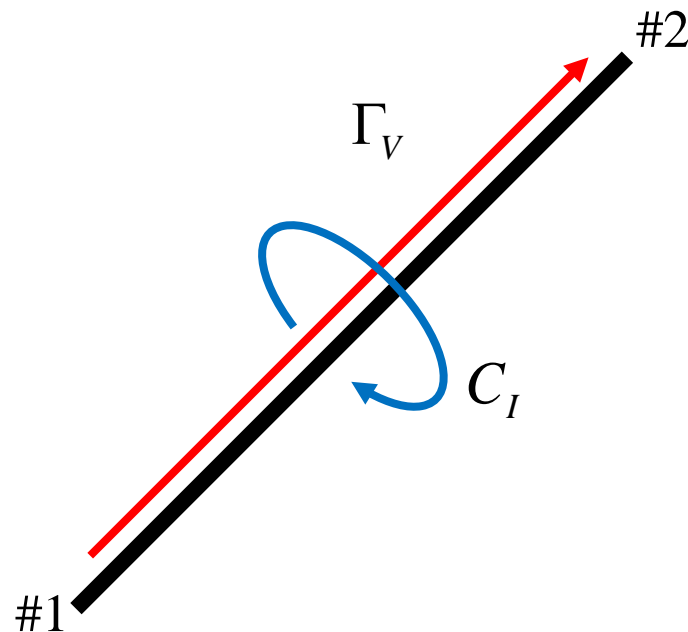


有限要素法による電磁界シミュレーション入門

第2回「集中ポートの解析」



東京工業大学 環境・社会理工学院
平野 拓一

E-mail: hirano.t.aa@m.titech.ac.jp

波動方程式(EまたはHのみの式)

マクスウェルの方程式

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

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

$$\frac{\nabla \times \mathbf{E}}{\mu_r} + j\omega\mu_0\mathbf{H} = 0 \quad \text{場所の関数}$$

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

∇ × 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

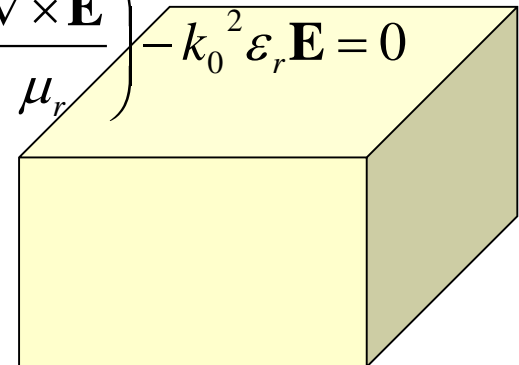
2-D

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

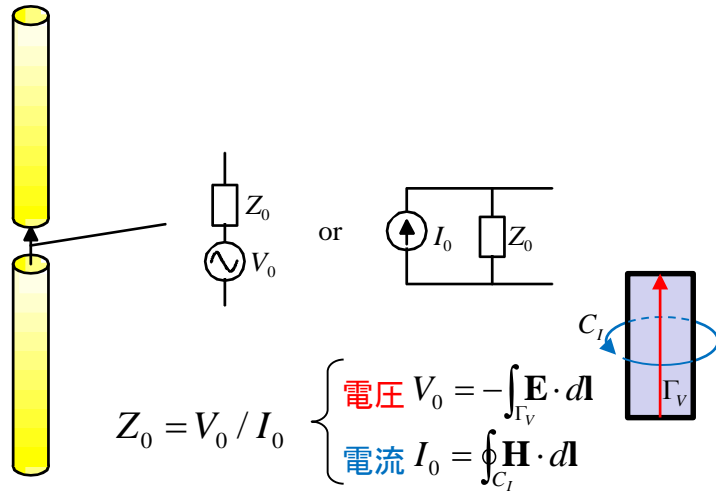
共振器

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

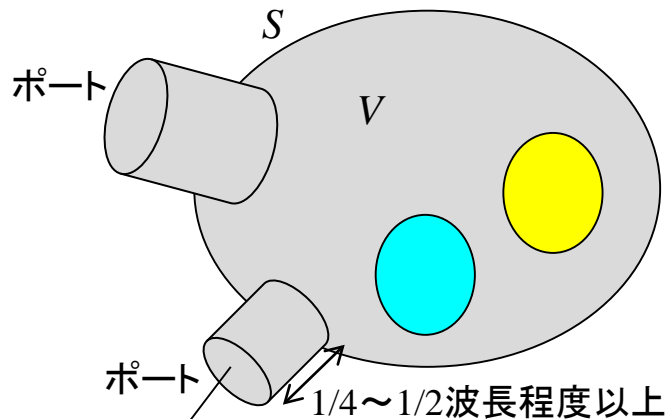
3-D



どの周波数でどのような形で共振するのか?



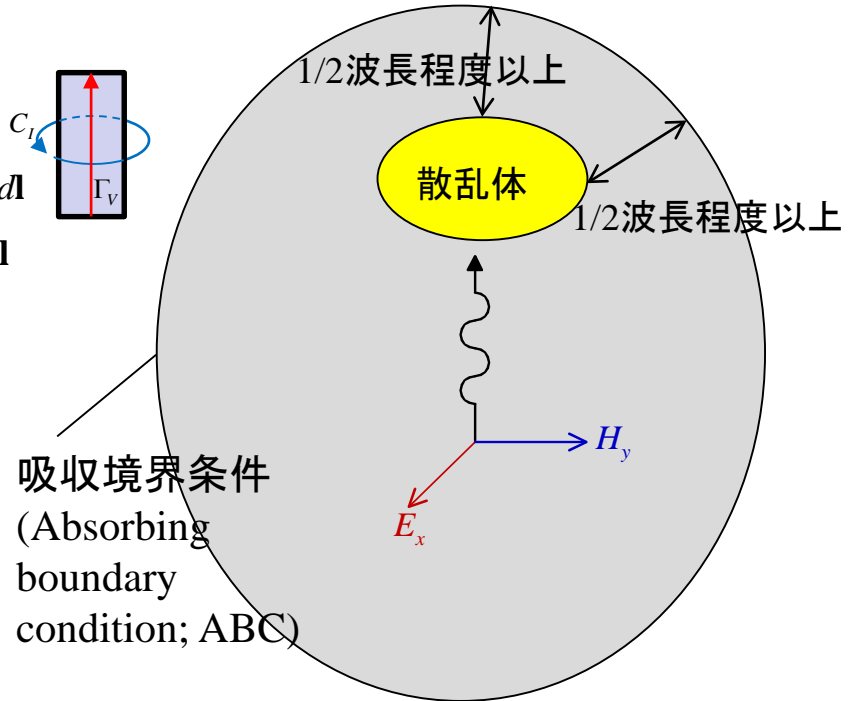
(a) 集中ポート



$$\mathbf{E} = \mathbf{E}_1^{(+)} + \sum_u \overset{\text{重み}}{B_u} \mathbf{E}_u^{(-)}$$

入射モード 反射モード

(b) 導波路ポート



(c) 平面波入射

ファラデーの法則

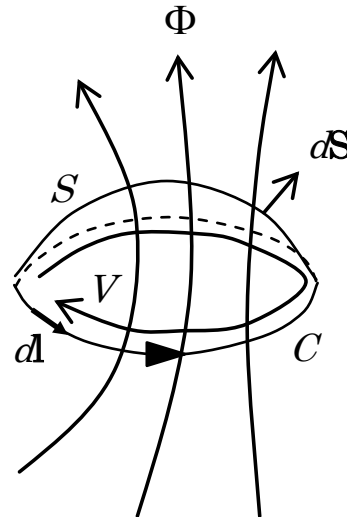
ファラデー: 近接作用、界の概念を提唱

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

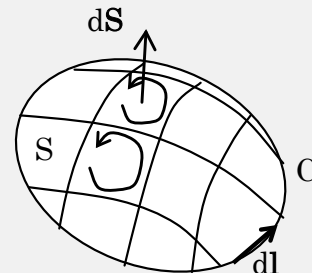
ストークスの定理を使って

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

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



ストークスの定理



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

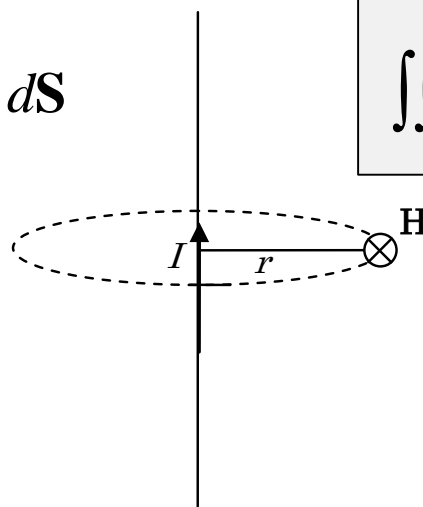
アンペアの法則

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

ストークスの定理を使って

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

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



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

積分形

ファラデーの法則

アンペアの法則

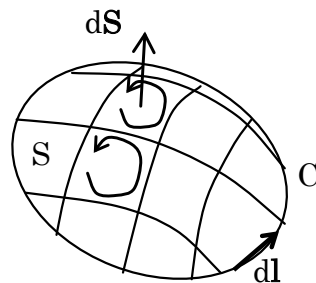
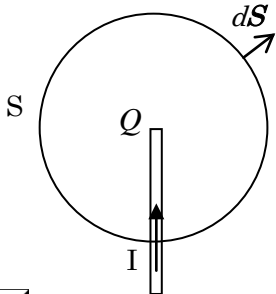
$$\left(\nabla \cdot \mathbf{i} = -\frac{\partial \rho}{\partial t} \right)$$

$$\begin{cases} \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} = \mathbf{i} + \frac{\partial \mathbf{D}}{\partial t} \\ \nabla \cdot \mathbf{D} = \rho \quad \text{変位電流} \\ \nabla \cdot \mathbf{B} = 0 \end{cases}$$

$$\begin{cases} \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \iint_S \mathbf{B} \cdot d\mathbf{S} \\ \oint_C \mathbf{H} \cdot d\mathbf{l} = \iint_S \mathbf{i} \cdot d\mathbf{S} + \frac{\partial}{\partial t} \iint_S \mathbf{D} \cdot d\mathbf{S} \\ \oiint_S \mathbf{D} \cdot d\mathbf{S} = \iiint_V \rho dV \quad \text{変位電流} \\ \oiint_S \mathbf{B} \cdot d\mathbf{S} = 0 \end{cases}$$

電流連続の式:

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



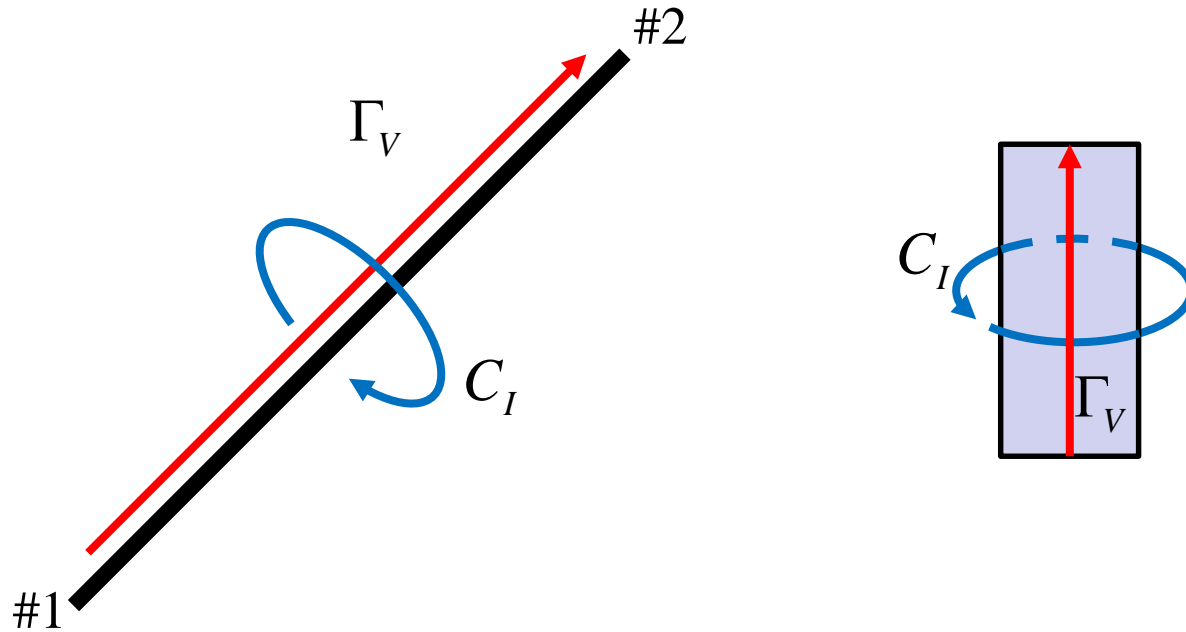
構成(媒質)方程式

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

電束密度 誘電率 電界
磁束密度 透磁率 磁界

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





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

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

$$Z_0 = V_0 / I_0$$

表面インピーダンス

表面インピーダンス

$$Z = \frac{V}{I} = \frac{E\Delta x}{H\Delta y} \quad [\Omega]$$

$$[\Omega]$$

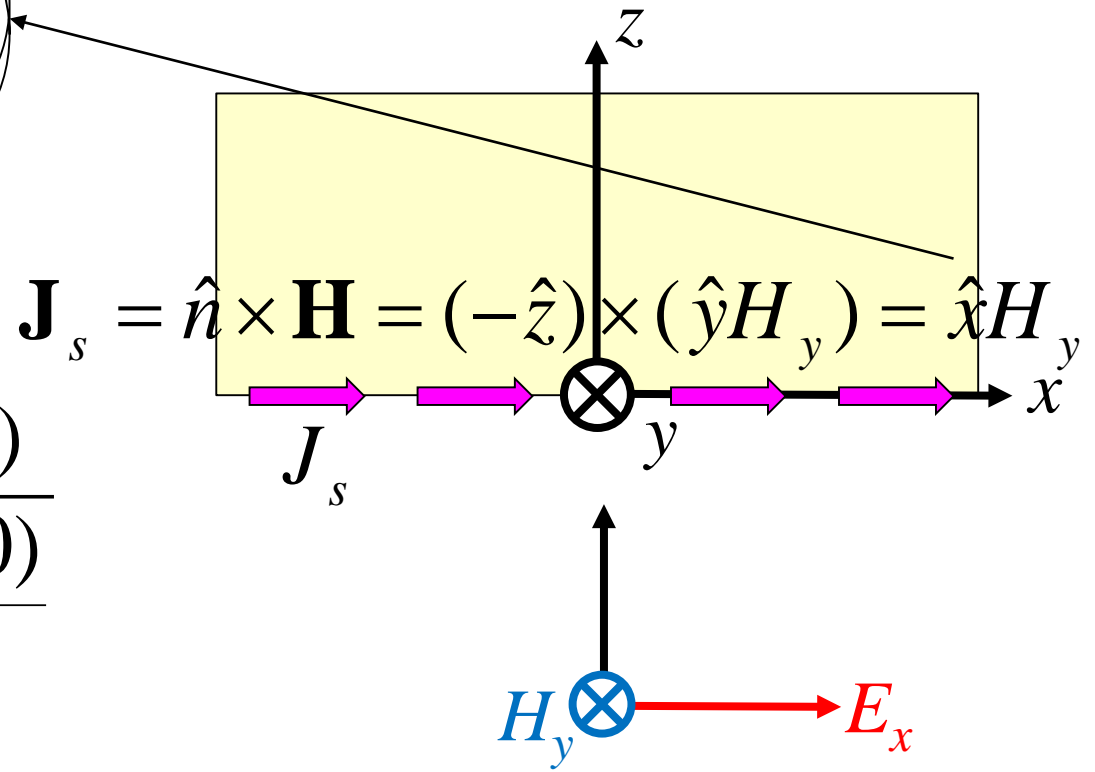
$$[\Omega/\square]$$

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

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

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

次ページ



HyをExで表す

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

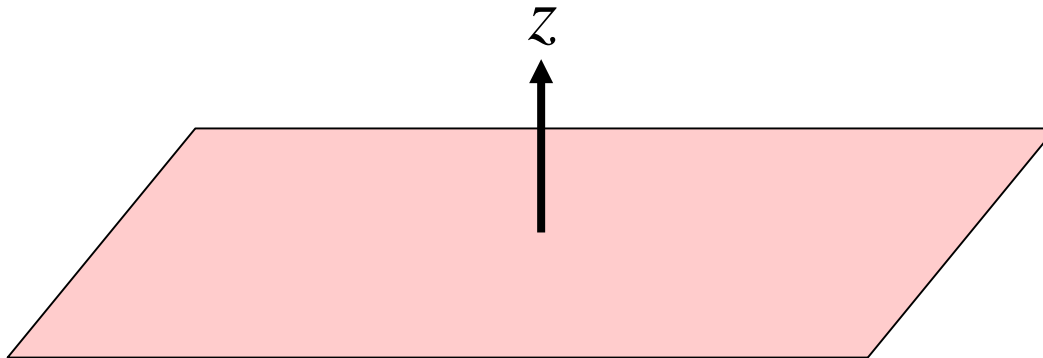
$$\nabla \times \mathbf{A} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \\ A_x & A_y & A_z \end{vmatrix} = \begin{bmatrix} 0 & -\partial/\partial z & \partial/\partial y \\ \partial/\partial z & 0 & -\partial/\partial x \\ -\partial/\partial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

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

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



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



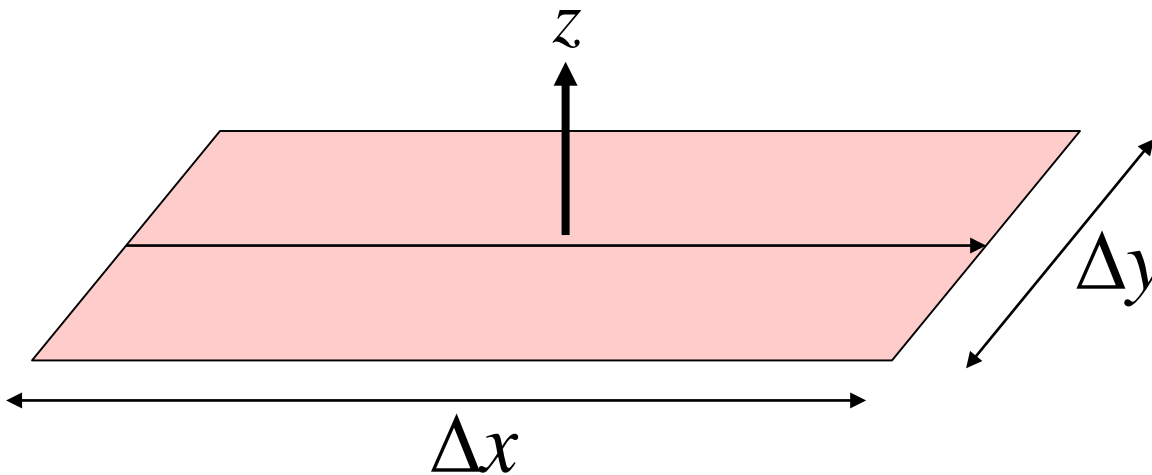
$$Z = \frac{V}{I} = \frac{E_x \Delta x}{H_y \Delta y} = j\omega\mu \frac{E_x \Delta x}{\frac{\partial E_x}{\partial z} \Delta y}$$

