Natural and Metamaterial Low-profile Antennas with Emphasis on Realization of Wideband Characteristics

- Antenna Height from λ/4 to λ/100 -

H. NAKANO

Hosei University
Tokyo
Japan

Recent developments in communication systems, e.g.,

Mobile, Digital TV, and Satellite Communication Systems,

require

Antennas

with

Dual-, Multi-, Moderately Wide-, and Extremely Wide-Band Operation

-:: categorized as either

Natural Antenna or Metamaterial (MTM) Antenna

Natural Antenna / EM Property Found in Nature (Right-Handed Property)

MTM Antenna / EM Property not Existing in Nature (Left-Handed Property)

Choice of either a **Natural** or an **MTM** Antenna depends on the requirements of the target communications system.

TALK PRESENTATION

recent progress in some

Natural and MTM Antennas.

Low-Profile Structure

realizing

Moderately wideband characteristics

Wideband characteristics

Extremely wideband characteristics

Key Words ::
Low Profile Structure
Wideband Characteristics

Out line

Section I Introduction

Section II Natural TW antennas

II-A Low-profile, moderately wideband **helical antenna**

II-B Extremely wideband **fan-shaped antennas**
for a base-station and a portable handset

II-C Low-profile, extremely wideband ***BOR-SPR antenna**
for a base-station antenna

***Body of Revolution with a Shorted Parasitic Ring**

II-D Low-profile, wideband **rhombic grid array antenna**
for frequency beam-scanning

Section III Metamaterial TW antennas

III-A History of the antenna height reduction of a spiral antenna

III-B   Extremely low-profile, moderately wideband **spiral antenna**
for **counter CP radiation**

Section IV   Remarks

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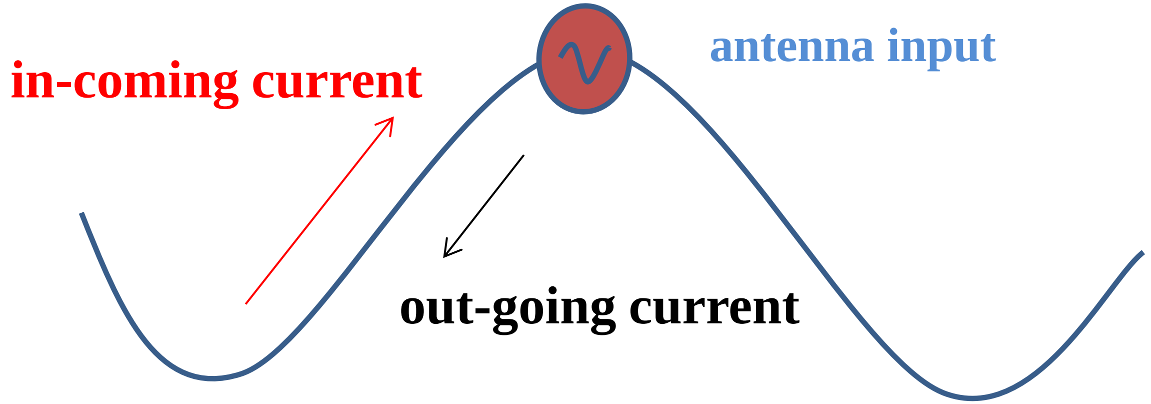


(Current Distribution along Antenna Arms)*

Practical Antenna Arms / / a Finite Length,

Current : composed of *

an out-going current & an in-coming current

The in-coming current

changes the situation at the antenna input.

~ changes **the antenna input impedance** in response to the **antenna shape & operating frequency.**

.. Reduce the In-coming Current &

.. Use Only the

Out-Going Traveling Wave (TW) Current

to Realize Wide Band Antennas

-: categorized as either

Positive-β TW current
or
Negative-β TW current.

