Structural Health and Strain Monitoring Through Fourier-based Transducers

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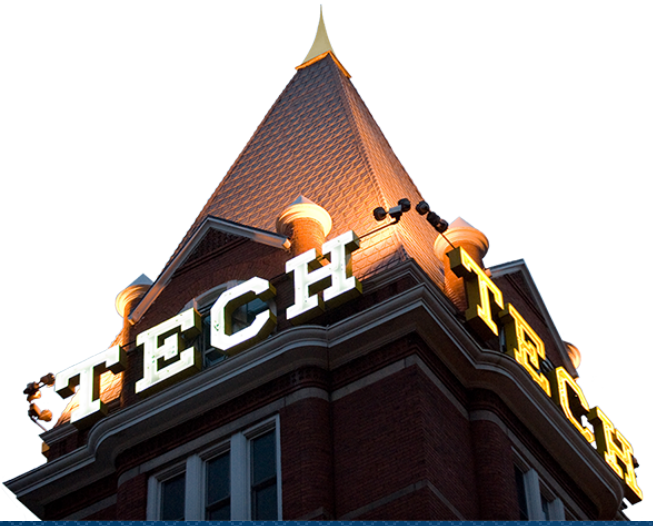


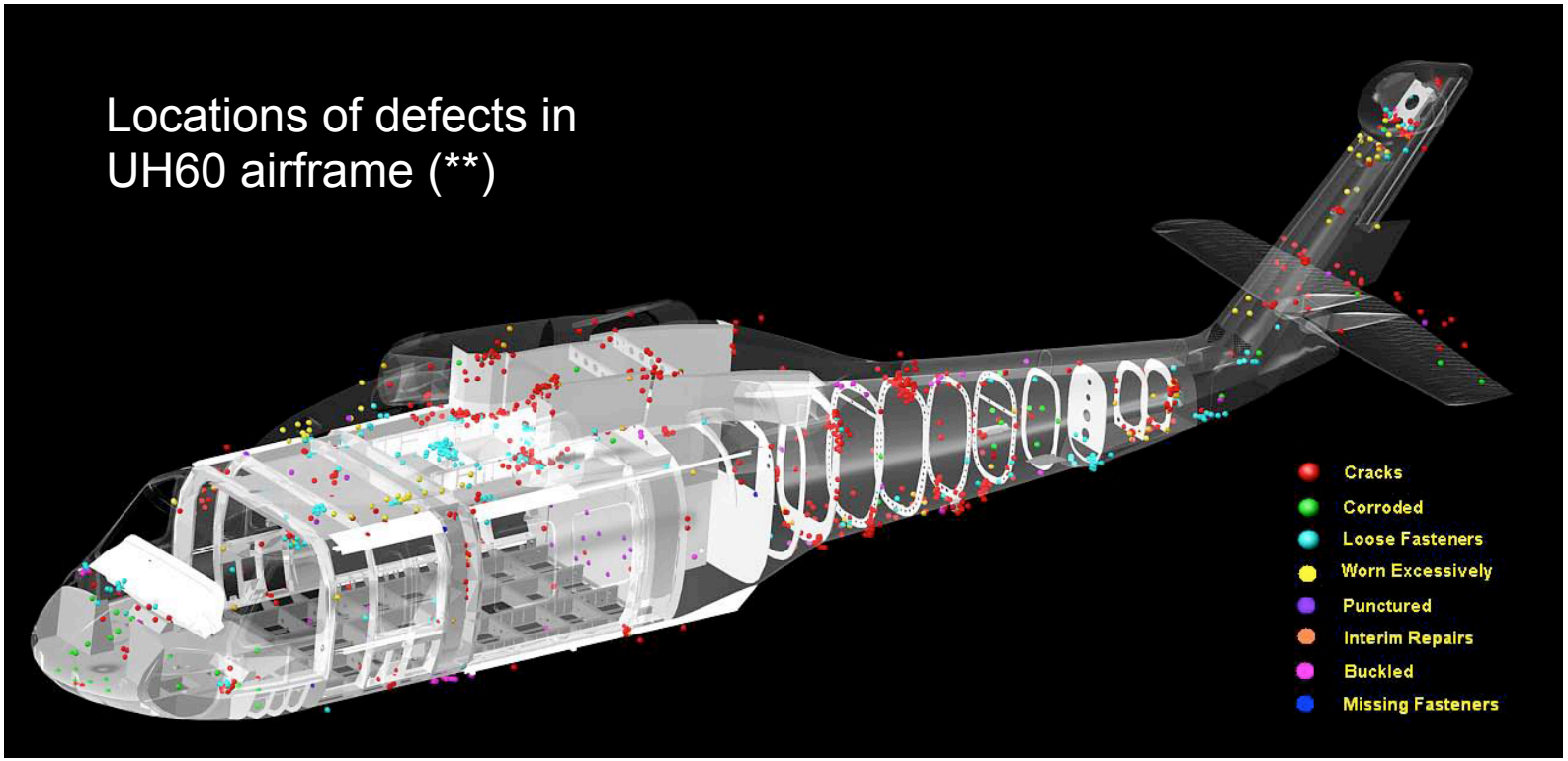
Background

- Structural Health and Usage Monitoring:
  - Loads monitoring: usage and fatigue
  - Health monitoring: damage
- Investigation of novel sensors for:
  - Strain measurements
  - Guided wave inspection
  - Integration (?)

Background

- Roadmap to structural health monitoring (SHM) and usage monitoring :

"…*in the not too distant future, to transition from usage monitoring to individual component damage tracking, to enhance our health assessment capability with better prediction of fatigue for each dynamic component and fatigue critical area…*"(*)

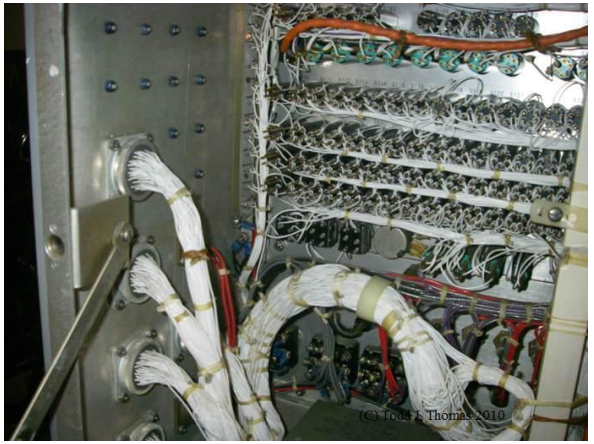


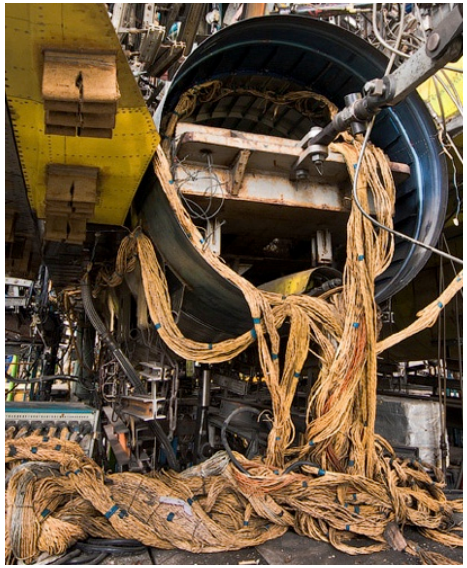
*Maley, S., Plets, J. and Phan, N.D.: "US Navy Roadmap to Structural Health and Usage Monitoring- The Present and Future." 63rd AHS Forum, Virginia Beach, VA, May 1-3, 2007.

***Uh-60 Airframe Condition Evaluation (ACE) Technical Review*, 17 February 2010, Aircraft Support Branch, Maintenance Engineering Division, Army Aviation and Missile Command.

Objectives

- Legacy sensors have inherent limitations related to:
  - Wiring
  - Hardware requirements
  - Power needs
  - Reliability





- Basic research is needed to:
  - Simplify health & usage monitoring tasks
  - Enable new functionalities

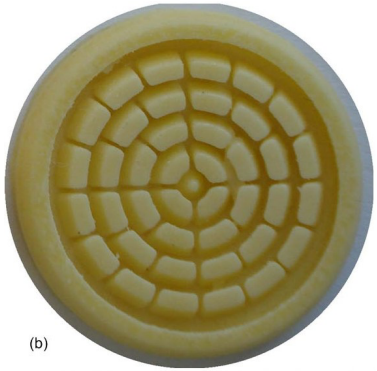
    (remote, wireless, distributed, embedded sensing….)

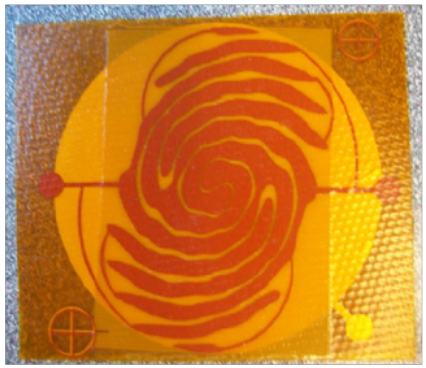
Objectives

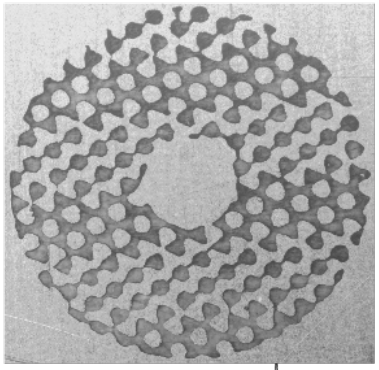
- Fundamentally new transducer concepts must support an integrated Health & Usage Monitoring process

- Opportunities offered by:
  - Additive manufacturing
  - Advanced micro/nano fabrication technologies
  - Direct write technology for in-situ deposition of sensing material

- Patterning of transducer surface/electrodes leads to novel and tailored functionalities





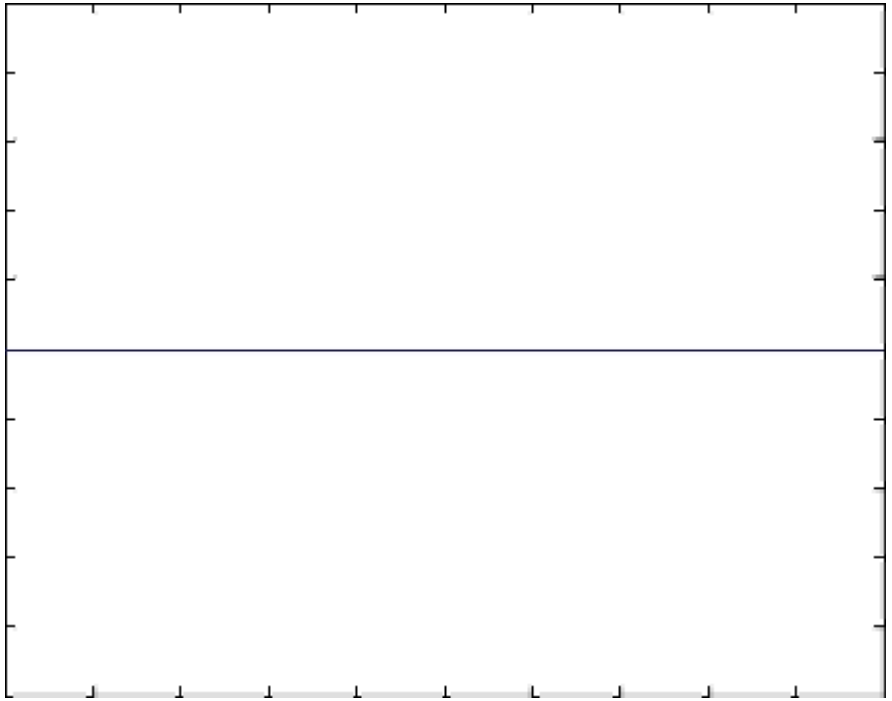


Outline

- Frequency Steerable Acoustic Transducers (FSATs) for directional sensing and actuation of guided waves
- Acoustic Wave Rosettes for multi-component strain sensing
- Conclusions & Outlook

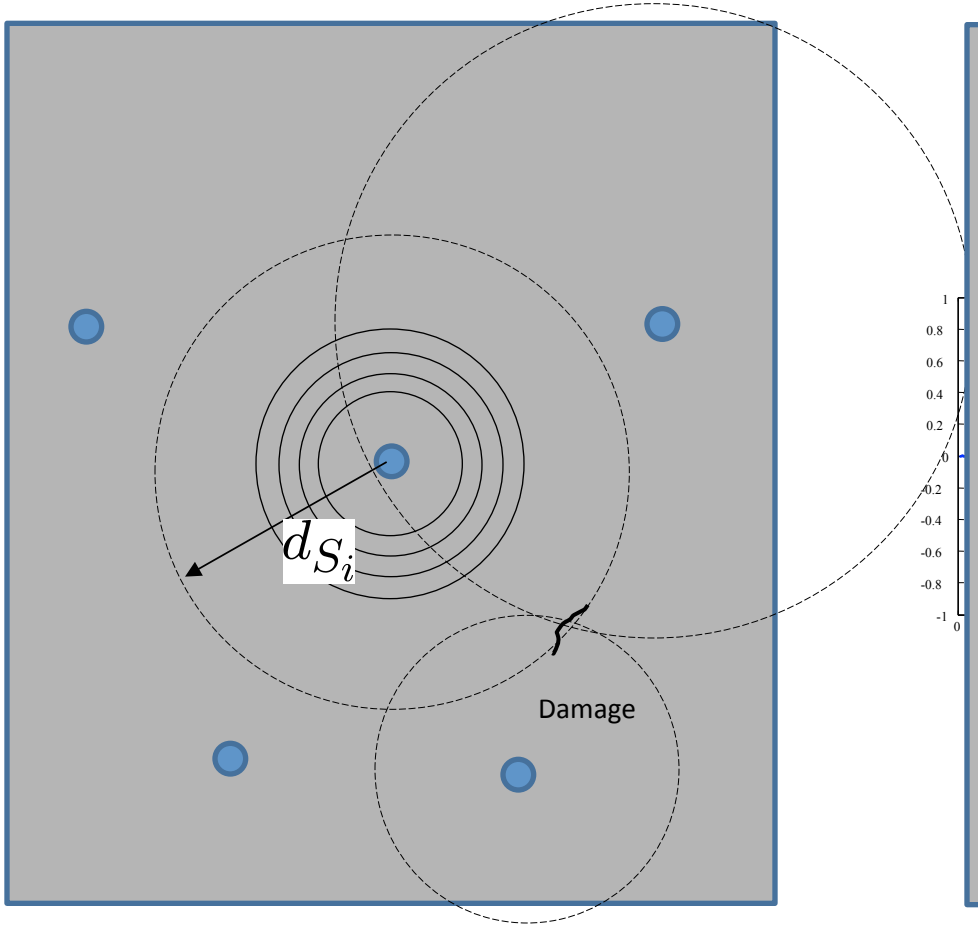
Wave-based techniques

F(t)

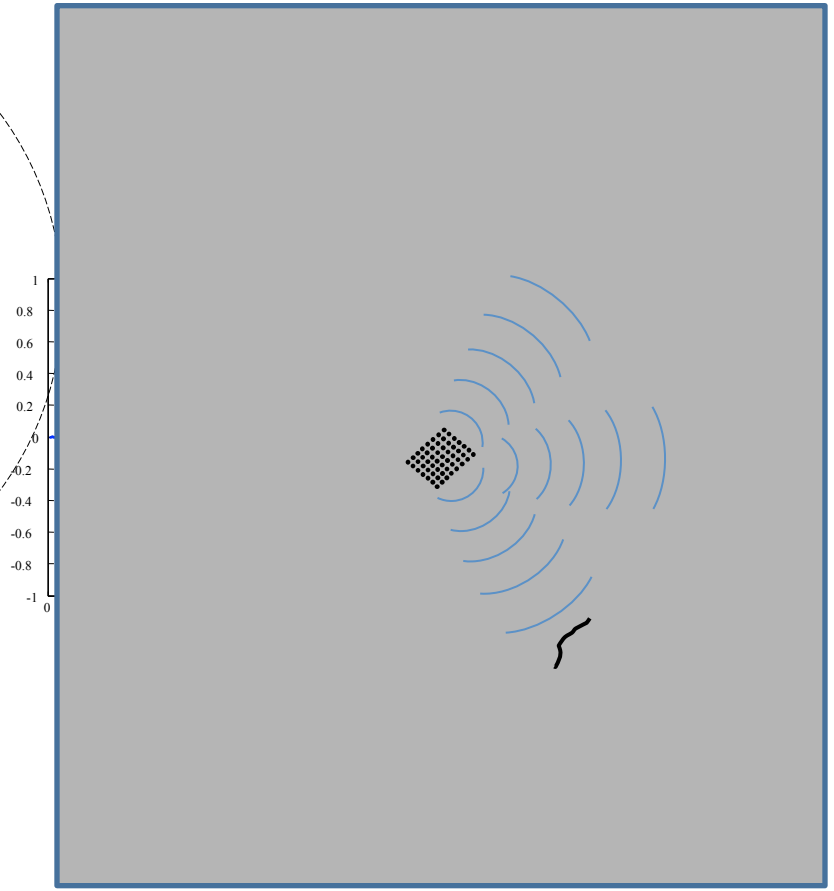


Directional wave generation

Omnidirectional tranducers



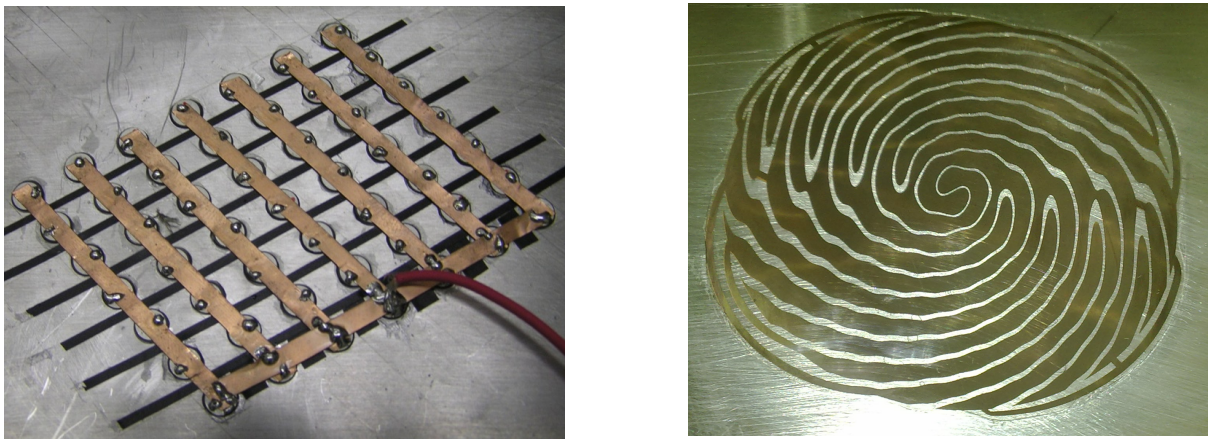
Directional transducers



Frequency Steerable Transducers

- Phased-array technology
  - Phasing/control of each component of an array
  - Hardware complexity

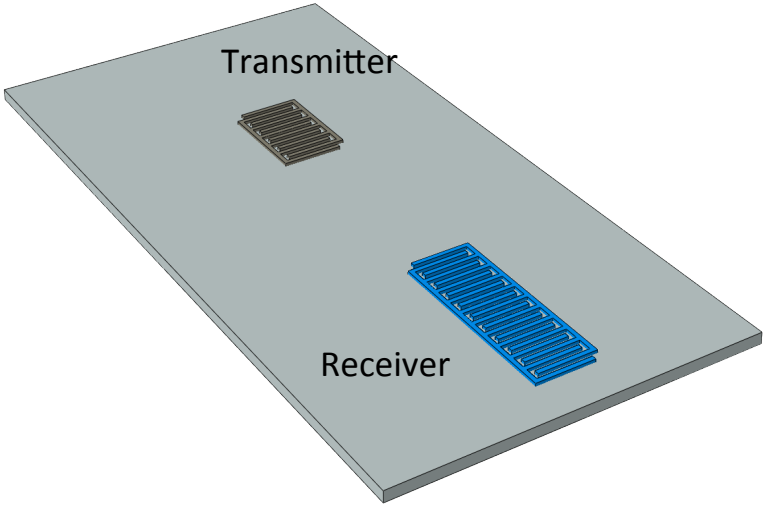
- Frequency Steerable Acoustic Transducer (FSAT):
  - Frequency-dependent directionality provided by spatial arrangement of active material
  - Patterning of sensing geometry leads to focused sensing/actuation with reduced hardware

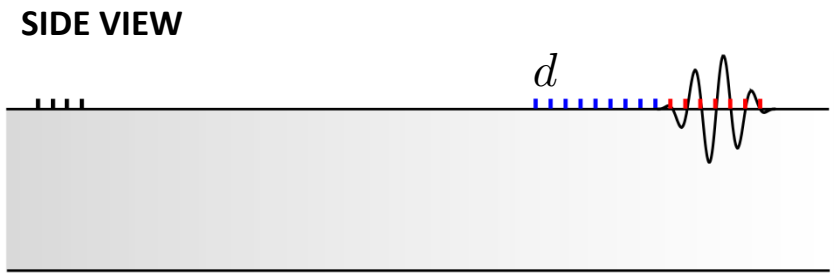


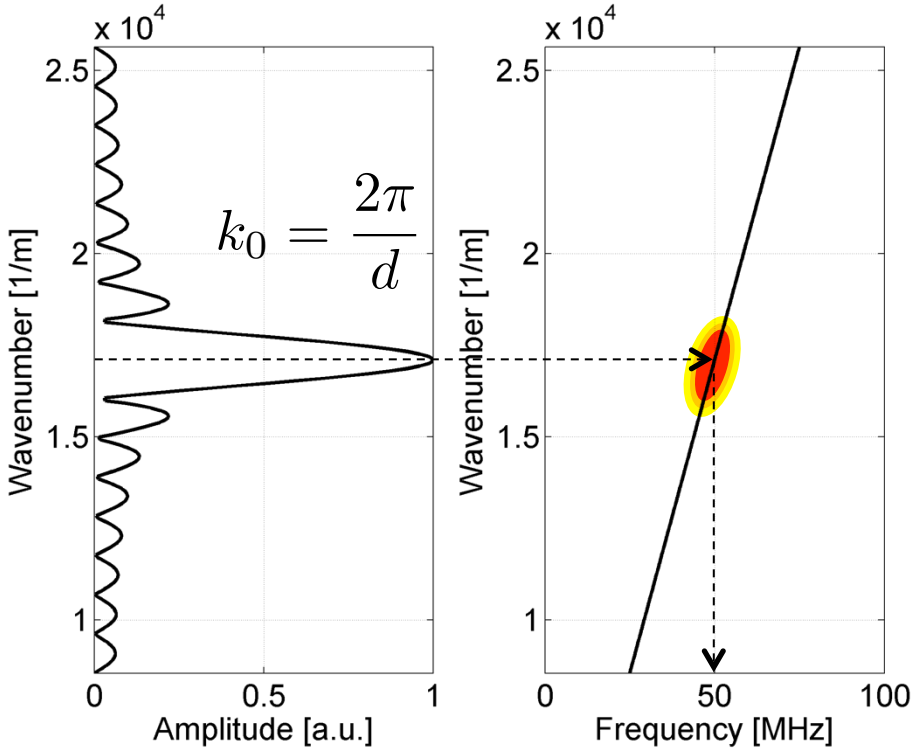
FSAT

- Array systems and related methods for structural health monitoring, *US Patent* 8,286,490
- Frequency-steered acoustic transducer using a spiral array *US Patent* 20140157898 A1

Concept: 1D Combs



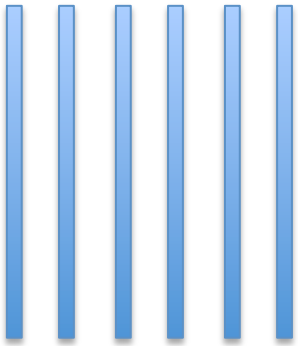




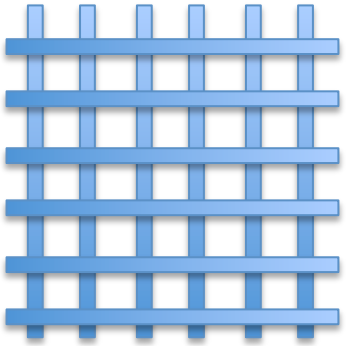
Rose, J., Pelts, S., and Quarry, M., "A comb transducer model for guided wave NDE," *Ultrasonics 36, 163-169* (1998).

