Gas and Liquid Phase Sensitivity of "Love" Waves

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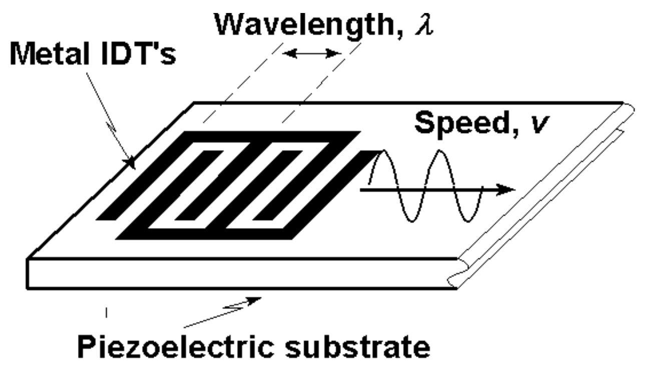
Overview

1. Layer-Guided Acoustic Waves
    - Love waves v SH-APMs
    - Dispersion curves and phase speed mass sensitivity
    - Dispersion and group velocity
    - Polymer waveguides and the “Sauerbrey” equation
2. Experimental Data
    - Existence of layer-guided SH-APMs
    - Group velocity mass and liquid sensitivity
3. Love Waves and Frequency
    - Higher frequency and multiple modes
    - Frequency hopping
4. Summary

Love Waves v SH-APMs

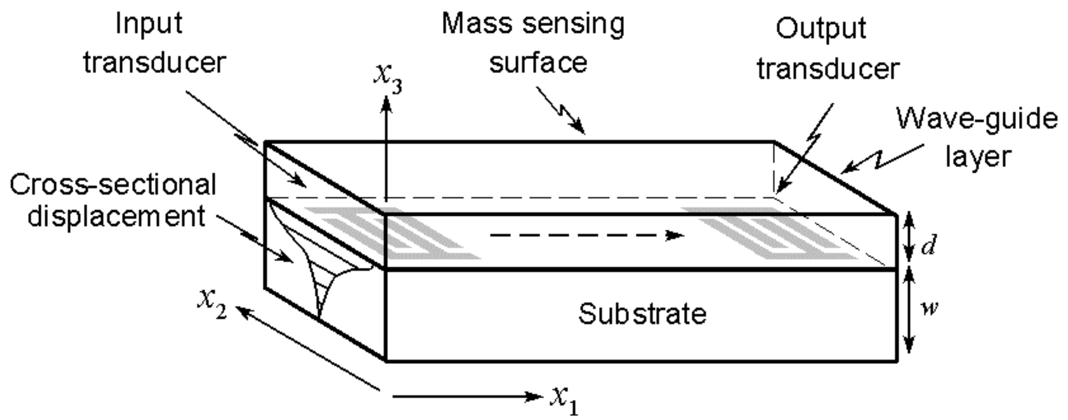
- Surface Acoustic Wave (SAW)



