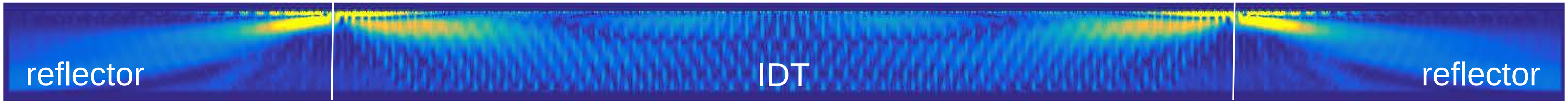
Fast Finite-Element 2D Simulation of Multi-Layered SAW Devices

By
Victor Plessky, Julius Koskela, Balam Willemsen, Patrick Turner,
Bob Hammond and Neal Fenzi

Resonant Inc., *Santa Barbara, California, USA*
GVR Trade SA, *Gorgier, Switzerland*



bhammond@resonant.com

Corporate Overview

Headquarters: Santa Barbara, CA
Additional Facility in Silicon Valley
Publicly traded on NASDAQ
Employees: 40

Resonant is an innovative developer of software design tools focused currently upon improving radio frequency (RF), front-ends, for the mobile device industry

Initial validation of the effectiveness of these tools is in the design of difficult filters, duplexers and quadplexers

Resonant has developed a filter design suite called Infinite Synthesized Networks®, or ISN®, which enhances design productivity and precision of complex filters and RF Front Ends

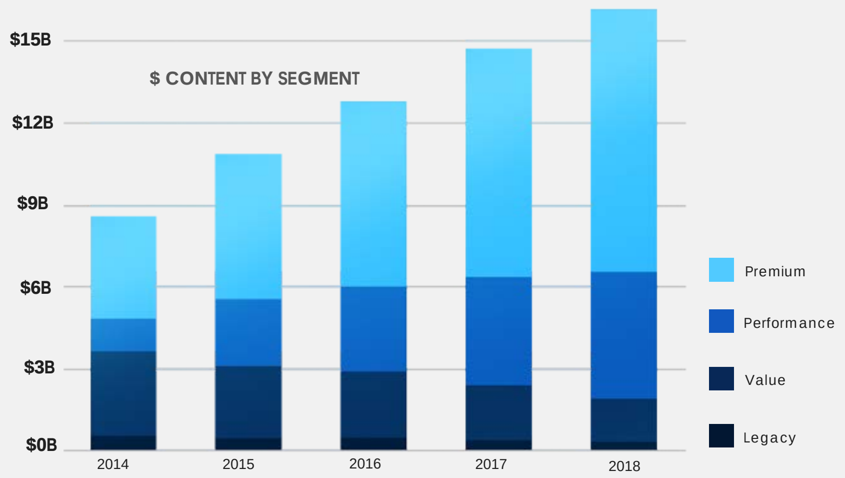
Santa Barbara, CA

Burlingame, CA

Filters: Principle RFFE BoM

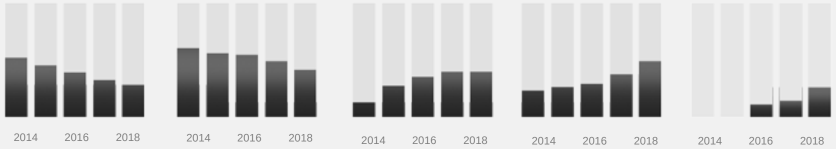
Increasing Value of RF Content | Higher RF Content Driving TAM Growth

Transition to Performance, Premium Driving up RF TAM

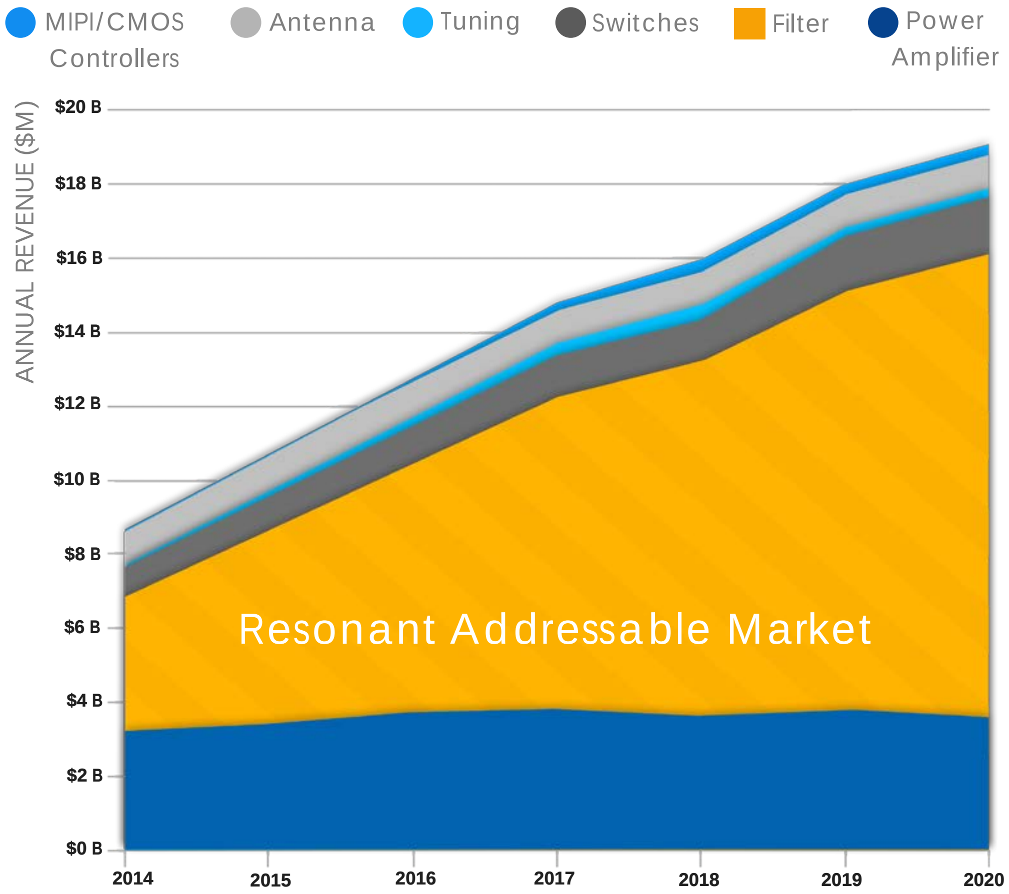


Average RF Content / Handset

Unit Shipments Trend



Source: Management Estimates, Barclays



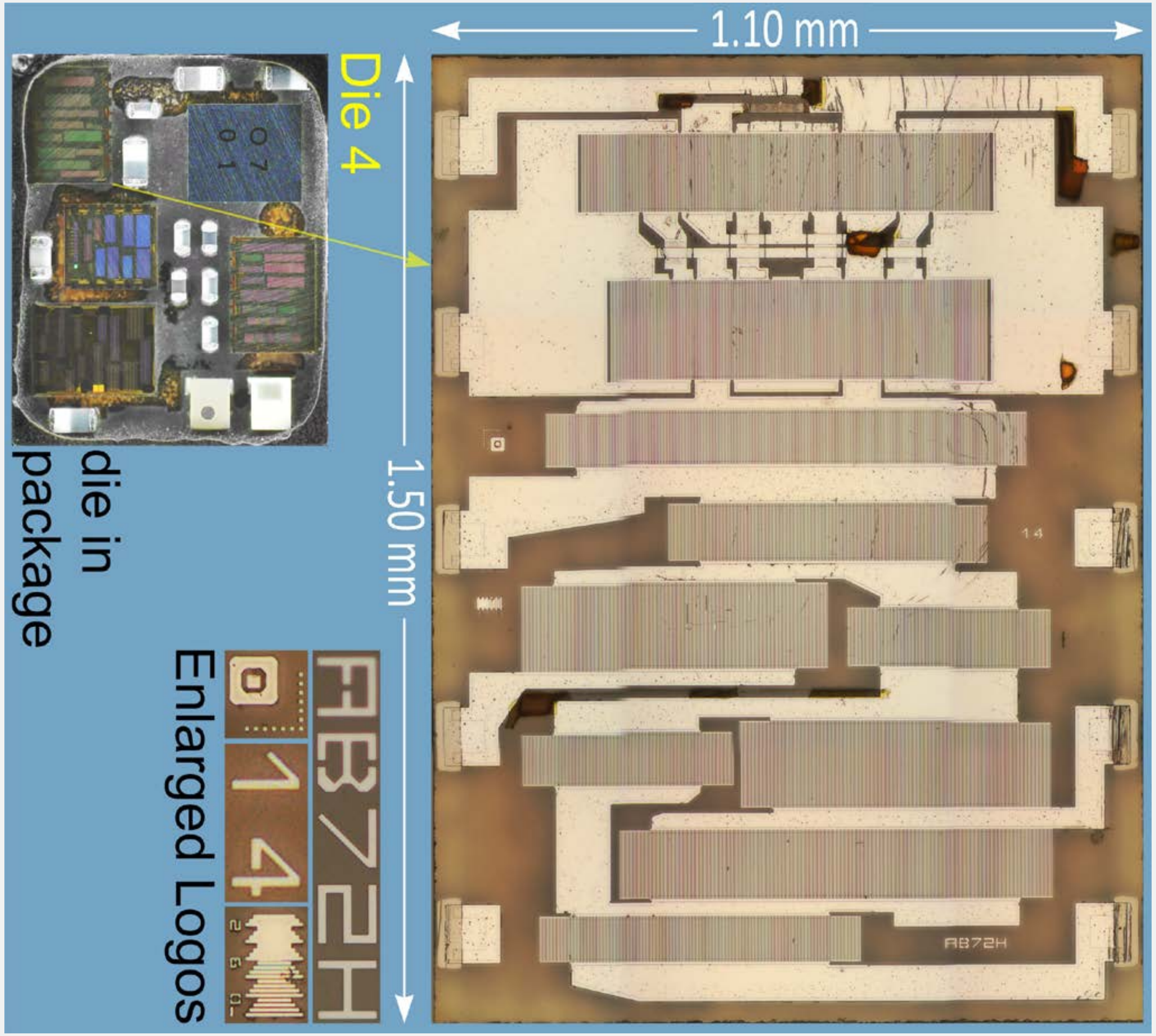
Source: Mobile Experts LLC

Filter Market to double in less than 4 years

Resonant Design Flow

- ❑ Filter Synthesis – Acoustic Resonators (BVD)
  - Custom Tool
- ❑ Filter Design Optimization – Fast Proxies for FEM
  - Custom Tools
- ❑ Filter Design Simulation – FEM Tools
  - Custom Acoustic Tool – “Layers”
    - SAW Resonators
  - Commercial EM Tool – “Sonnet EM”
    - Die Layout & Filter Package
- ❑ Process Characterization & Filter Simulation
  - Acoustic Resonators Simulation – “Layers”
    - Fast Proxy Interpolation Tables
  - Die Layout & Package EM Simulation – “Commercial EM”

