6th International Workshop on Laser-Ultrasound for Metals
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Kista, Sweden

Zero-Group-Velocity Lamb modes in Anisotropic Plates

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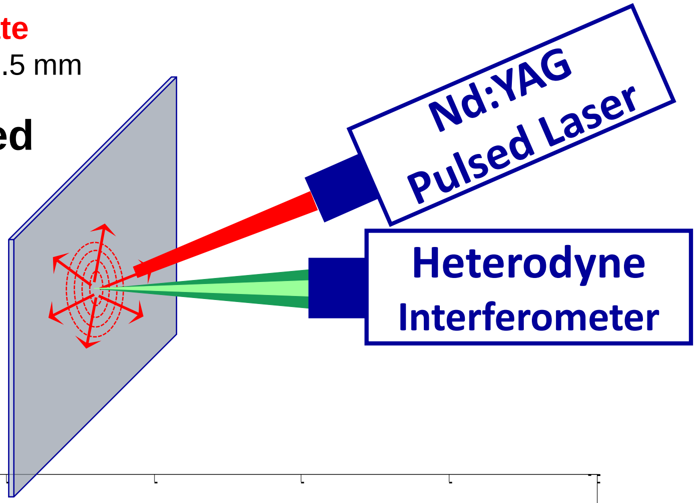
Institut Langevin ONDES ET IMAGES   ESPCI PARIS   PSL UNIVERSITÉ PARIS   cnrs dépasser les frontières

Laser impact on a plate induces narrow local resonances

Duralumin plate
Thickness d = 1.5 mm

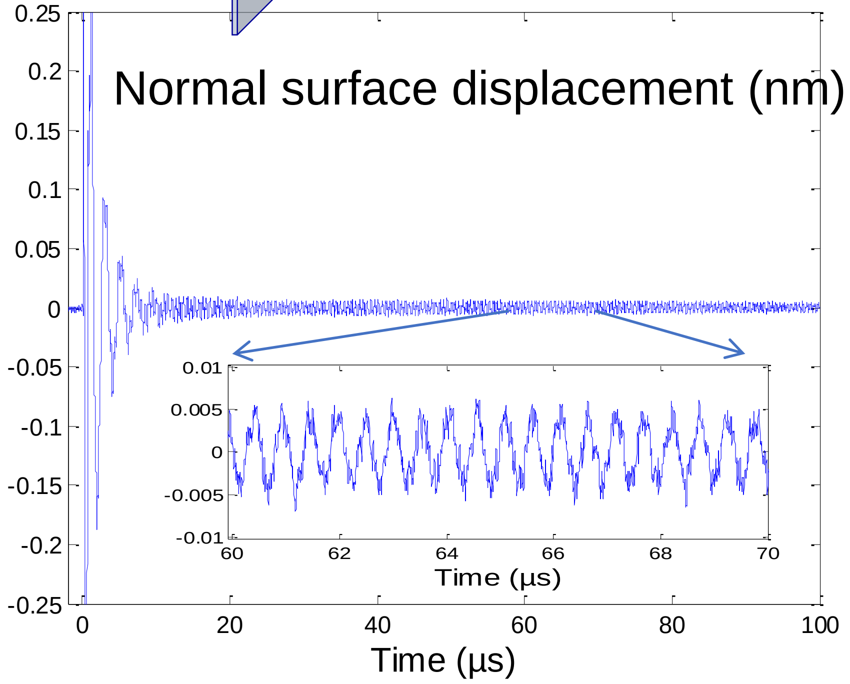
Superimposed
source
and probe



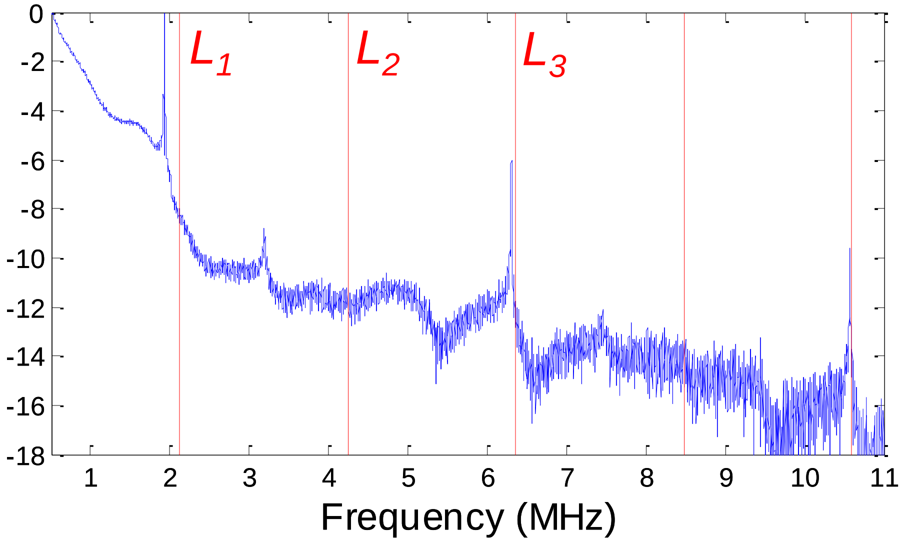
1064 nm
Pulse duration: 8 ns
Energy: 0.1-40 mJ

Thermoelastic regime

532 nm
BW: 10 kHz - 45 MHz – 120 mV/nm



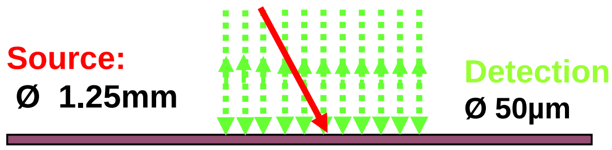
Frequency spectrum



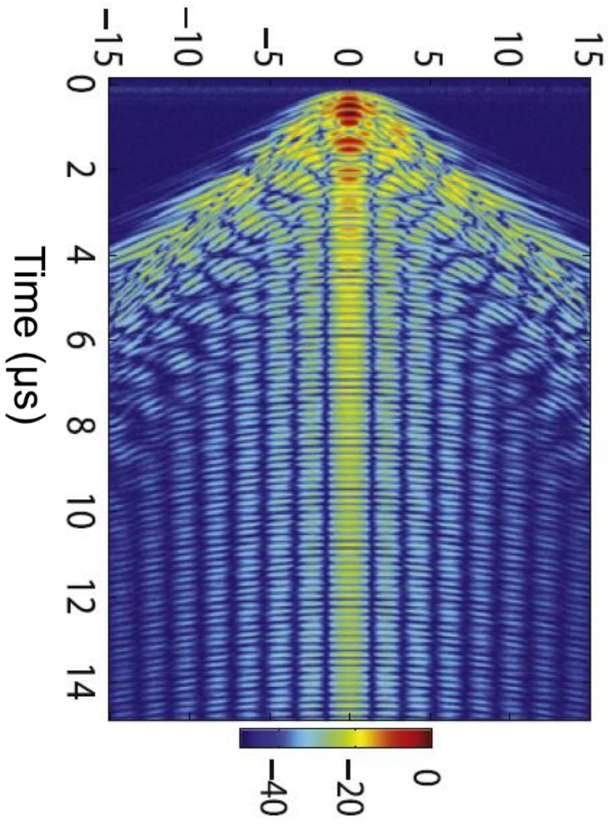
Longitudinal thickness resonance frequencies

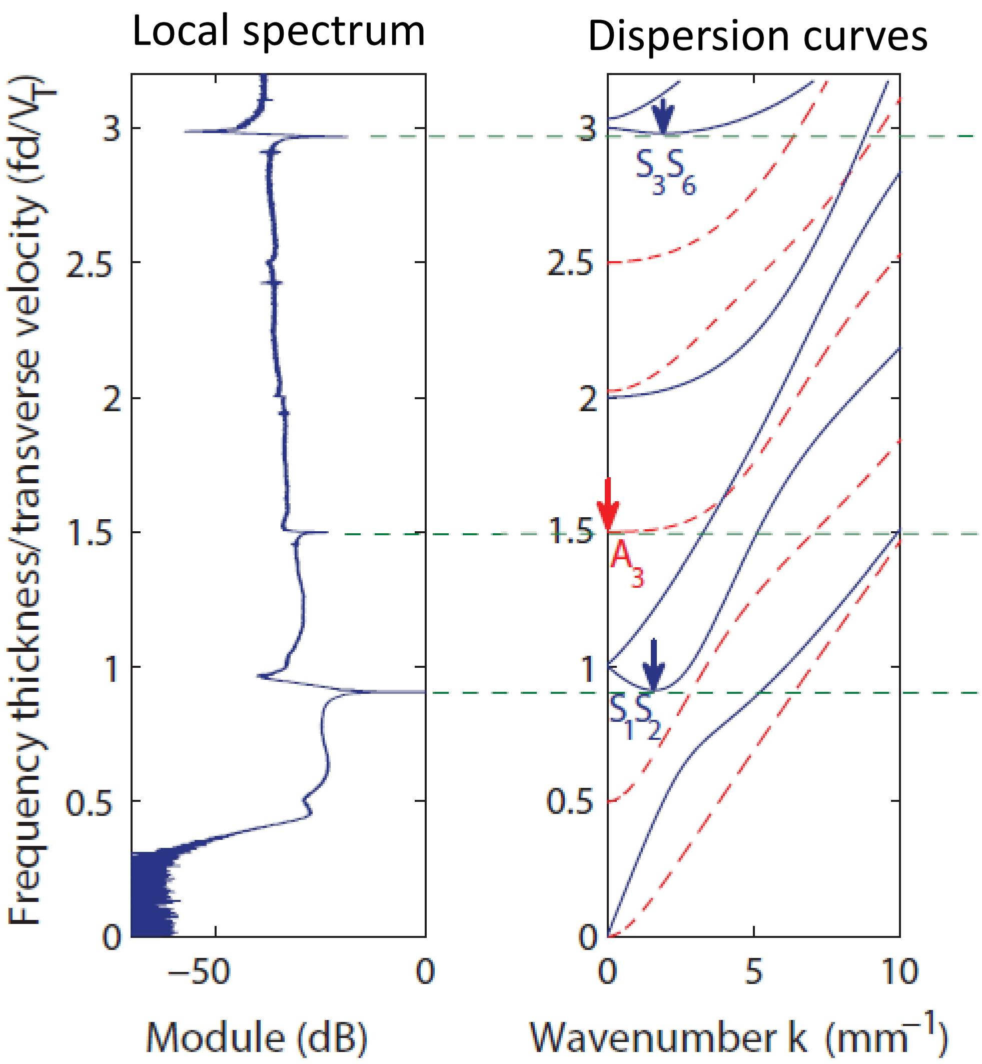
$L_n = nV_L/2d$ (V_L=6.14mm/µs)