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): $E_{x,ex}$

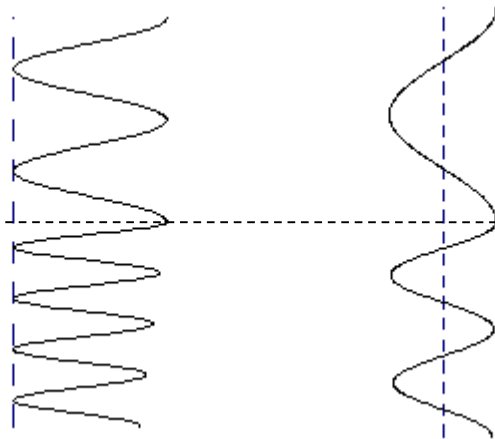
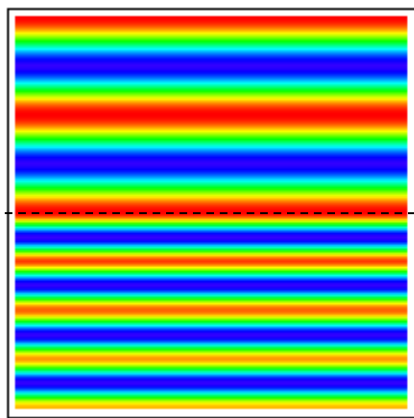
$$E_x \rightarrow E_x + E_{x,ex}$$

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

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

$$Z = V / I$$

$\epsilon r_1=1, \epsilon r_2=4, \sigma_2=0.001 \rightarrow 10.0$ (0.001,0.006,0.01,0.06,0.1,0.6,1.0,6.0,10.0)
 $\theta_i=0^\circ$



損失電力

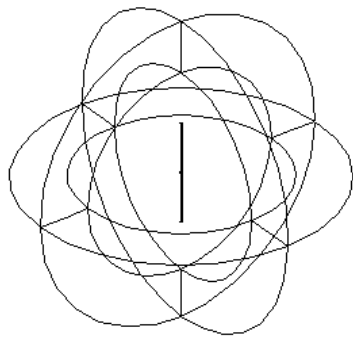
$$\begin{aligned}
 \frac{1}{2} \int_{z=-\infty}^0 \sigma |\mathbf{E}|^2 dz &= \frac{\sigma |\eta|^2}{2} \int_{z=-\infty}^0 |\mathbf{H}|^2 dz \\
 &= \frac{\omega \mu}{2} |\mathbf{H}_{t0}|^2 \int_{z=-\infty}^0 e^{2\alpha z} dz = \frac{\omega \mu}{4\alpha} |\mathbf{H}_{t0}|^2
 \end{aligned}$$

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

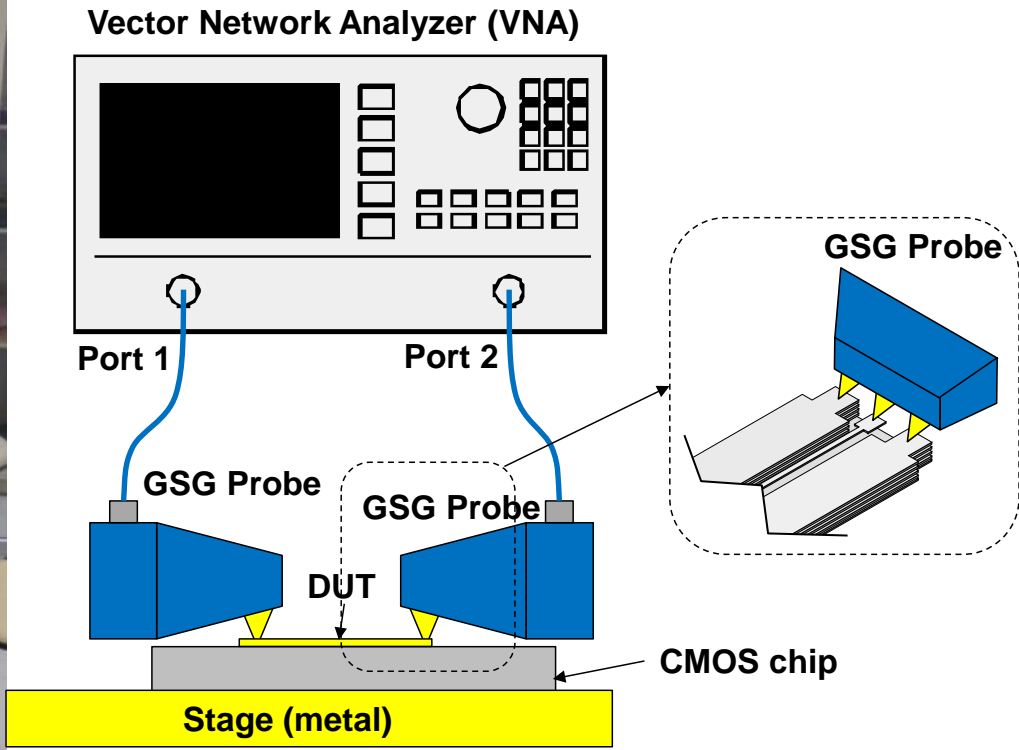
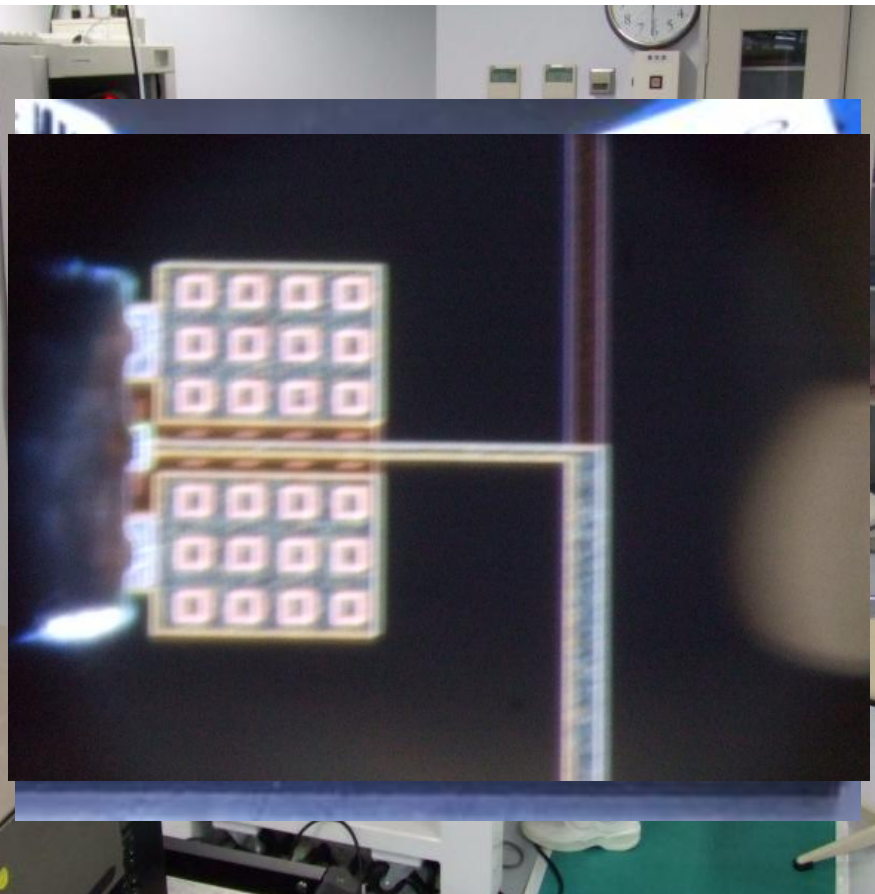
COMSOLによるダイポールアンテナの解析 No. 15



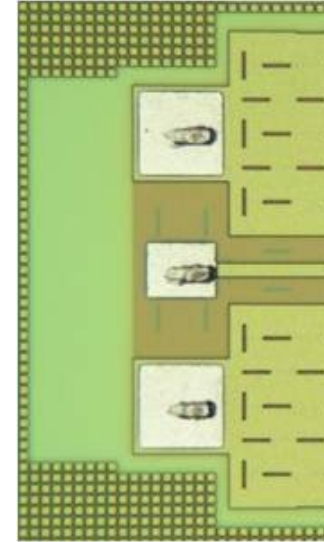
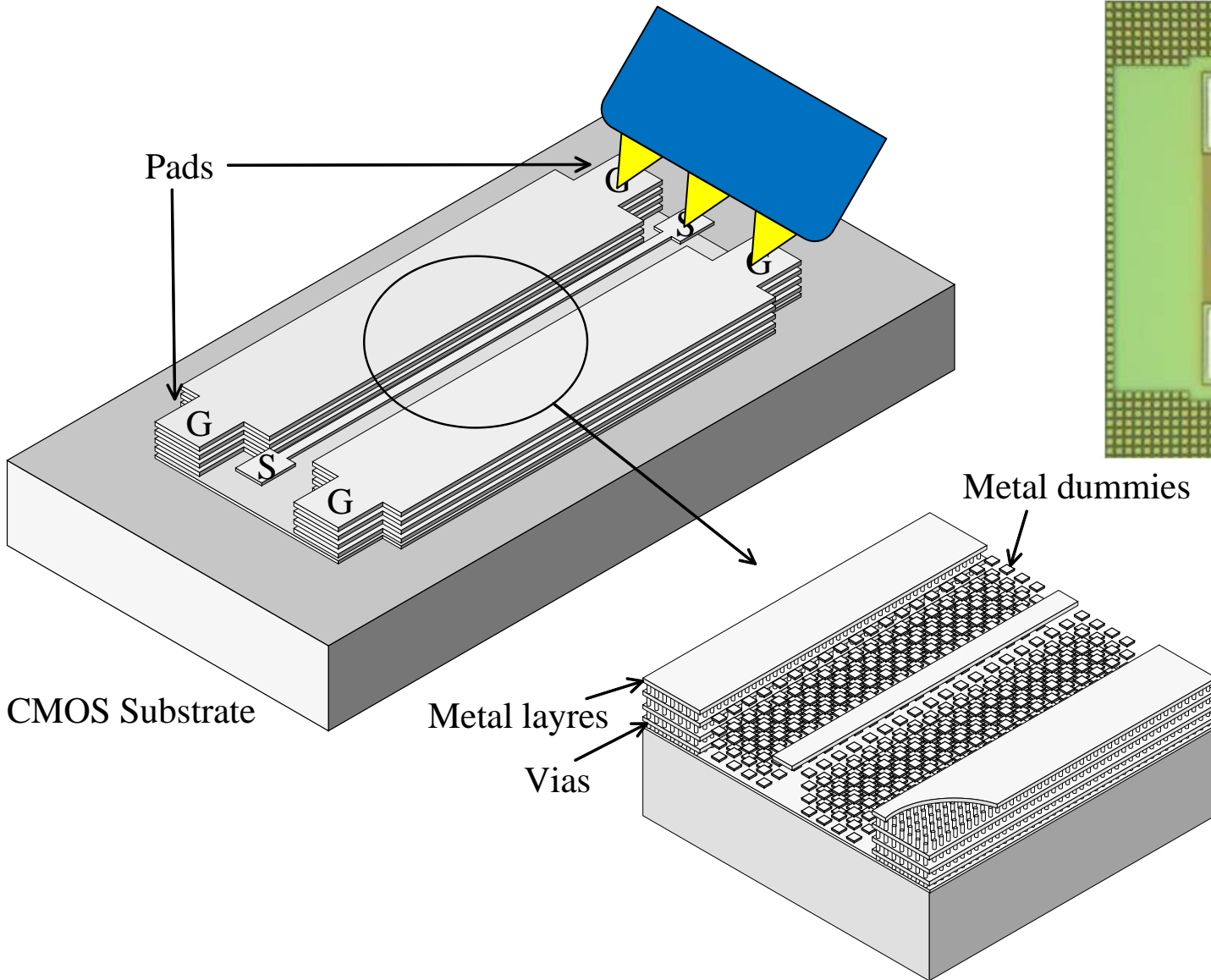
The screenshot displays the COMSOL Multiphysics software interface for a simulation titled "dipole_antenna.mph". The interface is divided into several main sections:

- Model Builder:** Located on the left, it shows a hierarchical tree of the model's components. The "Lumped Port 1" component is selected under the "Dipole (comp1)" node.
- Settings/Properties:** The central panel shows the configuration for the selected "Lumped Port".
 - Boundary Selection:** A list of boundaries is shown, with boundary "22" selected and marked as "Active".
 - 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: A table with values 0 for x, 0 for y, and 1 for z.
 - Terminal type: Cable
 - Wave excitation at this port: On
 - Voltage: V_0 1[V] V
 - Port phase: θ_{in} 0 rad
 - Characteristic impedance: Z_{ref} 50[ohm] Ω
- Graphics:** The right-hand side shows a 3D perspective view of the dipole antenna model. The central crossbar is highlighted in blue, corresponding to the selected lumped port.
- Messages:** The bottom right corner shows a log of messages, including "COMSOL Multiphysics 5.3.0.260" and "ジオメトリ 1: Changed representation to COMSOL kernel."

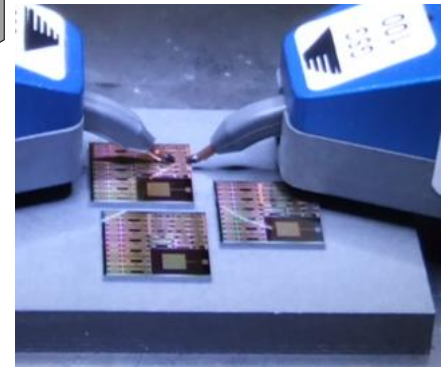
GSGパッドの励振モデル



GSGパッドの構造

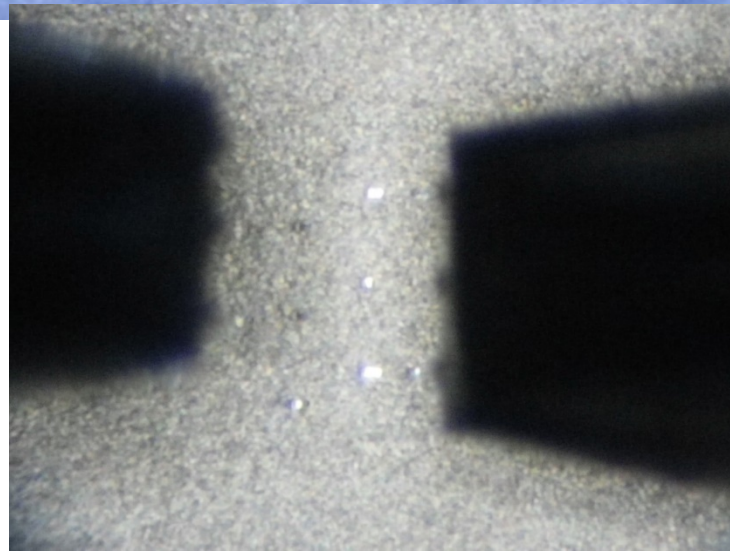
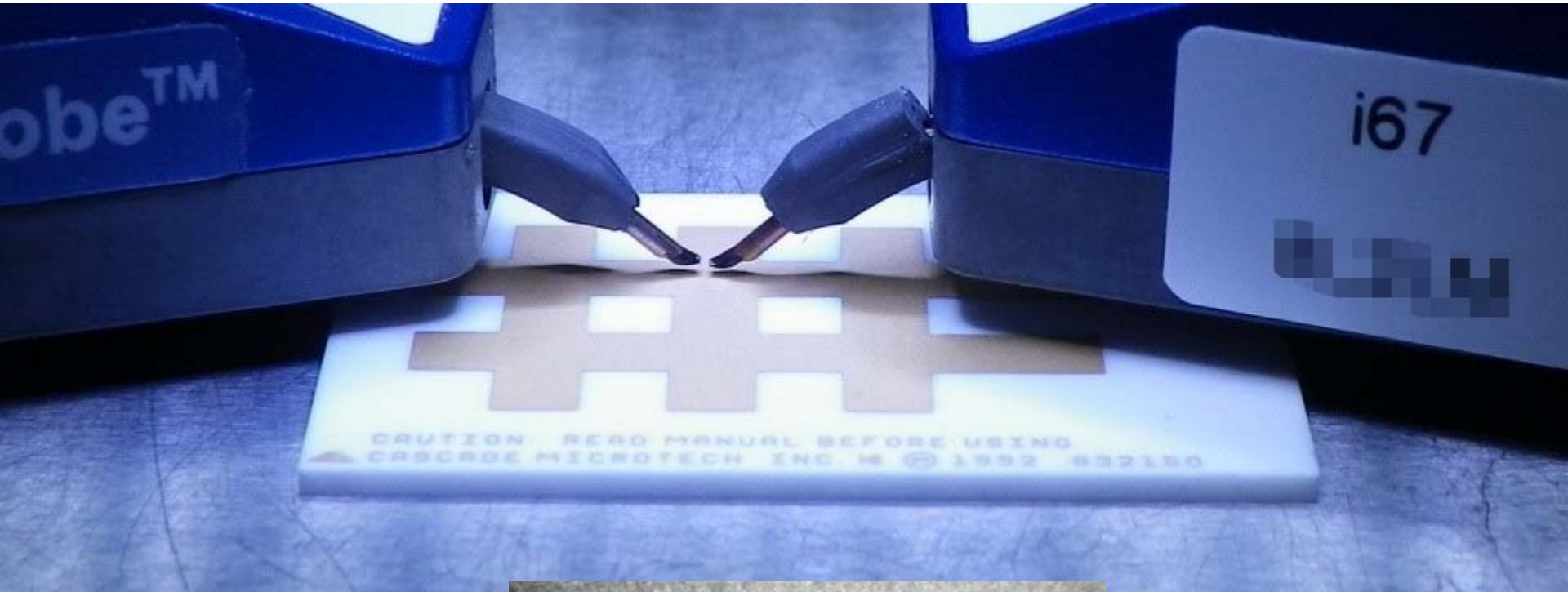


