Optimization of a Love Wave Surface Acoustic Device for Biosensing Application

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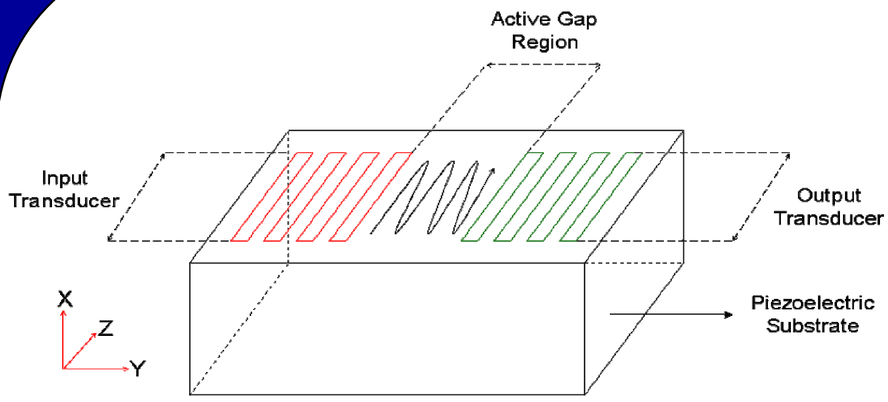
Outline

- Introduction
- SAW devices as biosensors
- Research objective
- Experimental design
- Results and analysis
- Computational modeling of a Love wave SAW device
- Summary and conclusion

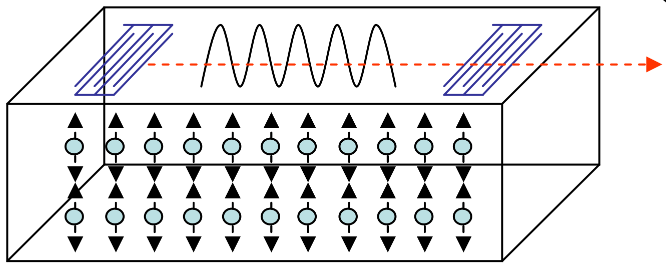
Why SAW devices?

- High frequency operation (MHz – GHz)
  - High resolution, high sensitivity
- Can be integrated on a wireless platform
- Can operate in dry and aqueous environments
- Simple fabrication techniques

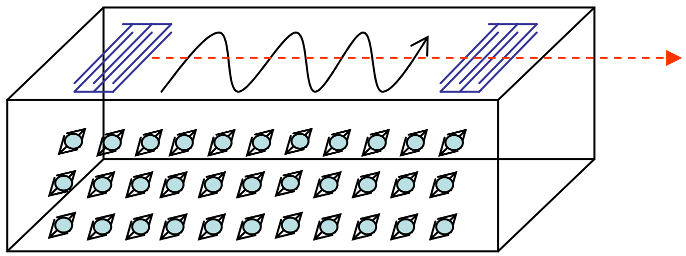
Modes of operation



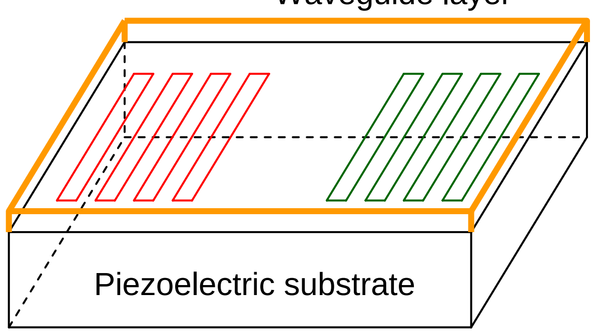
Two port configuration of a SAW sensor



Shear vertical mode



Shear horizontal mode



Love wave mode - waveguide layer:

Lower wave velocity than substrate

Low density, low acoustic loss

Influence of waveguide thickness

Proper thickness for the waveguide layer will help confine a maximum amount of acoustic energy near the surface of the piezoelectric substrate.