Concept

- A 1D periodic sensing surface behaves as a narrow band filter

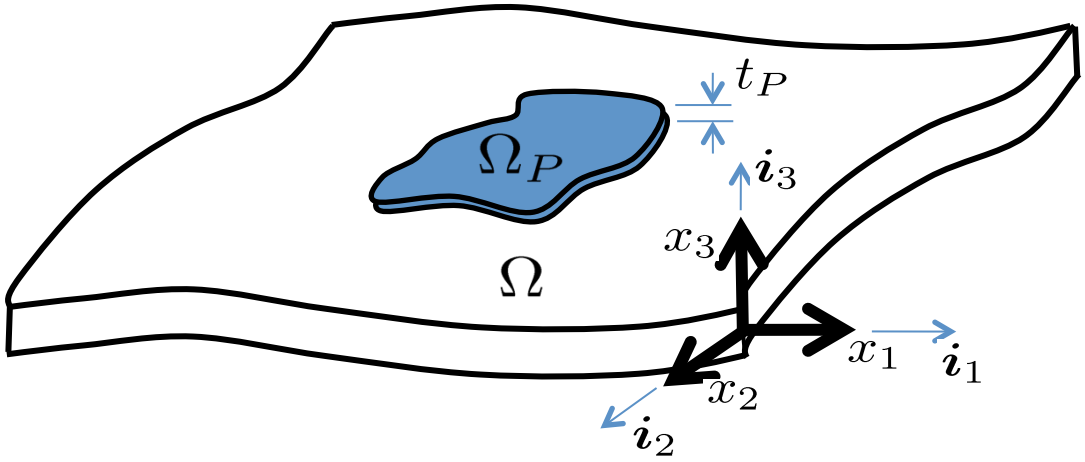


- A 2D periodic sensing surface behaves as a narrow band filter with directional sensitivity



- Same considerations apply for ACTUATION, i.e. wave generation

Configuration & Basic Relations: Sensing Mode



Constitutive relations (Piezo):

$$\boldsymbol{\sigma} = \boldsymbol{C}^E\boldsymbol{\varepsilon} - \boldsymbol{e}^T\boldsymbol{E}$$
$$\boldsymbol{D} = \boldsymbol{e}\,\boldsymbol{\varepsilon} + \boldsymbol{\epsilon}^{\varepsilon}\boldsymbol{E}$$

Matrix formulation

$$\left\{ \begin{array}{c} \boldsymbol{\sigma} \\ \boldsymbol{D} \end{array} \right\} = \varphi(\boldsymbol{x}) \left[\begin{array}{cc} \boldsymbol{C}^E & -f(\boldsymbol{x})\boldsymbol{e}^T \\ f(\boldsymbol{x})\boldsymbol{e} & \boldsymbol{\epsilon}^{\varepsilon} \end{array} \right] \left\{ \begin{array}{c} \boldsymbol{\varepsilon} \\ \boldsymbol{E} \end{array} \right\}, \quad \boldsymbol{x} \in \Omega$$

Distribution function

Measured Voltage

$$V = \frac{t_P}{A_P[\boldsymbol{b}^T(\boldsymbol{d}^{\sigma}\boldsymbol{C}^E\boldsymbol{d}^{\sigma T} - \boldsymbol{\epsilon}^{\sigma})\boldsymbol{b}]}\boldsymbol{b}^T\boldsymbol{d}^{\sigma}\boldsymbol{C}^E\int_{\Omega}\boldsymbol{\varepsilon}\,f(\boldsymbol{x})d\boldsymbol{x}$$

Sensor's directionality

- Measured voltage can be expressed as:

$$V(\omega) = jU_{1'_0}(\omega)k_0(\omega)\mathcal{H}(\theta)\mathcal{D}(\omega,\theta)$$

  - Where

$$\mathcal{H}(\theta) = \frac{t_P}{A_P}\frac{\boldsymbol{b}^T\boldsymbol{d}^\sigma\boldsymbol{C}^E\boldsymbol{r}(\theta)}{[\boldsymbol{b}^T(\boldsymbol{d}^\sigma\boldsymbol{C}^E\boldsymbol{d}^{\sigma T} - \boldsymbol{\epsilon}^\sigma)\boldsymbol{b}]} \longrightarrow \text{Material directionality}$$

$$\mathcal{D}(\omega,\theta) = \int_\Omega e^{jk_0(\omega)(x_1\cos\theta + x_2\sin\theta)} f(\boldsymbol{x})d\boldsymbol{x} \longrightarrow \text{Geometric directionality}$$

- Geometric directionality can be rewritten as

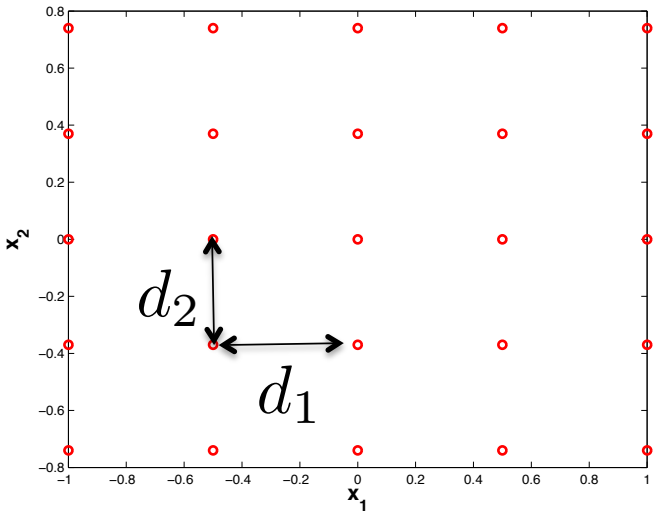
$$\mathcal{D}(\omega,\theta) = \int_{-\infty}^{+\infty} e^{-j\boldsymbol{k}_0(\omega)\cdot\boldsymbol{x}} f(\boldsymbol{x})d\boldsymbol{x}$$

$$\boxed{\mathcal{D}(\boldsymbol{k}_0(\omega),\theta) = \mathcal{F}[f(\boldsymbol{x})]} \quad \text{General framework for design}$$

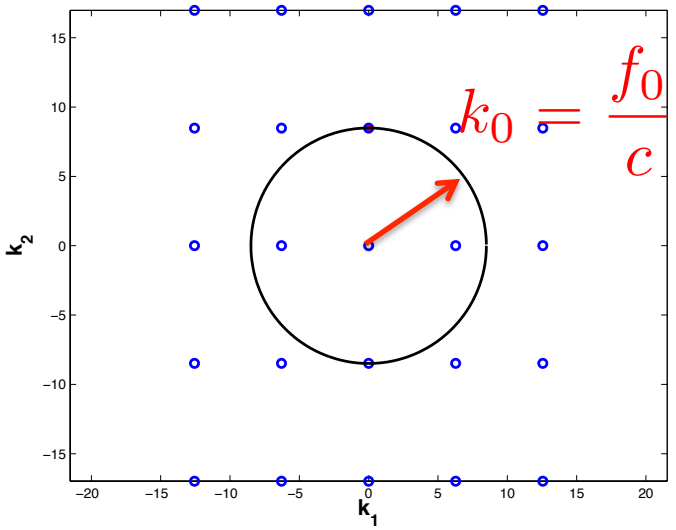
Example:
Rectangular array of point sources

$$f(x_1, x_2) = f_0 \sum_{n=1}^{N} \sum_{m=1}^{M} \delta(x_1 - nd_1)\delta(x_2 - md_2)$$

$$f(k_1, k_2) = f_0 \frac{\sin(\frac{Nk_1d_1}{2})}{\sin(\frac{k_1d_1}{2})} \frac{\sin(\frac{Mk_2d_2}{2})}{\sin(\frac{k_2d_2}{2})}$$

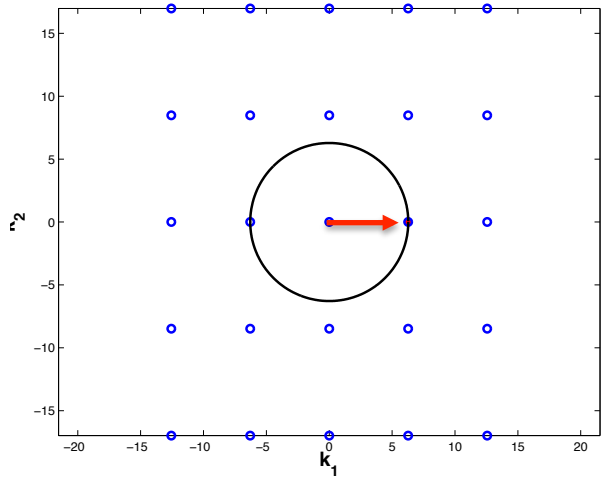


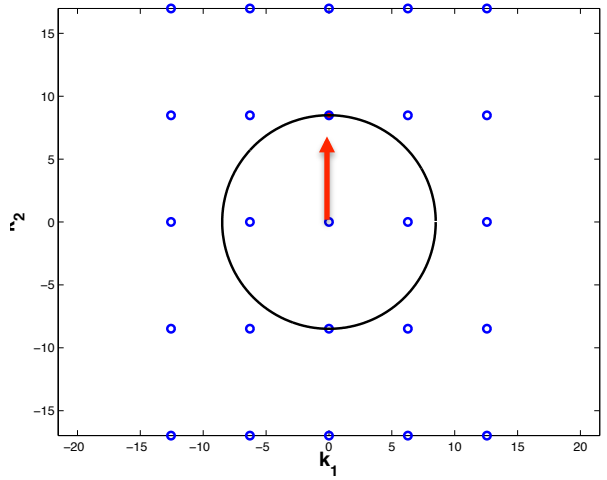
$\mathcal{F}$

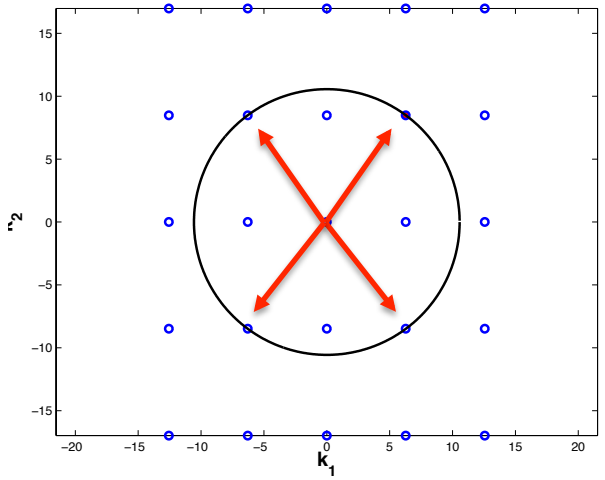


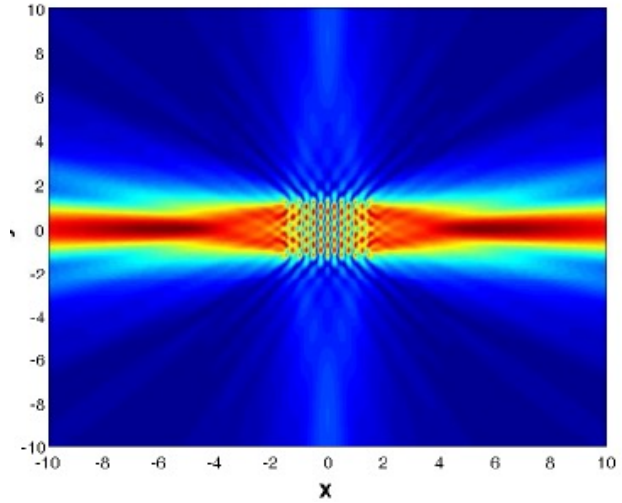
$$k_1 = p\frac{2\pi}{d_1}, k_2 = q\frac{2\pi}{d_2}, \quad p, q \in \mathbb{Z}$$

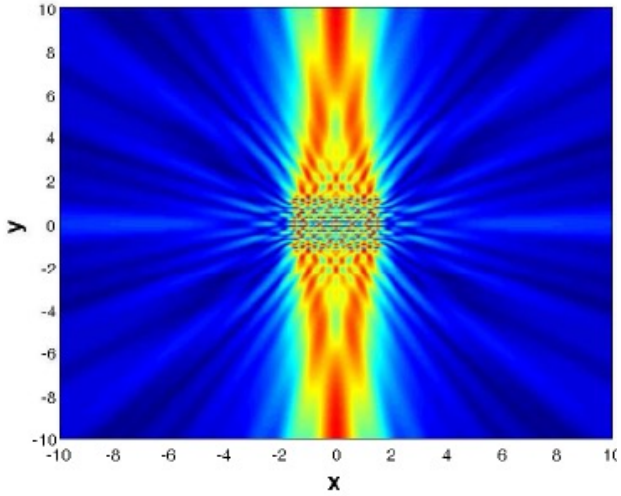
Frequency-dependent radiation

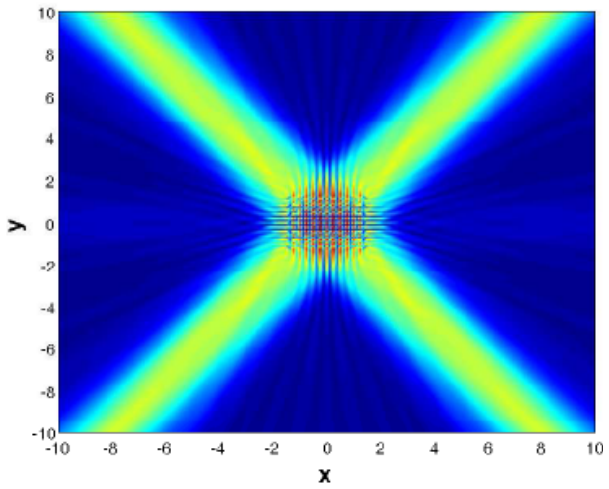








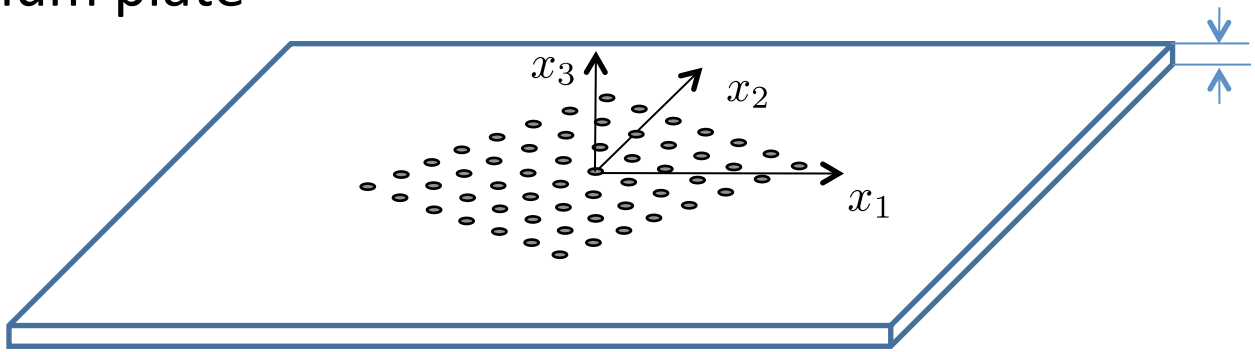




Experimental validation:
Plate and array configuration

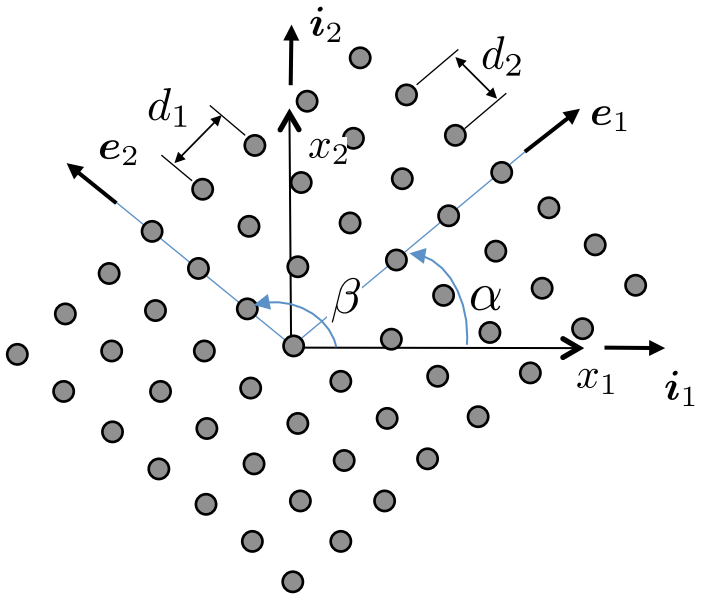
WAVE LAB

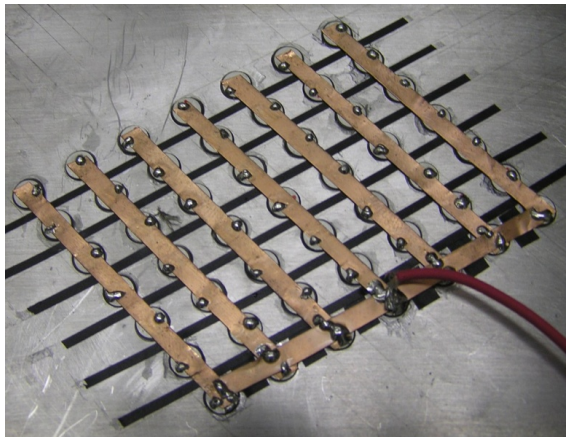
Thin aluminum plate



Array (7*7)

$d_1 = 4.3$ cm
$d_2 = 3.5$ cm,
$\alpha = 55^o$
$\beta = 165^o$





Romanoni, M., et al., *Two-dimensional periodic actuators for frequency-based beam steering.* Smart Materials & Structures, 2009. **18**(12).

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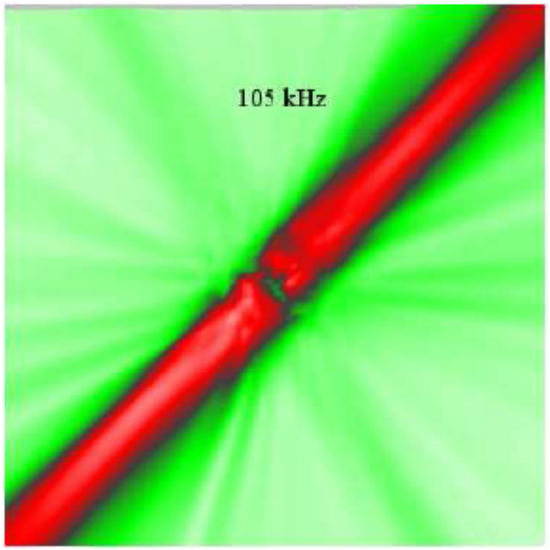
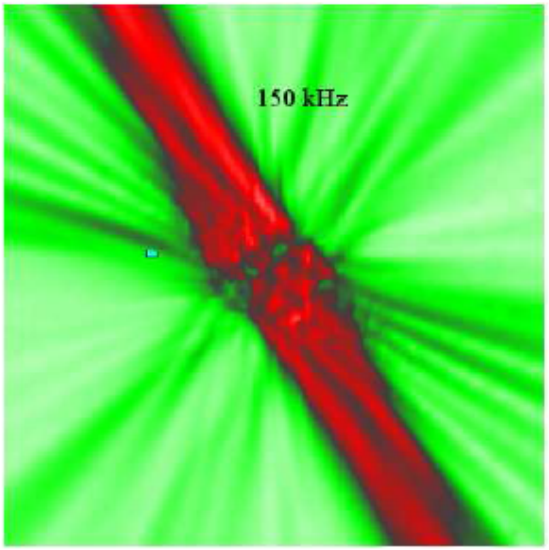
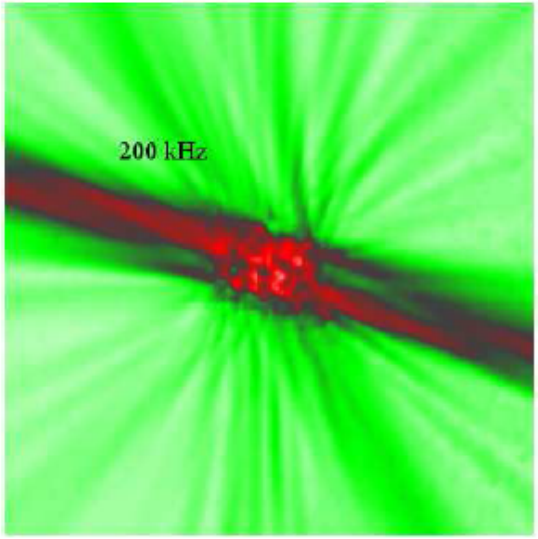
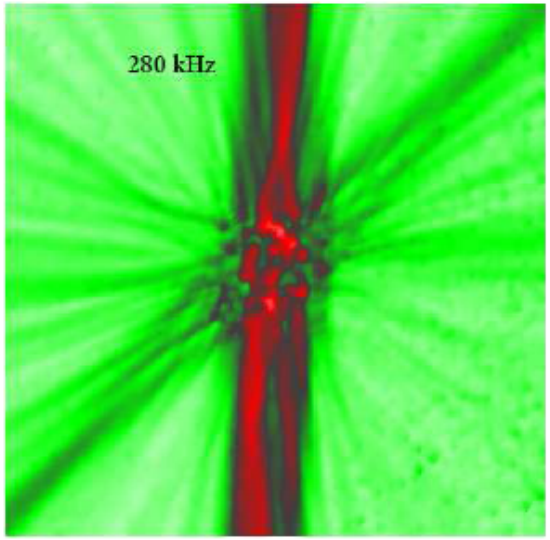
Experimental validation:
Directional Radiation





