SAW Device/Sensor Modeling for SPICE Simulation : MOS - AK / GSA INDIA 2012

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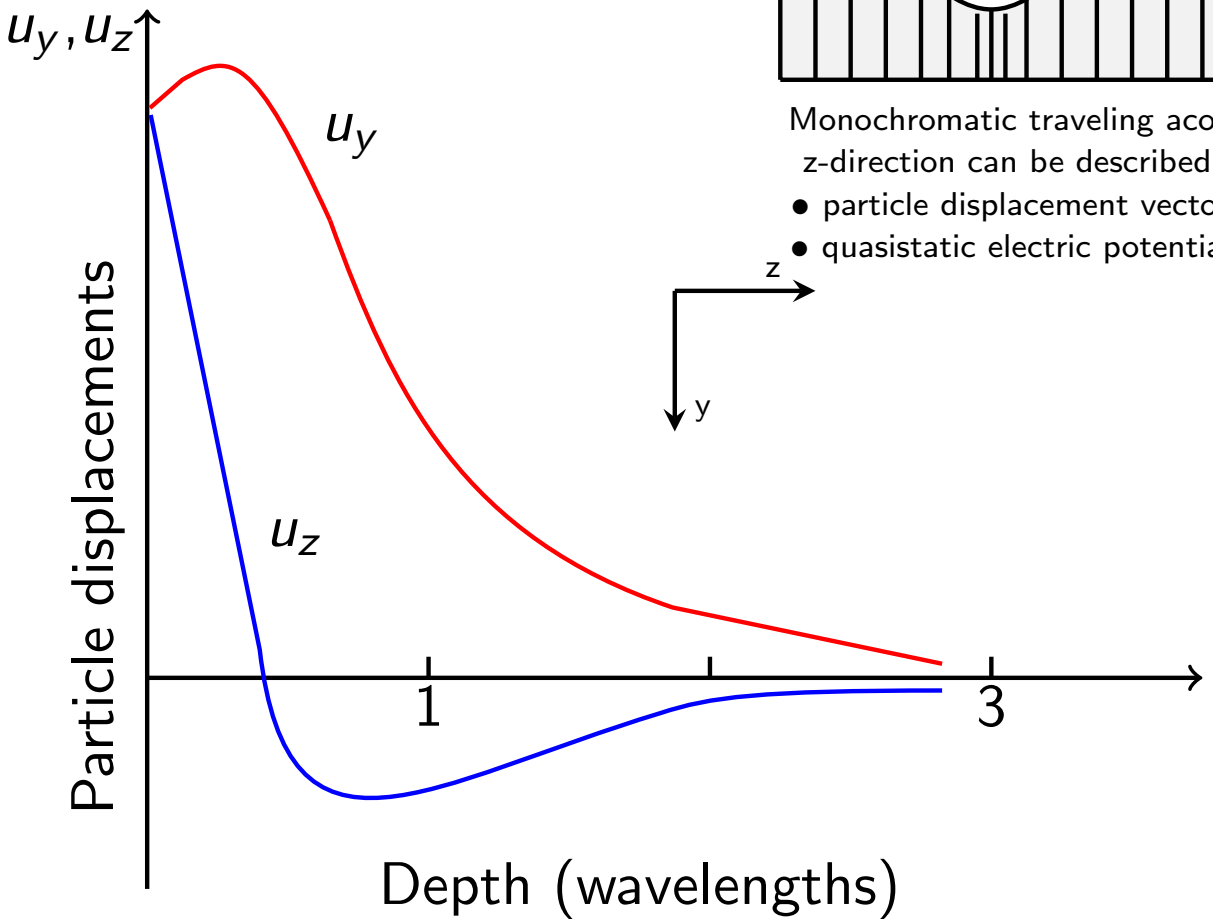
Programs at JIIT

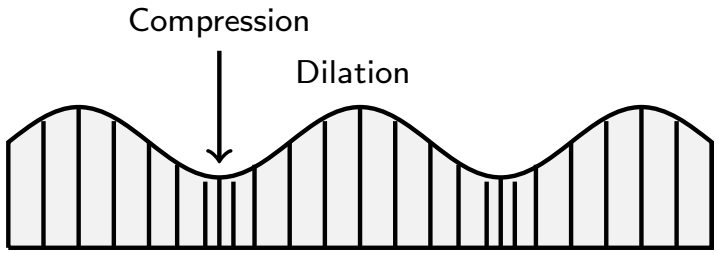
- PASSIVE COMPONENT COMPACT MODELING
  - Physical Modeling of Inductor - Inductor as an interconnect
  - SPICE Modeling of MEMS Micromechanical Structures - Cantilevers, Membranes
  - SAW Sensor Modeling
  - High Temperature MOS Modeling

Agenda

- SAW Basics
- Motivation
- Primitive Structures
- Benchmark Circuits
- Benchmark Tests
- Motivation For SAW SPICE Modeling
- Mason Equivalent Circuit
- SPICE Modeling
- Capacitance Modeling
- Simulation
- Validation
- Model Integration to SPICE Simulator in Verilog-A
- Conclusion
- References

SAW Basics





Monochromatic traveling acoustic wave in z-direction can be described by :

- particle displacement vector u(z,t),
- quasistatic electric potential $\phi(z, t)$

SAW Basics

- Surface Acoustic Wave(Rayleigh Wave) excitation on the surface of a piezoelectric substrate through interdigital transducer was realized by R.M. White[3], at the University of California, Berkeley in early 70's by R.M. White.
- The alternating electric field applied between finger pairs of IDT periodic strain field in the piezo-substrate to standing acoustic wave $\Rightarrow$ Propagating bidirectional wave in the medium.
- The elastic wave generated $\Rightarrow$ composition of compressional and shear waves in a fixed ratio.
- Typical mechanical wave velocity 3×10^5 cm/sec. $\Rightarrow$ Five order smaller than EM Wave Velocity $\Rightarrow$ Miniaturization of electronic components.
- SAW IDT structures are realized by standard micro lithographic technique.

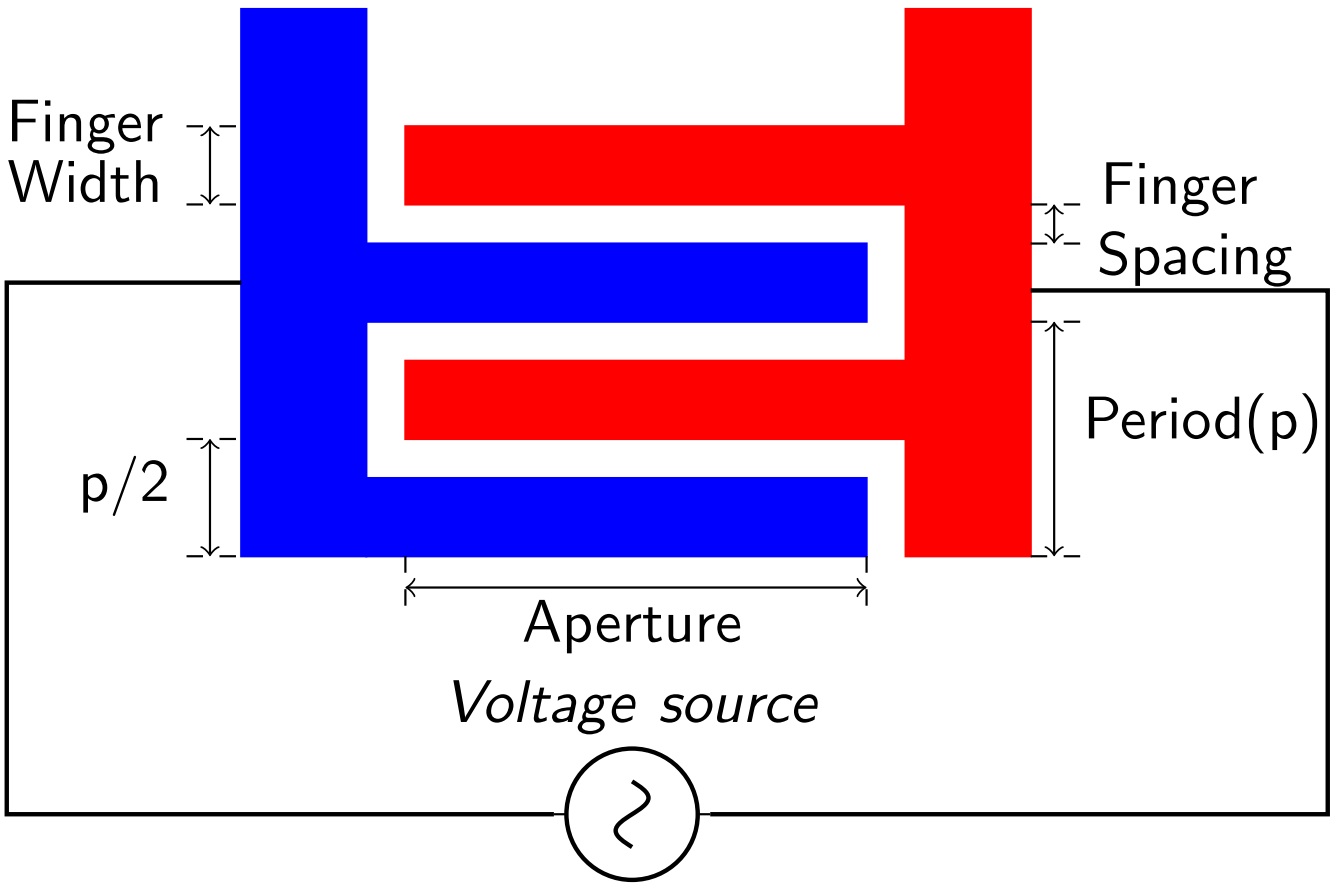
SAW Basics

- The Wave Energy is confined within wavelength distance/depth of the substrate $\Rightarrow$ acts as a wave guide.
- Surface confinement of wave energy makes it extremes sensitive to surface perturbation $\Rightarrow$ sensor application.
- Surface Potential of Wave / Applied voltage to IDT = Transfer Function $=\phi^{\pm} = \mu_s V_1$, where μ_s = substrate dependent (Freq. Independent)
- $\phi^{+}(z) = \mu_s \sum_{n=0}^{n-1} V_n \exp \text{ jk(z-}z_n\text{)}$, z_n : position of nth fingers pair.

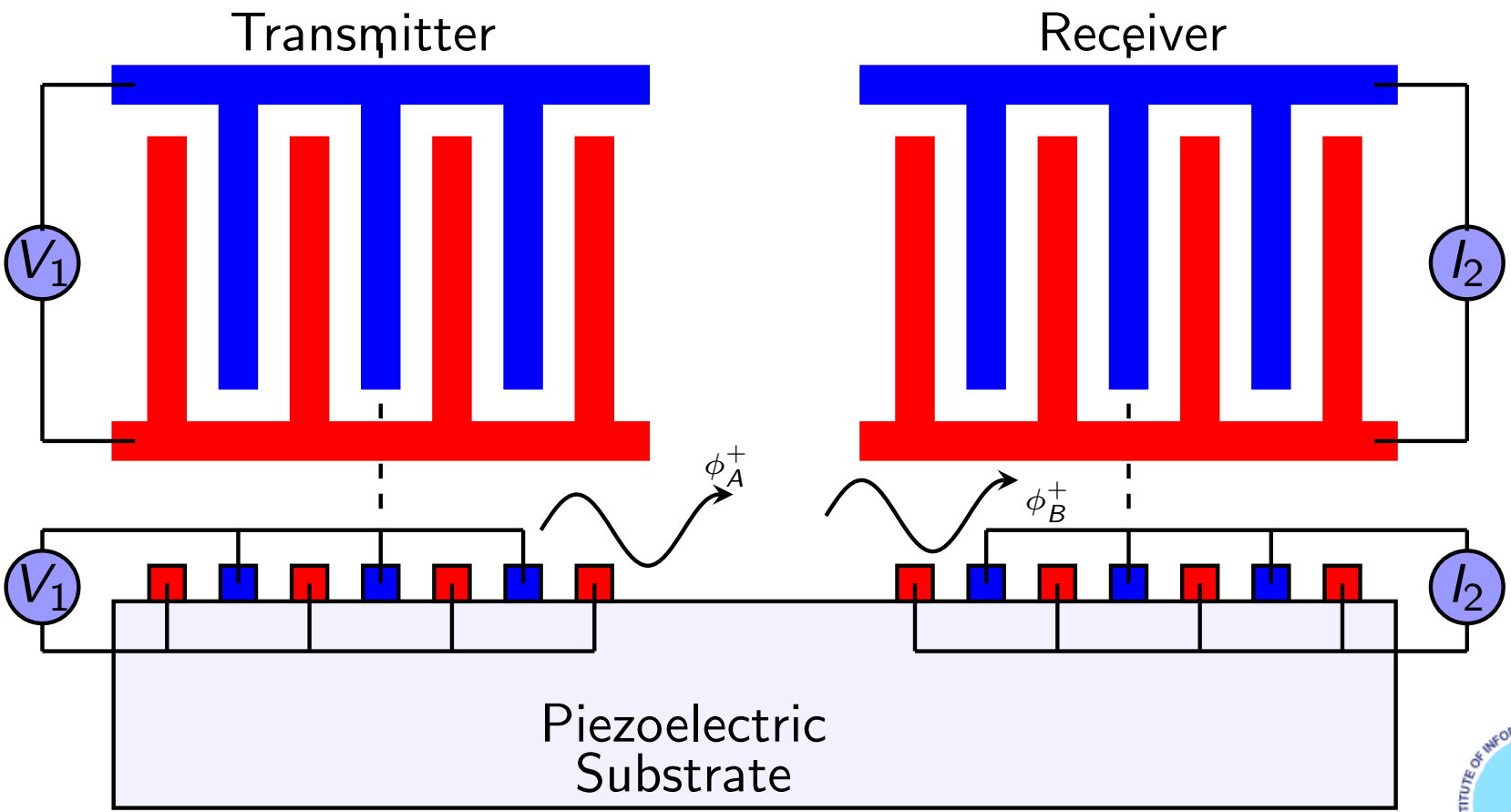
Motivation

- Surface Acoustic Waves are sensitive to
  - Ambient Temperature
  - Forces
  - Acceleration
  - Electric Field Strength
  - Dew Point
  - Gas concentration
  - Gas Flow
  - Pathogens,E-coli, virus, bacteria, DNA
  - Gas trace in environment(e-nose)
  - Automobile emission
- A wide range of sensors
  - In Communication:
    Delay Line, Band pass filters, Dispersive filters, Resonators, Convolvers, Correlators, RF ID...

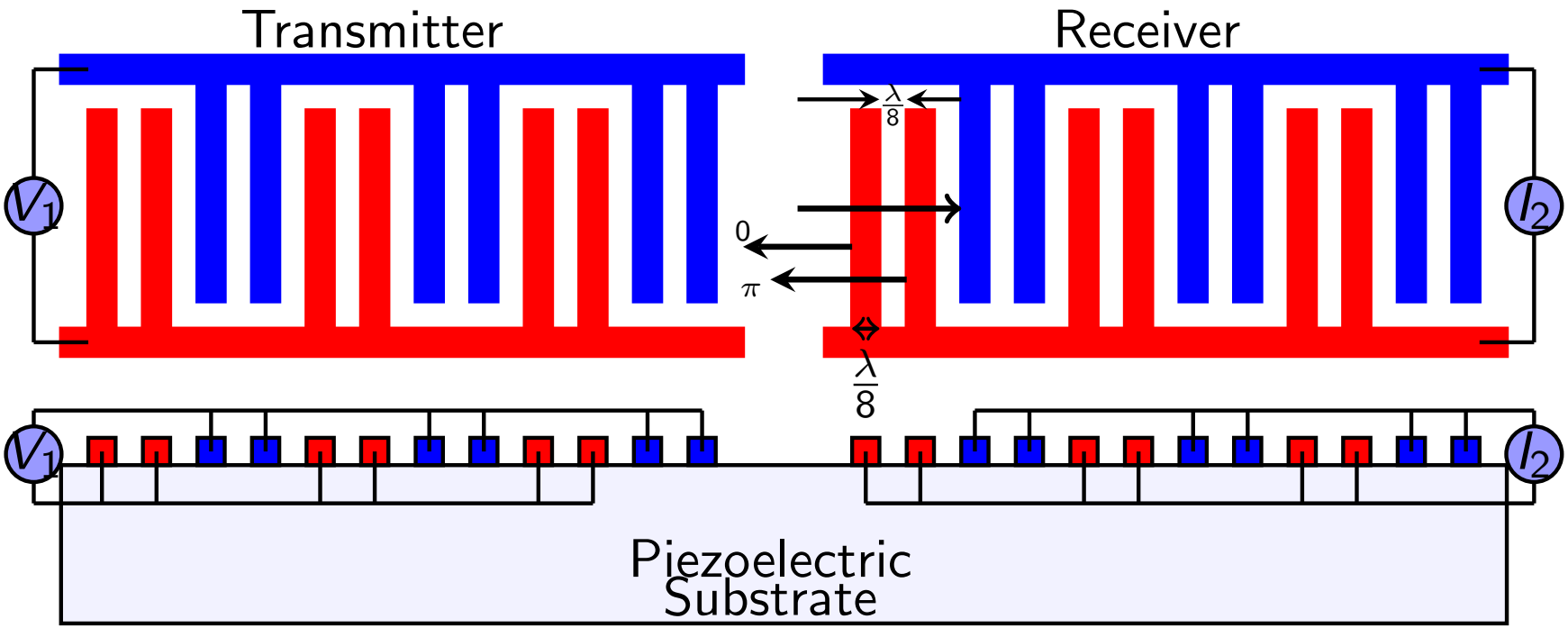
Primitive IDT Structures - I



Primitive IDT Structure - II Delay Line



Double-Electrode IDT Structure $\Longrightarrow$ Cancellation of Reflection from Metal Electrodes