Research Objective

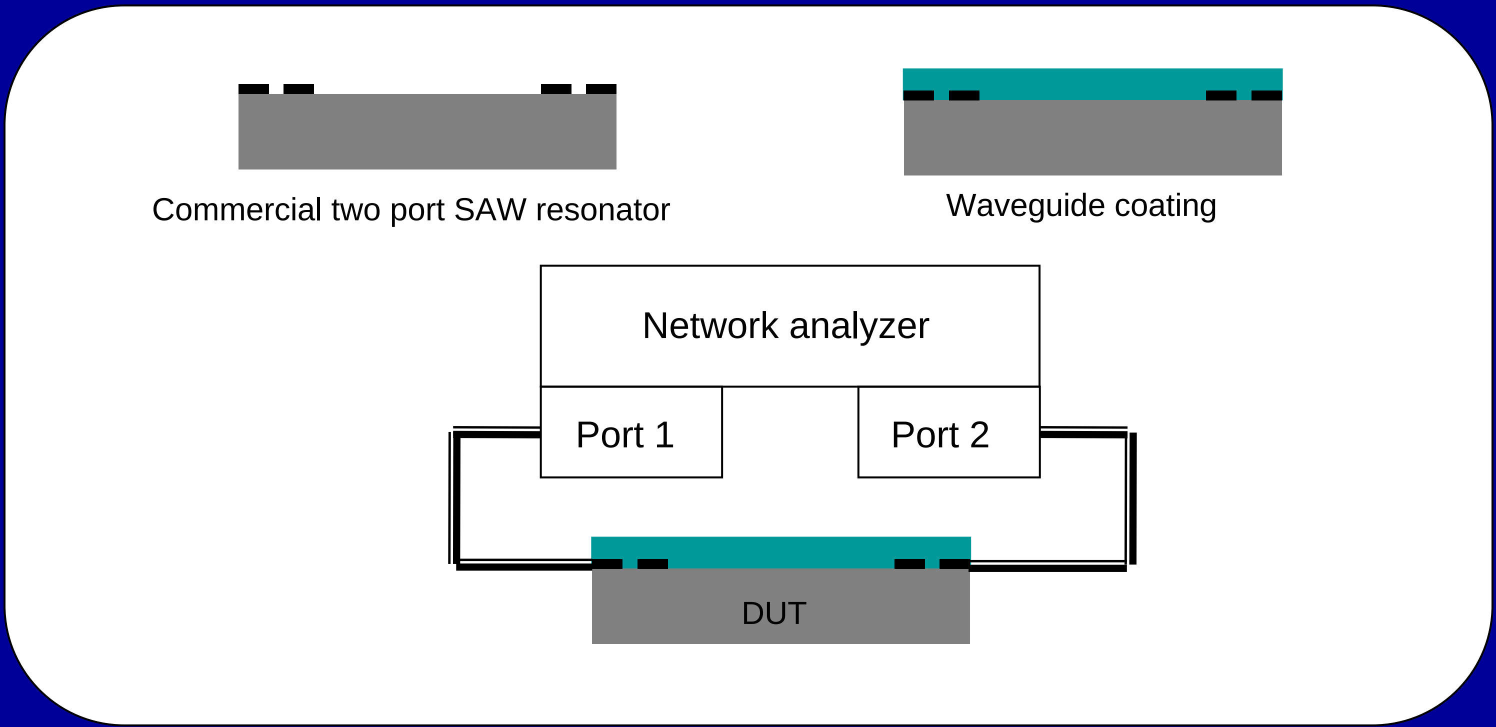
To understand the wave propagation phenomena in a Love wave SAW sensor and determine an optimal thickness of the waveguide layer for achieving high detection sensitivity.

Approach

- An integrated approach of experiments and simulations
- Experiments: optimization of waveguide thickness for high detection sensitivity
- Simulations: 3-D modeling of Love wave SAW devices

