Layer Guided SH-APM Sensors

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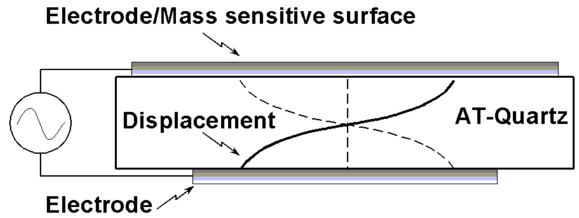
Overview

1. Acoustic Wave Sensor Principles
   - QCM v SAW
   - Vapour phase response
   - Liquid phase response
2. Layer Guided Acoustic Waves
   - Love waves v SH-APMs
   - Generalized dispersion curve
   - Mass sensitivity
   - Group and phase velocity
3. Love Waves and Frequency
   - Frequency dependence
   - Frequency hopping
4. Summary

Sensing Principles

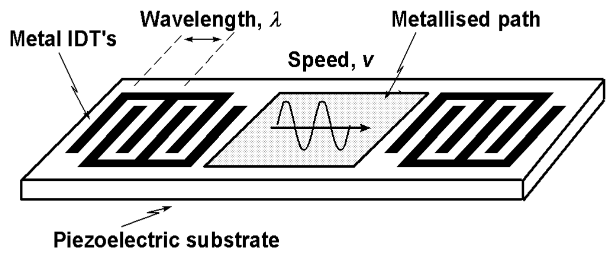
- Quartz Crystal Microbalance (QCM)

  Thickness shear mode oscillation



- Surface Acoustic Wave (SAW)

  Mechanical wave travelling along a surface



- Create Resonator or Measure Impedance/Spectrum

  QCM/SAW determines oscillation freq. $v = f\lambda$

- Mass (thin film) loading

  Main effect is change in frequency $\delta f \propto \rho f^2$

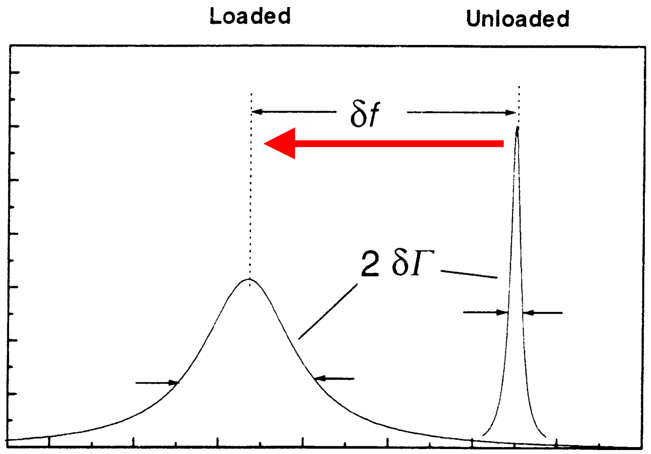
- Surface loading alters resonance

  Mass loading reduces frequency

  Non-rigid mass (e.g. polymers)

  broadens resonance

  (senses shear modulus)



- Liquid loading and penetration depth

  Need shear modes

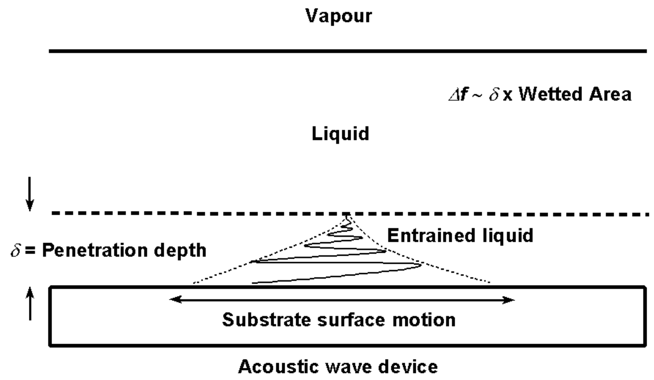
  (QCM, Shear type SAWs)

