COMSOLが拓く高周波弾性波素子シミュレーションの新たな展開

Quantum Leap in Simulation Technologies of Radio Frequency Acoustic Wave Devices Gifted by COMSOL

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Chiba University
University of Electronic Science and Technology of China

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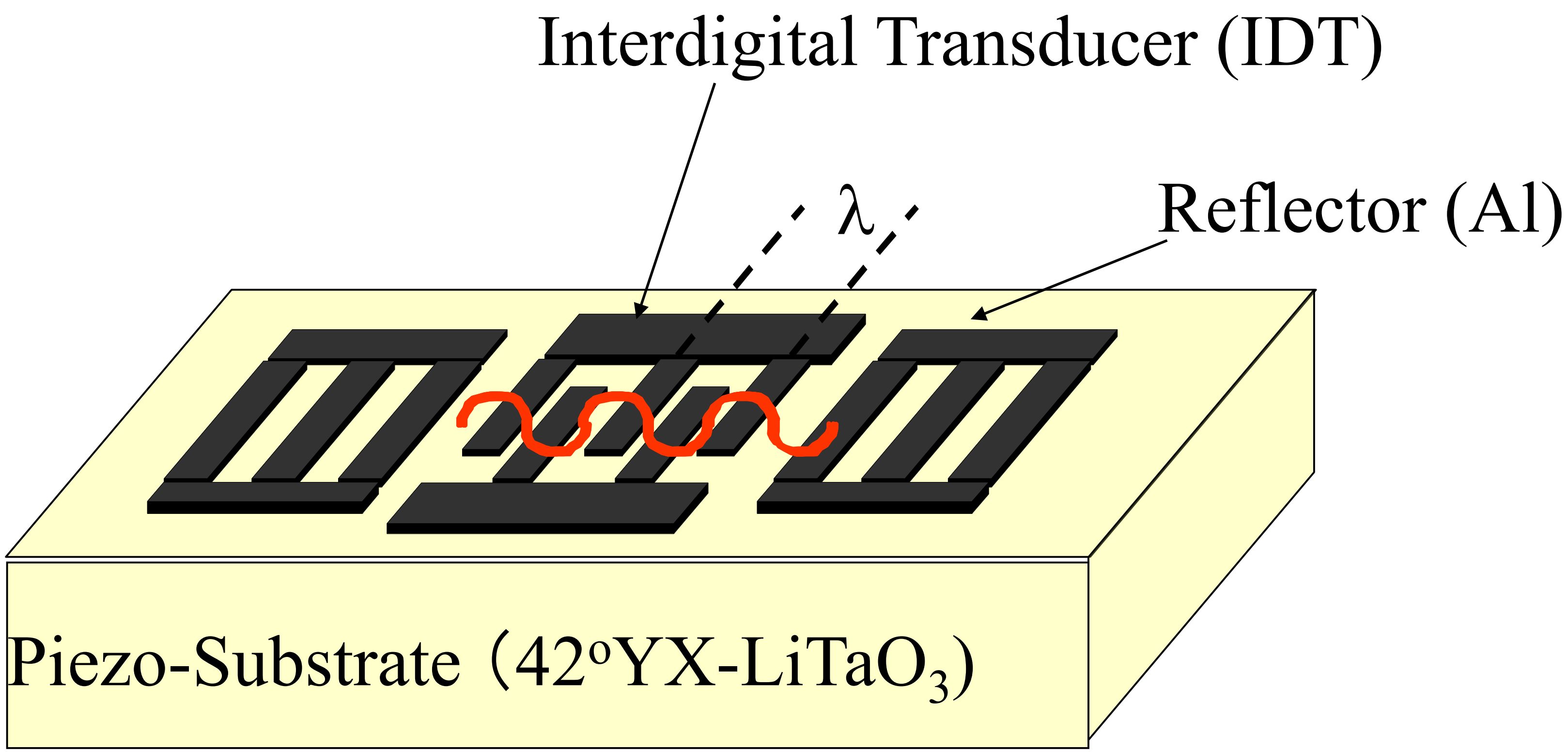
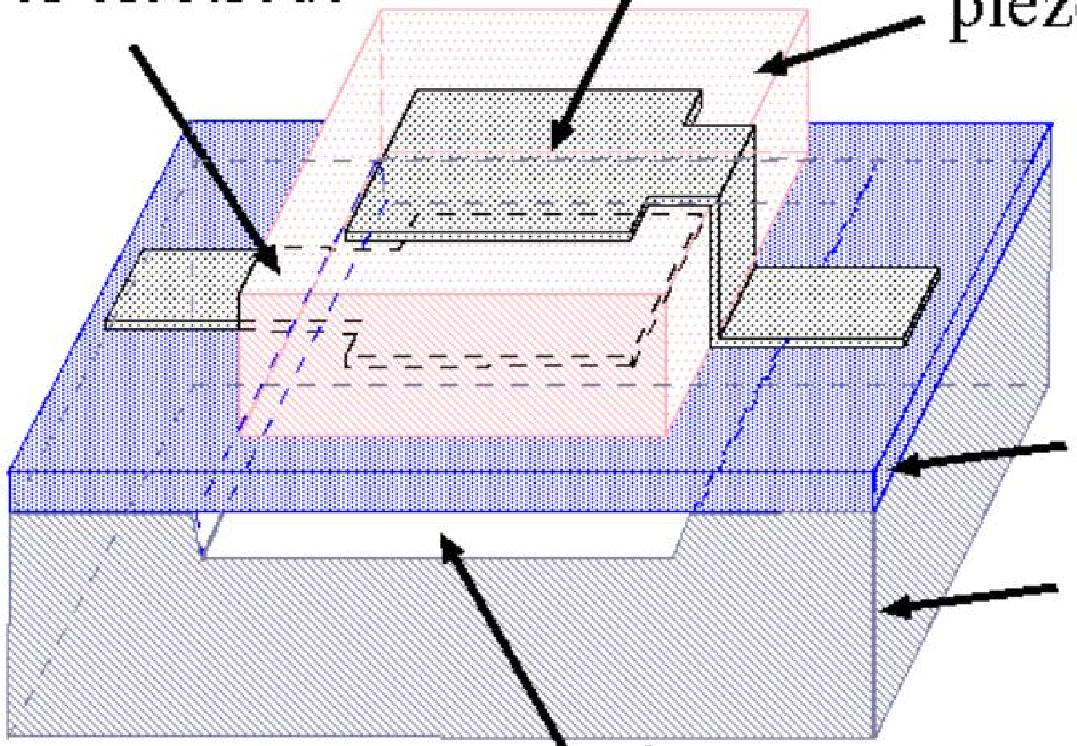
Surface Acoustic Wave (SAW) Resonator

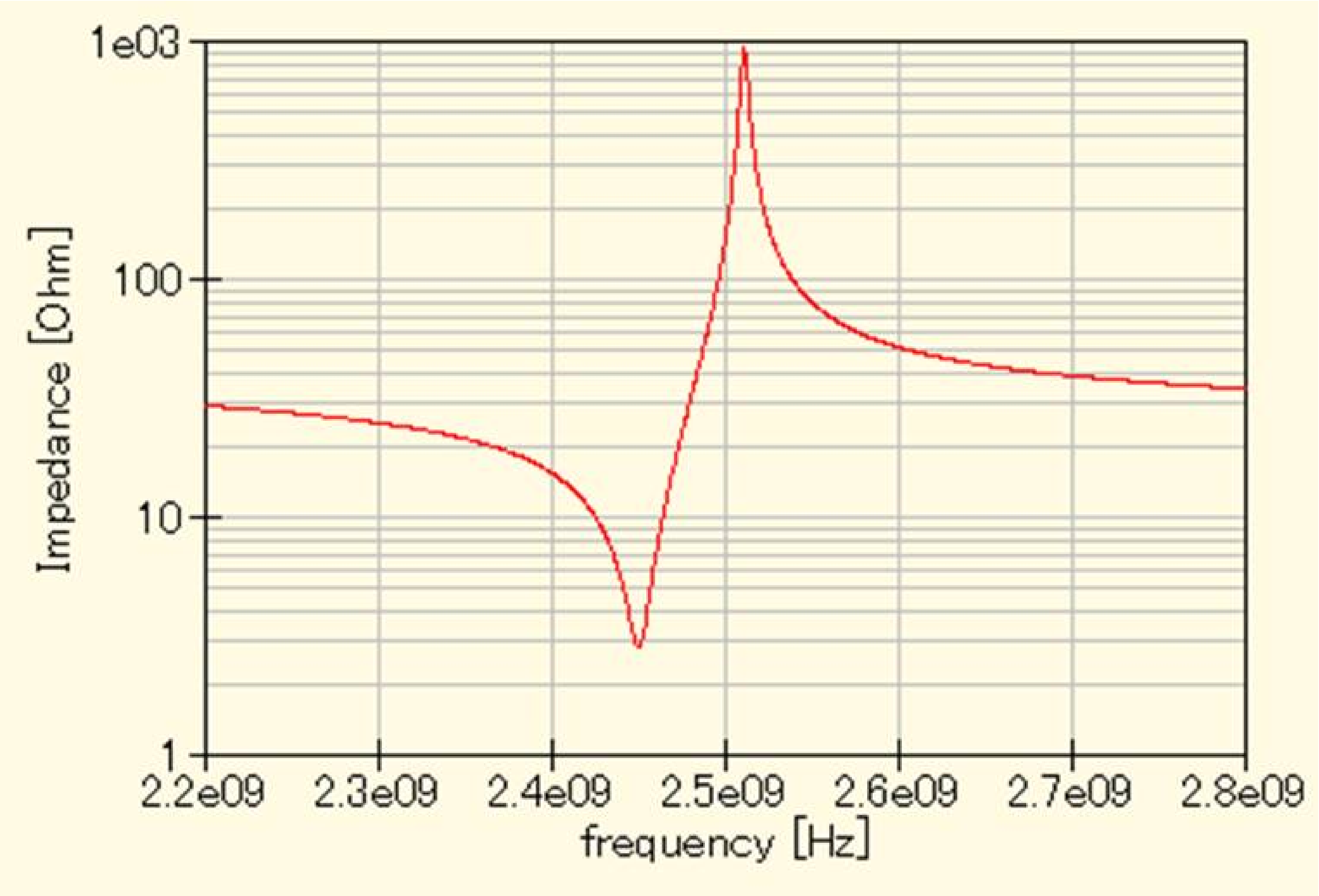


Mass Production by Photo Lithography

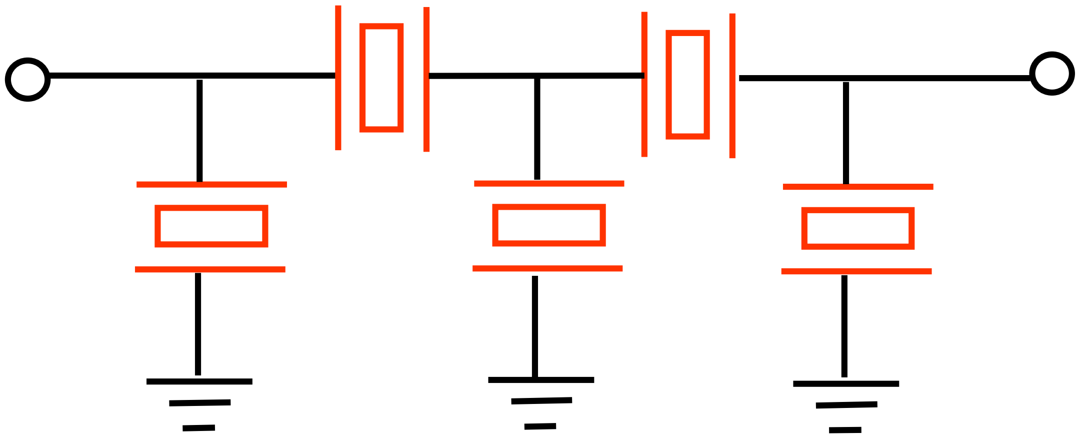
Bulk Acoustic Wave (BAW) Resonator



Mass Production by MEMS & Thin Film Tech.

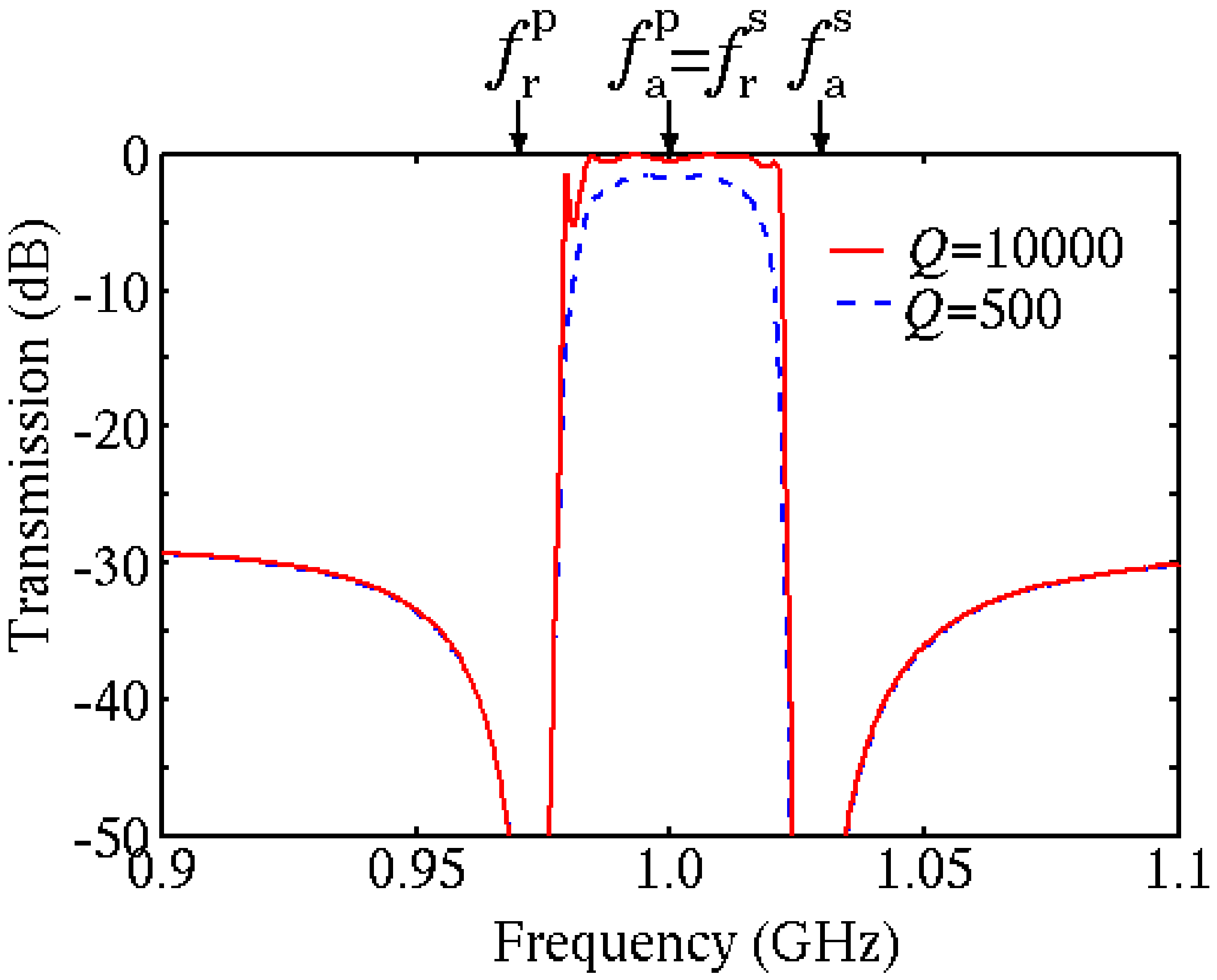

1e03
100
10
1
Impedance [Ohm]
2.2e09
2.3e09
2.4e09
2.5e09
2.6e09
2.7e09
2.8e09
frequency [Hz]

Ladder-Type Filter



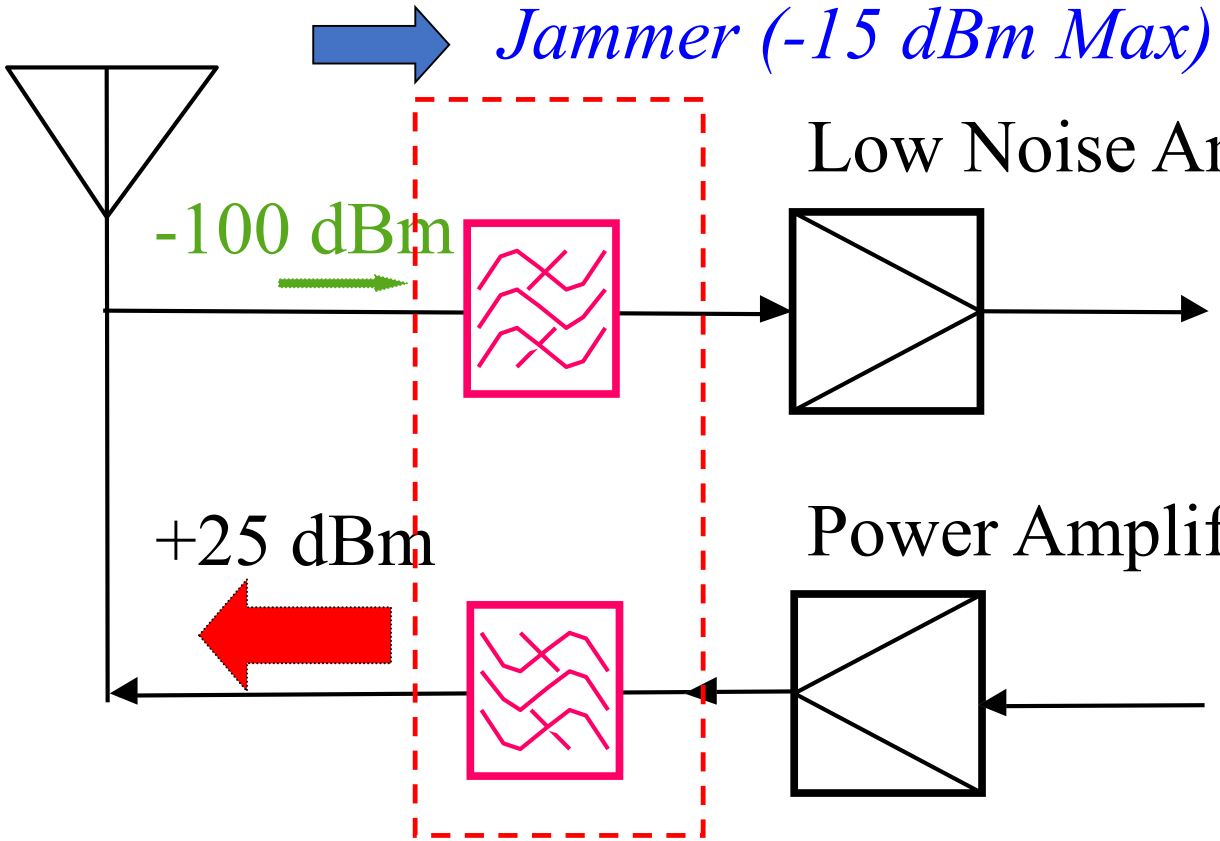
Fabrication of Multiple Resonators on a Chip

Why High Q is Necessary?



High Q Offers Low Insertion Loss & Steep Passband Corners

Role of Duplexer in FDD Transceiver



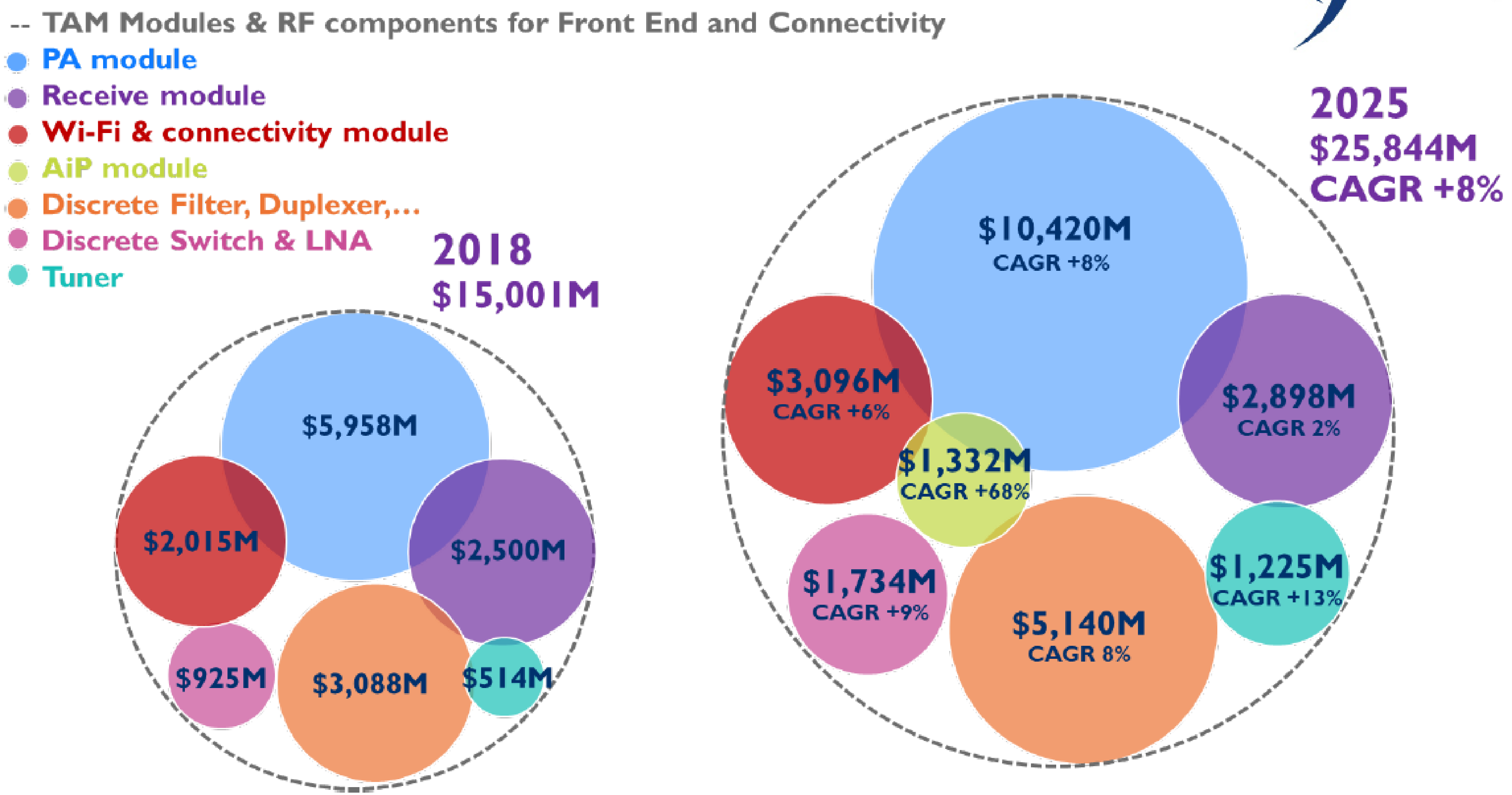
Tx->Rx Leakage Suppression in Tx Band = Duplexer

RF Acoustic Wave Devices

- Operation in Radio Frequency
- Wideband
- Low Loss (High Q)
- Good Temperature Stability
- Power Durable
- Extremely Weak Non-Linearity
- Small Size and Light Weight
- Cheap
- -------------

Only SAW/BAW Devices Fulfill All of Them.

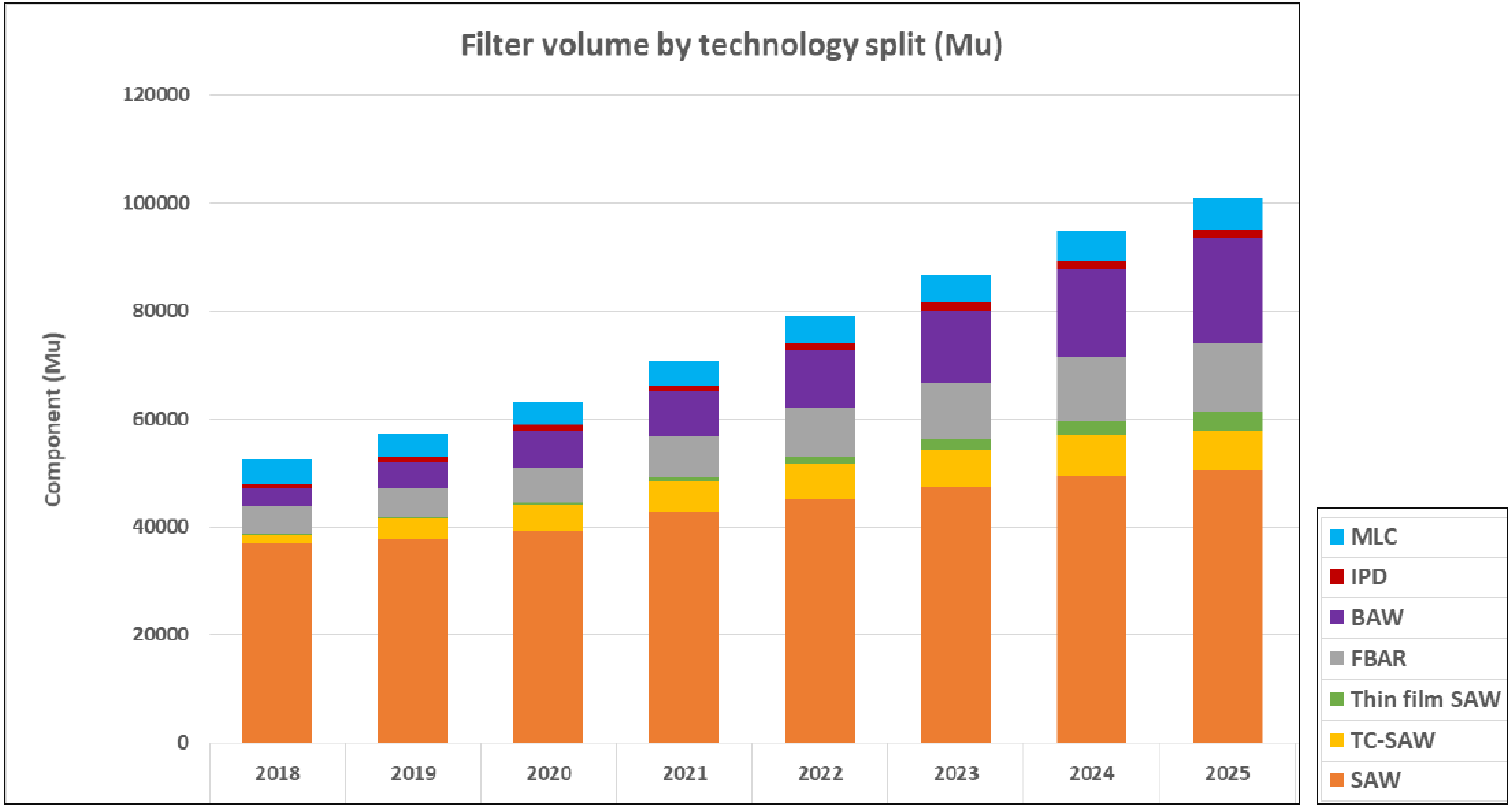
RF Front End & Connectivity Market Forecast



- RF module market represented 70% of the TAM in 2018.
- By 2025, we expect almost the same proportion as RF discrete market will remain strong with a demand from Chinese OEMs.

Source: SystemPlus Consulting, SAW Filters Comparison 2020

RF Filter technology Market Forecast



Installation of So Many RF SAW/BAW Devices in One Smart Phone

Source: SystemPlus Consulting, SAW Filters Comparison 2020

Contents

- What are Radio Frequency (RF) Surface and Bulk Acoustic Wave (SAW/BAW) Devices?
- Role of FEM Tools in SAW/BAW Device Design
- Hierarchical Cascading Technique (HCT)
- HCT Combined with Traveling Wave Source
- 3D HCT and Use of Graphic Processing Unit (GPU)
- Summary and Outlook

Computer Environment in Ken's Lab

- COMSOL Multi-Physics + MEMS Module + Livelink for Matlab + Matlab (6 Licenses)
- Windows Workstation (128 GB Memory) 6 Machines
- Nvidia GPU (GV100, FP64, 32 GB Memory) 4 Boards
- Nvidia GPU (RTX8000, FP32, 48 GB Memory) 1 Board
- Many Windows & Unix Machines for Desk Works (Documentations, E-Mailing and so on.)