Cascade Microtech
Infinity Probe

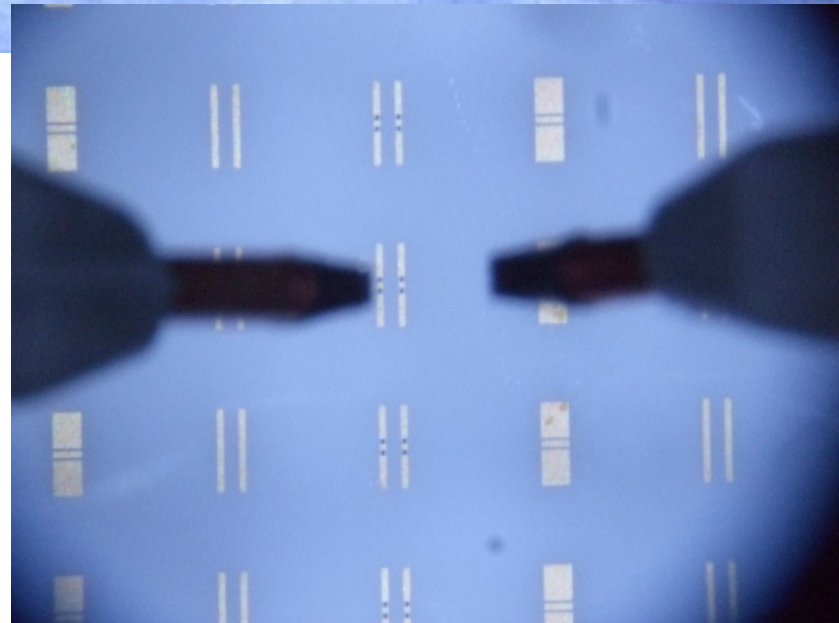
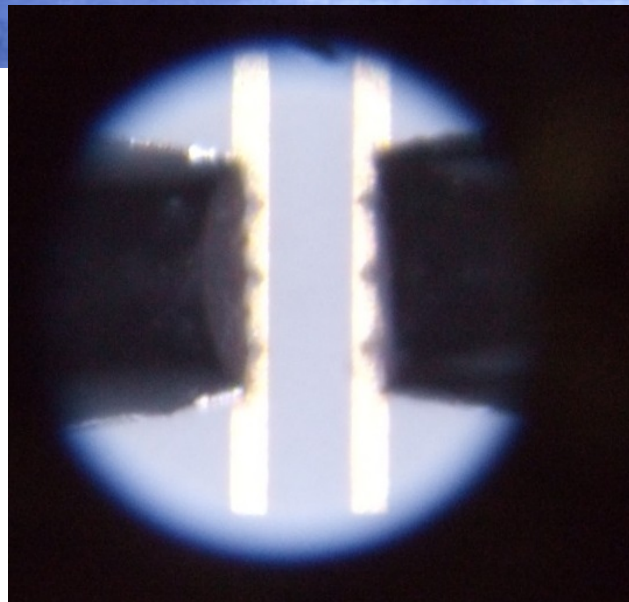
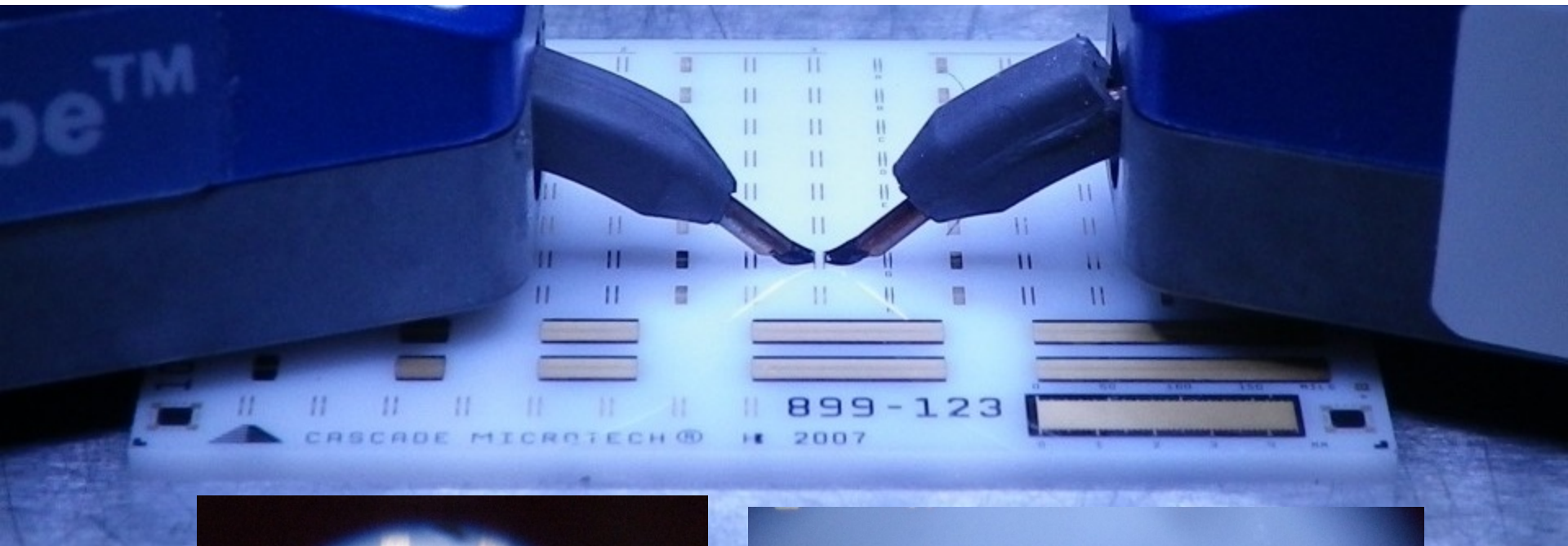


GSGプローブの写真(コンタクト基板)

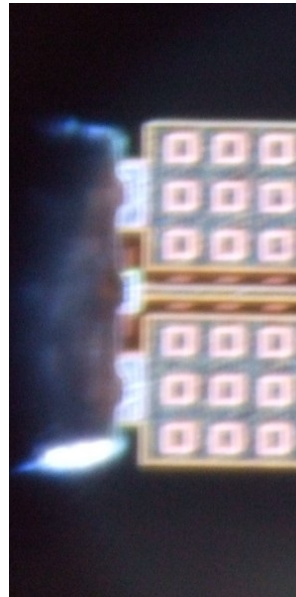
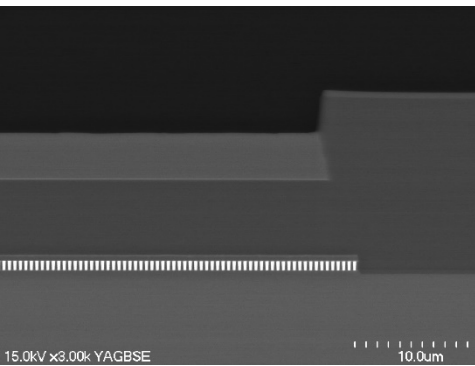
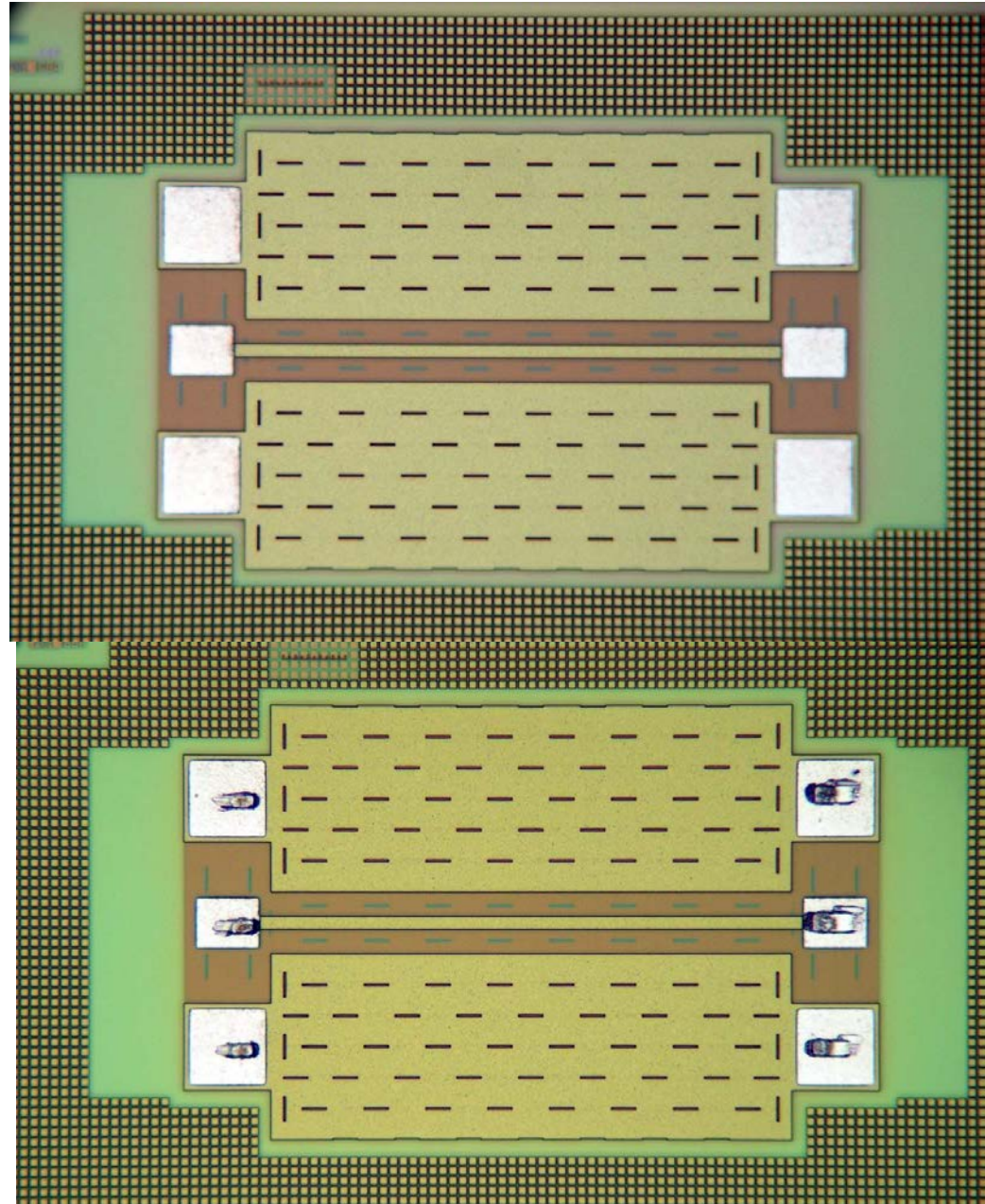
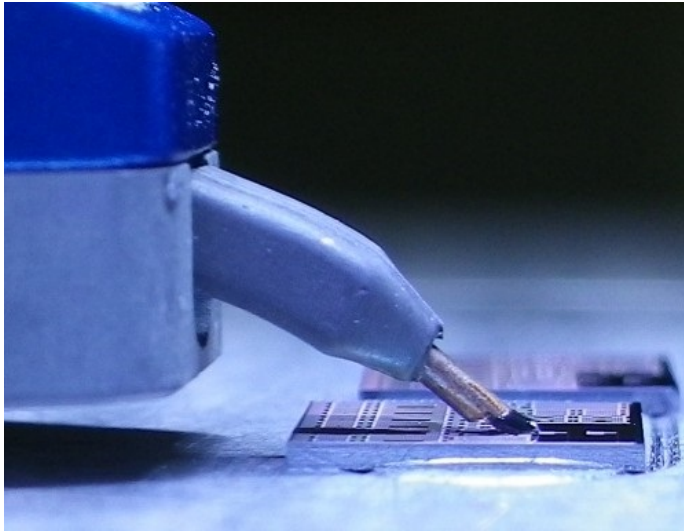
No. 19



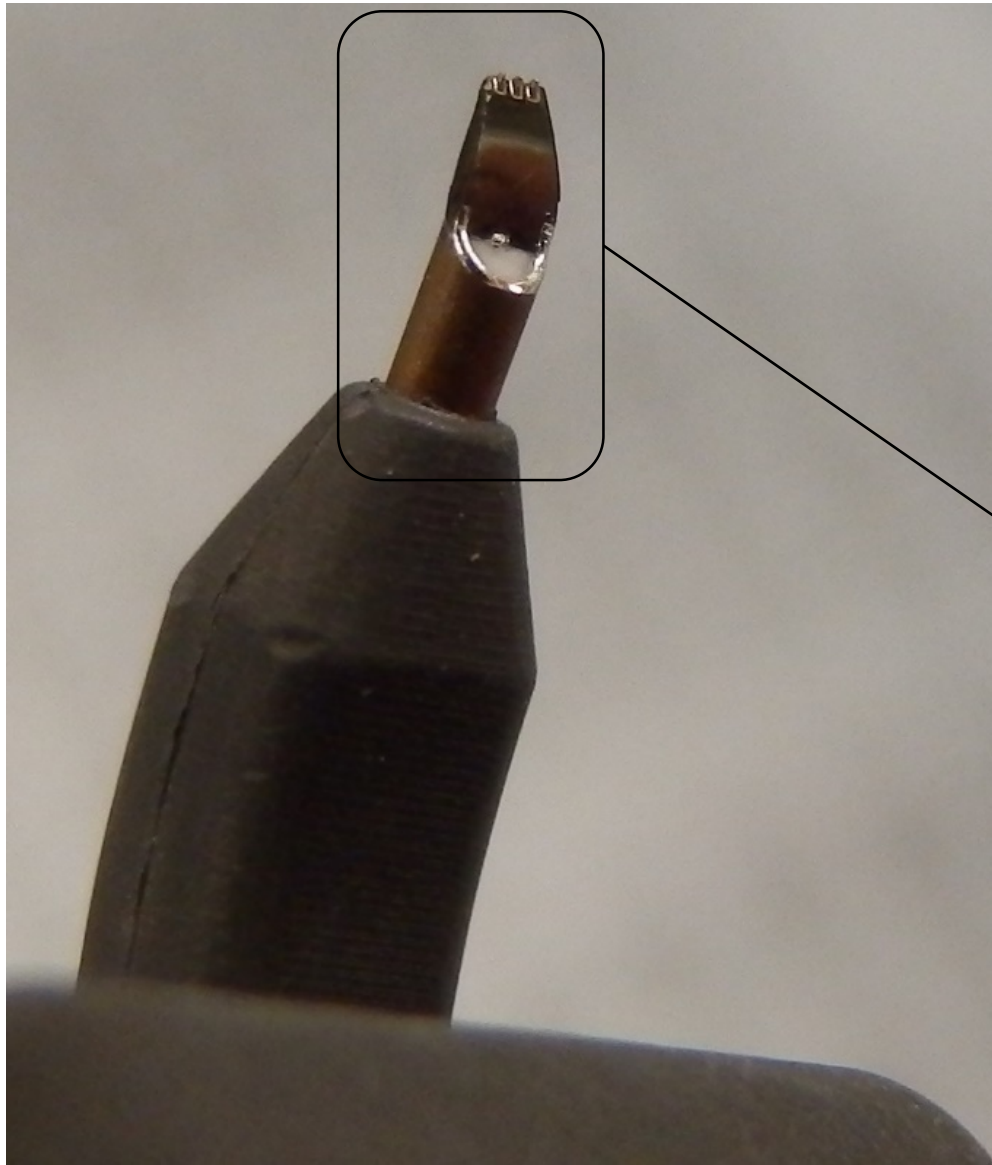
GSGプローブの写真(ISS; 校正基板)

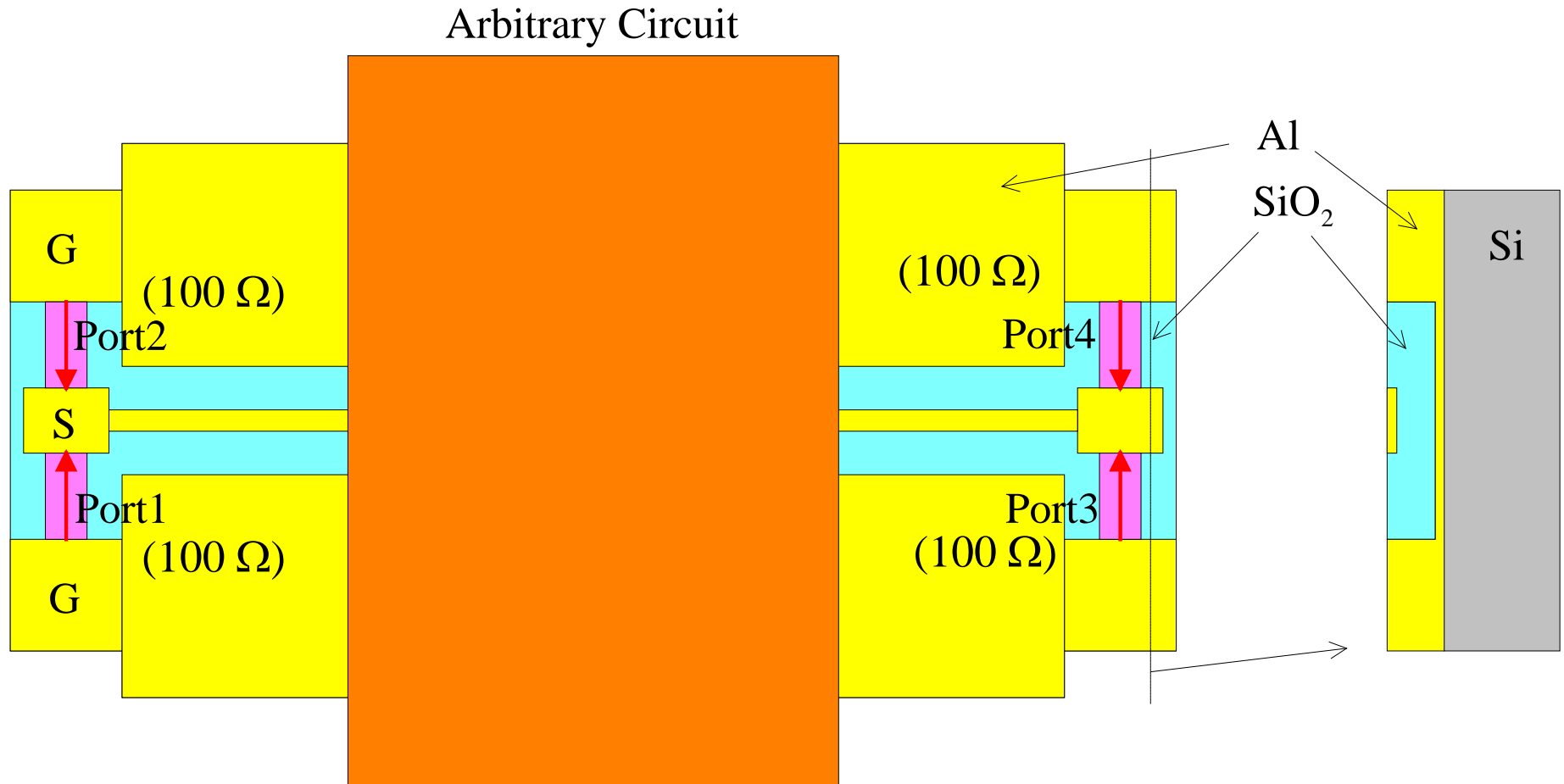


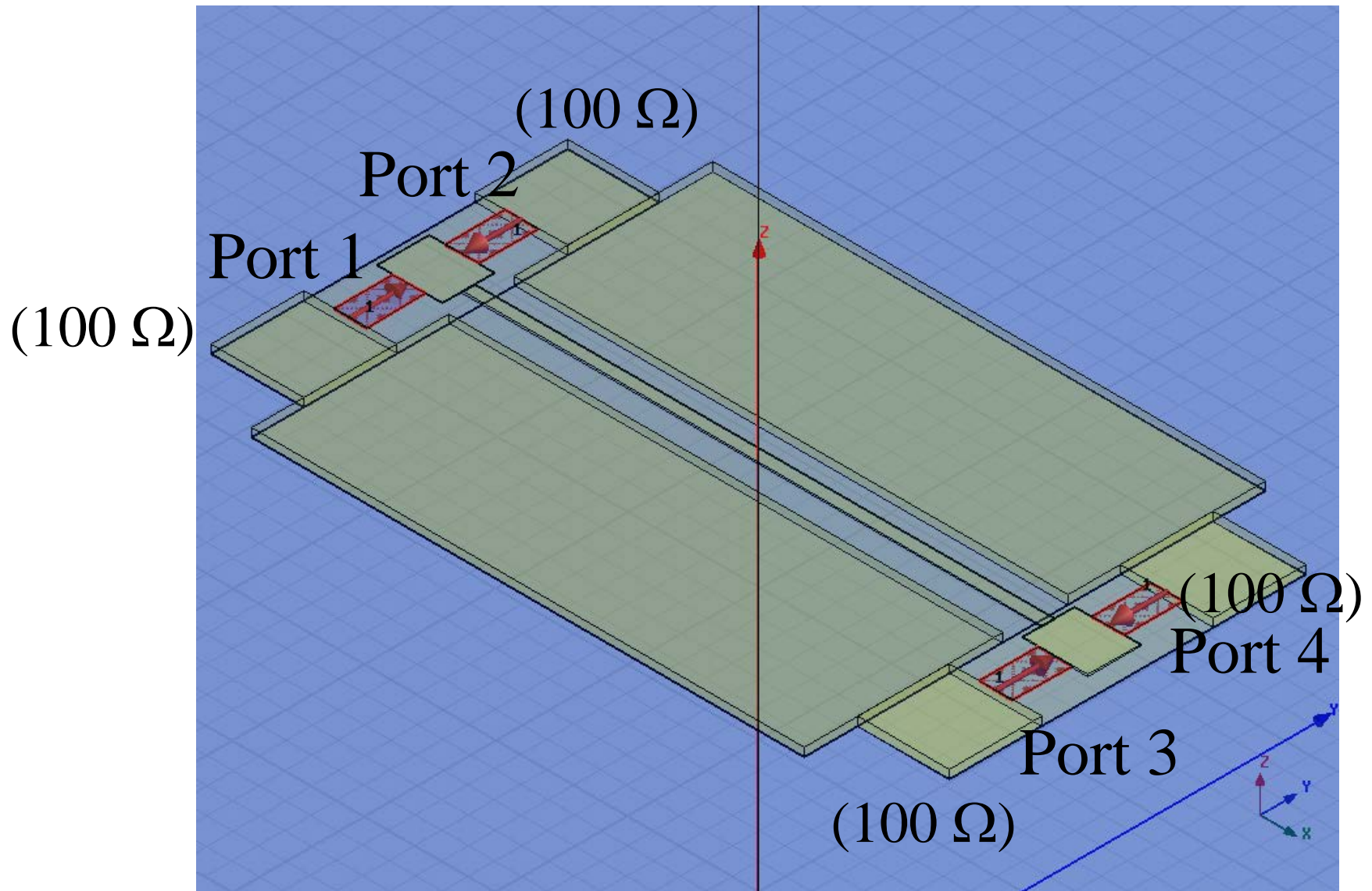
GSGプローブの写真(パッド)



