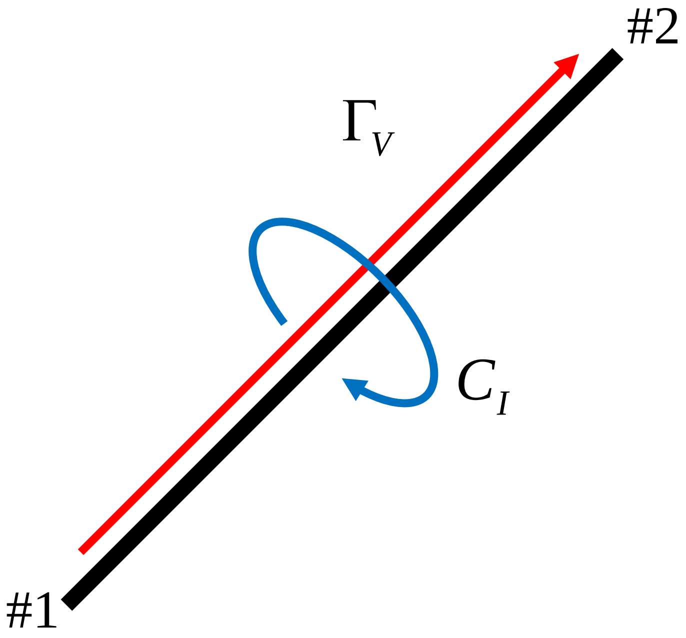
有限要素法による電磁界シミュレーション入門
第2回「集中ポートの解析」



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December 21, 2017

波動方程式(EまたはHのみの式)

マクスウェルの方程式

$$\begin{cases} \nabla\times\mathbf{E}+j\omega\mu\mathbf{H}=0 \\ \nabla\times\mathbf{H}-j\omega\varepsilon\mathbf{E}=\mathbf{J} \end{cases}$$

$$\nabla\times\mathbf{E}+j\omega\mu_0\mu_r\mathbf{H}=0$$

$$\frac{\nabla\times\mathbf{E}}{\mu_r}+j\omega\mu_0\mathbf{H}=0$$

場所の関数

$\nabla\times$

$$\nabla\times\left(\frac{\nabla\times\mathbf{E}}{\mu_r}\right)+j\omega\mu_0\nabla\times\mathbf{H}=0$$

$\nabla\times\mathbf{H}$ を消去

$$-\frac{1}{j\omega\mu_0}\nabla\times\left(\frac{\nabla\times\mathbf{E}}{\mu_r}\right)-j\omega\varepsilon\mathbf{E}=\mathbf{J}$$

Hを消去して**E**の方程式を導く

ヘルムホルツの波動方程式

（有限要素法の基礎方程式）

$$\nabla\times\left(\frac{\nabla\times\mathbf{E}}{\mu_r}\right)-k_0{}^2\varepsilon_r\mathbf{E}=-jk_0\eta_0\mathbf{J}$$

同様に、**E**を消去して**H**の方程式を導くこともできる

励振問題と非励振問題

ヘルムホルツの波動方程式

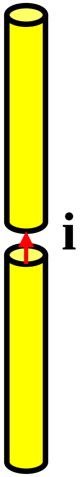
$$\nabla\times\left(\frac{\nabla\times\mathbf{E}}{\mu_r}\right)-k_0^{\ 2}\varepsilon_r\mathbf{E}=-jk_0\eta_0\mathbf{i}$$

励振波源あり

既知ベクトル（励振）

行列方程式 $A\mathbf{x}=\mathbf{b}$

未知ベクトル



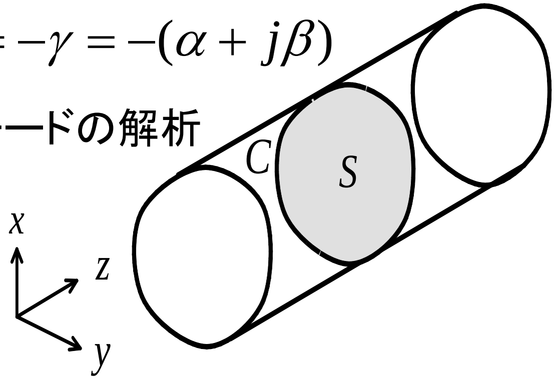
励振波源なし

固有値問題 $A\mathbf{x}=\lambda\mathbf{x}$

$$\partial/\partial z=-\gamma=-(\alpha+j\beta)$$

導波路, モードの解析

2-D

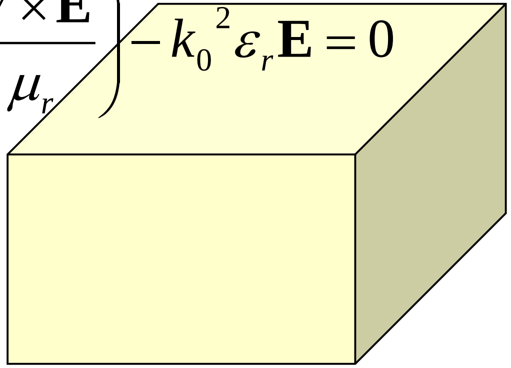


$$\nabla_t\times\left(\frac{\nabla_t\times\mathbf{E}_t}{\mu_r}\right)-\left(k_0^{\ 2}\varepsilon_r+\Gamma\right)\mathbf{E}_t=0$$

共振器

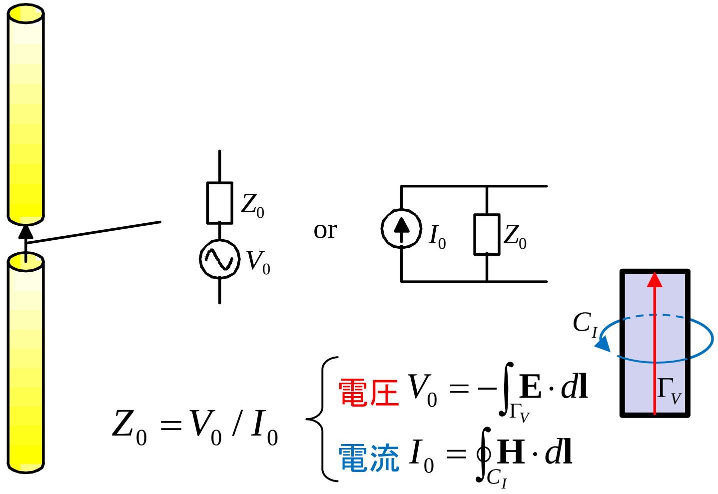
$$\nabla\times\left(\frac{\nabla\times\mathbf{E}}{\mu_r}\right)-k_0^{\ 2}\varepsilon_r\mathbf{E}=0$$

3-D



どの周波数でどのような形で共振するのか?

波源モデリング

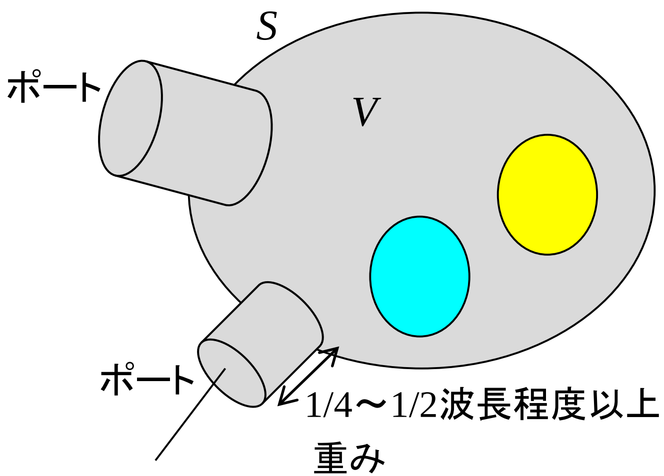


$Z_0 = V_0 / I_0$

電圧 $V_0 = -\int_{\Gamma_V} \mathbf{E}\cdot d\mathbf{l}$

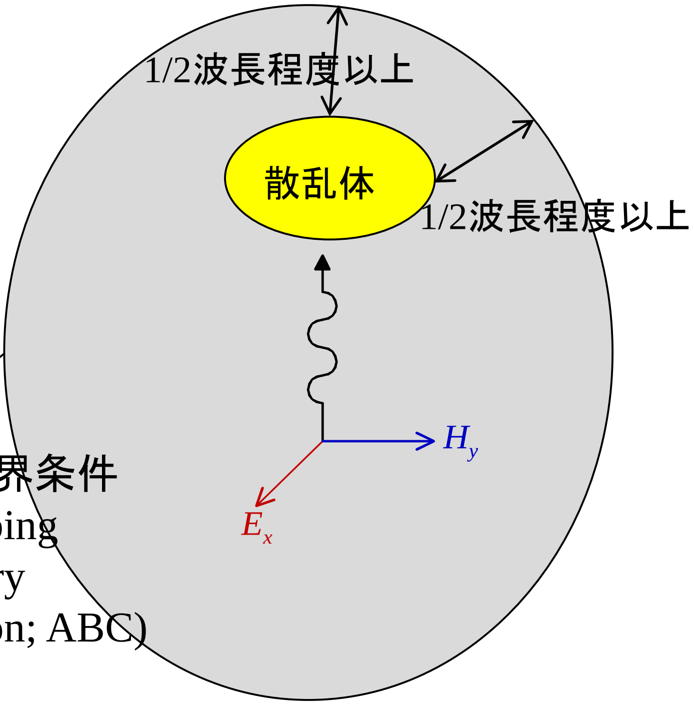
電流 $I_0 = \oint_{C_I} \mathbf{H}\cdot d\mathbf{l}$

(a) 集中ポート



$$\mathbf{E} = \underbrace{\mathbf{E}_1^{(+)}}_{\text{入射モード}} + \sum_u \overset{\text{重み}}{B_u} \underbrace{\mathbf{E}_u^{(-)}}_{\text{反射モード}}$$

(b) 導波路ポート



吸収境界条件
(Absorbing boundary condition; ABC)

(c) 平面波入射

電磁気学の知識からマクスウェルの方程式を導く

ファラデーの法則

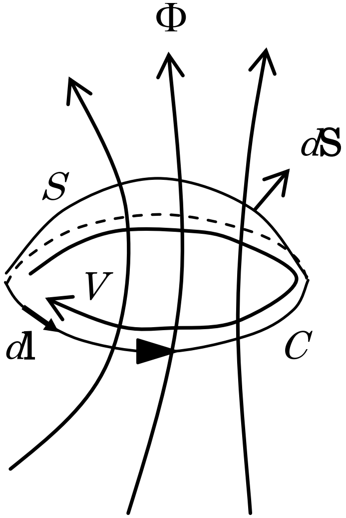
ファラデー：近接作用、界の概念を提唱

$$V = -\frac{d\Phi}{dt} \Rightarrow \oint_C \mathbf{E}\cdot d\mathbf{l} = -\frac{\partial}{\partial t}\iint_S \mathbf{B}\cdot d\mathbf{S}$$

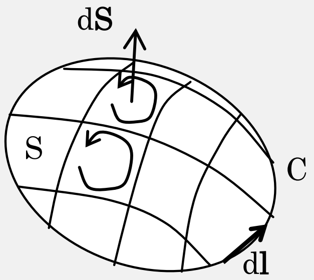
ストークスの定理を使って

$$\iint_S (\nabla\times\mathbf{E})\cdot d\mathbf{S} = -\frac{\partial}{\partial t}\iint_S \mathbf{B}\cdot d\mathbf{S}$$

$$\boxed{\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}}$$



ストークスの定理



$$\iint_S \nabla\times\mathbf{A}\cdot d\mathbf{S} = \oint_C \mathbf{A}\cdot d\mathbf{l}$$

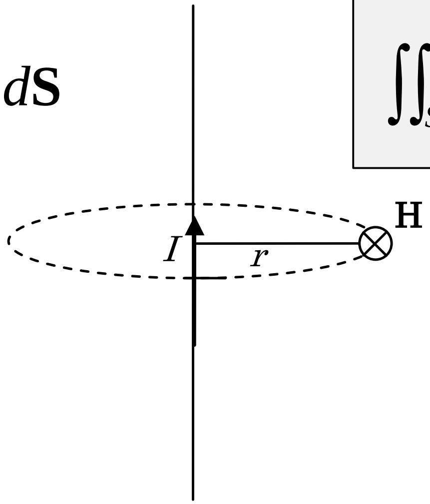
アンペアの法則

$$H = \frac{I}{2\pi r} \Rightarrow 2\pi r H = I \Rightarrow \oint_C \mathbf{H}\cdot d\mathbf{l} = \iint_S \mathbf{i}\cdot d\mathbf{S}$$

ストークスの定理を使って

$$\iint_S (\nabla\times\mathbf{H})\cdot d\mathbf{S} = \iint_S \mathbf{i}\cdot d\mathbf{S}$$

$$\boxed{\nabla\times\mathbf{H} = \mathbf{i}}$$



電磁界は空間全体に分布する

マクスウェルの方程式

微分形

ファラデーの法則

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

アンペアの法則

$$\nabla \times \mathbf{H} = \mathbf{i} + \boxed{\frac{\partial \mathbf{D}}{\partial t}}$$

$$\nabla \cdot \mathbf{D} = \rho$$

変位電流

$$\nabla \cdot \mathbf{B} = 0$$

$$\left(\nabla \cdot \mathbf{i} = -\frac{\partial \rho}{\partial t} \right)$$

積分形

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \iint_S \mathbf{B} \cdot d\mathbf{S}$$

$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \iint_S \mathbf{i} \cdot d\mathbf{S} + \boxed{\frac{\partial}{\partial t} \iint_S \mathbf{D} \cdot d\mathbf{S}}$$

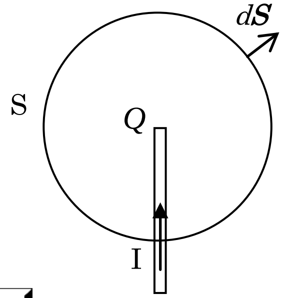
変位電流

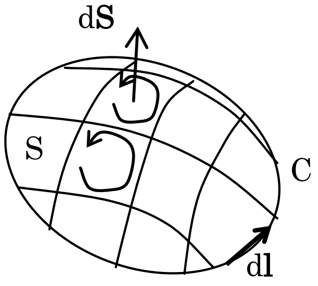
$$\oiint_S \mathbf{D} \cdot d\mathbf{S} = \iiint_V \rho \, dV$$

$$\oiint_S \mathbf{B} \cdot d\mathbf{S} = 0$$

電流連続の式:

$$I = -\frac{\partial Q}{\partial t}$$





構成（媒質）方程式

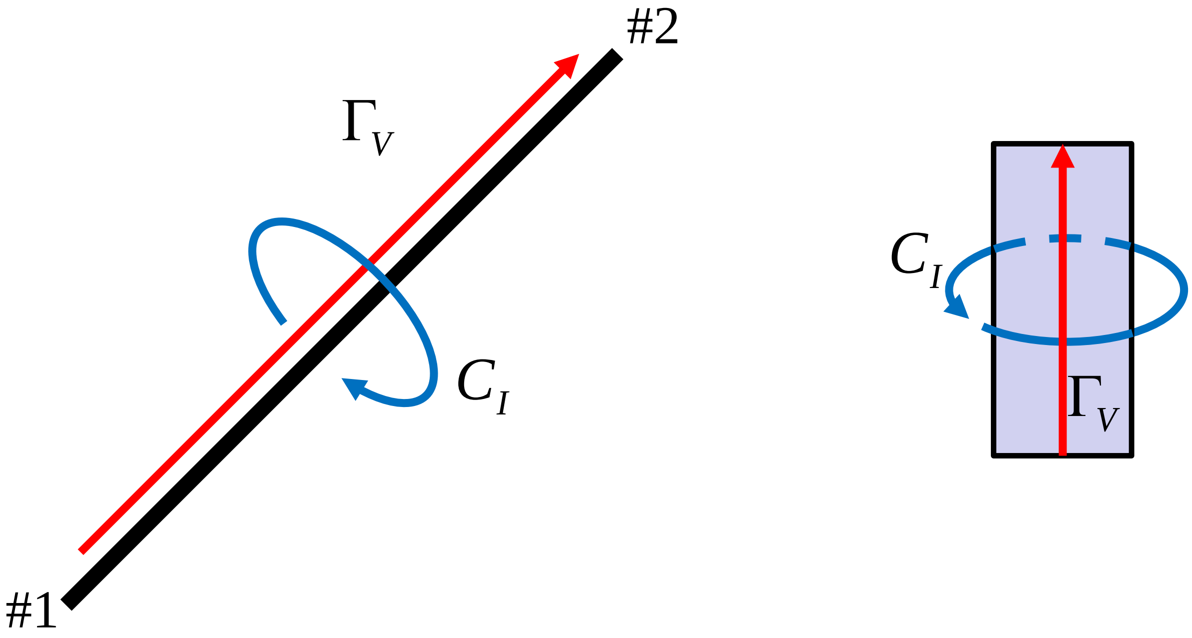
$$\begin{cases} \mathbf{D} = \varepsilon \mathbf{E} \\ \mathbf{B} = \mu \mathbf{H} \end{cases}$$

電束密度 → $\mathbf{D}$　誘電率 → ε　電界 → $\mathbf{E}$

磁束密度 → $\mathbf{B}$　透磁率 → μ　磁界 → $\mathbf{H}$

James Clerk Maxwell, “A Dynamical Theory of the Electromagnetic Field,”
Philosophical Transactions of the Royal Society of London, vol.155, pp.459-512, 1865.

集中ポート（電圧と電流）



$$\begin{cases}\oint_C \mathbf{E}\cdot d\mathbf{l} = -\dfrac{\partial}{\partial t}\iint_S \mathbf{B}\cdot d\mathbf{S}\\[2ex] \oint_C \mathbf{H}\cdot d\mathbf{l} = \iint_S \mathbf{i}\cdot d\mathbf{S} + \dfrac{\partial}{\partial t}\iint_S \mathbf{D}\cdot d\mathbf{S}\end{cases}$$

$$\begin{cases}\text{電圧}\quad V_0 = -\int_{\Gamma_V} \mathbf{E}\cdot d\mathbf{l}\\[2ex] \text{電流}\quad I_0 = \oint_{C_I} \mathbf{H}\cdot d\mathbf{l}\end{cases}$$

$$Z_0 = V_0 / I_0$$

表面インピーダンス

表面インピーダンス

$$Z_s = \frac{E_x(0)}{J_s}$$

$$= \frac{E_x(0)}{H_y(0)}$$

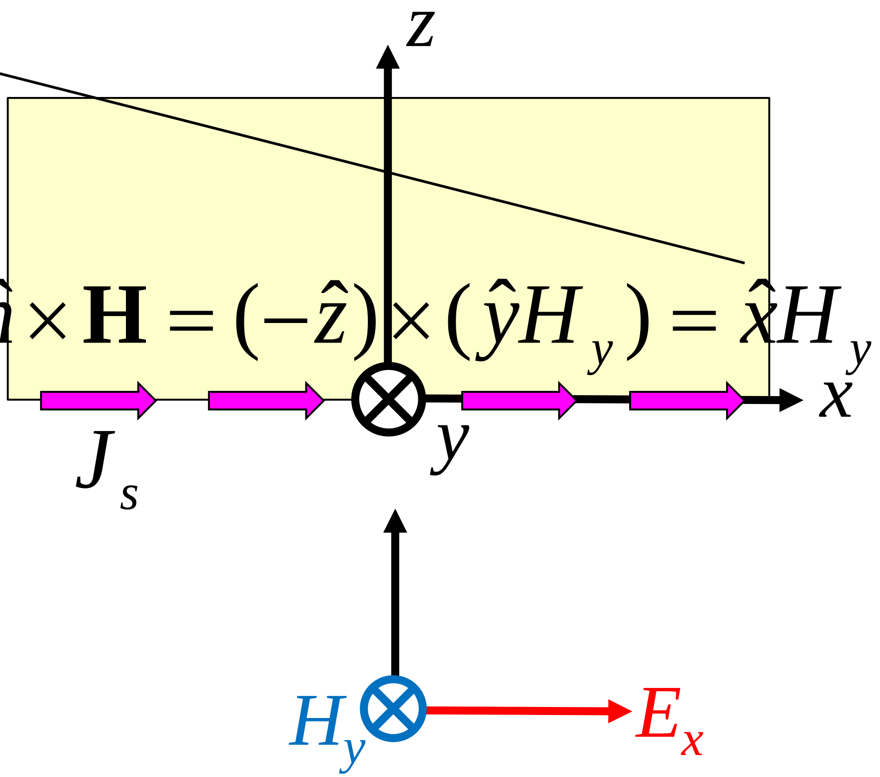
$$= -j\omega\mu \frac{E_x(0)}{\dfrac{\partial E_x(0)}{\partial z}}$$

次ページ

$$\boxed{Z = \frac{V}{I} = \frac{E\Delta x}{H\Delta y}}$$

$[\Omega]$

$[\Omega/□]$



$$\mathbf{J}_s = \hat{n}\times\mathbf{H} = (-\hat{z})\times(\hat{y}H_y) = \hat{x}H_y$$