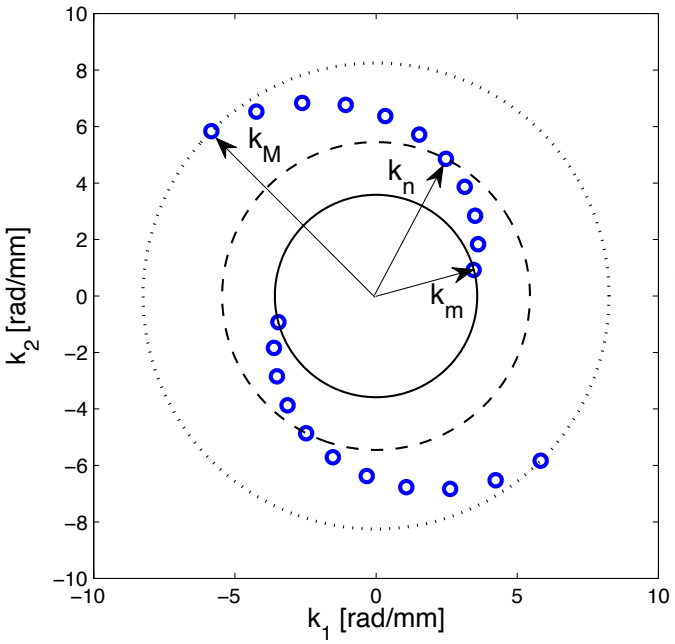




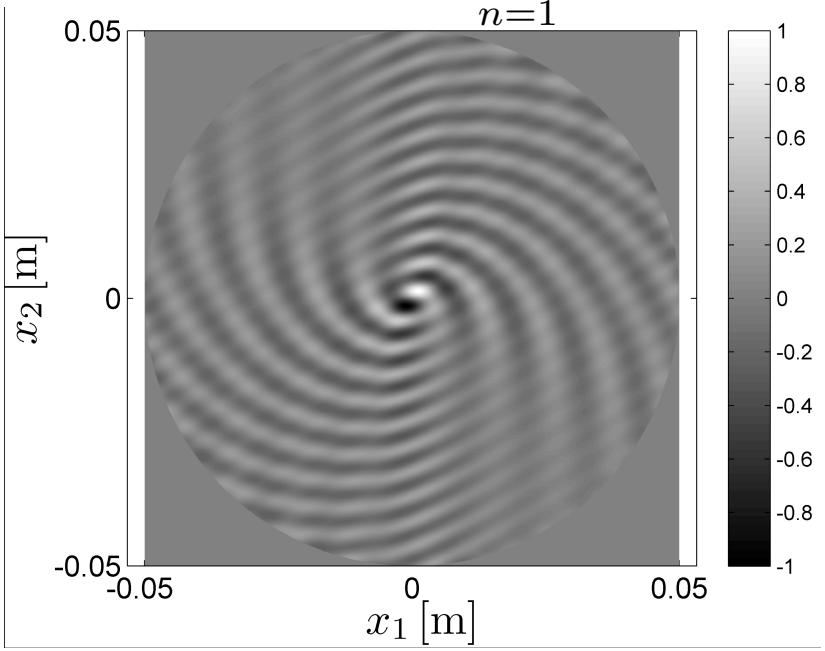
FSAT Spiral Array

$$\mathcal{D}(\boldsymbol{k}_0(\omega),\theta) = \mathcal{F}[f(\boldsymbol{x})]$$

$$f(\boldsymbol{x}) = \frac{1}{N}\mathrm{rect}\left(\frac{|\boldsymbol{x}|}{a}\right)\sum_{n=1}^{N}\sin(\boldsymbol{k}_n\cdot\boldsymbol{x})$$



$\mathcal{F}^{-1}$



$$\mathcal{D}(\boldsymbol{k}_0(\omega),\,\vartheta) = -j\frac{a}{N}\sum_{n=1}^{N}\left[\frac{J_1(a|\boldsymbol{k}_0-\boldsymbol{k}_n|)}{a|\boldsymbol{k}_0-\boldsymbol{k}_n|} - \frac{J_1(a|\boldsymbol{k}_0+\boldsymbol{k}_n|)}{a|\boldsymbol{k}_0+\boldsymbol{k}_n|}\right]$$

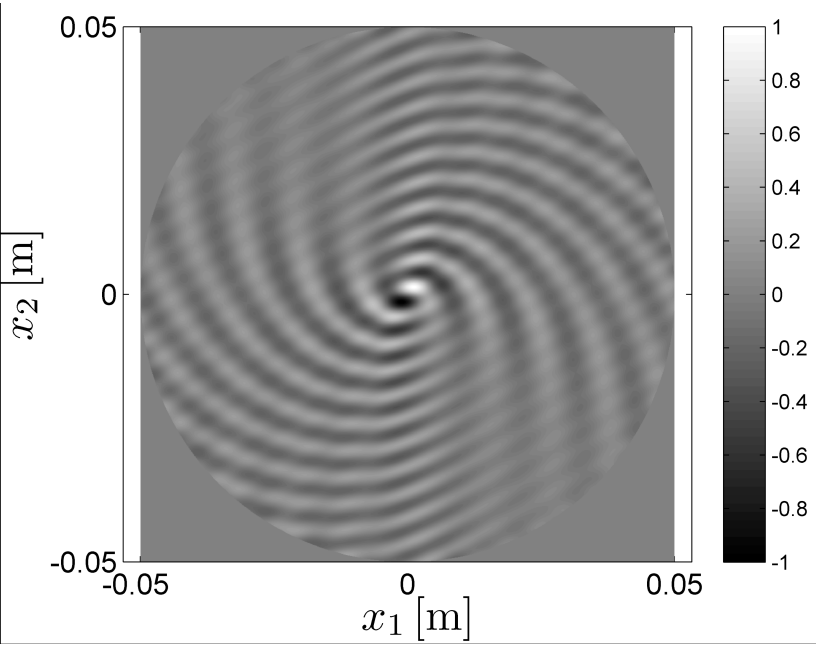
$$\boldsymbol{k}_n = [(k_M-k_m)\frac{\theta_n-\theta_m}{\theta_M=\theta_m}+k_m](\cos\theta_n\boldsymbol{i}_1+\sin\theta_n\boldsymbol{i}_2)$$

Each frequency corresponds to a given direction of sensing and radiation

FSAT Spiral Array

$$f(\boldsymbol{x}) = \frac{1}{N}\mathrm{rect}\left(\frac{|\boldsymbol{x}|}{a}\right)\sum_{n=1}^{N}\sin(\boldsymbol{k}_n \cdot \boldsymbol{x})$$

$$\mathcal{D}(\boldsymbol{k}_0(\omega),\theta) = \mathcal{F}[f(\boldsymbol{x})]$$



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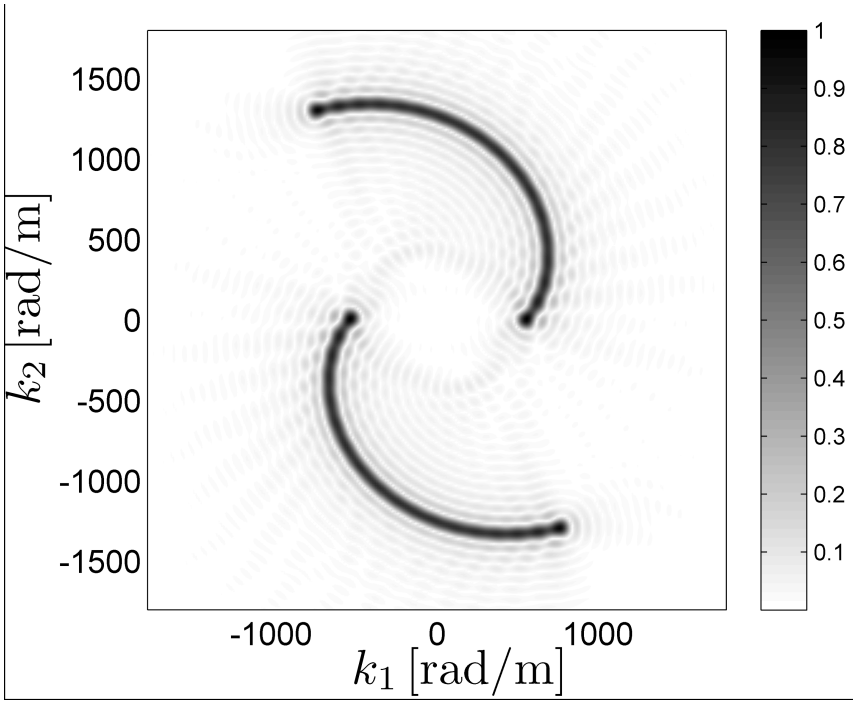
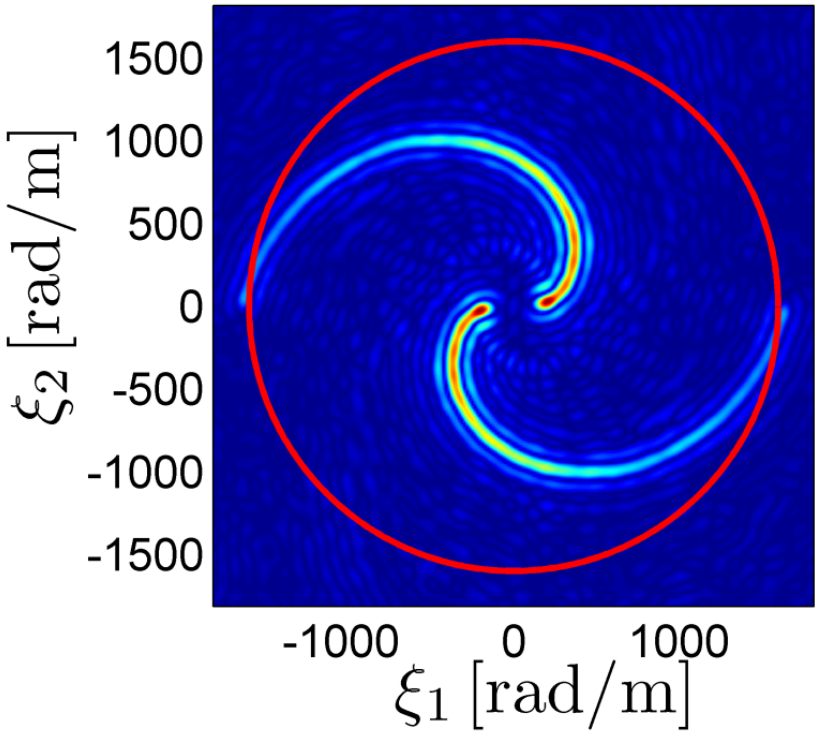
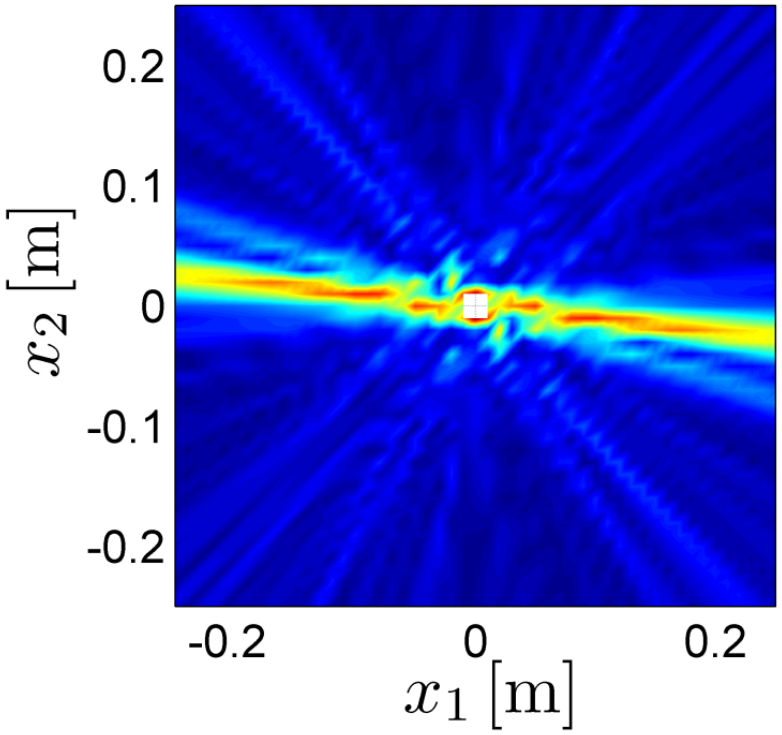
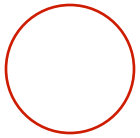


FSAT Spiral Array: radiation





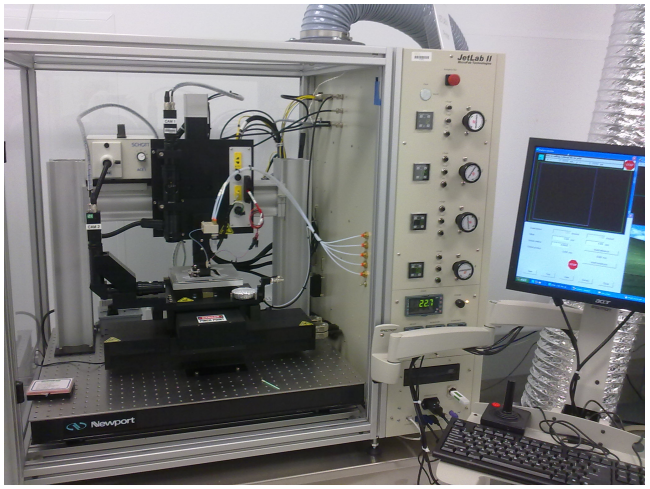


Iso-frequency circle
(radius proportional to excitation frequency)

FSAT Fabrication

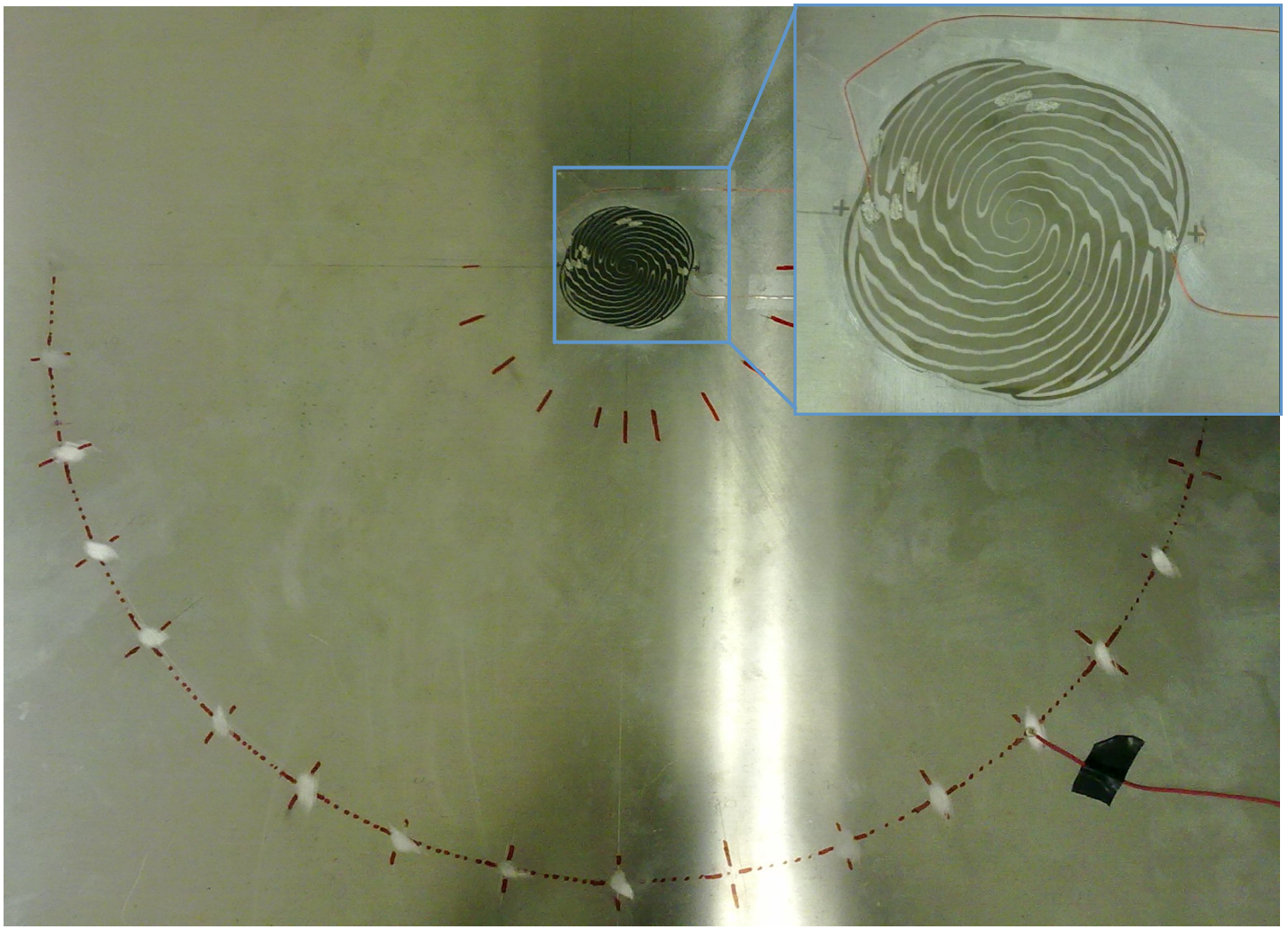
Printed bitmap image

- Diameter = 50 mm
- Bandwidth = [50, 350] kHz
- Angular range = [0, 180] deg.
- Double polarity
- Image resolution = 625 x 625 px
- Resulting pixel spacing = 80 µm



Baravelli, Emanuele, et al. "Photolithography-based realization of Frequency Steerable Acoustic Sensors on PVDF substrate." *Sensors Applications Symposium (SAS), 2012 IEEE*. IEEE, 2012.

Experimental Results



Experimental Results:
Plate response to chirp excitation

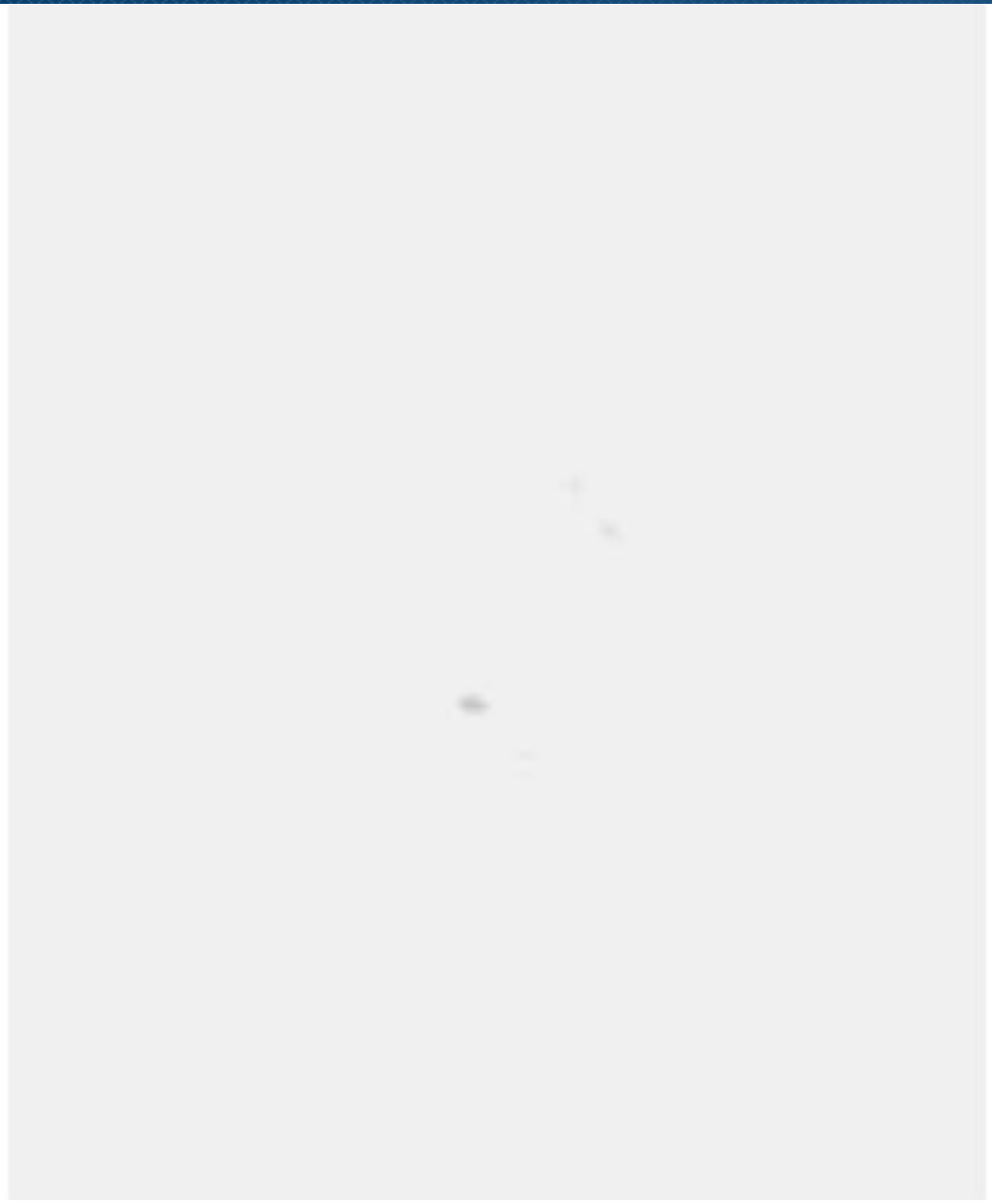


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Plate response to chirp excitation

