NIH Center for Medical Ultrasonic Transducer Technology

Development of High Frequency Ultrasound Transducers for Medical Imaging

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A NIH Resource Center on Medical Ultrasonic Transducer Technology (UTRC)

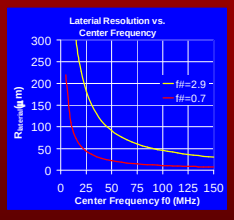
Mission to develop:
- High frequency (>20 MHz) ultrasonic transducers for biomedical applications
- Novel transducer materials (piezoelectric and passive)
- High frequency imaging electronics

Inception: 1997
- NIH/NIBIB funding
- EB002182

Our team:
- Professors Kirk Shung (PI), Jon Cannata (Transducers), Qifa Zhou (Materials), Jesse Yen and Chang-Hong Hu (Electronics)
- Jay Williams (Transducer Engineer), Peter Lee (Finance)
- 2 Post-Docs, 2 Visiting Scholars, 8 Graduate Students

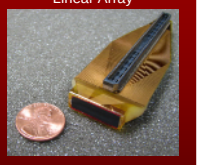
Rationale

Increase ultrasound frequency to improve image resolution
- Comes at a cost of limited penetration depth due to frequency dependent attenuation
- Good access to target tissues are necessary for success



Primary Applications
- Ophthalmology
- Dermatology
- Intravascular studies
- Small animal models

Current High Frequency Ultrasonic Transducers for Medical Imaging

Single Element	Annular Array	Linear Array
		
• Fixed geometric focus • Mechanically scanned to form image	✓ Variable electronic focus • Mechanically scanned to form image	✓ Variable electronic focus ✓ Electronically scanned to form image

Outline

- Traditional Ultrasound Biomicroscope (UBM)
- Single Element Transducers
- UBM Applications
- Annular Arrays
- Linear Arrays
- Future Technologies

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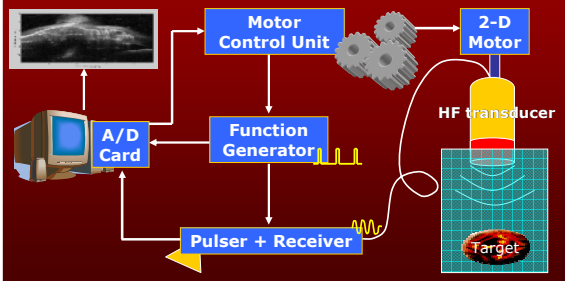
Ultrasonic Biomicroscope (UBM)



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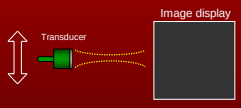
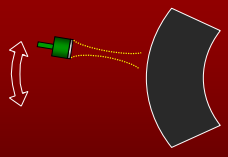
UBM Imaging
(Typical Image Scan Types)

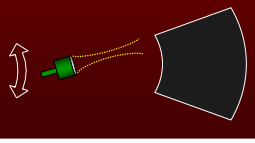
a) Linear Scan



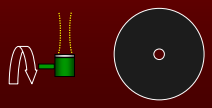
b) Arc Scan



c) Sector Scan



d) Rotational Scan



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Single Element Transducers

1) Standard
   - Linear and Arc Scanning
2) Light-weight
   - High Frame Rate Sector Scanner
3) Catheter
   - Rotational Scanning (IVUS)

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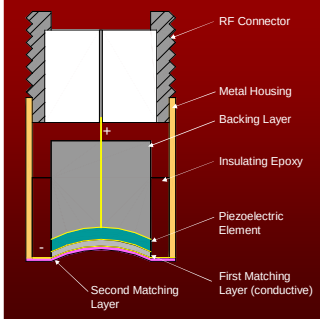
Typical Single Element Transducer



Major Components

- Piezoelectric Element
  - Convert electrical signals to mechanical/acoustical signals and vise versa
- Matching Layers
  - Acoustically match piezo-element to load medium (soft-tissue)
- Backing Layer
  - Provide rigid support to piezo-element and attenuate sound

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Choosing a Piezoelectric for…

Large Aperture Transducers (Single Element)

- Low Dielectric Permittivity ($\varepsilon_{33}^S/\varepsilon_0$)
  - For electrical impedance (Z_E) matching (large element area)
- High k_{ij} (Electro-mechanical Coupling Coefficient)
  - Improvement in bandwidth/resolution and image SNR
- Low Acoustic Impedance
  - To match the impedance of soft tissue (~1.5 MRayls)