Final Goal

Transfer Developed Technologies, Know-Hows and Human Resources to Partner SAW/BAW Industries

What are Necessary for Simulators?

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

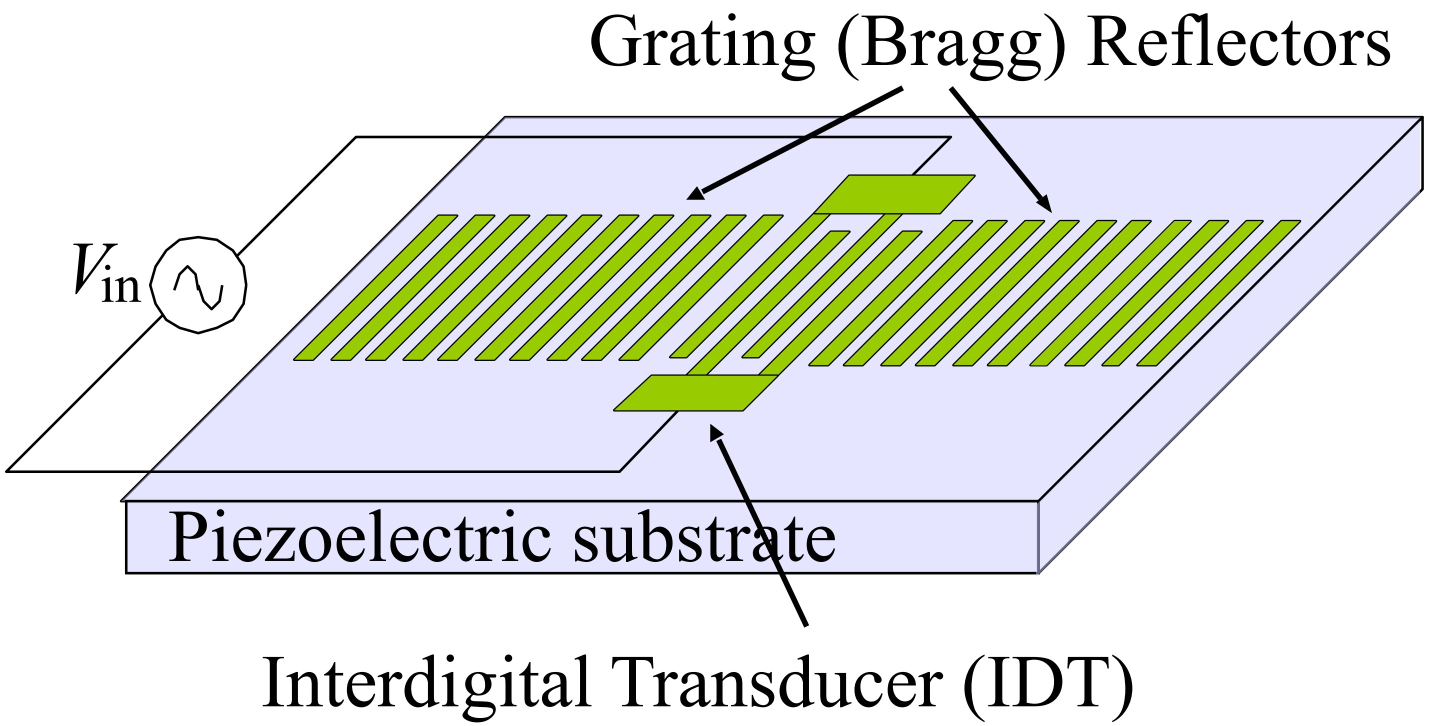
For Speedy Simulation

Behavior-Model Based Simulation

For Accurate Simulation

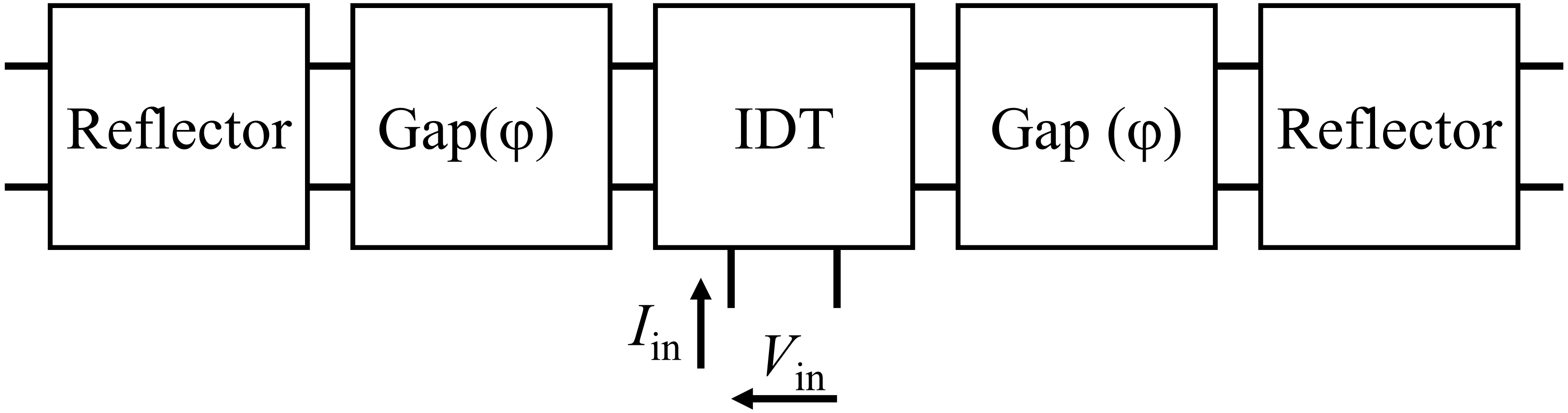
Full Wave Simulation

SAW Resonator Configuration



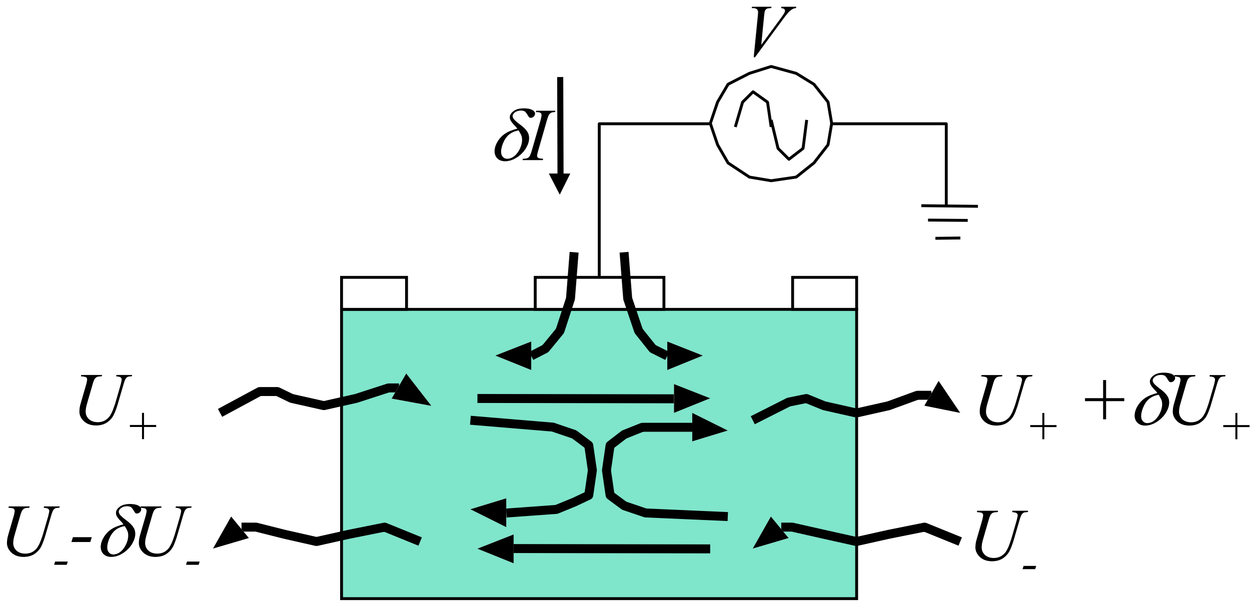
- ***Combination of Periodic Structures***
- ***Wide Aperture***

1D Model: Cascade-Connection of Elements



1. *Modelling of SAW Properties in an Infinitely long IDT*
2. *Determination of Model Parameters Using FEM*
3. *Simulation of SAW Structures Composed of Finite Gratings*
4. *Experimental Correction of Model Parameters*

Coupling of Modes (COM) Model for 1D Simulation of SAW Devices



$$\frac{\partial U_+}{\partial x} = -j\theta_u U_+ - j\kappa_{12} U_- + j\zeta V$$

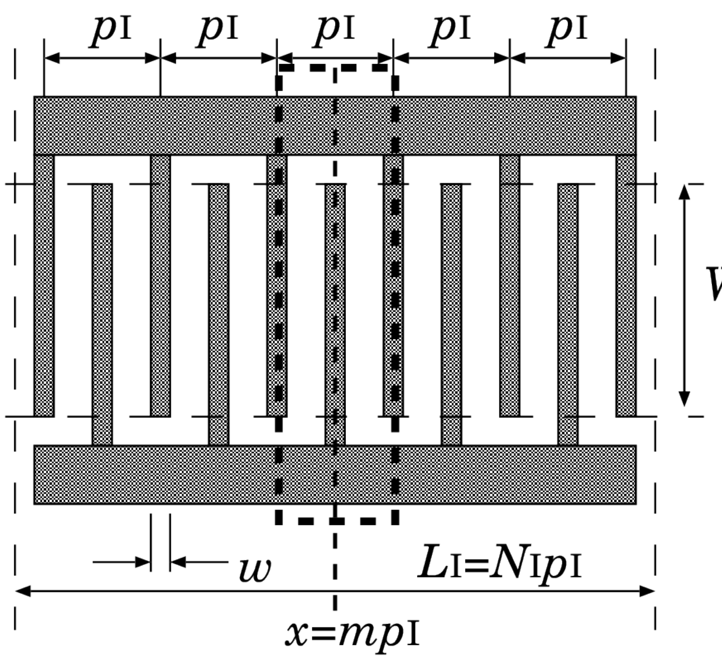
$$\frac{\partial U_-}{\partial x} = +j\kappa_{12} U_+ + j\theta_u U_- - j\zeta V$$

$$\frac{\partial I}{\partial x} = -4j\zeta U_+ - 4j\zeta U_- + j\omega C V$$

Provided that θ_u, κ_{12}, ζ, and C are Modelled Properly, We can Simulate SAW Device Behaviors in Surprisingly High Accuracy with Very High Speed

Note θ_u is Frequency Dependent (κ_{12} and ζ can be also)

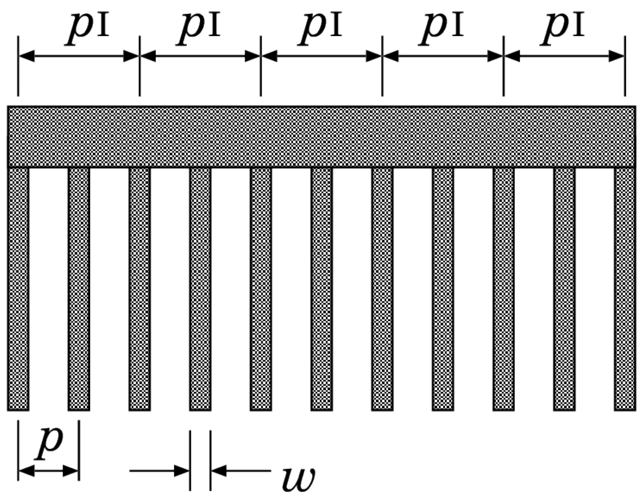
IDT



$$V=0$$

$$\delta I=0$$

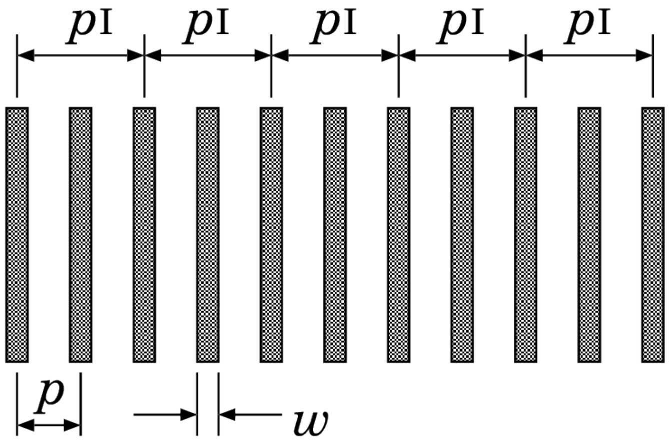
Short Circuited (SC) Grating



$$\frac{\partial U_+}{\partial x} = -j\theta_u U_+ - j\kappa_{12} U_-$$

$$\frac{\partial U_-}{\partial x} = +j\kappa_{12} U_+ + j\theta_u U_-$$

Open Circuited (OC) Grating



$$\frac{\partial U_+}{\partial x} = -j\hat{\theta}_u U_+ - j\hat{\kappa}_{12} U_-$$

$$\frac{\partial U_-}{\partial x} = +j\hat{\kappa}_{12} U_+ + j\hat{\theta}_u U_-$$

where

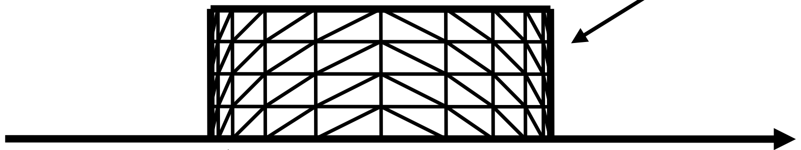
$$\hat{\theta}_u = \theta_u - 4\varsigma^2 / \omega C$$

$$\hat{\kappa}_{12} = \kappa_{12} - 4\varsigma^2 / \omega C$$

FEMSDA (Full Wave Simulator)

G.Endoh, K.Hashimoto and M.Yamaguchi, "Surface Acoustic Wave Propagation Characterisation by Finite Element Method and Spectral Domain Analysis," Jpn. J. Appl. Phys., **34**, 5B (1995) pp. 2638-2641

Metal Electrode



Finite Element Analysis

For Arbitrary Electrode Cross-Section

(+ Analytic Solution not Available)

SAW Propagation Direction

Piezoelectric Substrate

Spectral Domain Analysis

Flat Substrate Surface

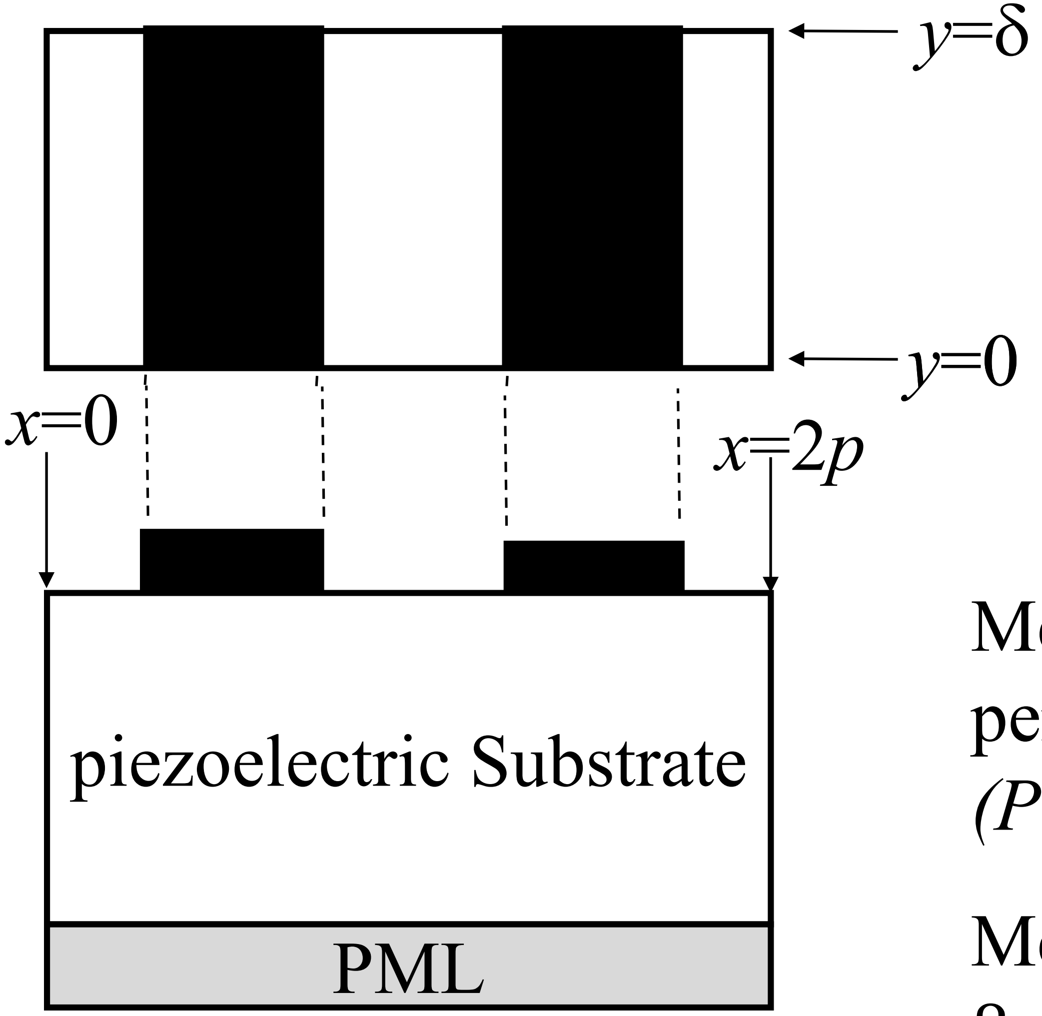
Analytic Solution = Fast Analysis

Boundary Condition: Minimization of Radiated Power (Error) from Boundary

Very Fast and Accurate, But Applicable Structures Limited

For More Complicated Structures: Use FEM

2.5D FEM for COM Parameter Extraction



Unit Cell for FEM

Boundary Conditions

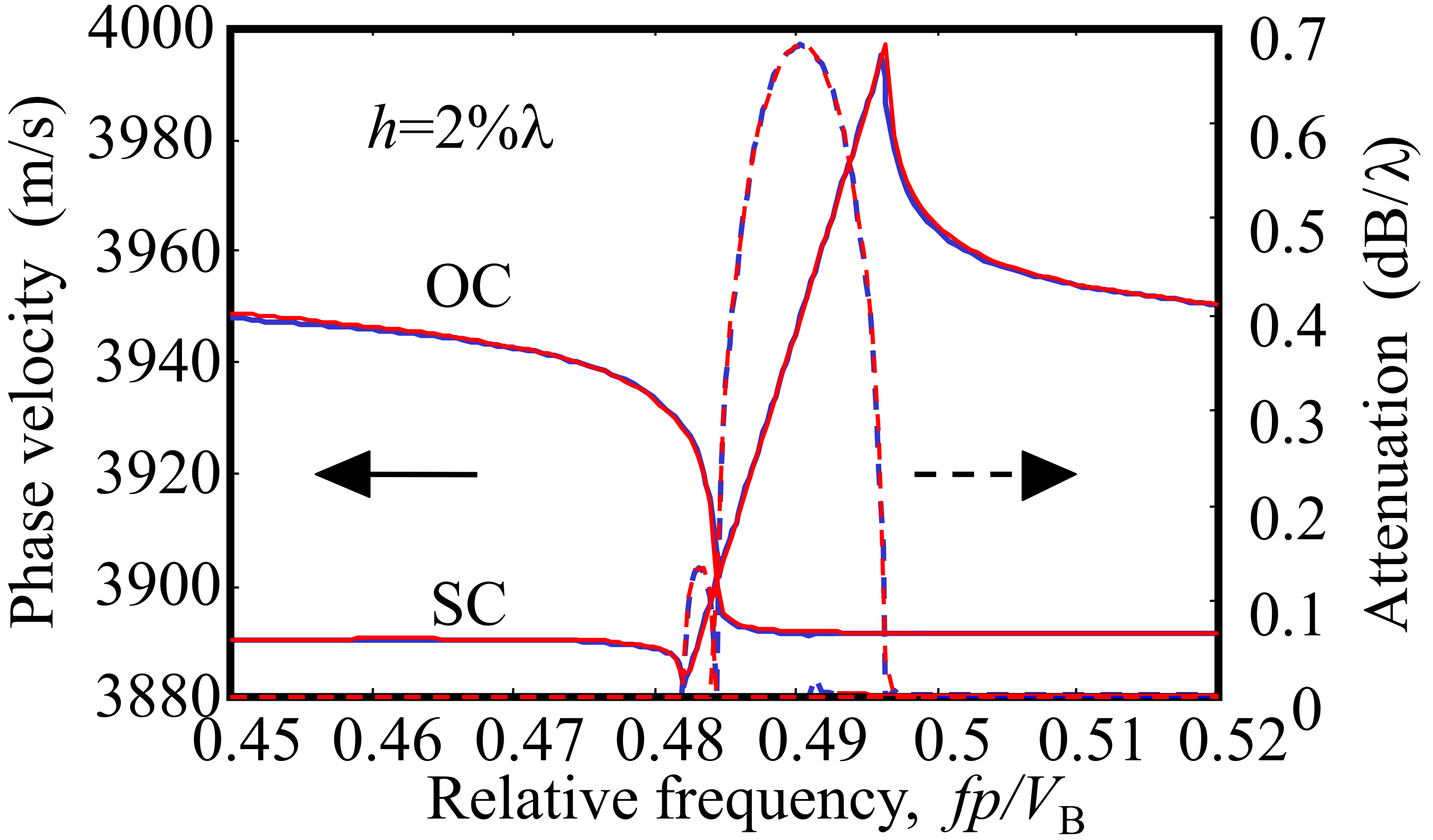
$$\mathbf{u}(x,\delta)=\mathbf{u}(x,0)$$

$$\mathbf{u}(2p,y)=\mathbf{u}(0,y)\exp(-2j\beta_x p)$$

PML: Perfect Matching Layer

Method 1: Calculation of Admittance per Period for Given ω Under $\beta_x p=\pi$ *(Periodic Boundary Condition)*

Method 2: Calculation of f for Given β_x *(Only Possible by **COMSOL**)*



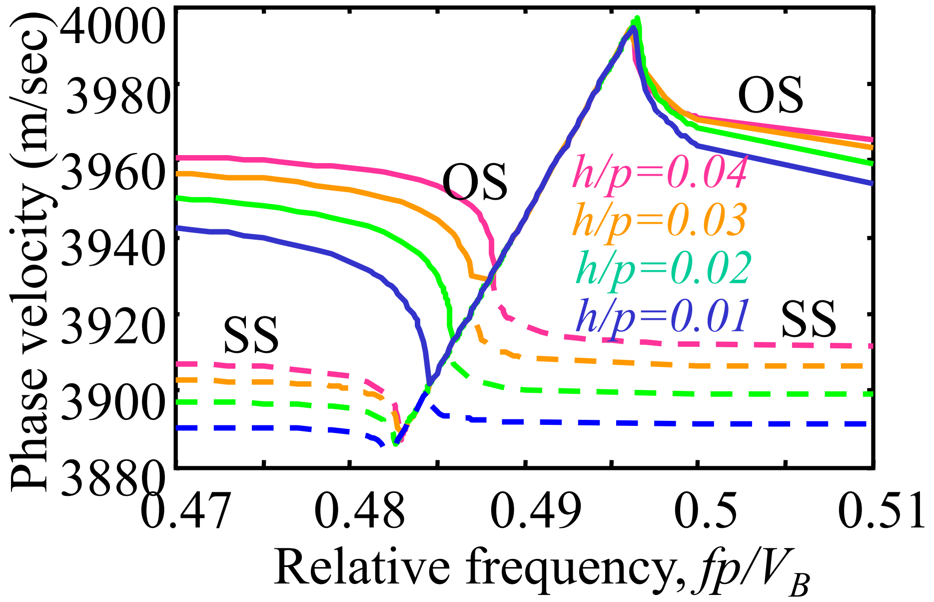
Dispersion of Rayleigh SAW on 128-LN

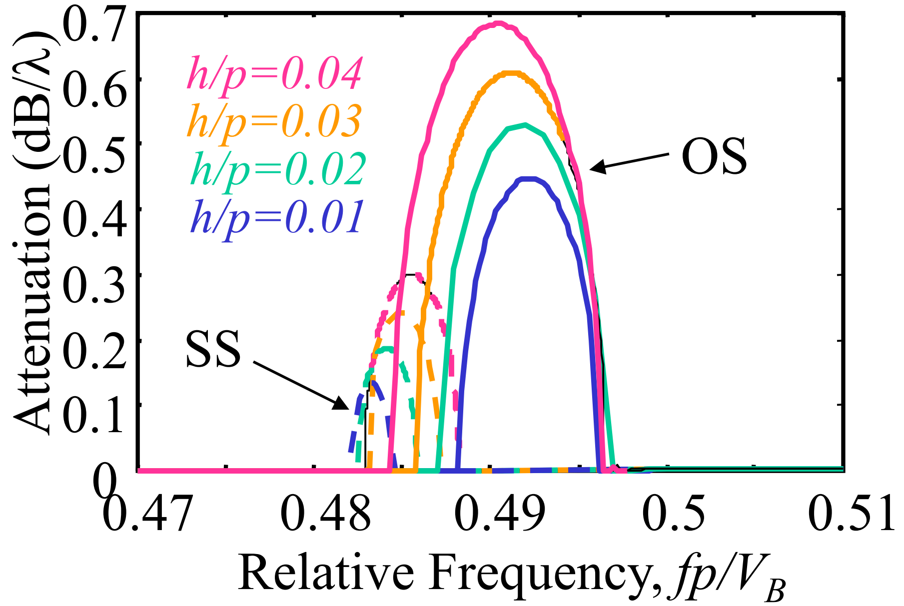
Blue: Full Wave Analysis

Red: Conventional COM Analysis

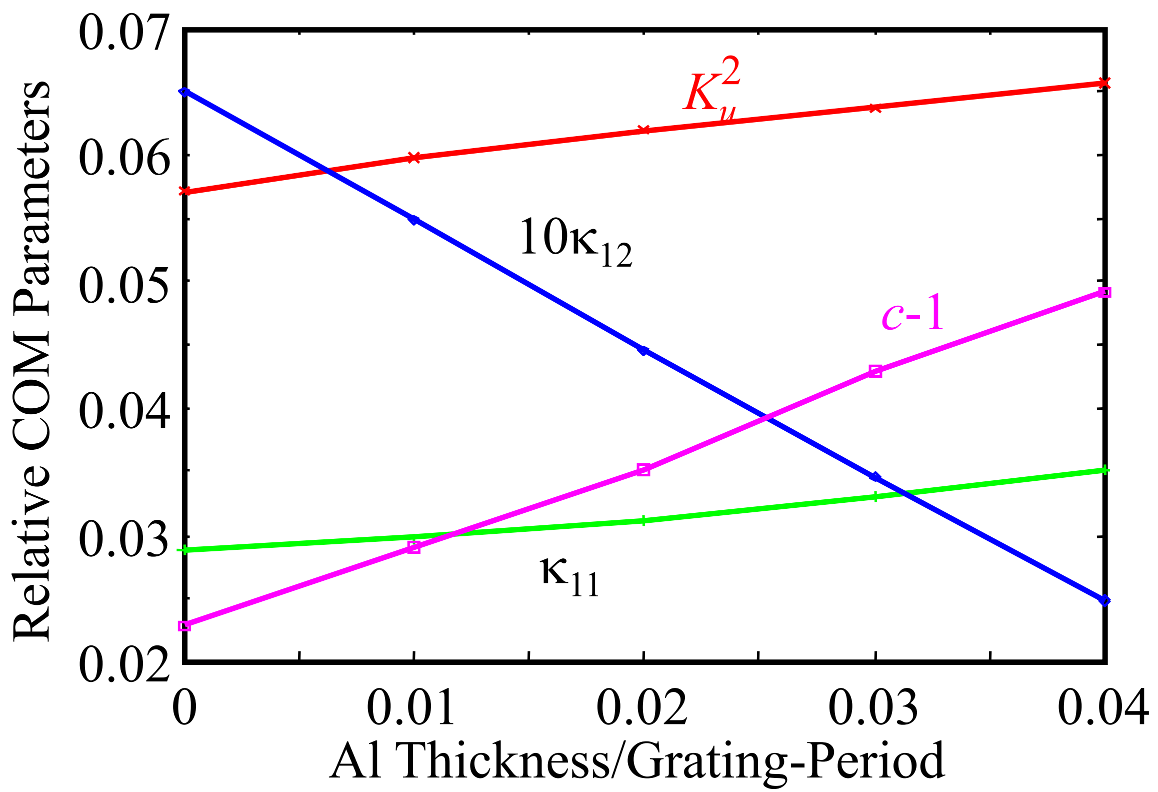
V_B=4,025 m/s (Slow-shear SSBW velocity)