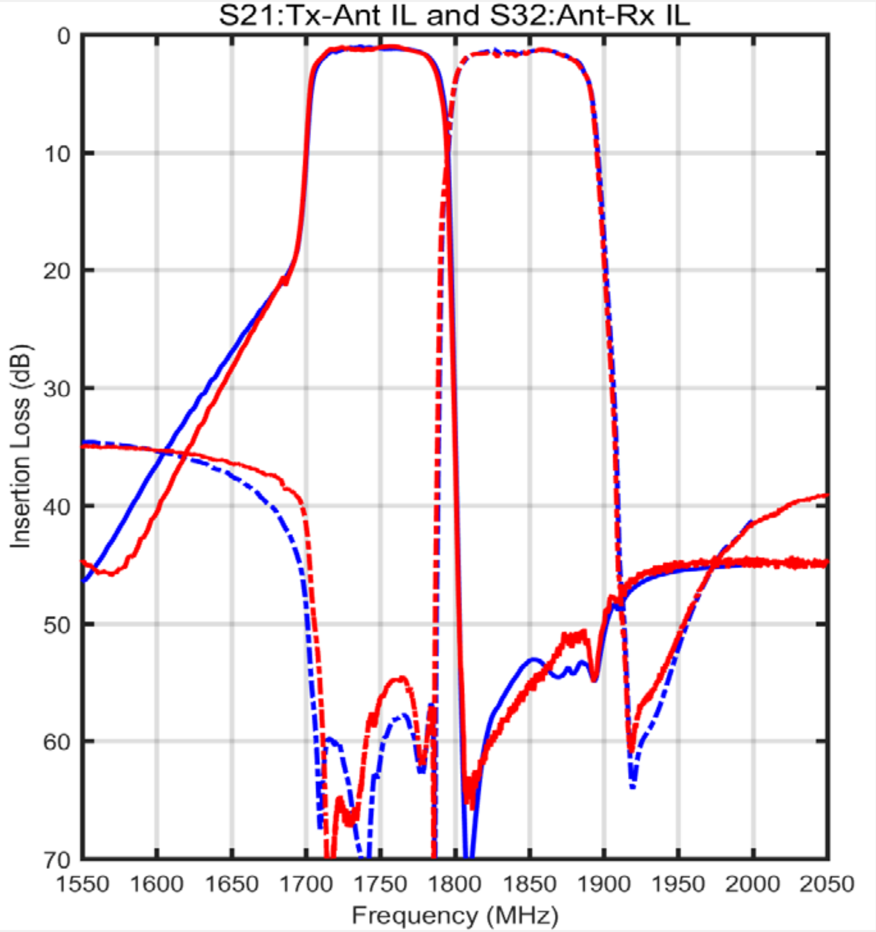
SAW Duplexer – Modeling Complex SAW Structures



1814 Band 3 - Pre-Fab Model vs. Measured

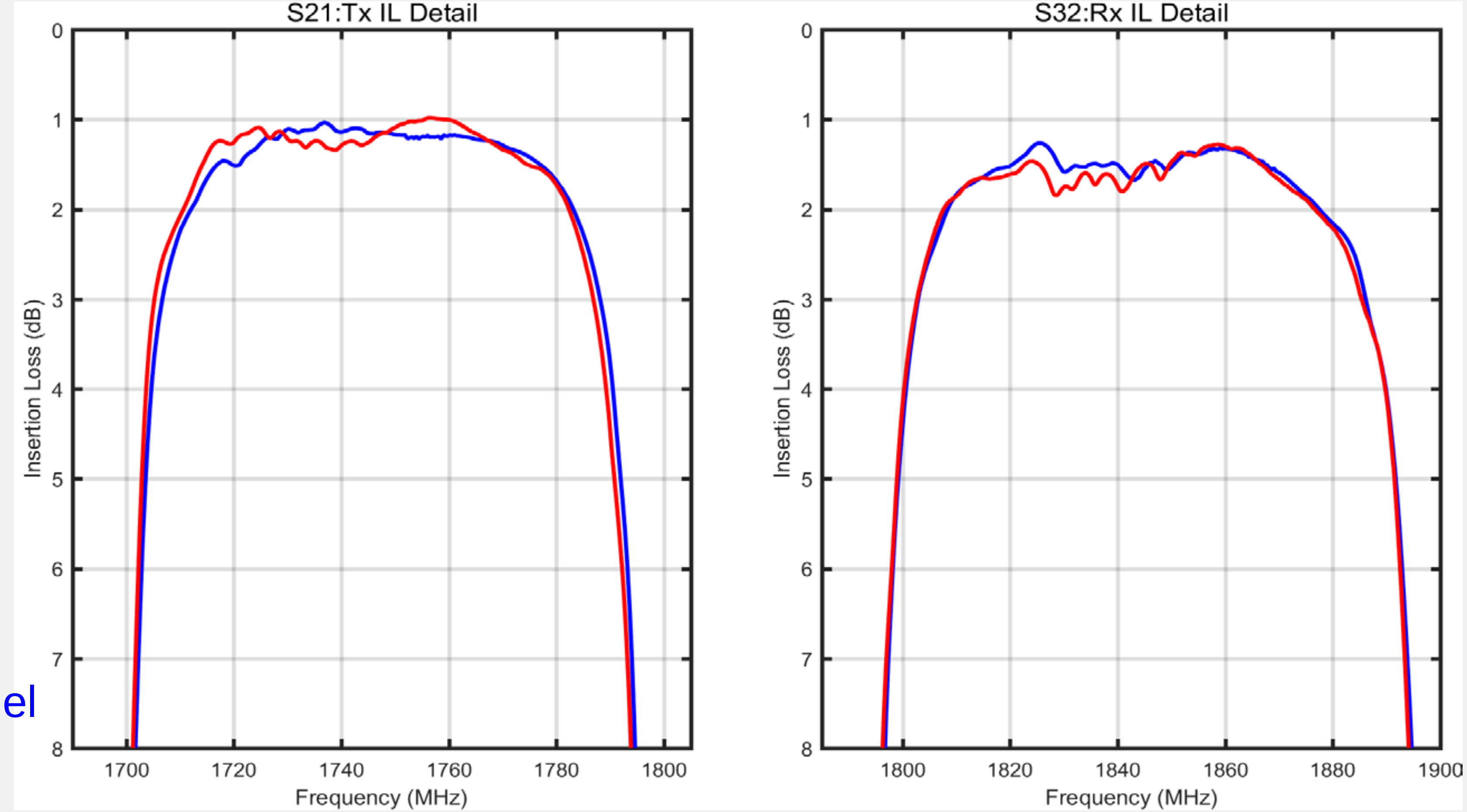
- ❑ Pre-Fab Model
  - Full FEM
  - Based on dimensions and materials proprieties

- ❑ Measurement
  - No frequency shift
  - CSP part, Measured on EVB
  - Ideal matching



Pre-FAB Model
Measured

1814 Band 3 - Pre-Fab Model vs. Measured



Pre-FAB Model

Measured

Measured to Model Summary

- Excellent agreement between measurements and Pre-Fab model
  - Resonant models highly accurate, even at 2.4GHz
  - Critical to our success over the past 18 months
  - Enables improved design efficiency and minimizes number of fab turns

- Accuracy enables additional model features
  - Manufacturing yield
  - Over-temperature performance
  - Power handling/durability

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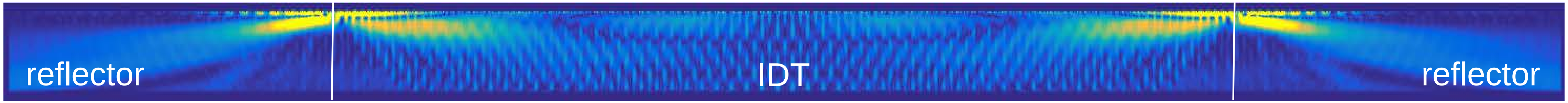

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  - Hic-cup Resonator
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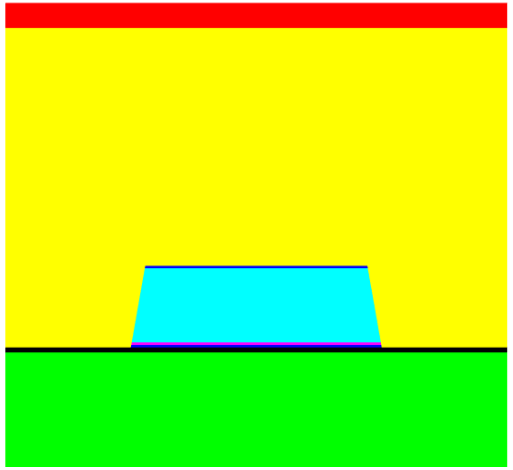
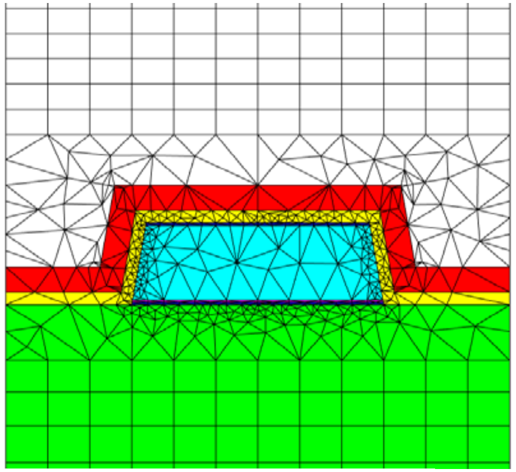
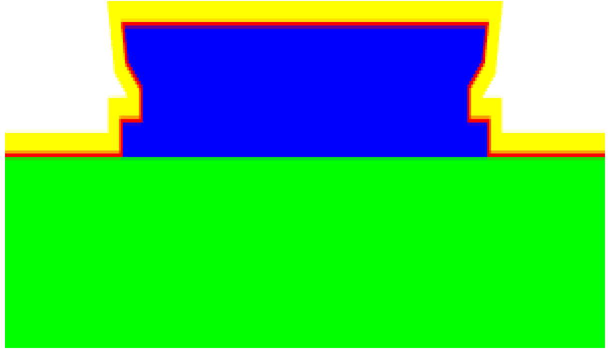
Introduction: FEM and SAW