Experiments: SAW devices

Change in waveguide thickness in a Love wave device

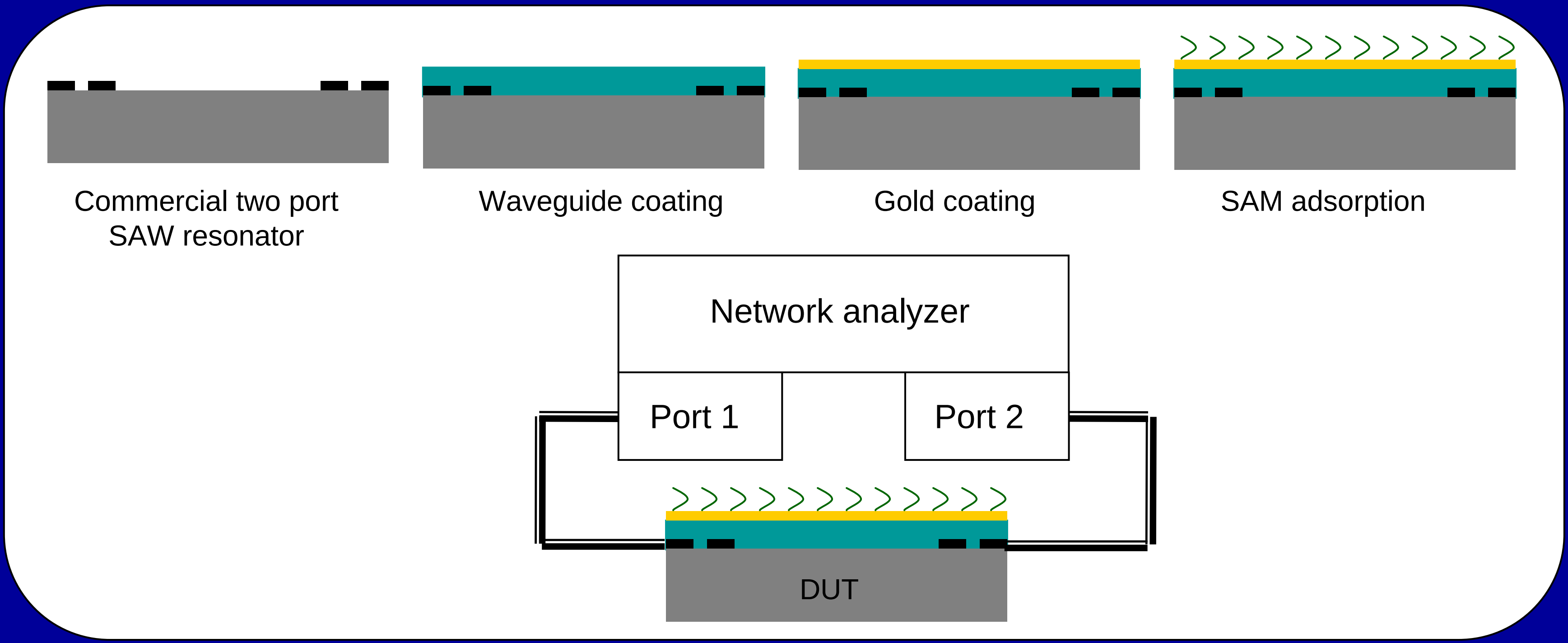


• Commercial SAW devices are coated with parylene in various thicknesses of 100 nm, 200 nm, 400 nm and 1 µm.

• Changes in insertion loss and frequency shift are determined against a control case (without a parylene coating).

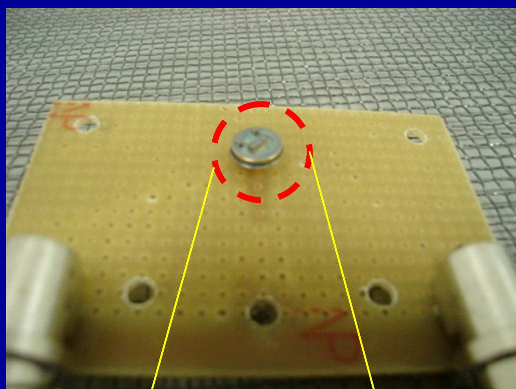
Experiments: SAW devices

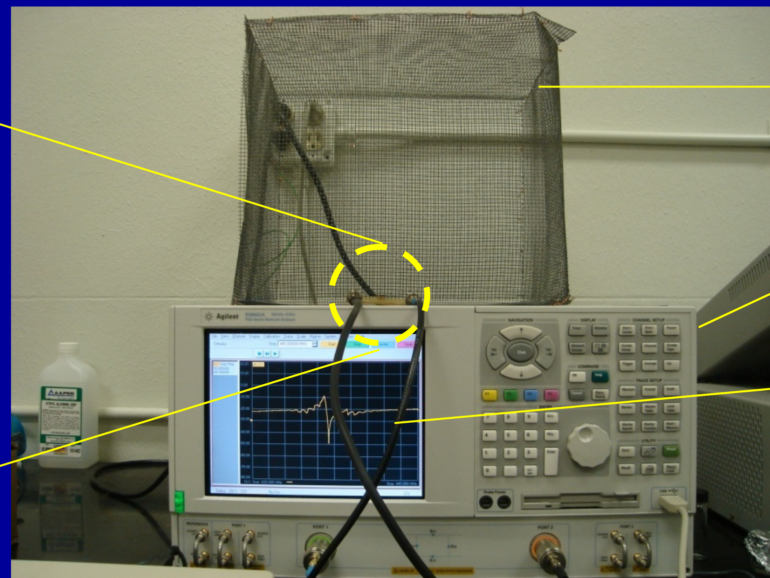
Detection of adsorption of SAM at various concentrations



- SAW sensors are coated, on top of the parylene waveguide layer, with a SAM of dithiobis succinimydyl propionate at various concentrations 0.5 mM. 0.75 mM, 1.0 mM, 2.5 mM, and 5.0 mM.
- Change in insertion loss and frequency shift are determined.

