High Resolution Ultrasound Transducers and Arrays for Medical Imaging Applications

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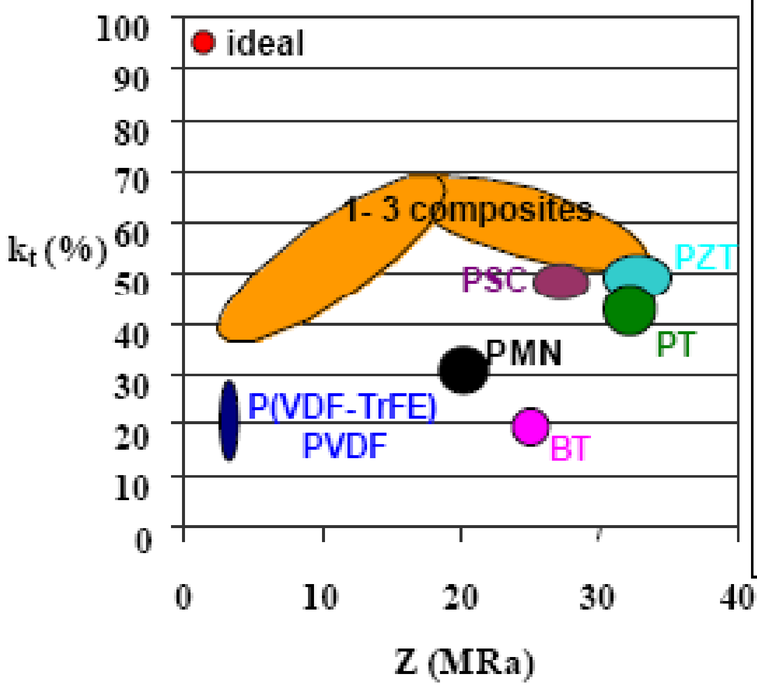
Outline

- Introduction
- Fabrication of high frequency piezocomposites and arrays
- Single element transducers
- Process improvements for HFUS arrays
- Array transducers
- Summary, commercial prospects and ongoing work

Introduction

Piezoelectric material selection



PZT: Lead zirconate titanate (types 100, 200, 300, 500, 600)
PT: Lead titanate (type 700)
PMN: Lead metaniobate (type 800)
PVDF : Polymer
P(VDF-TrFE) : Copolymer
BT : Bismuth titanate
PSC : Piezoelectric single crystals
1-3 composites : PZT and polymer.

- No available material combines a high coupling and a low acoustic impedance
- A good trade off is obtained from 1-3 piezocomposites

Levassort et al http://www.sea-acustica.es/Sevilla02/ult04010.pdf

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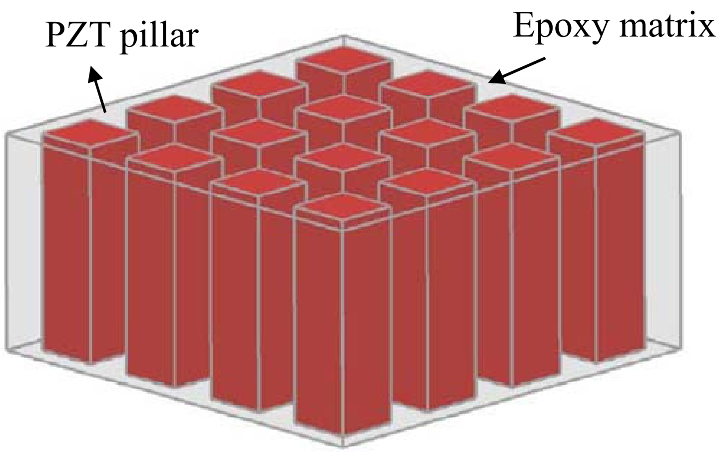
1-3 piezocomposites

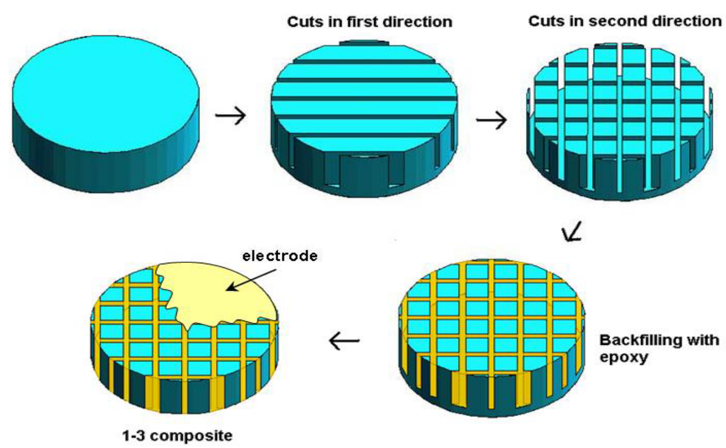


1-3 piezocomposite

Dimension requirements

Frequency	20 MHz	40 MHz
Pillar width	24 µm	14 µm
Kerf	20 µm	8 µm
Thickness	80 µm	40 µm

- Piezocomposites made almost exclusively by the dice-and-fill technique for f<20MHz
- Impossible to fabricate high frequency arrays by dice and fill because of the ultrafine feature size required.



Conventional dice-and-fill technique

High Frequency Ultrasound (HFUS)

- HFUS offers high spatial resolution (< 100 μm).
- Important clinical applications such as dermatology, ophthalmology, small parts imaging, oncology diagnosis and monitoring, intravascular ultrasound and dentistry.
- The development of miniaturised transducer arrays is critical to the successful adoption of HFUS systems.
- For example, a 50 MHz linear array specification:
  - Imaging wavelength: 30 μm,
  - Element pitch: 30 μm
  - Piezoelectric composite substrate thickness: 40 μm.
- Advances in fabrication techniques are needed.

A New Fabrication Concept

- New scalable and mask-based approach to device fabrication suitable for high frequency US arrays.
- Micromoulding for fine-scale 1-3 piezoelectric composites.
- Photolithographic definition of array elements on the composite substrates.
- High density interconnect and packaging solutions.
- Design approaches and fabrication processes that have the potential to produce arrays operating up to 100 MHz.
- Quantity scale-up via wafer-based routes leading to cost effective transducers.