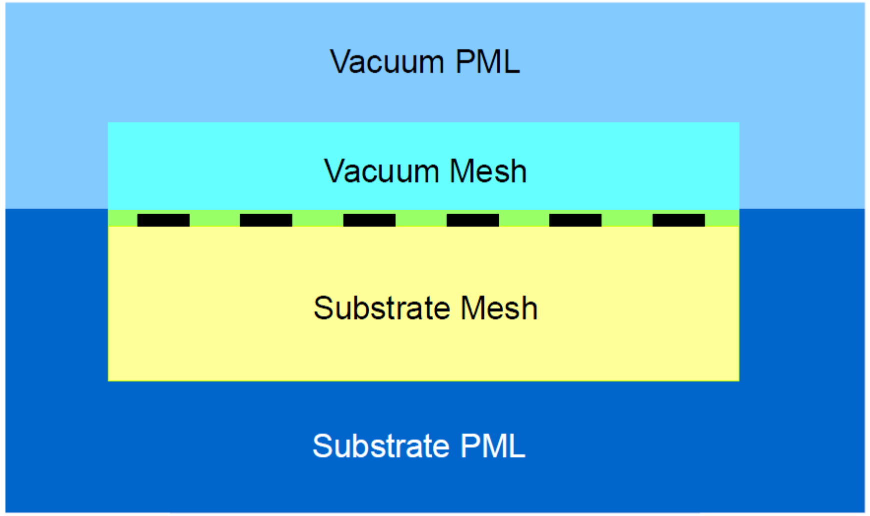
- Finite-Element Method (FEM) is astonishingly *versatile*.
  - **arbitrary materials** and **crystal cuts**
  - complex **electrode shapes**
  - **multilayered structures** with several dielectrics or metals
  - **thermal effects** are easy to simulate
  - well established numerically, available commercially
  - **no singularities** of the Green's function (à la BEM)
  - in principle, can be extended to 3D analysis
- Historically, two major obstacles for SAW simulation:
  1. **Very many degrees-of-freedom (DoF) are required**
     - Large memory requirements, long computation times
  2. **The difficulty with open boundary conditions**
     - Necessary for modeling effectively semi-infinite substrates
     - Numeric instability of PML and stable M-PML



Introduction: FEM and SAW

Berenger 1994: Perfectly Matched Layer (PML)

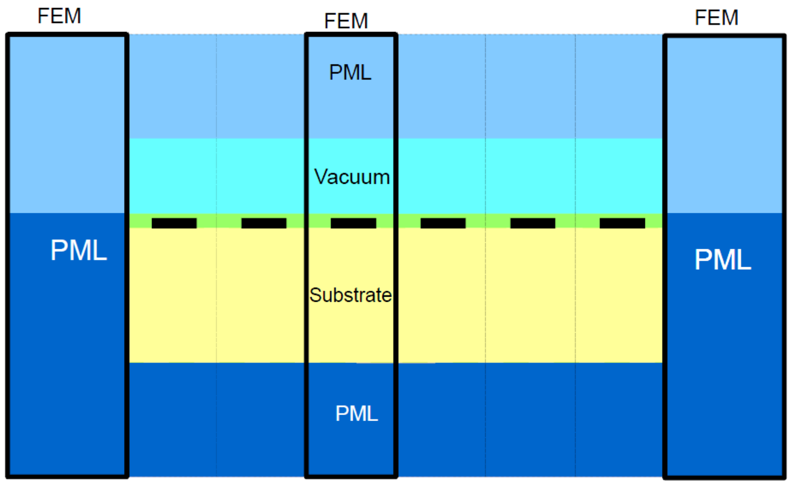
- Efficient way to implement open boundary conditions
- originally introduced in the context of electromagnetic waves, later generalized to elastic and piezoelectric waves
- The computational domain is surrounded with an absorbing, effectively reflectionless computational material
- Suitable for 2D FEM simulation of SAW devices [Bou Matar *et al*. 2007, Karim *et al.* 2013]
- Caveat: **unstable** in substrates with concave curvature of the slowness curves [Becache *et al*. 2003]
  - Fallback solution: domain dimensions, absorbing boundary conditions
- **Solution found** **(Meza-Fajardo, 2008) :** Multi-axial-PML



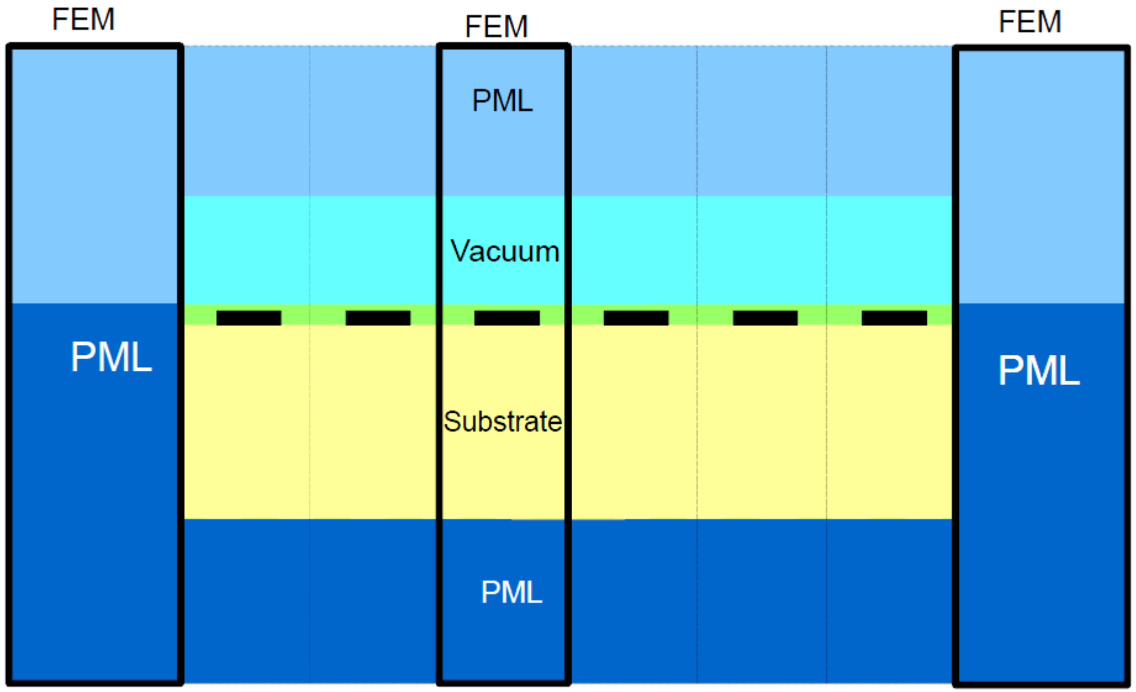
Introduction: FEM and SAW

Hierarchical Cascading

- our solution to the problem of many degrees-of-freedom.
- Periodicity is typical to SAW technology.
- The FEM equations describing identical periods are identical. It is sufficient to simulate each unique period type only once.
- The response of the SAW device can be simulated by cascading responses of unit blocks.
- the result is equivalent to full FEM simulation of the complete device, but with drastically reduced memory consumption and simulation time.



Hierarchical cascading in FEM simulation of finite SAW devices

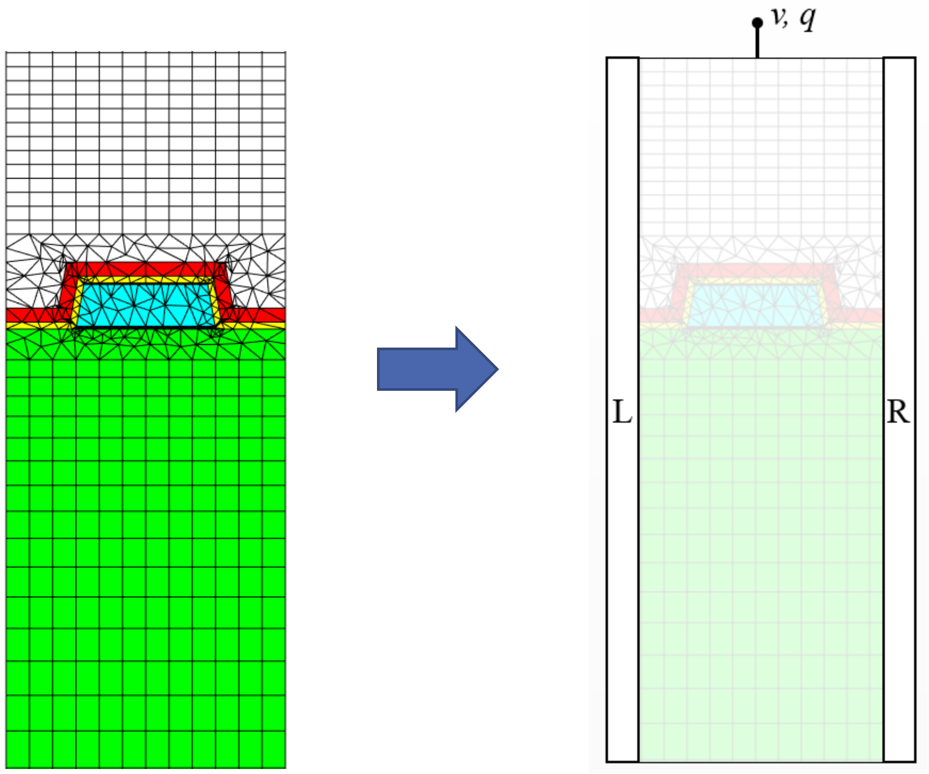


On a PC with 32 processors and 128 GB RAM, a 5-IDT CRF having 15 “building blocks” (274 electrodes) was simulated, with about 6 second simulation time per frequency point (~1.3 hours total time).

