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Simulation of Surface Acoustic Wave Devices

Current Status and Future Prospects

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SAW Device Simulation

- Background
- COM analysis for rapid simulation
- FEM/SDA analysis for parameter determination
- Correction for SH-SAW simulation
- Transverse-mode analysis
- FEM/BEM analysis for precise simulation
- Summary and remaining problems
SAW Device Simulation

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Rayleigh-Type SAW

Depth

Propagation Direction
Surface Acoustic Wave

Bulk Acoustic Wave (BAW):
- Longitudinal Wave (Primary Wave)
- Transverse Wave (Share Wave, Secondary Wave)

Surface Acoustic Wave (SAW): (Rayleigh SAW)

Propagation of Seismological Waves
SAW Transversal Filters

- Mass-Production by Photolithography
- Low-loss, Small-Size & Low Price
- Operation in VHF-UHF Range

Line width $\lambda/4=0.5\mu m$ ($f=2$GHz)
Delta Function Model

\[ \hat{N}_i = N_i - 1/2 \]

(a) surface deformation  \hspace{1cm} (b) SAW propagation
Reference: Influence of Internal Reflection

Delta Function Model Analysis

Coupling-of-Modes Analysis
"It seems well-developed. Why further research necessary?"

System designers need devices with zero insertion loss, zero TCF, 100dB out-of-band rejection, 200% bandwidth, one day delivery, and price minimization.
Why Fast & Precise Simulators Needed?

- Better Understanding of Underlying Physics
- Reducing Number of Trials
- Improving Production Yields
- Meaningful Optimal Design

Current Computers with Mass Memories are

- Low Price, Maintenance Free, Space Saving
- Working 365 days with 24 hours
- No Friction with Workers Union
What are Necessary for Simulators?

- Better Understanding of Underlying Physics
- Reducing Number of Trials
- Improving Production Yields
- Meaningful Optimal Design

For **Speedy Simulation**

Behavior-Model Based Simulation

For **Accurate Simulation**

Full Wave Simulation
Practical Simulation Procedure

3D Full Wave Simulation is not Realistic

Pseudo 2D Simulation of Whole Structure

Derivation of Simulation Parameters by 2D (X-Z) Simulation

Pseudo 3D Simulation of Whole Structure

Derivation of Simulation Parameters by 2D (X-Y) Simulation

Simulation Including Package Influence

Simulation of Package Characteristics by Commercial Tools
1nH (≈ gold wire of 1mm length)

\[ \Rightarrow 6\,\Omega/\text{mm} @ 1\text{GHz} \]

1pF (≈ 1mm×1mm pad on LiNbO₃ substrate)

\[ \Rightarrow 150\,\Omega/\text{mm}^2 @ 1\text{GHz} \]

Influence of parasitic impedances is significant in GHz range!
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Pseudo 2D Simulation of SAWR

- Combination of Periodic Structures
- Wide Aperture

Accurate Simulation by 1-D Model
Modeling of Element (IDT)

- Equivalent Circuit Analysis
- Coupling-of-Mode (COM) Analysis
- \(p\)-Matrix Analysis (Hybrid Scattering Matrix)

Compatible (Basically Equivalent)

- Number of Independent Parameters
- Simple to Use
- Easy to Extend
- Many Articles
COM Equation for Periodic Structure

\[ \beta_u: \text{ Wavenumber (Unperturbed)} \]
\[ \kappa: \text{ Reflection Coef.} \]
\[ \zeta: \text{ Transduction Coef.} \]
\[ \theta_u = \beta_u - 2\pi/p_I \]
\[ p_I: \text{ IDT Period} \]

\[ \frac{\partial U_+}{\partial x} = -j \theta_u U_+ - j \kappa U_+ + j \zeta V \]
\[ \frac{\partial U_-}{\partial x} = +j \kappa U_- + j \theta_u U_- - j \zeta V \]
\[ \frac{\partial I}{\partial x} = -4j \zeta U_+ - 4j \zeta U_- + j \omega CV_0 \]

