April 2, 2019

Introduction to Surface Acoustic Wave (SAW) Devices

Part 2: Getting Started

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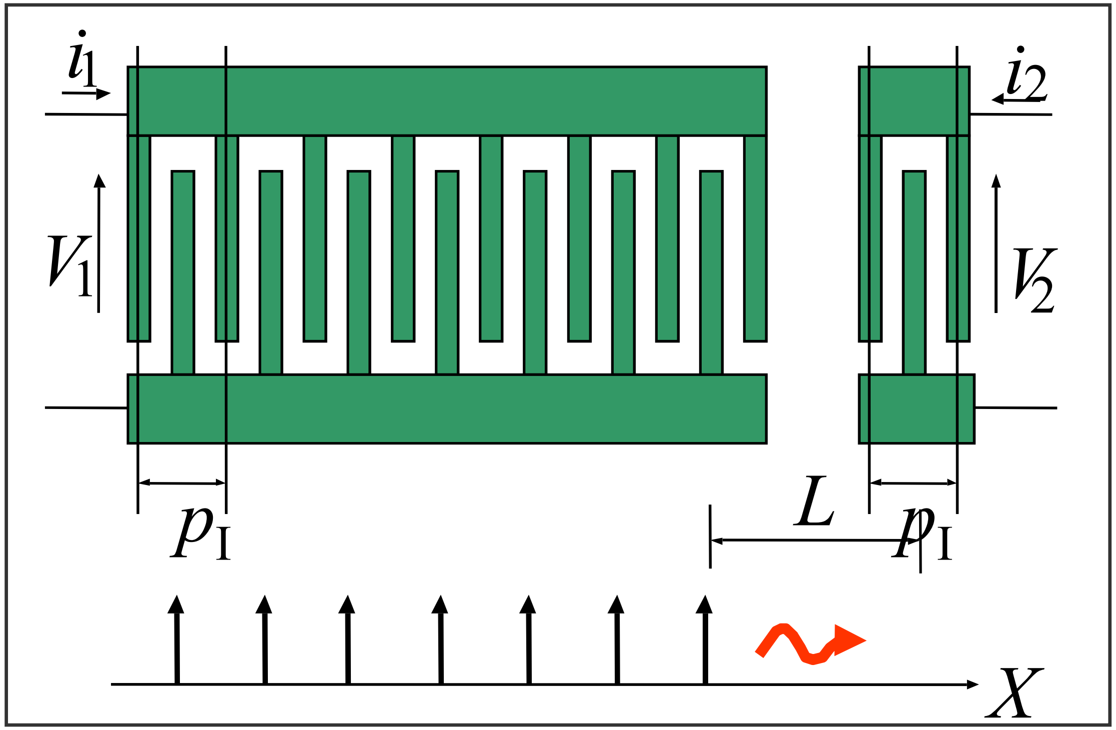
Delta Function Model



$$Y_{21} = \left.\frac{i_2}{V_1}\right|_{V_2=0} = \sum_{n=0}^{N-1} \omega h_n$$

h_n: Spatial Impulse Response

h_n: Spatial Impulse Response

$$h_n = h^e_n + h^S_n + h^B_n$$

- h^e_n : Contribution of Electrostatic Coupling
- h^S_n : Contribution of SAW Radiation

$$h^S_n \propto \exp[-\mathrm{j}\beta L_n]$$

- h^B_n : Contribution of BAW Radiation

  (Negligible near SAW Resonance)

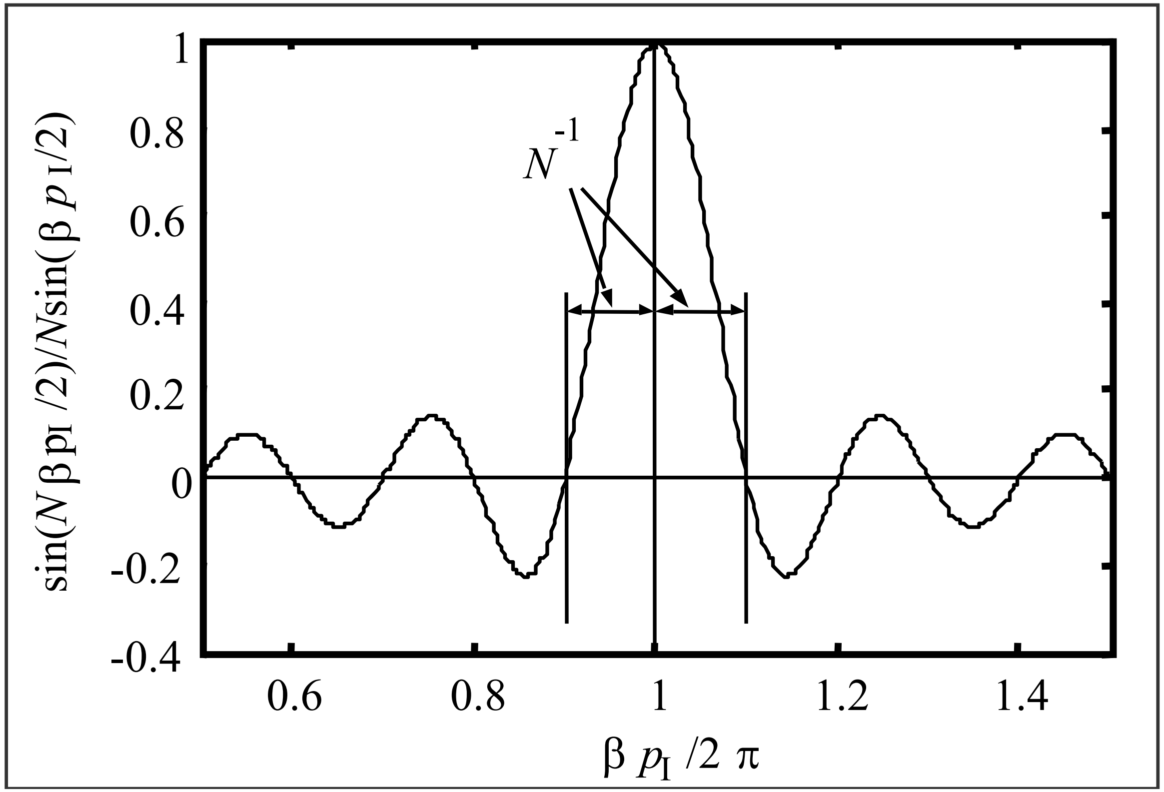
Transfer Admittance Between IDTs

$$Y_{21} \approx Y_{21}^{S} = \omega h_0 \sum_{n=0}^{N-1} e^{-j\beta(L+np_{\mathrm{I}})} = \omega h_0 e^{-j\beta L} \frac{e^{-j\beta N p_{\mathrm{I}}} - 1}{e^{-j\beta p_{\mathrm{I}}} - 1}$$

$$= \omega N h_0 e^{-j\beta\{L+(N-1)p_{\mathrm{I}}/2]} \frac{\sin(\beta N p_{\mathrm{I}}/2)}{N\sin(\beta p_{\mathrm{I}}/2)}$$

Where

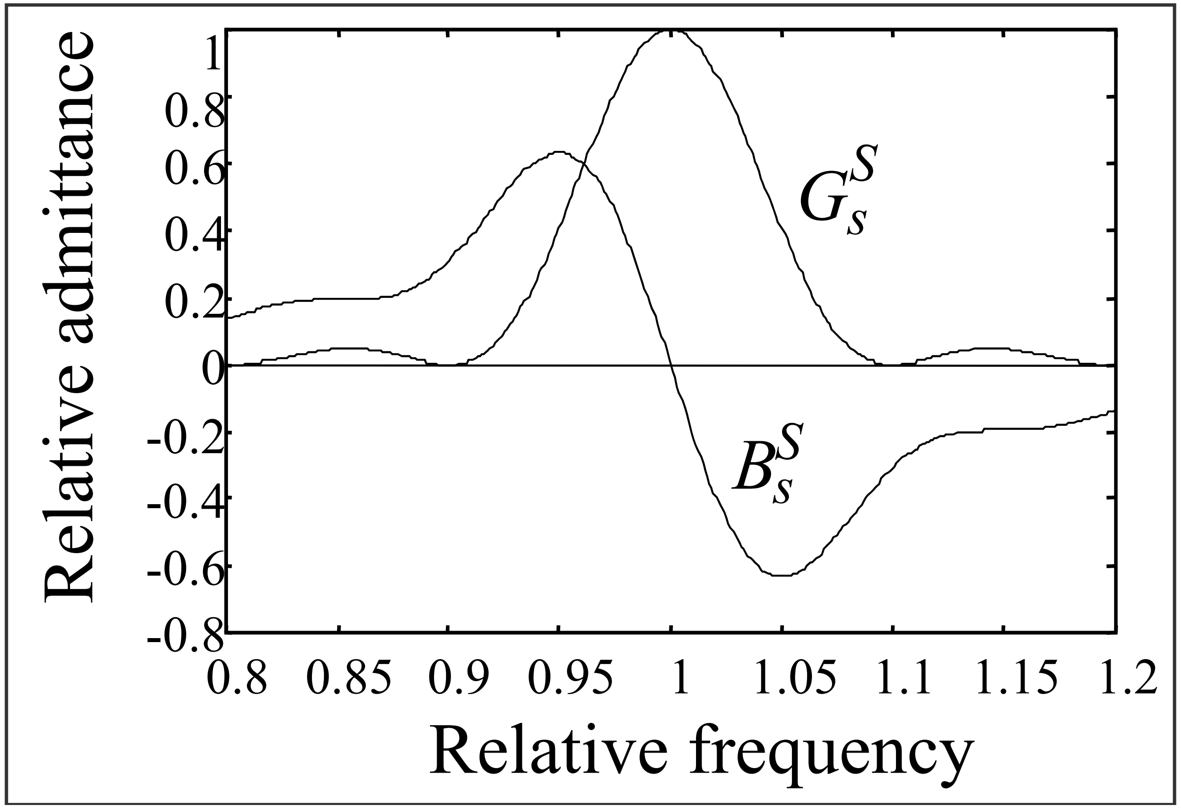
$h_0 = 2C_0\eta^2 K^2$



IDT Input Admittance

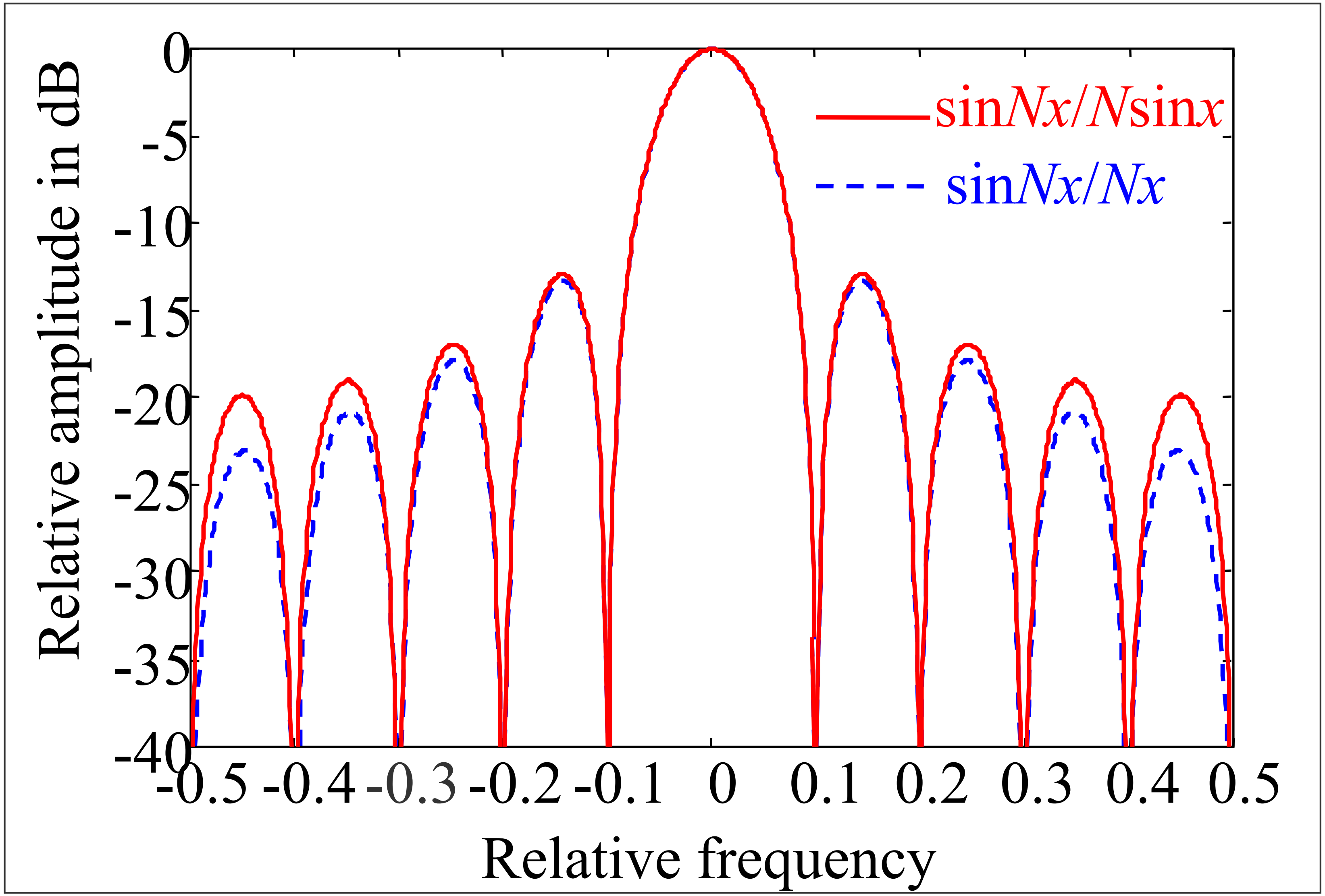
$$Y_{11}^{S} = \left.\frac{i_1}{V_1}\right|_{V_2=0} = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1} \omega h_0 e^{-j\beta|m-n|p_{\mathrm{I}}}$$

$$= \omega h_0 \frac{2\sin^2(N\beta p_{\mathrm{I}}/2) - jN\sin(\beta p_{\mathrm{I}}) + j\sin(N\beta p_{\mathrm{I}})}{2\sin^2(\beta p_{\mathrm{I}}/2)}$$



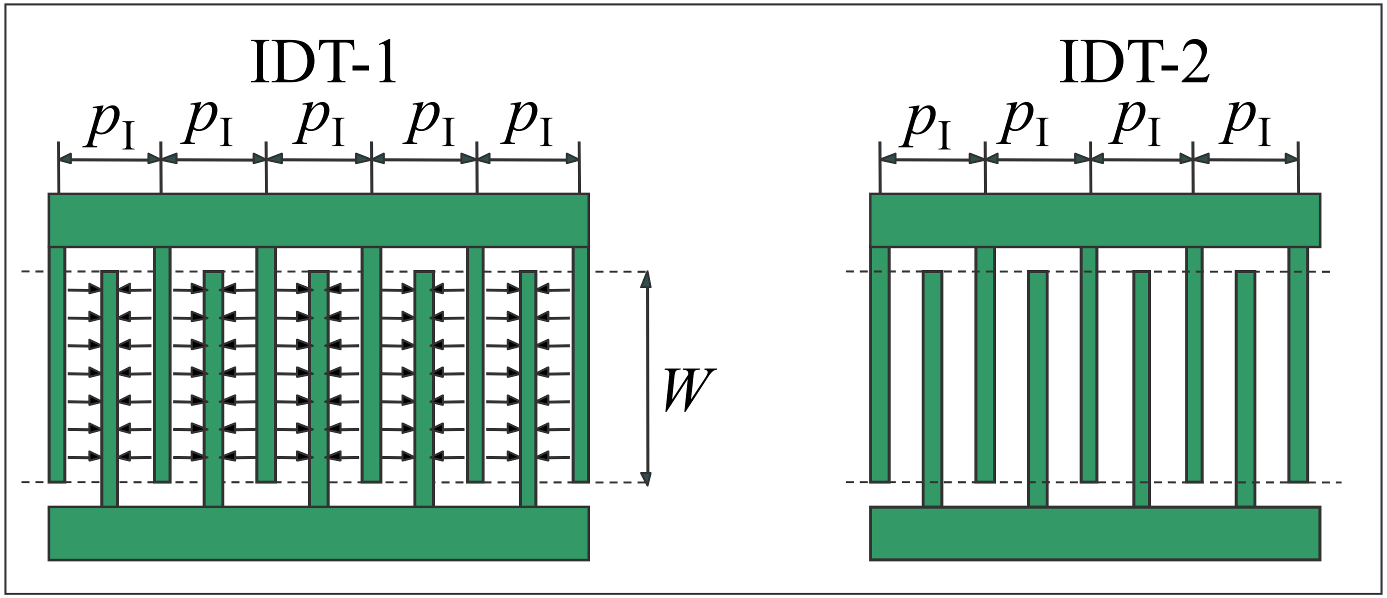
$$Y_{11} \cong Y_{11}^{S} + j\omega C_0 N$$

C_0: Static Capacitance per Period



Relative amplitude in dB
0
-5
-10
-15
-20
-25
-30
-35
-40
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Relative frequency
sinNx/Nsinx
sinNx/Nx

Transfer Between Two IDTs

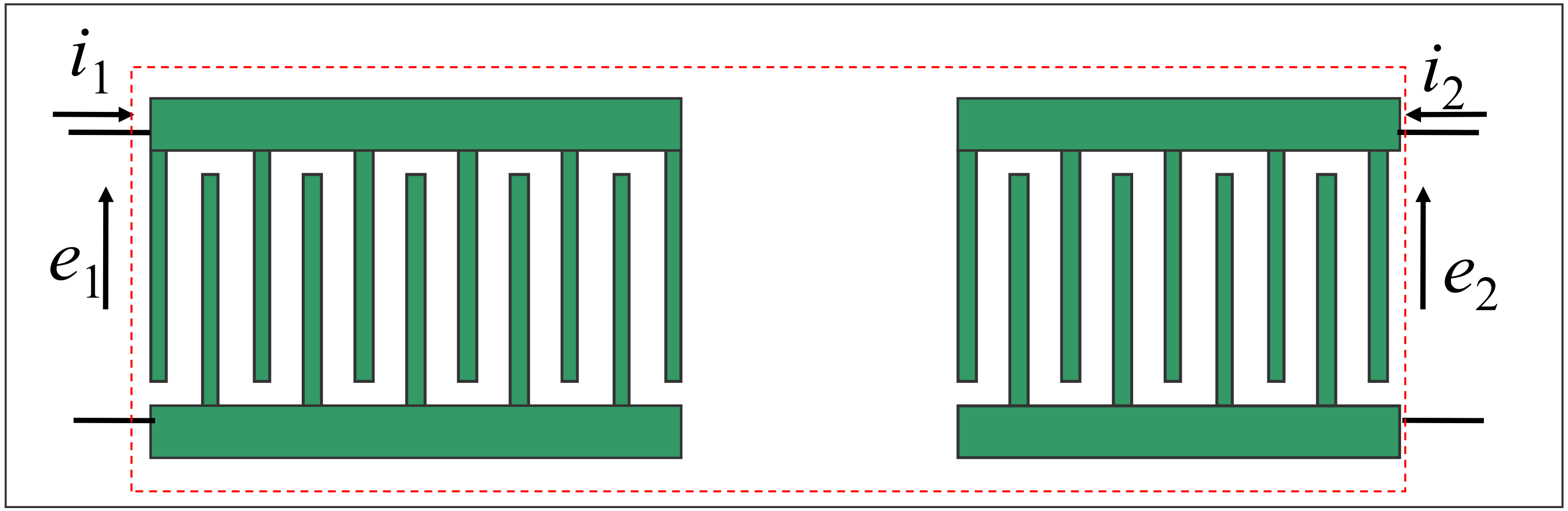


$$Y_{21} \approx Y_{21}^S = \omega h_0 \sum_{m=0}^{N_1-1} \sum_{n=0}^{N_2-1} e^{-j\beta\{L+(m+n)p_I\}}$$

$$= \omega h_0 \boxed{e^{-j\beta\{L+(N_1+N_2-1)p_I/2\}}} \boxed{\frac{\sin(\beta N_1 p_I/2)}{\sin(\beta p_I/2)}} \boxed{\frac{\sin(\beta N_2 p_I/2)}{\sin(\beta p_I/2)}}$$

Delay Between Center-to-Center　　***Freq. Response of IDT 1***　　***Freq. Response of IDT 2***

Admittance Matrix Representation



$$\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \end{pmatrix}$$

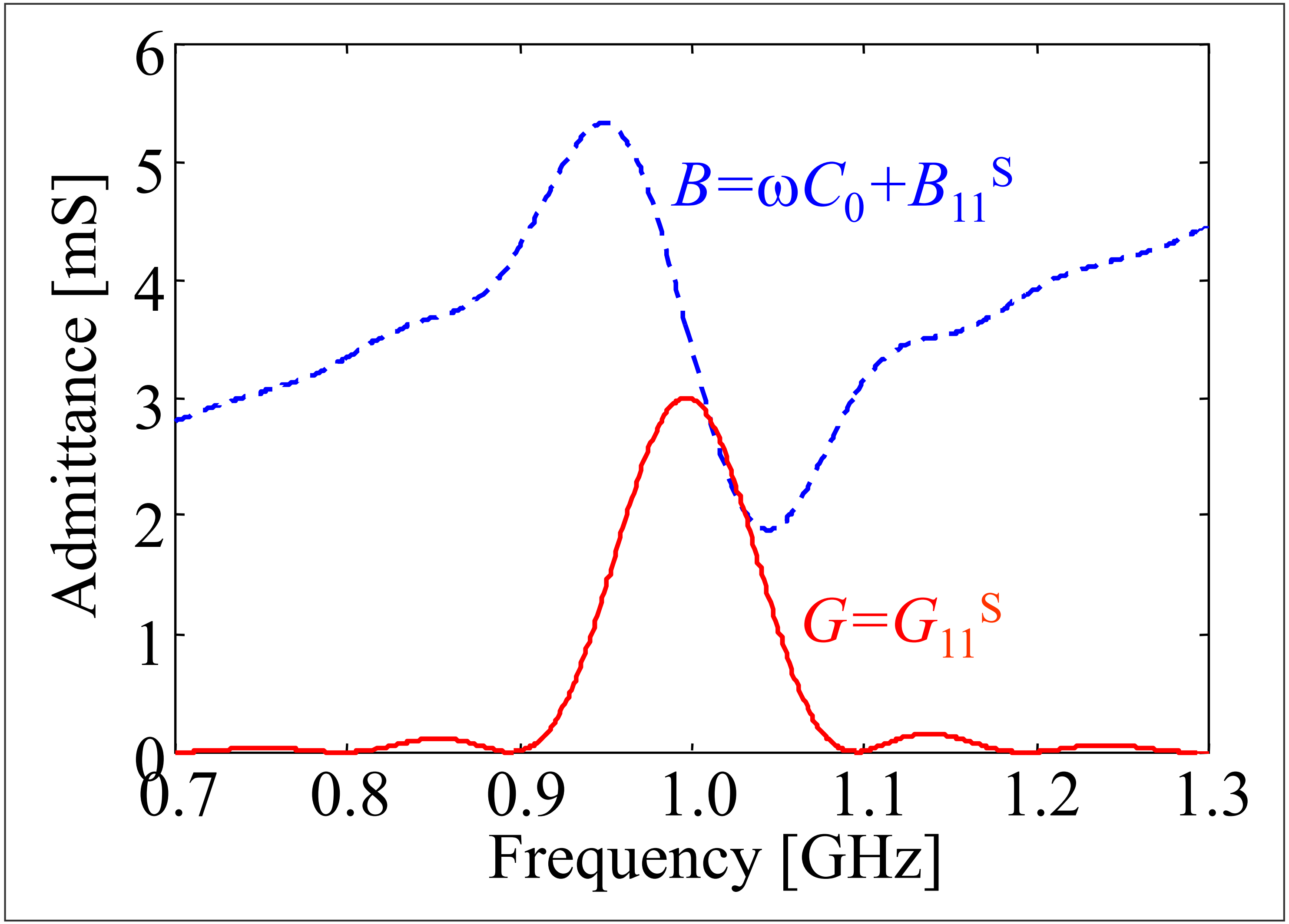
$$Y_{ij} = Y^e_{ij} + Y^S_{ij} + Y^B_{ij}$$

- Y^e_{ij} : Contribution of Electrostatic Coupling
- Y^S_{ij} : Contribution of SAW Radiation
- Y^B_{ij} : Contribution of BAW Radiation (Negligible near SAW Resonance)