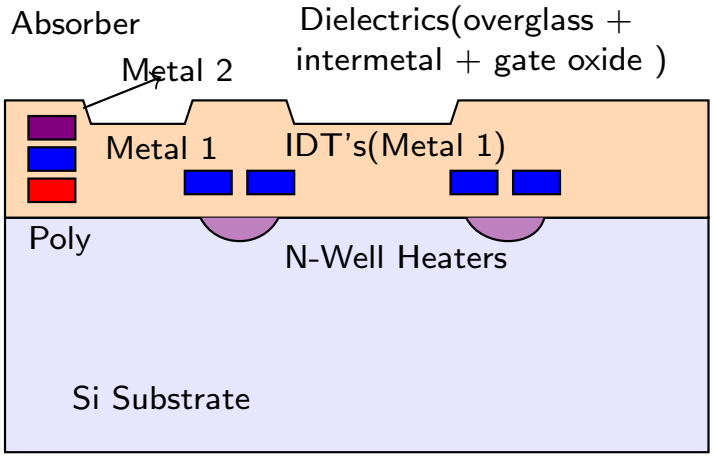
$$\frac{\Delta z}{z_0} = R_P \cdot \frac{K^2}{2} + R_m \cdot \frac{h}{\lambda} + \left(\frac{h}{\lambda}\right)^2 \quad [\text{For } \frac{h}{\lambda} << 0.2\%]$$

$\frac{\Delta \nu}{\nu} \approx \frac{K^2}{2}$

Mechanical loading

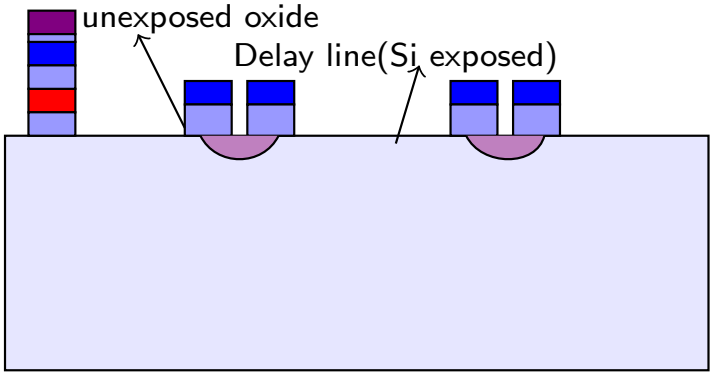
Energy storage

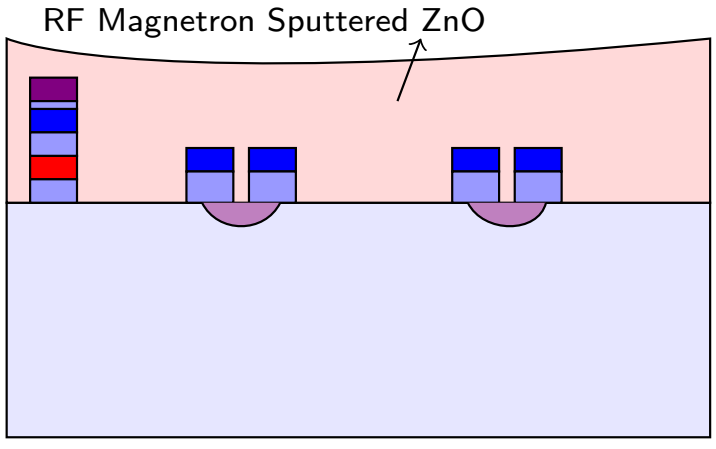
Monolithic SAW Structure : SAW -on - Silicon$(S - O - S)_{[12]}$



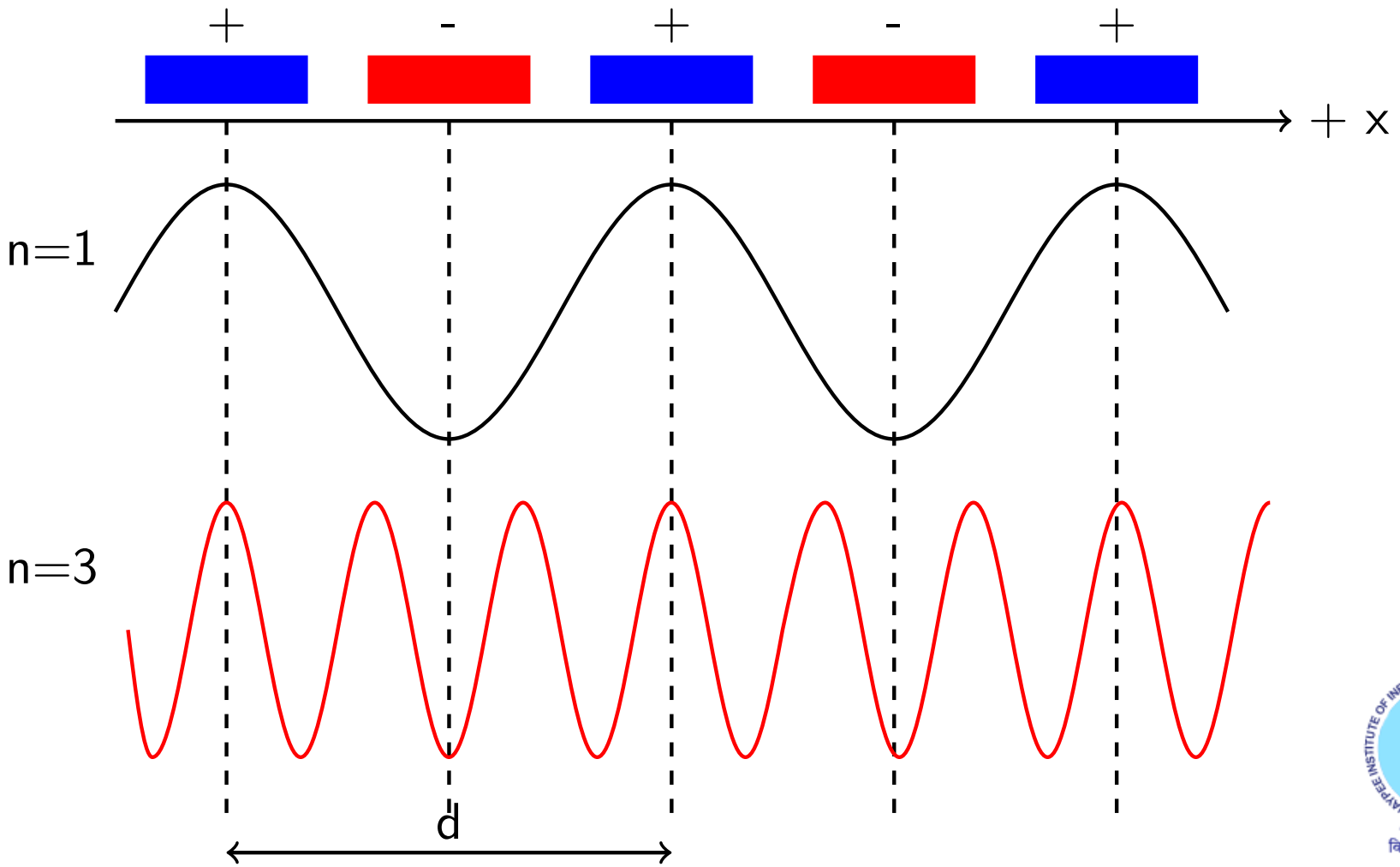
ZnO/Si in CMOS Technology

S/i(Smart/Intelligent) SAW

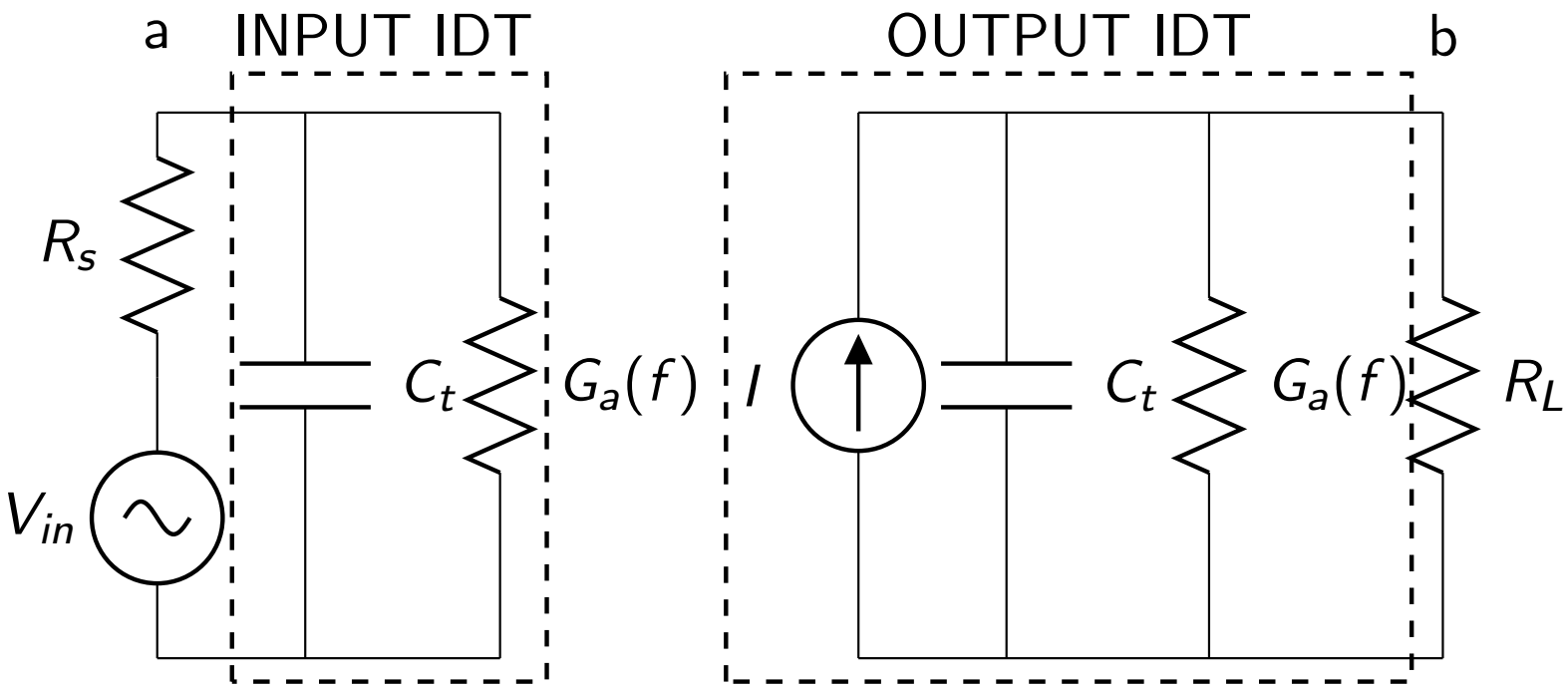




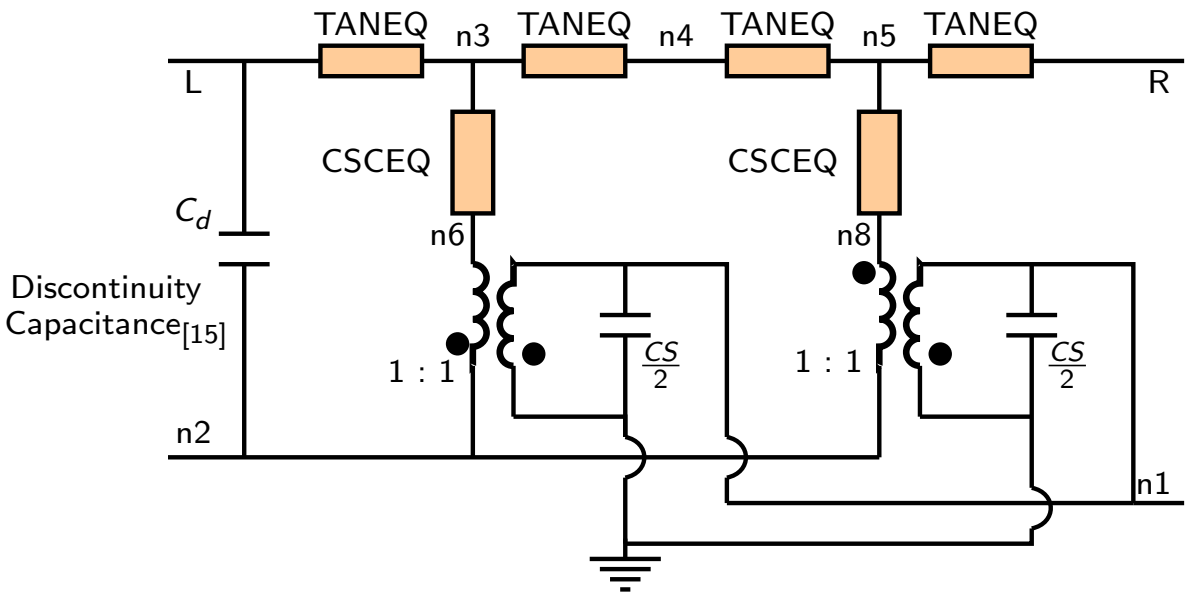
Relationship between Transducer Periodicity and Coherently Excited Waves



Input / Output Equivalent for a SAW Delay Line



Mason Crossed-Field Model[13]

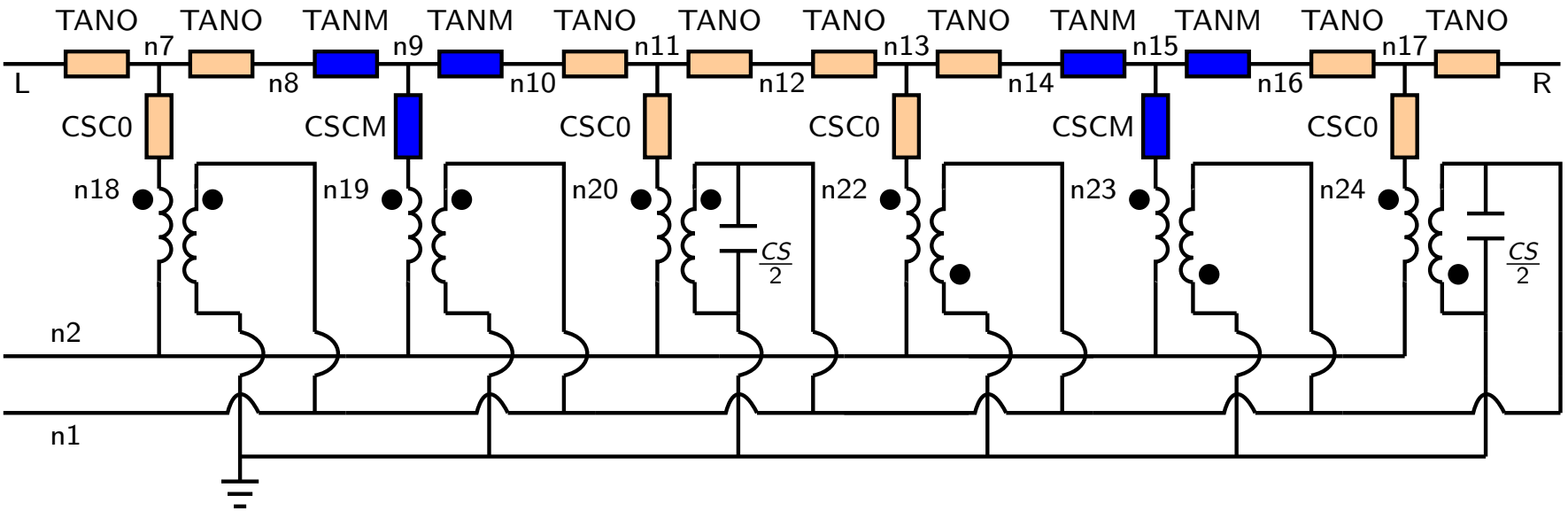


$$TANEQ = jZ_0 \tan\frac{\theta}{2},\ CSCEQ = -jZ_0 csc\theta,\ \theta = \pi\frac{f}{f_0},\ Z_0 = \frac{1}{k^2 C_s f_0},\ f_0 = \frac{\nu_0}{L}$$

k : electromechanical coupling constant ; C_s : electrode capacitance per section

ν_0 = SAW velocity for free region ; L : the length of one period

Mason Modified Crossed-Field Model[13]



$$TAN0 = jZ_0 \tan\frac{\theta_0}{2},\ CSC0 = -jZ_0 csc\theta_0,\ TANM = jZ_m tan\frac{\theta_m}{2},\ CSCM = -jZ_m csc\theta_m,$$

$$\theta_0 = \frac{\pi}{4}\frac{f}{f_0},\ \theta_m = \frac{\pi}{2}\frac{f}{f_m},\ Z_0 = \frac{1}{k^2 C_s f_0},\ Z_m = \frac{1}{k^2 C_s f_m},\ f_0 = \frac{\nu_0}{L},\ f_m = \frac{\nu_m}{L}$$

k : electromechanical coupling constant ; C_s : electrode capacitance per section

ν_0 = SAW velocity for free region ; ν_m : SAW velocity for metallized region ; L : the length of one period

Foster's Equivalent Network Steps to SPICE Modeling contd...