  Senses mass in penetration depth

  $\delta f \propto \sqrt{(\eta\rho)}\, f^{1/2}$

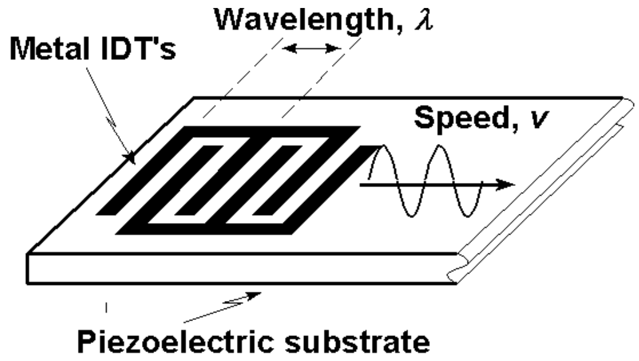
  For water penetration depth

  ~ 250 nm (at 5 MHz)



Love Waves v SH-APMs

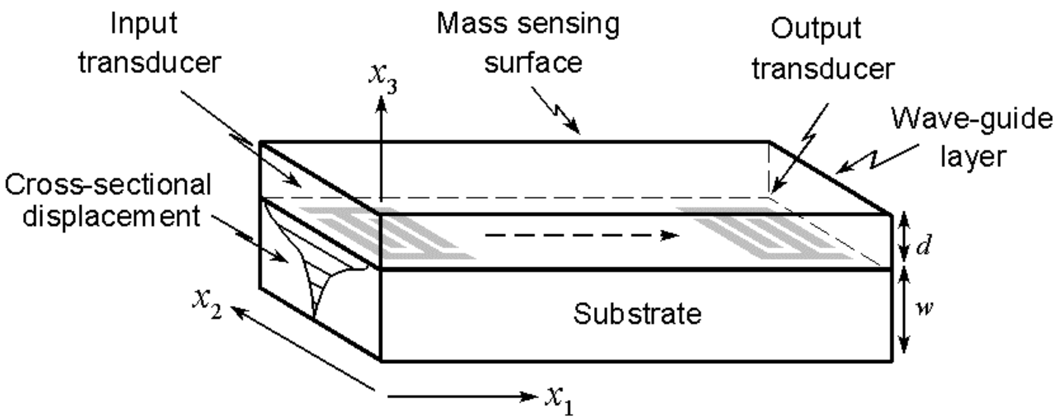
- Surface Acoustic Wave (SAW)