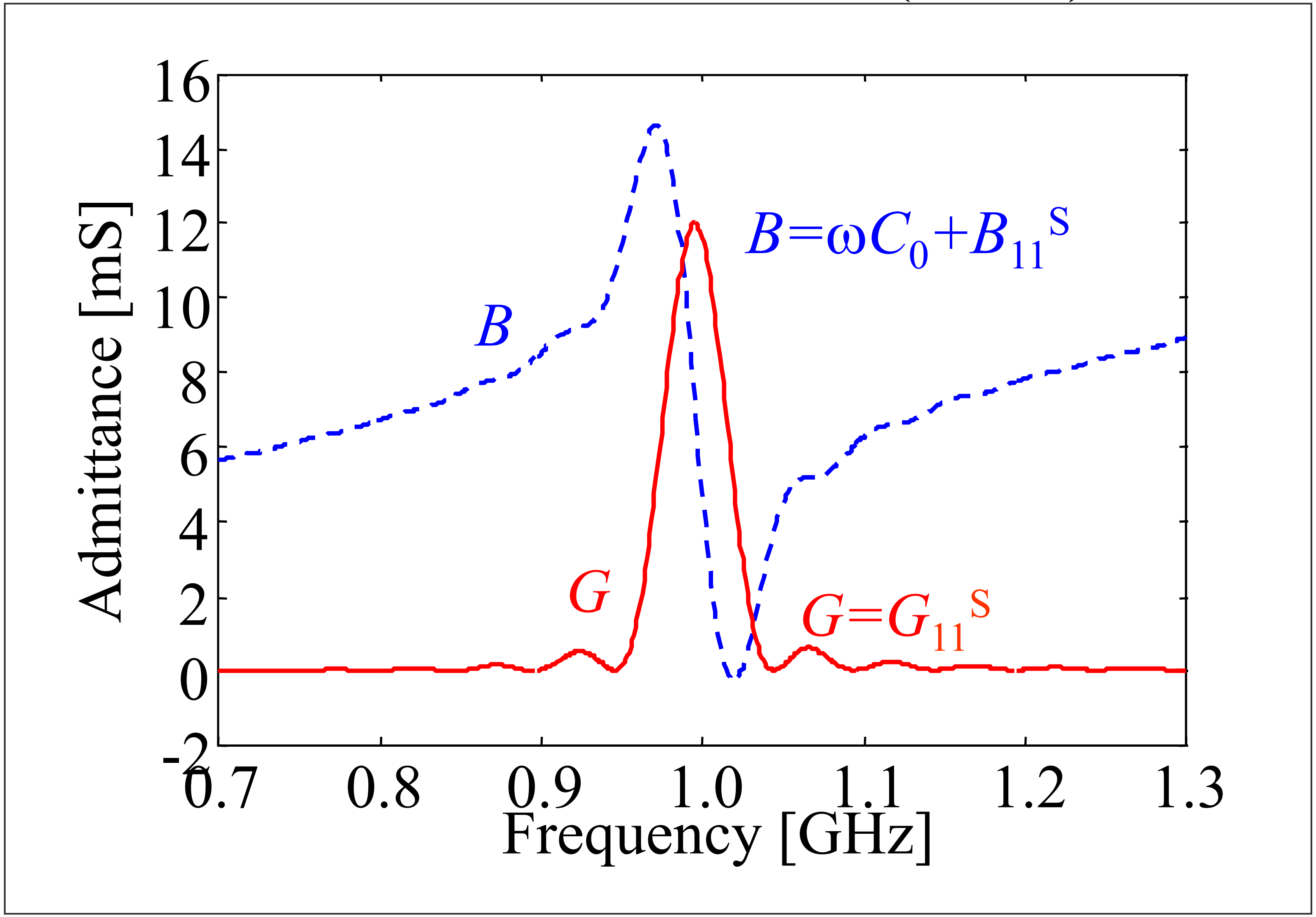
$$h^S{}_n = 2C_0\eta^2K^2\exp[-j\beta L_n]$$

- β : SAW Wavenumber (ω/V_{SAW})
- $L_n = L + np_{\mathrm{I}}$: Propagation Distance (n dependent)
- $C_0 = \varepsilon W$: Static Capacitance per Period (when $w/p_{\mathrm{I}} = 0.25$)
- W: Overlap Length
- K^2 : Electromechanical Coupling Factor
- η:Element Factor (finger configuration dependent)
  ($\eta^2 \approx 2/\pi$ for Single-Electrode IDTs with $w/p_{\mathrm{I}} = 0.25$)
- w: Electrode Width

Calculated IDT Admittance (N=10)



Calculated IDT Admittance (N=20)



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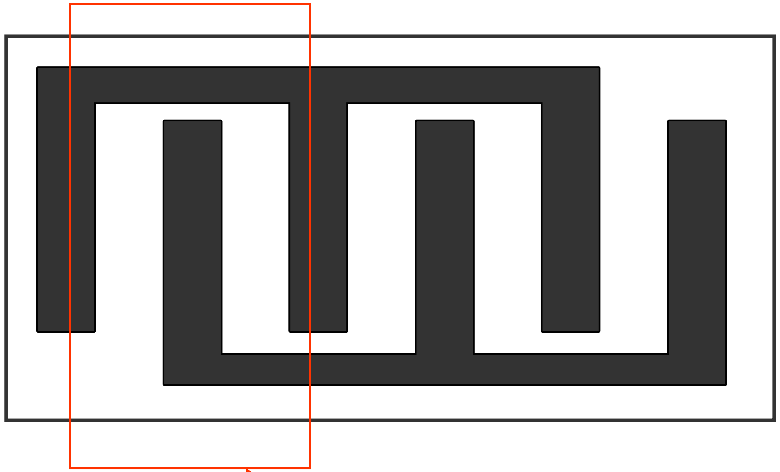
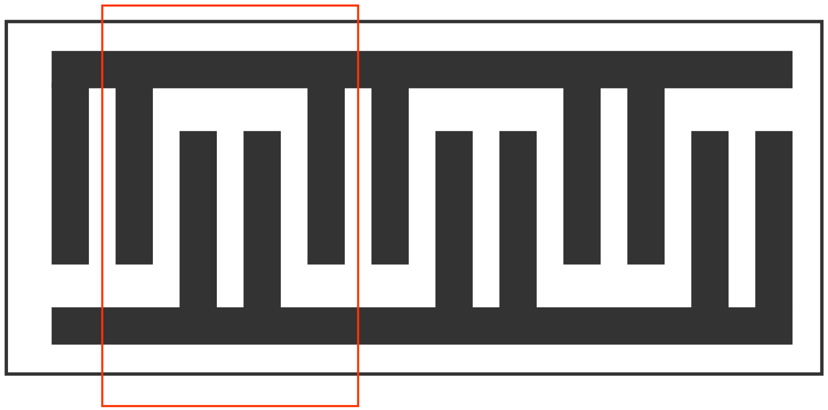
Electrode Geometries



IDT with Reflection
(Single-Electrode IDT)

Wider Line width

IDT Periodicity p_I

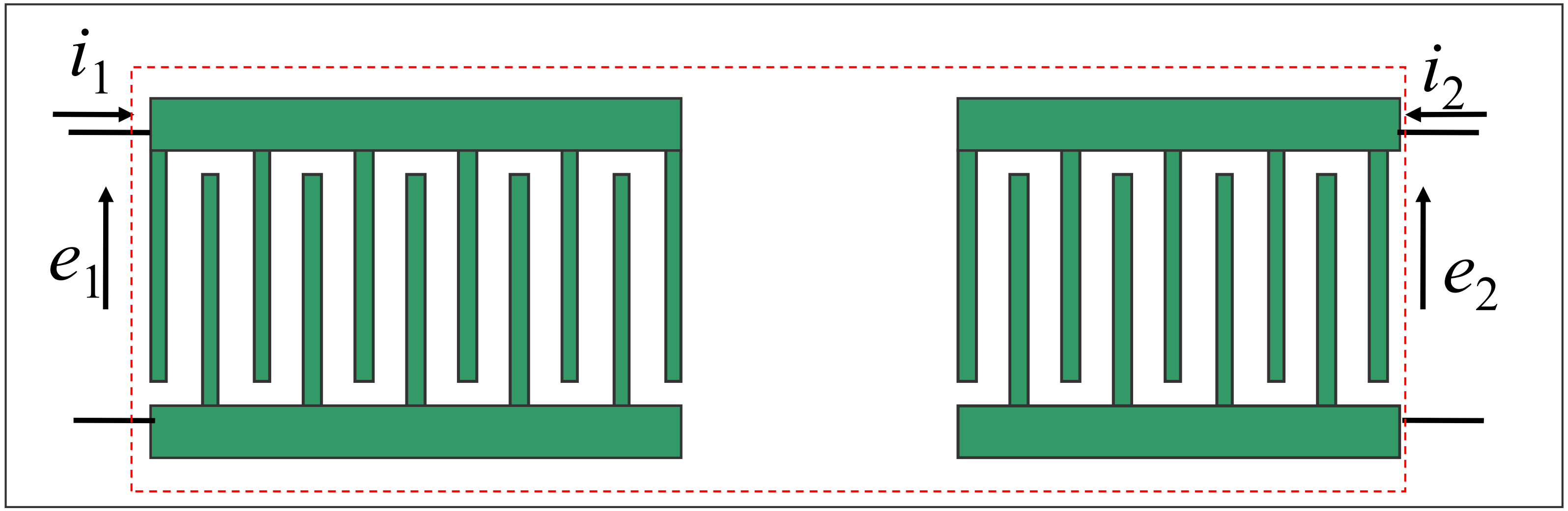


Reflection-less IDT

(Double-Electrode IDT)

Narrower Line width

Admittance Matrix Representation



$$\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \end{pmatrix}$$

$$Y_{ij} = Y^e{}_{ij} + Y^S{}_{ij} + Y^B{}_{ij}$$

- $Y^e{}_{ij}$: Contribution of Electrostatic Coupling
- $Y^S{}_{ij}$: Contribution of SAW Radiation
- $Y^B{}_{ij}$: Contribution of BAW Radiation (Negligible near SAW Resonance)

$$\begin{pmatrix} Y_{11}^e & Y_{12}^e \\ Y_{21}^e & Y_{22}^e \end{pmatrix} = \begin{pmatrix} j\omega C_{01} & 0 \\ 0 & j\omega C_{02} \end{pmatrix}$$

where $C_{0i} = \hat{N}_i C_\mathrm{p}$

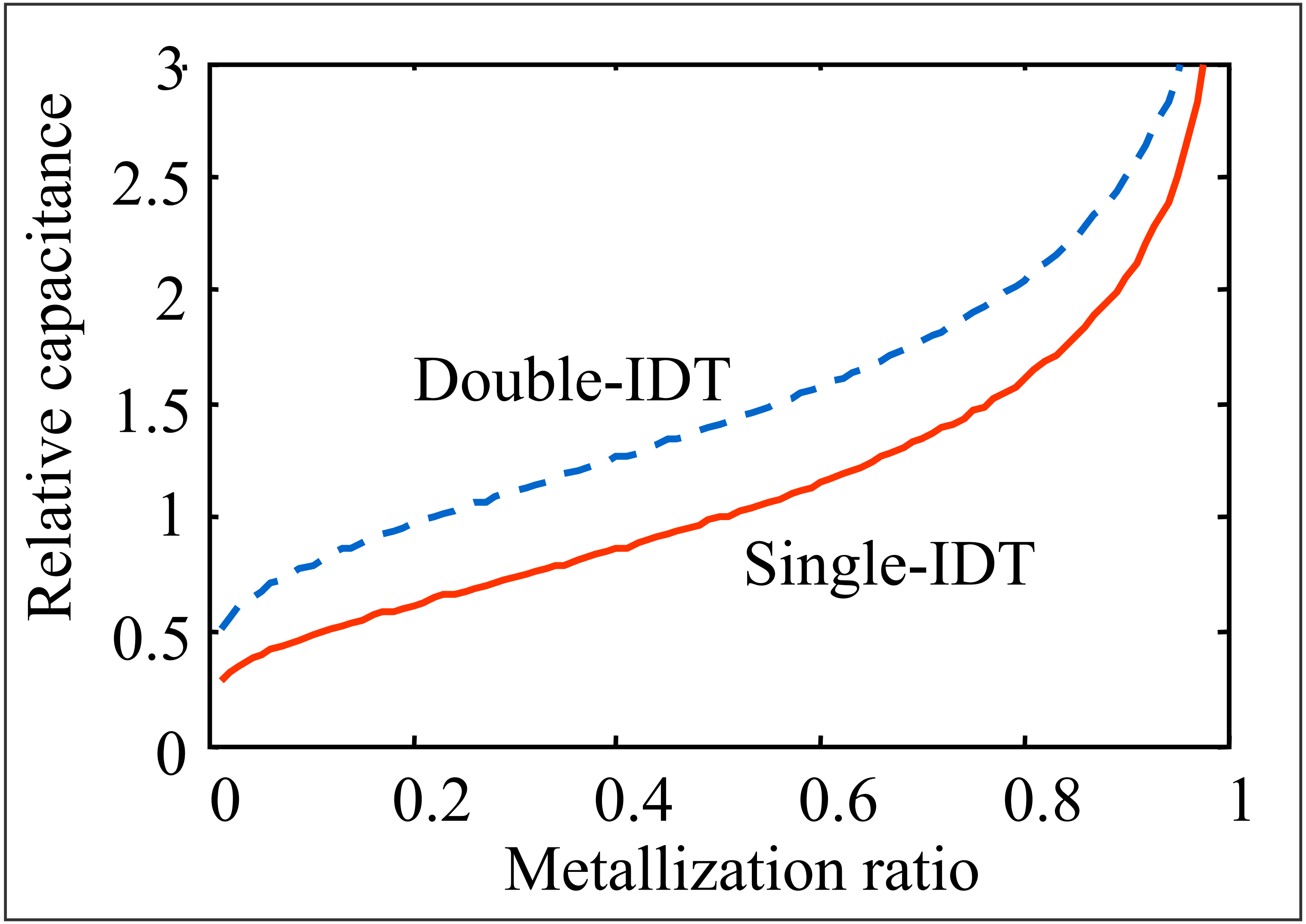
$$C_\mathrm{p} = \begin{cases} W\varepsilon(\infty)\dfrac{P_{-1/2}[\cos(2\pi w / p_\mathrm{I})]}{P_{-1/2}[-\cos(2\pi w / p_\mathrm{I})]} & \text{(Single IDT)} \\ W\sqrt{2}\varepsilon(\infty)\dfrac{P_{-1/4}[\cos(4\pi w / p_\mathrm{I})]}{P_{-1/4}[-\cos(4\pi w / p_\mathrm{I})]} & \text{(Double IDT)} \end{cases}$$

w: *Electrode Width*

$P_n(x)$: Legendre Function

$\varepsilon(\infty)$: Effective Permittivity

IDT Static Capacitances



When w/p_I=0.25, C=$\varepsilon(\infty)W$ (single IDT)

When $c_S{}^2=2\omega\eta^2K^2C_\mathrm{p}$

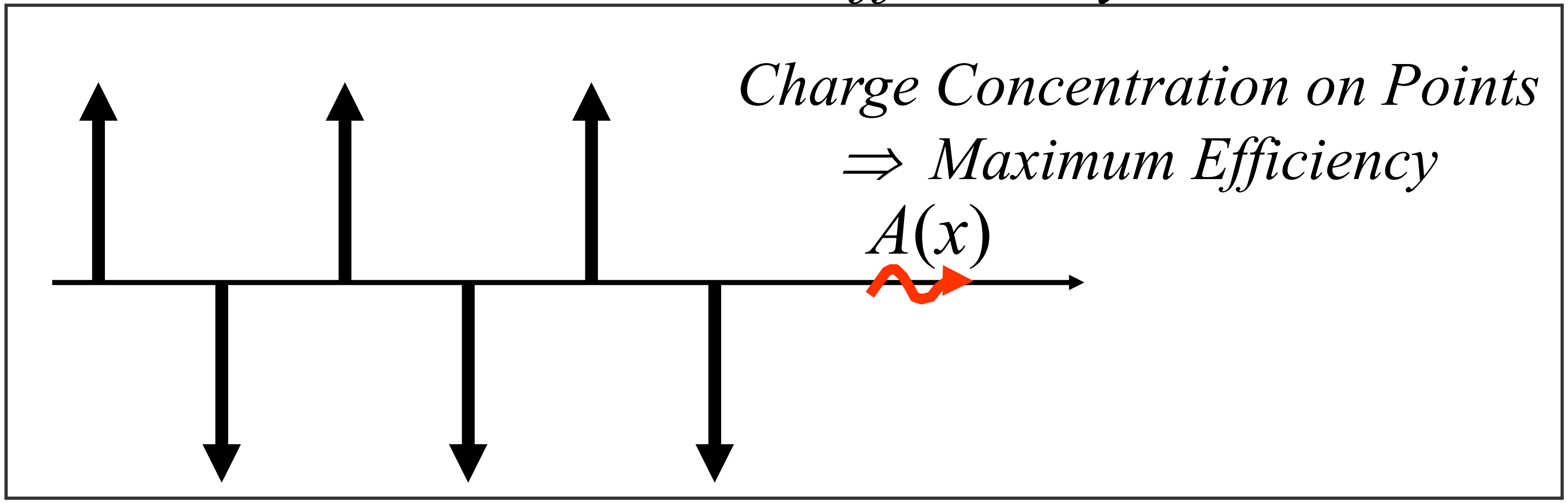
$$\begin{pmatrix} Y_{11}^S & Y_{12}^S \\ Y_{21}^S & Y_{22}^S \end{pmatrix} = \begin{pmatrix} H_{11}^S(f) & H_{12}^S(f) \\ H_{12}^S(f) & H_{22}^S(f) \end{pmatrix}$$

η: Element Factor

- $\eta^2 \approx 2/\pi$ for Single-Electrode IDTs with $w/p_\mathrm{I}=0.25$

Element Factor η

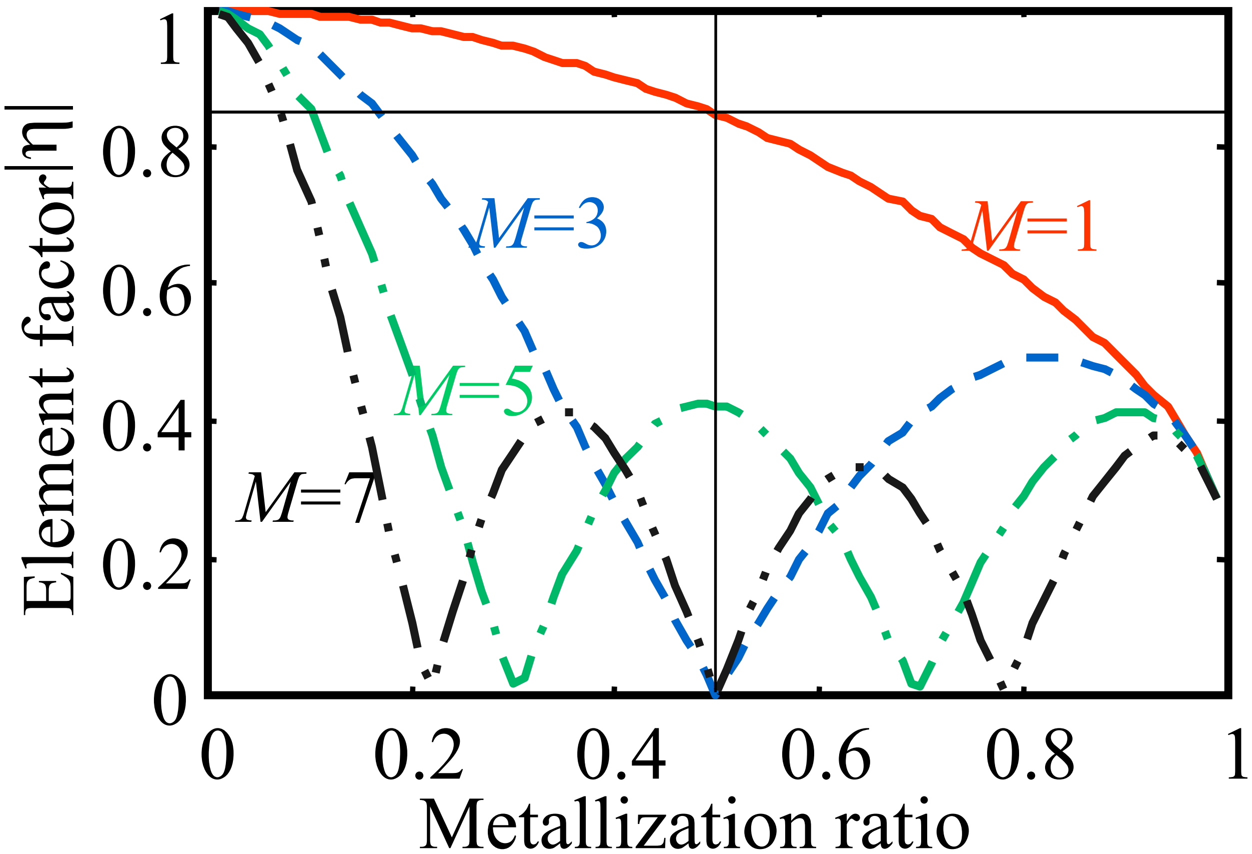
Relative Excitation Efficiency



$$A \propto \int_{-p_I/2}^{+p_I/2} q(x)\exp\{-j\beta(x-x')\}dx = Q(\beta)\exp(-j\beta x)$$

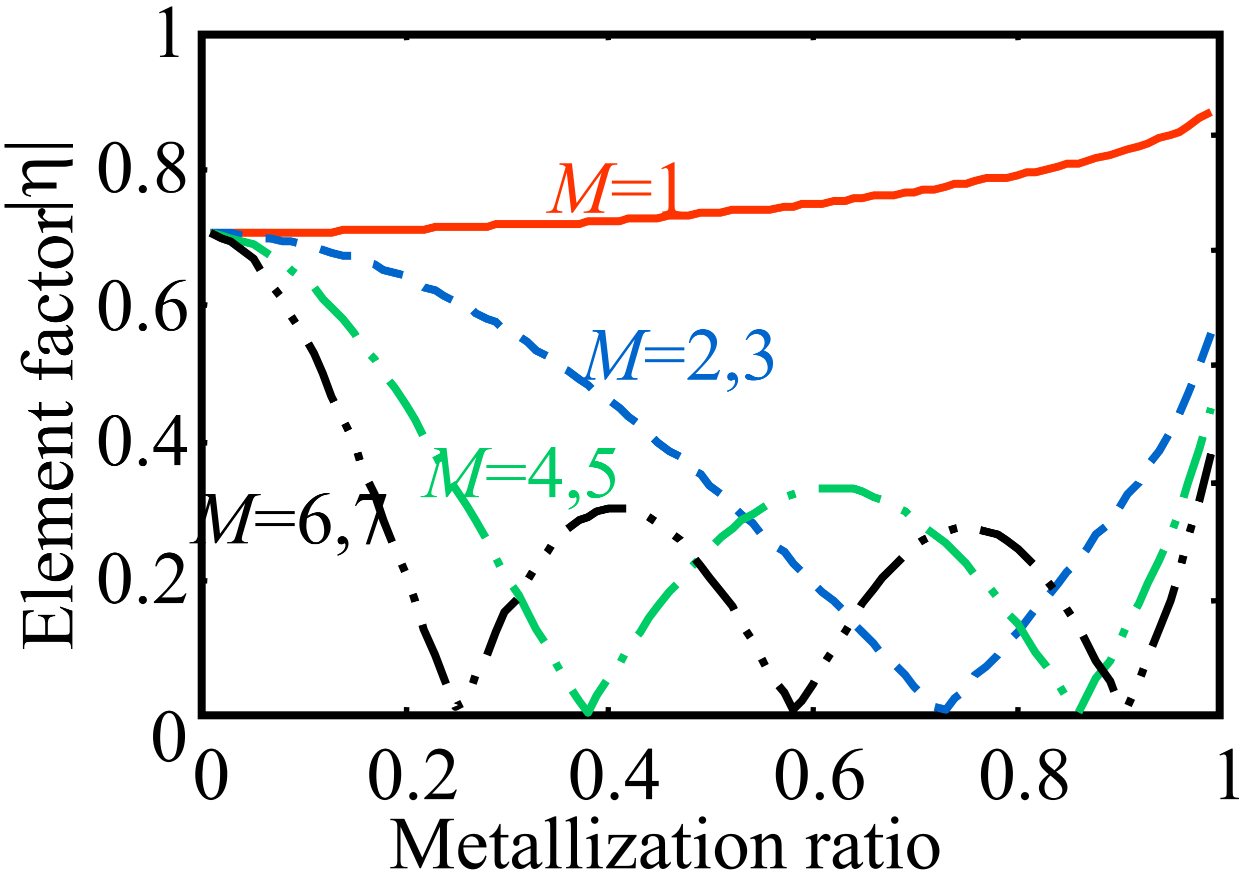
$$\Rightarrow \qquad \eta = \mathrm{Q}(\beta)/2\mathrm{C}_0$$

Q(β): Fourier Transform of q(x) in one Period



(a) Single Electrode

$$\eta = \frac{P_{(M-1)/2}[\cos(2\pi w / p_{\mathrm{I}})]}{P_{-1/2}[\cos(2\pi w / p_{\mathrm{I}})]}$$



(b) Double Electrode

$$\eta = (-1)^I \frac{P_{I-1/2}[\cos(4\pi w / p_\mathrm{I})]}{\sqrt{2}P_{-1/4}[\cos(4\pi w / p_\mathrm{I})]} \qquad \text{Where } I=\mathrm{int}[(M+1)/4]$$

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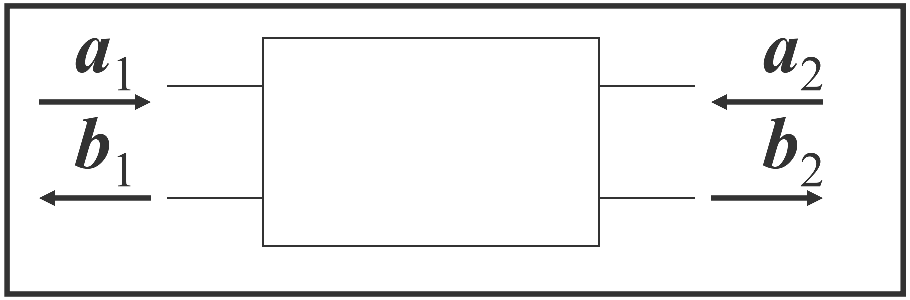
Scattering Parameter (Measurable by Network Analyzer)



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$\boldsymbol{a}_{\mathrm{m}}$: Normalized Amplitude of Incident Wave

$\boldsymbol{b}_{\mathrm{m}}$: Normalized Amplitude of Reflected Wave

For Linear Circuit,
$\boldsymbol{S_{ji}=S_{ij}}$

$$a_m = \frac{(e_m + R_0 i_m)}{2\sqrt{2R_0}}$$

$$b_m = \frac{(e_m - R_0 i_m)}{2\sqrt{2R_0}}$$

$\boldsymbol{R}_0$: Characteristic Impedance of Measurement System (Commonly 50Ω)

$\boldsymbol{S}_{21}$: Trans. Coef. → Insertion Loss: -20log$_{10}$ | $\boldsymbol{S}_{21}$|