Resonances and dispersion curves in a duraluminum plate



Normal surface displacement





$$\frac{d\omega}{dk} = 0$$

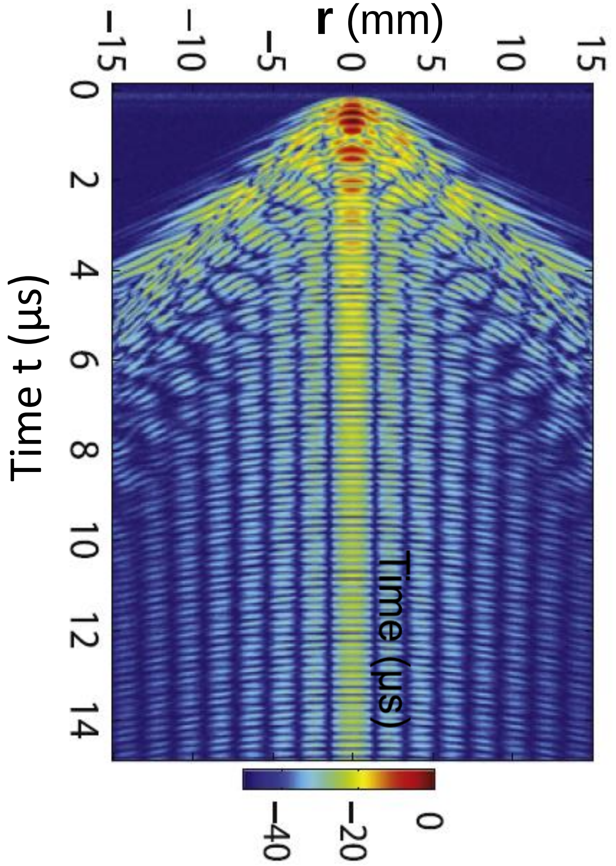
Zero Group Velocity

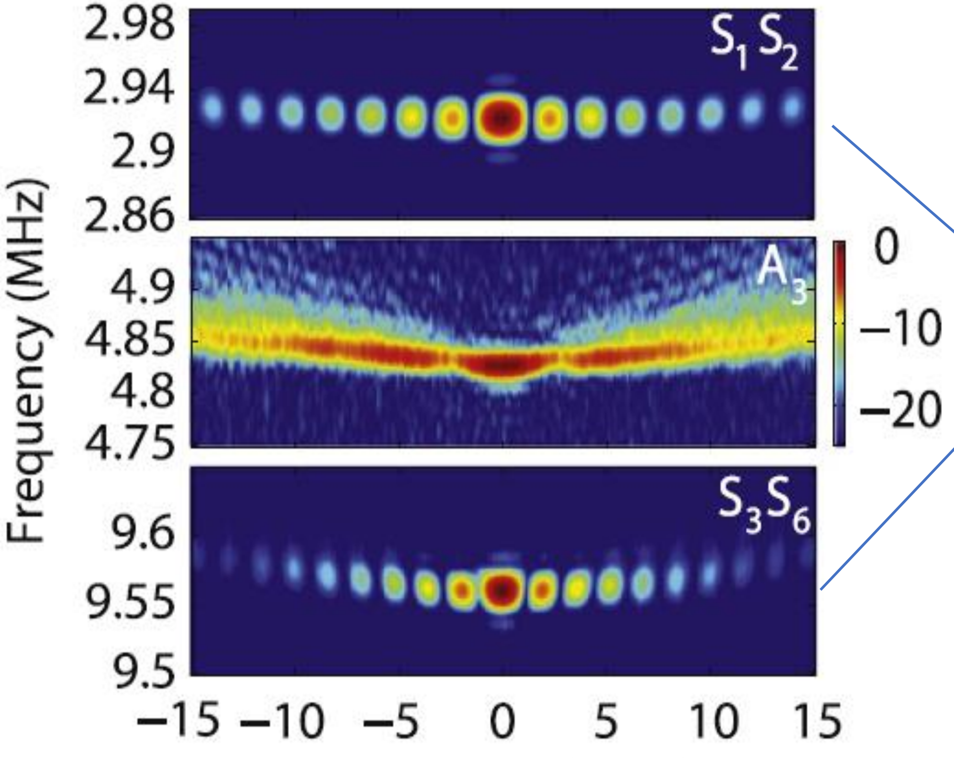
Energy is trapped

under the source

Laser impact induced resonances : spatial distribution

Normal surface displacement **u(r,t)** → Temporal Fourier Transform **u(r,f)**





ZGV mode : Interference of forward and backward modes

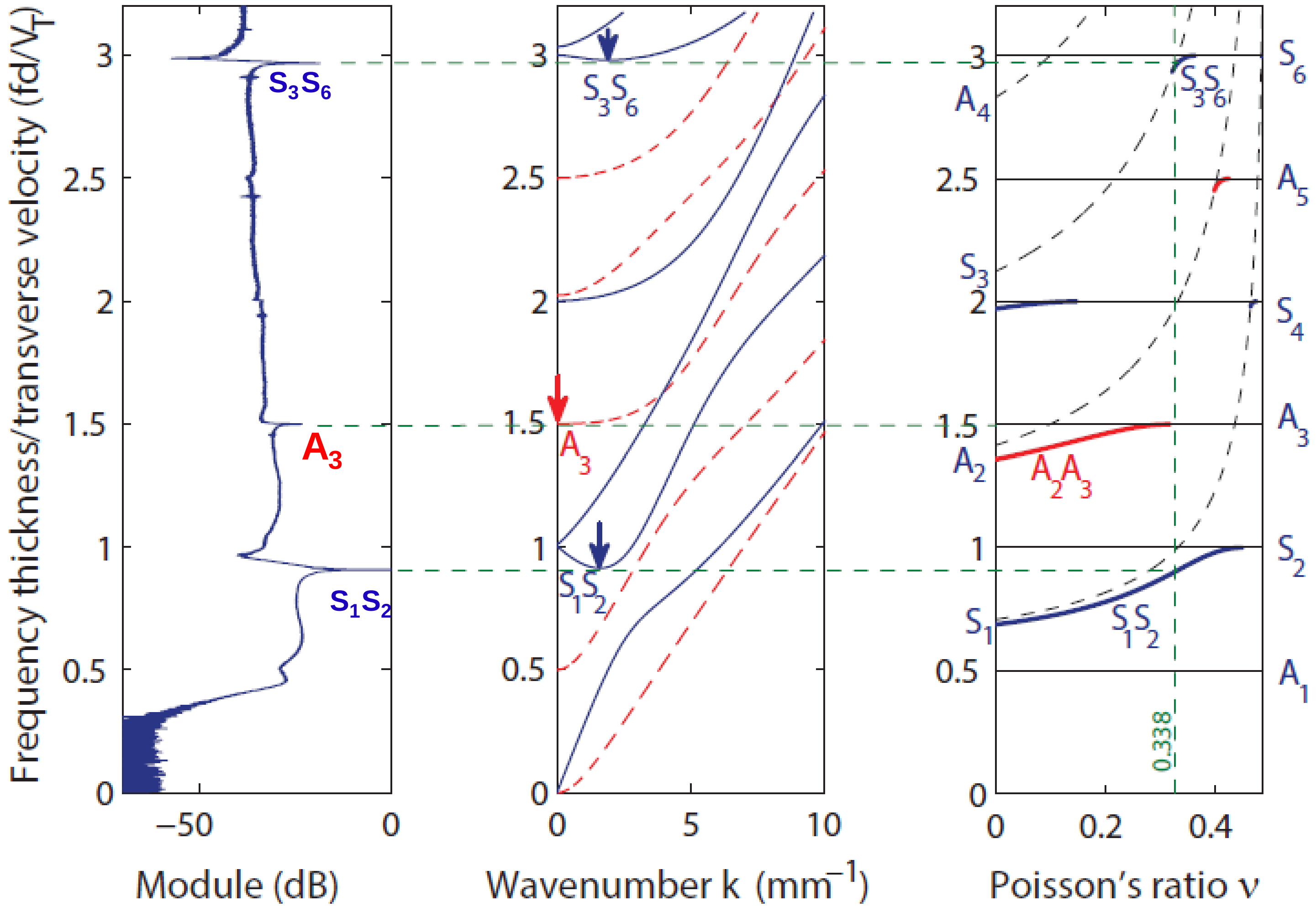
Plate thickness d

Wavelength $\lambda \sim 3d$

Optimal Gaussian source diameter to excite a ZGV mode $D = \dfrac{\lambda}{\pi}$

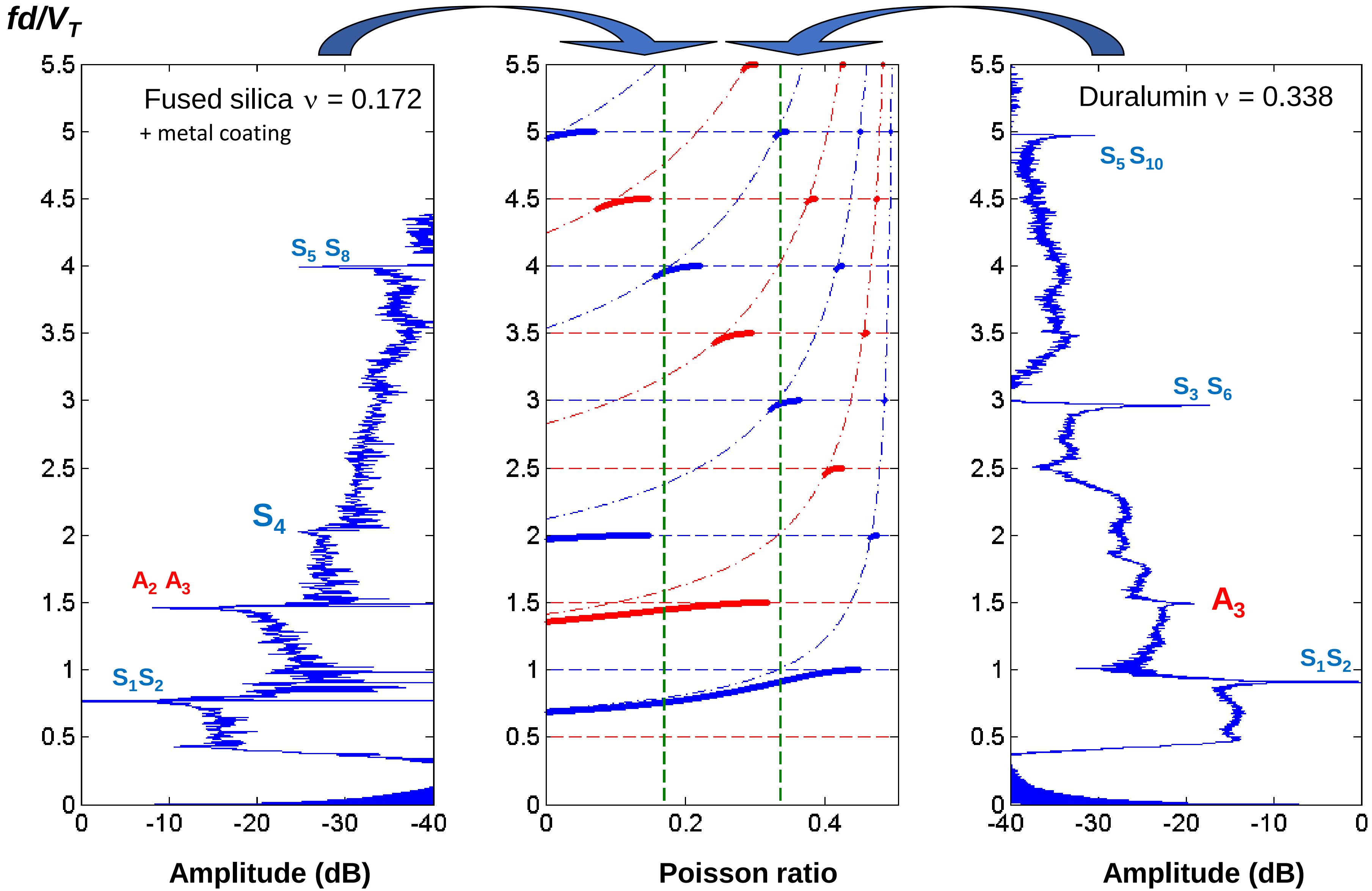
Laurent et al. Wave Motion 2014; Bruno et al. JASA 2015

Laser impact generated resonances and Poisson's ratio



Clorennec, Royer, Prada, Appl. Phys. Lett. (2006)

Application : Non contact Poisson's ratio measurement

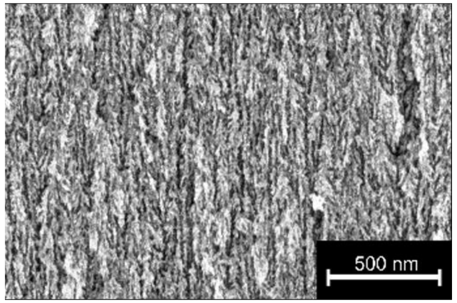


Prada, Clorennec, Royer J.Acoust. Soc. Am. (2008)

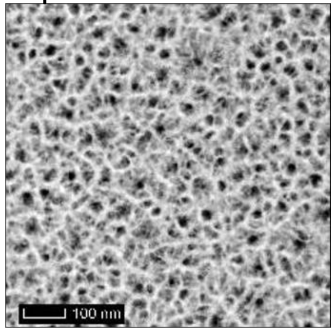
Application : effective Poisson’s ratio of nanoporous silicon

Scanning electron microscopy

Side view



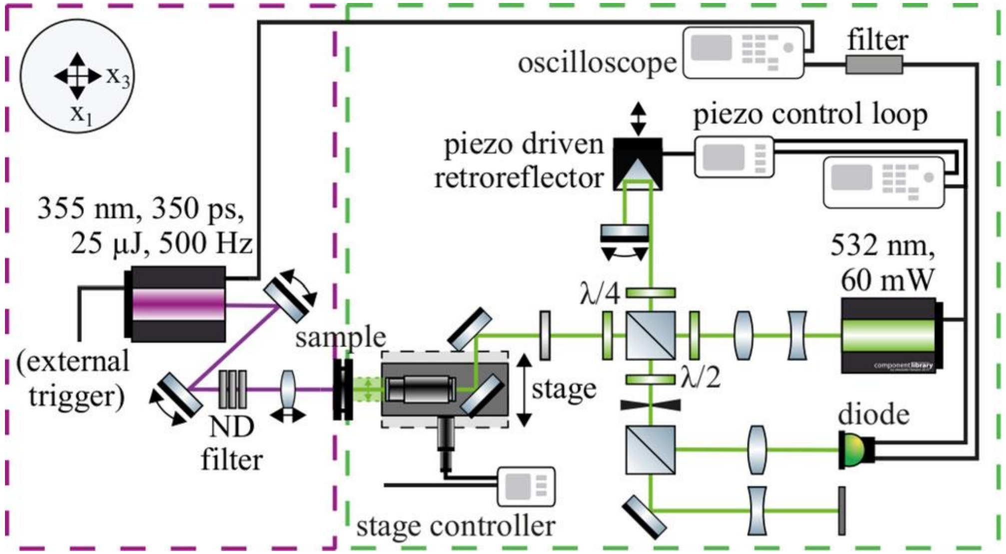
Top view



Porosity 55%

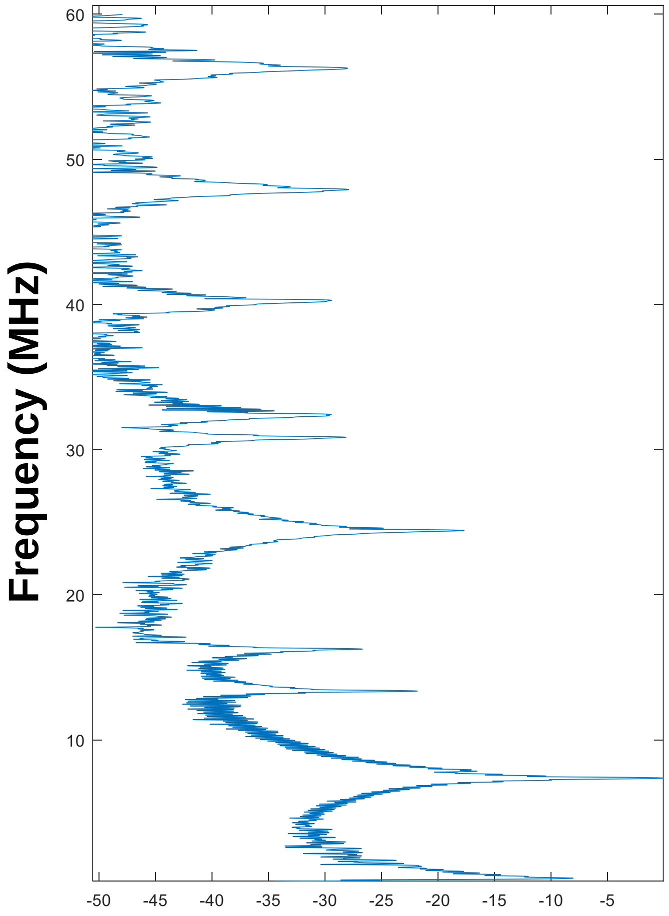
Mean pore radius 3.7 nm

Membrane thickness 250 µm



Thelen, Bochut, Brinker, Prada, Huber, Nature Comm. 2021

ZGV and thickness resonances



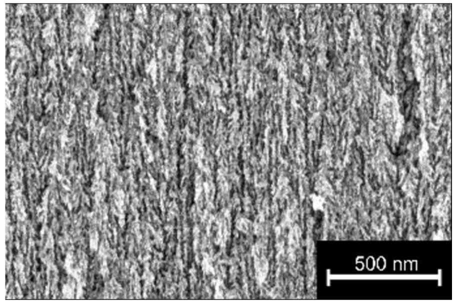
300 µm thick sample

20 nm silver coating for the detection

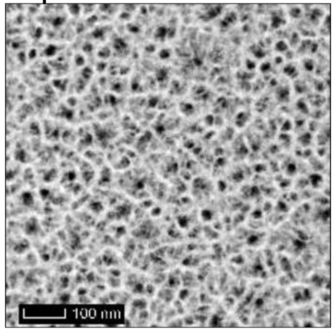
Application : effective Poisson's ratio of nanoporous silicon

Scanning electron microscopy

Side view



Top view



Porosity 55%

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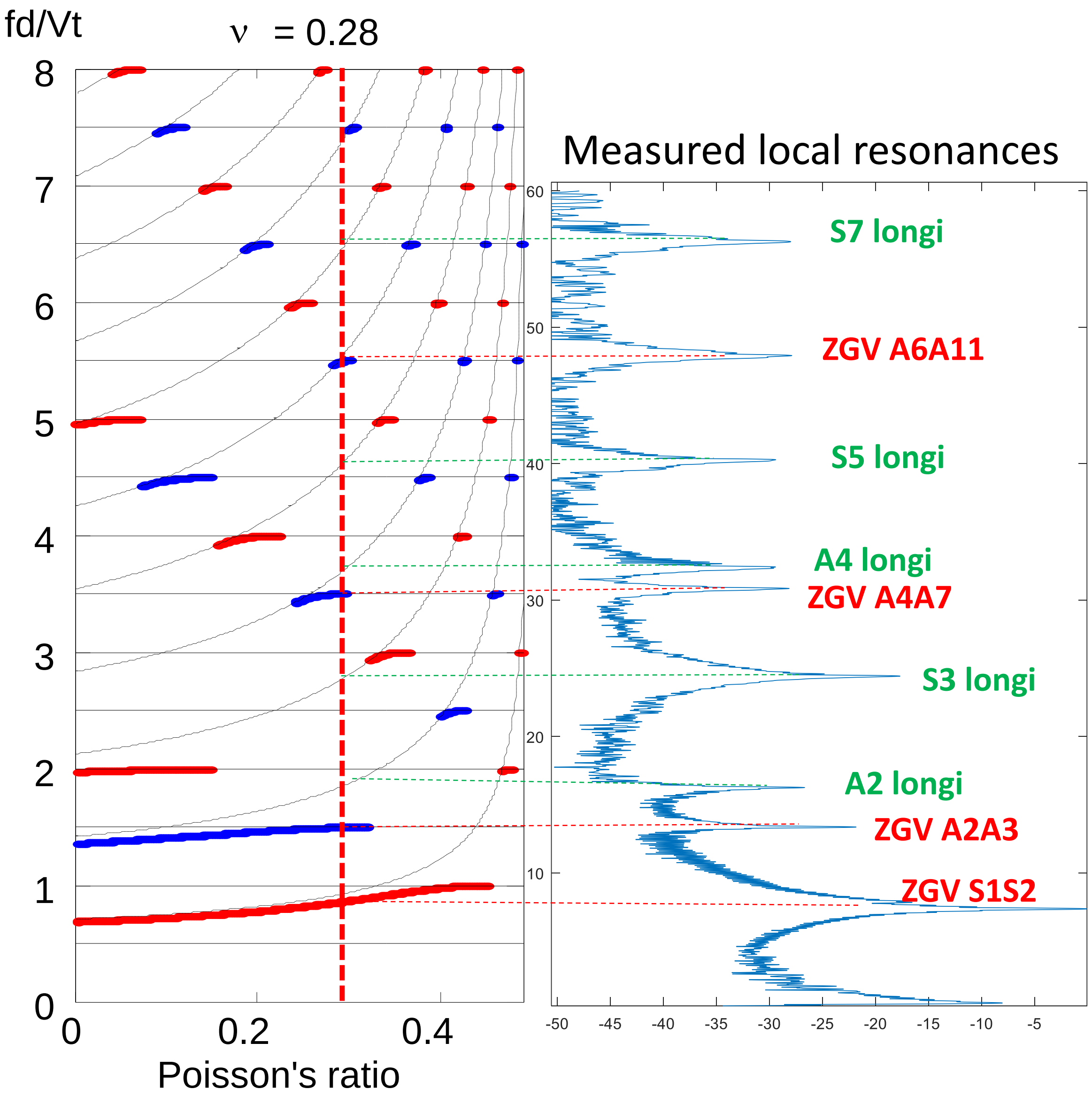


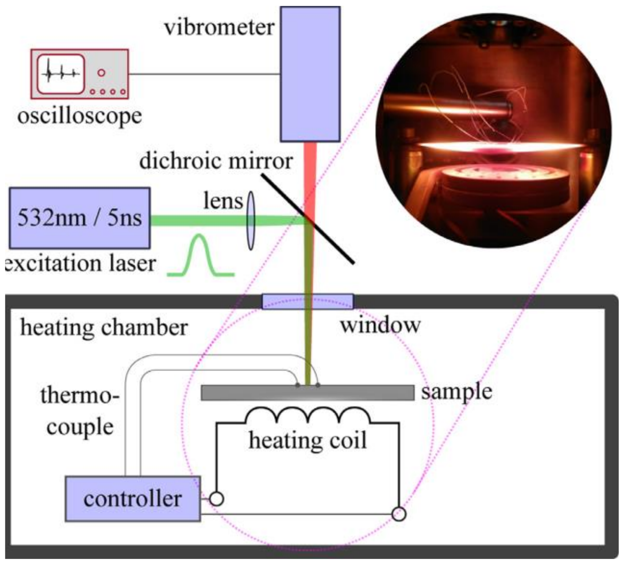
Provide an estimation of some elastic constants