Dispersion Relation vs. Al Thickness





Change in COM Parameters with Al Thickness



$$K_u^2 = \frac{\pi\chi|\zeta|^2 p_I}{4\omega C}$$: Electromechanical Coupling Factor for *Unperturbed Mode*

$c=V_B/V_{ref}$ V_B=4,025 m/s (Slow Shear SSBW)

1D COM Simulation Example

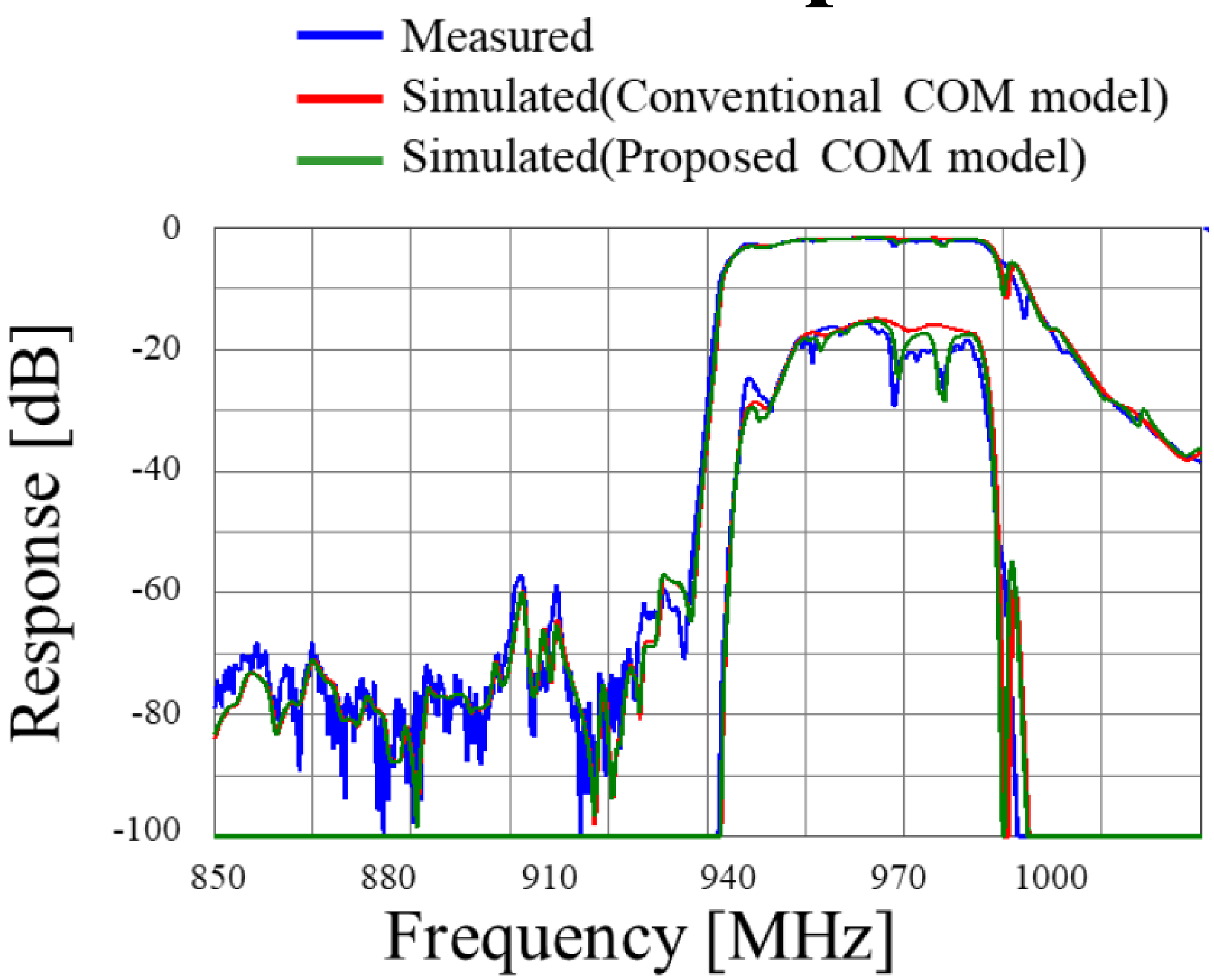
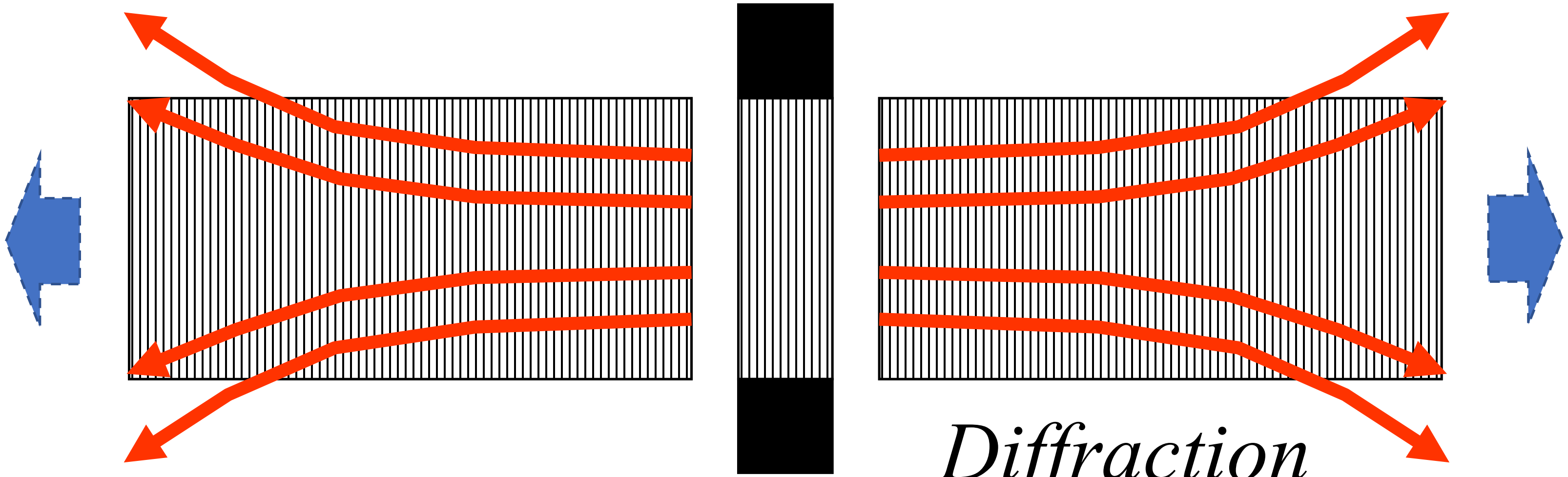


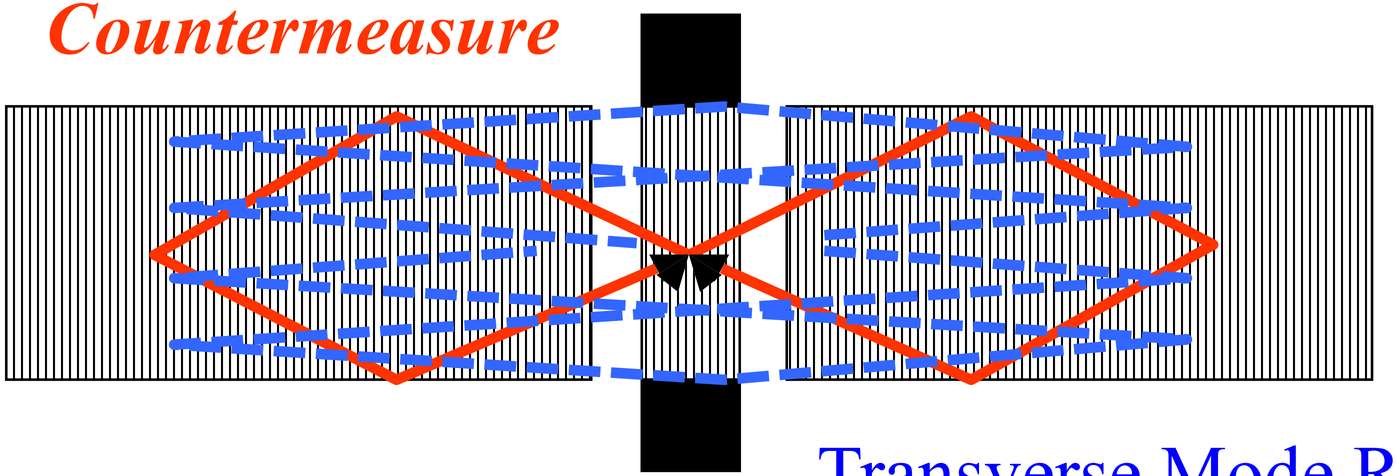
Fig. 4. Measured and simulated (Conventional COM model and propoesd COM model) transmission characteisics.

Two SAWs are Considered in New COM Model

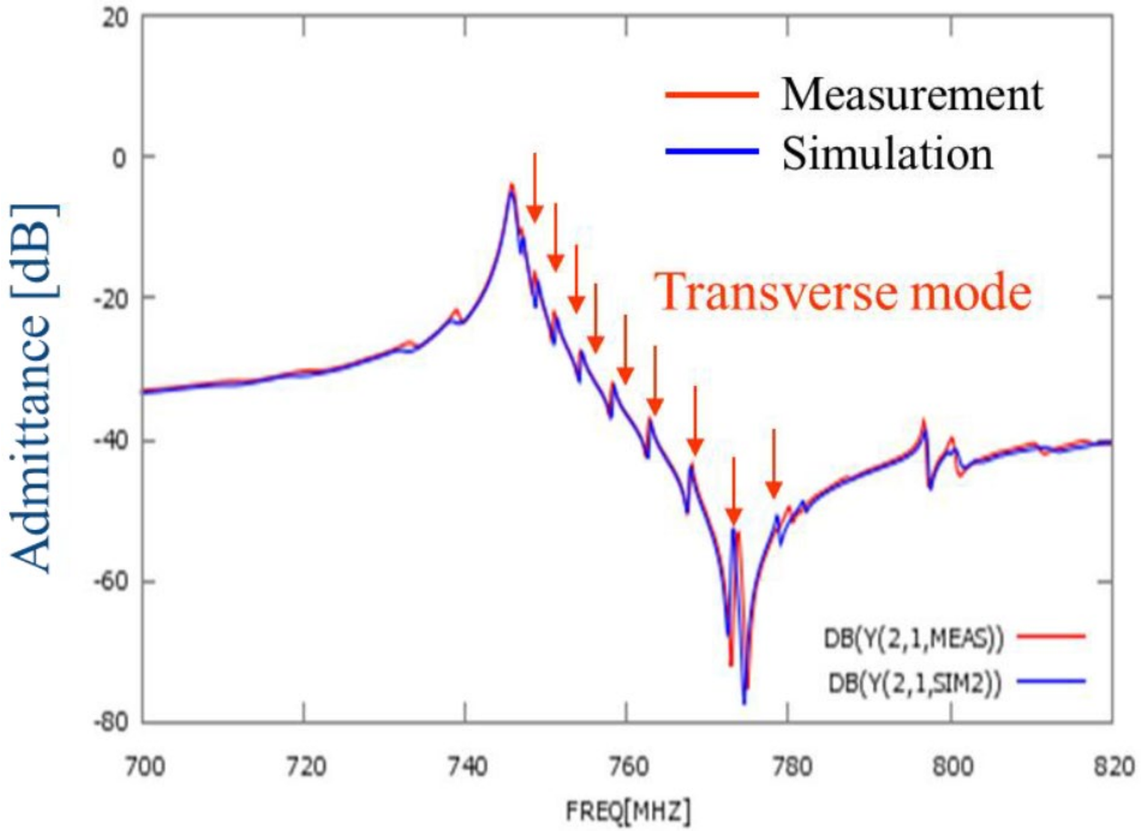
R.Goto, H.Nakamura, and K.Hashimoto, “Spurious Free TC-SAW Duplexer Using the $SiO_2/LiNbO_3$ structure,” Proc. IEEE Ultrason. Symp. (2019) 10.1109/ULTSYM.2019.8925829

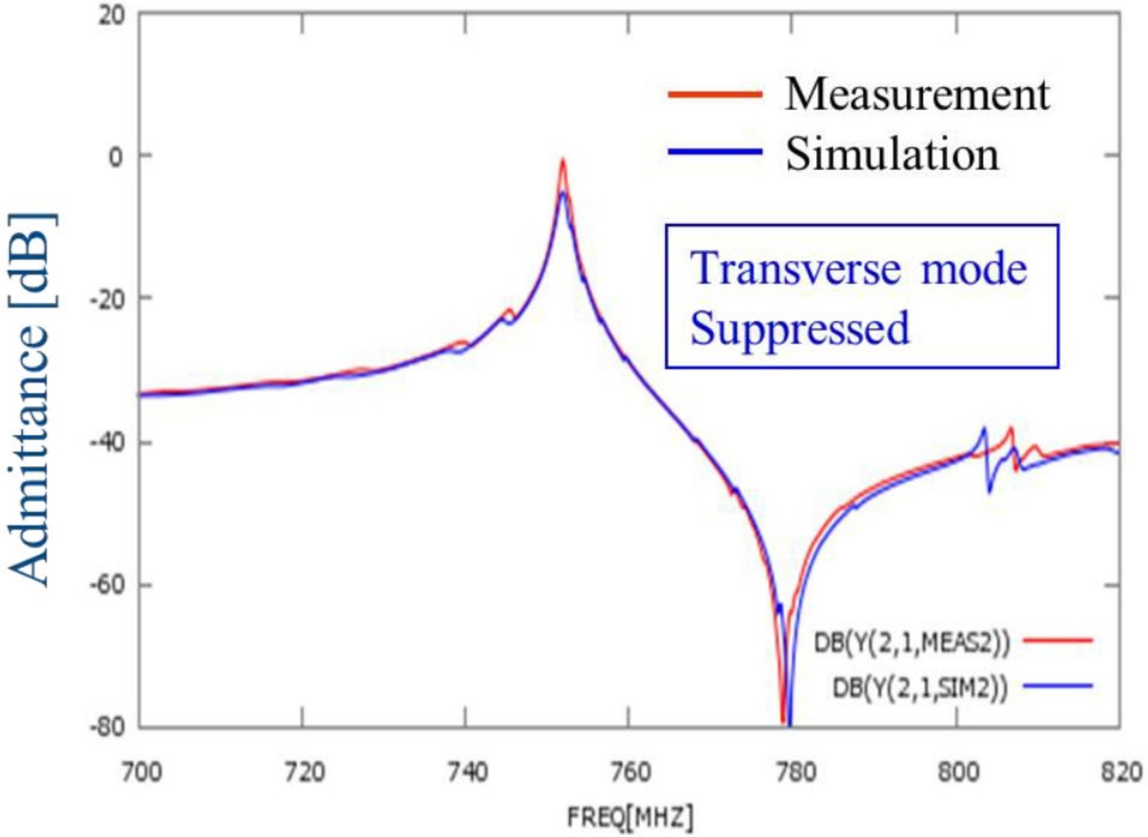
Effect of 2D SAW Propagation





Impact of Transverse Resonances

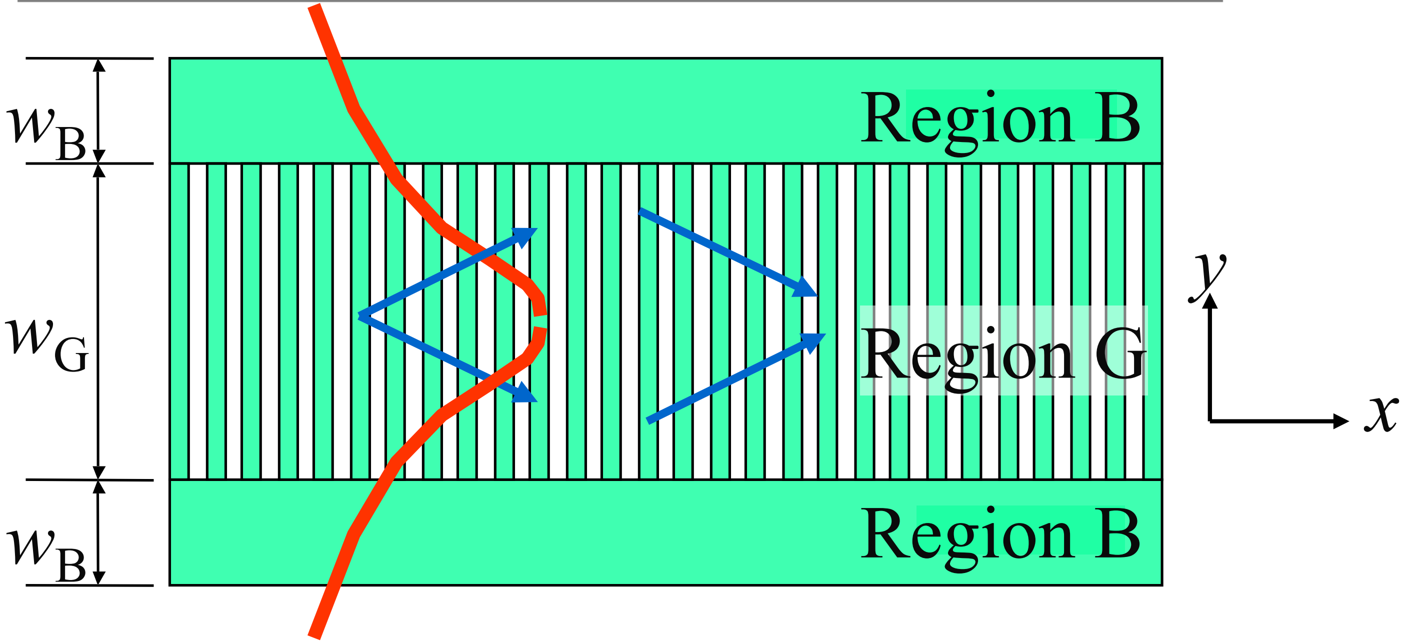




Necessity of Complete Suppression of Transverse Resonances Without Sacrificing the Main Mode Performances (How?)

R.Goto, PhD Dissertation, Chiba University (2019)

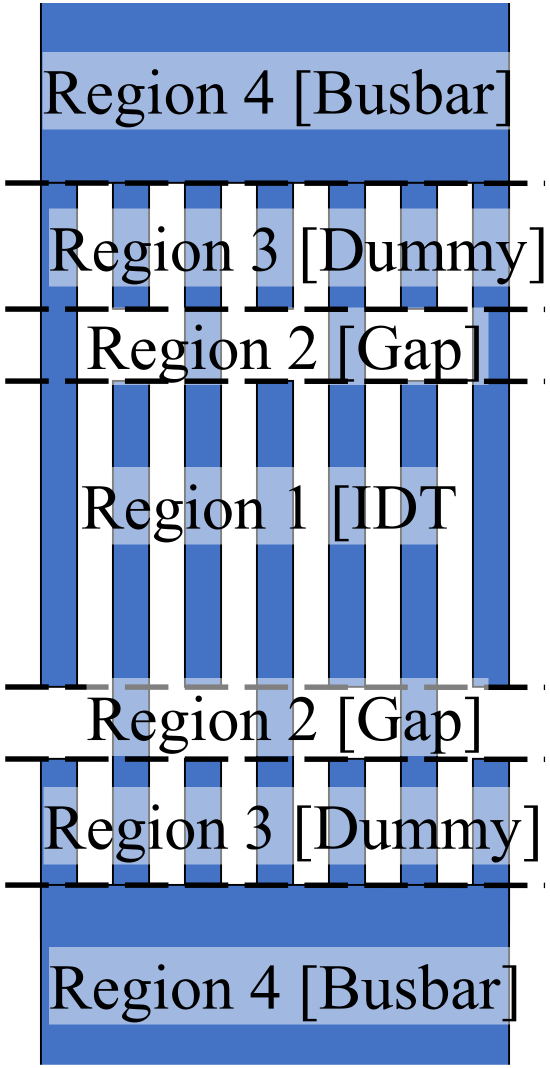
Scalar Potential Analysis for 2D SAW Propagation



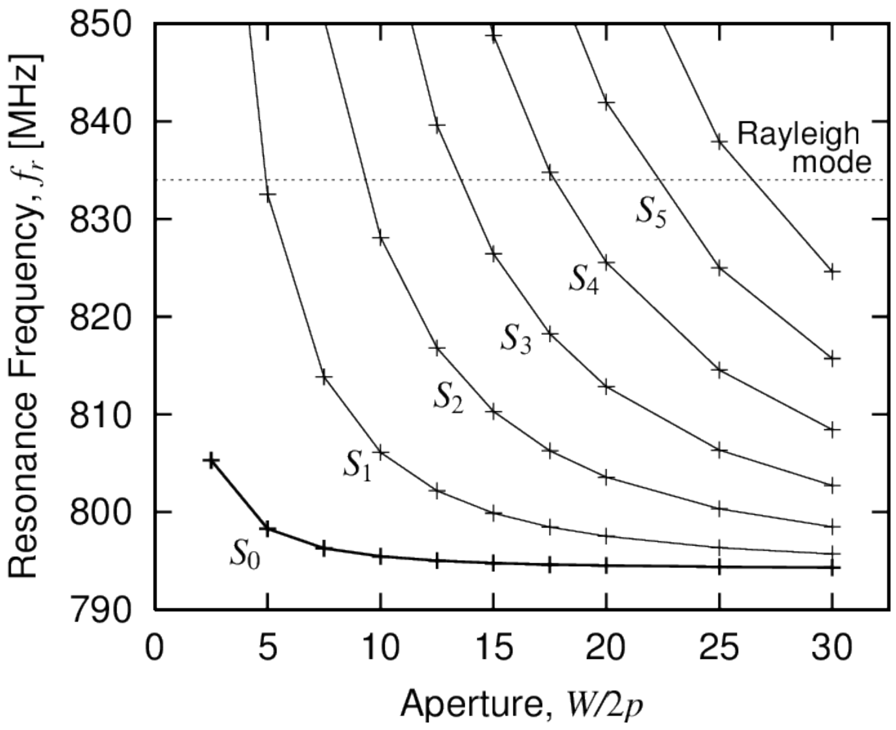
Approximated Governing Equation

$$-\beta_{G,B}^2 \phi = \frac{\partial \phi}{\partial x^2} + \gamma_{G,B} \frac{\partial \phi}{\partial y^2}$$

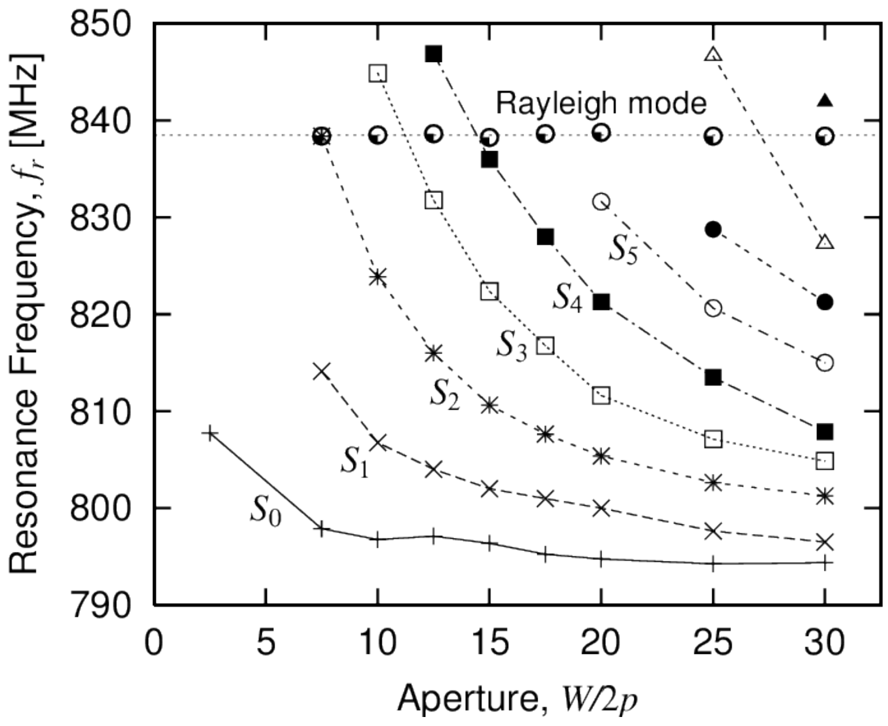
How Accurate Scalar Potential Method?



7 Layer Model



Simulation

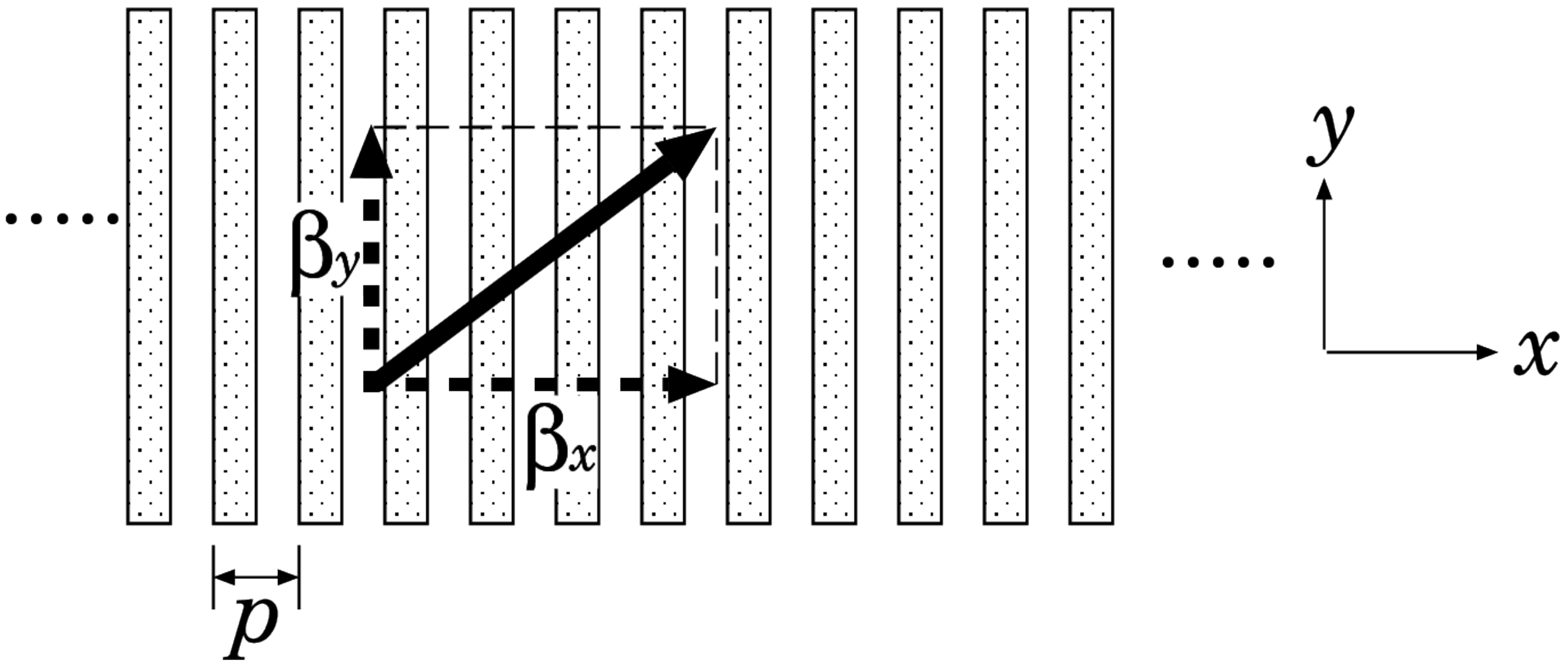


Experiment

Good Agreement!

T.Omori, K.Matsuda, N.Yokoyama, K.Hashimoto, and M.Yamaguchi, "Suppression of Transverse Mode Responses in Ultra-Wideband SAW Resonators Fabricated on a Cu-grating/15°YX-$LiNbO_3$ Structure", IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., **54**, 10 (2007) pp. 1943-1948.