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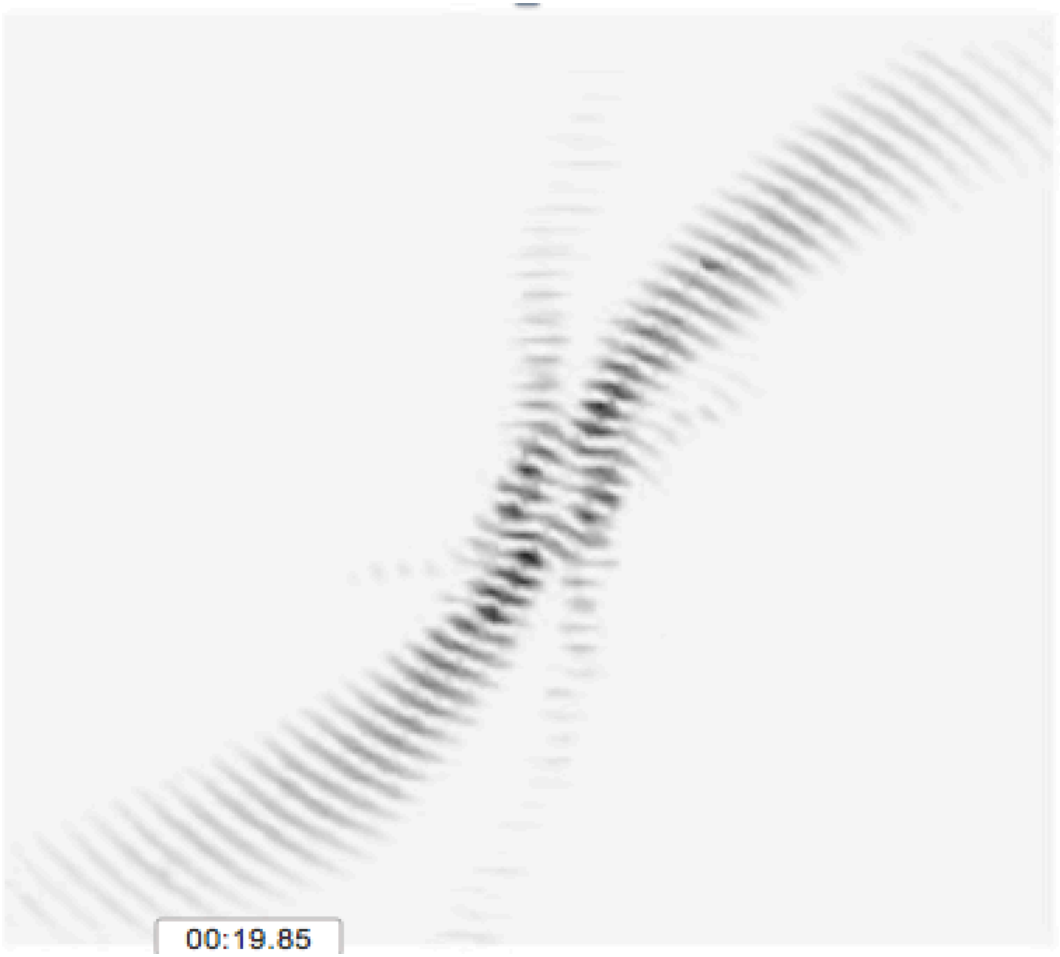
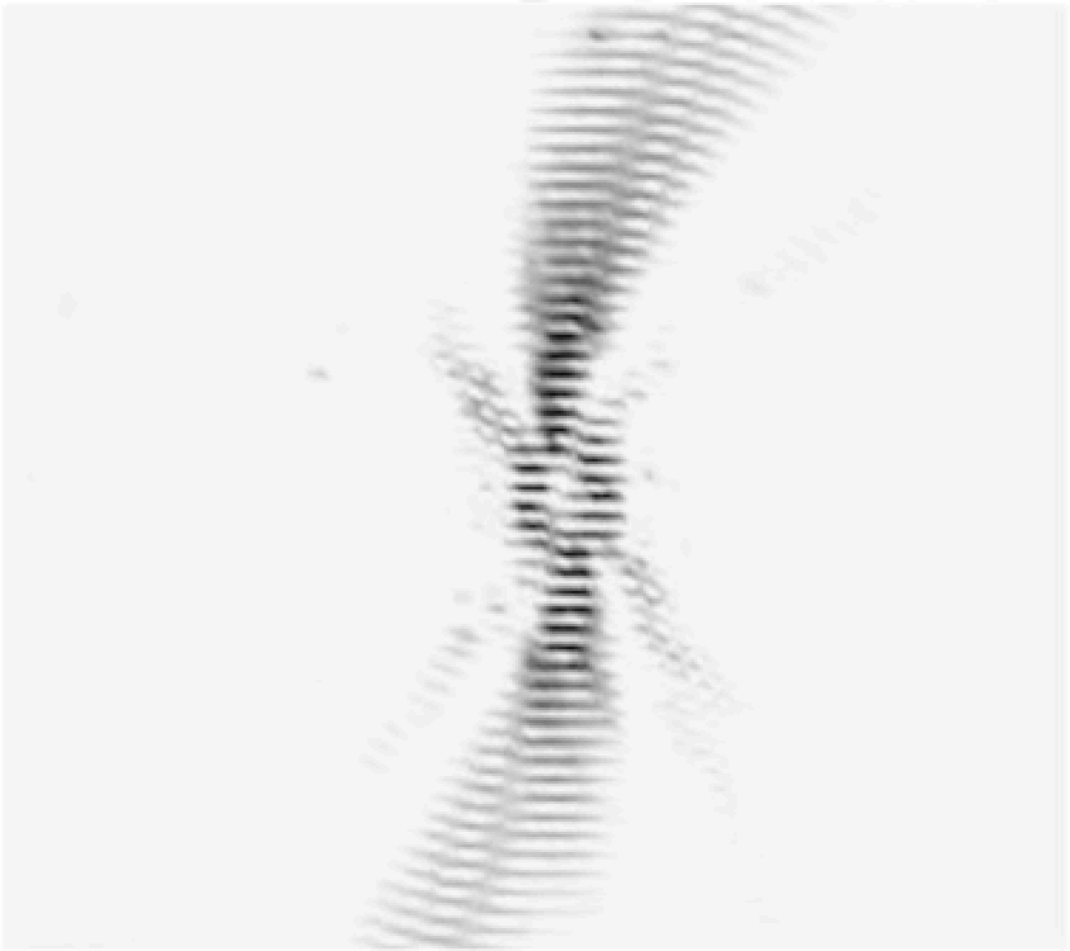
Plate response to chirp excitation

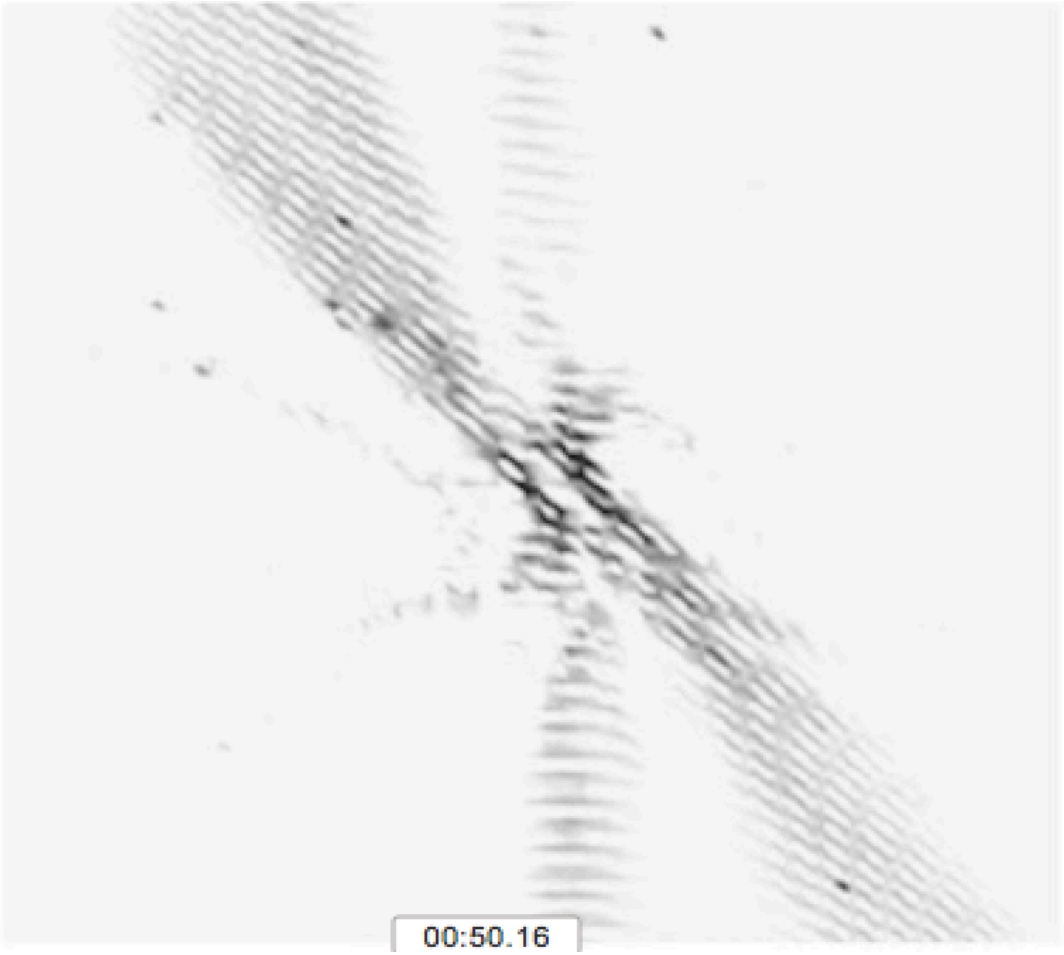


Experimental Results:
Plate response to chirp excitation

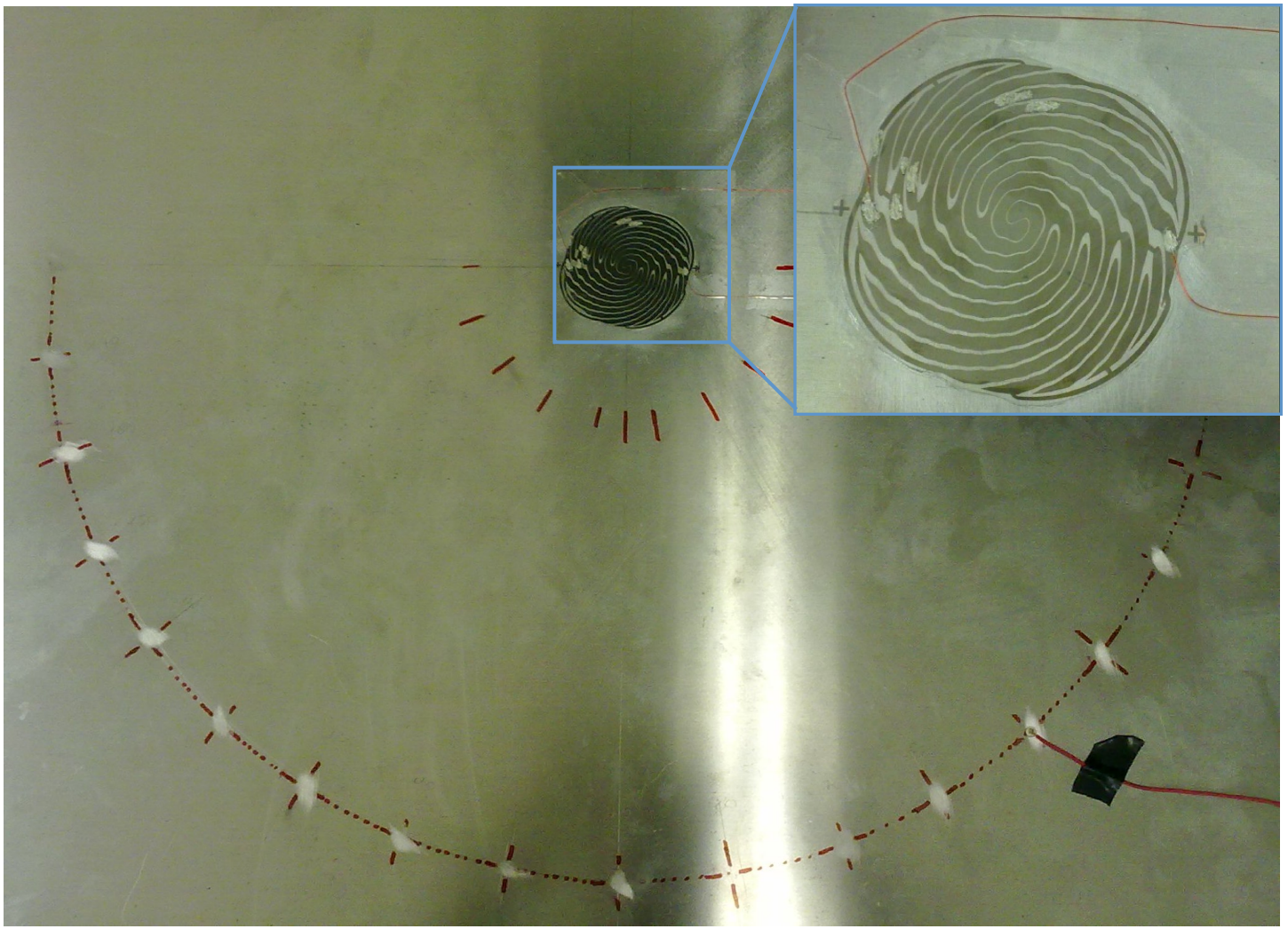


Experimental Results:
Plate response to chirp excitation

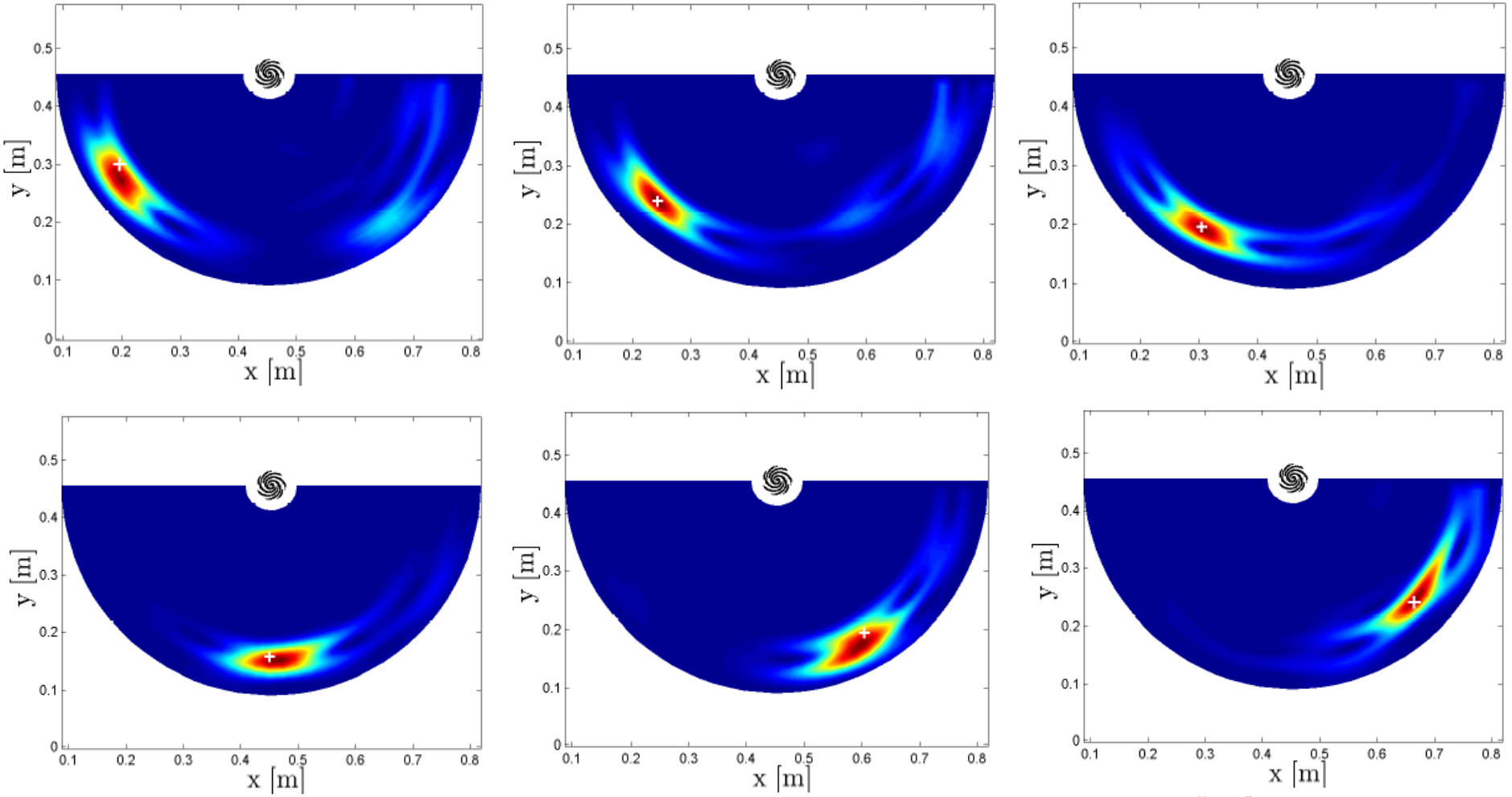
Experimental Results:
Plate response to chirp excitation



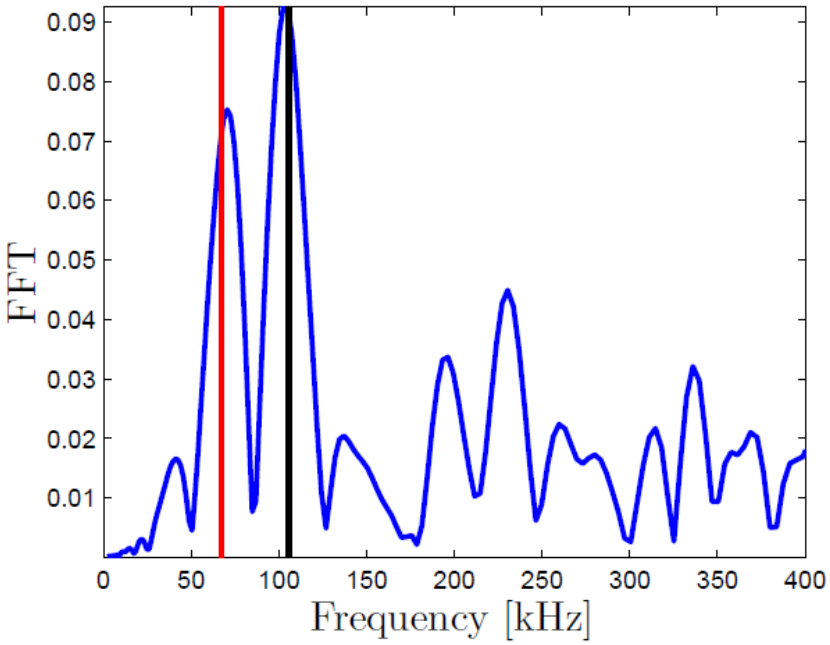
Experimental Results:
Source localization

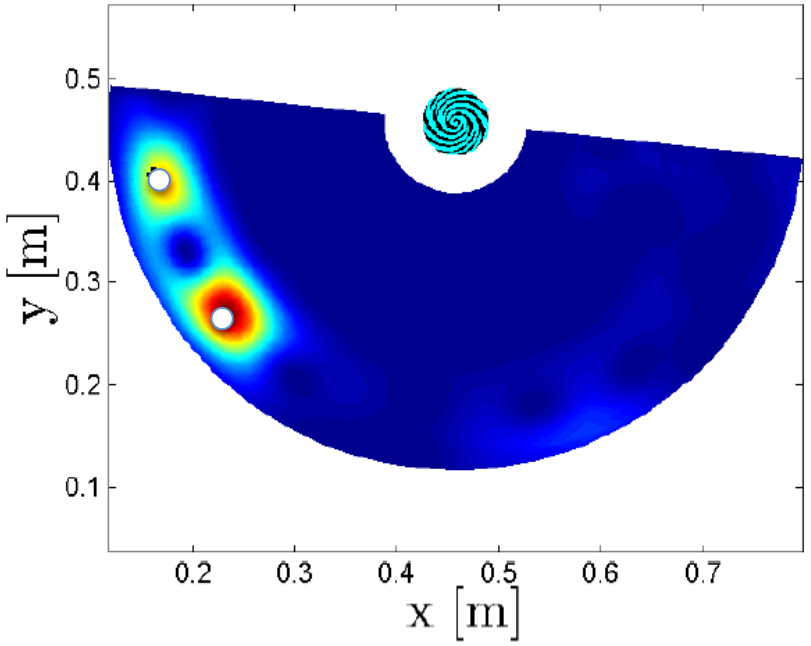


Experimental Results:
Source localization

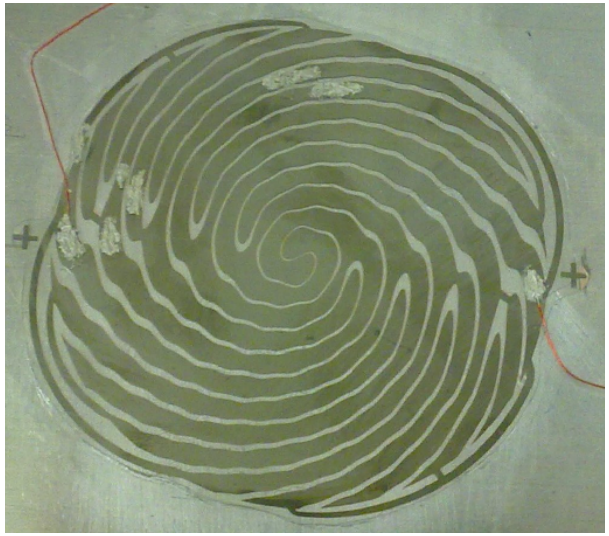


Experimental Results:
Two-source localization



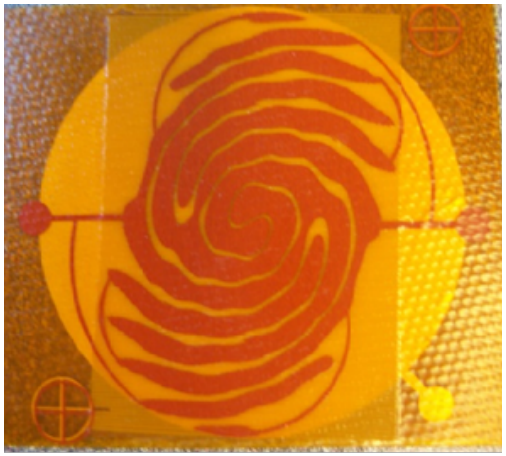


FSAT Fabrication on varied substrates



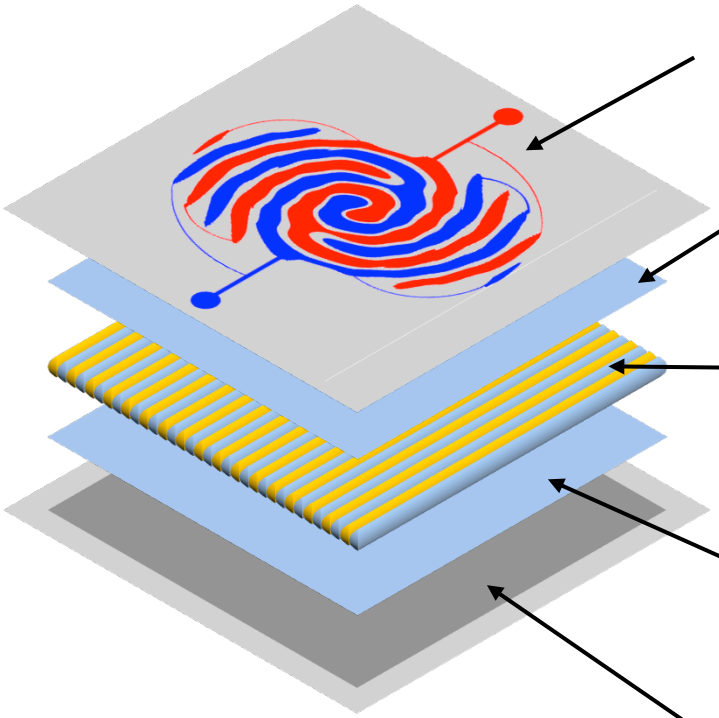
PVDF

PZT



MFC

MFC- FSAT



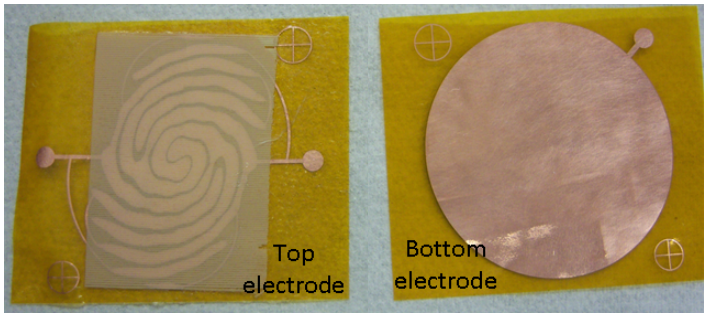
Apodized spiral FSAT
top electrode
on polyimide film