V_L = 5.54 mm/µs and V_T = 3.26 mm/µs through thickness

Thelen, Bochut, Brinker, Prada, Huber, Nature Comm. 2021

Application : Poisson's ratio measured along thermal cycles

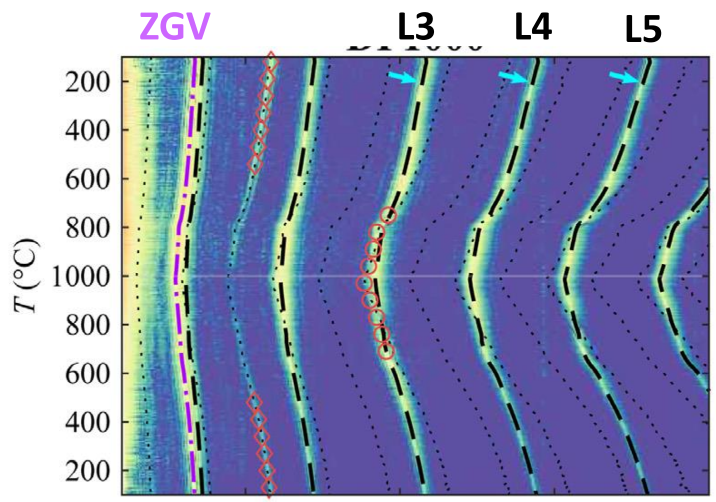
Johannes Keppler University
Voestalpine
Linz, Austria



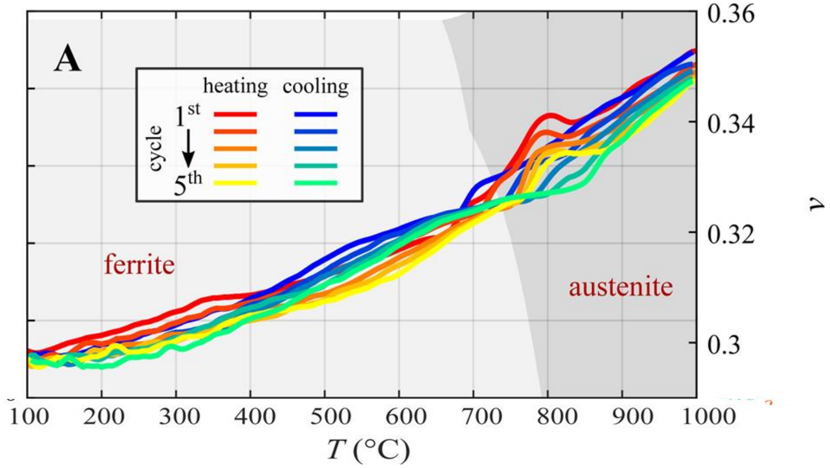
Local measurement in reflection
on 0.8 x 50 x 50 mm steel plates

Excitation slightly above ablation threshold
in order to excite both ZGV and longitudinal resonances

Local resonance spectrum along thermal cycles



Poisson's ratio deduced from f_{L3}/f_{ZGV}

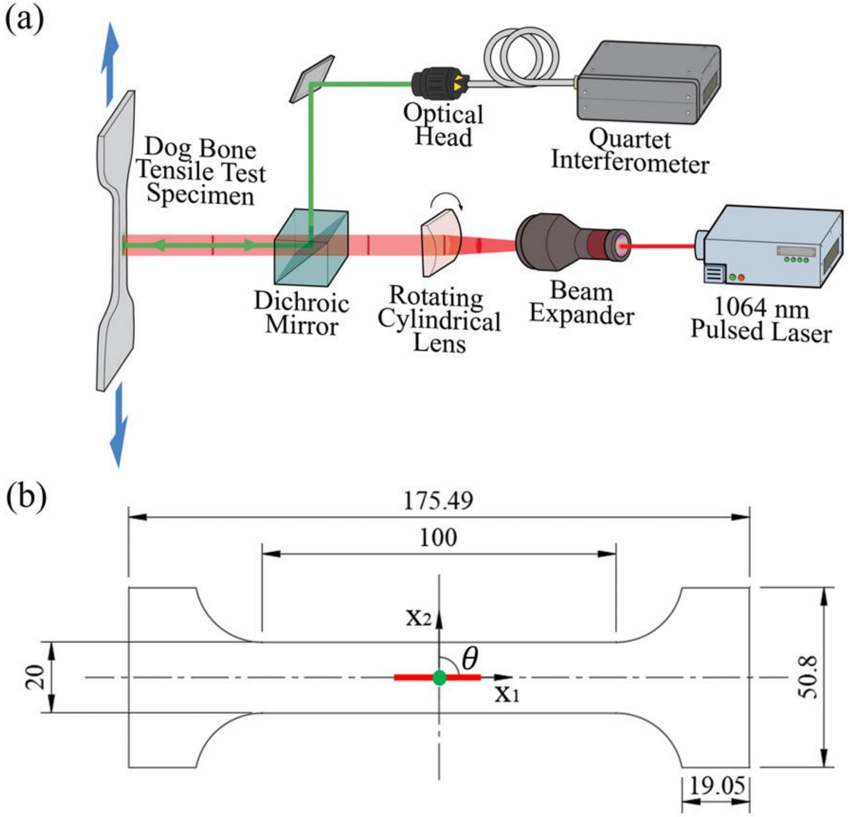


In situ laser-ultrasonic monitoring of Poisson's ratio and bulk sound velocities of steel plates during thermal processes, Watzl,…, Grunsteidl, Acta Materialia 235 (2022)

Application : ZGV and Acoustoelasticity

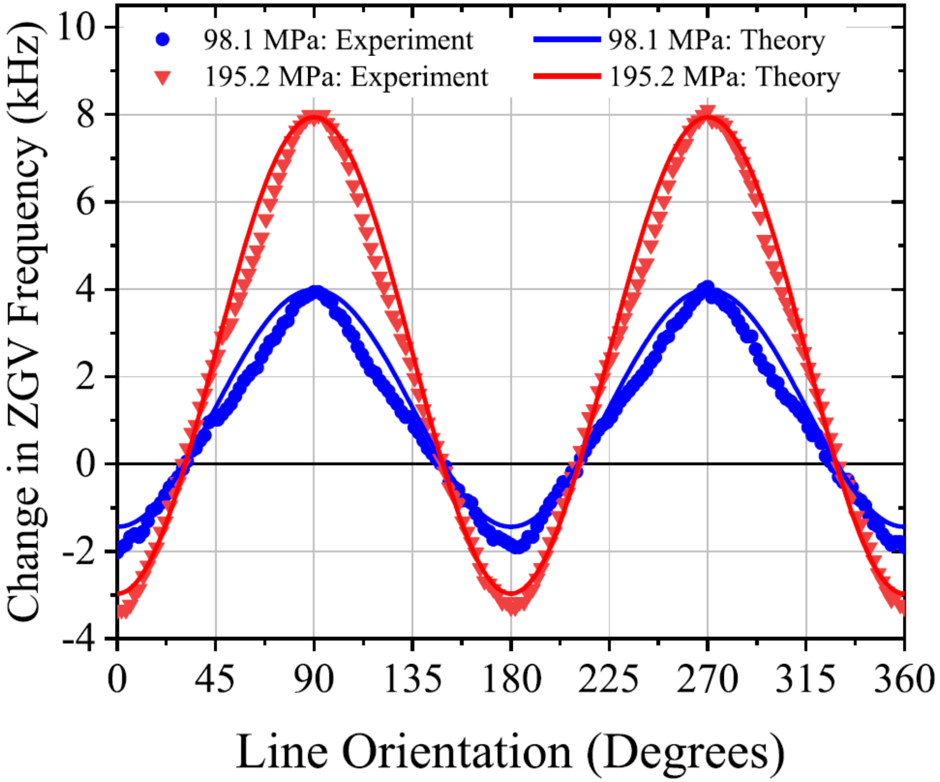
Lawrence Livermore National Laboratory

ZGV modes are measured using a line source



Aluminum 6061-T6

Strain induced anisotropy



Acoustoelastic characterization of plates using zero group velocity Lamb modes
Rosa Morales & al. Appl. Phys. Lett. 124, 084101 (2024)

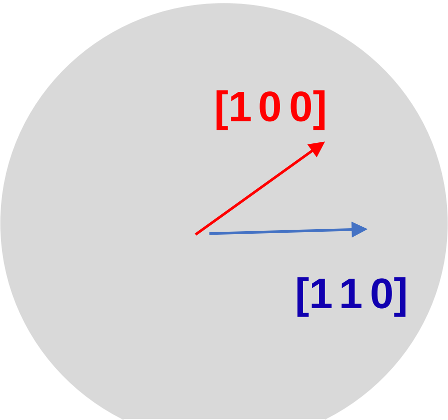
ZGV modes in anisotropic plates : silicon plate

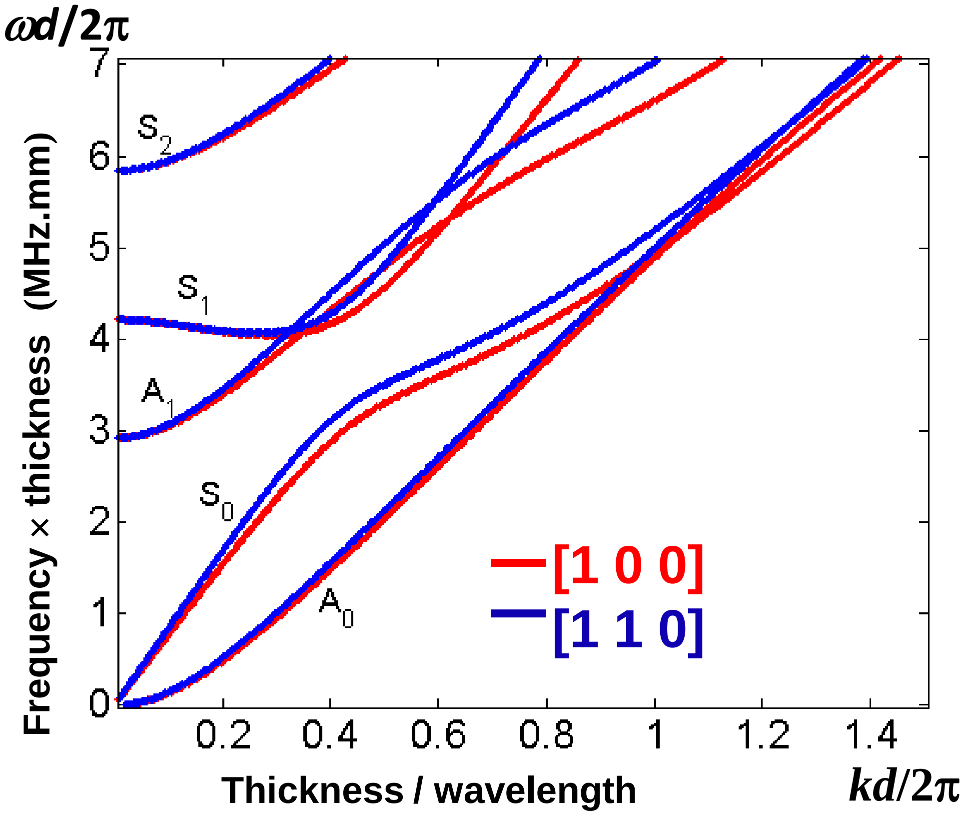
Silicon wafer

cut: [0 0 1]

thickness: 525µm

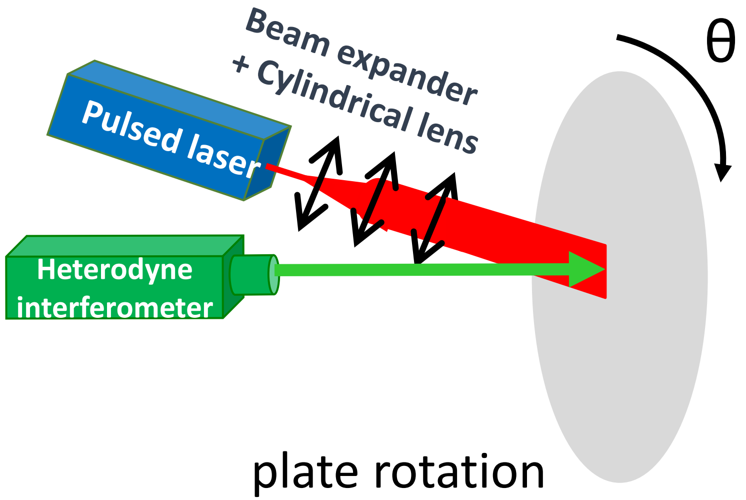
diameter: 5 ″





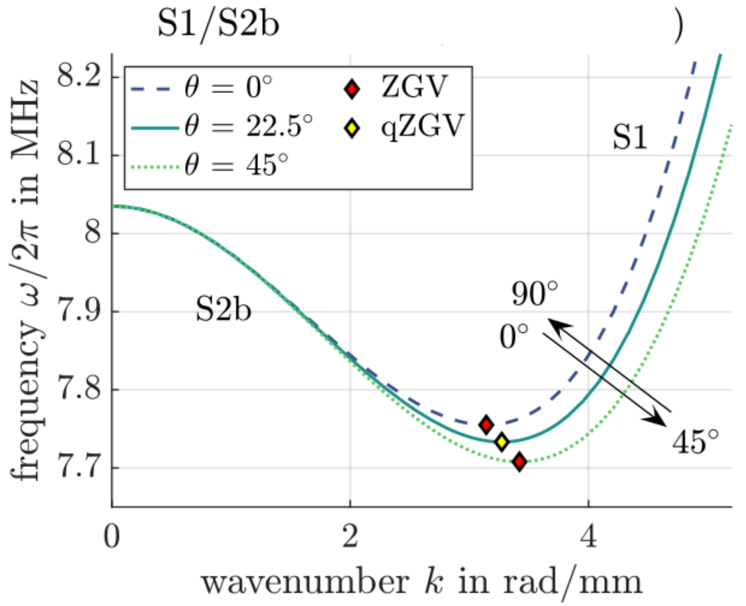
Prada, Clorennec, Murray and Royer, J. Acoust .Soc. Am. Vol.126 (2009)