- Love Wave

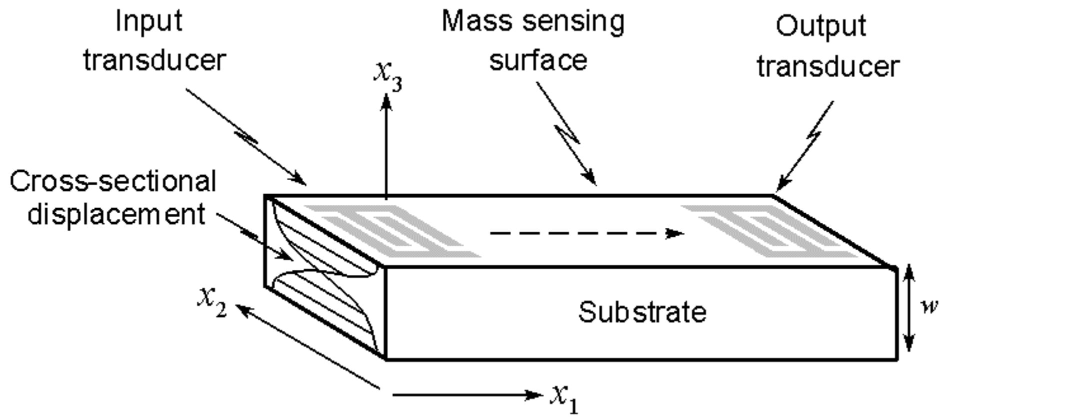
  Layer guided SH-SAW

  with $v_l < v_s$



- SH-APM

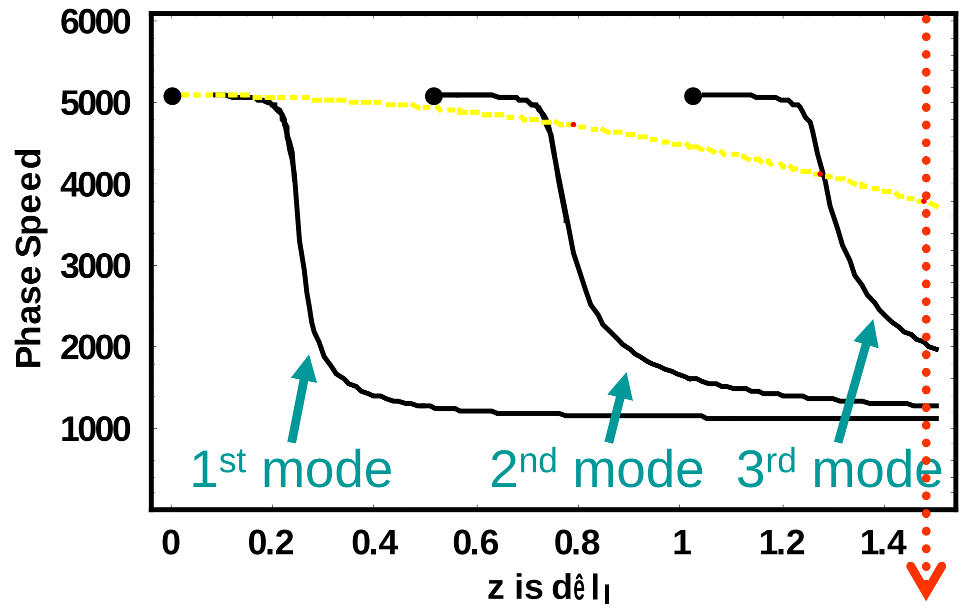
  Substrate resonance



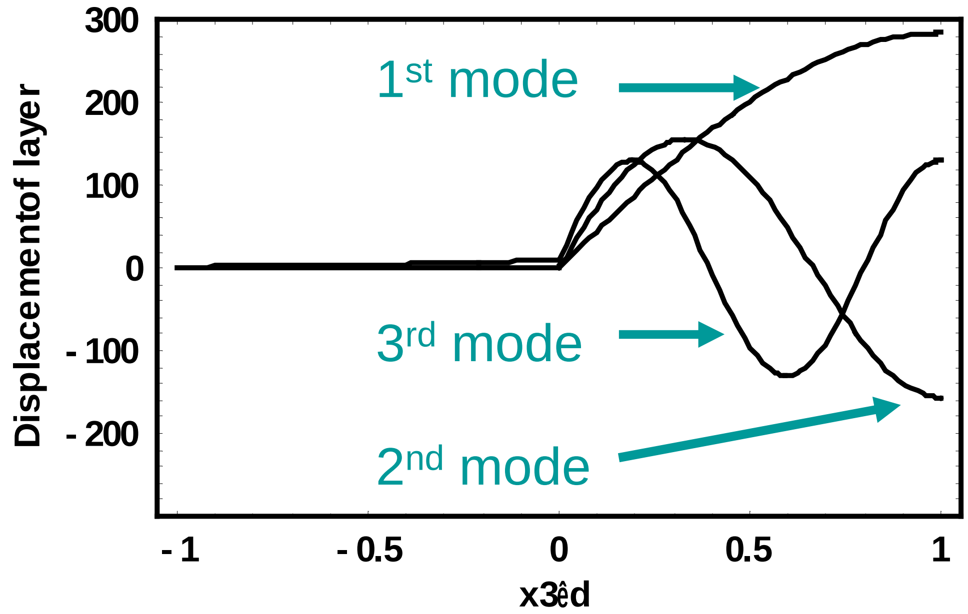
Love Waves

- Theoretical dispersion curve

(Insertion loss is unchanged by an elastic guiding layer)



- Displacements for first three modes (z=1.3)



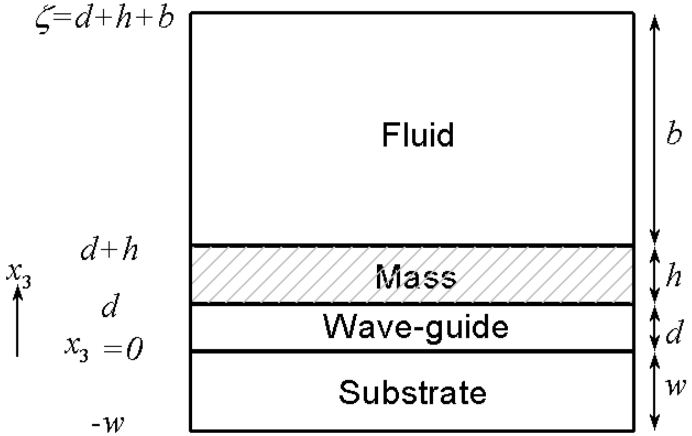
Layer-Guided SH-APMs

- Generalized Dispersion Equation[1]

  Layer and substrate displacements

$$\underline{u}_l = (0,1,0)\left[Ae^{-jT_l x_3} + Be^{jT_l x_3}\right]e^{j(\omega t - k_1 x_1)}$$

$$\underline{u}_s = (0,1,0)\left[Ce^{T_s x_3} + De^{-T_s x_3}\right]e^{j(\omega t - k_1 x_1)}$$



  Eqns of motion ⇒ T_l's and T_s

  Boundary conditions ⇒ dispersion eqn

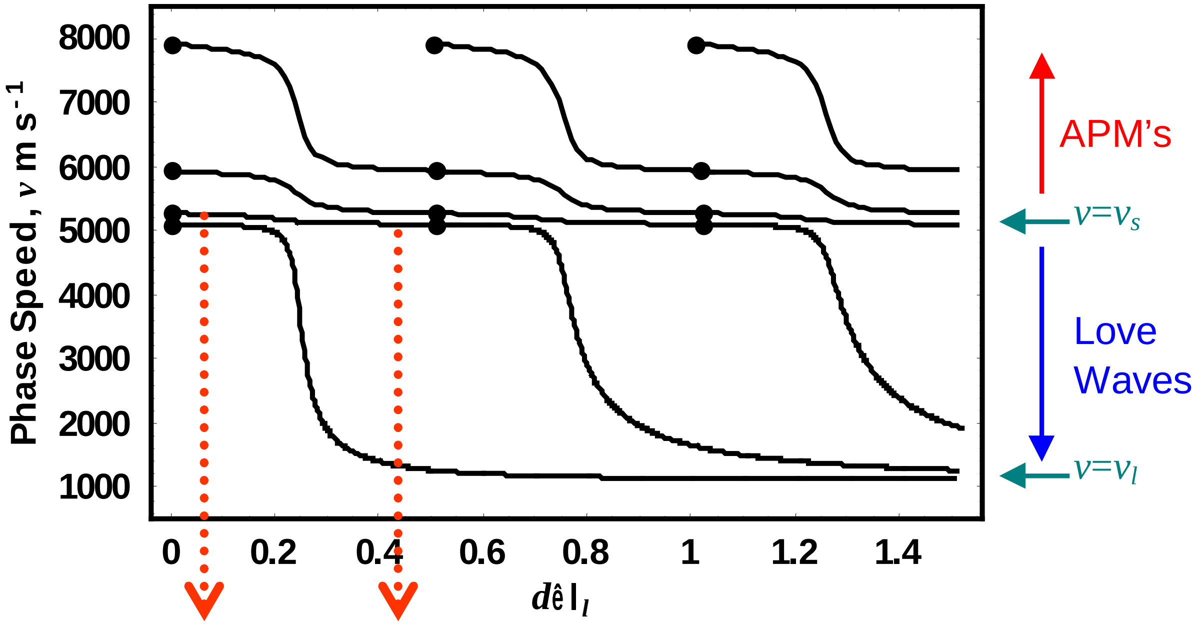
- Substrate + Layer Solutions

T_s real	⇒	$v<v_s$	⇒	"Love" Waves
$T_s=jk_s$ with k_s real	⇒	$v>v_s$	⇒	"Layer guided SH-APMs"

[1]McHale et al, Europhys. Lett. (2002) 58, 818-822, J. Appl. Phys. (2002) 91, 5735-5744.
McHale *et al*, *"Mass, liquid and polymer sensitivity ….."*, Accepted J. Appl. Phys. (2002).