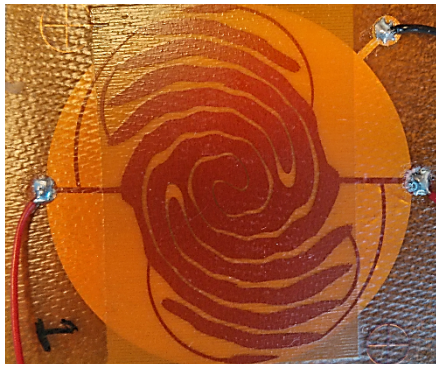
Structural
epoxy

Active layer
(PZT fibers + epoxy)

Structural
epoxy

Continuous back
electrode on
polyimide film



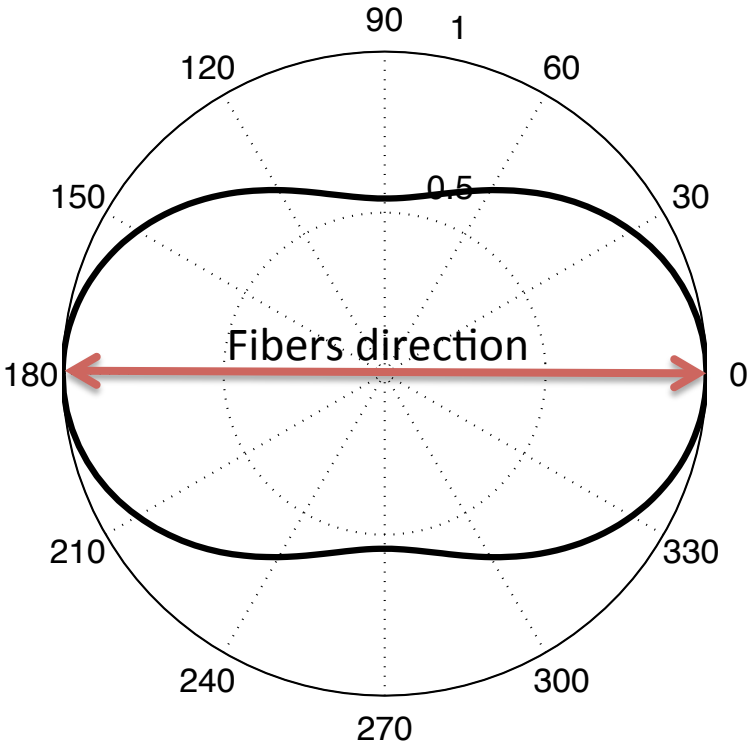


In collaboration with Prof. Cesnik @ UMich

Compensation Function

$$V(\omega) = jU_{1'_0}(\omega)k_0(\omega)\mathcal{H}(\theta)\mathcal{D}(\omega,\theta)$$

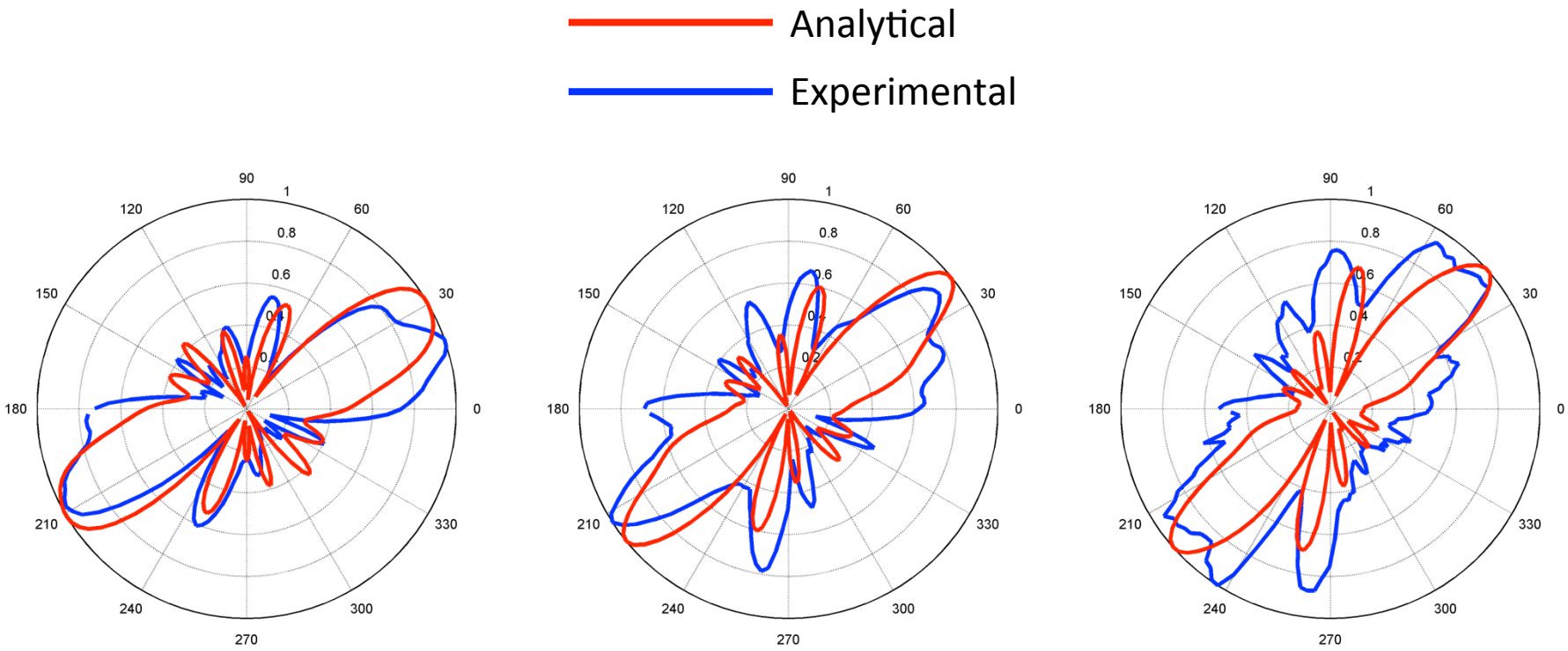
$$\mathcal{H}(\vartheta) = \frac{t_P}{A_P}\frac{(d_{31}c_{11} + d_{32}\nu_{12}c_{22})cos^2(\vartheta) + (d_{31}\nu_{12}c_{22} + d_{32}c_{22})sin^2(\vartheta)}{\boldsymbol{b}^T(\boldsymbol{d}^\sigma \boldsymbol{C}^E \boldsymbol{d}^{\sigma^T} - \epsilon^\sigma)\boldsymbol{b}}$$



$$\mathcal{C}(\vartheta) = \frac{1}{\mathcal{H}(\vartheta)}$$

$$a_n = a_0\bar{C}_n \quad \text{with} \quad \bar{C}_n = \frac{C_n}{max(C_n)}$$

Directionality Plots



80 kHz

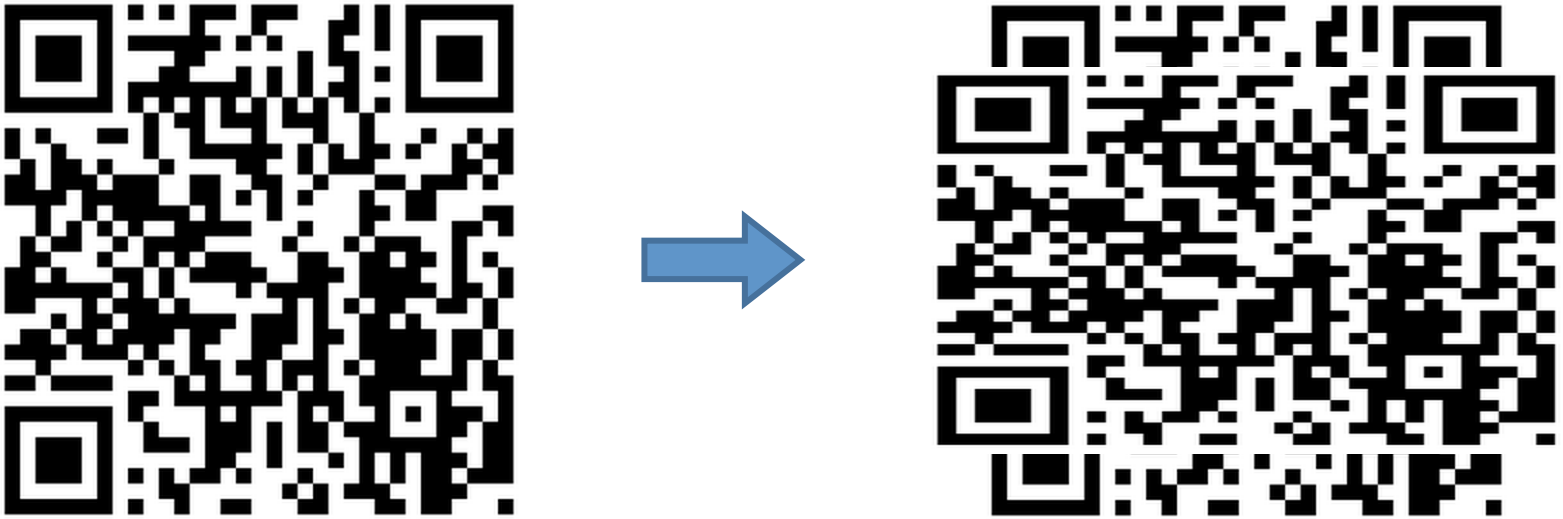
90 kHz

100 kHz

Acoustic Wave Rosettes for multi-component strain sensing

Conceptual Idea

- Think of patterning as a **QR code** where stretching of patterning carries information about strain components

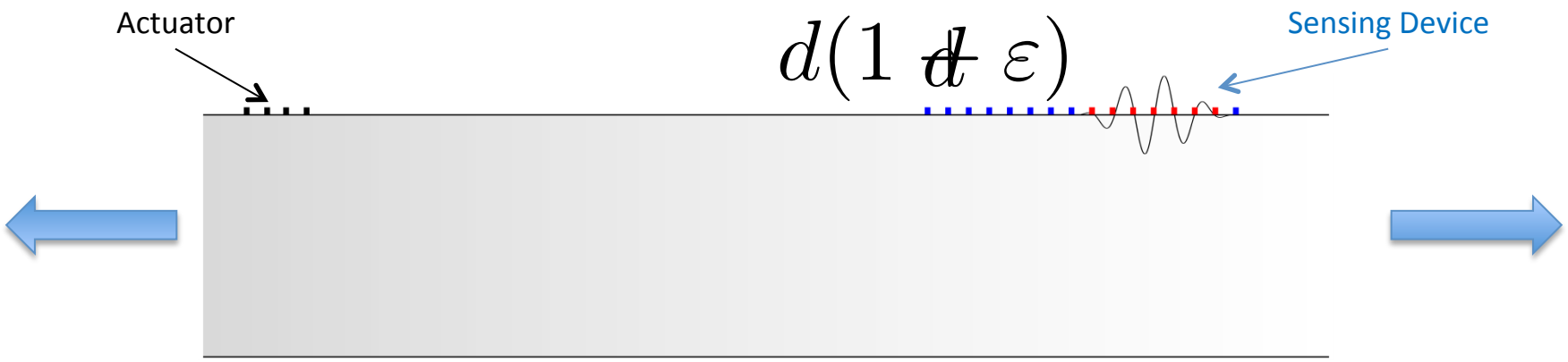


Scan info → No strain

Scan info → ϵ_x, ϵ_y, ϵ_{xy}

Scan device → Surface Acoustic Wave (SAW)

Surface Acoustic Wave (SAW) Strain Sensors



- Sensing material distribution

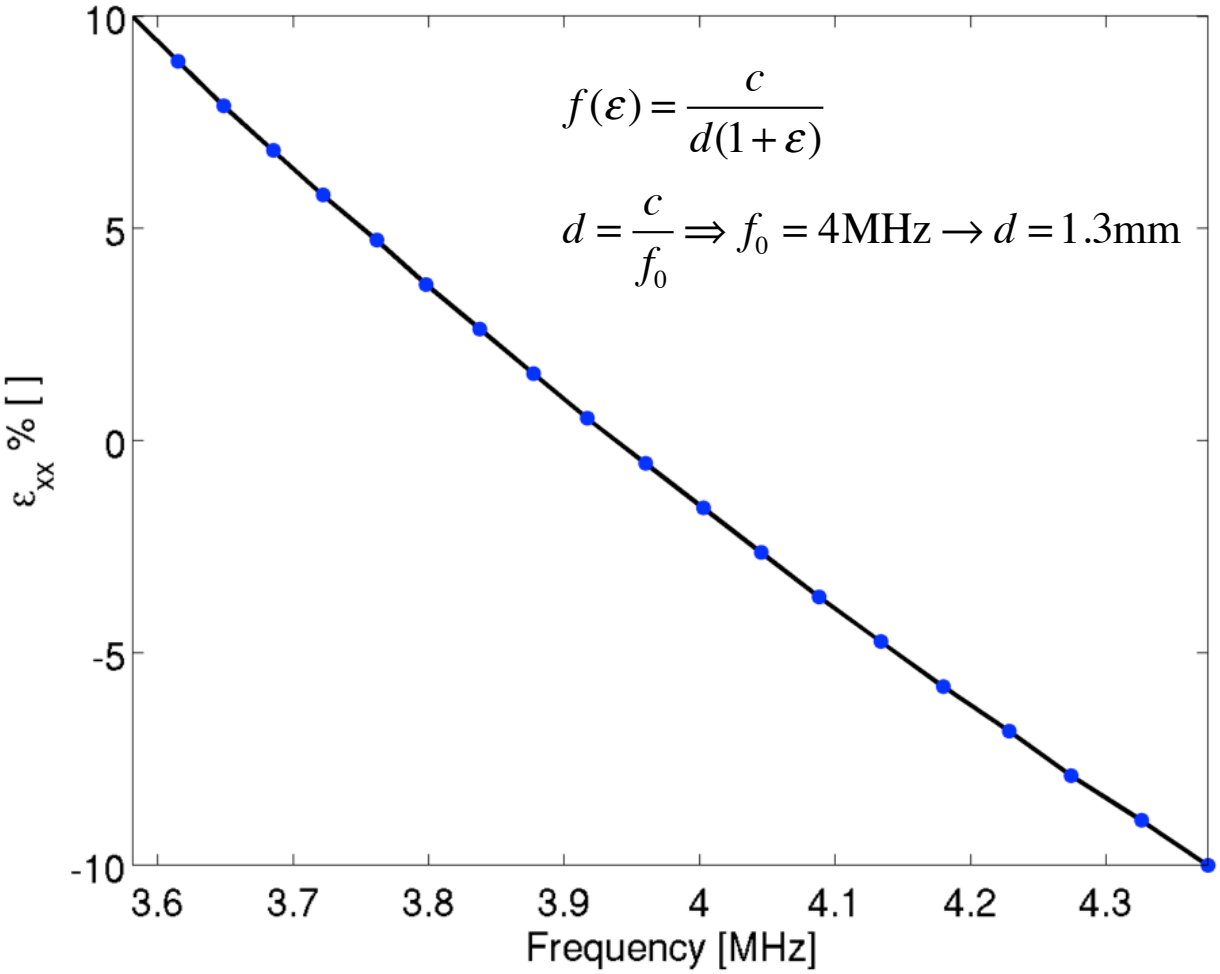
$$f(x) = \sum_{i=1}^{N} \delta(x - id(1+\varepsilon))$$

- Strain-Frequency relation

$$c_R = \frac{0.87 + 1.12\nu}{1+\nu}\sqrt{\frac{G}{\rho}}$$

$$f = \frac{c_R}{d(1+\varepsilon)}$$

Strain - Frequency relation



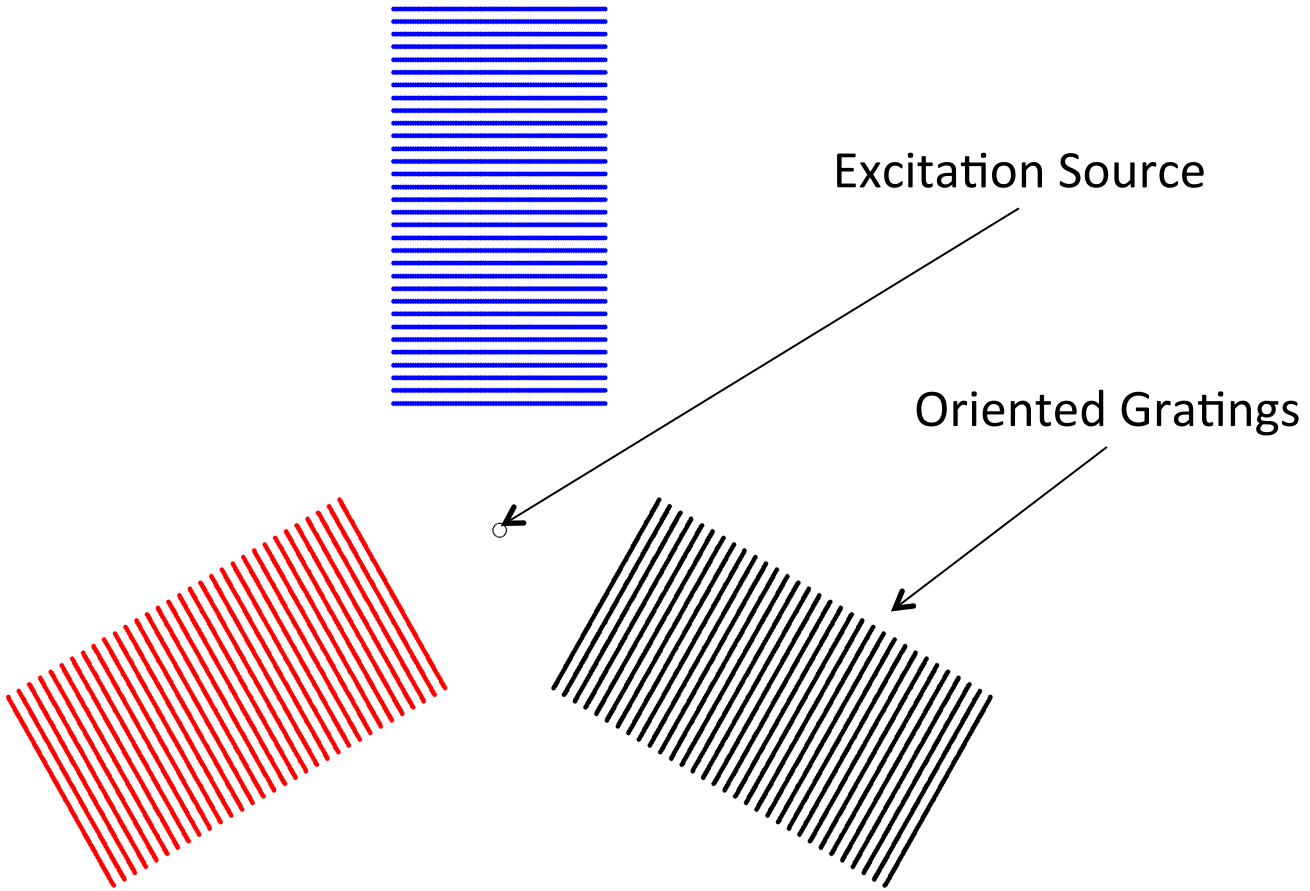
- Encoded surface acoustic wave based strain sensor (**US Patent** 6810750 B1, 2004)
- W.C. Wilson, and G.M. Atkinson, *Modeling of a Surface Acoustic Wave Strain Sensor*, **NASA Report**, 2012.
- B. Mc Cormak, D. Geraghty, and M. O'Mahony, *Modeling of Surface Acoustic Wave Strain Sensors Using Coupling-of-Modes Analysis*, **IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control**, 58(11) 2011.
- V. Olariu, A. Gnadinger, J. Bao and V. Giurgiutiu, *Autonomous Battery-Less Wireless Strain Gage for Structural Health Monitoring*

Rosette Configuration

f_0 = 50 MHz

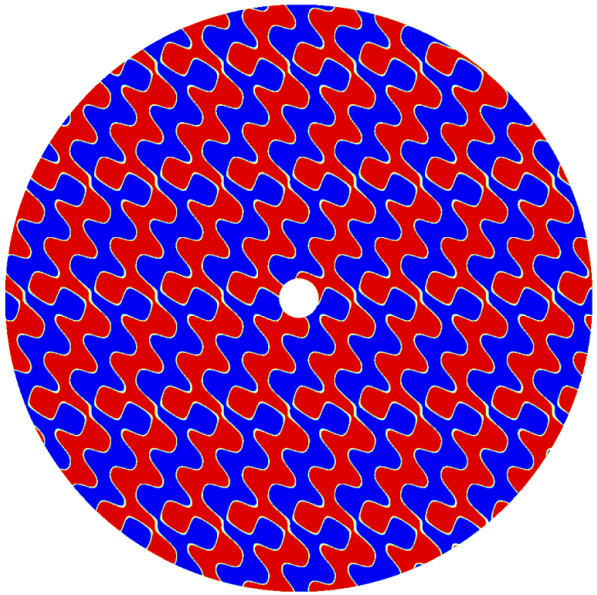
N = 32

-30°, 90°, 210°



2D Extension: Co-Located Rosette

Pattern is defined in the wavenumber domain



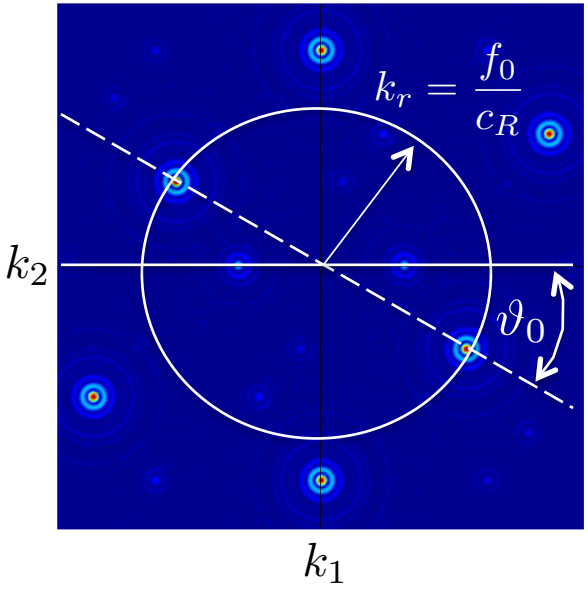
$$f(\boldsymbol{x}) = \frac{1}{N} rect\left(\frac{|\boldsymbol{x}|}{a}\right) \sum_{n=1}^{N} \sin(\boldsymbol{k}_n \cdot \boldsymbol{x})$$