HyをExで表す

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}$$

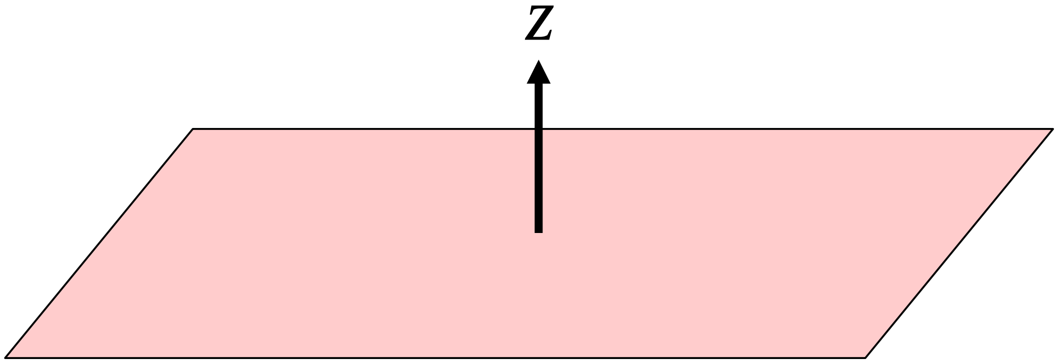
$$\nabla \times \mathbf{A} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \\ A_x & A_y & A_z \end{vmatrix} = \begin{bmatrix} 0 & -\partial/\partial z & \partial/\partial y \\ \partial/\partial z & 0 & -\partial/\partial x \\ -\partial/\partial y & \partial/\partial x & 0 \end{bmatrix} \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}$$

$$= \hat{x}\left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} \right) - \hat{y}\left(\frac{\partial A_z}{\partial x} - \frac{\partial A_x}{\partial z} \right) + \hat{z}\left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right)$$

$$\frac{\partial E_x}{\partial z} = -j\omega\mu H_y$$

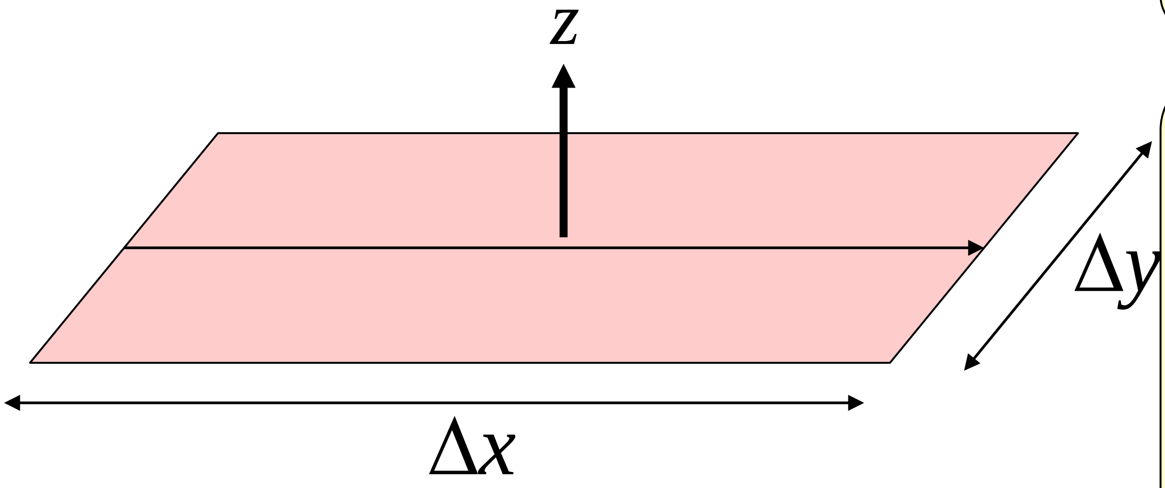
表面インピーダンス上の微分方程式

$$j\omega\mu E_x(0) - Z_s \frac{\partial E_x(0)}{\partial z} = 0$$



集中ポートと表面インピーダンス

$$Z=\frac{V}{I}=\frac{E_x}{H_y}\frac{\Delta x}{\Delta y}=j\omega\mu\frac{E_x}{\dfrac{\partial E_x}{\partial z}}\frac{\Delta x}{\Delta y}$$



励振方法1（電流源）: J_s

$$I=J_s\Delta y$$

$$V=E_x\Delta x$$

$$Z=V/I$$

励振方法2（電圧源）:$E_{x,ex}$

$$E_x\rightarrow E_x+E_{x,ex}$$

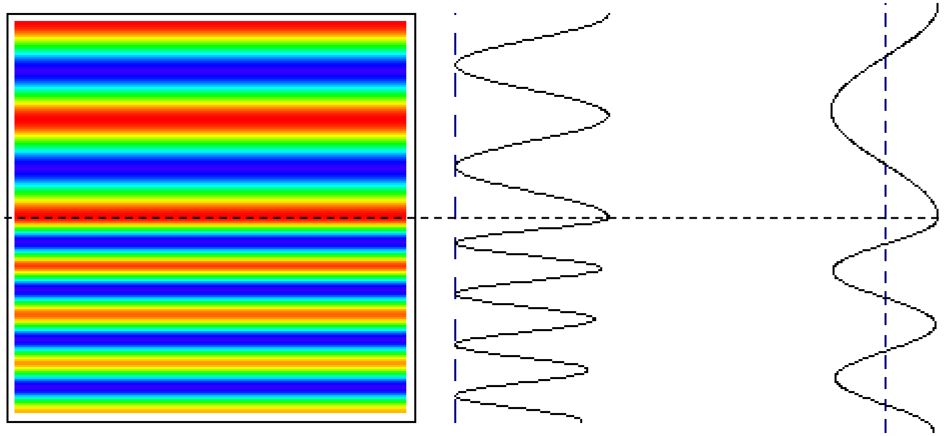
$$V=(E_x+E_{x,ex})\Delta x$$

$$I=H_y\Delta y=\frac{1}{j\omega\mu}\frac{\partial E_x}{\partial z}\Delta y$$

$$Z=V/I$$

導体の表面インピーダンス近似(1)

εr1=1, εr2=4, σ2=0.001→10.0 (0.001,0.006,0.01,0.06,0.1,0.6,1.0,6.0,10.0)
θi=0°



損失電力

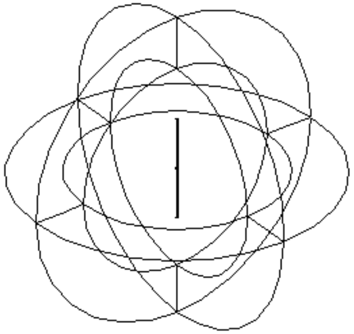
$$\frac{1}{2}\int_{z=-\infty}^{0}\sigma\left|\mathbf{E}\right|^2 dz = \frac{\sigma\left|\eta\right|^2}{2}\int_{z=-\infty}^{0}\left|\mathbf{H}\right|^2 dz$$

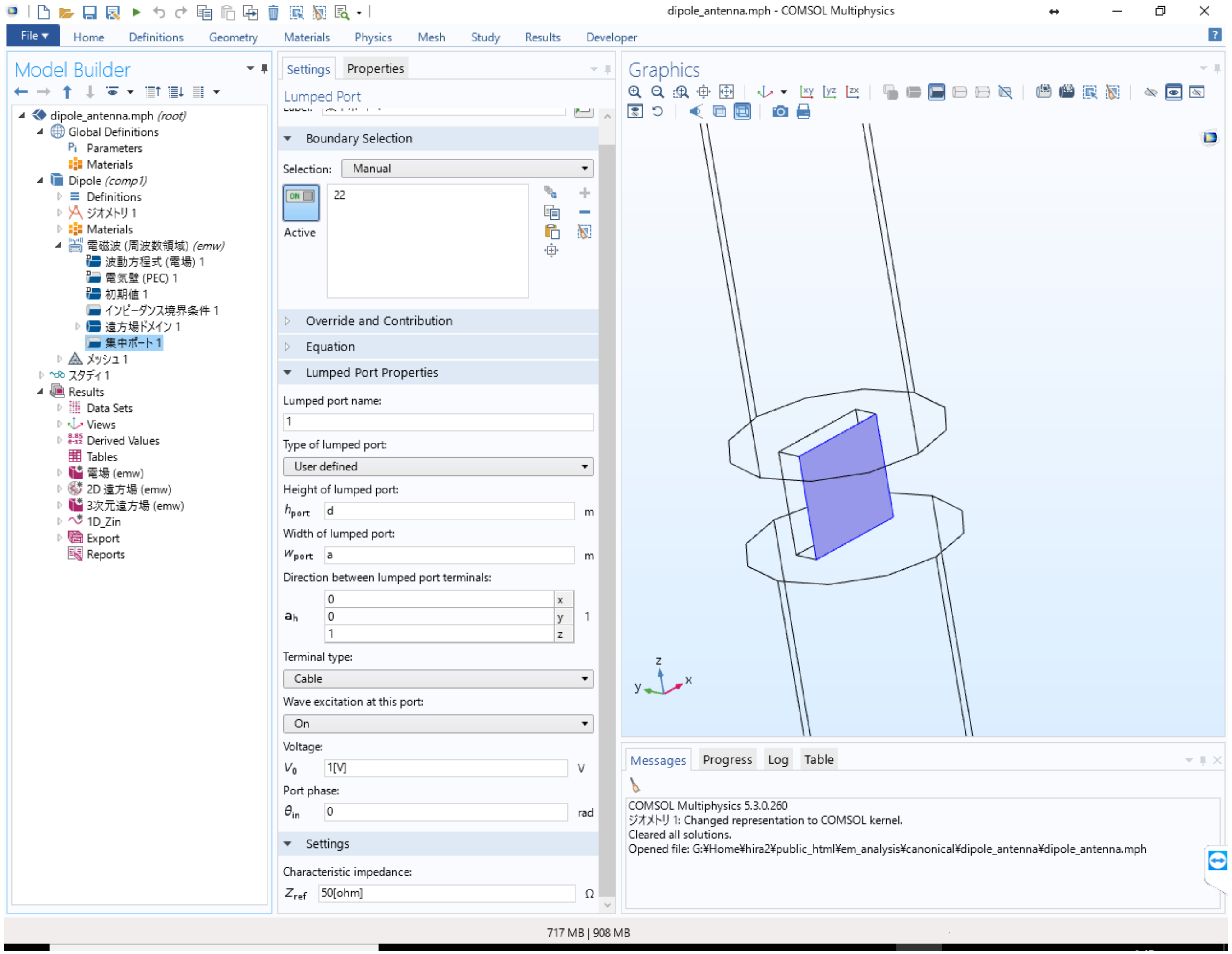
$$= \frac{\omega\mu}{2}\left|\mathbf{H}_{t0}\right|^2\int_{z=-\infty}^{0} e^{2\alpha z} dz = \frac{\omega\mu}{4\alpha}\left|\mathbf{H}_{t0}\right|^2$$

これより、導電率が高い極限では2つの見方ができる。
1. 境界条件は、あくまで面電流など存在しない。接線成分は連続であり、徐々に減衰してゆくという見方（ミクロな見方）。
2. 少し離れたところからマクロにみると、表面電流が流れ、その電流の奥では電界磁界がゼロとなってしまう。つまり、磁界の接線成分は不連続になる。その差が面電流であると見る見方

ダイポールアンテナ

COMSOLによるダイポールアンテナの解析





Lumped Port

Boundary Selection

Selection: Manual

22

Active

Override and Contribution

Equation

Lumped Port Properties

Lumped port name:
1

Type of lumped port:
User defined

Height of lumped port:
h_{port} d m

Width of lumped port:
w_{port} a m

Direction between lumped port terminals:
$\mathbf{a}_h$ 0 x, 0 y, 1 z 1

Terminal type:
Cable

Wave excitation at this port:
On

Voltage:
V_0 1[V] V

Port phase:
θ_{in} 0 rad

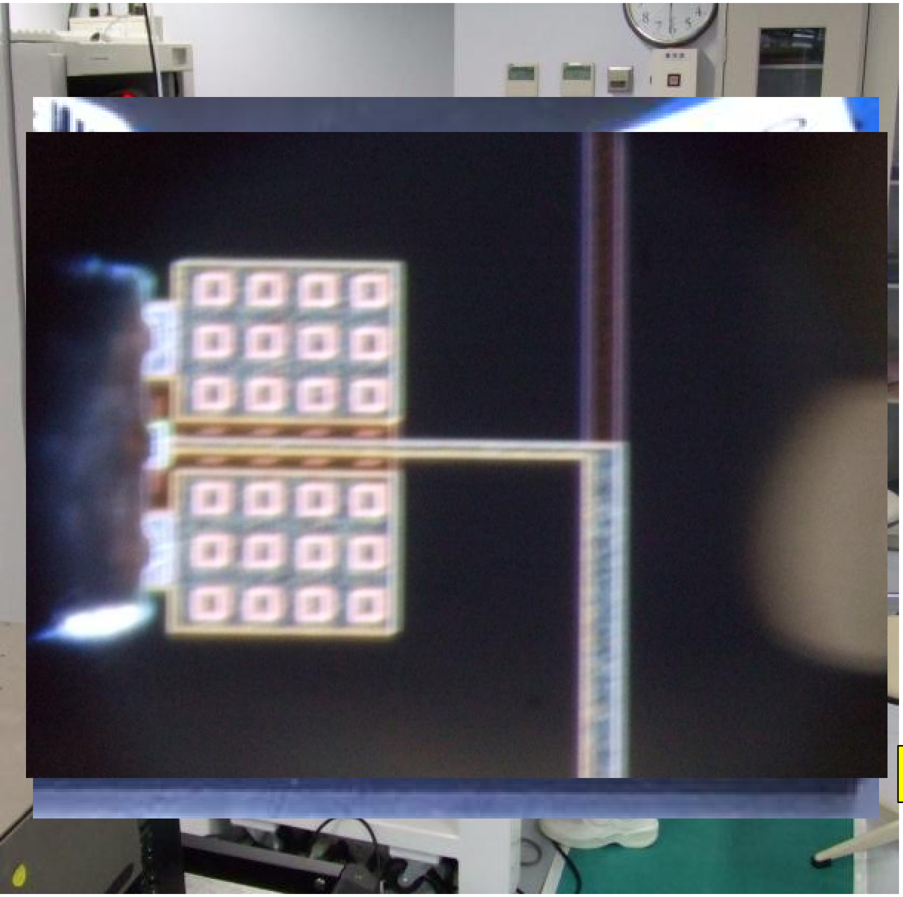
Settings

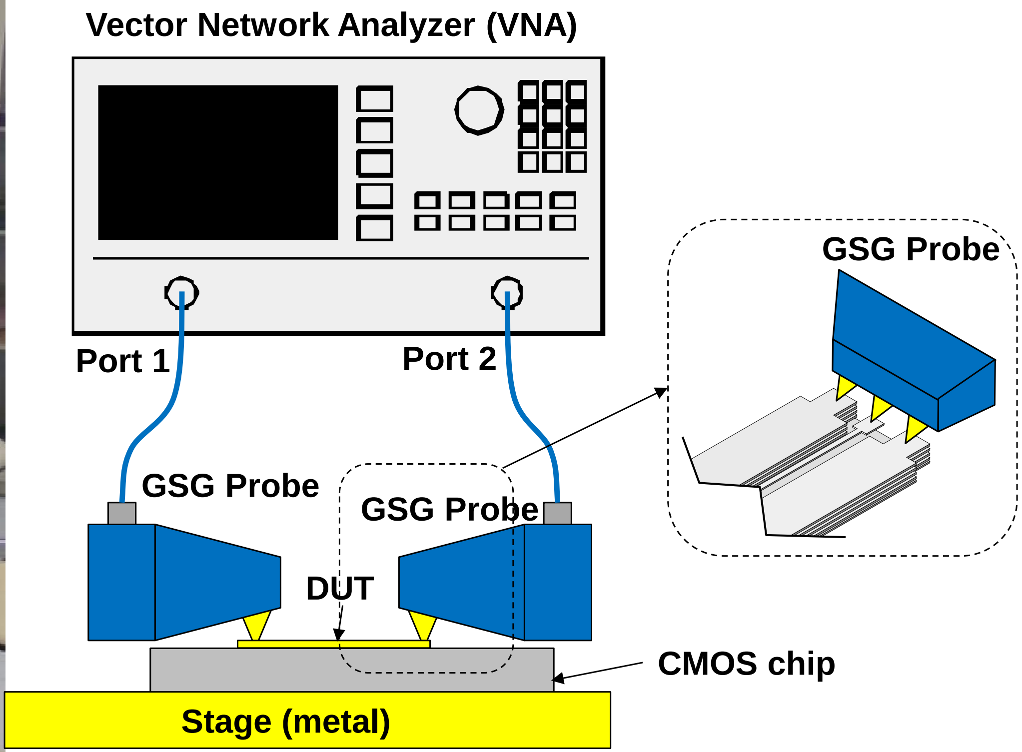
Characteristic impedance:
Z_{ref} 50[ohm] Ω

```
COMSOL Multiphysics 5.3.0.260
ジオメトリ 1: Changed representation to COMSOL kernel.
Cleared all solutions.
Opened file: G:¥Home¥hira2¥public_html¥em_analysis¥canonical¥dipole_antenna¥dipole_antenna.mph
```

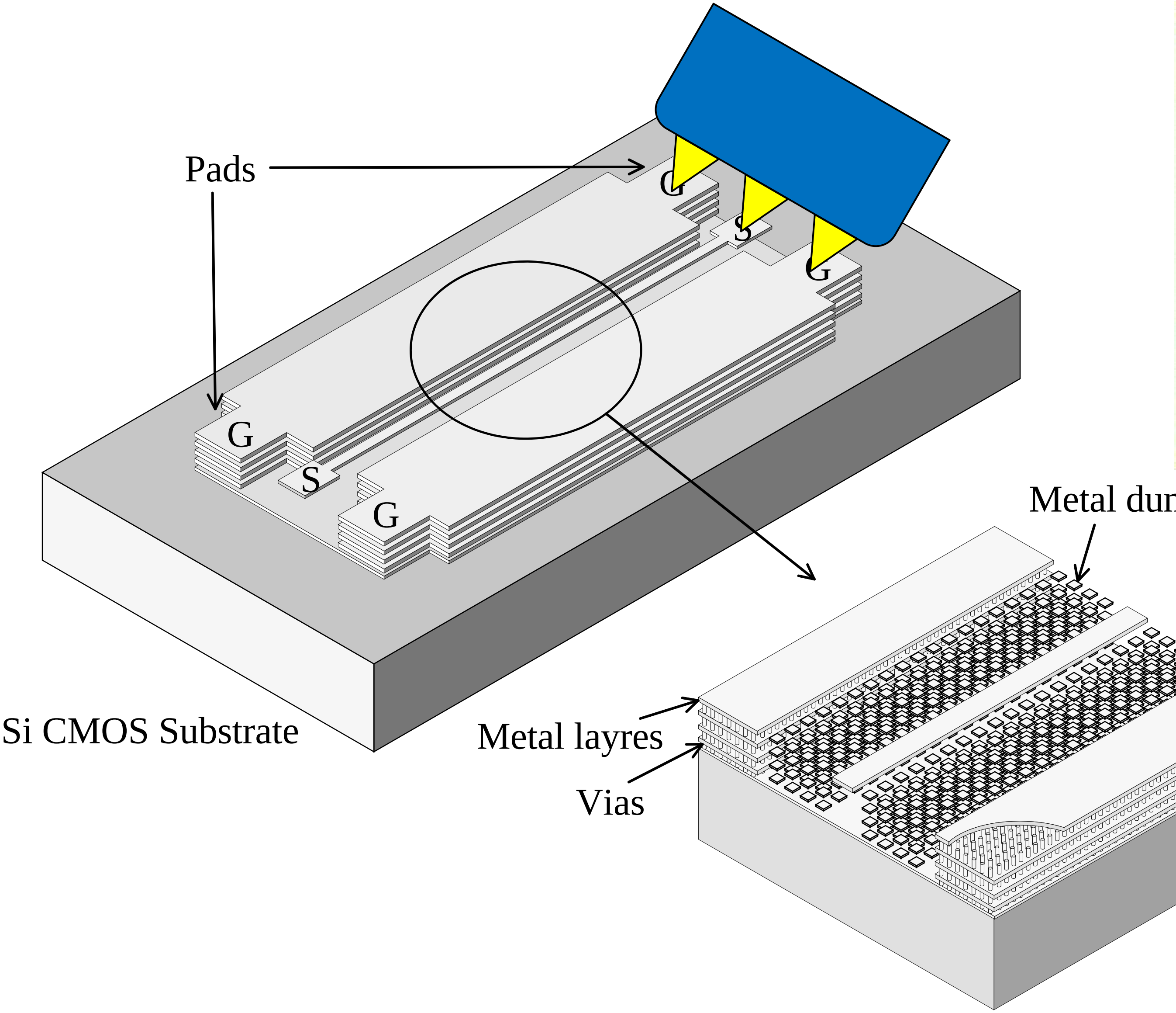
GSGパッドの励振モデル

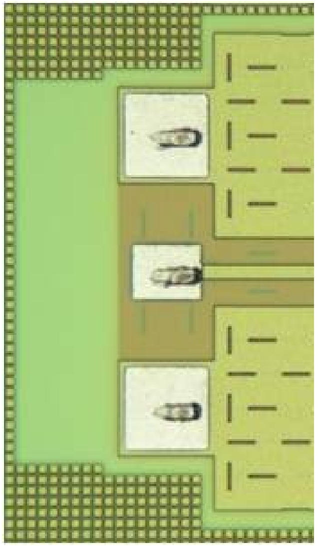
プローブ測定



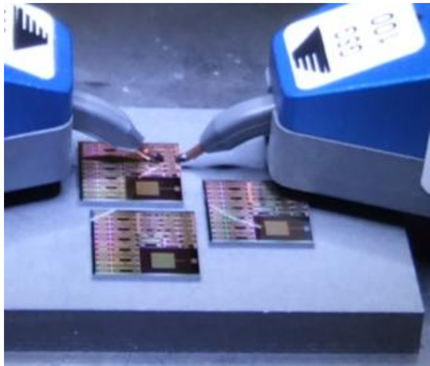

Vector Network Analyzer (VNA)
Port 1
Port 2
GSG Probe
GSG Probe
GSG Probe
DUT
CMOS chip
Stage (metal)