- Love Wave

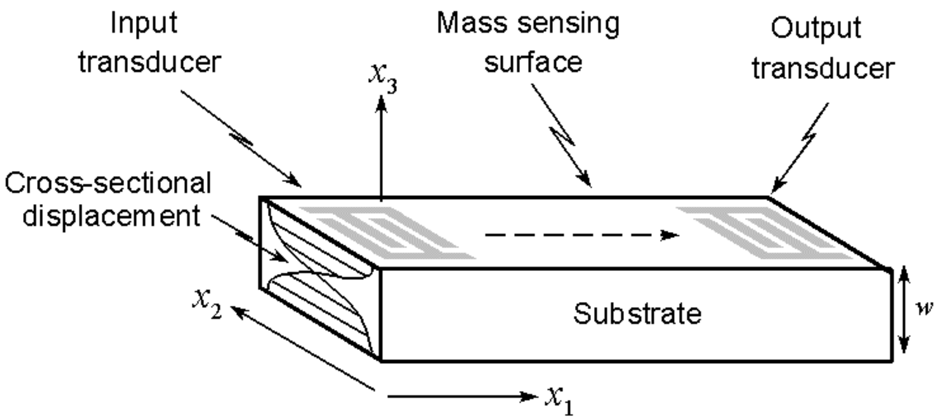
  Layer guided SH-SAW

  with $v_l < v_s$



- SH-APM

  Substrate resonance

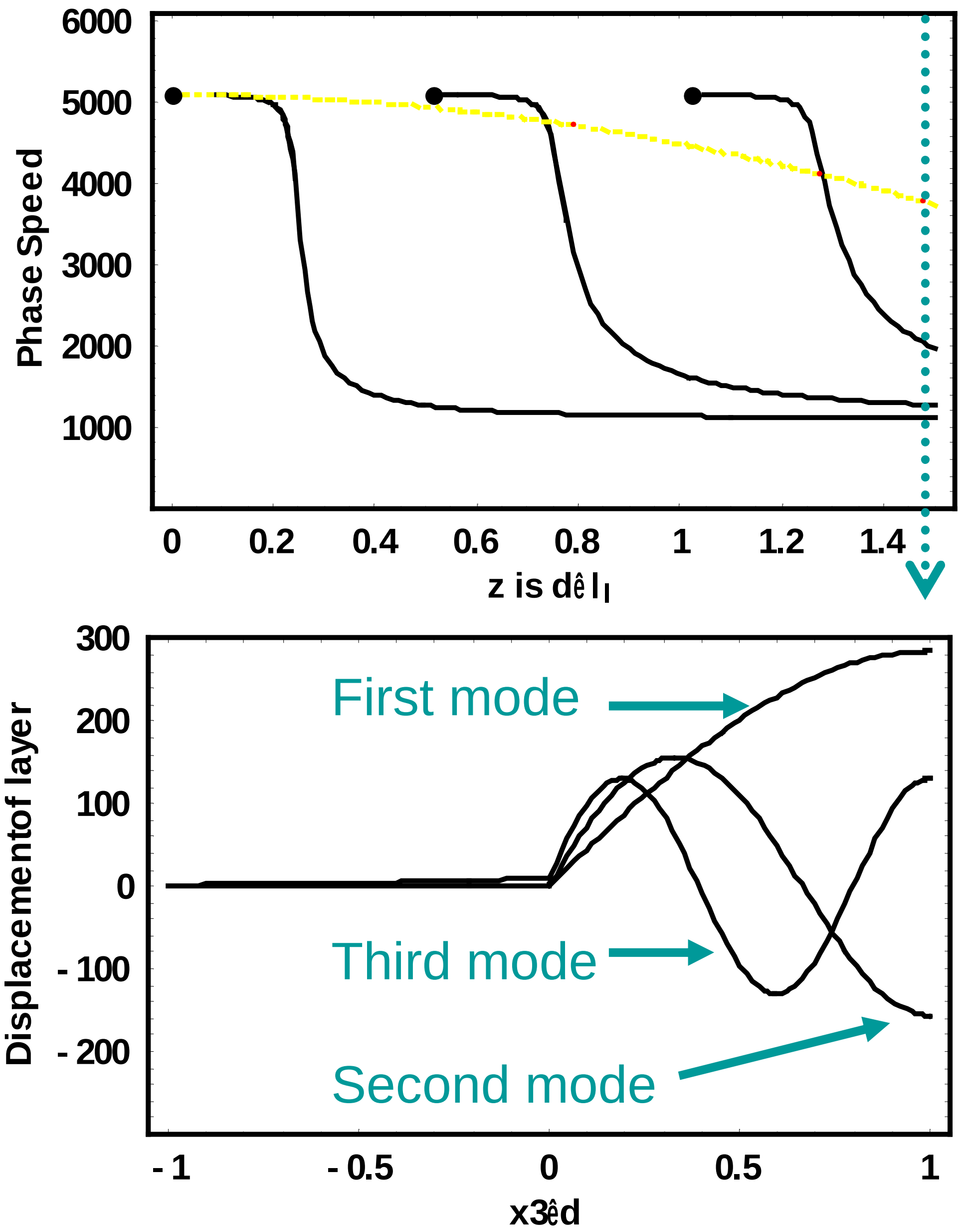


Love Waves

- Theoretical dispersion curve

  (Insertion loss is unchanged by guiding layer)

- Displacements for first three modes (z=1.3)



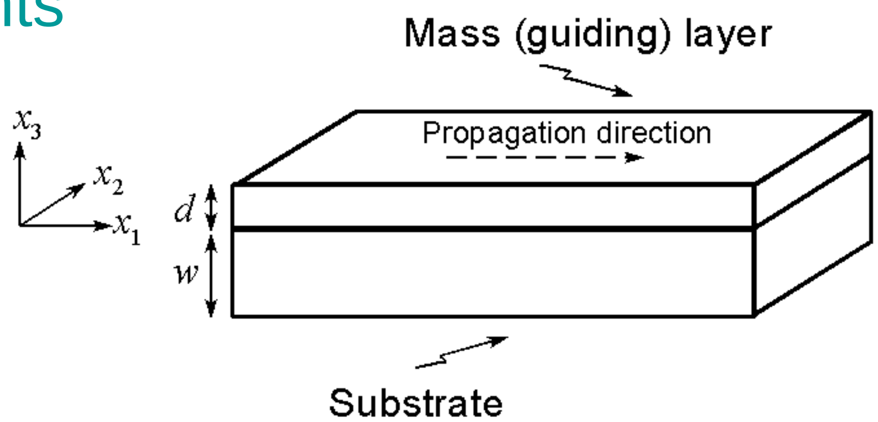
Layer Guided SH-APMs

- 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 $\Rightarrow$ T_l and T_s