Determination of surface strain components

- Strain rosette equation

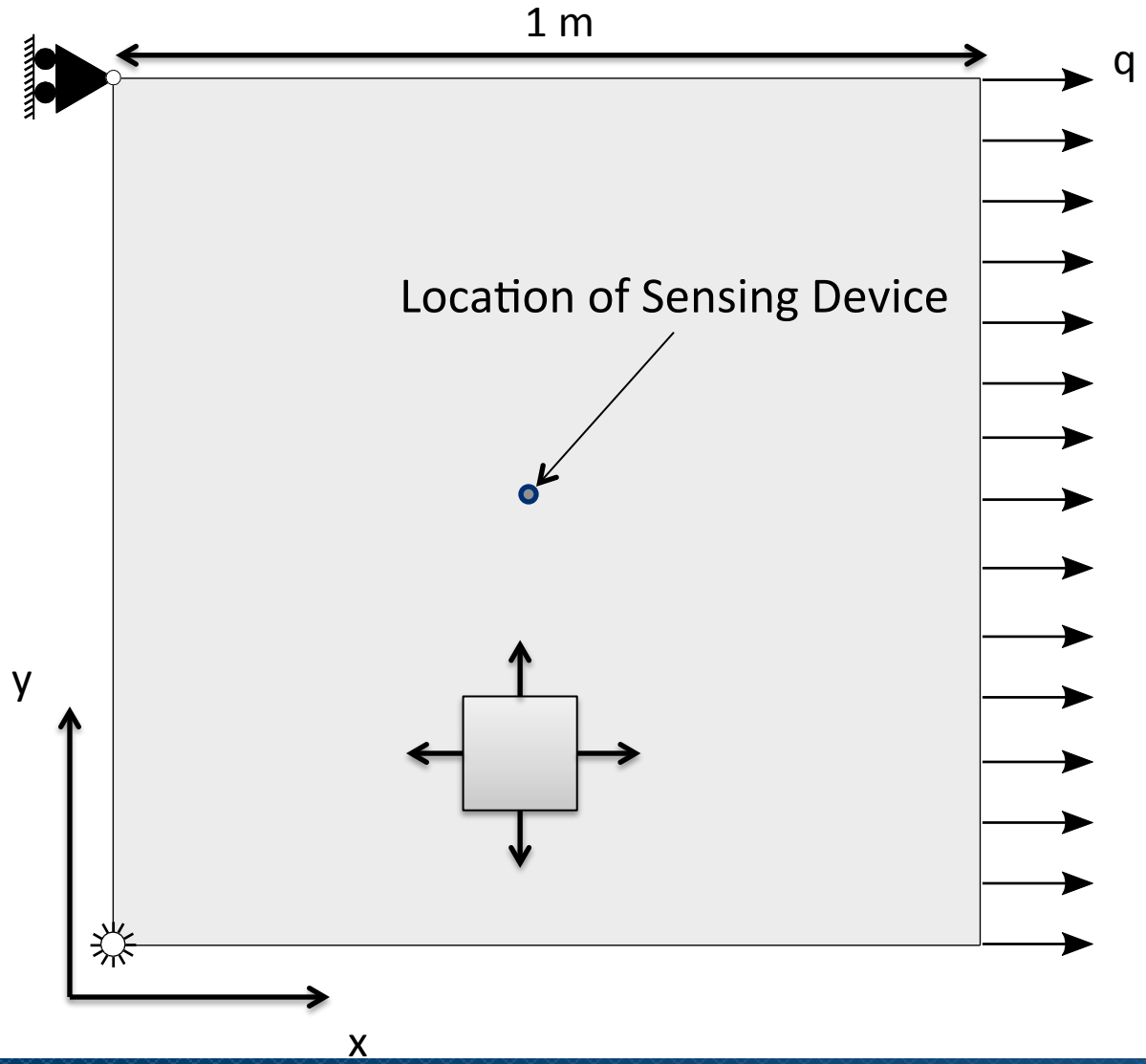
$$\varepsilon_x \cos^2(\vartheta_0) + \varepsilon_{xy} \sin(2\vartheta_0) + \varepsilon_y \sin^2(\vartheta_0) = \frac{1}{2}\left[1 - \left(\frac{f_d}{f_0}\right)^2\right]$$

  - f_0 and ϑ_0 assigned at design stage. They correspond to the radiation peak in wavenumber domain
  - f_d is a sensor output
  - ε_x, ε_y, ε_{xy} are the unknowns



$$\boldsymbol{A\epsilon = b}$$

Numerical test



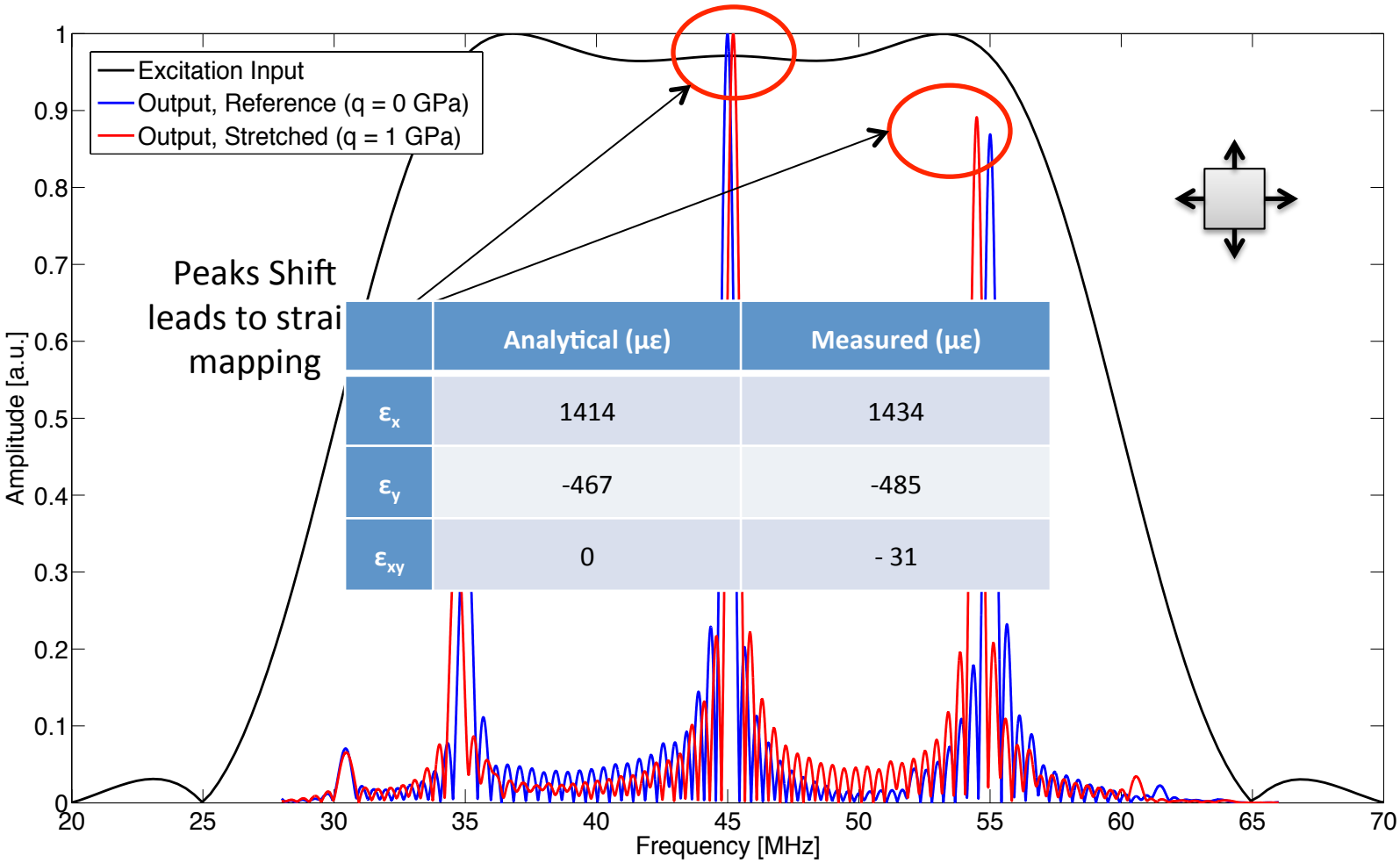
Displacement field

$$u = \frac{q}{E}x$$
$$v = -\nu\frac{q}{E}y$$

Strain Field

$$\varepsilon_x = \frac{q}{E}$$
$$\varepsilon_y = -\nu\frac{q}{E}$$
$$\varepsilon_{xy} = 0$$

Example Solution: q = 1 GPa

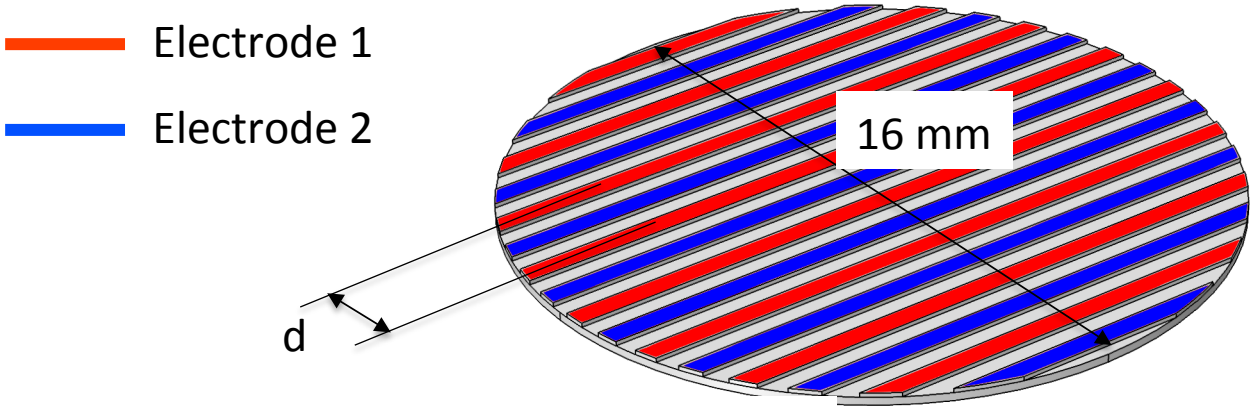


Peaks Shift leads to strai mapping

	Analytical (με)	Measured (με)
ε_x	1414	1434
ε_y	-467	-485
ε_{xy}	0	- 31

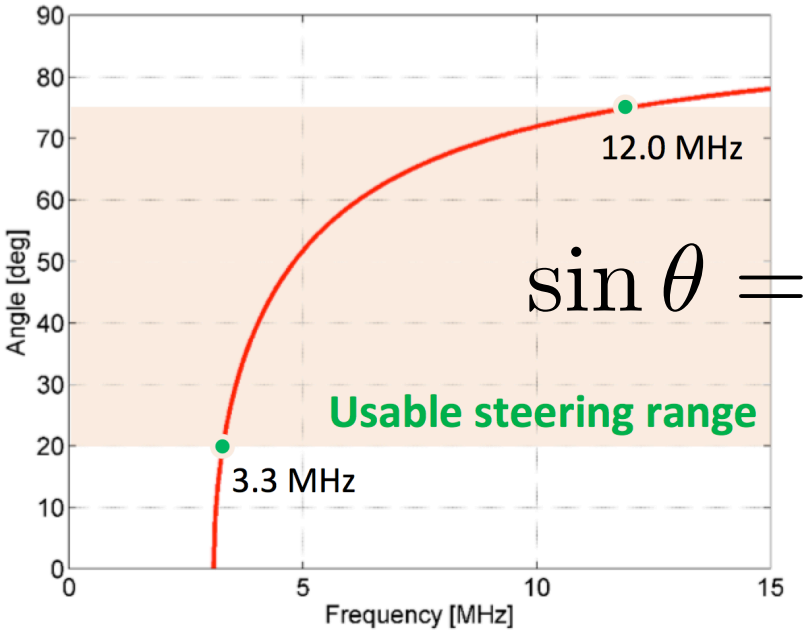
Steering of Bulk Waves
Transducer Design and Numerical Simulations