Propagation
Reflection
Excitation
Detection
Capacitance
General Solution

\[ U_+ (X) = A_+ \exp(-j\theta_p X) + \Gamma_0 A_- \exp(+j\theta_p X) + \xi V_0 \]
\[ U_- (X) = \Gamma_0 A_+ \exp(-j\theta_p X) + A_- \exp(+j\theta_p X) + \xi V_0 \]

where \( \theta_p = (\theta_u^2 - \kappa^2)^{0.5} \), \( \Gamma_0 = (\theta_p - \theta_u) / \kappa \), \( \xi = \xi/(\theta_u + \kappa) \)

Total Current Input

\[ I_0 = \int_{-L/2}^{+L/2} \frac{\partial I(X)}{\partial X} dX = \int_{-L/2}^{+L/2} [-j4(\xi^*U_+ + \xi U_-) + j\omega CV_0] dX \]

\( L \): IDT Length
P-Matrix Expression

\[
\begin{pmatrix}
U_+(0) \\
U_-(0)
\end{pmatrix}
= \begin{pmatrix}
P_{11} & P_{12} & P_{13} \\
P_{21} & P_{22} & P_{23} \\
-4P_{13} & -4P_{23} & P_{33}
\end{pmatrix}
\begin{pmatrix}
U_+(0) \\
U_-(L) \\
I_0
\end{pmatrix}
\begin{pmatrix}
U_+(L) \\
U_-(L)
\end{pmatrix}
\]
**Cascade-Connection**

Open-Circuited Grating = Open-Circuited IDT  
Short-Circuited Grating = Short-Circuited IDT  
Gap = IDT without reflection & Excitation

\[ \text{IDT Modeling} \quad \rightarrow \quad \text{Modeling of Whole Structure} \]
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Full Wave Analysis for Infinite Grating

- Perturbation or Functional Method ⇔ inaccurate (?)
SAW velocity on Al/128°YX-LiNbO₃

Complex variation at very thin film thickness

No guarantee of rapid convergence for perturbation analysis
Full Wave Analysis for Infinite Grating

- Perturbation or Functional Method ⇔ inaccurate (?)
- Boundary Element Method (BEM) ⇔ complex for Green function calculation
- Finite Element Method (FEM) ⇔ slow convergence (?)
**BEM calculation of IDT capacitance**

Piece-wise expression with $x^{-0.5}$ dependence

Used function

$$q(X) = \sum_{n=0}^{N-1} \frac{A_n (2X/w)^n}{\sqrt{1 - (2X/w)^2}}$$

What should be used for infinite case?

Charge concentration at electrode edges ($\propto x^{-0.5}$)
FEM Analysis Example

$z$ - Displacement
Full Wave Analysis for Infinite Grating

- Perturbation or Functional Method ⇔ inaccurate (?)
- Boundary Element Method (BEM) ⇔ complex for Green function calculation
- Finite Element Method (FEM) ⇔ slow convergence (?)
- Spectrum Domain Analysis (SDA) ⇔ simple analysis, fast convergence but applicable structure limited

FEM/SDA
Bløtekjær's Method for infinite IDTs

Field Expression (Rigorous for electro-statics)

\[ q(X) = \sum_{n=-\infty}^{+\infty} \frac{A_n \exp[-j\beta_G X (n - 1/2)]}{\sqrt{\cos(\beta_G X) - \cos(\beta_G w / 2)}} \]

\[ e(X) = \sum_{n=-\infty}^{+\infty} \frac{B_n \text{sgn}(X) \exp[-j\beta_g X (n - 1/2)]}{\sqrt{-\cos(\beta_G X) - \cos(\beta_G w / 2)}} \]

For non-piezoelectric case, \( B_m = -j\varepsilon A_m \)

How shall we include mechanical effects?
Characterization of Wave Properties in Infinite Structures