Experimental Setup



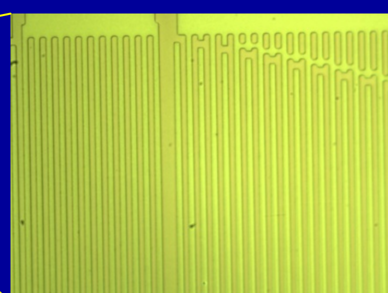


Faraday cage

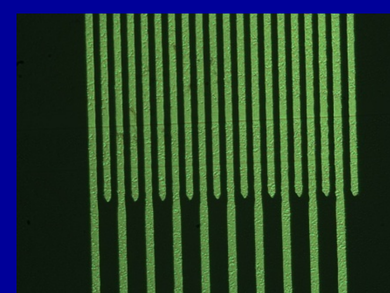
Network Analyzer

Insertion loss spectrum

Experimental setup for measuring insertion loss spectrum

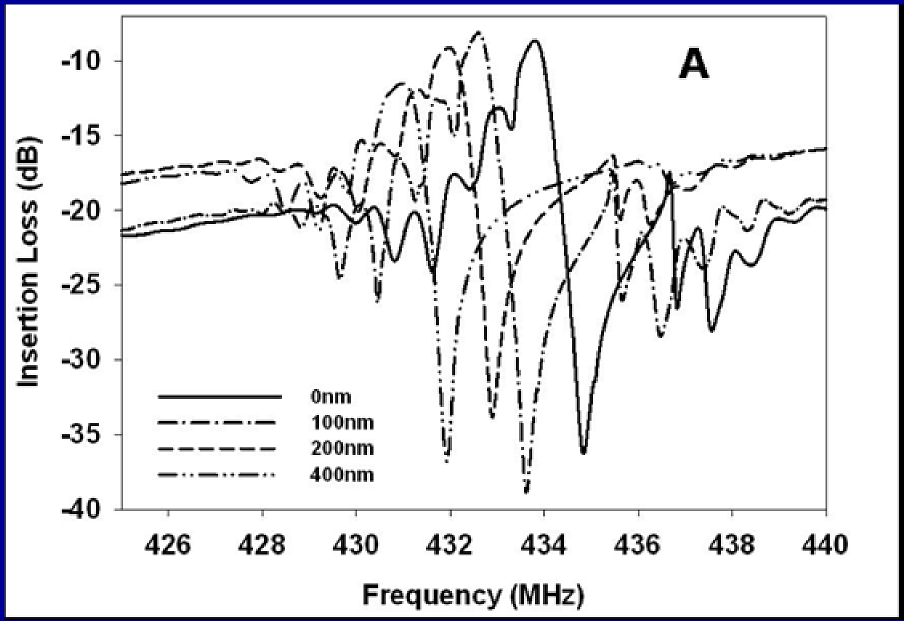


Commercial two port SAW resonator

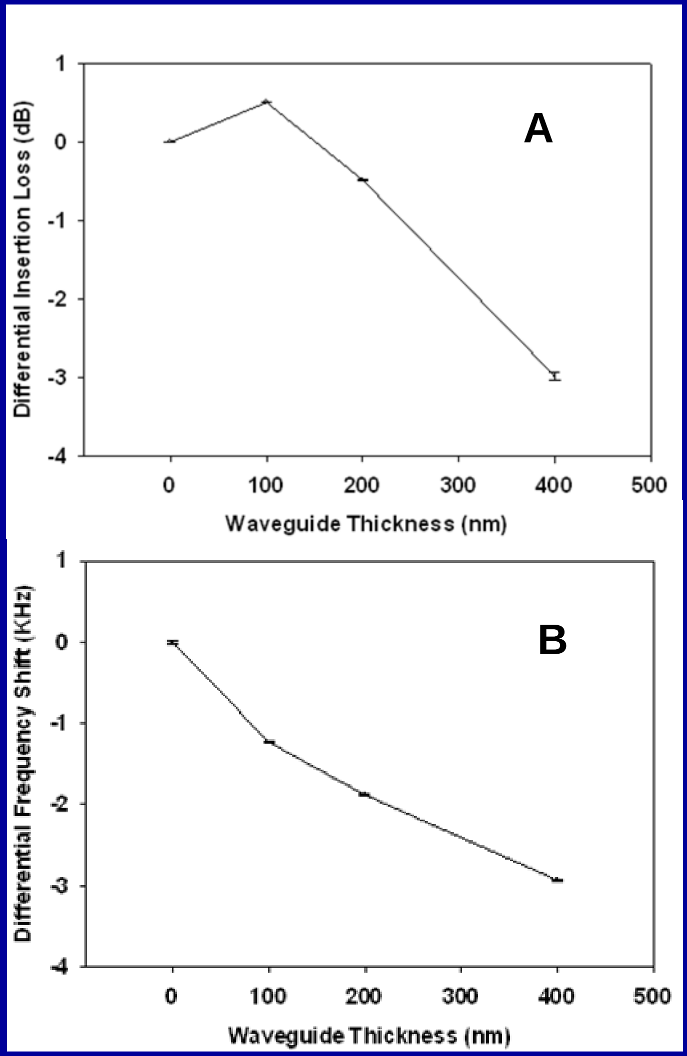


Delay line SAW device

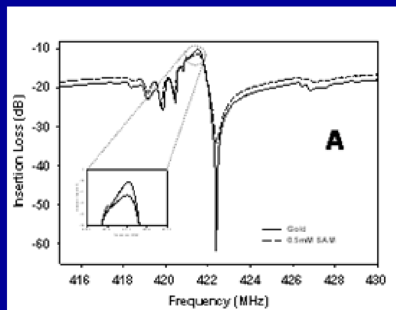
Results: waveguide thickness

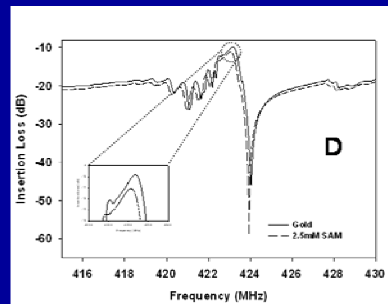


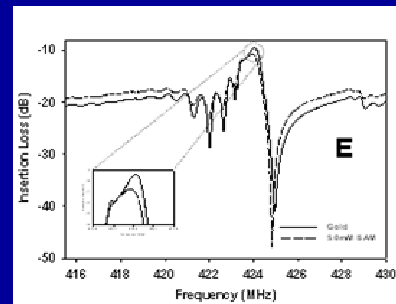
Insertion loss spectra of a SAW sensor with and without a parylene coating.