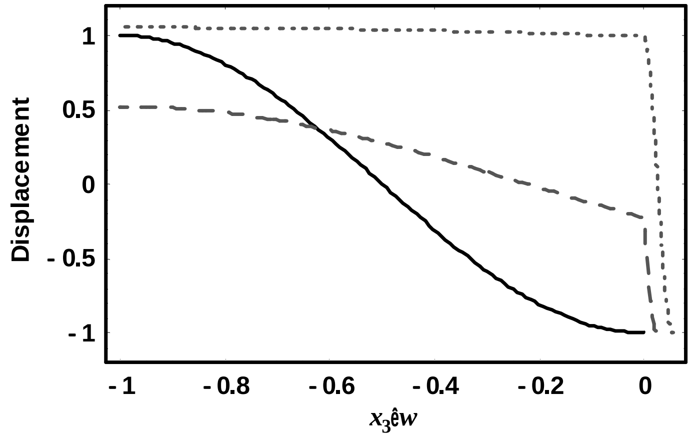
Substrate + Mass Guiding Layer

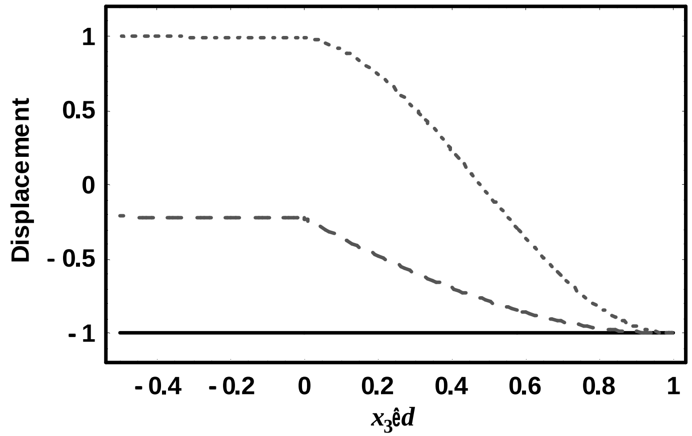
Dispersion Curve



Points = Anti-node moving from substrate to layer

Evolution of 1st SH-APM





Solid → dashed
with increasing guiding

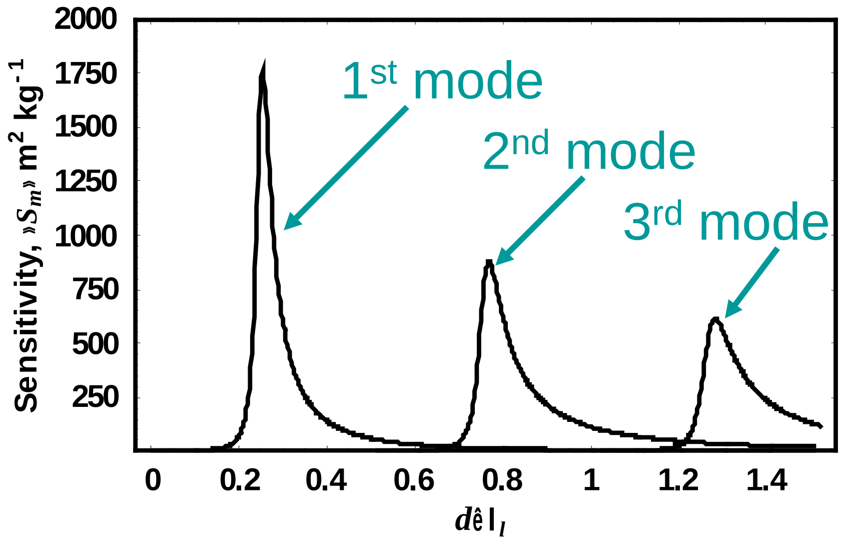
Phase Speed Mass Sensitivity

$$S_m = \lim_{\Delta m \to 0} \frac{1}{\Delta m}\left(\frac{\Delta v}{v_o}\right) \approx \frac{f_o}{\rho_l v_l}\left(\frac{d \log_e v}{dz}\right)_{z_0}$$

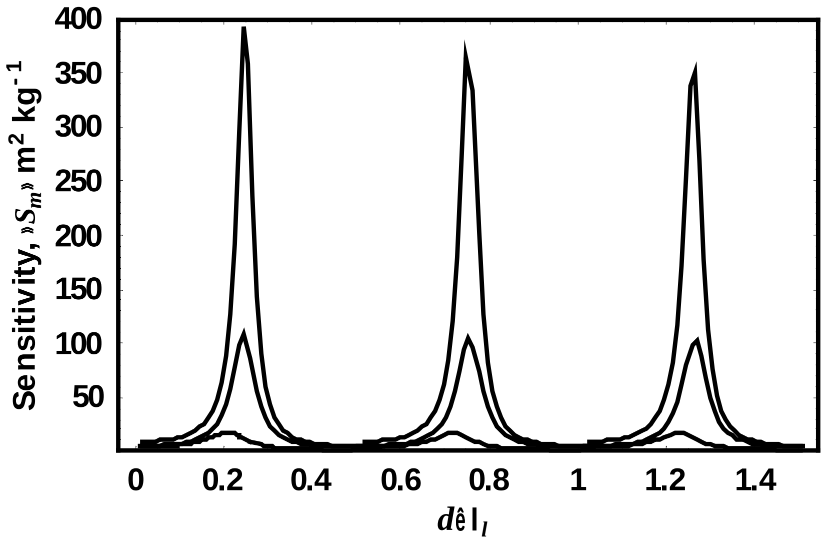
Δm is mass per unit area being sensed, $z=df/v_l$ is the normalized thickness

"Rigid" mass $\Rightarrow$ Mass sensitivity is slope of dispersion curve[1]

Love Waves



Layer-Guided SH-APMs



[1]McHale *et al*, J. Appl. Phys. (2002) 91, 9701-9710.

Dispersion and Group Velocity

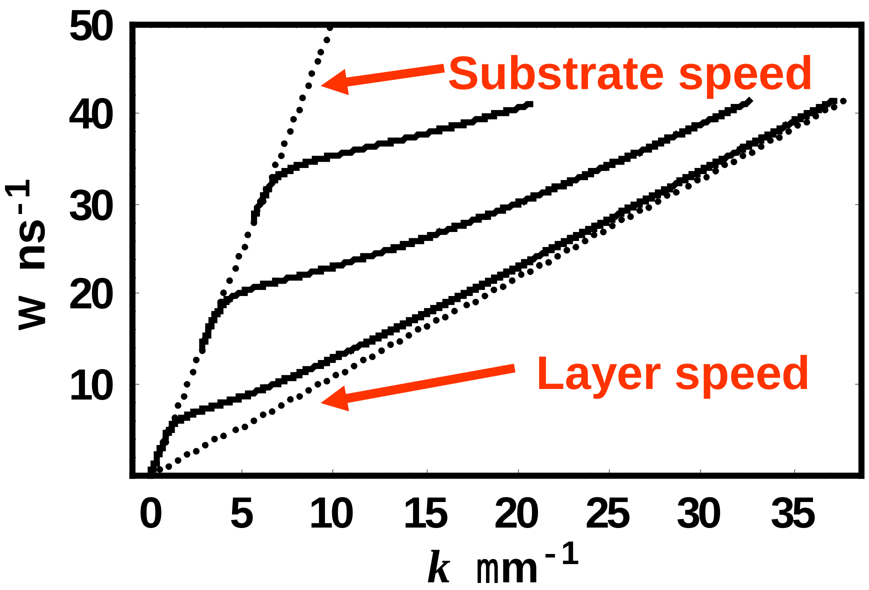
- Guiding Layer Induces Dispersion[1,2]