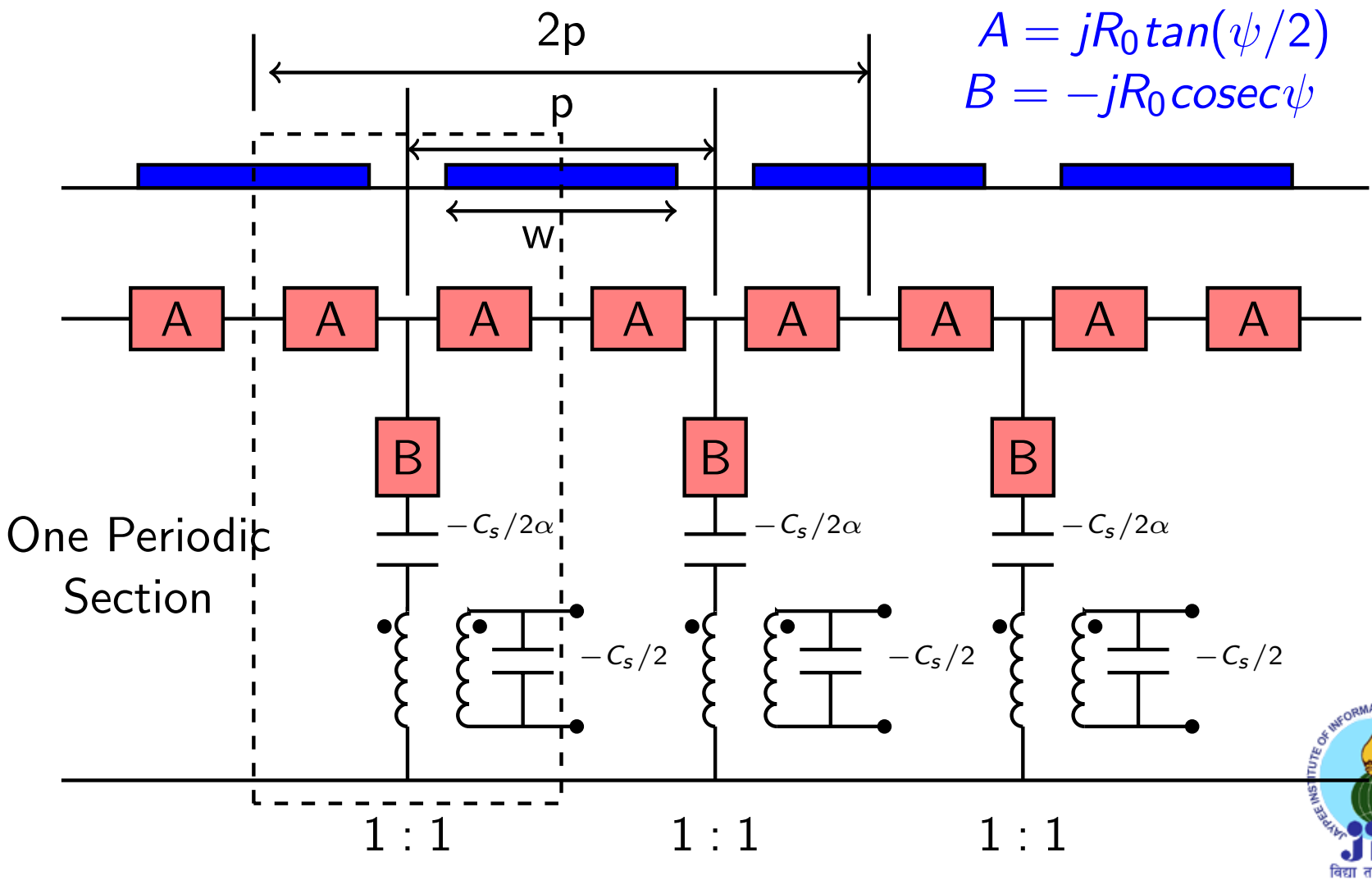
- T-network elements represent lossless transmission lines. The transformer figures due to electromechanical coupling of the piezoelectric medium.
- The entire transducer is consisting of N periodic section is in cascade acoustically and is parallel electronically.
- Mason's crossed-field model is believed to produce closer agreement with experimental data.
- The modeling part can be resolved into following components.

1. Transducer modeling(Transmitter and Receiver).
2. Delay path between Transmitter and Receiver
   $\Rightarrow$ perturbed/unperturbed.
3. Interface electronics modeling(matching network, layout parasitics, bonding/packaging and pcb integration, signal processing circuits etc.)

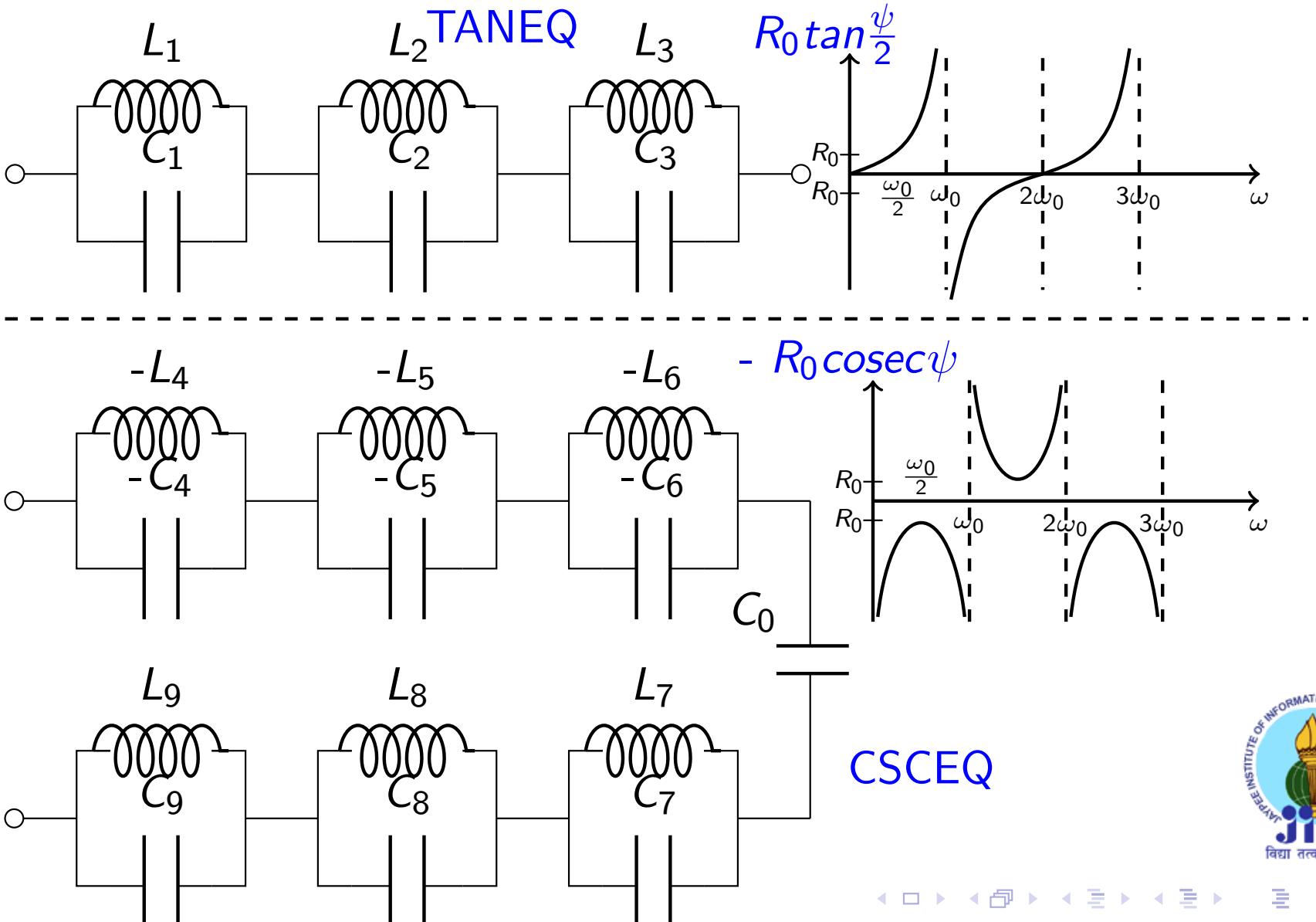
Foster's Equivalent Network

- In Mason's model, TANEQ, CSCEQ, TAN0, TANM, CSC0, CSCM are frequency dependent.
- Proposed model replaces above terms by LC network obtained using Foster's method yielding a network corresponding to the given functional behavior.
- Foster's method states that an input impedance function can be completed specified by a network
  - through its poles and zero locations and
  - its value at some non-zero / non-pole frequency.
- For compact modeling to ensure computational stability a small quantity($\epsilon > 0$) has been added to pole and zero frequencies without disturbing the function.

Mason's Circuit Representation of IDTs



SPICE Macro Model for SAW



Benchmark Circuits[9]

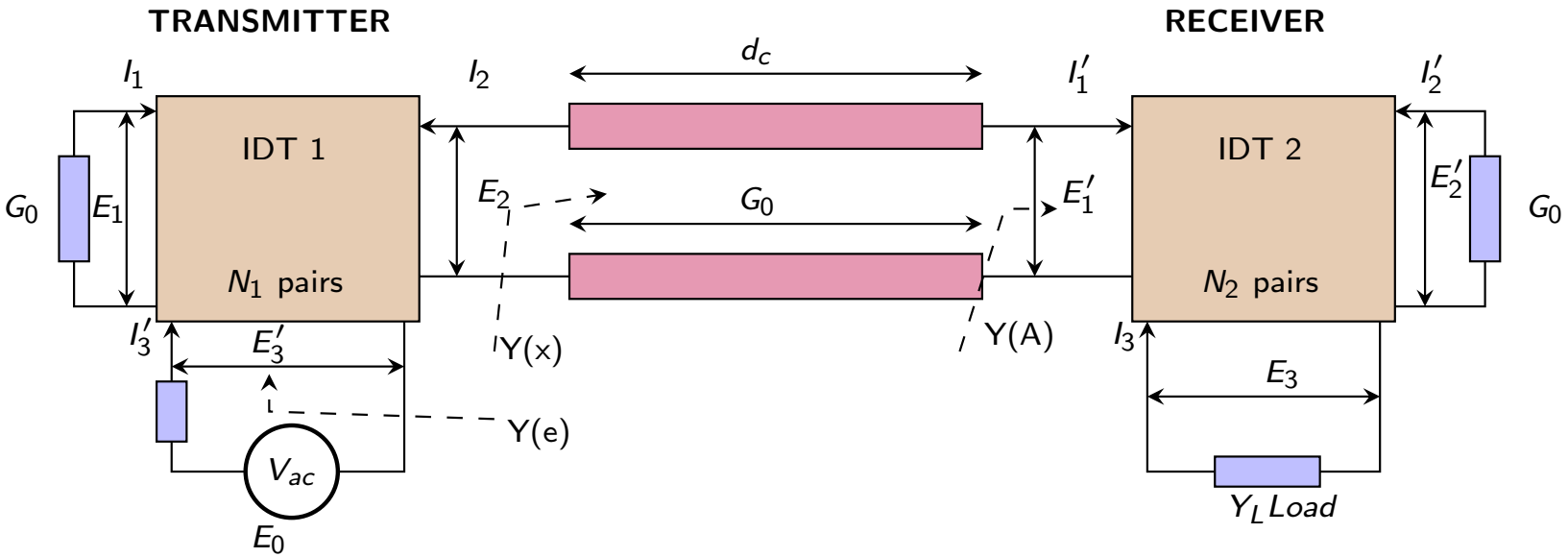


Figure: Complete model of a SAW device

Y(A), Y(x) = Acoustic Input Admittance

Y(e) = Primary - Input Admittance

$A_{3G} = \frac{E_3}{E_G}$; $A_{23} = \frac{E_2}{E_3}$; $A_{21} = \frac{E_1'}{E_2}$; $A_{31} = \frac{E_3'}{E_1'}$; Voltage ratio

Benchmark Tests IDT Frequency Response - Solid Structure

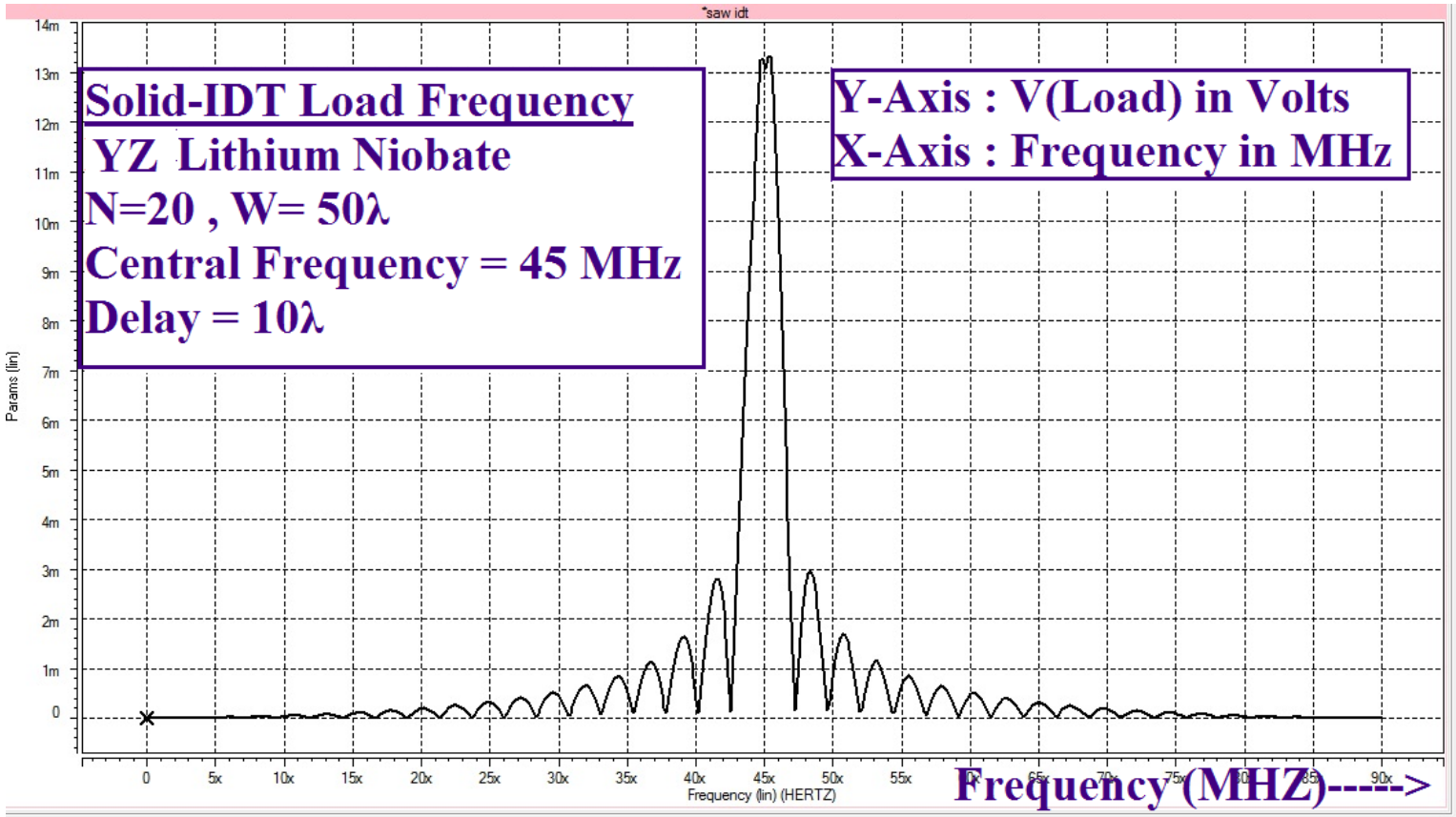


Figure: IDT Frequency Response - Solid Structure Load Characteristics

SAW Amplitude for 1V on IDT Terminal for $LiNbO_3$

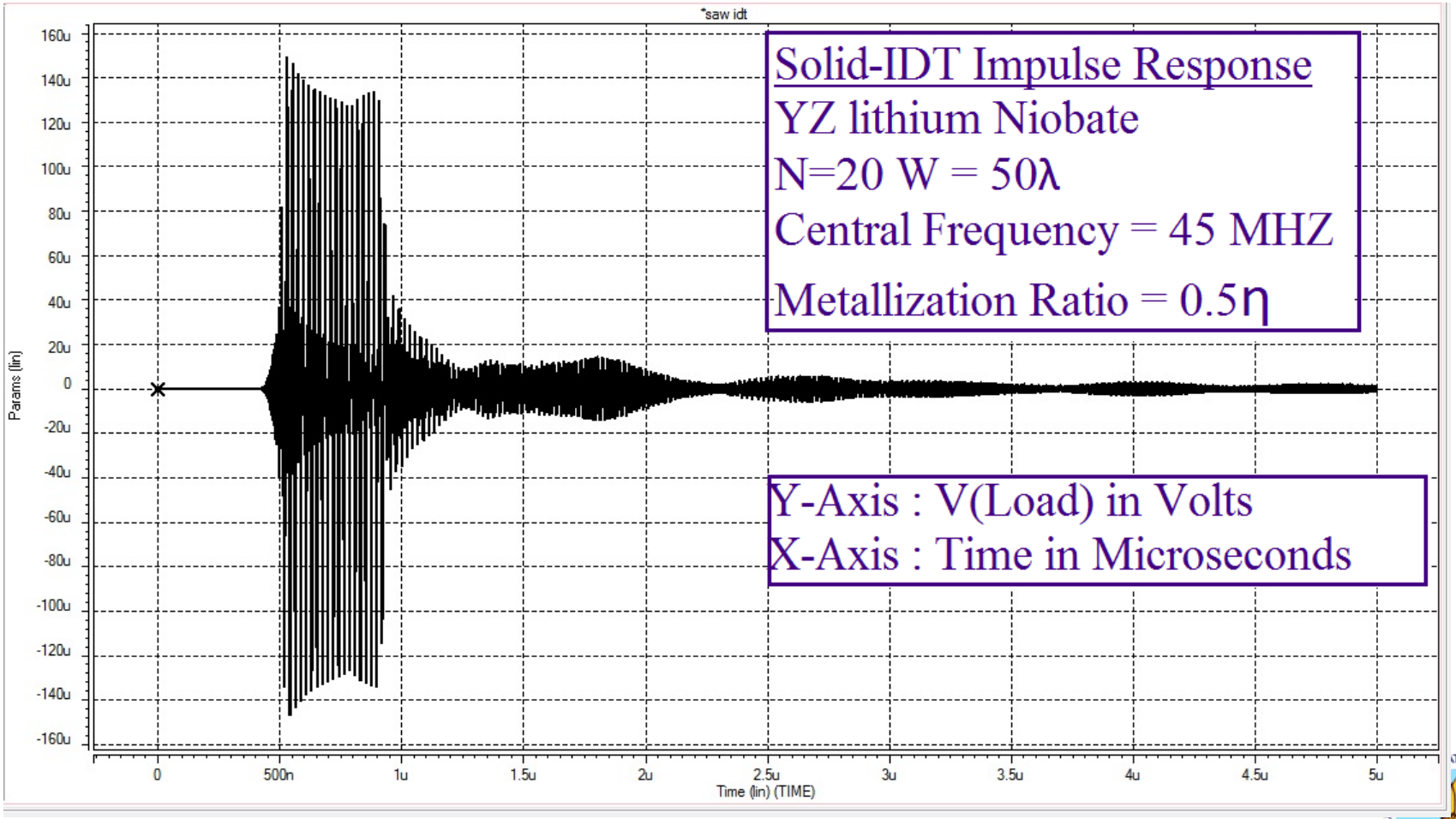


Figure: Overall SAW Impulse Response

Insertion Loss:Tuned SAW Insertion Loss($R_a G_a = 1$)[1]