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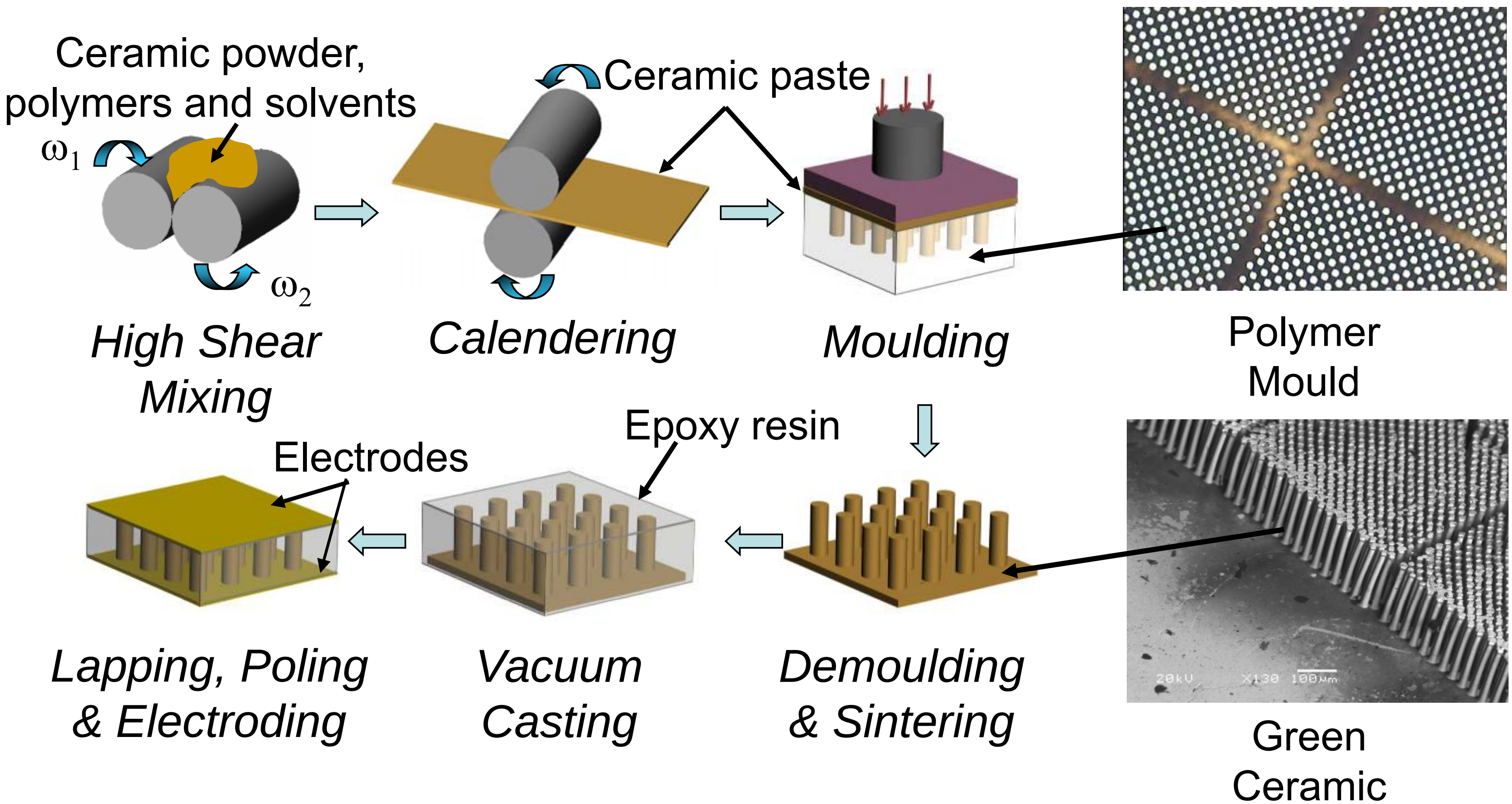
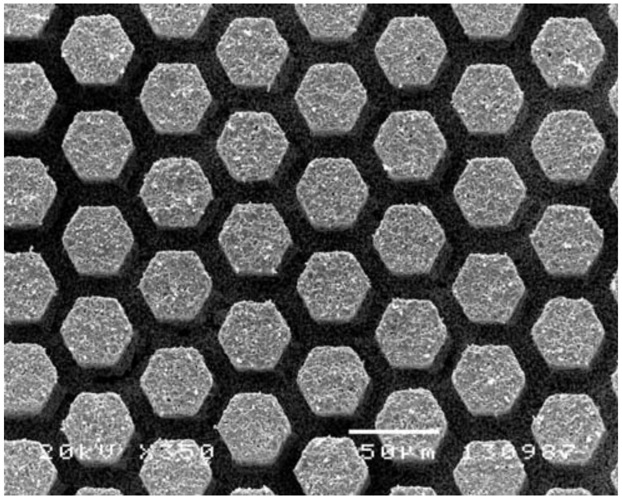
Composite Fabrication

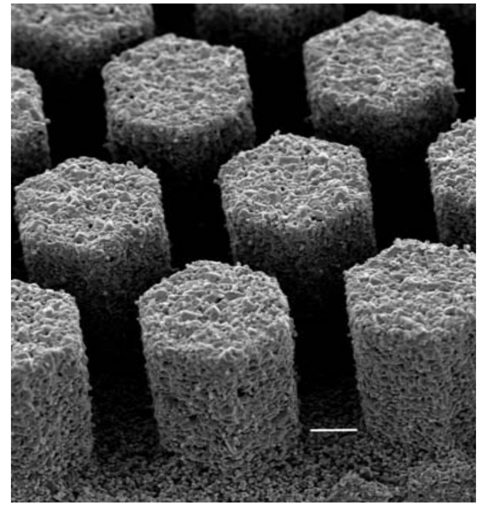
Fabrication of high frequency composites