[1] Koskela, J., Maniadis, P., Willemsen, B. A., Turner, P. J., Hammond, R. B., Fenzi, N. O., & Plessky, V., “*Hierarchical cascading in 2D FEM simulation of finite SAW devices with periodic block structure*”. In International Ultrasonics Symposium (IUS), 2016 IEEE (pp. 1-4)

FEM Model Reduction

Conceptual interpretation: each unit block is modeled as a multi-port, except that both ports contain many degrees-of-freedom.



Hierarchical Cascading

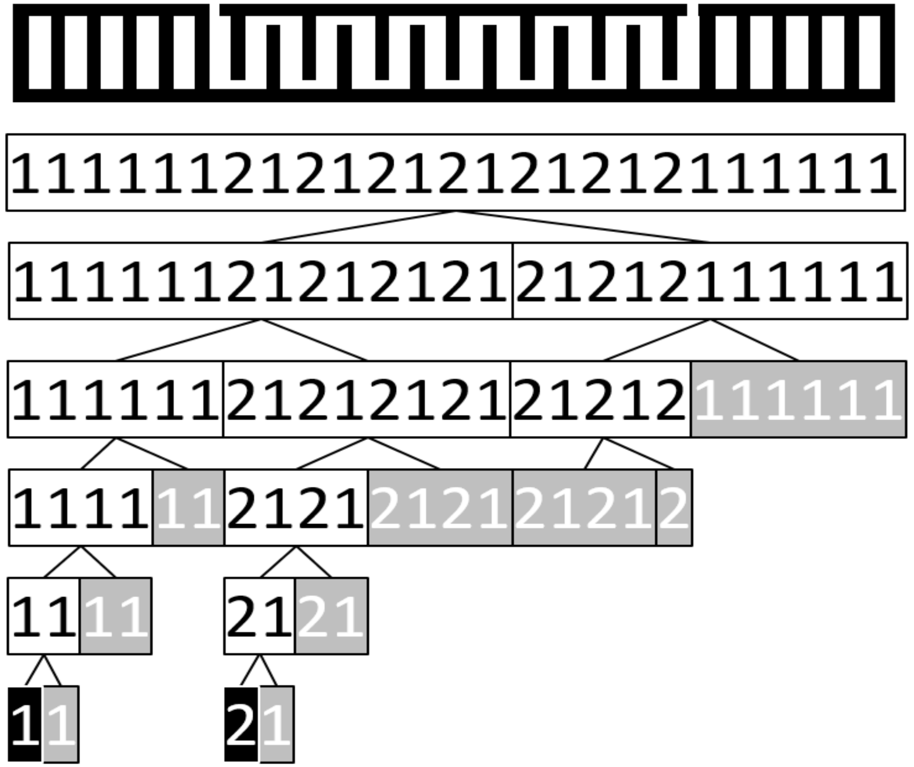
Toy resonator with 25 electrodes

- Analyze electrode structure
- Here, only two different voltages
- First model a single block
- Model reduction to obtain B-matrix

1111112121212121212111111

1

Idea of the hierarchical cascading



- Number of operations is proportionsl to ***log2(N)***
- The cascading procedure does not imply any periodicity of acoustic/electric fields in the structure
- any additional approximations and exact acoustic and electric field distributions can be obtained for all FEM grid points of the device.
- That gives us a unique possibility to look what happens inside such a device.
- Moreover, we can calculate the energy accumulated in the device and the power flows.

FEM Model Reduction

- The device structure is decomposed into unique, irreducible unit blocks.
- Each unit block is modeled with FEM.
- The degrees-of-freedom are classified into
  - those located at *the left edge* x_L
  - those located at *the right edge* x_R
  - those located in *the interior* x_I
  - electric potential *v*
  - net surface charge *q*
- The system matrix is symmetric and sparse.

The FEM system of equations

$$\begin{bmatrix} \mathbf{A}_{LL} & \mathbf{A}_{LI} & 0 & \mathbf{A}_{LV} \\ \mathbf{A}_{IL} & \mathbf{A}_{II} & \mathbf{A}_{IR} & \mathbf{A}_{IV} \\ 0 & \mathbf{A}_{RI} & \mathbf{A}_{RR} & \mathbf{A}_{RV} \\ \mathbf{A}_{VL} & \mathbf{A}_{VI} & \mathbf{A}_{VR} & \mathbf{A}_{VV} \end{bmatrix} \begin{pmatrix} \mathbf{x}_L \\ \mathbf{x}_I \\ \mathbf{x}_R \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -q \end{pmatrix}$$

FEM Model Reduction

- Next, the interior degrees-of-freedom are eliminated from the system matrix.

The FEM system of equations

$$\begin{bmatrix} \mathbf{A}_{\mathrm{LL}} & \mathbf{A}_{\mathrm{LI}} & 0 & \mathbf{A}_{\mathrm{LV}} \\ \mathbf{A}_{\mathrm{IL}} & \mathbf{A}_{\mathrm{II}} & \mathbf{A}_{\mathrm{IR}} & \mathbf{A}_{\mathrm{IV}} \\ 0 & \mathbf{A}_{\mathrm{RI}} & \mathbf{A}_{\mathrm{RR}} & \mathbf{A}_{\mathrm{RV}} \\ \mathbf{A}_{\mathrm{VL}} & \mathbf{A}_{\mathrm{VI}} & \mathbf{A}_{\mathrm{VR}} & \mathbf{A}_{\mathrm{VV}} \end{bmatrix} \begin{pmatrix} \mathbf{x}_{\mathrm{L}} \\ \mathbf{x}_{\mathrm{I}} \\ \mathbf{x}_{\mathrm{R}} \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -q \end{pmatrix}$$

$\Rightarrow$

Reduced system of equations

$$\begin{bmatrix} \mathbf{B}_{11} & \mathbf{B}_{12} & \mathbf{B}_{13} \\ \mathbf{B}_{21} & \mathbf{B}_{22} & \mathbf{B}_{23} \\ \mathbf{B}_{31} & \mathbf{B}_{32} & \mathbf{B}_{33} \end{bmatrix} \begin{pmatrix} \mathbf{x}_{\mathrm{L}} \\ \mathbf{x}_{\mathrm{R}} \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -q \end{pmatrix}$$

- The new, reduced system matrix describes the unit block entirely in terms of boundary conditions and the electric variables.
- We'll denote this quantity as the *B-matrix (Koskela-matrix)*.
- B-matrices are symmetric but full.

Examples

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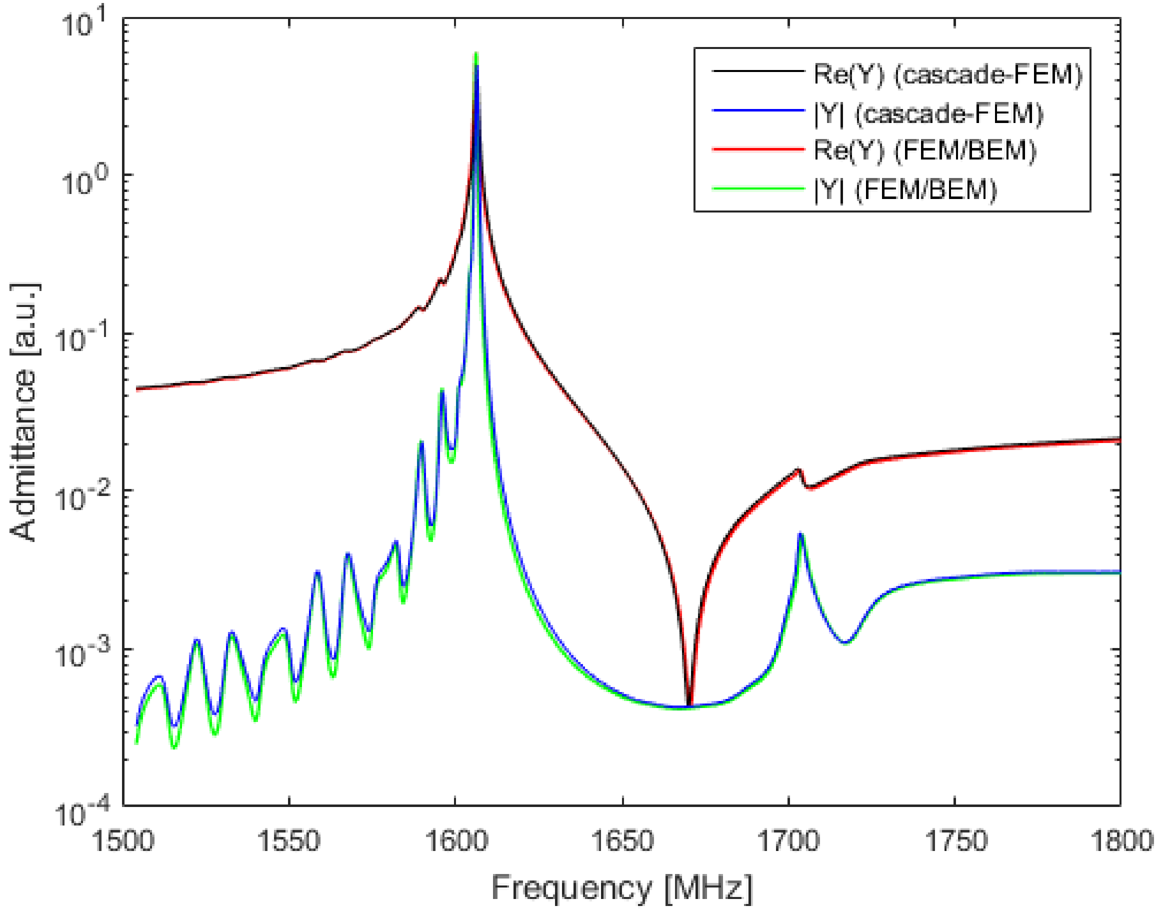
Synchronous Resonator