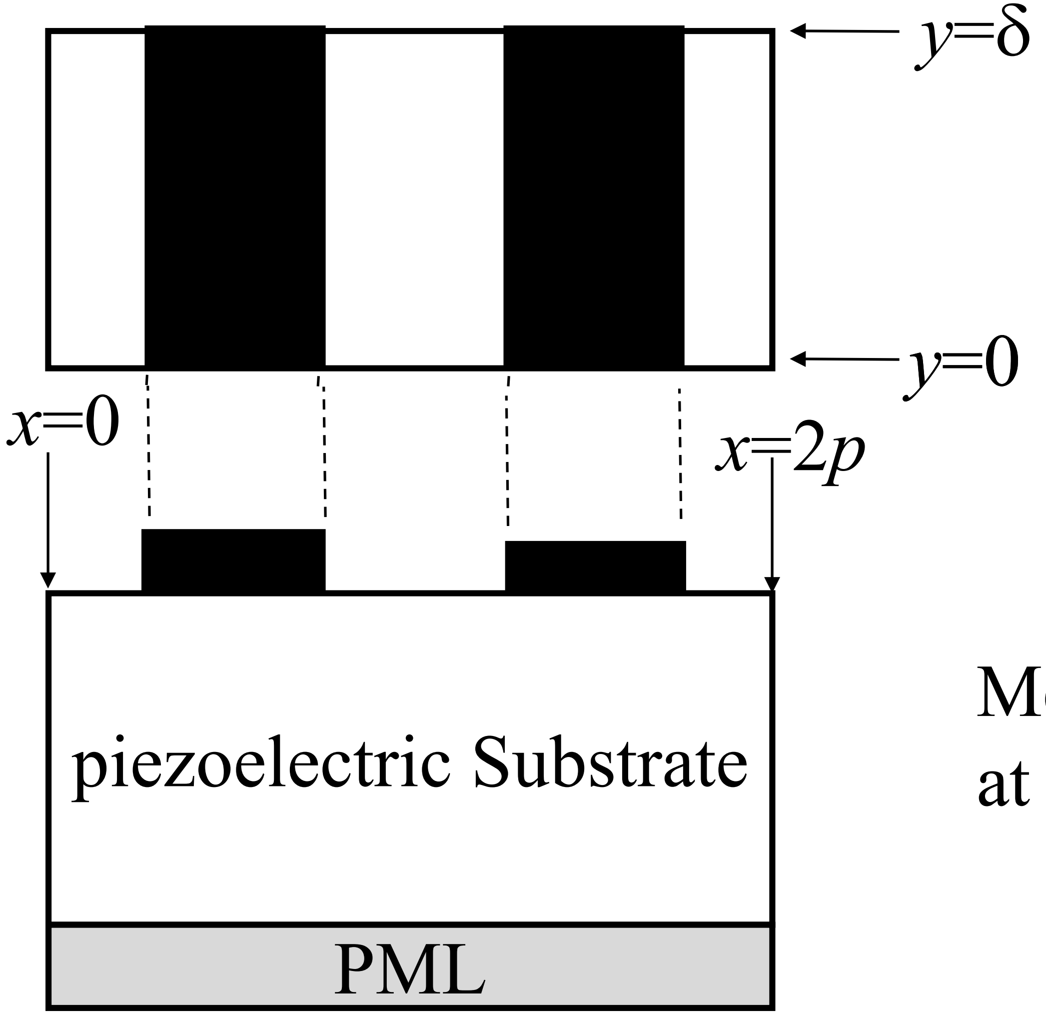
Model Parameter Extraction



Calculation of f Dependence of $\beta_y p$ Under $\beta_x p=\pi$ (Longitudinal Resonance Condition) and Fitting

G.Tang, T.Han, J.Chen, B.Zhang, T.Omori, and K.Hashimoto, "Model Parameter Extraction for Obliquely Propagating Surface Acoustic Waves in Infinitely Long Grating Structures," Jpn. J. Appl. Phys., **55**, 7 (2016) 07KD08

2.5D FEM for COM Parameter Extraction



Unit Cell for FEM

Boundary Conditions

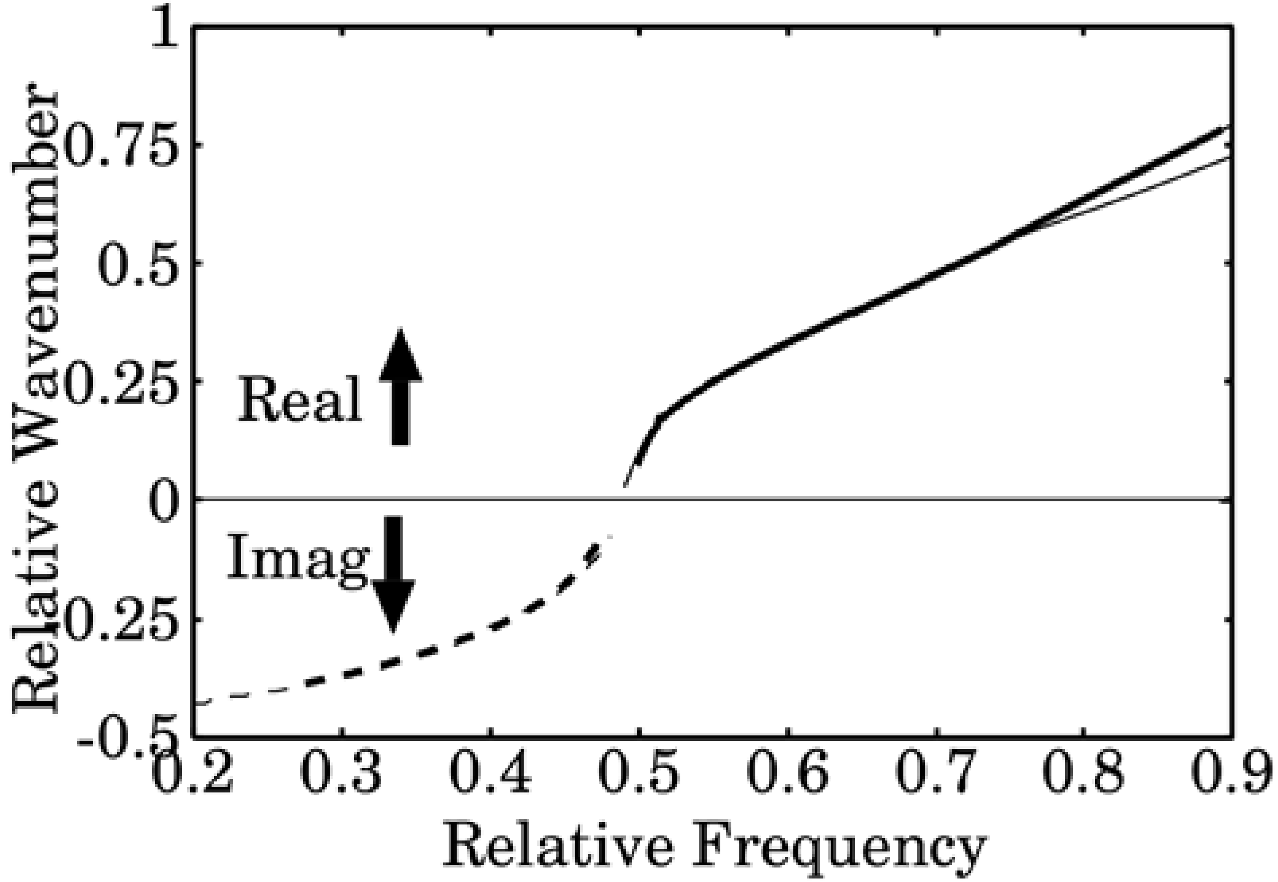
$$\mathbf{u}(x,\delta)=\mathbf{u}(x,0)\exp(-2j\beta_y\delta)$$

$$\mathbf{u}(2p,y)=\mathbf{u}(0,y)\exp(-2j\beta_x p)$$

Method : Calculation of f for Given β_y at $\beta_x p=\pi$ *(Only Possible by **COMSOL**)*

Dispersion Relation of β_y with *f* Obtained by Thin Plate Model (*r* Reflectivity)

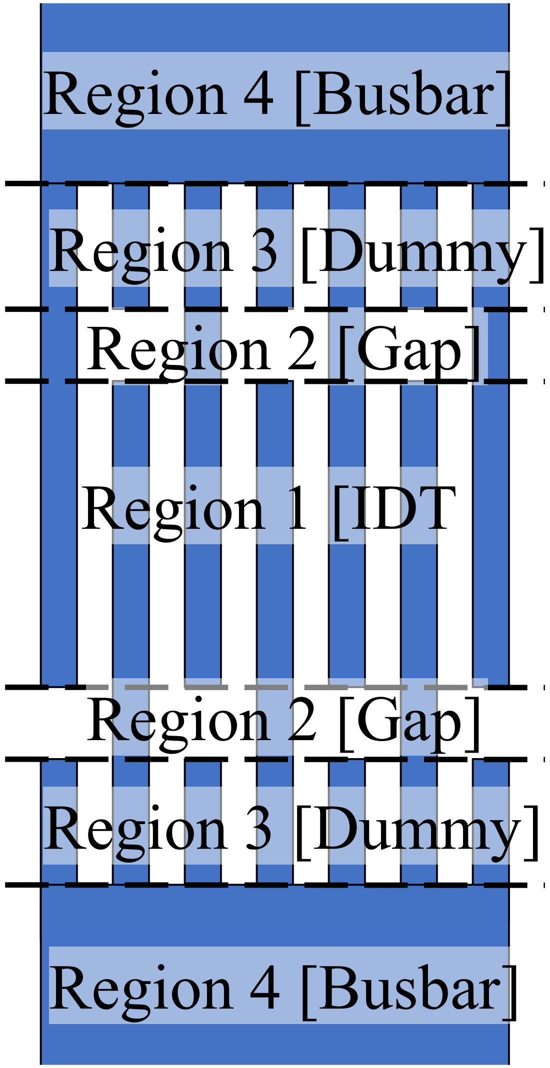
$$B_v^2 = \gamma^{-1}\left[F^2(1 \pm r) - 0.25\right]$$



Calculated by Full Wave Analysis (Bold) and Fitted (Thin)

G.B.Tang, T.Han, J.Chen, B.F.Zhang, T.Omori, and K.Hashimoto, "Model Parameter Extraction for Obliquely Propagating Surface Acoustic Waves in Infinitely Long Grating Structures," Jpn. J. Appl. Phys., **55**, 7 (2016) 07KD08

How to Solve Partial Differential Equation?



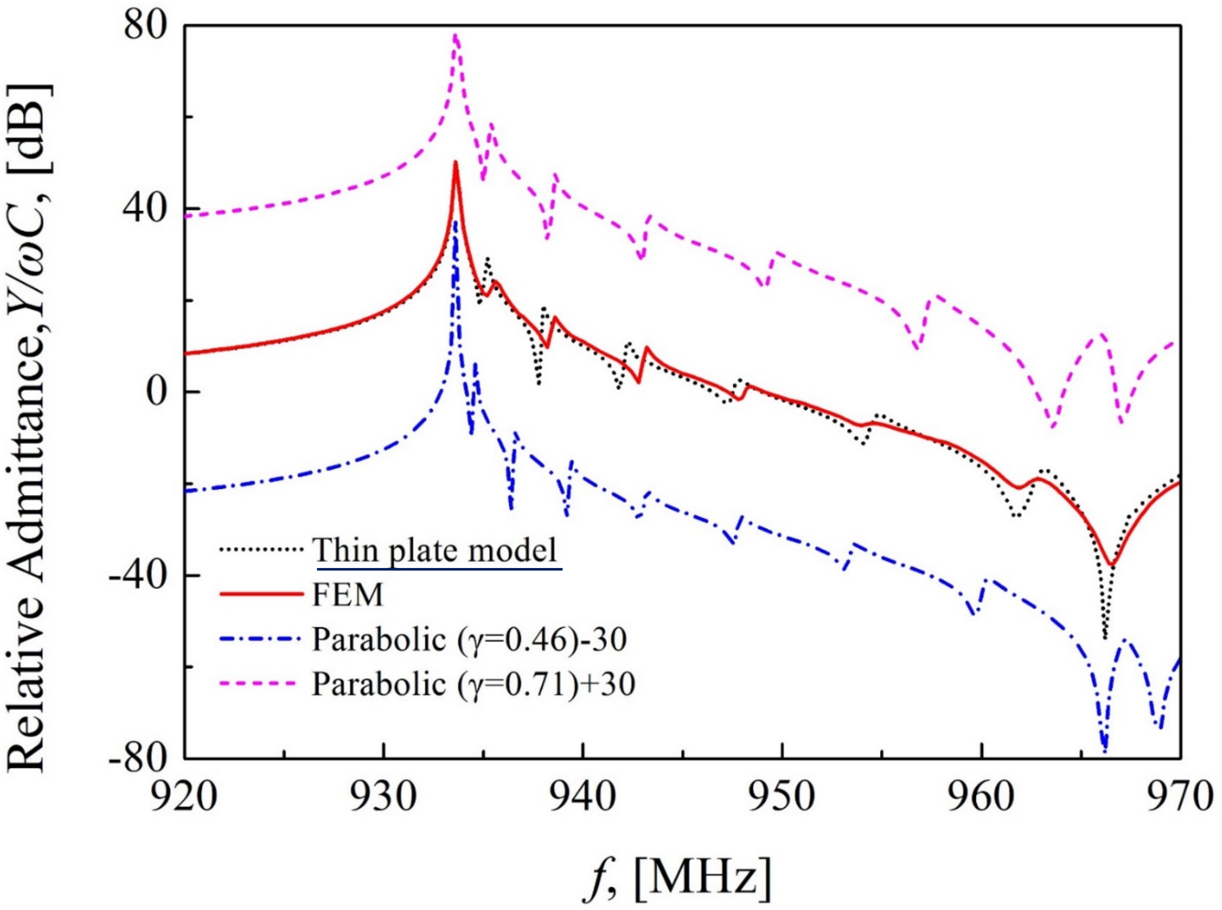
7 Layer Model

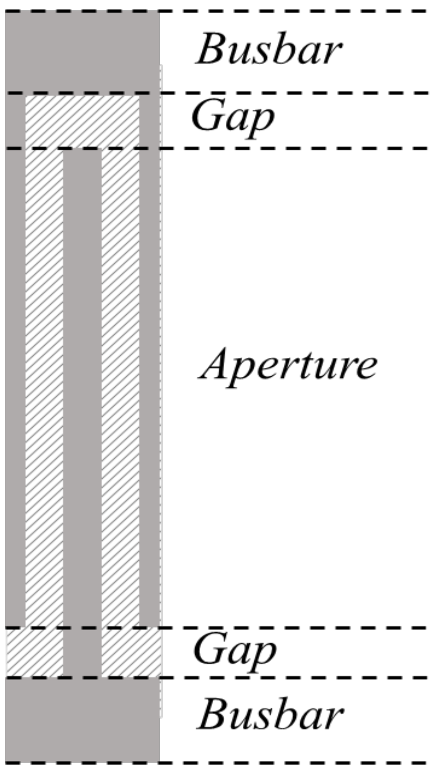
$$-\beta_n^2 \phi = \frac{\partial \phi}{\partial x^2} + \gamma_n \frac{\partial \phi}{\partial y^2}$$

Not Easy to Solve it for Complicated Structures

Use of COMSOL PDE (Partial Differential Equation) Mode

PDE Analysis Example (Al/128-LN)



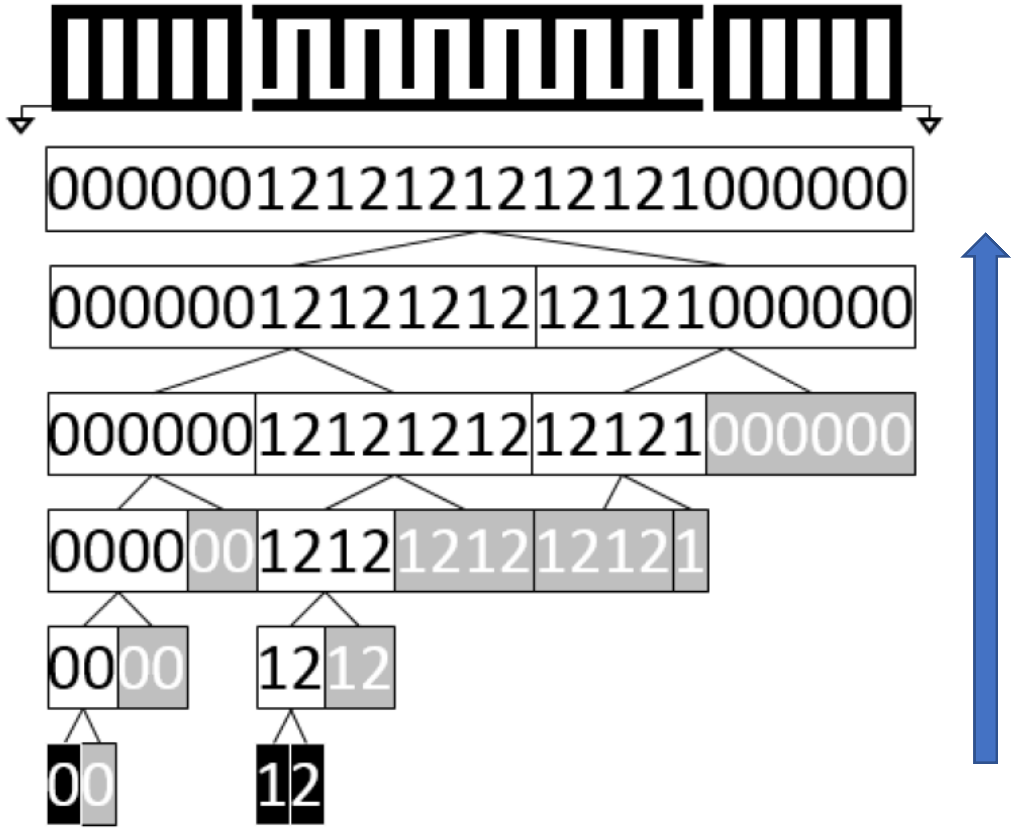


Good Agreement with Periodic 3D-FEM

B.F.Zhang, T.Han, G.B.Tang, Q.Z.Zhang, T.Omori, and K.Hashimoto, "Influence of Coupling with Shear Horizontal Surface Acoustic Wave on Lateral Propagation of Rayleigh Surface Acoustic Wave on 128^{o}YX-$LiNbO_3$," Jpn. J. Appl. Phys., **56**, 7 (2017) 07JD02-1~4

Contents

Hierarchical Cascading Technique (HCT)



Advantageous for FEM Analysis of Structures Including Periodic Ones

J.Koskela, V.Plessky, B.Willemsen, P.Turner, B.Hammond, and N.Fenzi, "Hierarchical cascading algorithm for 2D FEM simulation of finite SAW devices," IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., 2018, DOI:10.1109/TUFFC.2018.2852603.

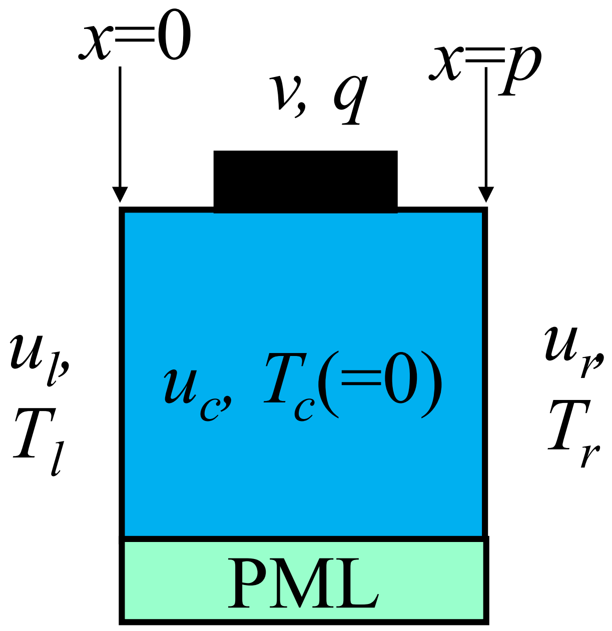
HCT Step 1

FEM Modeling of Unit Cell

$$\begin{pmatrix} A_{11} & A_{12} & 0 & A_{14} \\ A_{21} & A_{22} & A_{22} & A_{24} \\ 0 & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{34} & A_{44} \end{pmatrix} \begin{pmatrix} u_l \\ u_c \\ u_r \\ v \end{pmatrix} = \begin{pmatrix} T_l \\ 0 \\ T_r \\ q \end{pmatrix}$$

Removal of u_c

$$\begin{pmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{pmatrix} \begin{pmatrix} u_l \\ u_r \\ v \end{pmatrix} = \begin{pmatrix} T_l \\ T_r \\ q \end{pmatrix}$$



Unit Cell

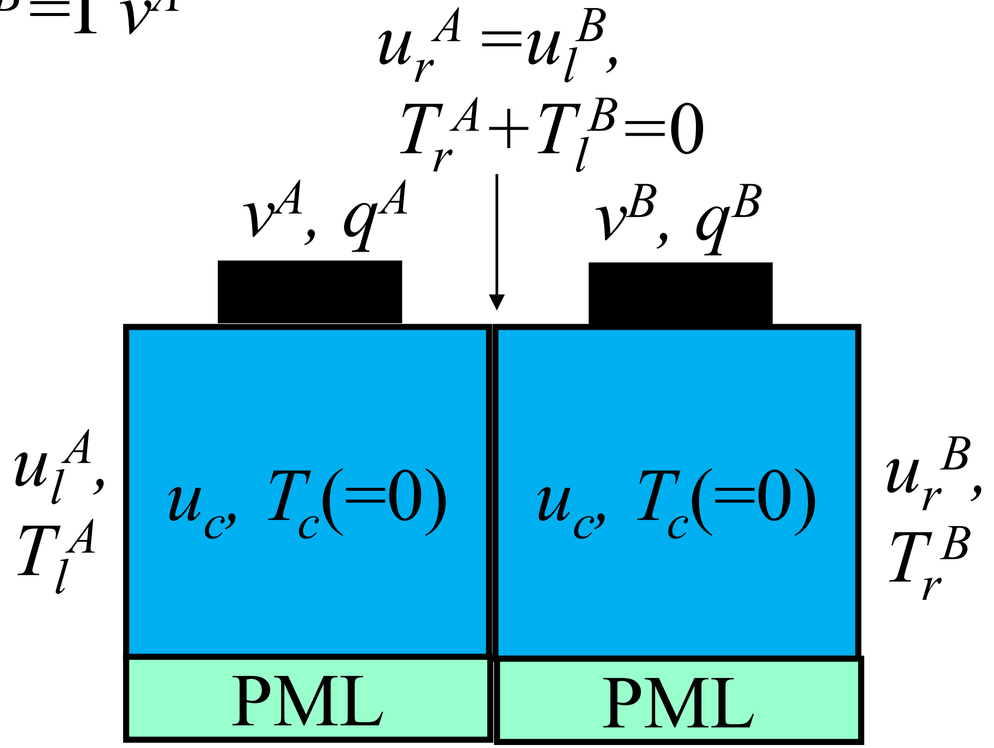
PML: Perfect Matching Layer

HCT Step 2

When $v^B = \Gamma v^A$

$$\begin{pmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{pmatrix} \begin{pmatrix} u_l^A \\ u_r^A \\ v^A \end{pmatrix} = \begin{pmatrix} T_l^A \\ T_r^A \\ q^A \end{pmatrix}$$

$$\begin{pmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{pmatrix} \begin{pmatrix} u_l^B \\ u_r^B \\ v^B \end{pmatrix} = \begin{pmatrix} T_l^B \\ T_r^B \\ q^B \end{pmatrix}$$



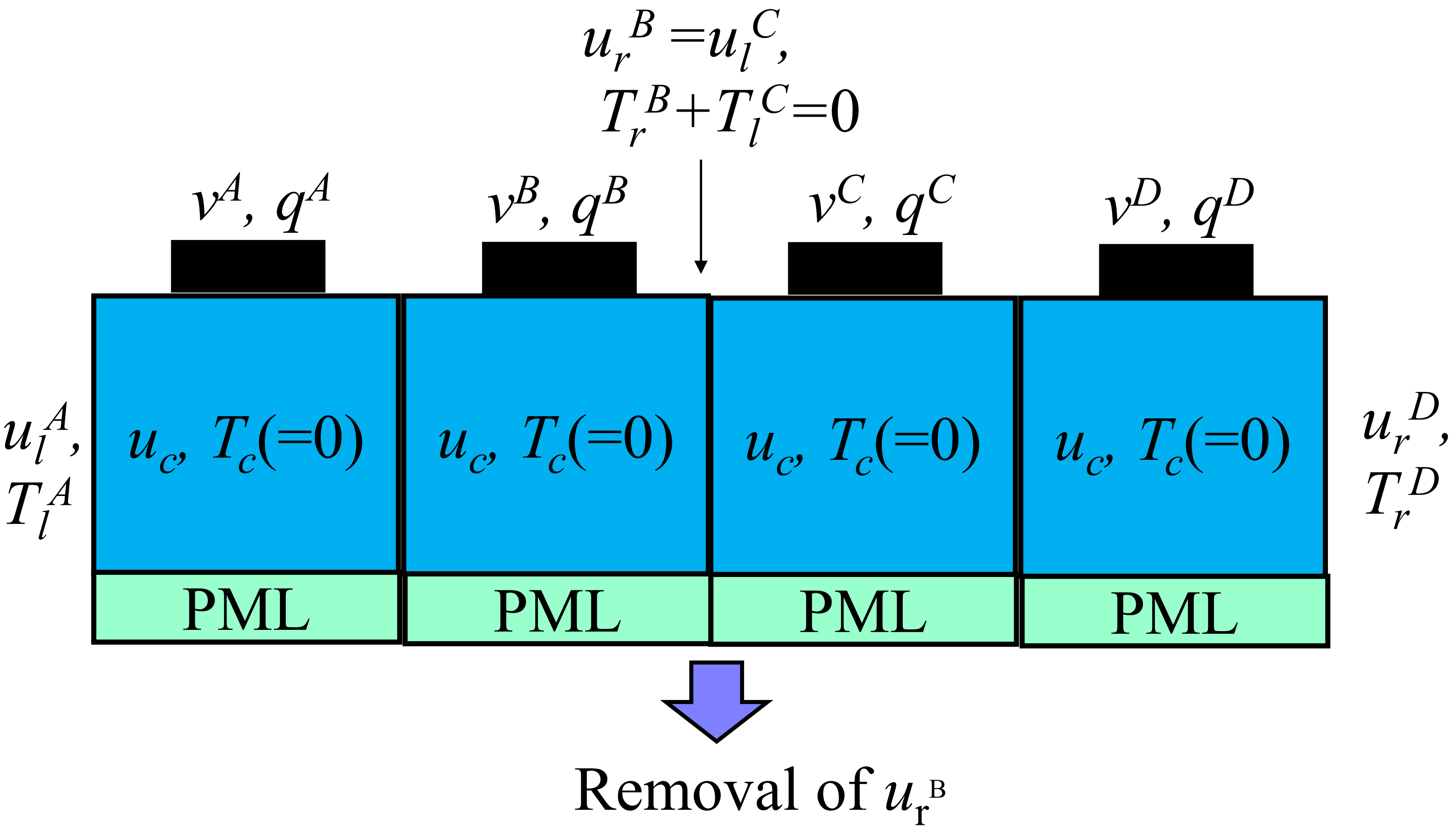
Cascading

$$\begin{pmatrix} B_{11} & B_{12} & 0 & B_{13} \\ B_{21} & B_{22}+B_{11} & B_{12} & B_{23}+\Gamma B_{13} \\ 0 & B_{21} & B_{22} & \Gamma B_{23} \\ B_{31} & B_{32}+\Gamma B_{31} & \Gamma B_{32} & (1+\Gamma^2)B_{33} \end{pmatrix} \begin{pmatrix} u_l^A \\ u_r^A \\ u_r^B \\ v \end{pmatrix} = \begin{pmatrix} T_l^A \\ 0 \\ T_r^B \\ q^A + \Gamma q^B \end{pmatrix}$$