GSGパッドの構造

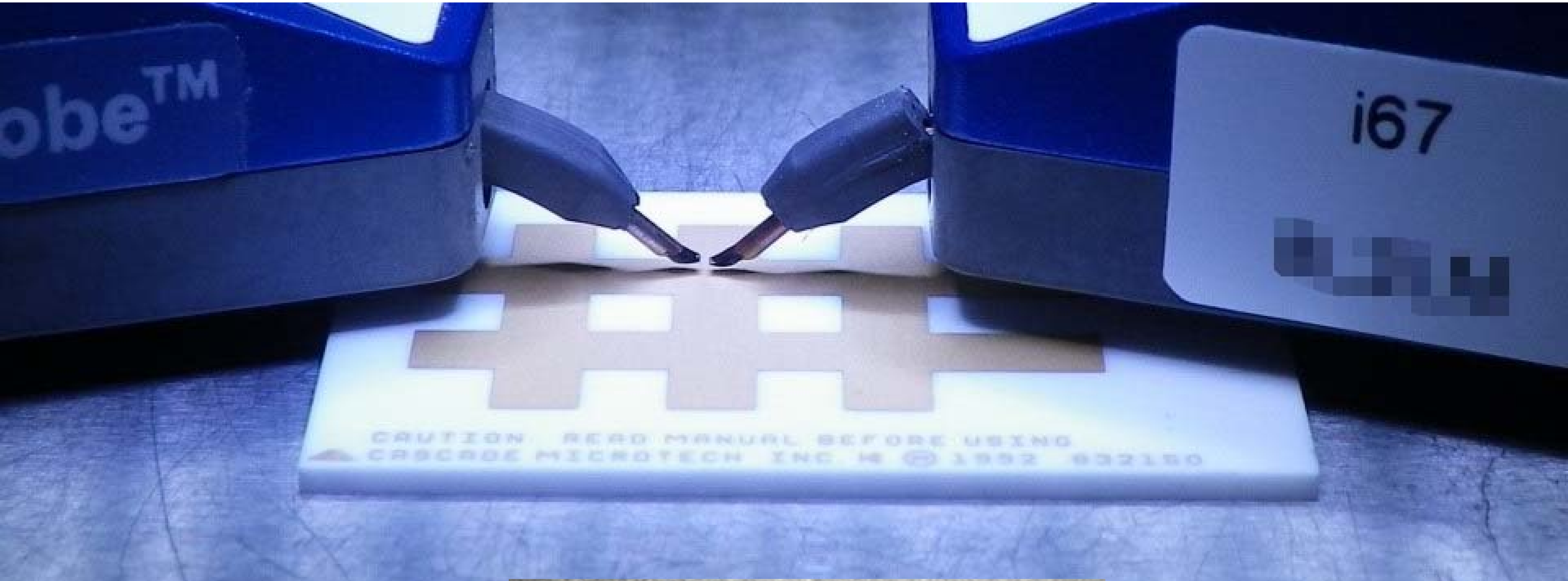


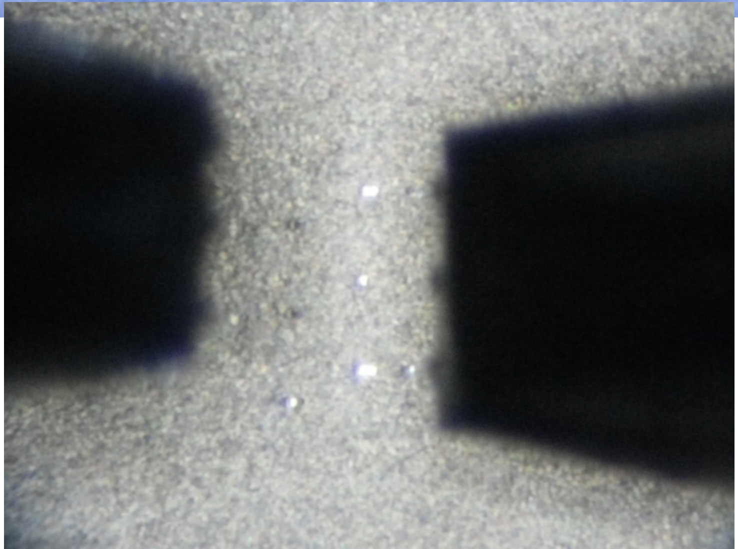


Cascade Microtech
Infinity Probe

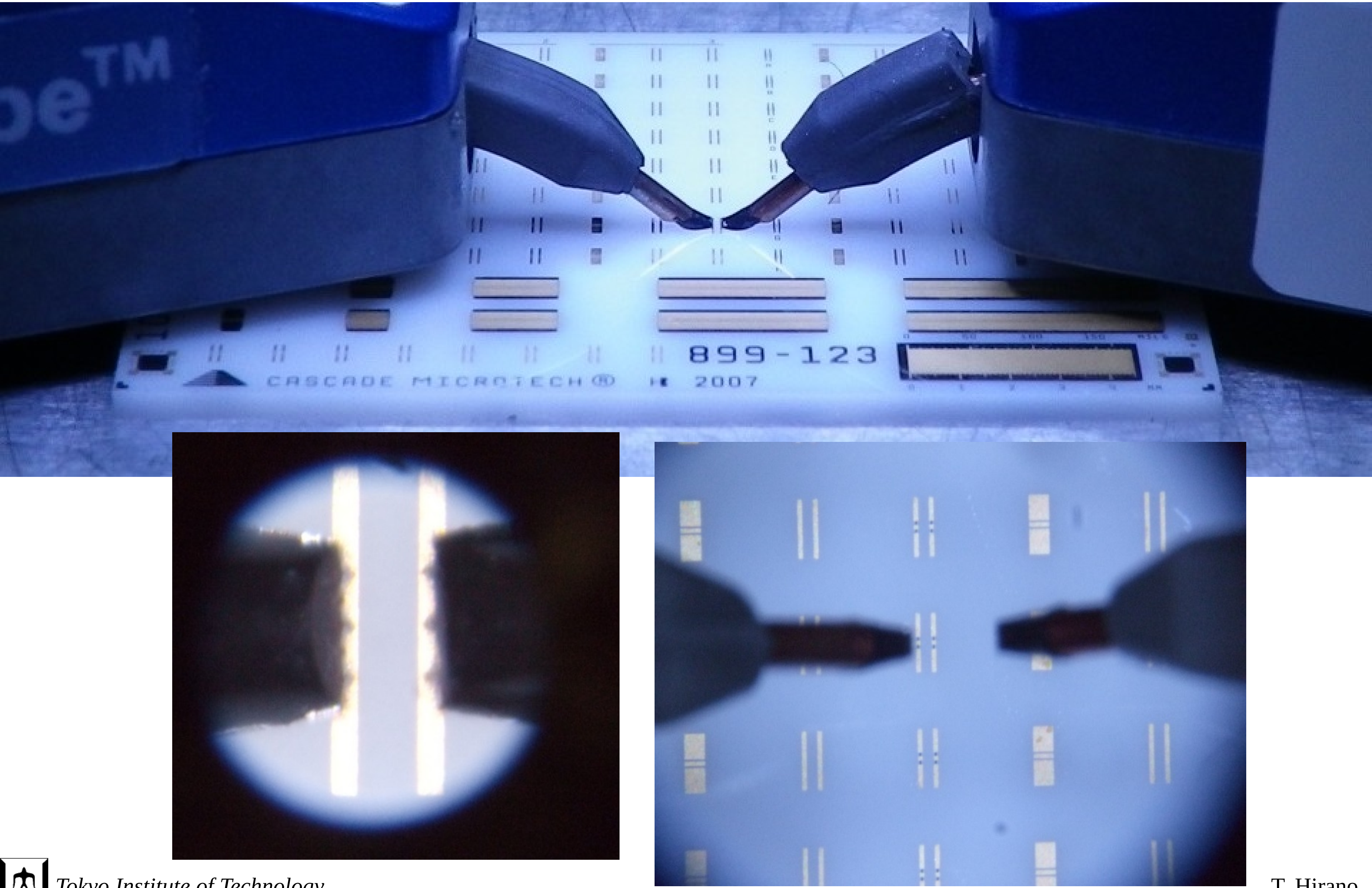


GSGプローブの写真（コンタクト基板）

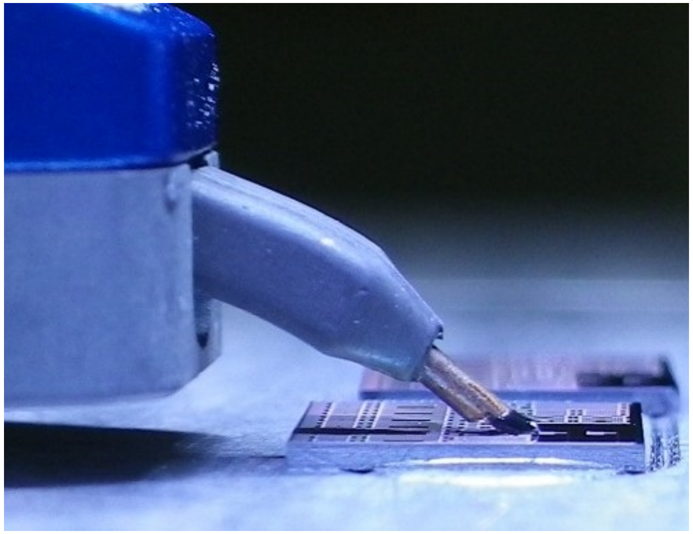


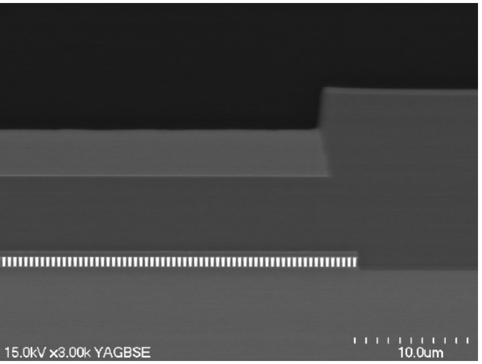


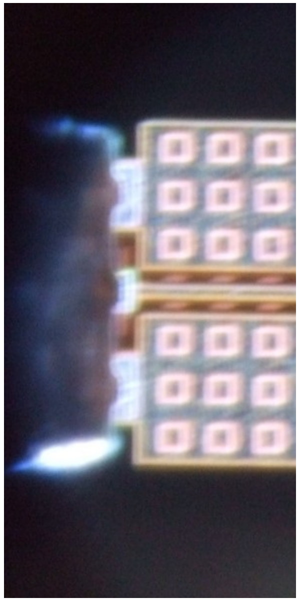
GSGプローブの写真(ISS; 校正基板)

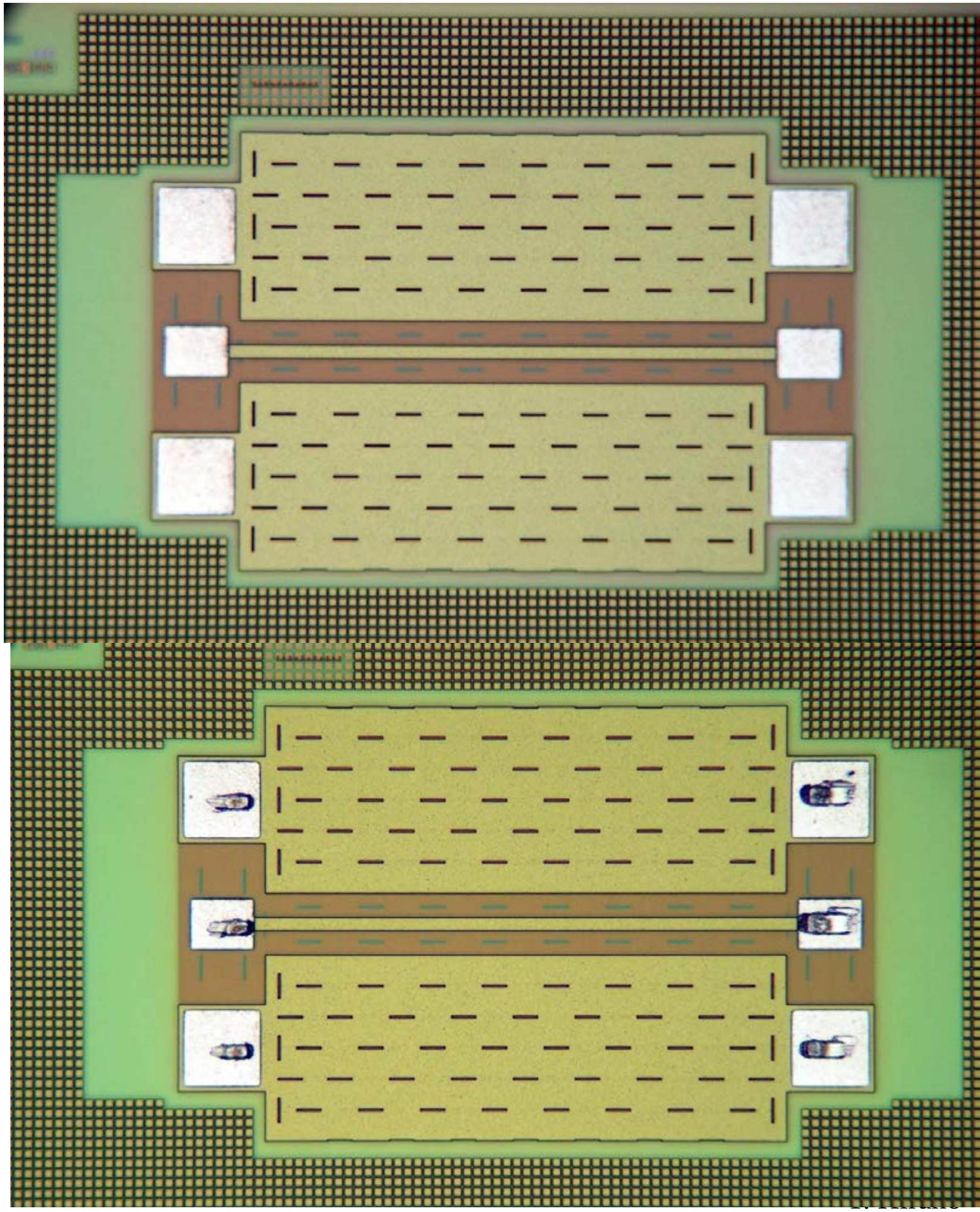


GSGプローブの写真(パッド)