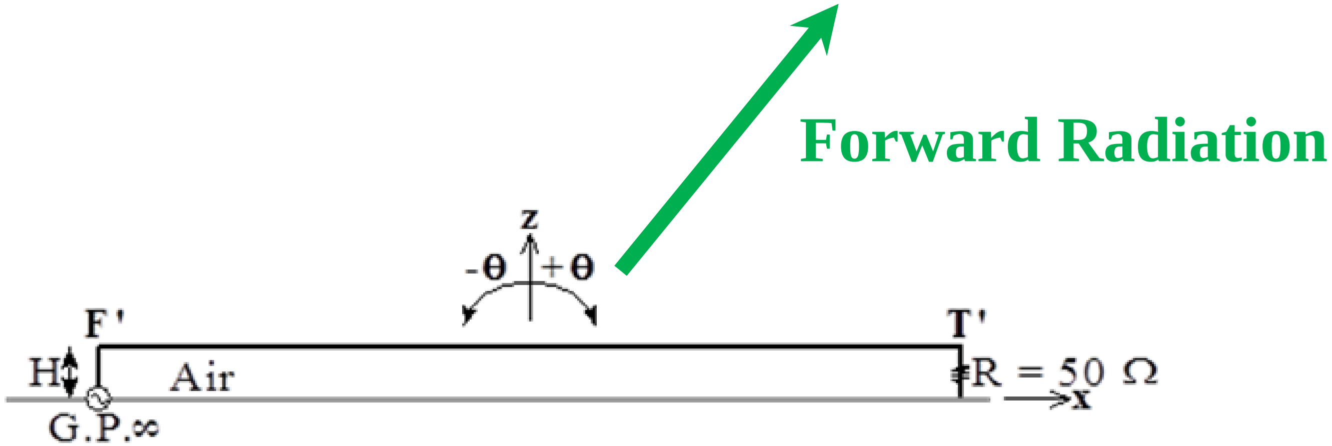
Antenna based on a positive-β TW current : defined as*

Natural (TW) Antenna*

Antenna based on a negative-β TW current : defined as

Metamaterial (TW) Antenna

Example of a Natural TW Antenna

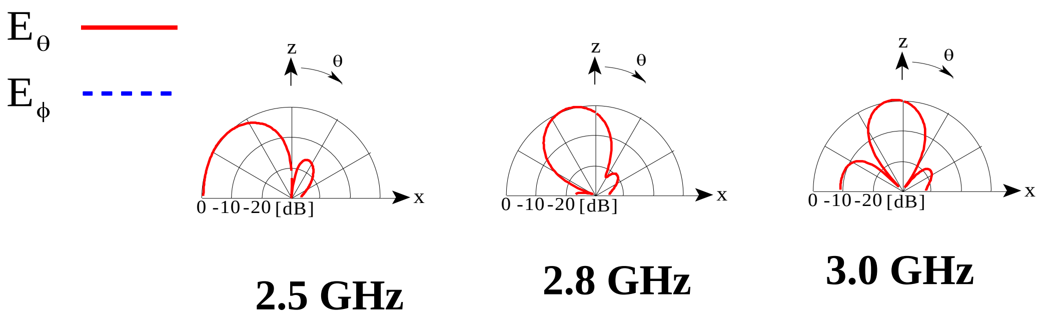


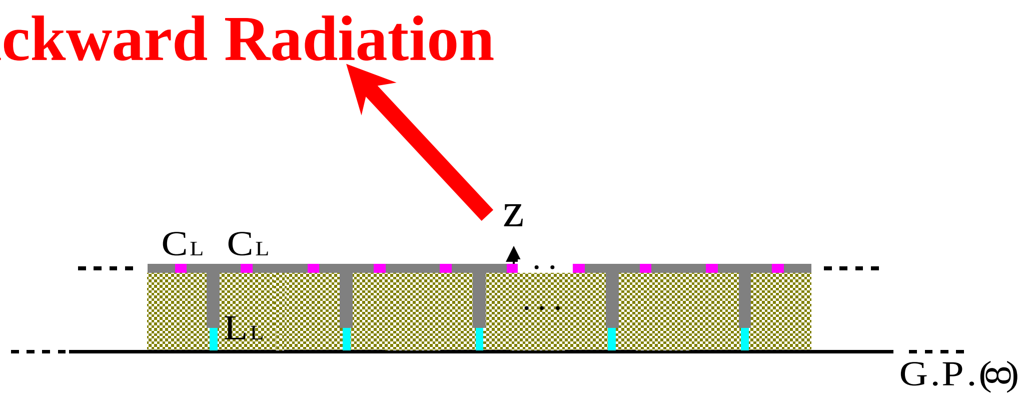
- - A positive-β current flows from F' to T'

A Phase-Lag Based on a positive-β Current

Forward Radiation*****

***Example of a MTM TW Antenna**





- - Capacitances and Inductances ::
inserted into a microstrip line*

A negative-β current flows from the left to the right.