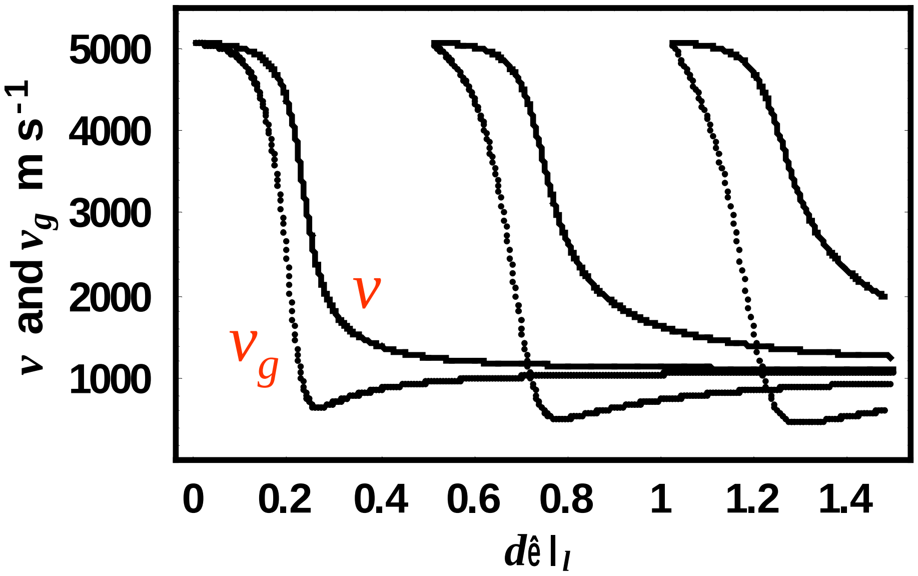
Phase velocity $v = f\lambda$ or $v = \omega/k$

Group velocity $v_g = \mathrm{d}\omega/\mathrm{d}k$

Group velocity is slope of the (ω, k) dispersion curve

Example 0.25 μm polymer guiding layer on Quartz with $w \rightarrow \infty$





[1]McHale *et al*, *"Sensitivity from group and phase …. "* , J. Appl.Phys. (2002) vol 92

[2]Martin *et al*, *"Experimental study of Love wave …. "* , IEEE Sensor Journal (2002)

Group Velocity Mass Sensitivity

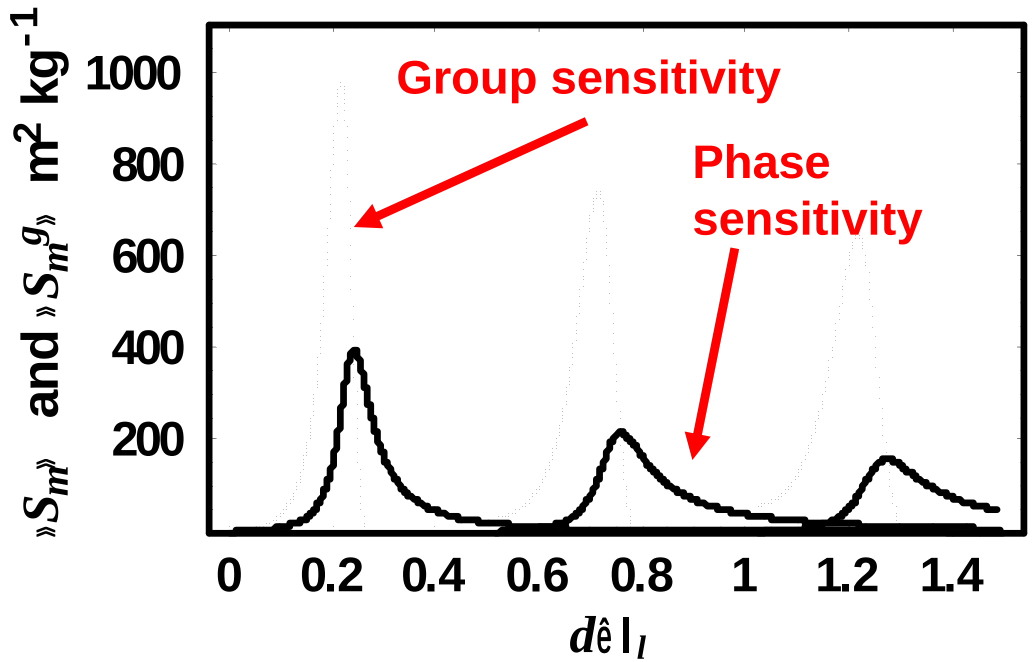
$$S_m \approx \frac{1}{\rho_l d}\left(1 - \frac{v}{v_g}\right) = \frac{1}{\rho_l d}\frac{(v_g - v)}{v_g}$$

"Rigid" mass

Mass sensitivity is fractional deviation of the phase velocity from the group velocity divided by mass per unit area due to the guiding layer

- Define a Group Velocity Sensitivity

$$S_m^g = \frac{f_o}{\rho_l v_l}\left(\frac{d \log_e v_g}{dz}\right)_{z=z_o}$$



Polymer Waveguide with Polymer Loading

Generalized Sauerbrey Equation

Complex velocity shift

$$\frac{\Delta v}{v_o} \approx \left(\frac{1 - v_f^2 / v_o^2}{1 - v_l^2 / v_o^2} \right) \left(\frac{d \log_e v}{dz} \right)_{z=z_o} \left(\frac{\tan\left(T_f^o h\right)}{T_f^o h} \right) \frac{\omega \rho_f h}{2\pi v_l^\infty \rho_l}$$

$\omega \Delta m / A$

$(\rho \eta \omega)^{1/2}$

Complex slope factor
from polymer waveguide

Care Needed

1. Dispersion
2. Slope depends on ω

tan*x*/*x* factor gives mass/liquid loading limits

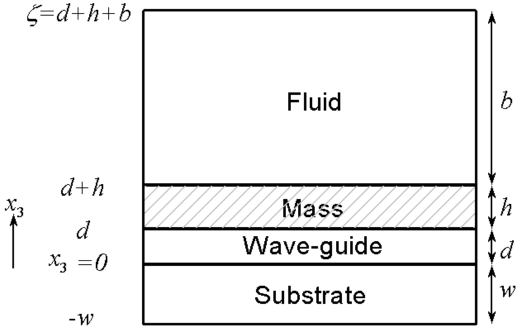
$$\left(\frac{\tan\left(T_f^o h\right)}{T_f^o h} \right) \to \begin{cases} 1 & h \to 0 \quad \text{solid limit} \\ \dfrac{-\sqrt{-2j}}{2h\left(1 - v_f^2 / v_o^2\right)} \sqrt{\dfrac{2\eta_f}{\omega \rho_f}} & h \to \infty \quad \text{and} \quad \omega\tau \to 0 \quad \text{liquid limit} \end{cases}$$

[1]McHale *et al*, *"Mass, liquid and polymer sensitivity ….."*, Accepted J. Appl. Phys. (2002).