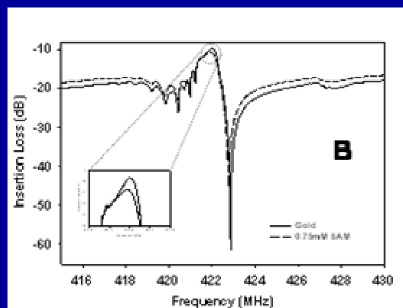


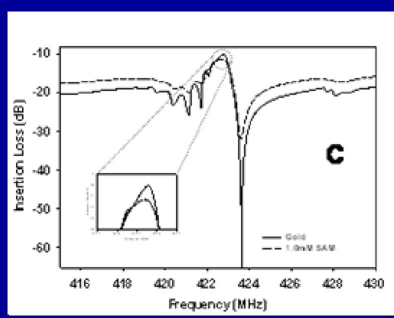
SAM detection sensitivity



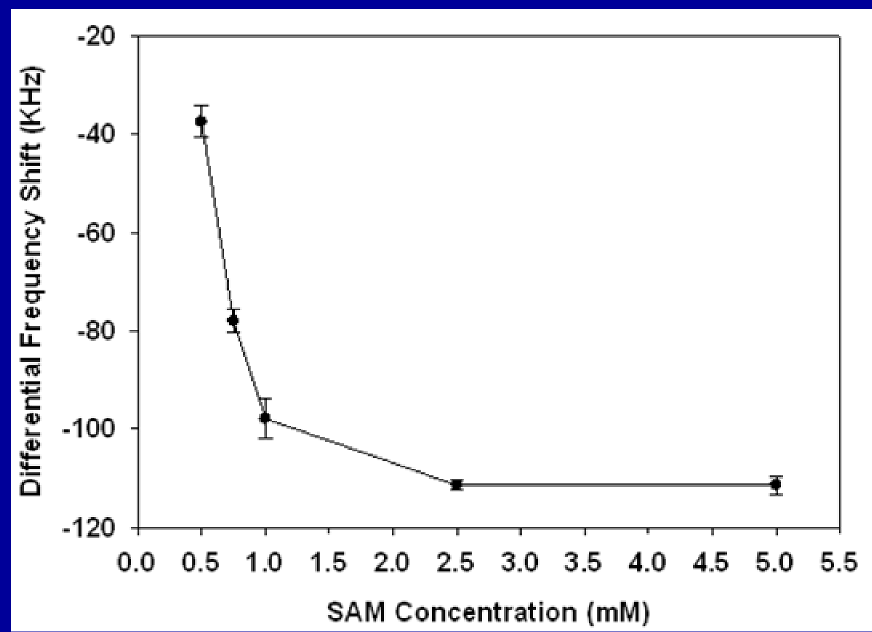




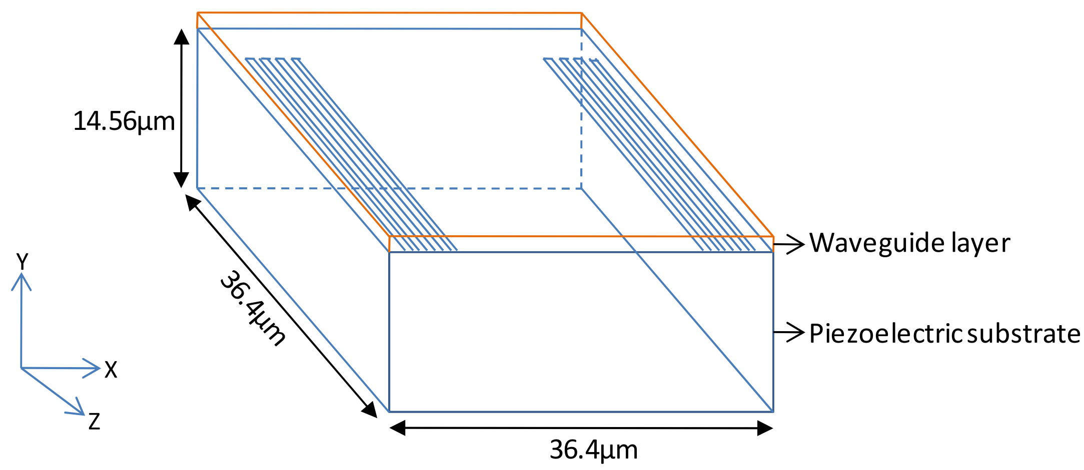




Insertion loss spectra of a SAW sensor to SAM adsorption at 0.5 mM (A), 0.75 mM (B), 1.0 mM (C), 2.5 mM (D) and 5.0 mM (E) of SAM.



Modeling: Love SAW devices



Piezoelectric substrate material	YX Quartz
Frequency of operation	433.92 MHz
Wavelength	7.28µm
IDT finger width and spacing	1.82µm
Waveguide material	Parylene
Waveguide dimensions	36.4µm x 14.56µm x 100nm

Governing Equations

$$T = C_E \bullet S - e^t \bullet E \qquad D = e \bullet S + \varepsilon_s \bullet E$$

$$C = \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} & 0 & 0 \\ C_{12} & C_{11} & C_{13} & -C_{14} & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ C_{14} & -C_{14} & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & C_{14} \\ 0 & 0 & 0 & 0 & C_{14} & (C_{11}-C_{12})/2 \end{pmatrix}$$

Elasticity Matrix for quartz