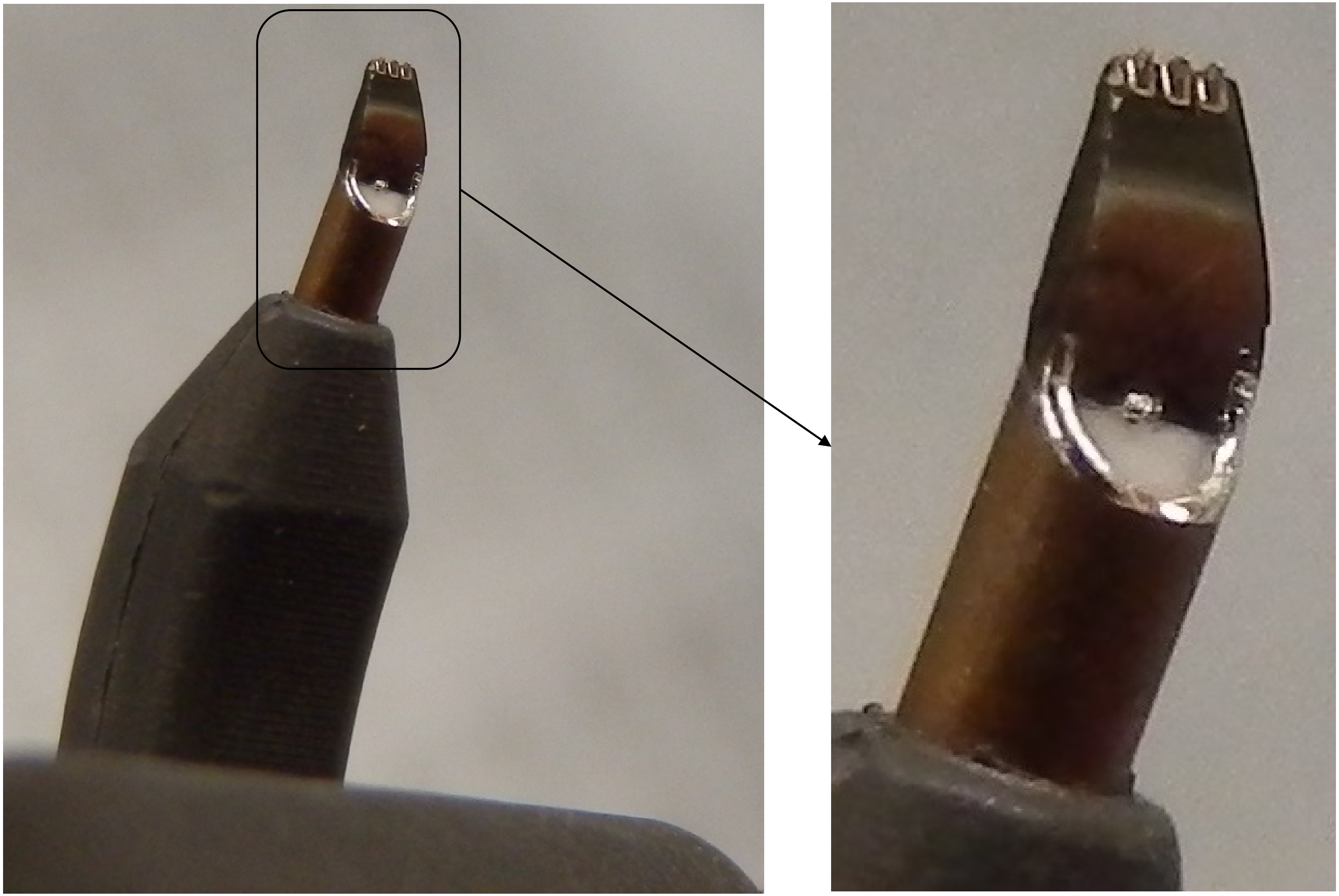




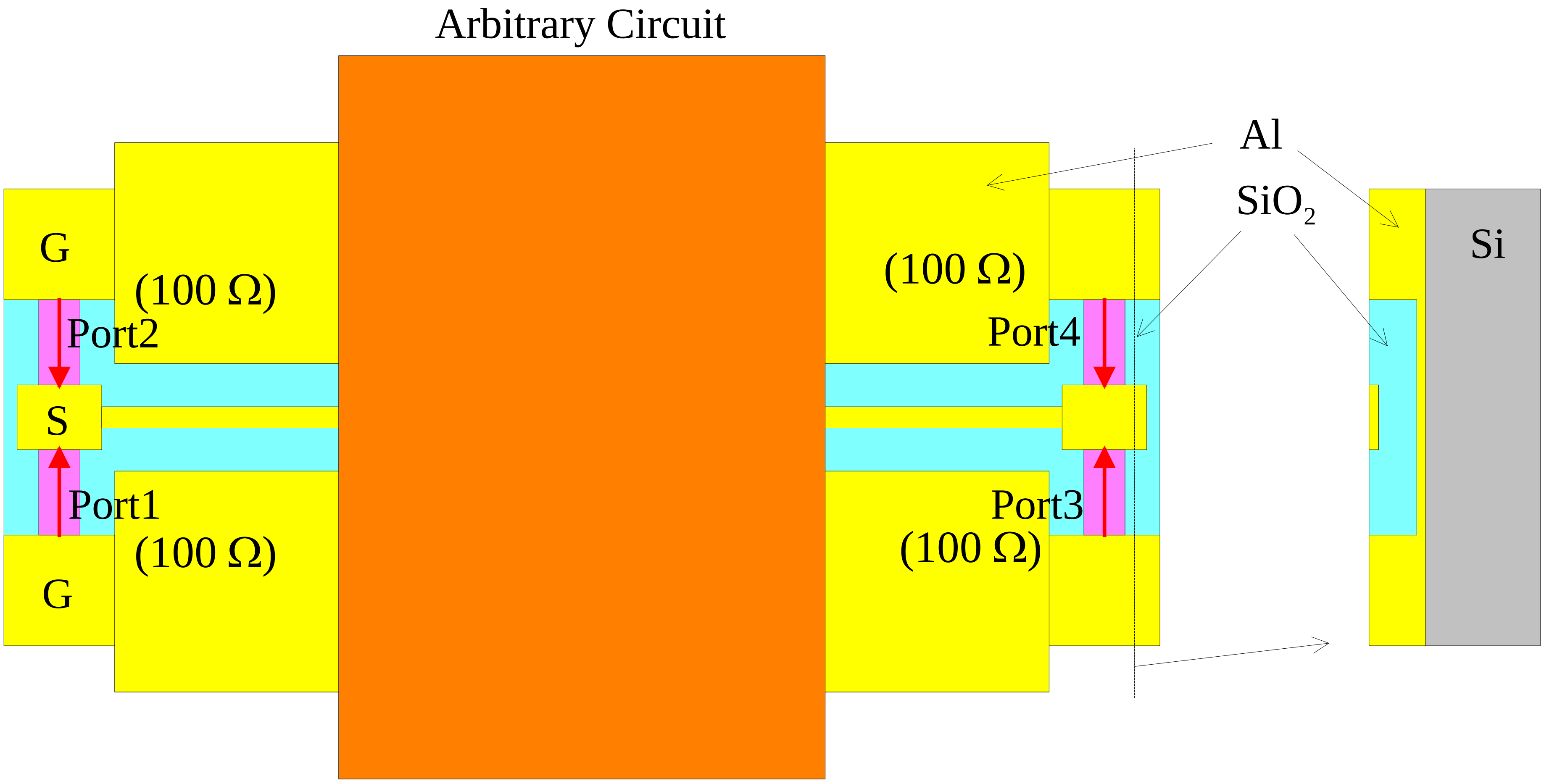




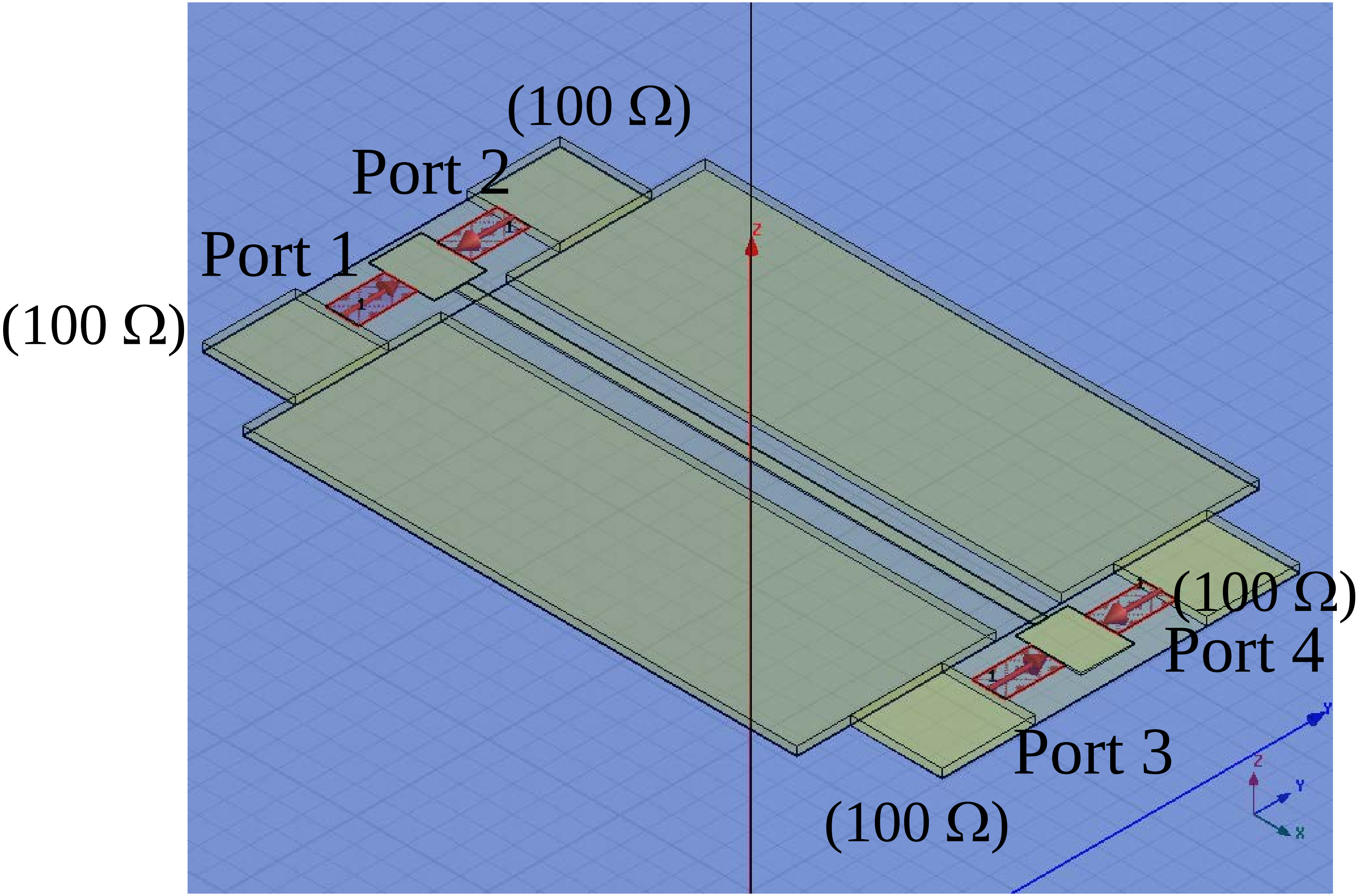
GSGプローブ先端の写真



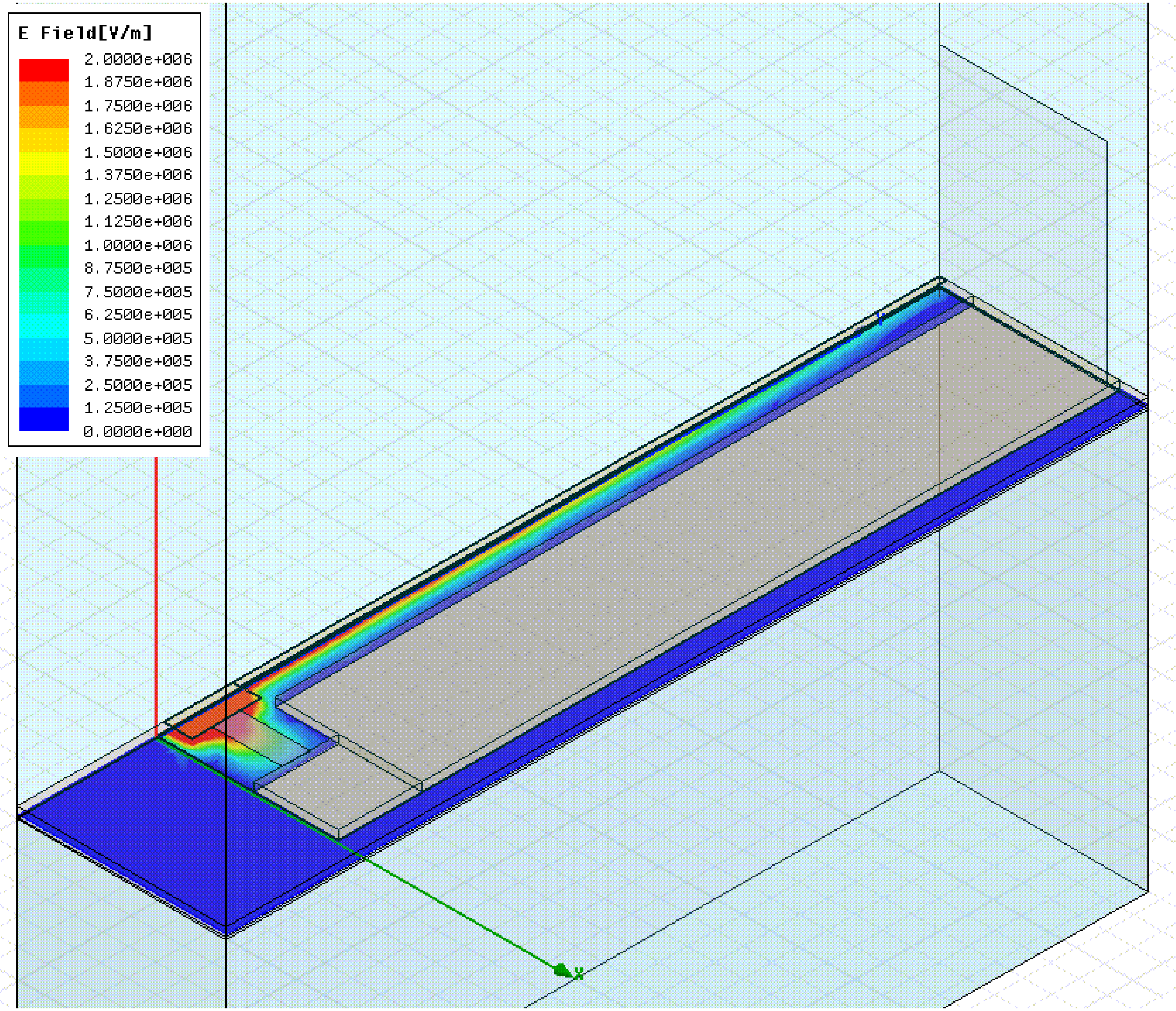
解析における励振部のモデル化



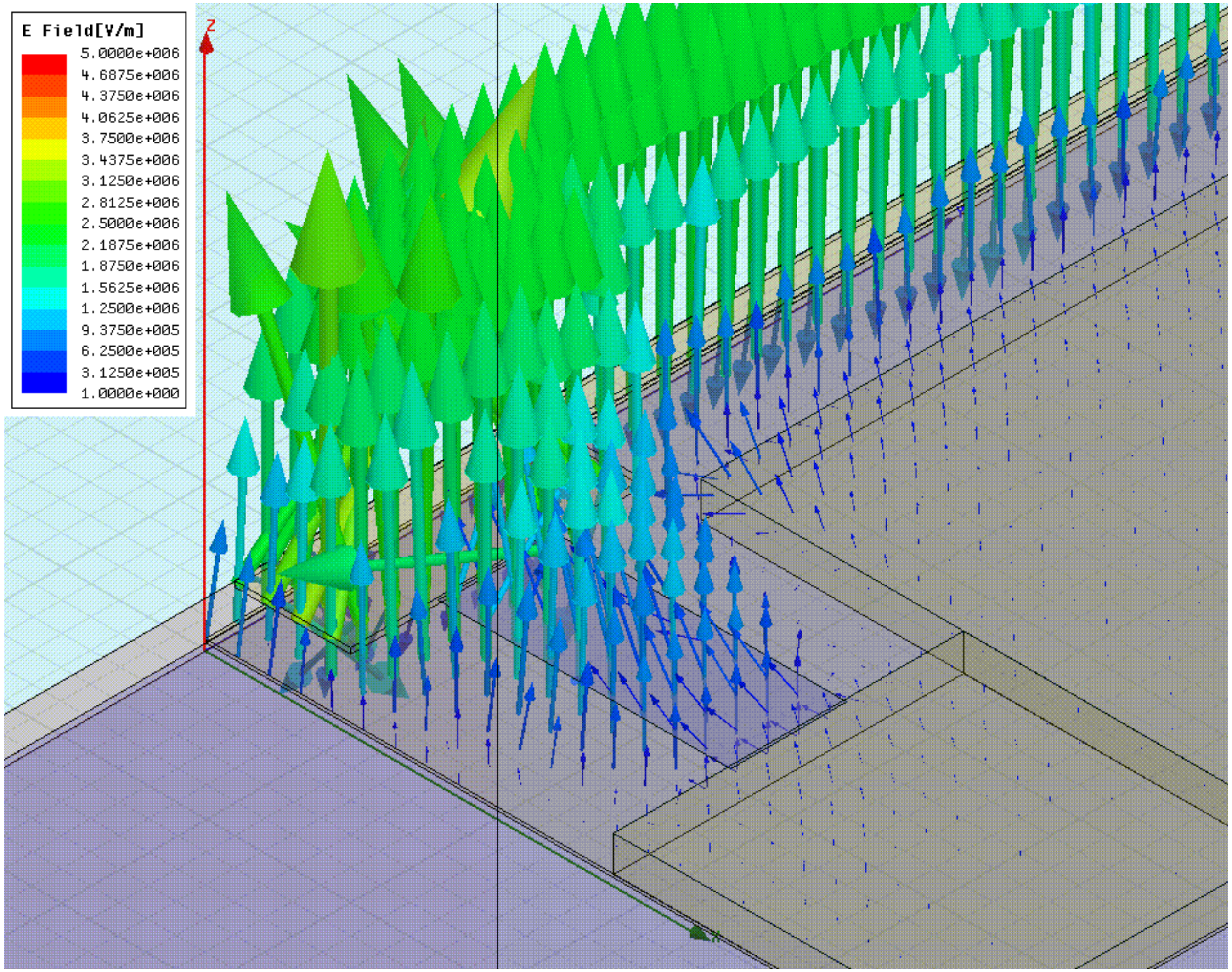
電磁界解析モデル



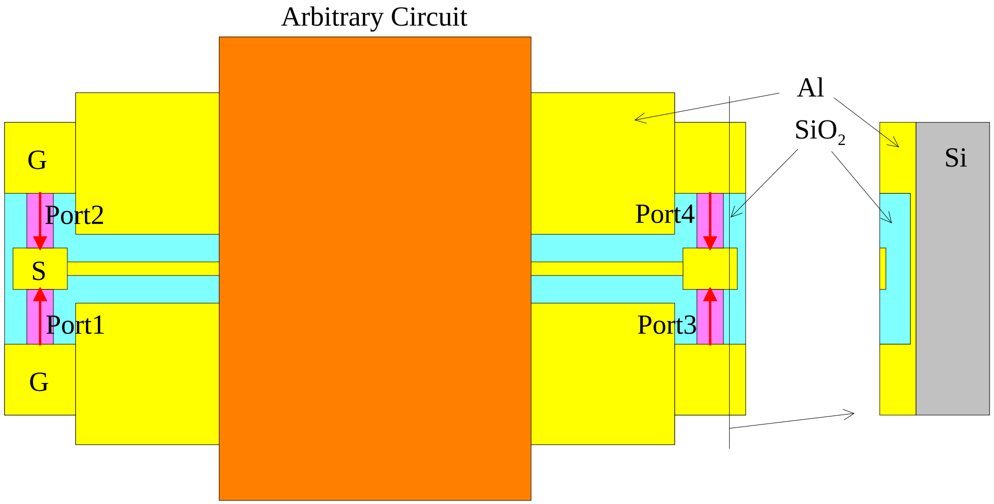
E-Field Animation



Vector E-Field Animation



解析結果4ポートから実測2ポートへの変換



$$\begin{bmatrix} b_1 \\ b_2 \\ \hline b_3 \\ b_4 \end{bmatrix} = \left[\begin{array}{cc|cc} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ \hline S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{array}\right] \begin{bmatrix} a_1 \\ a_2 \\ \hline a_3 \\ a_4 \end{bmatrix}$$

プローブ部の導波路はシングルモードなので、次の条件が成り立つ

$$a_1 = a_2 = a_1' \qquad a_3 = a_4 = a_2'$$

$$b_1 = b_2 = b_1' \qquad b_3 = b_4 = b_2'$$

$$\begin{bmatrix} b_1' \\ b_1' \\ \hline b_2' \\ b_2' \end{bmatrix} = \left[\begin{array}{cc|cc} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ \hline S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{array}\right] \begin{bmatrix} a_1' \\ a_1' \\ \hline a_2' \\ a_2' \end{bmatrix}$$

$$\begin{cases} b_1' = (S_{11} + S_{12})a_1' + (S_{13} + S_{14})a_2' \\ b_1' = (S_{21} + S_{22})a_1' + (S_{23} + S_{24})a_2' \\ b_2' = (S_{31} + S_{32})a_1' + (S_{33} + S_{34})a_2' \\ b_2' = (S_{41} + S_{42})a_1' + (S_{43} + S_{44})a_2' \end{cases}$$

パッド部の構造の対称性より、

$$S_{11} = S_{22} \qquad S_{12} = S_{21} \qquad S_{13} = S_{14} = S_{23} = S_{24}$$

$$S_{31} = S_{32} = S_{41} = S_{42} \qquad S_{33} = S_{44} \qquad S_{34} = S_{43}$$

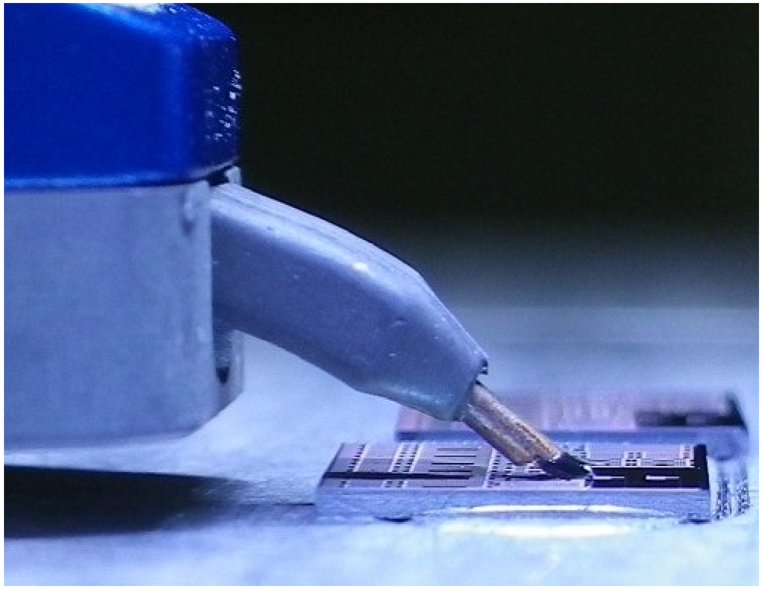
$$\boxed{\begin{bmatrix} S_{11}' & S_{12}' \\ S_{21}' & S_{22}' \end{bmatrix} = \begin{bmatrix} S_{11} + S_{12} & S_{13} + S_{14} \\ S_{31} + S_{32} & S_{33} + S_{34} \end{bmatrix}}$$

2 Lumped PortからGSG 1ポートへの変換

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

プローブ部の導波路はシングルモードなので、次の条件が成り立つ

$$a_1 = a_2 = a$$



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a \\ a \end{bmatrix}$$

$$\begin{cases} b_1 = (S_{11} + S_{12})a \\ b_2 = (S_{21} + S_{22})a \end{cases}$$

単モードとパッド部の構造の対称性より、

$$S_{11} = S_{22} \qquad S_{12} = S_{21}$$

$$b_1 = b_2 (= b)$$

反射係数

$$\Gamma = \frac{b}{a} = S_{11} + S_{12} = S_{21} + S_{22}$$

2 Lumped Portから差動GSSG 1ポートへの変換

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

プローブ部の導波路はシングルモードなので、
次の条件が成り立つ

$$a_1 = -a_2 = a$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a \\ -a \end{bmatrix}$$

$$\begin{cases} b_1 = (S_{11} - S_{12})a \\ b_2 = (S_{21} - S_{22})a \end{cases}$$

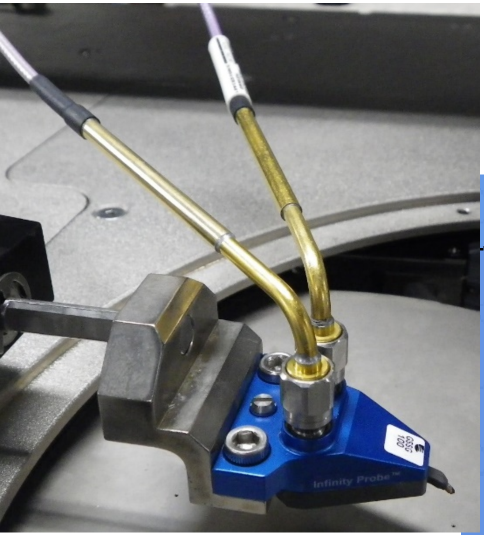
単モードとパッド部の構造の対称性より、

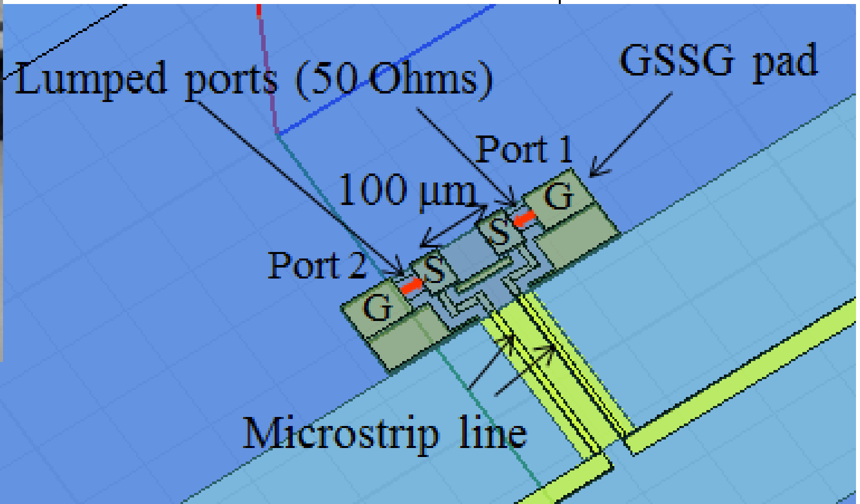
$$S_{11} = S_{22} \qquad S_{12} = S_{21}$$