A Phase-Progress Based on a Negative-β Current

Backward Radiation

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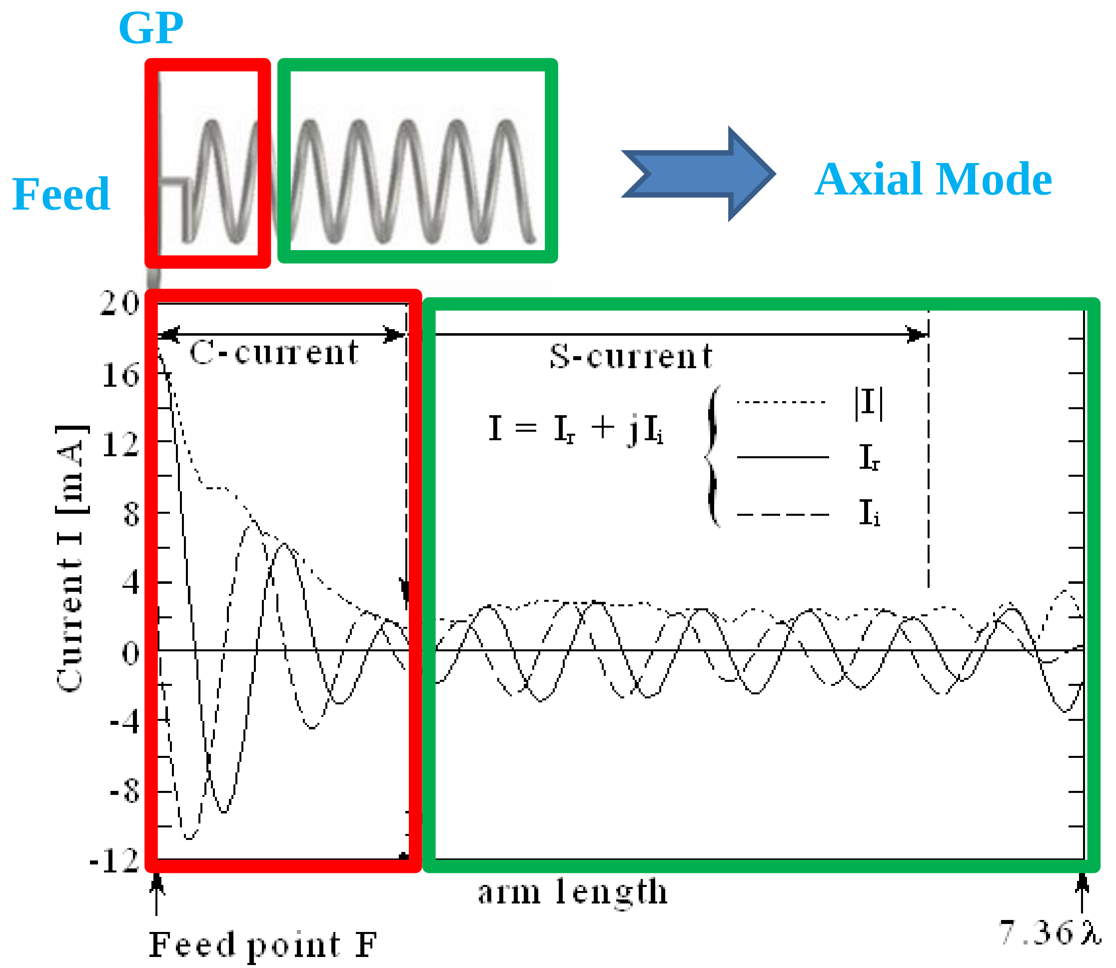
Helical Antenna