Boundary conditions $\Rightarrow$ dispersion eqn

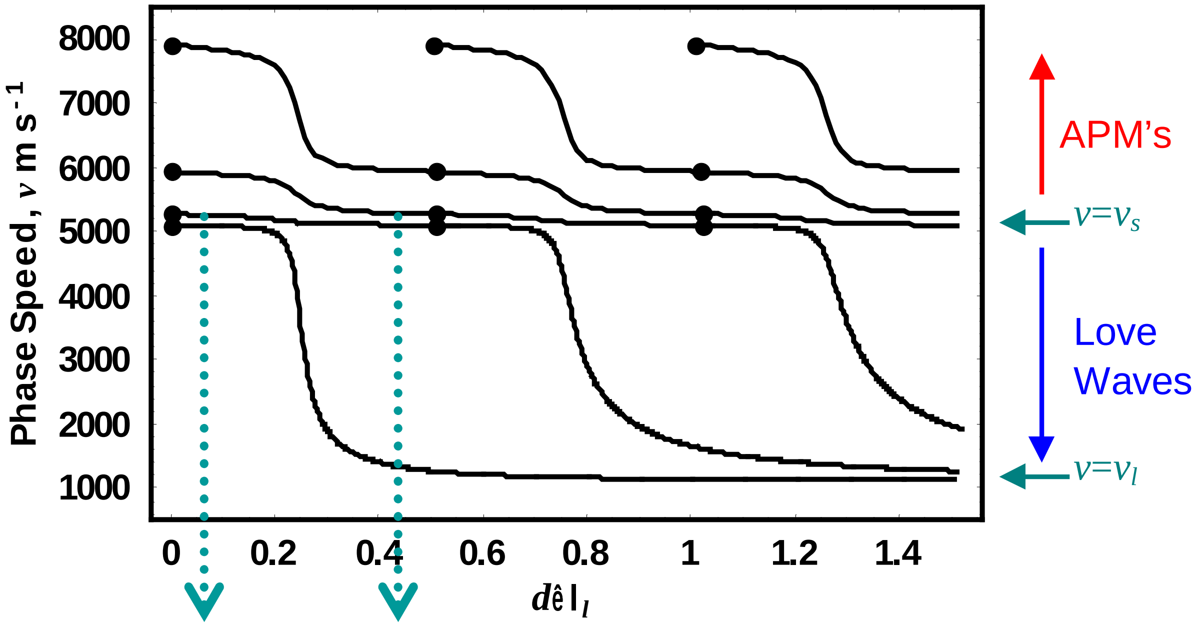
$$\tan(T_l d) = \xi \tanh(T_s w)$$

where $\xi = \mu_s T_s / \mu_l T_l$, $k_1 = (\omega/v)^{1/2}$ and $T_l^2 = \omega^2\left(\frac{1}{v_l^2} - \frac{1}{v^2}\right)$ and $T_s^2 = \omega^2\left(\frac{1}{v^2} - \frac{1}{v_s^2}\right)$

[1]McHale et al, Accepted Europhys. Lett. (2002), J. Appl. Phys. (2002) 91, 5735-5744.