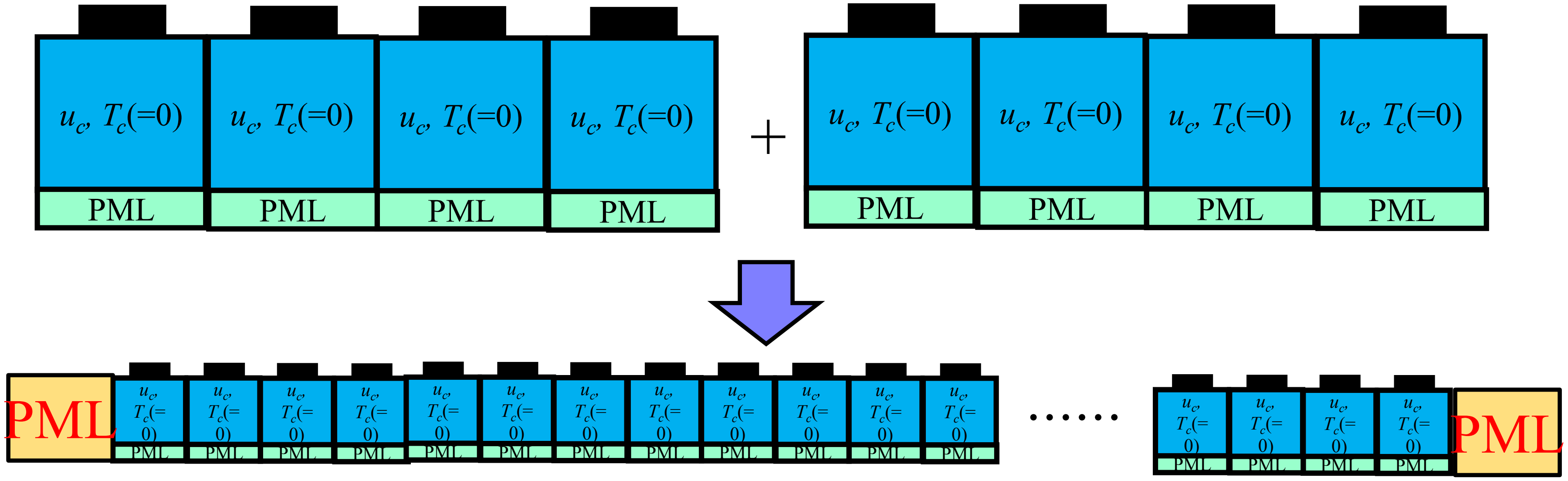
Removal of u_r^A

HCT Step 3

When $v^C = \Gamma^2 v^A$, $v^D = \Gamma^2 v^B$



HCT Step N



$$\begin{pmatrix} B_{11}^{T} & B_{12}^{T} & B_{13}^{T} \\ B_{21}^{T} & B_{22}^{T} & B_{23}^{T} \\ B_{31}^{T} & B_{32}^{T} & B_{33}^{T} \end{pmatrix} \begin{pmatrix} u_l^{\mathrm{T}} \\ u_r^{\mathrm{T}} \\ v^{A} \end{pmatrix} = \begin{pmatrix} T_l^{\mathrm{T}} \\ T_r^{\mathrm{T}} \\ q^{\mathrm{T}} \end{pmatrix}$$

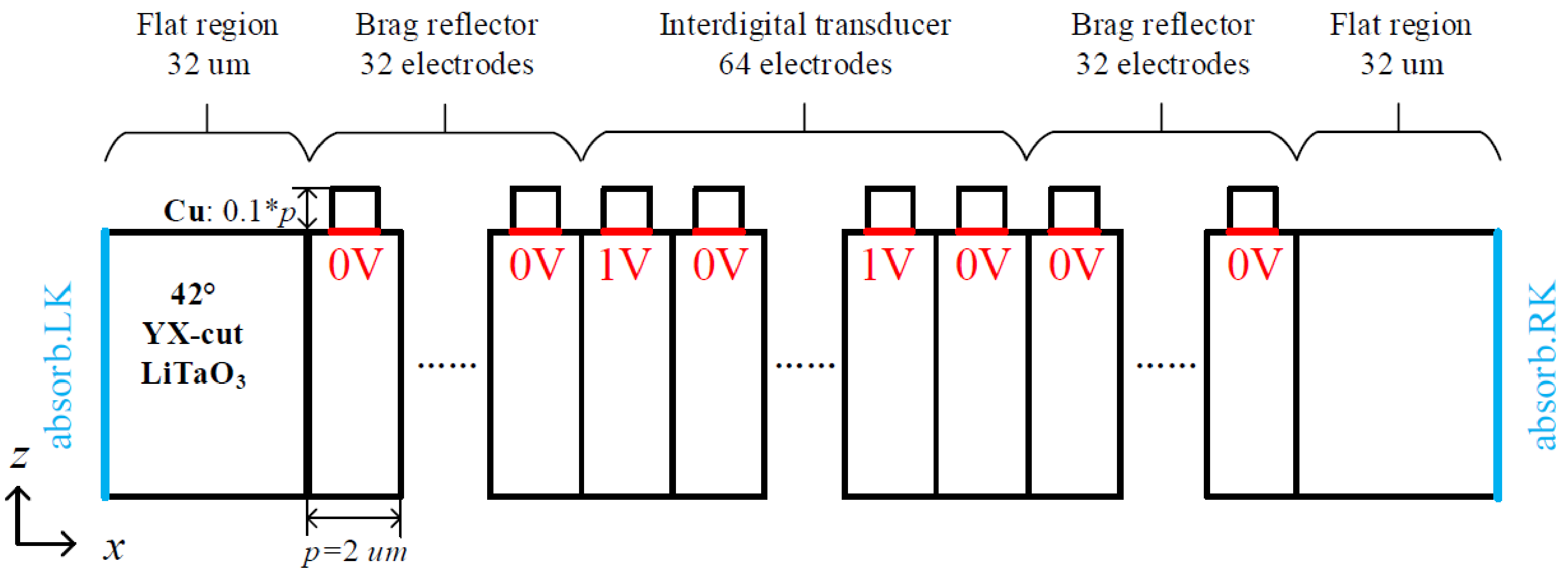
$$C_l^{\mathrm{PML}} u_l^{\mathrm{T}} = -T_l^{\mathrm{T}}$$

$$C_r^{\mathrm{PML}} u_r^{\mathrm{T}} = -T_r^{\mathrm{T}}$$

$$Y = \frac{q^{\mathrm{T}}}{v^{A}} = B_{33}^{T} - \begin{pmatrix} B_{31}^{T} & B_{32}^{T} \end{pmatrix} \begin{pmatrix} B_{11}^{T} + C_l^{\mathrm{PML}} & B_{12}^{T} \\ B_{21}^{T} & B_{21}^{T} + C_r^{\mathrm{PML}} \end{pmatrix}^{-1} \begin{pmatrix} B_{13}^{T} \\ B_{23}^{T} \end{pmatrix}$$

Set up Example for SAW Resonator on 42-LT

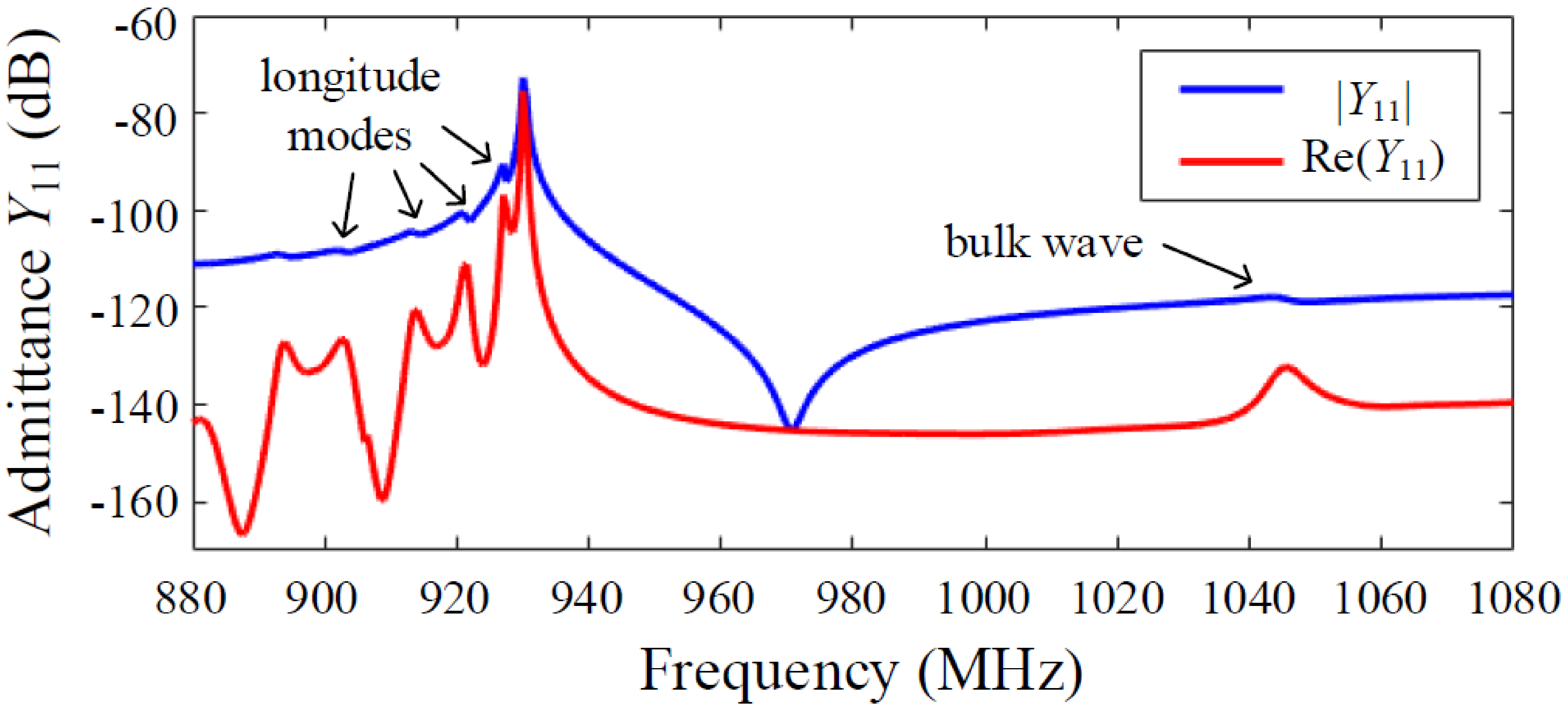
DOFs > 2,000,000



COMSOL 2.5 D Analysis + Matlab (Through Livelink)

X.Li, PhD Dissertation, Chiba University (2019)

Simulation Example



X.Li, PhD Dissertation, Chiba University (2019)

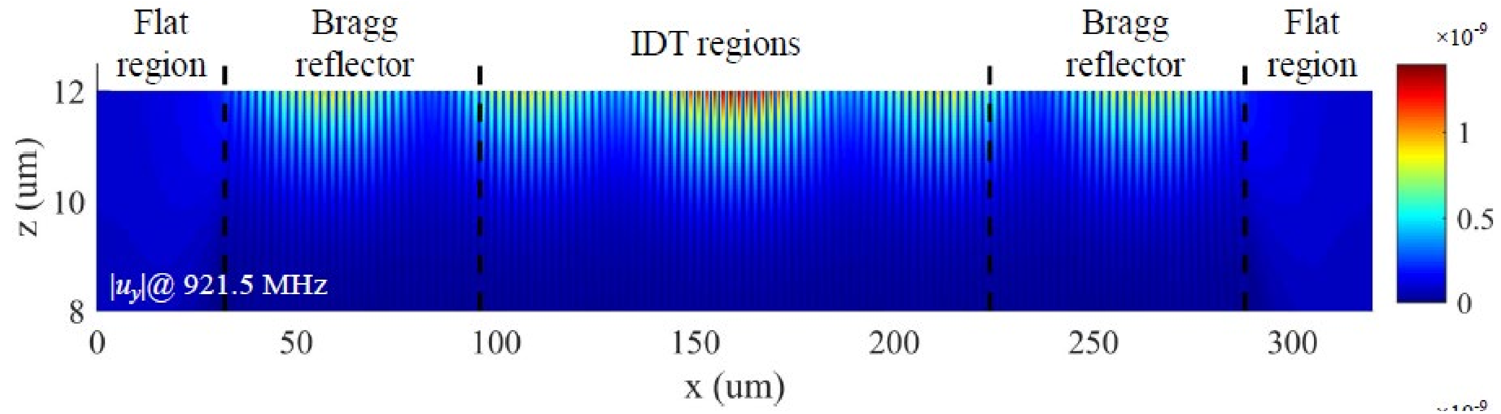
Execution Time with CPU (i7-5820K, 3.3 GHz)

Memory Size < 8 GB

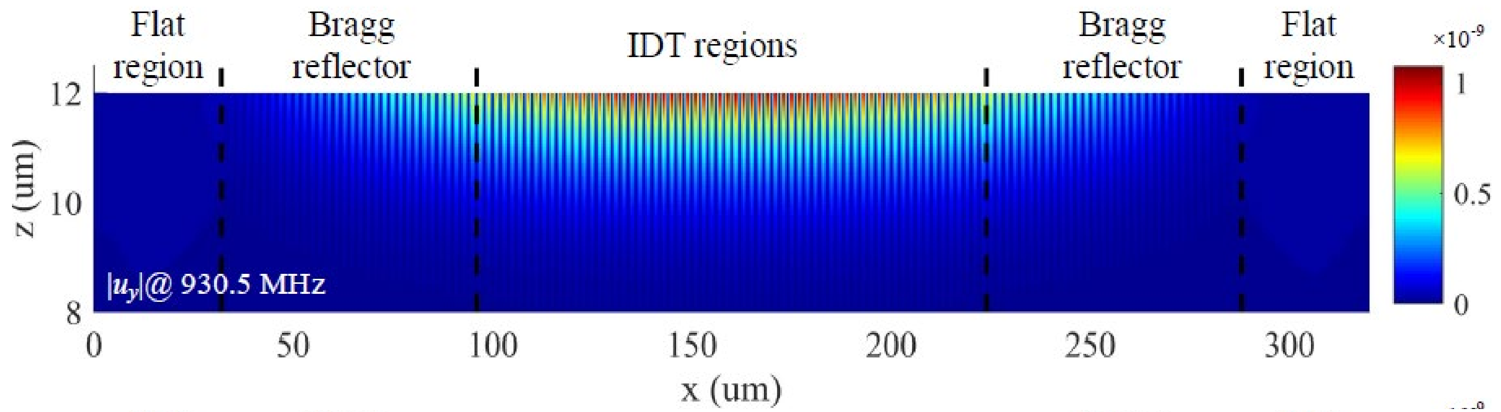
step	time (sec.)
Obtain absorbing lines	12.5
A matrices to B matrices	1.6
Cascade B matrices	3.0
Solve out all the DOFs	2.8
Total time	19.9

X.Li, PhD Dissertation, Chiba University (2019)

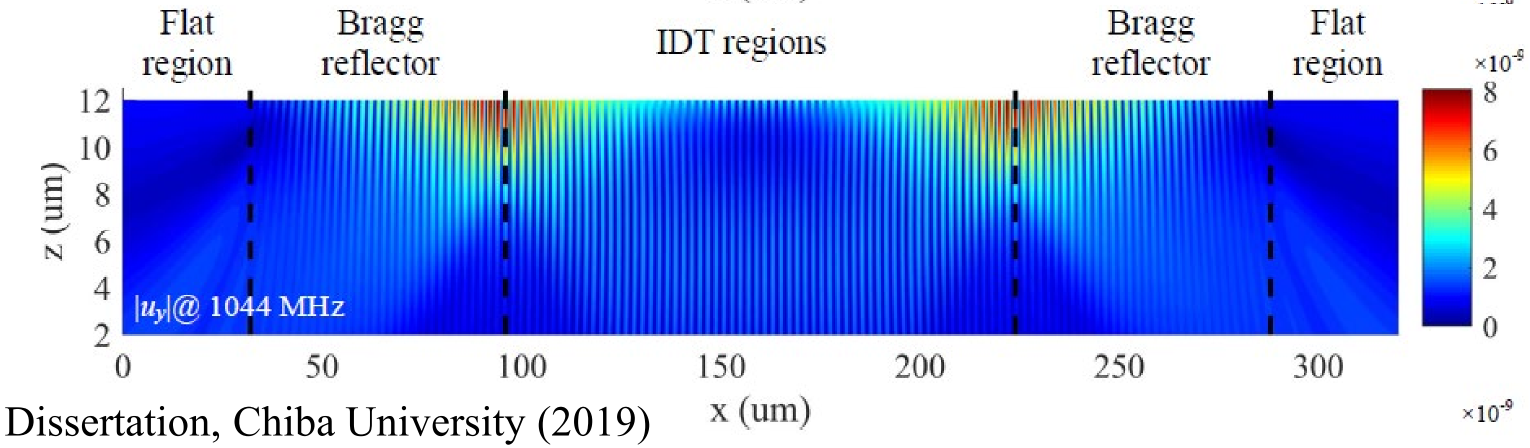
Calculate Field Distribution



At 921.5 MHz



At 930.5 MHz



At 1044 MHz

X.Li, PhD Dissertation, Chiba University (2019)

Contents

- What are Radio Frequency (RF) Surface and Bulk Acoustic Wave (SAW/BAW) Devices?
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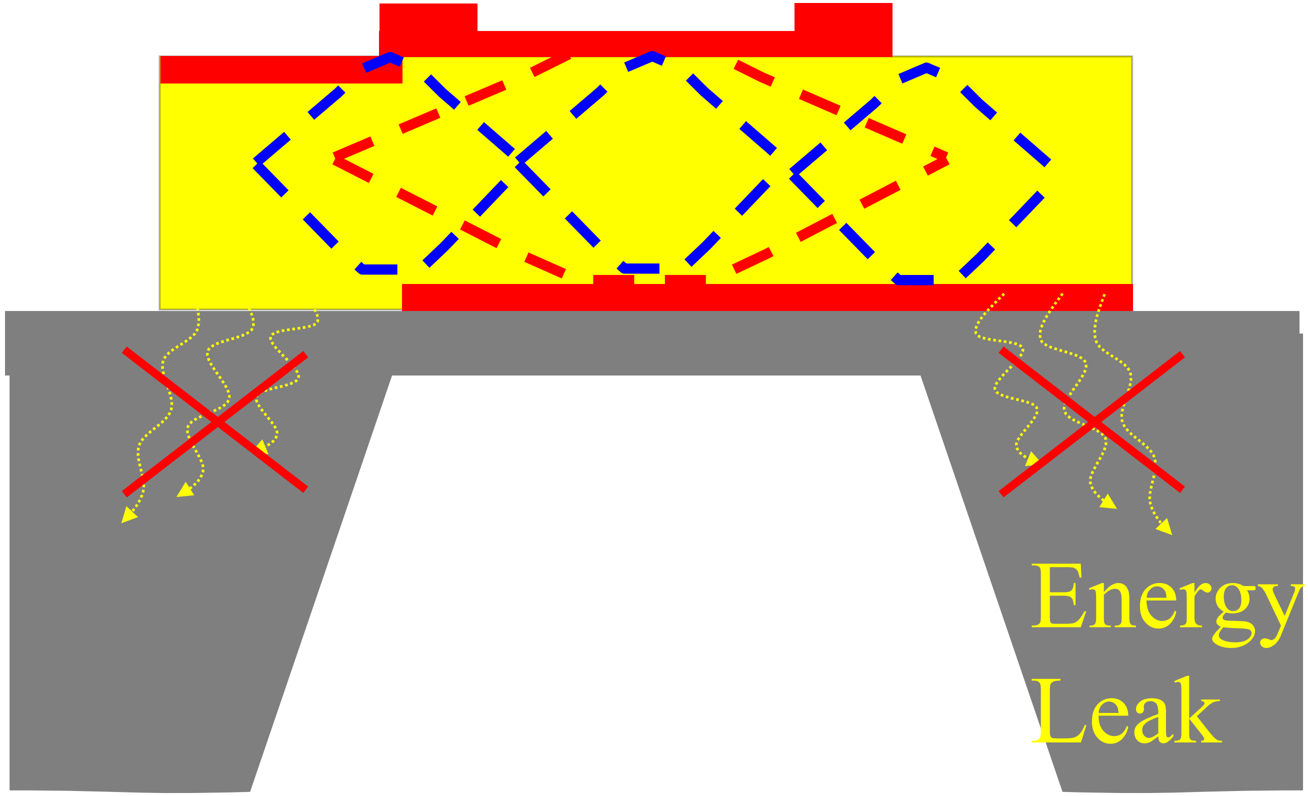
Lateral Effects in RF BAW Resonator

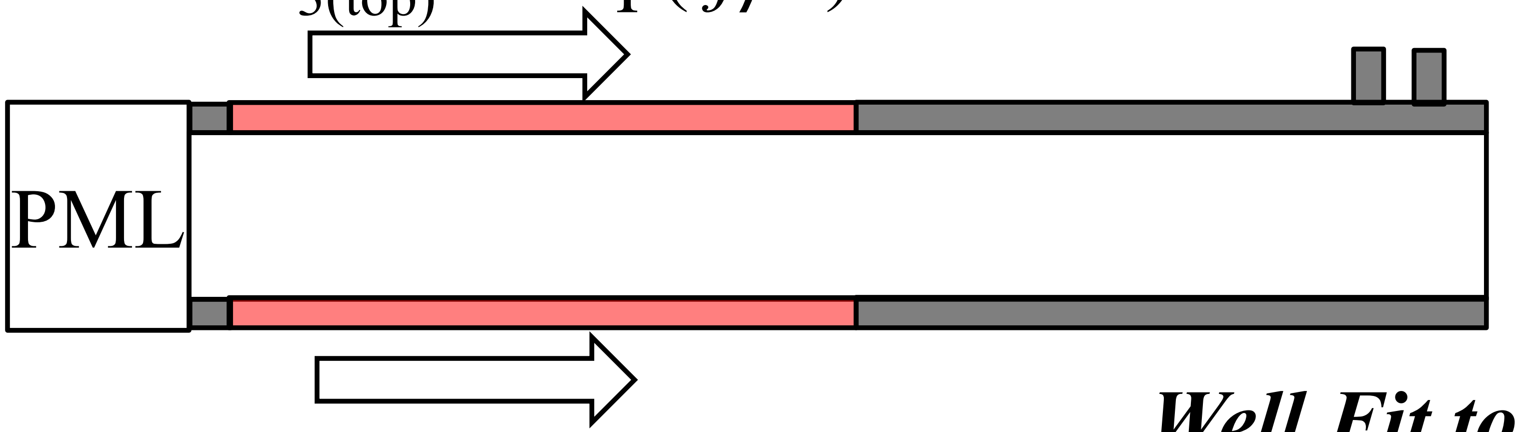


Design Challenge: Suppression of Inharmonic Resonances Without Badly Affecting Main Resonance

Traveling Wave Source for Analysis of Plate Wave Scattering

Selective Excitation of a Particular Eigen Mode (Plate Wave) with Wavenumber β for Given ω

$T_{3(\mathrm{top})} = A\exp(-j\beta x)$

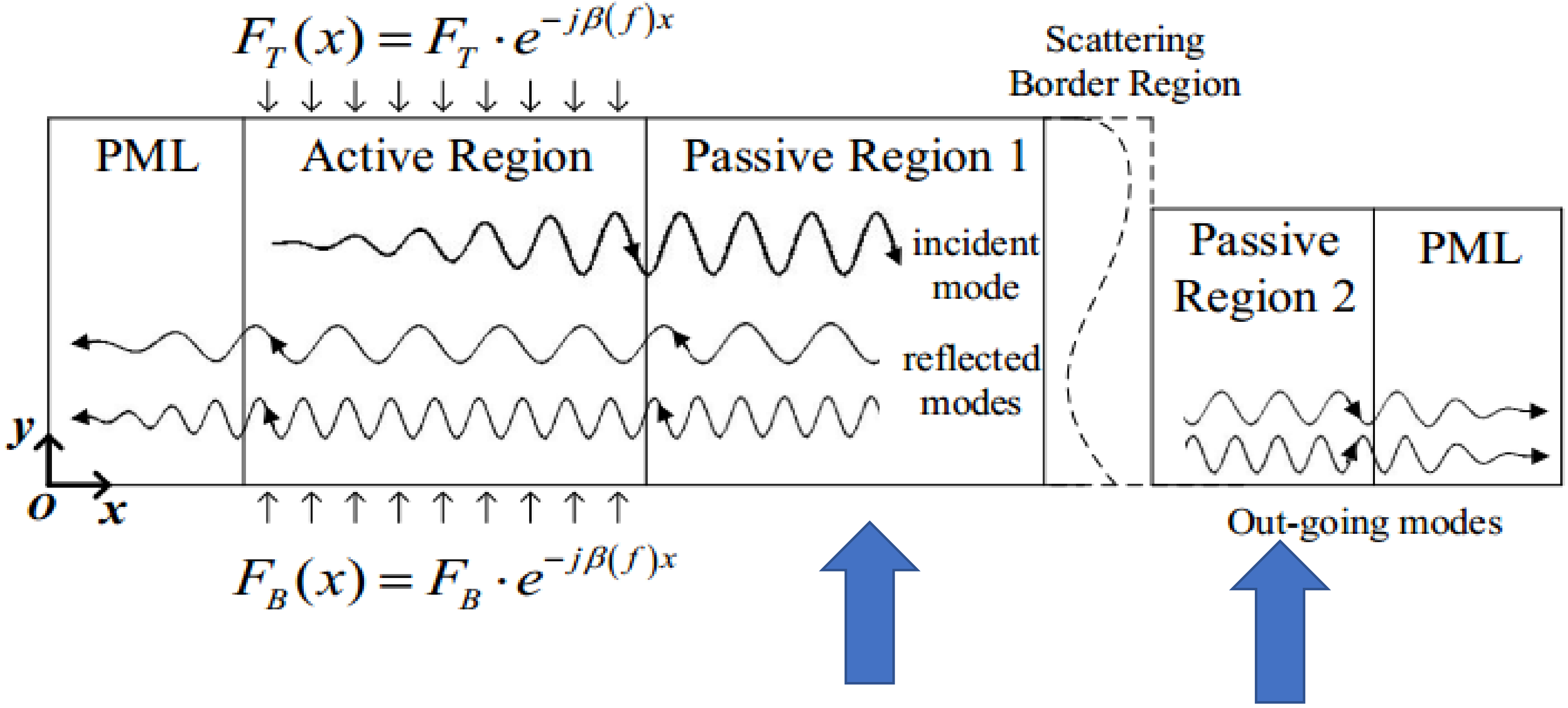


$T_{3(\mathrm{bottom})} = \pm A\exp(-j\beta x)$

Well Fit to Hierarchical Cascading Technique

X.Li, J.Bao, Y.Huang, B.Zhang, T.Omori and K.Hashimoto, "Traveling Wave Excitation Sources for FEM Analysis of Scattering in Acoustic Waveguide," Microsystem Technologies, **25**, 7 (2019) pp. 2783-2792

Analysis Model



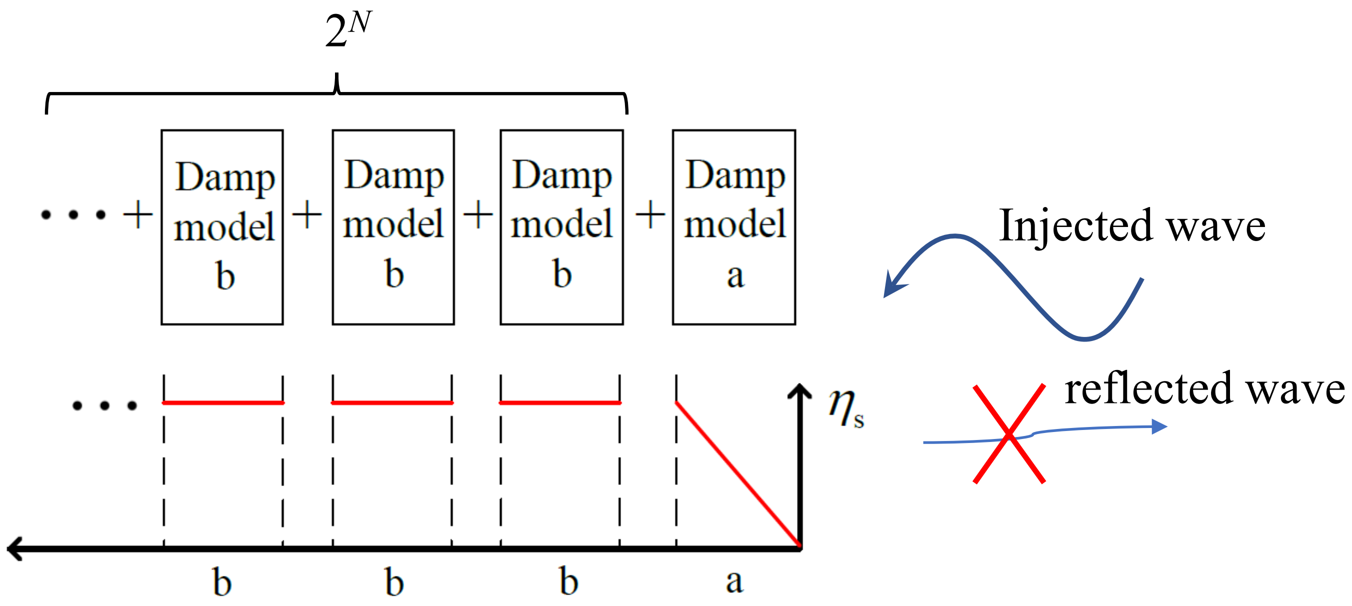
Application of Fourier Transform for Evaluation of Scattering Coefficients

X.Li, J.Bao, Y.Huang, B.Zhang, T.Omori and K.Hashimoto, "Traveling Wave Excitation Sources for FEM Analysis of Scattering in Acoustic Waveguide," Microsystem Technologies, **25**, 7 (2019) pp. 2783-2792

Comment on Perfect Matching Layer (PML)

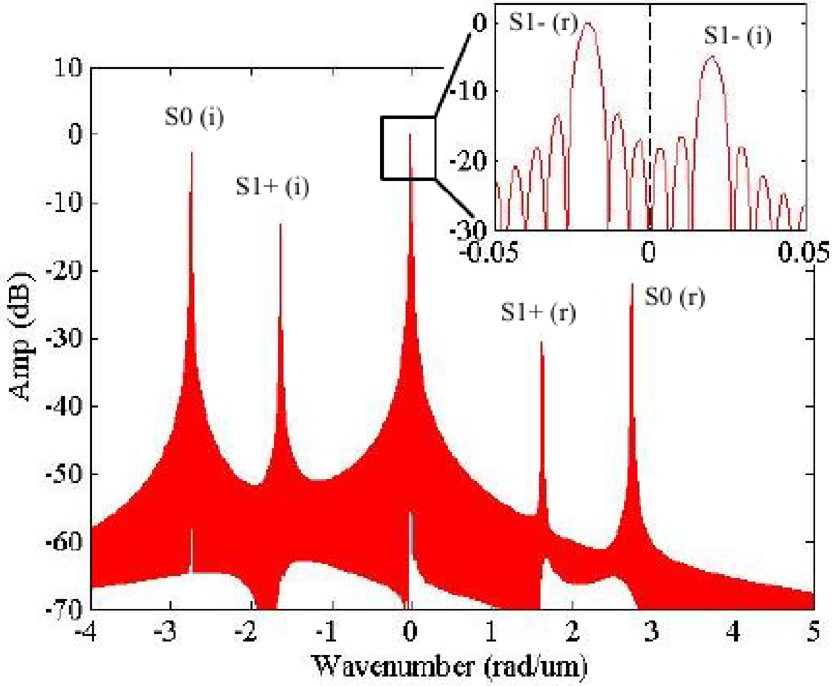
- PML Does not Work Properly for Backward Waves Where the Phase Velocity is Opposite to the Group Velocity.