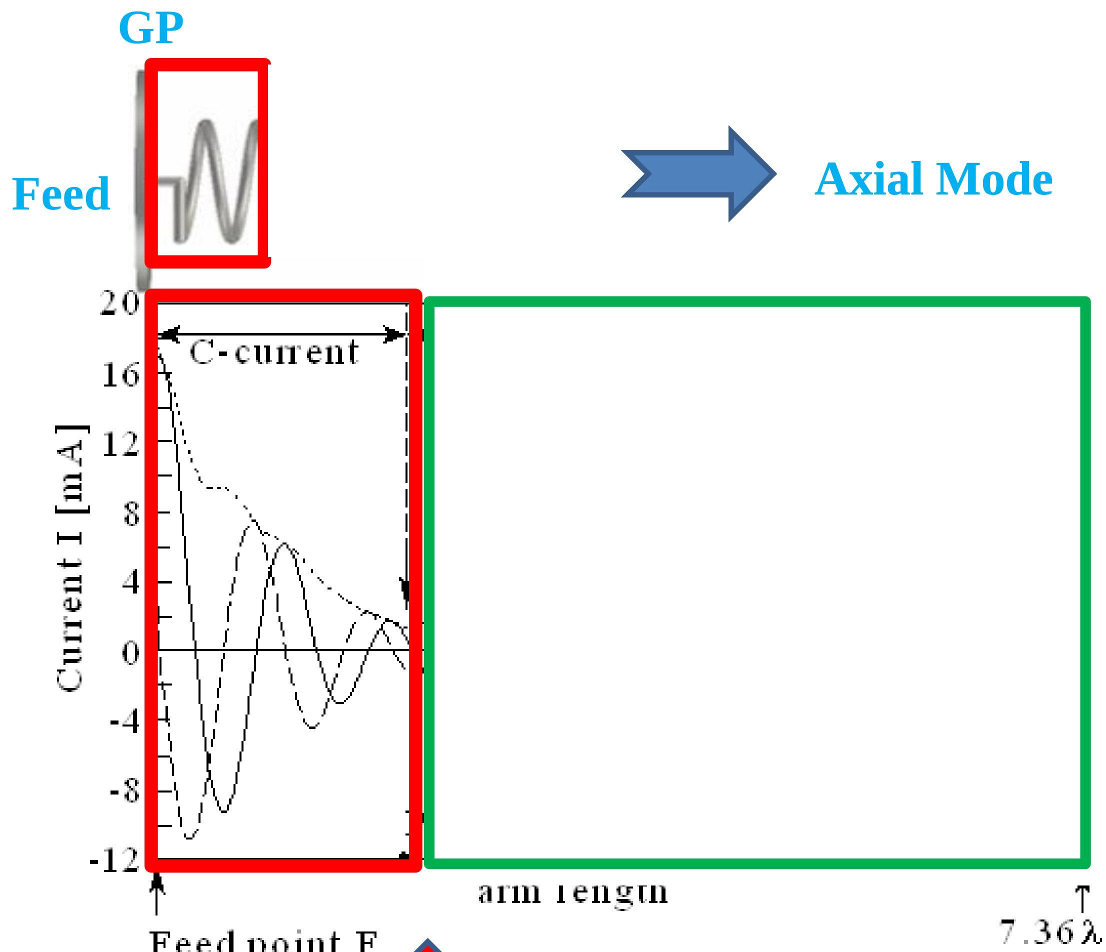


FINDING
Current /
two distinct regions
C-current region* &
S-current region*

.. Remove the S-current region* &
.. use only <u>the C-current region</u>
for CP radiation