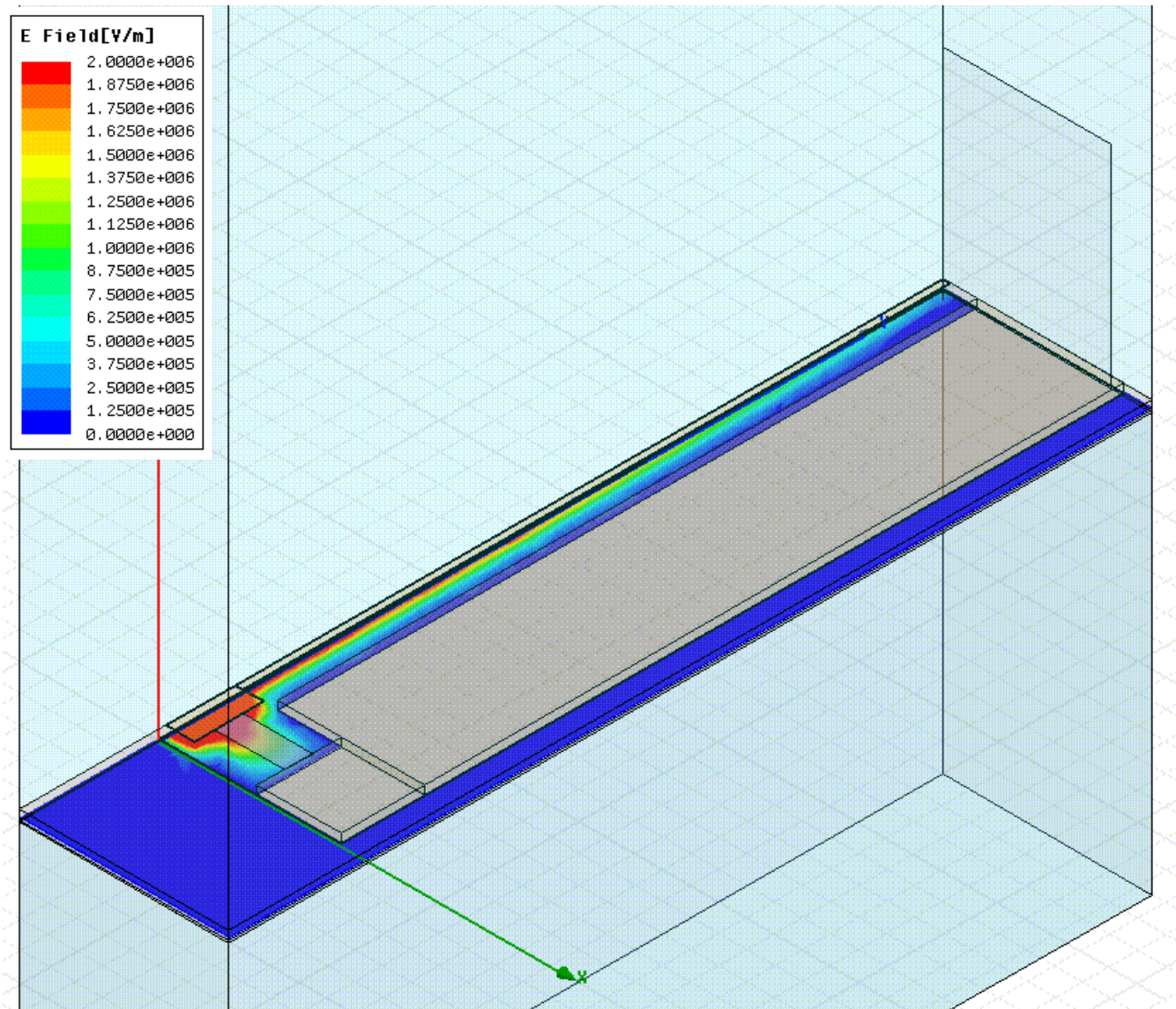
GSGプローブ先端の写真



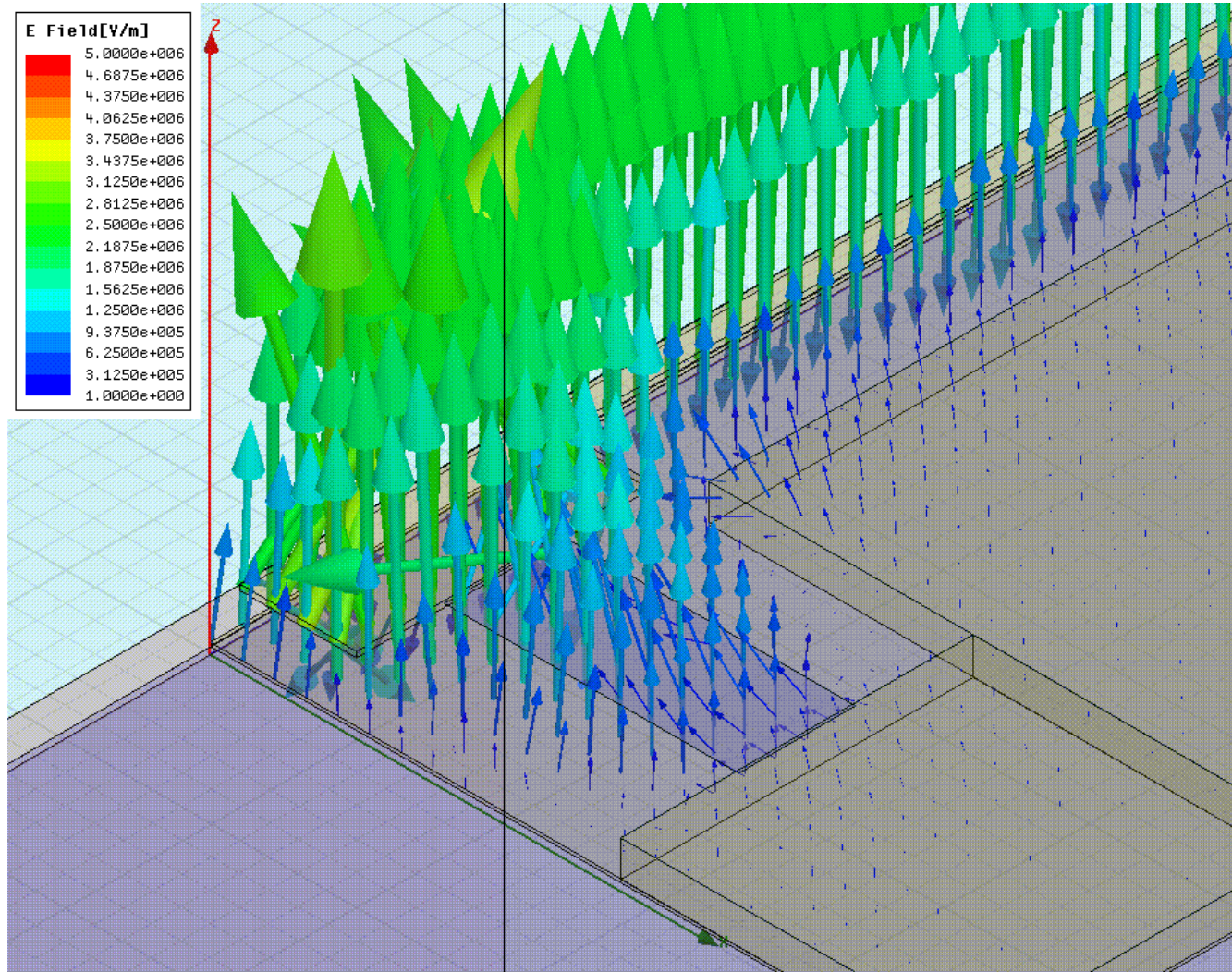




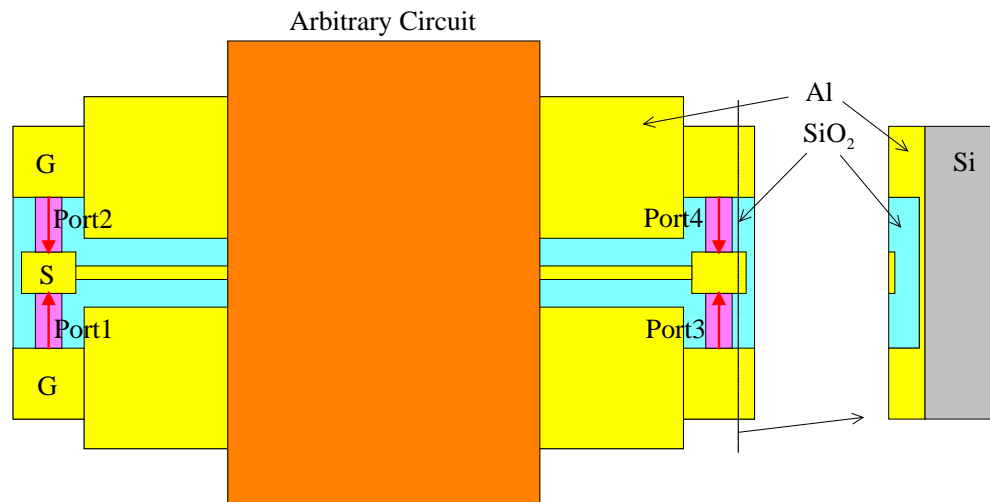
E-Field Animation



Vector E-Field Animation



解析結果4ポートから実測2ポートへの変換



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

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

$$a_1 = a_2 = a'_1 \quad a_3 = a_4 = a'_2$$

$$b_1 = b_2 = b'_1 \quad b_3 = b_4 = b'_2$$

$$\begin{bmatrix} b'_1 \\ b'_1 \\ b'_2 \\ b'_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} a'_1 \\ a'_1 \\ a'_2 \\ a'_2 \end{bmatrix}$$

$$\begin{cases} b'_1 = (S_{11} + S_{12})a'_1 + (S_{13} + S_{14})a'_2 \\ b'_1 = (S_{21} + S_{22})a'_1 + (S_{23} + S_{24})a'_2 \\ b'_2 = (S_{31} + S_{32})a'_1 + (S_{33} + S_{34})a'_2 \\ b'_2 = (S_{41} + S_{42})a'_1 + (S_{43} + S_{44})a'_2 \end{cases}$$

パッド部の構造の対称性より、

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

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

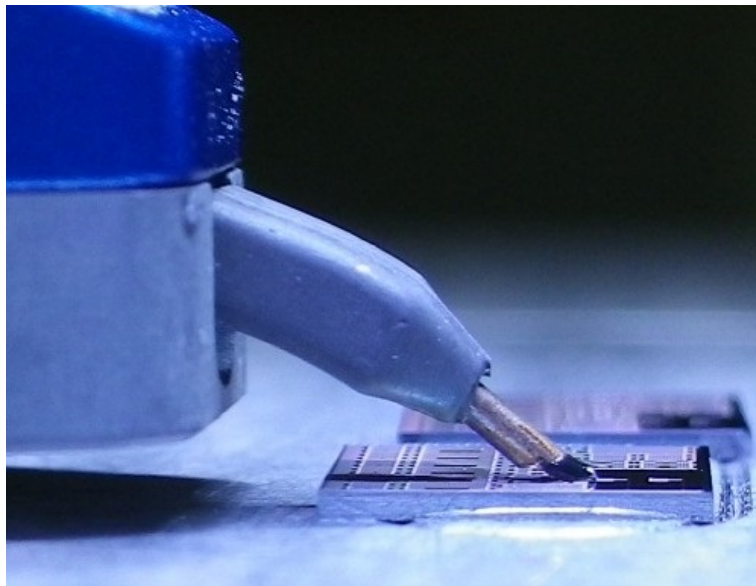
$$\begin{bmatrix} S'_{11} & S'_{12} \\ S'_{21} & S'_{22} \end{bmatrix} = \begin{bmatrix} S_{11} + S_{12} & S_{13} + S_{14} \\ S_{31} + S_{32} & S_{33} + S_{34} \end{bmatrix}$$

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、

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

$$b_1 = b_2 (= b)$$

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²⁹

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

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

$$a_1 = -a_2 = a$$

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

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

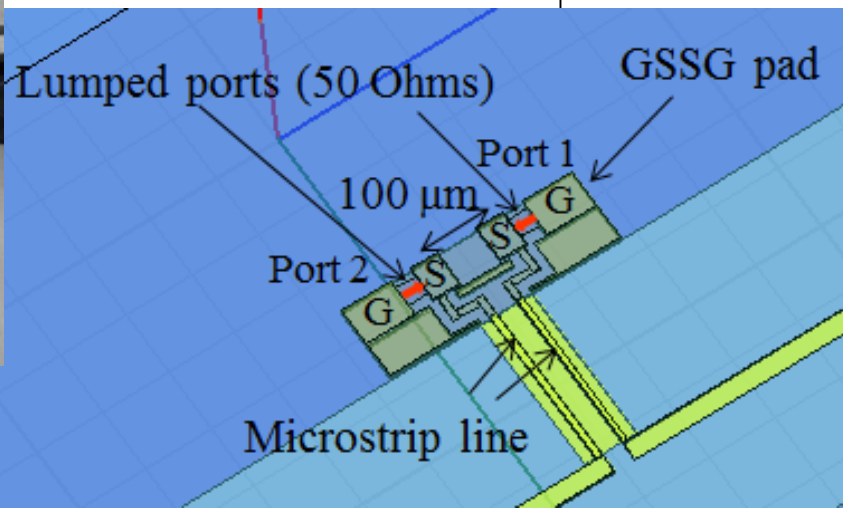
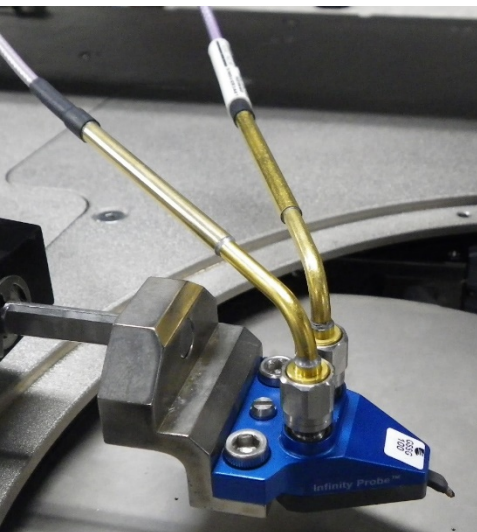
単モードとパッド部の構造の対称性より、

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

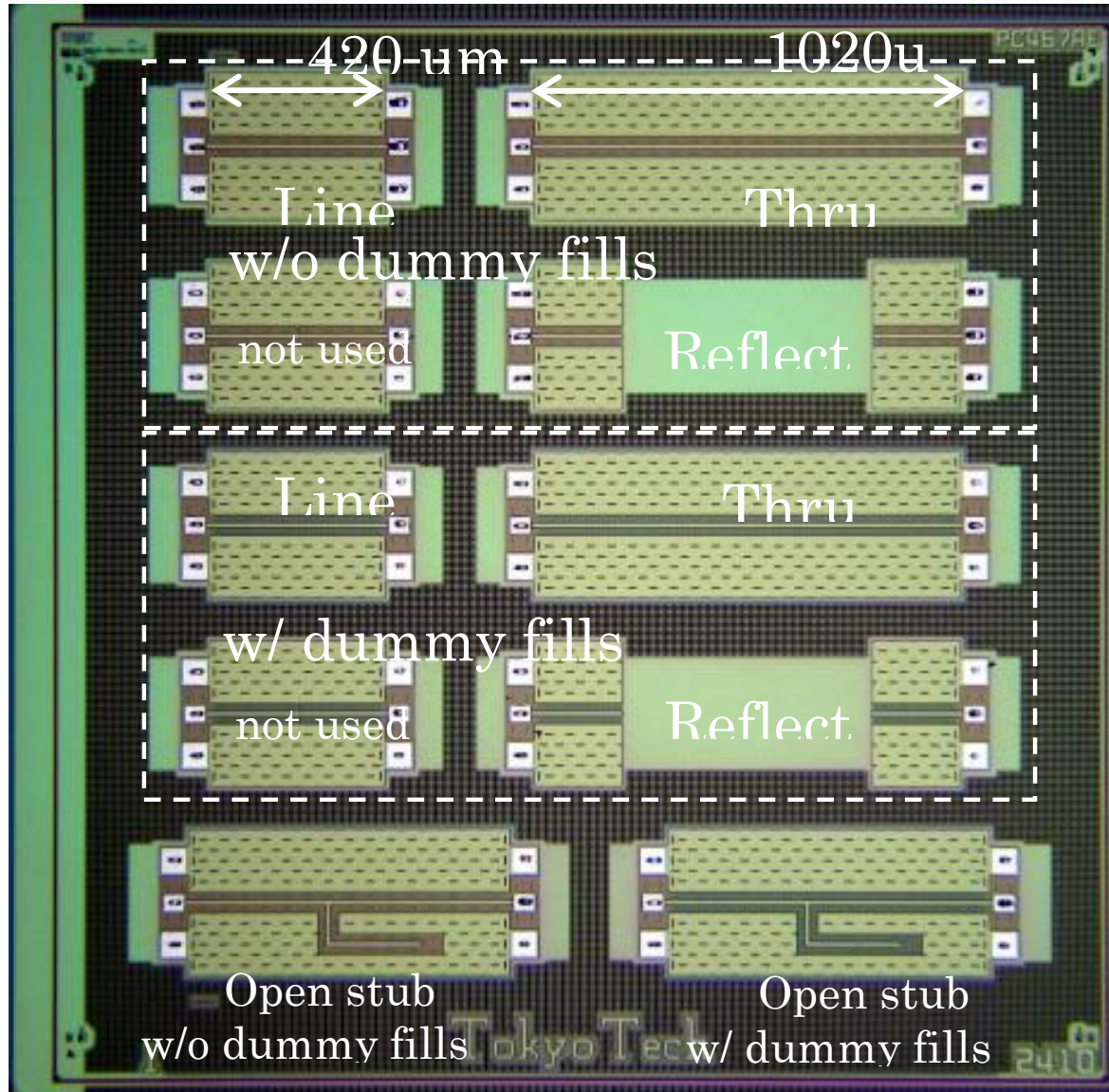
$$b_1 = -b_2 (= b)$$

反射係数

$$\begin{aligned} \Gamma &= \frac{b}{a} = S_{11} - S_{12} \\ &= S_{22} - S_{21} \end{aligned}$$