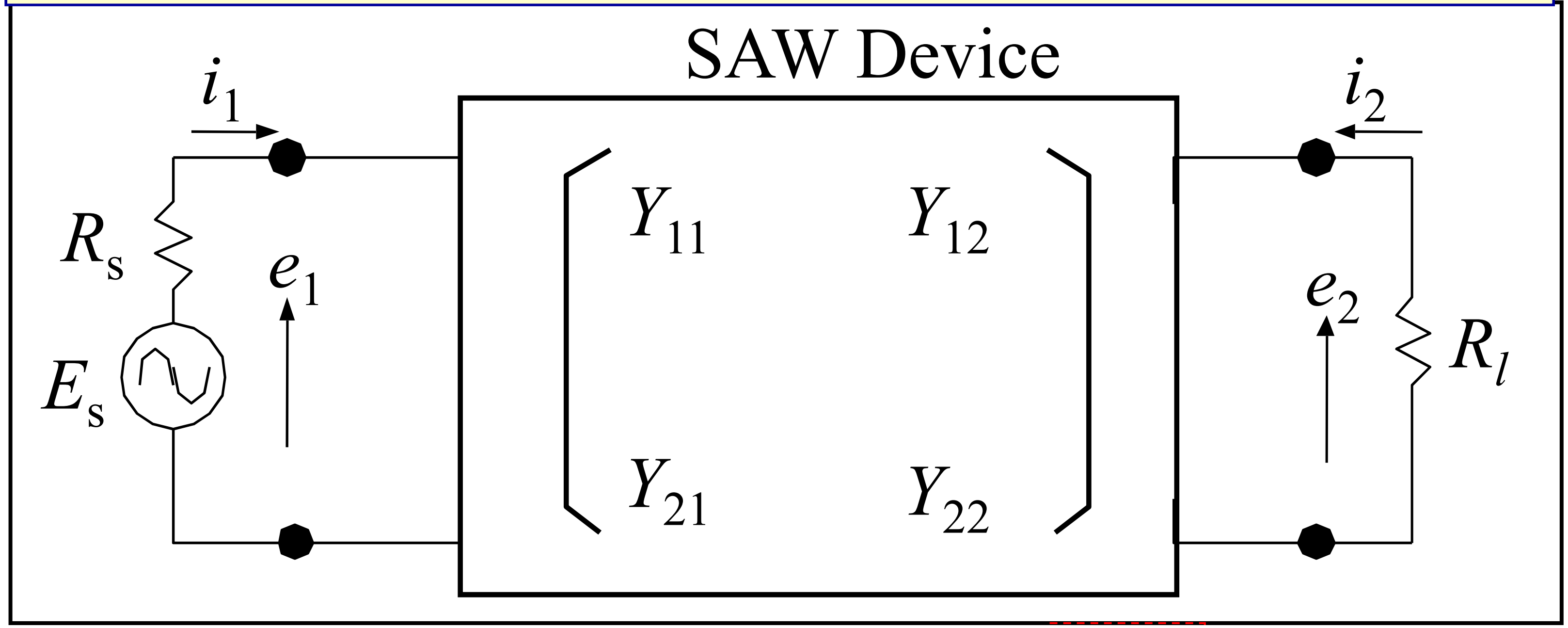
$\boldsymbol{S}_{11}$: Ref. Coef. → Return Loss: -20log$_{10}$ | $\boldsymbol{S}_{11}$|

Since $\mathbf{a}=\dfrac{(\mathbf{e}+R_0\mathbf{i})}{2\sqrt{2R_0}}, \mathbf{b}=\dfrac{(\mathbf{e}-R_0\mathbf{i})}{2\sqrt{2R_0}}, \mathbf{b}=\mathbf{S}\mathbf{a}, \mathbf{i}=\mathbf{Y}\mathbf{e}$

$$\mathbf{Y}=R_0^{-1}(\mathrm{I}-\mathbf{S})(\mathrm{I}+\mathbf{S})^{-1}$$

$$\mathbf{S}=(\mathrm{I}-R_0\mathbf{Y})(\mathrm{I}+R_0\mathbf{Y})^{-1}$$

Influence of Peripheral Circuits

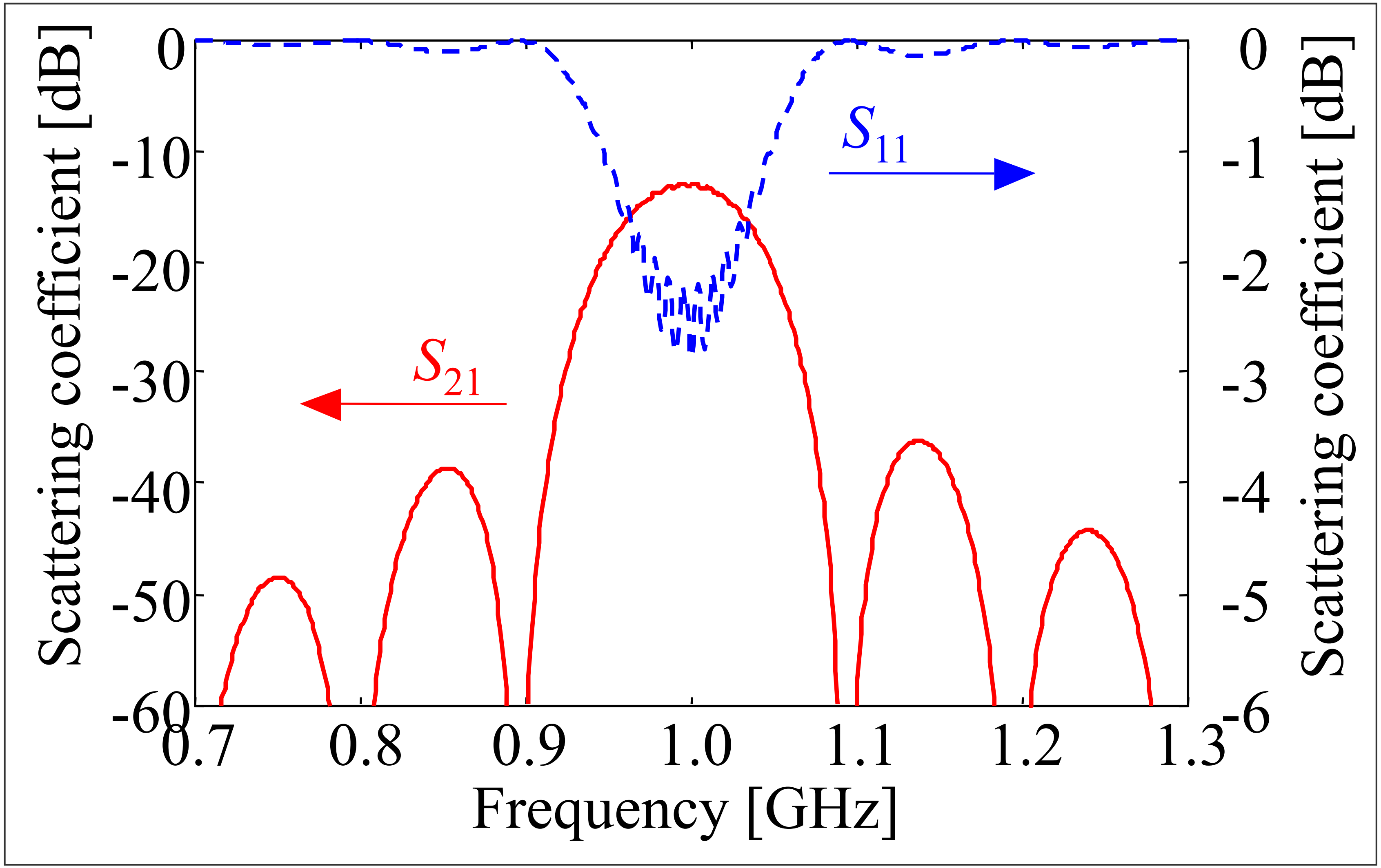


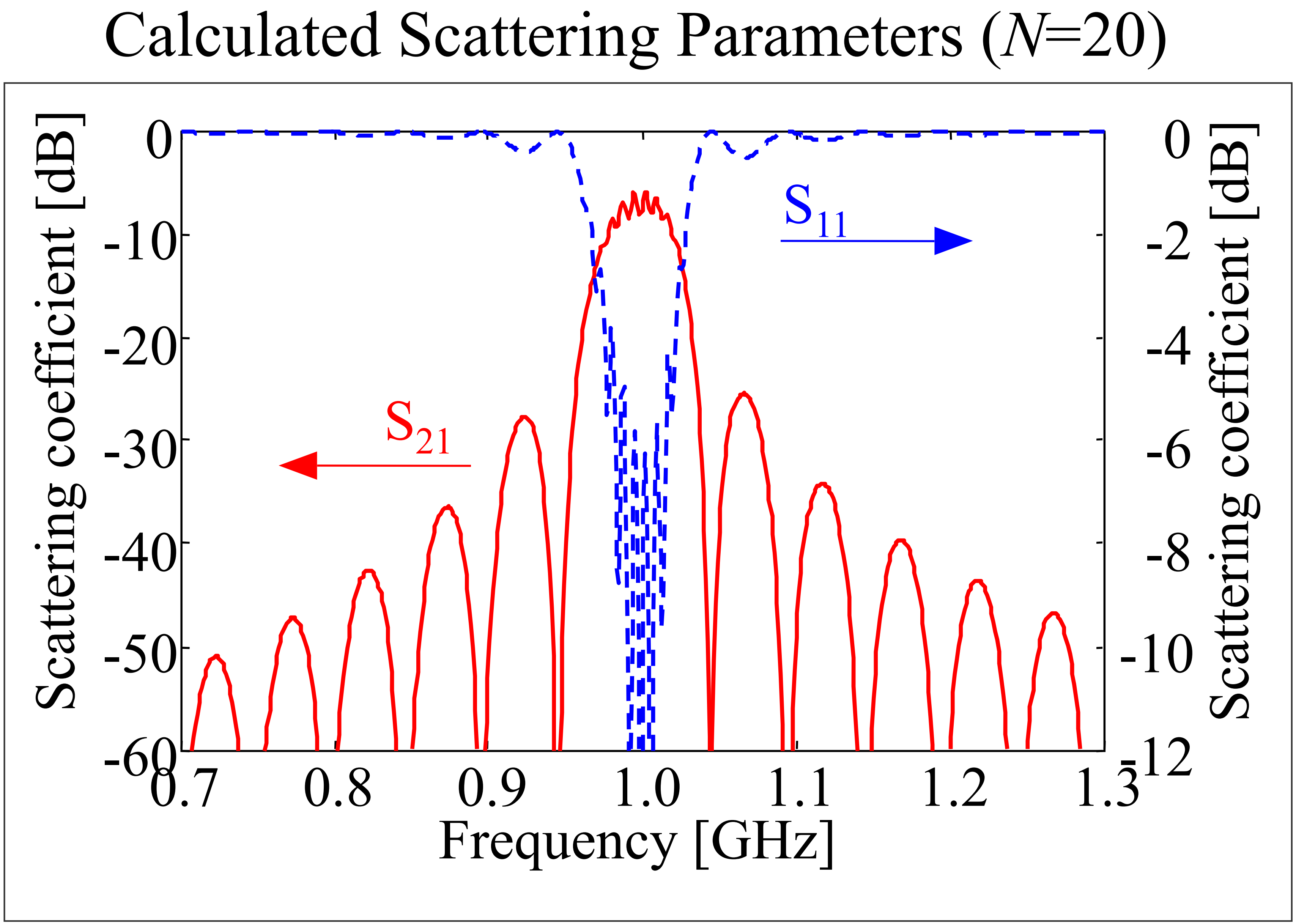
$$S_{11} = \frac{(-Y_{11} + G_s)(Y_{22} + G_l) + \boxed{Y_{21}Y_{12}}}{(Y_{11} + G_s)(Y_{22} + G_l) - \boxed{Y_{21}Y_{12}}}$$

$$S_{22} = \frac{(Y_{11} + G_s)(-Y_{22} + G_l) + \boxed{Y_{21}Y_{12}}}{(Y_{11} + G_s)(Y_{22} + G_l) - \boxed{Y_{21}Y_{12}}}$$

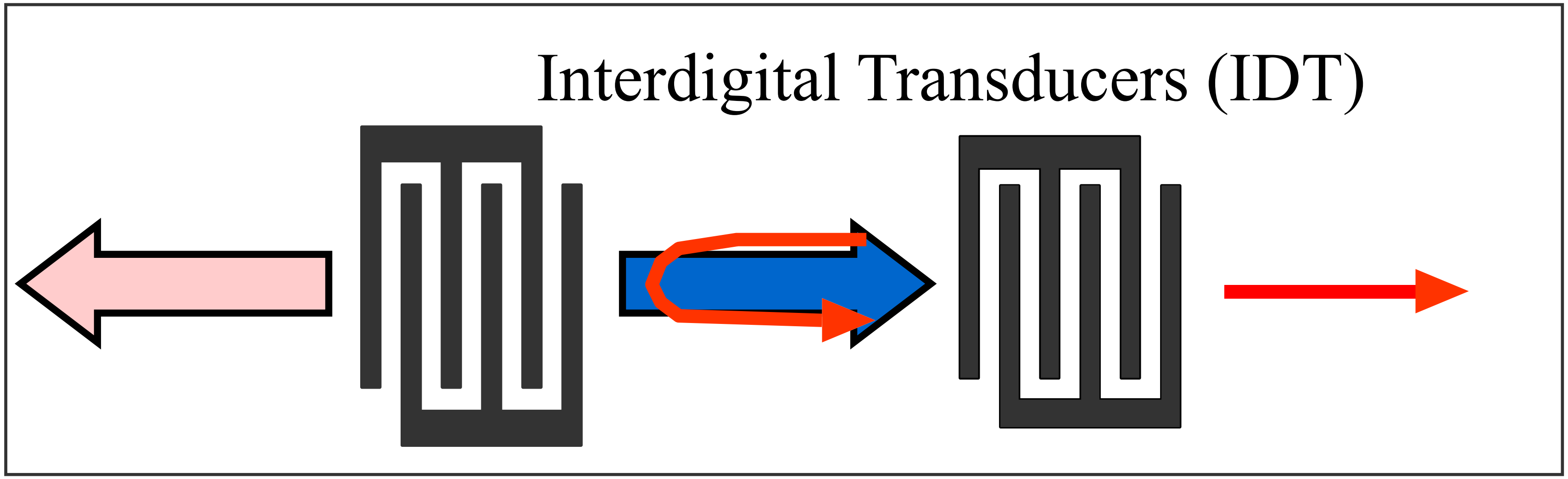
$$S_{21} = S_{12} = \frac{-2Y_{21}\sqrt{G_s G_l}}{(Y_{11} + G_s)(Y_{22} + G_l) - \boxed{Y_{21}Y_{12}}}$$

Calculated Scattering Parameters (N=10)



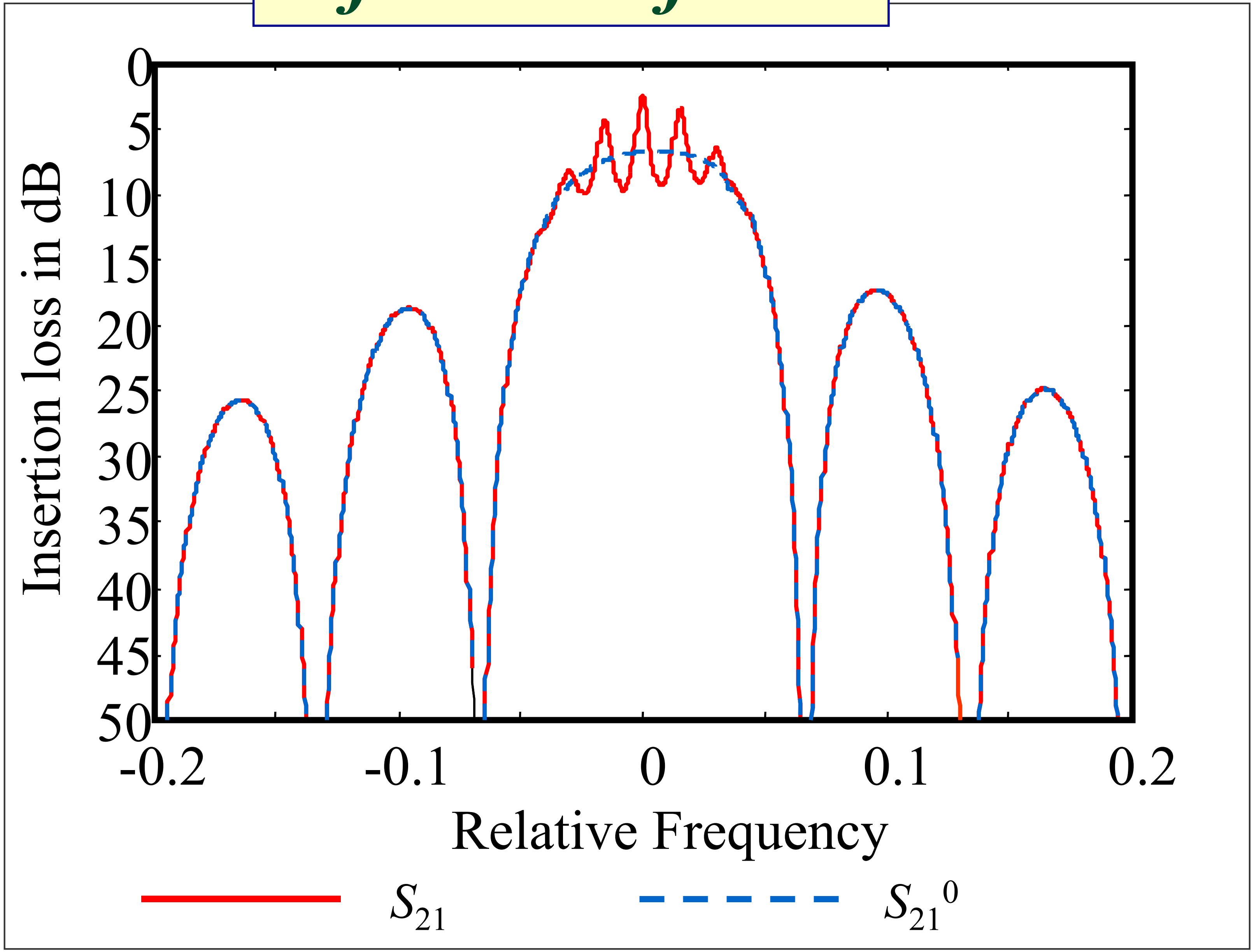

Calculated Scattering Parameters (N=20)
Scattering coefficient [dB]
0
-10
-20
-30
-40
-50
-60
S21
S11
0
-2
-4
-6
-8
-10
-12
0.7
0.8
0.9
1.0
1.1
1.2
1.3
Frequency [GHz]

Triple Transit Echo (TTE)



- Mechanical Reflection + Electrical Regeneration $\Rightarrow$ Mutual-Connection Dependent
- Trade-Off: TTE $\Leftrightarrow$ Insertion Loss
- Intrinsic for Bidirectional IDTs

Influence of TTE



Ideal Response (TTE Ignored)

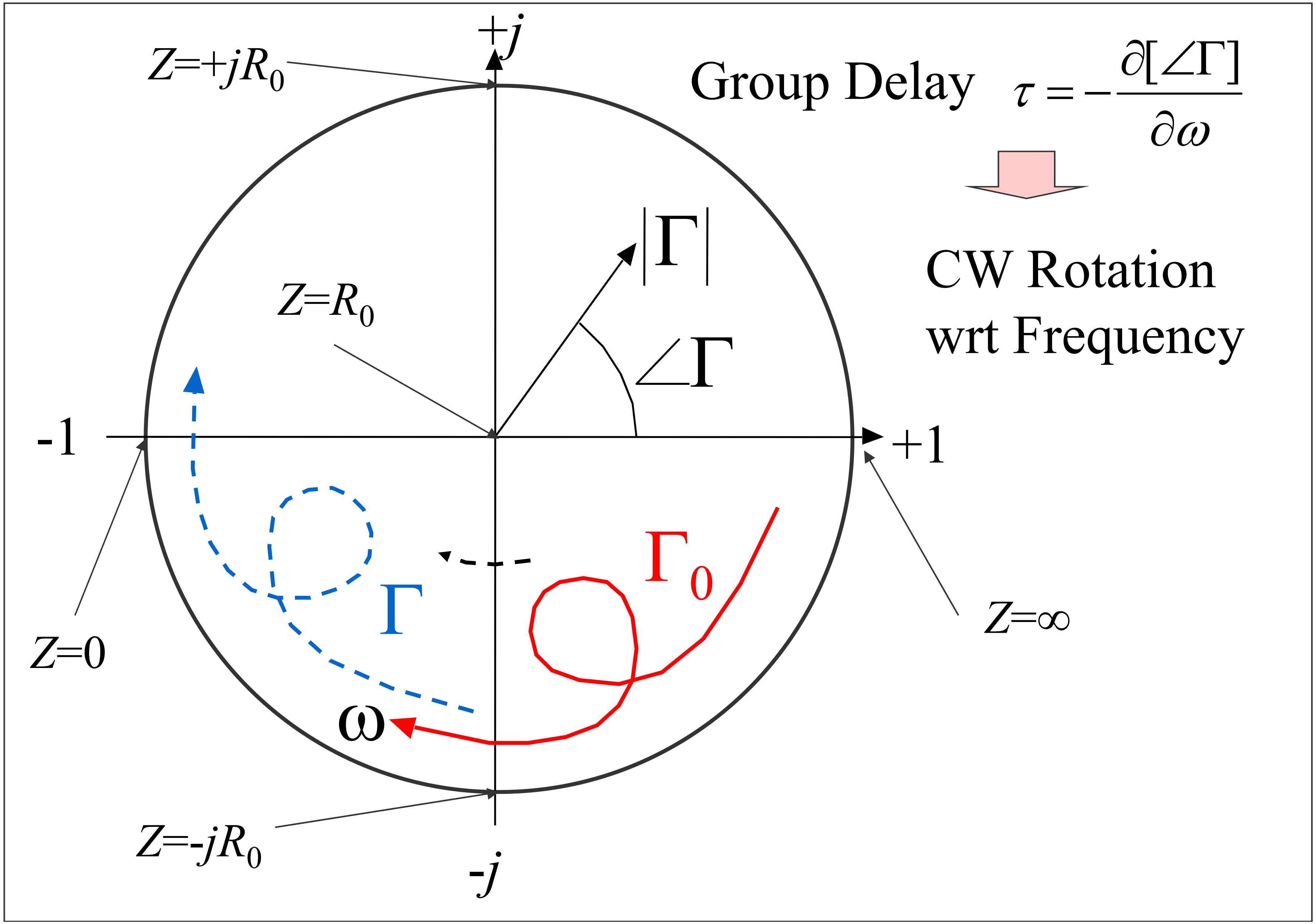
$$S_{21}^{0} = \frac{-2Y_{21}\sqrt{G_s G_l}}{(Y_{11}+G_s)(Y_{22}+G_l)}$$

$$\Downarrow$$

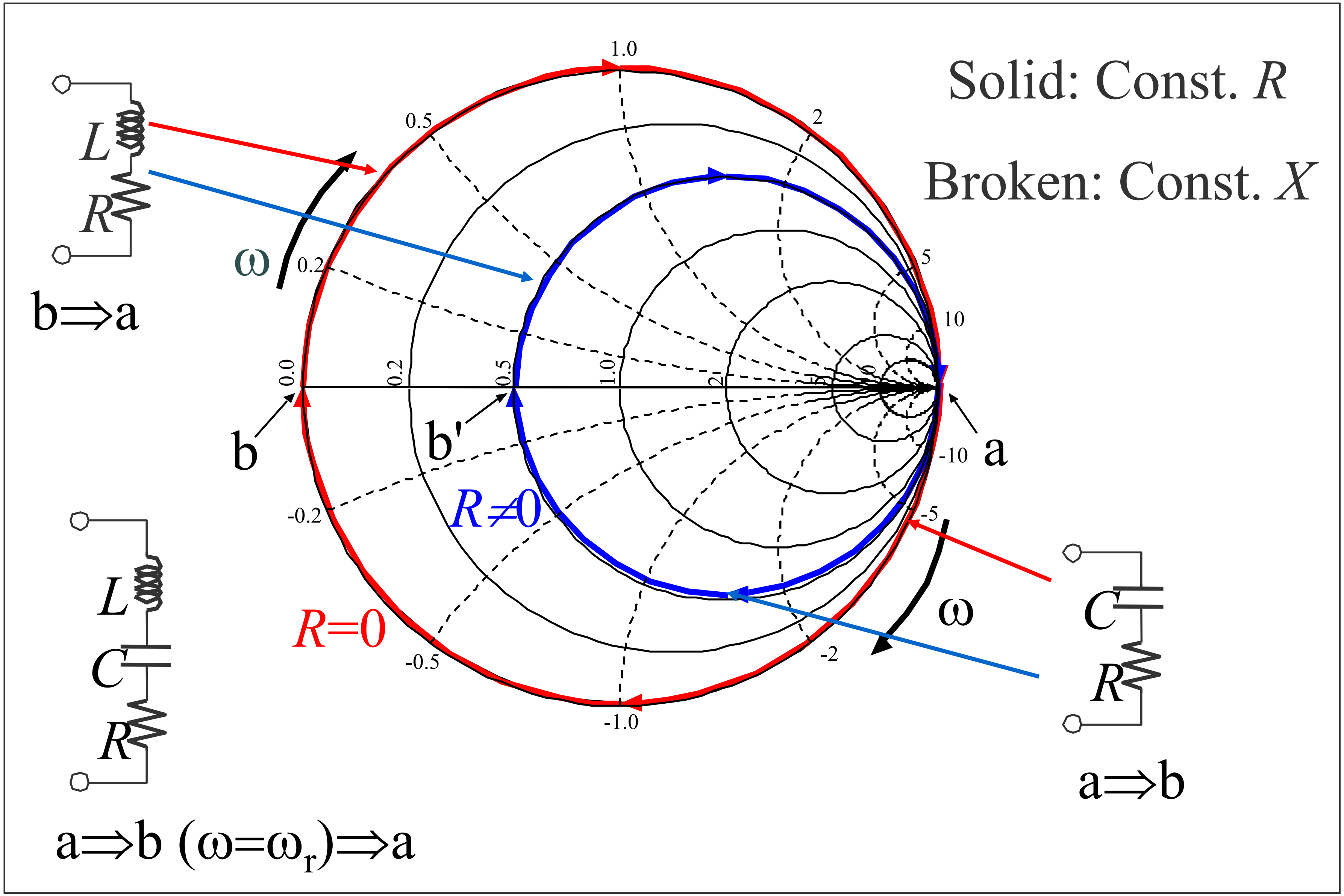
$$S_{21}^{0} \cong \frac{-2Y_{21}}{\sqrt{G_s G_l}} \quad \text{When } G_s \gg |Y_{11}|, G_l \gg |Y_{22}|$$