Small Aperture Transducers (Array Elements)

- High Dielectric Permittivity ($\varepsilon_{33}^S/\varepsilon_0$)
- High k_{ij} and Low Acoustic Impedance

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Piezoelectric Materials for UBM Transducers

Material	$\varepsilon_{33}^S/\varepsilon_0$	k_t	Acoustic Impedance
P(VDF-TrFE) piezo-polymer	6-9	~0.30	4 MRayls
$LiNbO_3$ (36° Y cut) single cystal	40	0.49	34 MRayls
$PbTiO_3$ piezo-ceramic	200	0.50	36 MRayls
PMN-33%PT single crystal 1-3 composite*	500	0.71	20 MRayls
PZT-5H piezo-ceramic	1400	0.51	36 MRayls

* Ref: Yuan J.R., Jiang X., Cao P.J., Sadaka A., Bautista R., Snook K., Rehrig P.W., "High frequency piezo composites microfabricated ultrasound transducers for intravascular imaging, Proceed. of the 2006 IEEE Ultrason. Symp., pp. 264-268.

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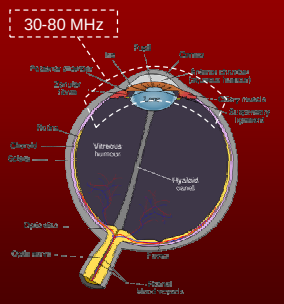
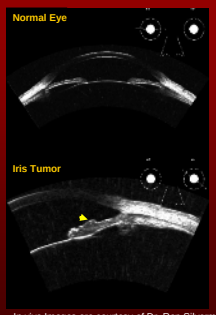
UBM Applications: Ophthalmology



Arc scan image @ 50 MHz



In vivo Images are courtesy of Dr. Ron Silverman at Weill Medical College at Cornell University

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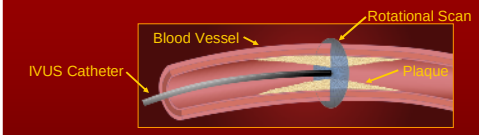
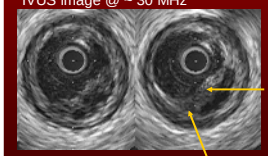
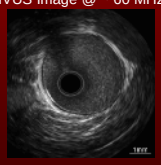
UBM Applications: Intravascular Ultrasound (IVUS)



IVUS image @ ~ 30 MHz



IVUS Image @ ~ 60 MHz



Images are from www.bostonscientific.com

UBM Applications: Small Animal Imaging

Mice, rats, zebrafish, chick embryos are good models for study of…

- Developmental Biology
- Cancer Biology
- Neurobiology
- Cardiovascular Disease

Need

- Real-time high resolution non-invasive imaging at low cost

Visualsonics Vevo 770 Sector Scanner

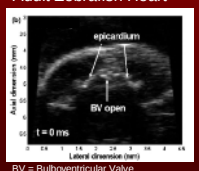
Mouse Embryo

www.visualsonics.com

USC-UTRC/Capistrano Labs High Frame Rate Sector Scanner

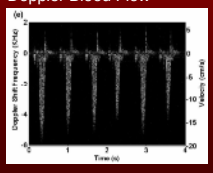
- Cap. Labs. scan-head and motor controller
- UTRC lightweight transducer
  - $LiNbO_3$-based , (<.3 grams)
- UTRC imaging electronics and software
- Frame rate up to 130 fps (one-way scanning)

Adult Zebrafish Heart



BV = Bulboventricular Valve

Doppler Blood Flow



Ref: Sun L., Lien C.-L., Xu X., Shung K.K., "In vivo cardiac imaging of adult zebrafish using high frequency ultrasound (45-75 MHz)", *Ultrasound in Medicine and Biology*, vol. 34, no. 1, pp. 31-39, (2008)

UBM Improvements Needed

Needs
- ↑ Depth of Field
  - Quantitative measurements of structures
- ↑ Frame Rate
  - Cardiac Imaging
- Color Doppler Blood Flow Visualization

Solutions
- High Frequency Annular and Linear Arrays

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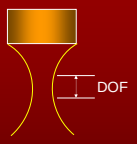
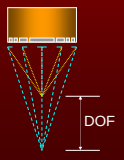
Annular Arrays Improve Image Depth of Field (DOF)