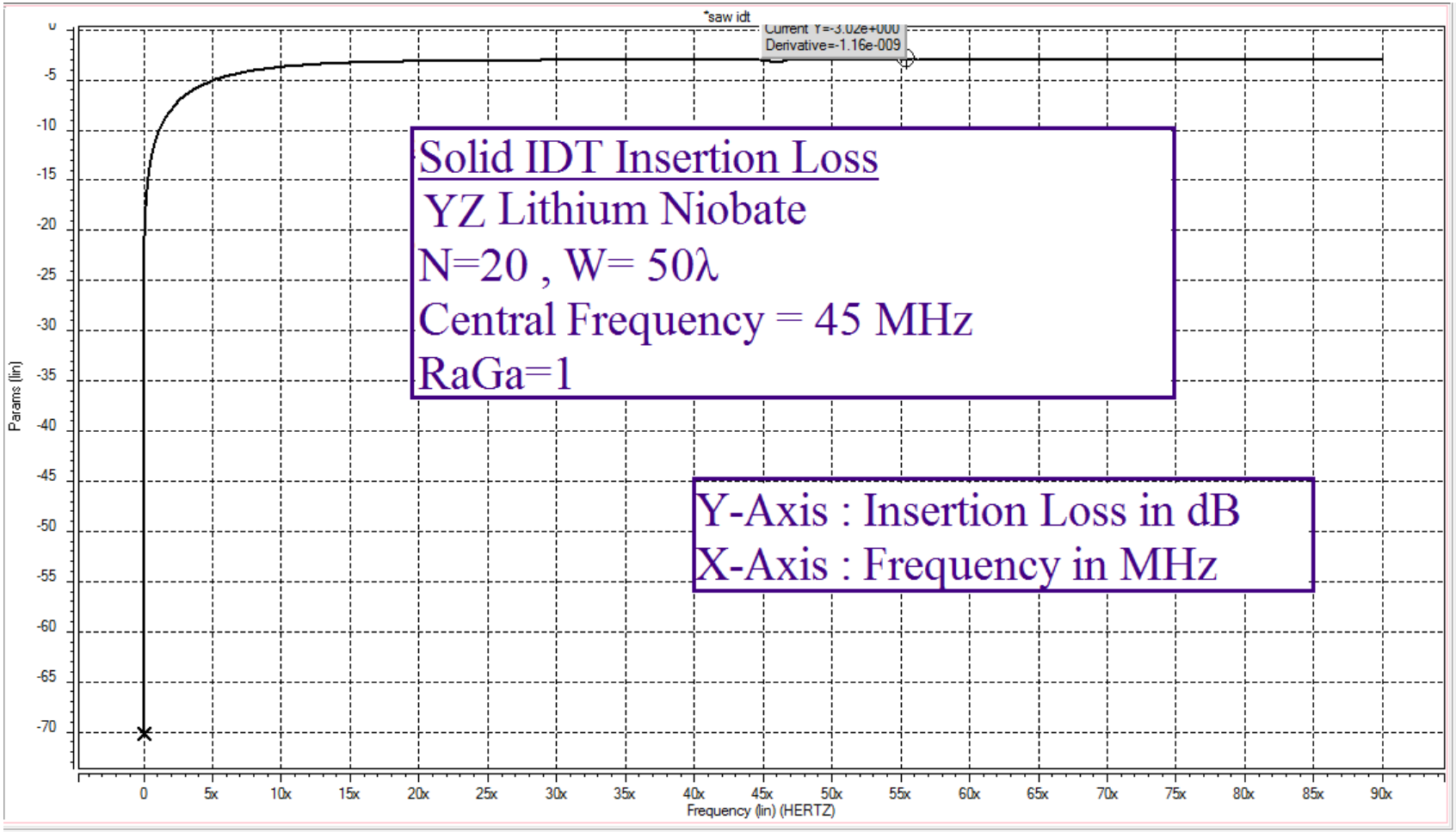
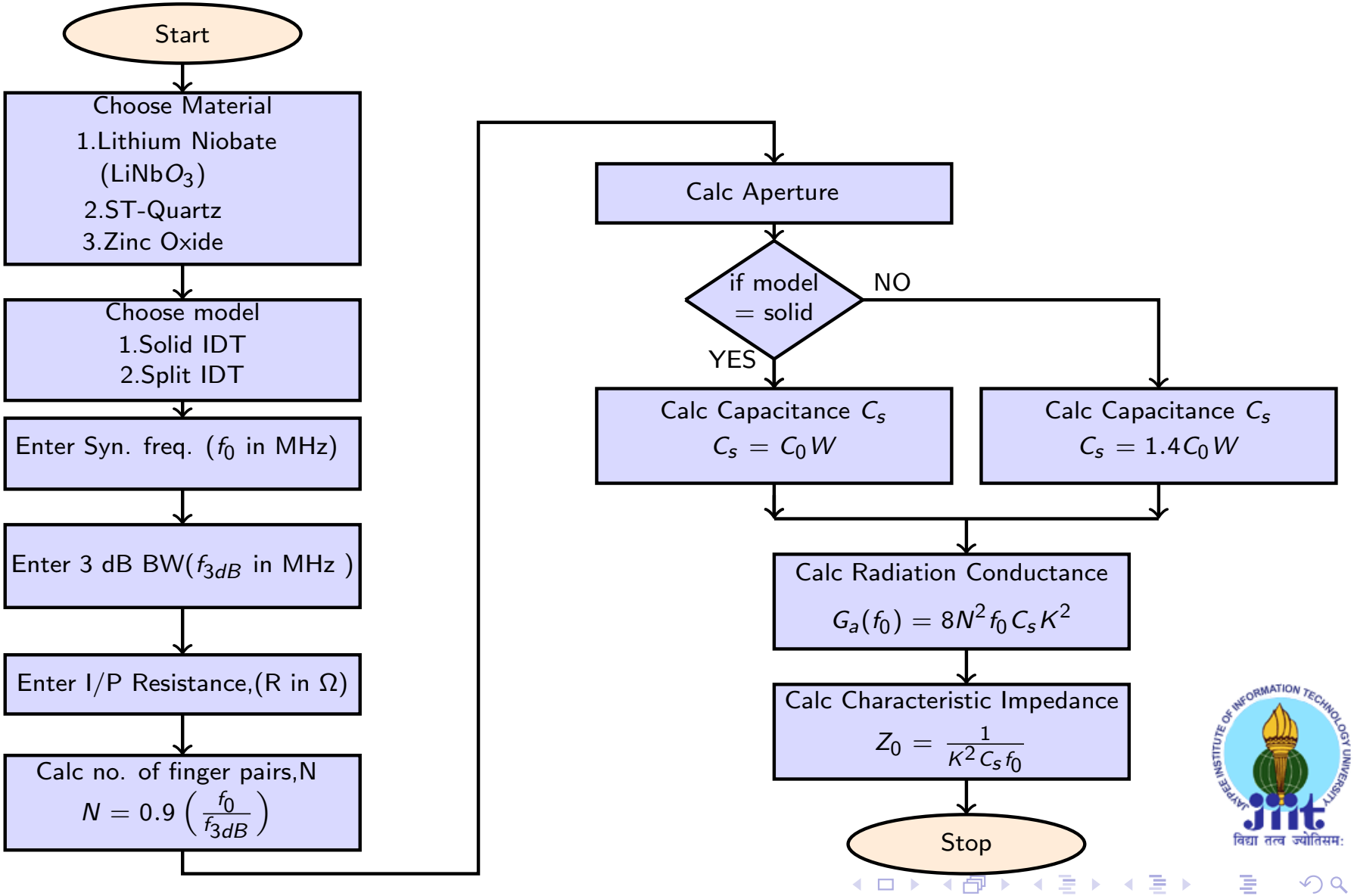
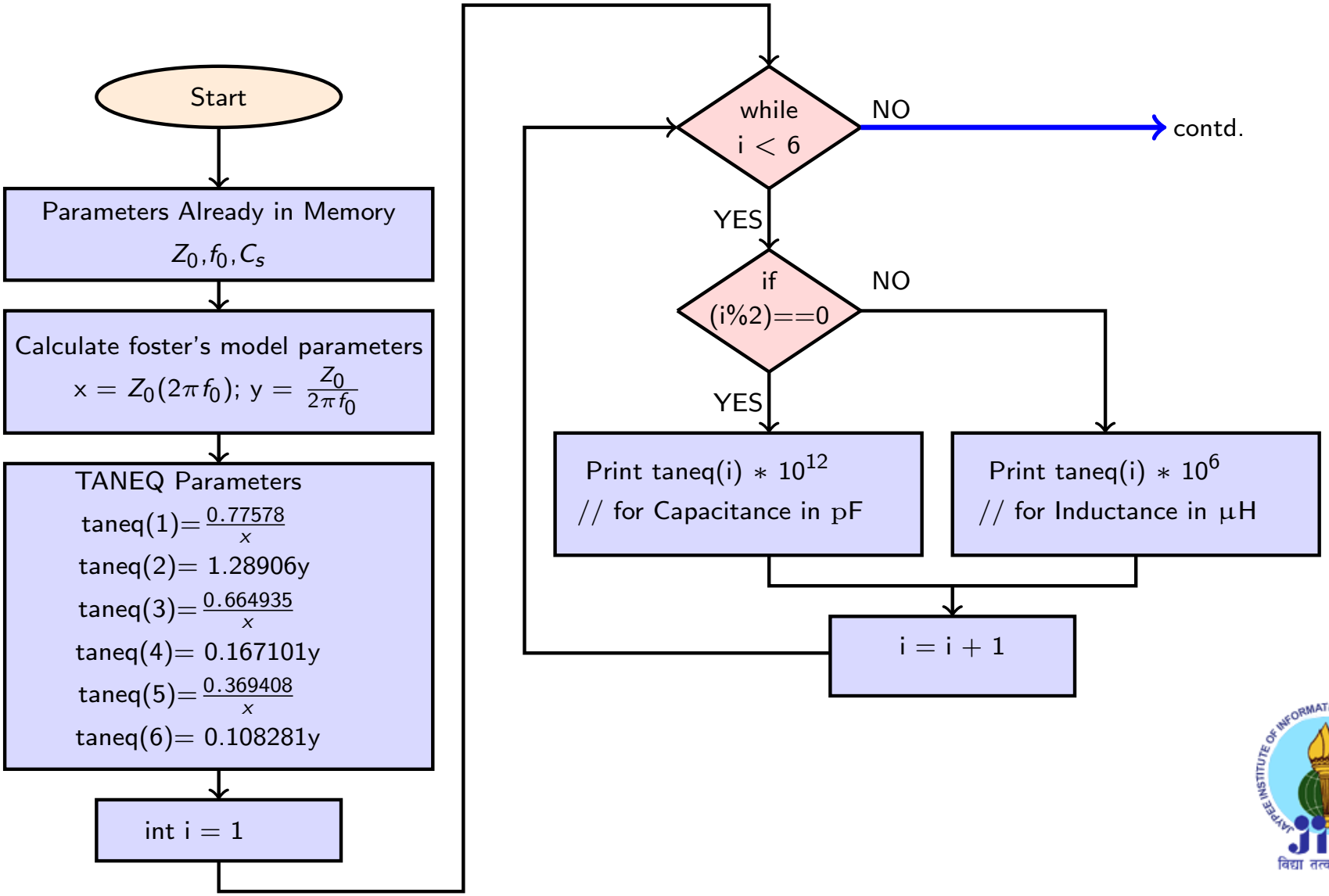


Figure: Tuned SAW Insertion Loss Plot - I

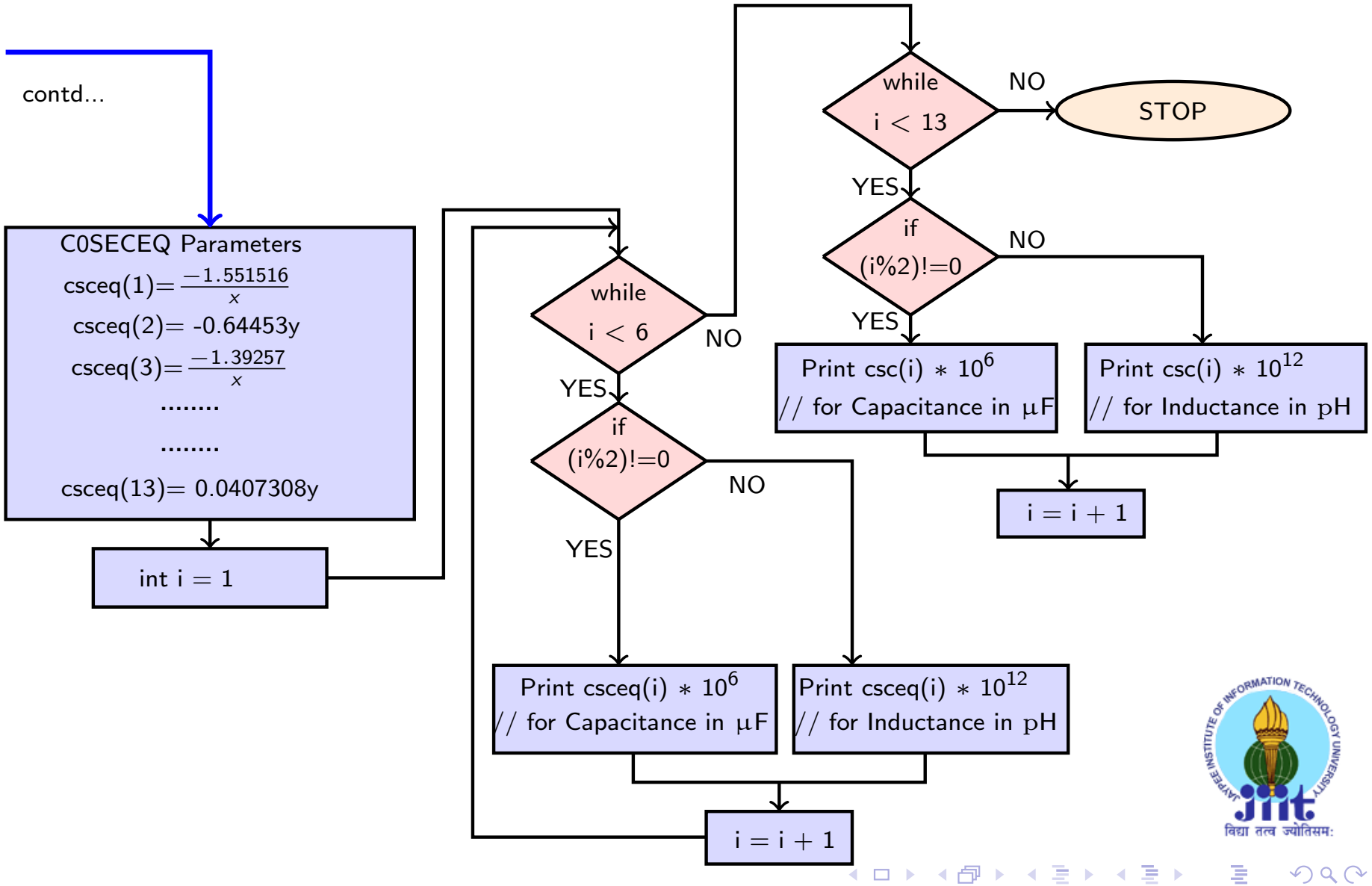
SAW Device Design - Flow Chart



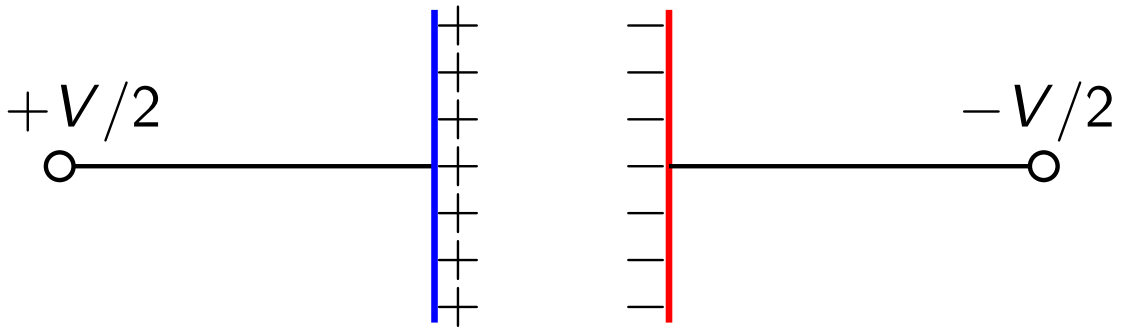
SPICE SAW Model Parameter - Foster's Network Model

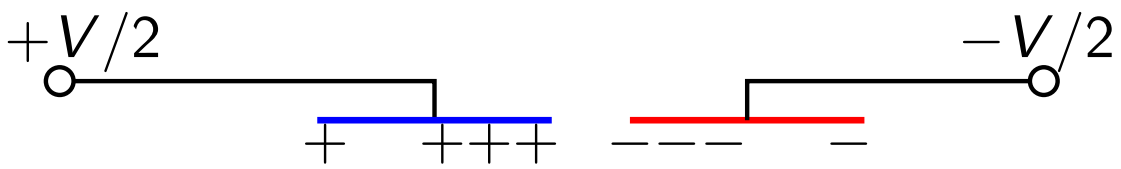


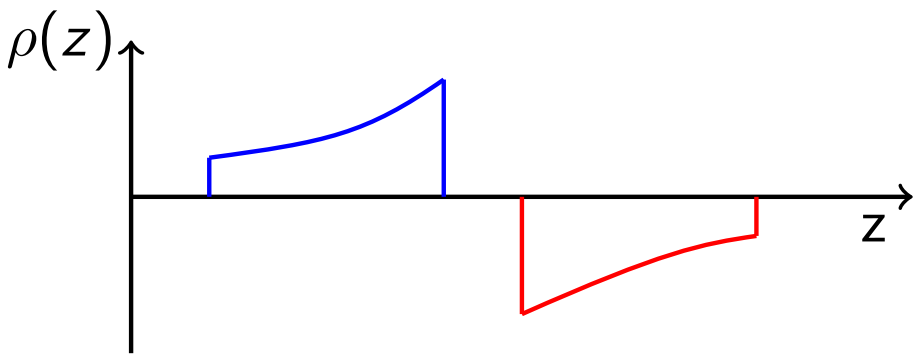
SPICE SAW Model Parameter - Foster's Network Model