Insertion Loss for Polymer Waveguide

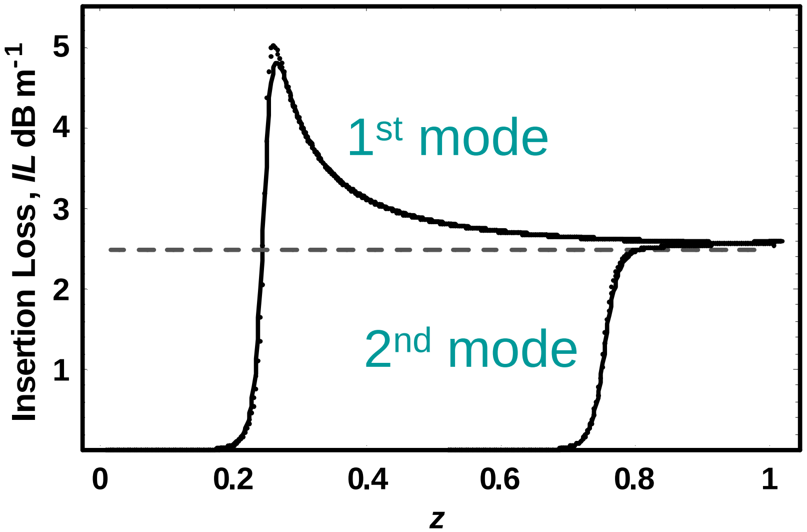
Cases considered

1. Wave-guide layer is viscoelastic
2. Mass layer deposited from liquid or from vacuum
3. Mass may be omitted (i.e. liquid phase sensitivity)

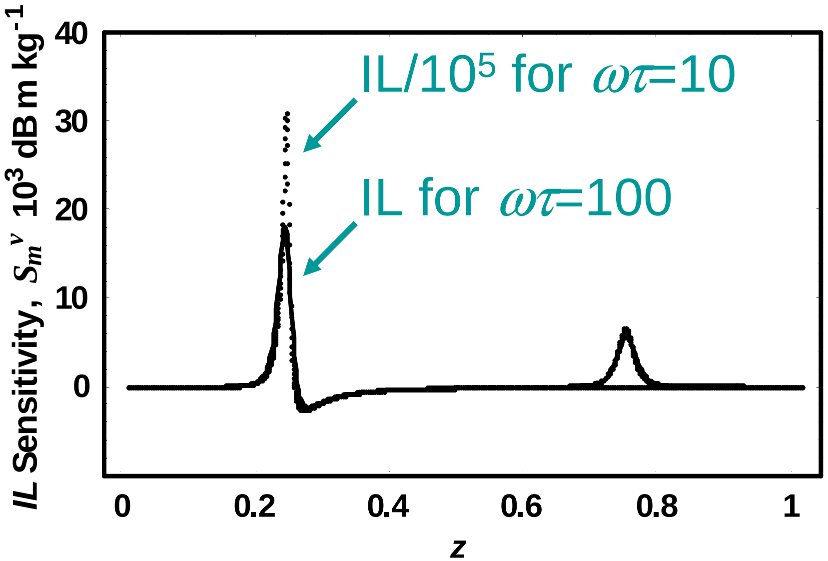


Mass/liquid sensitivity can be derived for phase velocity & insertion loss

Love Wave Insertion Loss



Love Wave IL Sensitivity



[1]McHale *et al*, *"Mass, liquid and polymer sensitivity …..",* Accepted J. Appl. Phys. (2002).