Line source excitation of ZGV mode in a silicon wafer

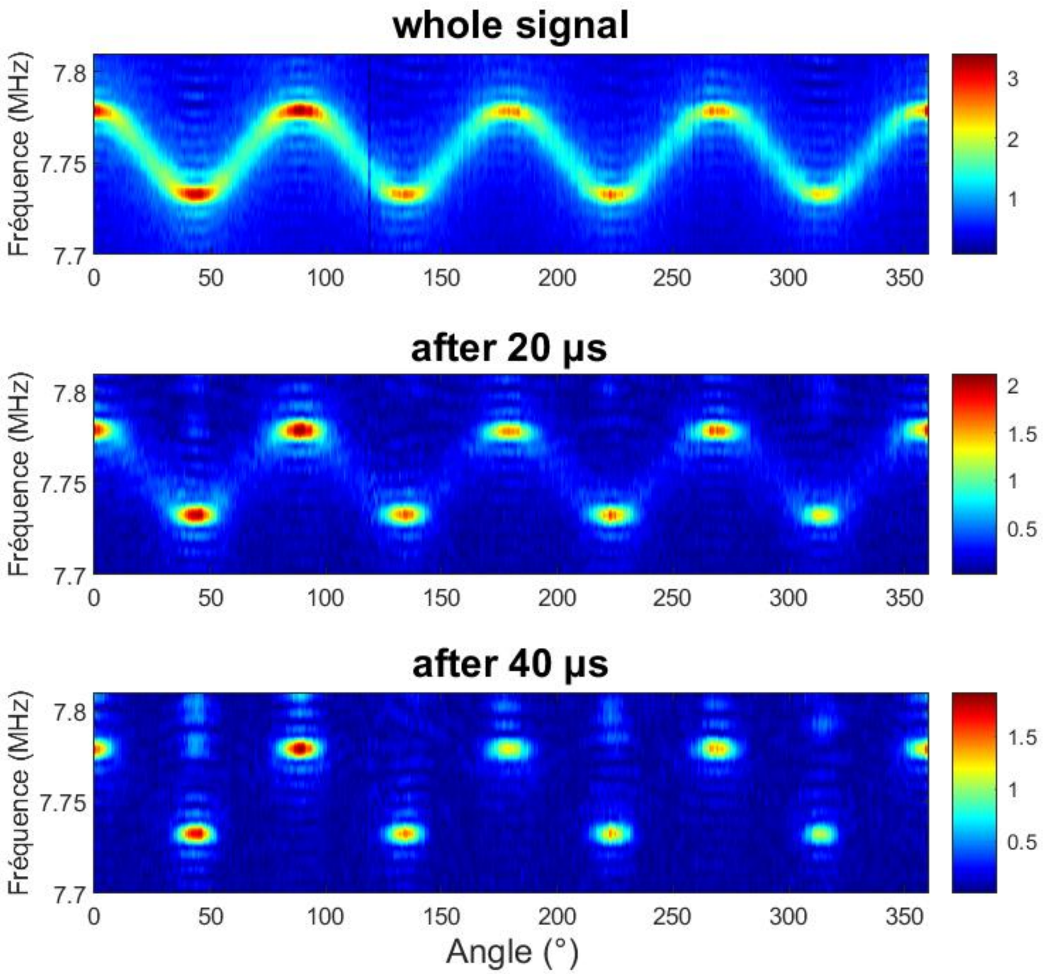


0° 110
45° 100

plate rotation



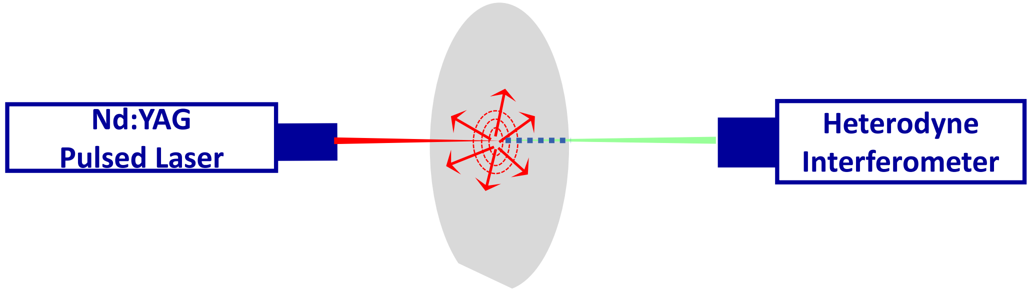
Angle dependance of $S_1 S_2$ ZGV mode



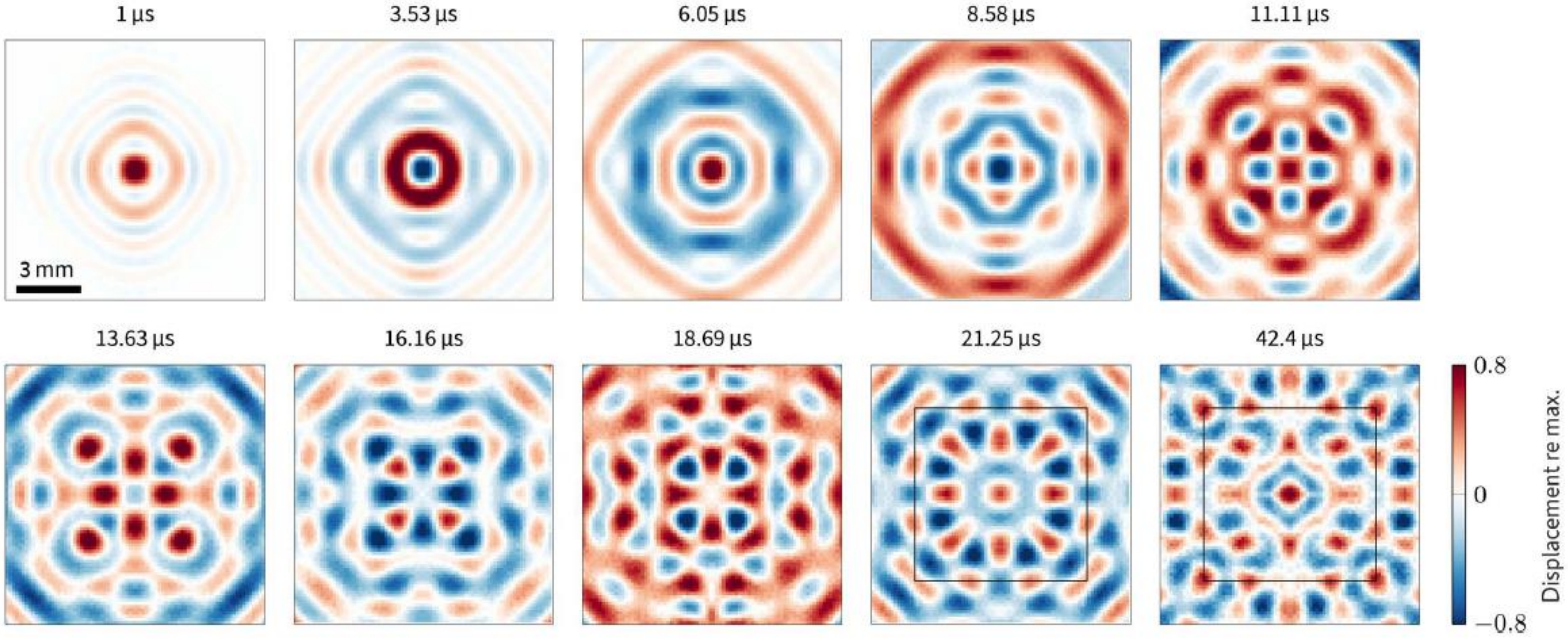
Prada, Clorennec, Murray and Royer, J. Acoust .Soc. Am. Vol.126 (2009)

Point source excitation in a silicon plate

2D scan
of the source

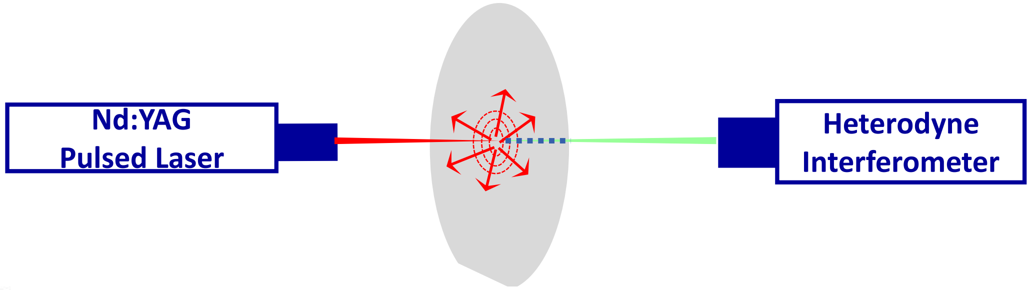


Normal surface displacement

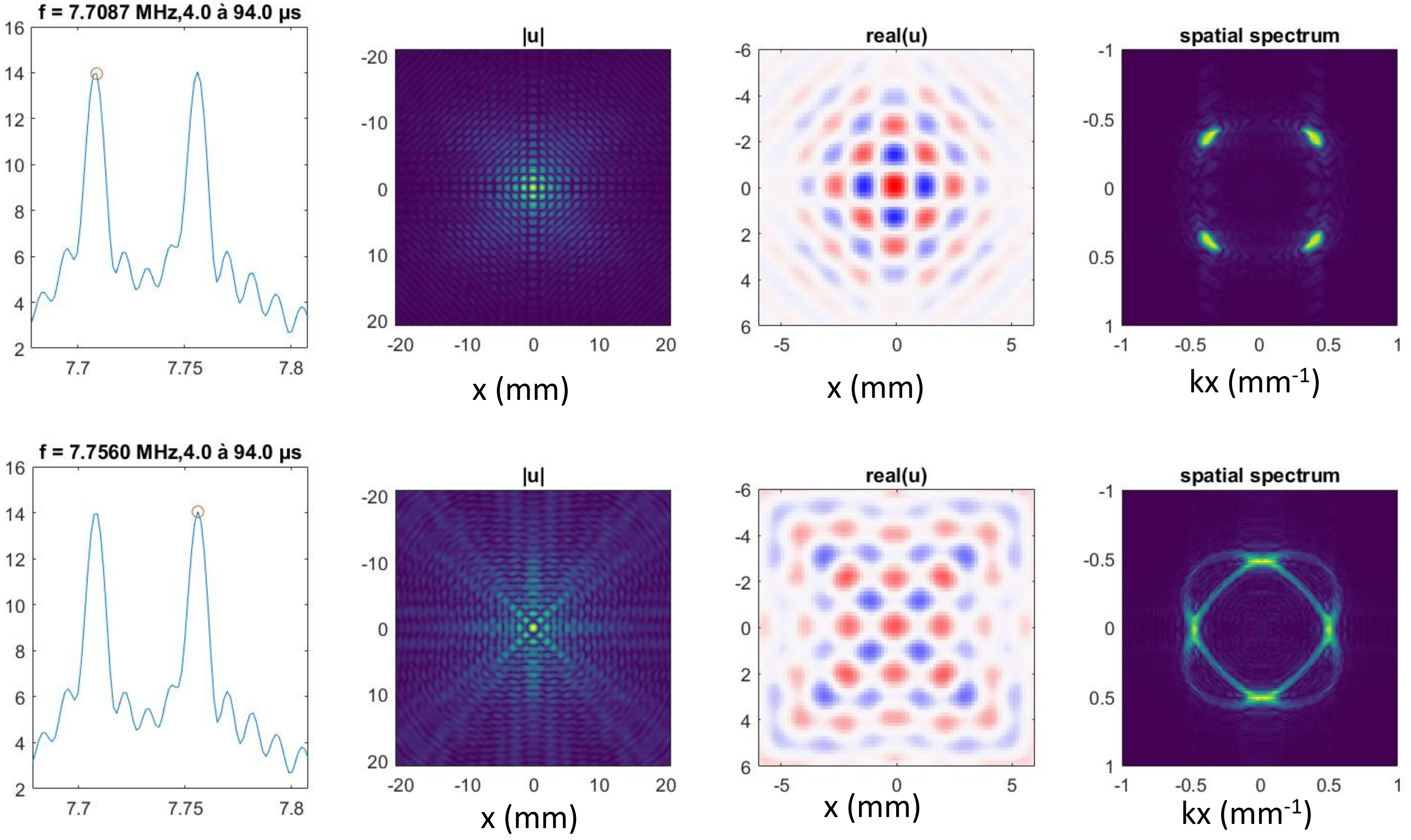


D.A. Kiefer, S. Mezil, C. Prada, Science Advances 2023

ZGV modes excited with a point source in a silicon plate



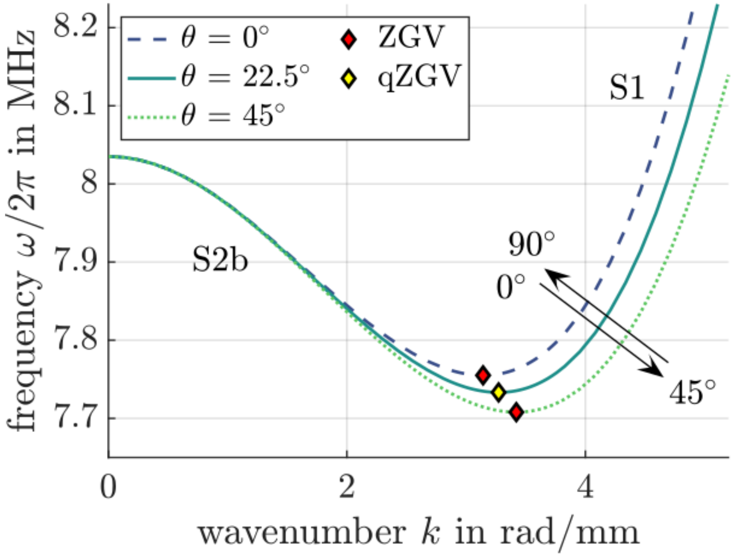
Local spectrum



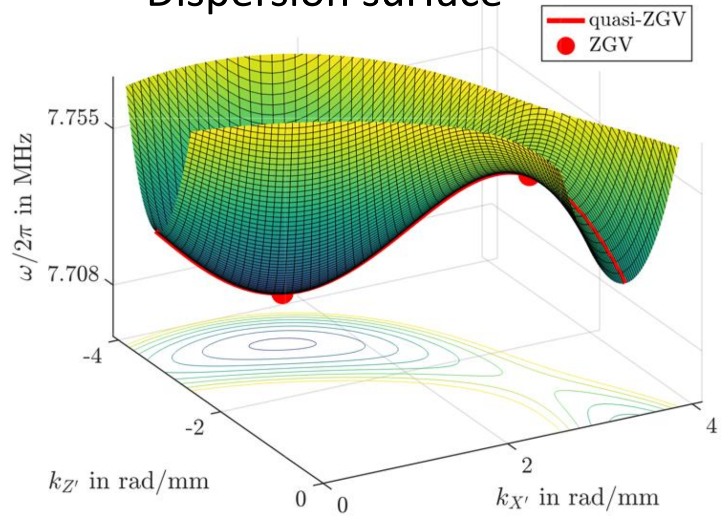
D.A. Kiefer, S. Mezil, C. Prada, Science Advances 2023

Dispersion surface and ZGV modes in a cubic silicon plate

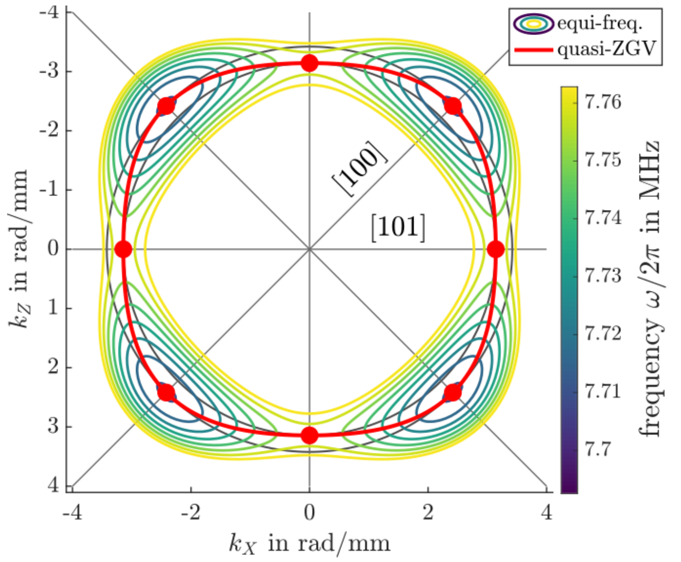
Dispersion curves



Dispersion surface



Isofrequency contours



The **group velocity**

$$V_g(\omega,\theta) = \frac{\partial \omega}{\partial k} e_r + \boxed{\frac{1}{k}\frac{\partial \omega}{\partial \theta} e_\theta}$$

$V_g(\omega,\theta) = 0$ only on principal axes

- 4 minima at 45°+ n 90° (n=0-3)
- 4 saddle points at n 90°
- ➢ **8 ZGV points**

Caclulated with GEW dispersion script (2022)
https://github.com/dakiefer/GEW_dispersion_script

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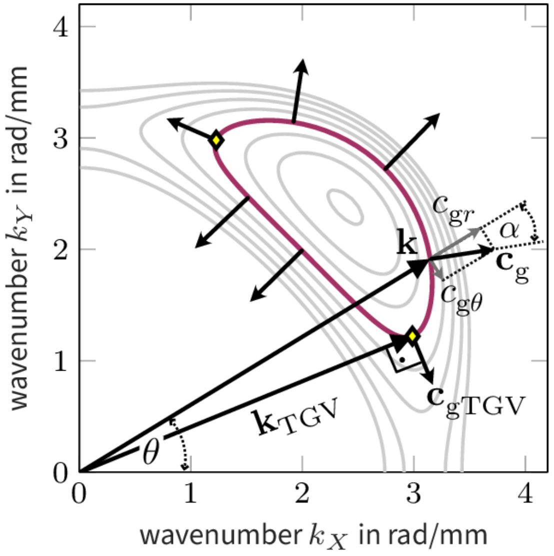
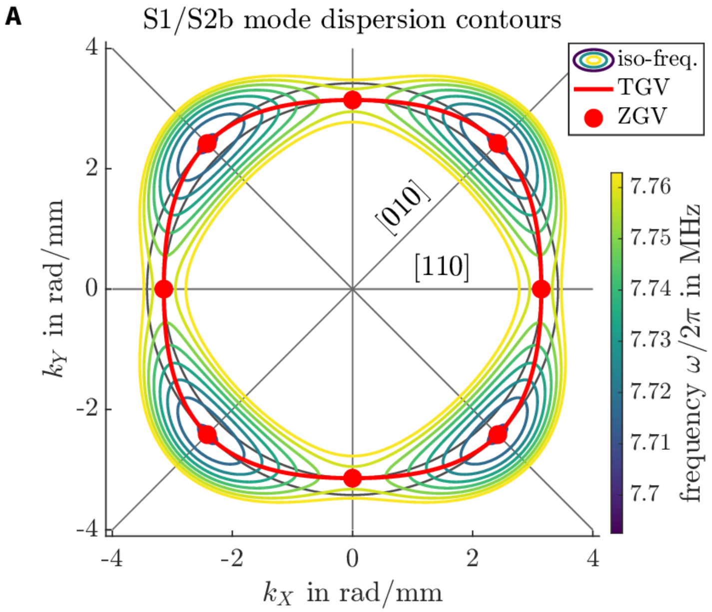
ZGV and Transverse Group Velocity (TGV) modes

