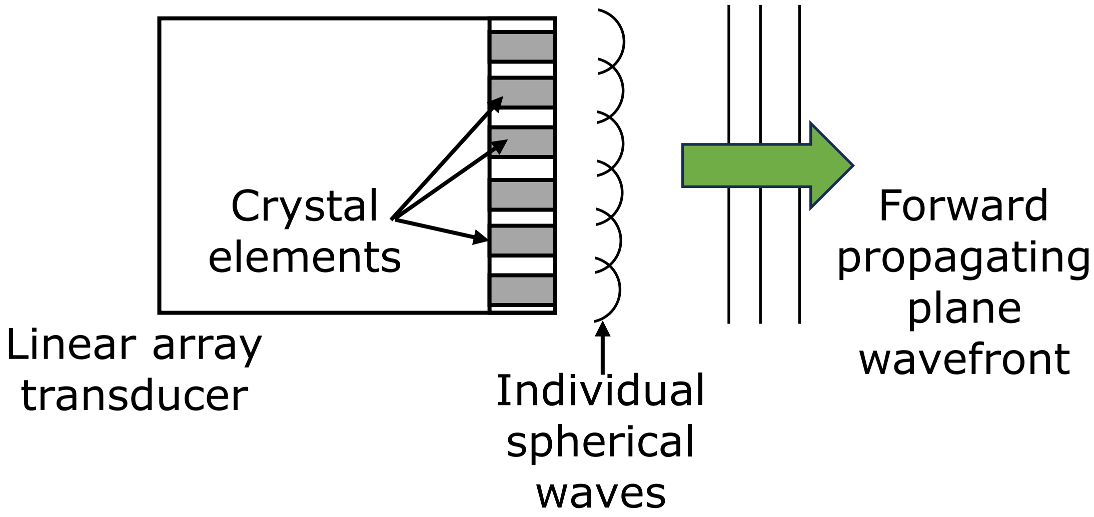
Pitch < λ

<u>For phased arrays</u>

Pitch <$\lambda/2$, for avoiding grating lobes

Transducer arrays

- Linear array transducer: Contain 32, 64, 128, or 256 crystal elements arranged in a row
- Individual elements create a spherical wave when fired
- If all elements are fired together, the individual spherical wavefronts interfere to create a "plane wavefront"



Plane-wave imaging can create images faster, but the lateral resolution is poor due to larger beamwidth