When $|S_{21}|$<<1 (less than -15 dB), $S_{21} \propto Y_{21}$

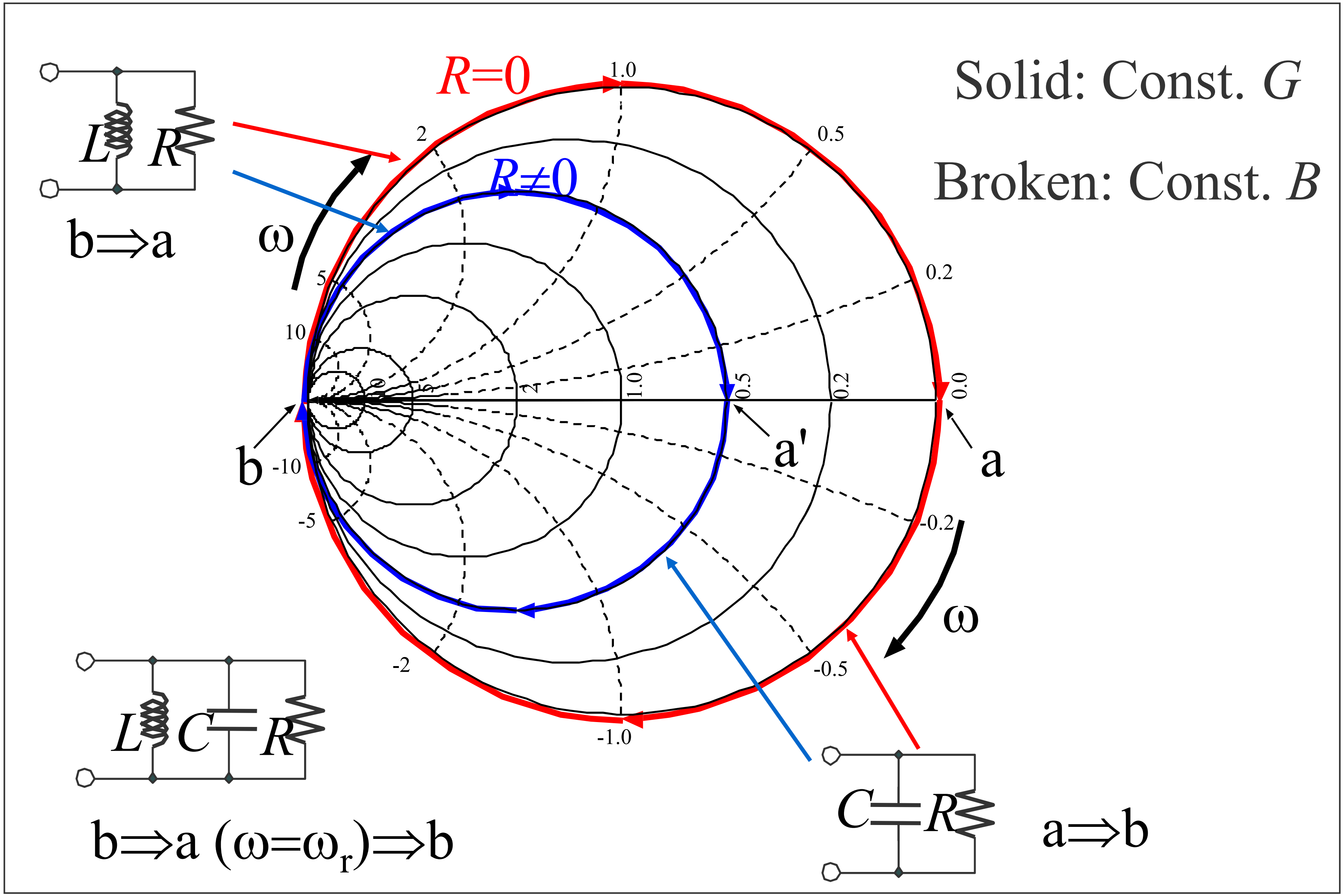
Variation of Reflection Coef. S_{11}

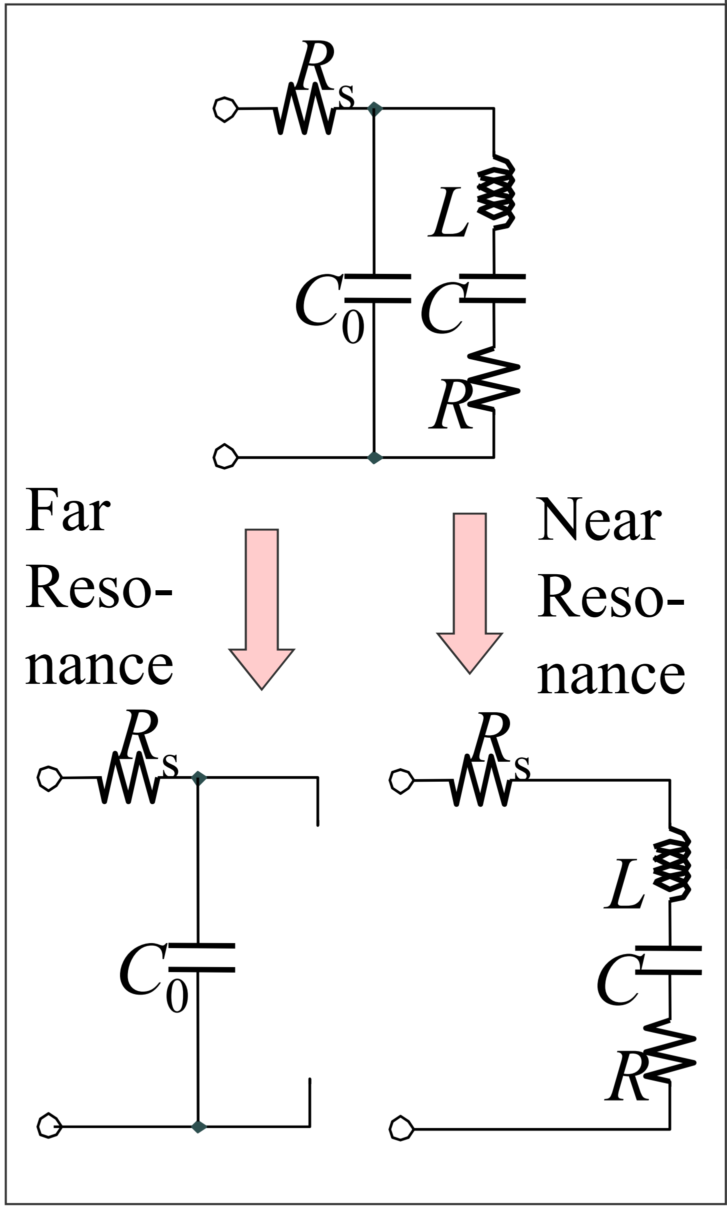


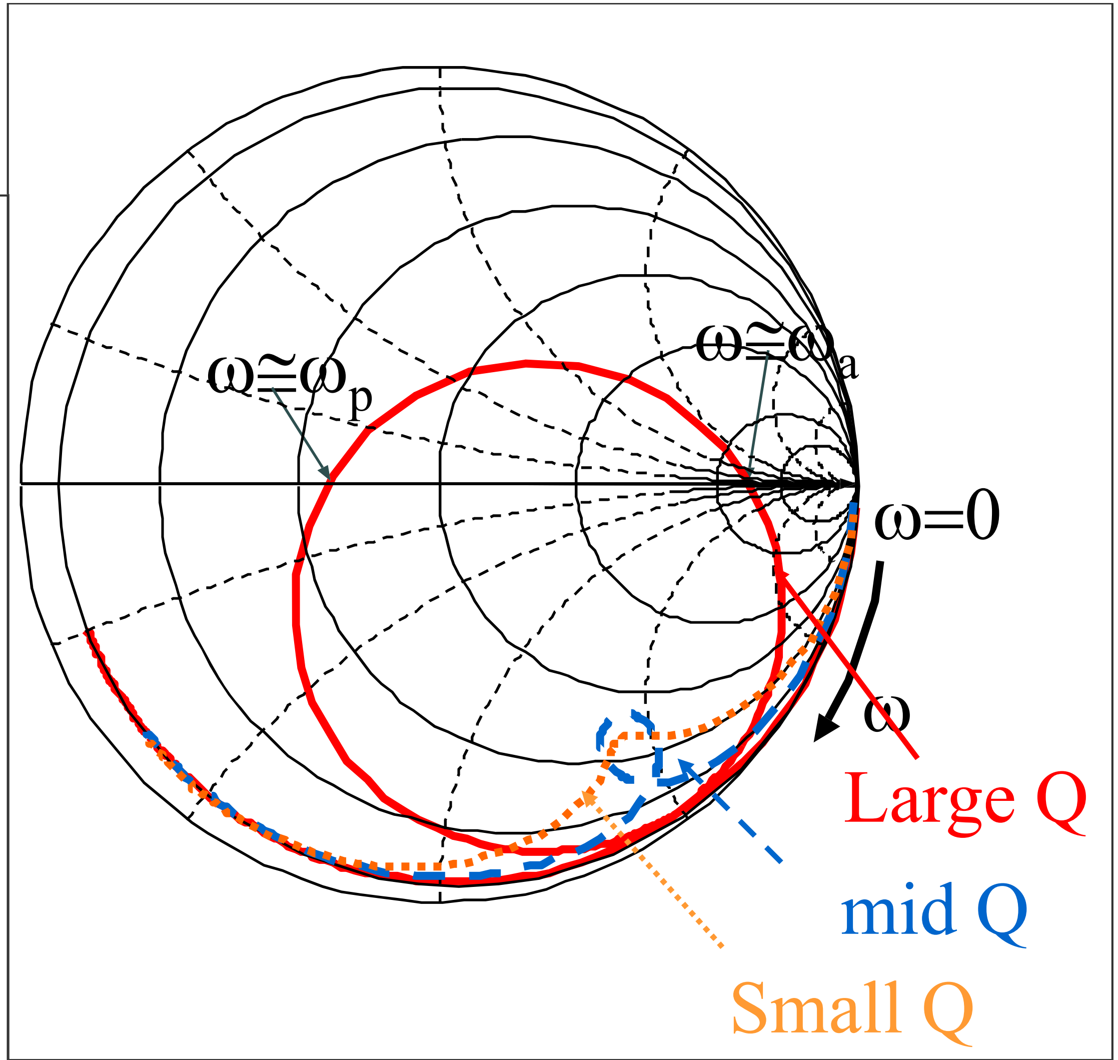
Smith Chart (Impedance Plot)



Smith Chart (Admittance Plot)

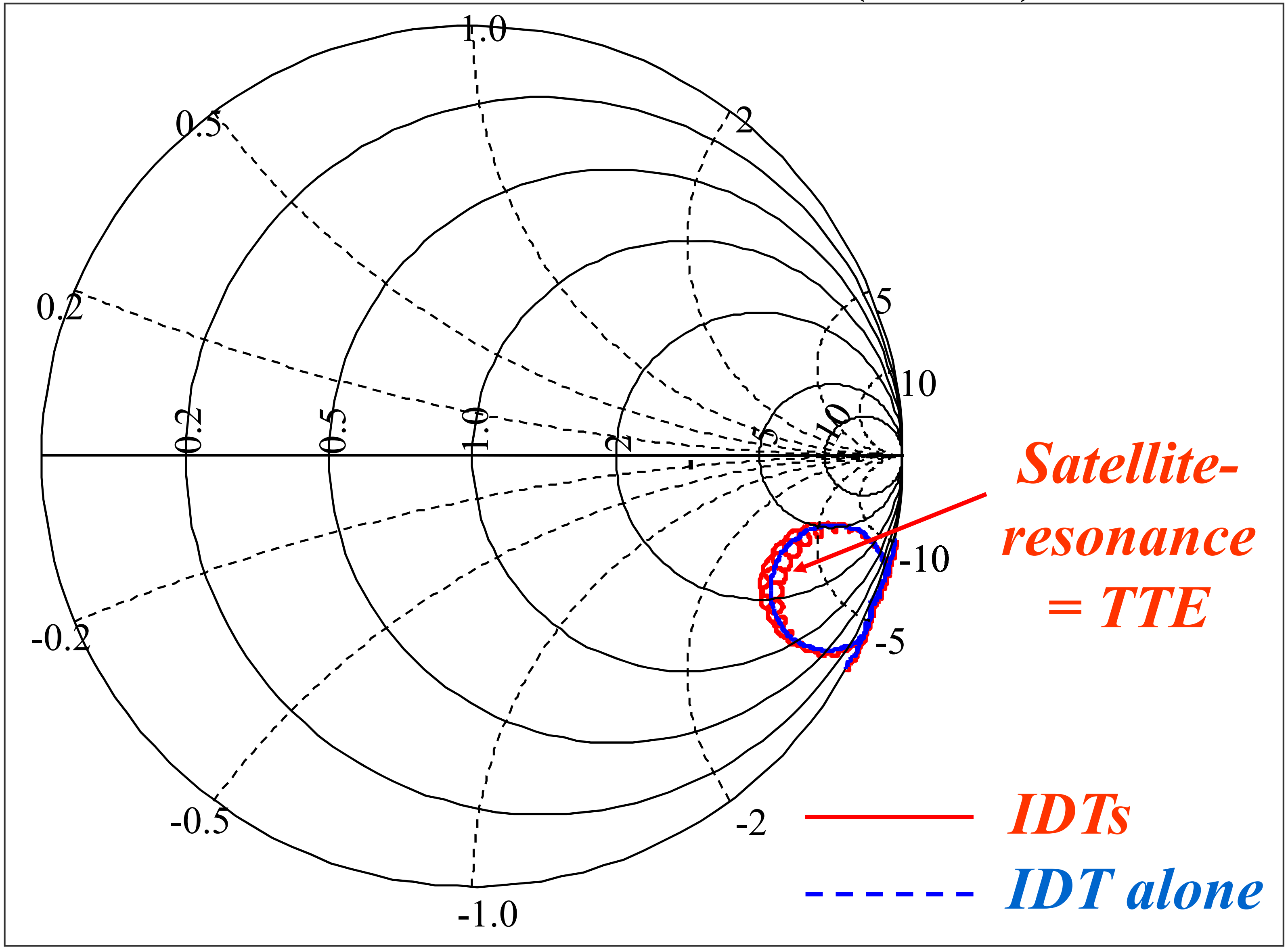




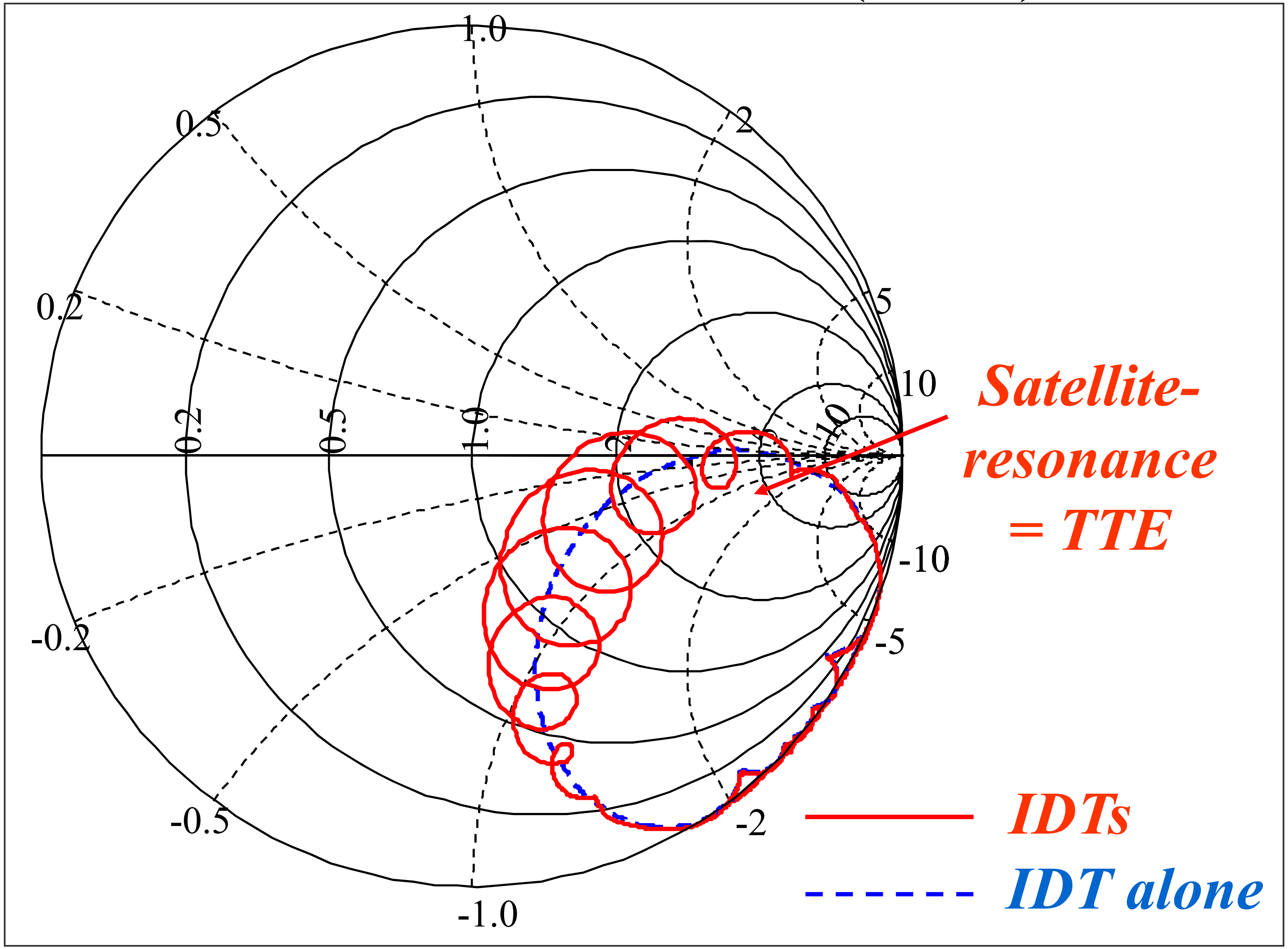


- Resonance $\omega_r = 1/\sqrt{CL}$
- Anti-Resonance $\omega_a = 1/\sqrt{L(C^{-1}+C_0^{-1})^{-1}}$
- Resonance $Q = \omega_r L/R$

Calculated IDT Admittance (N=10)



Calculated IDT Admittance (N=20)



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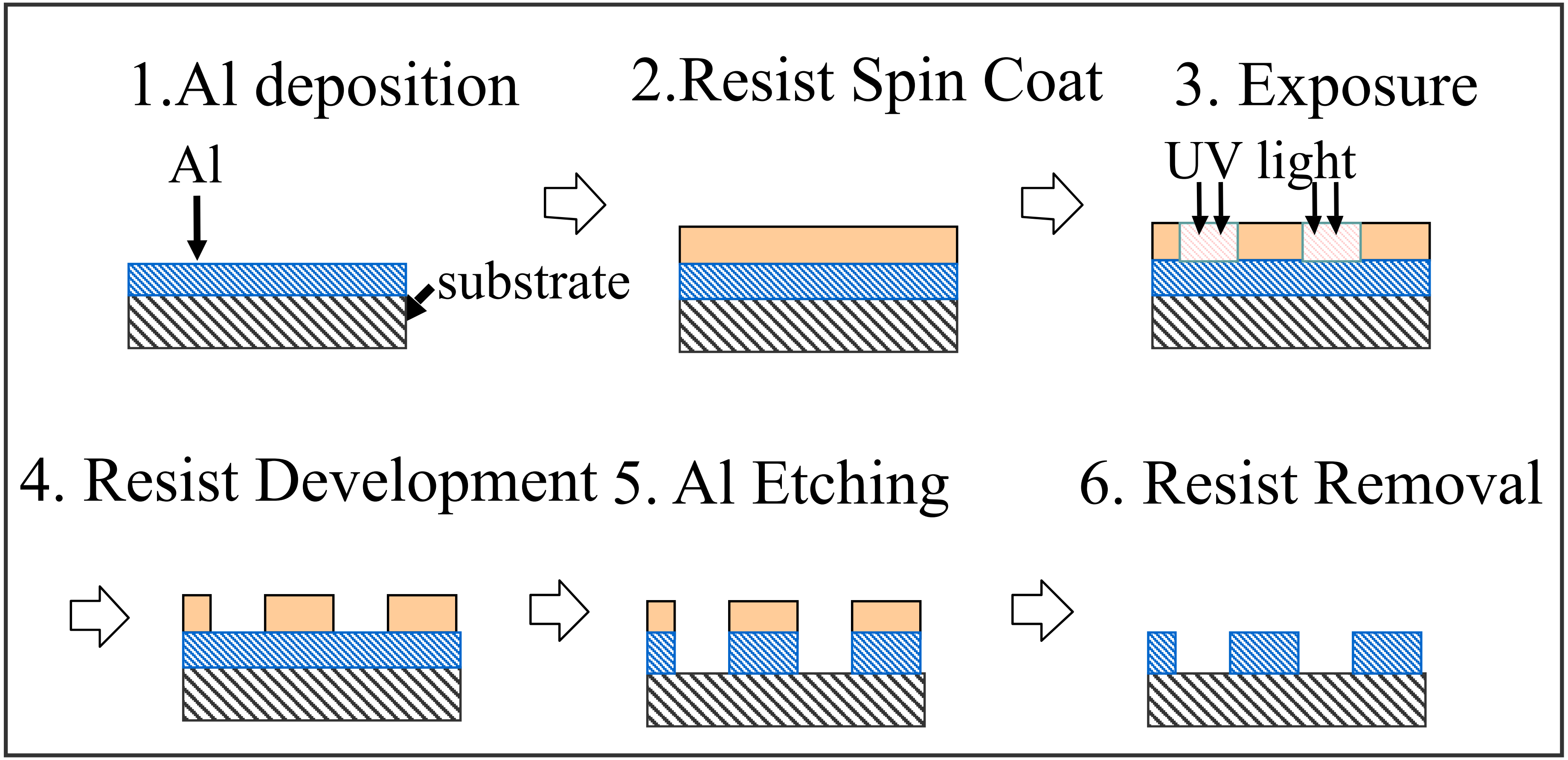
Conventional Photolithography



·Al Etching

1) Wet Process: H_3PO_4 System (or NaOH system)