Data for Layer-Guided SH-APM

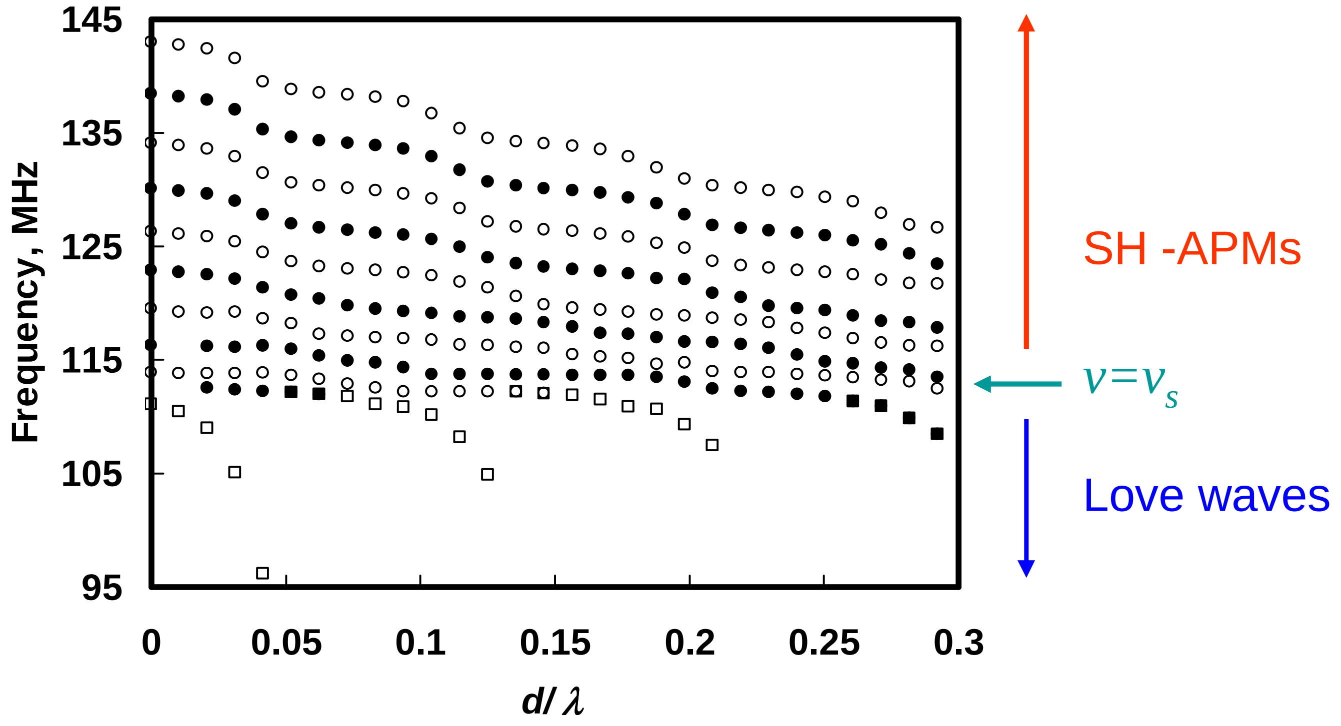
- Layer-Guided SH-APM Modes

    Prop. Orthog. to *x*-axis of thinned (200 μm) ST-Q substrate

    110 MHz surface skimming bulk wave (SSBW)

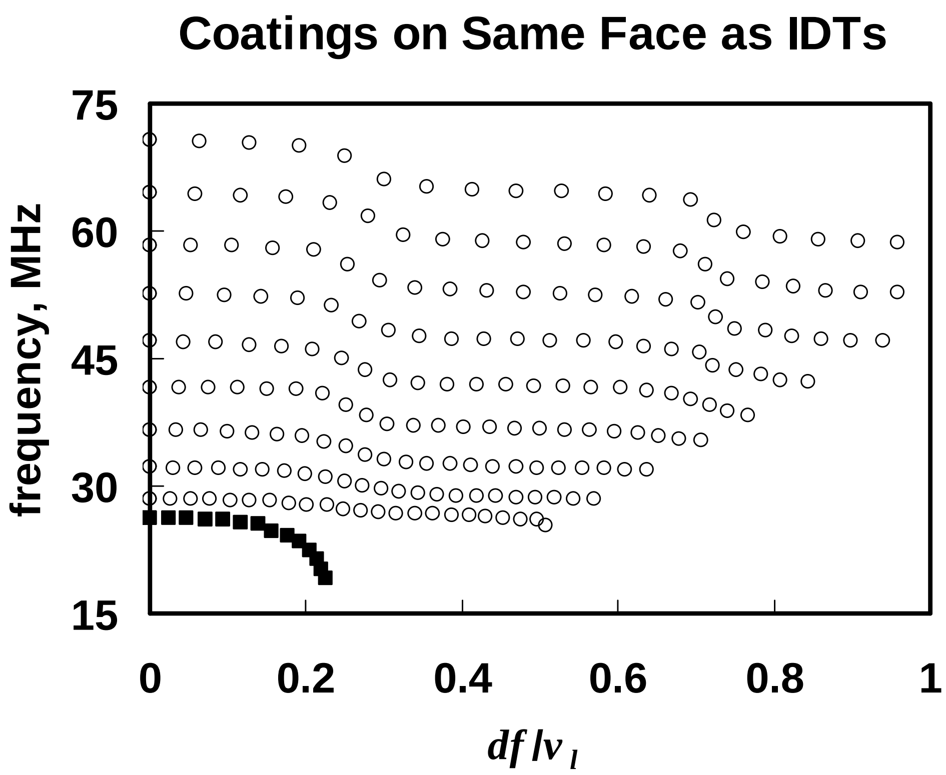
    SSBW → Love wave by a spin-coated photoresist layer

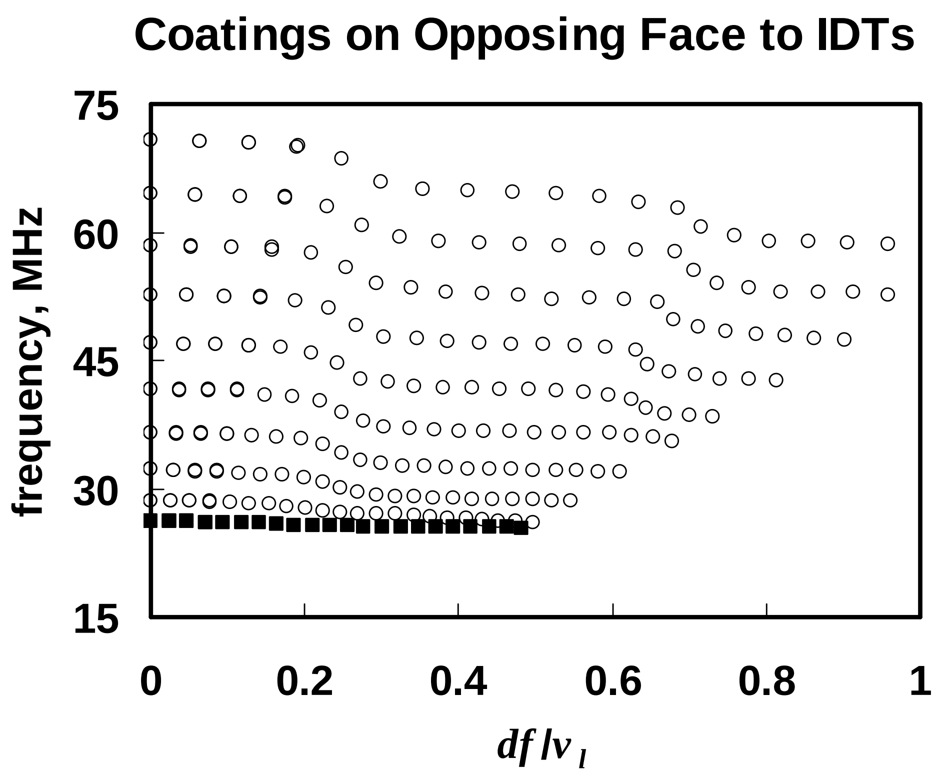
    Old mask so insertion loss high (axis is d/λ with λ=IDT period)



Experimental Data for SH-APM

- Layer-Guided SH-APM Modes[1]
  - Prop. Orthog. to *x*-axis of thinned (200 μm) ST-Q substrate
  - 25 MHz surface skimming bulk wave (SSBW)
  - Plate modes clearly resolved





[1]F. Martin, PhD Thesis, Nottingham Trent University (2002)