Metal Electrode

Piezoelectric Substrate

SAW Propagation Direction

Finite Element Analysis
For Arbitrary Electrode Cross-Section (+ Analytic Solution not Available)

Spectral Domain Analysis
Flat Substrate Surface
Analytic Solution = Fast Analysis

Boundary Condition: Minimization of Radiated Power (Error) from Boundary
Dispersion Characteristics of Rayleigh-type SAW on 128-LN. Blue: **FEMSDA**, Red: COM

$V_B = 4,025$ m/s (Slow-shear SSBW velocity)
Dispersion Relation vs. Al Thickness

Phase velocity (m/sec) vs. Relative frequency, $f_p/V_B$

Attenuation (dB/λ) vs. Relative Frequency, $f_p/V_B$
Change in COM Parameters with Al Thickness

\[ K_u^2 = \frac{\pi |\zeta|^2 p_I}{\omega C} \] : Electromechanical Coupling Factor for **Perturbed Mode**

\[ c = \frac{V_B}{V_{ref}} \quad V_B = 4,025 \text{ m/s (Slow Shear SSBW)} \]
Comparison with Experiment

Rayleigh-type SAW on 128°YX-LiNbO₃
Solid Lines: FEMSDA, +×: Experiment
Correction of Simulation Parameters

- Uncertainties in Substrate Material Constants (Supplier and Lot Dependent)
- Uncertainties in Film Material Constants (Fab. Process Dependent)
- Electrode Cross-Section (Fab. Process Dependent)

Although their Absolute Values may be Doubtful, Dependencies on Device Parameters might be held
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SH(Shear-Horizontal)-Type SAW
Properties of SH-type SAWs

Similar to Rayleigh-Type SAWs (SV+L) at First Look

- Influence of Bulk Wave Radiation
- Frequency Dependent Velocity
- Frequency Dependent Piezoelectricity
Back-Scattering to BAW

For SH-type SAW,
Cutoff For BAW Back-Scattering ≈ SAW Resonance Frequency
Dispersion in phase velocity & attenuation of *SH-type SAW* on SC grating on 42-LT. Blue: calculated by FEMSDA, and red: calculated by conventional COM.
Frequency
Amplitude

SAW Response

BAW Radiation

Backscattered BAW cutoff

Stored Energy
($\propto$ Velocity Reduction)

Origin of dispersion near stopband
Phase velocity of *SH-type SAW* for grating structure on 42-LT. Blue: calculated by FEMSDA, and red: calculated by Plessky's model.
Coupling between SAW and BAW radiation through internal reflection.
Simulation of SAW Resonator for *Ladder-Type* Filters

Experimental (blue) and calculated (red) input admittance of finite synchronous resonator. \((G_0=20 \text{ mS})\)
Experimental (blue) and calculated (red) input admittance of finite synchronous resonator. \( G_0 = 20 \text{ mS} \)
Slowness Surface of SH-type SAW on 36-LT

- Beam-like Propagation (No Guided Transverse Mode)
- Power Leakage through Bus-Bar Regions
- Frequency Dependent Behavior
Laser Probe Image

Impact of Metallization Ratio to Transverse Leakage

Presented at 2003 IEEE FCS By Tstutsumi, et al. (Fujitsu Labs)
COM analysis of DMS Filters

-100 -80 -60 -40 -20 0
800 850 900 950 1000 1050 1100
Frequency (MHz)

Scattering Parameter (dB)

S11
S21

Overestimated Propagation Loss
Influence of Discontinuities
No Practical Theory ⇒ Phenomenological Model (additional phase shift)

Influence of BAWs
Modeling has not been Established yet
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Origin of Transverse Mode

3D Simulation of Whole Structure

Admittance vs. Frequency

- \( G \)
- \( B \)
- \( \omega_r \)
- \( \omega_a \)
SAW Resonator

1-port SAW Resonator
Period: 7.18 µm
Substrate: ST-Cut Quartz
Electrode: Al (140 nm)