Side Etch Generation = Hard to Line-width Control

2) Dry Process: Cl_2 gas System

Anisotropic Etching = Precise Line-Width Control

Toxic, reactive = Maintenance trouble

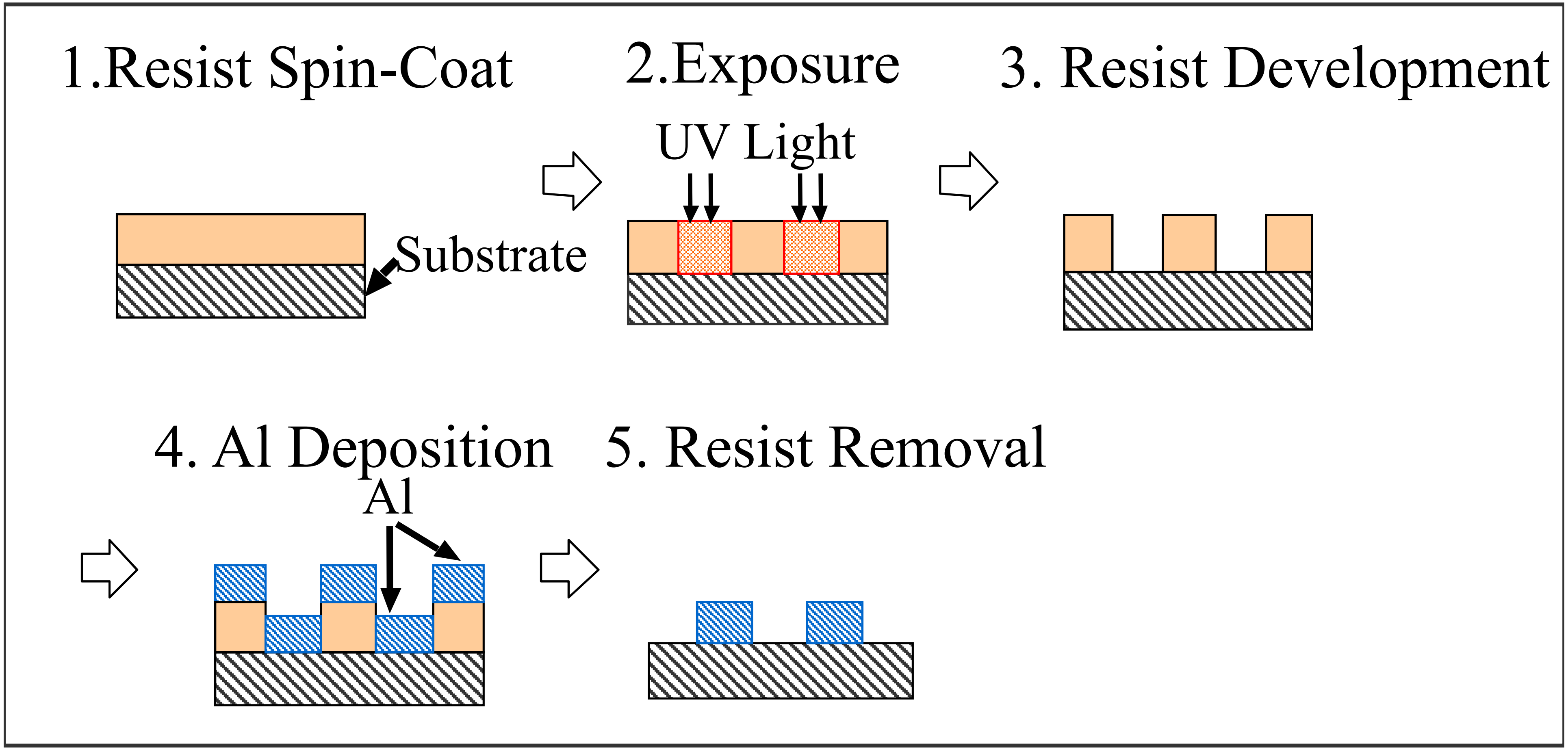
·UV Exposure Equipment

1) Contact Type：Mid Resolution, Photomask Damage

2) Stepper)：High Resolution, High Running-Cost

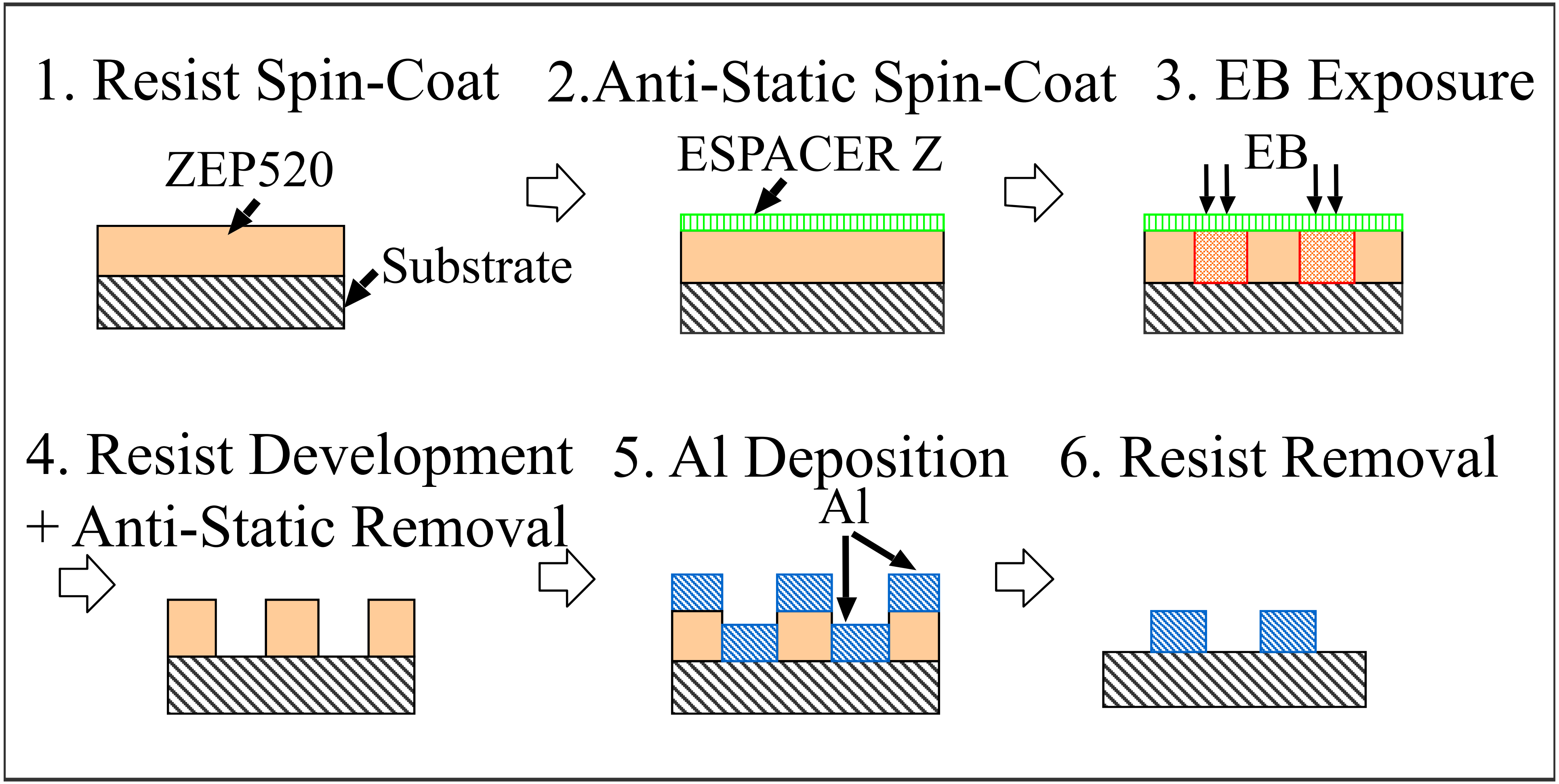
For University Use?

Lift-Off Process

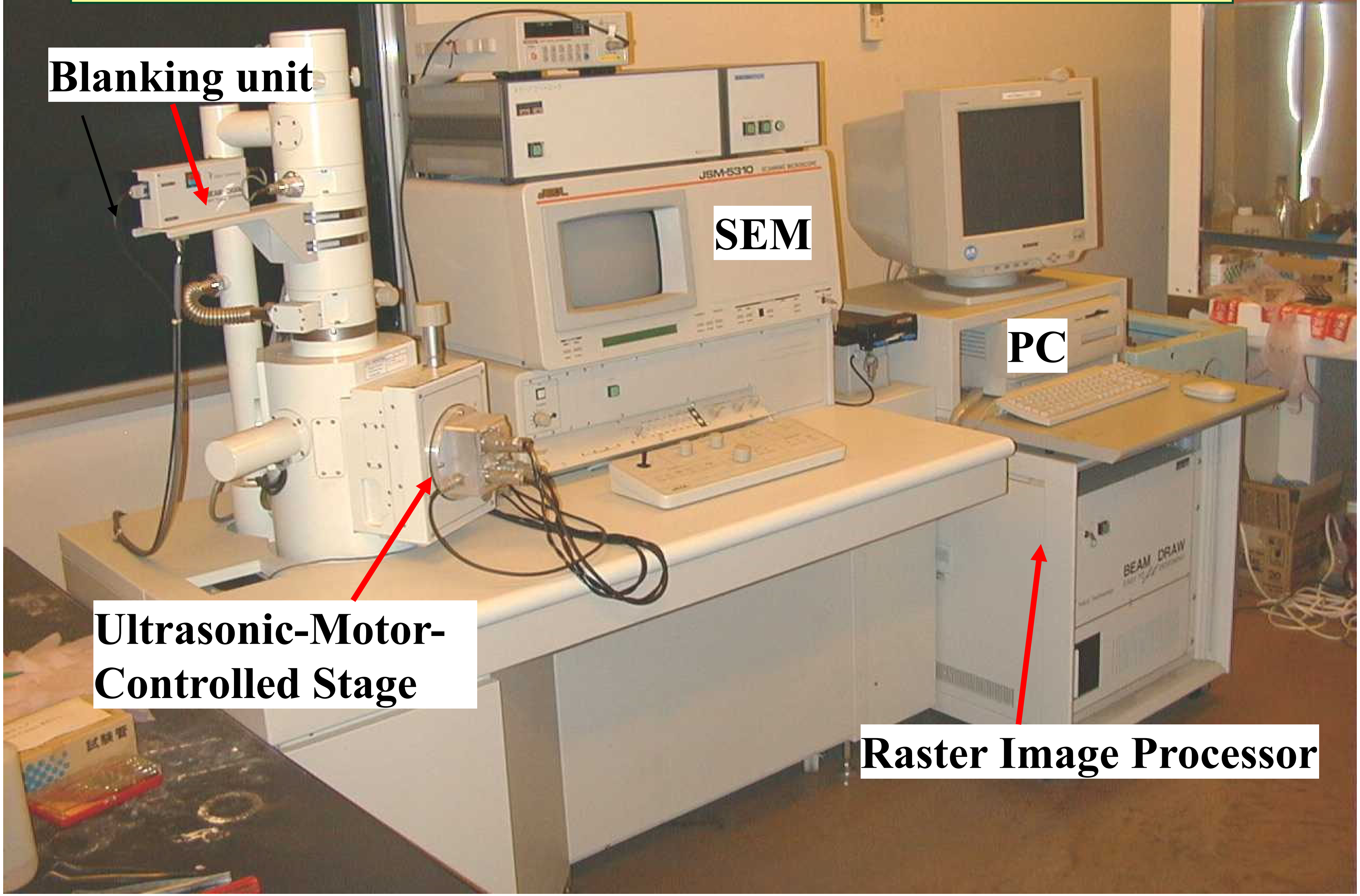


Sputter-Deposition Applicable?

Electron-Beam Exposure + Lift-Off



Current EB Lithography System



▪Al & Cu Deposition

1) Low Resistivity

2) Small Grain Size

3) Safe

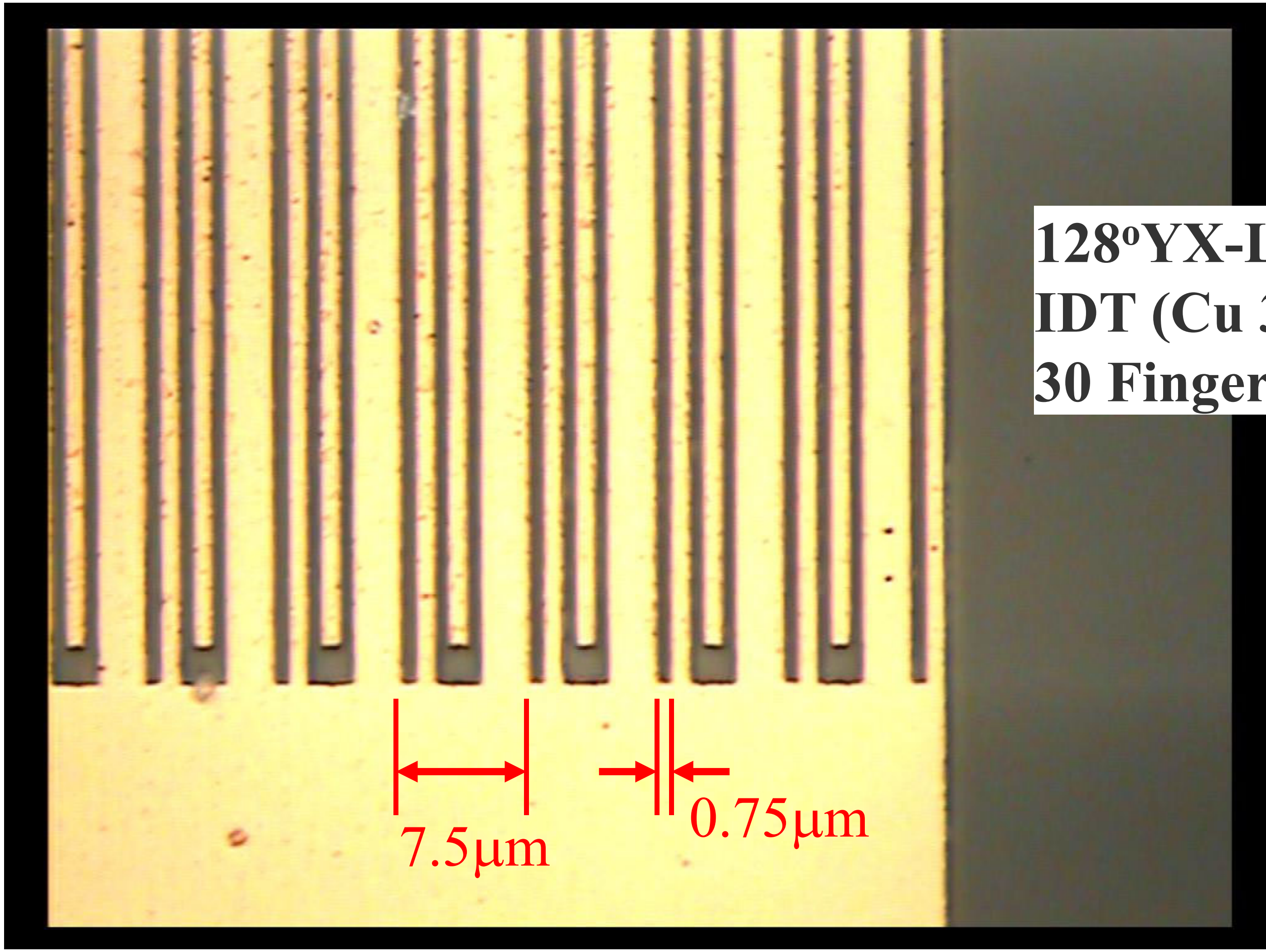
Thermal Deposition in High-Vacuum

•High Speed TMP (300*l*/s)

•Metal Seal, Metal Valve

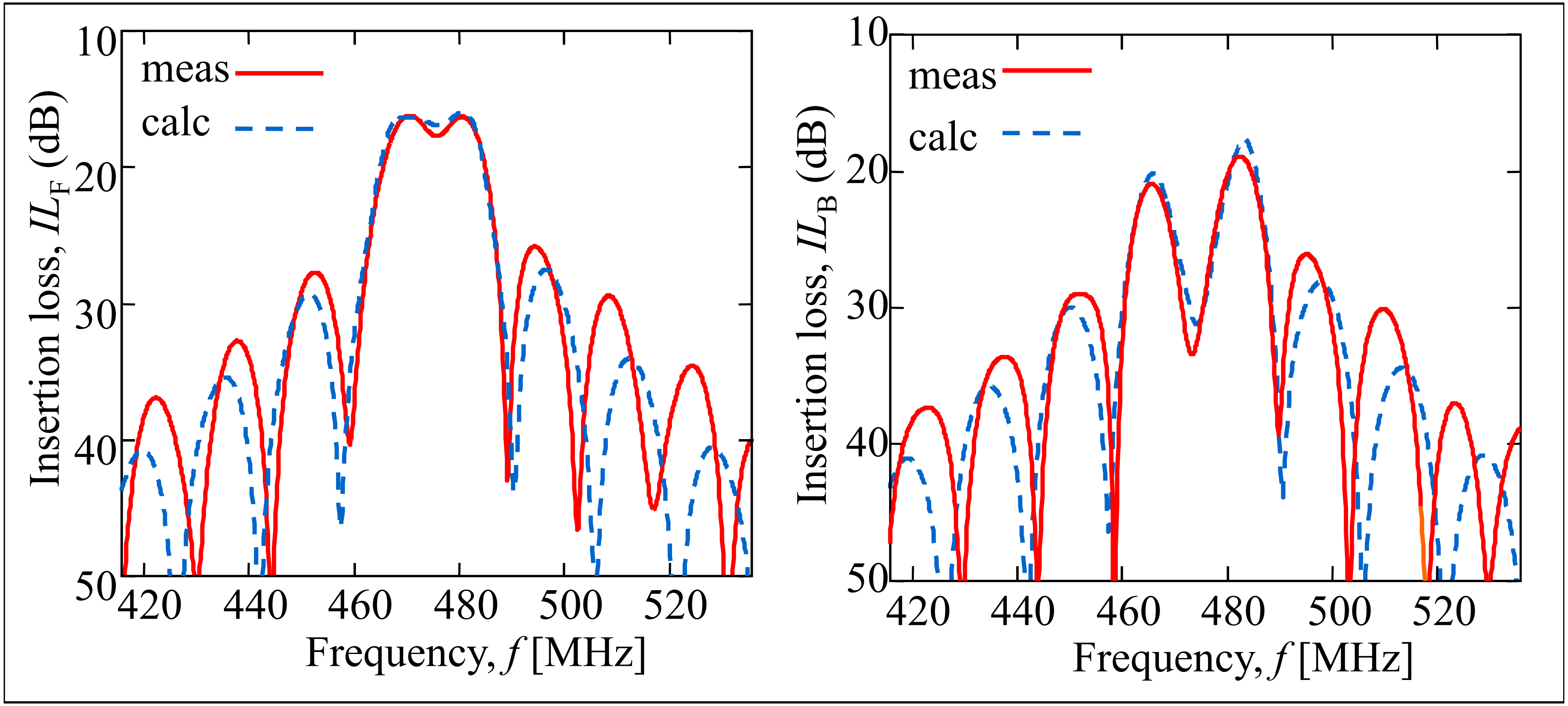
•BN Boat

Fabricated UDT Pattern



128°YX-LiNbO$_3$
IDT (Cu 300 nm)
30 Finger Pairs

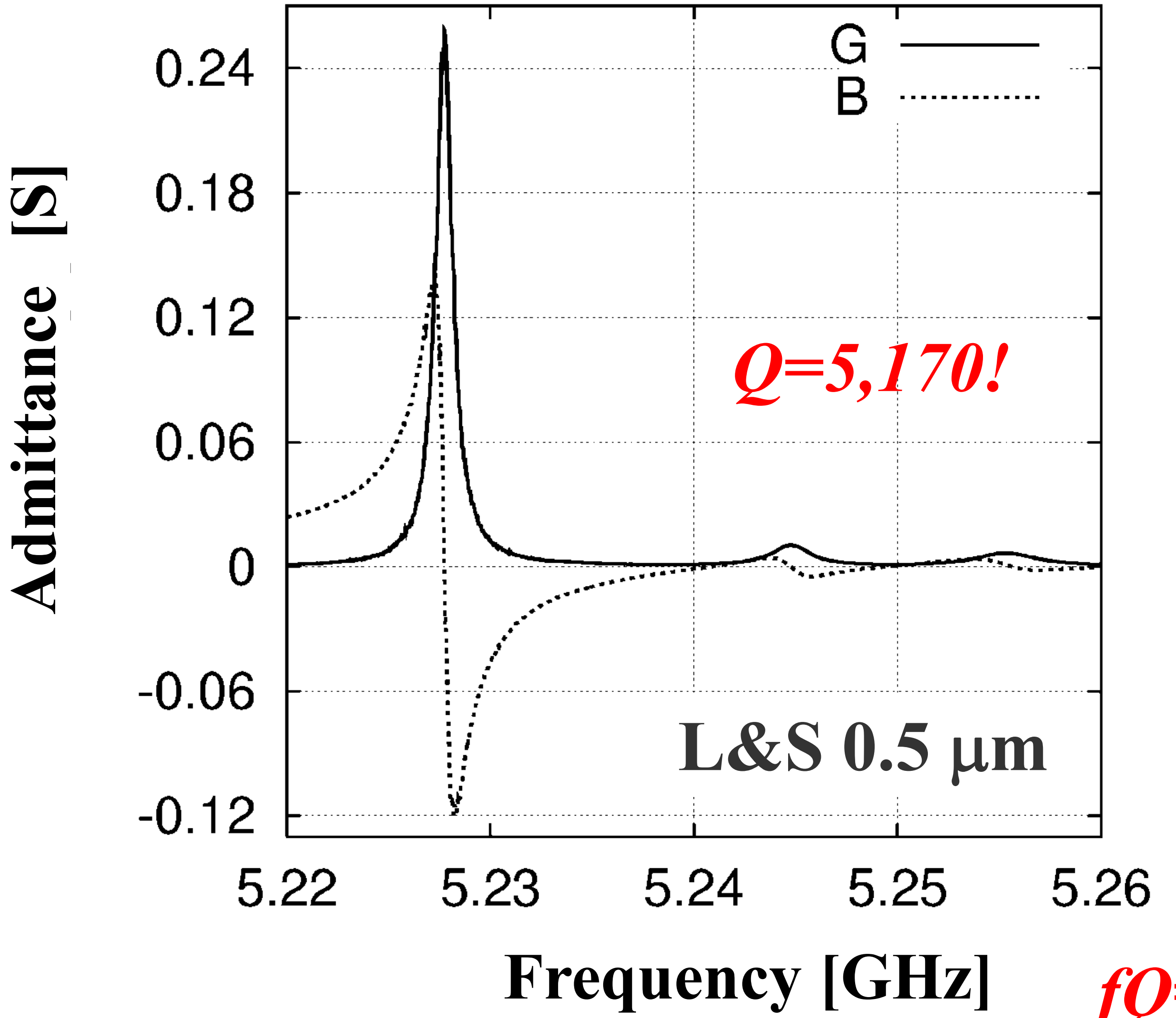
Fabricated UDT Performance



Use of Cu (not Al) Electrodes Offers

- Larger Reflection Coefficient & Directivity
- Good Agreement between Theory and Experiment

SAW Resonator on AlN/Diamond



$fQ=2.7\times10^{13}$!

