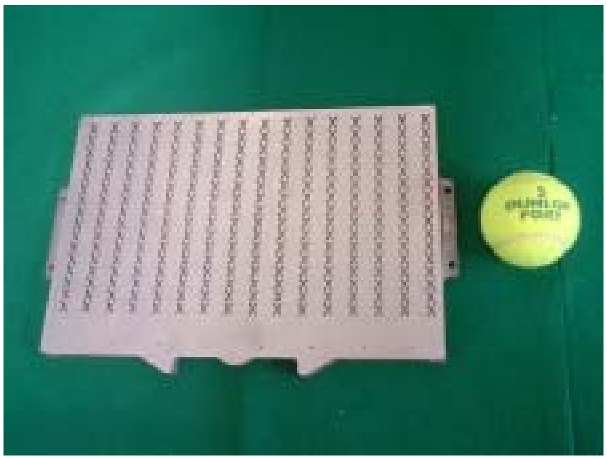
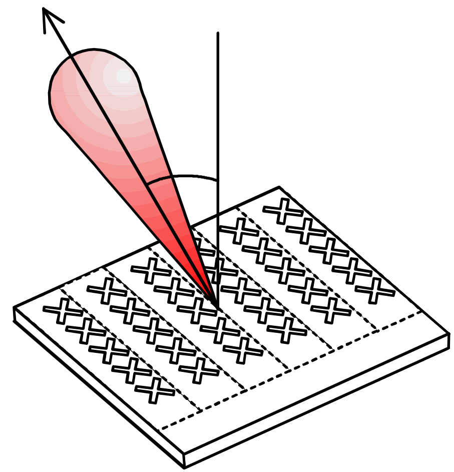
導波管スロットアンテナの数値固有モード基底関数を用いたモーメント法解析





Tokyo Institute of Technology
Ando and Hirokawa Lab.
Takada Lab.

Takuichi Hirano

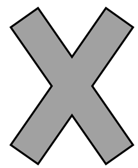
Outline

- ✧なぜMoM/FEM解析法が必要になったのか？
- ✧MoM/FEM解析法の説明
- ✧導波管クロススロットアレーの設計

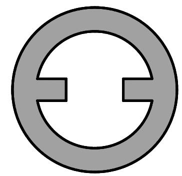
Objective

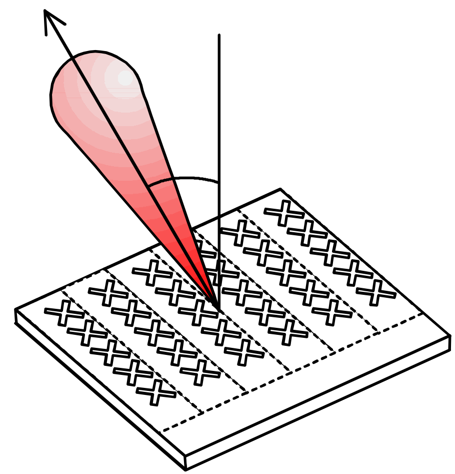
導波管クロススロットアレーの設計
複雑 (任意) な形状を有するスロットの解析

円偏波放射素子



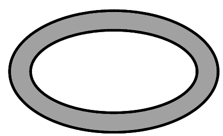
クロススロット





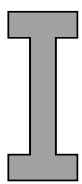
ノッチ付リングスロット

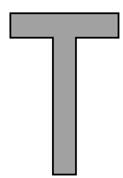
楕円スロット



など

円偏波放射素子

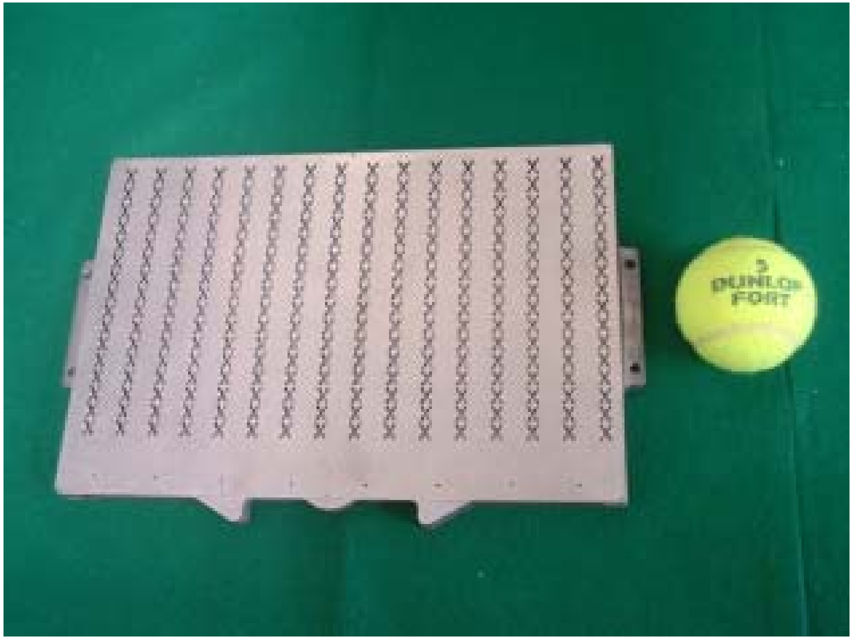


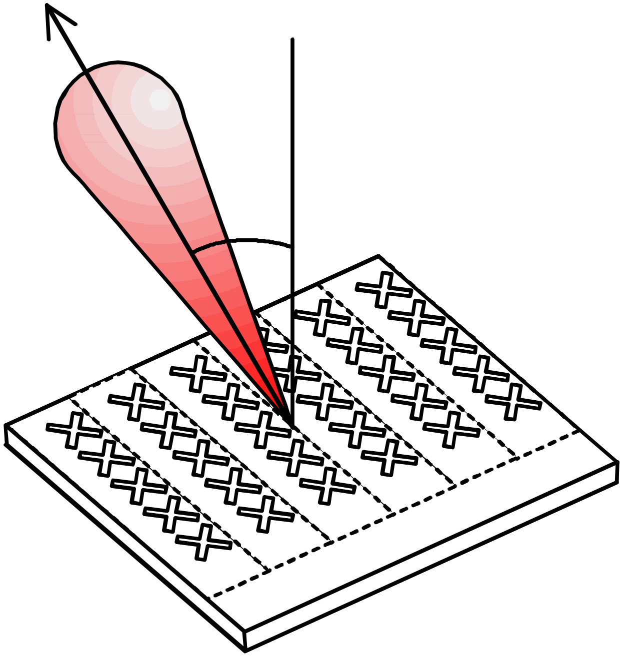


I字型スロット

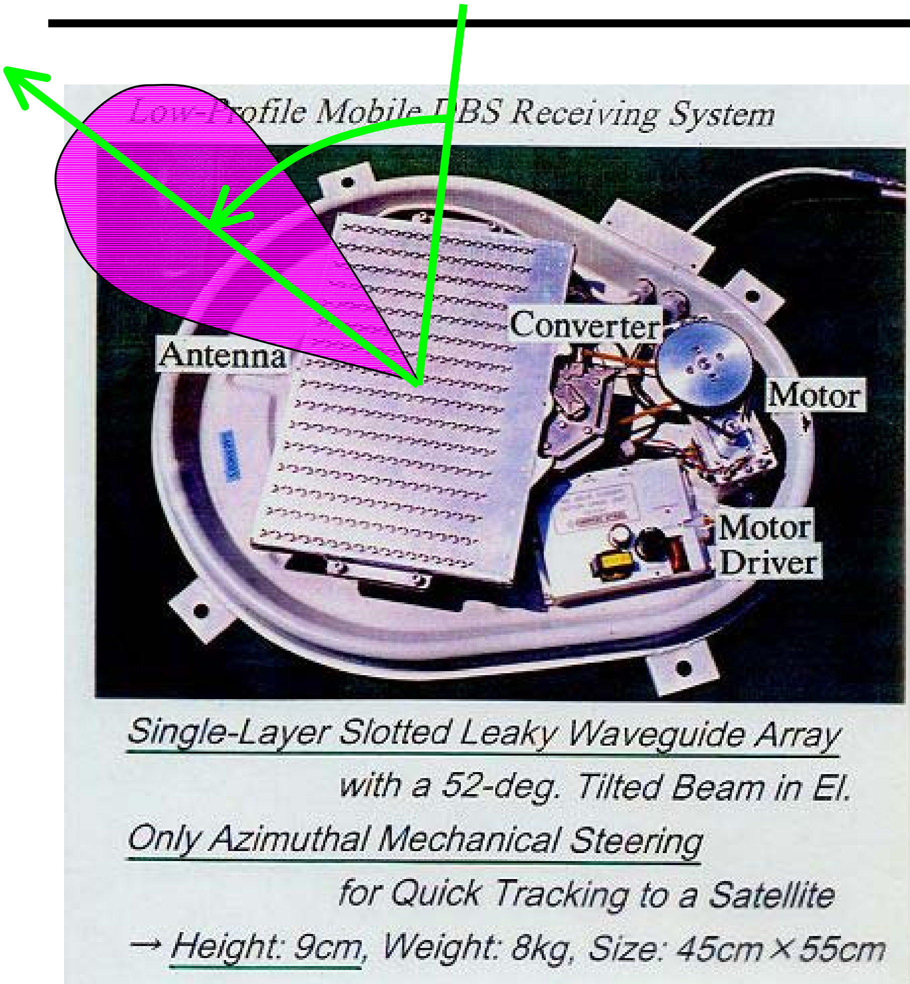
T字型スロット

Waveguide Crossed Slot Array





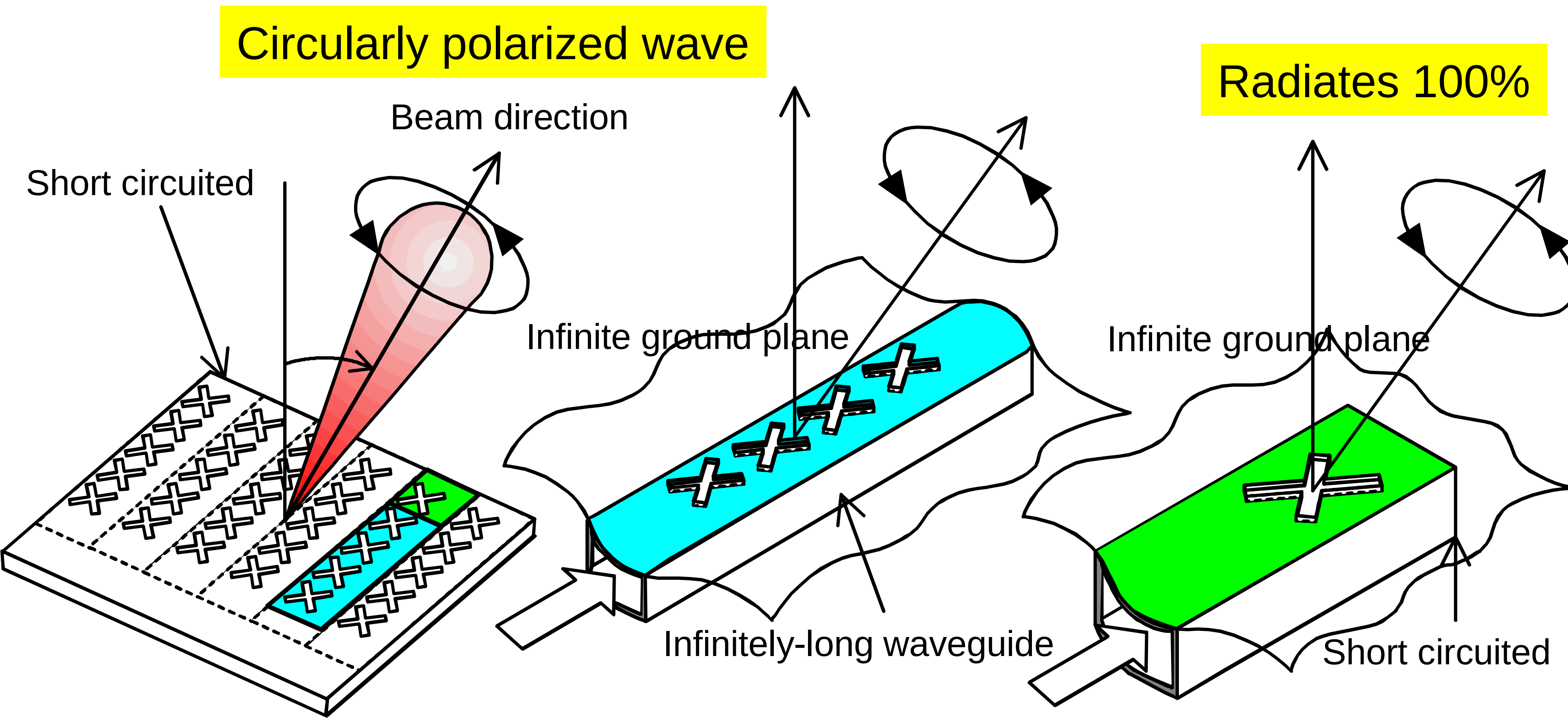
Past Work



MotorFan 1994. 11

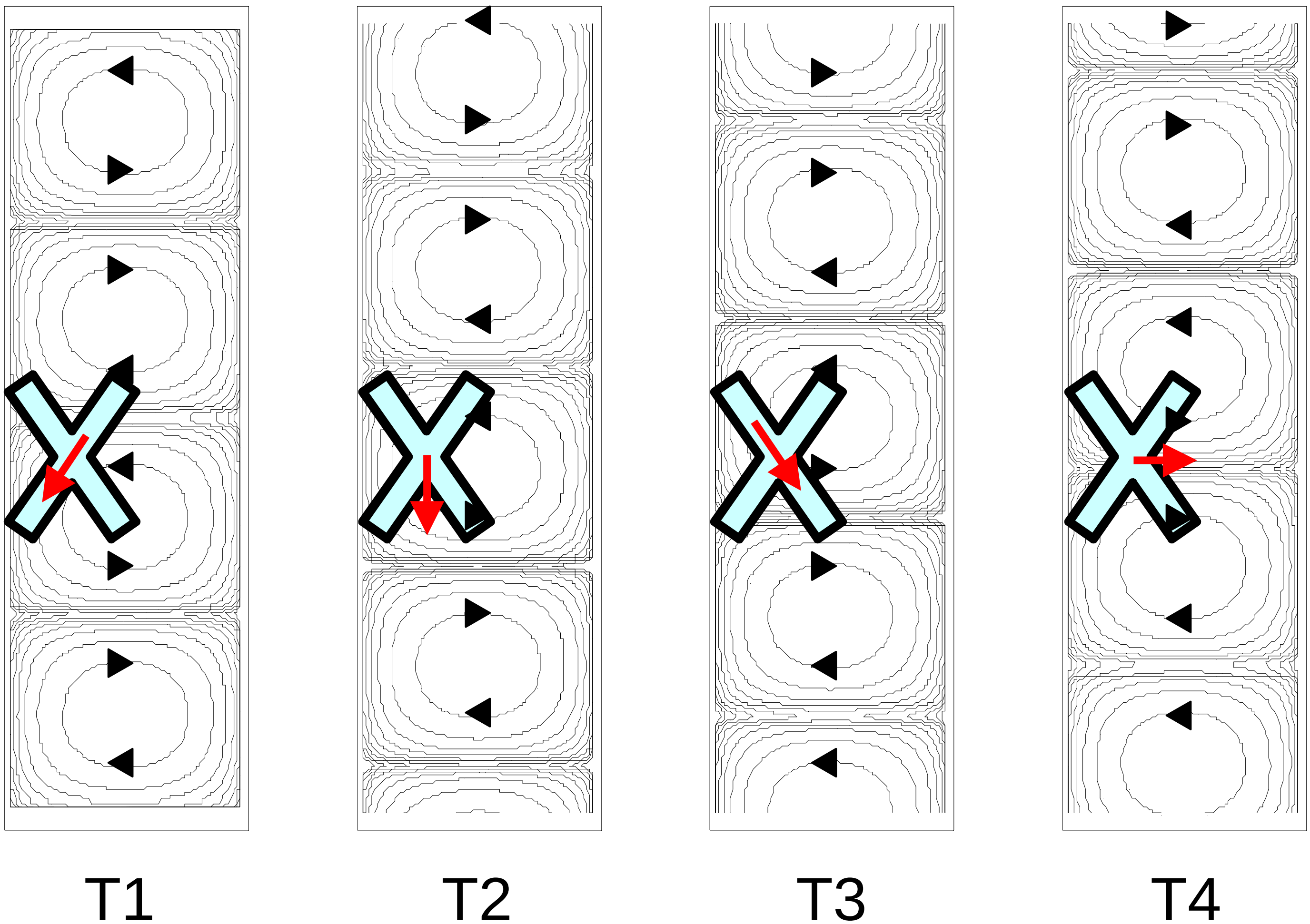
2本の直線スロットの合成として解析 → 正確ではない

A Waveguide Crossed Slot Array



(a) A waveguide crossed-slot array (b) A waveguide crossed-slot linear array (c) A waveguide matching crossed-slot