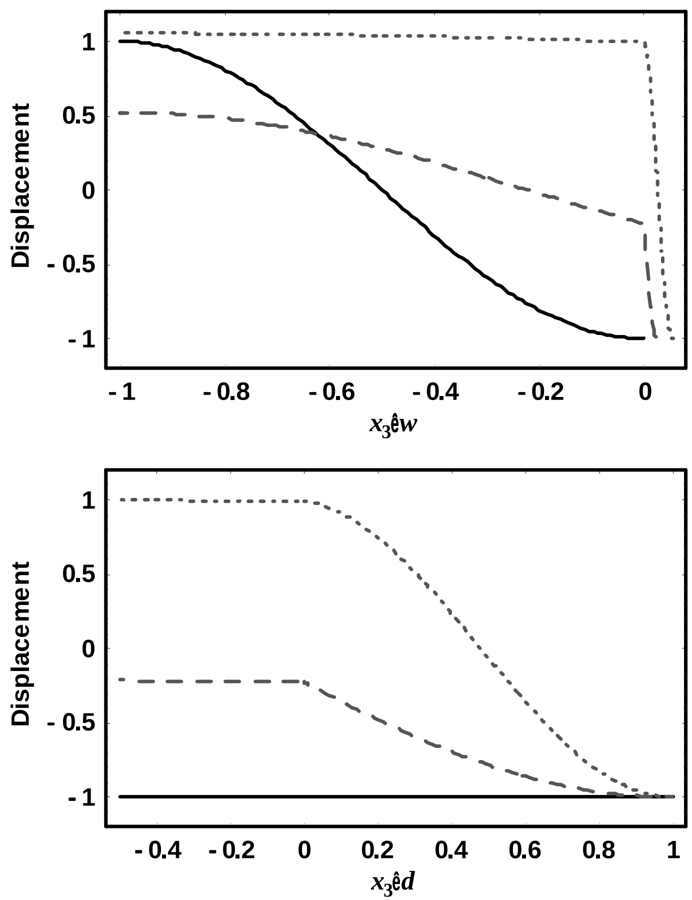
- # Solutions

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



Points = Anti-node moving from substrate to layer

Evolution of 1st SH-APM



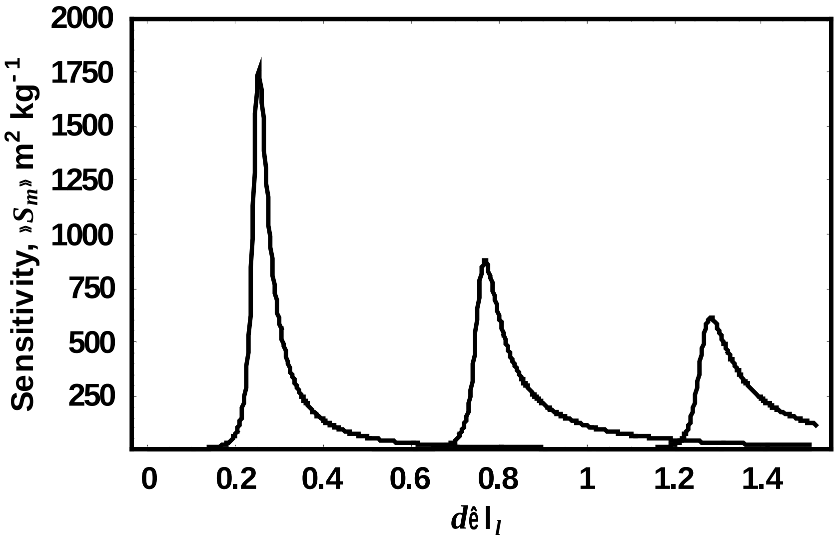
- Mass Sensitivity (Arb. d) - with 3 layer model[1]

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

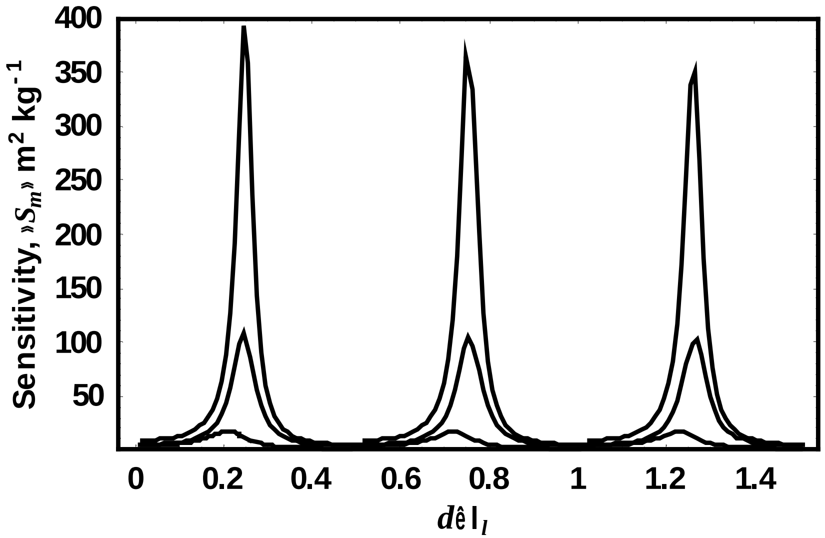
Δm is mass per unit area being sensed, $z = df/v_l$ is the normalized thickness

"Rigid" mass $\Rightarrow$ Mass sensitivity is slope of dispersion

Love Waves



Layer-Guided SH-APMs



[1]McHale *et al*, J. Appl. Phys. Accepted (2002).