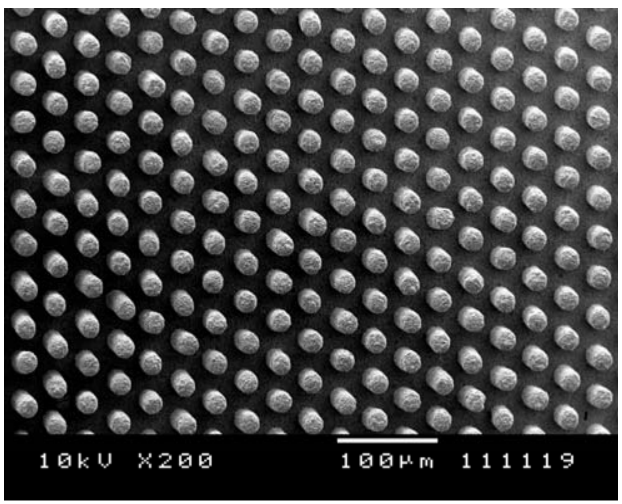
Viscous Polymer Processing - VPP

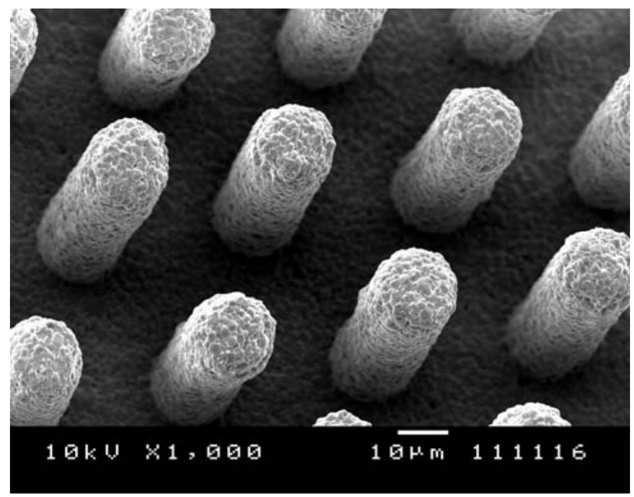


Micropillar Structures fabricated by VPP









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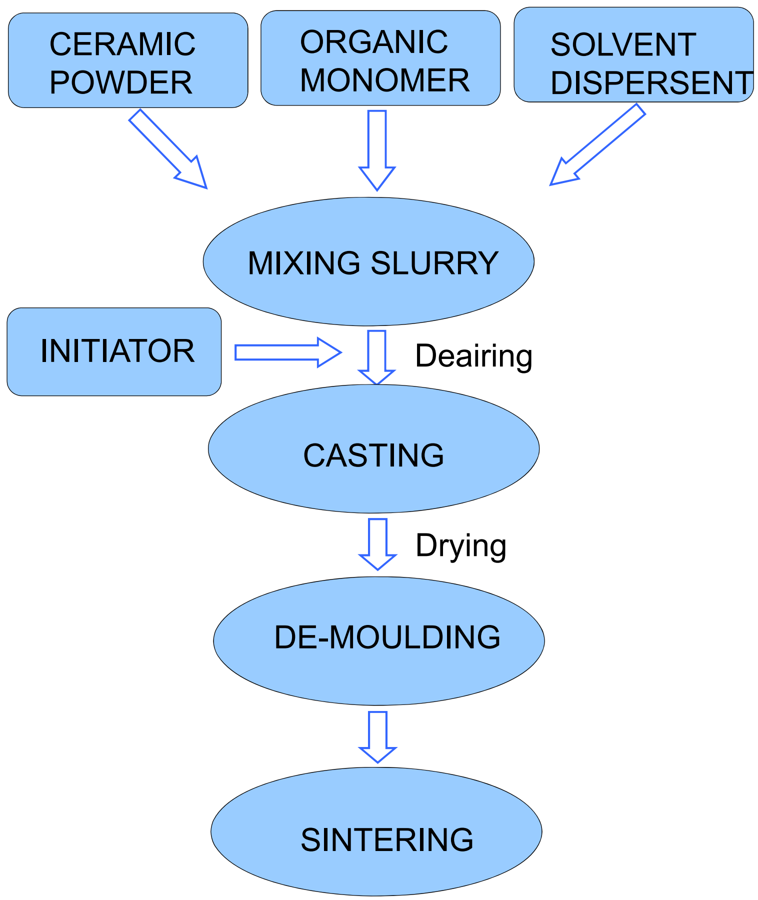
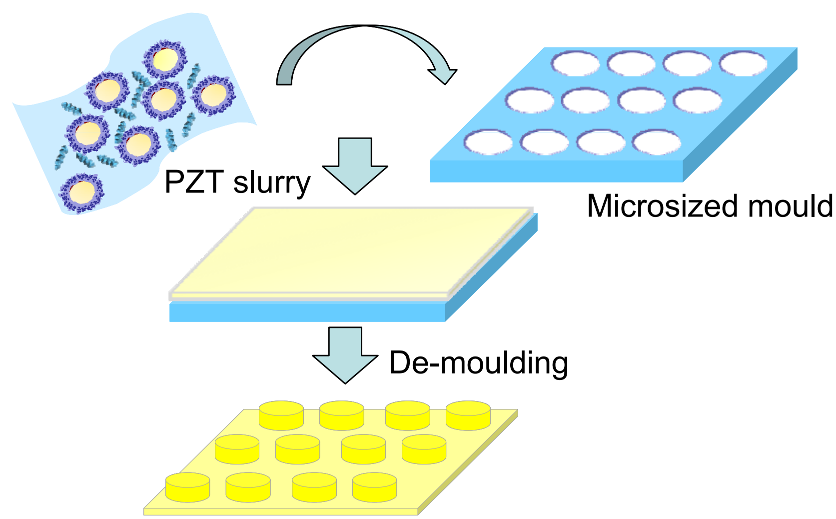
Alternative Fabrication Technique
Gel casting



Flow chart of gel casting process.

- Capability of producing complex parts
- Homogeneous material properties
- Rapid forming circle
- Low capital equipment cost.



Gel casting for 1-3 piezocomposite fabrication.