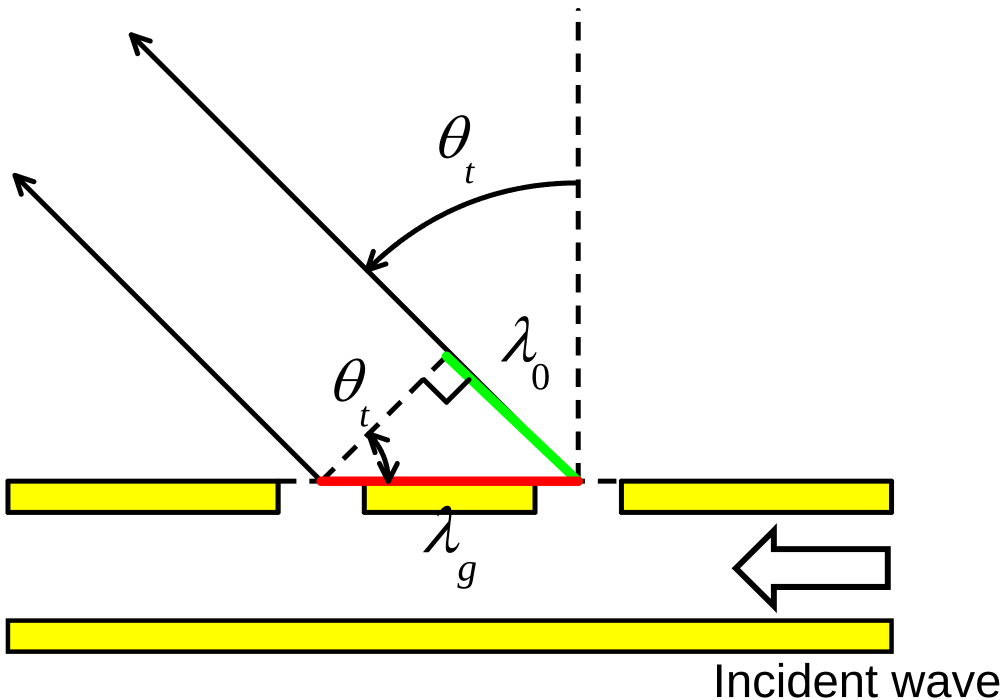
クロススロットの円偏波放射原理（直感的説明）



Principle of Leaky-wave Operation

$$\lambda_g \sin\theta_t = \lambda_0$$

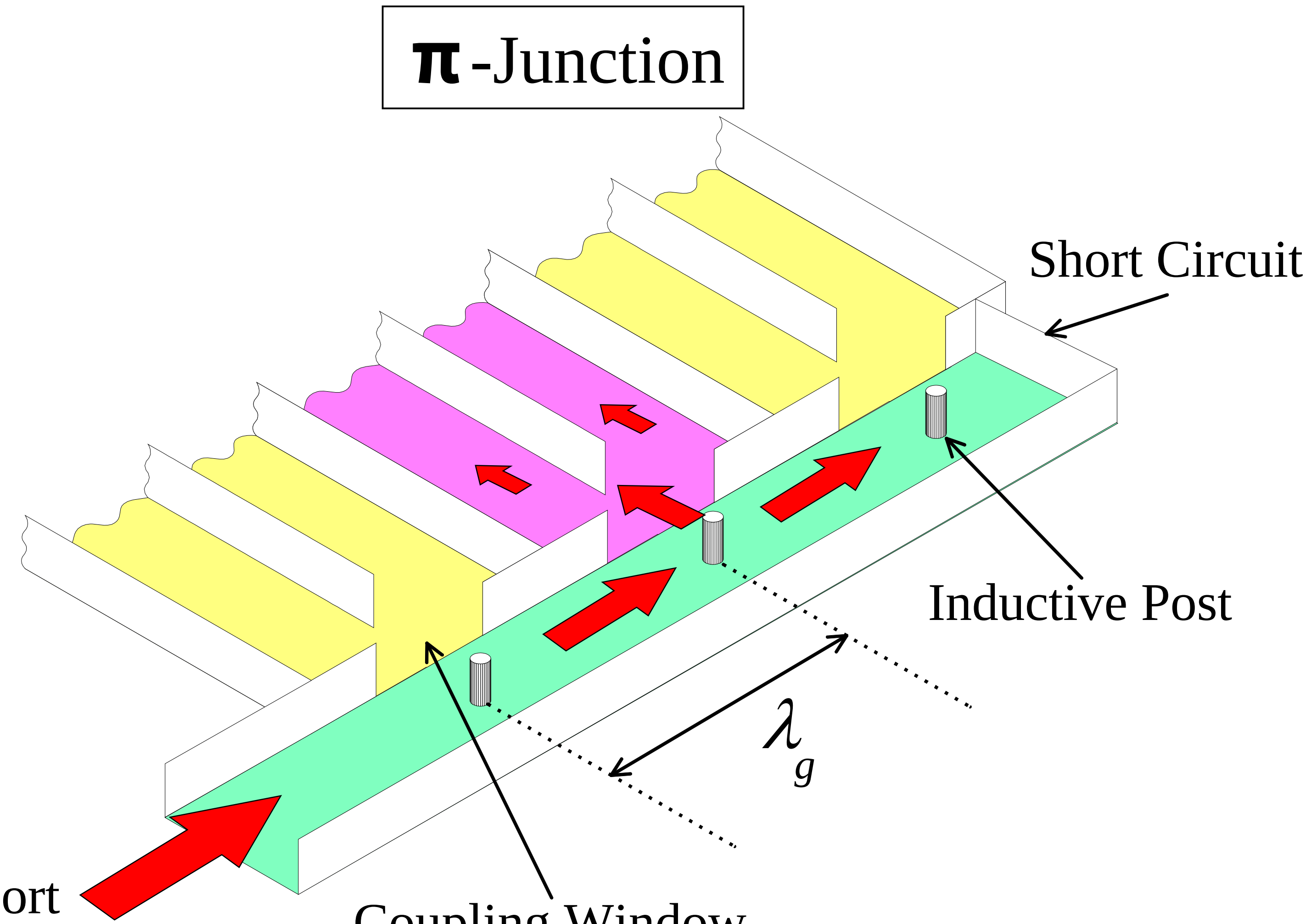
$$\sin\theta_t = \frac{\lambda_0}{\lambda_g}$$



This relation is satisfied when the slot spacing is not equal to one guide wavelength.

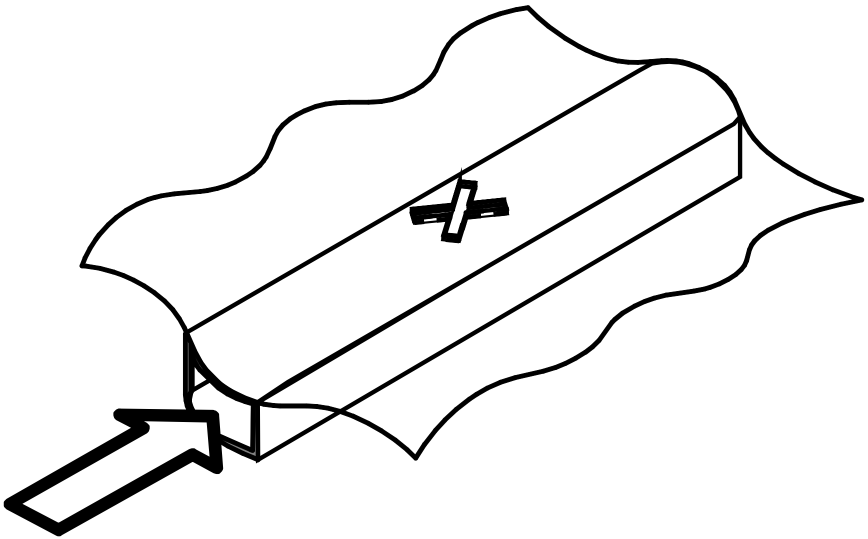
Beam direction is independent of slot spacing

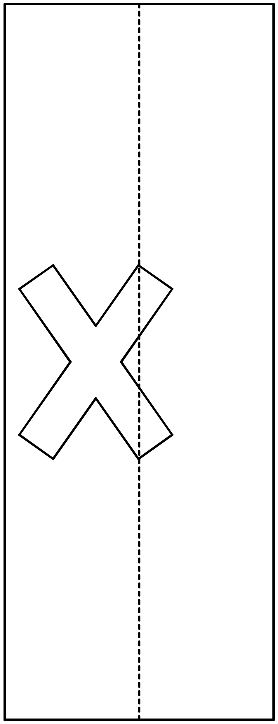
Feeding Waveguide



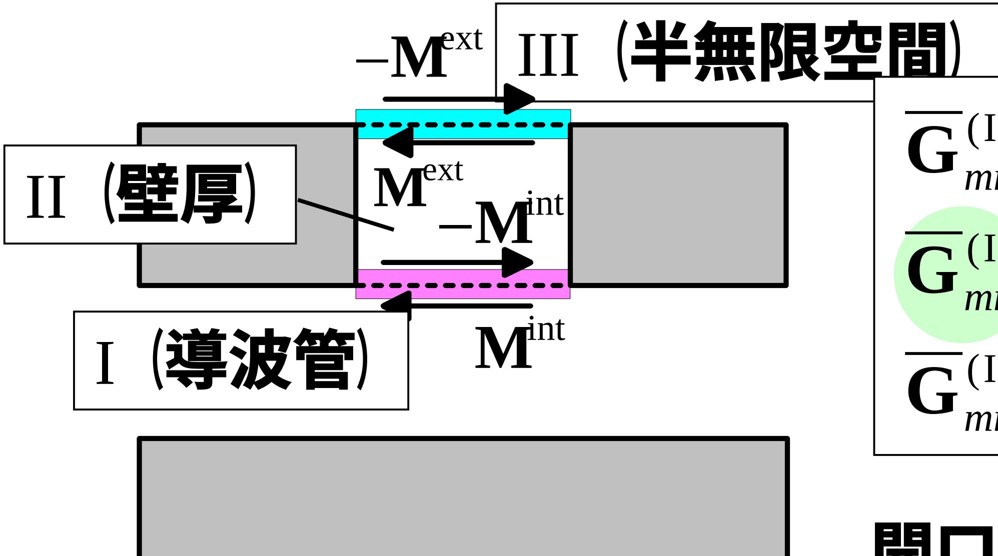
Analysis of One Slot

解析法の確立＆確認





Integral Equations



$\overline{\mathbf{G}}_{mm}^{(\mathrm{I})}$　領域 I のグリーン関数

$\overline{\mathbf{G}}_{mm}^{(\mathrm{II})}$　領域 II のグリーン関数

$\overline{\mathbf{G}}_{mm}^{(\mathrm{III})}$　領域 III のグリーン関数

開口面上の磁界の連続条件

$$\iint_{S_{\mathrm{int}}} \overline{\mathbf{G}}_{mm}^{(\mathrm{II})} \cdot (-\mathbf{M}^{\mathrm{int}})\, dS + \iint_{S_{\mathrm{ext}}} \overline{\mathbf{G}}_{mm}^{(\mathrm{II})} \cdot \mathbf{M}^{\mathrm{ext}}\, dS = \iint_{S_{\mathrm{int}}} \overline{\mathbf{G}}_{mm}^{(\mathrm{III})} \cdot (-\mathbf{M}^{\mathrm{ext}})\, dS$$

$$\iint_{S_{\mathrm{int}}} \overline{\mathbf{G}}_{mm}^{(\mathrm{I})} \cdot \mathbf{M}^{\mathrm{int}}\, dS = \iint_{S_{\mathrm{int}}} \overline{\mathbf{G}}_{mm}^{(\mathrm{II})} \cdot (-\mathbf{M}^{\mathrm{int}})\, dS + \iint_{S_{\mathrm{ext}}} \overline{\mathbf{G}}_{mm}^{(\mathrm{II})} \cdot \mathbf{M}^{\mathrm{ext}}\, dS$$

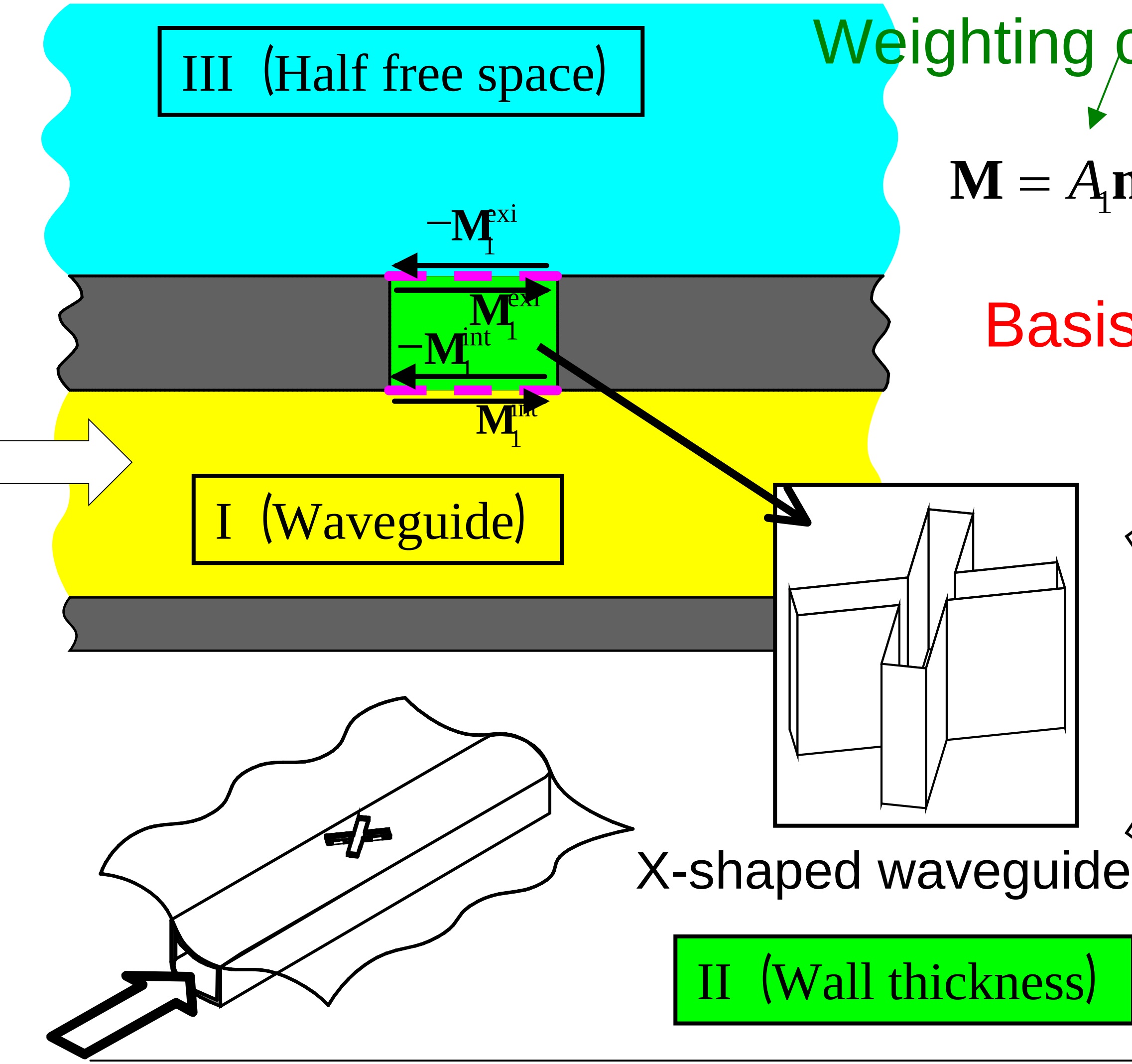
→ 連立積分方程式

MoM/FEM Analysis

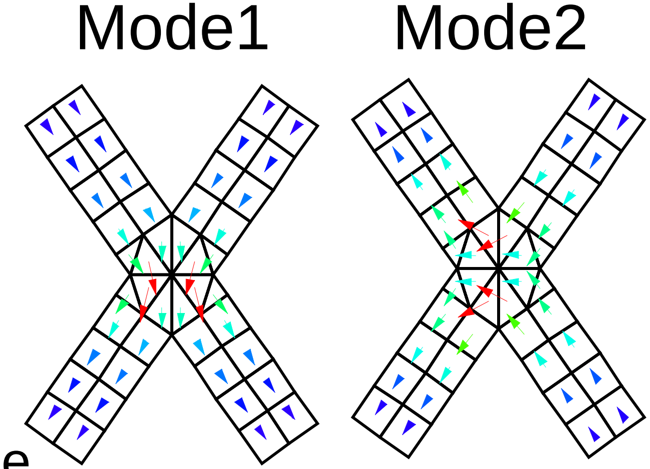
Weighting coefficients (by MoM)

$$\mathbf{M} = A_1\mathbf{m}_1 + A_2\mathbf{m}_2 + A_3\mathbf{m}_3 + \cdots$$

Basis functions (by FEM)

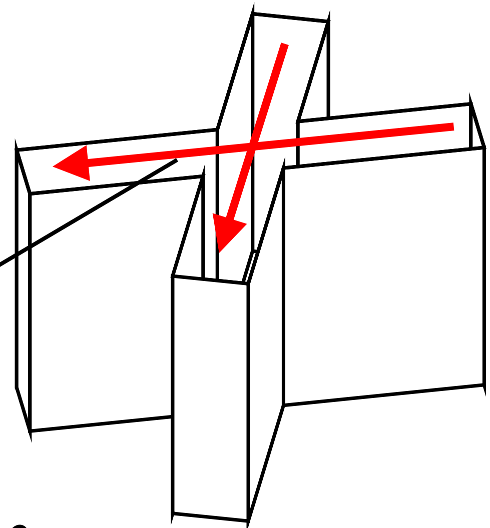


X-shaped waveguide



Eigenmode functions

Effect of the Wall Thickness



Self-reaction

Magnetic field mode function

Electric field mode function

$$y_{ii} = -\sum_{u} \coth(\gamma_u t) \underbrace{\iint_{S_1} \overbrace{(\mathbf{e}_i \times \hat{\mathbf{n}})}^{\mathbf{m}_i} \cdot \mathbf{h}_u \, dS_o}_{(=\delta_{iu})} \iint_{S_1} (\mathbf{e}_i \times \hat{\mathbf{n}}) \cdot \mathbf{h}_u \, dS_s$$