Steering properties in the bulk

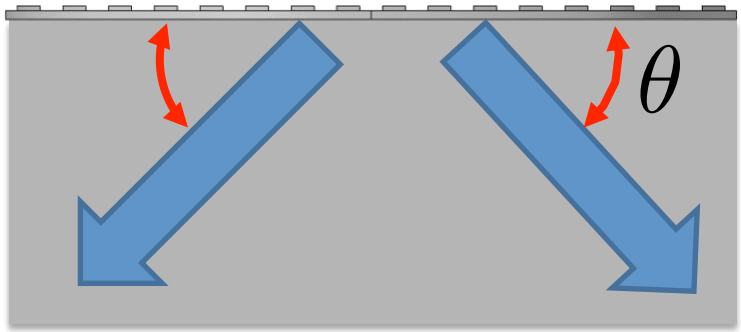


d = 2 mm

f_0 = 3.1 MHz

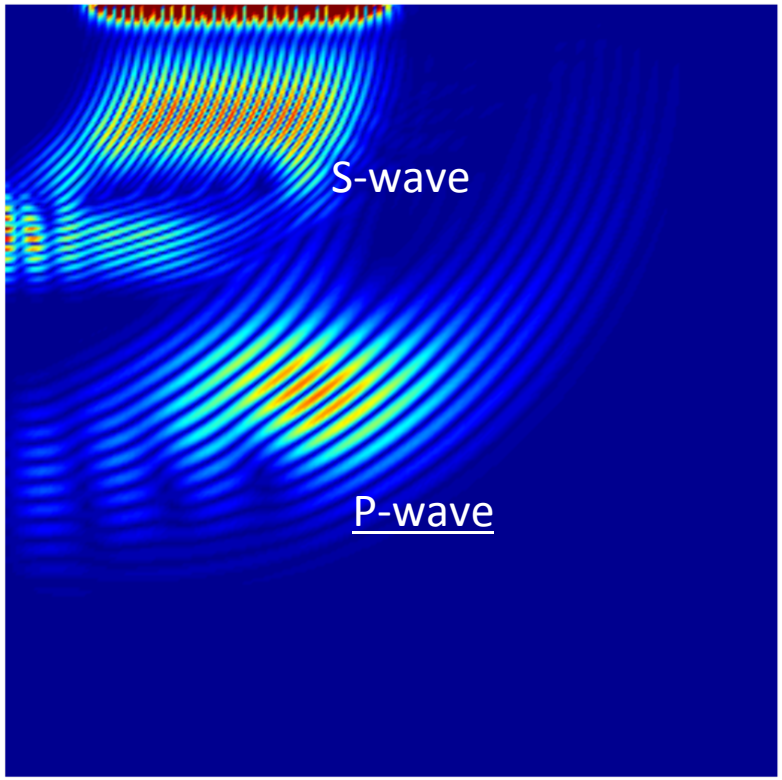


$$\theta \qquad \sin\theta = \frac{dc}{2f}$$

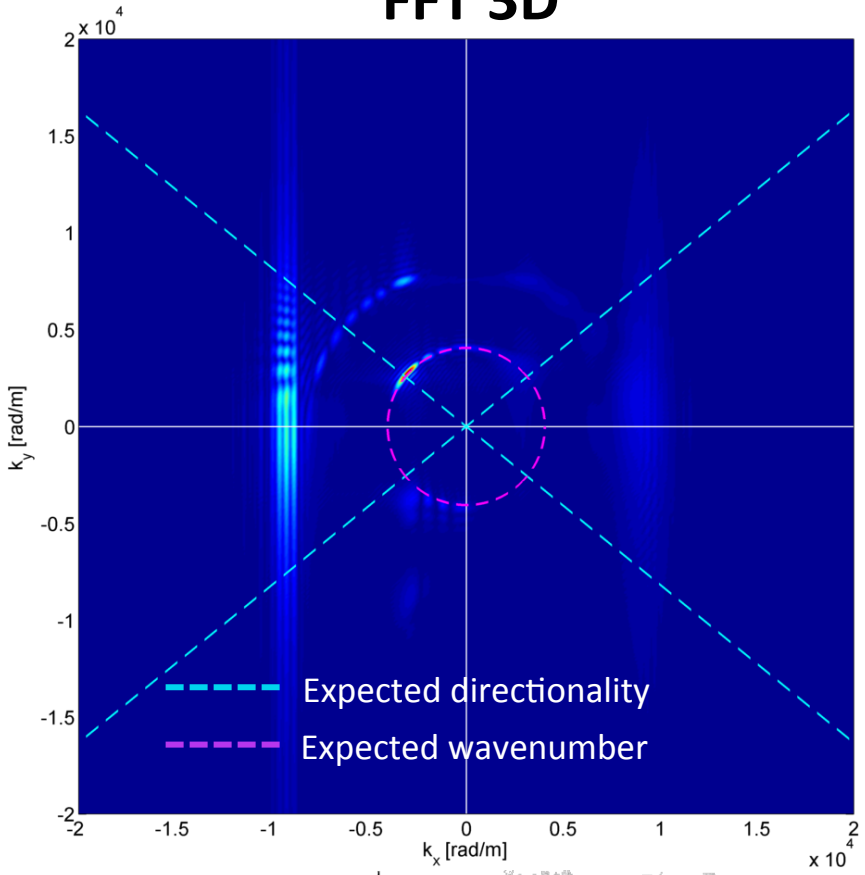


f = 4 MHz, Angle = 39.2°

Time snapshot

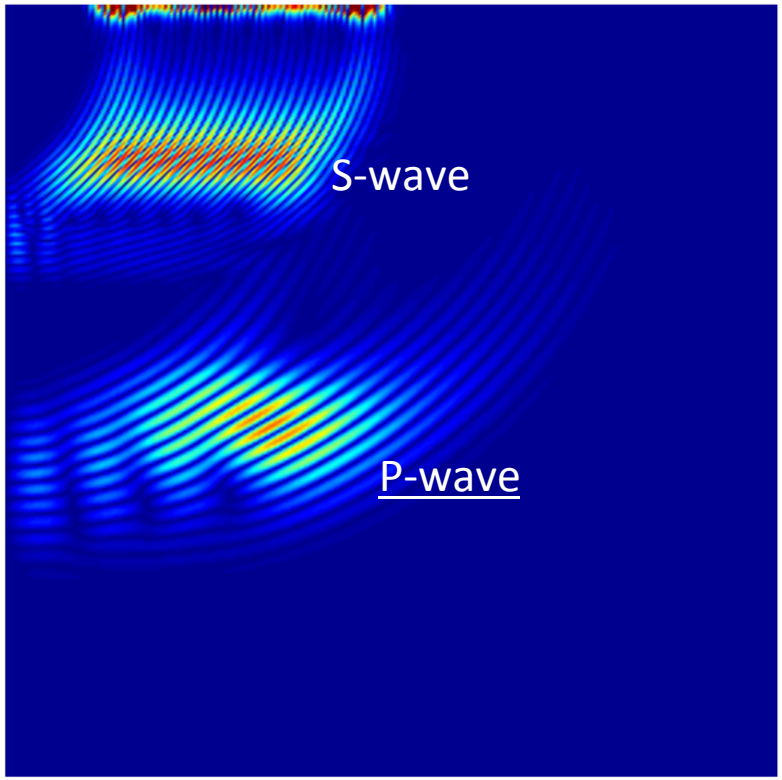


FFT 3D

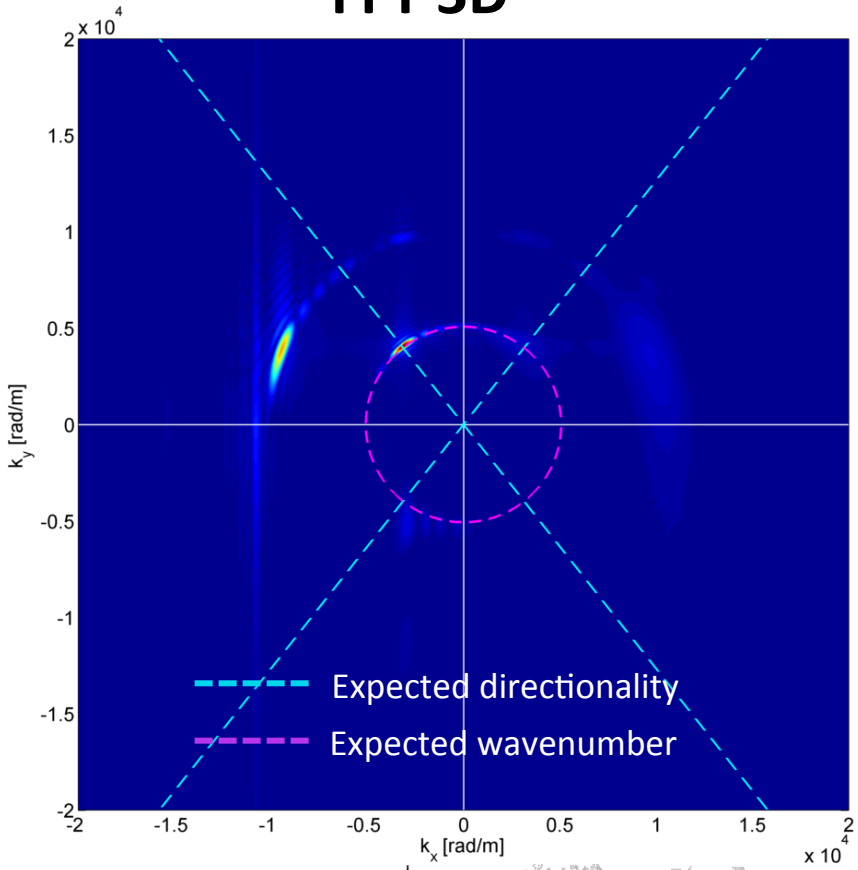


f = 5 MHz, Angle = 51.7°

Time snapshot

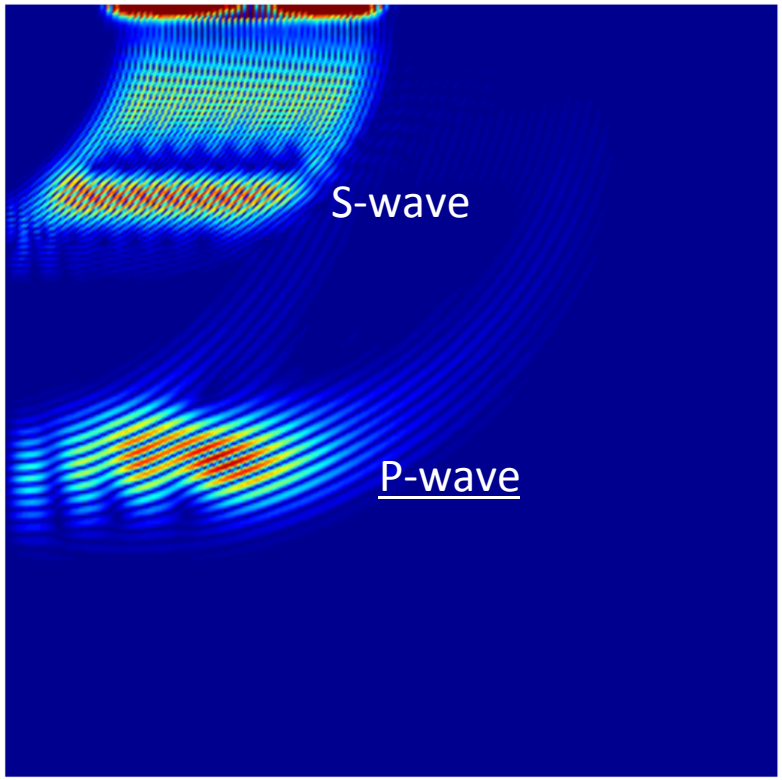


FFT 3D

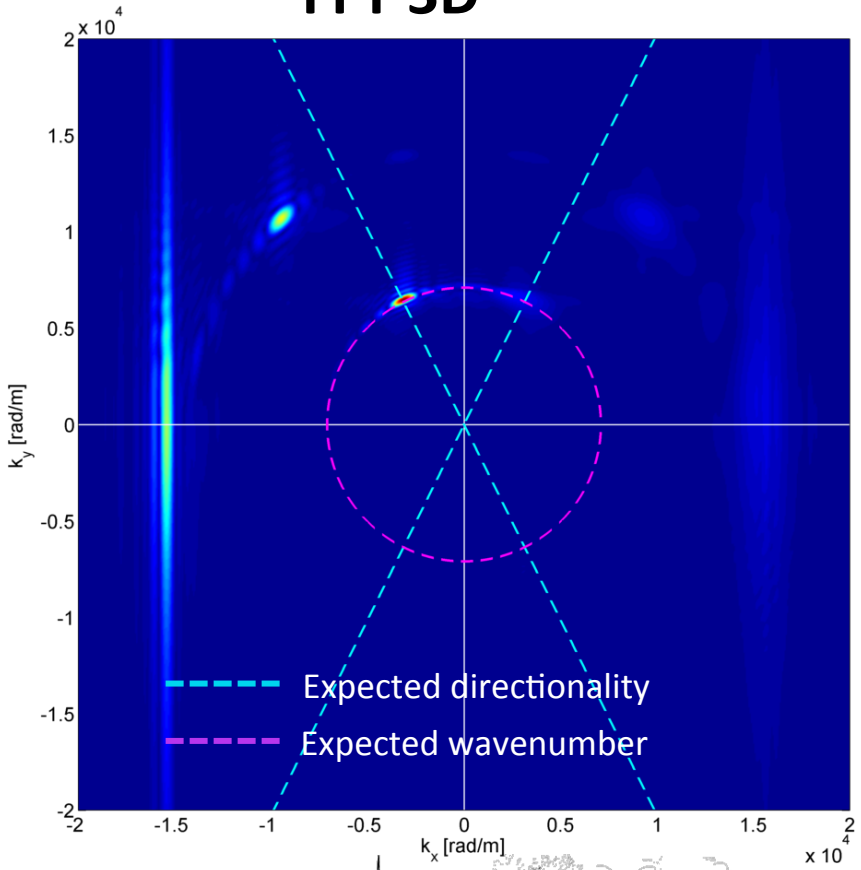


f = 7 MHz, Angle = 63.7°

Time snapshot

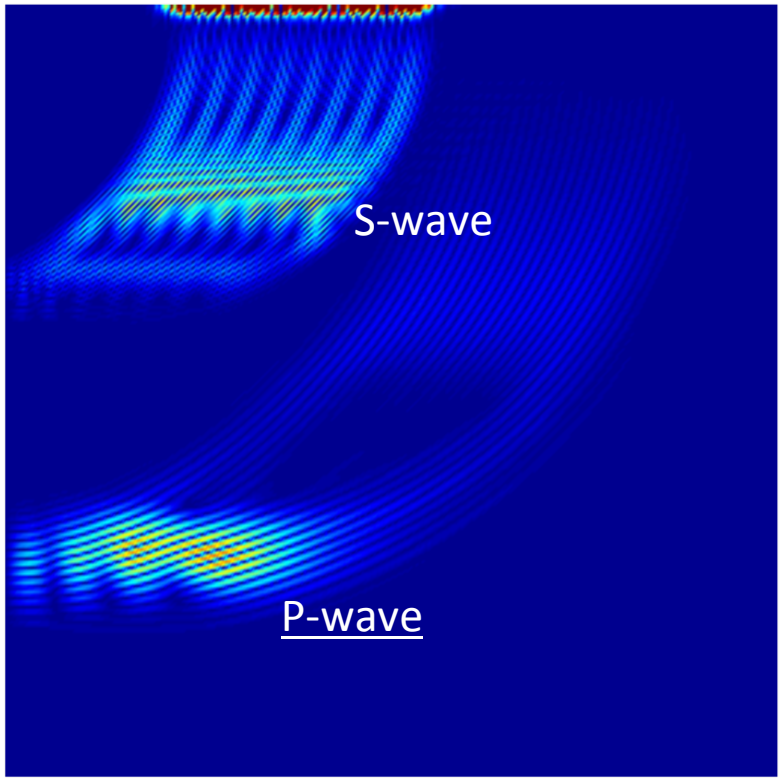


FFT 3D

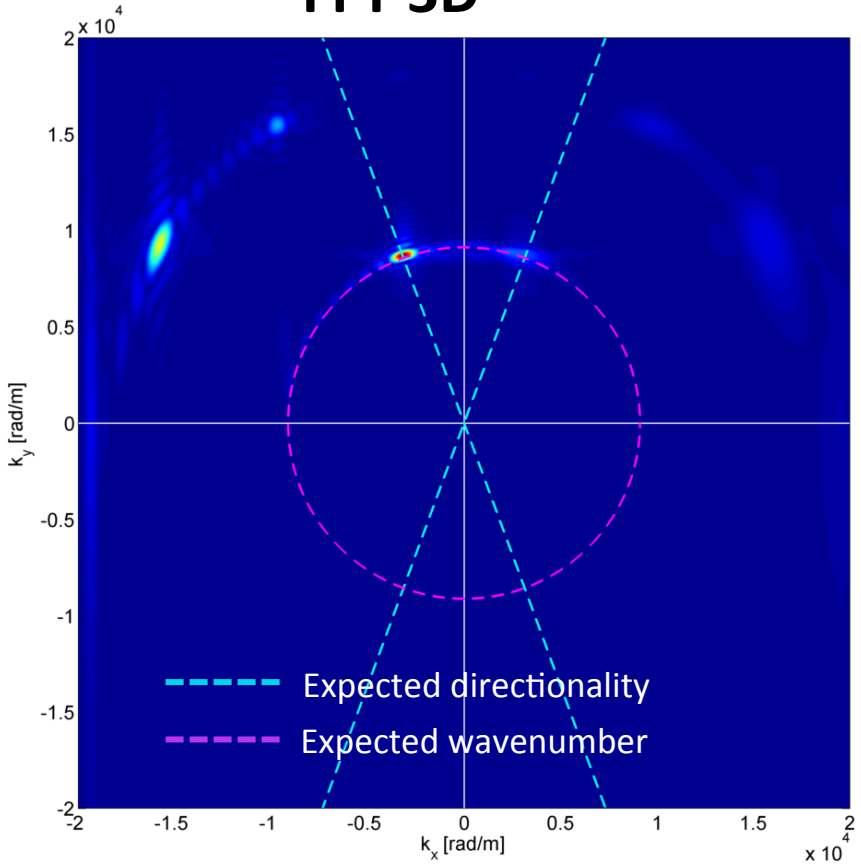


f = 9 MHz, Angle = 69.9°

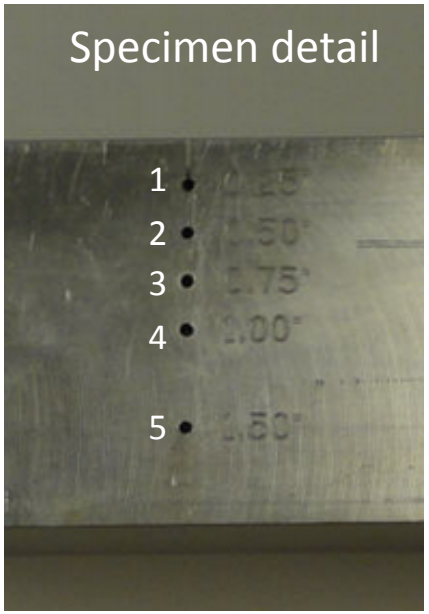
Time snapshot

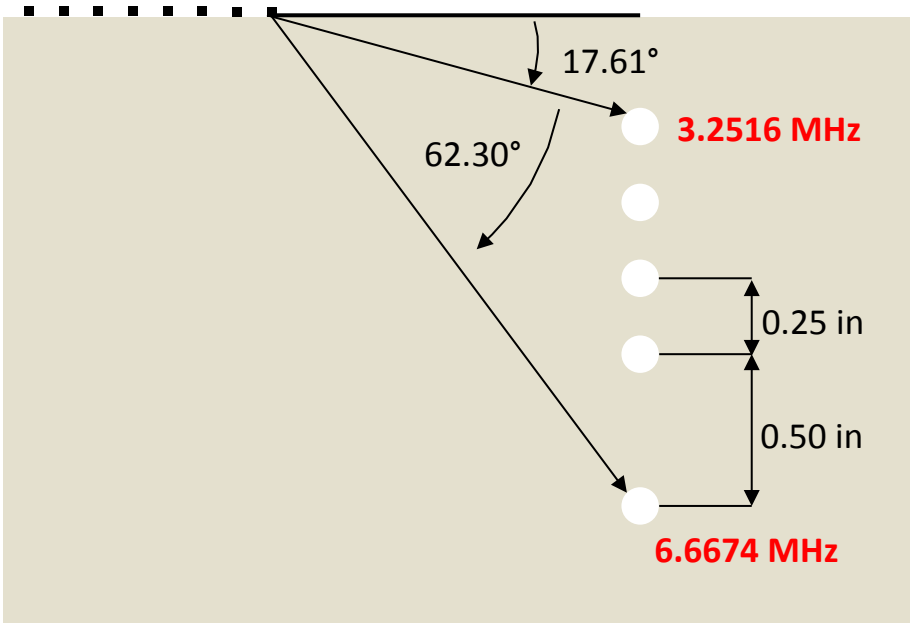


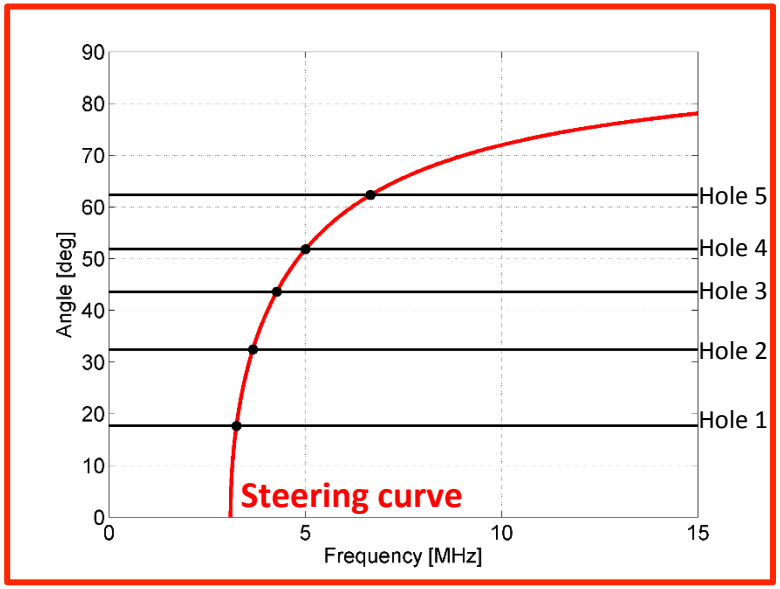
FFT 3D



Inspection scenario

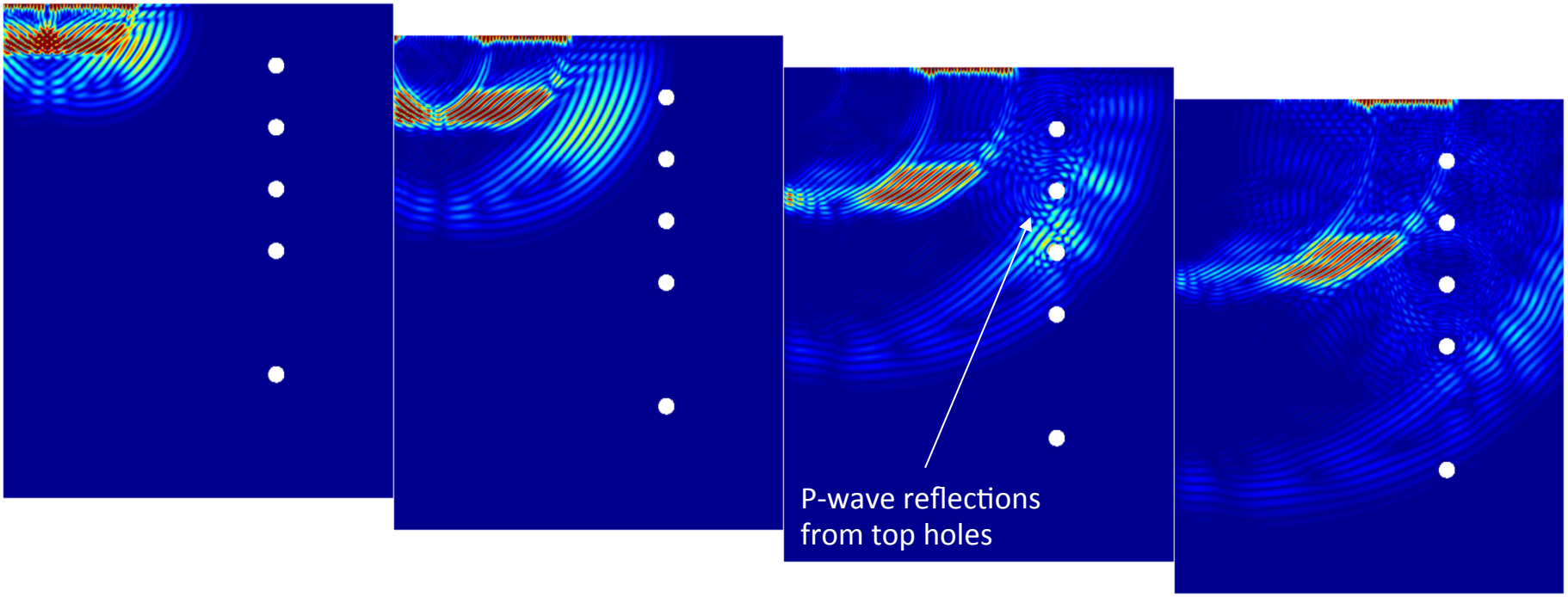




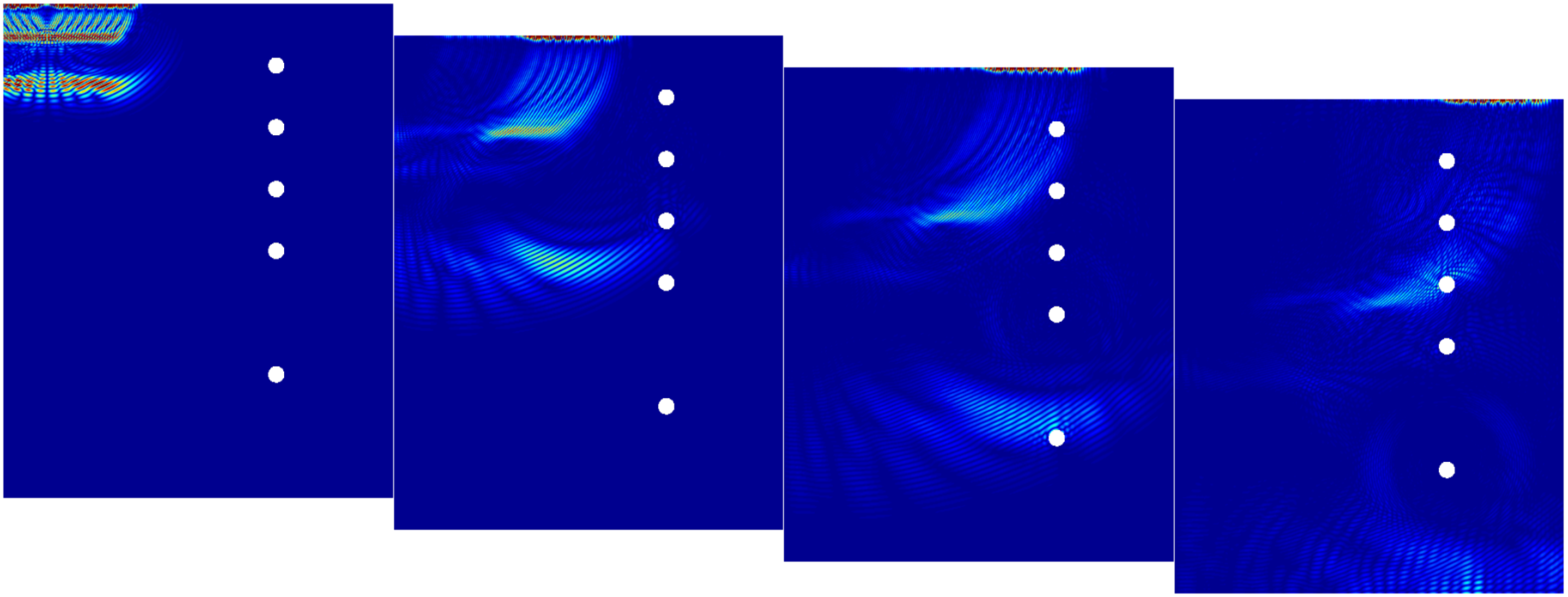


Hole	Angle [deg]	Frequency [MHz]
1	17.6	3.3
2	32.4	3.7
3	43.6	4.3
4	51.8	5.0
5	62.3	6.7

Results: f = 3.25 MHz

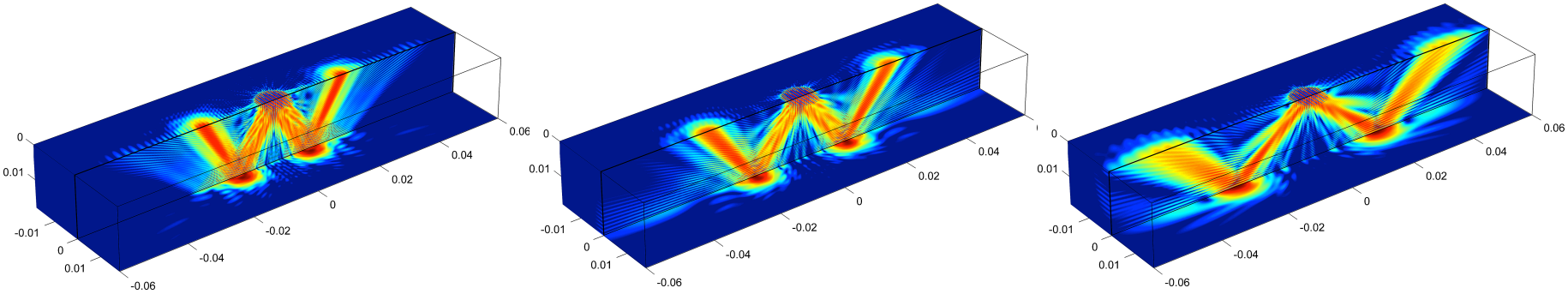


Results: f = 6.67 MHz

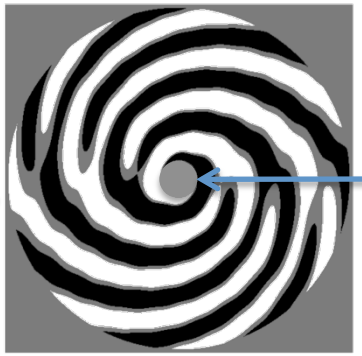


Summary and Outlook

- Class of transducers designed through a Fourier-based approach
  - Sensing material distribution is designed and analyzed in spatial Fourier domain
  - Exploitation of inherent frequency-dependent directional properties (SHM application)
  - Frequency shifts of radiation associated with local straining (strain sensing application)
- Currently working on Bulk wave FSAT for thickness steering/interrogation



- Potential for integration for a health&usage monitoring device



Strain Sensor
(Rayleigh wave based)

SHM Transducer
(Lamb wave based)

Thank you

Collaborators

M. Carrara, B. Xu,

E. Baravelli, M. Senesi, S. Gonella

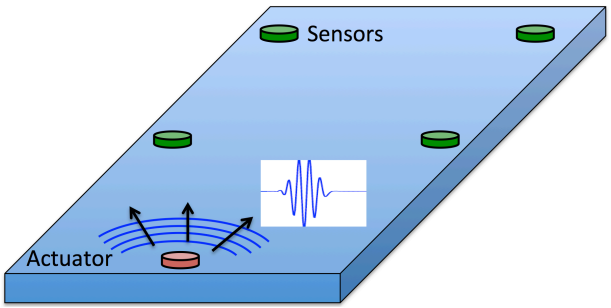
Task 11 *Multifunctional Sensors for Loads Monitoring and Structural Diagnostic*

Georgia Tech VLCROE (2011-2016).