AlN is Still Polycrystalline…

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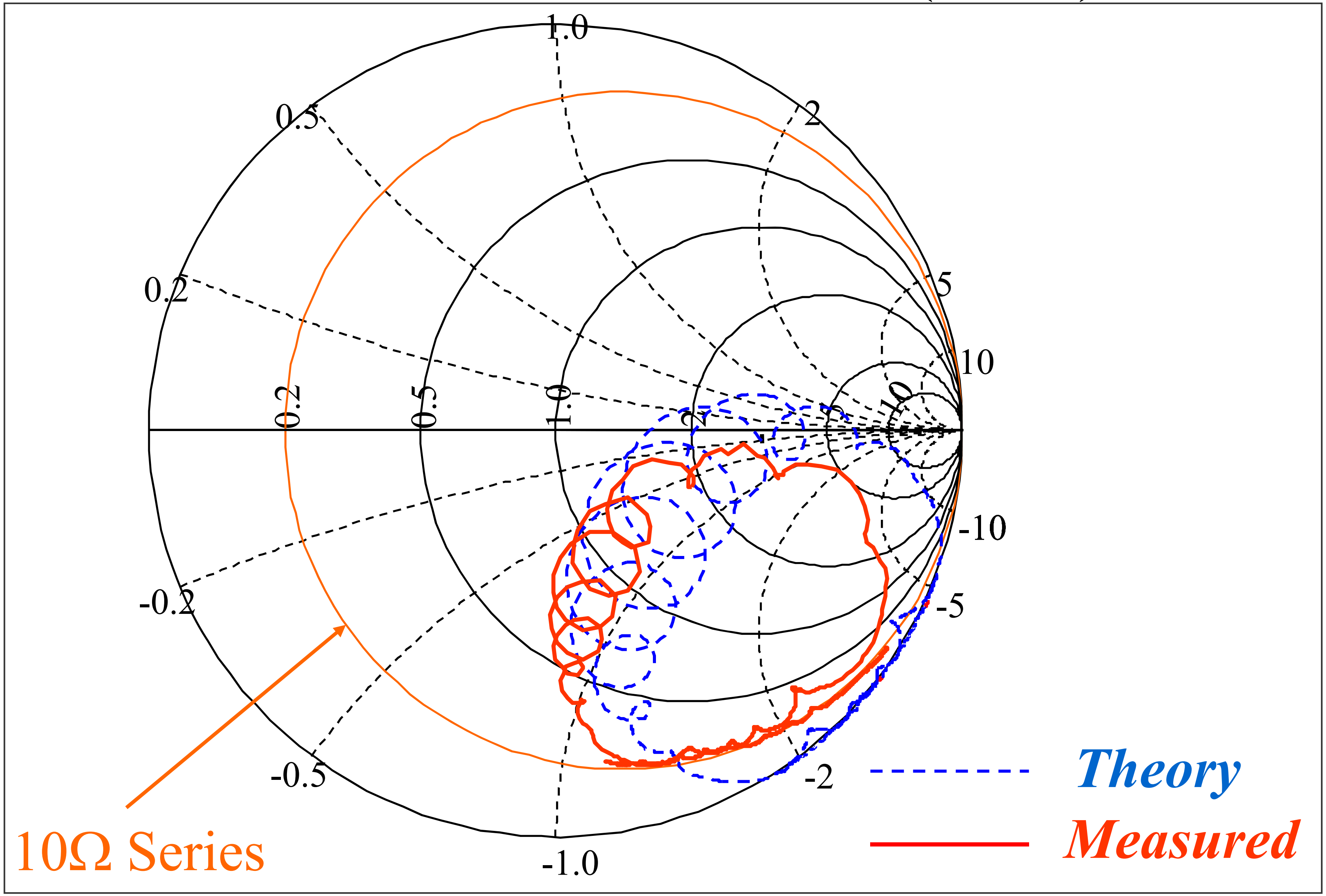
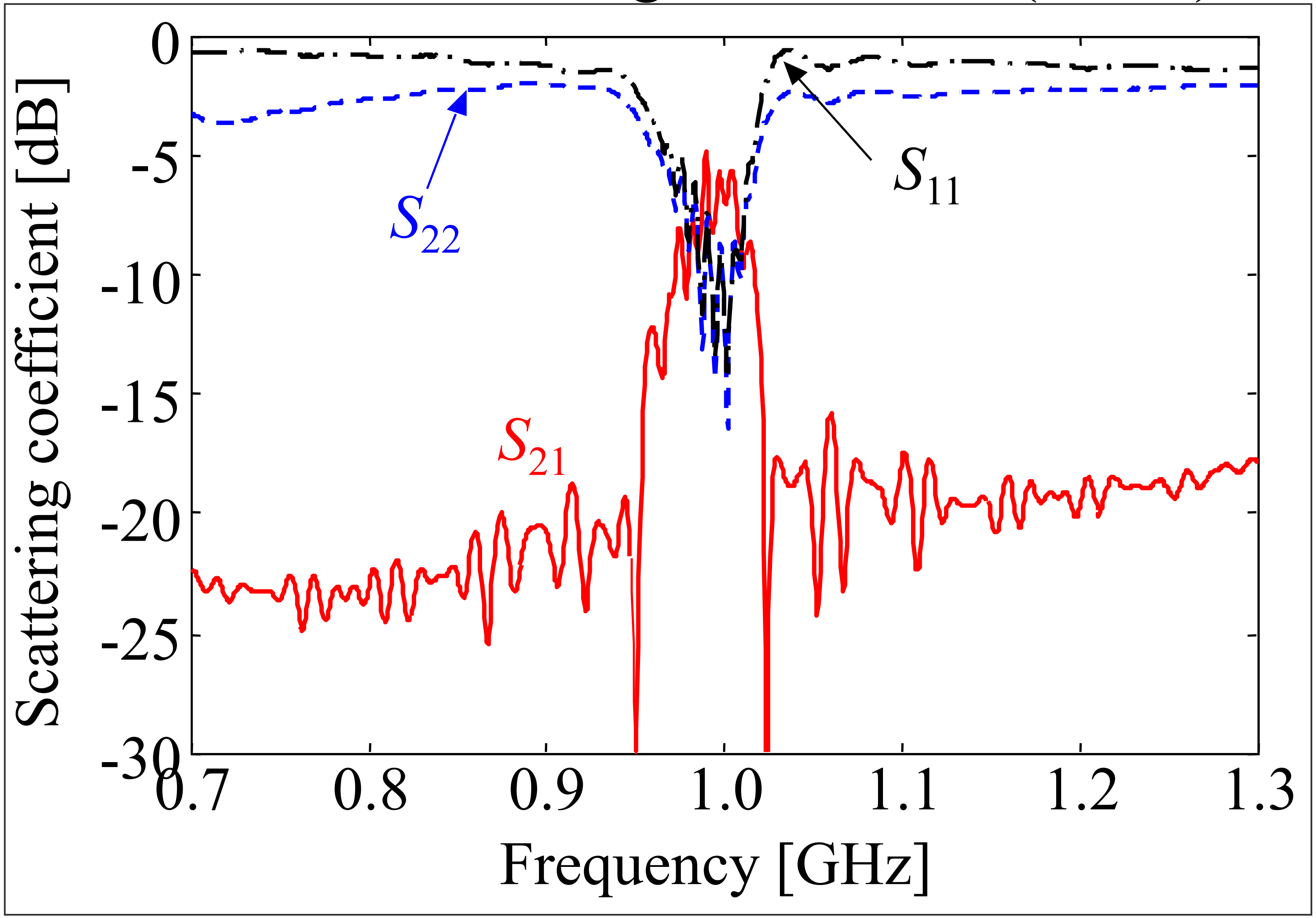
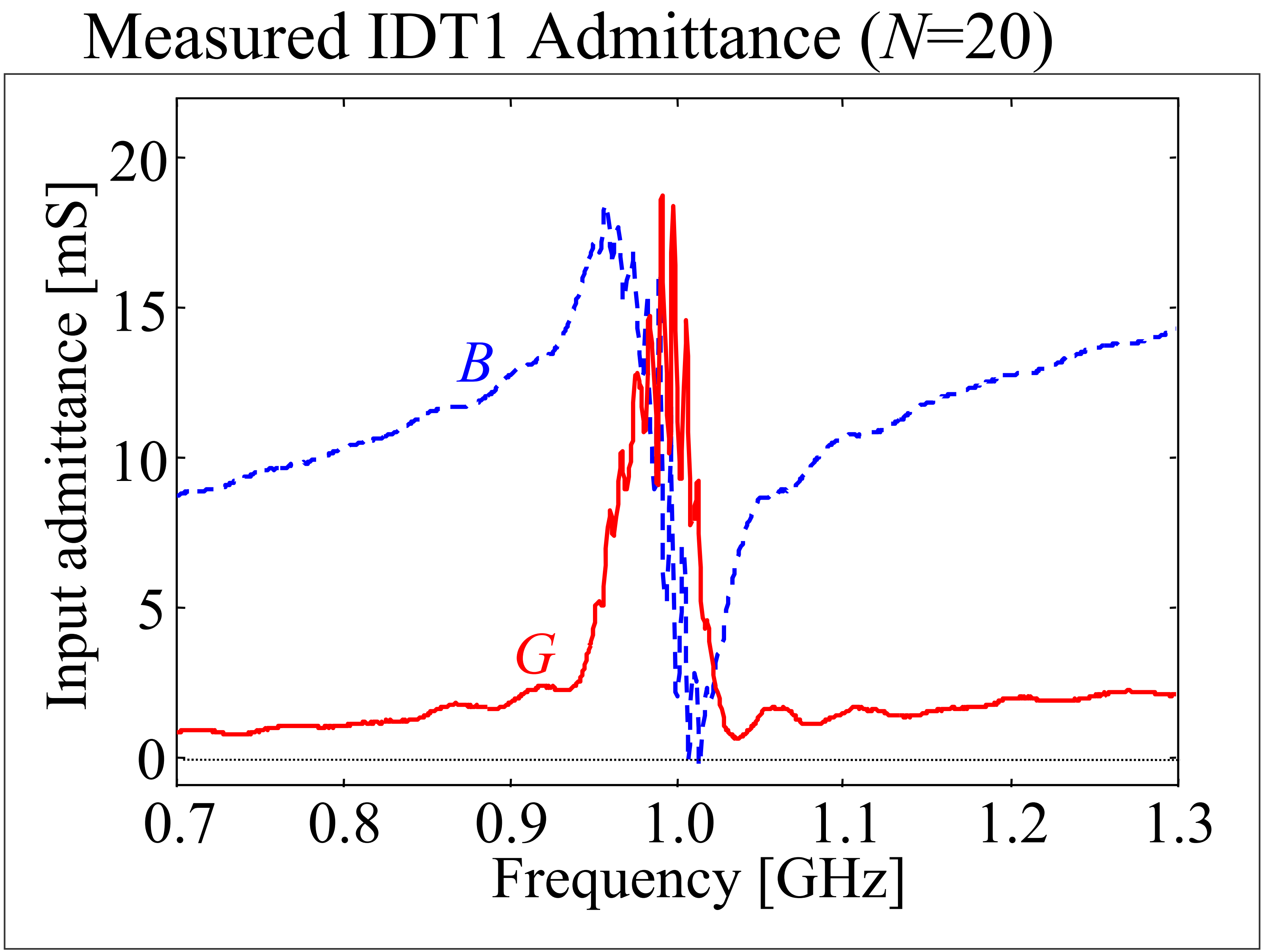
RF Measurement with Temp. Scan

Measured IDT1 Admittance (N=20)

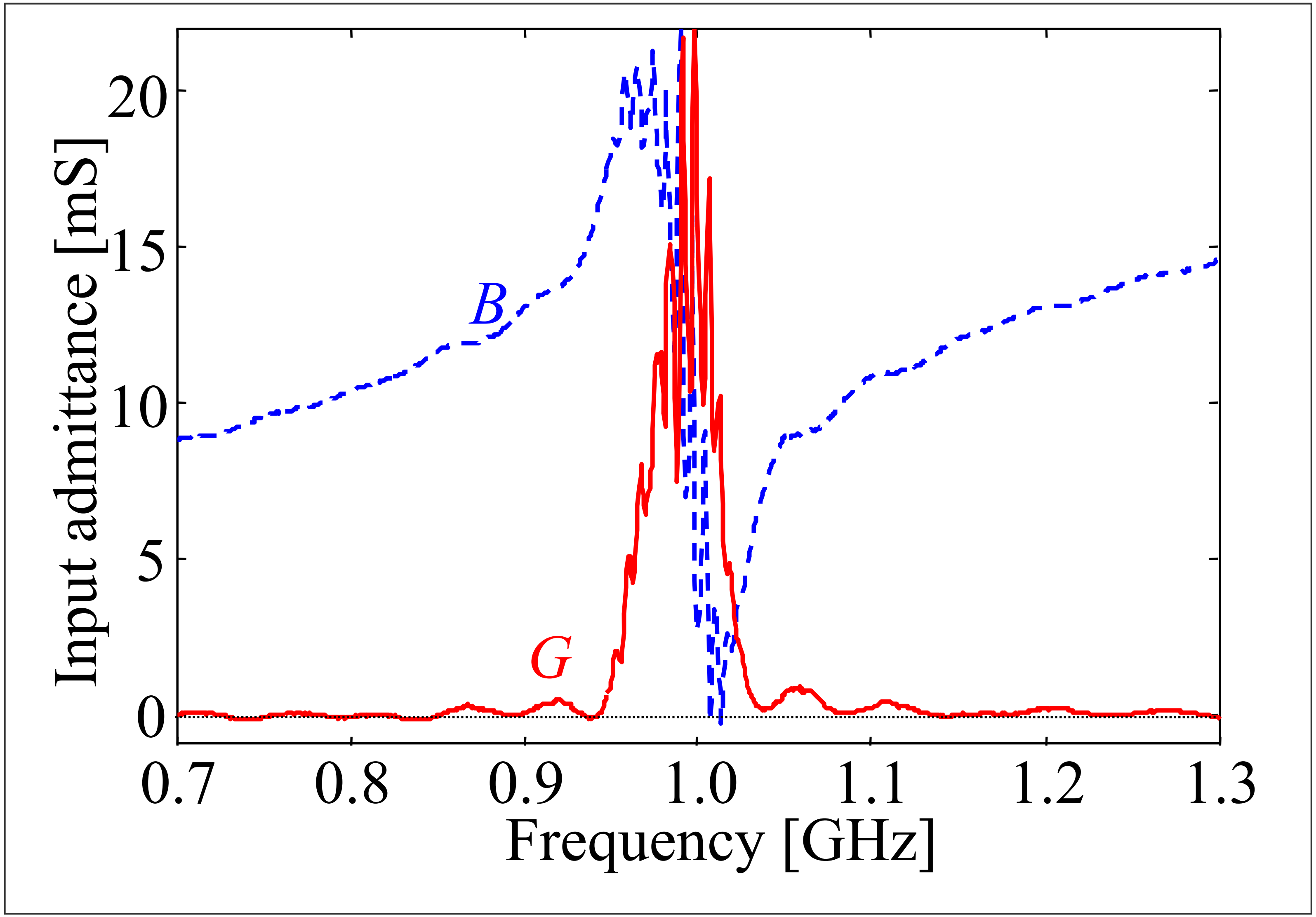


Measured Scattering Parameters (N=20)

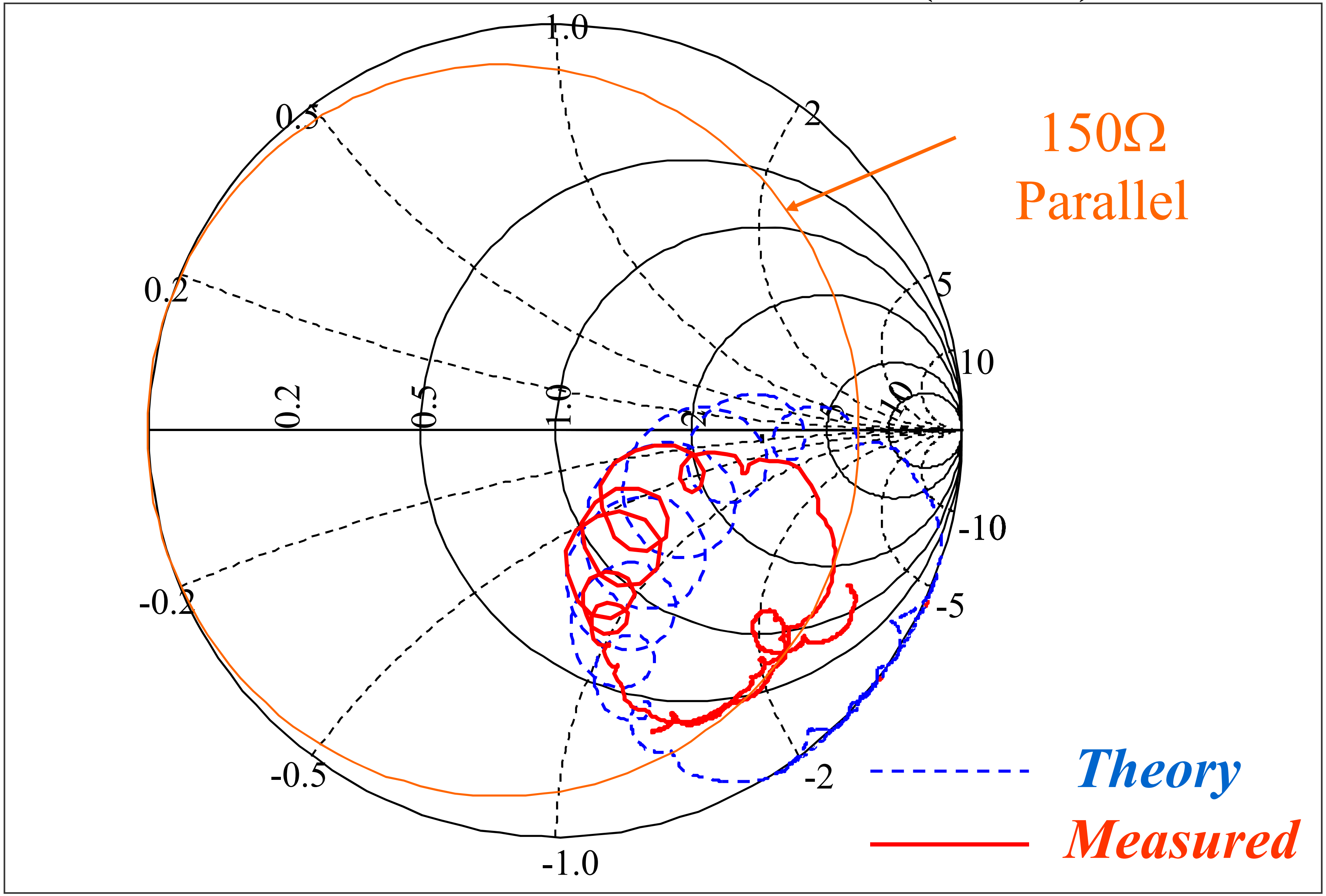



Measured IDT1 Admittance (N=20)
Input admittance [mS]
Frequency [GHz]
B
G
0
5
10
15
20
0.7
0.8
0.9
1.0
1.1
1.2
1.3

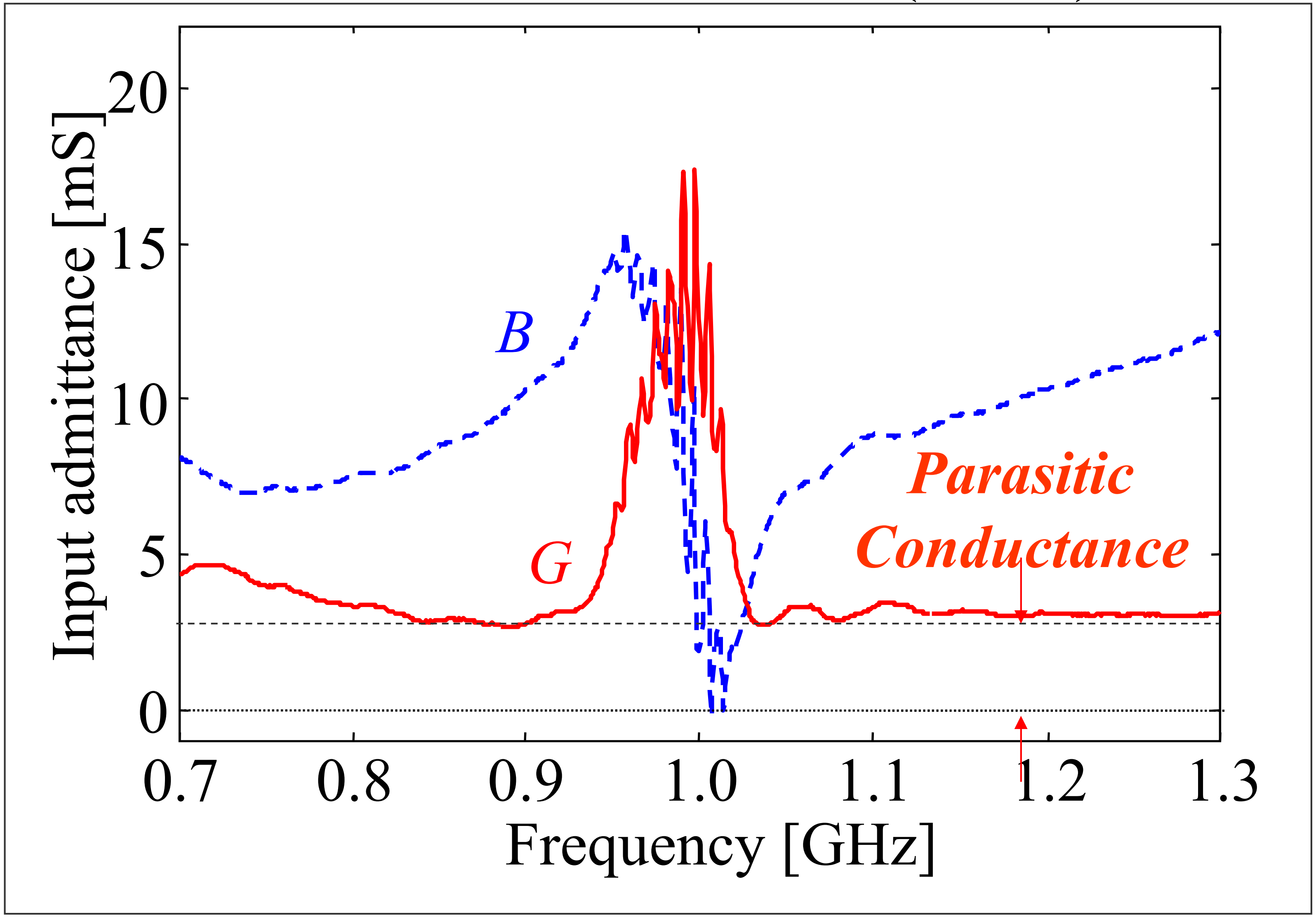
After Numerical Removal



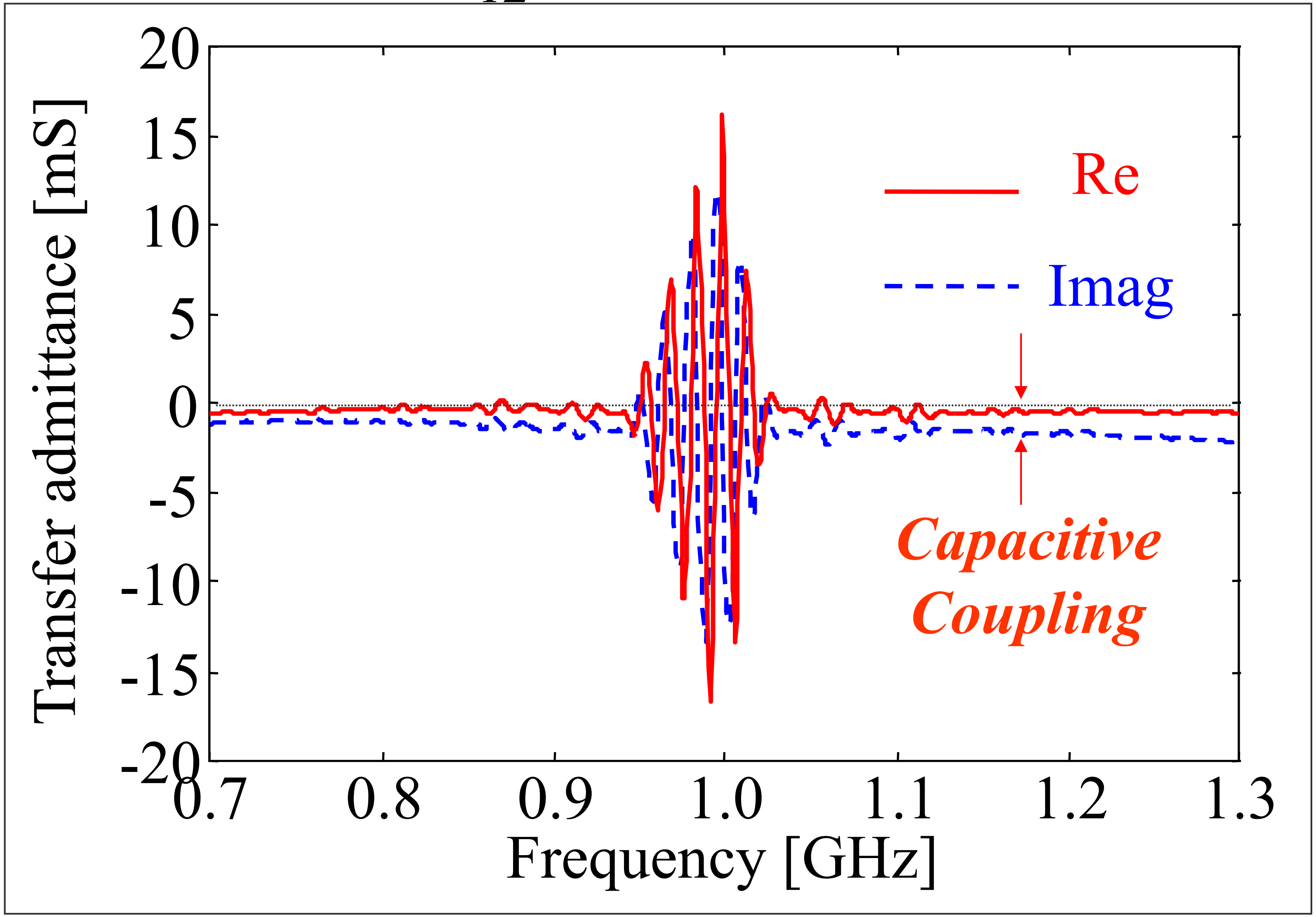
Measured IDT2 Admittance (N=20)



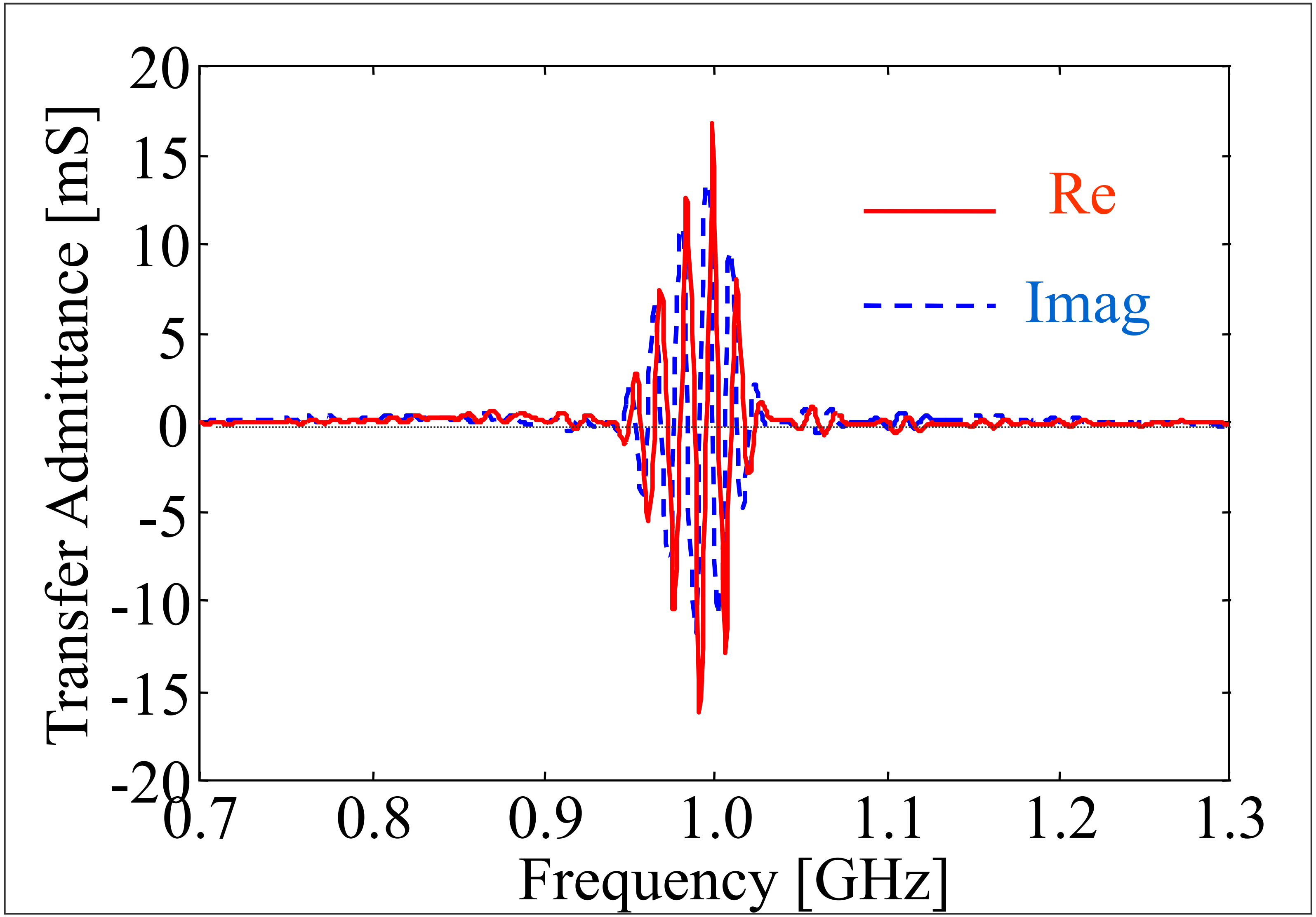
Measured IDT2 Admittance (N=20)