HCT-Based Damping Mechanism

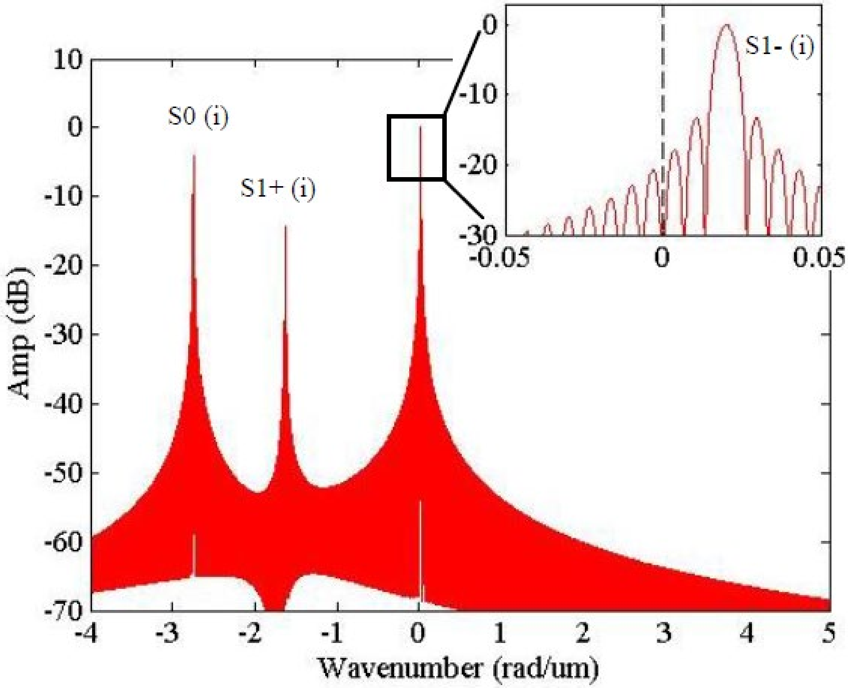


X.Li, J.Bao, Y.Huang, B.Zhang, T.Omori and K.Hashimoto, "Traveling Wave Excitation Sources for FEM Analysis of Scattering in Acoustic Waveguide," Microsystem Technologies, **25**, 7 (2019) pp. 2783-2792

Impact of HCT-Based Damping Mechanism



(a) Normal PML

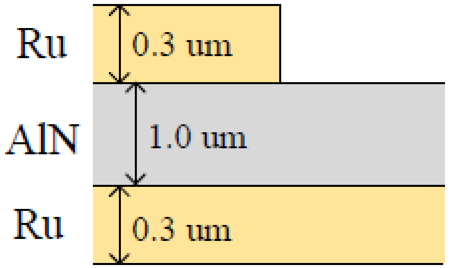


(b) Proposed Damping Mechanism

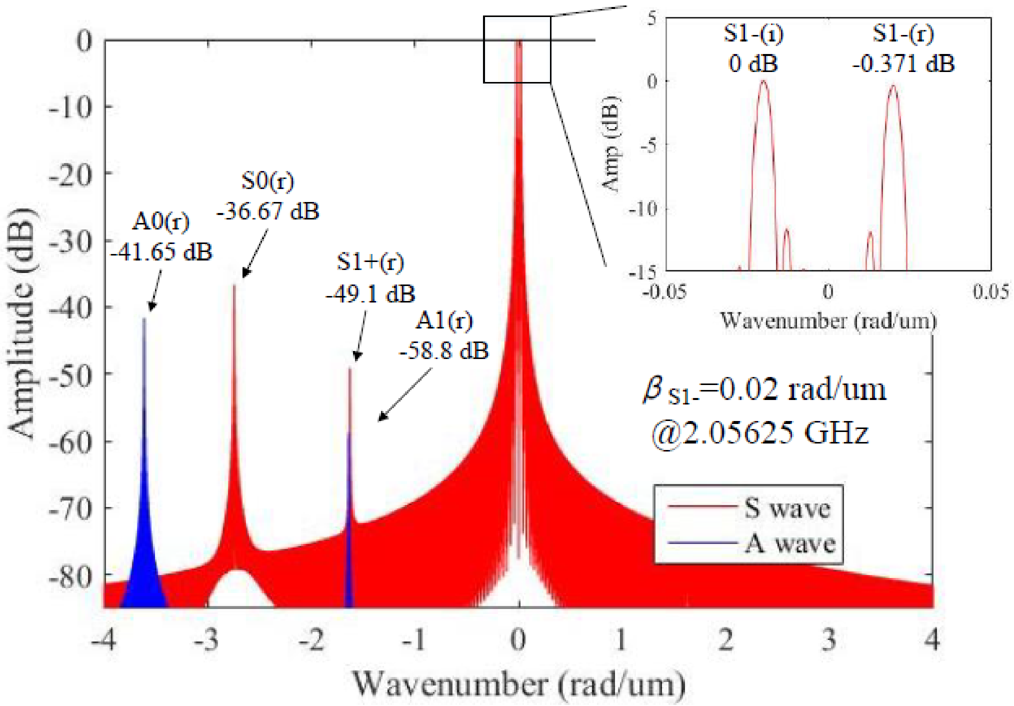
Complete Suppression of Non-Physical Reflection

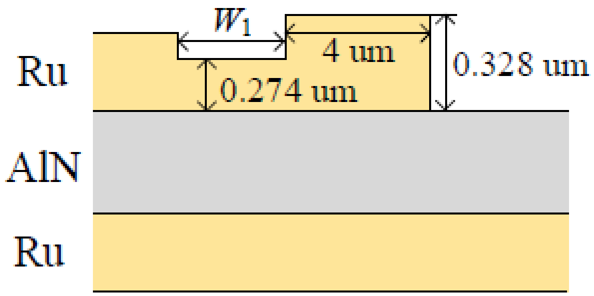
X.Li, J.Bao, Y.Huang, B.Zhang, T.Omori and K.Hashimoto, "Traveling Wave Excitation Sources for FEM Analysis of Scattering in Acoustic Waveguide," Microsystem Technologies, **25**, 7 (2019) pp. 2783-2792

Calculated Scattered Wave Spectra

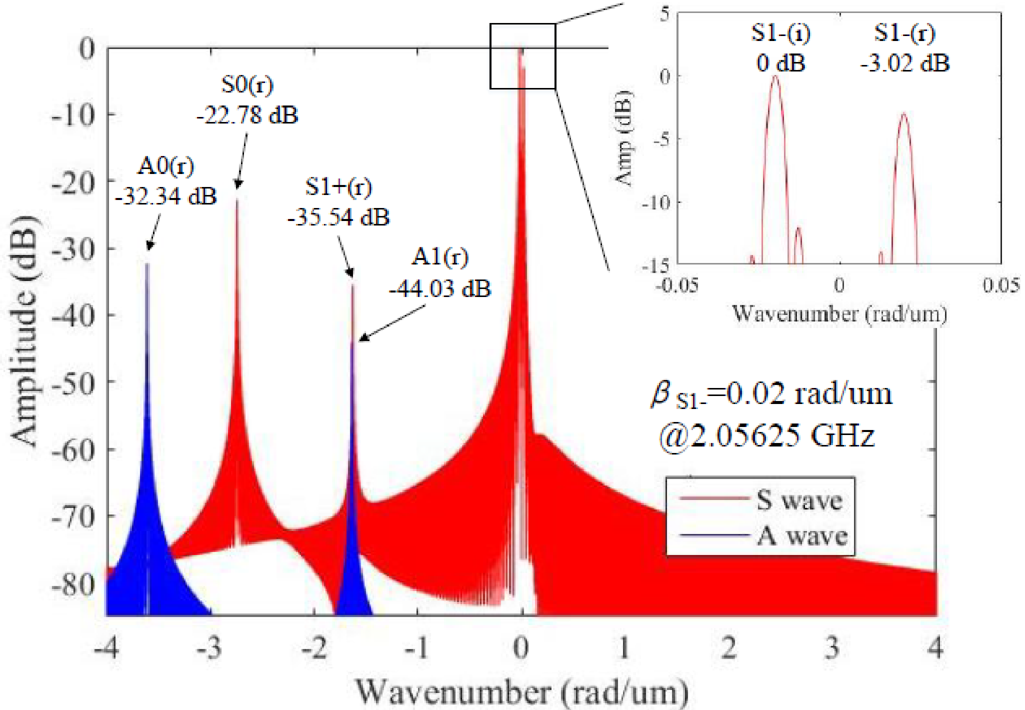


(a) normal border

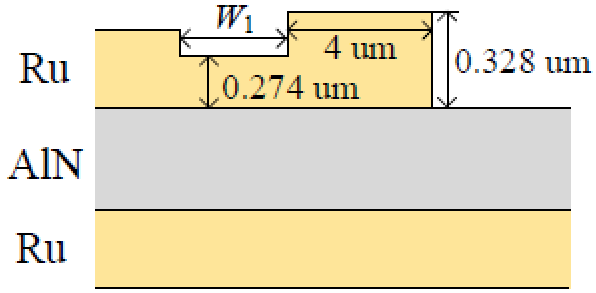




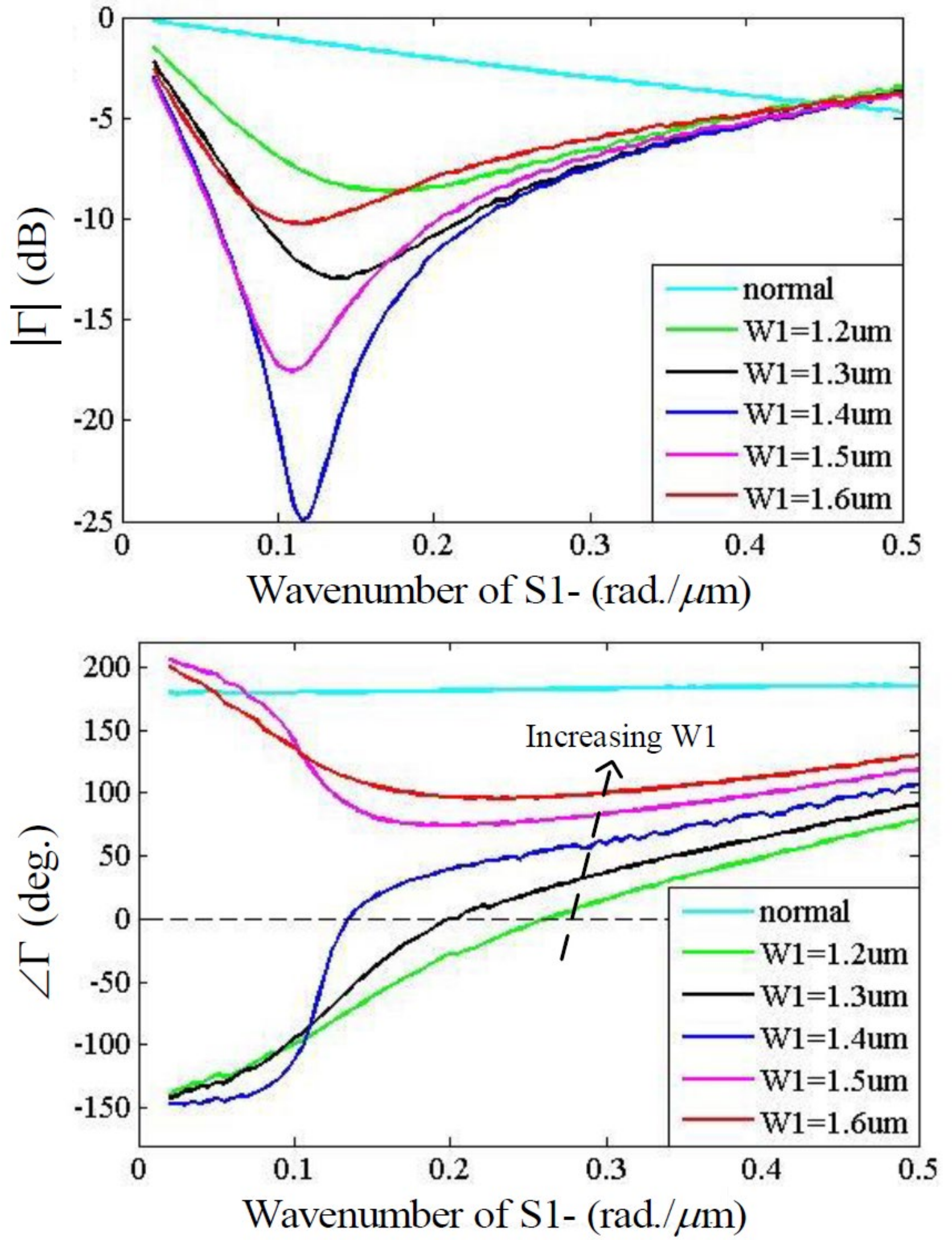
(b) piston mode border



Variation of Γ with W_1



(b) piston mode border



X.Li, J.Bao, Y.Huang, B.Zhang, T.Omori and K.Hashimoto, "Traveling Wave Excitation Sources for FEM Analysis of Scattering in Acoustic Waveguide," Microsystem Technologies, **25**, 7 (2019) pp. 2783-2792

Execution Time

Method 1: Hierarchical Cascading
Method 2: Conventional FEM
CPU i7-5820K, 3.3 GHz, 128 GB RAM

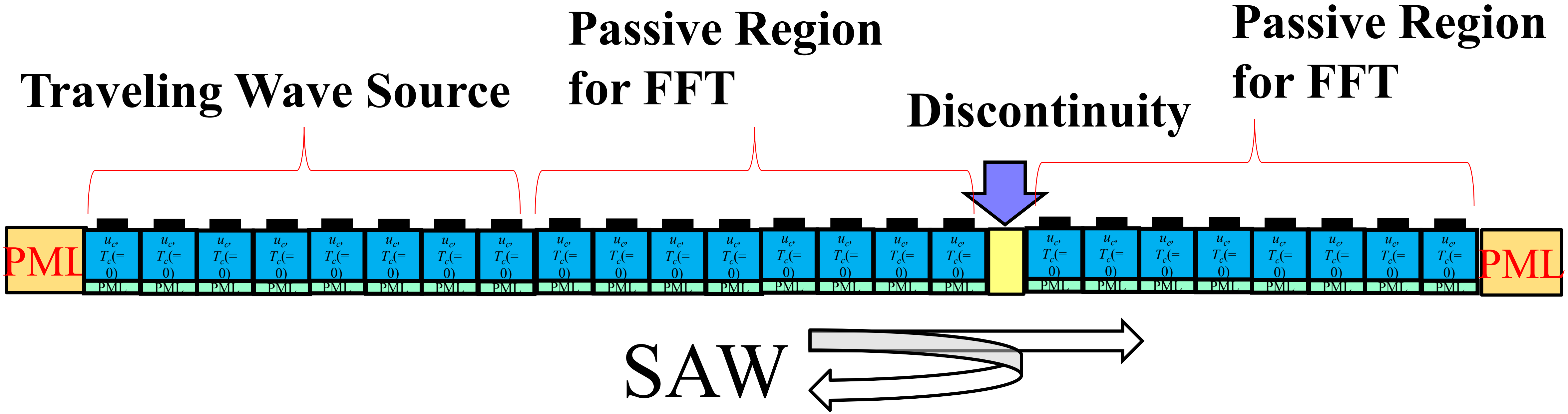
	total	Computing main-body	Damping matrix	Parametric sweep
Method 1	8.7s	0.5s	8.2s	1s for each case
Method 2	42s			42s for each case

For 1 frequency point

Acceleration by Parameter Sweep!

X.Li, J.Bao, Y.Huang, B.Zhang, T.Omori and K.Hashimoto, "Traveling Wave Excitation Sources for FEM Analysis of Scattering in Acoustic Waveguide," Microsystem Technologies, **25**, 7 (2019) pp. 2783-2792

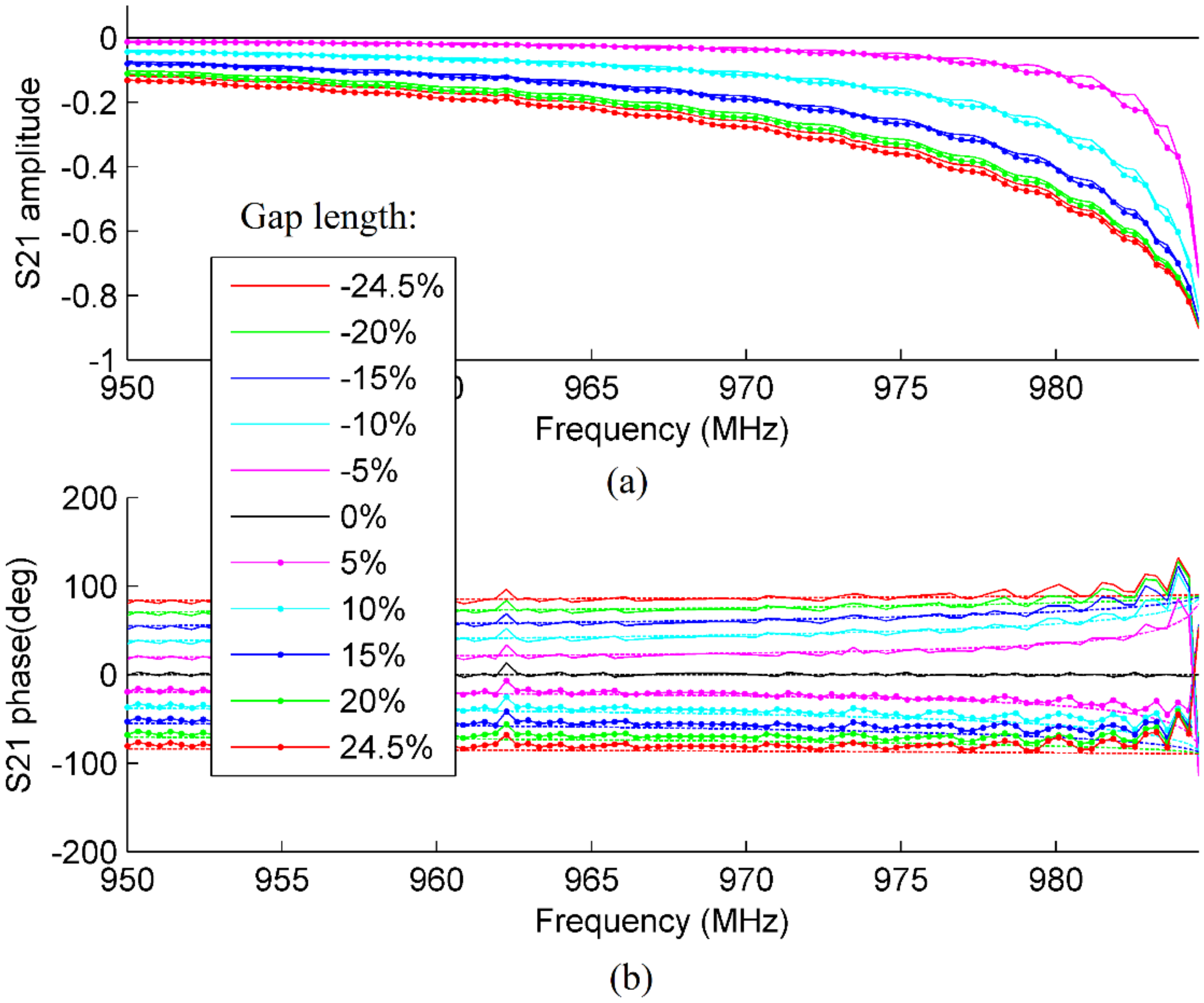
SAW Scattering at Grating Discontinuity



- PML Does not Work Properly for Inhomogeneous Cases such as Semi-infinite Grating. → HCT-Based Damping Mechanism

Y.Huang, J.Bao, X.Li, B.F.Zhang, L.Qiu, T.Omori, and K.Hashimoto, "Analysis of SAW Scattering with Discontinuous Periodic Gratings Using Travelling Wave Excitation and Hierarchical Cascading Technique," IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., **66**, 7 (2019) pp. 1255-1263

Scattering Coefficient at Discontinuity in SAW Grating on 128-LN



New Technique for Theoreticians!

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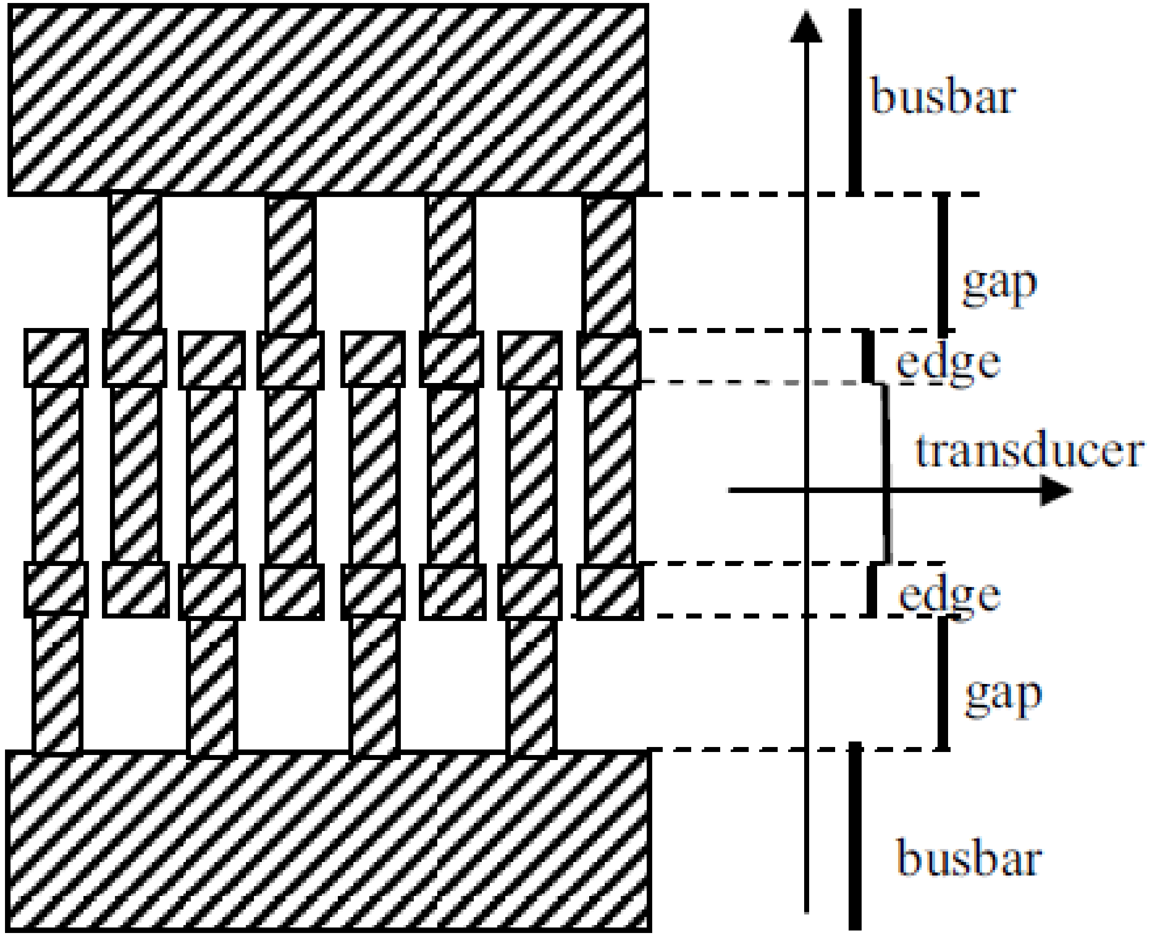
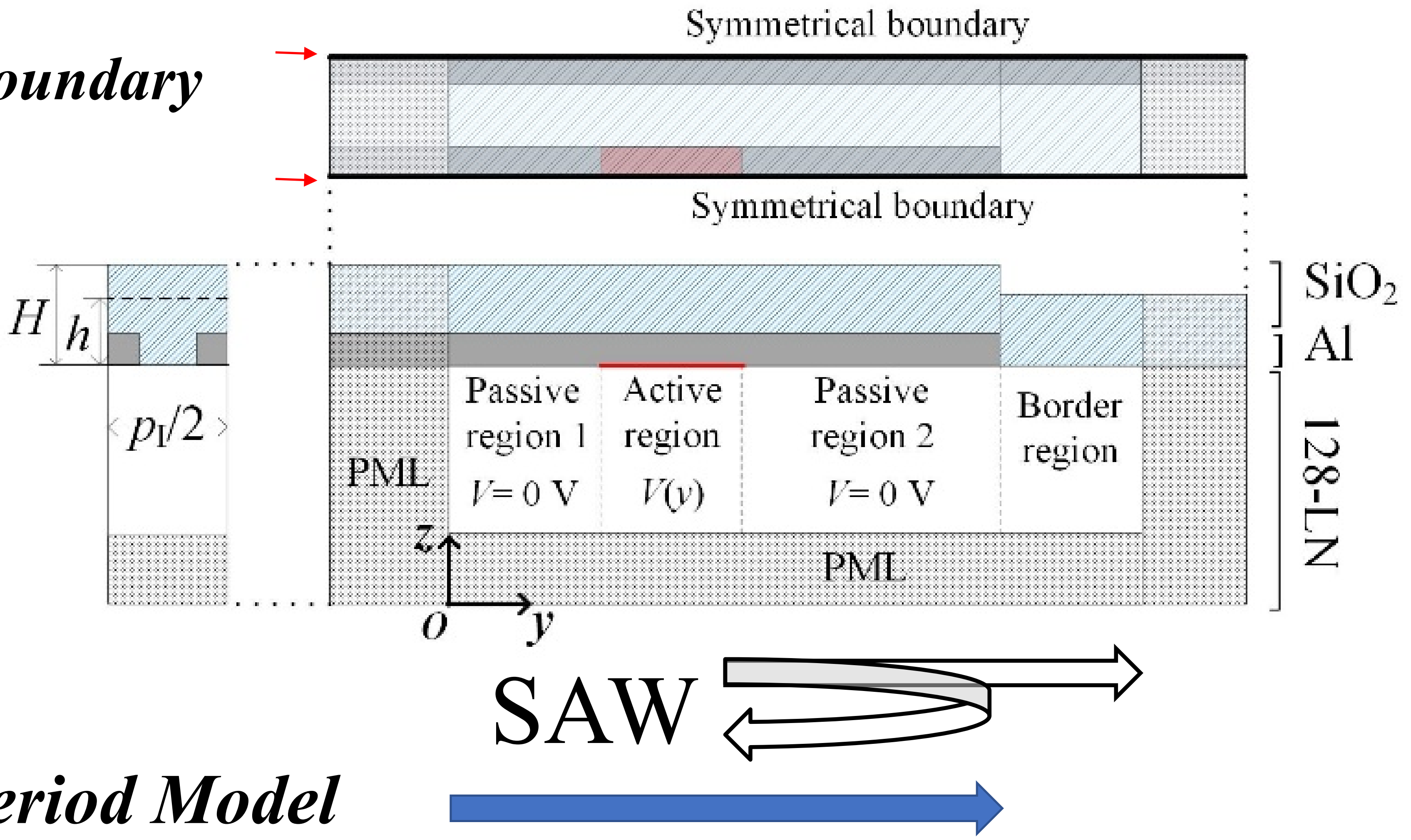
Piston Mode SAW Resonator



