Nanoacoustic guided waves

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Additional details / nanoultrasonic imaging
How does one measure picosecond ultrasound in practice?

- Sun et al., APL 2001
- Change the delay between the pump and the probe pulses
  - \(\rightarrow\) measure transmission coefficient of the probe pulse as a function of delay (delay generated with translation stages)
    - No picosecond scope needed!

FIG. 1. Schematics of the experimental setup.
What are the ultrasonic characteristics of the pulses generated by an OPT?

- Not the same system, but similar
  - 0.7-0.9 THz -3 dB band
Guided waves
Guided waves

- Waves propagating along a structure
  - Guided by the boundaries of the material
- Guided wave testing: probe long distances along the guiding structure
- Most commonly used: Lamb waves

http://www.ndt.net/article/wcndt00/papers/idn508/fig1.gif
Guided waves: modes

- Important factors:
  - Attenuation in length direction
  - Displacement direction
    - Affects pickup and launch
  - Velocity
    - Different modes travel at different velocities
Guided waves: Lamb waves

- Two different types
  - Symmetric
  - Asymmetric
- Solutions to two Lamb equations
  - Has to be solved numerically

Dispersion curves

- Describe the propagating modes
  - Phase/group velocity as a function of frequency
  - Thickness dependent
- Obtained as a solution to Lamb dispersion equations
Practical use: Lamb waves

- Detection of defects
  - Polytec commercial device
  - Detection of impacts
Interface waves

- Rayleigh
- Scholte
- Stoneley
Complex geometries: Curvature

- Curved surfaces cause the modes to change
  - Quasi-plate modes
  - Difference in curvature between inner and outer surfaces
Guided waves in complex structures: pipe

• Cylindrical geometry
  • Plate in the longitudinal direction
• Ultrasound propagation depends on the frequency
• At high frequencies, gives rise to a problem: multiple roundtrips
  • Solved by signal processing
    – Pre-information on the structure
    – Differential measurements
• Lamb modes
Example: Multiple roundtrips

Guided waves in complex structures: pipe / rod

- At low frequencies, modes differ from Lamb modes:
  - Torsional T(0,y)
  - Flexural F(x,y)
  - Longitudinal L(0,y)
- The (x,y) notation: x is the circumferential order and y the ‘order’ of the mode
Circumferential order

- Changes in amplitude as a function of radial direction
  - Shin et al., 1999
Practical use: Tube waves

- Lowe et al., Ultrasonics 1998
- Detection of notches in oil pipes
- L-modes
Guided waves in complex structures: Whispering gallery mode

- Quasi-$A_0$ modes at high frequencies
- Due to difference of curvature, energy concentrates on the outer surface
- "Curved Rayleigh modes"
Guided waves in complex structures: spheres

- Solid spheres: Rayleigh waves (naturally collimated)
- Tsukahara *et al.*, APL 2000 & 2003
  - Line source
Practical use: waves on spheres

- Ultrasonic gas sensor
  - Yamanaka et al., IEEE trans. Ult. 2006
Guided waves in nanoscale

- Some differences
  - High frequencies required to achieve meaningful fd products
  - Elasticities very high $\Rightarrow$ wave velocities very high
Nanoplates

(Plate-like structures with a thickness in the range of nm)
Nanometrology by surface acoustic waves (SAWs)

- Nardi et al., Proc. SPIE 8681, 2013
  - Generate SAWs (Rayleigh waves) on thin film-substrate structures
  - Measure mechanical properties of the thin films
Nanometrology by surface acoustic waves (SAWs)

- Sample used: 50-100 nm thick SiC:H films deposited on silicon substrates
- Metallic periodic nanostructures on the surface
  - These absorb the pump pulse (800 nm, d = 500 µm, fluence 10 mJ/cm²
Nanometrology by surface acoustic waves (SAWs)

- The metallic structures are the transducers
  - Absorb the pump pulse and expand from the temperature
  - Frequency adjustable by the period
- Also longitudinal waves generated from the film
Nanometrology by surface acoustic waves (SAWs)

- Probe pulse
  - Extreme ultraviolet (30 nm wavelength)
  - Diffracts from the nanograting
    - → displacement from the diffraction pattern
Nanometrology by surface acoustic waves (SAWs)

- How do you get an EUV beam?
- Rundquist *et al.*, Science 1998
- Ti:SA laser @ 800 nm
- Use higher harmonic generation in a gas (argon)
  - Ionization of gas atoms in a tight focus
  - Change gas pressure to adjust the phase between the light and emitted soft x-rays
Nanometrology by surface acoustic waves (SAWs)

- Results: both SAWs and longitudinal waves (LAW) visible
Nanometrology by surface acoustic waves (SAWs)

- Results: SAW velocity approaches the Rayleigh velocity of silicon when wavelength is increased.
2nd order SAW?