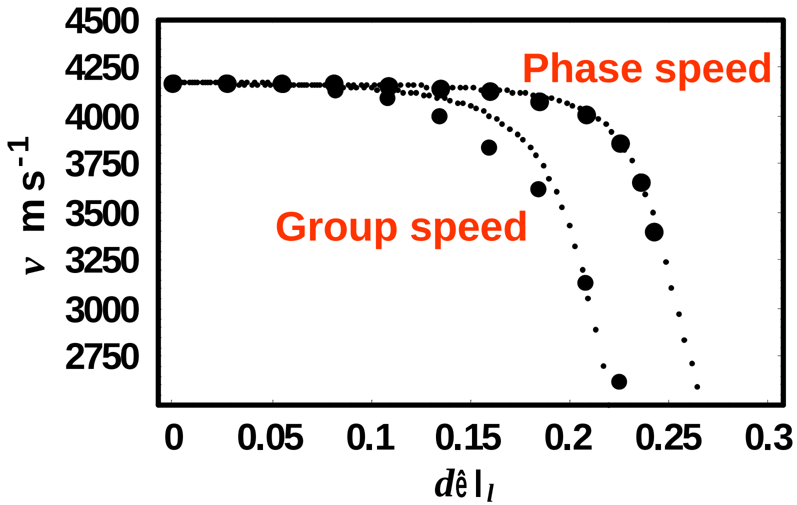
Group Velocity Data - Solids

- Phase and Group Velocity

  36º XY $LiTaO_3$

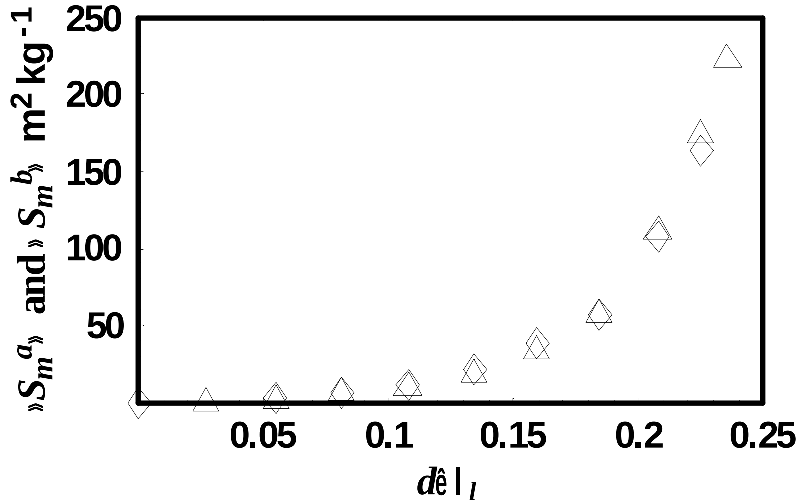
  Hardbaked photoresist

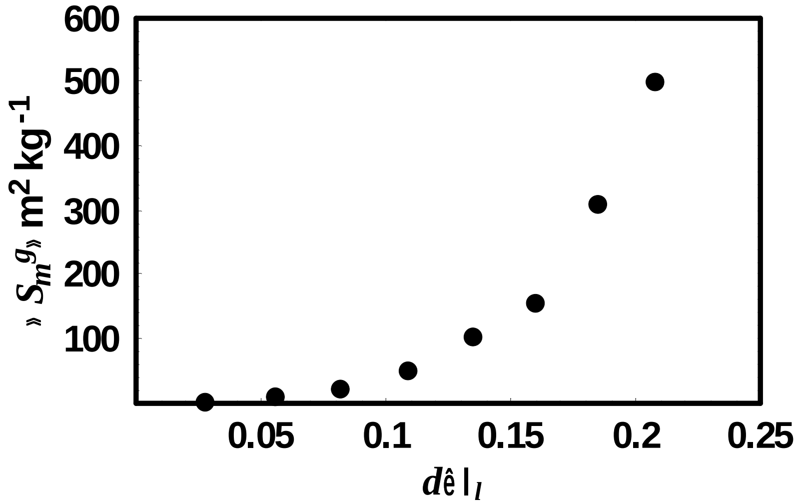
  Dotted curves are fits



- Mass Sensitivity

$$S_m^b = \frac{1}{\rho_l d}\left(1 - \frac{v}{v_g}\right) \qquad S_m^a = \frac{1}{\rho_l}\left(\frac{d \log_e v}{dx}\right)_{x=d} \qquad S_m^g = \frac{1}{\rho_l}\left(\frac{d \log_e v_g}{dx}\right)_{x=d}$$