Single Element Transducer
- Fixed focus and limited image DOF



Annular Array
- Electronic beamforming for a movable focus and enlarged DOF



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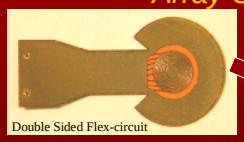
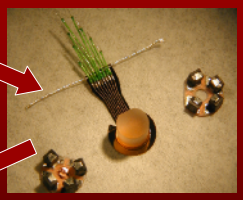
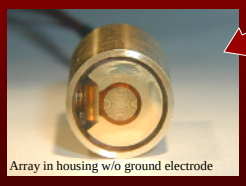
P(VDF-TrFE) Annular Array Construction


Double Sided Flex-circuit




Array in housing w/o ground electrode

Performance
- 8 Elements
- 55 MHz, 47% bandwidth (-6dB)
- 34 dB insertion loss
- -26 dB max crosstalk

Ref: Gottlieb E.J., Cannata J.M., Hu C.-H., Shung K.K., "Development of a high-frequency (>50 MHz) copolymer annular-array, ultrasound transducer", *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 53, no. 5, pp. 1037-1045, (2006)

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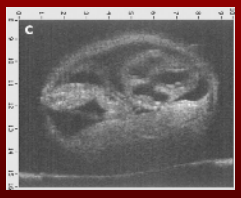
Mouse Embryo Images with a 40 MHz Annular Array

Fixed Transmit/Receive Focus



Fixed Transmit/Dynamic Rx Focus

Ref: Aristizábal O., Turnbull D.H., Ketterling J.A., "Mouse embryo imaging with a 40 MHz annular array", *Proceedings of the 2005 IEEE Ultrasonics Symposium*, pp. 361-364.

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High Frequency Linear Arrays

- Allow for higher image frame rates over single element or annular array systems
  - Electronic vs. mechanical scanning
- Clinical convenience
  - Lack movable parts that can be patient hazards
- Fabrication difficulties and cost are limiting factors in widespread use

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HF Linear Array Design Challenges

- Suppression of grating lobes (1λ element spacing)

30 MHz	50 µm
50 MHz	30 µm
70 MHz	22 µm

- Suppression of electrical and acoustical crosstalk
  - Element separation and electrical shielding are very important
- Electrical impedance matching the small array elements to the 50 Ω send/receive electronics

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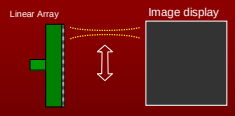
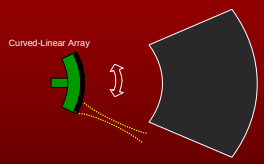
UBM Array Imaging
(Typical Image Scan Types)

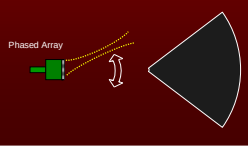
a) Linear Scan



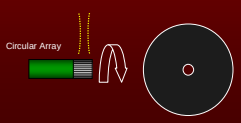
b) Sector Scan



c) Sector Scan 2



d) Rotational Scan



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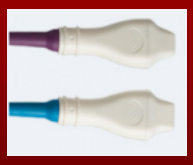
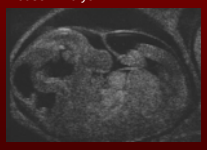
Visualsonics Vevo 2100
Linear Array System

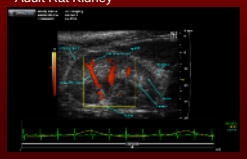


- Linear Arrays ranging from 20-50 MHz
  - 1.5 λ spacing
- Up to 1000 fps
- Color and Power Doppler blood flow analysis

Mouse Embryo



Adult Rat Kidney



www.visualsonics.com

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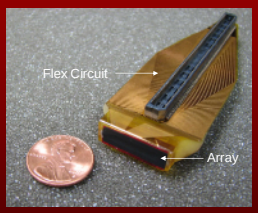
256-Element 30 MHz Linear Array

Design Components

- Element spacing: 50µm (1λ)
  - Image footprint: 9.6 mm with 64-channel beam-former
- 1-3 composite element
- Elevation width: 2mm
  - Self focused (f#=4)



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Future Technologies

- At the UTRC
  - 20 MHz curved-linear and 30 MHz phased arrays for sector imaging
  - 40 MHz annular-array-based sector scanner
  - 100 + MHz transducers/arrays for cellular imaging
- 2D Arrays for Volumetric Imaging
  - Silicon-based CMUT arrays
  - Integrated electronics
- Multi-modality Transducers/Arrays
  - UBM + Photoacoustic
  - UBM + Fluorescence Spectroscopy
  - UBM + Therapy

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NIH Center for Medical Ultrasonic Transducer Technology

Thank you for your attention!