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & -e_{22} \\ -e_{22} & e_{22} & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix}$$

Stress Matrix for quartz

$$\varepsilon = \begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix}$$

Dielectric Matrix for quartz

Where *T* is the stress tensor, C_E is the stiffness matrix, *S* the strain tensor, *e* the piezoelectric coupling tensor, *E* the electric field vector, *d* the electric displacement, ε the dielectric matrix, and the superscript *t* represents the transpose of a matrix.

YX Quartz	
C_{11}	8.674×10^{10} Nm^{-2}
C_{12}	0.699×10^{10} Nm^{-2}
C_{13}	1.191×10^{10} Nm^{-2}
C_{14}	-1.791×10^{10} Nm^{-2}
C_{33}	10.72×10^{10} Nm^{-2}
C_{44}	5.794×10^{10} Nm^{-2}
E_{11}	0.171 Cm^{-2}
e_{14}	0.0403 Cm^{-2}
ε_{11}	4.42
ε_{33}	4.63
ρ	2650 Kg m^{-3}

	Parylene
E	0.4MPa
v	0.40
ρ	1289 Kg m^{-3}

Simulation procedure

• An impulse signal is applied to the alternating electrodes of the generator IDT (i.e., *V*i+ at the first and third electrodes, and *V*i- at the second and fourth electrodes).