-/ a decaying TW current
along the helical arm of
~ two turns* *

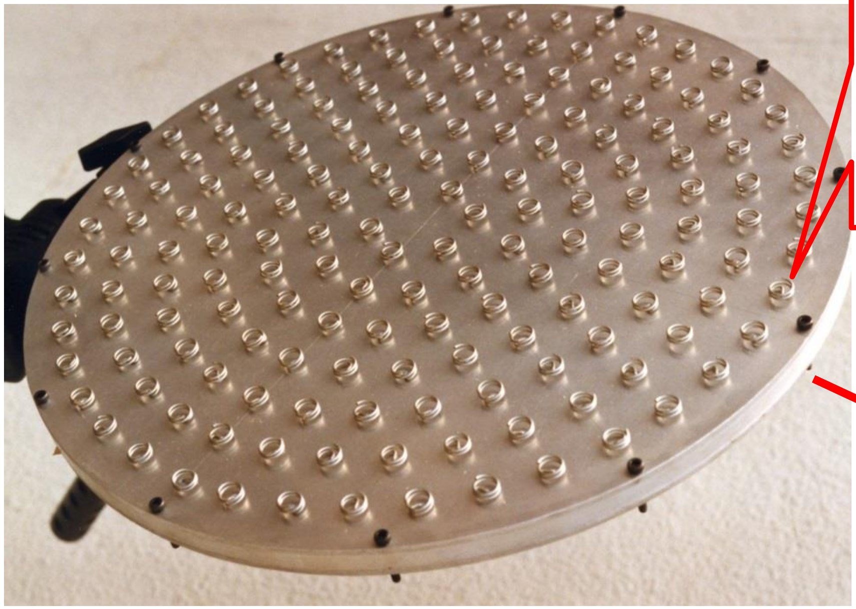
~ an antenna height of
0.19 wavelength
above the GP



2 turns

*Application of Low-Profile Helical Element

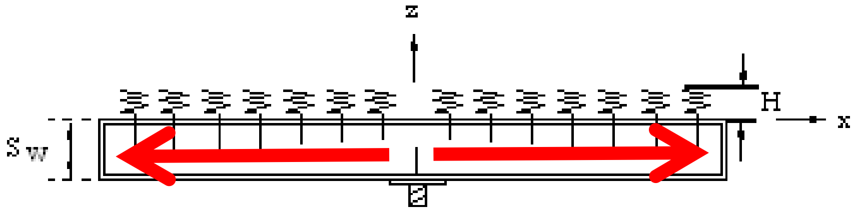
Each element : arrayed on a cavity
Vertical line of the helix : inserted into a cavity* &
excited by a traveling EM wave*
Aperture Efficiency :
extremely high and approx. 90%.



Circular cavity

Aperture Efficiency ~ 90%

Phase :
controlled by rotating the element around its axis.
Amplitude :
controlled by the vertical length inserted into the cavity.



Side view of a cavity

<u>ARRAY</u> /: used as

Indoor Broadcasting Satellite Receiving Antenna

Dia. = 27.8 cm
G = 29.5 dBi,

/ Dia. = 33 cm
G = 31.7 dBi,
Aperture efficiency of η = 88%

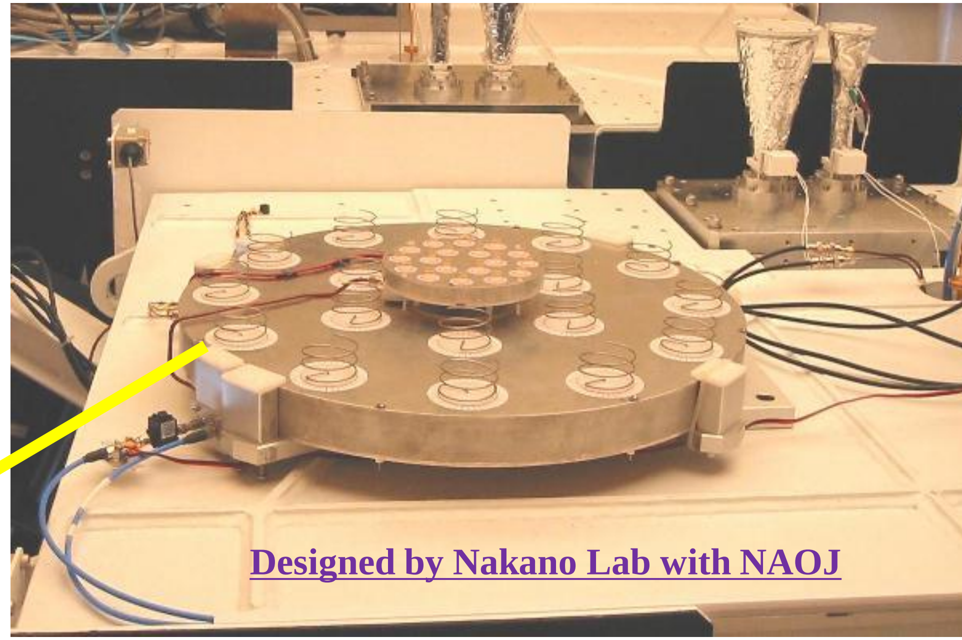
Designed by Nakano Lab
Produced by Yagi Antenna Co.