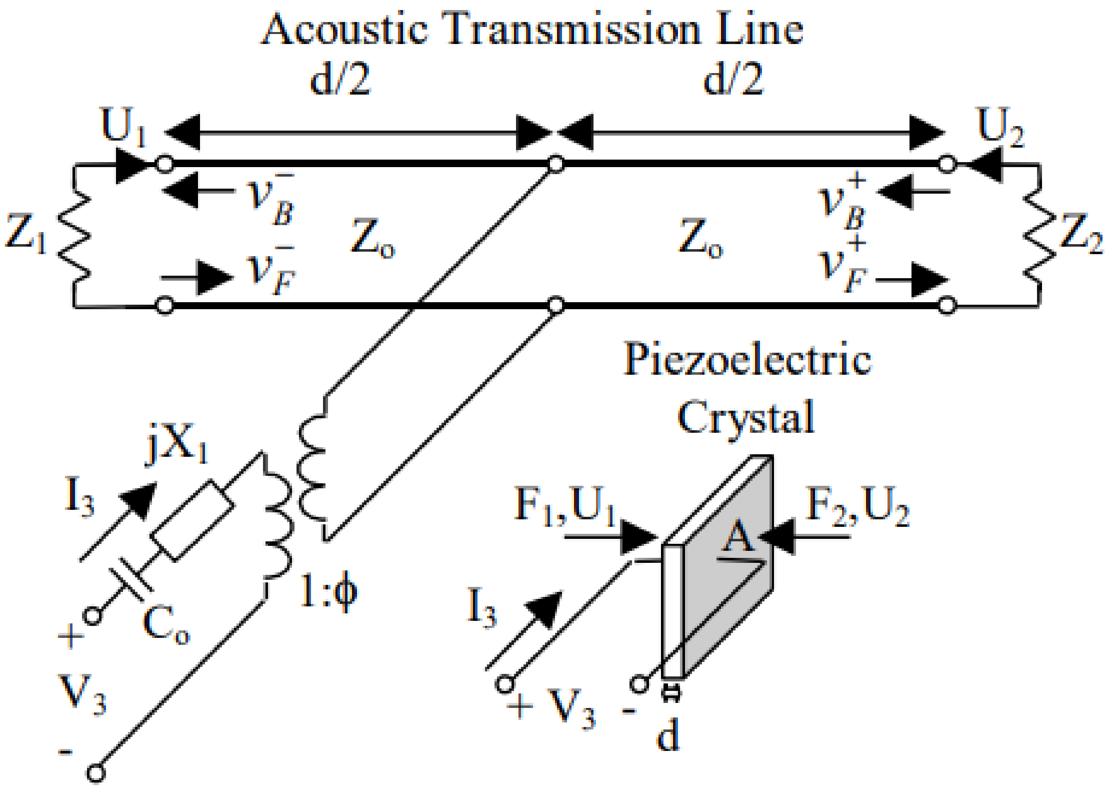
The KLM Model

- **Krimholtz, Leedom, and Matthaei (KLM)** model **-** an equivalent circuit model used to analyze piezoelectric transducers.

- Can model the frequency-dependent pressure radiated by the transducer.
- Helps identify the Resonant frequency of crystals, based on material properties
- Calculate the electrical impedance of transducer→ useful for matching to 50 ohm
- Optimizing the matching and backing layers of a transducer (based on impedance calculations).

The KLM Model

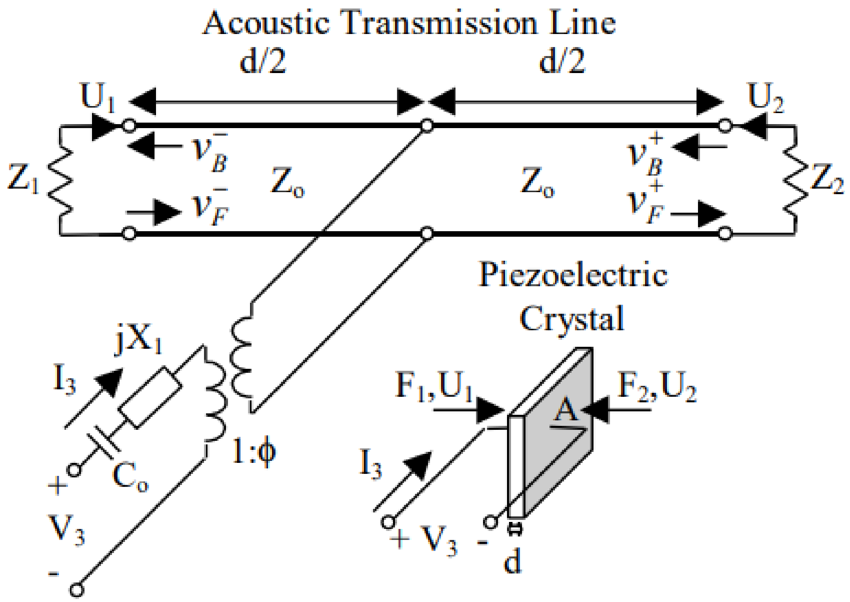
- The KLM model uses a three-port network to model the acoustic and electrical sections of a piezoelectric transducer



- Acoustic modelling is done through a transmission line
- Electrical modelling is done as a coupled transformer

Krimholtz, et al, "New equivalent circuits for elementary piezoelectric transducers," Electron. Lett., vol. 6, no. 13, p. 398, 1970.
Unknown_author, "APPENDIX B: THE KLM MODEL."