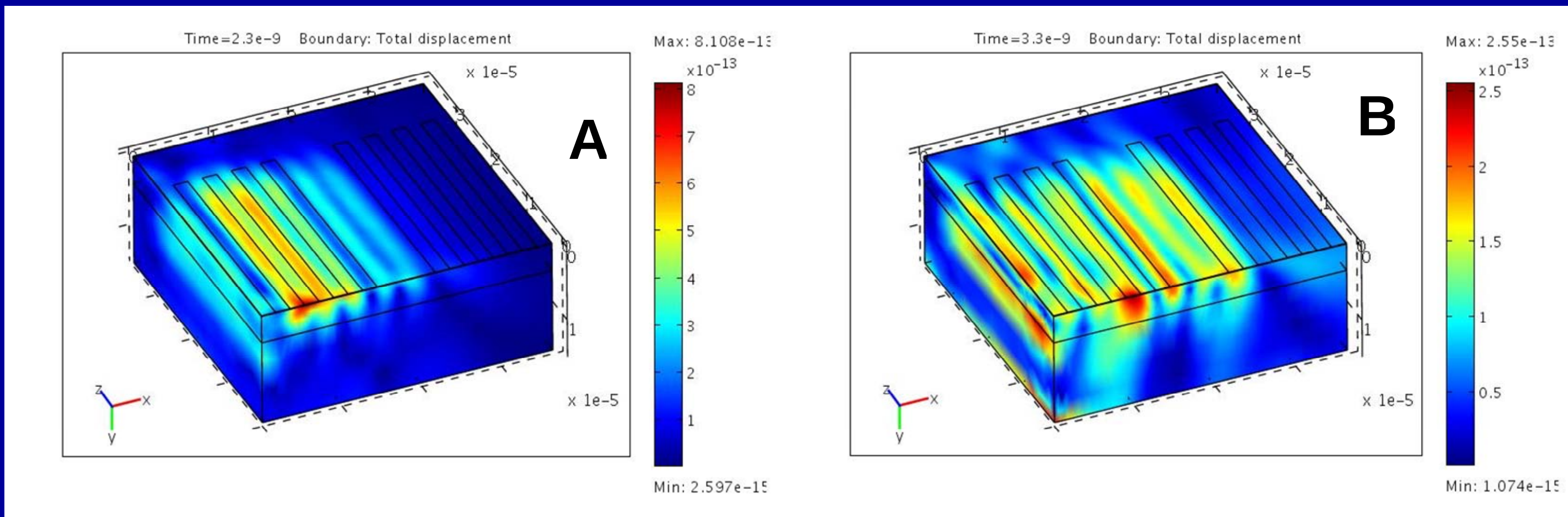
$$V_{i+} = \begin{cases} +0.5V, t \le 1ns \\ 0V, t \ge 1ns \end{cases}, \qquad V_{i-} = \begin{cases} -0.5V, t \le 1ns \\ 0V, t \ge 1ns \end{cases}$$

• Output voltage is measured at the alternating electrodes of the receiver IDT and the insertion loss (IL) is calculated by taking the ratio of output signal to input signal.

$$IL = 20 \times \log_{10} \left| V_{output} / V_{input} \right|$$

• Parylene waveguide layer with different thickness is added and the changes in insertion loss and resonant frequency are measured with respect to the control (sensor with no waveguide coating).

Results: Wave propagation



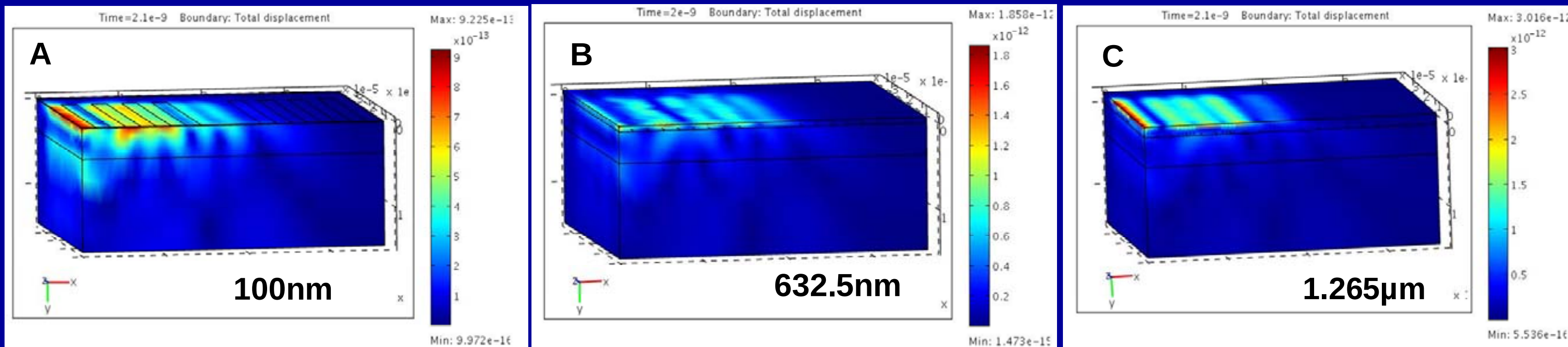
Snap shots of wave propagation at 2.3 ns (A) and at 3.3 ns (B).