$$= -\coth(\gamma_i t)$$

Orthogonality of mode functions

No mode summation

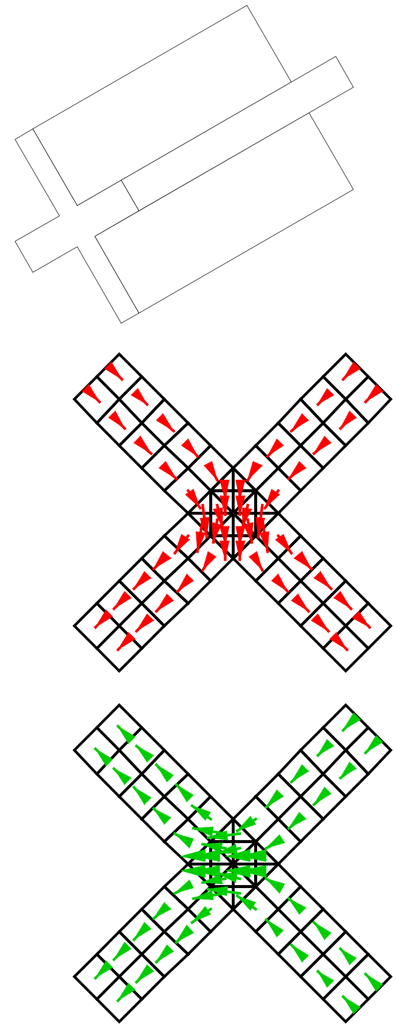
Edge-based FEM

固有値問題

$$A\mathbf{x} = \lambda \mathbf{x}$$

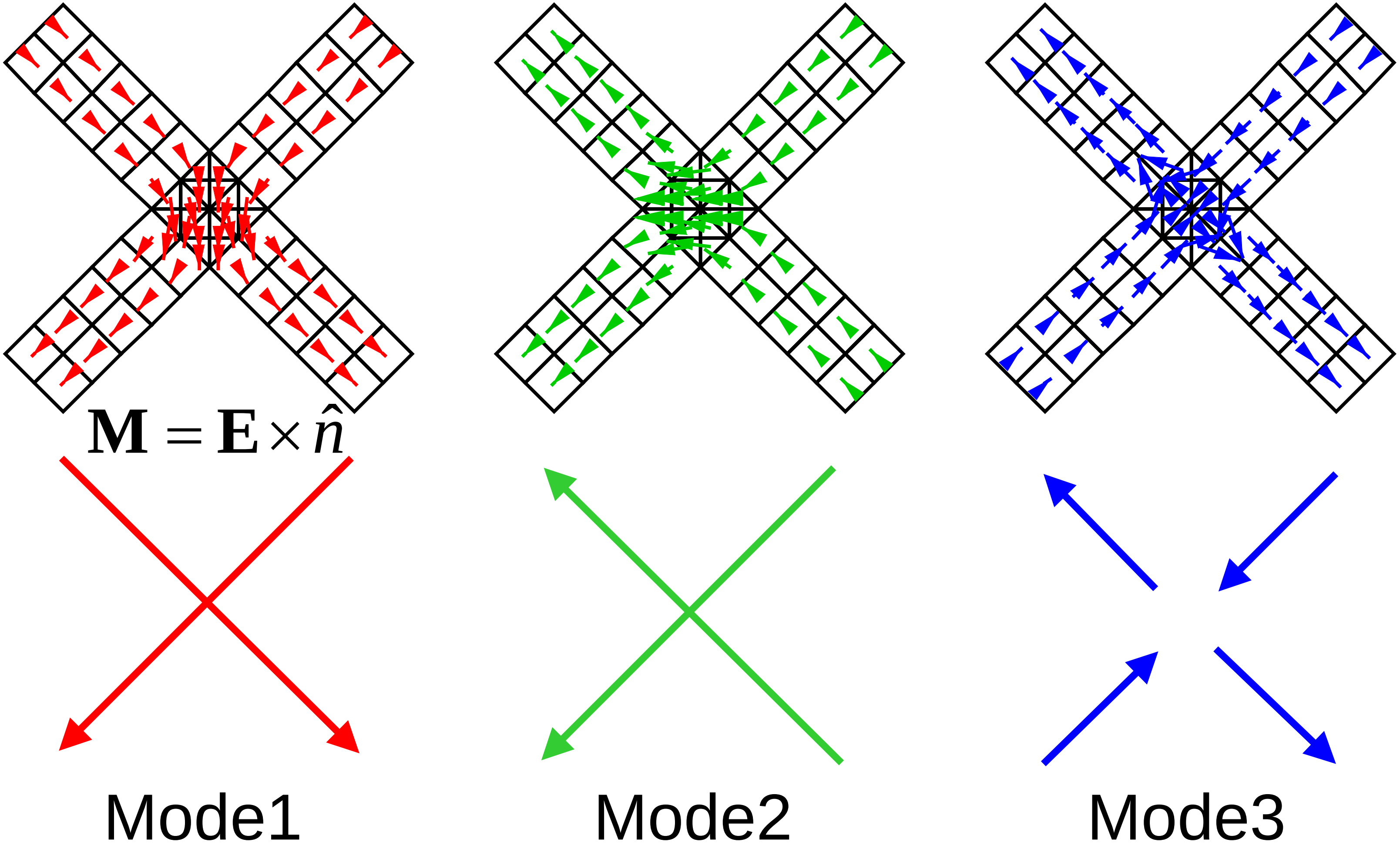
固有値
→カットオフ周波数fcu

固有ベクトル
→固有モード関数の界分布

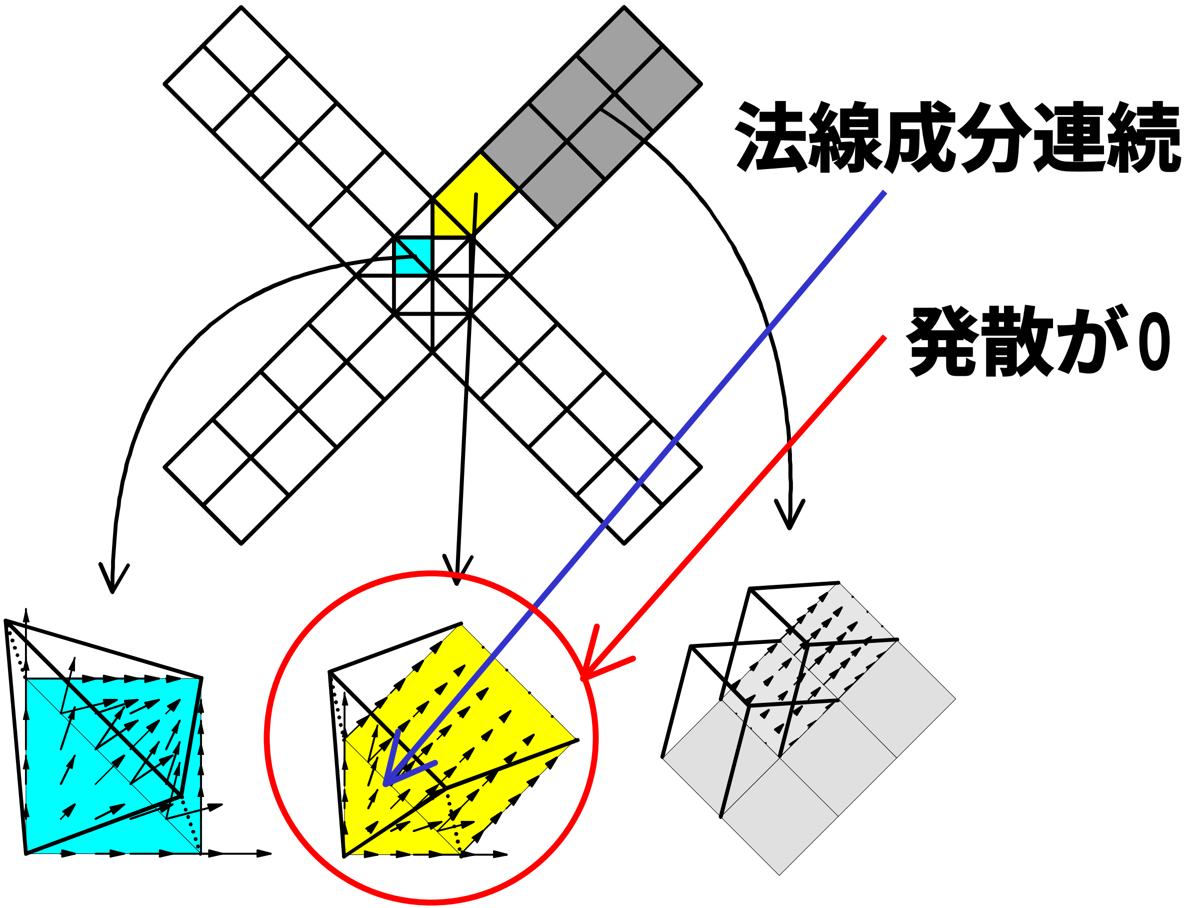


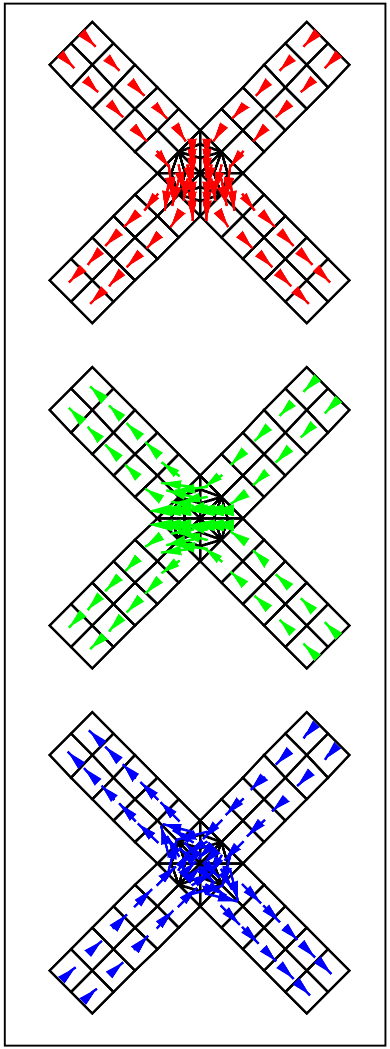
$$\mathbf{E}_u(\mathbf{r}) = \left\{ \mathbf{e}_{ut}(\mathbf{r}) + \mathbf{e}_{uz}(\mathbf{r}) \right\} e^{-\gamma_u z}$$