M.Solal , J.Gratier, R.Aigner, K.Gamble, B.Abbott, T.Kook, A.Chen, and K.Steiner, “Transverse modes suppression and loss reduction for buried electrodes SAW devices,” Proc. IEEE Ultrason. Symp. (2010) pp. 624-628

SAW Scattering at IDT Side Edges

Periodic Boundary Condition

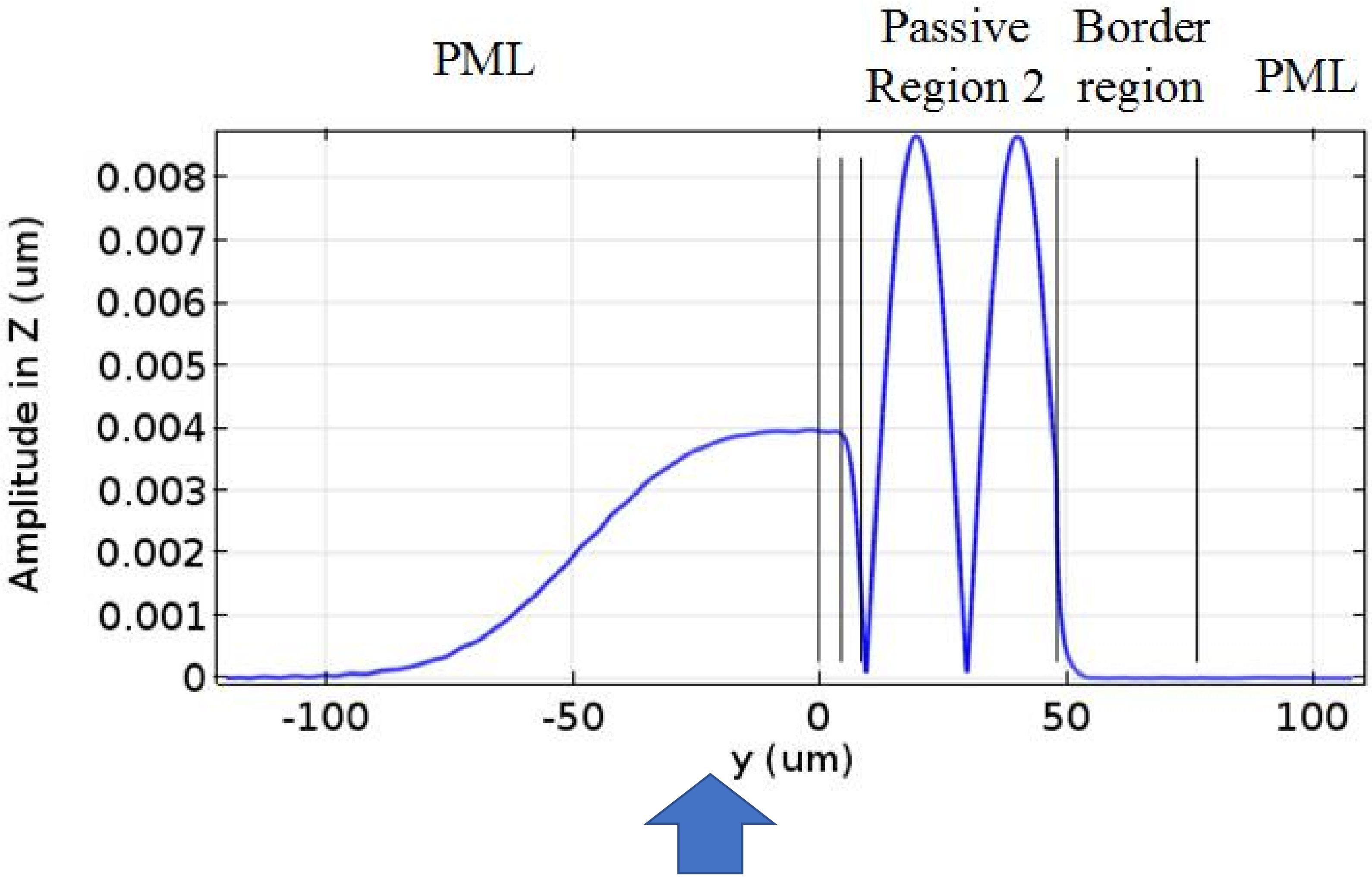


3D One Period Model

HCT Application

X.Li, J.Bao, Y.Huang, B.F.Zhang, T.Omori, and K.Hashimoto, "Use of Hierarchical Cascading Technique for FEM Analysis of Transverse Mode Behaviors in Surface Acoustic Wave Devices," IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., **66**, 12 (2019) pp. 1920-1926

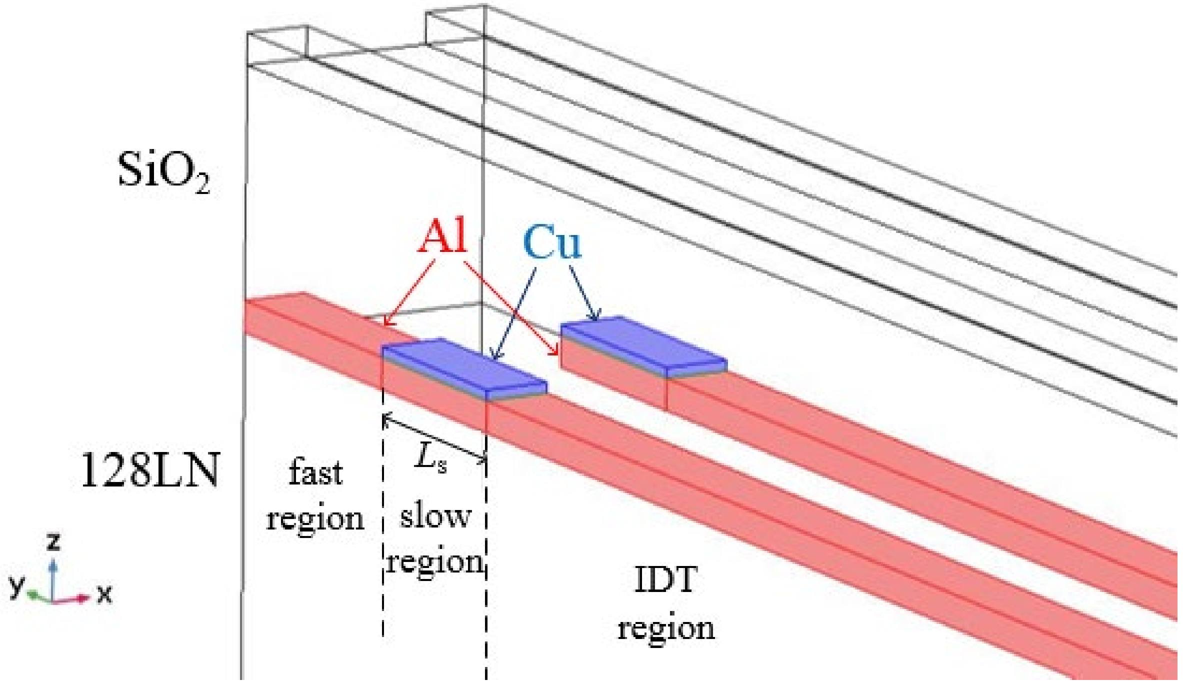
Calculated SAW Field

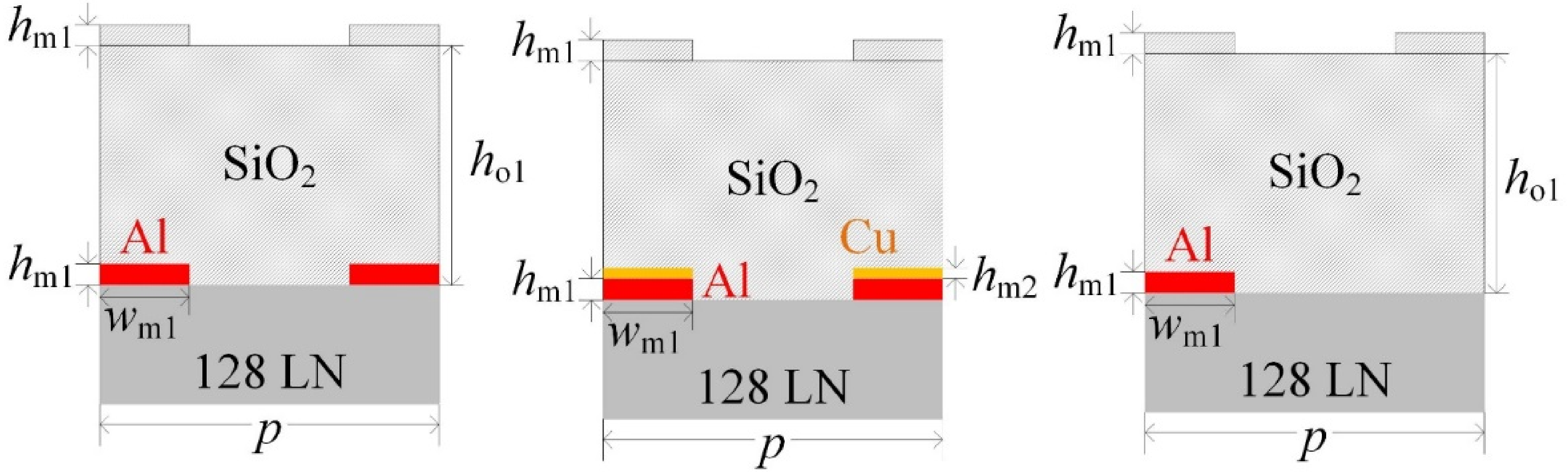


Traveling Wave Source

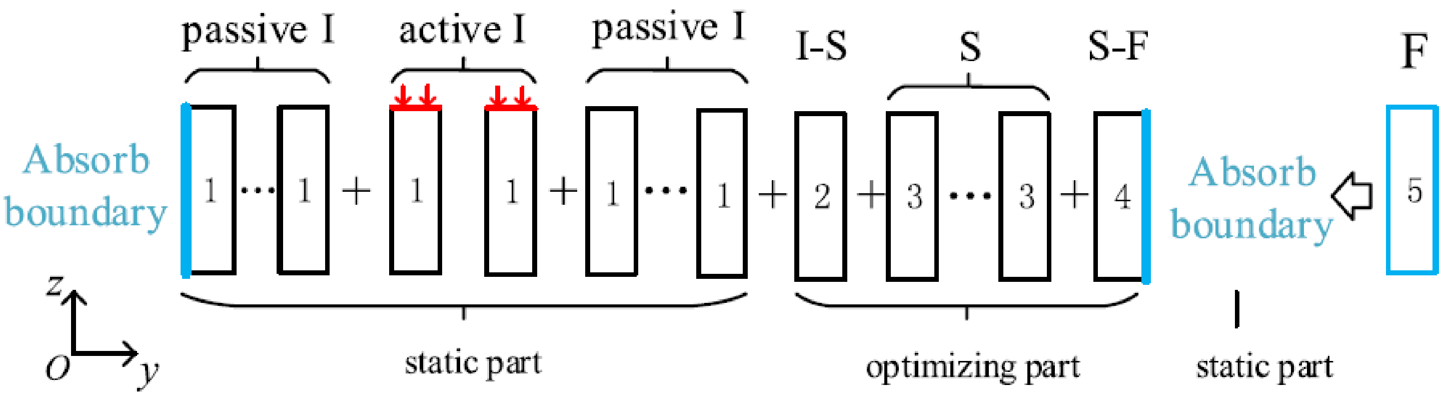
X.Li, J.Bao, Y.Huang, B.F.Zhang, T.Omori, and K.Hashimoto, “Use of Hierarchical Cascading Technique for FEM Analysis of Transverse Mode Behaviors in Surface Acoustic Wave Devices,” IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., **66**, 12 (2019) pp. 1920-1926

For 3D Analysis

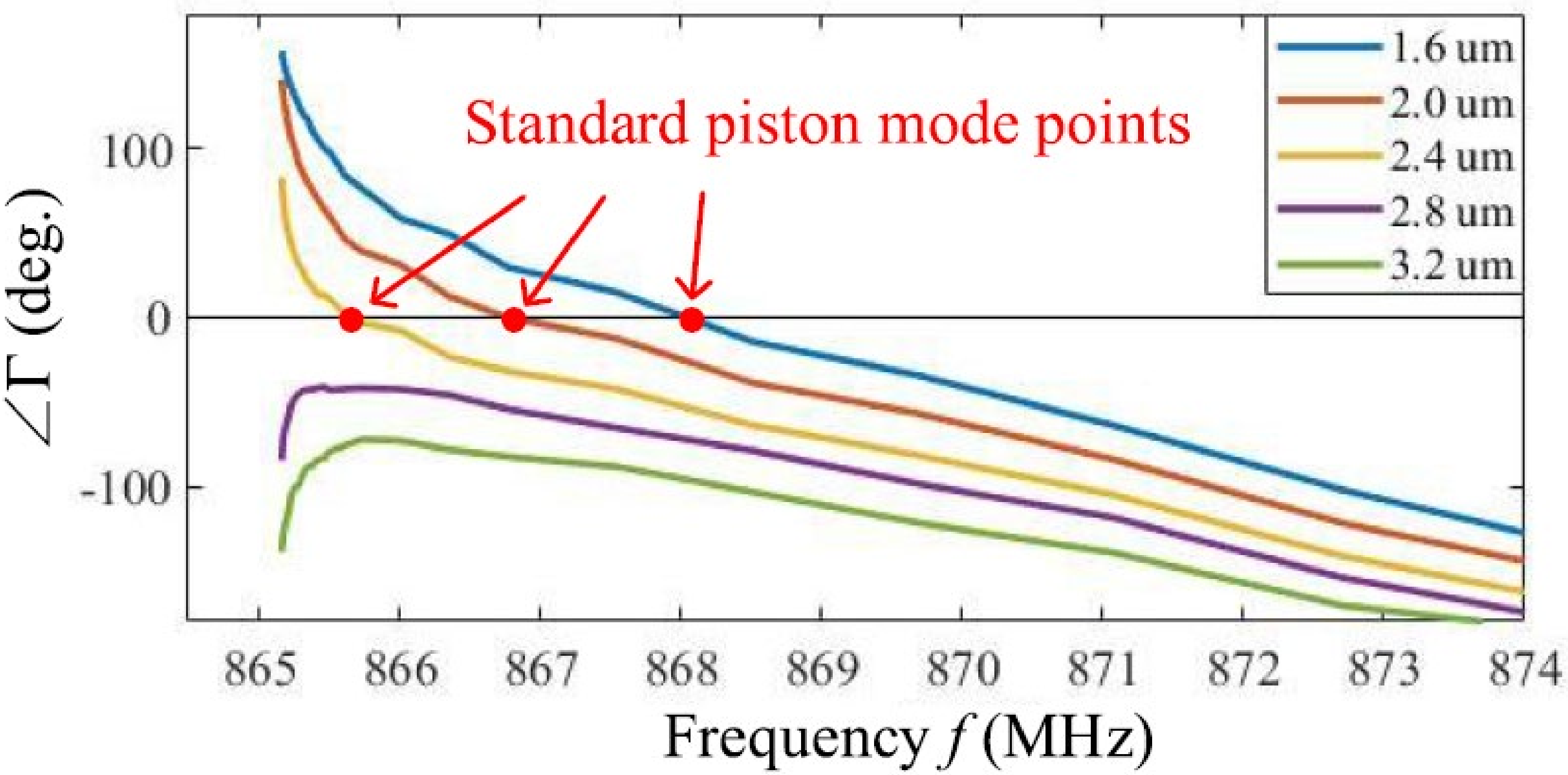




HCT Segmentation



Calculated Reflection Phase



X.Li, J.Bao, Y.Huang, B.F.Zhang, T.Omori, and K.Hashimoto, "Use of Hierarchical Cascading Technique for FEM Analysis of Transverse Mode Behaviors in Surface Acoustic Wave Devices," IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., **66**, 12 (2019) pp. 1920-1926

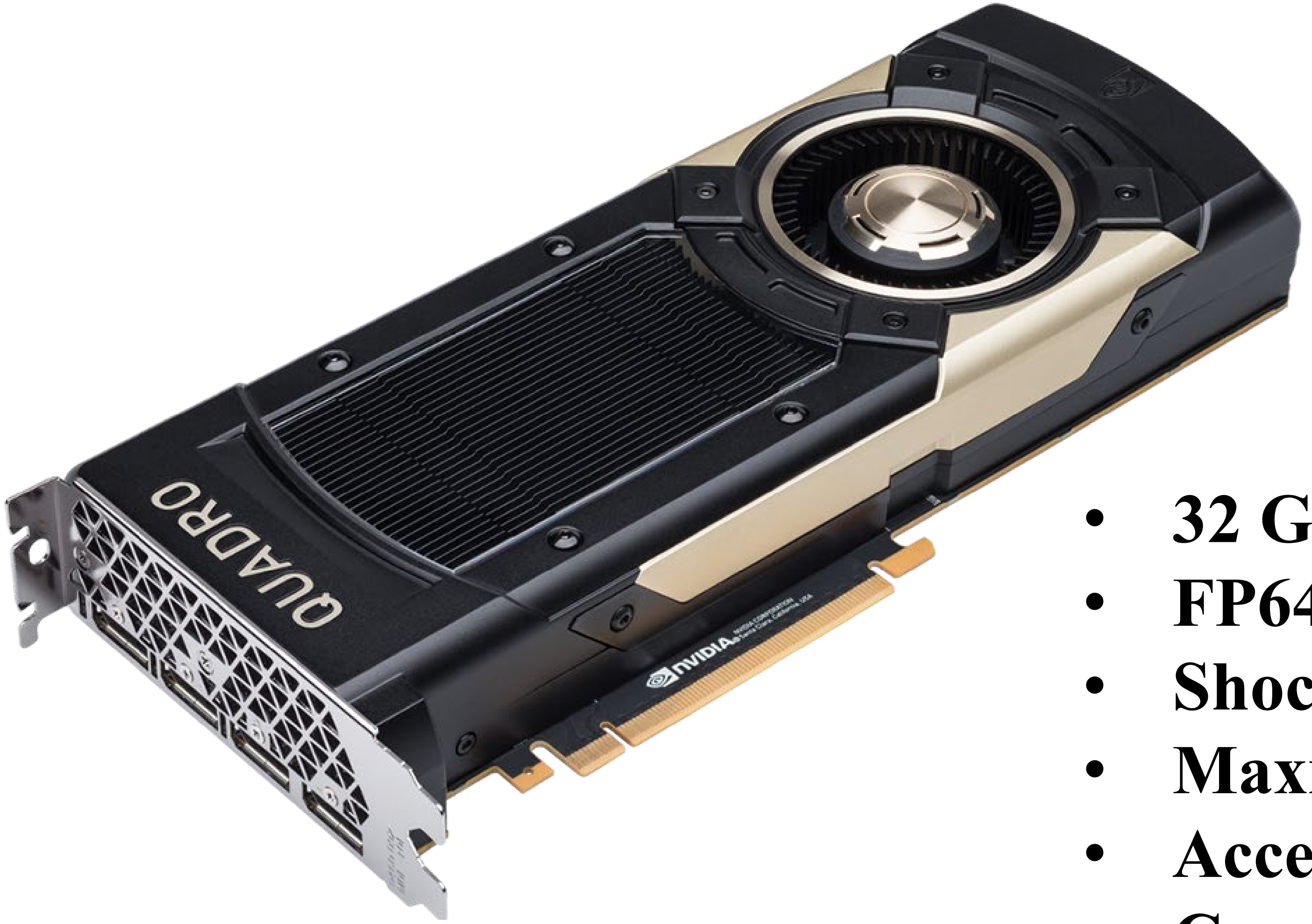
Execution Time

*CPU: Intel Xeon W-2123 @ 3.60GHz

Preparation	**Damping boundary**	**920 sec.**
	HCT of active region	255 sec.
Parametric sweep	sweep h_{m2}	315 sec.
	sweep L_s	160 sec.

X.Li, J.Bao, Y.Huang, B.F.Zhang, T.Omori, and K.Hashimoto, "Use of Hierarchical Cascading Technique for FEM Analysis of Transverse Mode Behaviors in Surface Acoustic Wave Devices," IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., **66**, 12 (2019) pp. 1920-1926

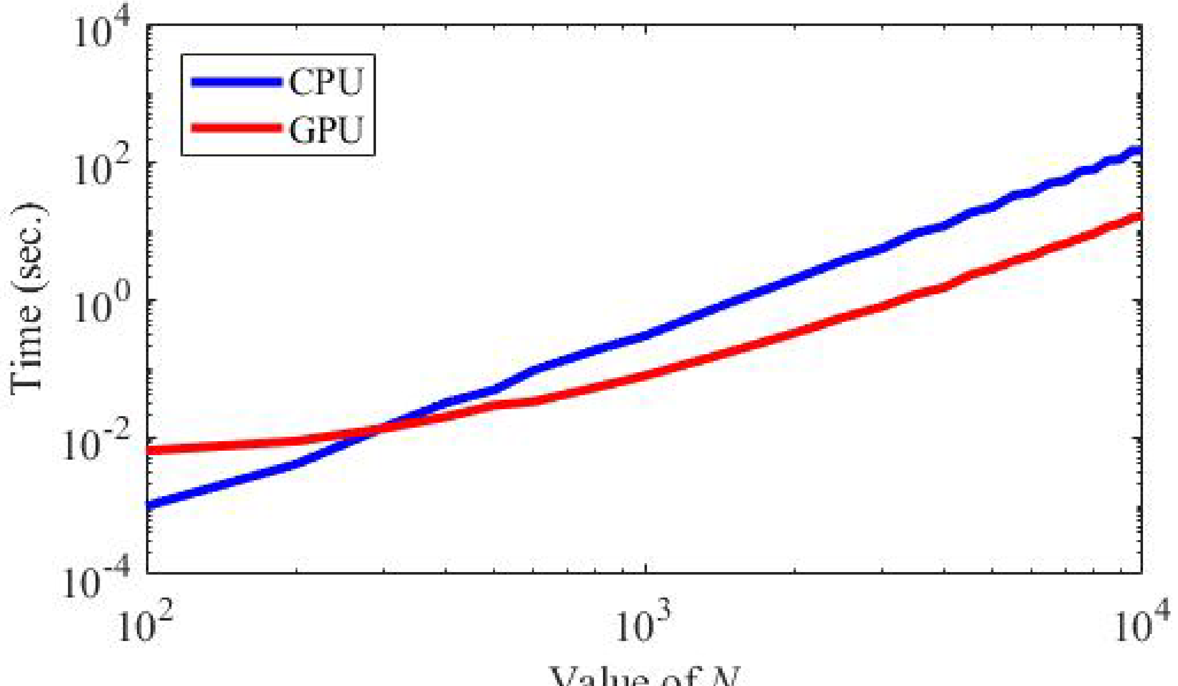
Use of High End GPU
NVIDIA Quadro GV100



- **32 GB Memory**
- **FP64 Calculation**
- **Shocking Price 1.5 M JPY**
- **Maximum Power 250 W**
- **Accessible by Matlab Parallel Computing Toolbox**

Comparison between CPU and GPU

	Intel Xeon W-2123	NVIDIA GV100
Cores	4	5,120
Frequency	3.6 GHz	1.132 GHz
FP64 Performance	0.23 TFLOPS	7.4 TFLOPS
Configured Memory	128 GB DDR4	32 GB HBM2



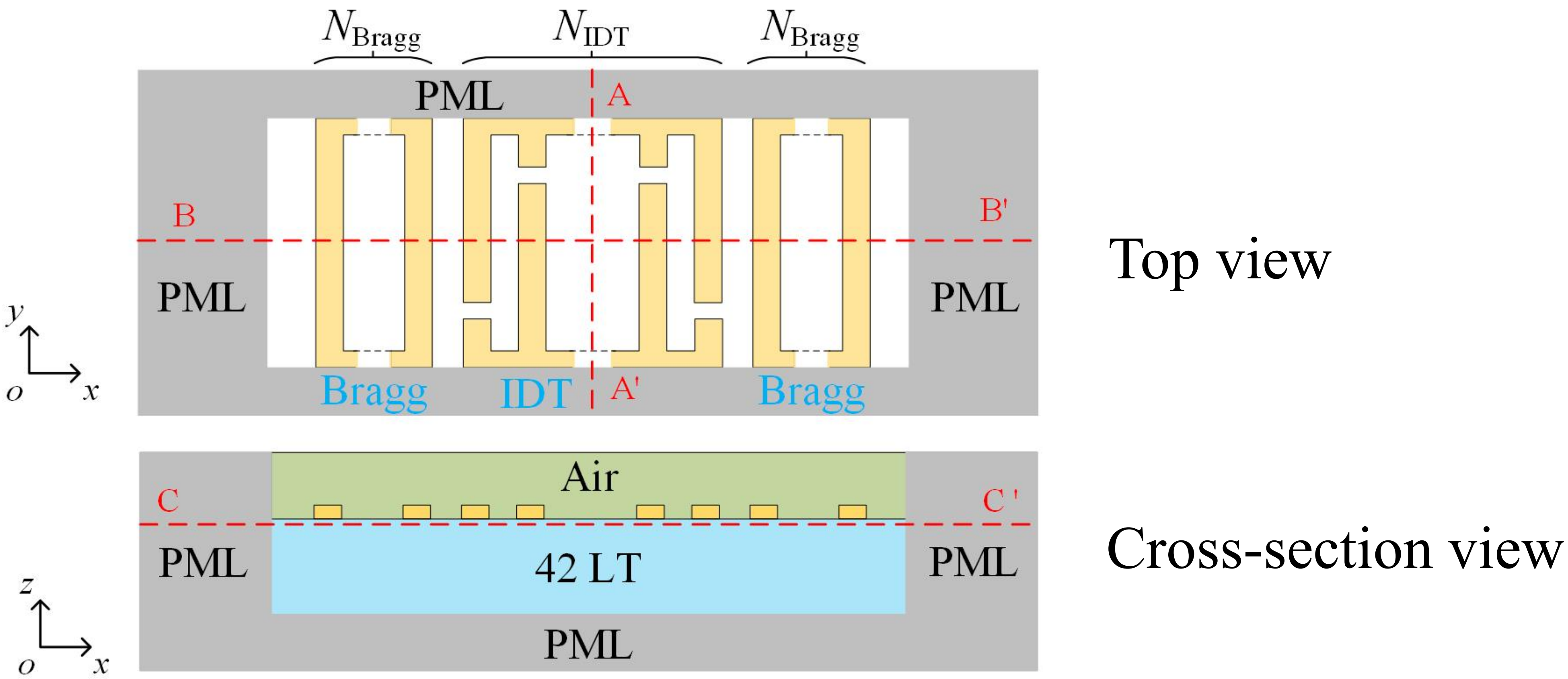
Execution Time

CPU: Intel Xeon W-2123 @ 3.60GHz

		Method 1	Method 2	Method 3
HCT		No	Yes	Yes
main processor*		CPU	GPU GV100	GPU GV100
precision		Double	Double	Single
Run Time	First Run	800 sec.	124 Sec.	75.3 Sec.
	Parameter sweep	800 sec.	85 Sec.	35 sec.
Memory used		12 GB	6+4.6 GB	6+2.7 GB