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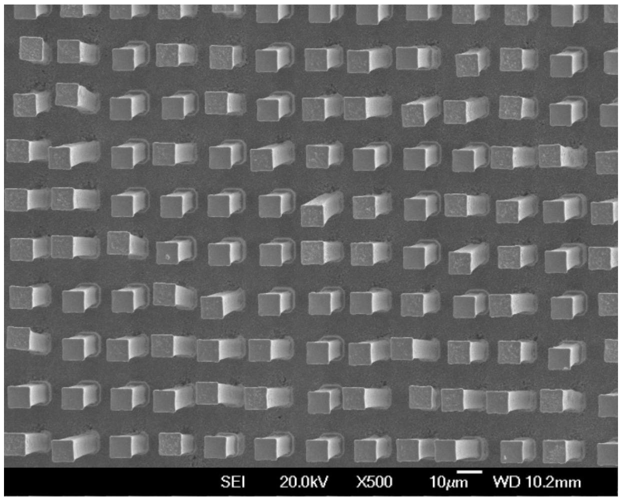
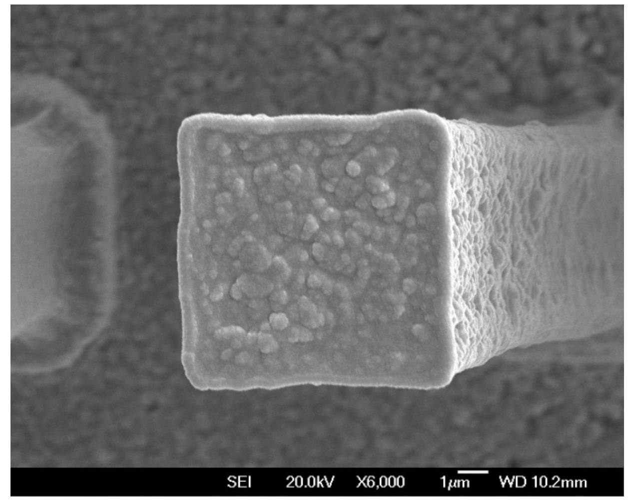
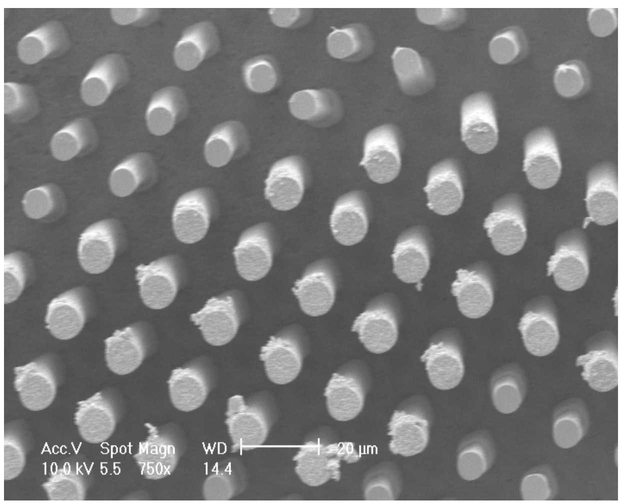
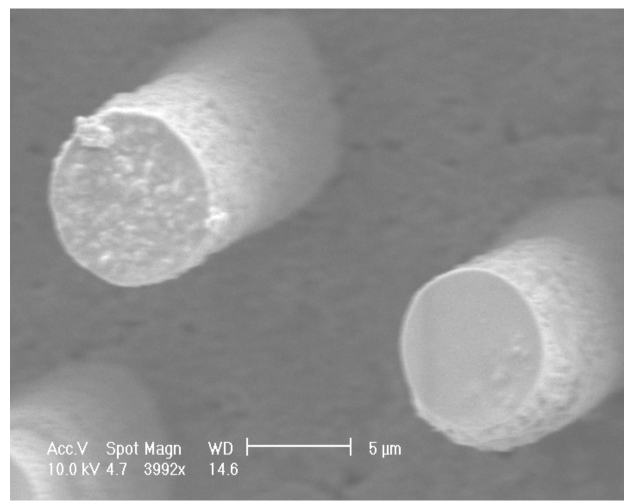
Micropillar Structures fabricated by Gel casting