Eigenmode Basis Functions



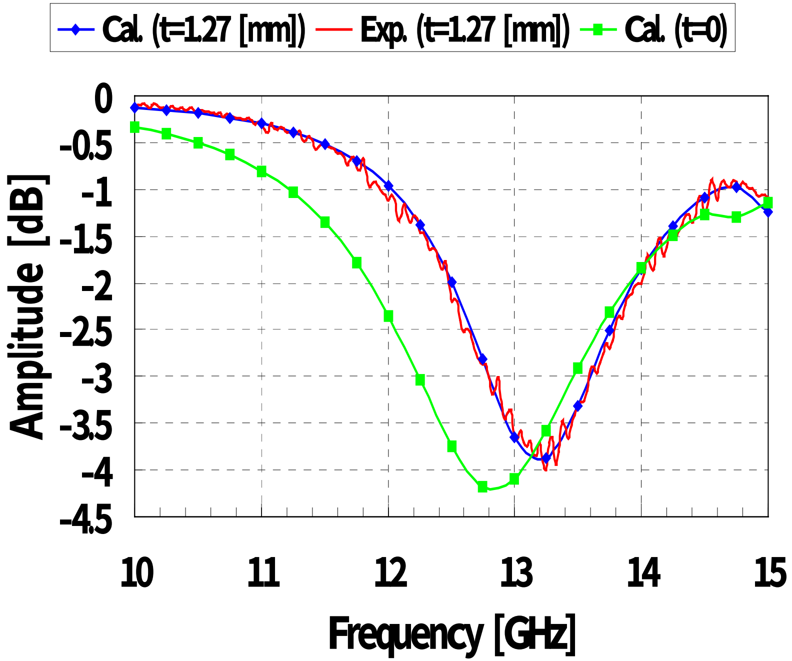
ルーフトップ関数

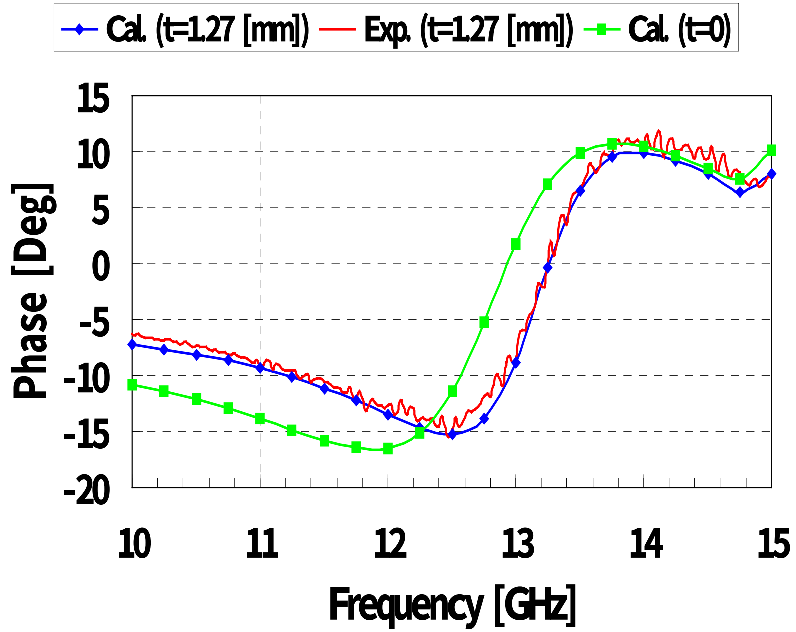


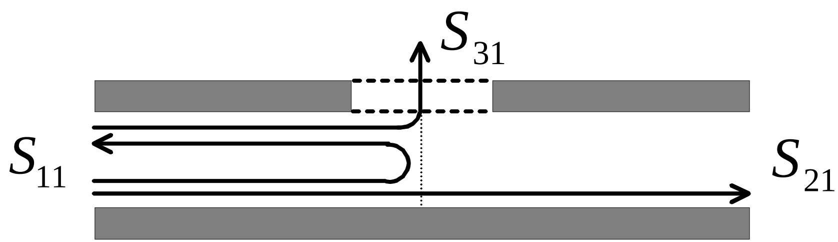


Edge-based FEM 基底関数=MoM ルーフトップ関数
→ MoM のリアクションを従来の方法で計算できる

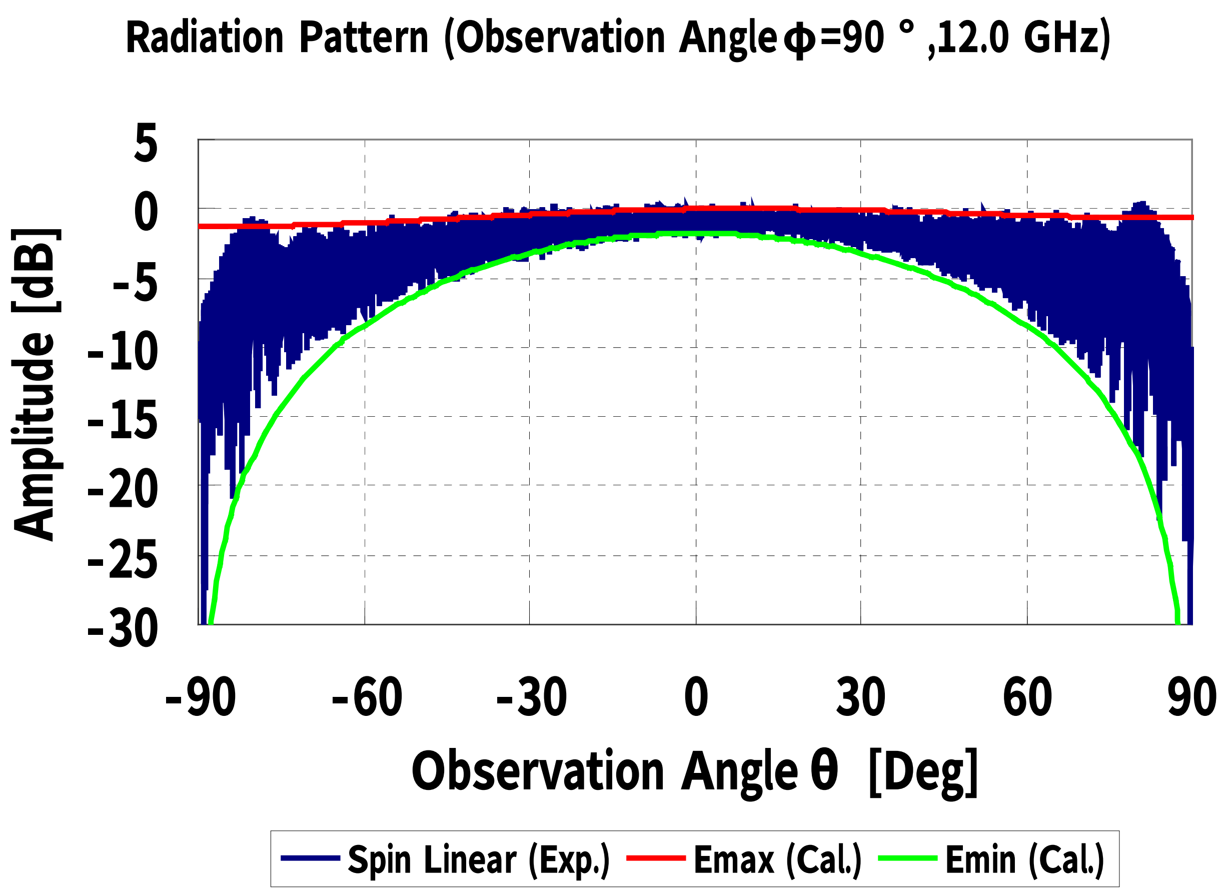
Frequency vs. S21

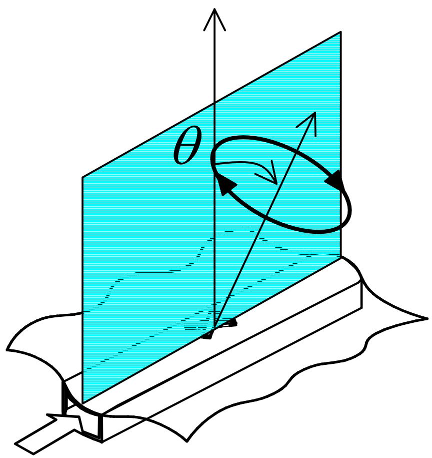


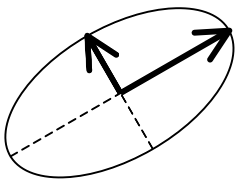




Radiation Pattern

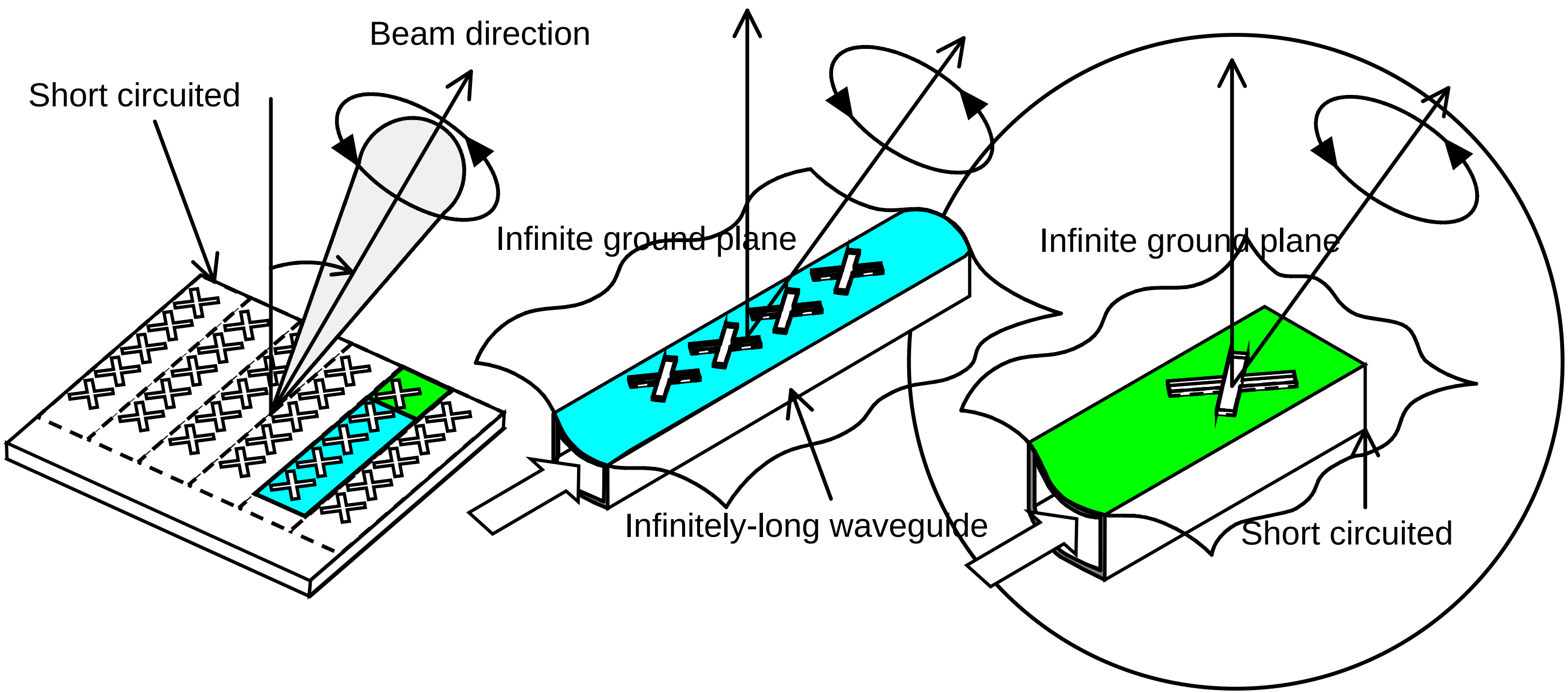




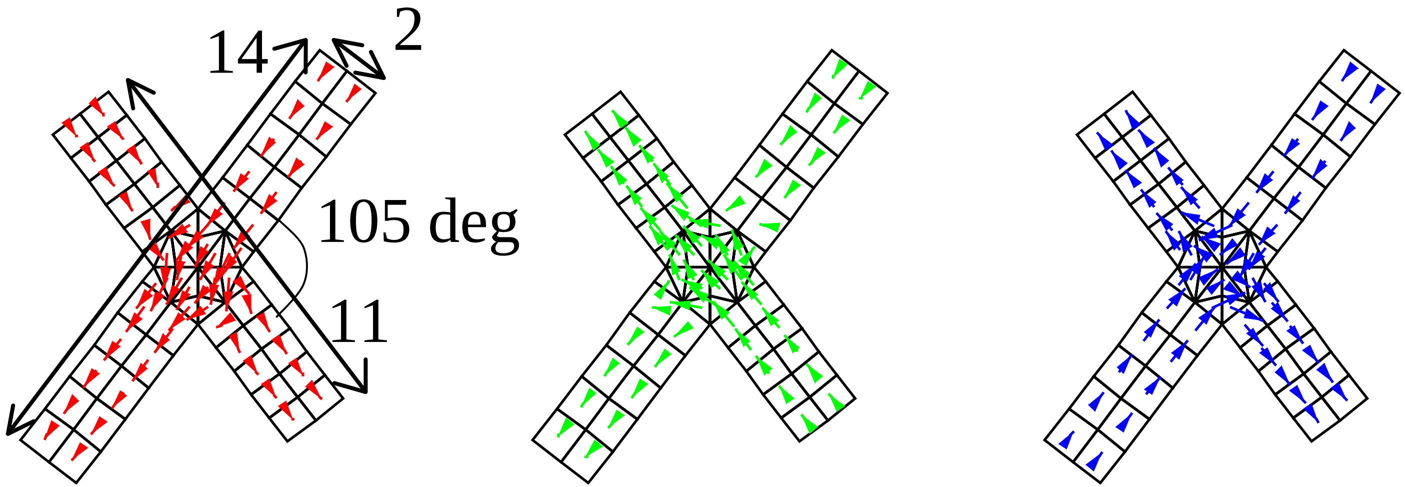


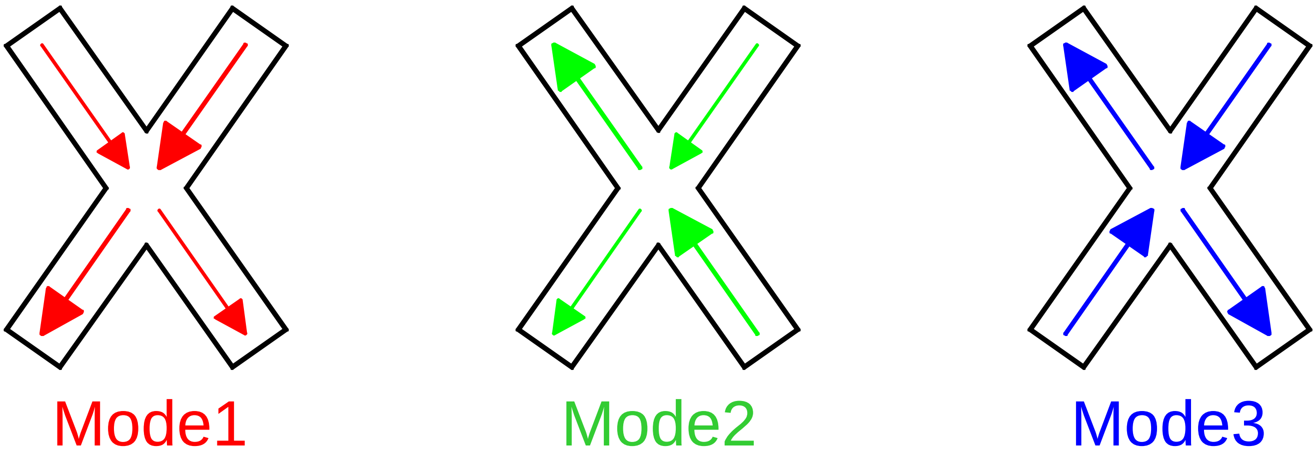
解析法の信頼性を確認できた

Analysis of a Matching Crossed Slot



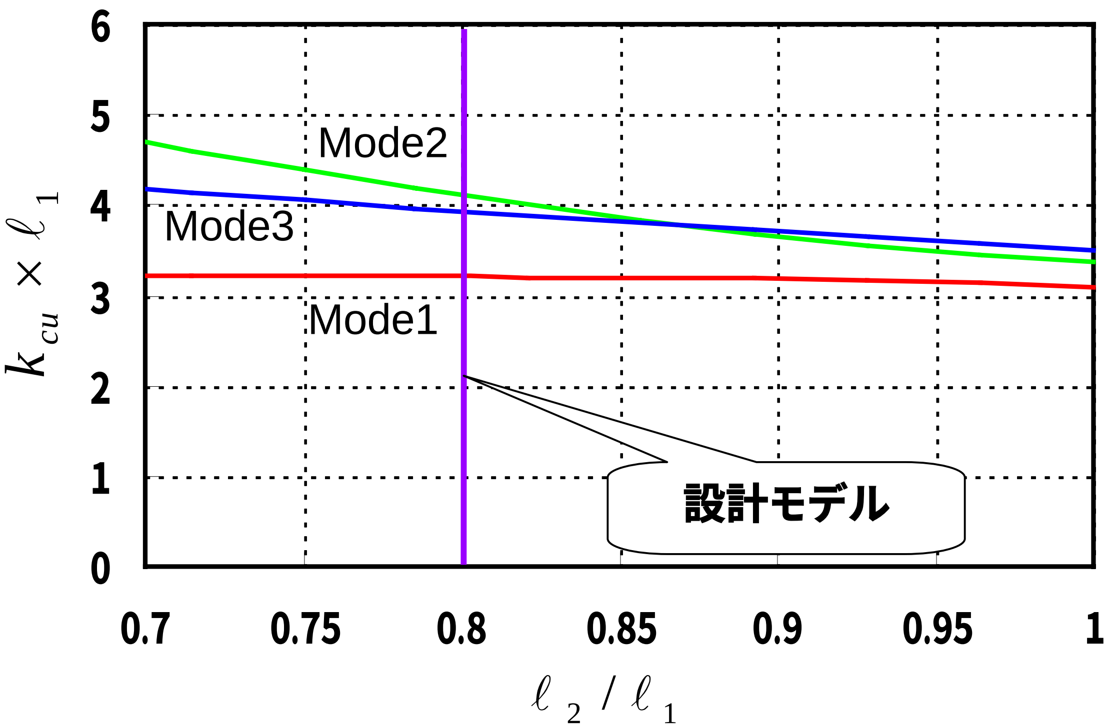
X字型導波管の固有モード関数（磁流基底関数）

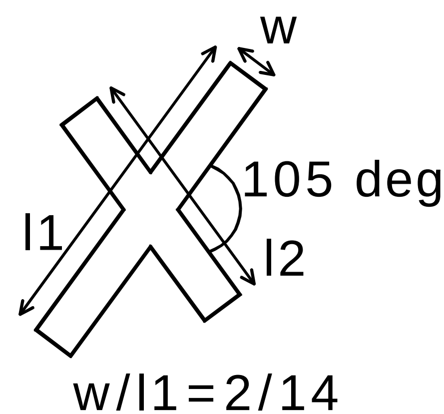


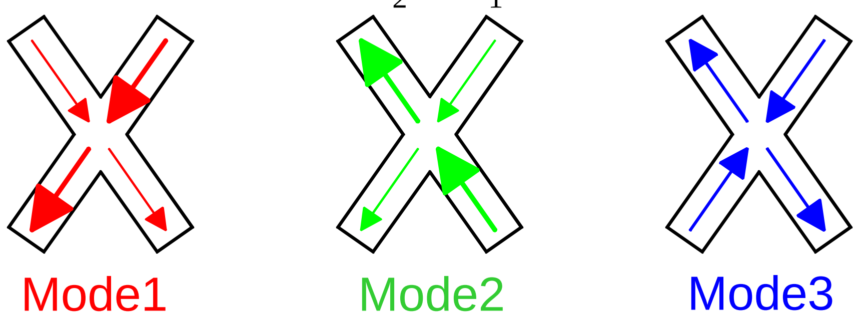


Cutoff Wavenumbers 1:1.3:1.24, Excitation coefs 1.1:1.18:0.00079

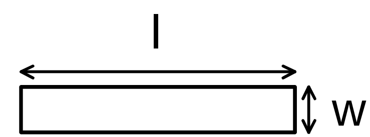
カットオフ波数の変化





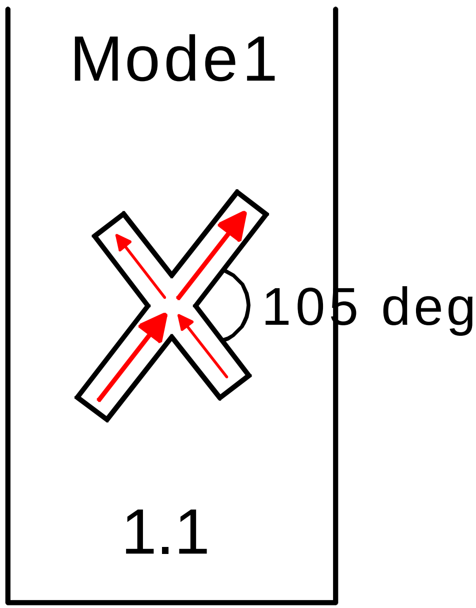


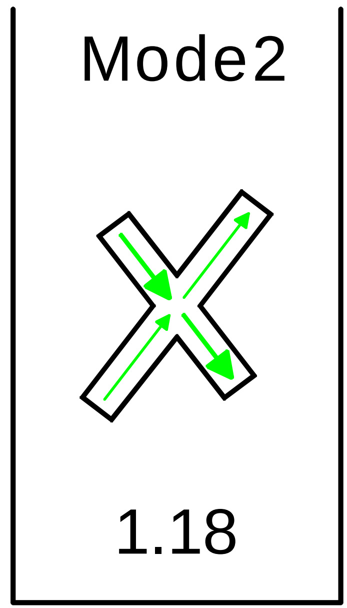
c.f. 方形導波管のカットオフ波数

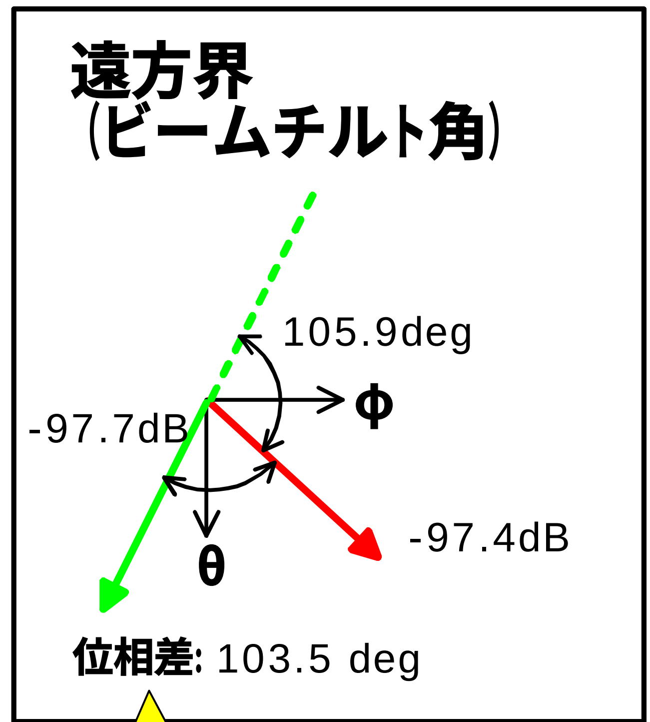


$$k_{cu} = \frac{\pi}{\ell}$$

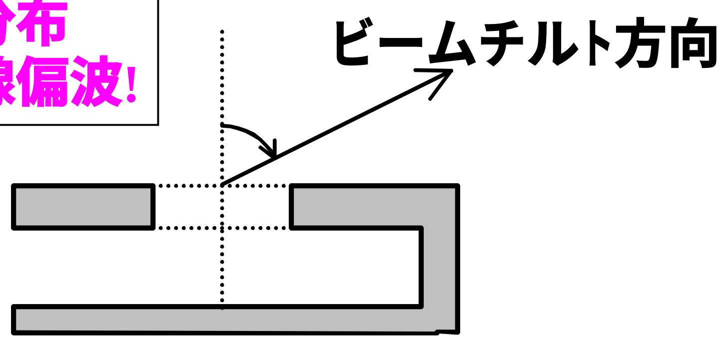
円偏波放射原理





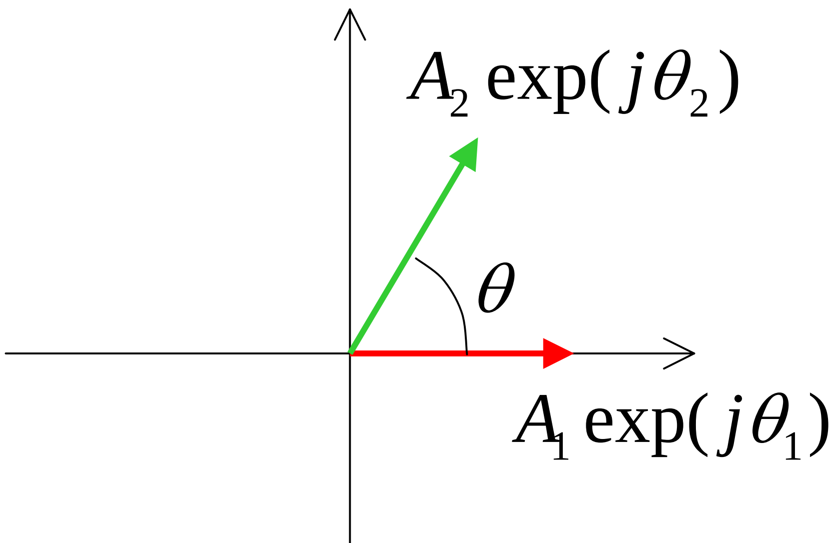


実数分布
→直線偏波!



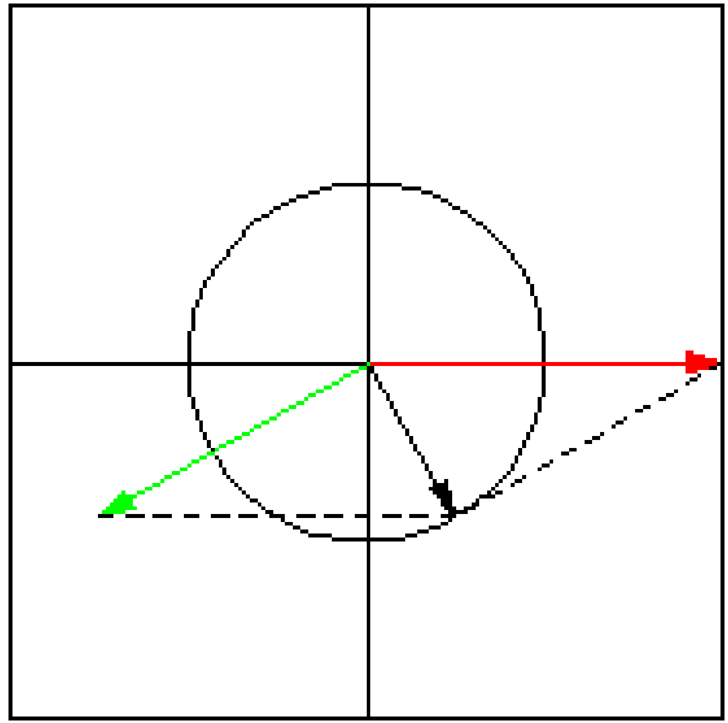
スロット長 (共振周波数)の差による

円偏波放射原理アニメーション



円偏波放射条件

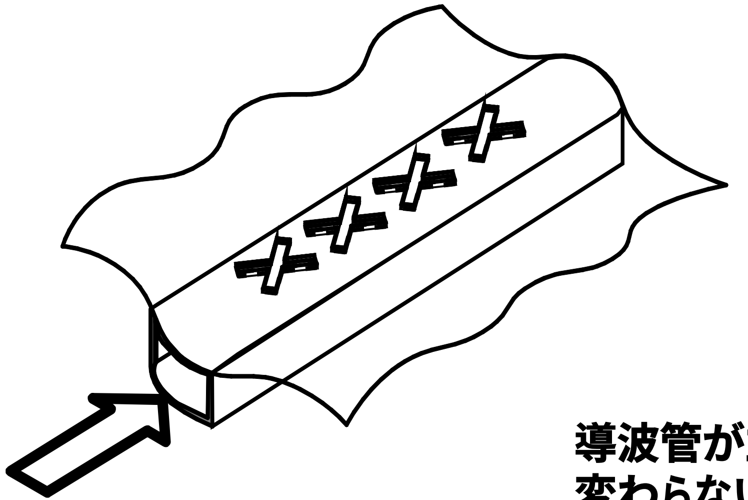
$$\begin{cases} A_1 = A_2 \\ \theta_2 - \theta_1 = \pm\theta + \pi + 2n\pi \end{cases}$$



$\theta = 30^\circ$ **の例**

Array Design

導波管1本



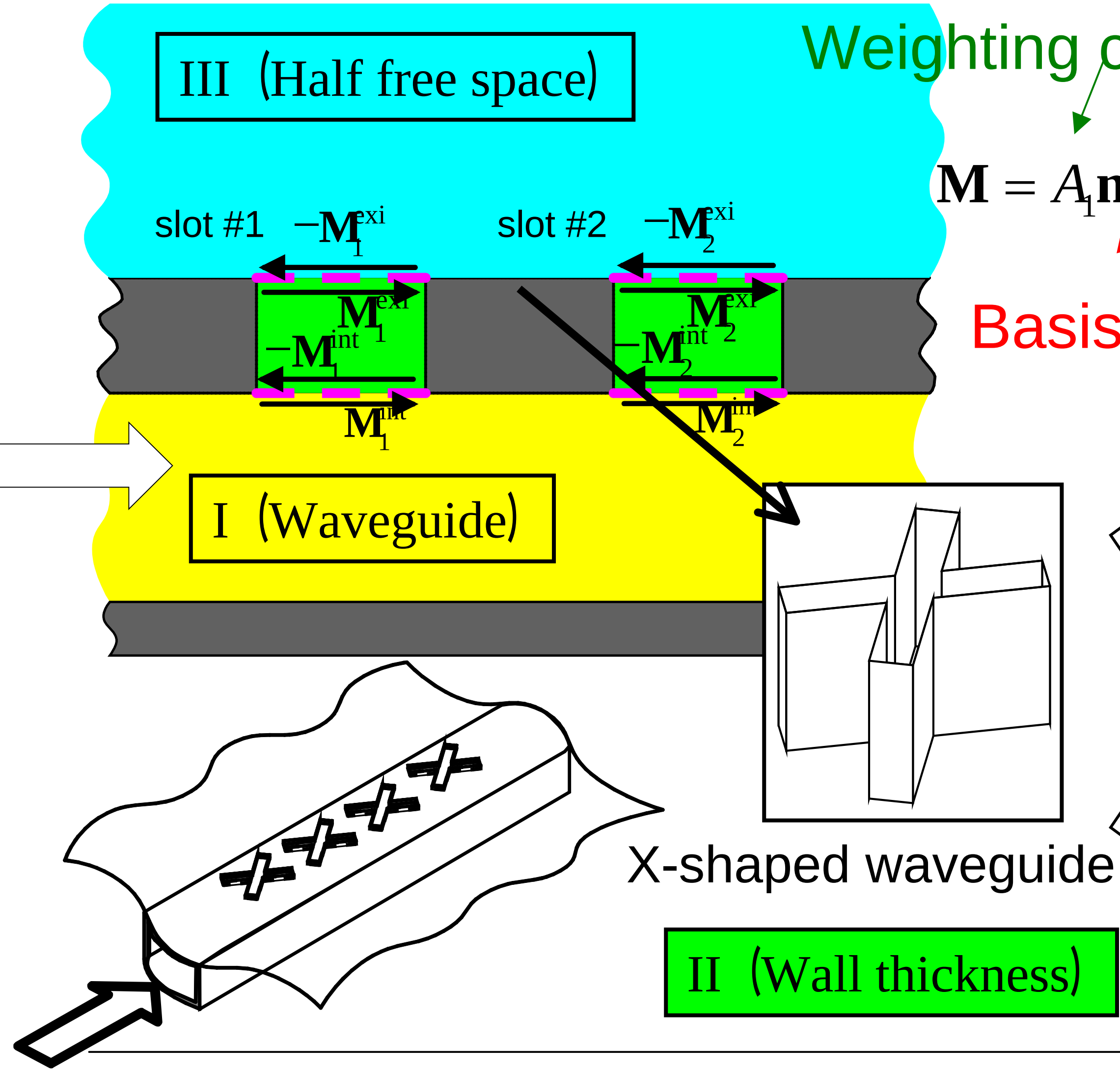
導波管が並んだ2次元アレーの設計と基本的に
変わらない。

MoM/FEM Analysis

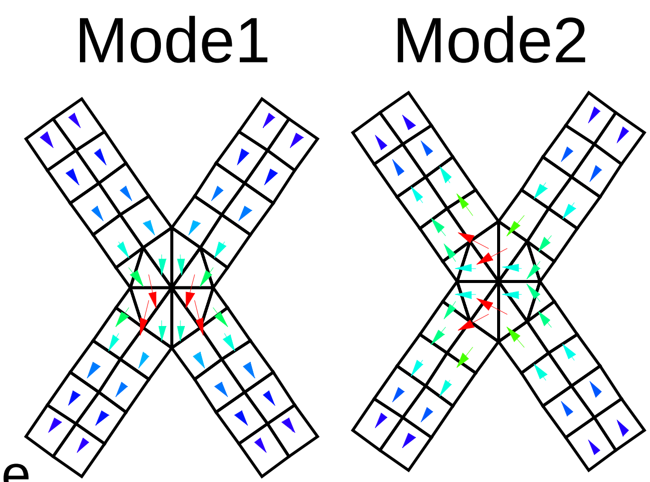
Weighting coefficients (by MoM)

$$\mathbf{M} = A_1\mathbf{m}_1 + A_2\mathbf{m}_2 + A_3\mathbf{m}_3 + \cdots$$

Basis functions (by FEM)