Simulation with cascade-FEM

- MatLab platform, 64-bit Windows
- CPU i7-2600k, 3.4 GHz, 16 GB RAM
- quadratic elements: 6636 DoFs/period, computation time 2.4 s / frequency
- cubic elements: 14625 DoFs/period, computation time 9.6 s / frequency
- comparison to FEM/BEM simulation

42°YX-cut $LiTaO_3$, Al electrodes $h/\lambda \approx$ 8%

p = 1.23 µm, a/p = 0.55, Nt = 241, Ng = 40



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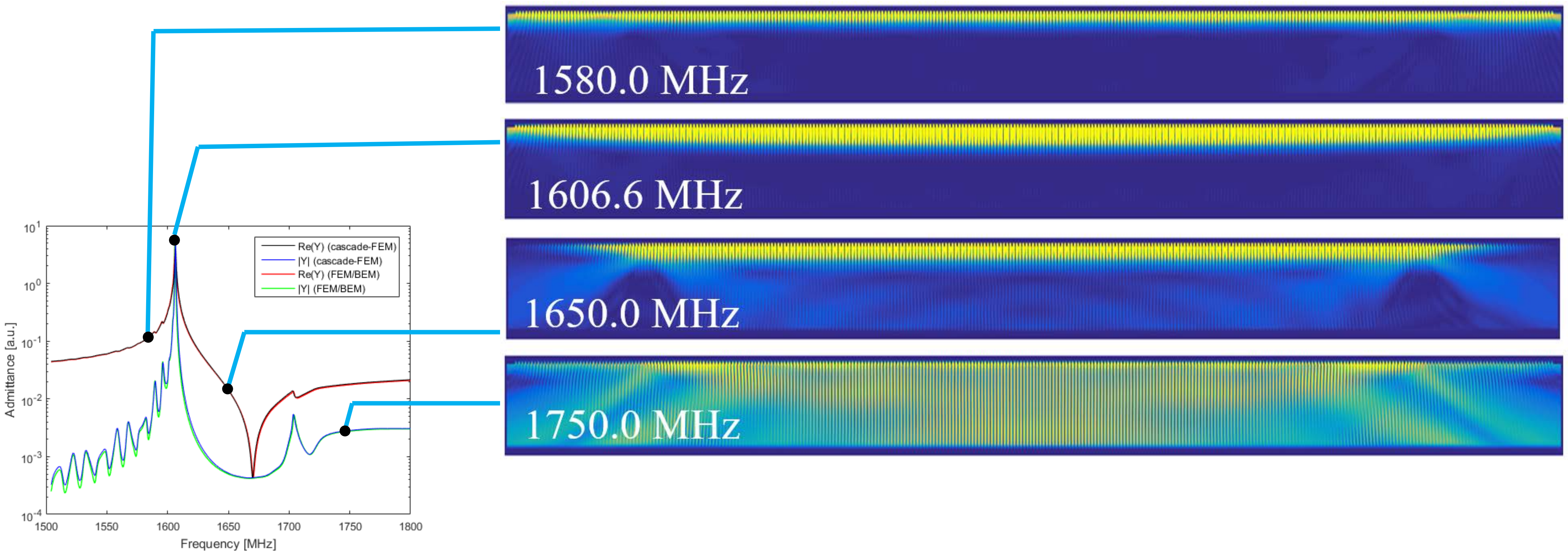
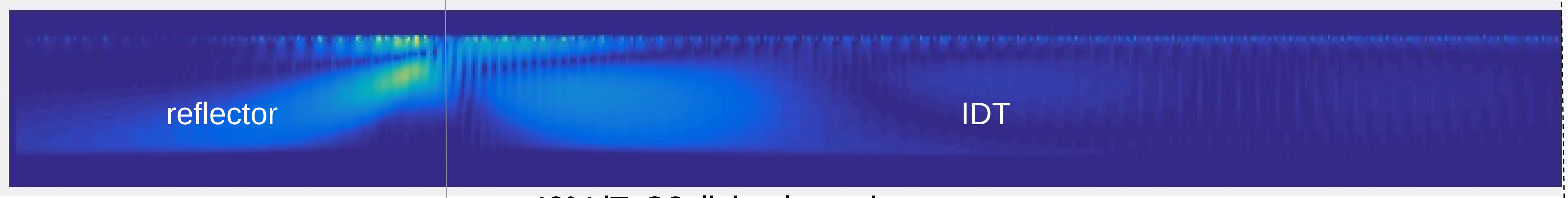
Synchronous Resonator

Shear displacement profiles $|u_y|$ at various frequencies

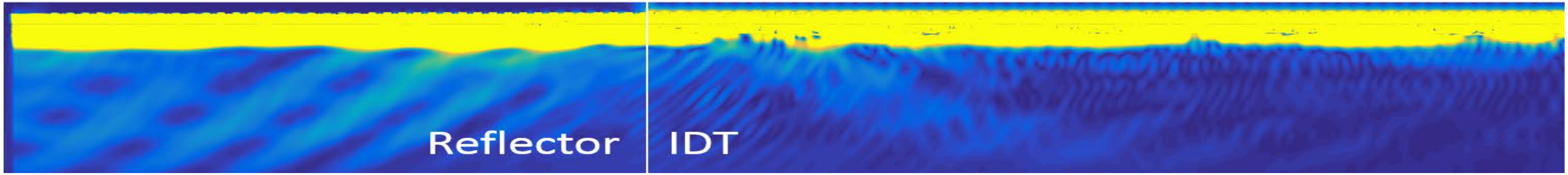


Bulk wave radiation: synchronous resonator

Symmetry line



42° LiTaO3, light electrodes

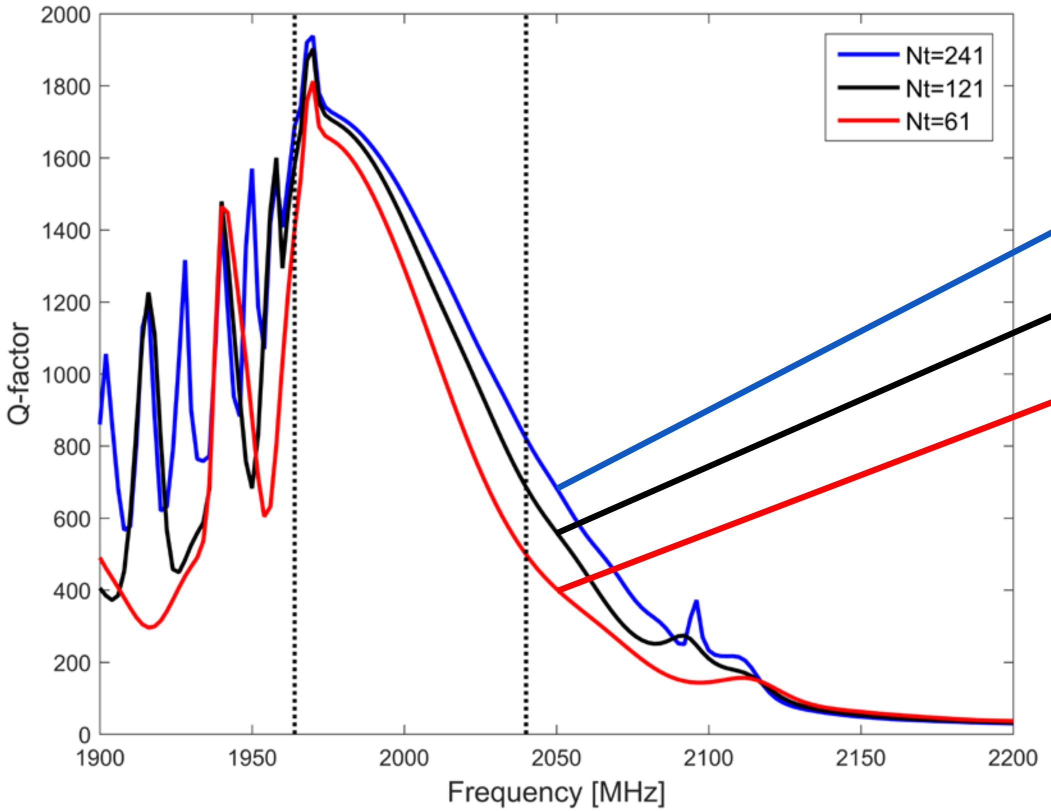


I.H.P.- type structure

More detail see in:

[2] *V. Plessky, J. Koskela, et al., "Acoustic Radiation from Ends of IDT in Synchronous Resonators", paper 5F-4, IUS 2017*