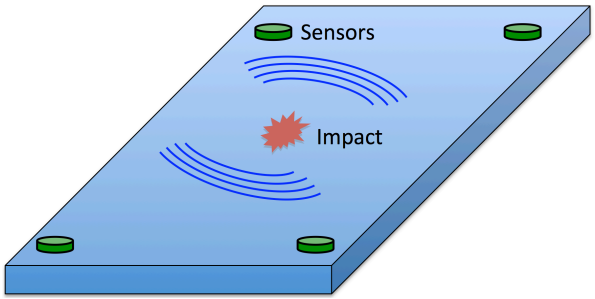
Background

- Monitoring issues:
  - Airframe:
    - Fatigue cracking and corrosion drivers of inspections and maintenance
    - Damage from impact/ballistic events
  - Rotor hub:
    - Dynamic components subject to high-cycle fatigue
    - Impact damage (ballistic damage, delaminations, voids)

- Structural Health and Usage Monitoring strategies:
  - Loads monitoring through strain measurements for fatigue estimation
  - Active monitoring of large areas or inaccessible hotspots
  - Passive sensing and localization of impacts

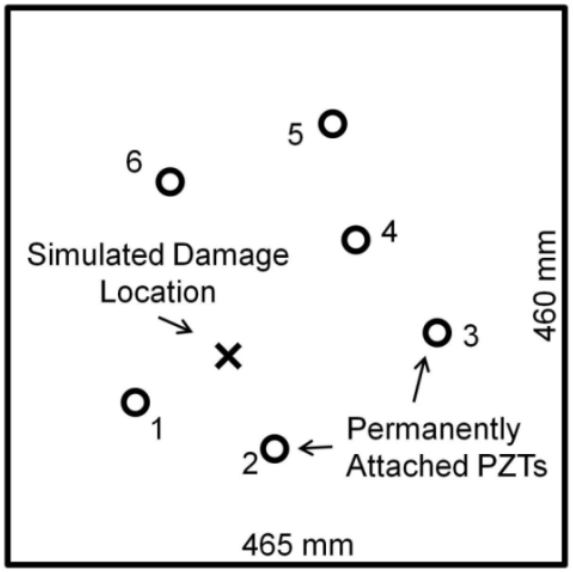


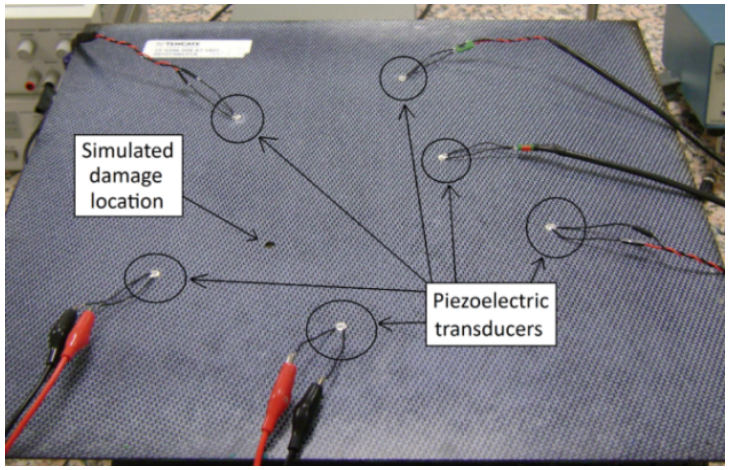
Active SHM

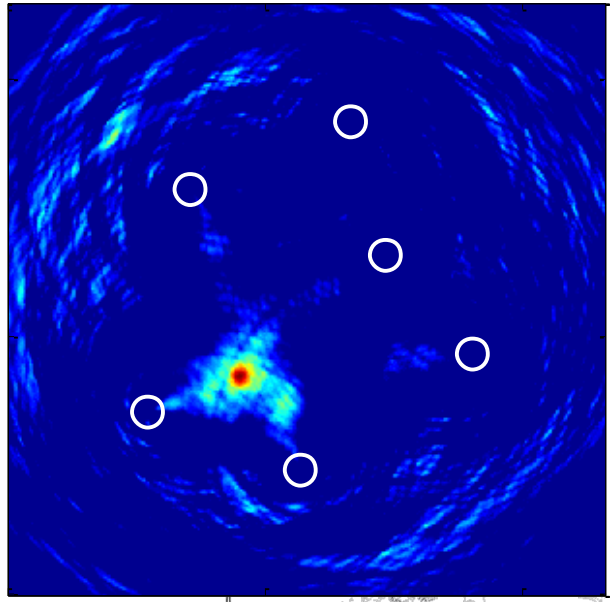


Passive SHM

SHM Distributed Transducer Arrays





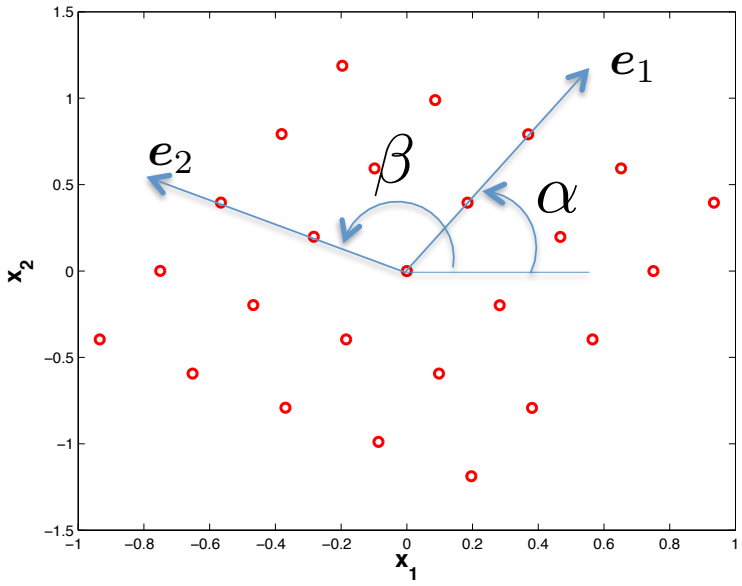


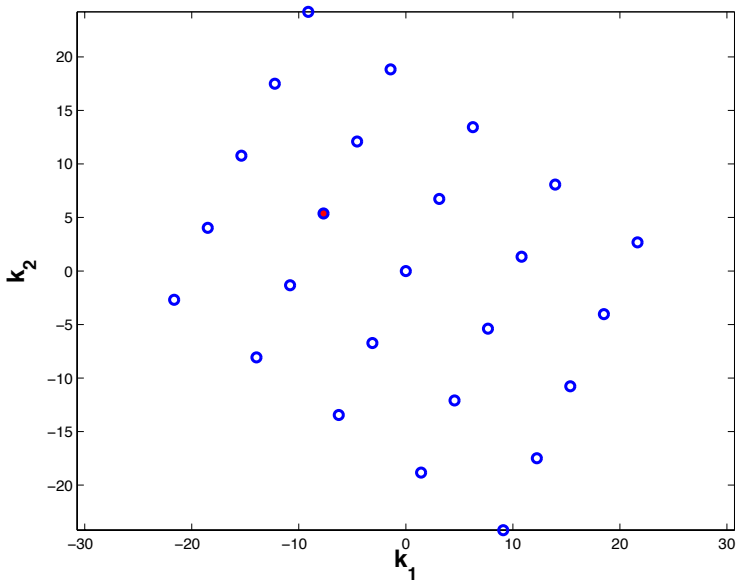
- CFRP composite panel
- Quasi-isotropic layup of $[0/90/-45/45]_2$

Courtesy of J. & T. Michaels – Georgia Tech

Quadrilateral array

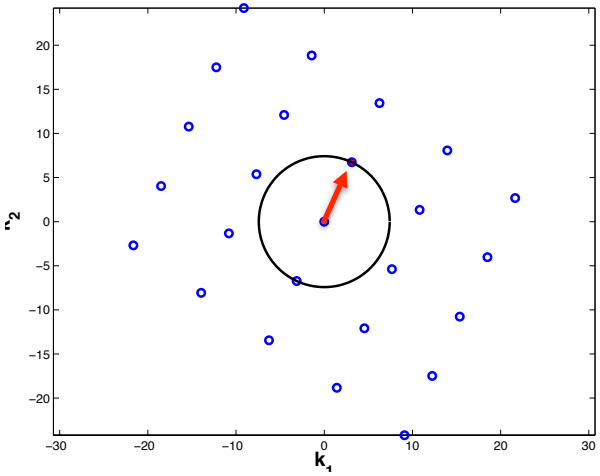
$$f(x_1, x_2) = f_0 \sum_{n=1}^{N} \sum_{m=1}^{M} \delta(\boldsymbol{x} - \boldsymbol{x}_{n_1,n_2}) \qquad \boldsymbol{x}_{n_1,n_2} = n_1 \boldsymbol{e}_1 + n_2 \boldsymbol{e}_2$$

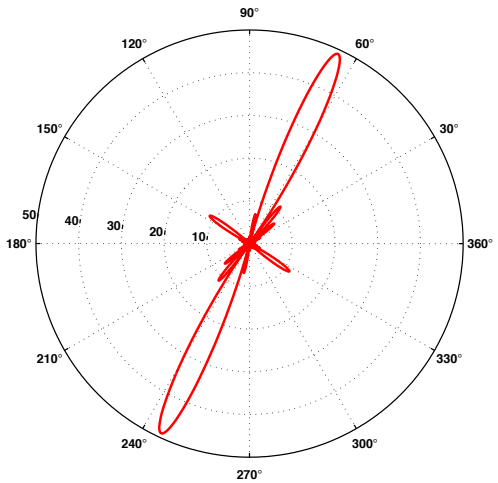


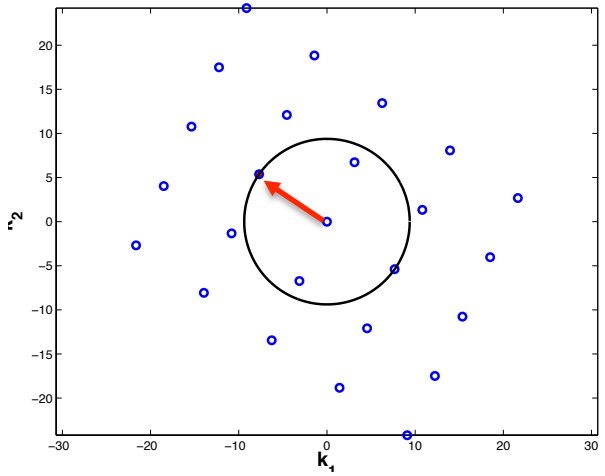


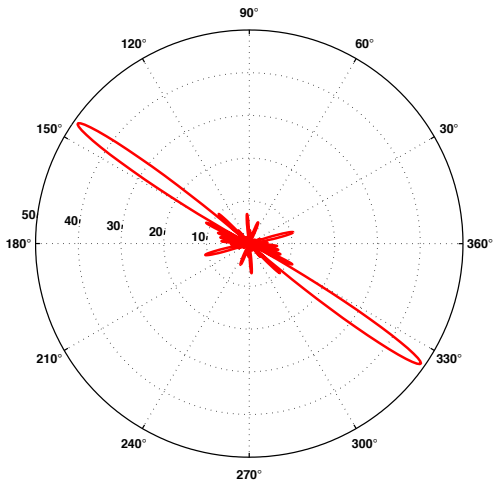
$$\boldsymbol{e}_1 = d_1 \cos\alpha \boldsymbol{i}_1 + d_1 \sin\alpha \boldsymbol{i}_2$$
$$\boldsymbol{e}_2 = d_2 \cos\beta \boldsymbol{i}_1 + d_2 \sin\beta \boldsymbol{i}_2$$

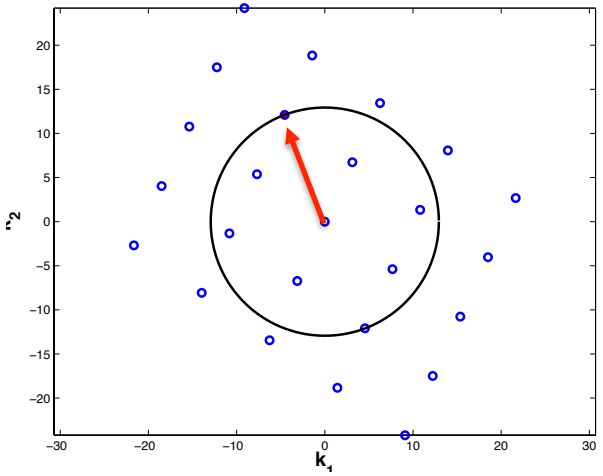
Romanoni, M., et al., *Two-dimensional periodic actuators for frequency-based beam steering.*art Materials & Structures, 2009. **18**(12).

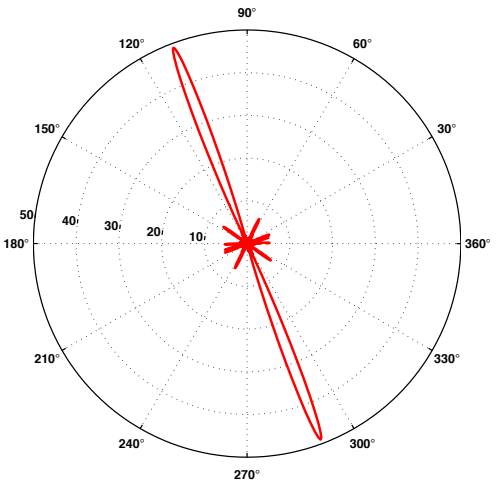








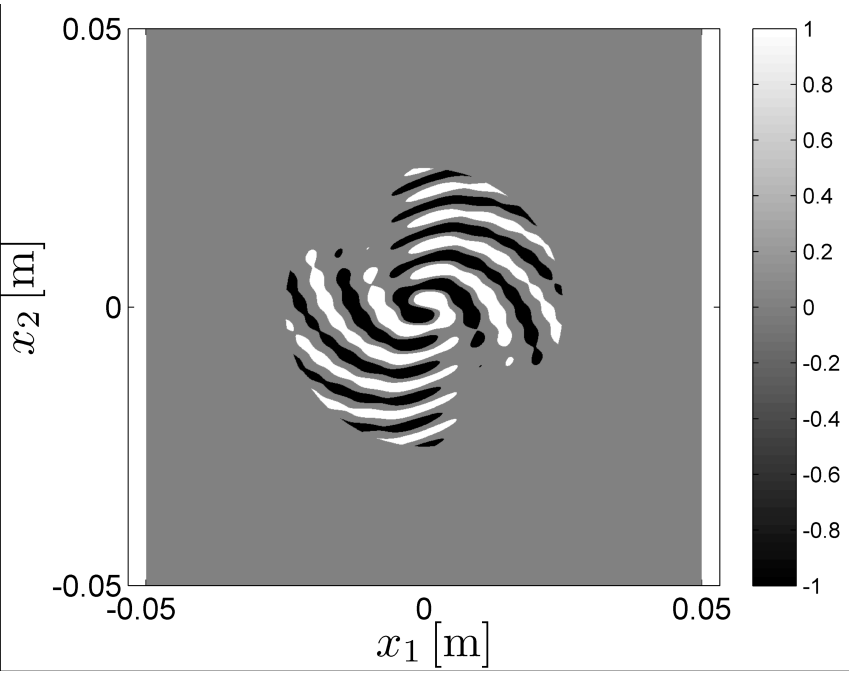


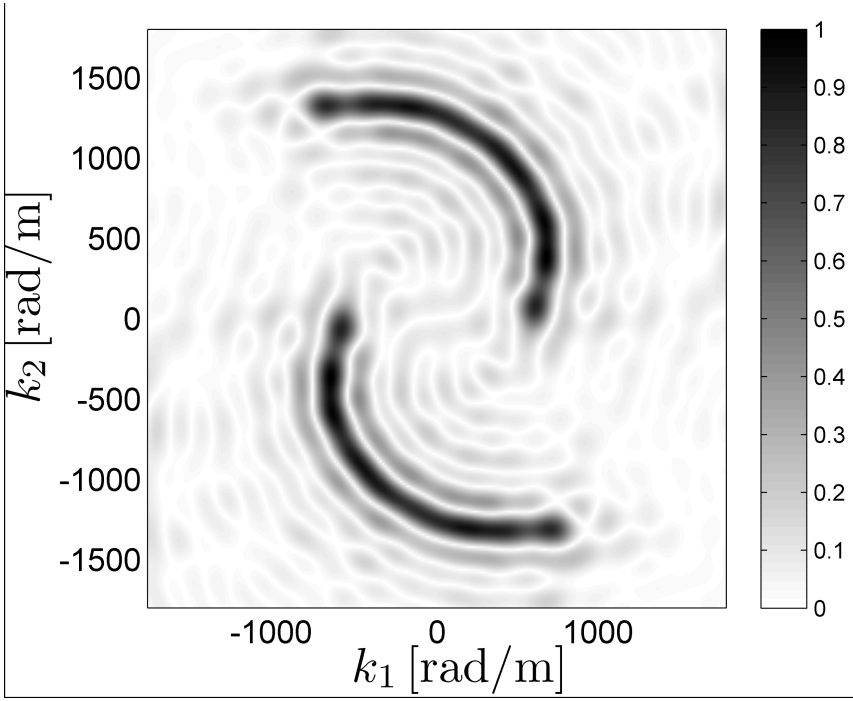


Frequency-dependent radiation

FSAT Spiral Array: thresholding

$$\bar{f}(\boldsymbol{x}) = \begin{cases} 1, & f(\boldsymbol{x}) \geq \varepsilon \\ 0, & f(\boldsymbol{x}) < |\varepsilon| \\ -1, & f(\boldsymbol{x}) \leq -\varepsilon \end{cases}$$





Numerical Results:
Chirp Excitation

Determination of surface strain components

- Three equations needed to solve for strain components (linear system)

$$\boldsymbol{A}\boldsymbol{\epsilon} = \boldsymbol{b} \quad \Longrightarrow \quad \boldsymbol{\epsilon} = \boldsymbol{A}^{-1}\boldsymbol{b}$$

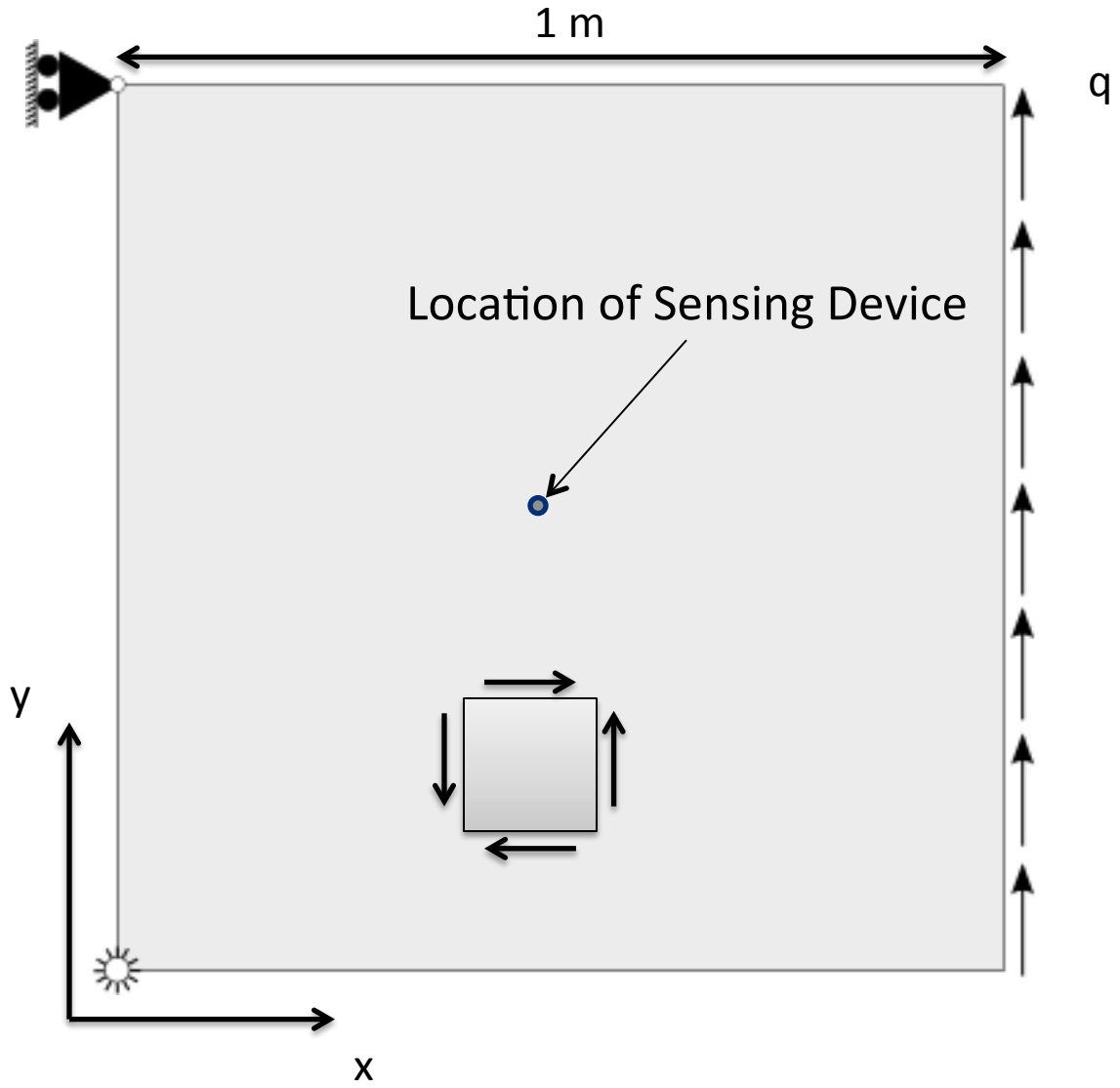
  - where:

$$\boldsymbol{\epsilon} = [\varepsilon_x,\, \varepsilon_y,\, \varepsilon_{xy}]^T$$

$$b_i = 1/2\left[\left(\frac{f_{d_i}}{f_{0_i}}\right)^2 - 1\right]$$

$$\boldsymbol{A}(i,:) = \left[\cos^2(\vartheta_{0_i}),\, \sin^2(\vartheta_{0_i}),\, \sin(2\vartheta_{0_i})\right]$$

Numerical Test



Displacement field

$$u = 0$$

$$v = \frac{q}{2G}x$$

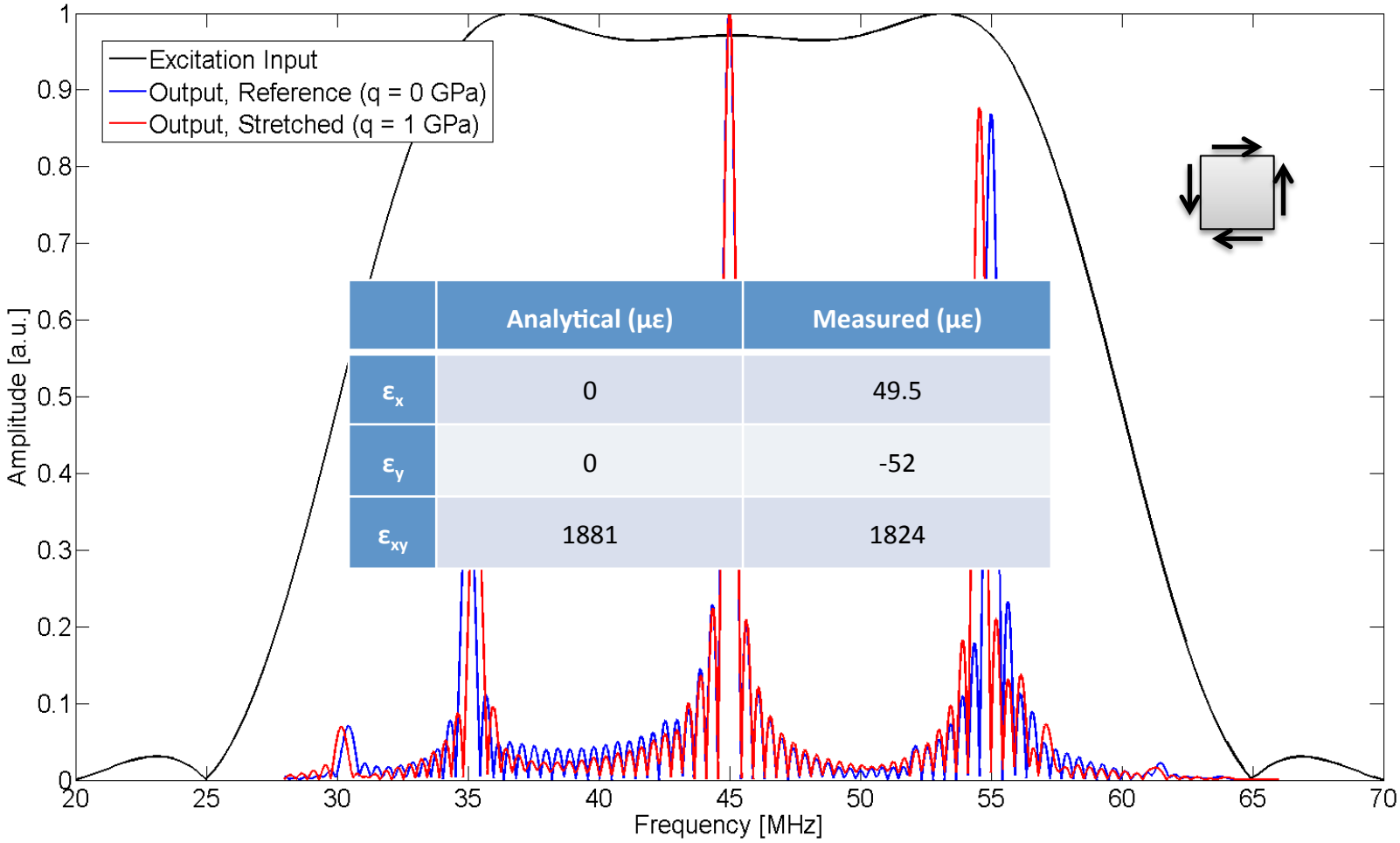
Strain Field

$$\varepsilon_x = 0$$

$$\varepsilon_y = 0$$

$$\varepsilon_{xy} = \frac{q}{2G}$$

Example Solution: q = 1 GPa



	Analytical (με)	Measured (με)
ε_x	0	49.5
ε_y	0	-52
ε_{xy}	1881	1824

Outlook: higher order symmetries