Capacitance Modeling



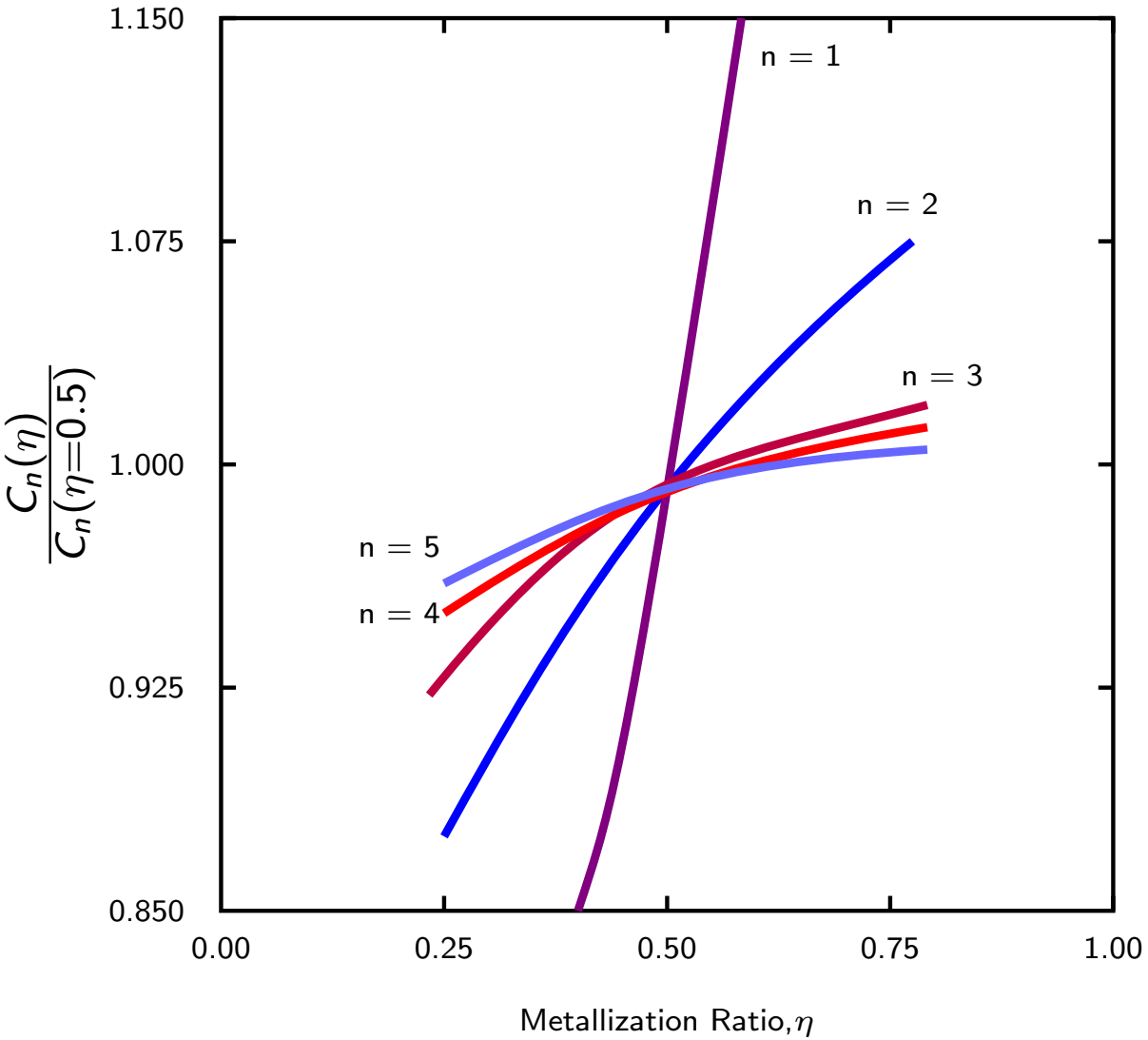




At $\eta = 0.5$,

$$C_n = \frac{4}{\pi} C_s . W . \frac{1}{4n^2 - 1}$$

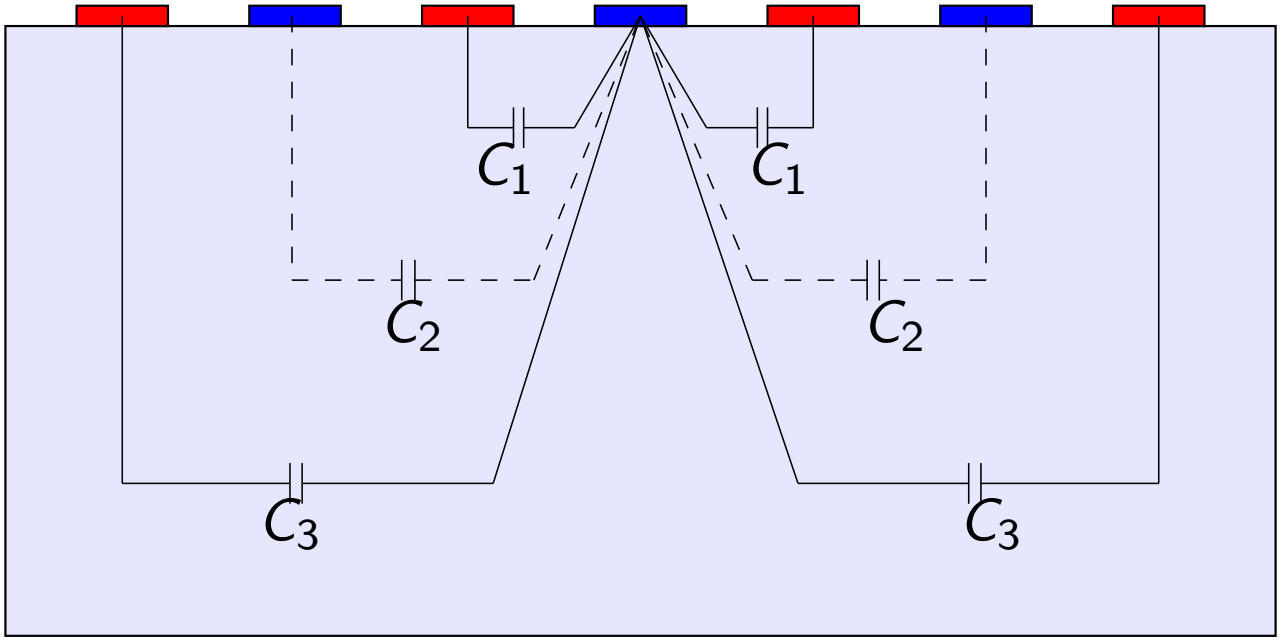
Variation of C_n with Metallization Ratio,η



At $\eta = 0.5$,

$$C_n = \frac{4}{\pi} C_s . W . \frac{1}{4n^2 - 1}$$

Capacitance Connecting Electrodes to its Neighbours[1]