Preliminary Experimental Data

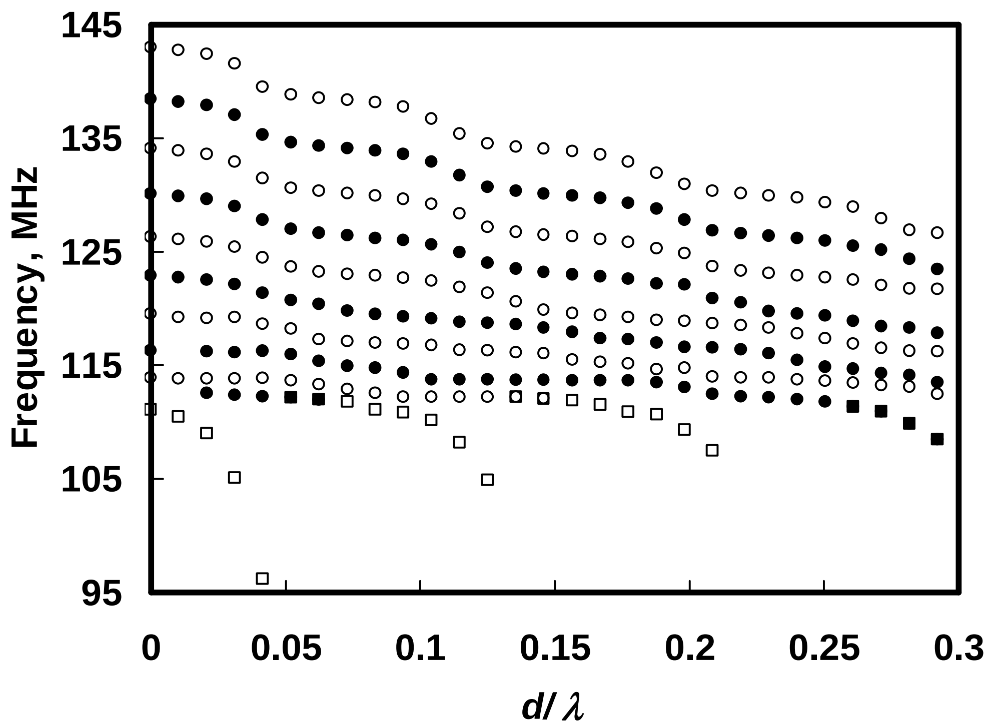
- Dispersion Curve Experiment

  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)



Dispersion and Group Velocity

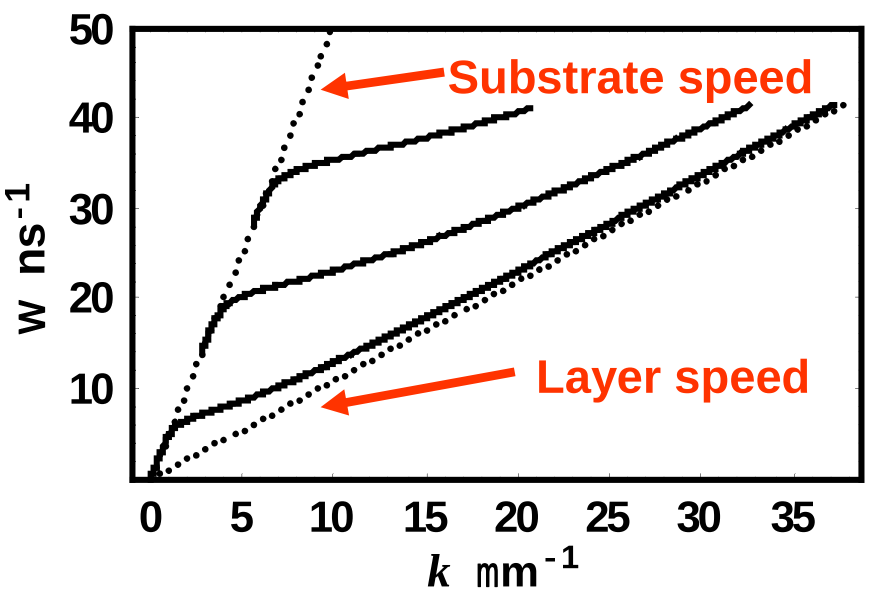
- Guiding Layer Induced Dispersion[1]