$$b_1 = -b_2 (= b)$$

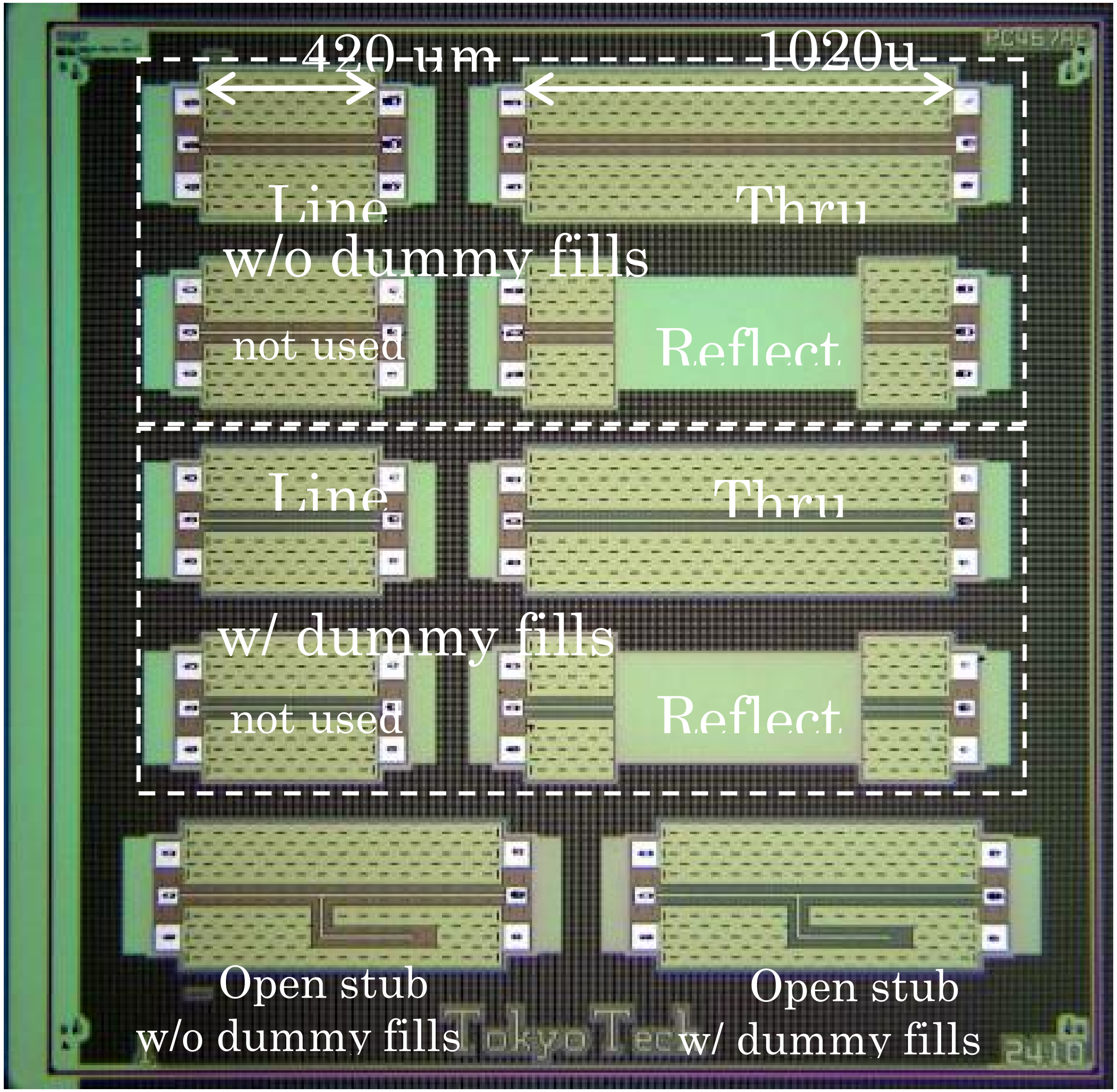
反射係数

$$\Gamma = \frac{b}{a} = S_{11} - S_{12}$$
$$= S_{22} - S_{21}$$



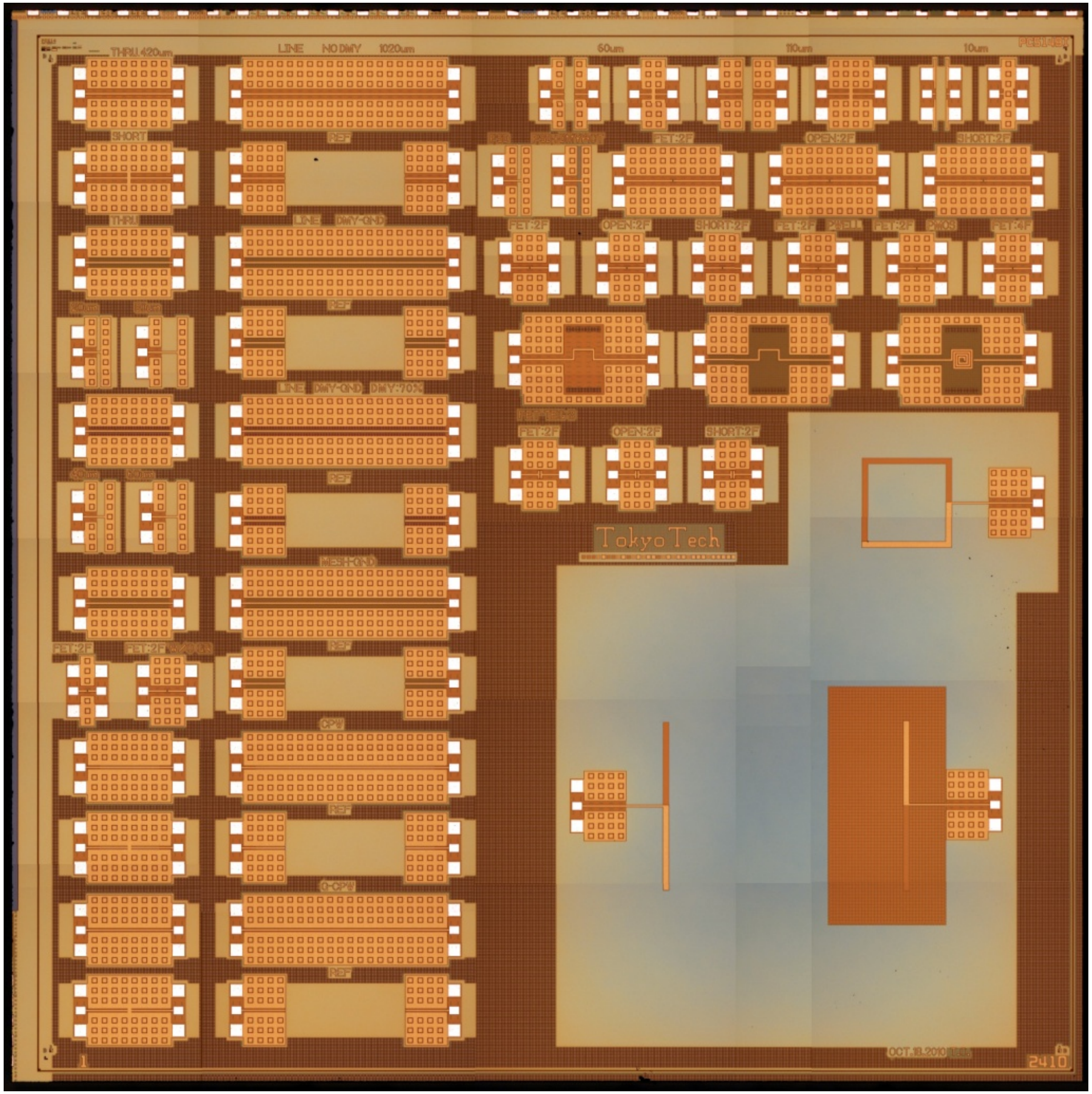


チップ写真1



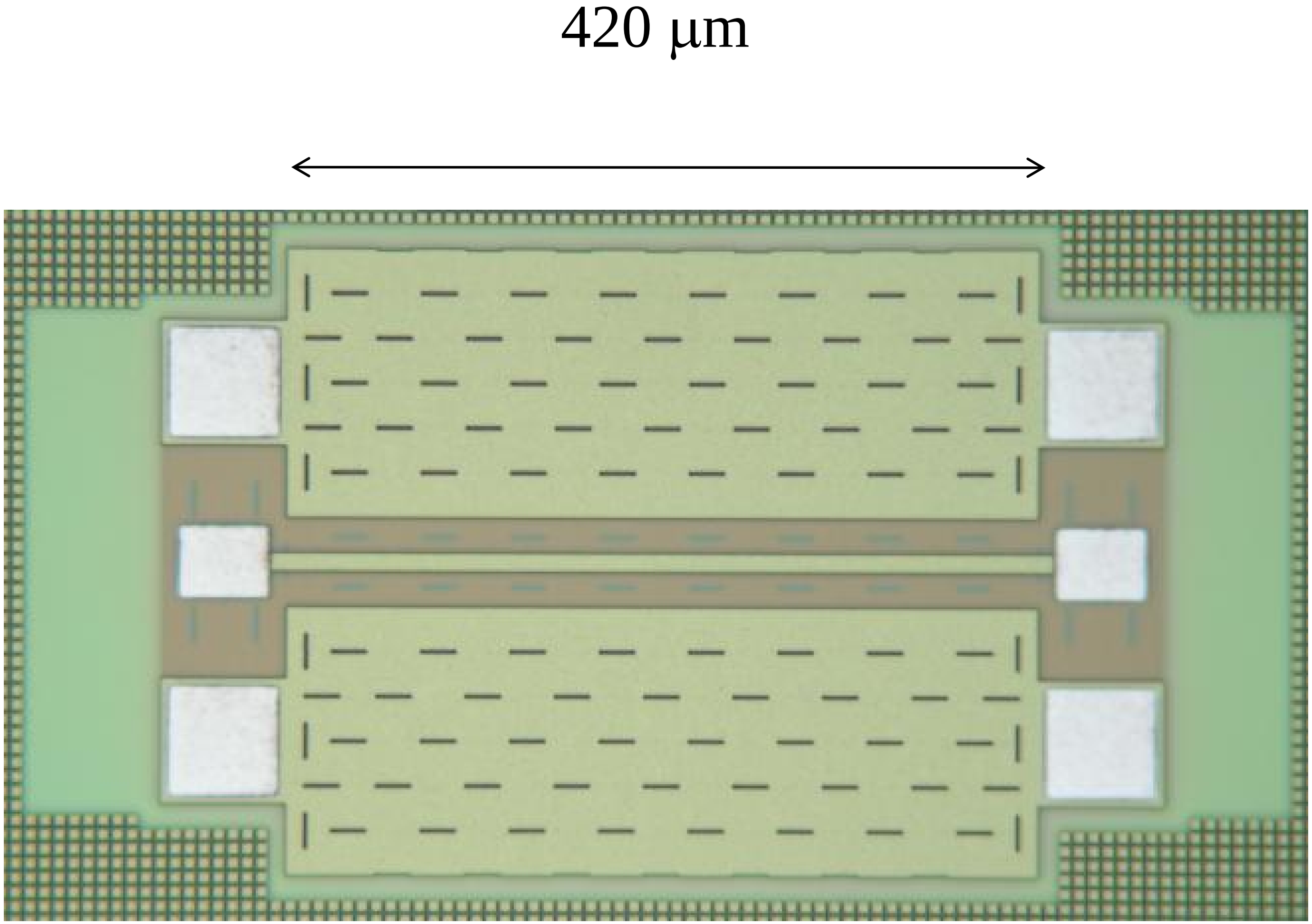
2.5 mm x 2.5 mm
CMOS 0.18 um

チップ写真2

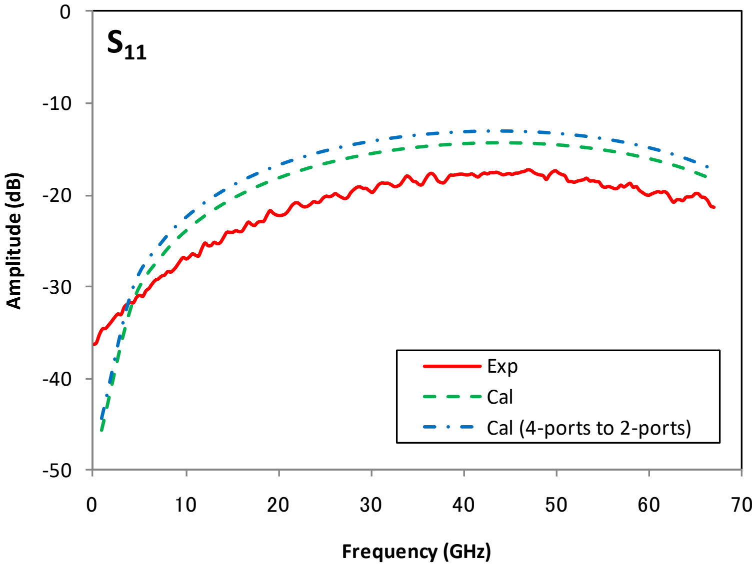


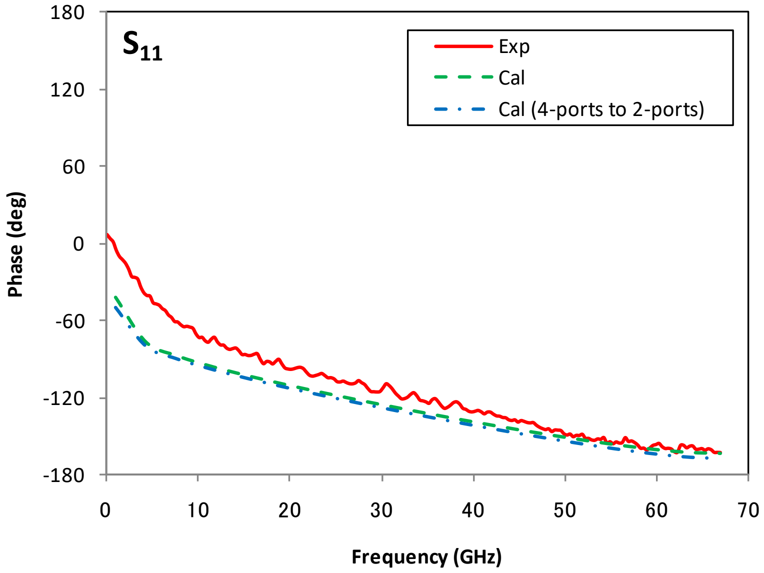
5 mm x 5 mm
CMOS 0.18 μm

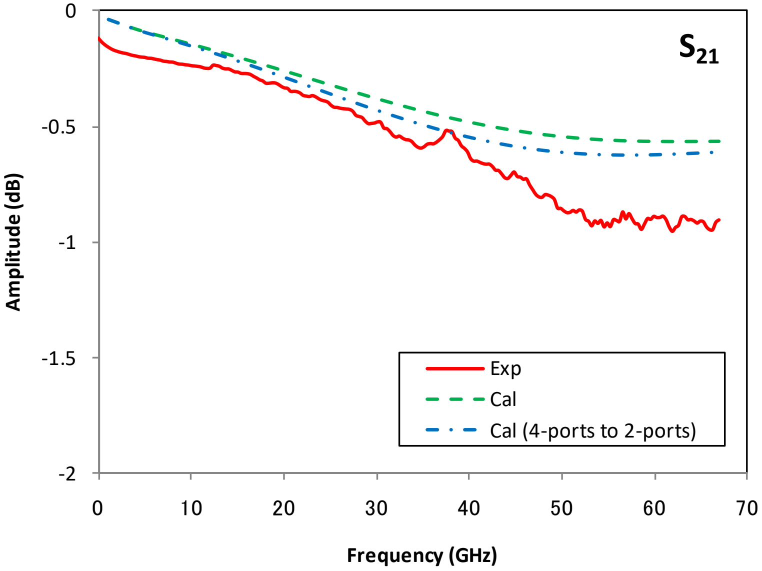
Thruパターン

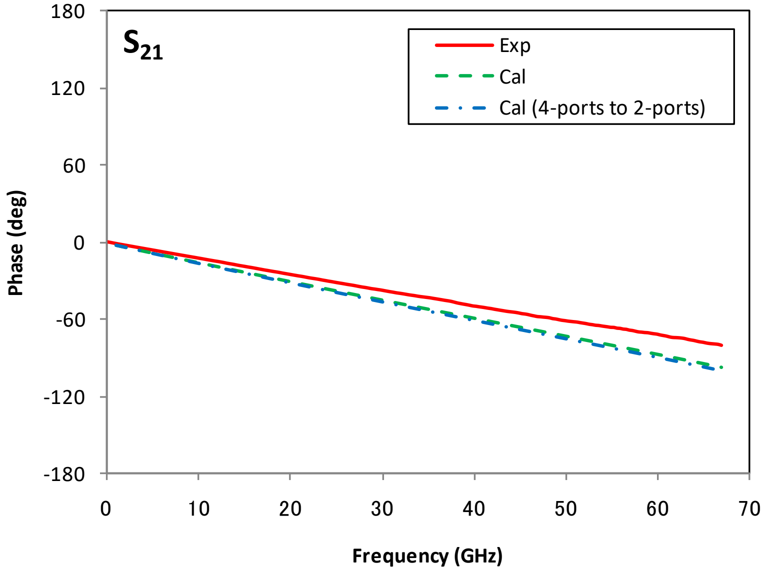


Thruパターン (Sパラメータ)

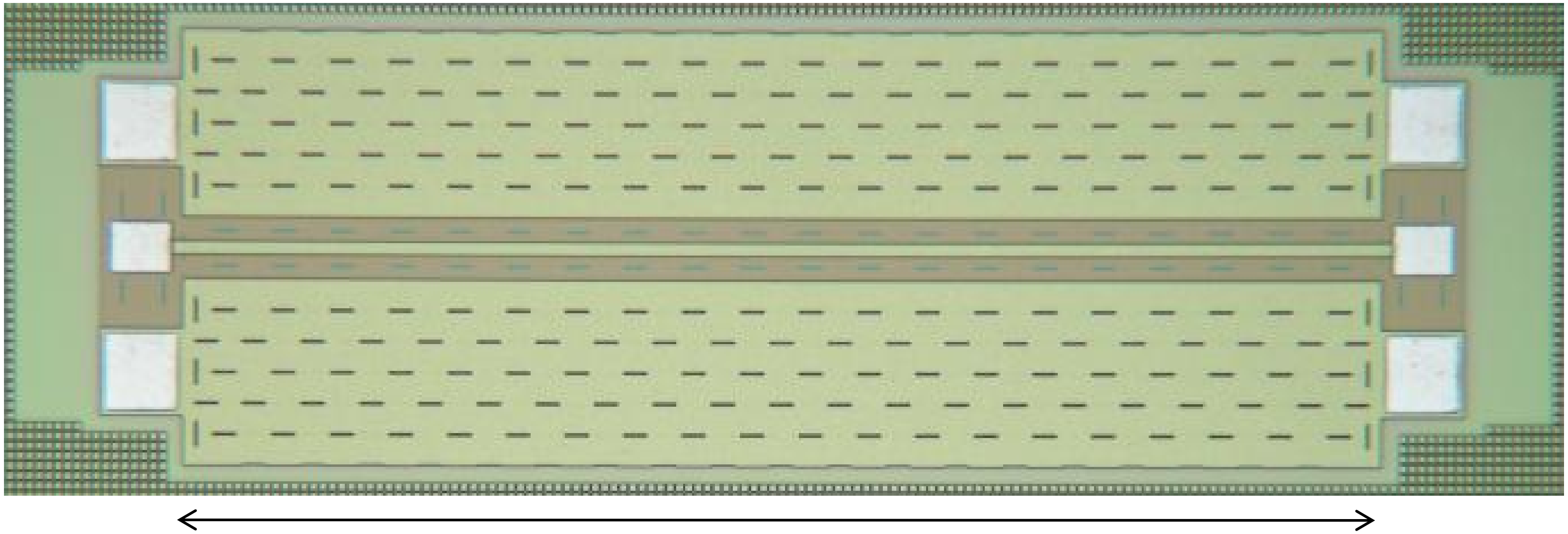






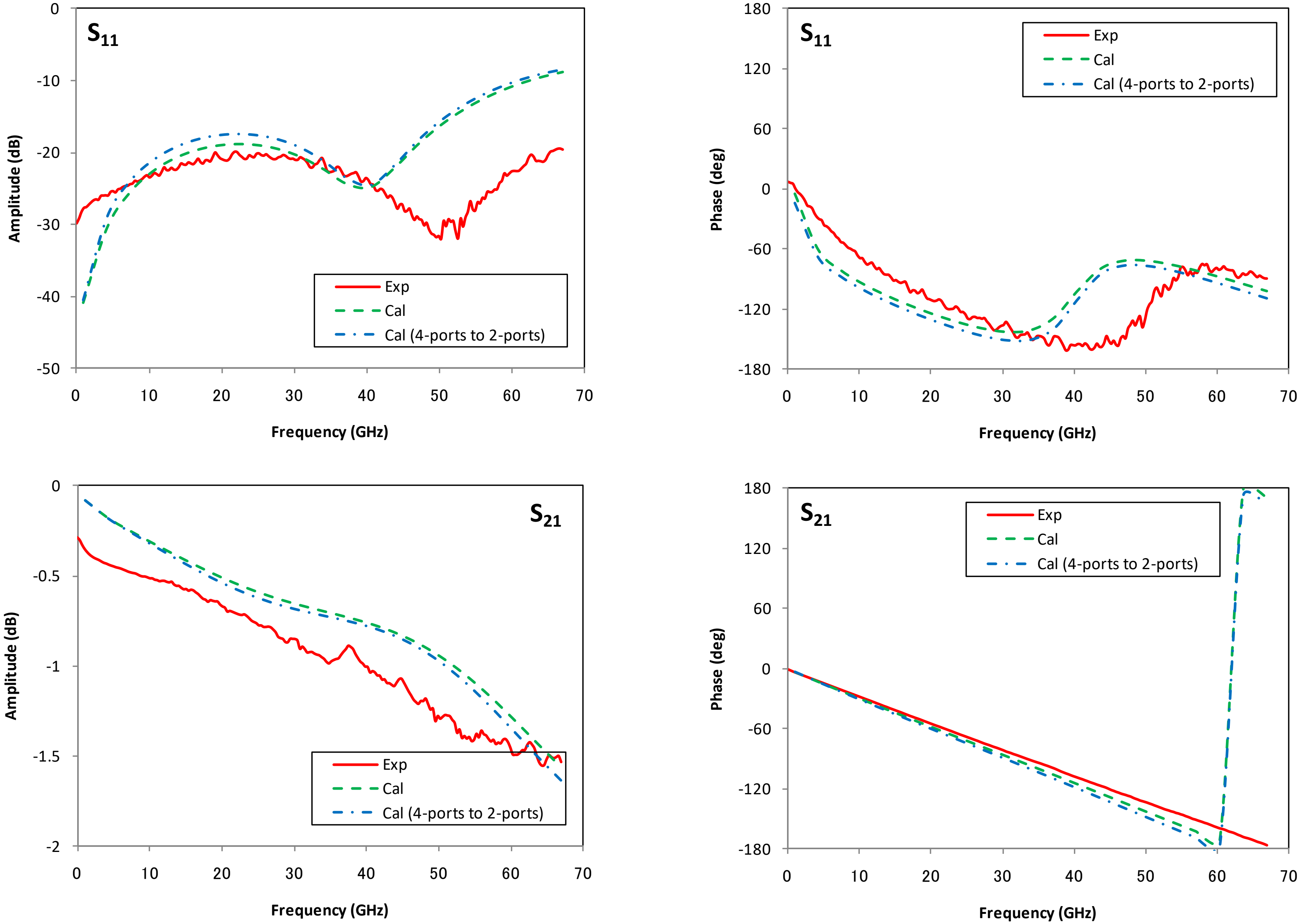


Lineパターン

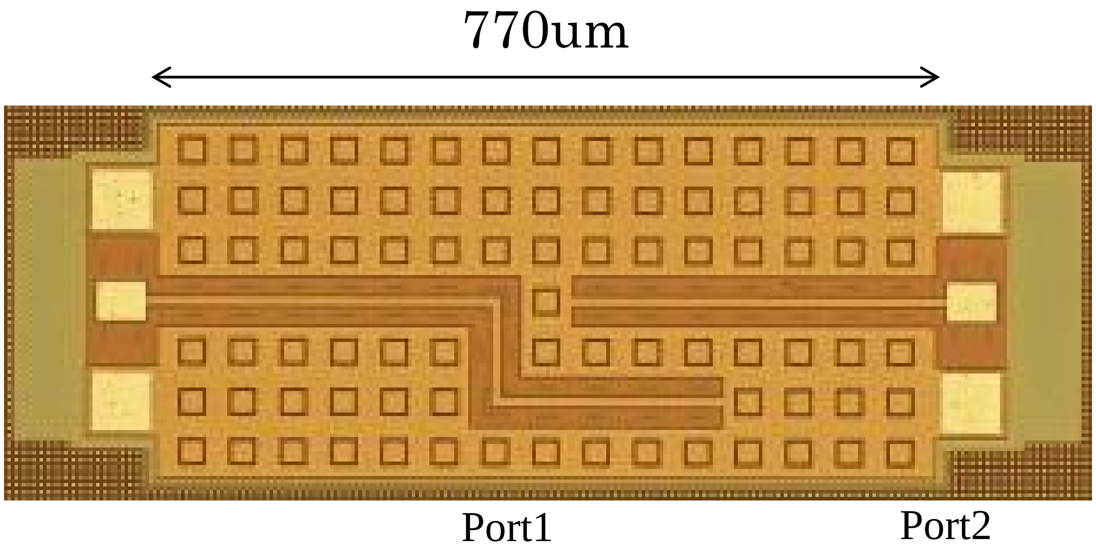


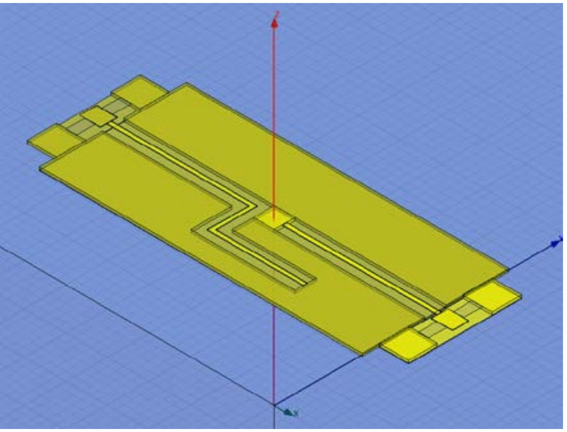
1020 μm

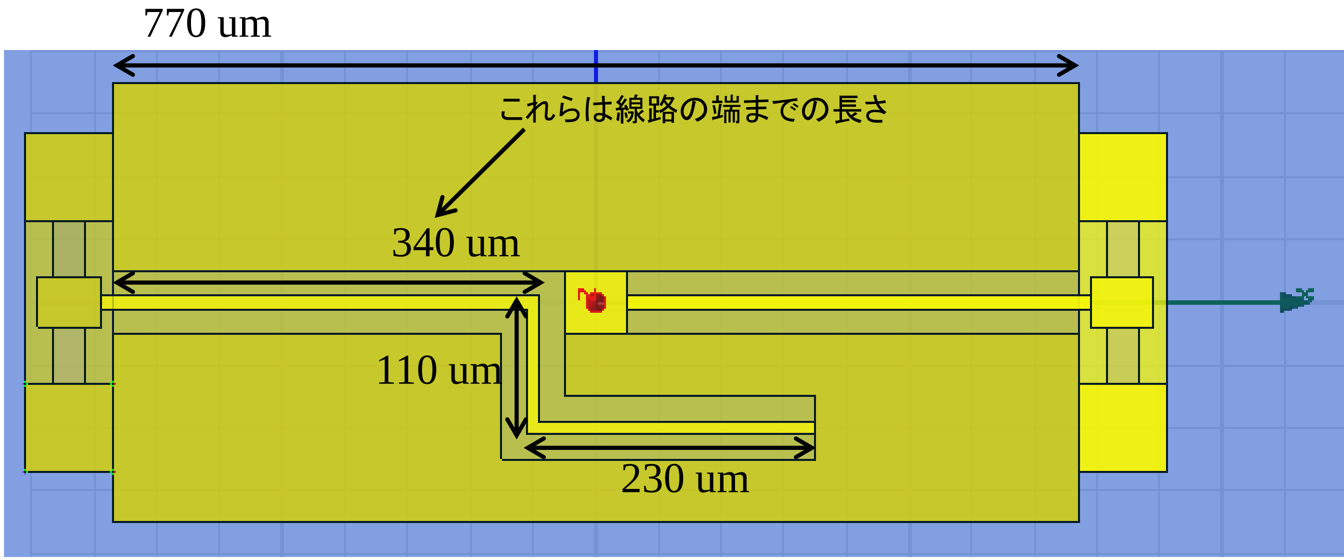
Lineパターン (Sパラメータ)