LSAW Resonator on 42°$LiTaO_3$



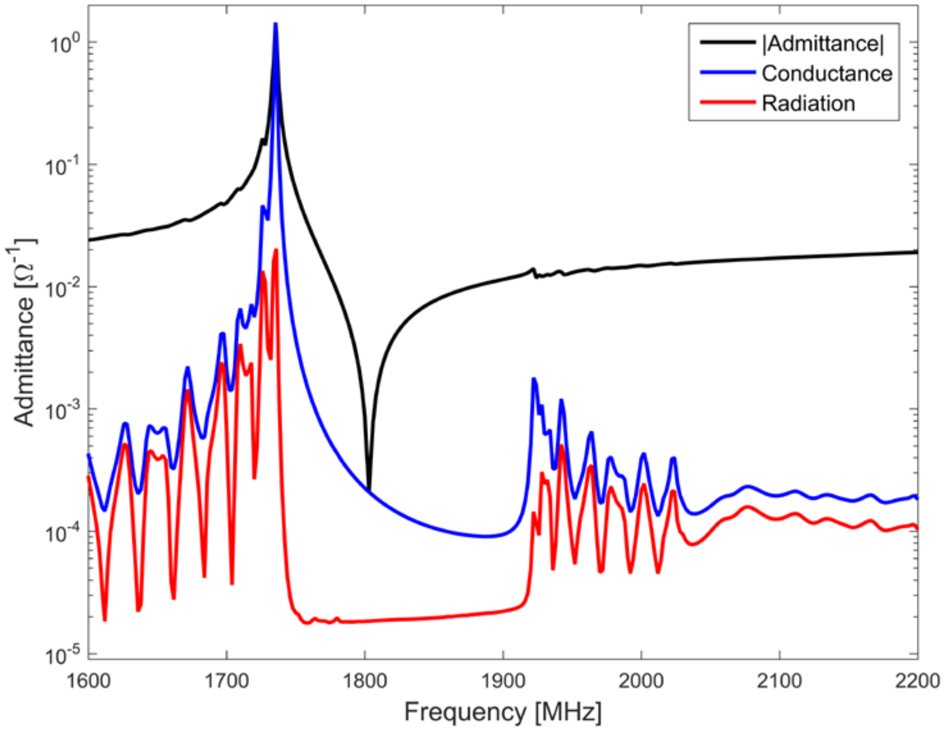
2050 MHz

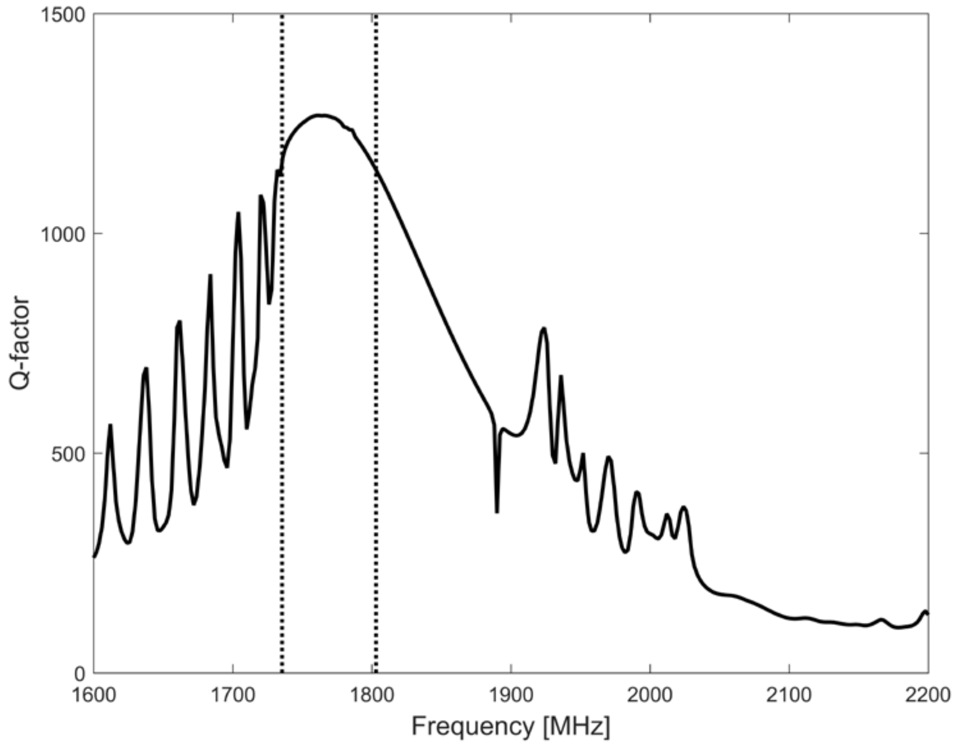
N_t = 241: edges 24%

N_t = 121: edges 47%

N_t = 61: edges 89%

TCSAW Resonator on 128°$LiNbO_3$





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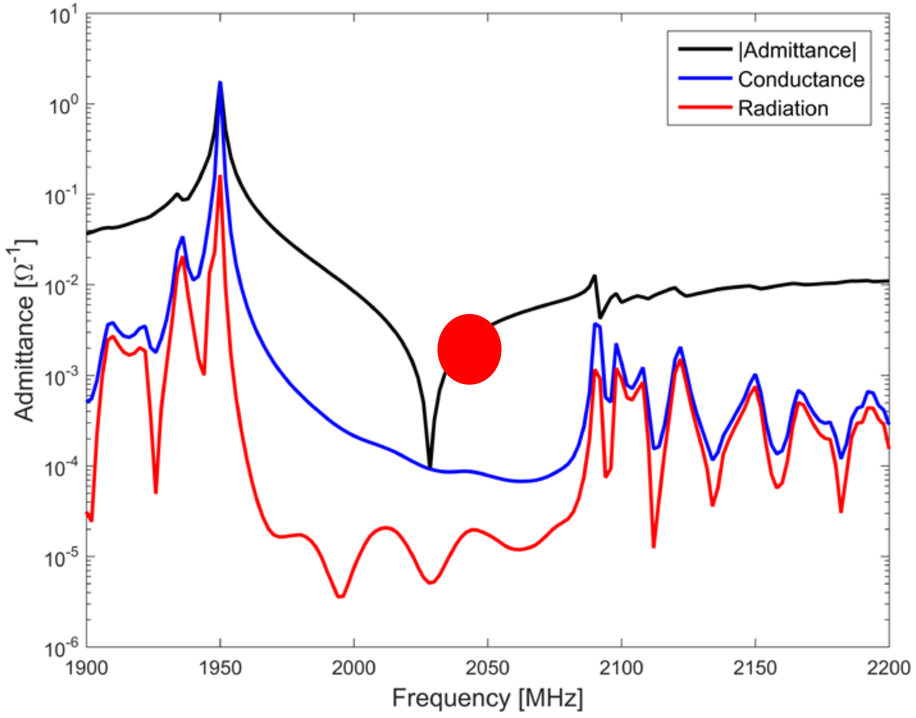
IHP Multi-Layer Resonator

- LSAW → plate-mode wave in thin-film $LiTaO_3$ layer
- constrained below by SiO_2/AlN mirror, silicon substrate
  - single SiO_2 layer is enough in synchronous resonators
  - very thin layers to suppress spurious modes

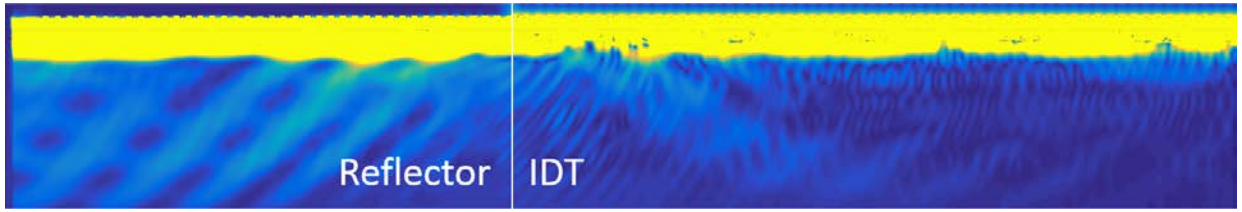
Amazing solution to BAW radiation problems.

T. Takai, H. Iwamoto, Y. Takamine, H. Yamazaki, T. Fuyutsume, H. Kyoya, T. Nakao, H. Kando, M. Hiramoto, T. Toi, M. Koshino, N. Nakajima, *"Incredible high performance SAW resonator on novel multi-layered substrate"*, 2016 IEEE International Ultrasonics Symposium.

IHP Multi-Layer Resonator



p = 1 μm, *8% Al*, $LiTaO_3/SiO_2/AlN$ 1 μm/500 nm/500nm



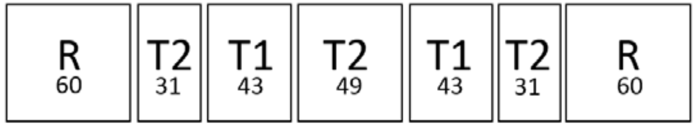
- 2040 MHz
- Essentially free of all BAW radiation
- Tiny residual from IDT edges
- Tiny scattering from reflectors