For $\eta < 0.75$

$$C_1 = C_1(\eta = 0.5)\exp[1.75(\eta - 0.5)]$$

$$C_2 = C_2(\eta = 0.5)(\eta/0.5)^{(}0.18)$$

Total Capacitance $C_T = \sum_{odd\ n} 2C_n = NC_sW$

For Split electrode $C_T = 1.4NC_sW$

Driving Pt Impedance vs Frequency

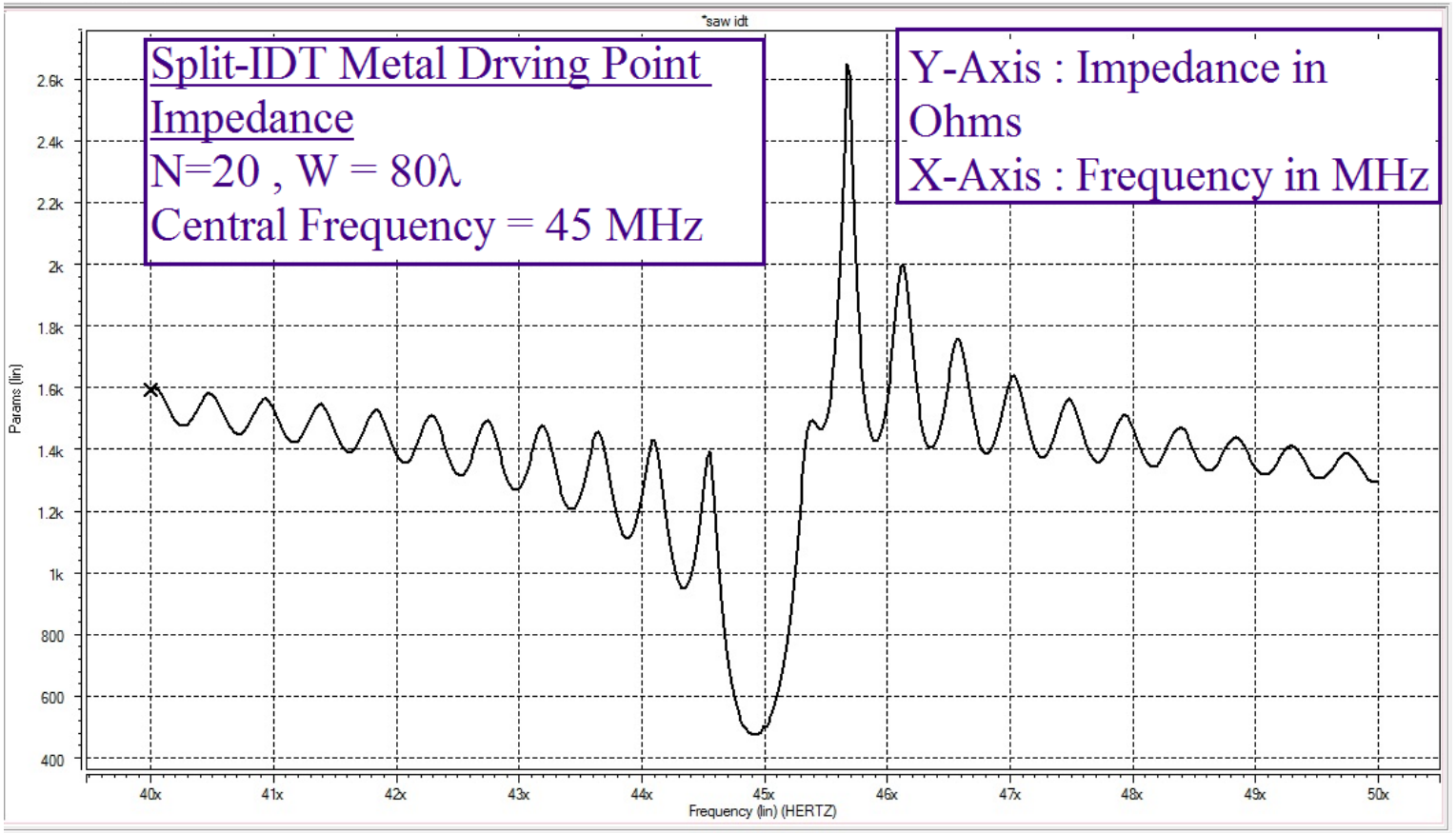


Figure: Z0 vs Freq

Conductance vs Frequency : G_0 vs frequency

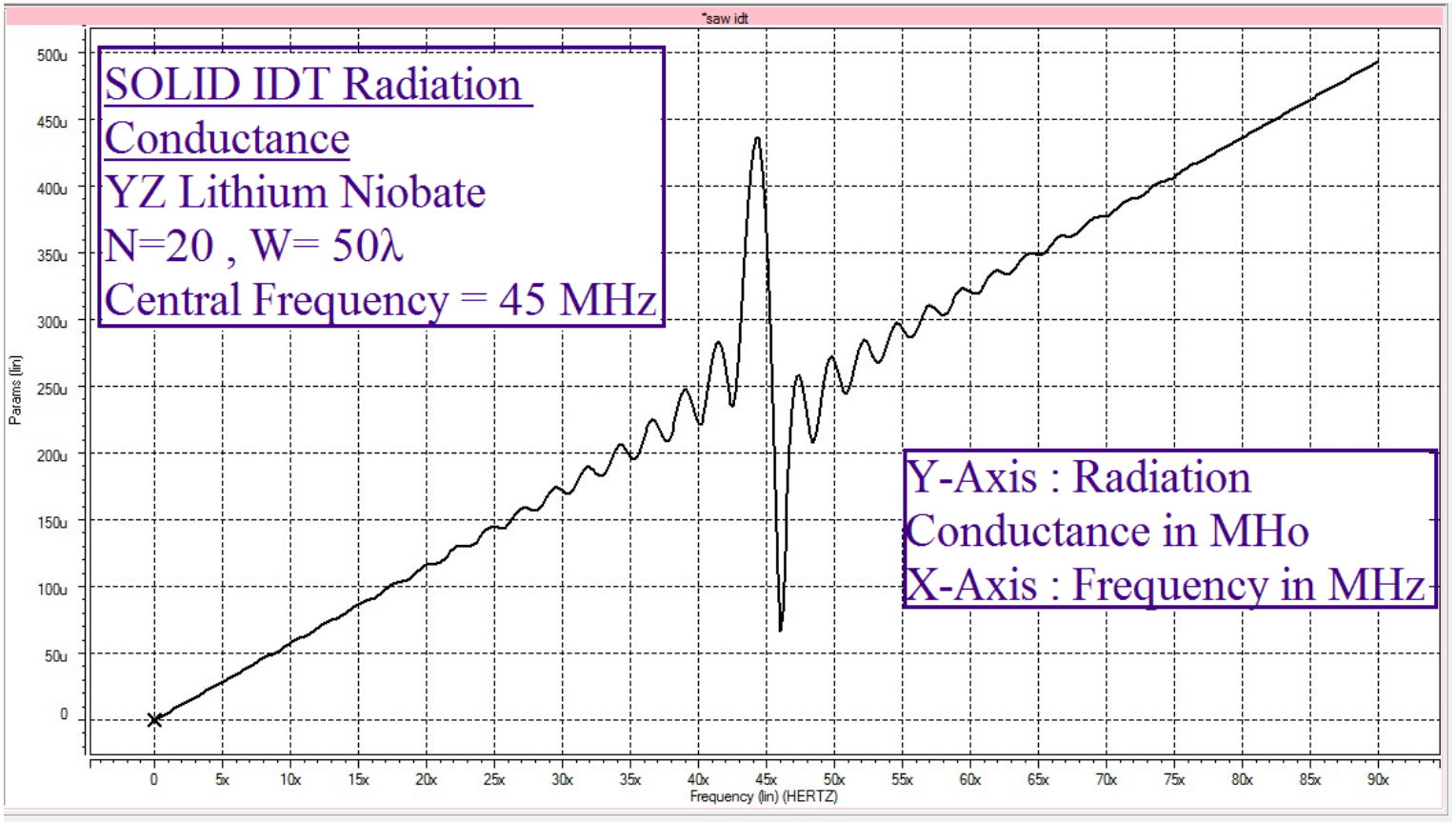


Figure: Go vs Freq

Susceptance vs Frequency : B_a vs frequency

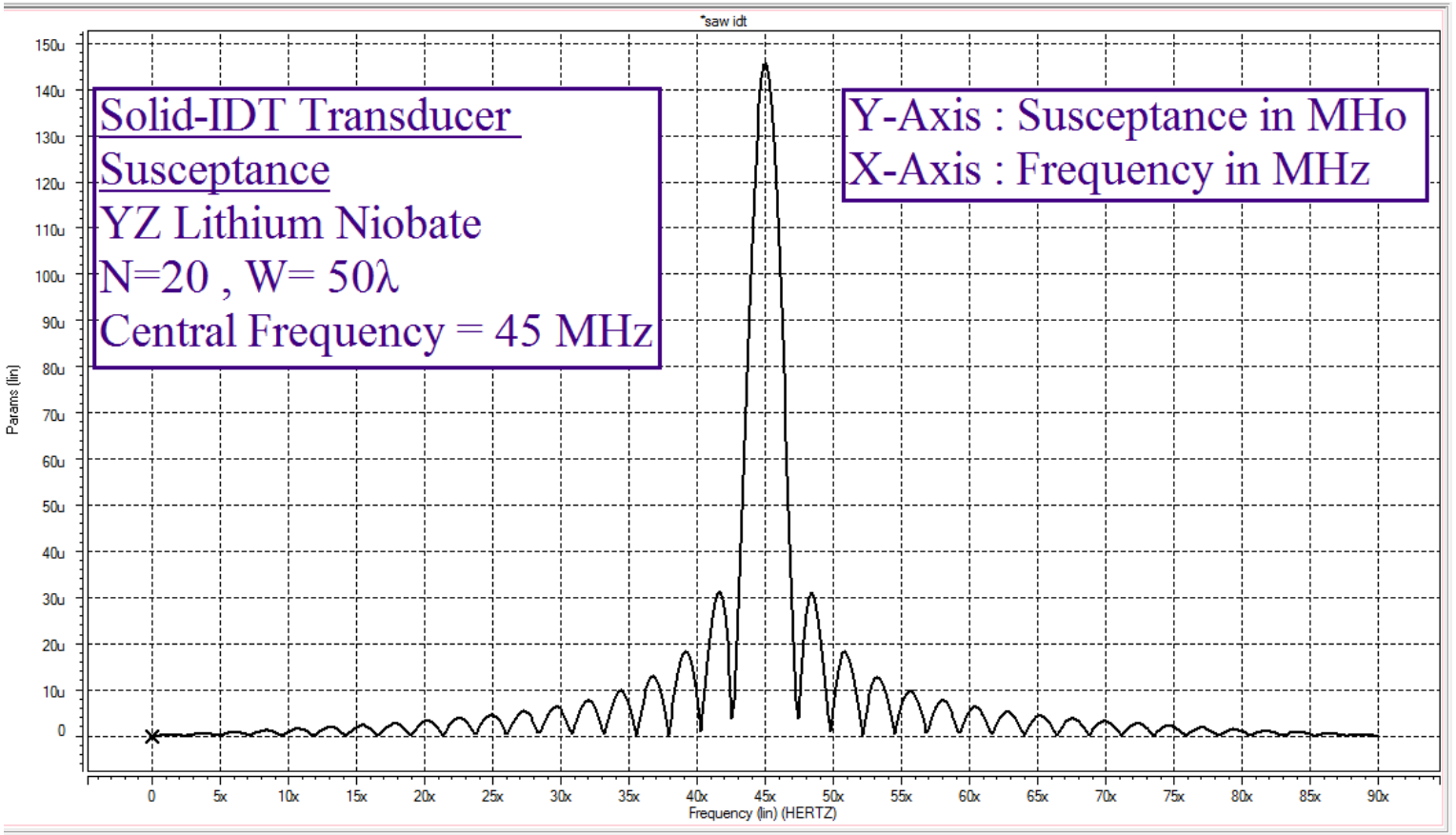


Figure: Ba vs Freq

Simulation : SAW Solid Electrode Frequency Response

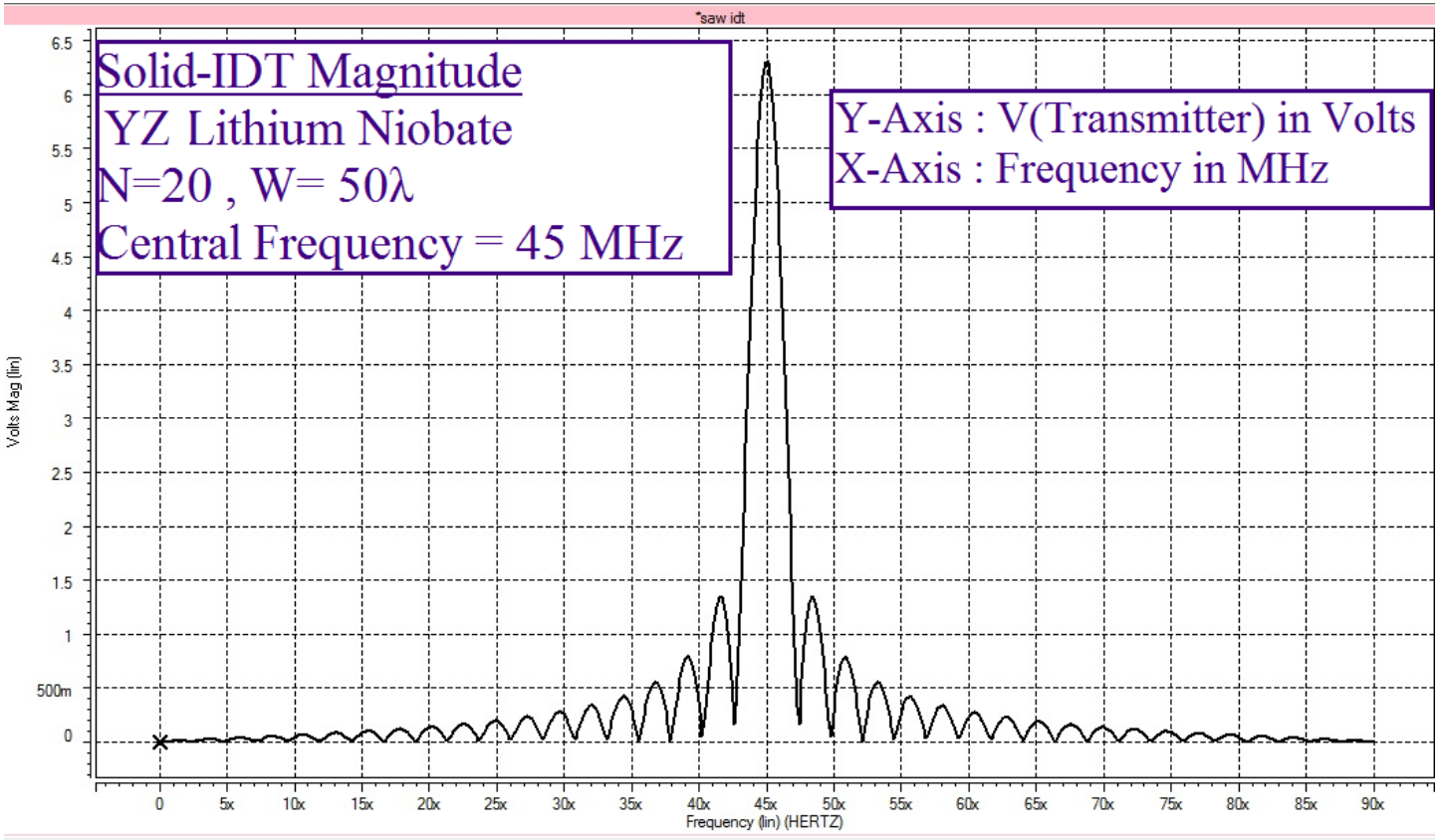


Figure: SAW Solid Electrode Frequency Response

Simulation : SAW modified crossed-field model frequency response

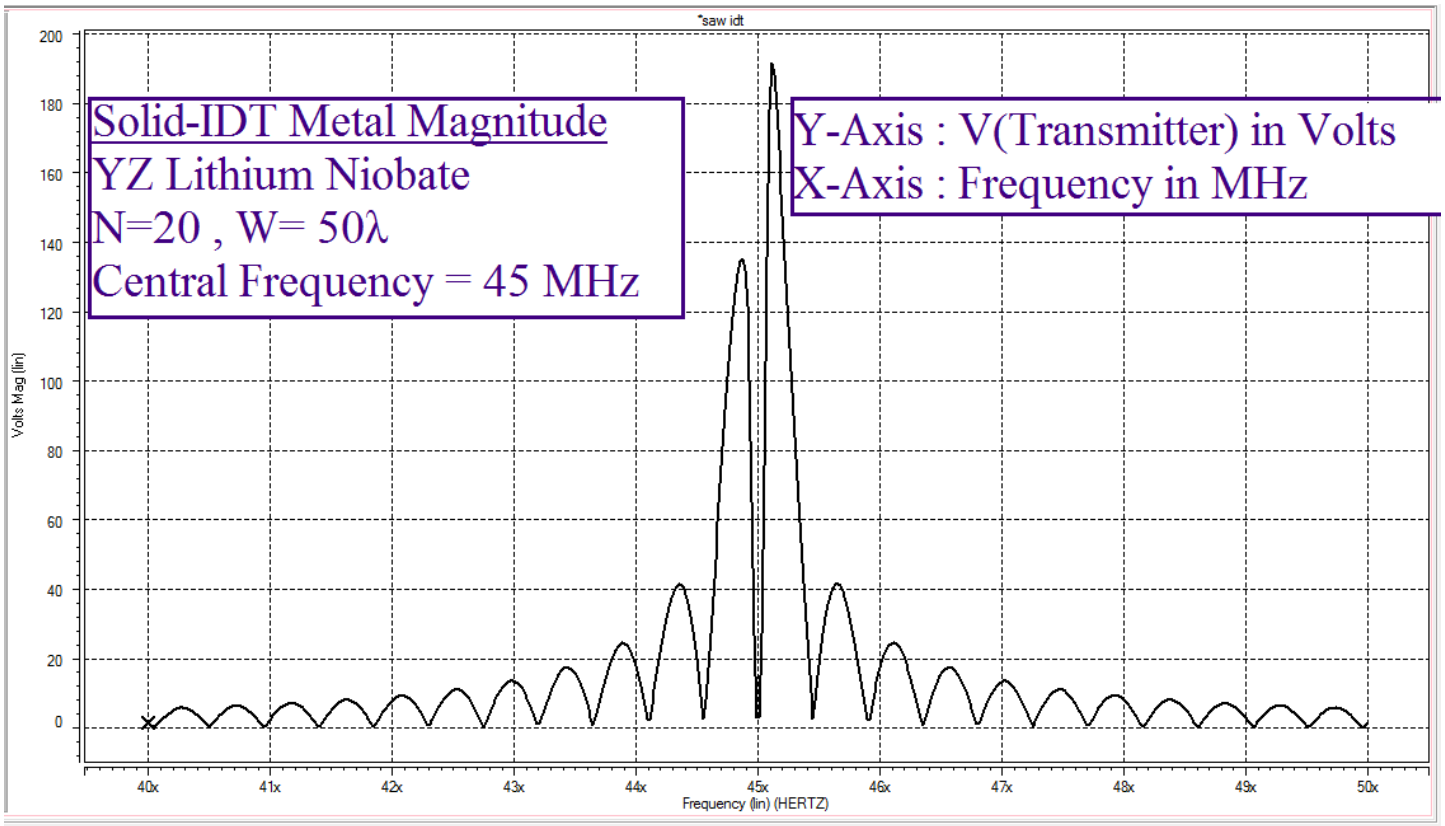


Figure: SAW modified crossed-field model frequency response

Simulation : SAW split electrode modified crossed-field frequency response

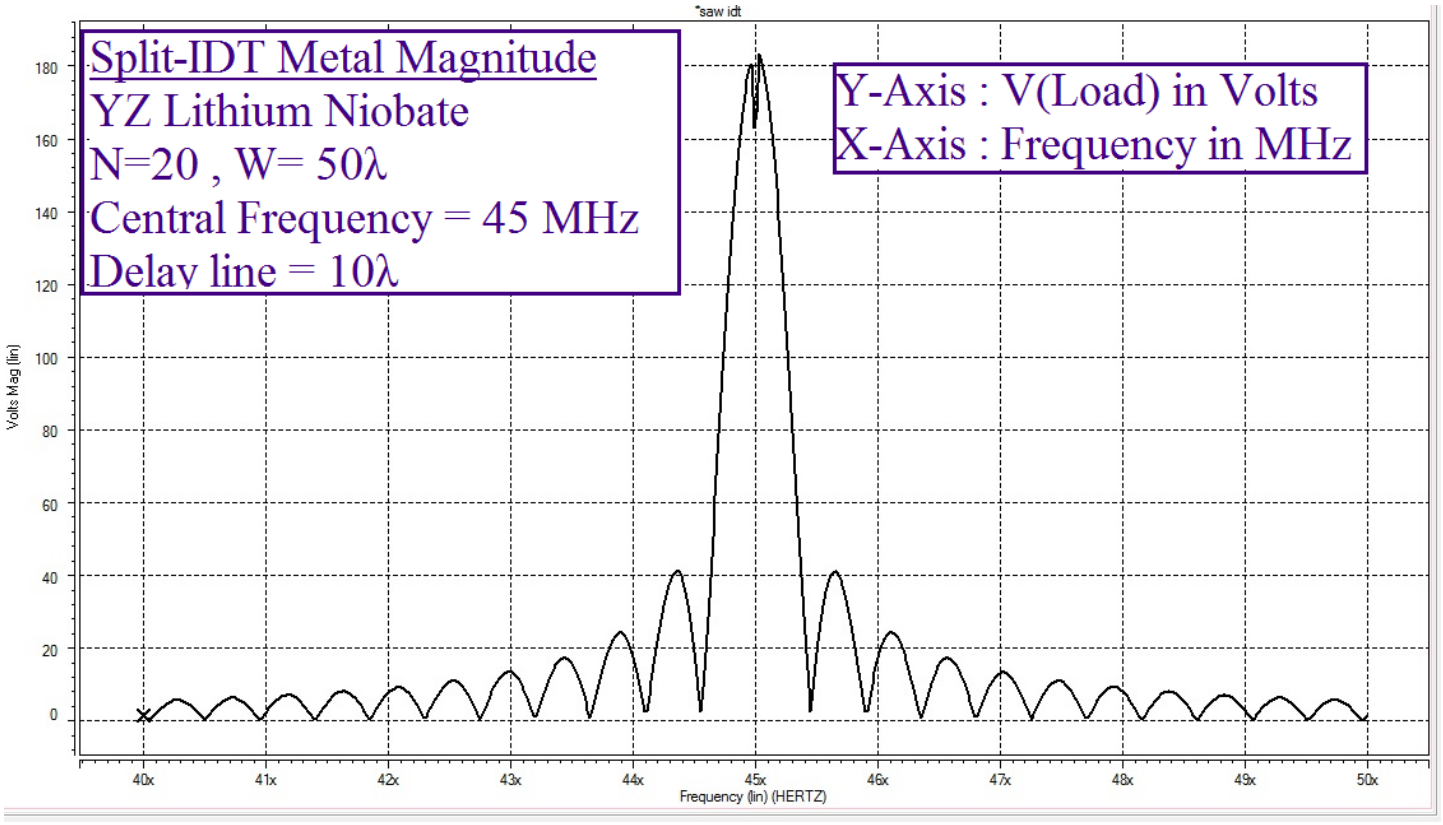


Figure: SAW Split electrode modified crossed-field frequency response

Validation :SAW metallization ratio-effect impluse response(η=0.25)[9]

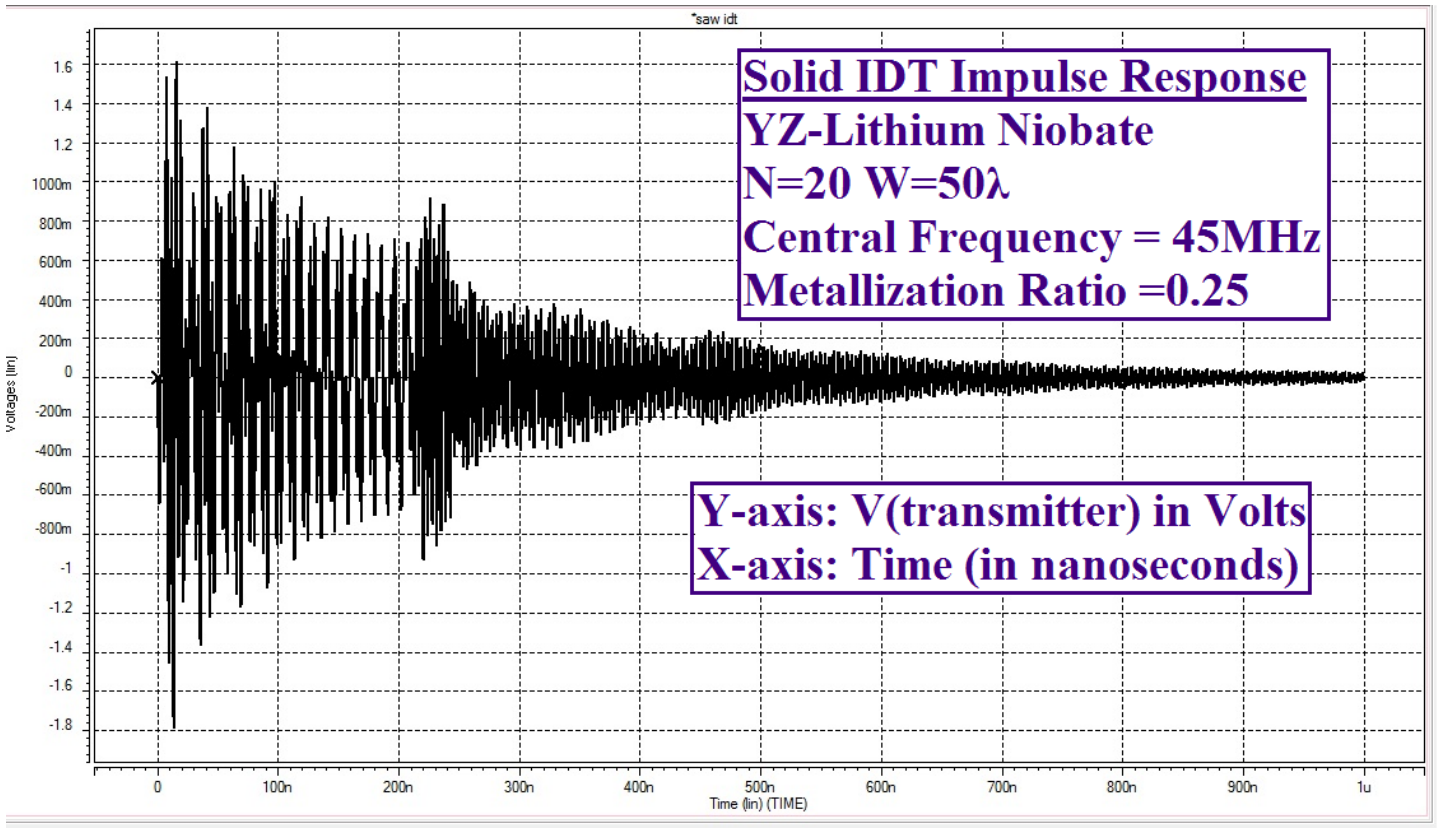


Figure: SAW Metallization ratio - effect impluse response plot -I

Validation :SAW metallization ratio-effect impluse response(η=0.5)[9]

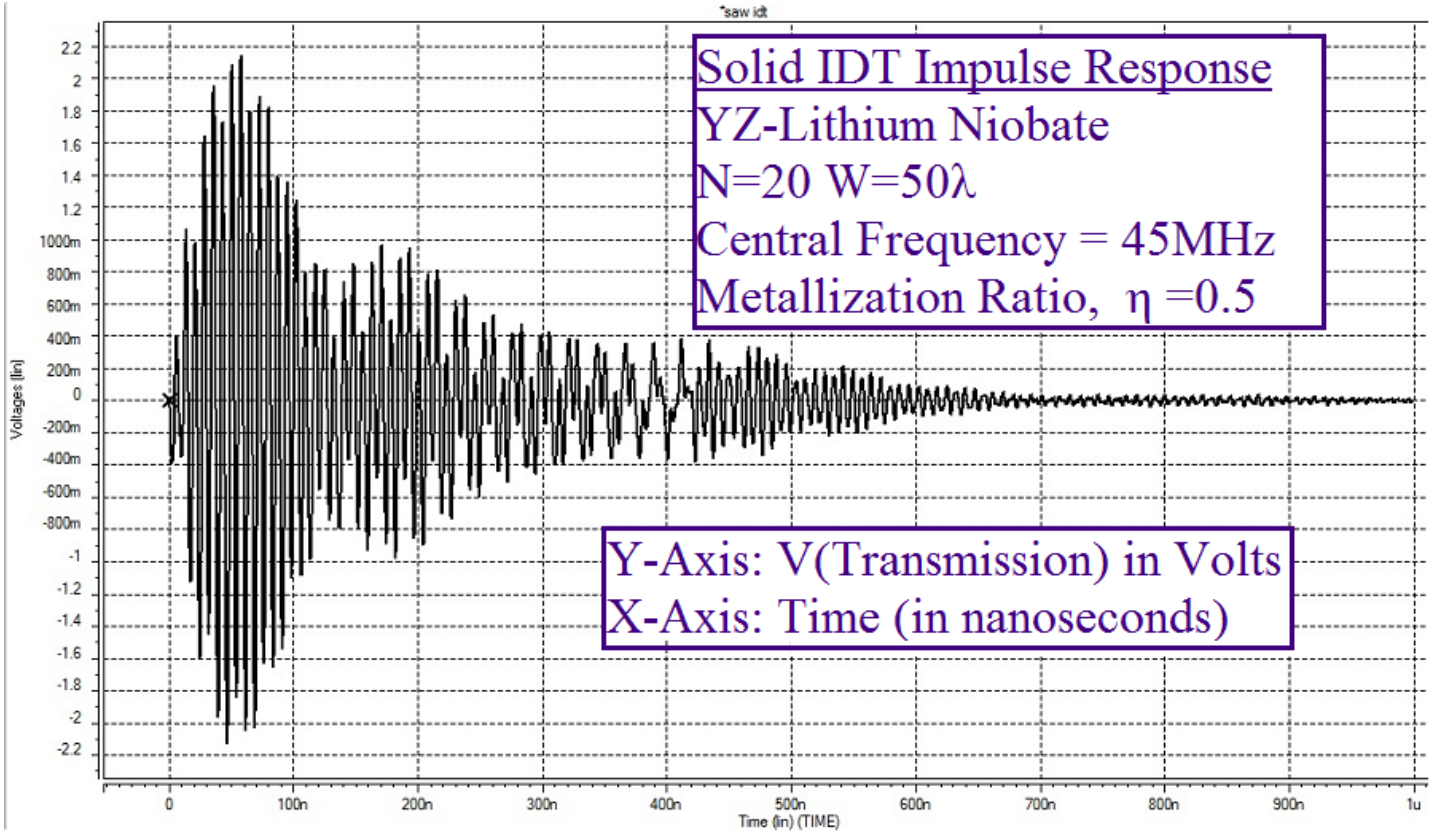


Figure: SAW Metallization ratio - effect impluse response plot -II

Validation :SAW metallization ratio-effect impluse response(η=0.75)[9]