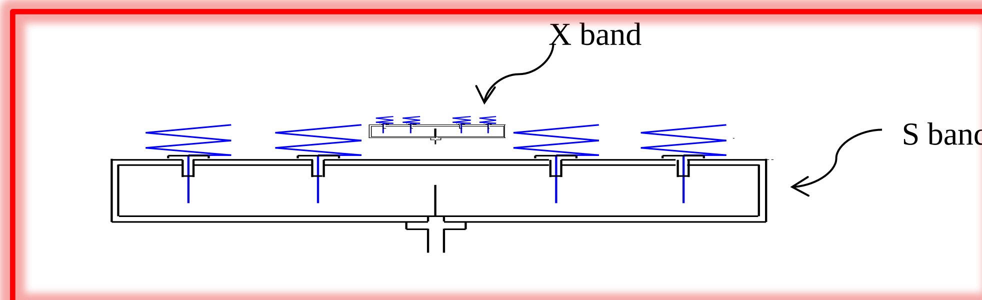
Designed by Nakano Lab
Produced by TDK Co.

Cassegrain reflector /

a main dish of diameter of 20 m * & a sub-dish of diameter of 2.6 m.

Focal length of main dish : 6 m. *





Primary feed /a two-layer structure.

X band (8.1-8.9 GHz, BW = 9.4%).

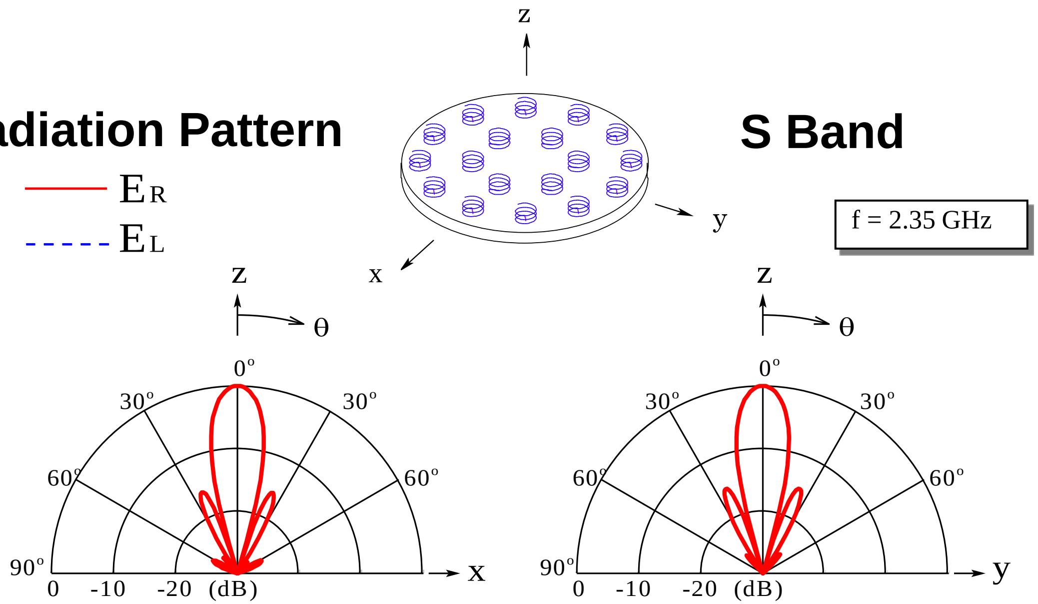
S band (2.1-2.6 GHz, BW = 21.3%)

Helical elements: plated with Gold

http://veraserver.mtk.nao.ac.jp/restricted/status05.pdf (Japanese)