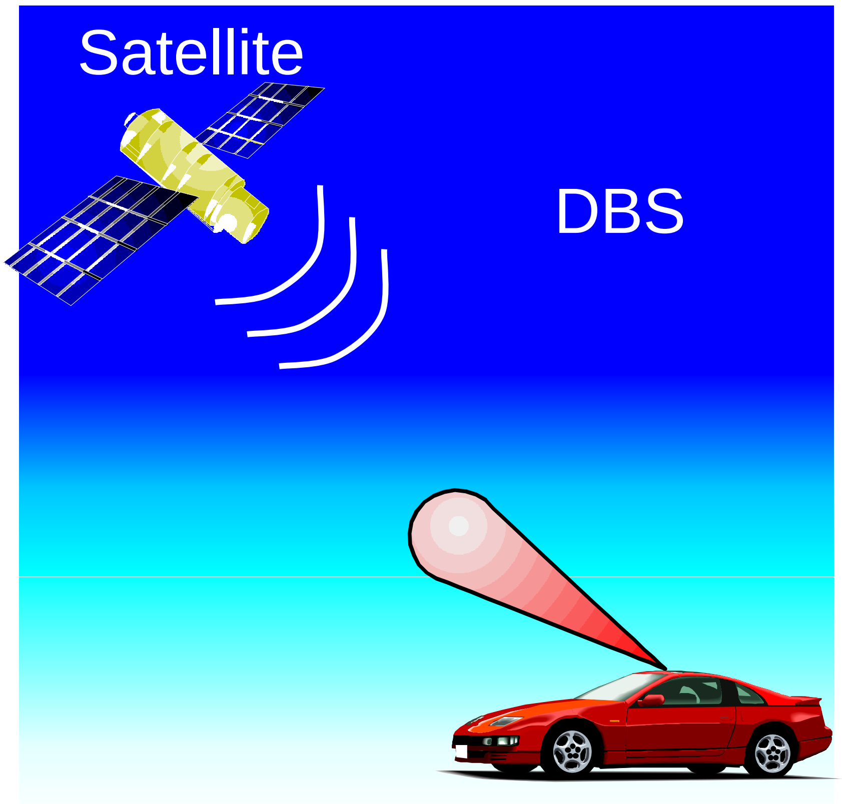
X-shaped waveguide



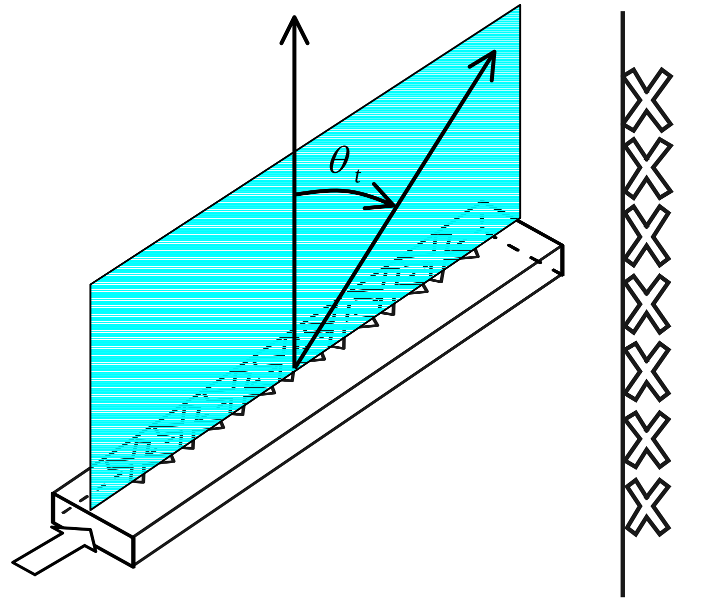
Eigenmode functions

Setting of the Problem

Frequency: 11.85GHz
Beam-tilting angle : 50deg



One waveguide

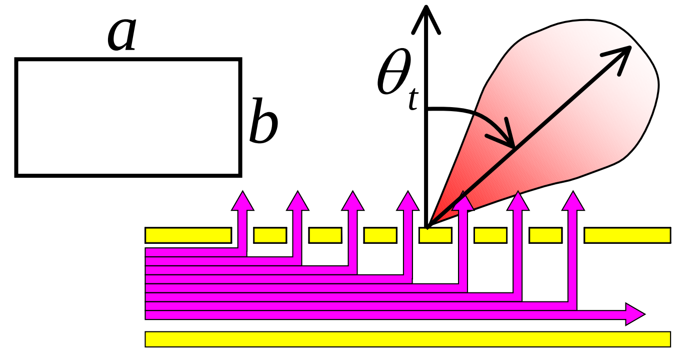


Purpose

✓Uniform illumination
✓Circularly polarized wave
at a beam direction

Design Procedure

1. Determine
   the waveguide size and
   the number of elements

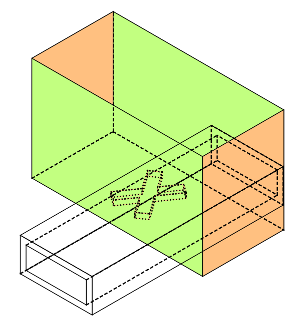


$\theta_t \Rightarrow a = 16.0mm$ Leaky-wave

Beam width $\Rightarrow$ Number of slots=8

2. Determine initial slot lengths
   using infinite periodic model

   Simulate mutual couplings

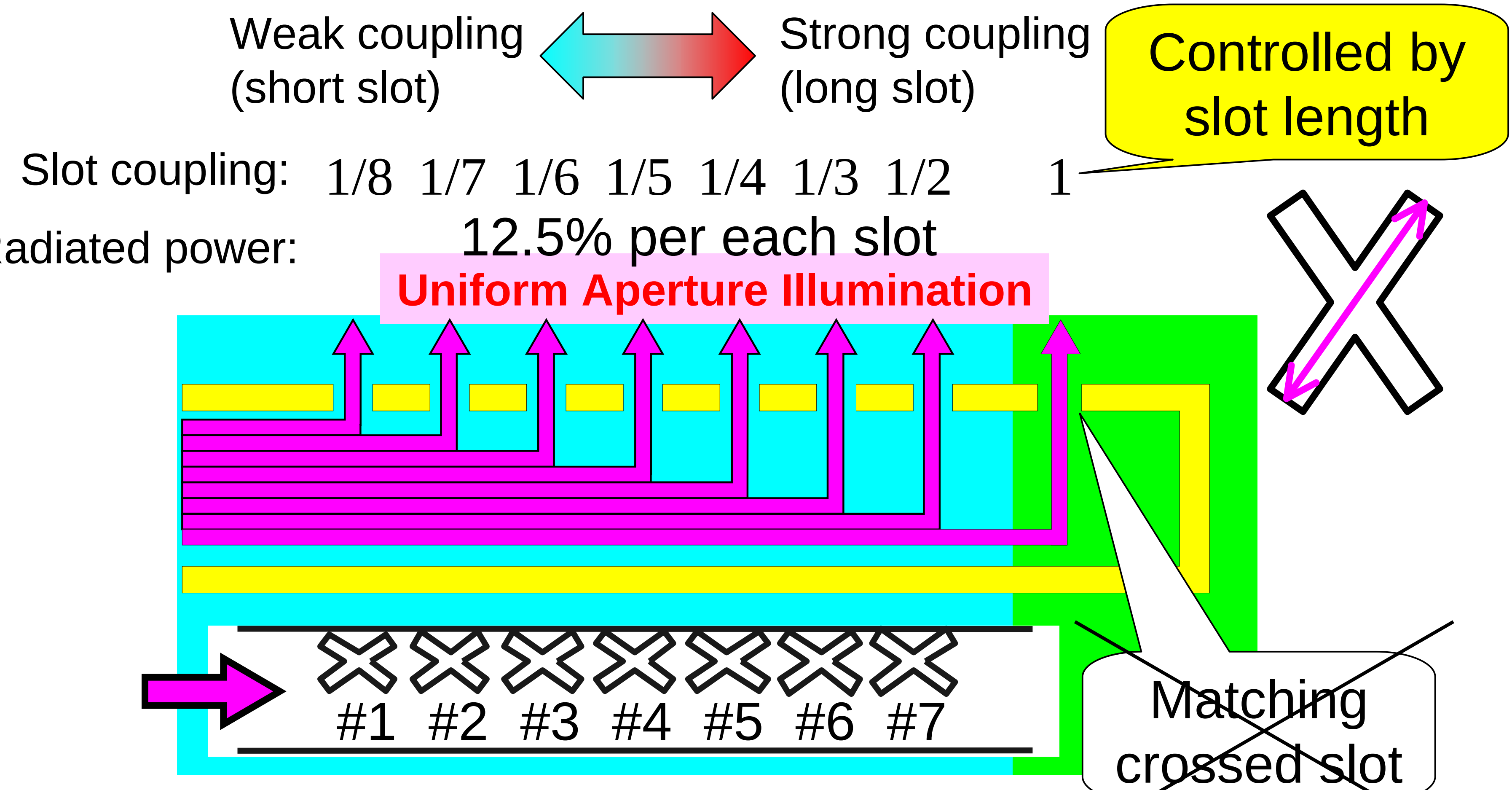


3. Finite array analysis

   MoM/FEM

4. Modify slot parameters

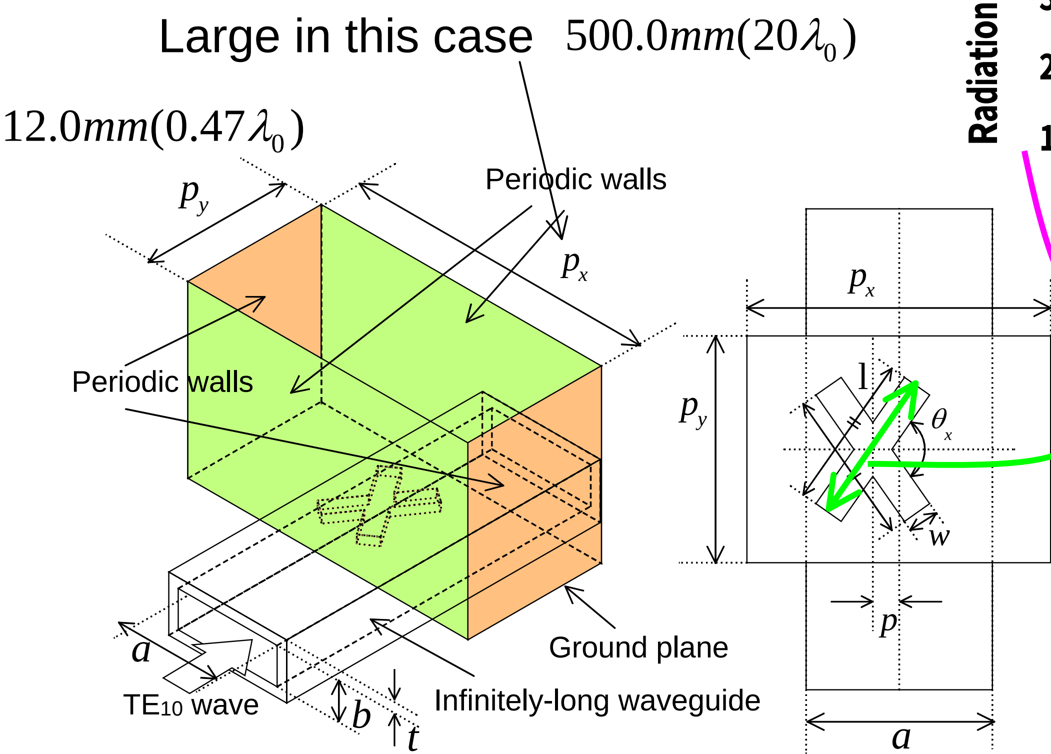
Power Relation and Slot Coupling

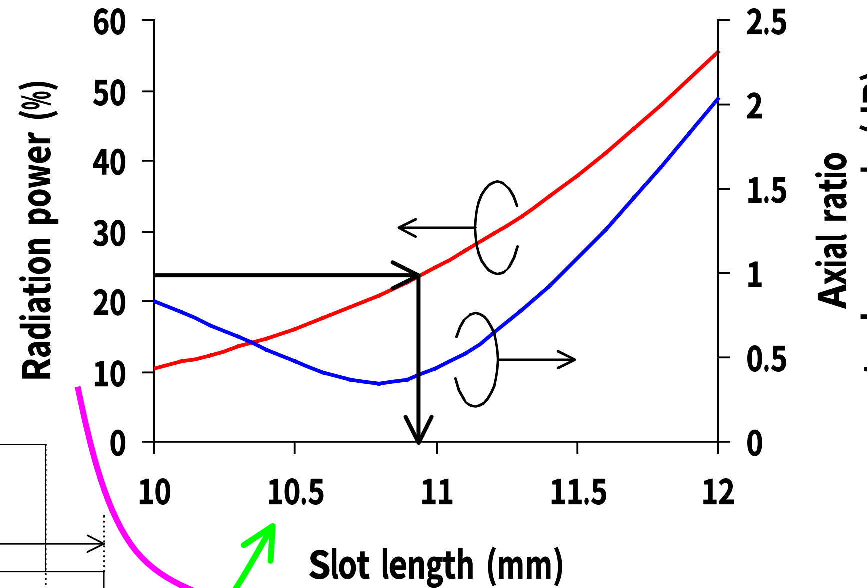


- 12.5% of incident power per each slot
- 87.5% (7 slots), 100% (8 slots)

Determine Initial Slot Parameters

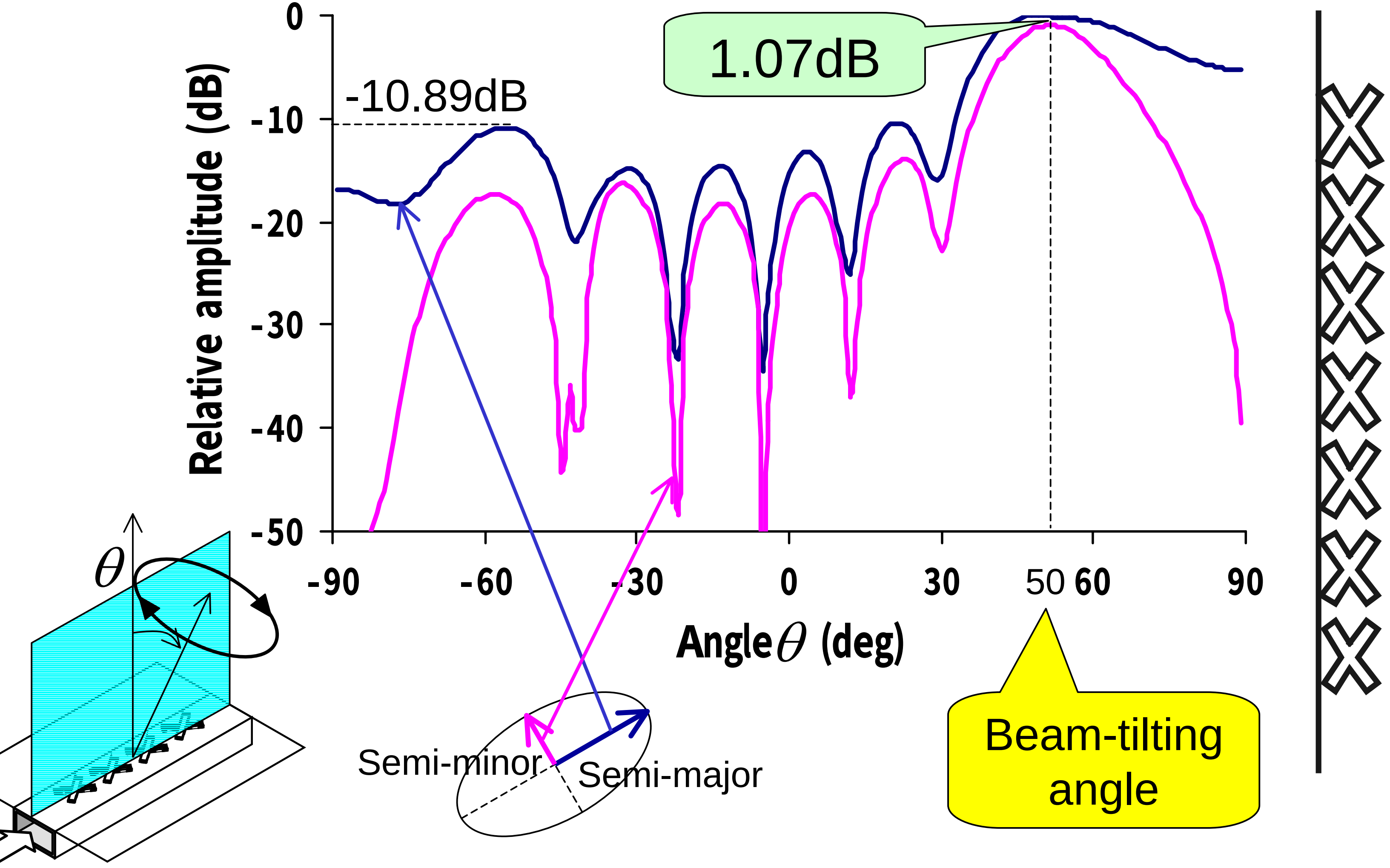
Infinite periodic model



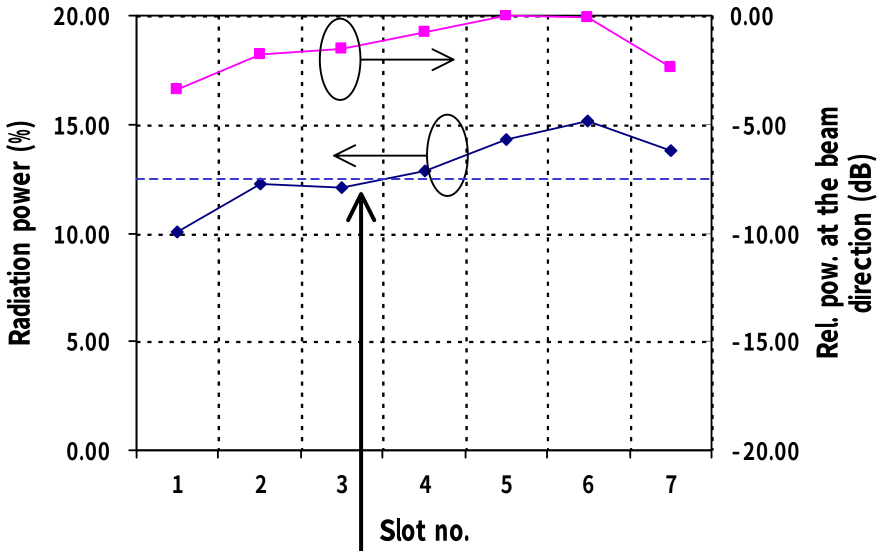


slot no.	coupling (%)	slot length (mm)
1	12.5	10.21
2	14.3	10.37
3	16.7	10.53
4	20.0	10.75
5	25.0	11.01
6	33.3	11.35
7	50.0	11.86
~~8~~	~~100.0~~	

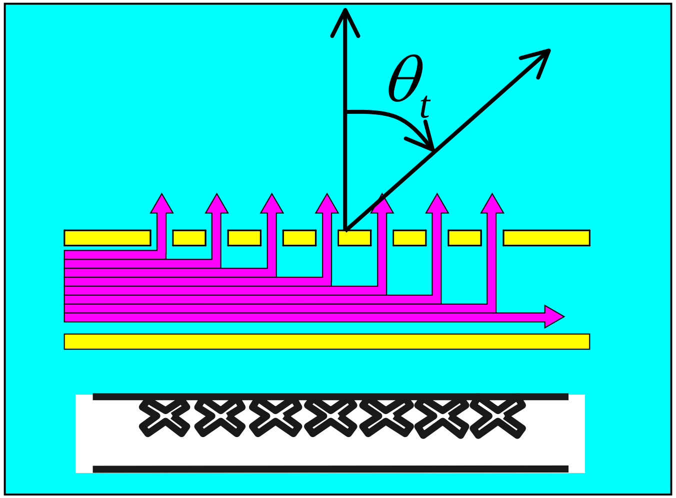
Radiation Pattern (Init.)