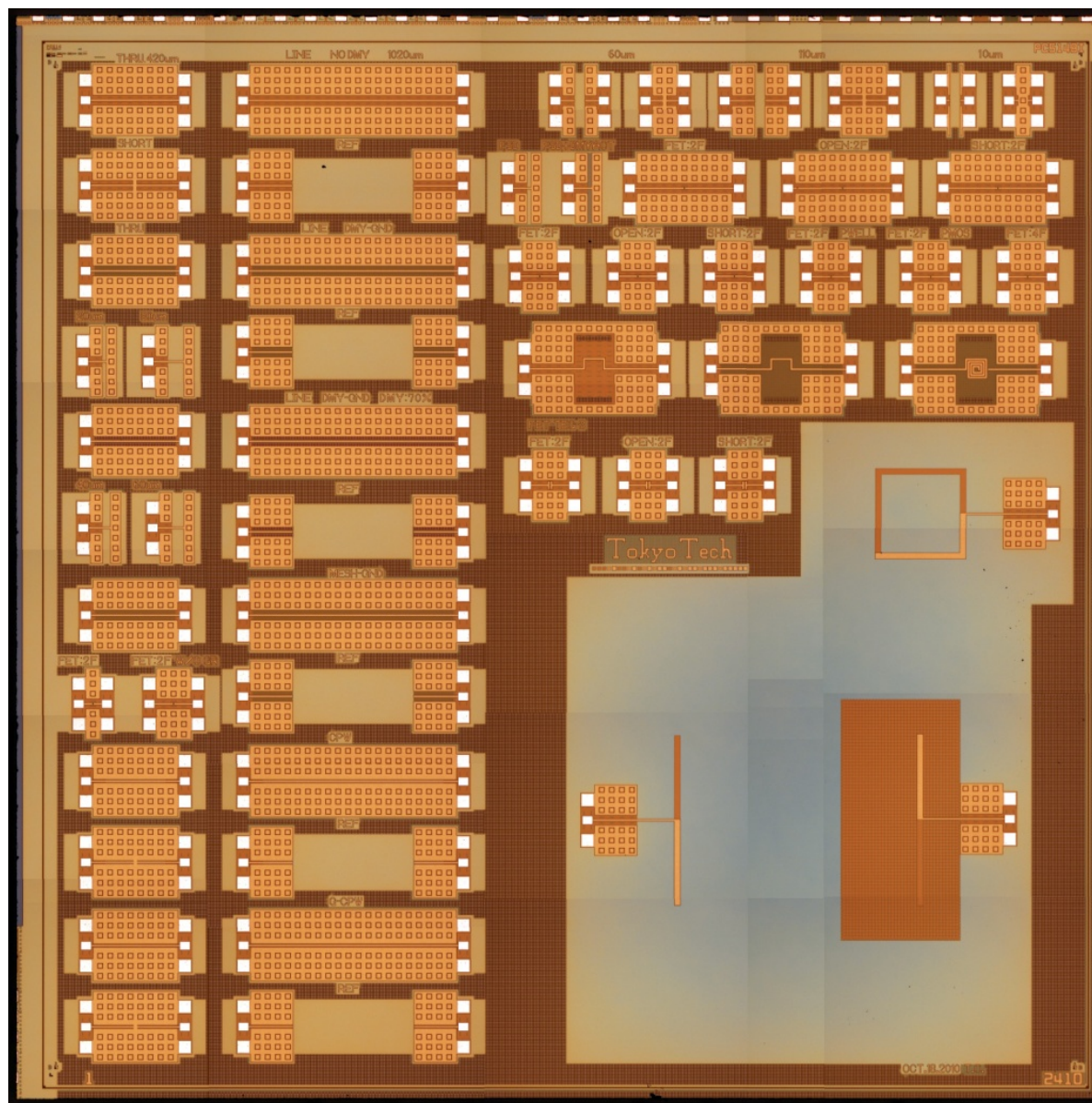


チップ写真1



2.5 mm x 2.5 mm
CMOS 0.18 μm

チップ写真2

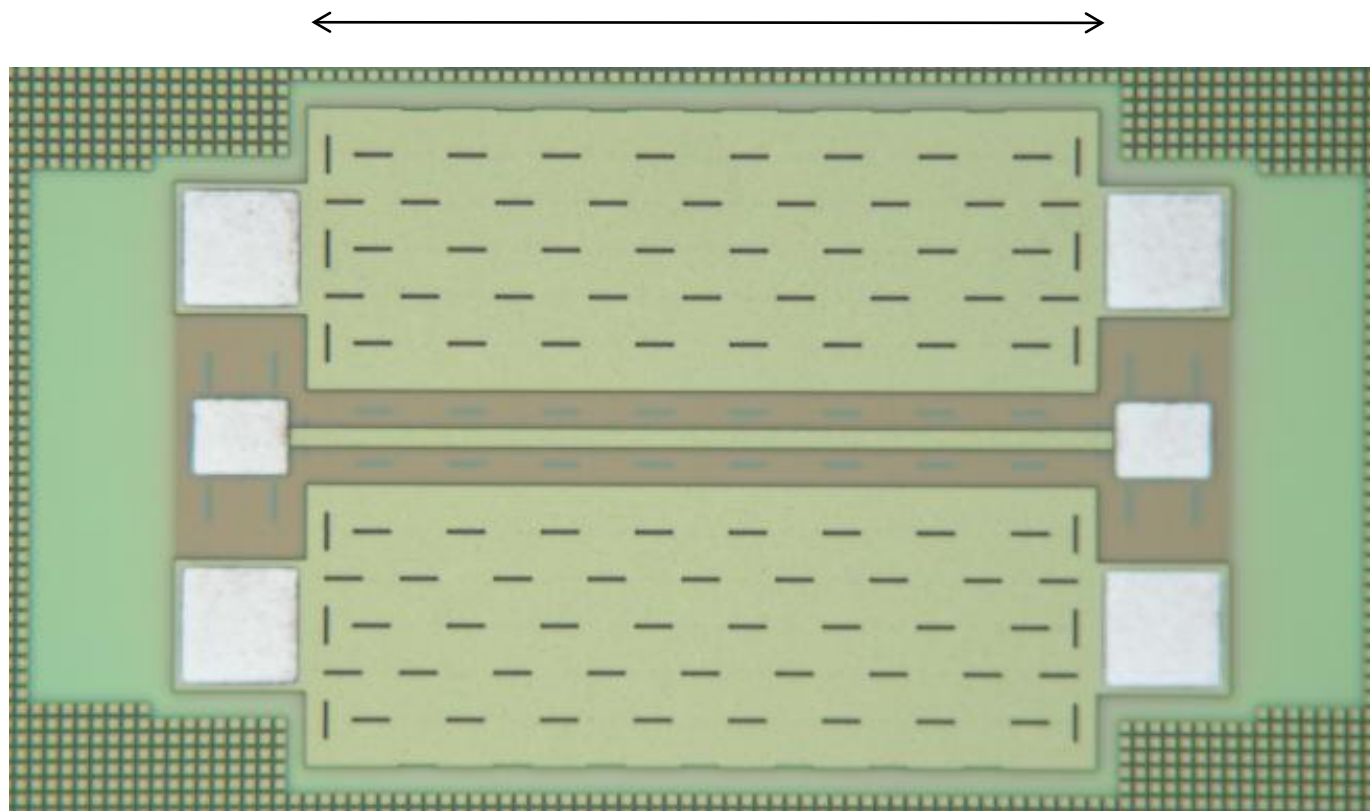


5 mm x 5 mm
CMOS 0.18 μm

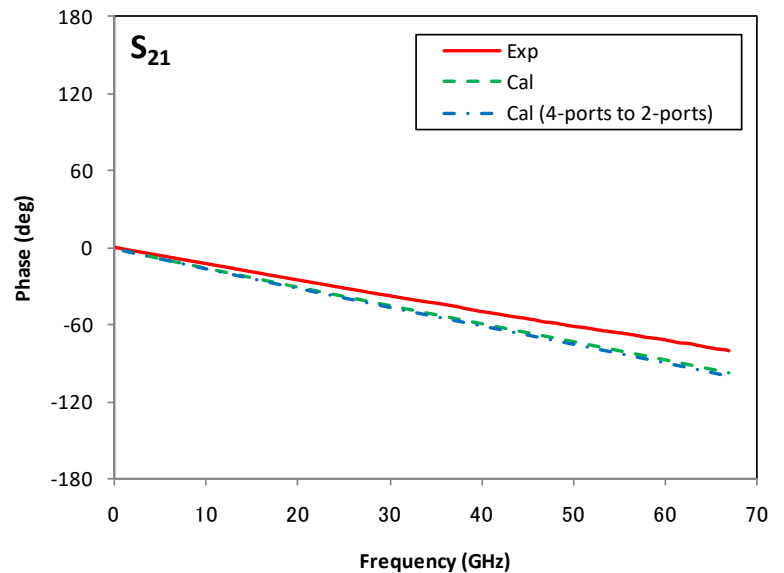
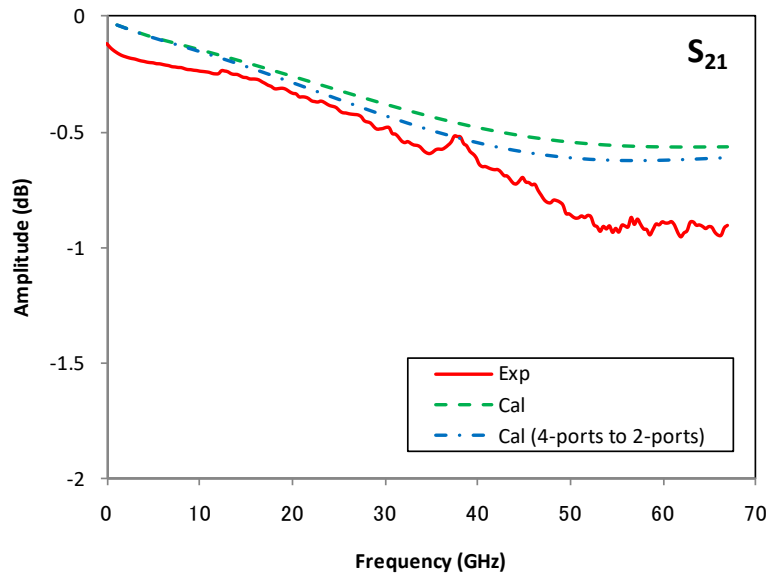
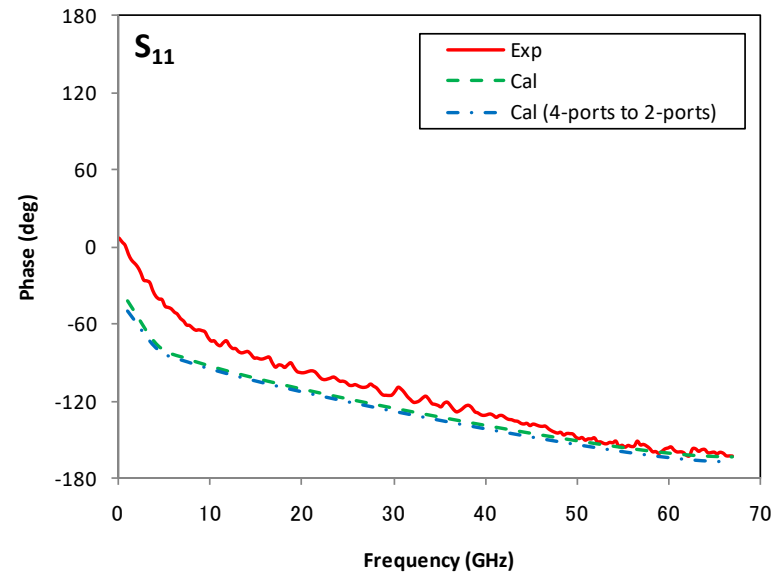
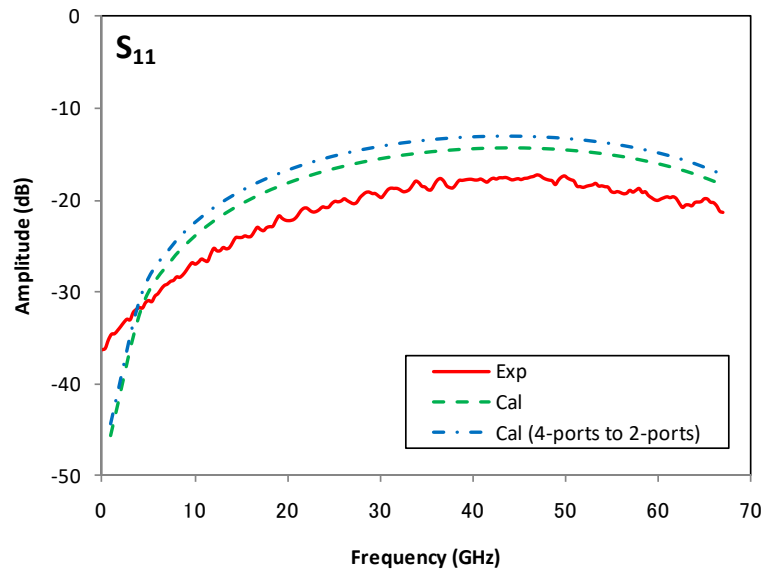