- Higher harmonics of the surface wave
Nanometrology by surface acoustic waves (SAWs)

- Results: Calculated isotropic Young’s moduli match nanoindentation results quite well
  - Both LAW and SAW velocities considered
Even higher frequency SAW’s

- 22 GHz surface waves
Even higher frequency SAW’s

- Siemens et al., Applied Physics Letters 2009
- 50 GHz surface waves
  - 125 nm wavelength
Even higher frequency SAW’s

• Nardi et al., Applied Physics Letters 2012
  • 100 GHz surface waves (theoretical)
    – 63 nm wavelength
Tubular structures on the nanoscale

Rod/tube like structures with a nanometer radius
Tubular structures in nanoscale

- Carbon nanotubes
- Nanowires (aspect ratio > 20)
  - E.g. Gold
- Nanorods (aspect ratio ~5)
  - E.g. ZnO
Sound propagation in carbon nanotubes

- Carbon nanotubes are over 40 years old
  - First paper out 1952
- Up to date, no experimental paper exists studying propagating waves on CNT’s
  - Only temperature conductivity via phonons
- Many theoretical papers
Sound propagation in SWCNTs

- Heireche *et al.*, Physica E 2008
- Nonlocal Timoshenko beam model
  - Local vs nonlocal
  - Nonlocal theory of elasticity: stress at \( x \) is a functional of the strain field at every point of a body
  - Local (classical) theory -> only strain at \( x \) matters
Sound propagation in SWCNTs

- Phase velocity vs local or nonlocal elasticity
- F mode
- Scale parameter $e_0a$ ($a =$ internal characteristic length)
Sound propagation in MWCNTs

- Yoon et al., JAP 2003
  - Critical frequencies after which several speeds of sound coexist (several modes)
    - Van der Waals forces between the tubes make them vibrate together
Sound propagation in nanowires

- Mante *et al.*, Nano Letters 2013 (February)
  - AlN/GaN nanowire superlattices
  - Coherent guided acoustic phonons (CGAPs)
Sound propagation in nanowires

- CGAPs have a peculiar dispersion relation
  - In circular GaN nanorods \((d = 75 \text{ nm})\), quite normal
  - In superlattices, the modes fold into a Brillouin zone
Info: Sound propagation in periodic structures

- James et al., JASA 1995
  - Take 1-D column of water, assume that it is comprised of periodic units of length L
  - From dispersion relation $\omega(k)$ plot has two straight lines
  - From periodicity $\Rightarrow$ propagation can be described as an unit cell
This unit cell in case of water can be plotted in a momentum space unit cell ($|kL| \leq \pi$)
Info: Brillouin zone

- This momentum space unit cell is a Brillouin zone
- Propagation of waves can be completely characterized by their behavior in a single zone!

![Brillouin zone diagram]
Sound propagation in nanowires

- Two modes detected (at 25 GHz and 60 GHz)
- Negative dispersion @ 60 GHz
- Times of arrival match the expected ones
Sound propagation in silica microwires

- Beugnot et al., arXiv 10.1.2014
- ~micrometer diameter optical fibers
- Light propagating in the fiber generates surface waves
  - GAWBS and SBS well known
  - SAWBS!
Absorbed and emitted phonons have different energy

For example, Santori *et al.*, Nature Photonics 2012
Sound propagation in silica microwires

- Measurement of the SAWs with Brillouing scattering
  - Stimulated Brillouin scattering (phonons from the light)
  - The surface wave visible!
Take-home
Take-home: Nanoacoustic guided waves

- Most of the work in nanoplates and rods
  - No work on propagating modes on nanospheres
  - No work on Scholte or Stoneley waves
  - Some work on whispering gallery modes (only in resonance → lecture on trapped modes)
- Propagation velocities very high
- Guided sound excitation very hard at the moment