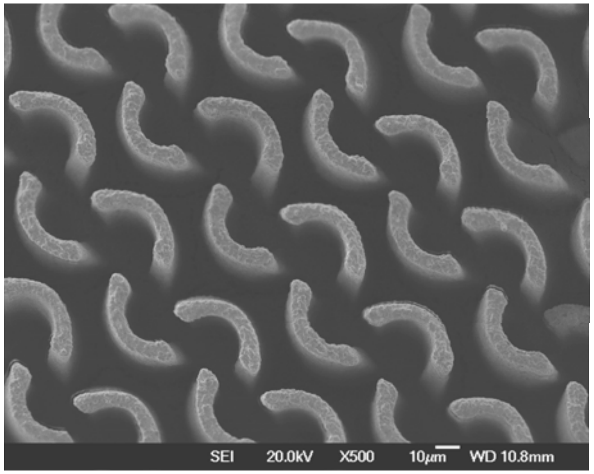


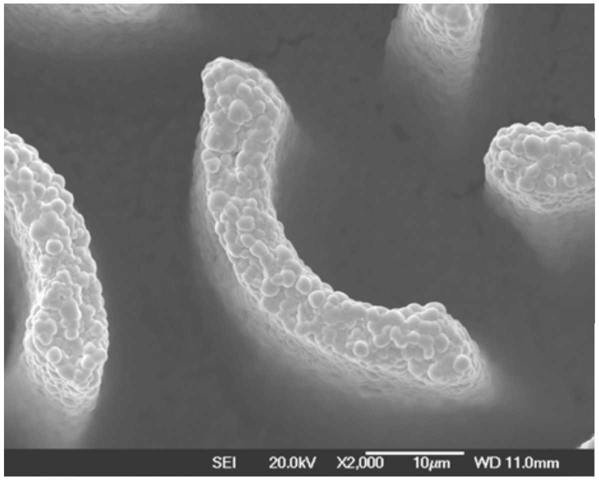


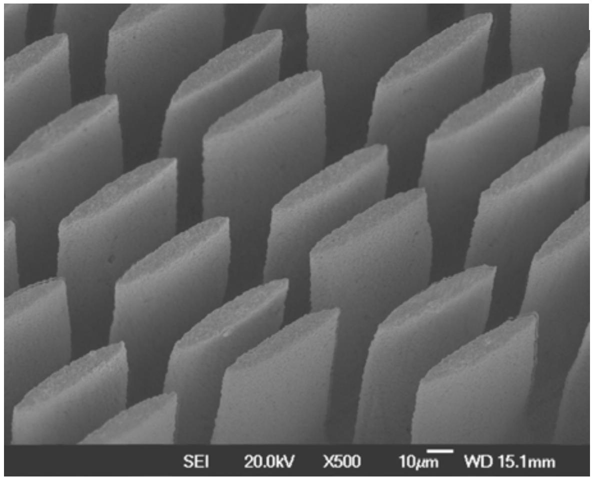




Other pillar shapes and configurations – Gel casting







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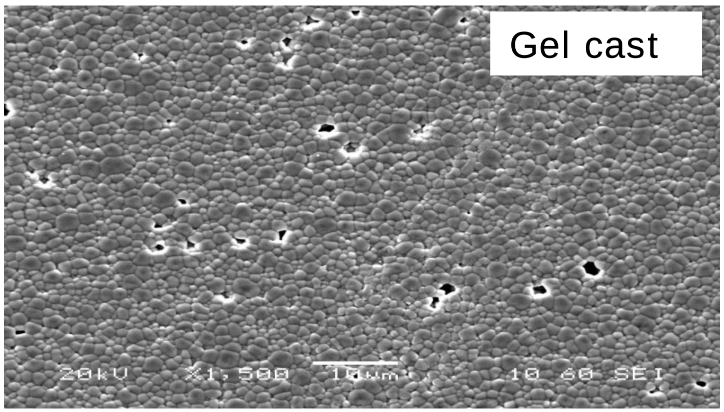
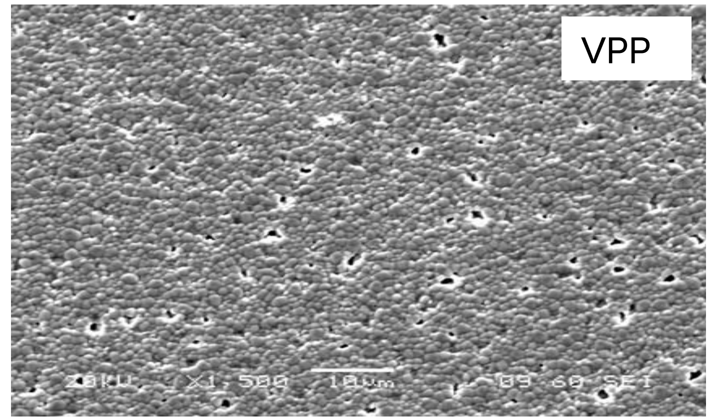
Gel casting Vs VPP

Comparison of microstructure and properties of sintered bulk ceramics (TRS610C)





Sample	Density (g/cm^3)	d_{33} (pC/N)	k_t	Permitivity	Dielectric loss
Gel casting	7.70 ± 0.02	632 ± 9.3	0.56 ± 0.001	3200	0.019
VPP	7.65 ± 0.05	586 ± 10.5	0.52 ± 0.002	3040	0.018

Piezocomposite Material Characterisation

- Material parameters determined by fitting electrical impedance to model
- Representative results for high frequency composite:

  Resonant frequency: 30 MHz

  Ceramic volume fraction: 50 %

  k_T = 0.51

  d_{33} = 130 pm/V

  Z_A = 17 MRayl

  ε_R^S = 460

- Parameters indicative of significant potential for biomedical imaging

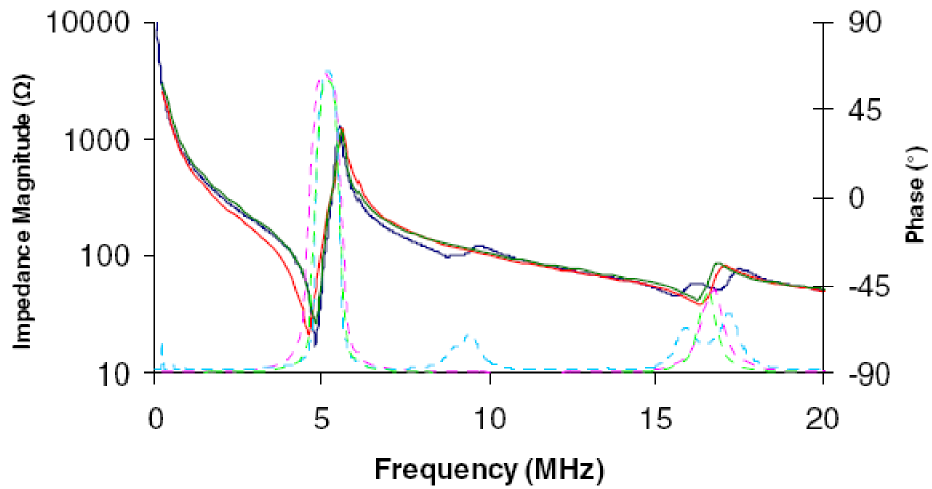


Figure 1. Measured, theoretical, and fitted electrical impedance magnitude and phase for a reference composite operating at a frequency around 5 MHz. Impedance magnitude: Measured — Theoretical — Fitted — Impedance phase: Measured — Theoretical - - Fitted - -

D. MacLennan, et al., "Fundamental performance characterisation of high frequency piezocomposites made with net-shape viscous polymer processing for medical ultrasound transducers," in *Proceedings 2008 IEEE Ultrasonics* Symposium, pp. 58-61, 2008.

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Single Element Transducers

30MHz single element transducers

- Transducer: piezoelectric composite,
  1.6 mm diameter, 3 mm geometric focus
- Piezoelectric composite:
  - 20 µm diameter pillars
  - 29 µm pitch, hexagonal packing
  - lapped to 54 µm thick
- Packaged and backed with tungsten-loaded epoxy

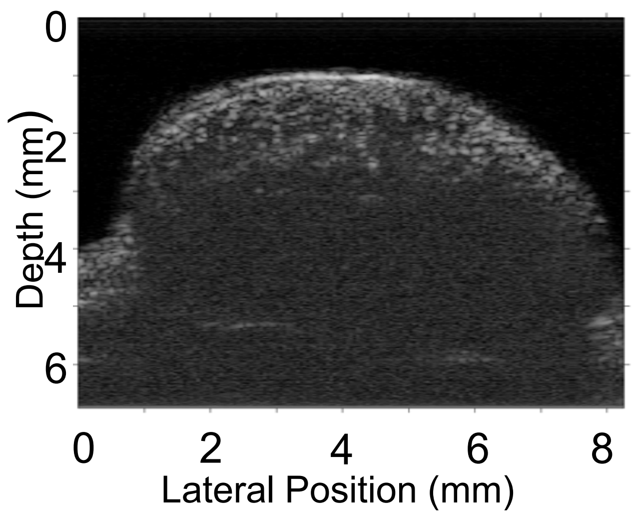

Image of mouse subcutaneous tumour xenograft acquired by mechanically scanning transducer across specimen

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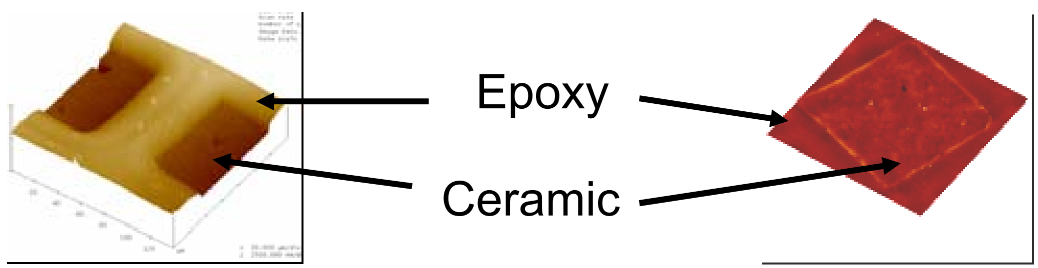
Process Improvements for transducer arrays