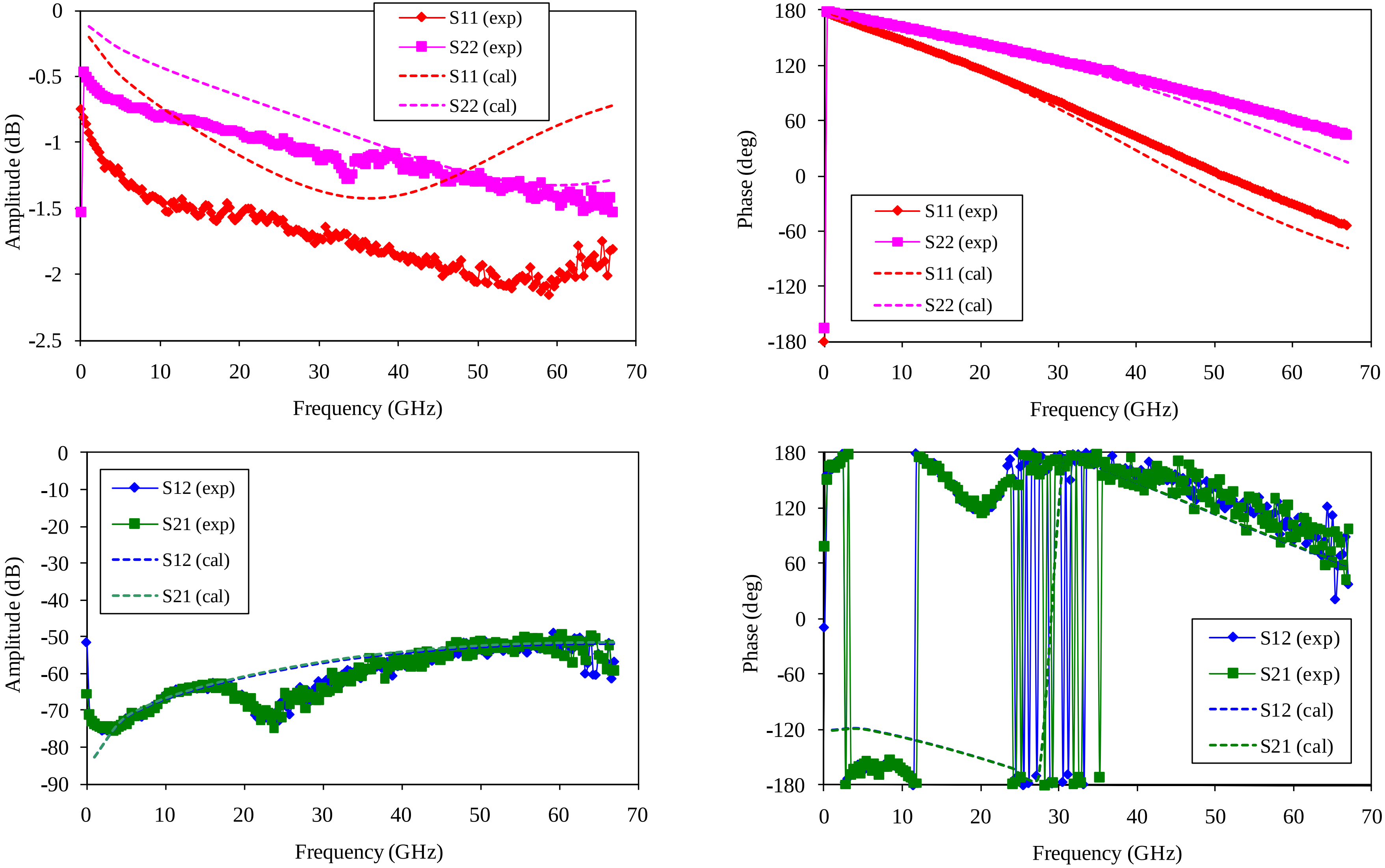
クロストークによる結合量評価パターン



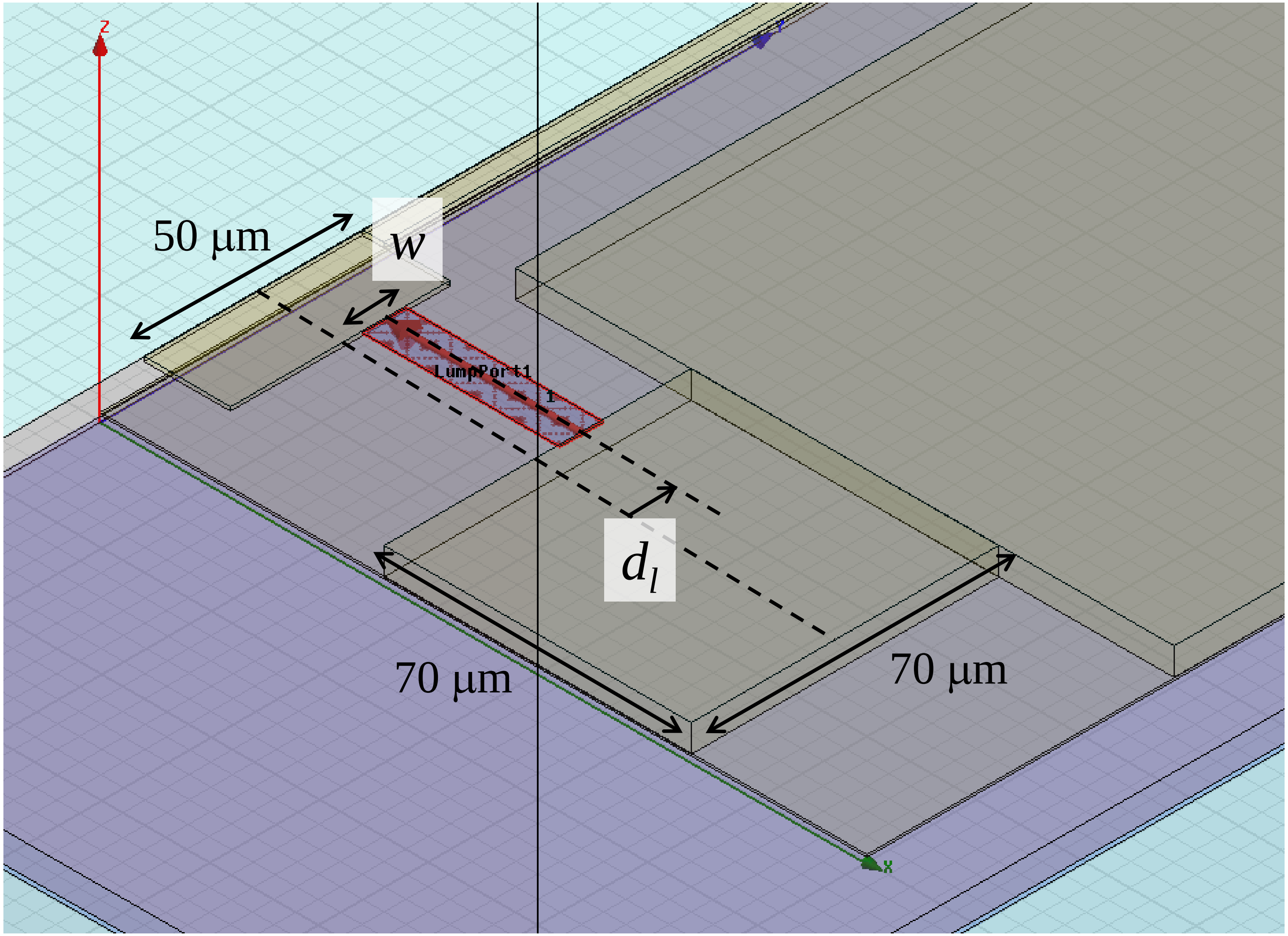




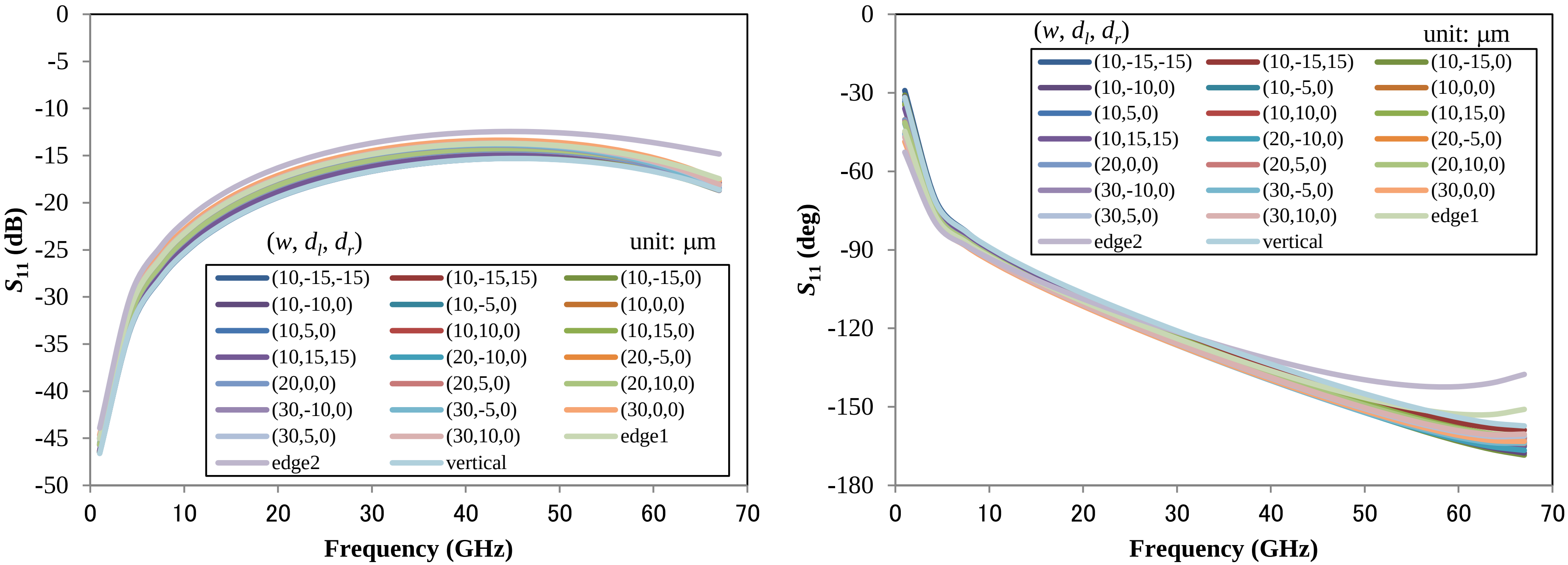
クロストークによる結合量評価パターン(Sパラメータ)