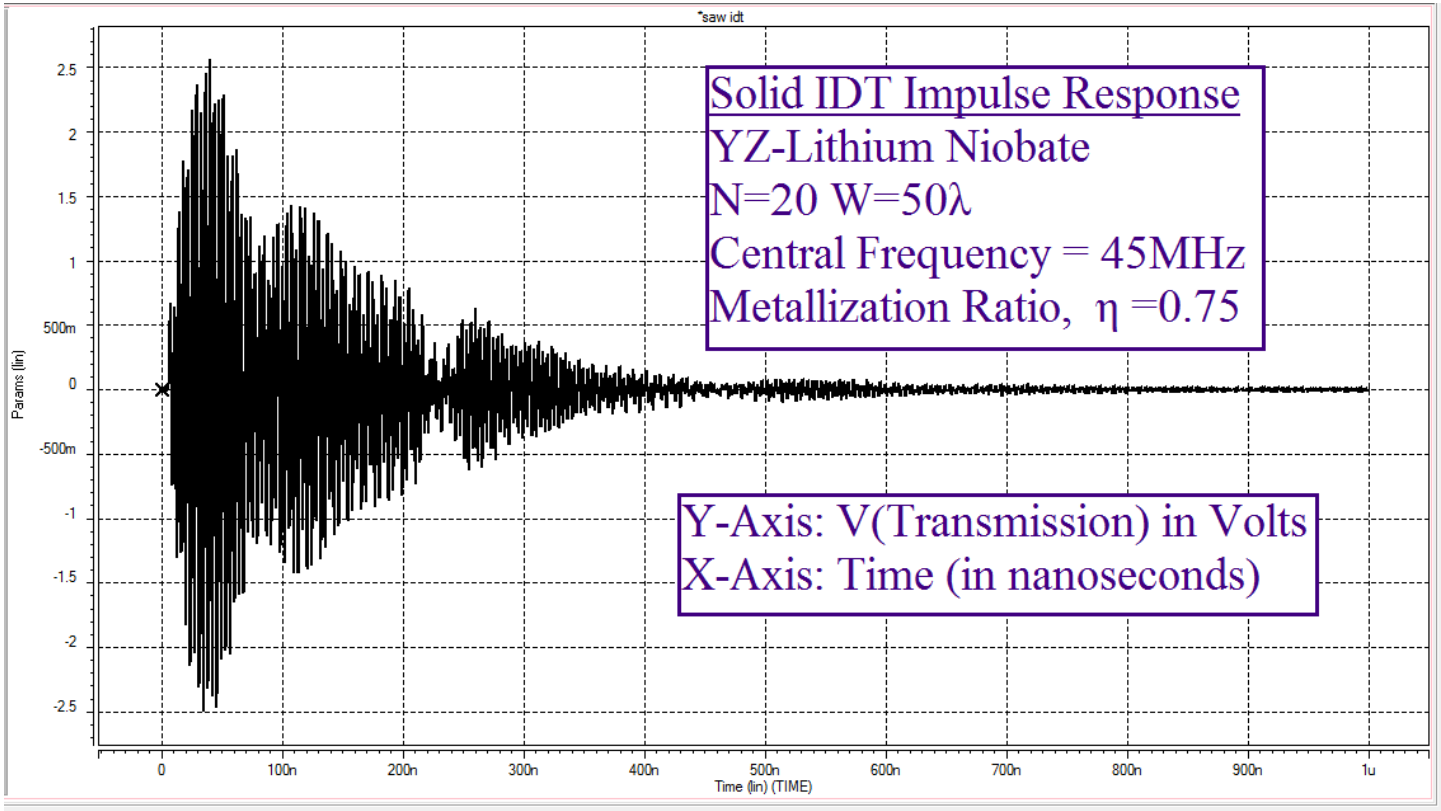


Figure: SAW Metallization ratio - effect impluse response plot -III

Validation : Lithium Niobate Re(input admittance)[5]

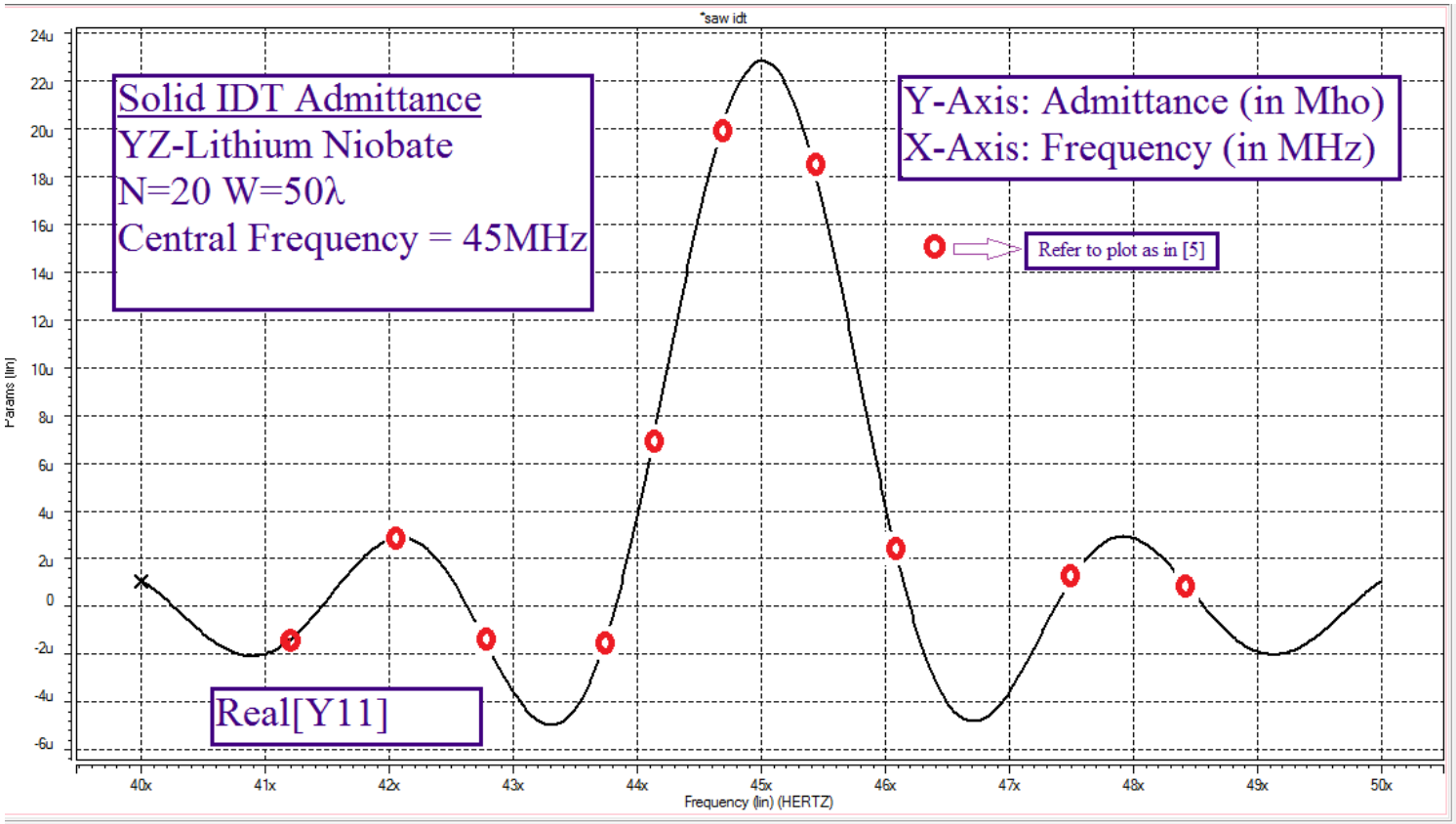


Figure: Lithium niobate Re(input admittance)

Validation : Lithium Niobate Imag(input admittance)[5]

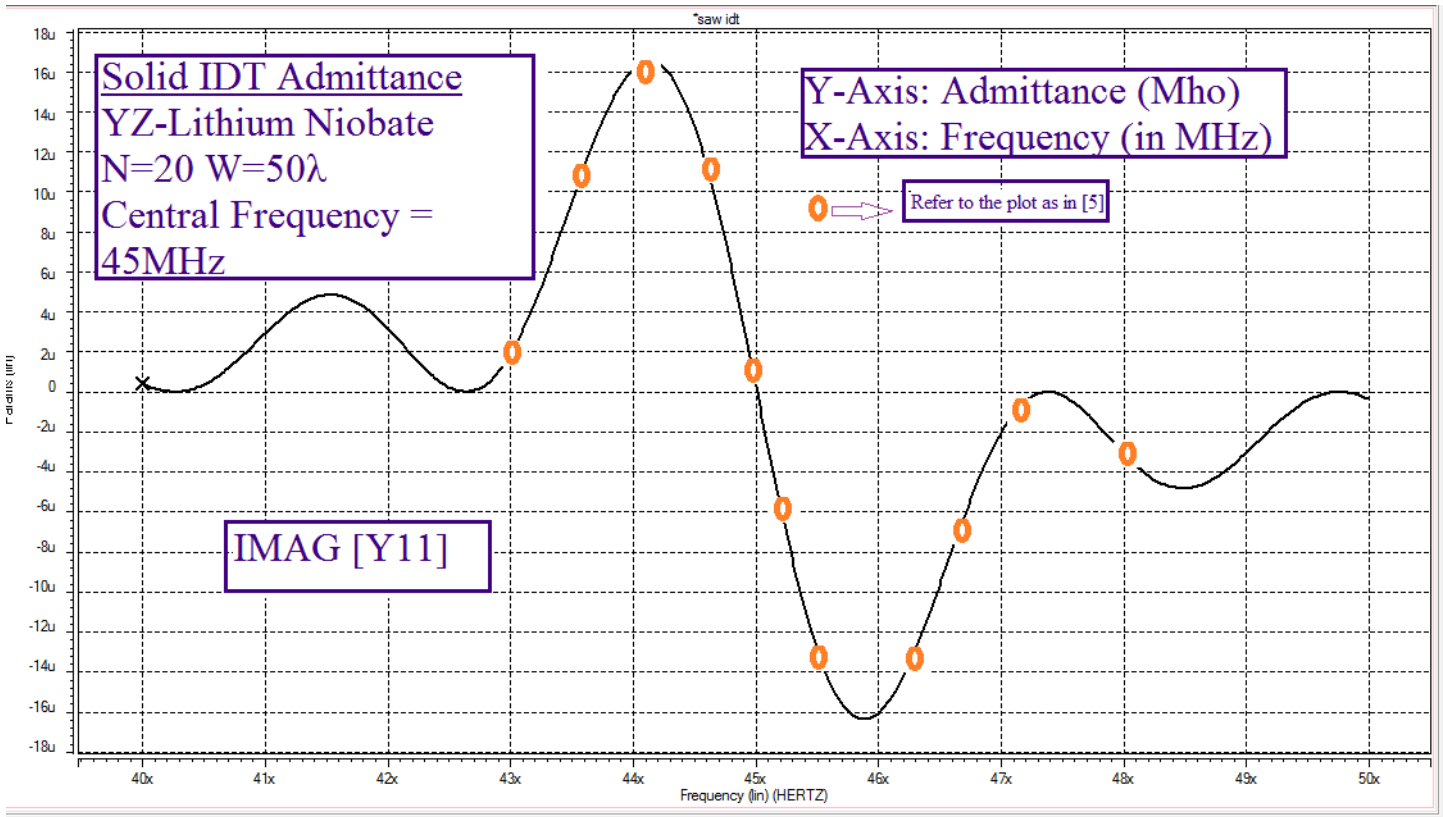


Figure: Lithium niobate Imag(input admittance)

Validation : Zinc oxide frequency response[12]

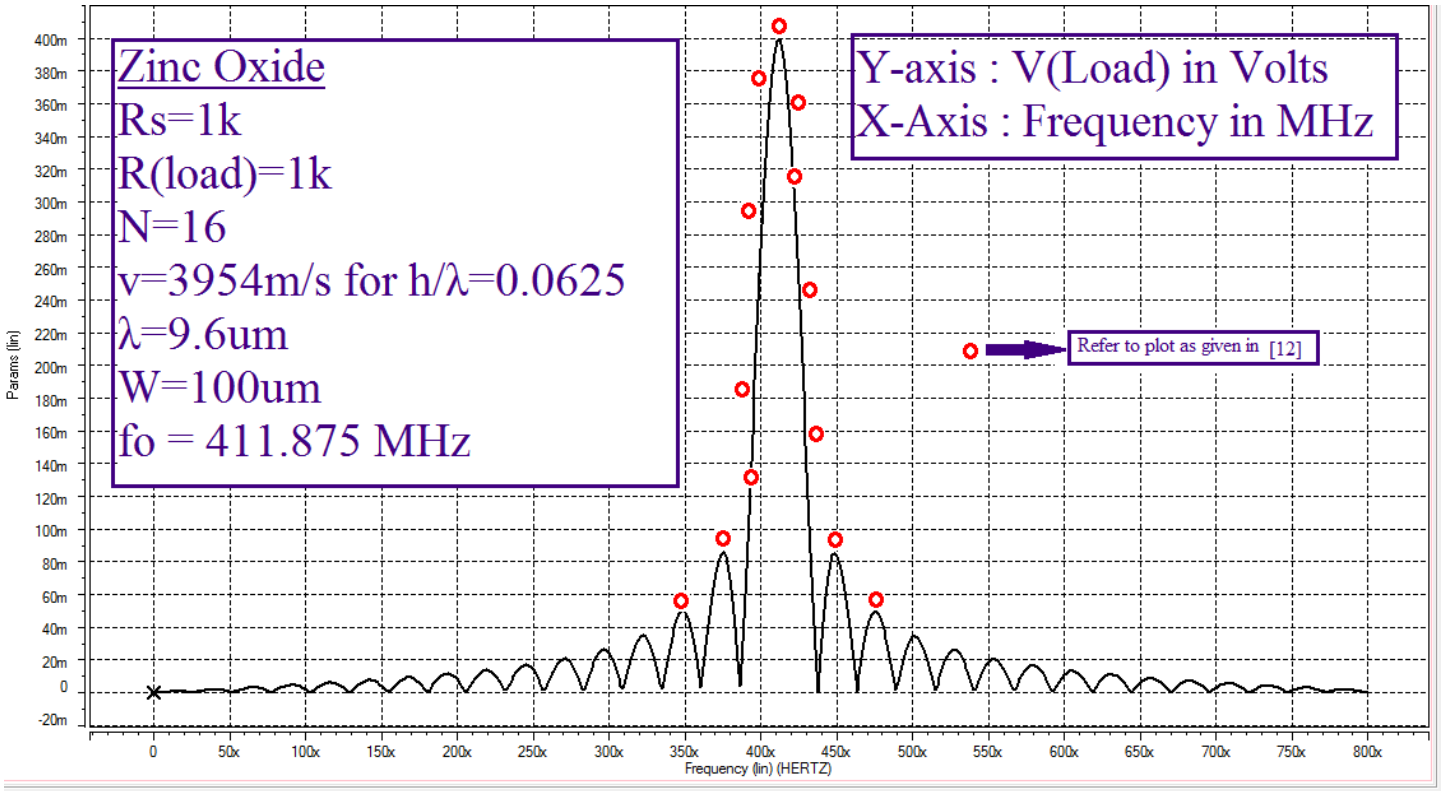
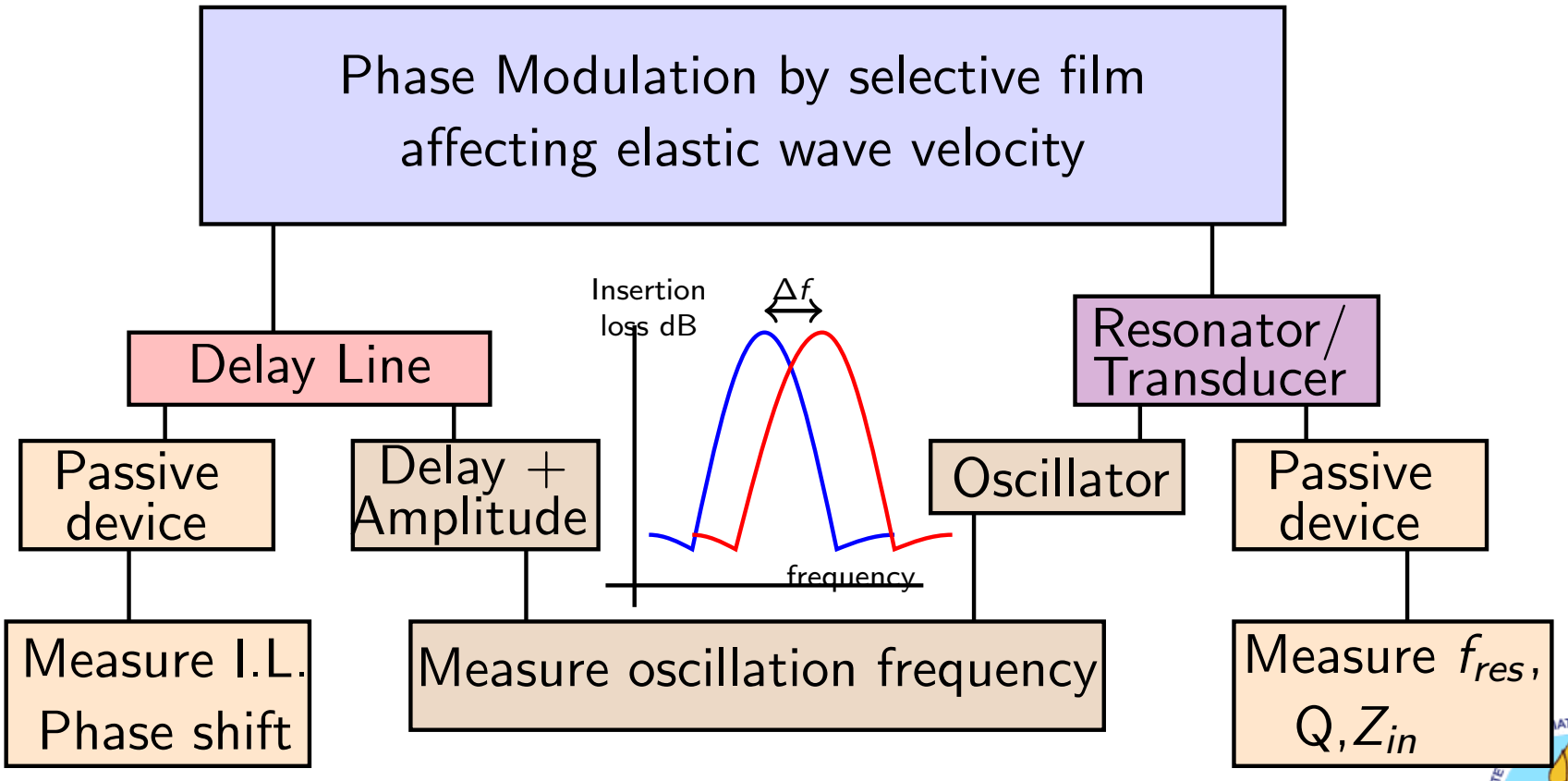
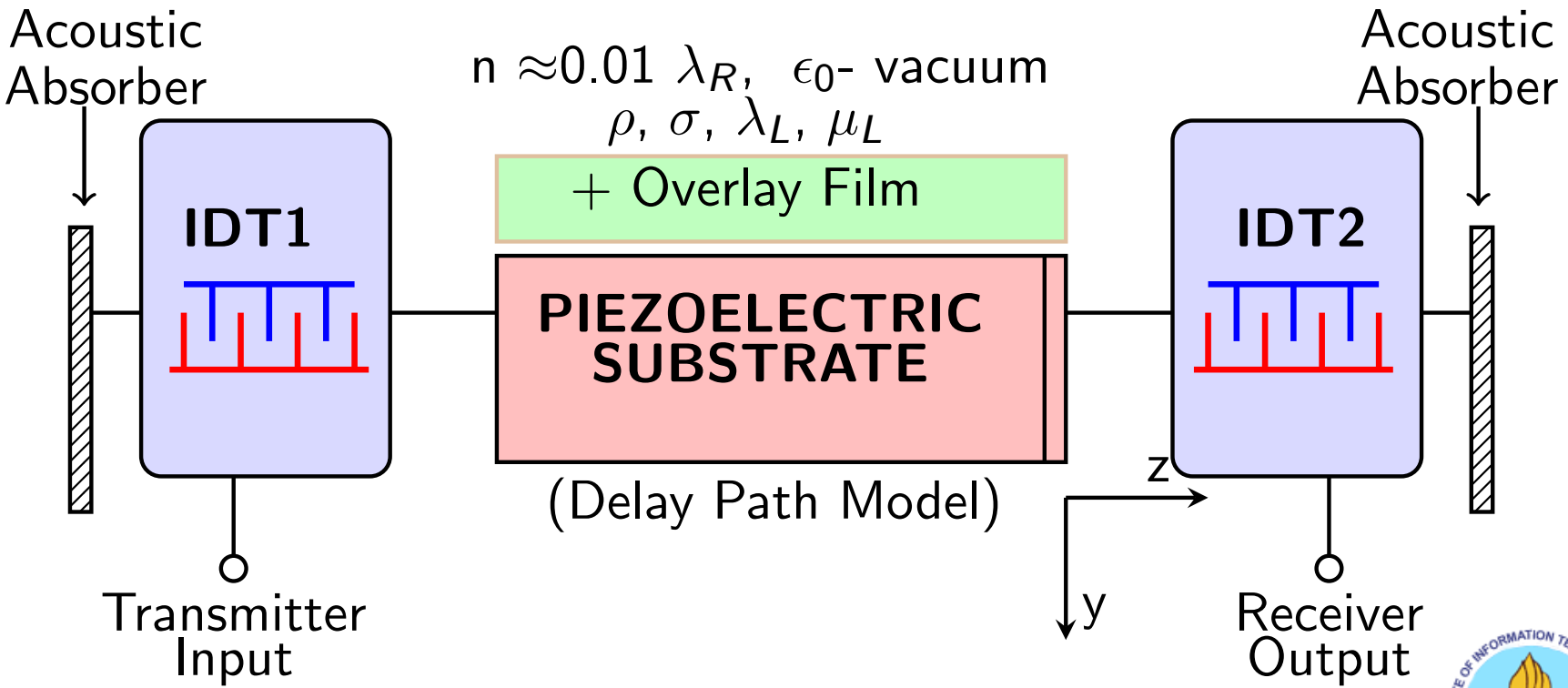