Advanced surface finishing

- Surfaces of composite must be flat, parallel and smooth in preparation for photolithography
- After standard processing, the two dissimilar materials in the composite retain surface relief
- Lapping and polishing processes have been adapted to provide flat and smooth surfaces

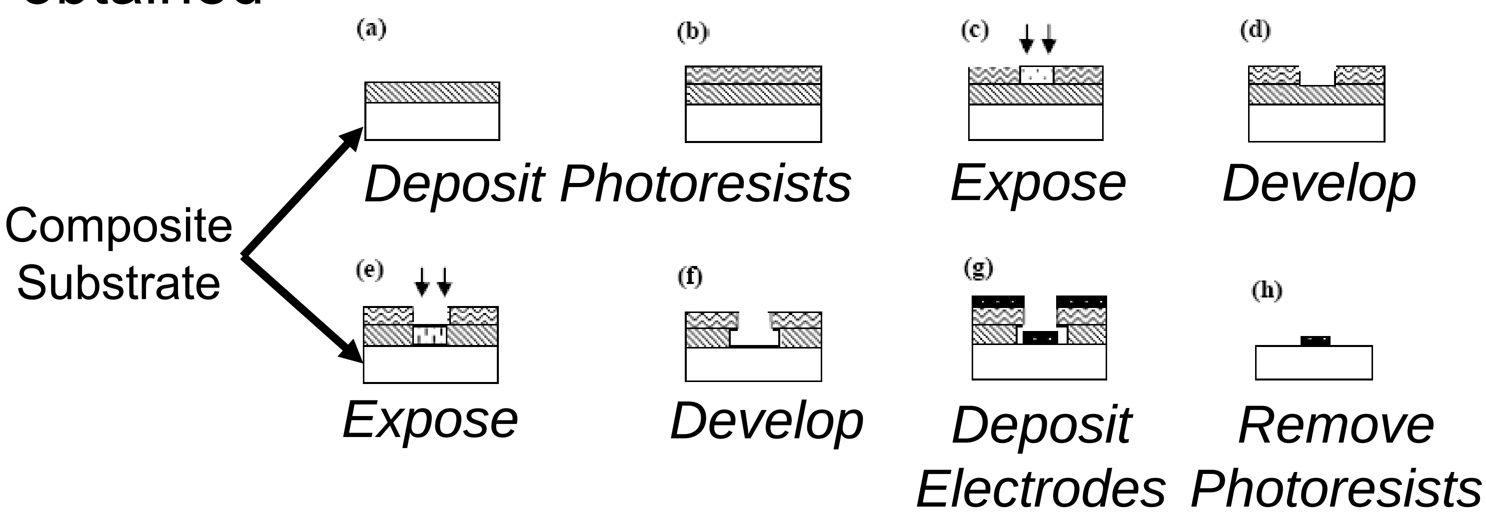


Standard processing:
~1 μm height difference

Advanced processing:
60 nm height difference

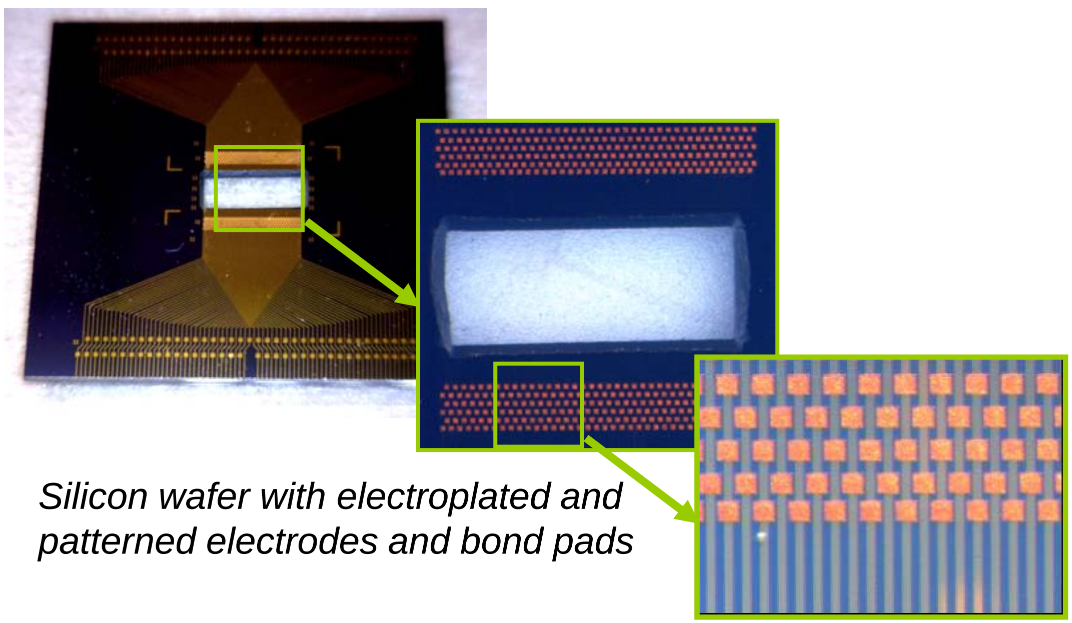
Electrode Patterning

- Lift-off photolithography process adapted for patterning electrodes on composite material
- Solvent-resistant epoxy used for composite fill
- Excellent edge definition and adhesion have been obtained

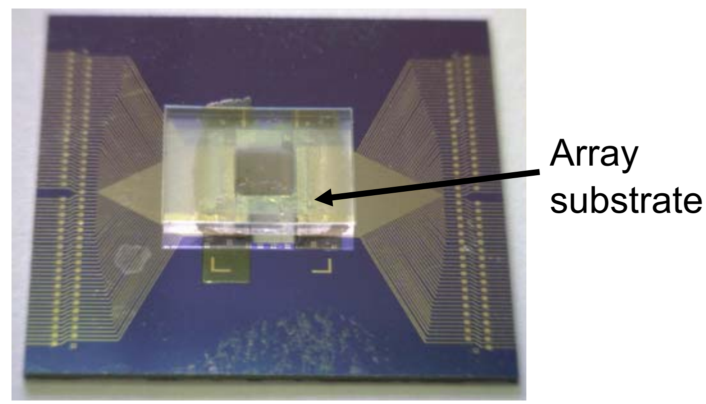


Mask-based Interconnect

- Standard wirebonding of array element electrodes to flex-circuits does not scale well for arrays above 50 MHz.
- Silicon wafer interconnect solution enables wafer scale production and can be used as a platform for further electronics integration.