Distance traveled = 7.35 µm
Time taken = 2.3 ns
Calculated wave velocity = 3152 m/s
Theoretical wave velocity = 3159 m/s

Wavelength = 7.28 µm

Calculated frequency = 431.80 MHz
Theoretical frequency = 432.96 MHz

Waveguide thickness



Snap shots of wave propagation in a Love wave SAW sensor with parylene coatings in a thickness of 100 nm (A), 632.5 nm (B) and 1.265 µm (C).

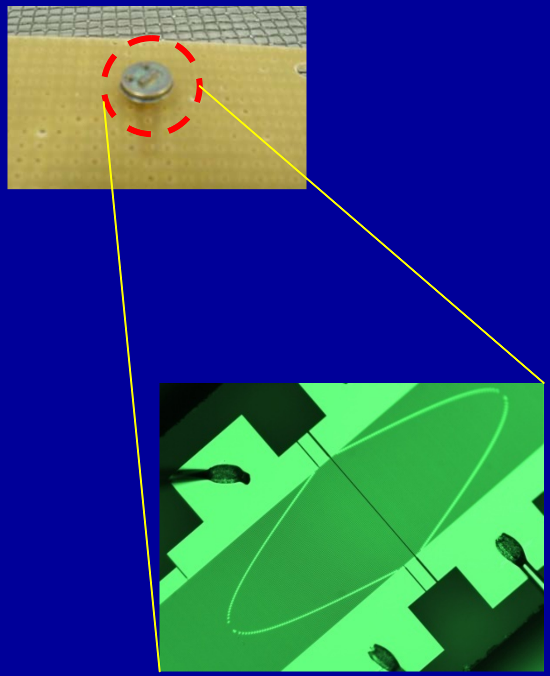
Theoretical determination of critical waveguide thickness

$$h = \lambda_{waveguide} / 4 \qquad \lambda_{waveguide} = V_w / f_o = 2.55\mu m$$

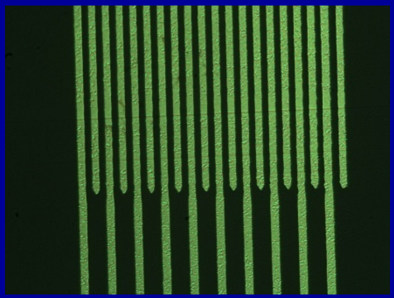
$$h = 637.5nm \qquad V_w = 1100m/sec \qquad f_0 = 431.318MHz$$

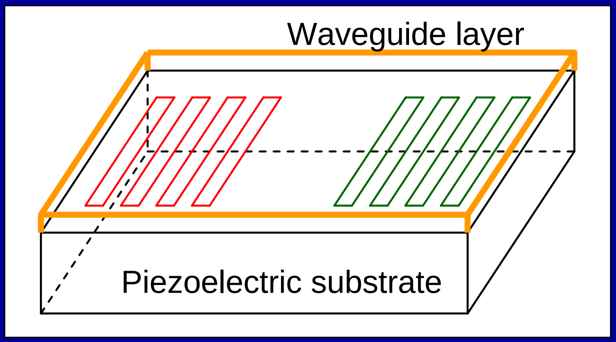
Where h is the thickness of the waveguide layer, $\lambda_{waveguide}$ is the wavelength of the waveguide, f_o is the resonant frequency of the device, V_w is the wave velocity of waveguide layer

Different SAW transducers



Tested commercial SAW device





Simulated SAW device

Summary

- An optimal wave propagation occurs at a waveguide thickness of 100 nm for the devices tested.
- Beyond this critical thickness, the insertion loss increases due to high energy dissipation.
- With a waveguide layer of this critical thickness, a sensitive SAM detection range from 0 to 2.5 mM is found, beyond which the detection signal saturates.
- At a critical thickness of the waveguide layer, the wave is effectively trapped at the surface for detection purpose.
- A thinner waveguide layer will cause the wave to scatter into the piezoelectric substrate and a thicker layer will cause the wave to travel in the waveguide.

Conclusions

- To design a Love wave SAW sensor for bio-environment operation, it is essential to use a waveguide layer with a critical thickness.
- This critical thickness may vary depending on the actual layout of the SAW transducers.

Acknowledgements

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