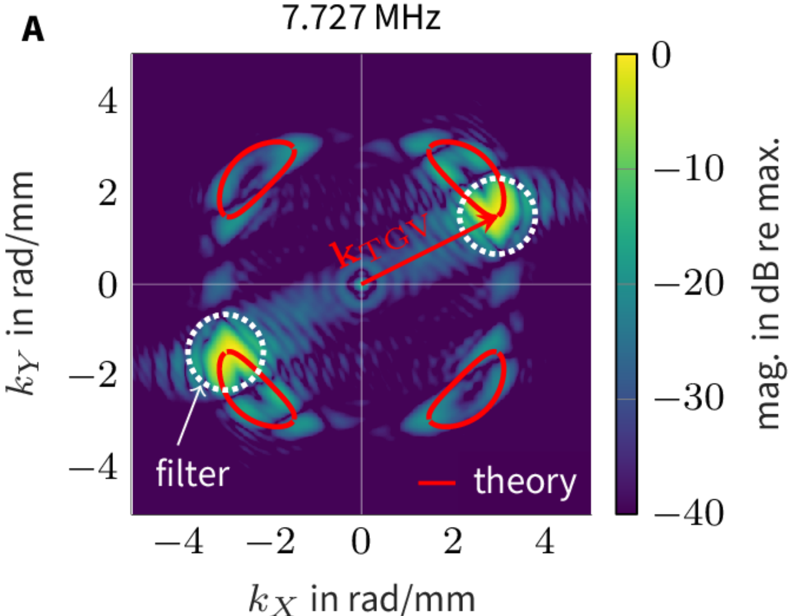


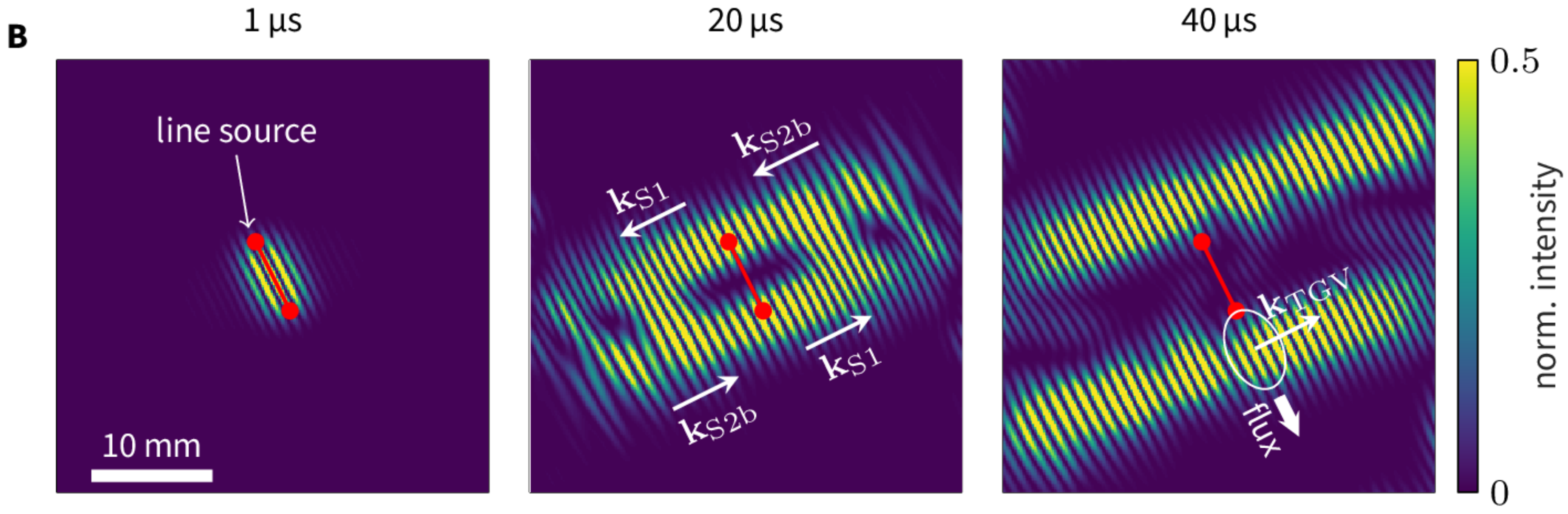
The group velocity vector c_g is orthogonal to the isofrequency contours

Squewing angle α between wavevector k and c_g

α = 90° > Transverse Group Velocity mode

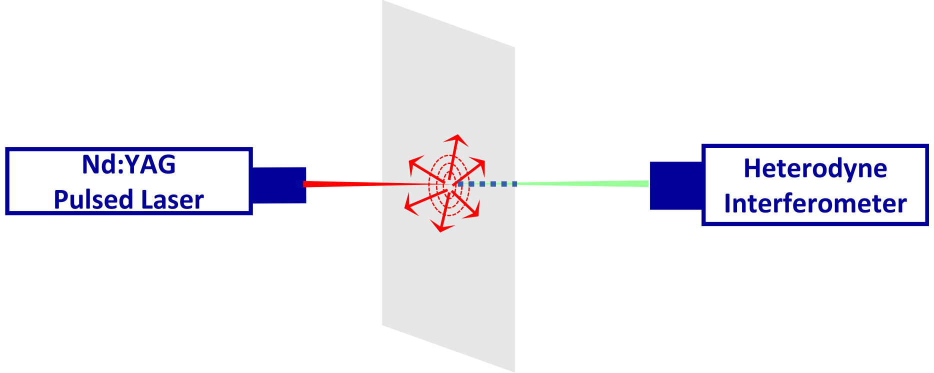


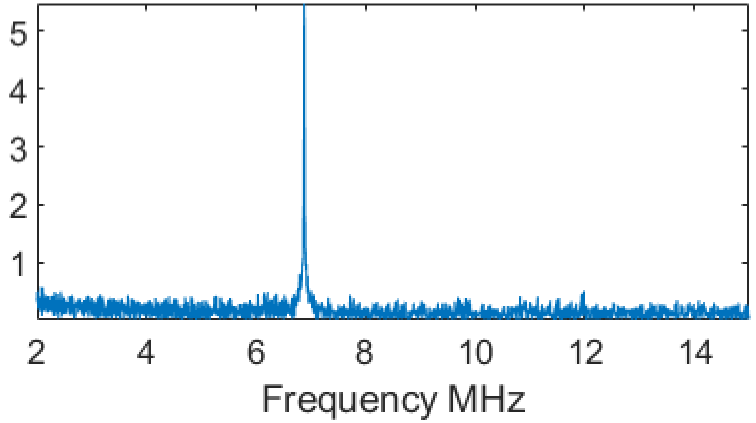




D.A. Kiefer & al. Science Advances 2023

ZGV resonance measured in a cold rolled carbon steel plates

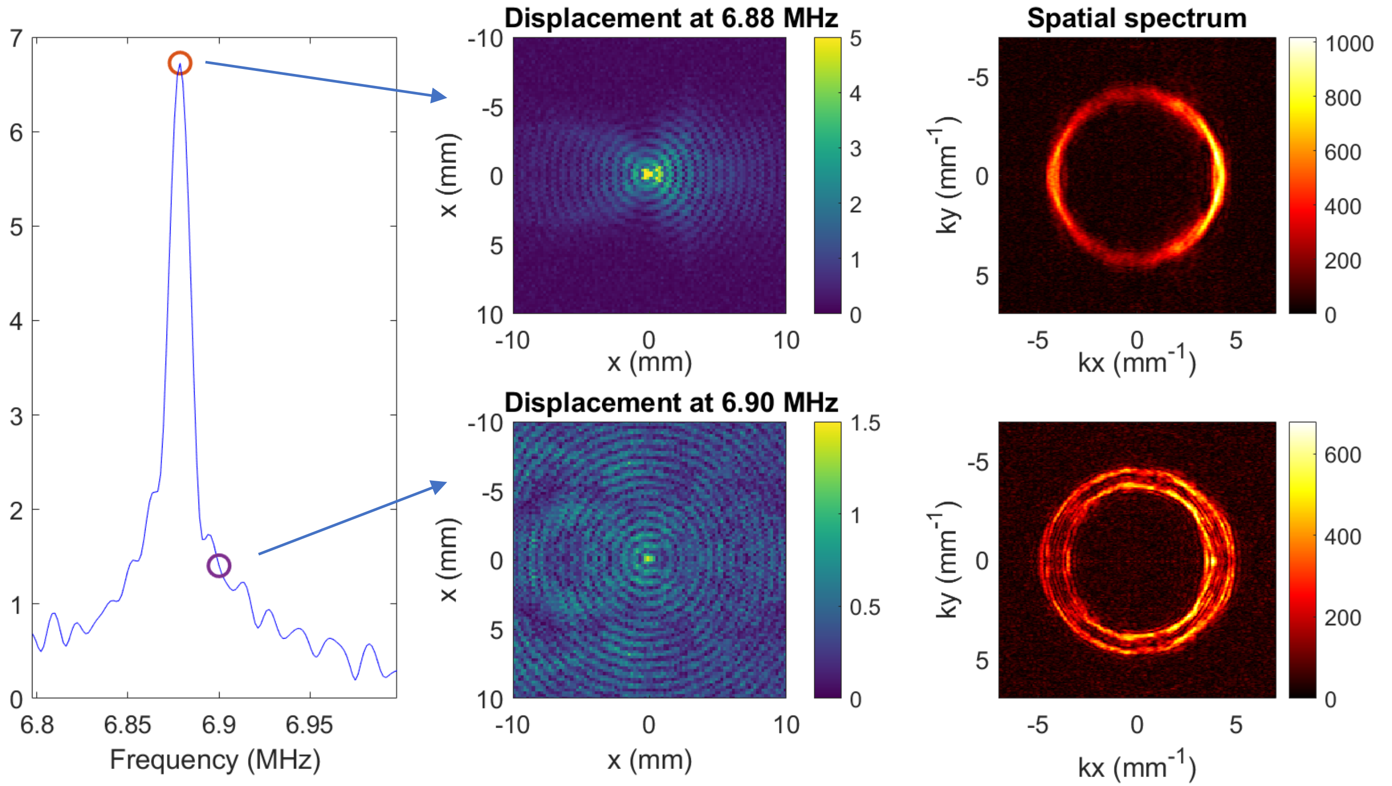




Thickness-gauge-strip
50x300mm ; 400µm
Carbonsteel 1.1274
Cold rolled, hardened

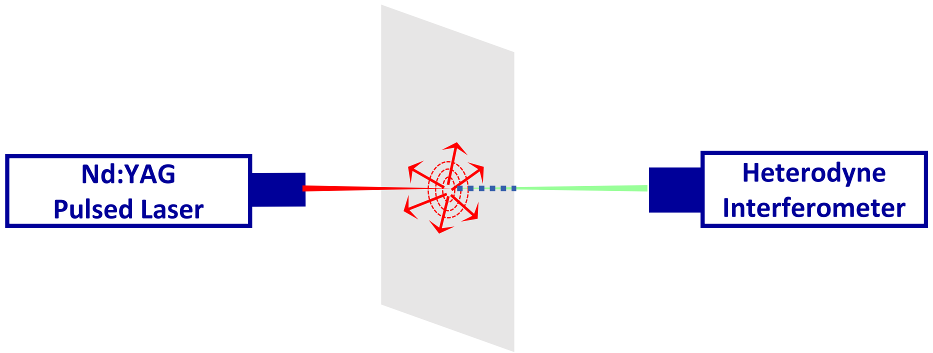
Chemische Analyse:
C = 0,95 – 1,05 %
Si = 0,10 – 0,30 %
Mn = 0,30 – 0,50 %
P = max. 0,02 %
S = max. 0,03 %

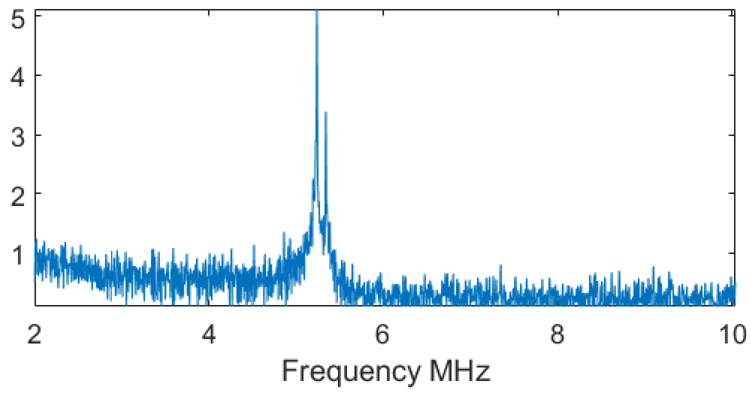
hasberg
SCHNEIDER GMBH



Single resonance
Isotropy

ZGV measured in a cold rolled stainless steel plates

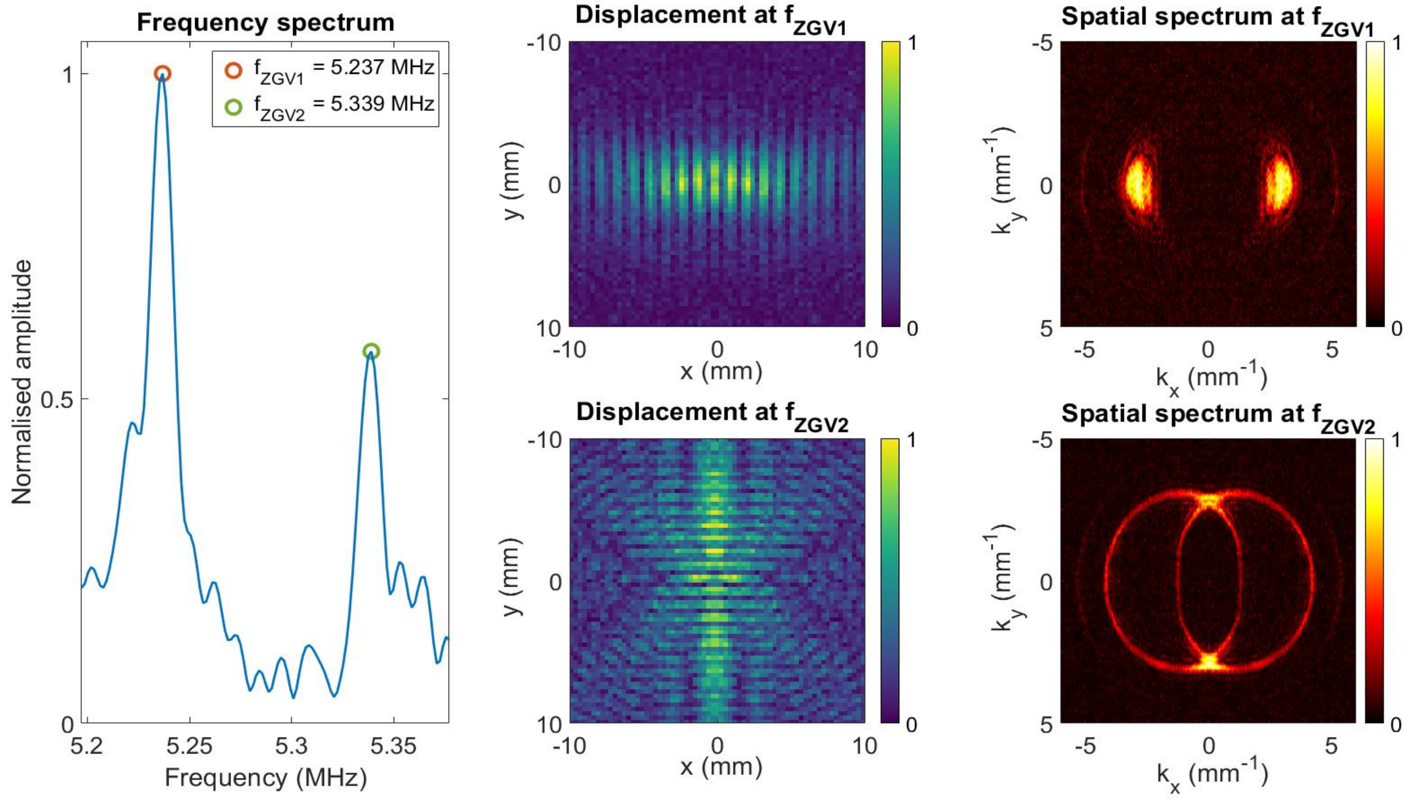




Thickness-gauge-strip
100x500mm ; 500 µm
Steel 1.4310 (301)
Cold rolled, hardened