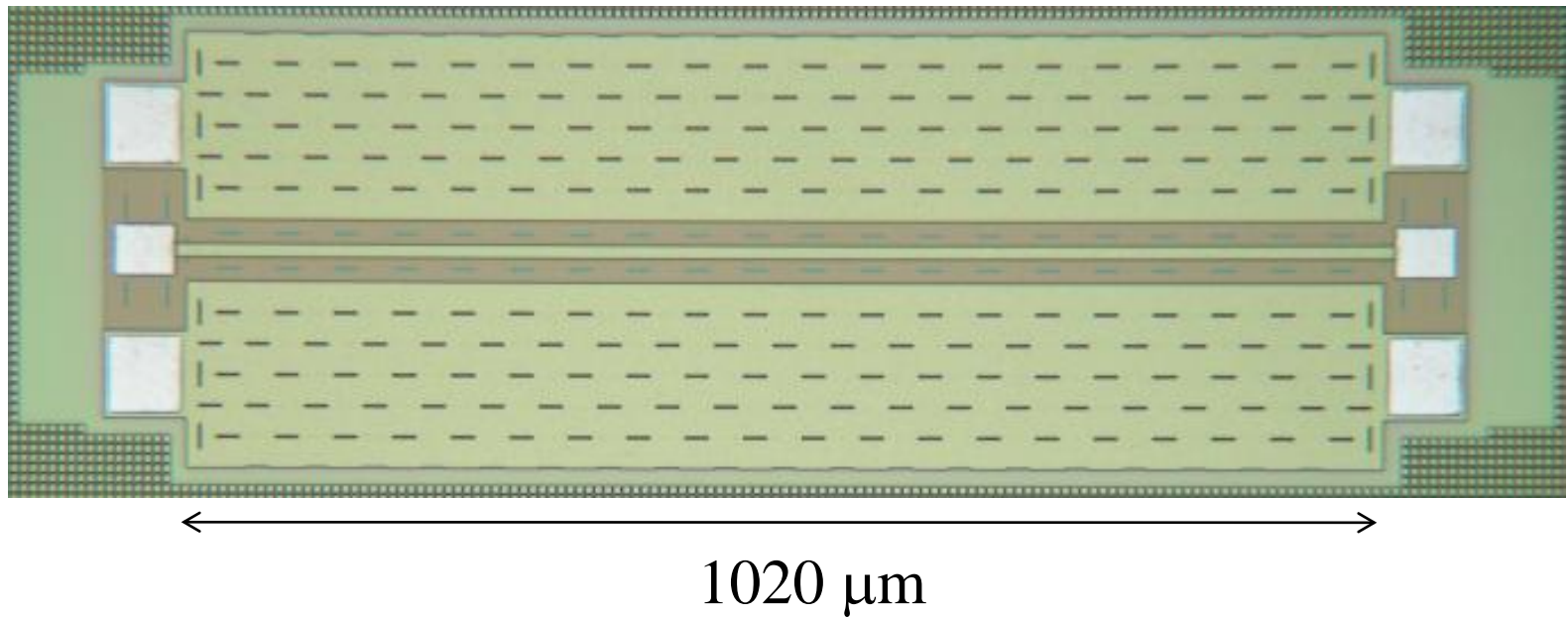
Thruパターン

420 μm

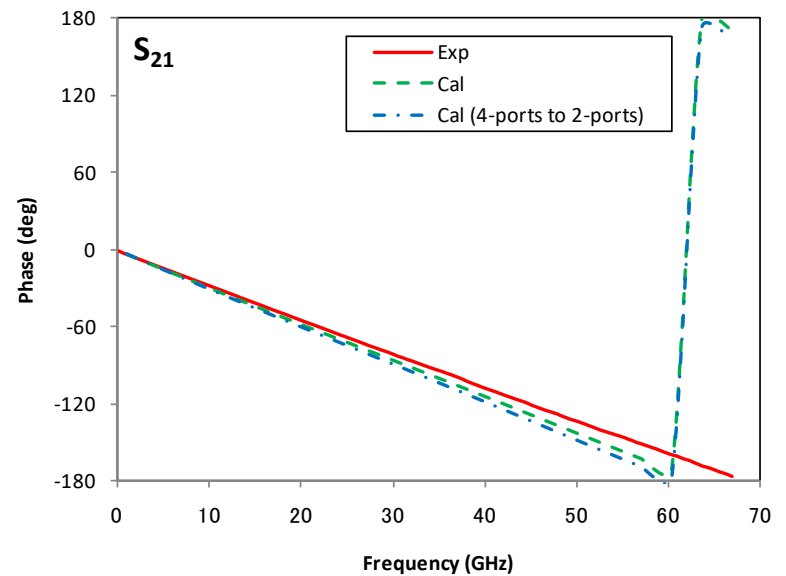
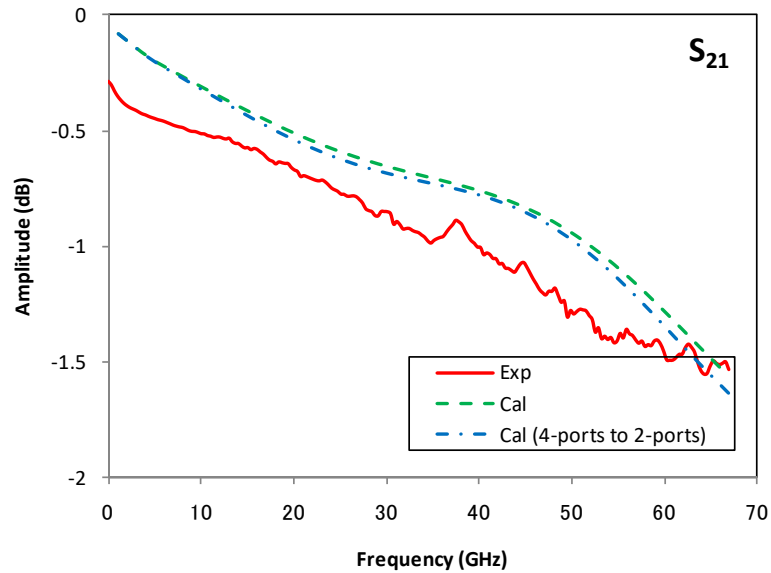
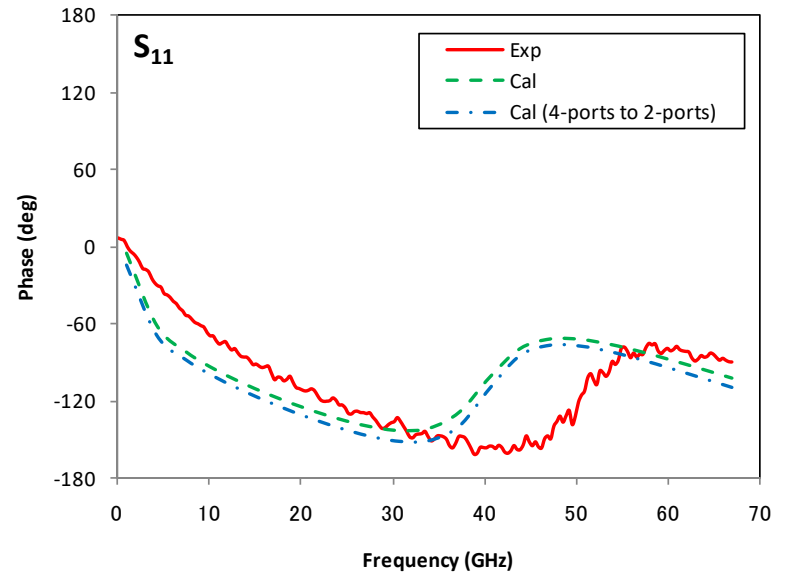
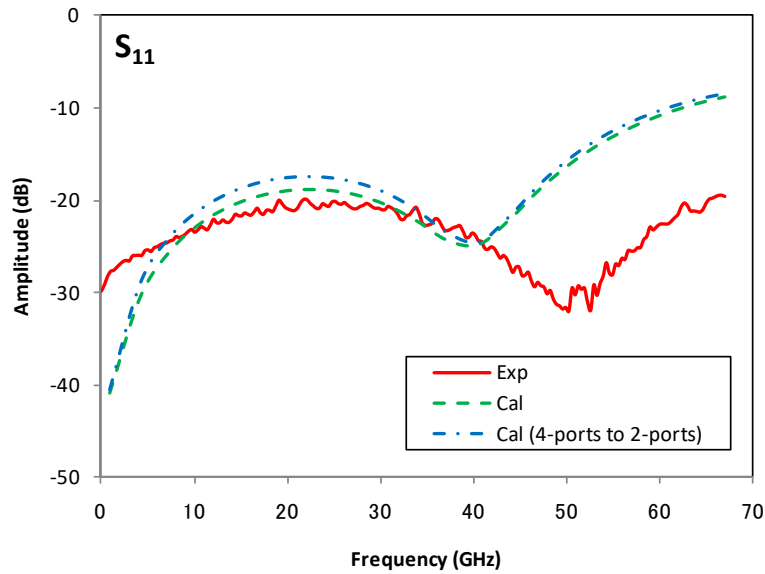


Thruパターン (Sパラメータ)

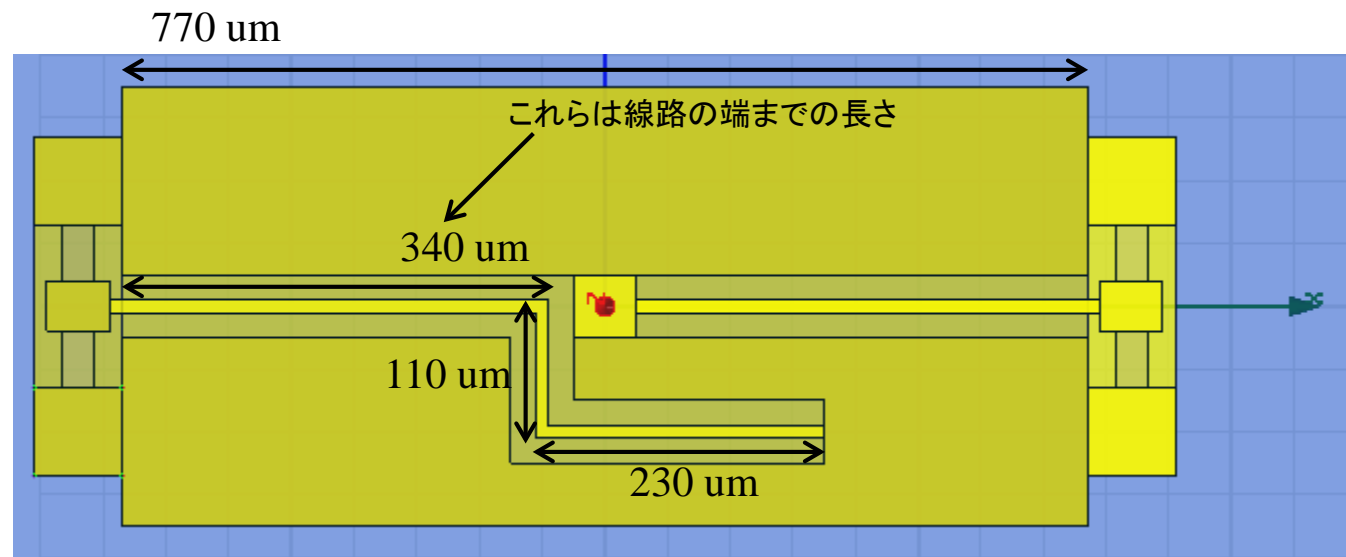
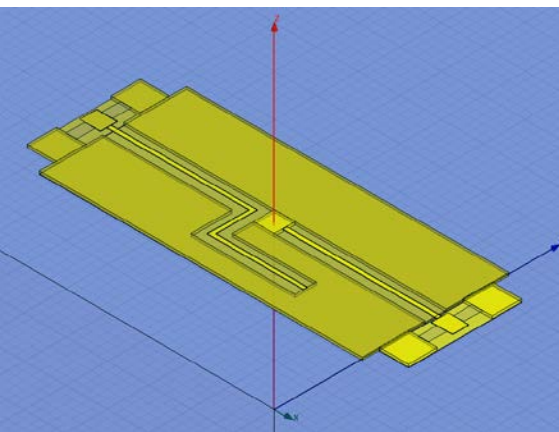
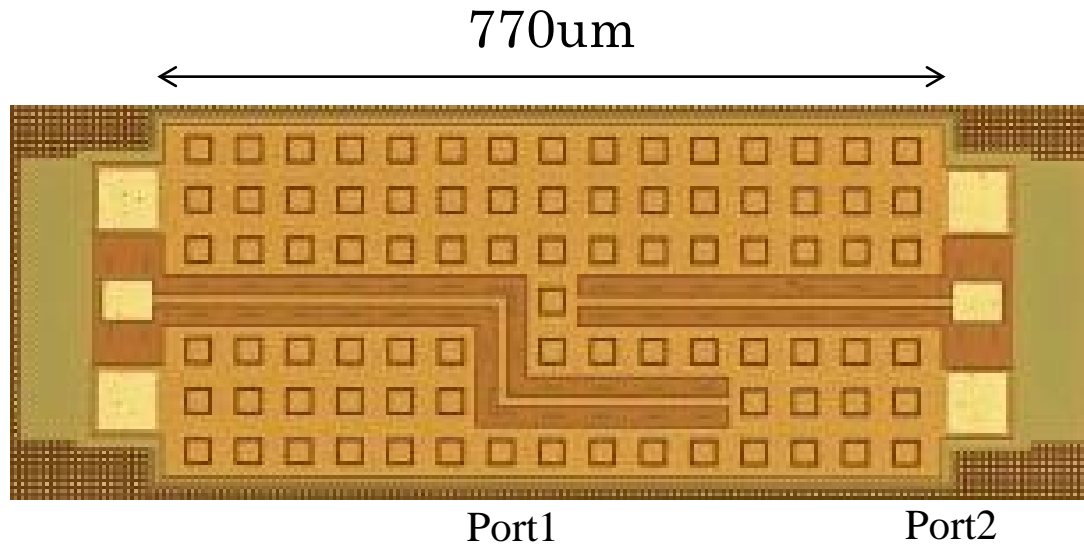




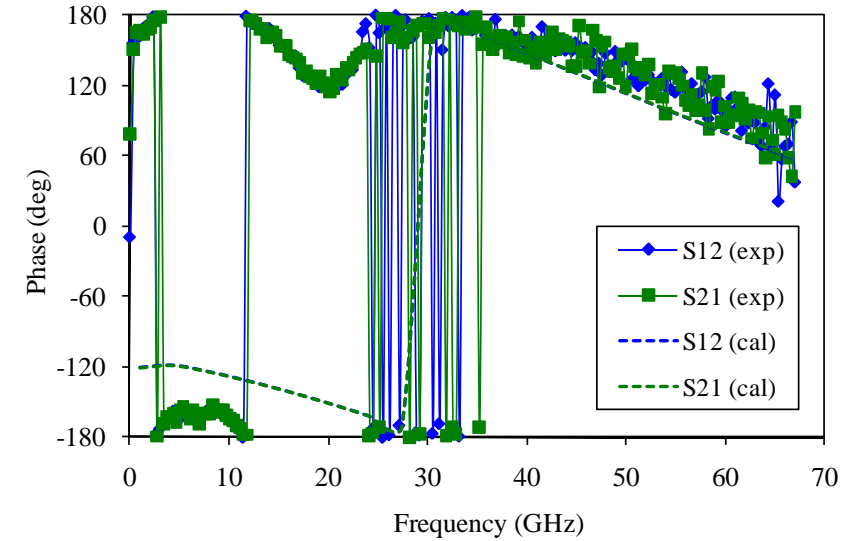
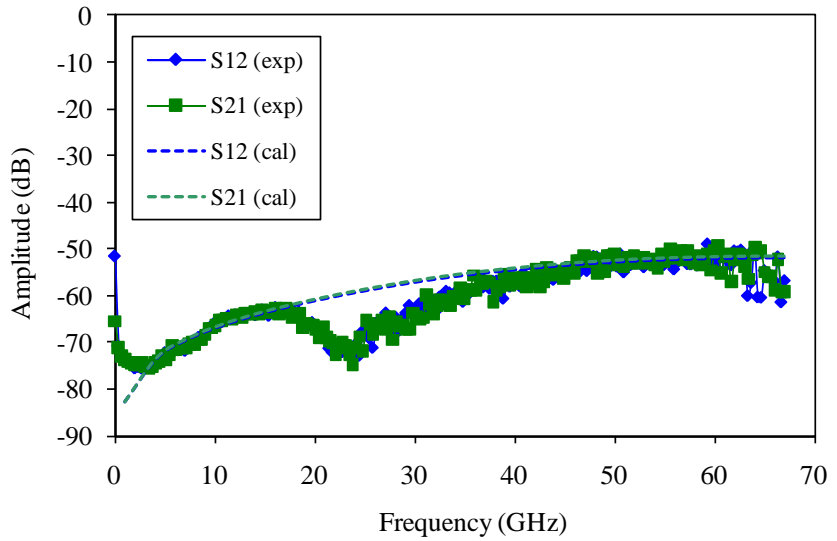
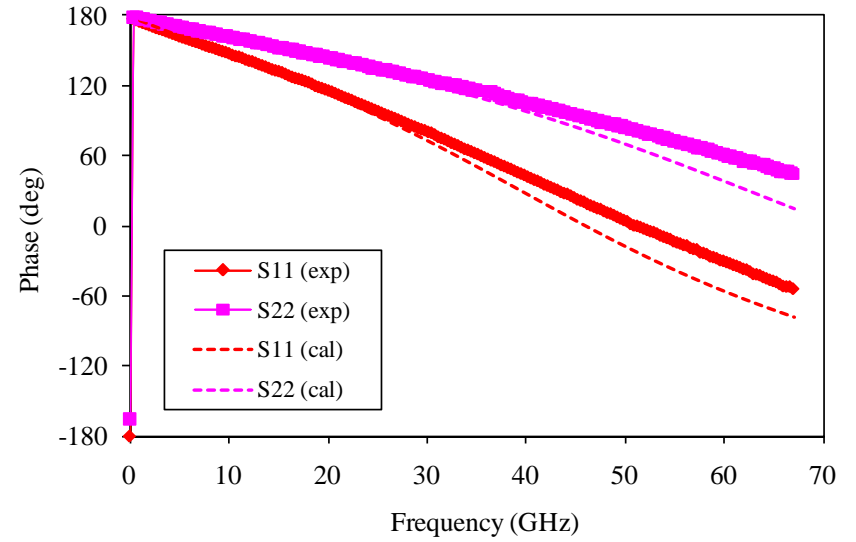
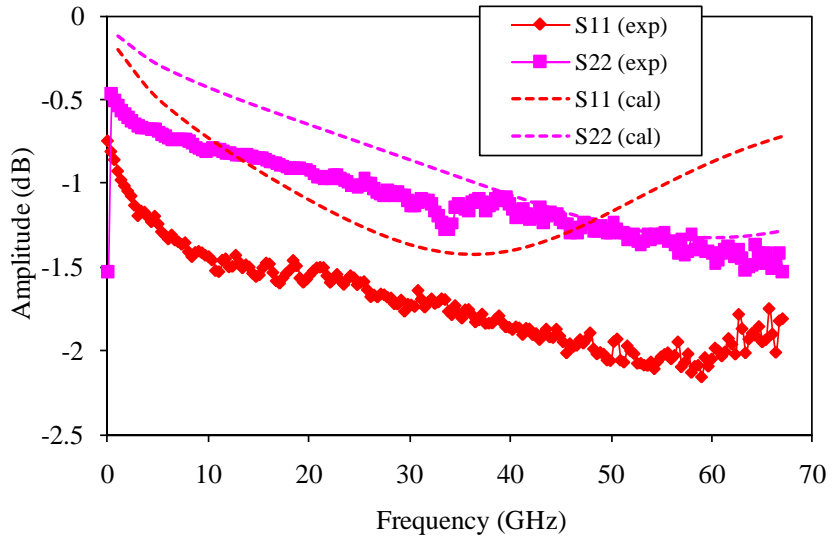
Lineパターン (Sパラメータ)



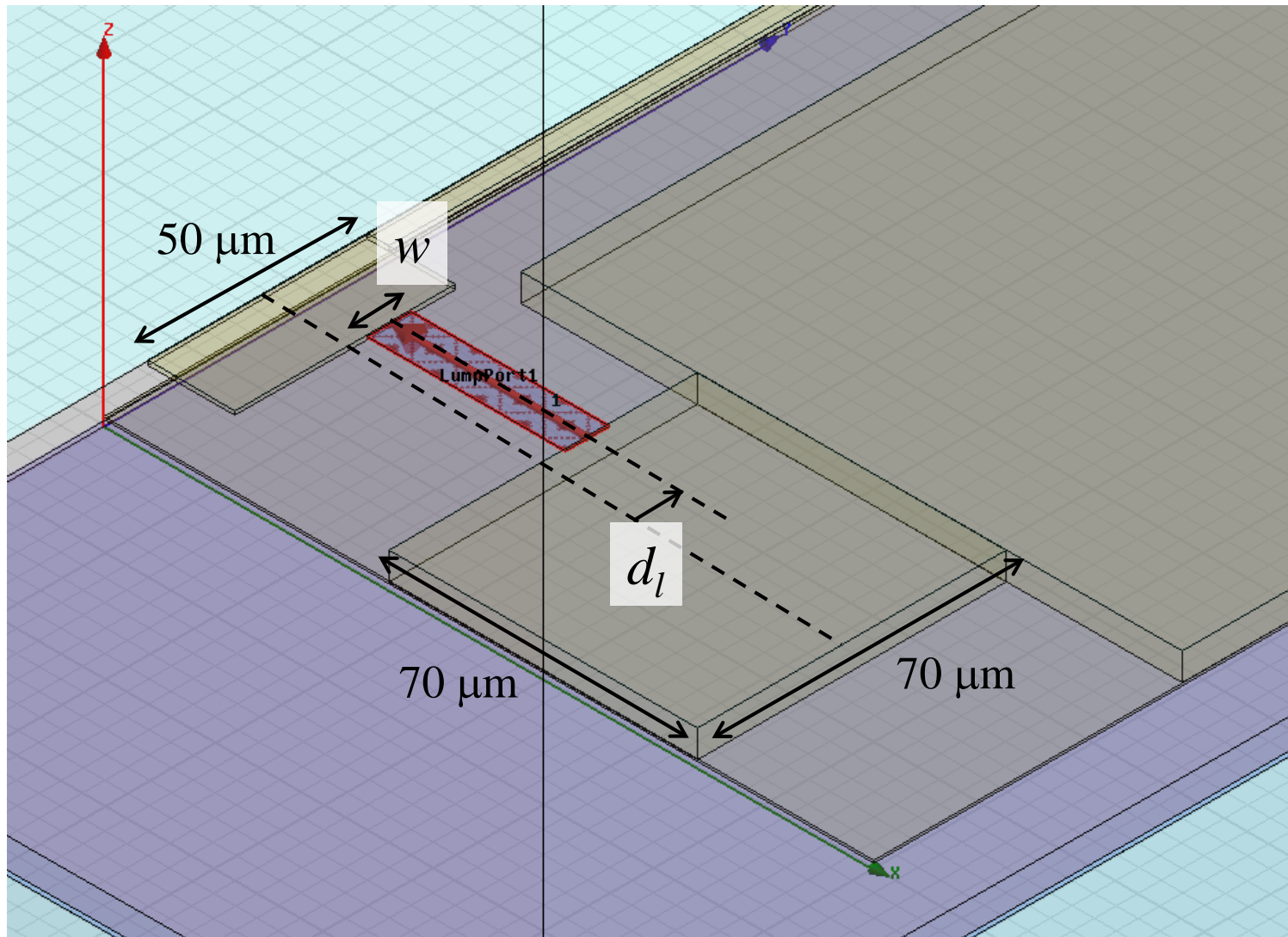
クロストークによる結合量評価パターン



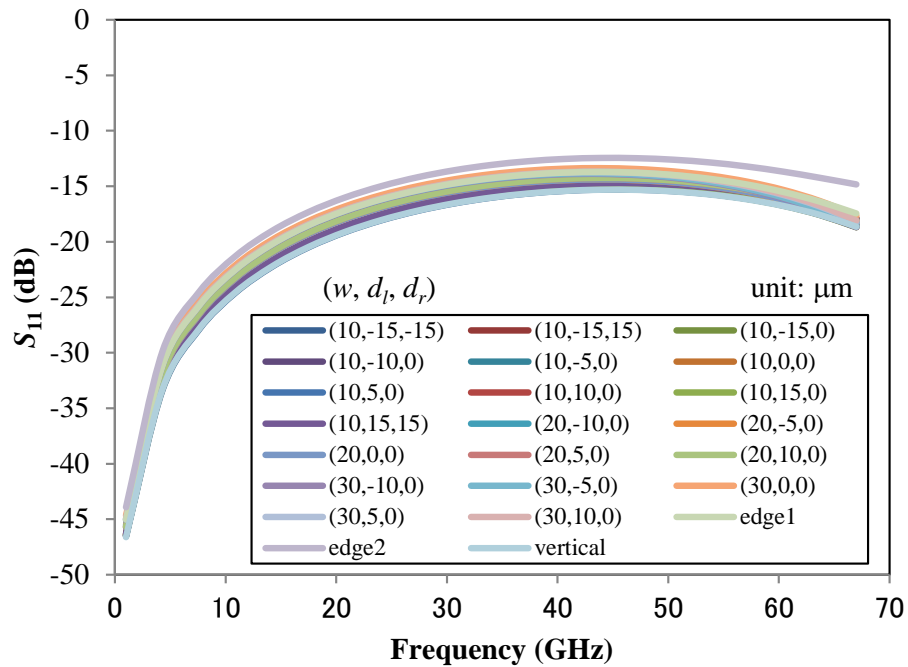
クロストークによる結合量評価パターン(Sパラメータ)