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Appendix

- Further Information

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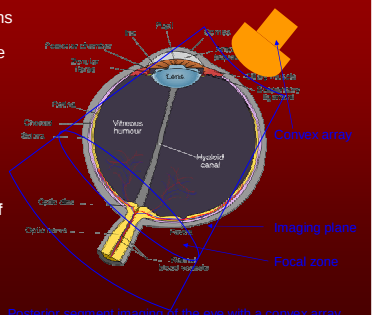
20MHz Convex Array Transducers

- For imaging small organs near the skin (e.g. posterior segment of the eye)
- **Wider view angle** than linear arrays with the same number of elements
- Larger pitch i.e. **ease of fabrication** and **better image quality at sides** than phased arrays



Posterior segment imaging of the eye with a convex array

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Finer Pitch Linear Arrays

Development Plan

- 30 MHz Phased- and 50 MHz Linear-Arrays
  - 30 µm pitch with up to 128 elements

Challenge

- Pattern finely spaced electrodes over 2-2 and/or 1-3 composites
  - Photolithography, laser, or…?

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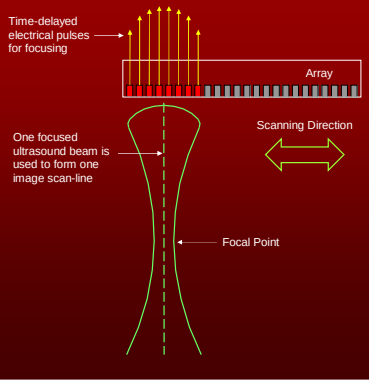
Linear Array Imaging



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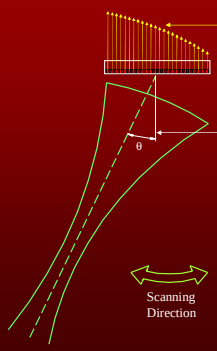
Phased Array Imaging



Electrical pulse are sent to all elements with time delays for focusing and steering

Sector scanning is achieved electronically by varying the steering angle θ

Scanning Direction

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HF Annular Arrays

Development Plan

- 40+ MHz Arrays for high frame rate sector imaging
  - 1-3 composite arrays in lightweight assemblies

LW Single Element TDS (<0.3 grams)

Concept: LW Annular Array

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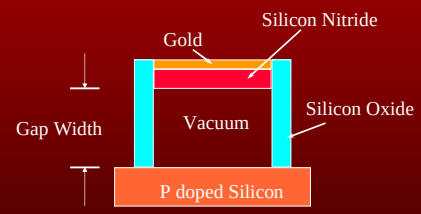
CMUT Transducers



Gap width ~ sensitivity, Sensitivity increases as gap width decreases

Resonant frequency is determined by membrane elasticity

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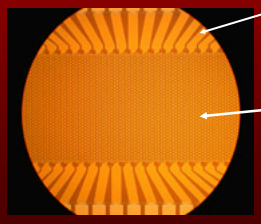
CMUT Linear Array



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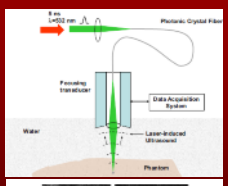
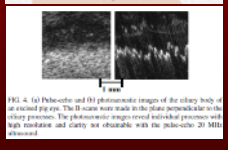
High Resolution Photoacoustic Imaging (R. Silverman)

High-resolution photoacoustic imaging with focused laser and ultrasonic beams





USC's Contribution

- Focused Ring Transducer development
  - 20 MHz
  - OD: 10 mm
  - ID: 5 mm
  - Focus: 30 mm

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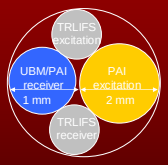
Multi-Modality Imaging of Atherosclerotic Plaques (L. Marcu)

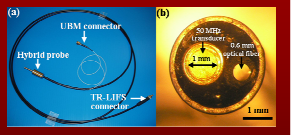
Ultimate Goal

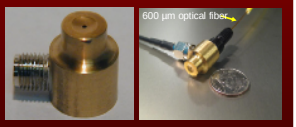
- Combine UBM, PAI (Photoacoustic Imaging) and TR-LIFS (Time Resolved Light Induced Fluorescence Spectroscopy) in a single probe