Coupled-Resonator Filter

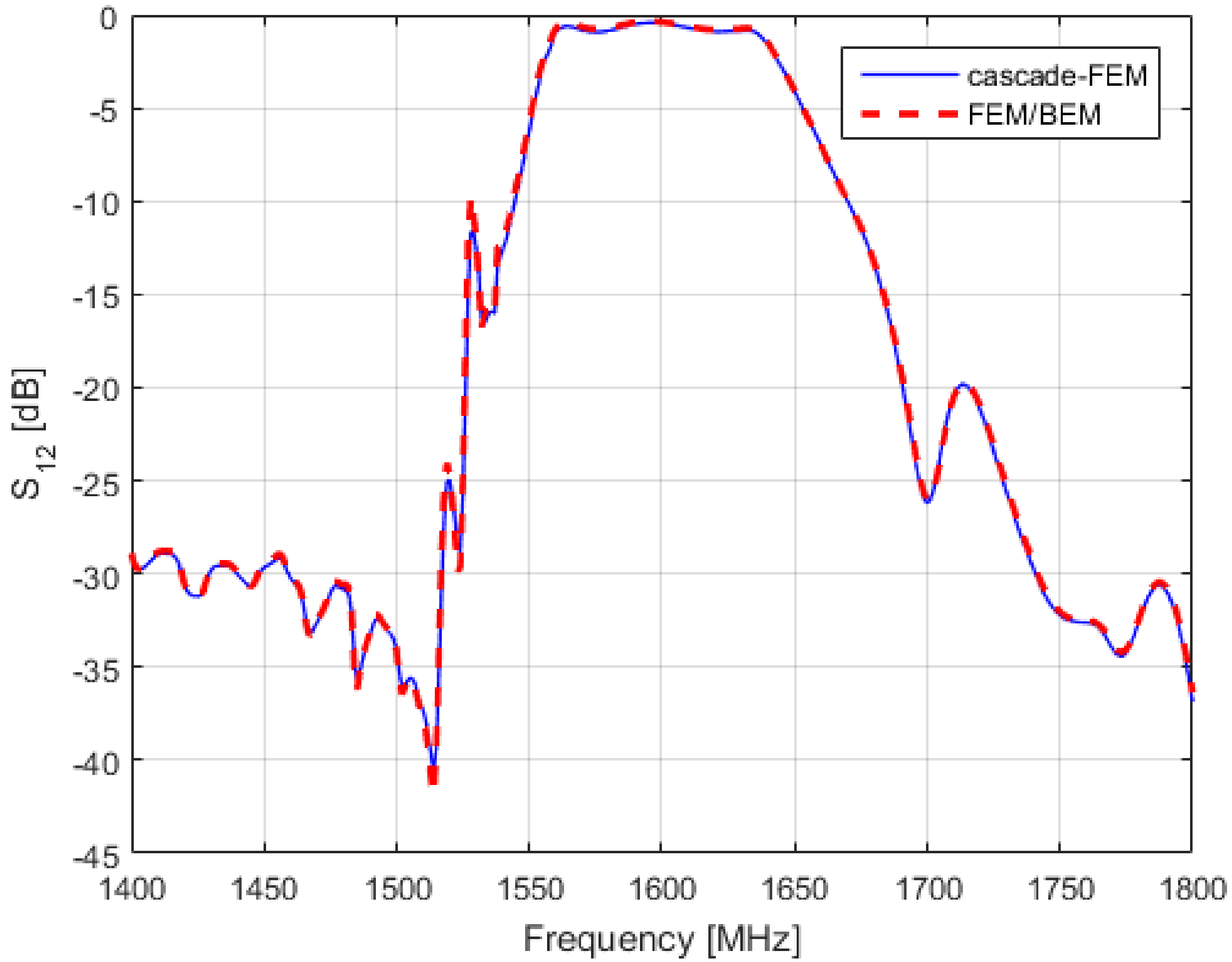
Complex 5-IDT structure

42°YX-cut $LiTaO_3$, Al electrodes $h/\lambda \approx 8\%$

$p = 1.26 \ldots 1.28\ \mu m$, $a/p = 0.6$

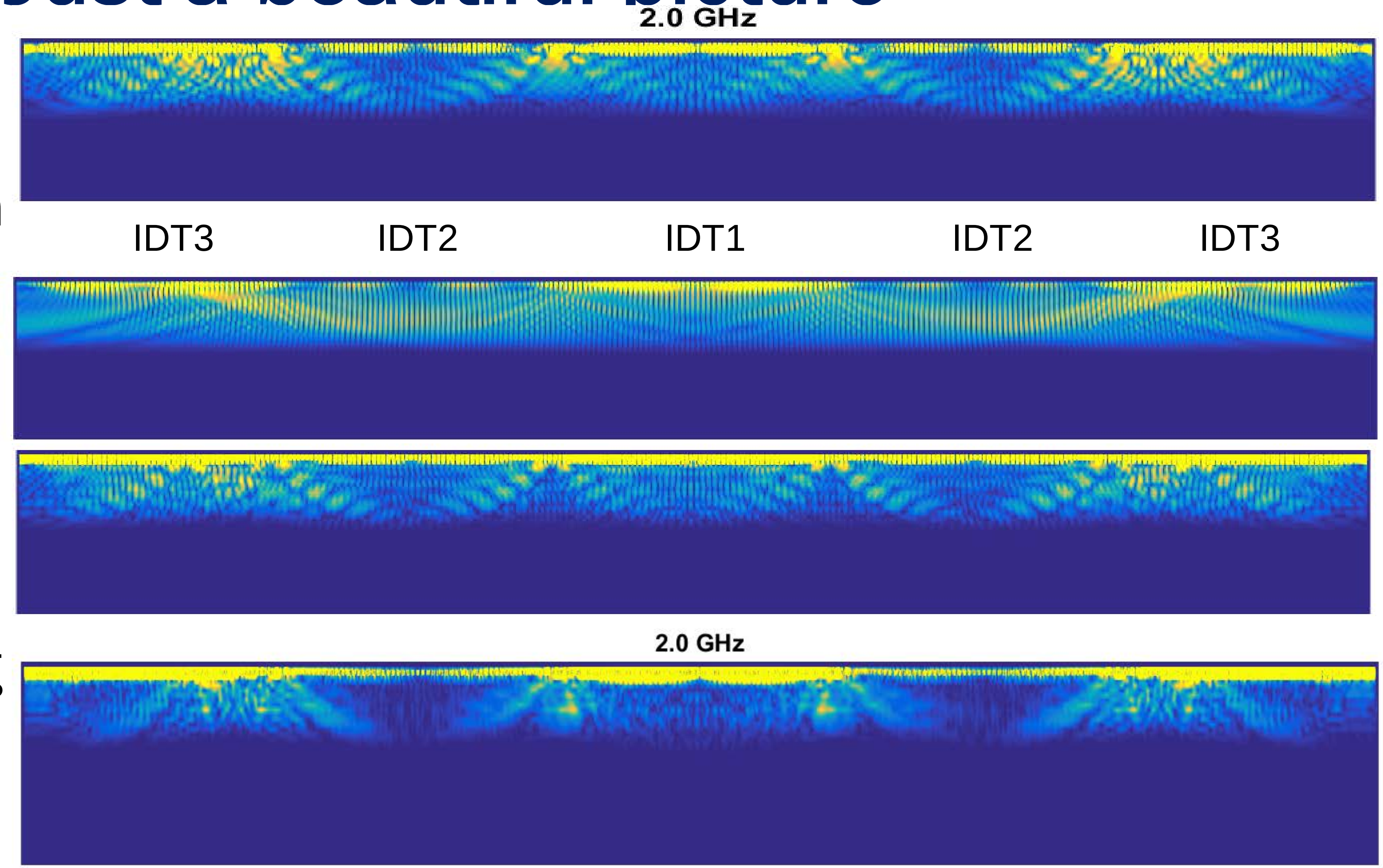


- 6643–7749 DOFs / period
- 15 184 DOFs / PML block
- computation on 4 parallel threads
- simulation time 3.6 s / frequency point
- comparison to FEM/BEM simulation

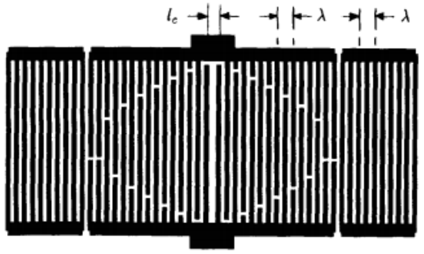


Just a beautiful picture

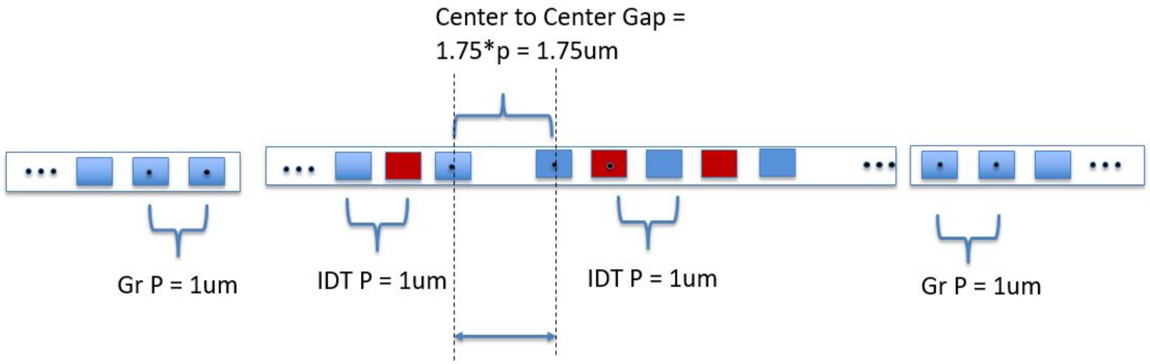
- Complete real TCSAW CRF: we can calculate all fields in all points!
- Simulated |*ux*|, |*uy*|, |*uz*| and power flow (bottom picture) in a TCSAW-coupled resonator filter at 2 GHz, using and M-PML.