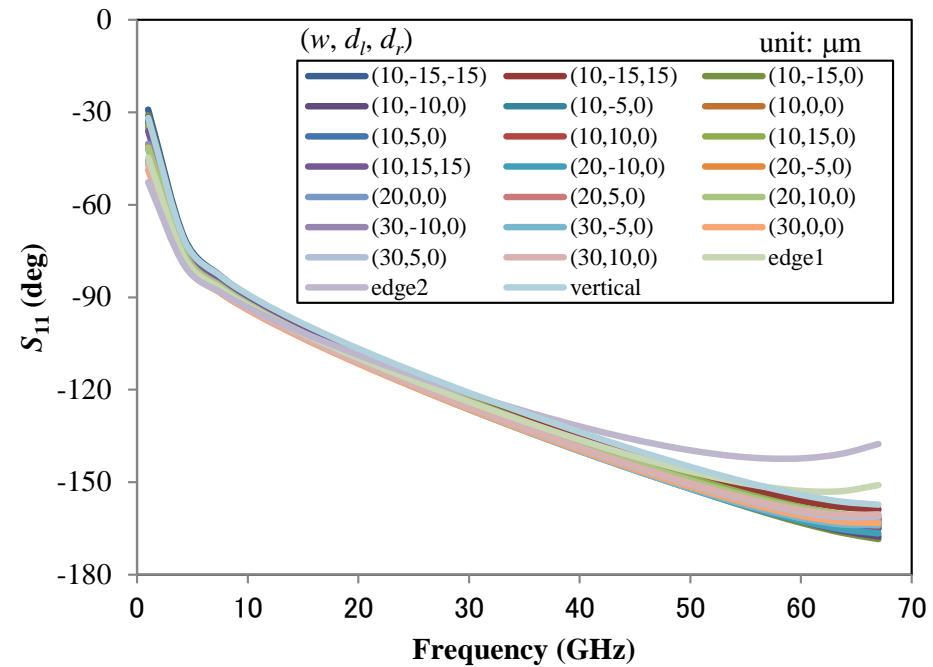
Lumped Portの位置 d_l および幅 w 依存性



反射係数 S_{11}

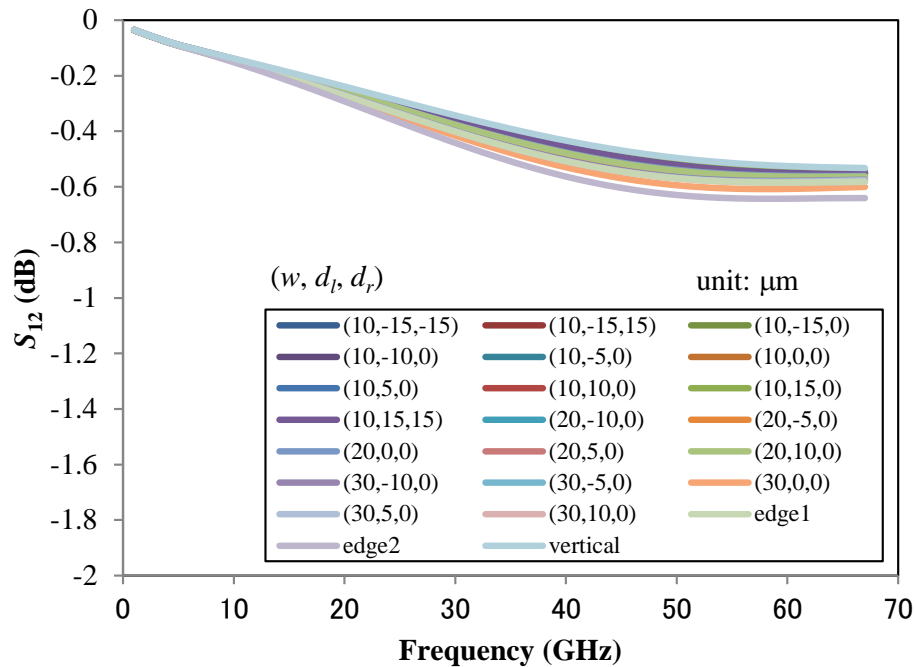


(a) Amplitude

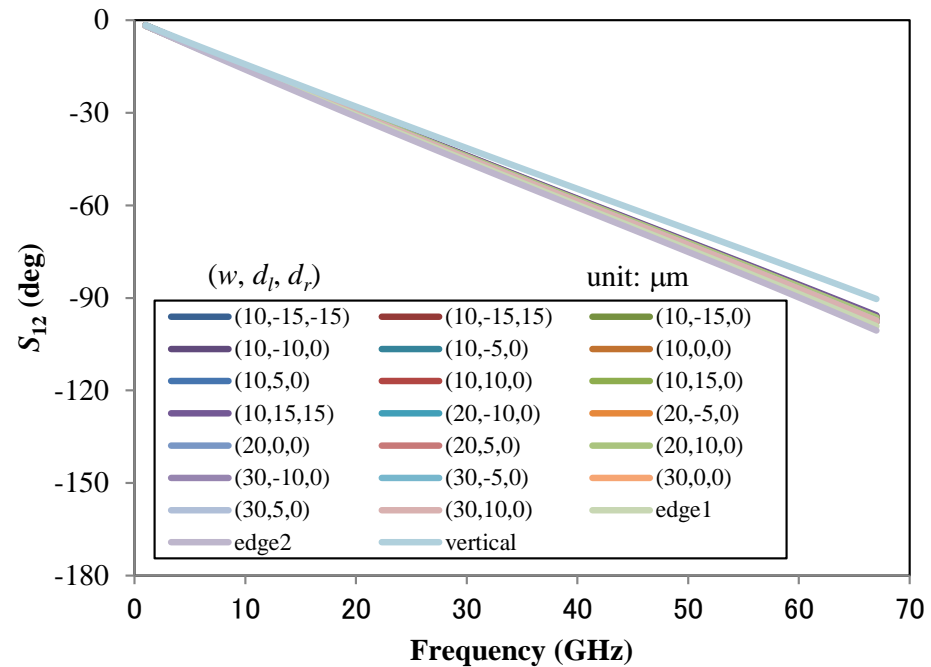


(b) Phase

透過係数 S_{21}



(a) Amplitude

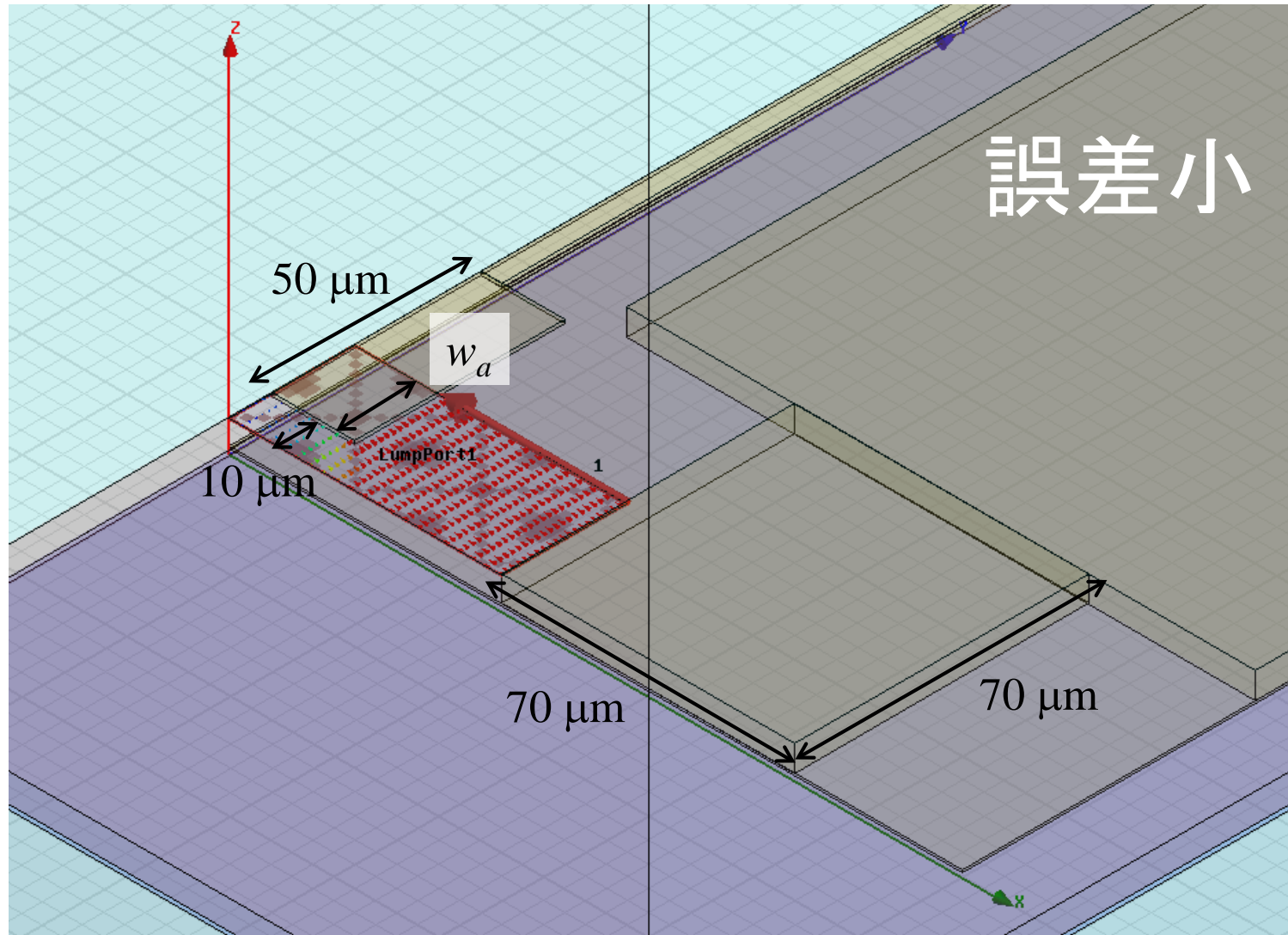


(b) Phase

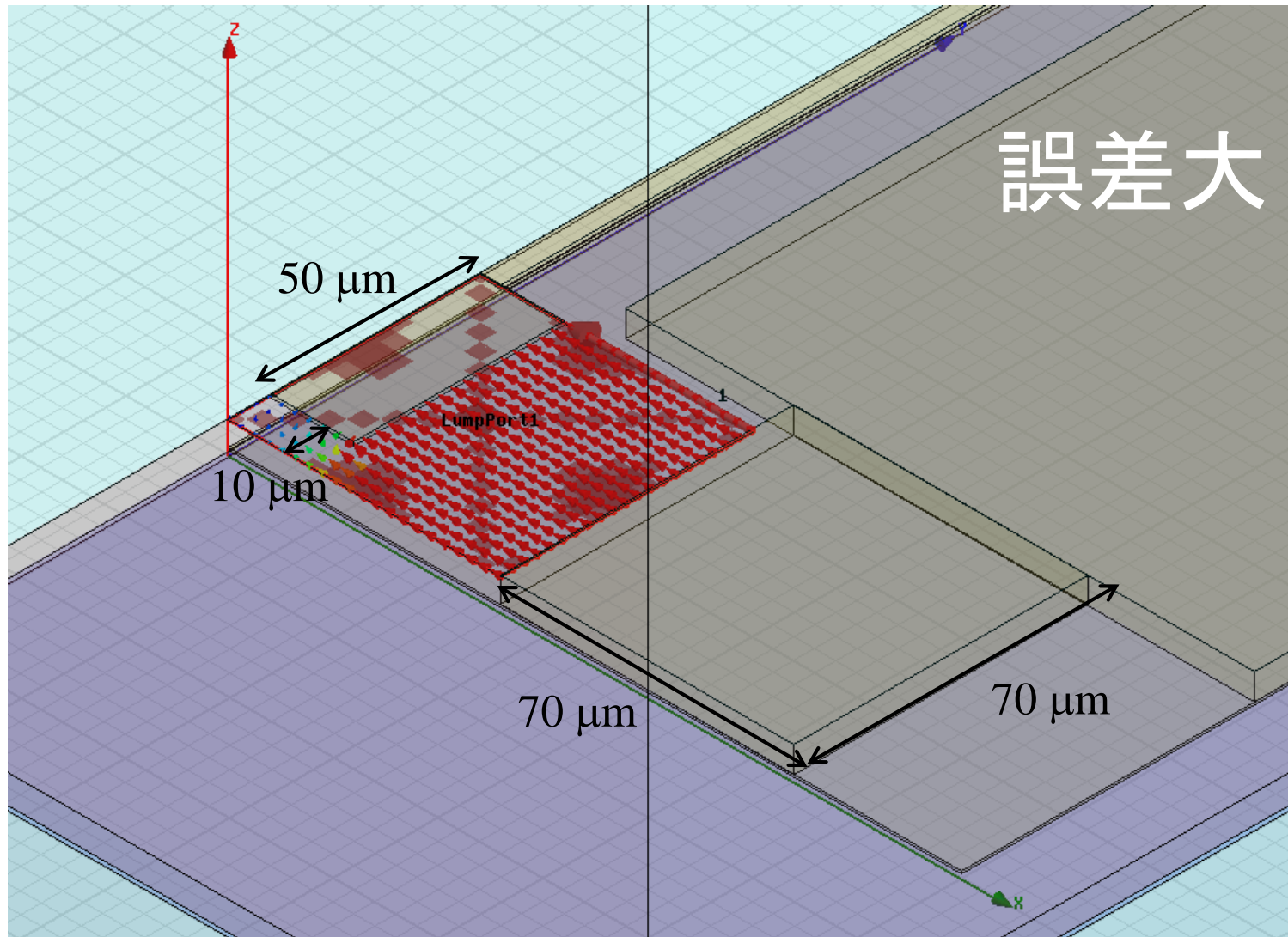
位置ずれおよび幅の影響は小さい



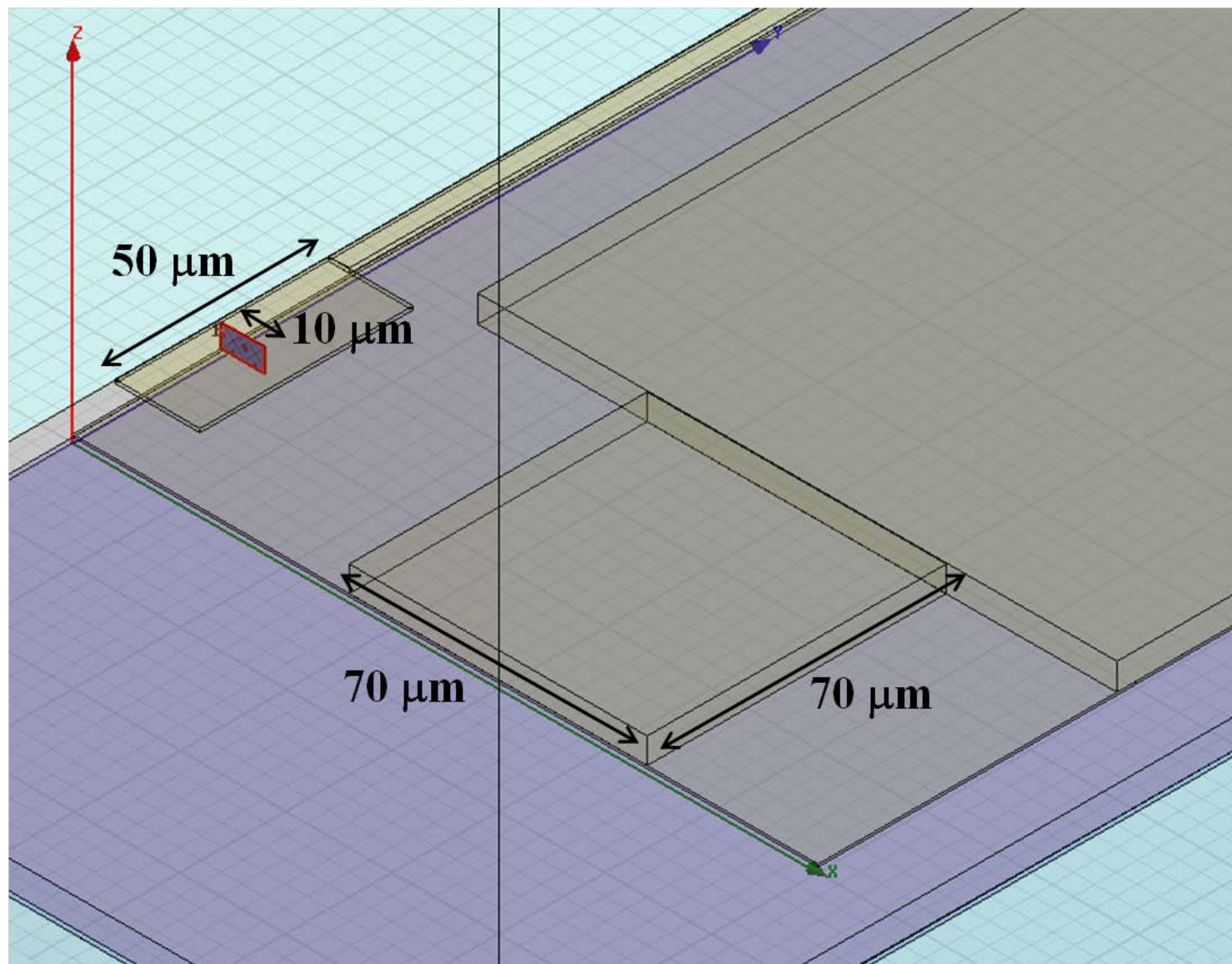
端部励振モデル1



端部励振モデル2

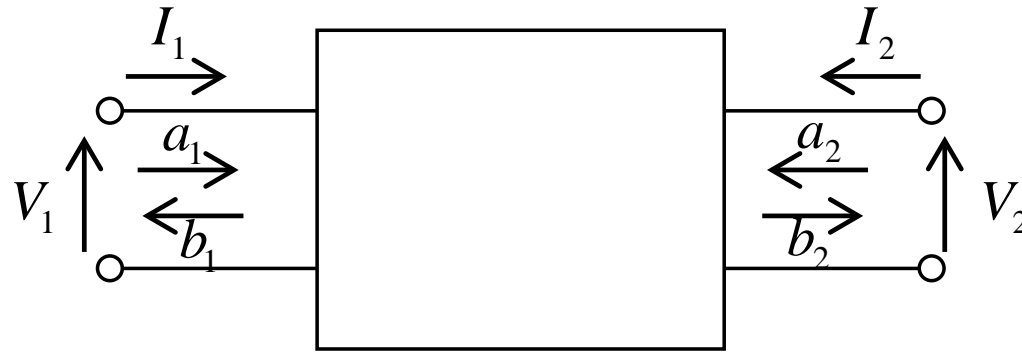


パッド下垂直励振モデル



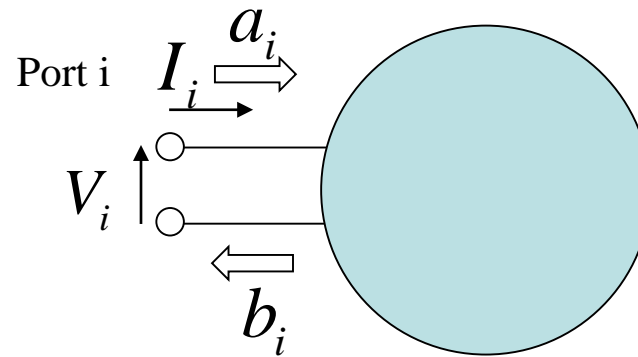
SパラメータとZパラメータ

2端子



$$\left\{ \begin{array}{l} V_i = (a_i + b_i)\sqrt{Z_i} \\ I_i = \frac{a_i - b_i}{\sqrt{Z_i}} \end{array} \right. \iff \left\{ \begin{array}{l} a_i = \frac{V_i / \sqrt{Z_i} + I_i \sqrt{Z_i}}{2} \\ b_i = \frac{V_i / \sqrt{Z_i} - I_i \sqrt{Z_i}}{2} \end{array} \right.$$