The KLM Model



Parameters related to acoustic port

- Z_o – specific acoustic impedance of the crystal
- Z_1 and Z_2 –acoustic impedance of backing and matching layers

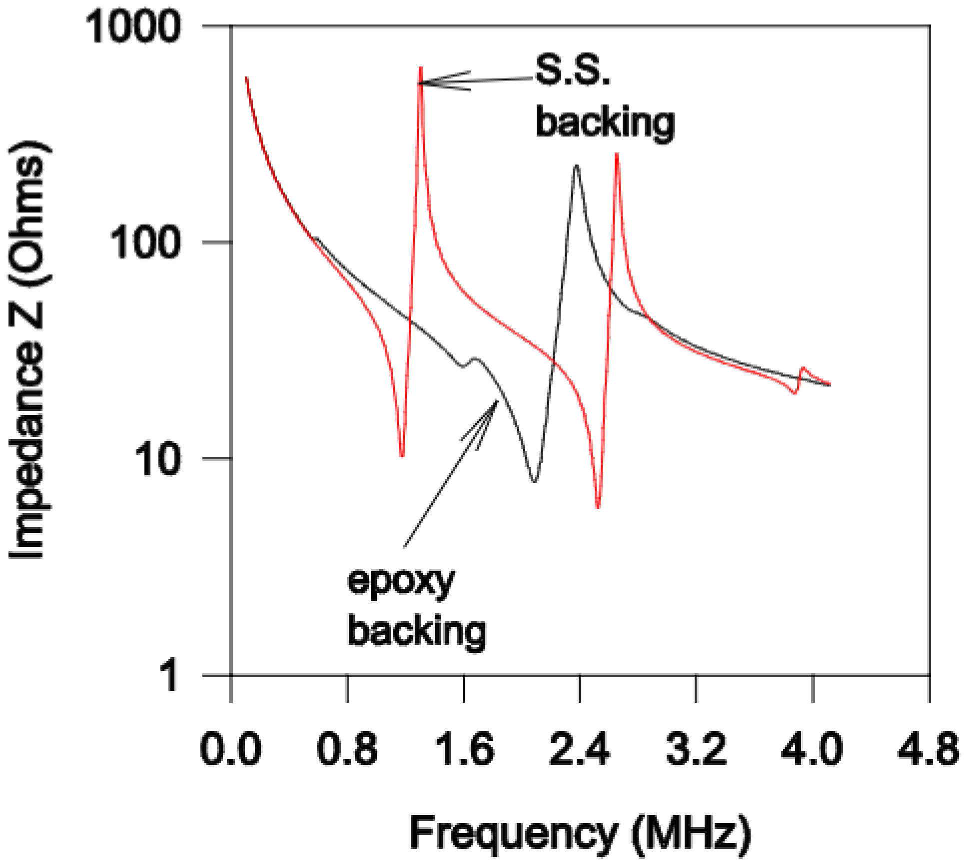
Geometric and other general parameters

- d - thickness of crystal
- A - Area of crystal
- F_1, F_2 radiating acoustic forces
- U_1, U_2 particle velocities on the face
- v_B, v_F particle velocities inside the crystal