Chemische Analyse:
C = max. 0,15 %
Si = max. 2,00 %
Mn = max. 2,00 %
P = max. 0,045 %
S = max. 0,015 %
Cr = 16,0 – 19,0 %
Ni = 6,0 – 9,5 %

hasberg
SCHNEIDER GMBH

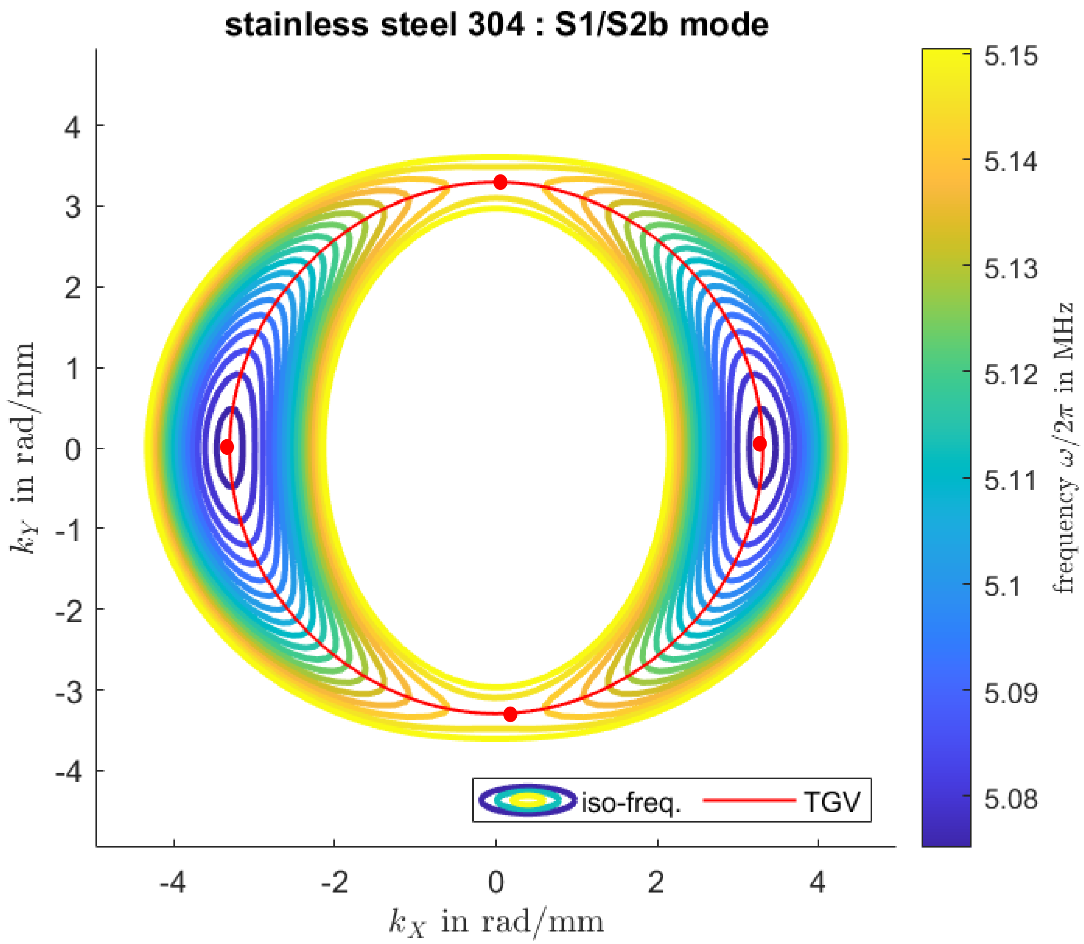


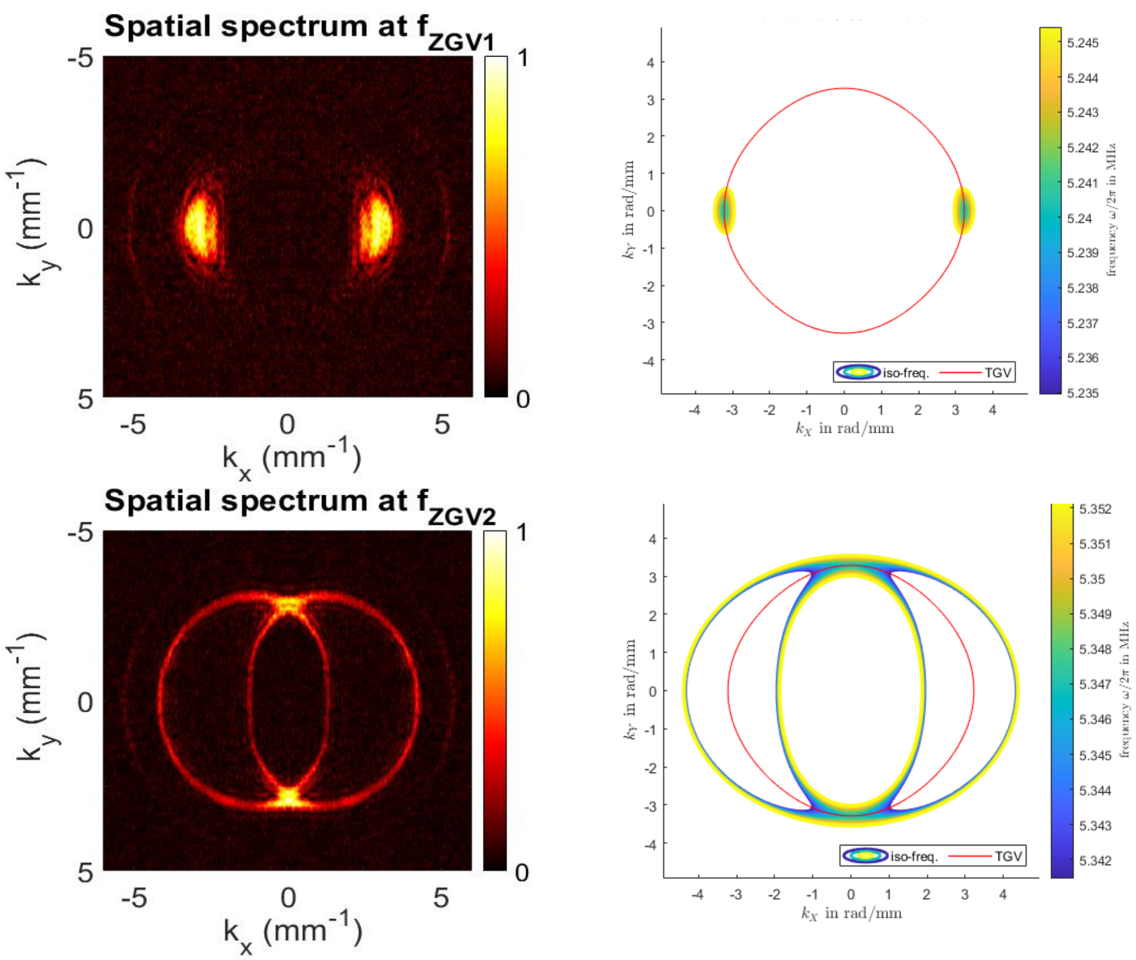
2 ZGV points
Minimum

2 ZGV points
Saddle Point

Transverse Anisotropy

ZGV in a cold rolled stainless steel plate and dispersion surface

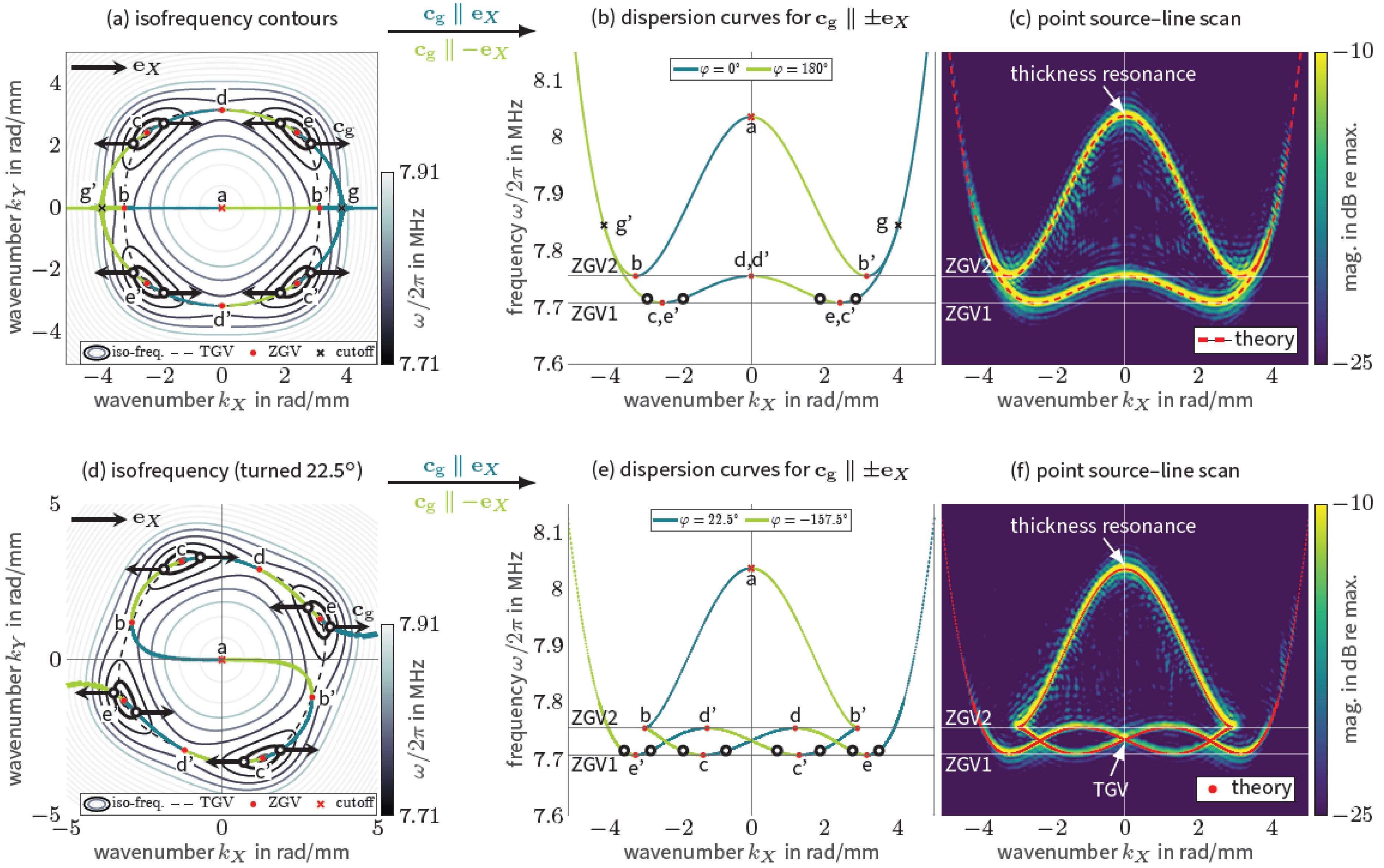




Transverse isotropic elastic constant taken from
Laurent & al. JASA 137 (6) 2015

TO DO : built an inversion procedure

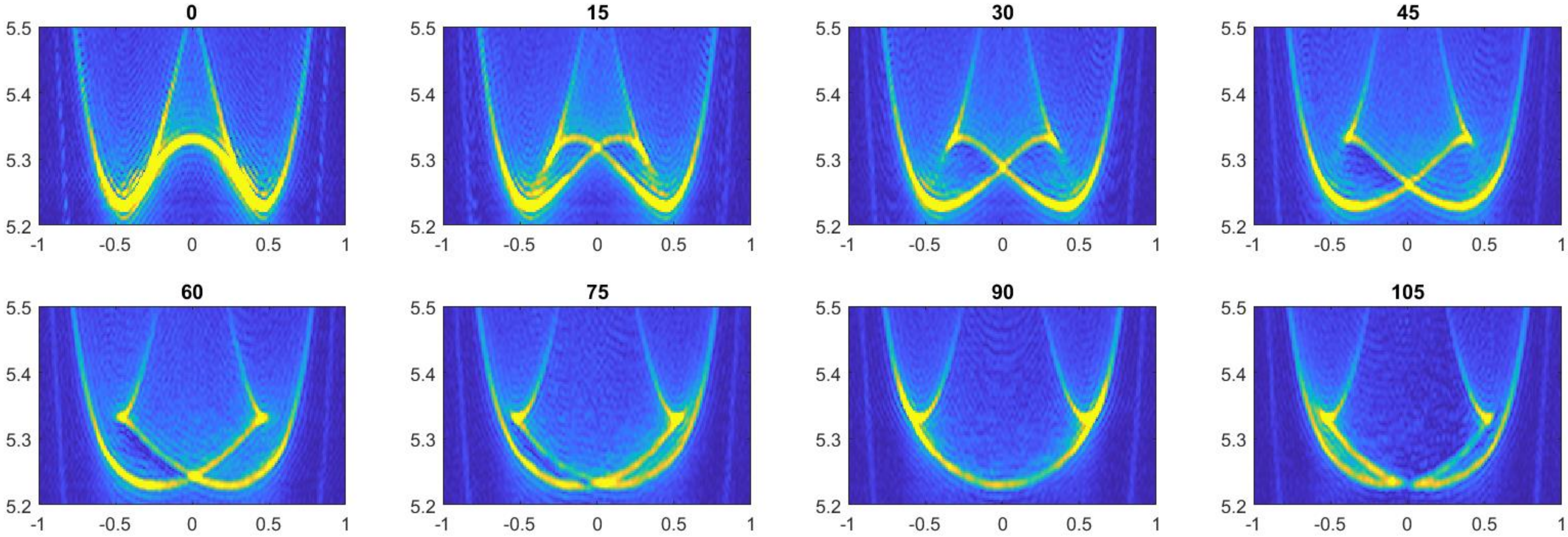
Dispersion curves from 1D scan in silicone



Kiefer, Mezil, Prada, Arxive 2024

Dispersion curves from 1D scan in stainless steel 301

Line scan orientation 0 to 105 degres by 15° steps



A 1D scan carries information from all propagation directions

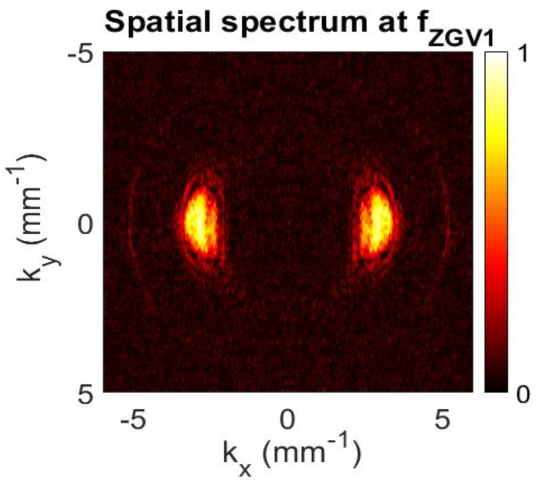
Would inversion be possible from a single line scan ?

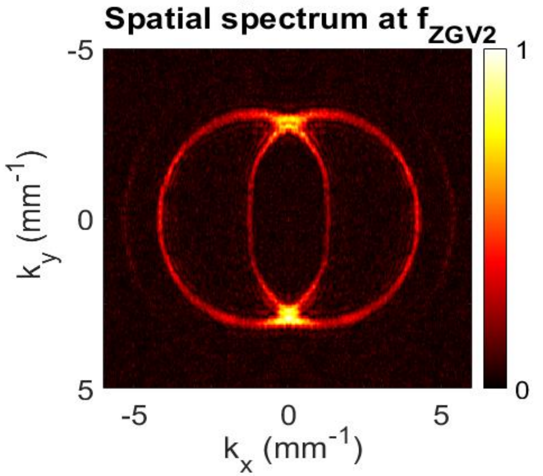
Conclusion

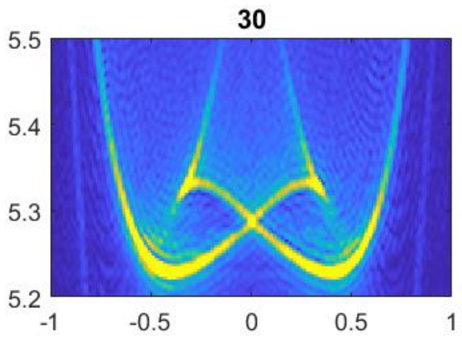
- ZGV mode resonances provide local non-contact evaluation of Poisson's ratio
- Anisotropic plates exhibit several ZGV resonance frequencies associated minima and saddle points of the same mode surface
- These resonances are highly sensitive to elastic constants
- Due to large beam skewing around ZGV poins, 1D scan reveal several dispersion branches associated to same mode.