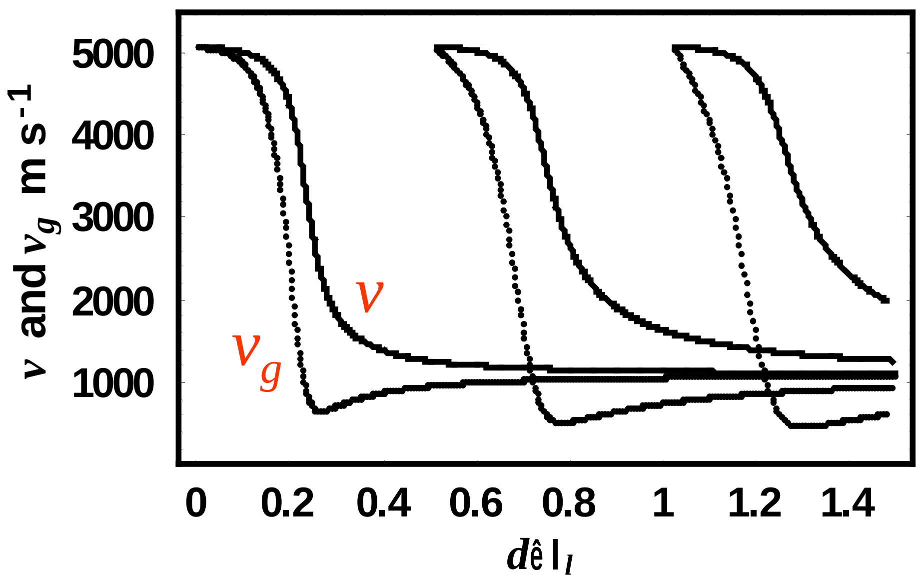
Phase velocity $v = f\lambda$ or $v = \omega / k$

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]Submitted to J. Appl.Phys. (2002)

- Mass Sensitivity and Dispersion

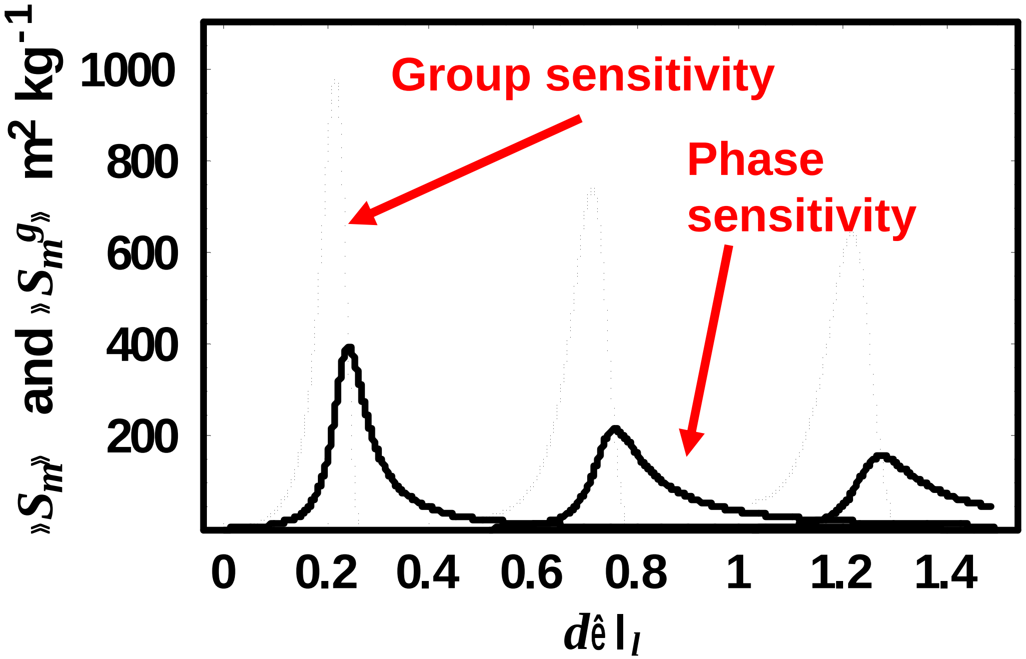
$$S_m \approx \frac{1}{\rho_l d}\left(1-\frac{v}{v_g}\right)=\frac{1}{\rho_l d}\frac{(v_g - v)}{v_g}$$