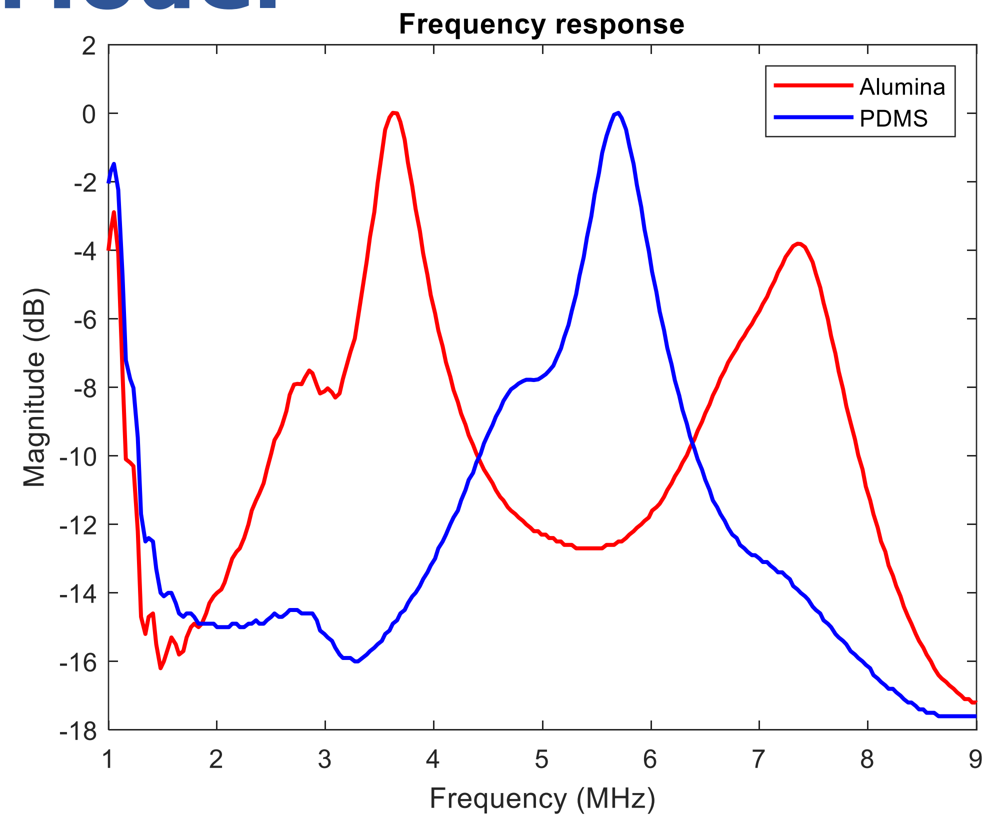
Parameters related to electrical port

- V_3, I_3 –applied voltage and current
- C_o – lumped capacitor
- X_1 – lumped reactance
- Φ – transformation ratio of transformer

The KLM Model



Electrical impedance predicted from KLM model for different backing layers



Frequency response predicted by KLM model for alumina and PDMS as the matching layer

Sherrit, Stewart, and Binu K. Mukherjee. "Characterization of piezoelectric materials for transducers." *arXiv preprint arXiv:0711.2657* (2007).

Simulated using BioSono 2.0

The KLM Model

$$Z_o = \rho c A$$

$$C_o = \frac{\varepsilon A}{d}$$

$$X_1 = \frac{h^2}{\omega^2 Z_o} \sin\left(\frac{\omega \cdot d}{c}\right)$$

$$\phi = \frac{\omega Z_o}{2h} \operatorname{cosec}\left(\frac{\omega \cdot d}{2c}\right)$$

ξ -permittivity of the piezoelectric
h - piezoelectric pressure constant

Material properties

- Input impedance is defined by looking in through the electrical port.

$$Z_{in\_KLM} \cong \left(\frac{1}{j\omega C_o} + \frac{jh^2\pi}{\omega^2 Z_o}\left(1 - \frac{\omega}{\omega_o}\right) + \frac{4h^2}{\omega^2}\frac{1}{Z_1 + Z_2}\right)$$

The input electrical impedance, near resonance

The KLM Model

- The pressure radiated from the surface can be evaluated as:

Pressure radiated outward →

$$P_2(\omega) = \frac{Z_2 V_3(\omega)}{\phi Z_{in\_KLM}} \frac{\left(\Gamma_1 e^{-jkd/2} - e^{jkd/2}\right)}{e^{jkd} - \Gamma_1 \Gamma_2 e^{-jkd}} (1 + \Gamma_2)$$

$$\Gamma_2 = \frac{Z_o - Z_2}{Z_o + Z_2}$$

Where, Γ is the current transmission coefficient

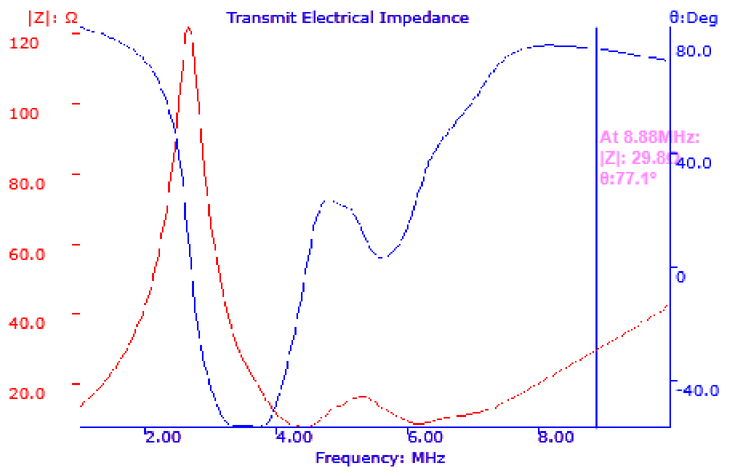
The pressure radiated by any excitation waveform denoted by V(ω) can be evaluated

hands-on "KLM" fun!

https://biosono.com/TrnsLgd20/TrnsLgd.php

BioSono KLM 2.0 [Technical Description]

Graph Window



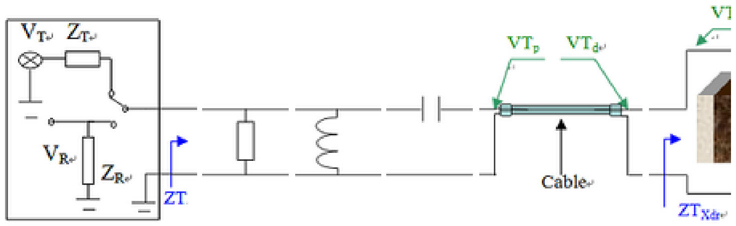
Transmit Electrical Impedance | Z-theta | Calculate | Dsplay Option

View in a New Window | Print

Save the Current Graph Data CSV file, Excel support

Add to Comparison | Help

Simulation Circuit



Proximal Electrical Matching Network:

No.	Connect	Type	Value		
0	Series	C: uF	1.00	Insr	Del
1	Shunt	L: uH	2.00	Insr	Del
2	Shunt	R:ohm	150	Insr	Del

User Name:

Password: Login

Sign Up | Forgot Password

Current Design: Default

Open | Save | Delete

Upload | Download

Input Report | Help

Frequency: MHz

5.00 Center Frequency

1.00 Scan Start Frequency

10.0 Scan Stop Frequency

Please Login to enable frequency input | Help

Output Data:

Impedance: At 5.00MHz

|Z|	θ	Real	Imaginary
14.2Ω	21.8°	13.2Ω	5.29Ω

Recommended Impedance Match Network:

Proximal: Single Inductor Tuning

Distal: Single Inductor Tuning

Backing Layer

No.	Thickness					
B0	1.50 mm	3.75 λ	Insr	Del	Material
B1	4.00 mm	10.0 λ	Insr	Del	Material

Help

Active Material

Thickness

0.392 mm | 0.450 λ | Material

Help

Matching Layer

No.	Thickness				
M0	0.125 mm	0.250 λ	Insr	Del	Material
M1	0.100 mm	0.250 λ	Insr	Del	Material

Help

Summary

- Ultrasound transducers
- Transducer resonance frequencies
- Transducer construction
- Focusing lens and impedance matching
- Transducer arrays – Linear and Phased
- KLM Model

Sets the foundation for image reconstruction