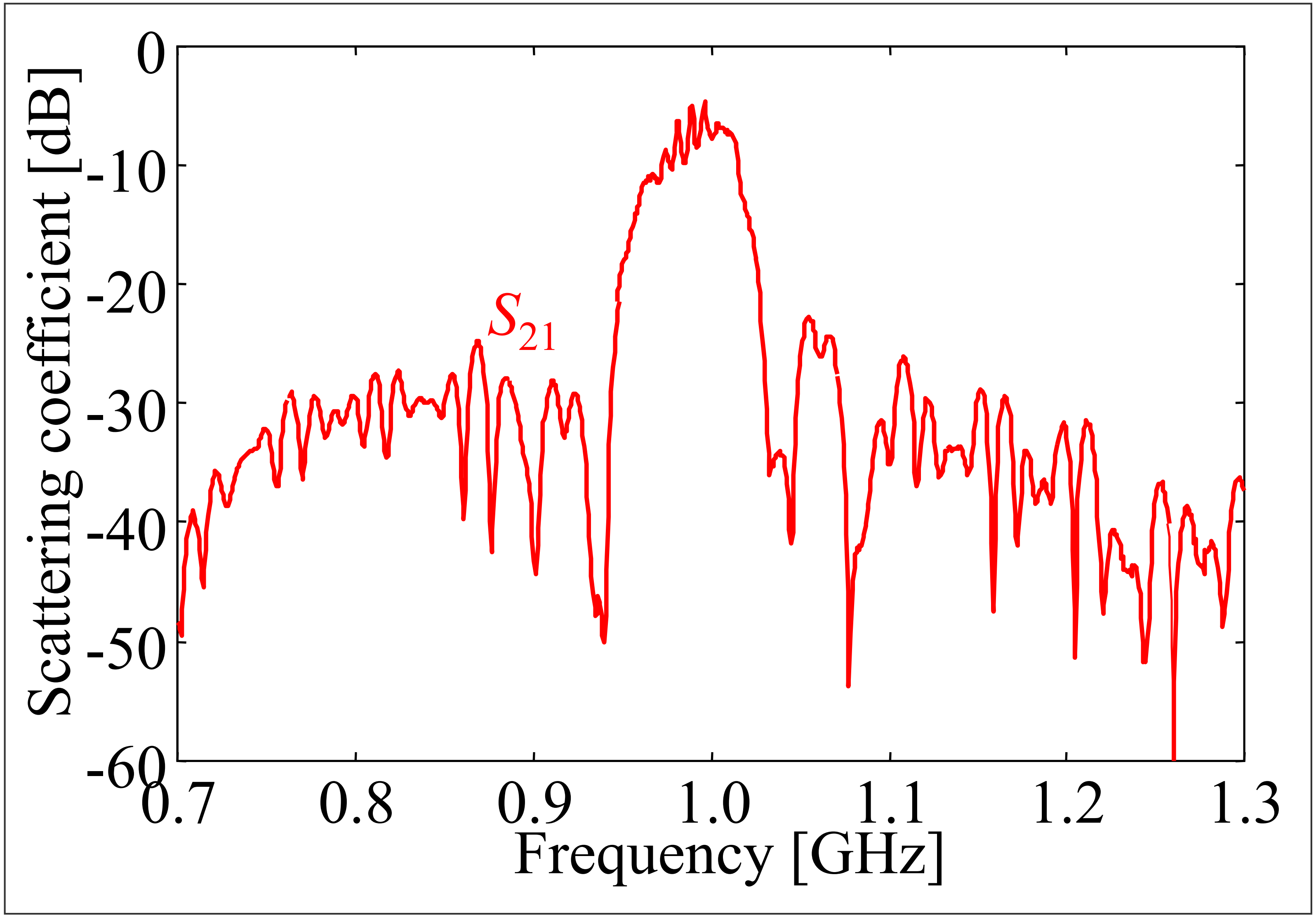
Measured Y_{12} Admittance (N=20)



After Numerical Removal



After Numerical Removal



Contents

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- Time Domain Analysis

Impulse Response

$$h(t)=\int_{-\infty}^{+\infty}H(f)\exp(2\pi jf)df$$

Since $H(-f)=H(f)^{*}$

$$h(t)=\Re\left[\int_{f_c-\Delta}^{f_c+\Delta}H(f)\exp(2\pi jft)df\right]=\Re\left[\exp(2\pi jf_c t)\hat{h}(t)\right]$$

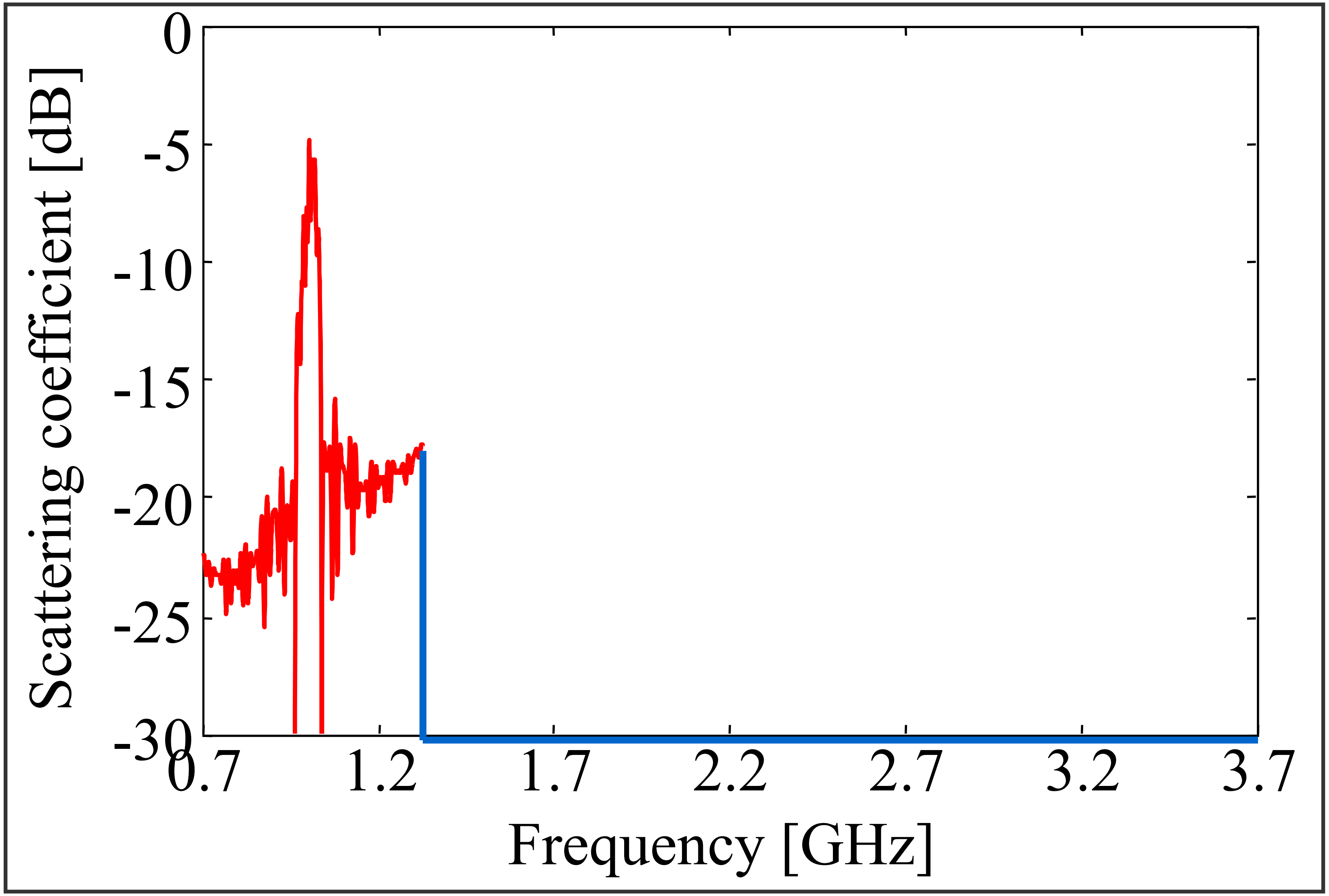
where $\boxed{\hat{h}(t)=\int_{-\Delta}^{+\Delta}H(f-f_c)\exp(2\pi jft)df}$

$\Uparrow$

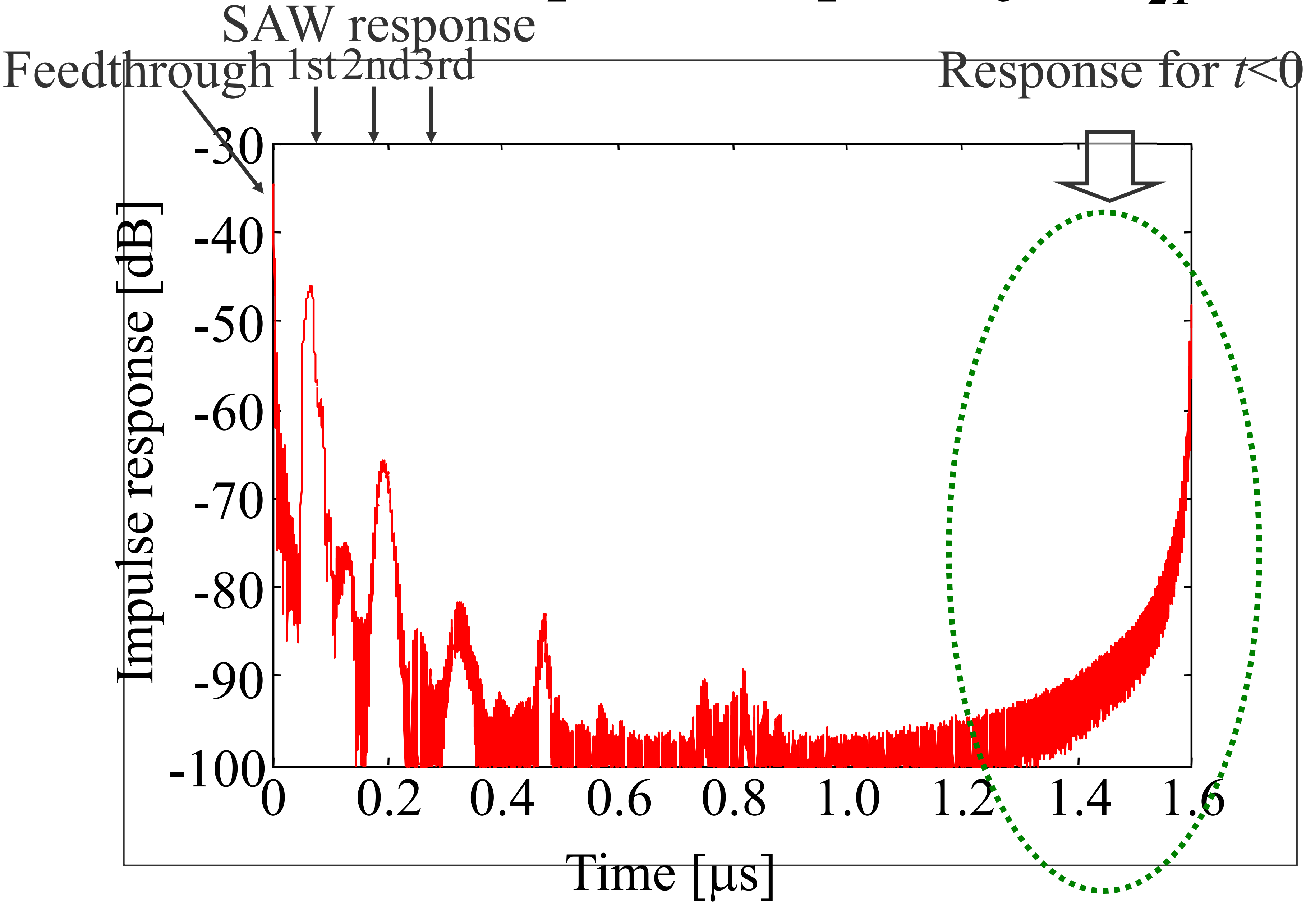
Envelope Function (IFFT Applicable)

Time Resolution=1/2Δ

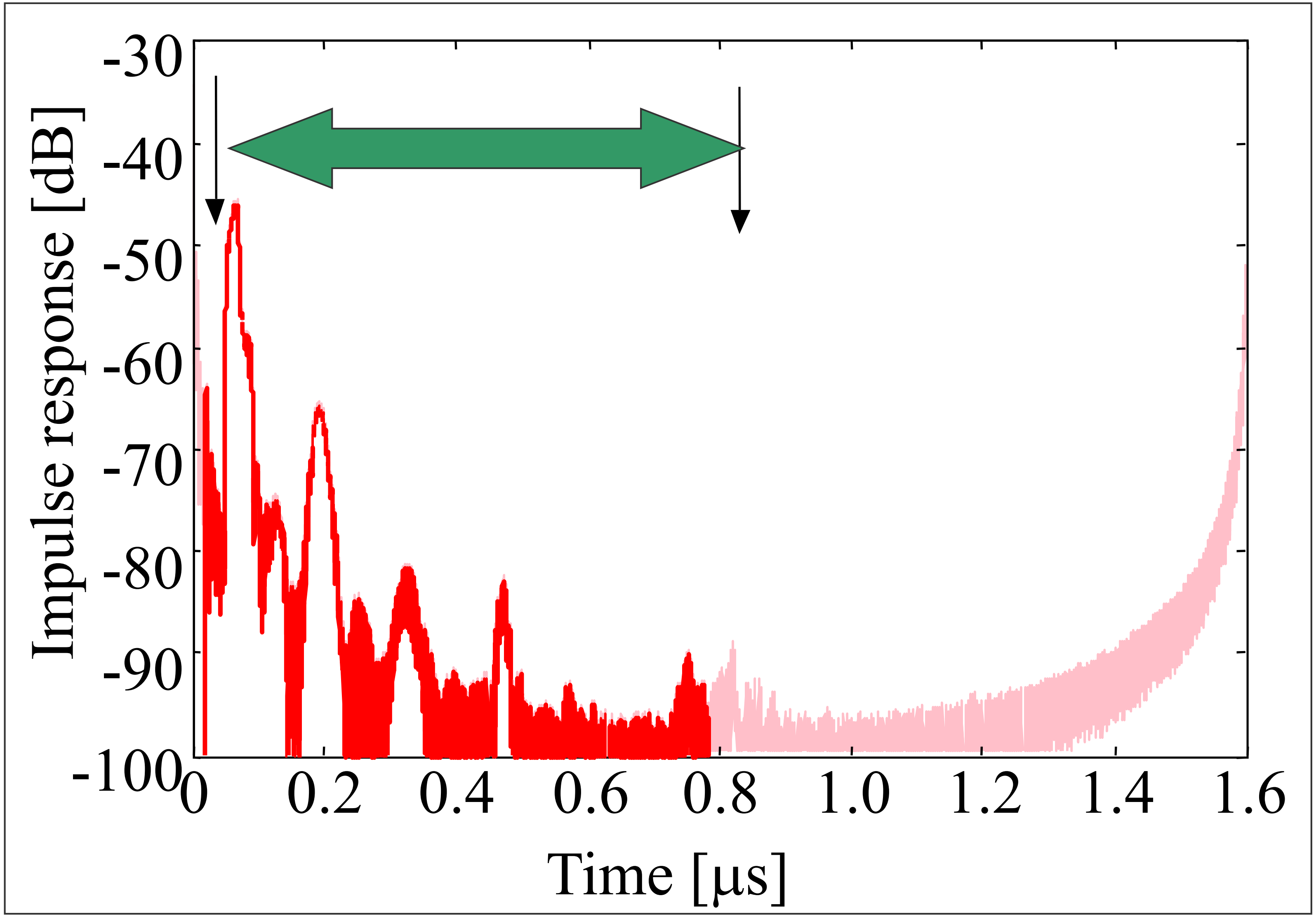
For Better Time Resolution ⇒ Zero Filling



Estimated Impulse Response for S_{21}



Removal of EM Feedthrough



Fourier Transform

$$H(f) = \int_{-\infty}^{+\infty} h(t)\exp(-2\pi jft)\,dt$$

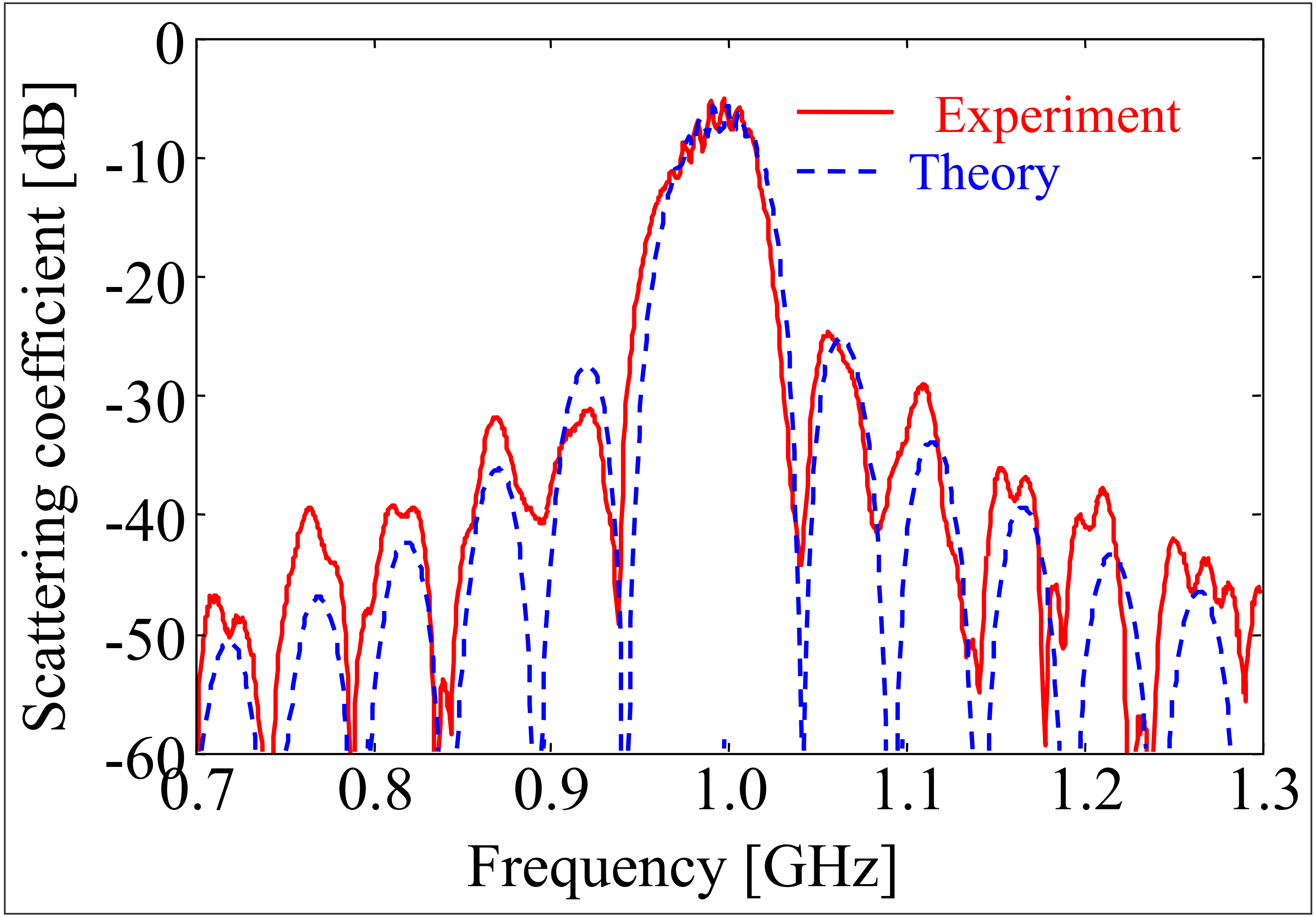
$$\boxed{H(f - f_c) = \int_{-\delta}^{+\delta} \hat{h}(t)\exp(-2\pi jft)\,dt}$$

δ: $(\Delta f)^{-1}$

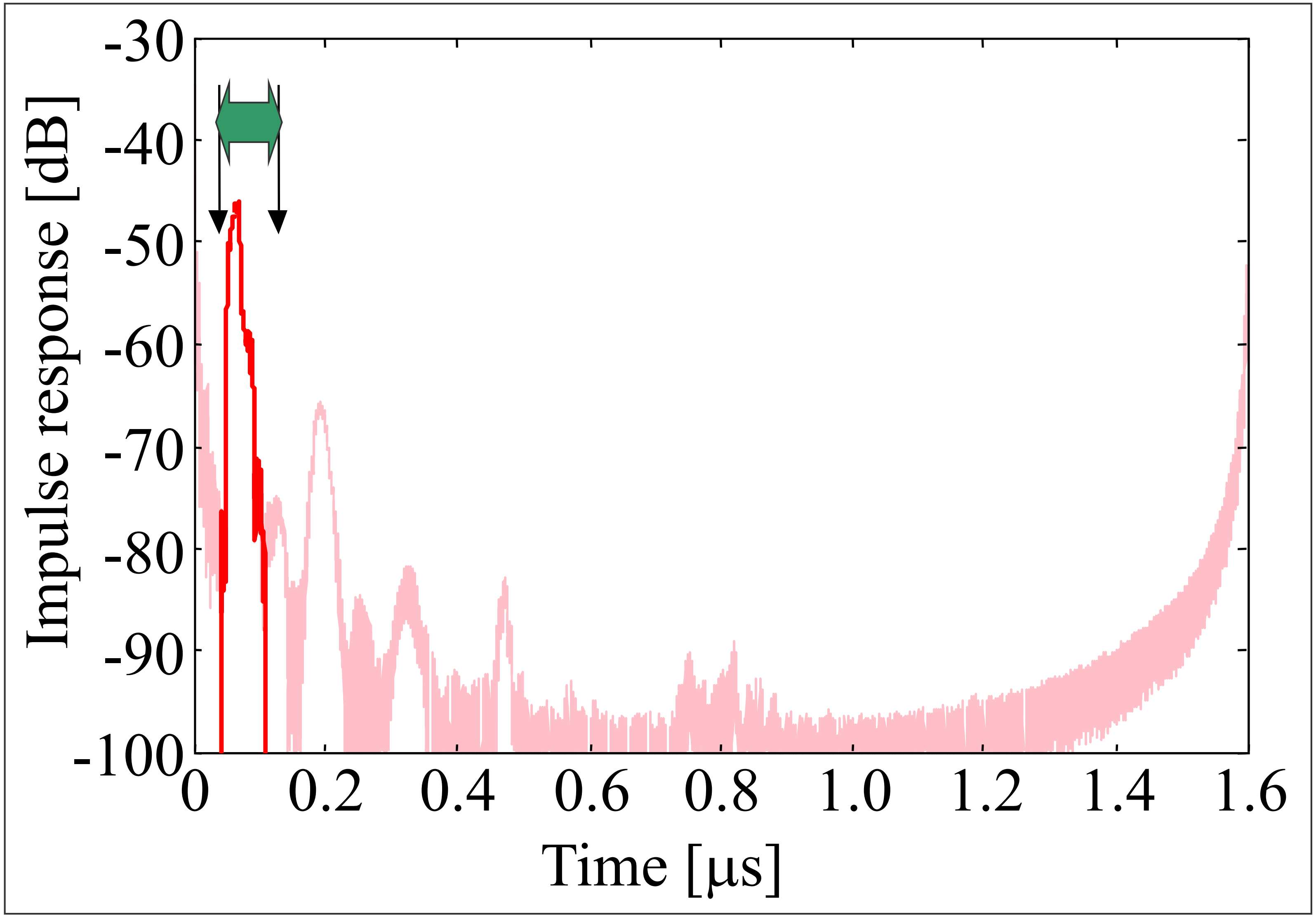
FFT Applicable

Attention to Aliasing due to Finite BW!