Silicon wafer with electroplated and patterned electrodes and bond pads



Array substrate connected to contact pads on silicon wafer with flip-chip bonding process

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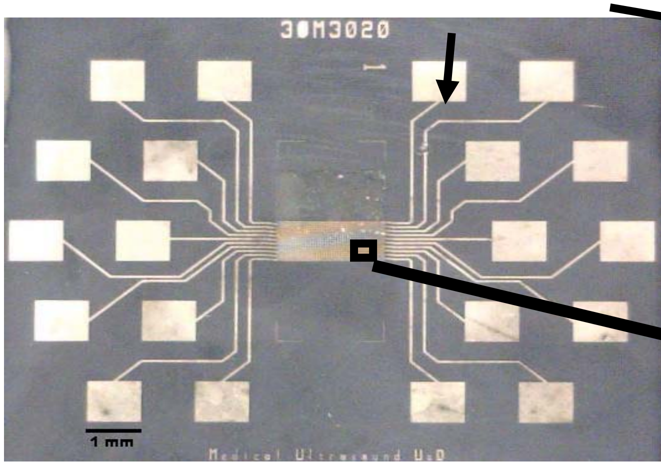
Transducer Arrays

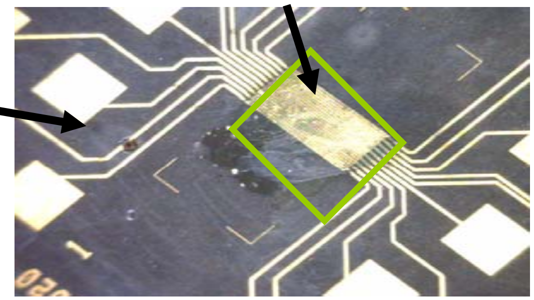
30MHz linear arrays

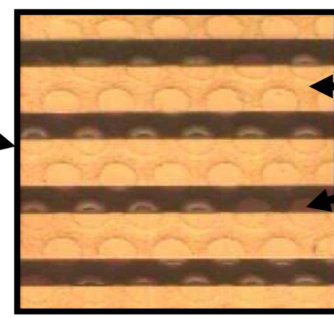
- Arrays: 20 and 32 element designs, 30 μm wide, 50 μm pitch
- Piezoelectric composite: 20 μm diameter pillars, 29 μm pitch, hexagonal packing, lapped to 55 μm thick
- Wired, packaged and backed with unloaded epoxy for preliminary testing

Fan-out and bond pads for preliminary testing

2 mm x 2 mm composite







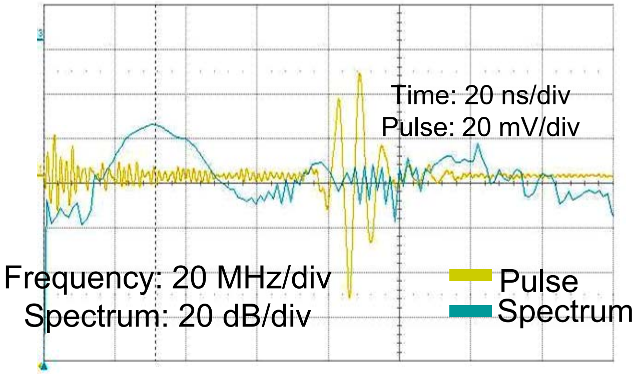
Array electrodes

Ceramic Pillars

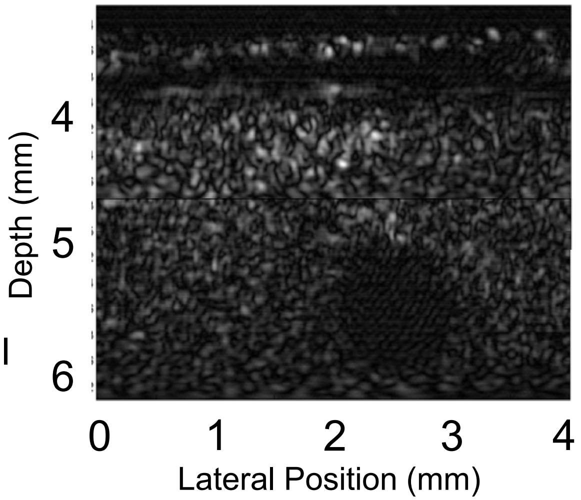
Array substrate with patterned electrodes defining elements

30MHz linear arrays

Packaged Prototype Array



Pulse-echo response of single element from quartz flat
Centre Frequency: 31 MHz, Bandwidth: 50 %



Synthetic aperture Image of 1 mm cylindrical cyst phantom in scattering background. Synthesised aperture: 4 mm, pitch: 10 μm.

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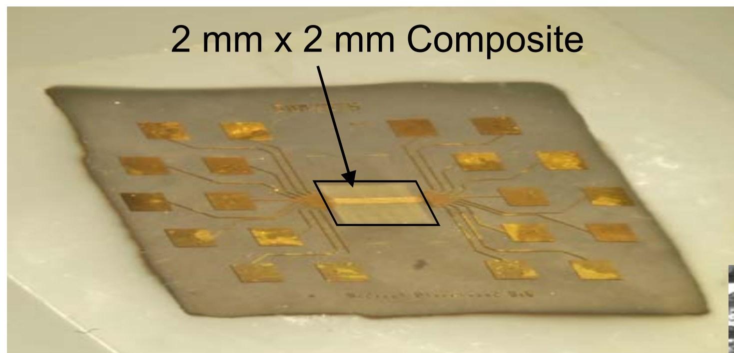
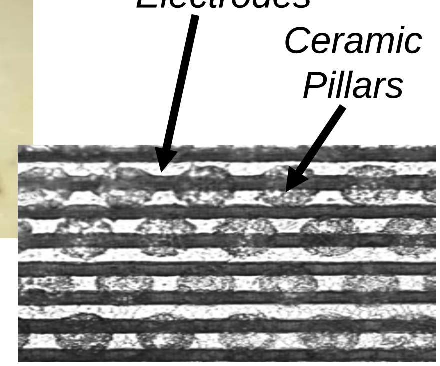
100MHz linear array pattern
Proof of Concept

- Array: 20 elements, 7.5 μm wide, 15 μm pitch
- Piezoelectric composite:
  40 μm thick (for 50MHz operation)
- Wired, packaged and backed with unloaded epoxy for preliminary testing