Multi-Modal Devices built in 2008

- Side-by-side Transducer for 50 MHz UBM + TR-LIFS or UBM + PAI
- 50 MHz Ring Transducer for UBM + TR-LIFS or UBM + PAI





Preliminary PAI Ring Transducer Results


Development of a Multi modal Tissue Diagnostic System Combining High Frequency Ultrasound and Photoacoustic Imaging with Lifetime Fluorescence Spectroscopy

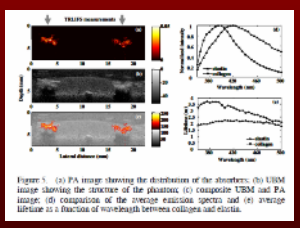
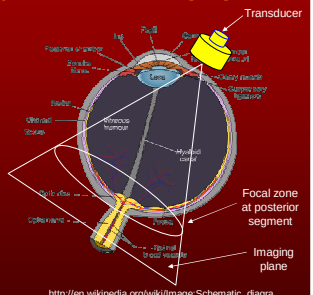


Figure 5. (a) PA image showing the distribution of the absorbers; (b) UBM image showing the structure of the phantom; (c) composite UBM and PA images; (d) comparison of the average emission spectra and (e) average lifetime as a function of wavelength between collagen and elastin.

Dual Element Transducers for High Frequency Harmonic Imaging

Imaging the posterior segment of the eye

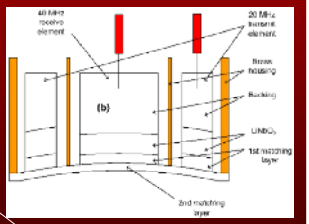
- High frequency harmonic imaging with 20 MHz transmit and 40 MHz receive elements
  - 20 MHz single element: better spatial resolution desired
  - 30 - 40 MHz single element: more penetration desired
- 20 MHz / 40 MHz dual element, harmonic imaging: improved spatial resolution and deeper penetration can be achieved?



http://en.wikipedia.org/wiki/Image:Schematic_diagram_of_the_human_eye_with_English_annotations.svg

Structure of Dual Element Transducers

The inner circular element: 40 MHz receive



The outer ring element: 20 MHz transmit

Concentric annular type, Dual element

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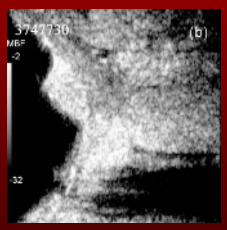
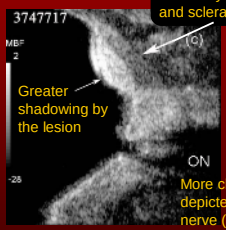
Clinical Images: Single vs. Dual
(Courtesy of Ron Silverman)





Improved depiction of the overlying retina and scleral border

Greater shadowing by the lesion

More clearly depicted optic nerve (ON) cup

Single

Dual

Ref: H. H. Kim, J. M. Cannata, R. Liu, J. H. Chang, R. H. Silverman, and K. K. Shung, "20 MHz / 40 MHz dual element transducers for high frequency harmonic imaging," accepted to *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, 2008.

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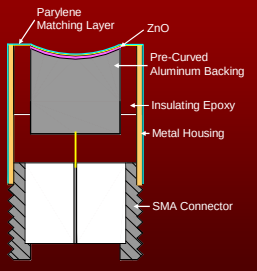
100 MHz Sputtered ZnO Transducers



Design

- ZnO is sputtered directly on a pre-curved aluminum backing layer
- Two Device Geometries
  - 2mm Aperture, f#=1
  - 3mm Aperture, f#=1

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ZnO Film Deposition

- MRC (Mat. Res. Corp.) 822 Sputtersphere
  - ~300 °C operating temp.
  - ~0.5 µm/hr deposition rate
  - 50 % O_2 and 50 % Ar @ 10 mTorr
  - 230 W RF-Power

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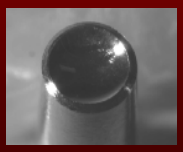
Al Backing Preparation