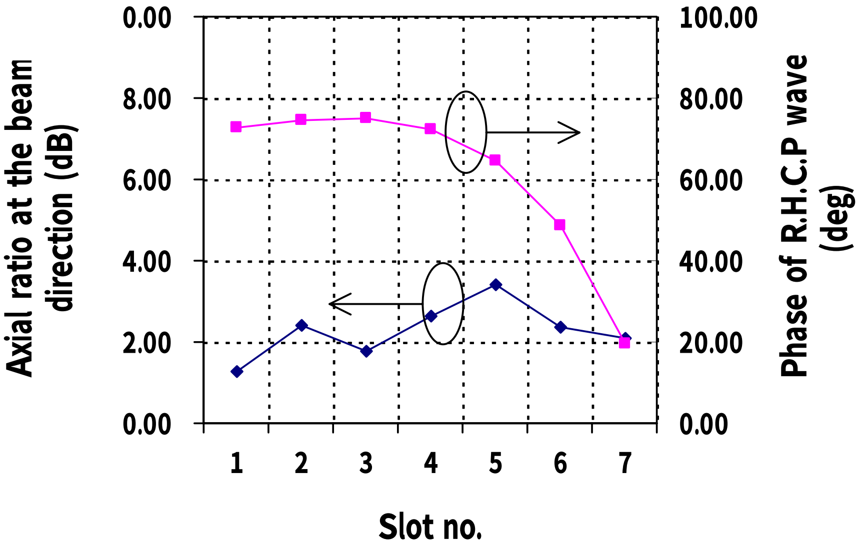


E-field Radiated by Each Slot (Init.)



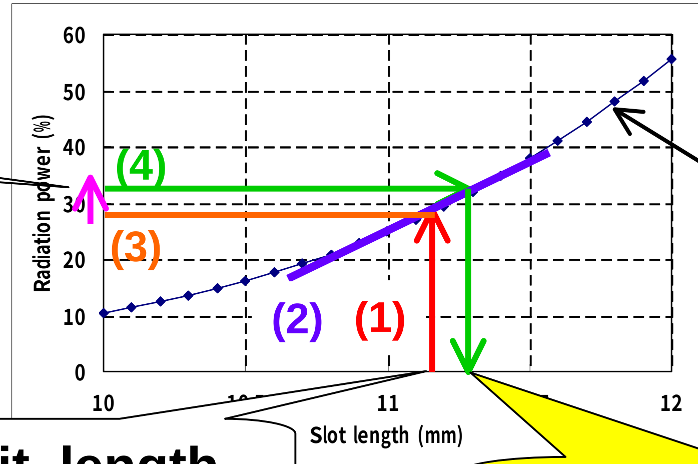
Not uniform enough

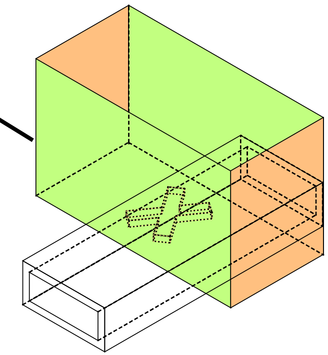




Correction of the Power

Error of the radiation power





Init. length

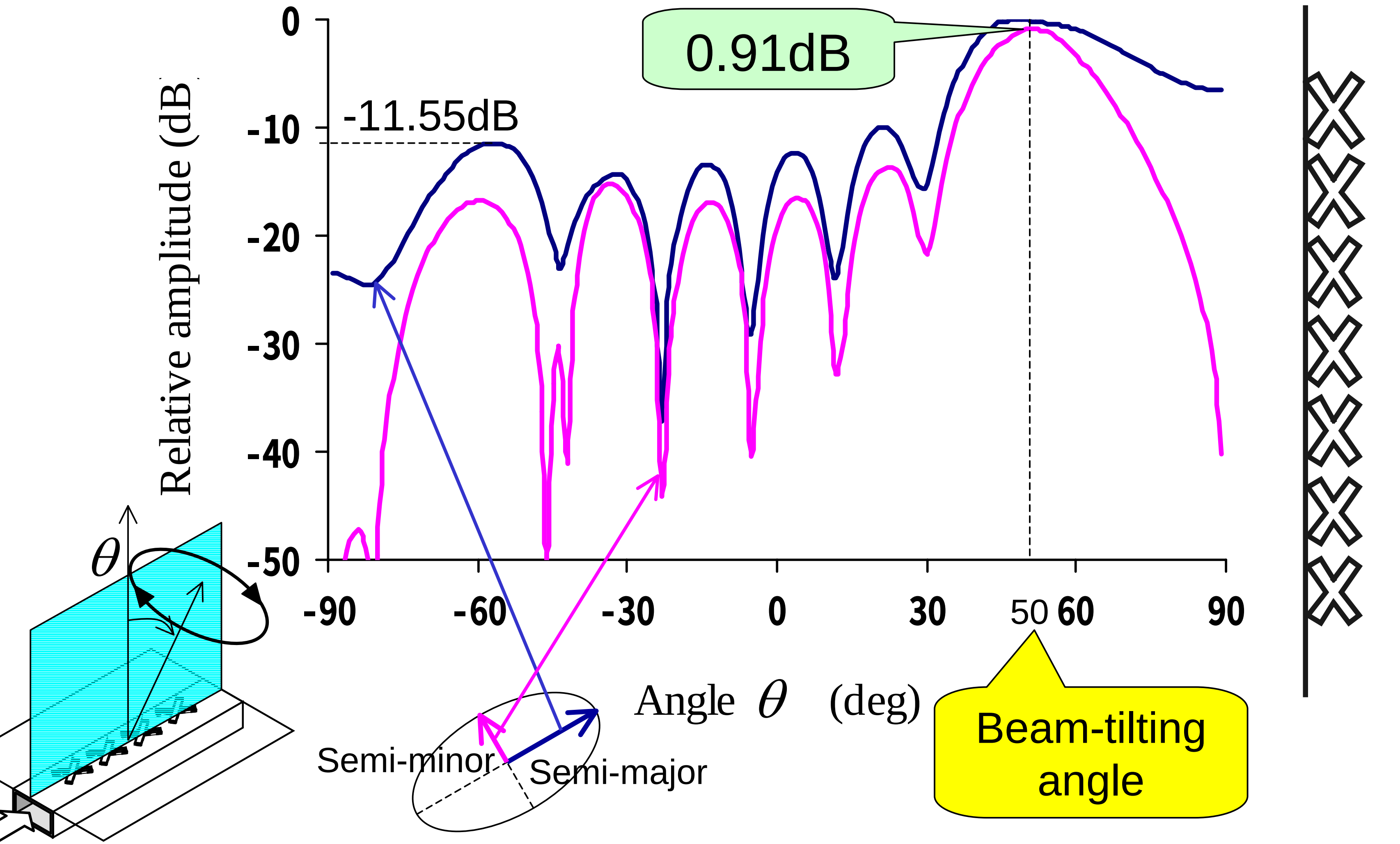
Corrected slot length

- At the present slot length (1), differential coefficient (2) is calculated numerically
- Slot length is corrected by the 1st order approximation using the difference between the present (3) and desired power (4) and the differential coefficient.

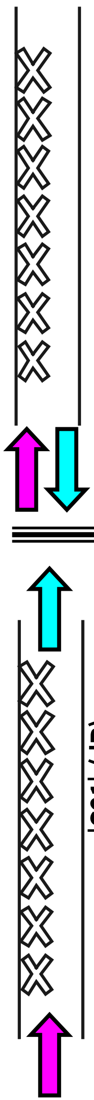
Rep.

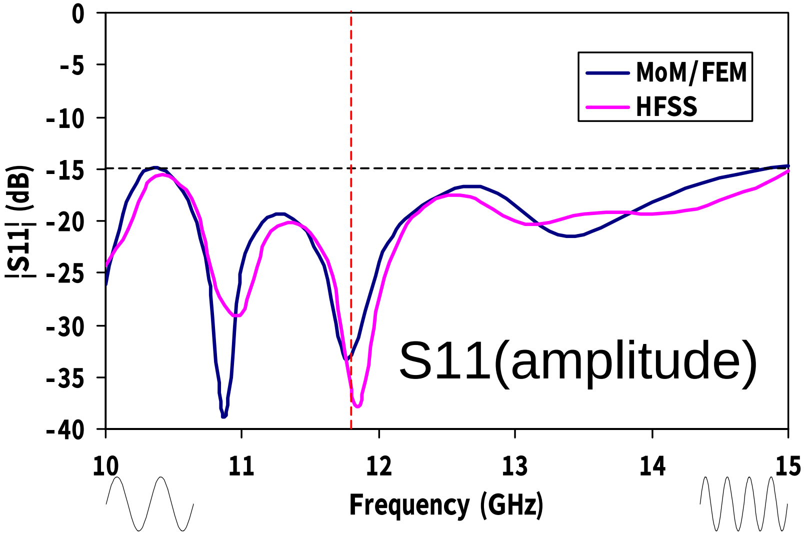
- Above procedure is applied to all the slots simultaneously

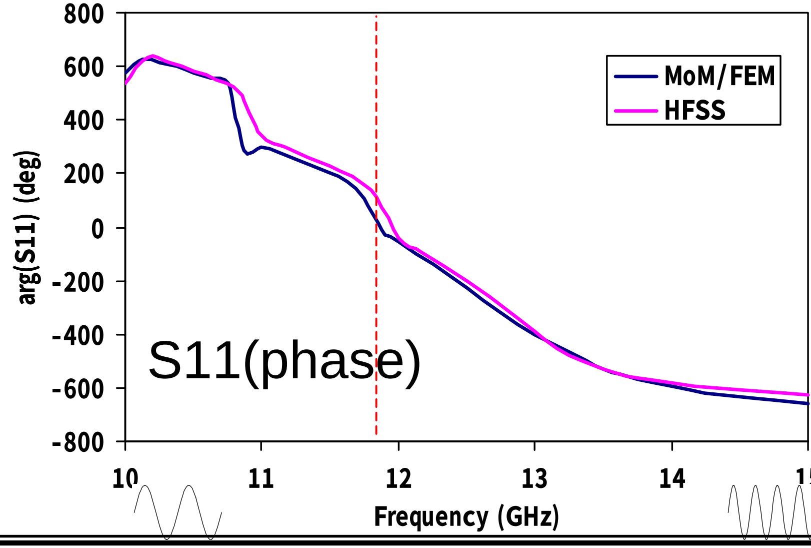
Radiation Pattern (Corrected, 3 Iterations)

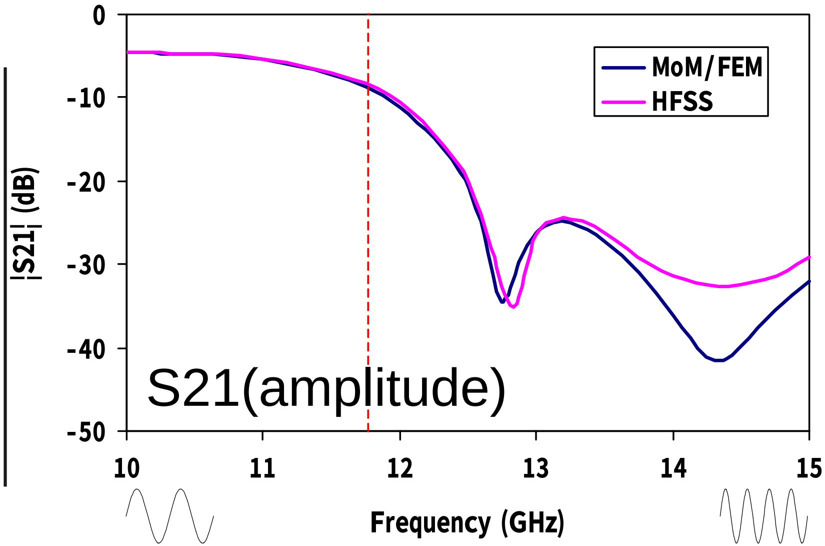


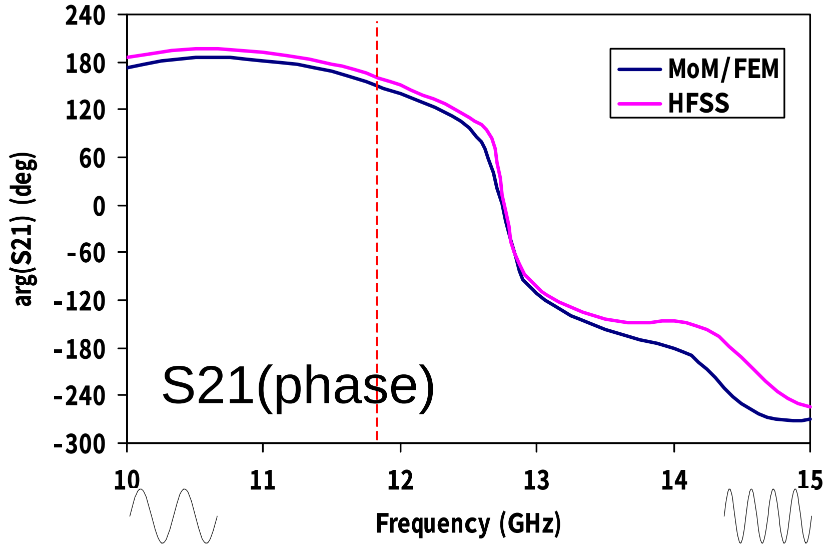
Freq. vs. S11 and S21 (Corrected, 3 Iterations)



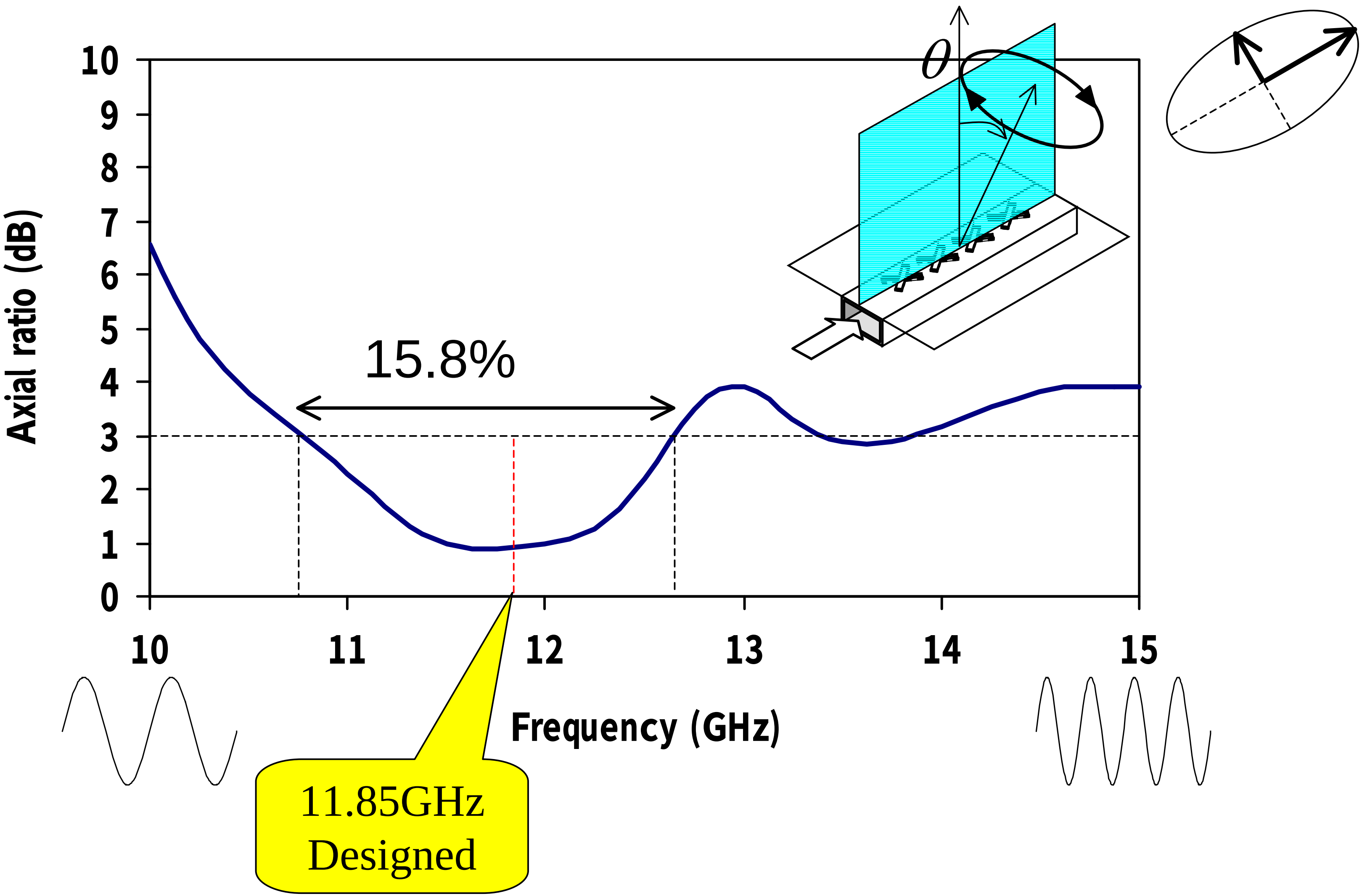




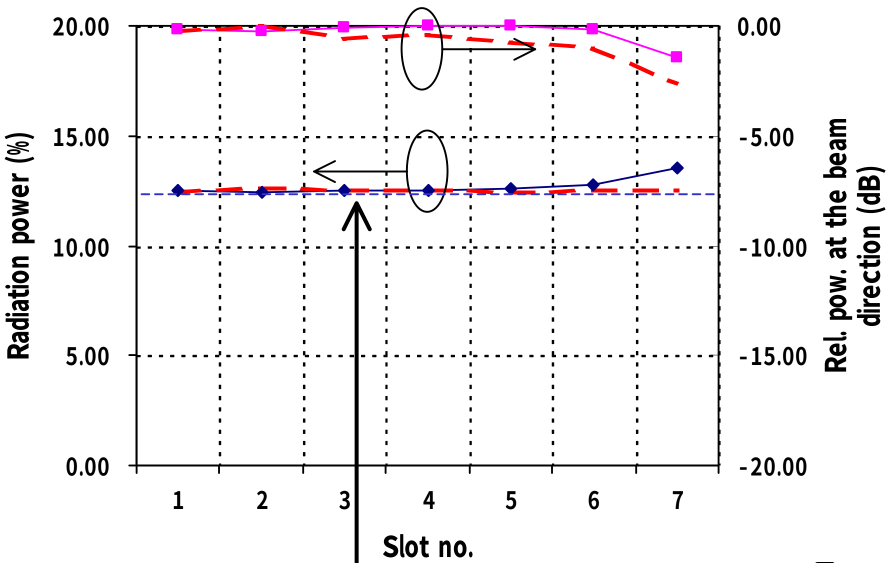


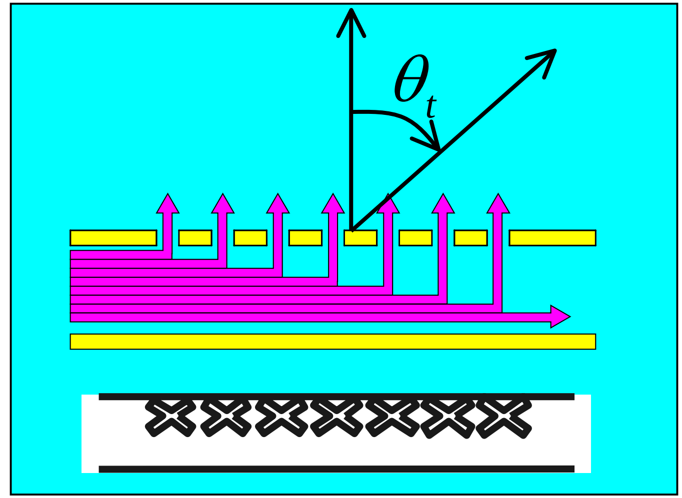


Freq. vs. Axial Ratio (Corrected, 3 Iterations)