To do :

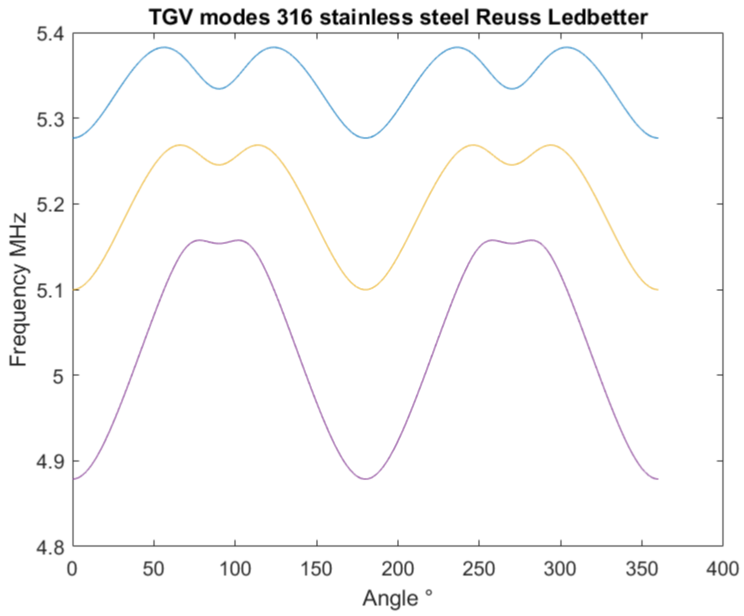
Inversion procedures for 2D and for 1D scan.

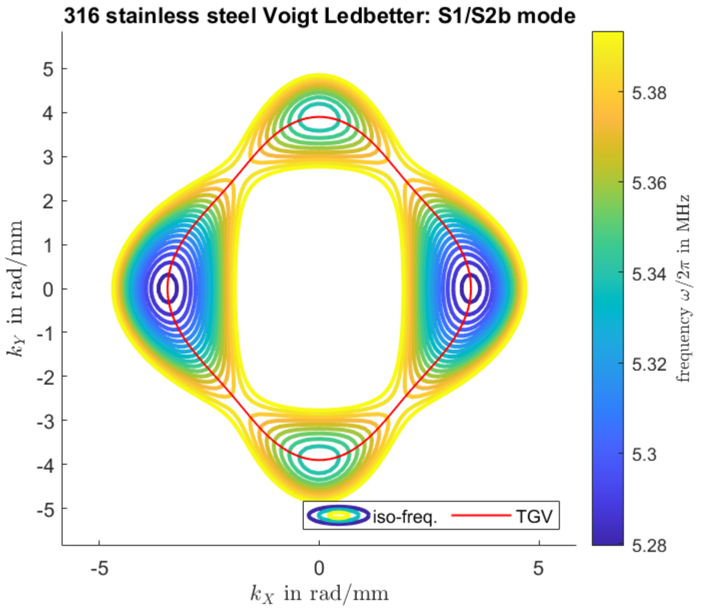


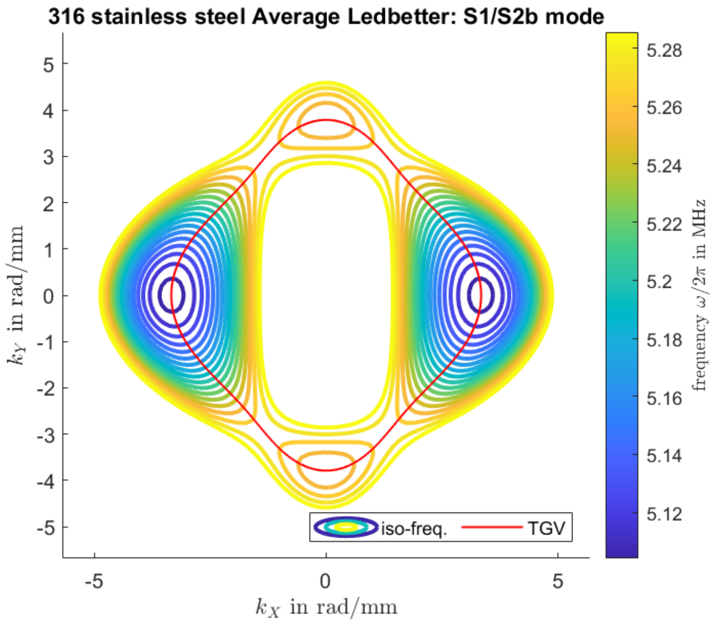


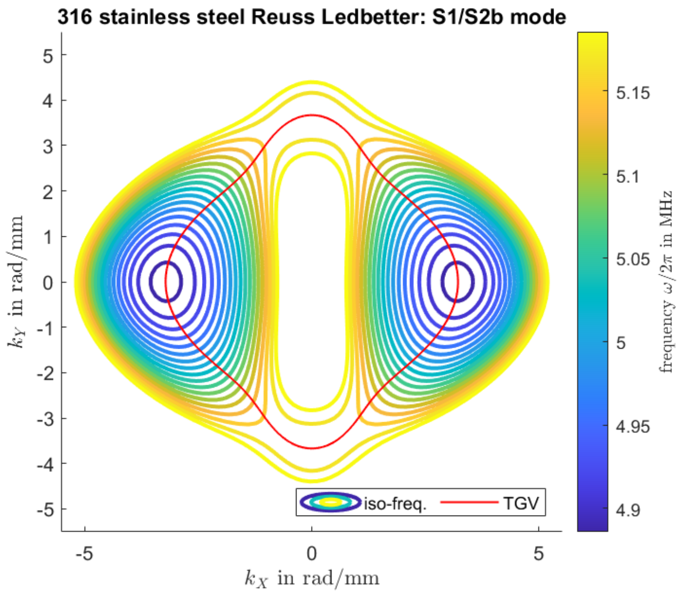


Constant taken from
Austenitic-steel elastic constants (MONOCRYSTAL/POLYCRYSTAL RELATIONSHIPS)
R. P. Reed et al. (eds.), *Austenitic Steels at Low Temperatures*

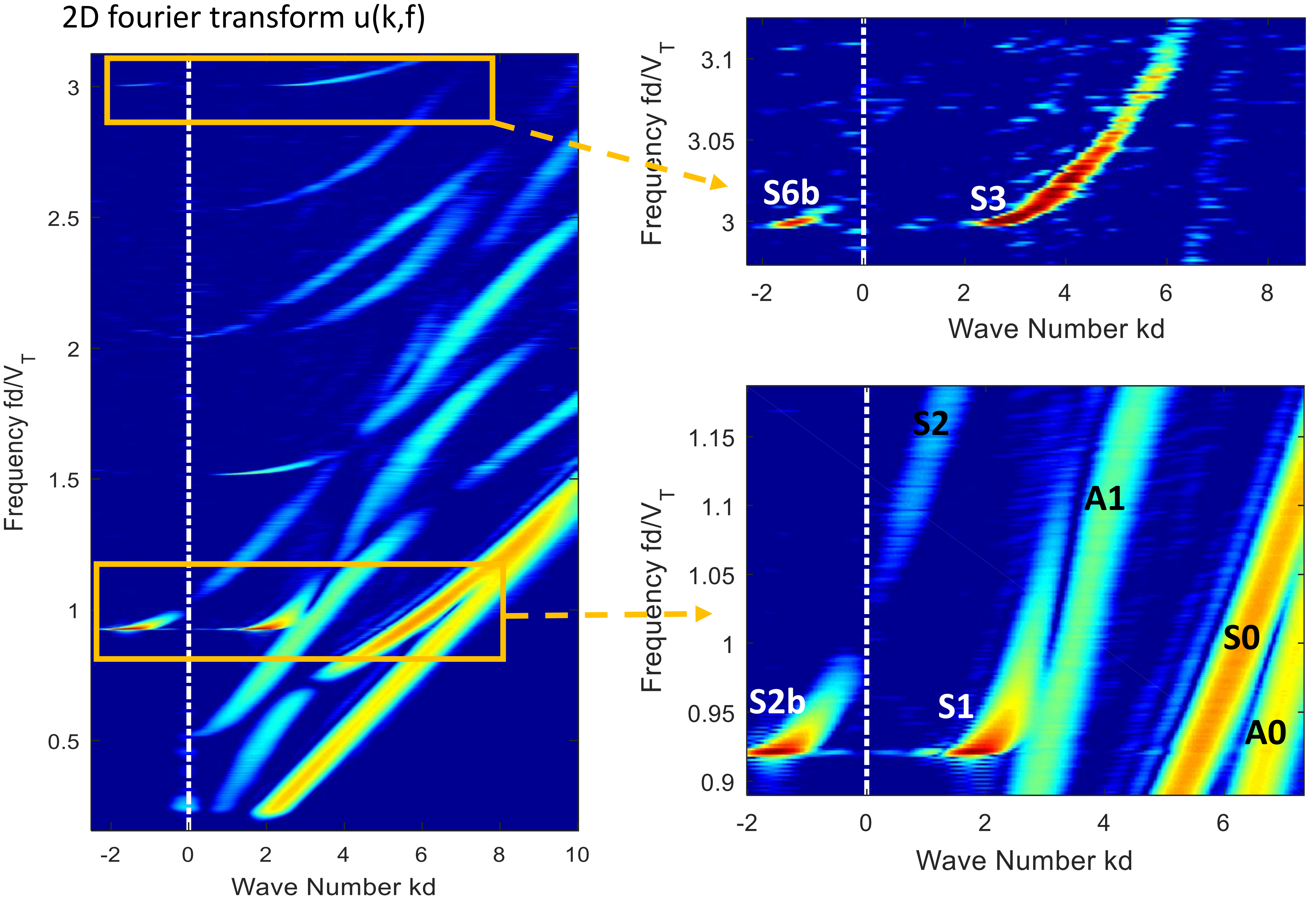




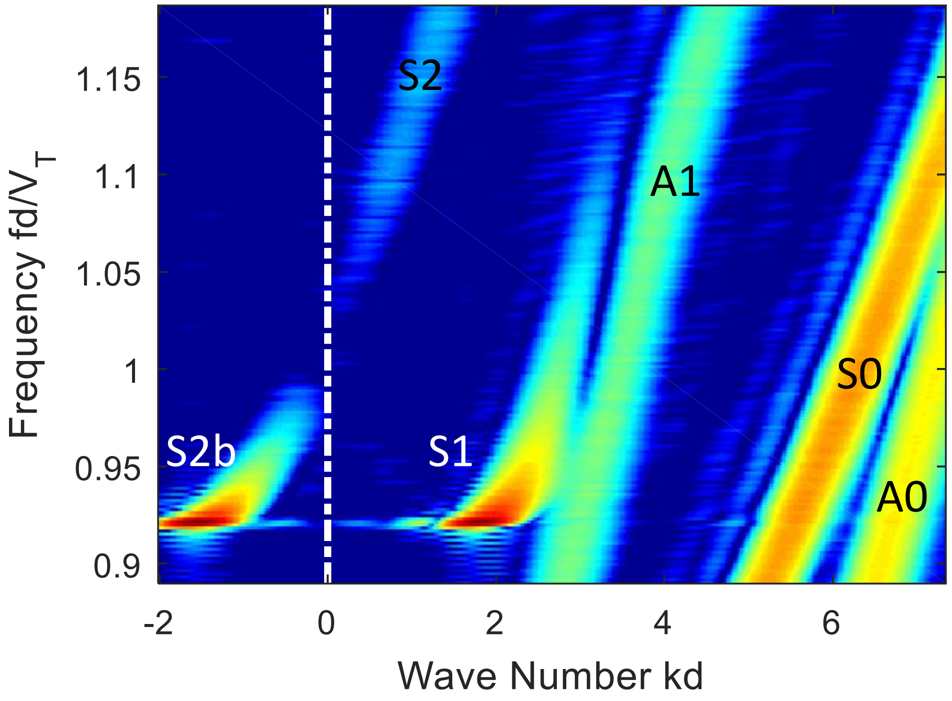




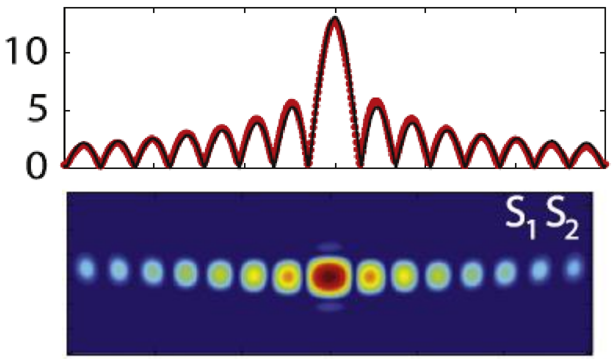
Measured dispersion curves of modes with positive group velocity



S_1S_2 Zero Group velocity mode: interference of S1 and S2b mode

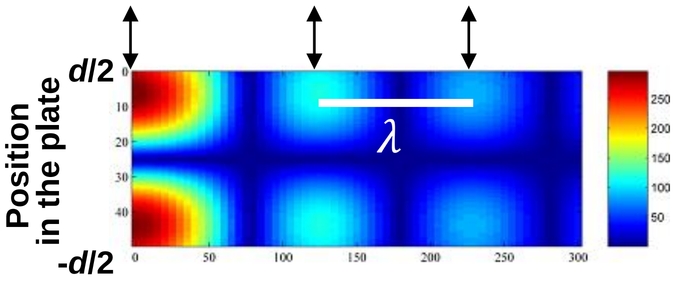


Out-of-plane surface displacement

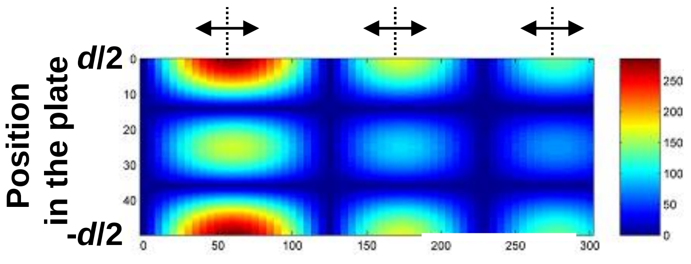


$$\left|J_0\left(\frac{2\pi}{\lambda}x\right)\right|$$

Displacement inside the plate simulated with Spicer model (APL 1990)

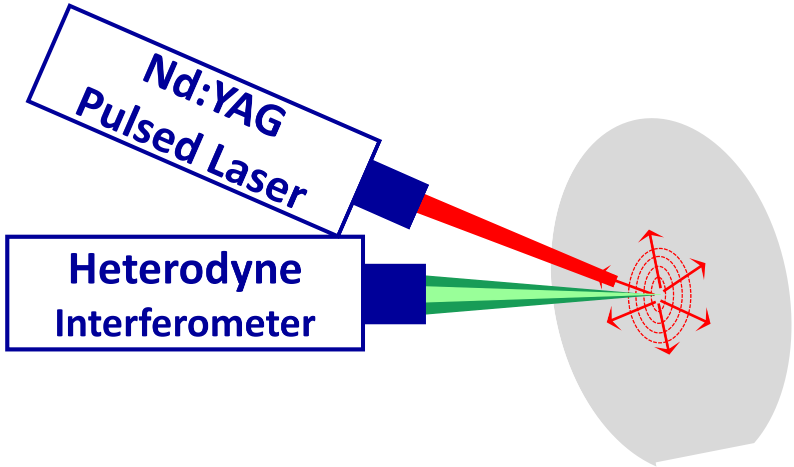


Out-of-plane displacement



In-plane displacement

ZGV modes measured in a silicon plate



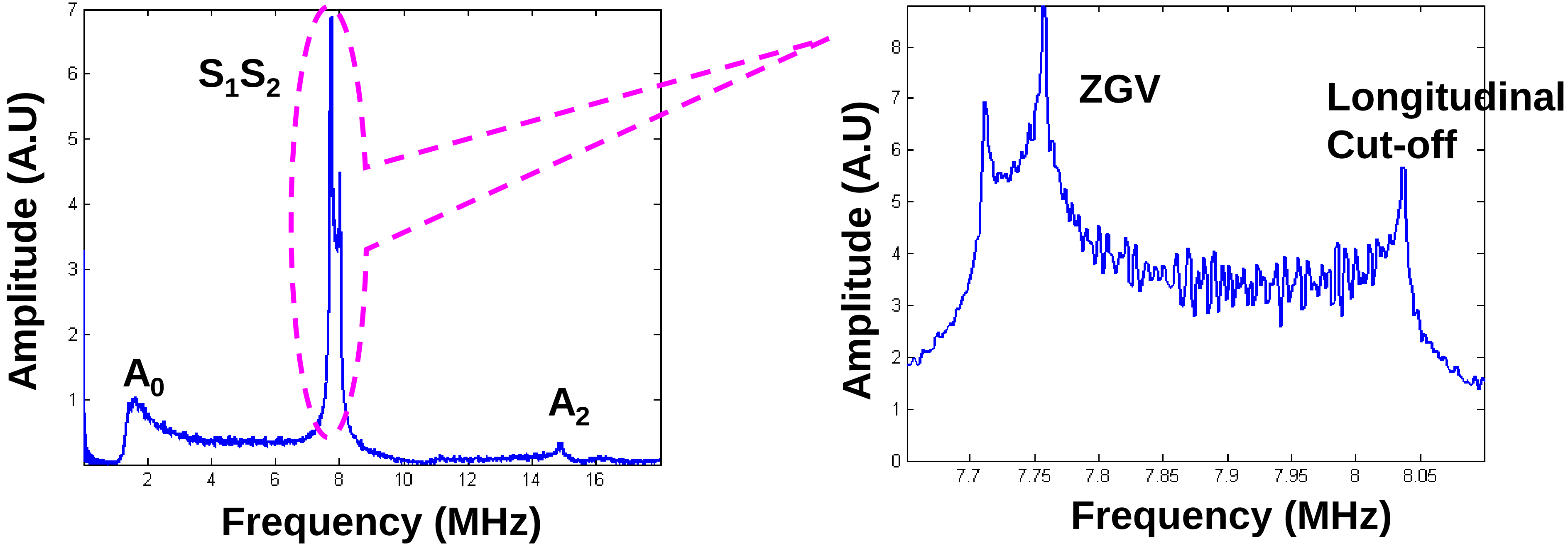
Silicon wafer

cut: [0 0 1]