Figure: Zinc oxide frequency response

Measurement Schemes used with the Acoustic Sensors[3]



SAW Delay Line with Selective Film in Wave Propagation Path - Sensor Application



Surface Acoustic Wave Sensor Application - Principles

- The change in velocity of the wave in the SAW delay line varies as

$$\frac{\Delta f}{f} = \frac{\Delta V}{V} = k_1 fhp' - k_2 fh\left(\frac{4\mu'}{V_R^2}\frac{\lambda' + \mu'}{\lambda' + 2\mu'}\right)$$

- This change in velocity causes a change in the phase of the wave, when the delay line length is changed or a film of different material is deposited on the delay line. This phase change indicates the physical change in parameters such as temperature, concentration of gases etc.

Frequency selection plot

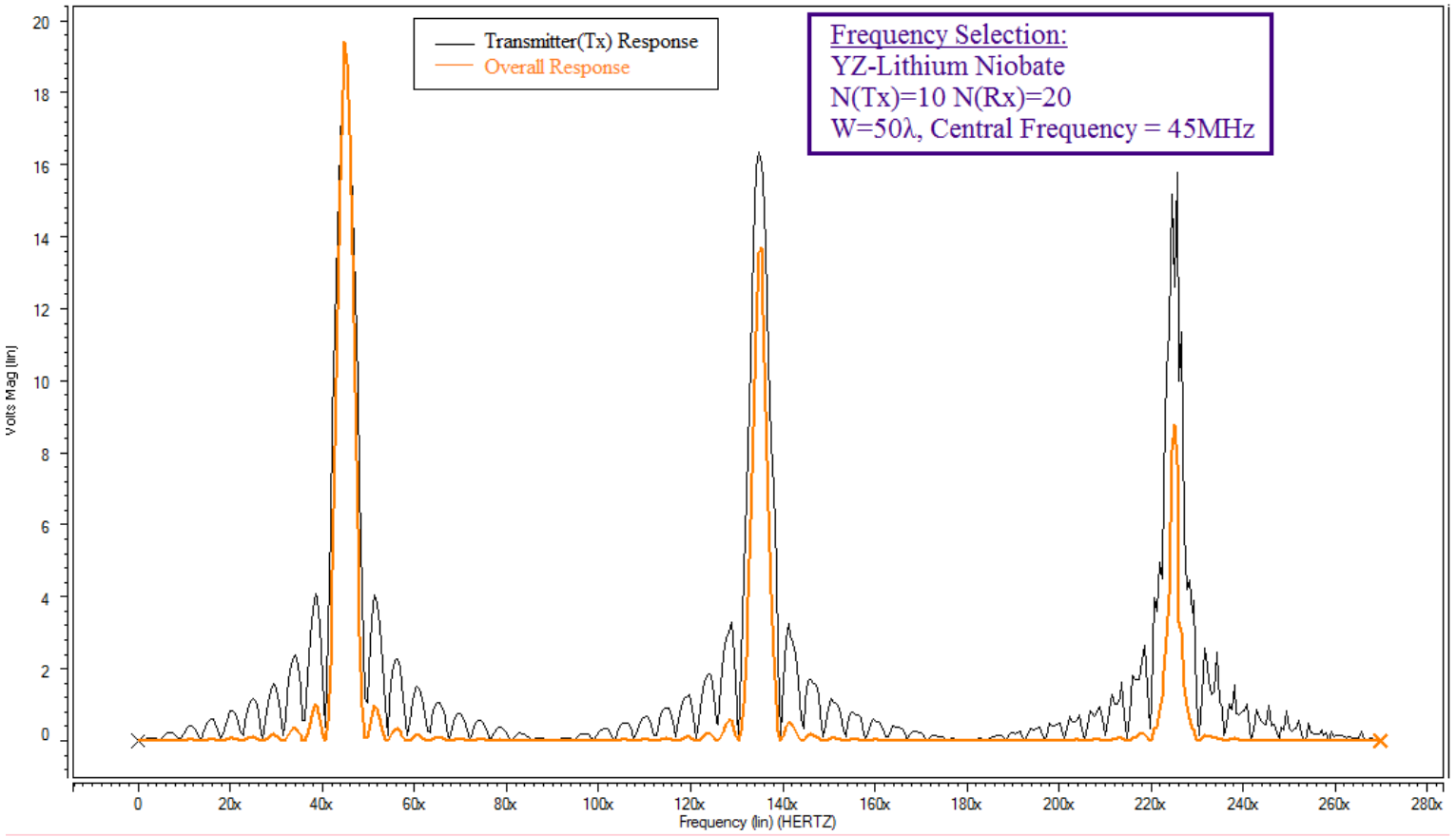


Figure: frequency selection plot

Verilog-A SAW Model Implementation in SPICE

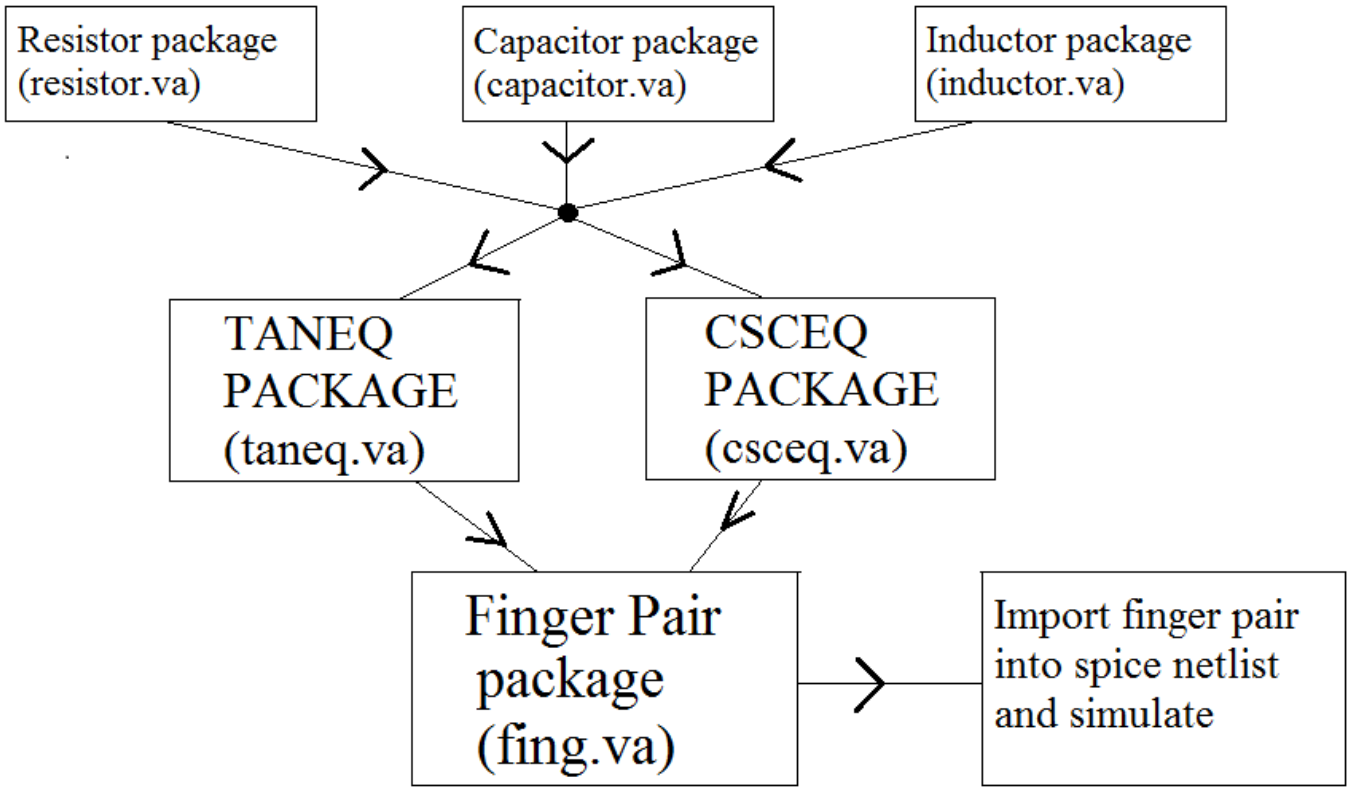


Figure: verilog-A SAW model implementation in SPICE

Verilog-A : SAW Solid Electrode Frequency Response

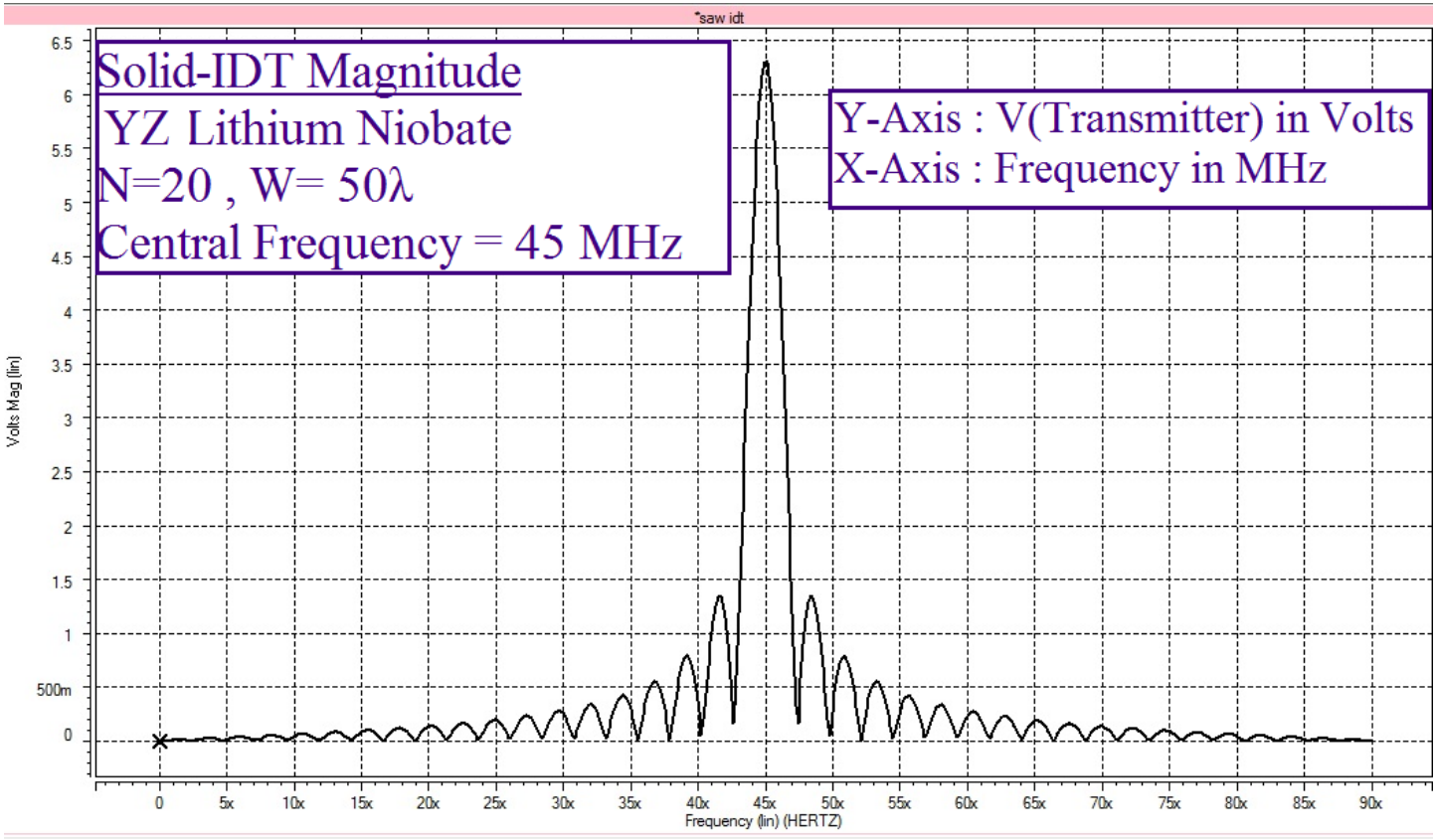


Figure: SAW Solid Electrode Frequency Response

Conclusion

- A Compact SPICE compatible macromodel for SAW has been developed suitable for SAW sensor system development which, presently is an early version undergoing benchmarking.
- SAW IDT integrated with extrinsic interface matching circuits has been validated.
- Validation of SAW SPICE Model Parameters has been made on ST-Quatrz, $LiNbO_3$, ZnO/Si in the range of 40 MHz - 450 MHz
- Mason's improved model can be SPICED to capture more accurate reflection from metal electrodes.
- Presently, only primitive structures, have been investigated.withdrawal weighting, floating electrodes, unidirectional IDTs are eminent candidates for inclusion in SPICE model.

Conclusion contd...

- Applicability of SPICE Model for modes such as Love Wave, Shear Horizontal Surface Acoustic Wave(SH-SAW), Shear Transverse Wave(STW), Flexural Plate Wave (FPW), Shear Horizontal Acoustic Plate Mode(SH-APM),Layered Guided Acoustic Plate Mode(LG-APM) that is currently used for high sensitive bio and gas sensor developments to be extended.
- SAW SPICE Model is integrated in CAD-package that where design inputs are material, process and layout.
- Ricco Criteria
  - Oscillator Δf for bio/gas: wide range of sensing option
  - Model Challenge: Mass loading, shiftness, dielectric constant,temperature, pressure changes in overlay film interacting with SAW.

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