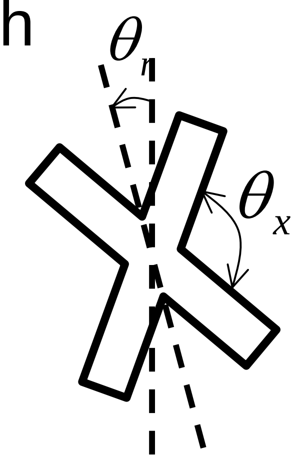


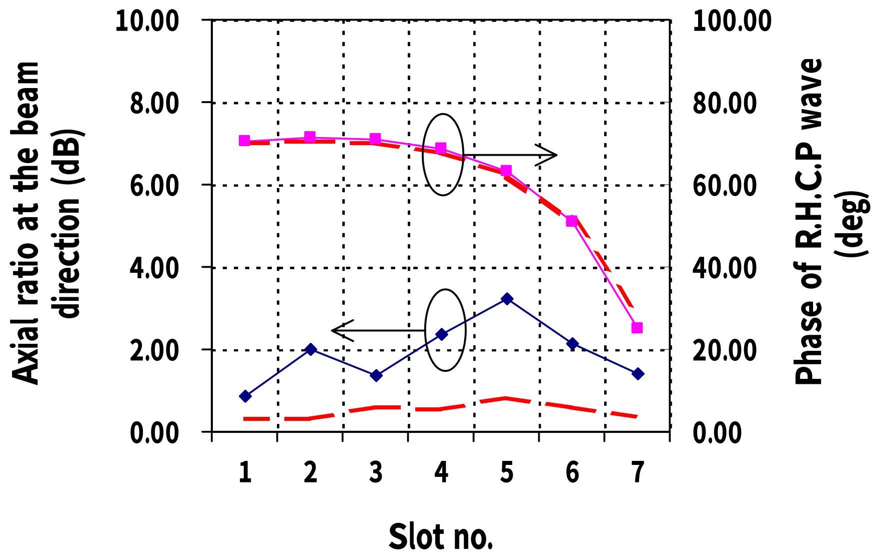
E-field Radiated by Each Slot (Corrected, 3 Iterations)



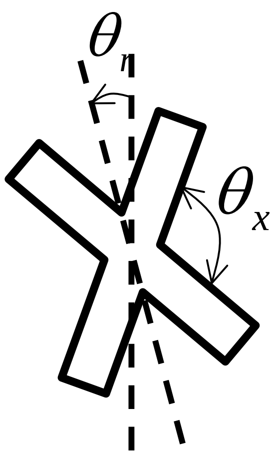


Uniform enough

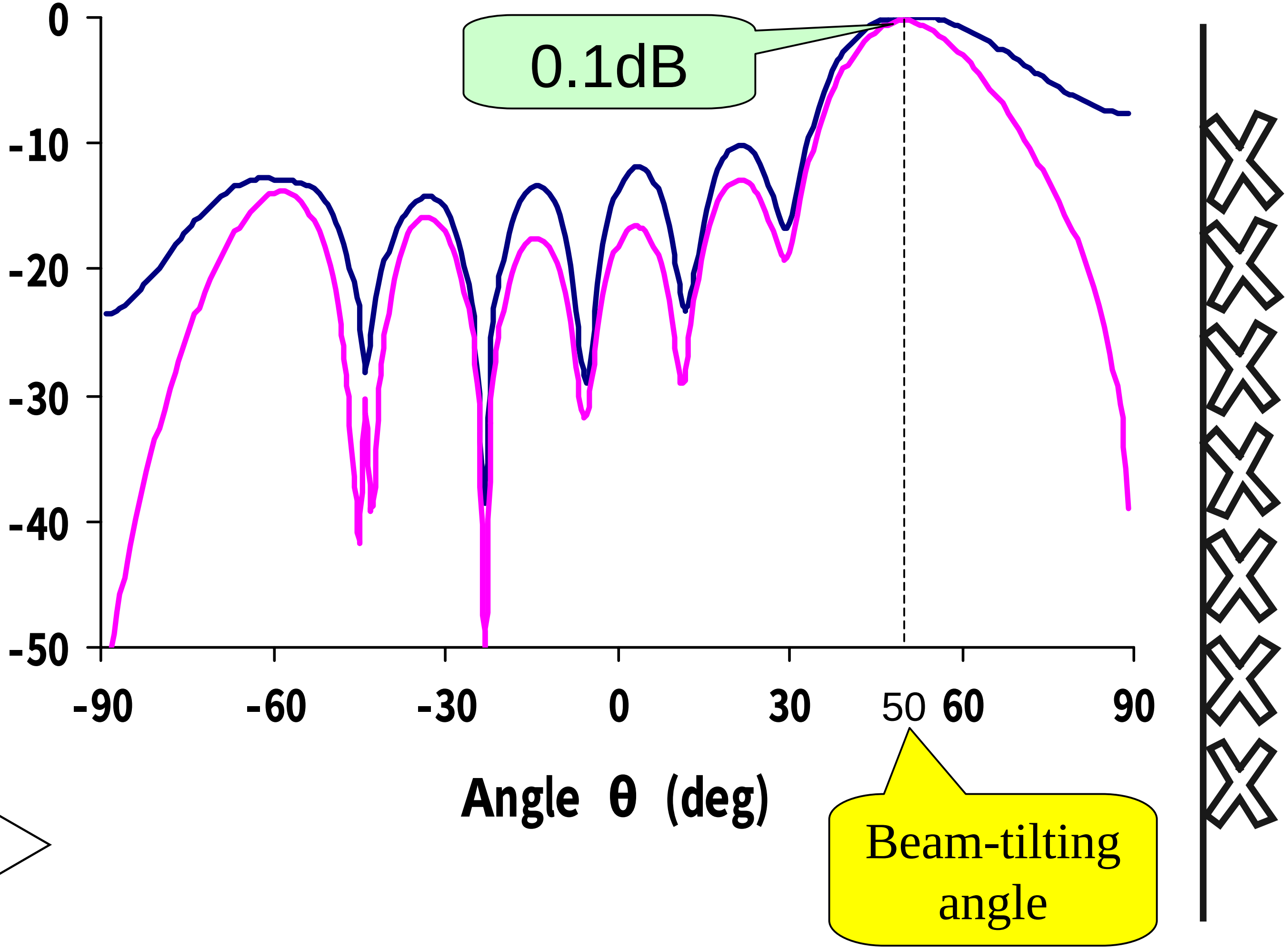


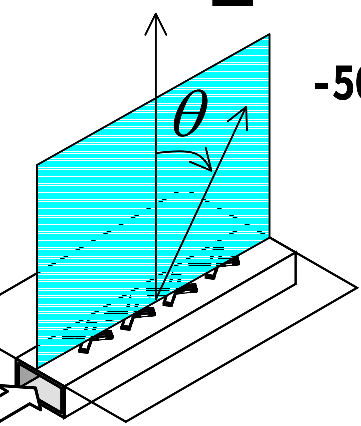


Correction (Method 2)

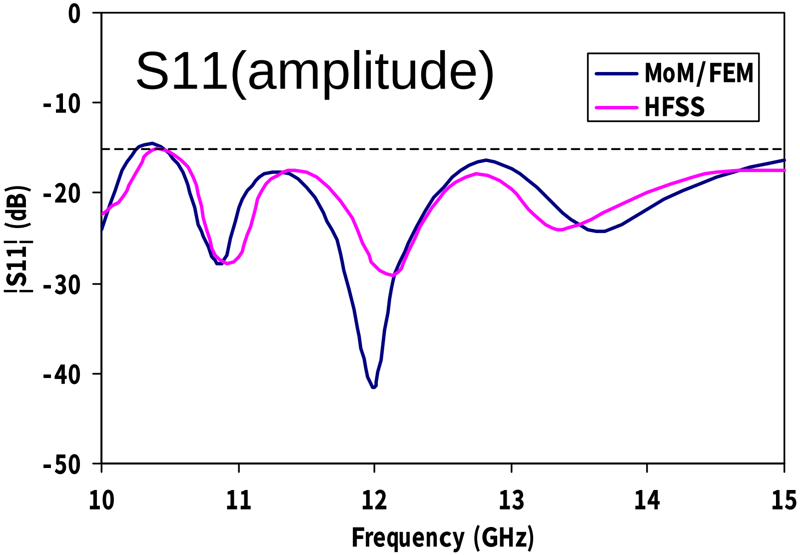


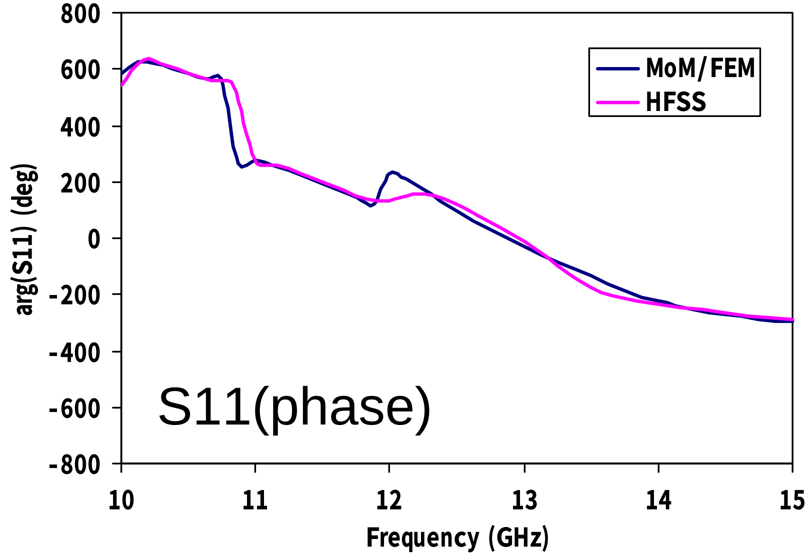
Radiation Pattern

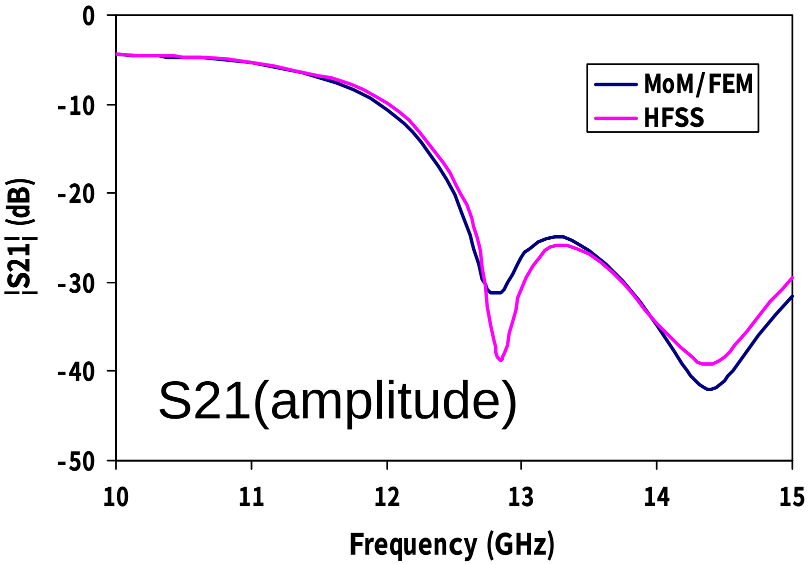


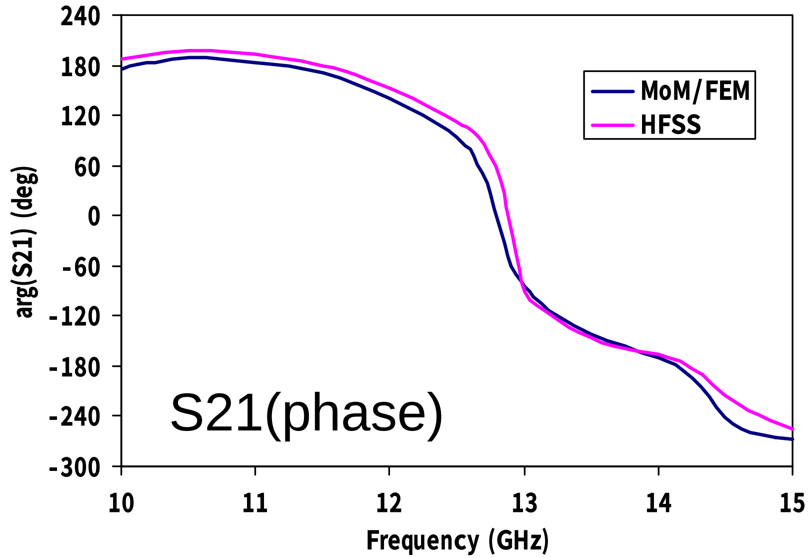


S11 and S21

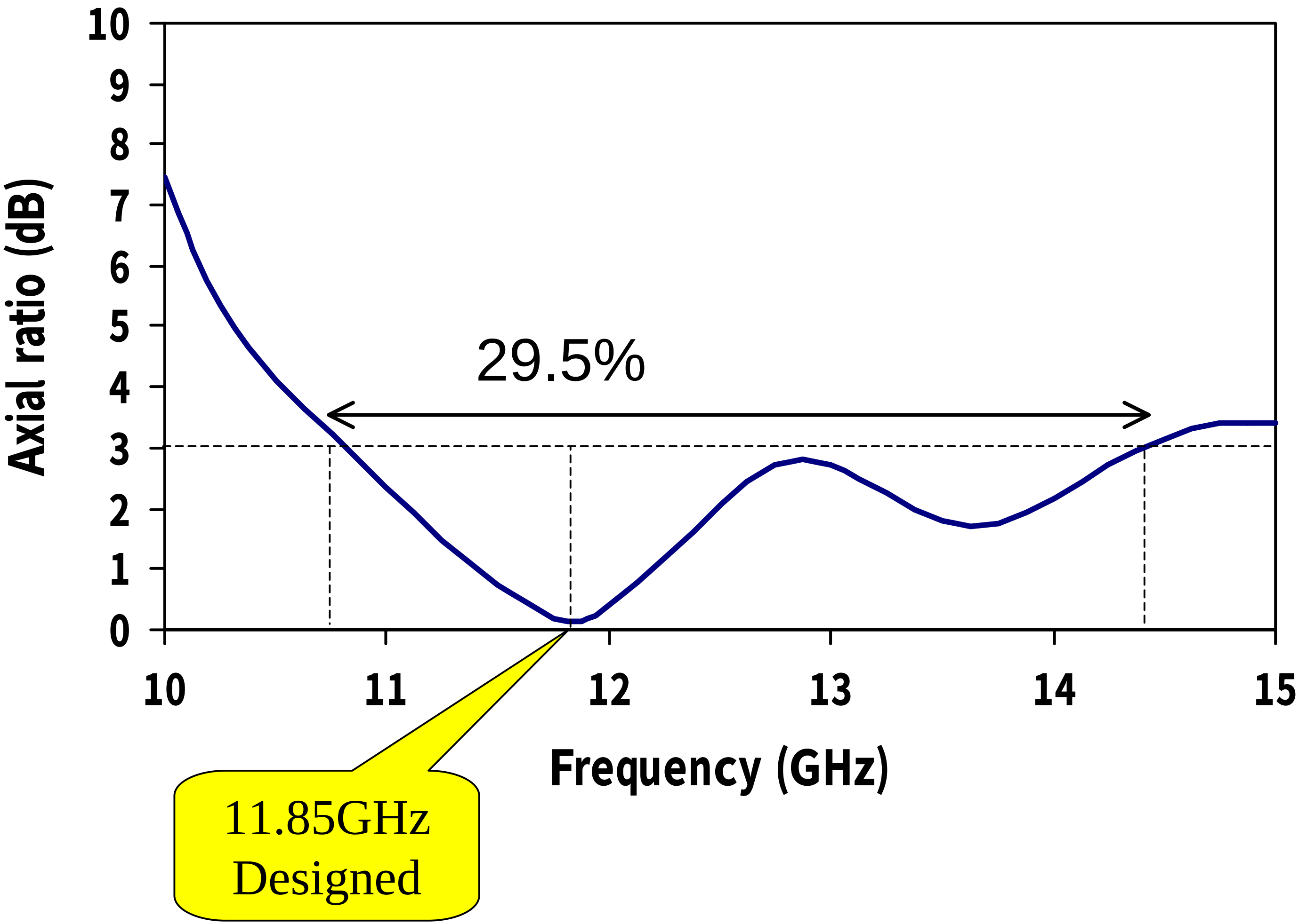

S11(amplitude)
MoM/FEM
HFSS
|S11| (dB)
0
-10
-20
-30
-40
-50
10
11
12
13
14
15
Frequency (GHz)


S11(phase)
MoM/FEM
HFSS
arg(S11) (deg)
800
600
400
200
0
-200
-400
-600
-800
10
11
12
13
14
15
Frequency (GHz)