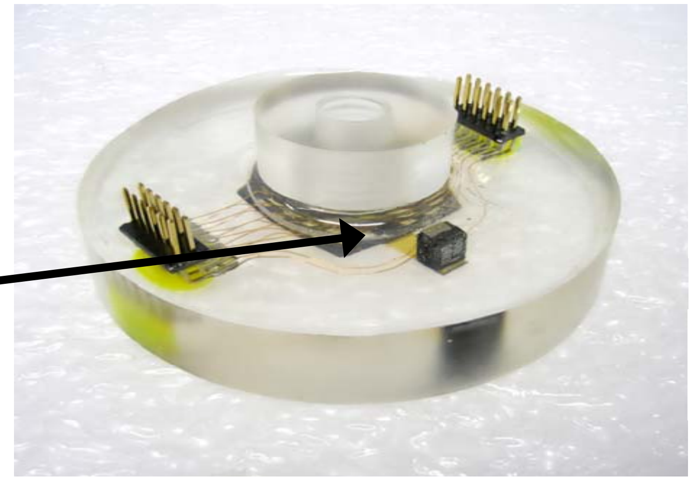
Composite substrate with patterned array electrodes

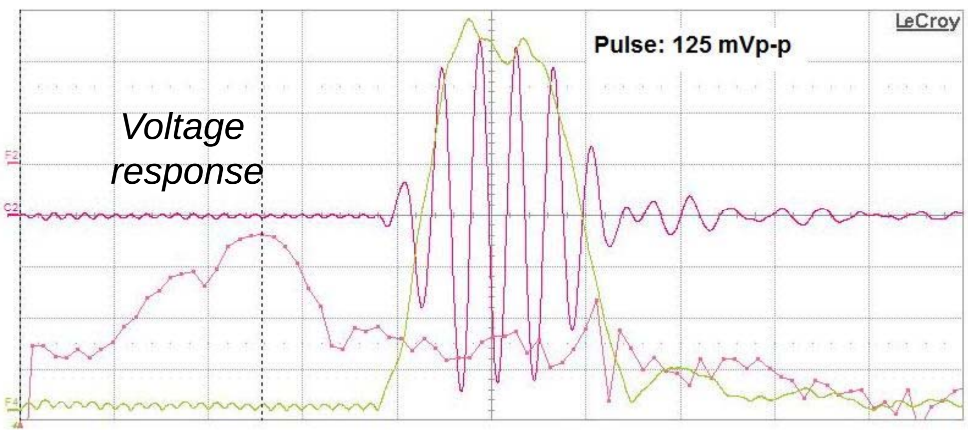


100MHz linear array pattern

Array wired to connectors and packaged for testing

Array substrate





Pulse-echo response of single element from quartz flat. Centre Frequency: 51 MHz, Bandwidth: 25 %

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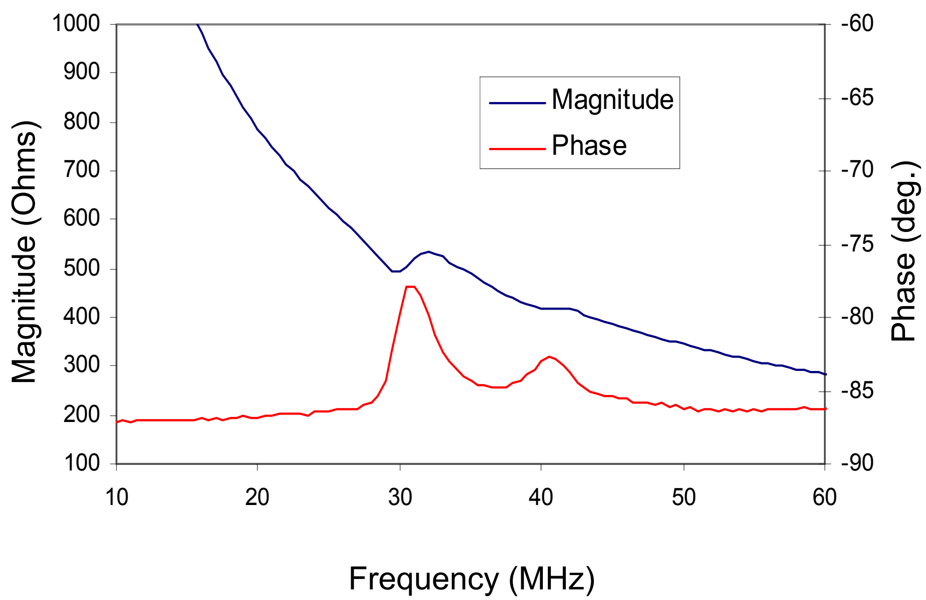
Electrical Impedance

Electrical Impedance of representative element in 30 MHz array



30 MHz array

- Thickness mode frequency at 30 MHz
  - Lateral mode at 40 MHz due to unoptimised composite
- Elements across array have uniform performance
  - Response consistent with expected performance

100 MHz array

- Elements show piezoelectric response
  - 45 MHz thickness mode
  - Response is highly damped because array pattern very small relative to composite

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Potential Applications

Applications for 30 – 100 MHz arrays can be found in the many clinical disciplines which require:

- High spatial resolution
- Real-time imaging

- Example: Dermatology
  - High frequency arrays can be used to enhance 3D and reflex transmission imaging (RTI) by varying the focus through the depth of the tissue in real time
    - RTI measures the attenuation of tissue at the focus of a strongly focused transducer
  - RTI with high frequency arrays has potential for improving the accuracy and efficiency of diagnosis of melanoma
- Example: Ultrasonic and optoacoustic scanning of vasculature
  - The synthetic focusing possible with arrays is required for optoacoustic imaging of oxygenated and deoxygenated blood
  - With high frequency arrays, accurate imaging of microvasculature becomes possible, leading to improved diagnosis and monitoring of many diseases

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Summary

- Micromoulding and microfabrication processes have been developed for fabricating fine-scale, HFUS transducer arrays.
- Micromoulded piezoelectric composites with material properties suitable for high frequency imaging have been made.
- Surface finishing and photolithography techniques have been developed and adapted to pattern fine-scale arrays directly on composite surfaces.
- Prototype arrays have been fabricated and perform as expected.

Commercial Prospects

- HFUS is already here!
  - VisualSonics, SonoSite ……
- Interest in HF from most major Ultrasound players
- Specific applications for HF single element devices
- Cost effective fabrication for HF Arrays (>15 MHz) required
- Wide range of potential applications

Future Work

- Optimise piezoelectric composite and array designs for improved performance at 50 MHz and above.
- Further develop technologies for interconnect between arrays and silicon wafers.
- Integration of HFUS arrays with electronics to minimise cable issues
  - preliminary demonstration of combining a HFUS transducer with an ASIC in collaboration with Penn State

    (Bernassau et al, IEEE Ultrasonics Symp, Rome 2009).
- Application specific programmes.

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