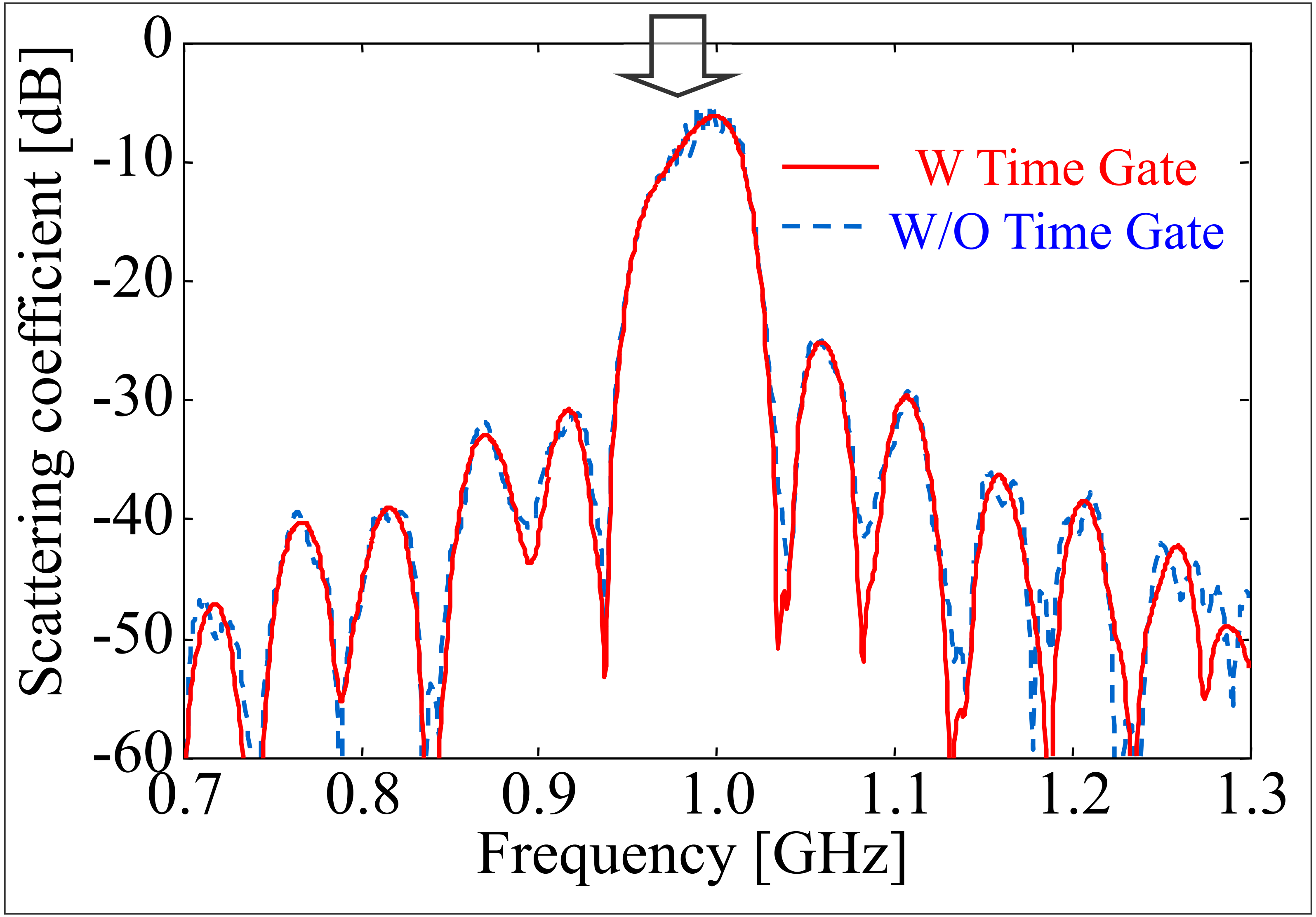
Comparison with Simple Theory



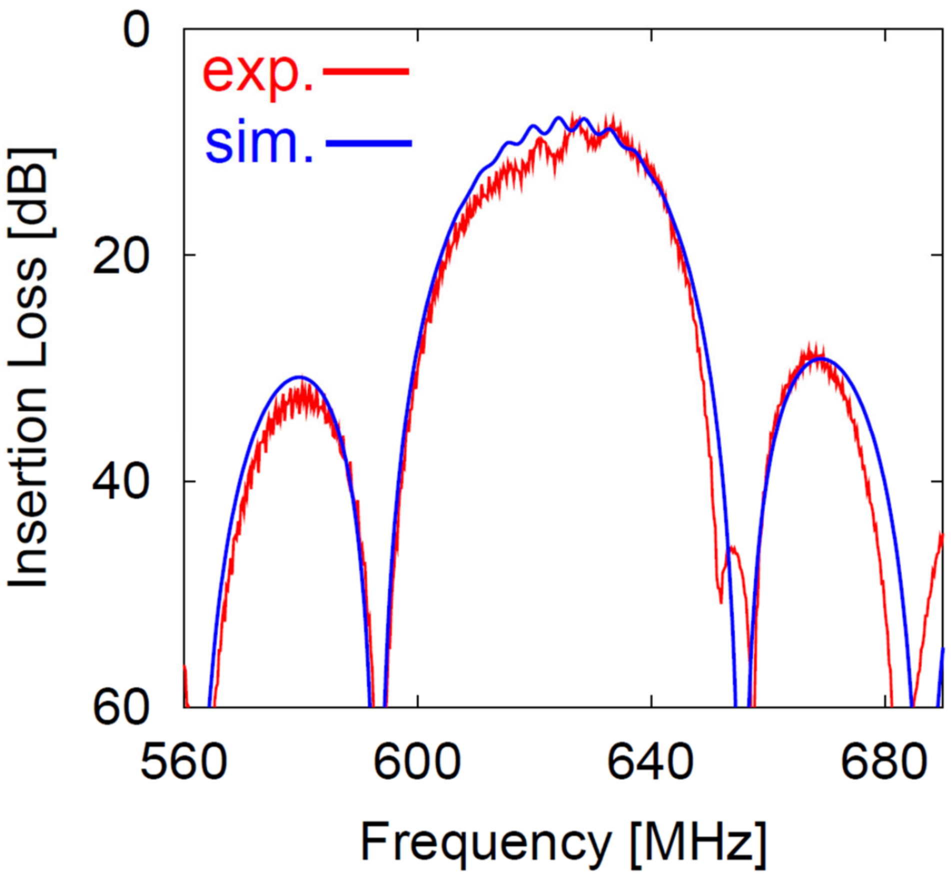
Removal of EM & TTEs



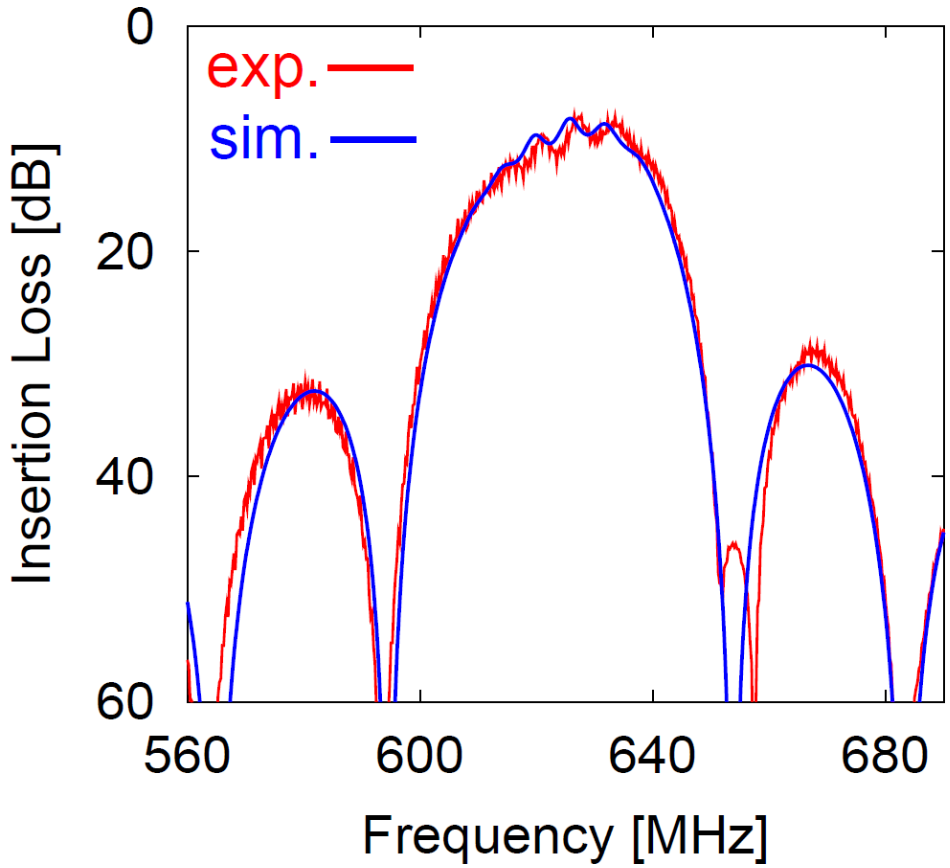
Estimated S_{21} (After EM & TTE Removal)



Reference: Influence of Internal Reflection

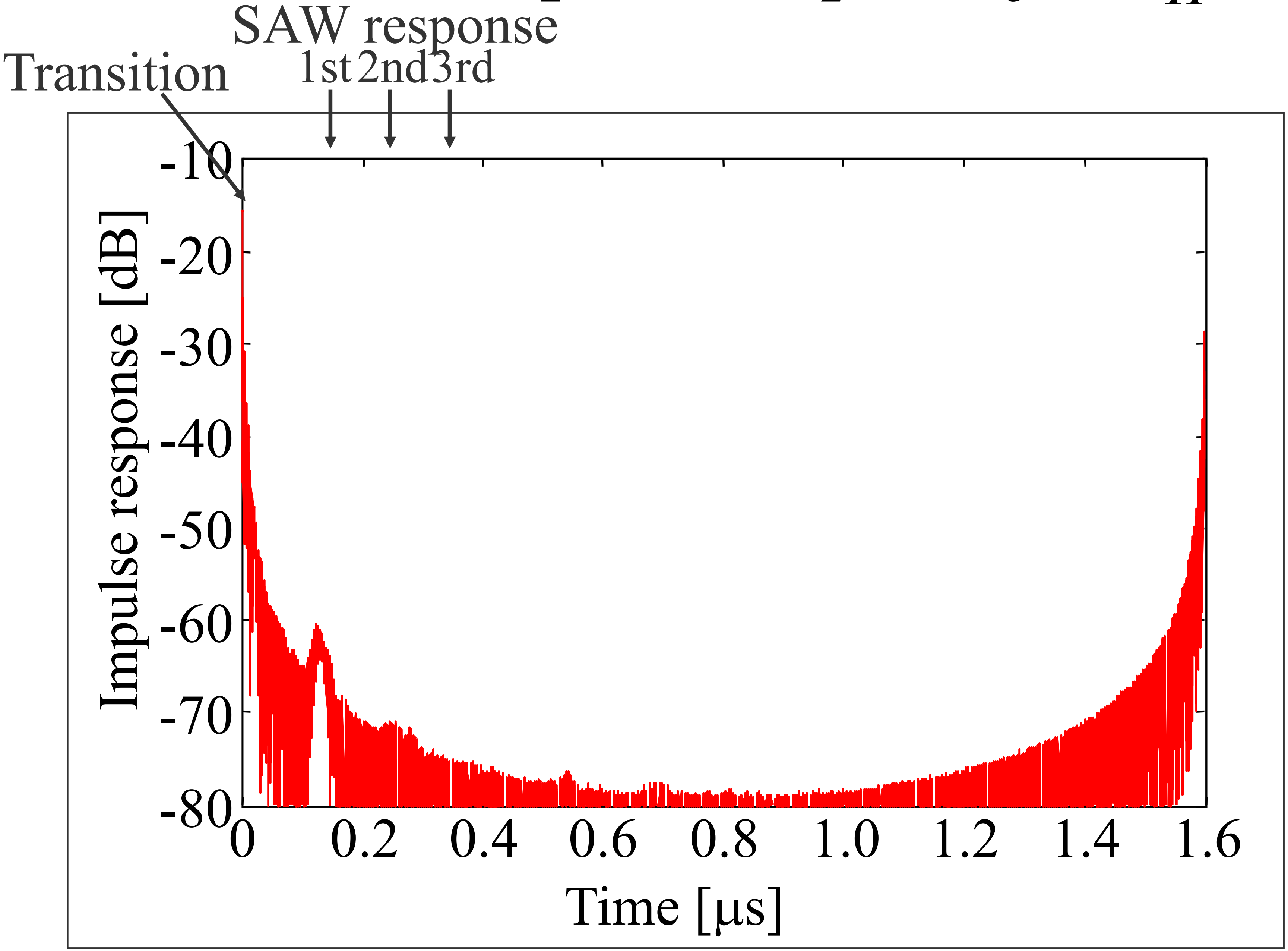


Delta Function Model Analysis

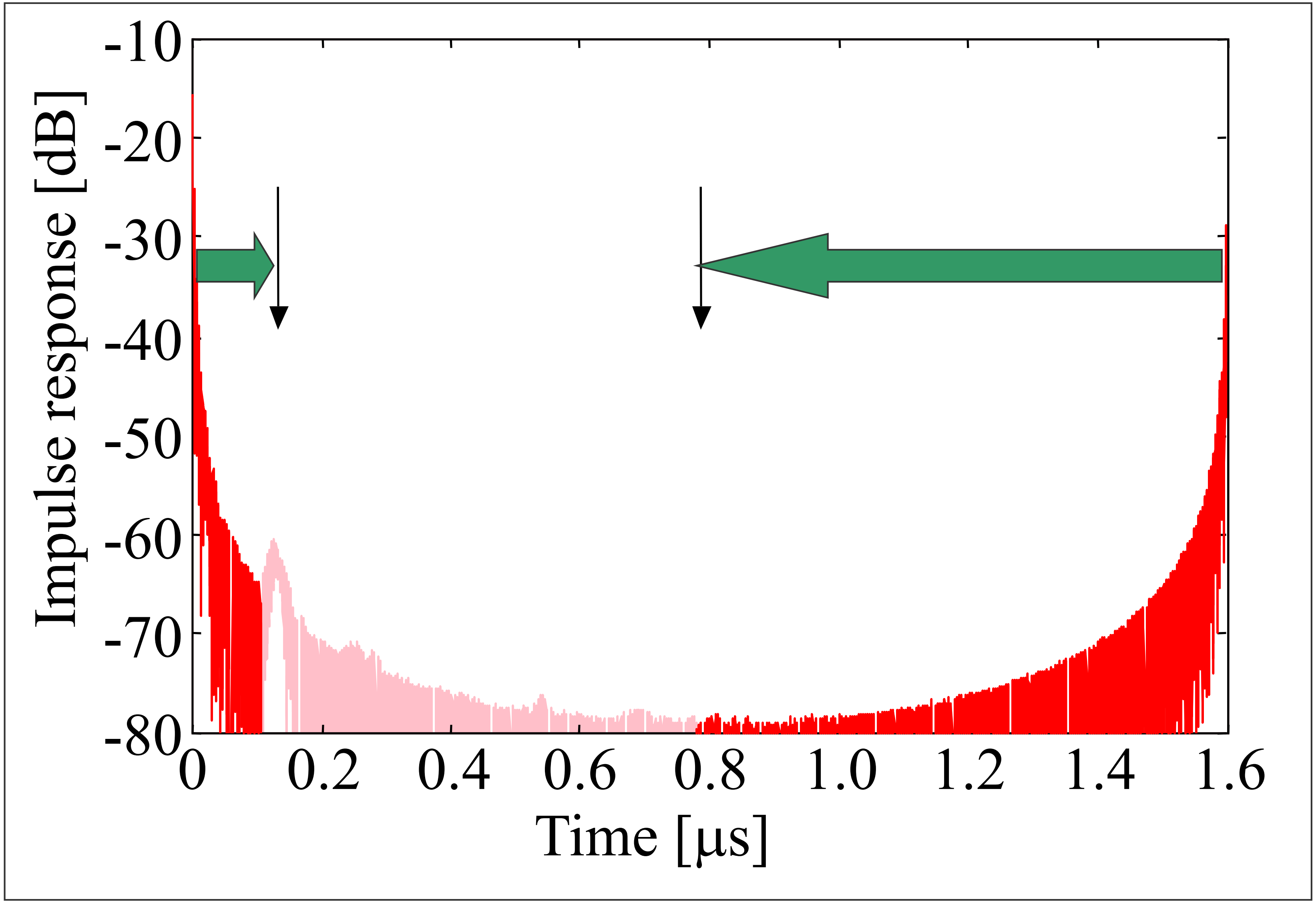


Coupling-of-Modes Analysis

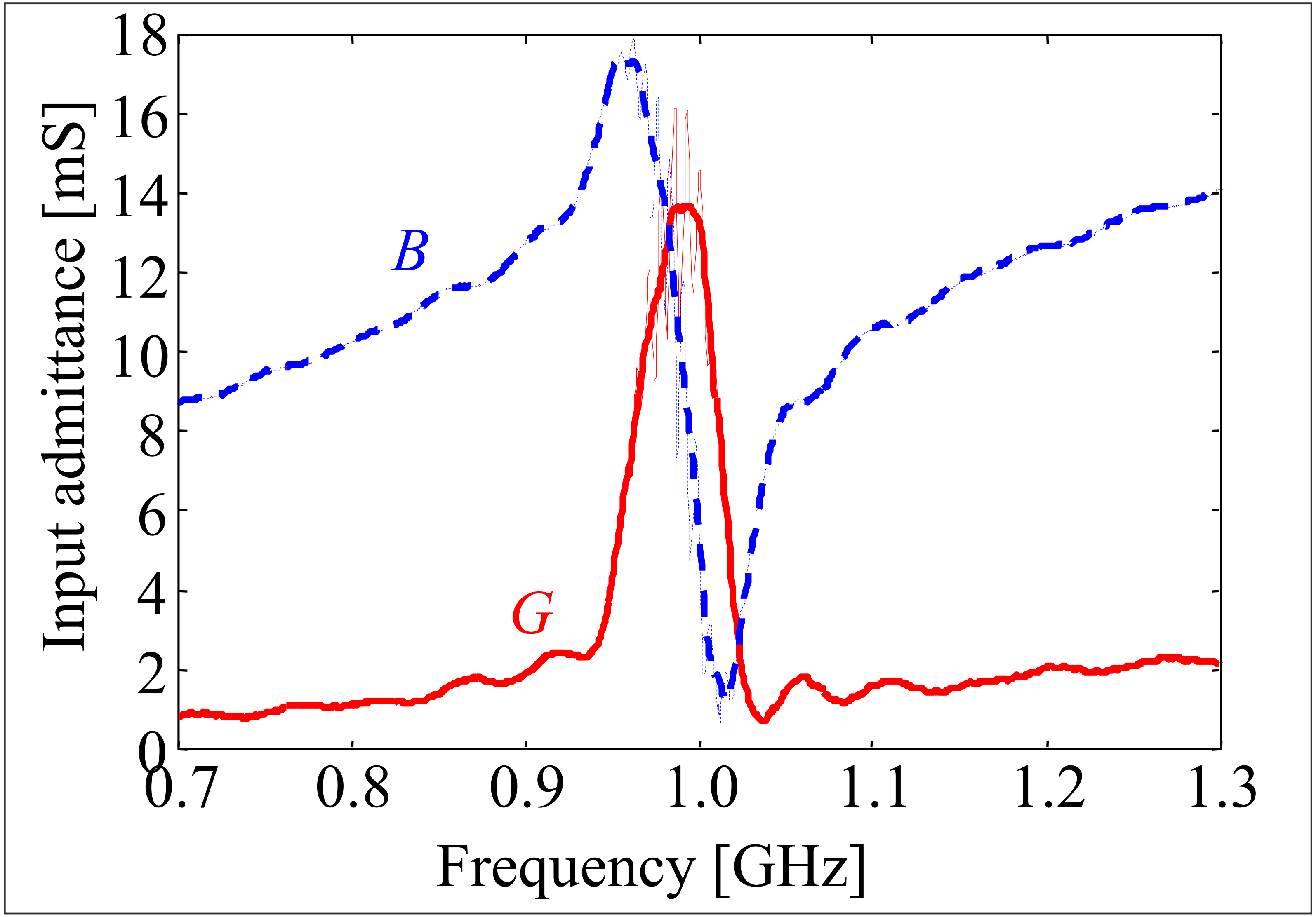
Estimated Impulse Response for S_{11}



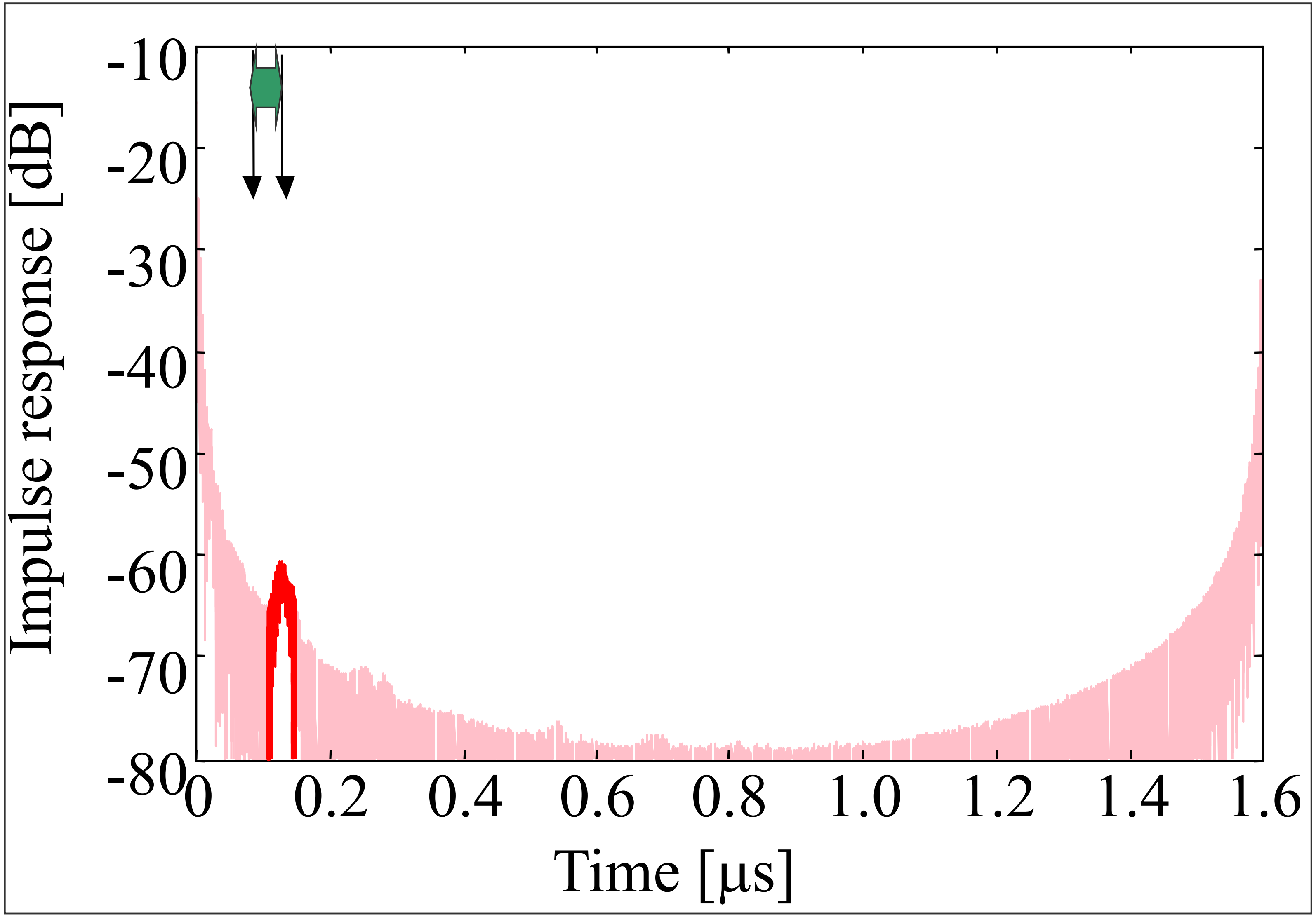
Removal of SAW Response for S_{11}

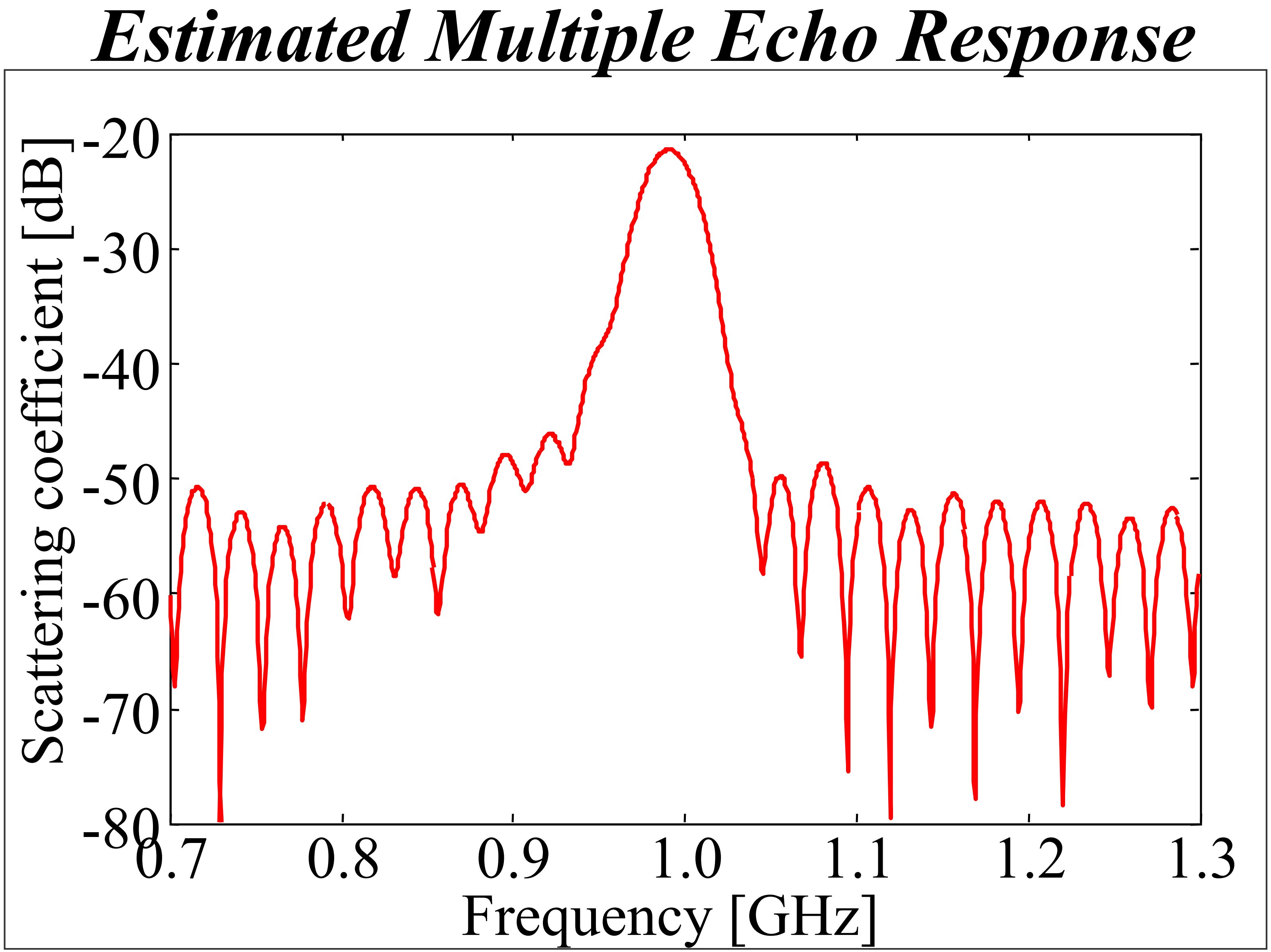


Estimated IDT Input Admittance



Extraction of SAW Response for S_{11}





Estimated Multiple Echo Response
Scattering coefficient [dB]
-20
-30
-40
-50
-60
-70
-80
0.7
0.8
0.9
1.0
1.1
1.2
1.3
Frequency [GHz]