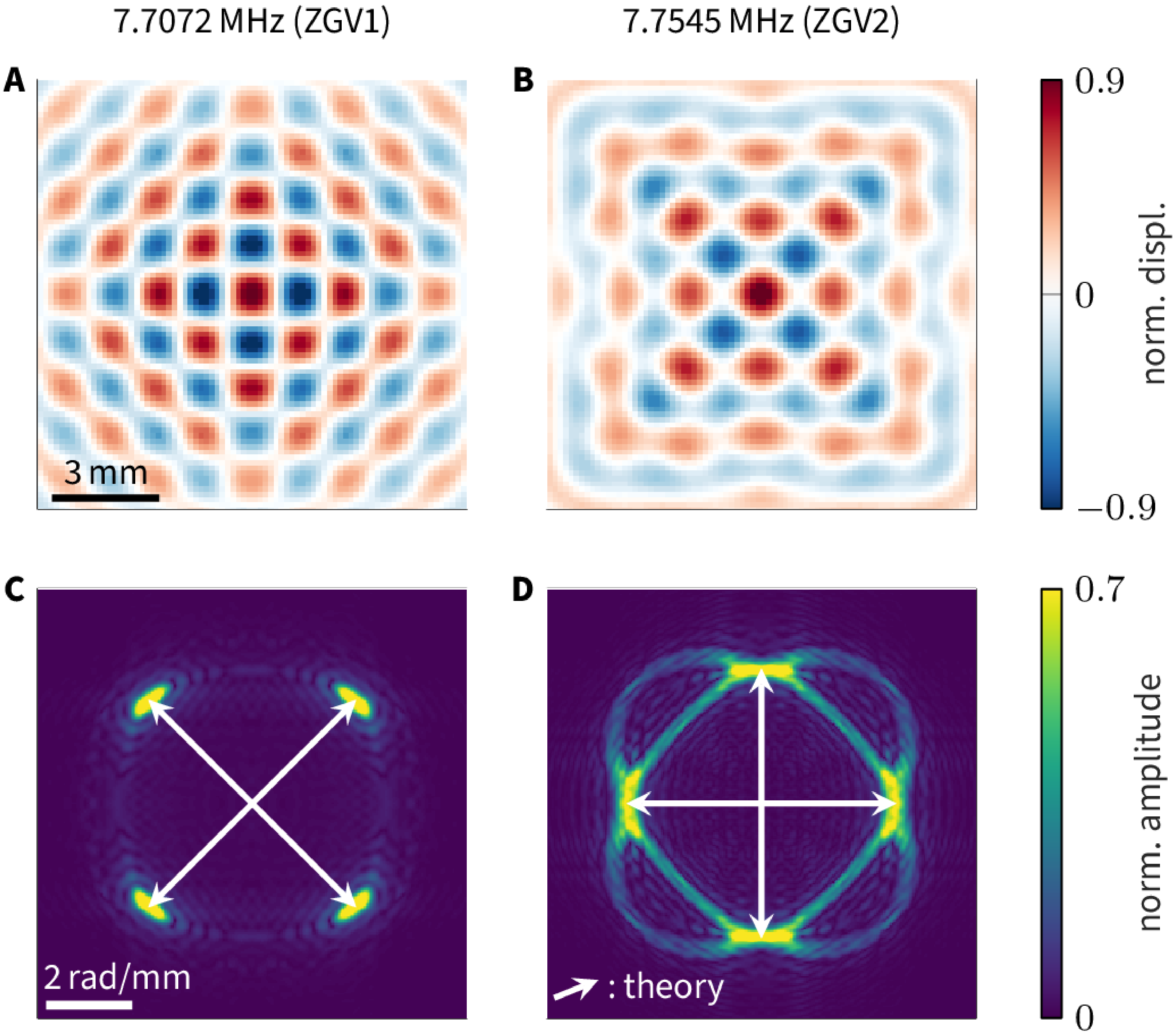
thickness: 525µm

diameter: 5 ″

Normal displacement spectrum



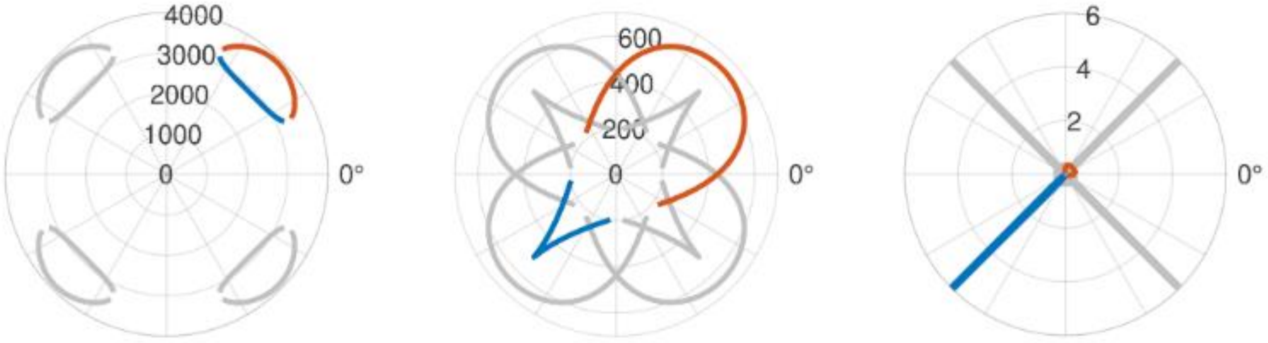
Prada, Clorennec, Murray and Royer, J. Acoust .Soc. Am. (2009)


7.7072 MHz (ZGV1)
7.7545 MHz (ZGV2)
A
B
C
D
3 mm
2 rad/mm
: theory
0.9
0
−0.9
norm. displ.
0.7
0
norm. amplitude

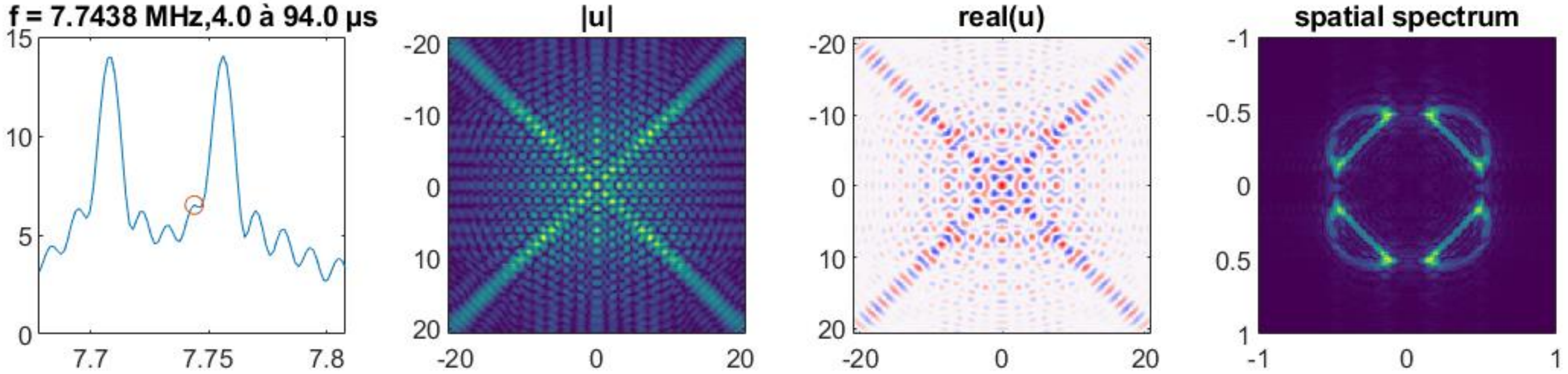
Experiment : below the saddle point frequency

Slowness curves | Energy Velocity | Maris Factor

$k(\theta)$ | $V_g(\varphi)$ | $\left(\frac{d\varphi}{d\theta}\right)^{-1}$



Fourier Transform of the measured field



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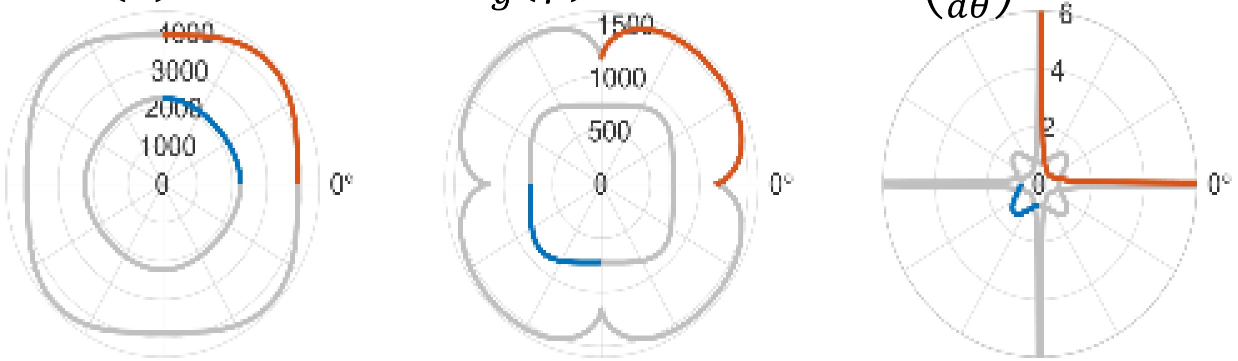
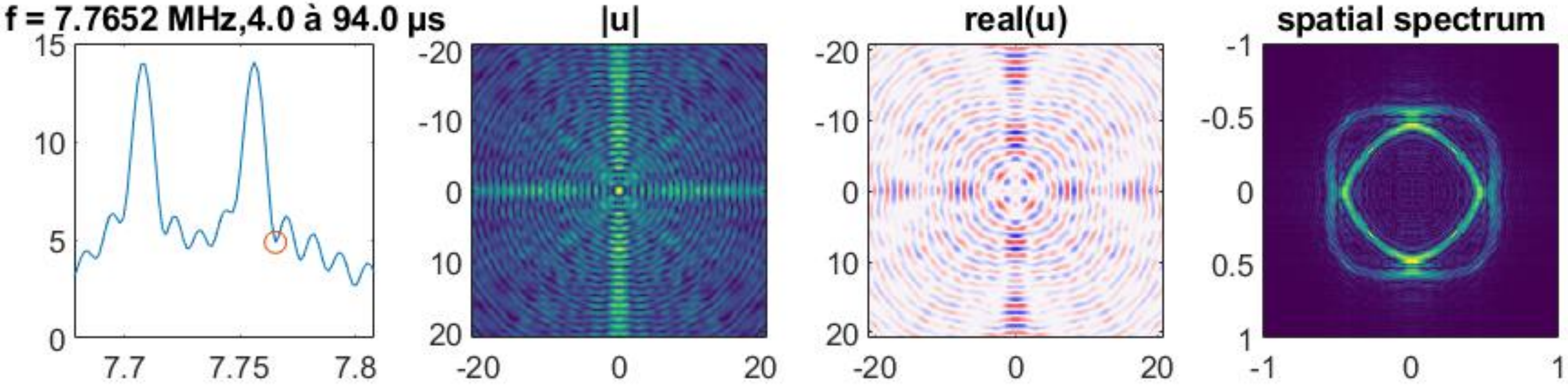
Experiment : above the saddle point frequency

Slowness curves | Energy Velocity | Maris Factor

$k(\theta)$ | $V_g(\varphi)$ | $\left(\frac{d\varphi}{d\theta}\right)^{-1}$

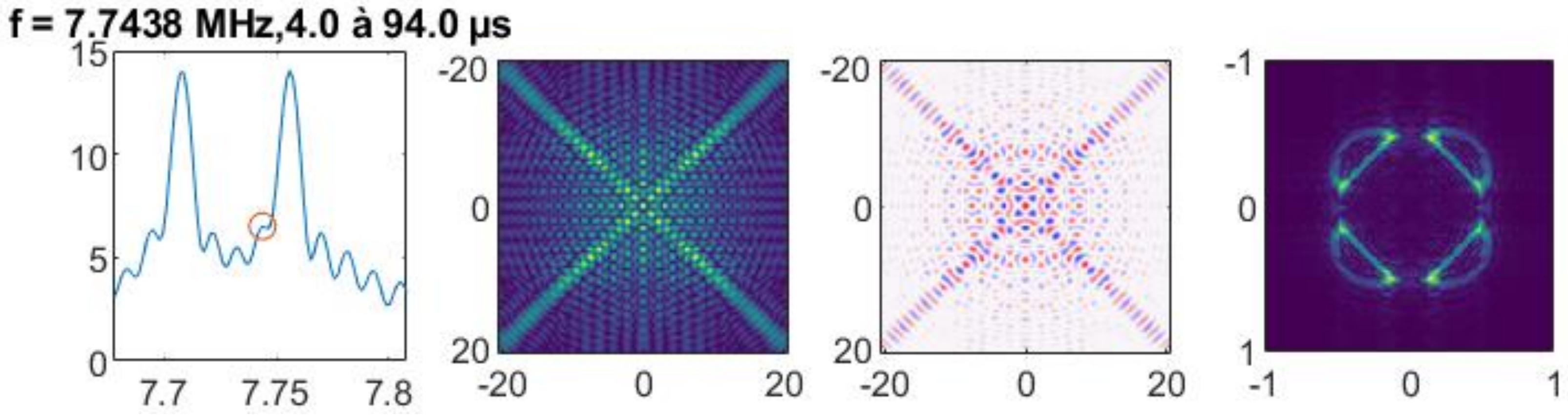


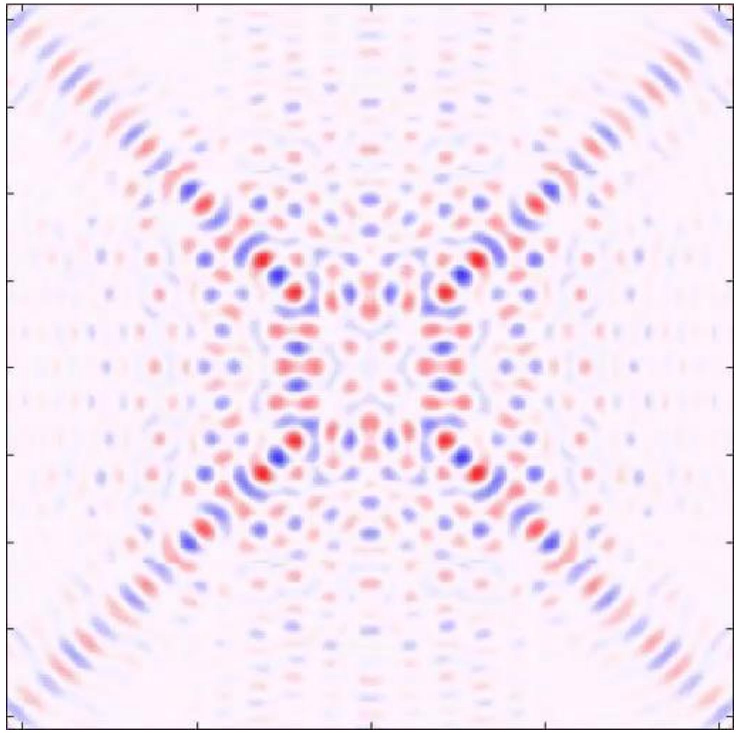
Temporal Fourier Transform of the measured field



With Daniel Kiefer and Sylvain Mezil

Backward Beam steering





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