Full 3D Simulation of SAW Resonator

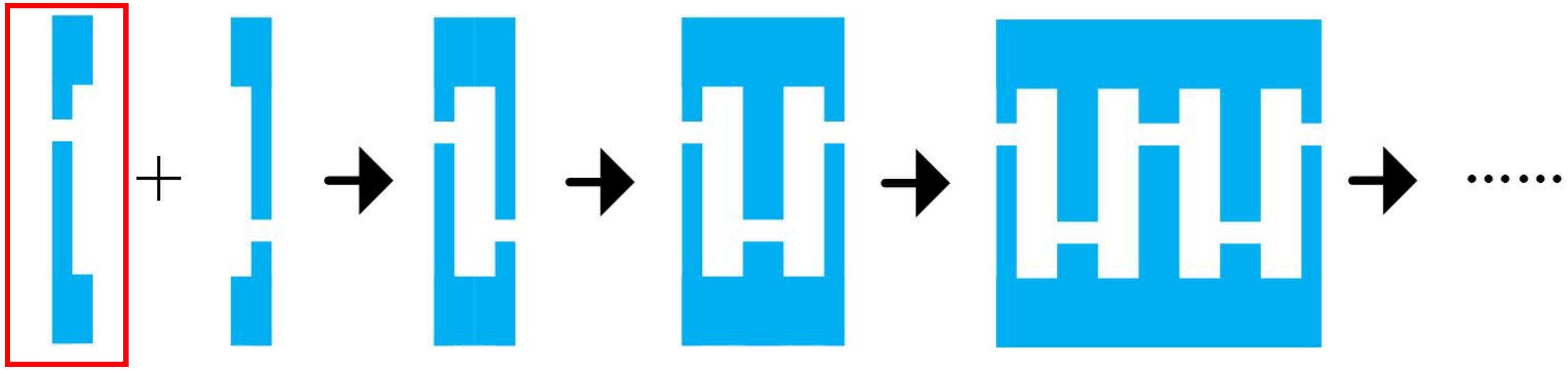
The whole structure of SAW resonator on 42-LT

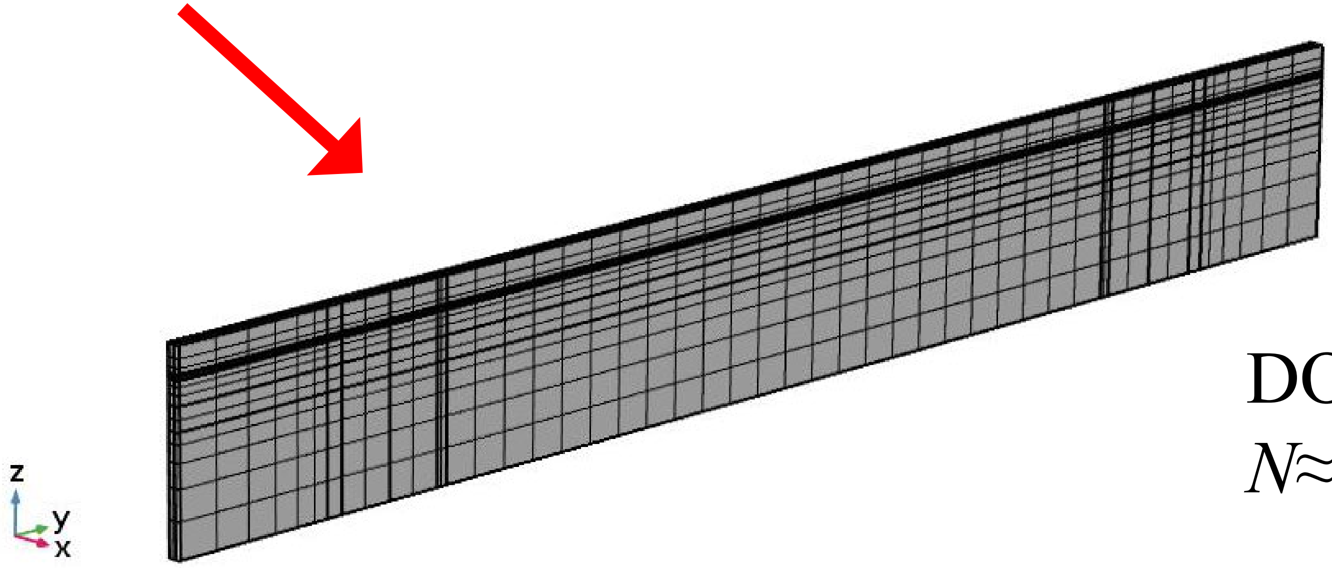


M.Solal, M.Gallagher, and A.Tajic, "Full 3D Simulation of SAW Resonators Using Hierarchical Cascading FEM," Proc. IEEE Ultrason. Symp. (2017) 10.1109/ULTSYM.2017.8092166

X.Li, J.Bao, L.Qiu, N.Matsuoka, T.Omori and K.Hashimoto, "3D FEM Simulation of SAW Resonators Using Hierarchical Cascading Technique and General-Purpose Graphic Processing Unit," Jpn. J. Appl. Phys., **58**, 7 (2019) SGGC05

Full 3D SAW resonator simulation





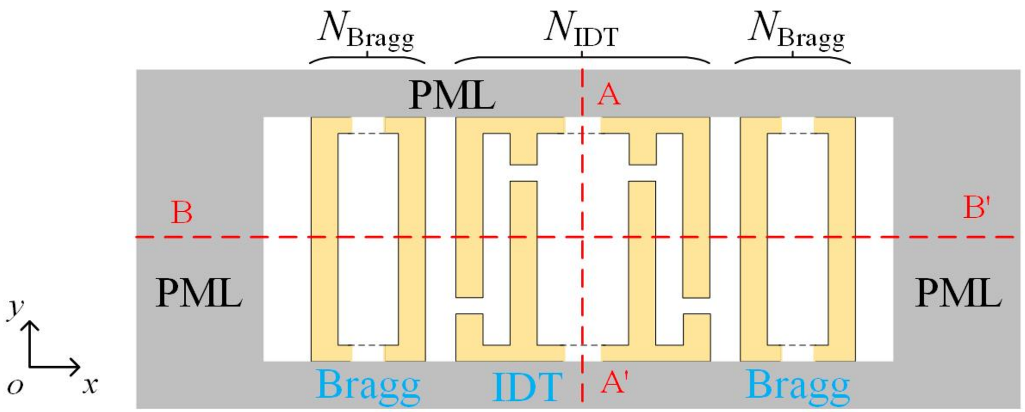
DOFs at interface
$N \approx 6{,}000$

X.Li, J.Bao, L.Qiu, N.Matsuoka, T.Omori and K.Hashimoto, "3D FEM Simulation of SAW Resonators Using Hierarchical Cascading Technique and General-Purpose Graphic Processing Unit," Jpn. J. Appl. Phys., **58**, 7 (2019) SGGC05

Full 3D SAW resonator simulation

Case 1: N_{IDT}=5, N_{Bragg}=2

Total DOFs in the model: about 900,000



	COMSOL directly	GPU based HCT
Time for 1 frequency point	745 s	133 s
Memory	110 GB (CPU)	2 GB(CPU)+28 GB(GPU)

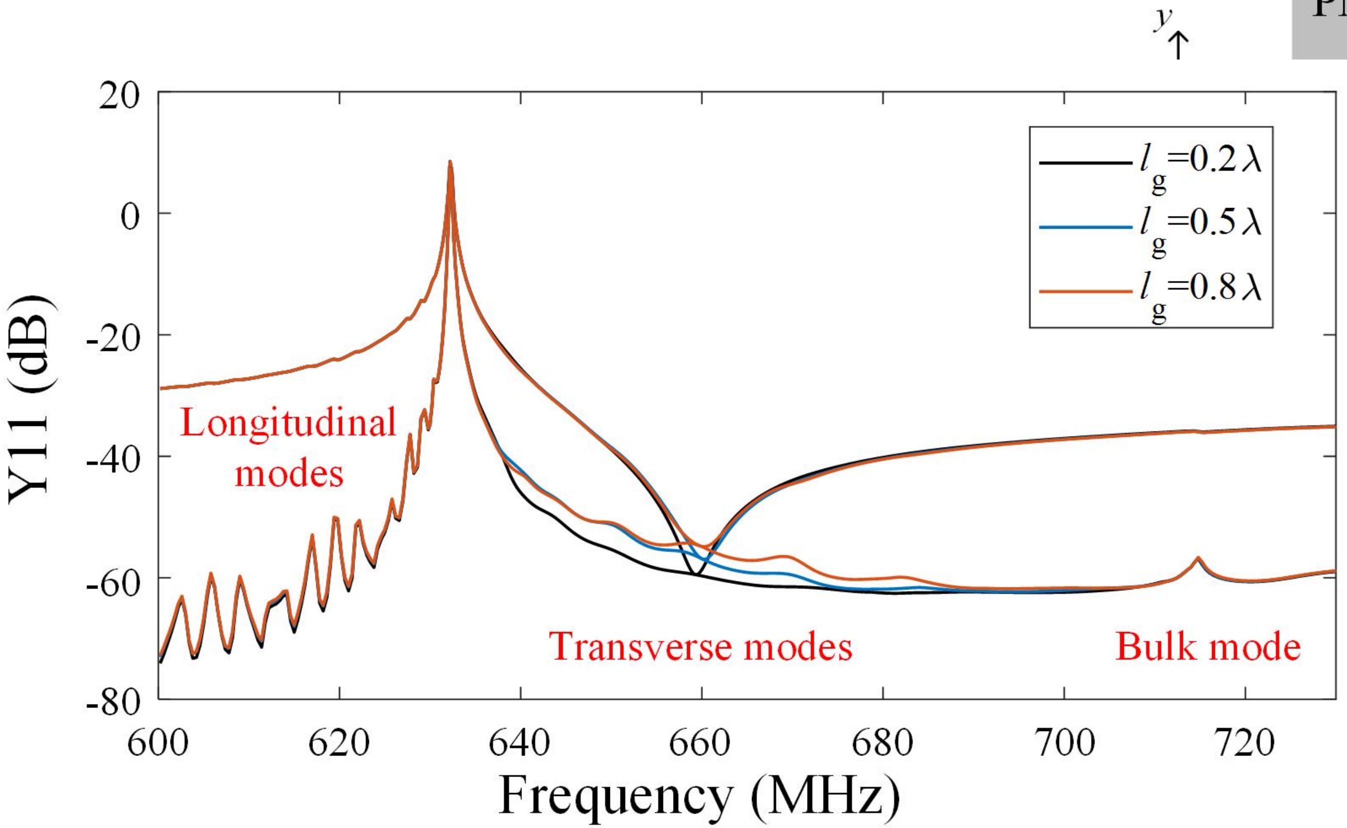
Calculated Admittances are Exactly the Same!

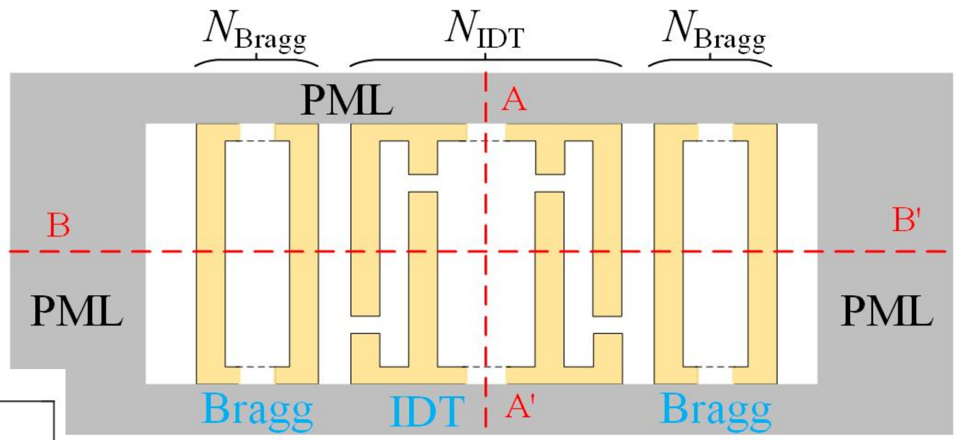
X.Li, J.Bao, L.Qiu, N.Matsuoka, T.Omori and K.Hashimoto, “3D FEM Simulation of SAW Resonators Using Hierarchical Cascading Technique and General-Purpose Graphic Processing Unit,” Jpn. J. Appl. Phys., **58**, 7 (2019) SGGC05

Full 3D SAW resonator simulation

Case 2: N_{IDT}=257, N_{Bragg}=33

Total DOFs in the model: >30, 000, 000

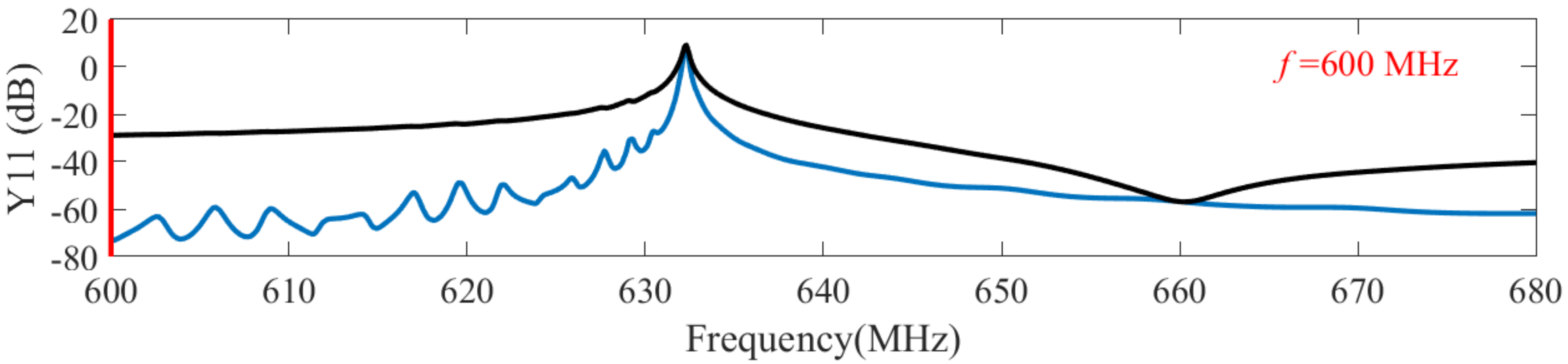


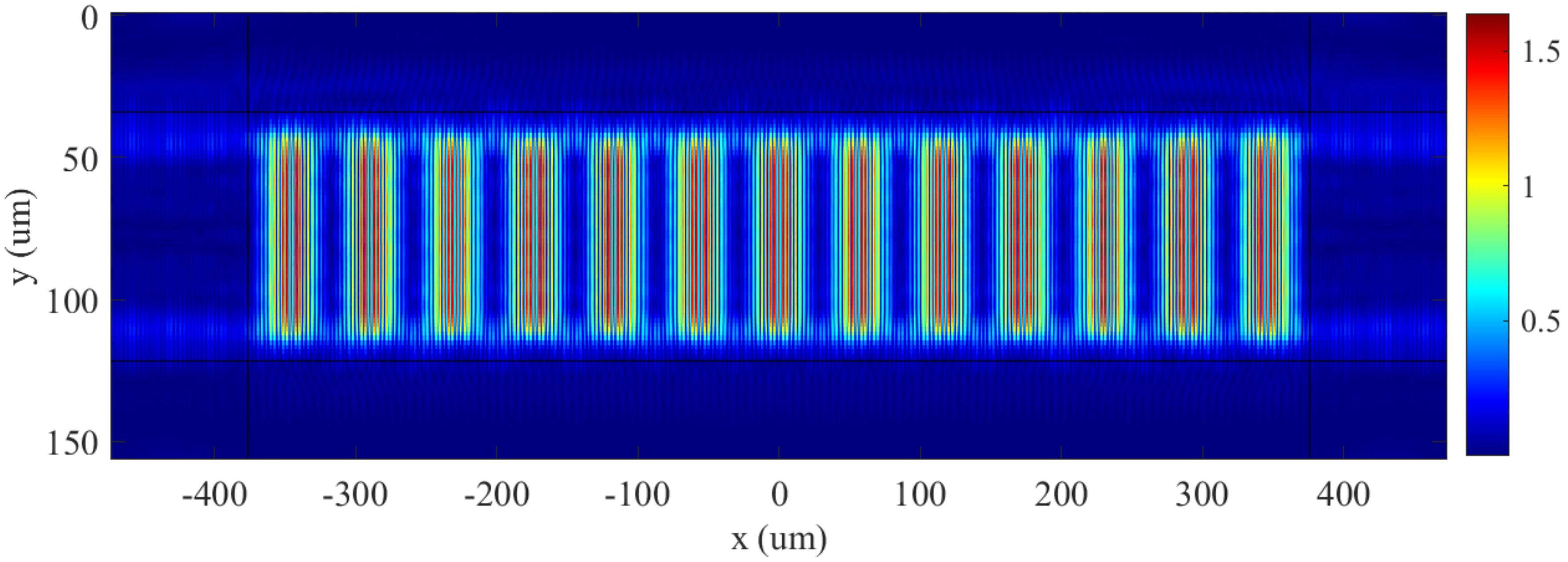


153 s for 1 freq. point!

X.Li, J.Bao, L.Qiu, N.Matsuoka, T.Omori and K.Hashimoto, "3D FEM Simulation of SAW Resonators Using Hierarchical Cascading Technique and General-Purpose Graphic Processing Unit," Jpn. J. Appl. Phys., **58**, 7 (2019) SGGC05

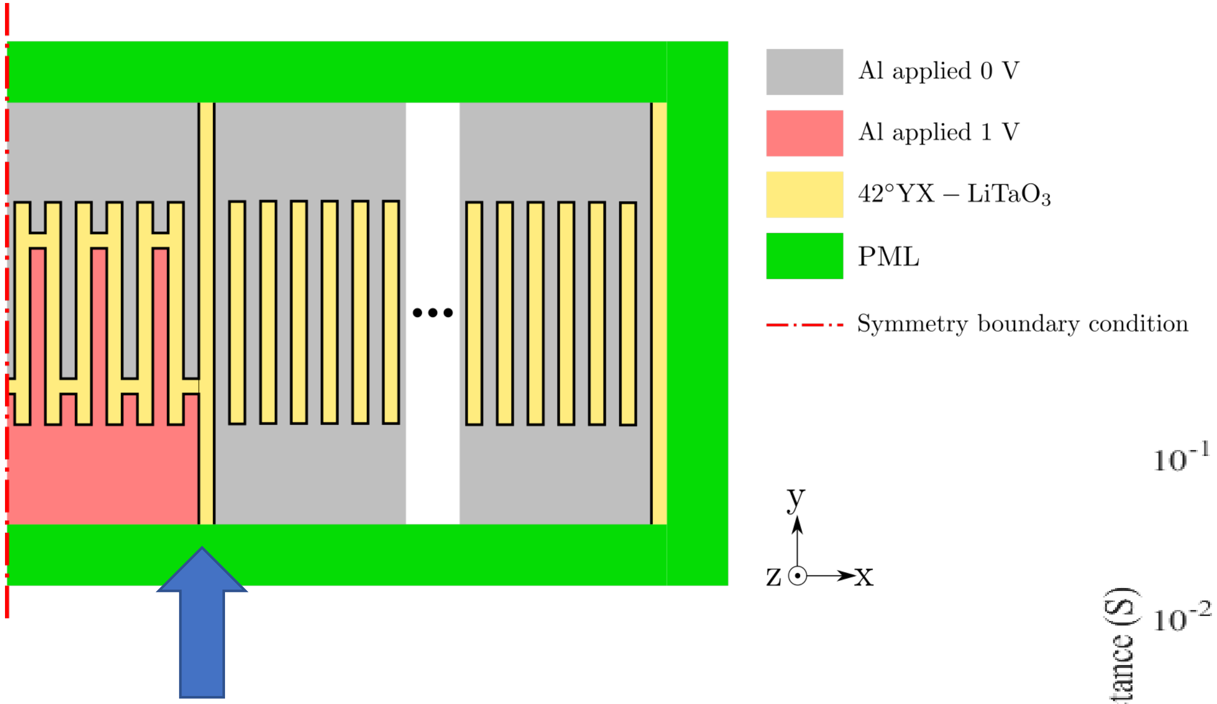
Full 3D SAW resonator simulation



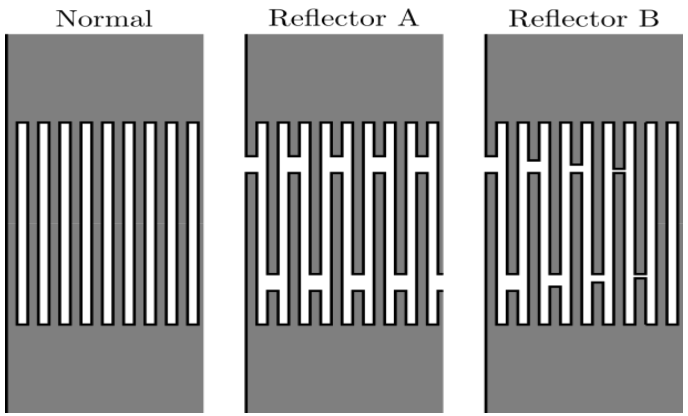


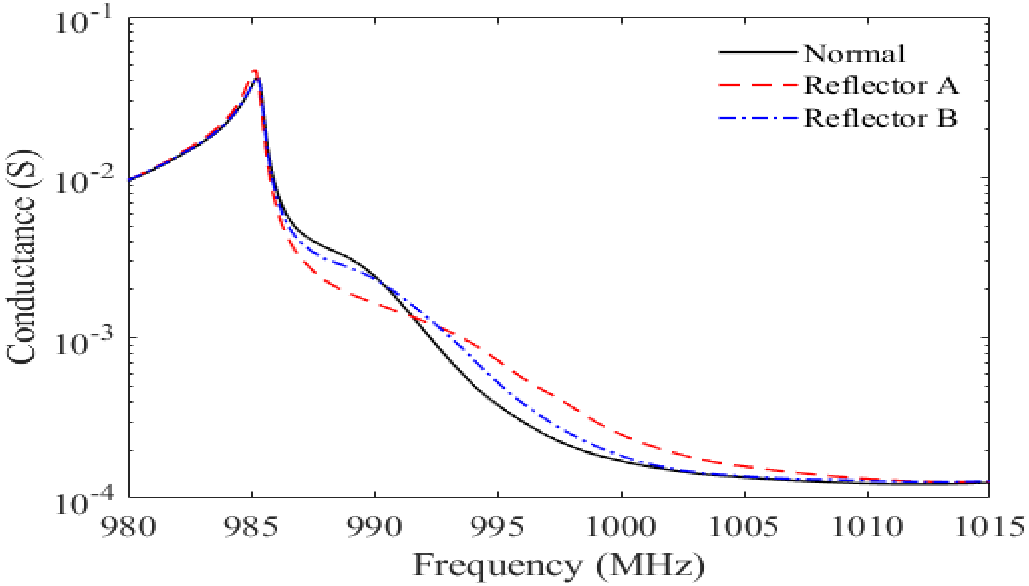
X.Li, J.Bao, L.Qiu, N.Matsuoka, T.Omori and K.Hashimoto, "3D FEM Simulation of SAW Resonators Using Hierarchical Cascading Technique and General-Purpose Graphic Processing Unit," Jpn. J. Appl. Phys., **58**, 7 (2019) SGGC05

Application to Numerical Experiment



Influence of This Discontinuity?





A.Iyama, X.Li, T.Omori, and K.Hashimoto, “Full 3D FEM Analysis of Scattering at a Border Between IDT and Reflector in SAW Resonators,” Proc. IEEE Ultrason. Symp. (2019) 10.1109/ULTSYM.2019.8925826

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COMSOL in RF SAW/BAW Devices

- § Parameter Derivation for 1D COM Model
- § Parameter Derivation for Lateral SAW/BAW Propagation
- § 2D Simulation of Behavior Model Using PDE Mode

HCT Enabled

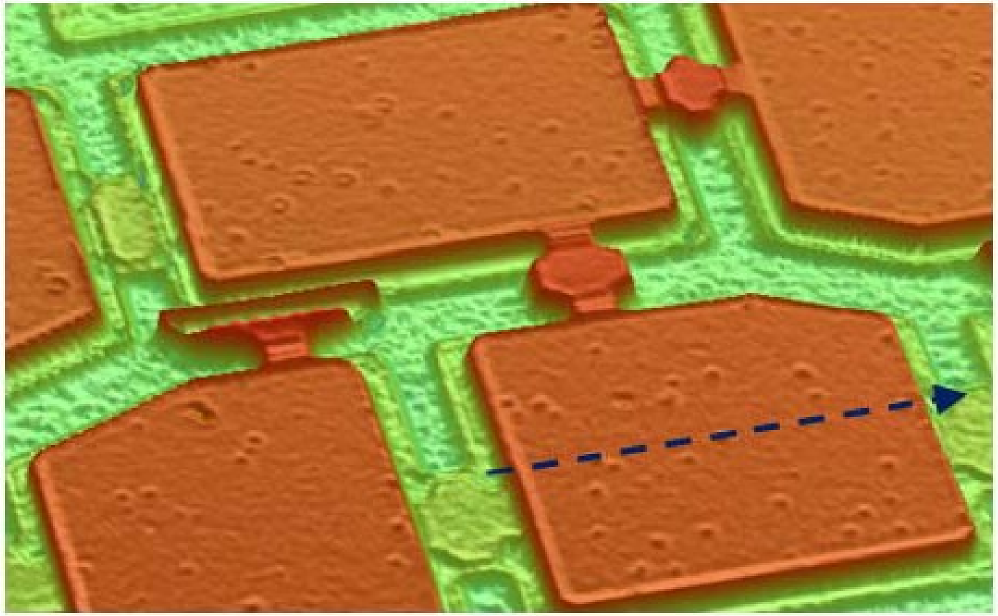
- § Optimization of Lateral Edges of SAW/BAW Devices Using Traveling Wave Source and Parameter Sweep
- § Analysis of Discontinuities in Periodic Structures
- § Full 3D Simulation of Practical SAW Devices Using GPU
- § Numerical Experiments

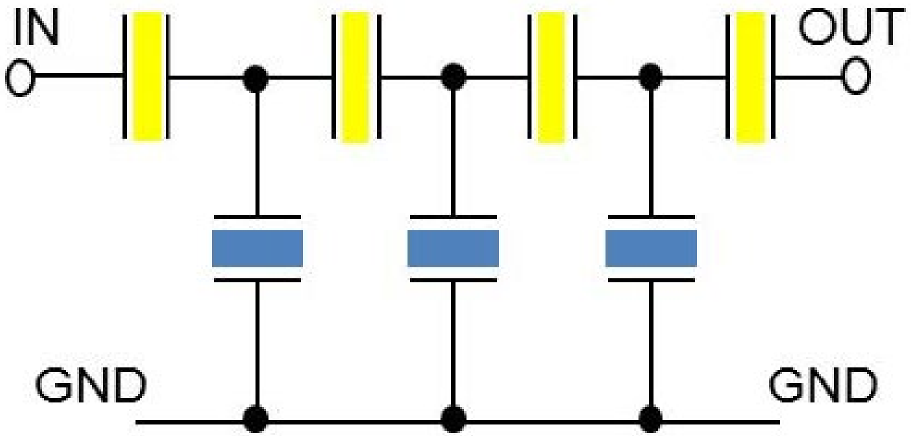
COMSOL in RF SAW/BAW Devices

What are Next?

- § Further Speed Up (Further Parallelize?)
- § Easy Setup Environment for HCT, Especially 3D
- § Fast Full 3D Simulation of BAW Devices

Surface Photo of RF BAW Device Chip





Apodization for Suppression of Transverse Mode Resonances

R.K.Thalhammer, and J.D.Larson, "Finite-Element Analysis of Bulk-Acoustic-Wave Devices: A Review of Model Setup and Applications," IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., **63**, 10 (2016) pp. 1624-1635.

Full 3D FEM Necessary for Analysis of Transverse Mode Resonances

Thank you for your attention!

Acknowledgments

Excellent Works of My Former and Current Colleagues: Dr. Yupo Wong, Dr. Xinyi Li, Dr. Luyan Qiu, Dr. Benfeng Zhang, Dr. Yulin Huang, Dr. Gongbin Tan, Dr. Jiansong Liu, Dr. Florian Thalmayr, Mr. Masahiro Iyama

Note KH has never used COMSOL…

For Questions and Suggestions

Please Contact Me Through k.hashimoto@ieee.org