Lumped Portの位置d_lおよび幅w依存性



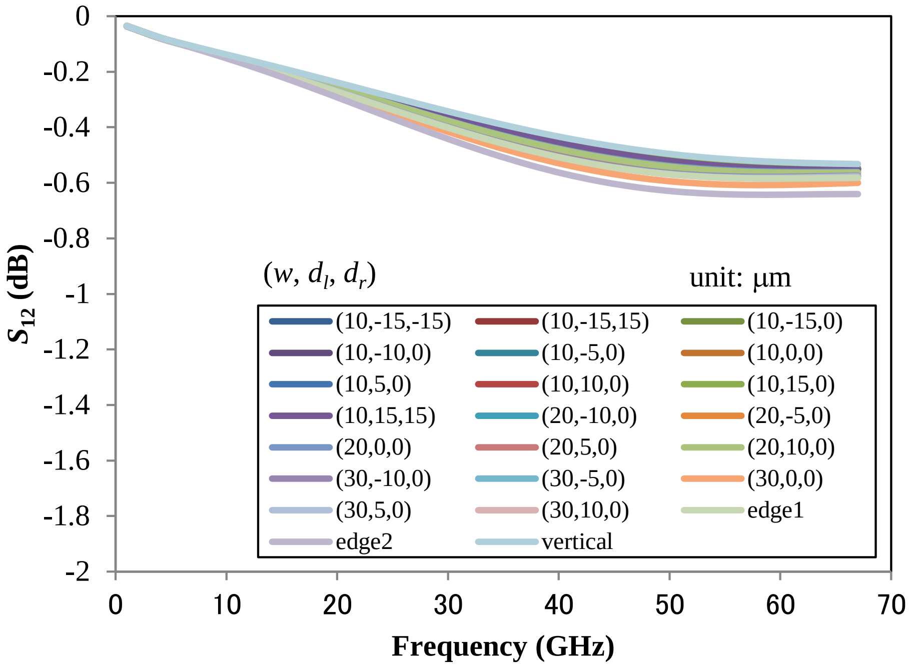
反射係数 S_{11}



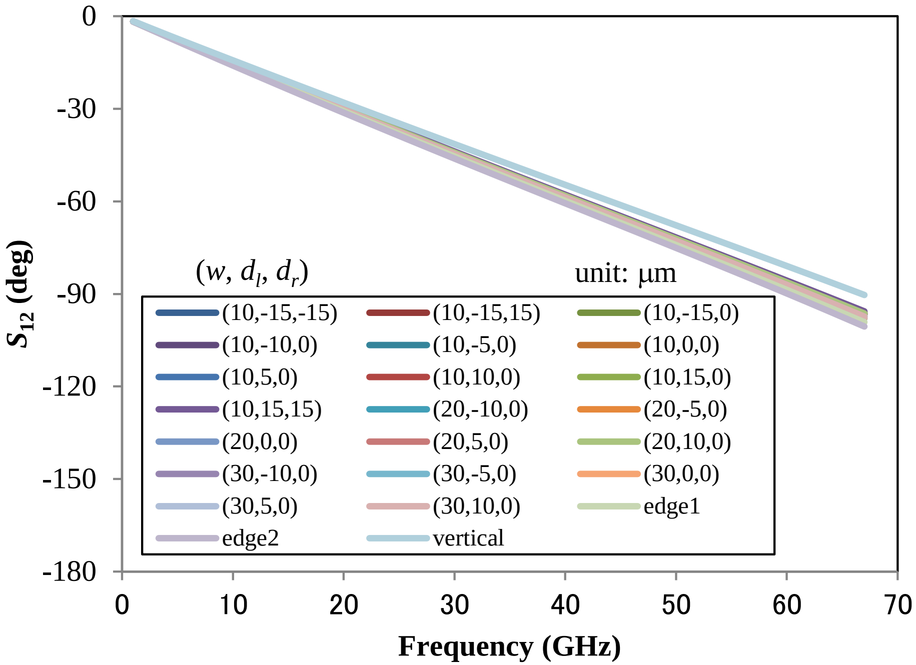
(a) Amplitude

(b) Phase

透過係数 S_{21}



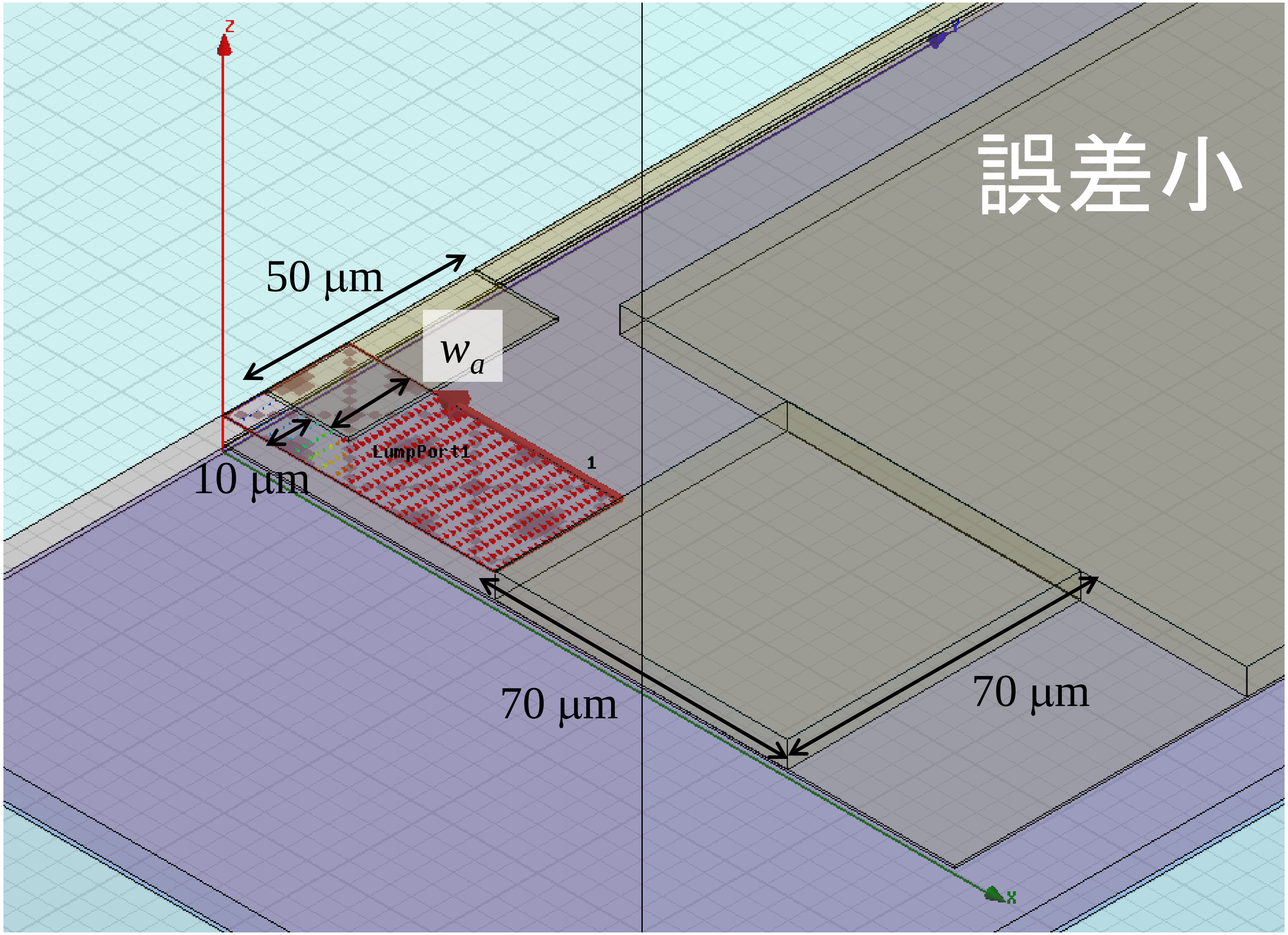
(a) Amplitude



(b) Phase

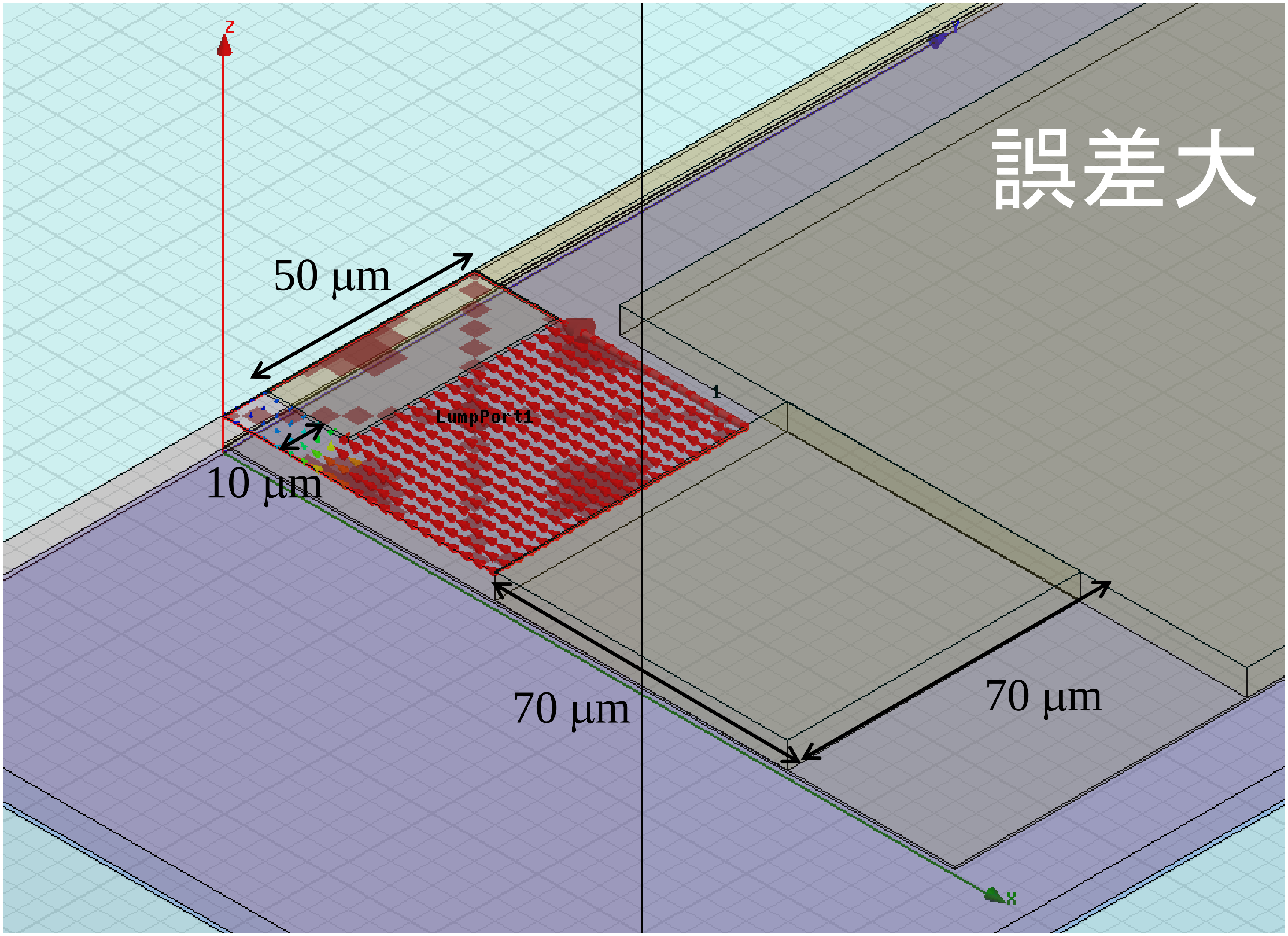
位置ずれおよび幅の影響は小さい

端部励振モデル1

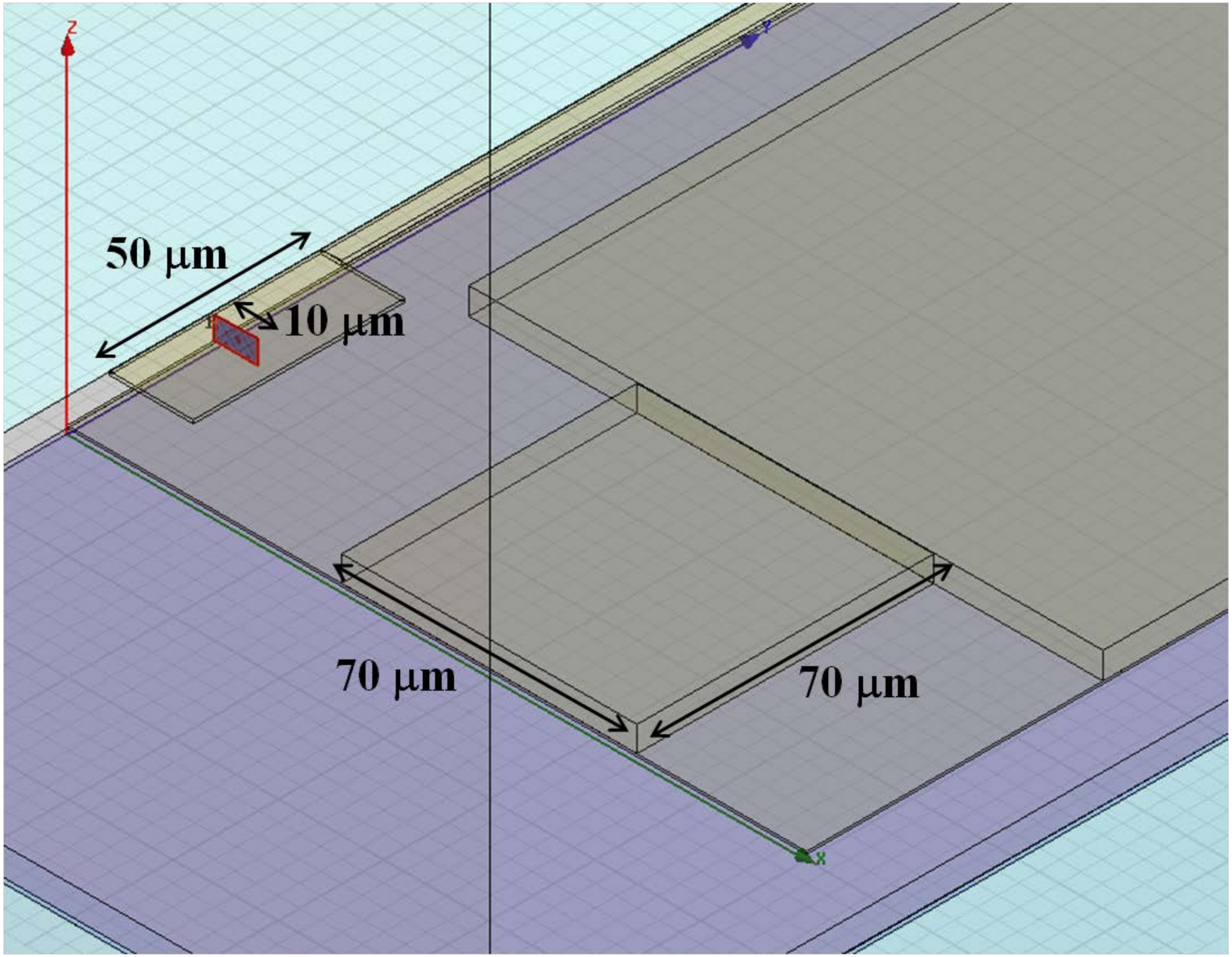


誤差小

端部励振モデル2



パッド下垂直励振モデル

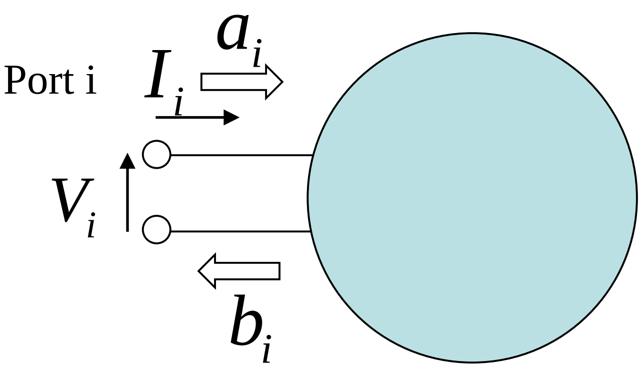


Ｓパラメータと Zパラメータ

2端子

$$\begin{cases} V_i = (a_i + b_i)\sqrt{Z_i} \\ I_i = \dfrac{a_i - b_i}{\sqrt{Z_i}} \end{cases} \quad \Longleftrightarrow \quad \begin{cases} a_i = \dfrac{V_i / \sqrt{Z_i} + I_i\sqrt{Z_i}}{2} \\ b_i = \dfrac{V_i / \sqrt{Z_i} - I_i\sqrt{Z_i}}{2} \end{cases}$$

N端子



$$\begin{cases} \mathbf{V} = \mathrm{diag}(\sqrt{Z_i})(\mathbf{a}+\mathbf{b}) \\ \mathbf{I} = \mathrm{diag}(1/\sqrt{Z_i})(\mathbf{a}-\mathbf{b}) \end{cases} \Longleftrightarrow \begin{cases} \mathbf{a} = \dfrac{\mathrm{diag}(1/\sqrt{Z_i})\mathbf{V} + \mathrm{diag}(\sqrt{Z_i})\mathbf{I}}{2} \\ \mathbf{b} = \dfrac{\mathrm{diag}(1/\sqrt{Z_i})\mathbf{V} - \mathrm{diag}(\sqrt{Z_i})\mathbf{I}}{2} \end{cases}$$

$$\mathrm{diag}(1/\sqrt{Z_i})\mathrm{diag}(\sqrt{Z_i}) = U$$

Z行列⇒S行列

$$\begin{cases} \mathbf{a} = \dfrac{\mathrm{diag}(1/\sqrt{Z_i})\mathbf{V} + \mathrm{diag}(\sqrt{Z_i})\mathbf{I}}{2} \\ \mathbf{b} = \dfrac{\mathrm{diag}(1/\sqrt{Z_i})\mathbf{V} - \mathrm{diag}(\sqrt{Z_i})\mathbf{I}}{2} \end{cases}$$

$$\mathbf{V} = Z\mathbf{I}$$

$$\begin{cases} \mathbf{a} = \dfrac{\mathrm{diag}(1/\sqrt{Z_i})Z + \mathrm{diag}(\sqrt{Z_i})U}{2}\mathbf{I} \\ \mathbf{b} = \dfrac{\mathrm{diag}(1/\sqrt{Z_i})Z - \mathrm{diag}(\sqrt{Z_i})U}{2}\mathbf{I} \end{cases}$$

$$\longrightarrow \quad \mathbf{I} = 2\left[\mathrm{diag}(1/\sqrt{Z_i})Z + \mathrm{diag}(\sqrt{Z_i})U\right]^{-1}\mathbf{a}$$

$$\mathbf{b} = \underbrace{\left[\mathrm{diag}(1/\sqrt{Z_i})Z - \mathrm{diag}(\sqrt{Z_i})U\right]\left[\mathrm{diag}(1/\sqrt{Z_i})Z + \mathrm{diag}(\sqrt{Z_i})U\right]^{-1}}_{S}\mathbf{a}$$

$$[S] = ([Z]-[D])([Z]+[D])^{-1}$$

S行列⇒Z行列

$$[S]=([Z]-[D])([Z]+[D])^{-1}$$

$$[S]([Z]+[D])=([Z]-[D])$$

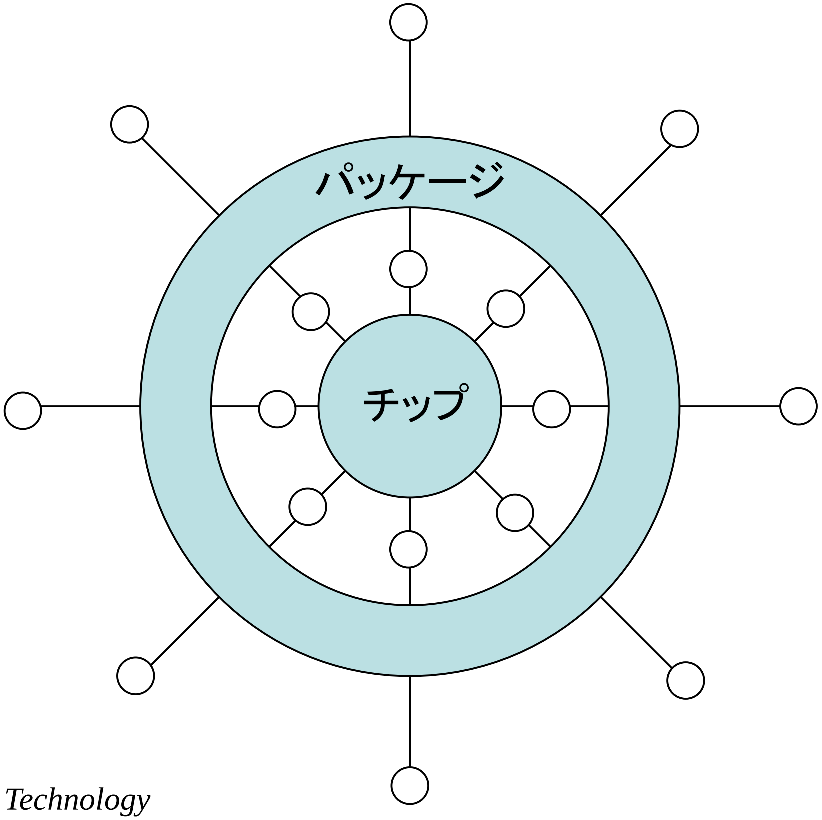
$$([S]-[U])[Z]=-([S]+[U])[D]$$

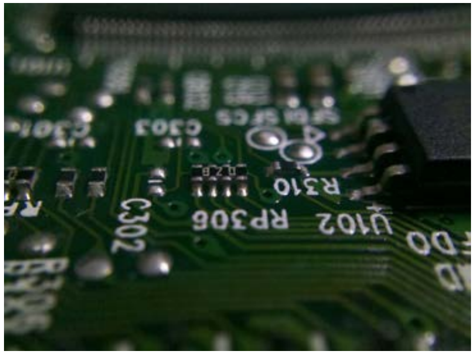
$$[Z]=-([S]-[U])^{-1}([S]+[U])[D]$$

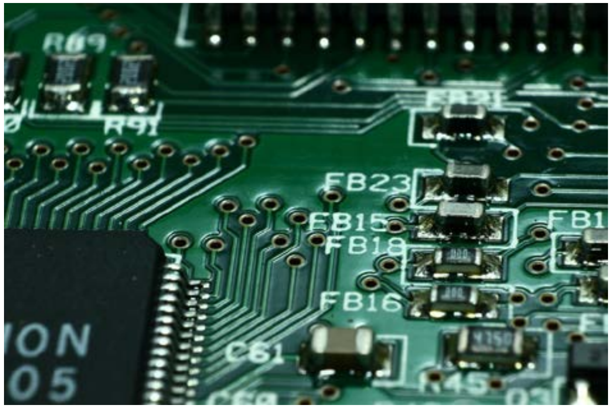
ICとの接続

概説

- ICをパッケージに実装した際の特性変化をシミュレーションするときなどに使われる。
- チップは集中定数素子として動作することを想定する。
- チップのパッドからボンディングワイヤ等で外部端子に出すが、その際の特性変化を電磁界シミュレーションする。



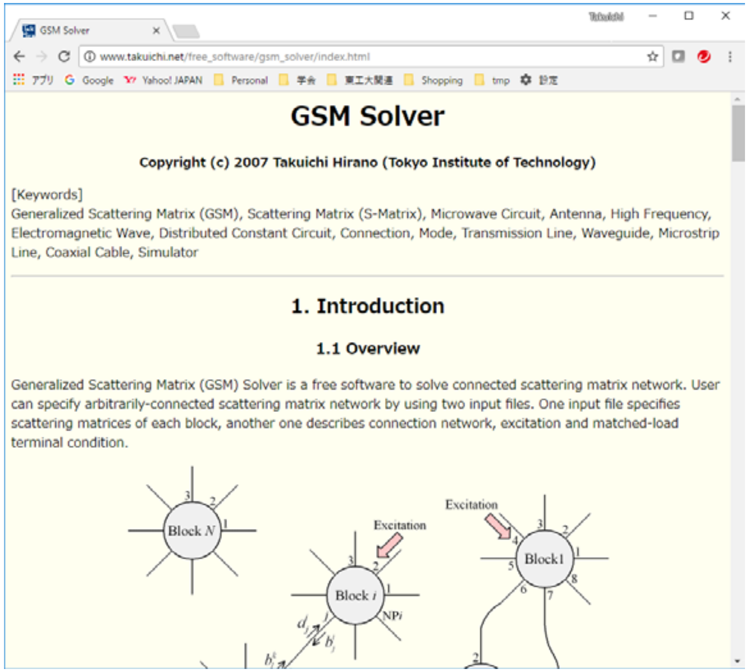




GSM Solver

GSM Solver

Generalized Scattering Matrix (GSM) Solver is a free software to solve connected scattering matrix network. User can specify arbitrarily-connected scattering matrix network by using two input files. One input file specifies scattering matrices of each block, another one describes connection network, excitation and matched-load terminal condition.



GSM Solver

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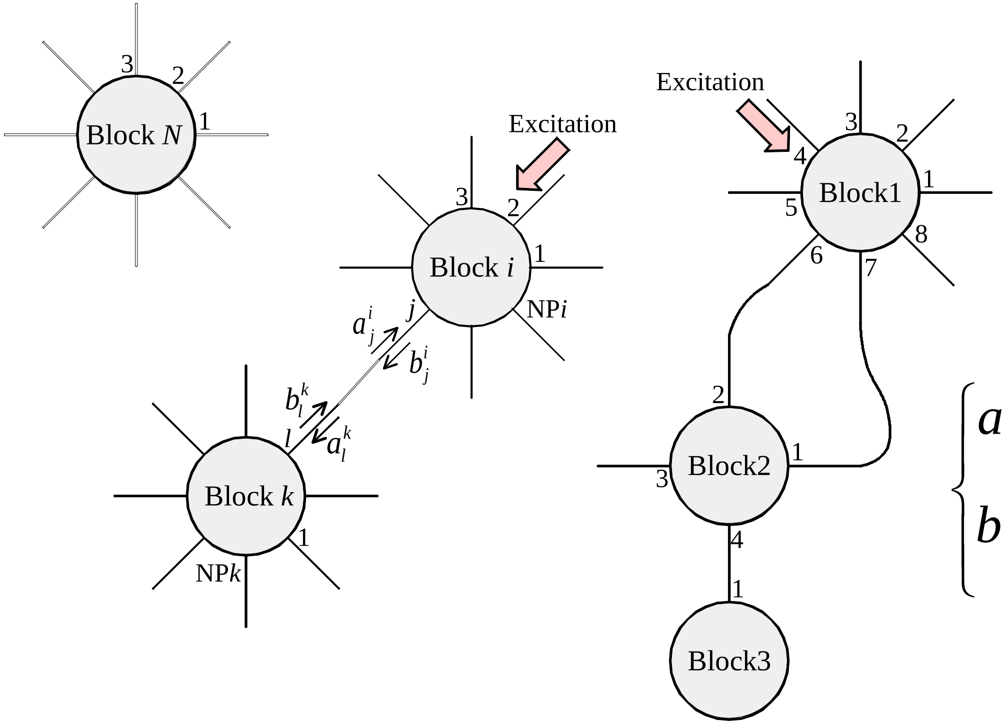
[Keywords]
Generalized Scattering Matrix (GSM), Scattering Matrix (S-Matrix), Microwave Circuit, Antenna, High Frequency, Electromagnetic Wave, Distributed Constant Circuit, Connection, Mode, Transmission Line, Waveguide, Microstrip Line, Coaxial Cable, Simulator

1. Introduction

1.1 Overview

Generalized Scattering Matrix (GSM) Solver is a free software to solve connected scattering matrix network. User can specify arbitrarily-connected scattering matrix network by using two input files. One input file specifies scattering matrices of each block, another one describes connection network, excitation and matched-load terminal condition.



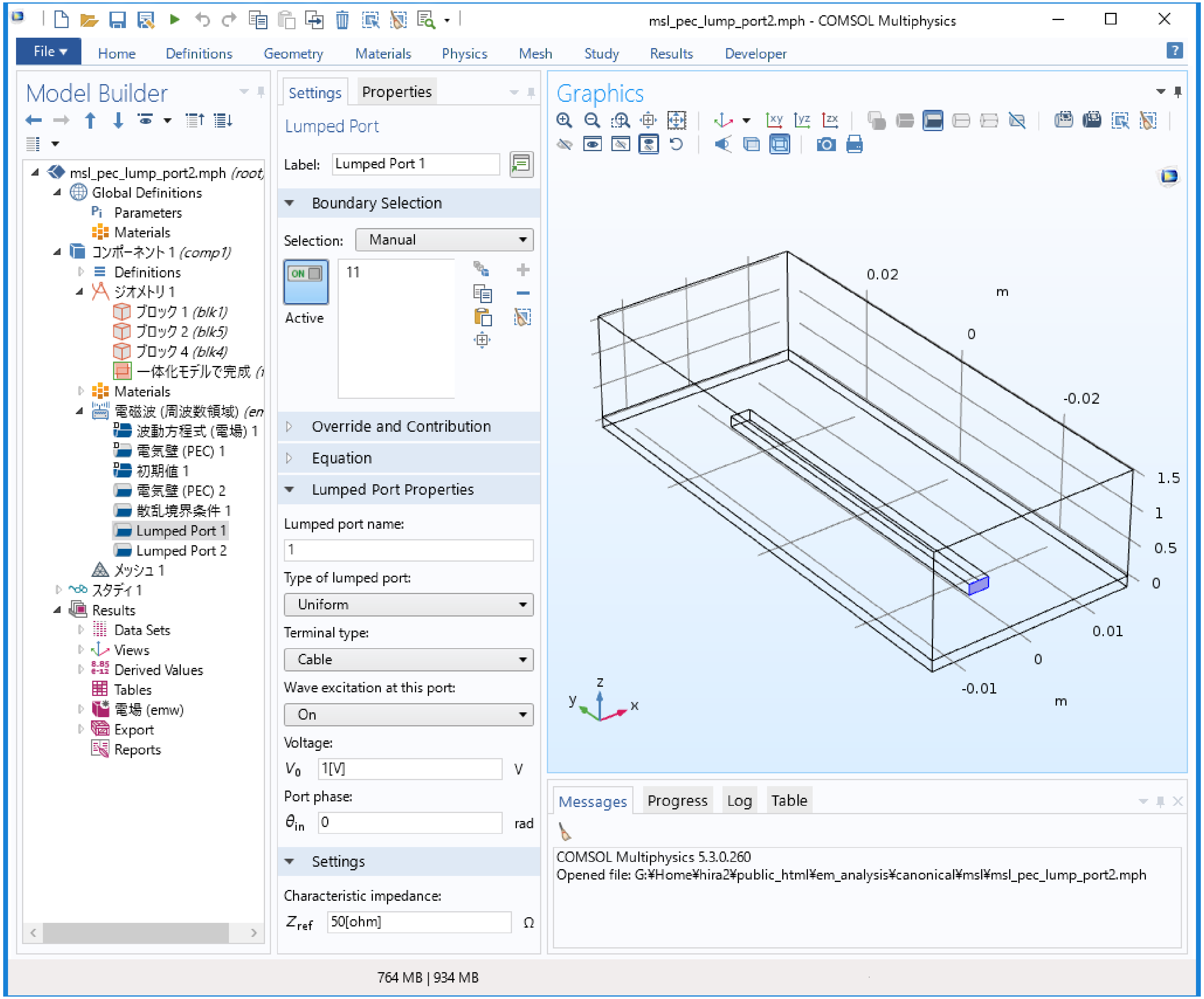
$$
\begin{cases}
a_j^i = b_k^l & \text{(input)} \\
b_j^i = \displaystyle\sum_{n=1}^{NP_i} a_n^i S_{jn}^{(i)} & \text{(output)}
\end{cases}
$$

Sパラメータを任意に接続する解析

http://www.takuichi.net/free_software/gsm_solver/

COMSOLによるMSL解析の実例

1: モデル化 (Port1)