20 min. for 2,620×410 pixels
IDT Resonator on Cu-Grating/15°YX-LiNbO₃
Wideband SAW filter on Cu/15°YX-LiNbO₃ structure

- **Minimum Insertion Loss (IL)**: 0.5 dB
- **Bandwidth (BW) at 3 dB (BW₃dB)**: 152 MHz (15%)

Presented at IEEE 2004 UFFC Conf.
Measured Field distribution by Laser Probe

340.30 MHz
350.00 MHz
363.24 MHz
373.75 MHz

20min. for each image
Presented at 2005 IEEE Ultrasonics Symp.
Transverse Mode Analysis

Ignoring Depth Dependence
Simplifying IDT Region as Uniform Layer

Mode Orthogonality + Completeness Enable us to Estimate Mode Excitation Efficiency
Calculated and Experimental Spectra of Transverse Modes

Rayleigh mode
Weighted Dummy Electrodes for Suppression of Transverse Modes

Scattering of Unnecessary Modes Through Coupling with Dummy Electrode Modes
1.3

Frequency, $f$ [GHz]

Insertion loss [dB]

0 10 20 30 40

W Weighted Dummy Electrodes
W/O Weighted Dummy Electrodes

0.7 0.8 0.9 1 1.1 1.2 1.3

Frequency, $f$ [GHz]
SAW Filter Using Cu/15°YX-LiNbO₃ Structure

Frequency, $f$ [GHz]

Insertion loss [dB]

0 10 20 30 40

0.7 0.8 0.9 1 1.1 1.2 1.3

Frequency, $f$ [GHz]
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Full Wave Analysis for Finite Structure

- Perturbation or Functional Method $\iff$ inaccurate
- Boundary Element Method (BEM) $\iff$ complex for Green function calculation
- Finite Element Method (FEM) $\iff$ slow conversion

Rigorous Analysis of arbitrary 2D structure

This simulation is time consuming but current computers are a little powerful
Structure of **Pitch-Modulated IDT & Reflector**

### Conventional Structure

### Pitch-Modulated Structure

**Gap Controlled**

Presented at IEEE 2004 UFFC Conf.
Designed Results

Wideband & Without gaps between IDTs

Presented at IEEE 2002 Ultrasonics Symp.
Remaining Loss \( (1-|S_{21}|^2-|S_{11}|^2) \)

**COM Analysis (BAW Ignored)**

- Red line: Modulated-Pitch Structure \( (L_g=0\lambda) \)
- Blue line: Unmodulated-Pitch Structure \( (L_g=0.3\lambda) \)

**FEM/BEM Analysis (BAW Incl.)**

- \( \Delta IL = 0.1 \text{dB} \)
- \( \Delta IL = 0.4 \text{dB} \)

Presented at IEEE 2004 UFFC Conf.
Experimental Verification

Red line: Modulated-Pitch Structure
Blue line: Unmodulated-Pitch Structure ($L_g=0.3\lambda$)

Remaining Loss

$\Delta IL=0.4$dB

Presented at IEEE 2004 UFFC Conf.
DMS Filter Using Modulated Structure

Presented at IEEE 2004 UFFC Conf.
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What we can do ......

- Pseudo 2D Simulation of Whole Structure
- Derivation of Simulation Parameters by 2D (X-Z) Simulation
- Correction of Simulation Parameters
- Simulation of SH-type SAW
- Precise Simulation of Ladder-Type Filters
- Transversal Mode Analysis
- Package Modeling
What we should do next?

- Fast & Precise Simulation of DMS-Type Filters (Including Frequency Dependent $K^2$ and Attenuation)
- Pseudo 3D Simulation of Whole Structure (Including Lateral Leakage)
- Rapid Package Simulation for Optimal Design
- Finding Remaining Loss Mechanism
- Precise Simulation Tools for More Complicated Structures