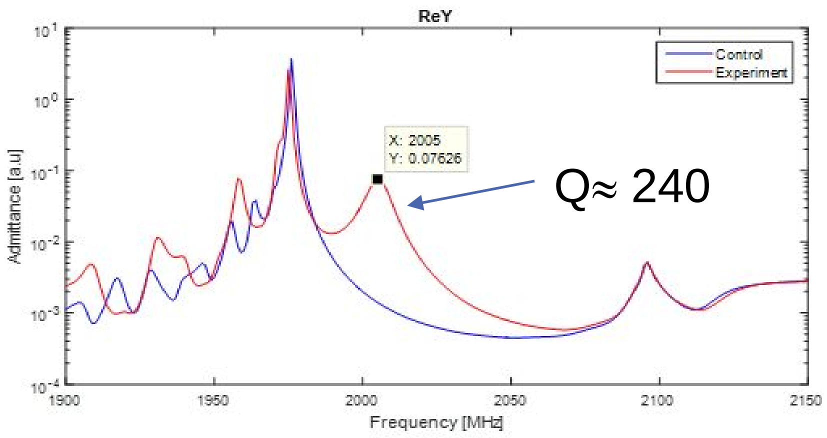
“Hiccup”- like structure

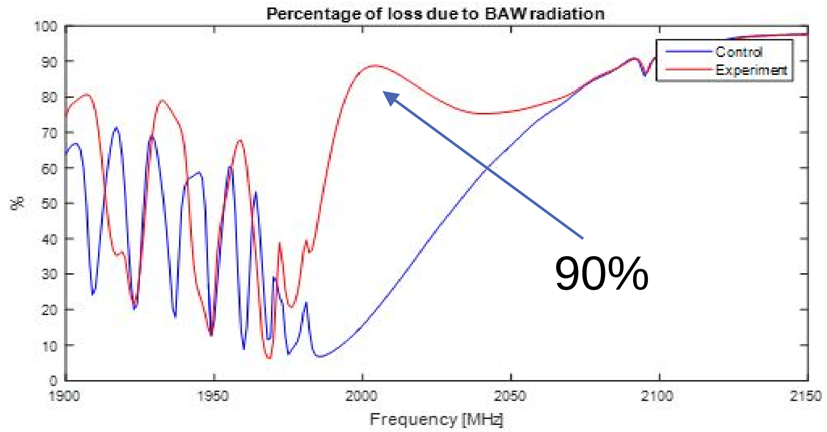


P. Wright’s «hiccup» resonator on ST quarts

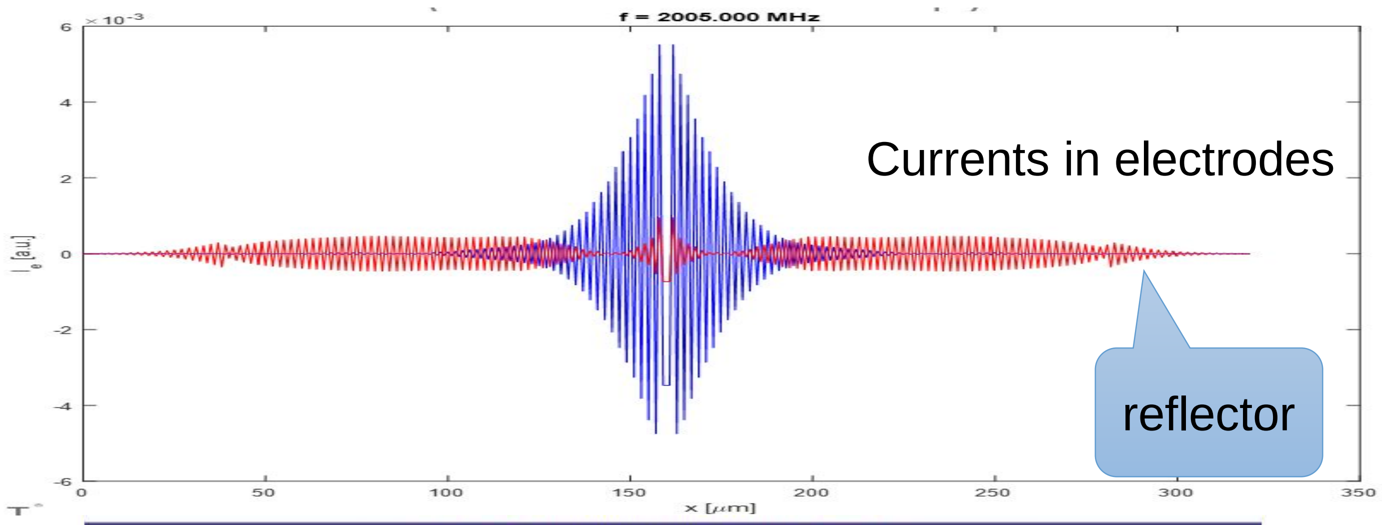


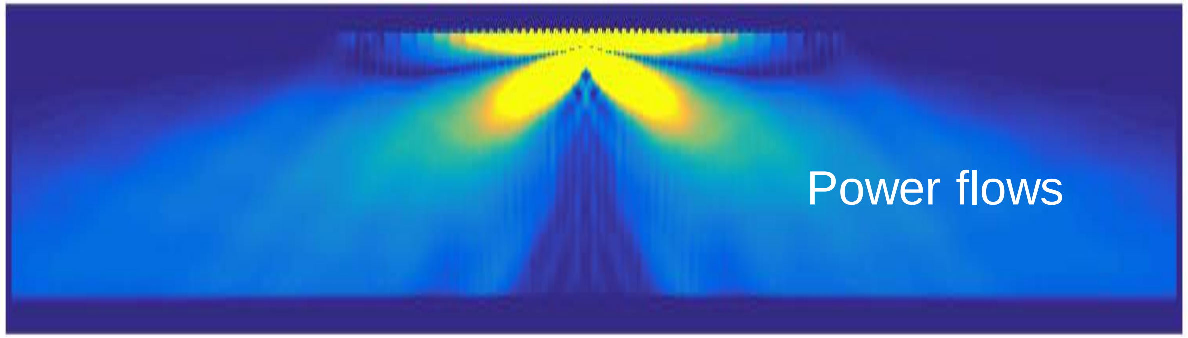
Our structure on 42° LiTaO3, h/λ=8%, Al





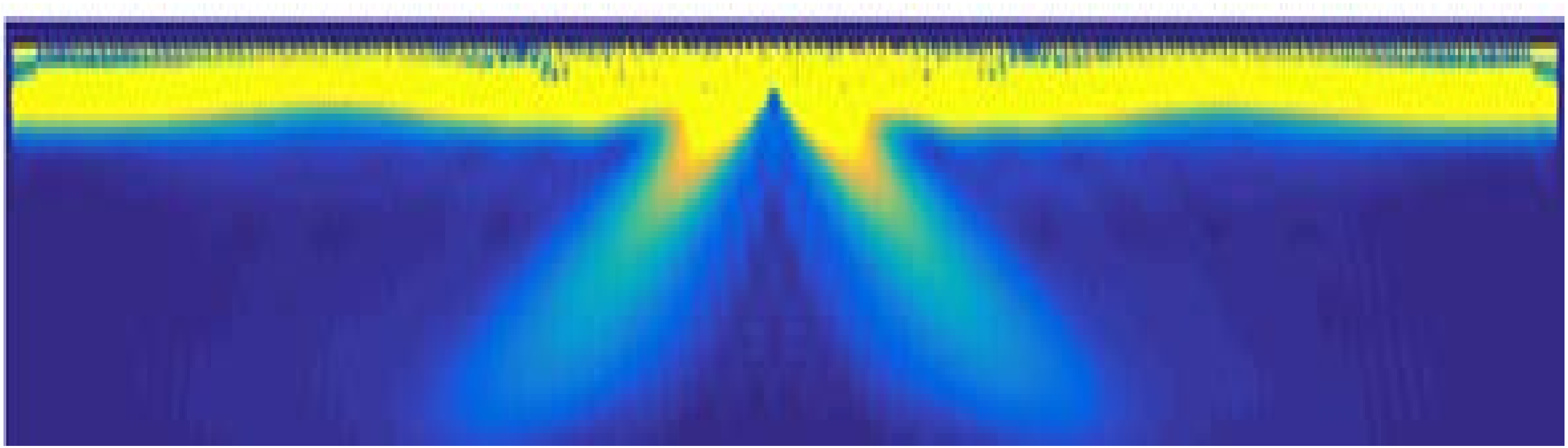
Hiccup resonator on 42°LiTaO3





The device has two resonances: at the left edge of stopband – resonance oflong ransducers And the «hiccup» resonance located near the gap. Because of the high loss, this device is not used on leaky wave substrates. Replacing the gap by a “distributed gap” can significantly reduce the radiation loss.

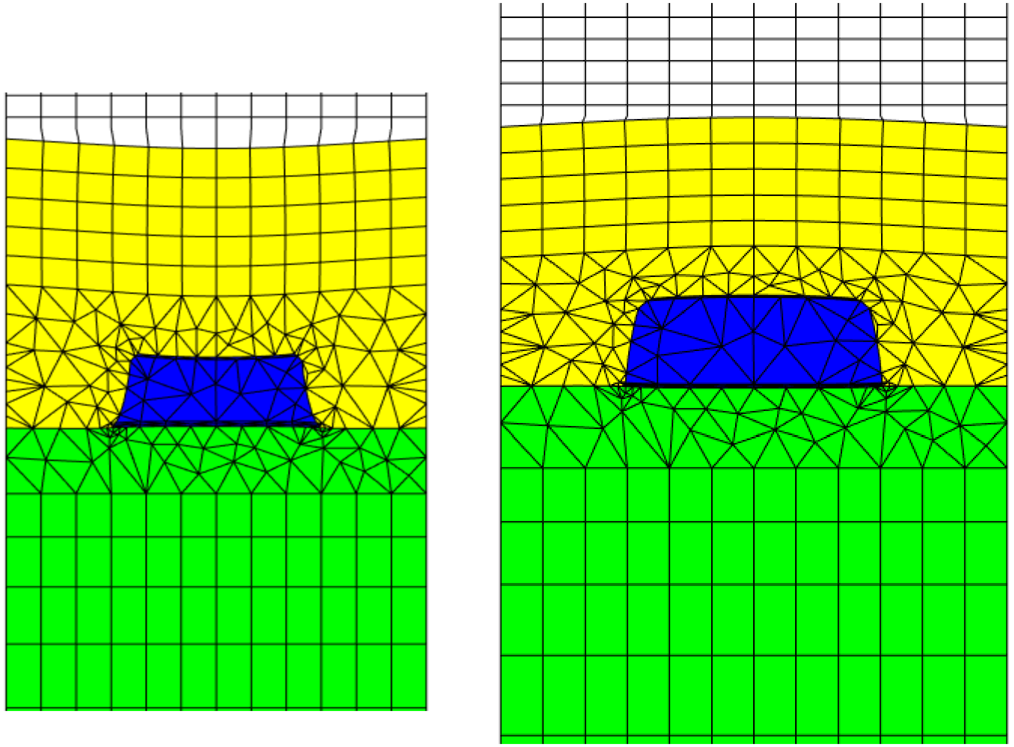
«Hiccup» resonator on I.H.P.- similar structure



Thermal Effects Simulation

We account for:

- Changes in materials parameters with temperature
  - Elastic constants (stiffnesses)
  - Piezoelectric constants
  - Dielectric permittivity
  - Density
- Thermal deformation
  - Generally anisotropic
  - Impacted by fixture (low TCE-substrates and packages, etc.)
  - *Package is not modeled in Layers2 – substrate may expand freely*.



Strongly amplified view

Conclusions

- Hierarchical cascading allows fast, accurate 2D FEM simulation of finite SAW devices.
  - The memory requirements and the achieved computational speed are drastically reduced as compared to conventional FEM.
  - Numerical instability is avoided using multi-axial PML (M-PML)
- Thermal effects can be simulated
- “X-ACT” software can be used for the visualization of acoustic/electric fields at every point in the studied device, including visualization of the accumulated energy, power flows and the quantitative estimation of losses caused by the bulk wave radiation.
  - Conventional LSAW resonators suffer from both distributed BAW radiation from the entire IDT range, and from concentrated BAW radiation from the IDT-reflector edge. Electric discontinuity at the IDT–reflector transition range can contribute significantly to losses, especially at the antiresonance frequency, and in short resonators.