Group Velocity Data - Liquids

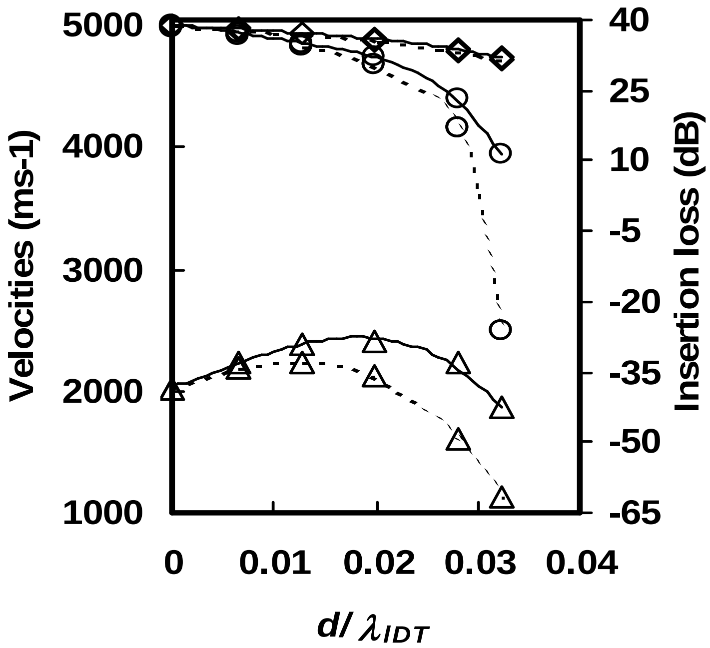
- Deposition of Guiding Layer

  ST-Quartz + photoresist

  Poly (ethylene glycol) solutions

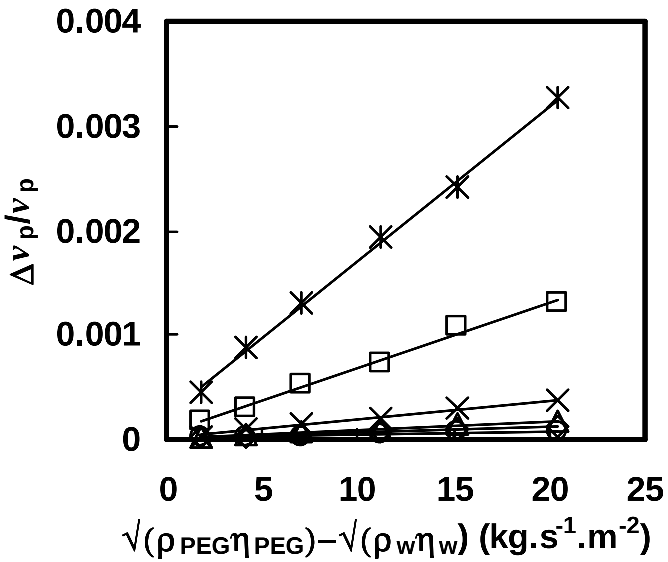
  ◊ = Phase velocity o = Grp Velocity

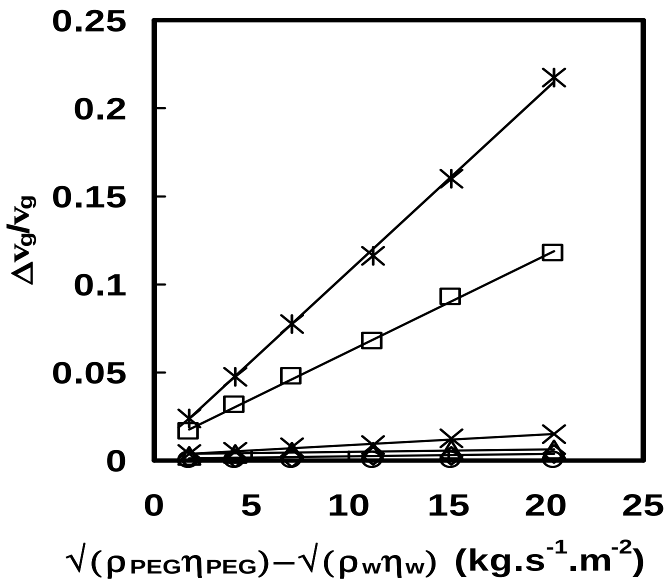
  Δ = Insertion loss Dotted = water



- Sensitivity at Operating Points

  Phase and group velocities





Love Waves and Higher Frequency

- Established QCM Sensor Principle

Mass sensitivity $\propto$ Fundamental frequency

Higher frequency $\Rightarrow$ Higher mass sensitivity

- Love Waves on a (Semi-) Infinite Substrate

Controlling dimensionless variable is $z = d/\lambda_l = df/v_l$

$$S_m = \lim_{\Delta m \to 0} \frac{1}{\Delta m}\left(\frac{\Delta v}{v_o}\right) \approx \frac{f_o}{\rho_l v_l}\left(\frac{d \log_e v}{dz}\right)_{z_0}$$

Mass Sensitivity $\propto$ Frequency $\times$ Function of z_o

Normalized thickness at operating point $z_o \propto d \times f$

Higher Frequency Operation[1,2]

Routes

1. Increase fundamental frequency

2. Hop the frequency to a harmonic

Issues

1. Change of Love wave mode?

2. Const. guiding layer thickness?

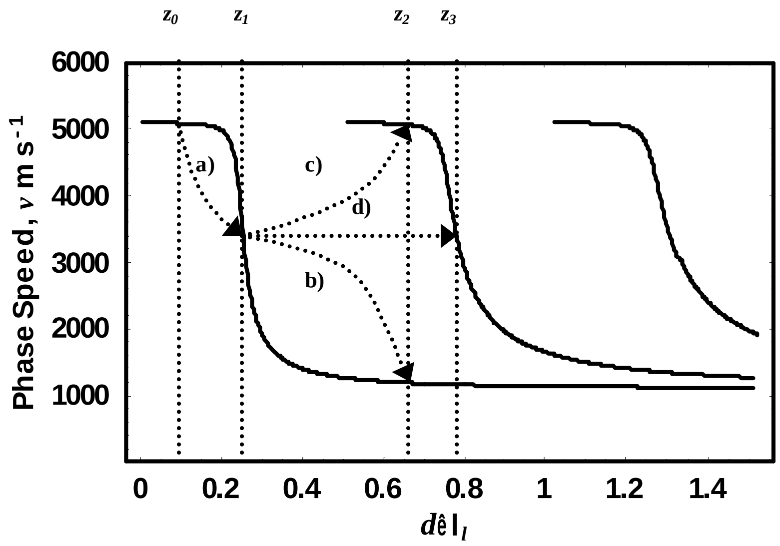
- Frequency Increase at Constant z_o

Reduce d as $1/f$ ⇒ No change on dispersion curve
⇒ Mass sensitivity scales with f

- Frequency Hopping at Constant d

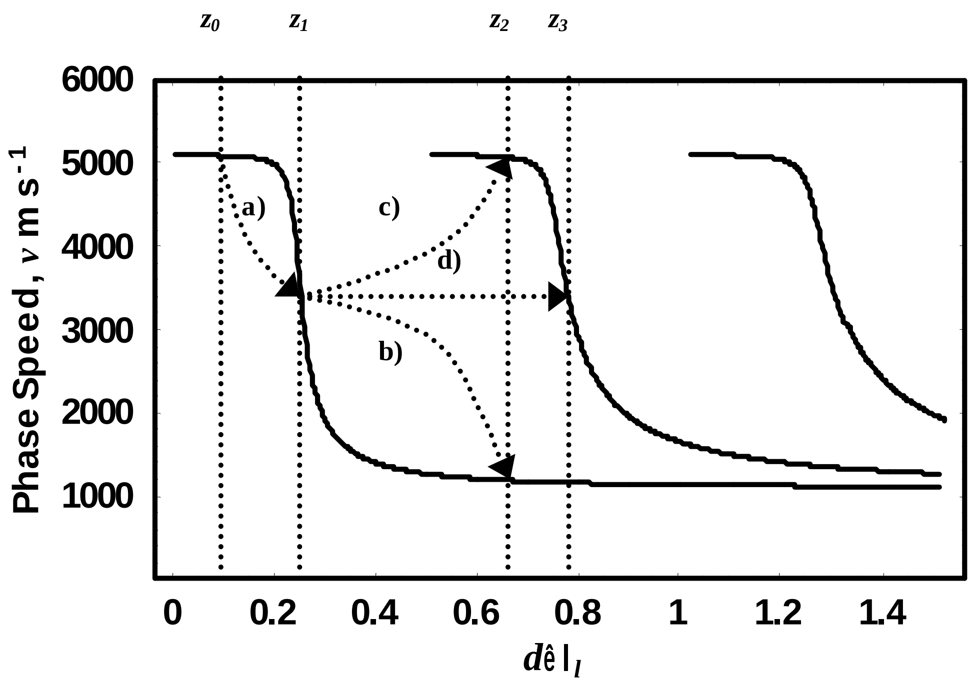
Four example transitions

Same mode ⇒ lower/higher sensitivity
Change mode ⇒ lower/higher sensitivity



[1]M.I. Newton *et al*, Electron. Lett. (2001) 36, 340-341;[2]G. McHale *et al*, J. Appl. Phys. (2002), 91, 5735-5744

Frequency Hopping Transitions



No Mode Change

Transition a) ⇒ Higher mass sensitivity

Transition b) ⇒ Lower mass sensitivity

Mode Change

Transition c) ⇒ Lower mass sensitivity

Transition d) ⇒ Higher mass sensitivity

Maximum Increase in Mass Sensitivity

Ratio of frequencies × ratio of max slopes of modes

i.e. scales by less than by the frequency ratio

Summary

Achievements

- Unifying theory
  - Love wave and SH-APM's
- New sensor
  - Layer-guided SH-APM's
- Mass/liquid sensitivity predictions
  - Phase velocity and insertion loss
  - Relation to group velocity
- Love wave frequency response
  - Mode and non-mode changes

Lessons

- Higher order Love waves
  - from SH-APM's
- Guiding layer on SH-APM's
  - significant increase in sensitivity
- Higher frequency
  - Higher or lower sensitivity
  - Frequency scaling of mode peak
- Love waves $\Rightarrow$ strong dispersion
  - Group and phase velocity differ

The End