1. Machined Al Rod

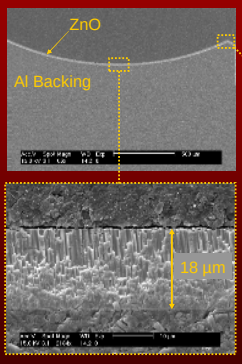
2. Lap/Polish Flat End

3. Press Spherical Shape

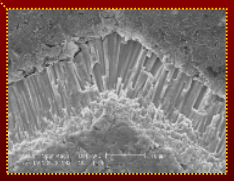
4. Machine to Final Dimensions



ZnO Film



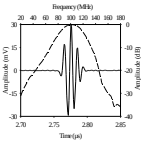
Note: Crystal growth is perpendicular to Al surface



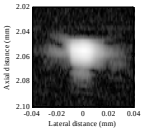
ZnO TD Performance

Transducer #	Aperture (mm)	CF (MHz)	-6 dB BW (%)	IL (dB)	Axial/Lat. Resolution -6dB (µm)
1	2	107	43	45	14.4/16.7
2	2	101	49	44	-
3	2	105	51	47	-
4	3	96	42	42	-
5	2	106	46	41	-

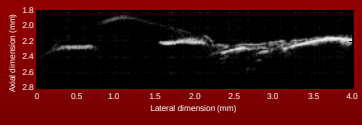
Echo Response: TD #2

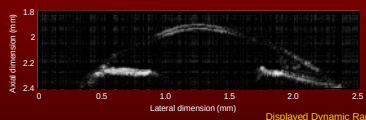


Wire Phantom Image: TD #1



Zebrafish Eye Images 2mm dia. TD (#1)





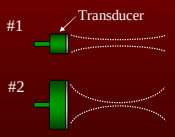
Displayed Dynamic Range: 45 dB

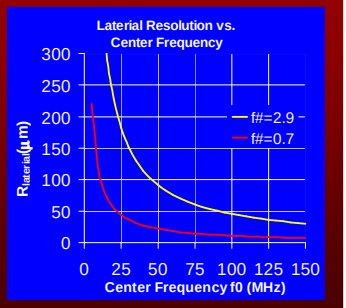
Ref: Cannata J., Williams J., Zhou Q., Yu H., Sun L., Kim E.S., Shung K.K., "Self-Focused ZnO Transducers for Ultrasonic Biomicroscopy", *Journal of Applied Physics*, Accepted Feb. 2008.

Spatial Resolution (I)

Lateral Resolution:

- -3dB or -6dB beamwidth for a transducer
- $R_{lateral} \sim f\#\cdot\lambda$
  - f# = Aperture/Focal Length





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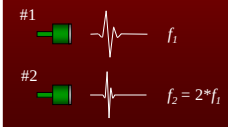
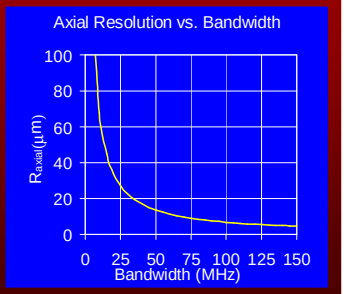
Spatial Resolution (II)

Axial Resolution:

- R_{axial} = Pulse duration ~ 1/Bandwidth





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Attenuation in Tissue at High Frequencies

At 50 MHz

- $\alpha_{blood} \approx 2.5$ dB/mm
- $\alpha_{cornea} \approx 1.1$ dB/mm
- $\alpha_{iris} \approx 1.7$ dB/mm
- $\alpha_{skin} \approx 10$ dB/mm

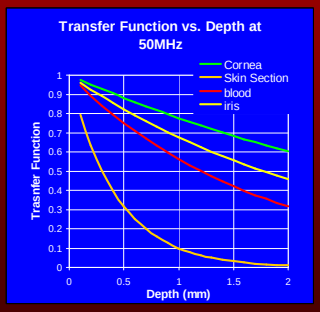

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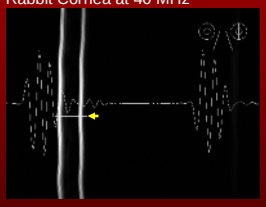
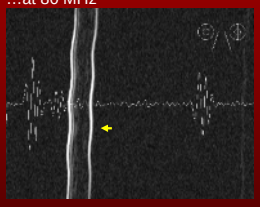
Image Resolution versus Depth-of-Penetration

Rabbit Cornea at 40 MHz



- Only front and back surfaces of cornea are visible

...at 80 MHz



- Better delineation of cell layers, but SNR is worse

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