N端子



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

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

Z行列 \Rightarrow S行列

$$\begin{cases} \mathbf{a} = \frac{\text{diag}(1/\sqrt{Z_i})\mathbf{V} + \text{diag}(\sqrt{Z_i})\mathbf{I}}{2} \\ \mathbf{b} = \frac{\text{diag}(1/\sqrt{Z_i})\mathbf{V} - \text{diag}(\sqrt{Z_i})\mathbf{I}}{2} \end{cases} \quad \mathbf{V} = \mathbf{Z}\mathbf{I}$$

$$\begin{cases} \mathbf{a} = \frac{\text{diag}(1/\sqrt{Z_i})\mathbf{Z} + \text{diag}(\sqrt{Z_i})\mathbf{U}}{2} \mathbf{I} \\ \mathbf{b} = \frac{\text{diag}(1/\sqrt{Z_i})\mathbf{Z} - \text{diag}(\sqrt{Z_i})\mathbf{U}}{2} \mathbf{I} \end{cases} \quad \mathbf{I} = 2 \left[\text{diag}(1/\sqrt{Z_i})\mathbf{Z} + \text{diag}(\sqrt{Z_i})\mathbf{U} \right]^{-1} \mathbf{a}$$

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

S

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



S行列 \Rightarrow Z行列

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

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

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

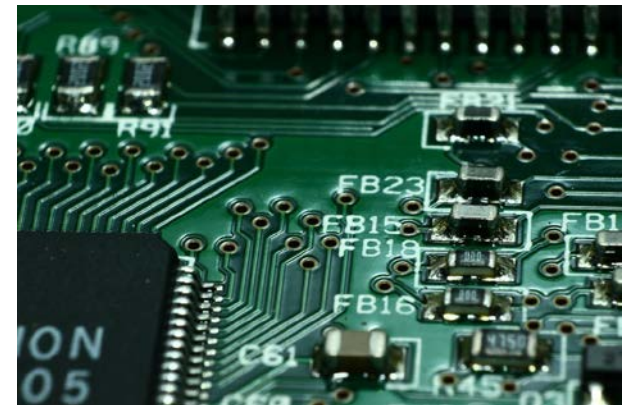
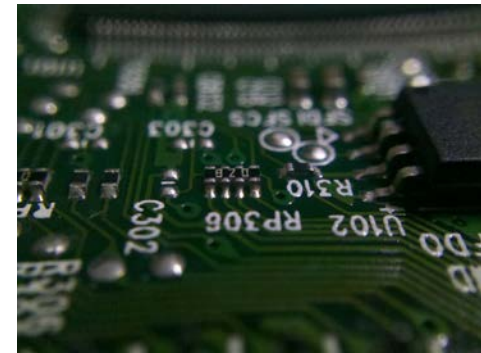
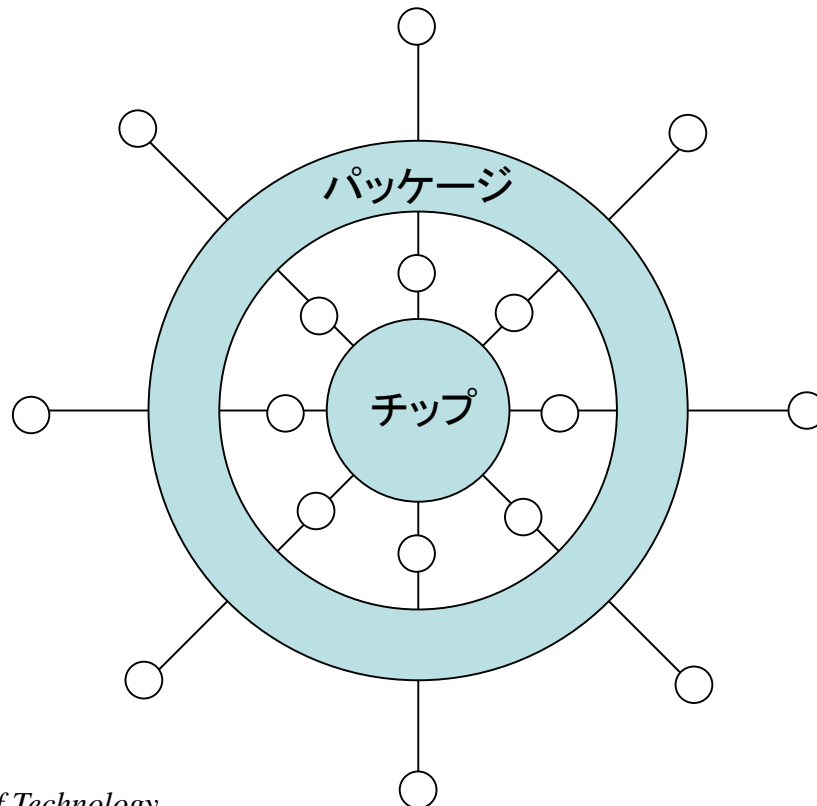
$$[Z] = -([S] - [U])^{-1}([S] + [U])[D]$$



ICとの接続

概説

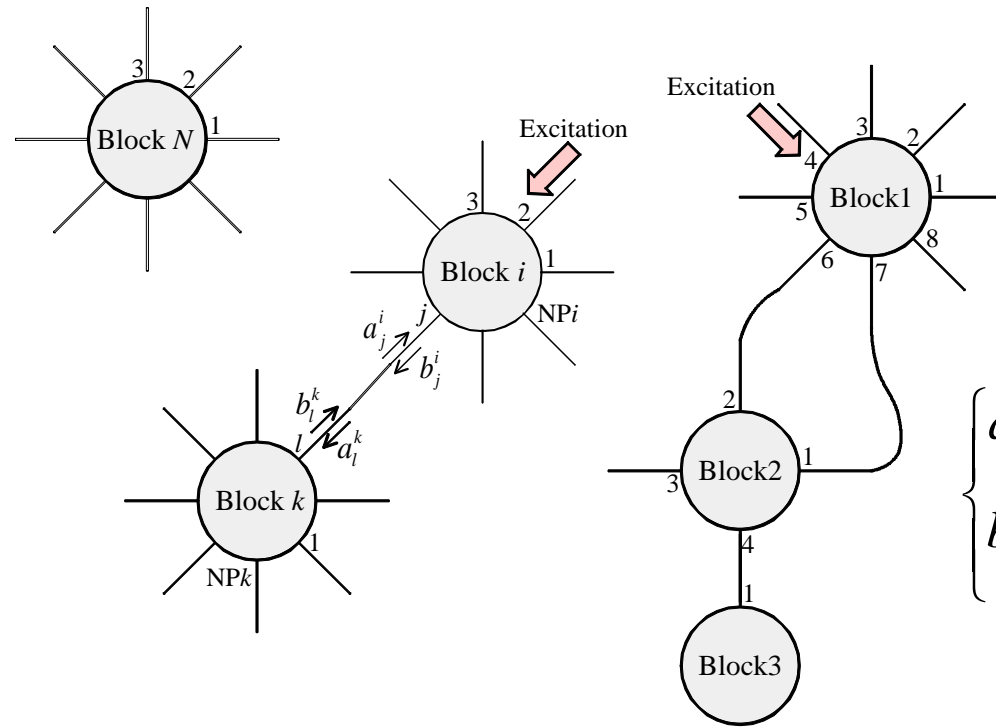
- ICをパッケージに実装した際の特性変化をシミュレーションするときなどに使われる。
- チップは集中定数素子として動作することを想定する。
- チップのパッドからボンディングワイヤ等で外部端子に出すが、その際の特性変化を電磁界シミュレーションする。



GSM Solver

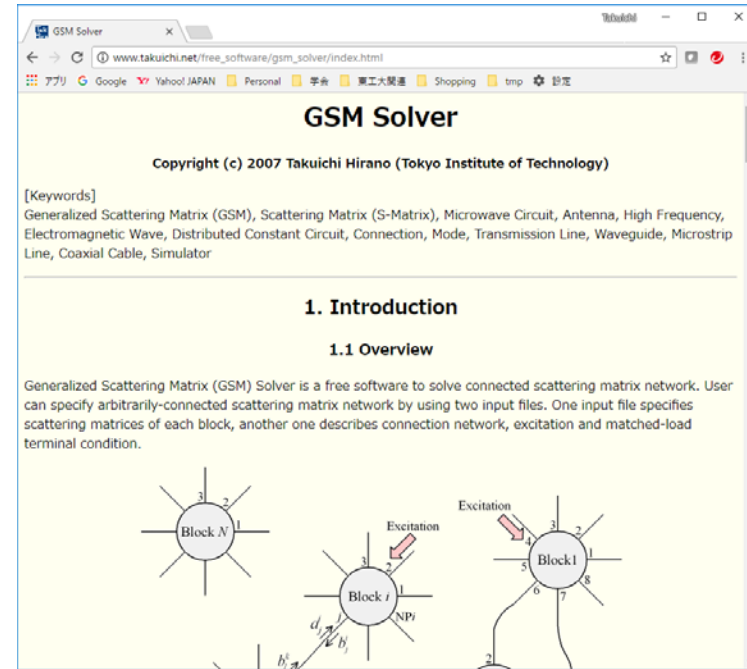
GSM Solver

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.



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

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)

The screenshot displays the COMSOL Multiphysics interface for a model named 'msl_pec_lump_port2.mph'. The left-hand 'Model Builder' shows a hierarchical tree with components like 'Global Definitions', 'Materials', 'Definitions', 'ジオメトリ 1' (containing blocks 1, 2, 4), 'Materials', '電磁波 (周波数領域) (em)', 'メッシュ 1', 'スタディ 1', and 'Results'. The central 'Properties' panel is set to 'Lumped Port 1' and shows the following configuration:

- Label: Lumped Port 1
- Boundary Selection: Manual, Selection: 11, Active
- Override and Contribution: (empty)
- Equation: (empty)
- 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

The right-hand 'Graphics' window shows a 3D wireframe model of a rectangular waveguide. The dimensions are indicated as 0.02 m in height, 0.01 m in width, and 1.5 m in length. A small blue rectangular lumped port is attached to the bottom surface of the waveguide. A coordinate system with x, y, and z axes is visible at the bottom left of the graphics window.

At the bottom of the interface, the 'Messages' window shows the following text:

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

764 MB | 934 MB



1: モデル化 (Port2)

The screenshot displays the COMSOL Multiphysics interface for a model named `msl_pec_lump_port2.mph`. The **Model Builder** on the left shows a hierarchical tree with components like `コンポーネント 1 (comp1)`, `ジオメトリ 1`, and `電磁波 (周波数領域) (em)`. The **Properties** panel in the center is set to `Lumped Port 2`. It shows a `Boundary Selection` of 14 active faces. Under `Lumped Port Properties`, the `Lumped port name` is `2`, the `Type of lumped port` is `Uniform`, the `Terminal type` is `Cable`, and the `Wave excitation at this port` is `Off`. The `Settings` section shows a `Characteristic impedance` of `50[ohm]`. The **Graphics** window on the right shows a 3D wireframe model of a rectangular waveguide with a small blue rectangular lumped port on the top surface. The dimensions are indicated as `0.02 m` for the width and `0.01 m` for the depth. The **Messages** window at the bottom shows the file path: `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)

The screenshot displays the COMSOL Multiphysics interface for a model named 'msl_pec_Jump_port2.mph'. The 'Model Builder' tree on the left shows the hierarchy: Global Definitions, Parameters, Materials, Component 1 (comp1), Definitions, Geometry 1, and Materials. Under Materials, the 'Scattering Boundary Condition 1' is selected. The 'Properties' pane on the right shows the configuration for this boundary condition: Label '散乱境界条件 1', Boundary Selection 'Manual' (with a list of active boundaries 1, 2, 4, 5, 7, 8), Coordinate System 'Global coordinate system', Incident field 'No incident field', Scattered wave type 'Plane wave', and Order 'First order'. The 'Graphics' window shows a 3D perspective view of a rectangular block with dimensions 0.02 m (width), 0.01 m (depth), and 1.5 m (height). The top surface is highlighted in blue, indicating the selected boundary condition. A coordinate system (x, y, z) is shown at the bottom left of the graphics window. The 'Messages' pane at the bottom right shows the file path: 'G:\Home\hira2\public_html\em_analysis\canonical\msl\msl_pec_Jump_port2.mph'. The status bar at the bottom indicates '735 MB | 916 MB'.

1: モデル化 (電気壁1)

The screenshot displays the COMSOL Multiphysics interface for a model named `msl_pec_lump_port2.mph`. The **Model Builder** on the left shows a hierarchical tree with components like **Global Definitions**, **Materials**, **コンポーネント 1 (comp1)**, **ジオメトリ 1**, and **電磁波 (周波数領域) (em)**. Under **電磁波 (周波数領域) (em)**, the **電気壁 (PEC) 1** component is selected.

The **Properties** panel in the center shows the settings for **Perfect Electric Conductor**. The **Label** is `電気壁 (PEC) 1`. Under **Boundary Selection**, the **Selection** is set to `All boundaries`. A list of boundaries is shown, with `1 (overridden)` through `5 (overridden)` listed. The **Active** checkbox is checked.

The **Graphics** window on the right shows a 3D perspective view of the model. It features a rectangular domain with a central slot. The dimensions are indicated: the width of the slot is `0.01` m, the depth is `0.02` m, and the height is `1.5` m. The **PEC 1** boundary is highlighted in blue. A coordinate system with `x`, `y`, and `z` axes is visible at the bottom left of the graphics window.

The **Messages** window at the bottom shows the following text:

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

At the bottom of the interface, the memory usage is displayed as `745 MB | 929 MB`.

1: モデル化 (電気壁2)

The screenshot displays the COMSOL Multiphysics interface for a model named `mst_pec_lump_port2.mph`. The **Model Builder** on the left shows the following structure:

- 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 (i)
 - Materials
 - 電磁波 (周波数領域) (em)
 - 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
- Results
 - Data Sets
 - Views
 - Derived Values
 - Tables
 - 電場 (emw)
 - Export
 - Reports

The **Properties** panel in the center shows the settings for the selected **Perfect Electric Conductor** (Label: 電気壁 (PEC) 2):

- Boundary Selection
 - Selection: Manual
 - Active: 13
- Override and Contribution
- Equation

The **Graphics** window on the right shows a 3D view of a rectangular cavity with a blue rectangular PEC strip on the bottom surface. The dimensions are indicated as 0.02 m in the x-direction, 0.01 m in the y-direction, and 1.5 m in the z-direction. The PEC strip is centered along the x-axis and extends from $y = -0.01$ to $y = 0.01$ and $z = 0$ to $z = 0.01$.

The **Messages** window at the bottom shows the following text:

```
COMSOL Multiphysics 5.3.0.260
Opened file: G:\Home\hira2\public_html\em_analysis\canonical\mst\mst_pec_lump_port2.mph
```

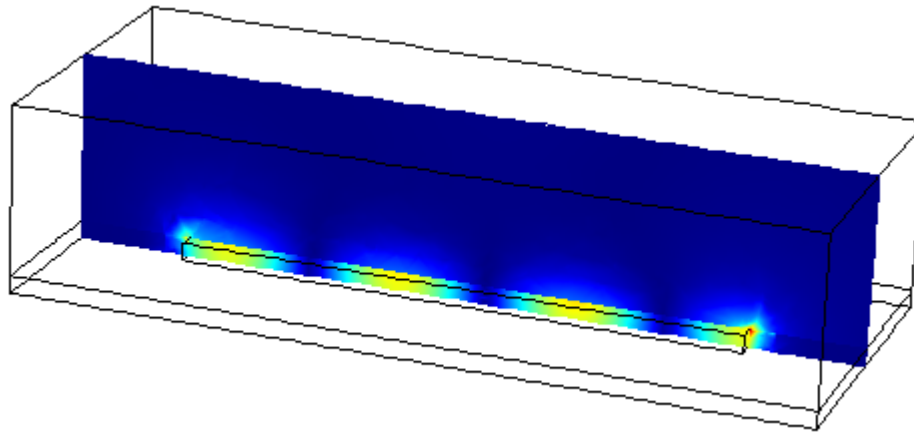
744 MB | 931 MB

2: 解析条件 (周波数領域)

The screenshot displays the COMSOL Multiphysics software interface for a model named 'msl_pec_lump_port2.mph'. The interface is divided into several main sections:

- Model Builder:** Shows a hierarchical tree of the model. The 'Study 1' is set to 'Frequency Domain'. The physics interface is 'Electromagnetics (emw)'. The study step is 'Step 1: Frequency Domain'.
- Settings / Properties:** The 'Frequency Domain' settings are visible. The label is '周波数領域'. The frequency unit is 'GHz' and the frequency is '5 GHz'. The 'Load parameter values' and 'Reuse solution from previous step' options are also shown.
- Graphics:** A 3D wireframe view of the model is shown. It depicts a rectangular waveguide structure with a central rod. The dimensions are indicated in meters (m), with values like 0.02, 0, -0.02, 0.01, 0, 0.5, and 1. A coordinate system (x, y, z) is shown at the bottom left.
- Messages:** The bottom right panel shows the message log, indicating the file path: 'G:\Home\hira2\public_html\em_analysis\canonical\msl\msl_pec_lump_port2.m'.

At the bottom of the window, the memory usage is shown as '766 MB | 941 MB'.



freq (GHz)
5.0000

S パラメーター (dB), 11 成分 (dB)
-18.779

S パラメーター (dB), 21 成分 (dB)
-0.35669