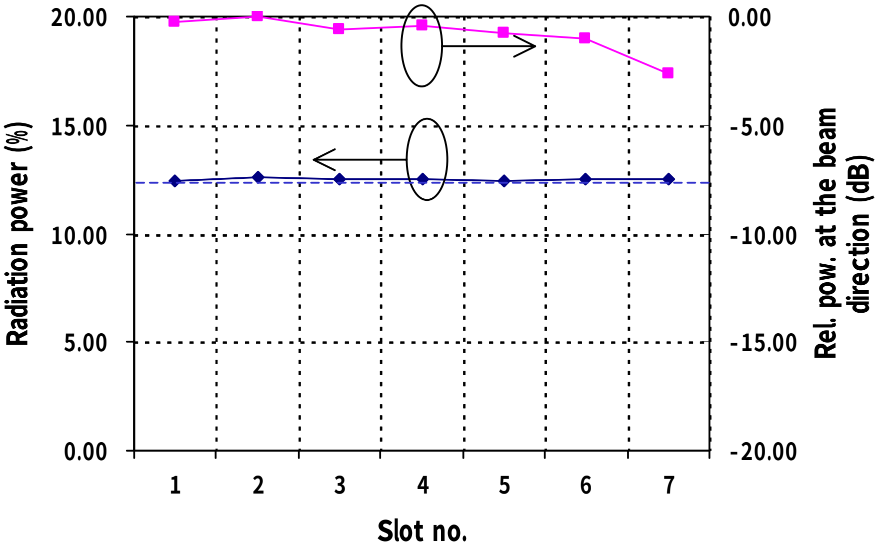

S21(amplitude)
MoM/FEM
HFSS
|S21| (dB)
0
-10
-20
-30
-40
-50
10
11
12
13
14
15
Frequency (GHz)

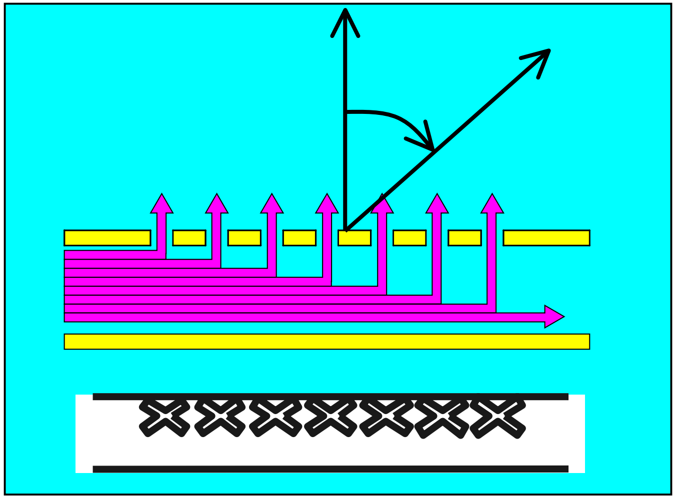

S21(phase)
MoM/FEM
HFSS
arg(S21) (deg)
240
180
120
60
0
-60
-120
-180
-240
-300
10
11
12
13
14
15
Frequency (GHz)

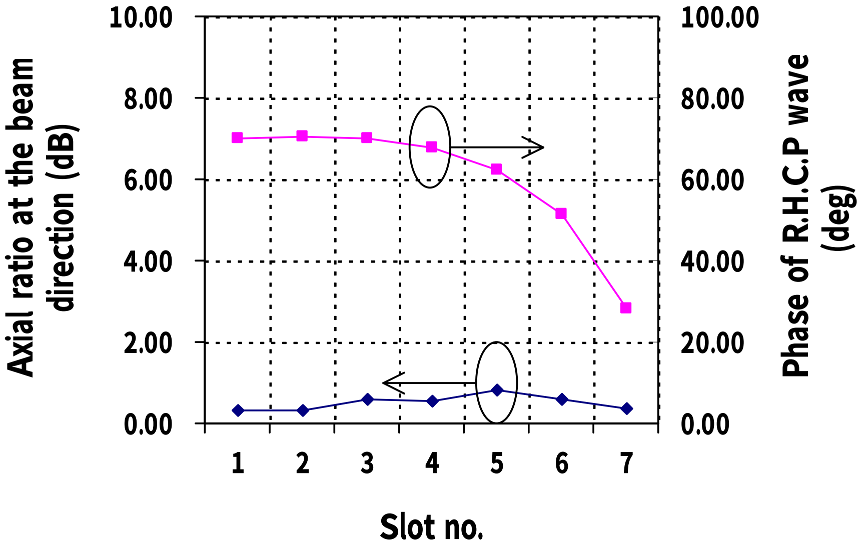
Axial Ratio


10
9
8
7
6
5
4
3
2
1
0
Axial ratio (dB)
29.5%
10
11
12
13
14
15
Frequency (GHz)
11.85GHz
Designed

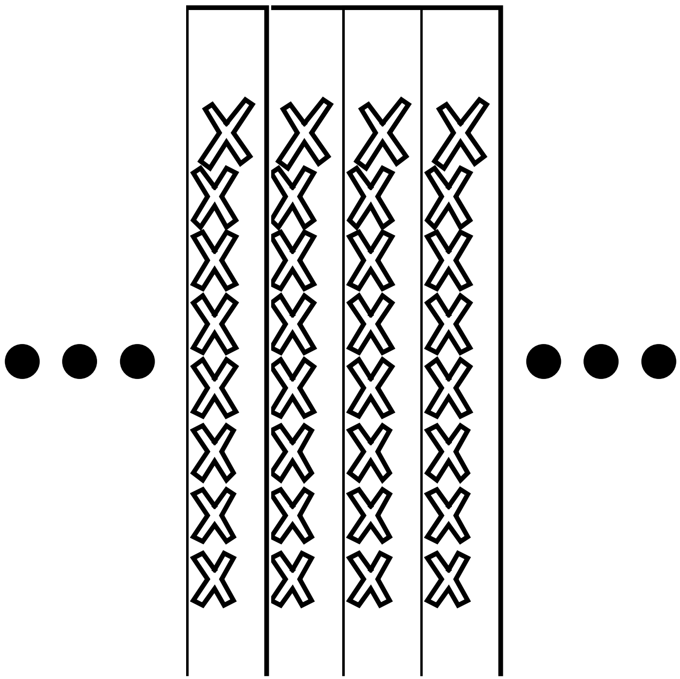
E-field Radiated by Each Slot



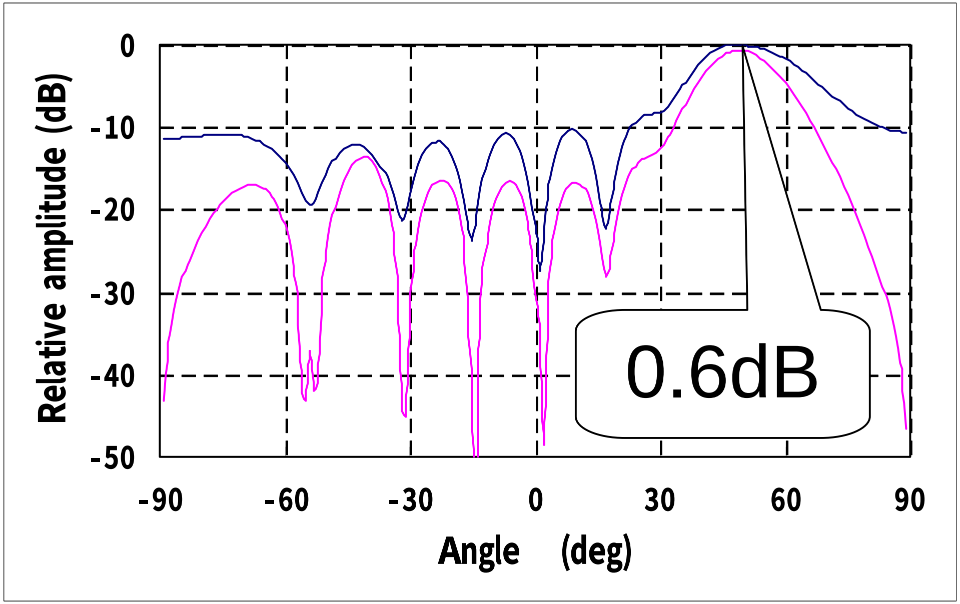


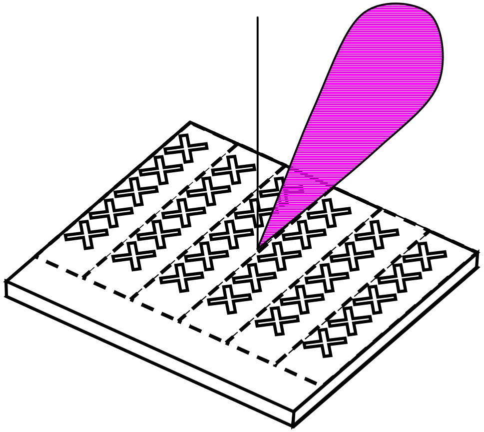


Array Design 2

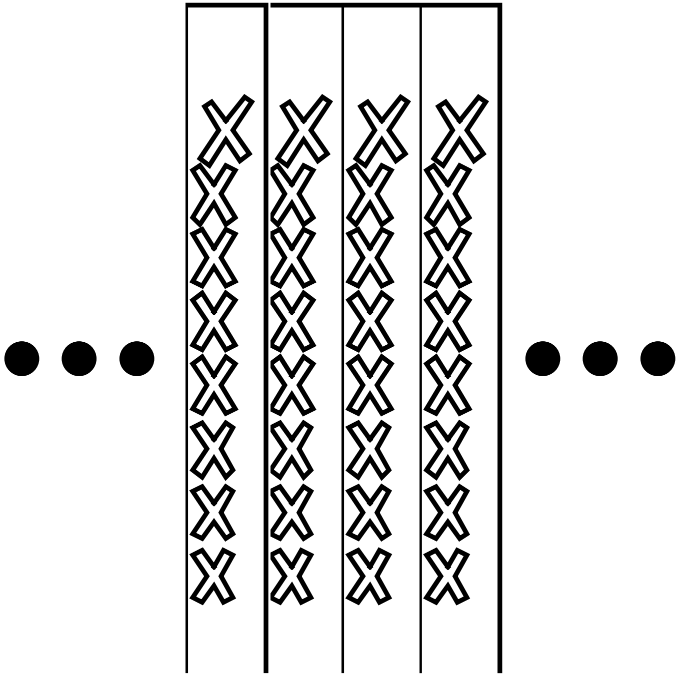


W.G. Crossed Slot Array

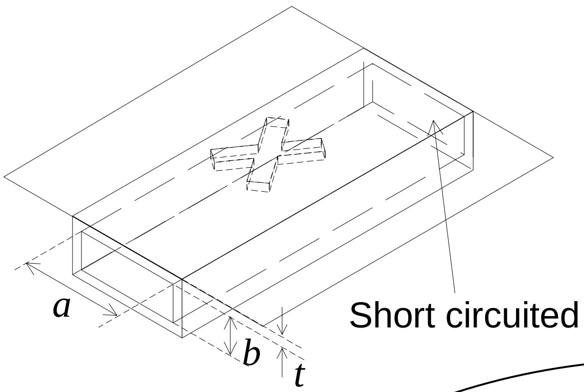


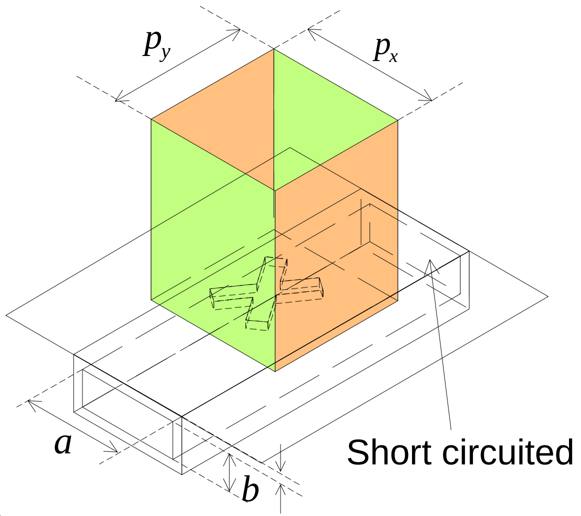


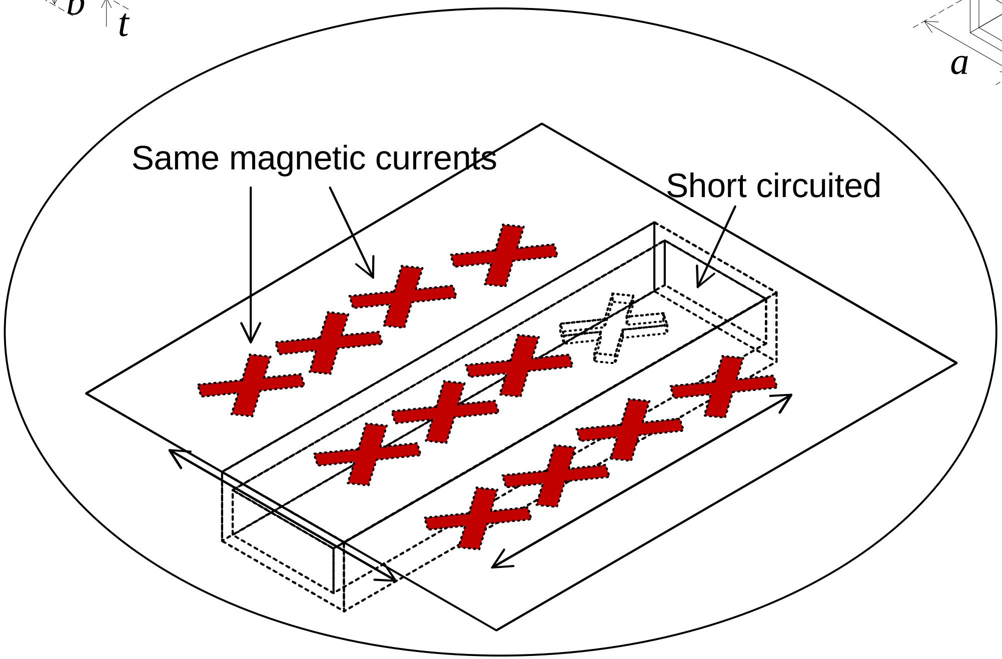
99.8% Radiates



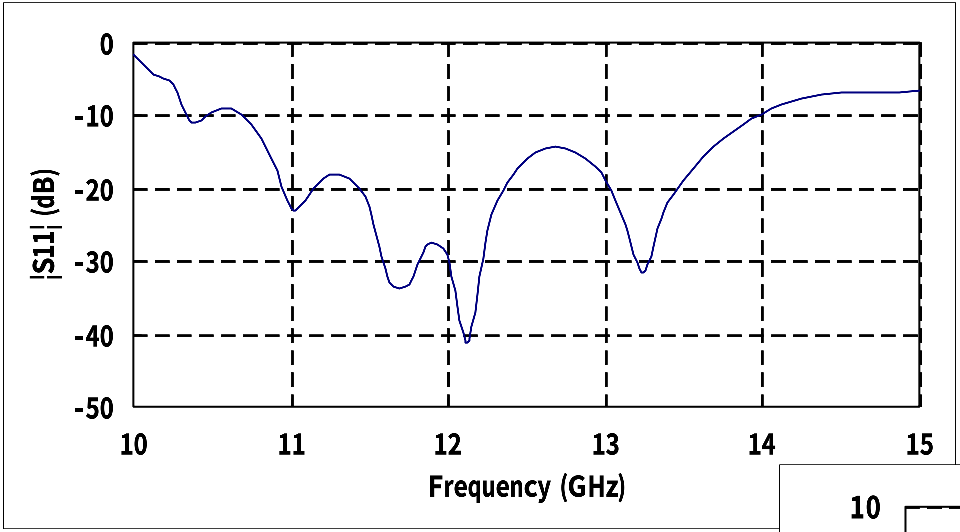
Design Model for a Matching Crossed Slot

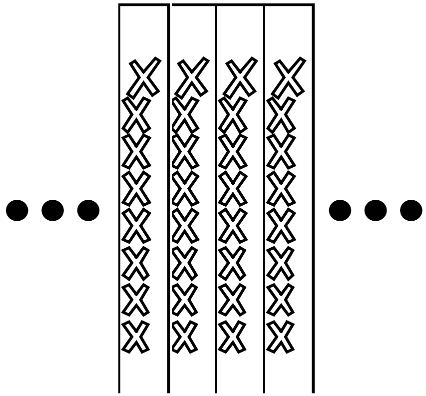


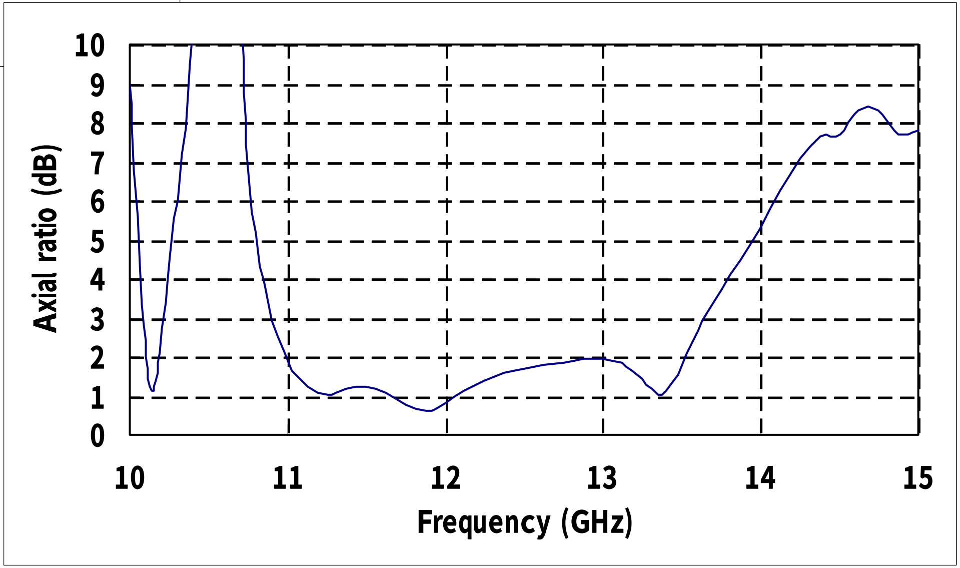




Frequency Characteristics

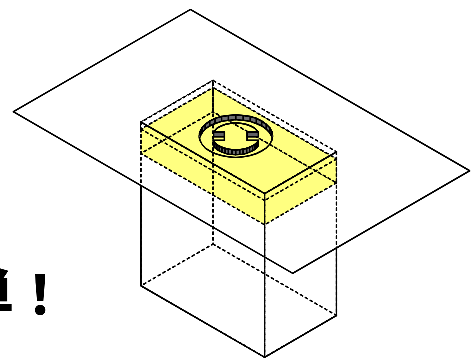


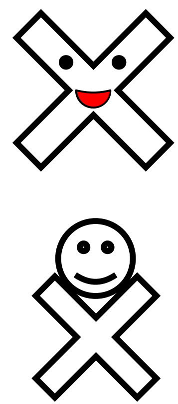


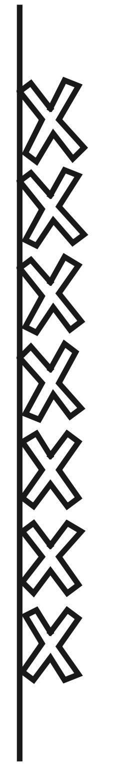


Conclusion

- ○ MoM/FEM解析法を1素子で確認した
  (→任意形状スロットの解析も可能)
- ○ MoM/FEM解析法で終端の整合クロススロットを設計した
- ○ MoM/FEM解析法を用いて一次元導波管
  クロススロットアレーの設計を行った
- ○ リングスロット、楕円スロットの解析を行った







MoM/FEM解析法の利点

- ◎ 速い！
- ◎ 壁厚の影響の評価が簡単！
- ◎ 正確！
- ◎ 円偏波の動作原理（物理現象）が理解できる！