"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

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



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

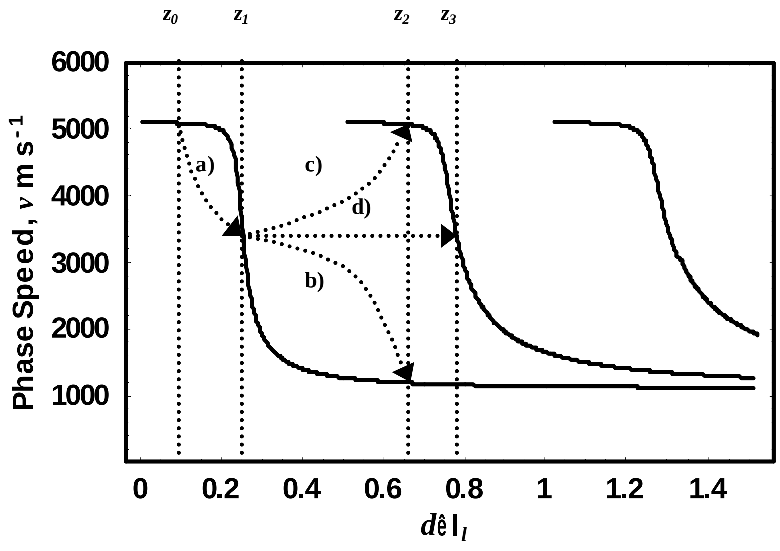
⇒ Mass sensitivity scales with f

- Frequency Hopping at Constant d

Four example transitions

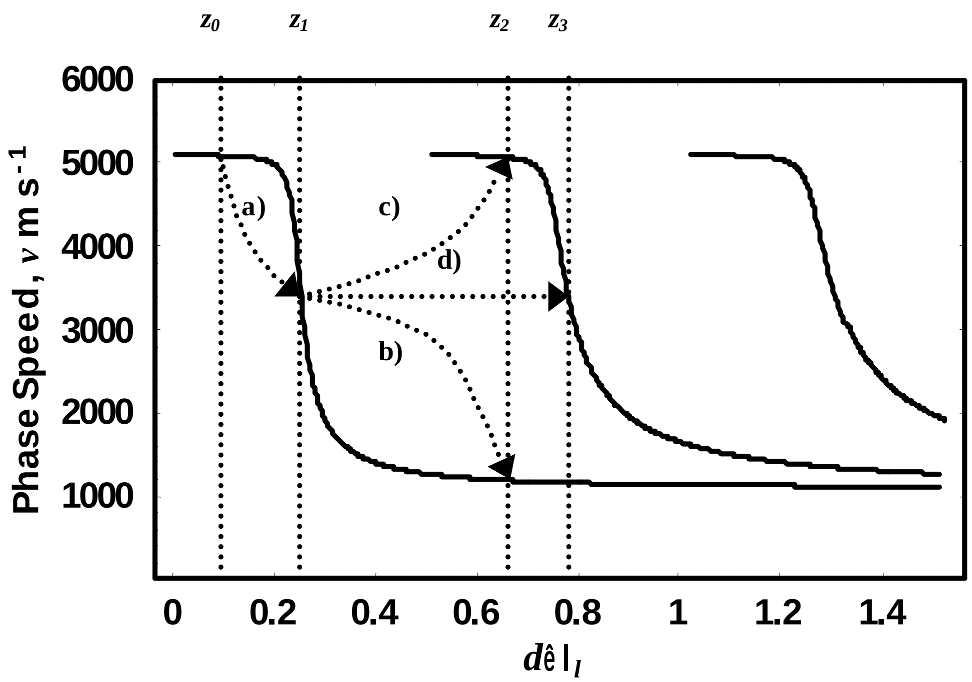
Same mode ⇒ lower/higher sensitivity

Change mode ⇒ lower/higher sensitivity



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

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 sensitivity predictions
  - Phase velocity
  - 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