Lumped Port

Label: Lumped Port 1

Boundary Selection

Selection: Manual

11

Active

Override and Contribution

Equation

Lumped Port Properties

Lumped port name: 1

Type of lumped port: Uniform

Terminal type: Cable

Wave excitation at this port: On

Voltage: V_0 1[V] V

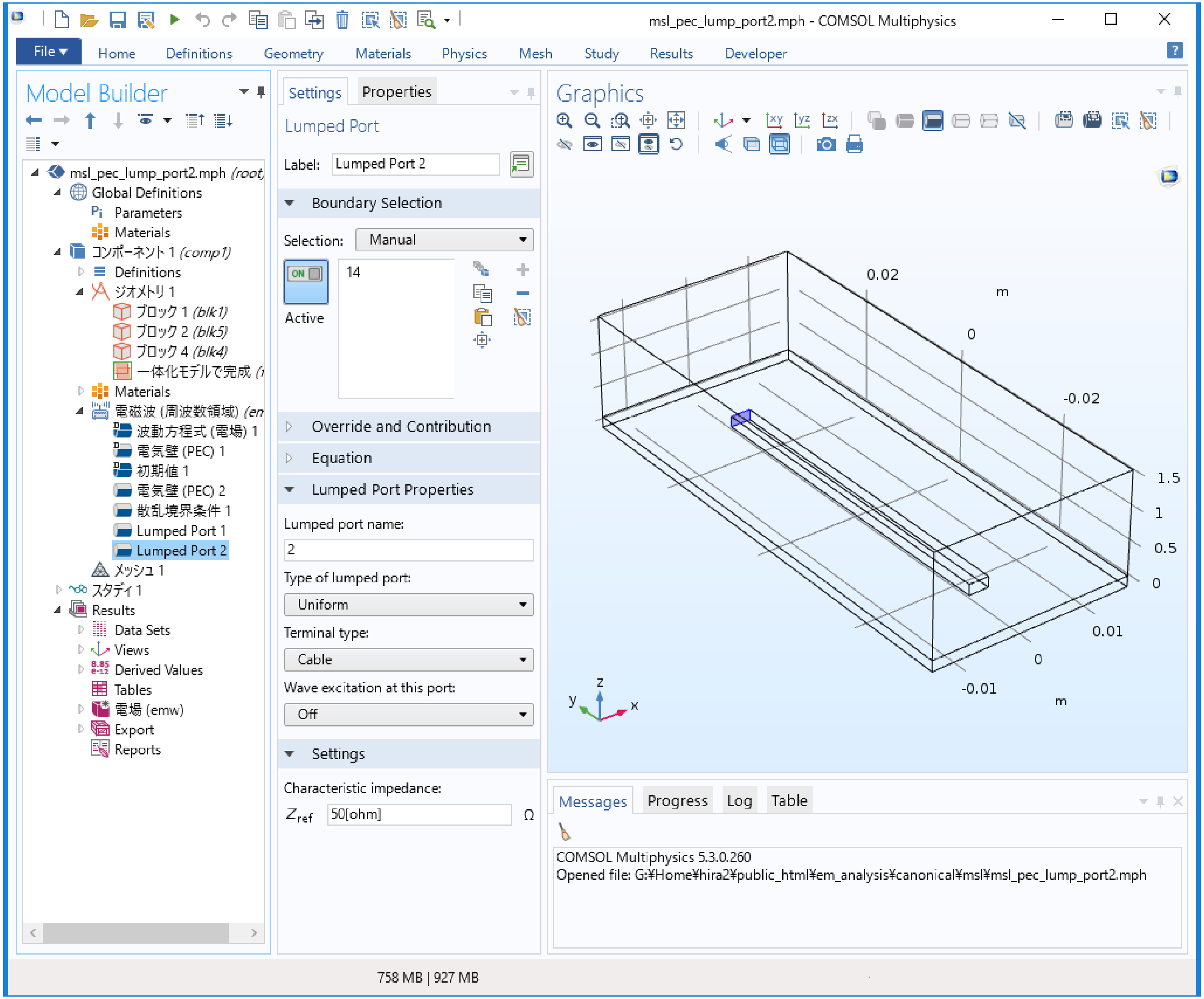
Port phase: θ_{in} 0 rad

Settings

Characteristic impedance: Z_{ref} 50[ohm] Ω

```
COMSOL Multiphysics 5.3.0.260
Opened file: G:¥Home¥hira2¥public_html¥em_analysis¥canonical¥msl¥msl_pec_lump_port2.mph
```

1: モデル化 (Port2)



Lumped Port

Label: Lumped Port 2

Boundary Selection

Selection: Manual

14

Active

Override and Contribution

Equation

Lumped Port Properties

Lumped port name:

2

Type of lumped port:

Uniform

Terminal type:

Cable

Wave excitation at this port:

Off

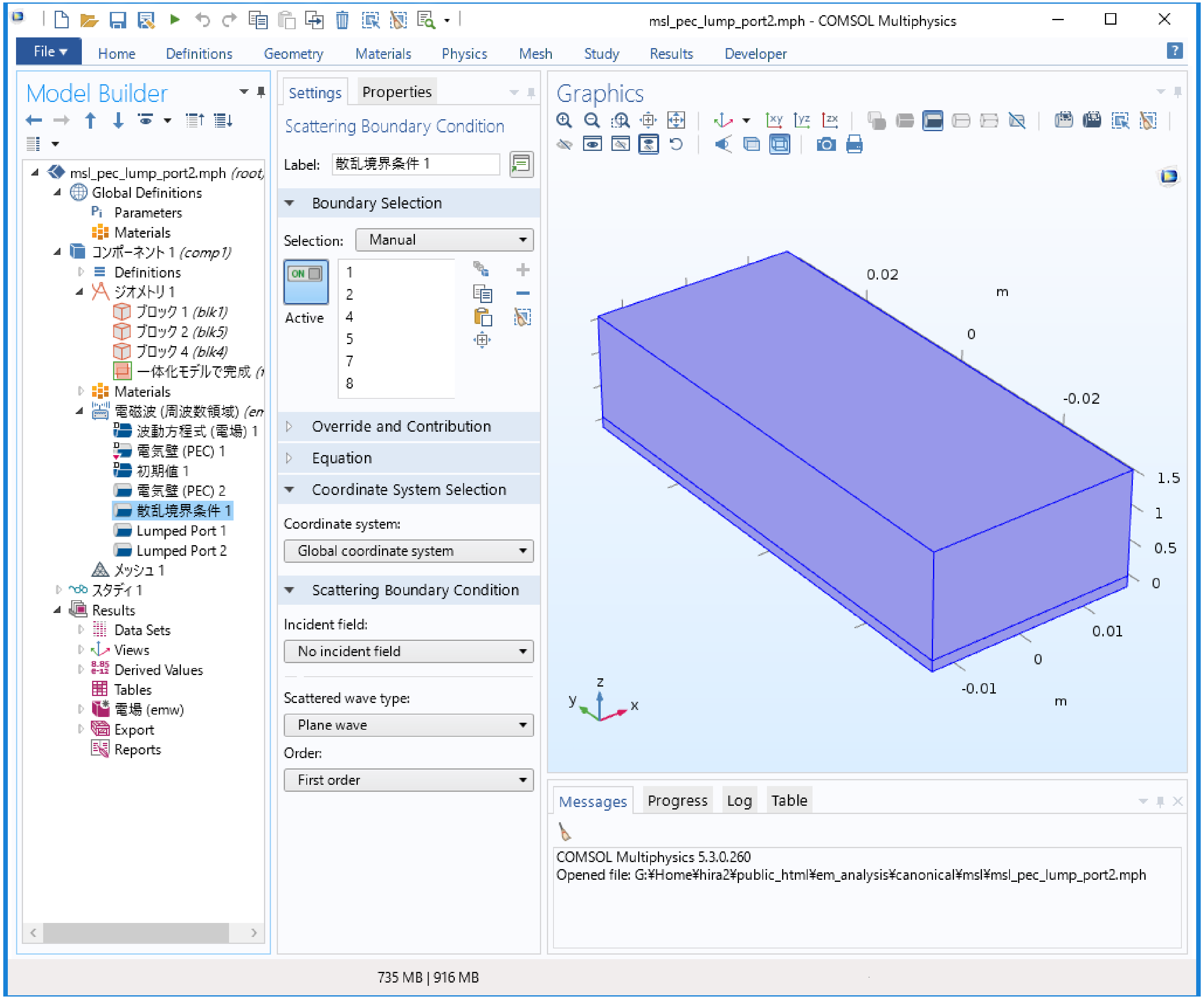
Settings

Characteristic impedance:

Z_{ref} 50[ohm] Ω

```
COMSOL Multiphysics 5.3.0.260
Opened file: G:¥Home¥hira2¥public_html¥em_analysis¥canonical¥msl¥msl_pec_lump_port2.mph
```

1: モデル化 (散乱境界条件)



Scattering Boundary Condition

Label: 散乱境界条件 1

Boundary Selection

Selection: Manual

Active

1
2
4
5
7
8

Override and Contribution

Equation

Coordinate System Selection

Coordinate system: Global coordinate system

Scattering Boundary Condition

Incident field: No incident field

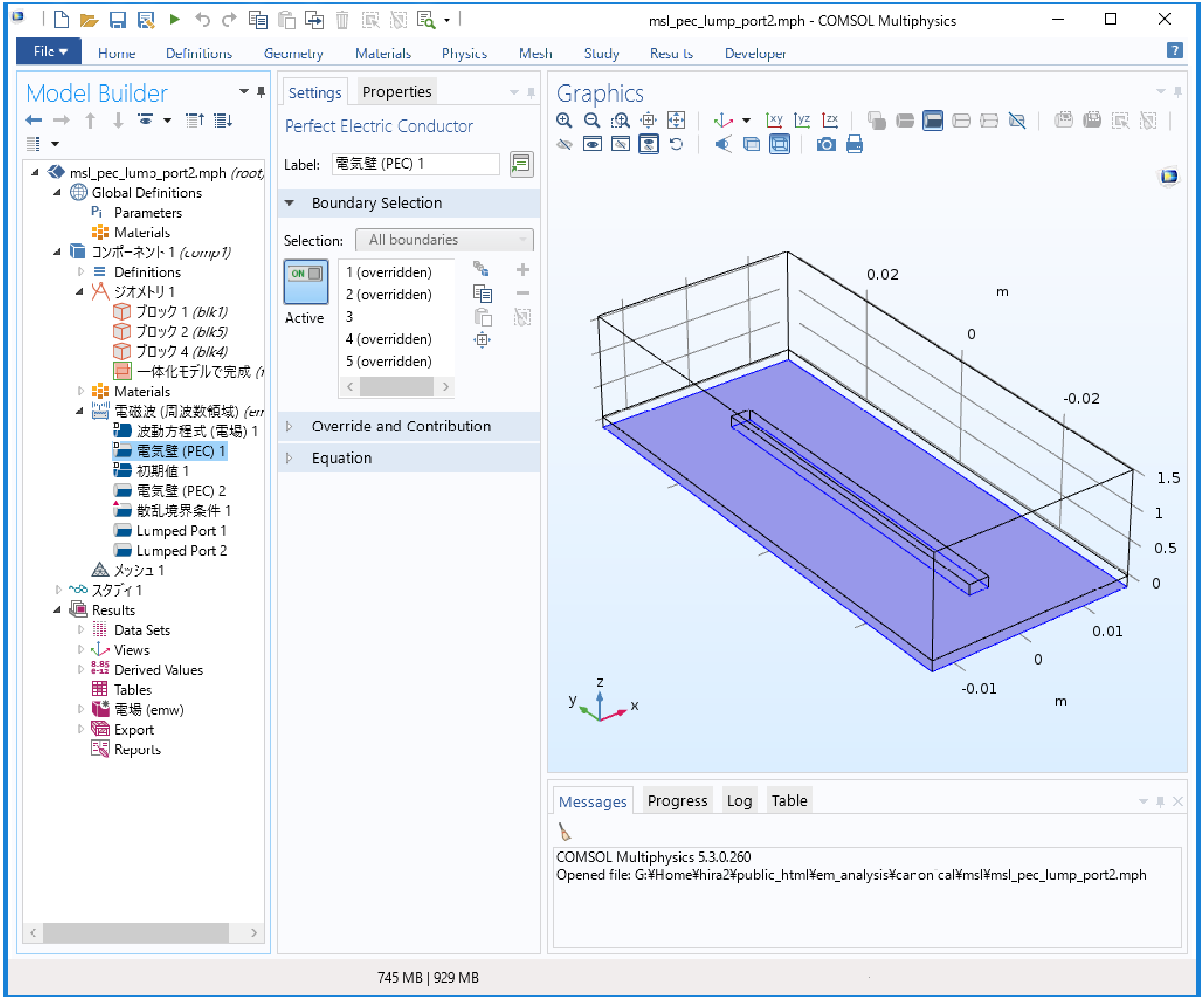
Scattered wave type: Plane wave

Order: First order

```
COMSOL Multiphysics 5.3.0.260
Opened file: G:¥Home¥hira2¥public_html¥em_analysis¥canonical¥msl¥msl_pec_lump_port2.mph
```

735 MB | 916 MB

1: モデル化 (電気壁1)



Perfect Electric Conductor

Label: 電気壁 (PEC) 1

Boundary Selection

Selection: All boundaries

Active

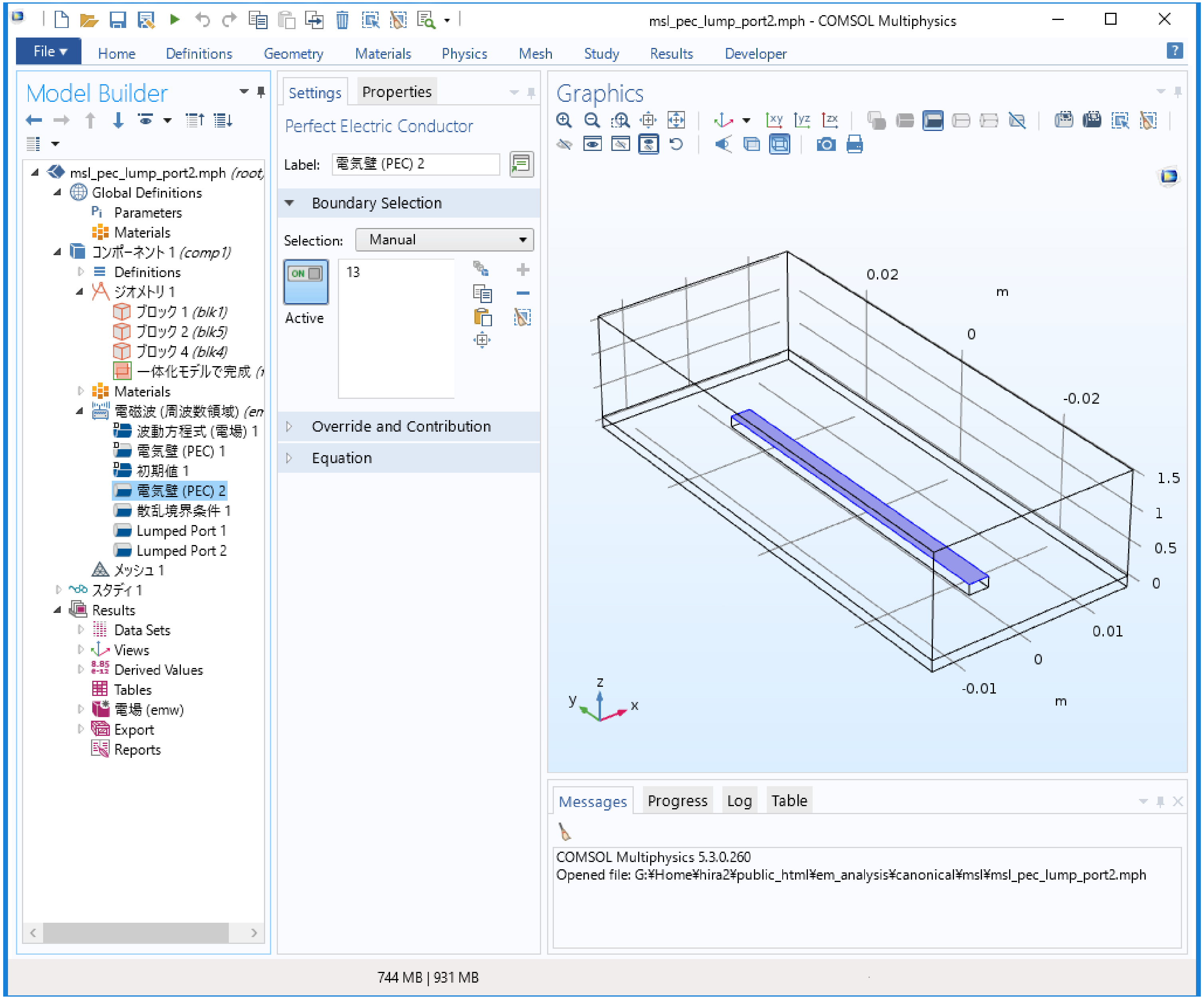
1 (overridden)
2 (overridden)
3
4 (overridden)
5 (overridden)

Override and Contribution

Equation

COMSOL Multiphysics 5.3.0.260
Opened file: G:¥Home¥hira2¥public_html¥em_analysis¥canonical¥msl¥msl_pec_lump_port2.mph

1: モデル化 (電気壁2)



Perfect Electric Conductor

Label: 電気壁 (PEC) 2

▾ Boundary Selection

Selection: Manual

ON Active

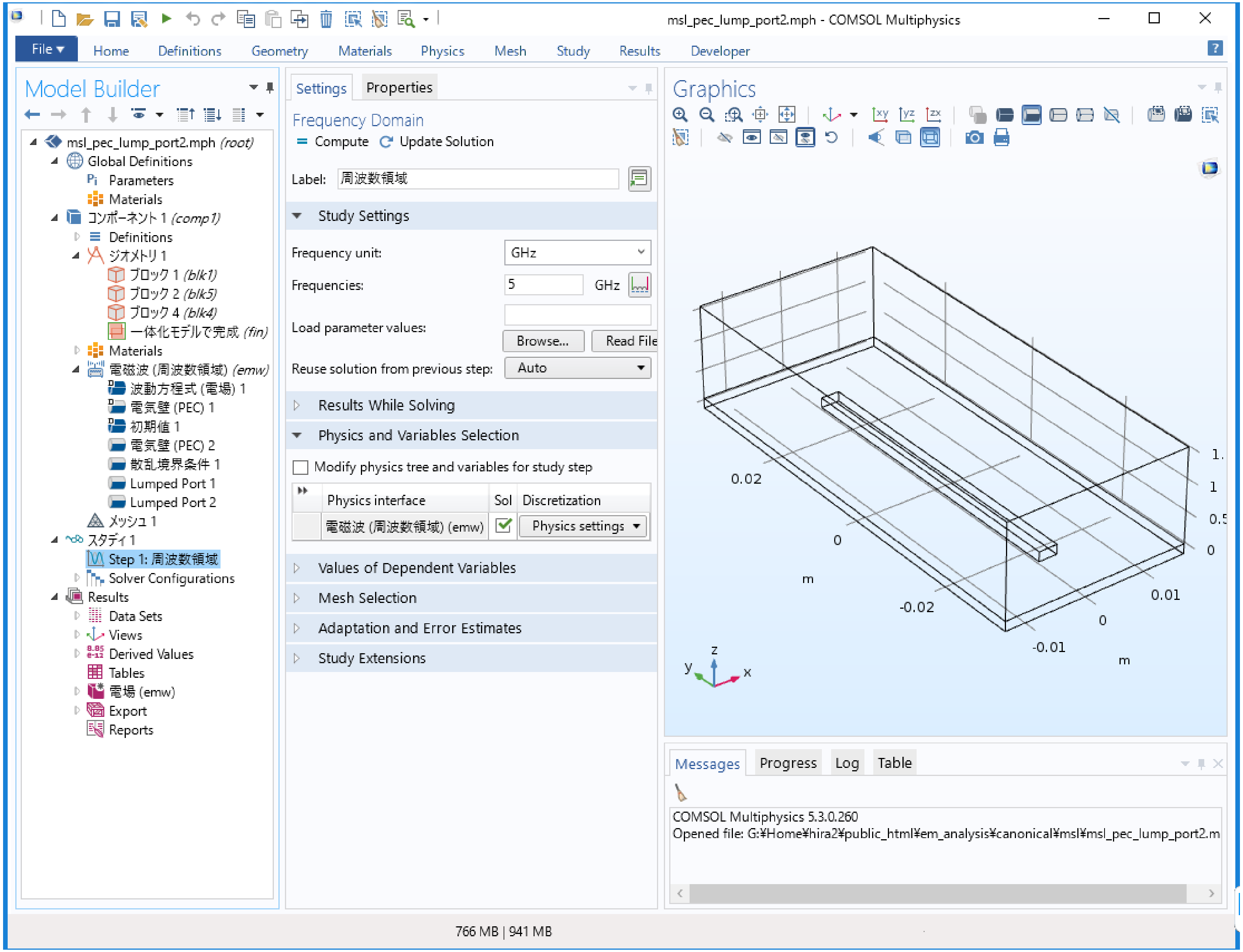
13

▹ Override and Contribution

▹ Equation

```
COMSOL Multiphysics 5.3.0.260
Opened file: G:¥Home¥hira2¥public_html¥em_analysis¥canonical¥msl¥msl_pec_lump_port2.mph
```

2: 解析条件 (周波数領域)



- msl_pec_lump_port2.mph *(root)*
  - Global Definitions
    - Parameters
    - Materials
  - コンポーネント 1 *(comp1)*
    - Definitions
    - ジオメトリ 1
      - ブロック 1 *(blk1)*
      - ブロック 2 *(blk5)*
      - ブロック 4 *(blk4)*
      - 一体化モデルで完成 *(fin)*
    - Materials
    - 電磁波 (周波数領域) *(emw)*
      - 波動方程式 (電場) 1
      - 電気壁 (PEC) 1
      - 初期値 1
      - 電気壁 (PEC) 2
      - 散乱境界条件 1
      - Lumped Port 1
      - Lumped Port 2
    - メッシュ 1
  - スタディ 1
    - Step 1: 周波数領域
    - Solver Configurations
  - Results
    - Data Sets
    - Views
    - Derived Values
    - Tables
    - 電場 (emw)
    - Export
    - Reports

Frequency Domain

Compute　Update Solution

Label: 周波数領域

▼ Study Settings

Frequency unit: GHz

Frequencies: 5 GHz

Load parameter values: Browse... Read File

Reuse solution from previous step: Auto

▷ Results While Solving

▼ Physics and Variables Selection

☐ Modify physics tree and variables for study step

Physics interface	Sol	Discretization
電磁波 (周波数領域) (emw)	☑	Physics settings

▷ Values of Dependent Variables

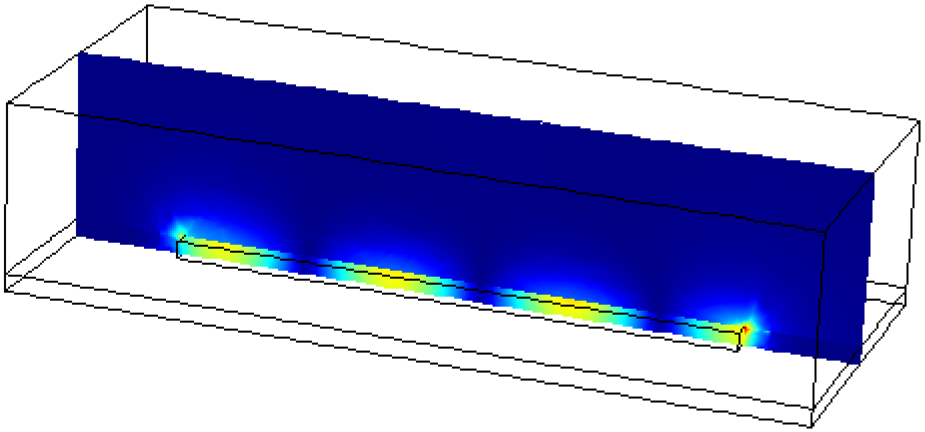
▷ Mesh Selection

▷ Adaptation and Error Estimates

▷ Study Extensions

```
COMSOL Multiphysics 5.3.0.260
Opened file: G:¥Home¥hira2¥public_html¥em_analysis¥canonical¥msl¥msl_pec_lump_port2.m
```

3: 結果



freq (GHz)	S パラメーター (dB), 11 成分 (dB)	S パラメーター (dB), 21 成分 (dB)
5.0000	-18.779	-0.35669