Radiation Pattern

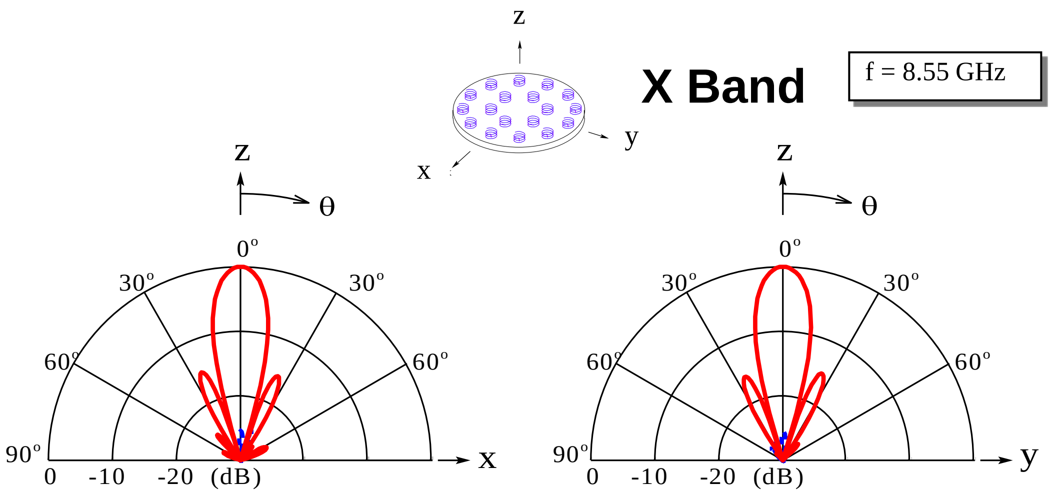
S Band



Symbol	Value
D_{HLX}	41.38 mm ≈ $0.3241\lambda_{2.35}$
n	3.1 turns
α	4°
ρ	0.5 mm ≈ $3.917\times10^{-3}\lambda_{2.35}$
H_{CAV}	495 mm ≈ $3.8775\lambda_{2.35}$
D_{CAV}	36 mm ≈ $0.282\lambda_{2.35}$
S_{cir}	109 mm ≈ $0.8538\lambda_{2.35}$
S_{rad}	104 mm ≈ $0.8147\lambda_{2.35}$

* $\lambda_{2.35}$ ≈ 127.66 mm

X Band



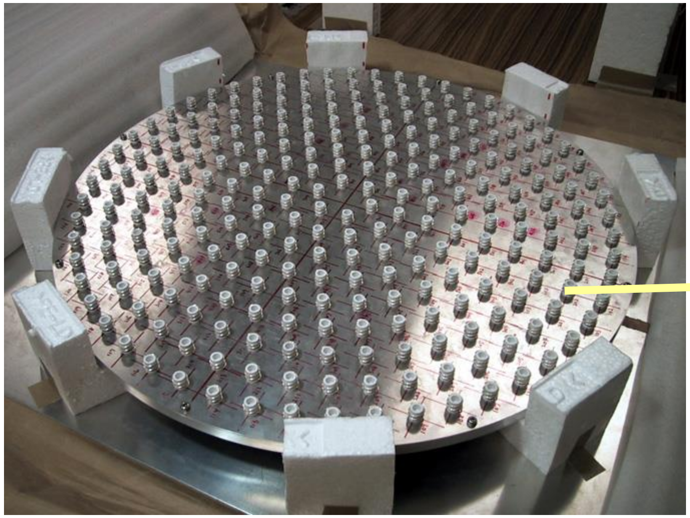
Symbol	Value
D_{HLX}	11.169 mm ≈ $0.3183\lambda_{8.55}$
n	2.8 turns
α	4°
ρ	0.2 mm ≈ $5.7\times10^{-3}\lambda_{8.55}$
H_{CAV}	142 mm ≈ $4.047\lambda_{8.55}$
D_{CAV}	9.7 mm ≈ $0.27645\lambda_{8.55}$
S_{cir}	29.4 mm ≈ $0.8379\lambda_{8.55}$
S_{rad}	28.1mm ≈ $0.8009\lambda_{8.55}$

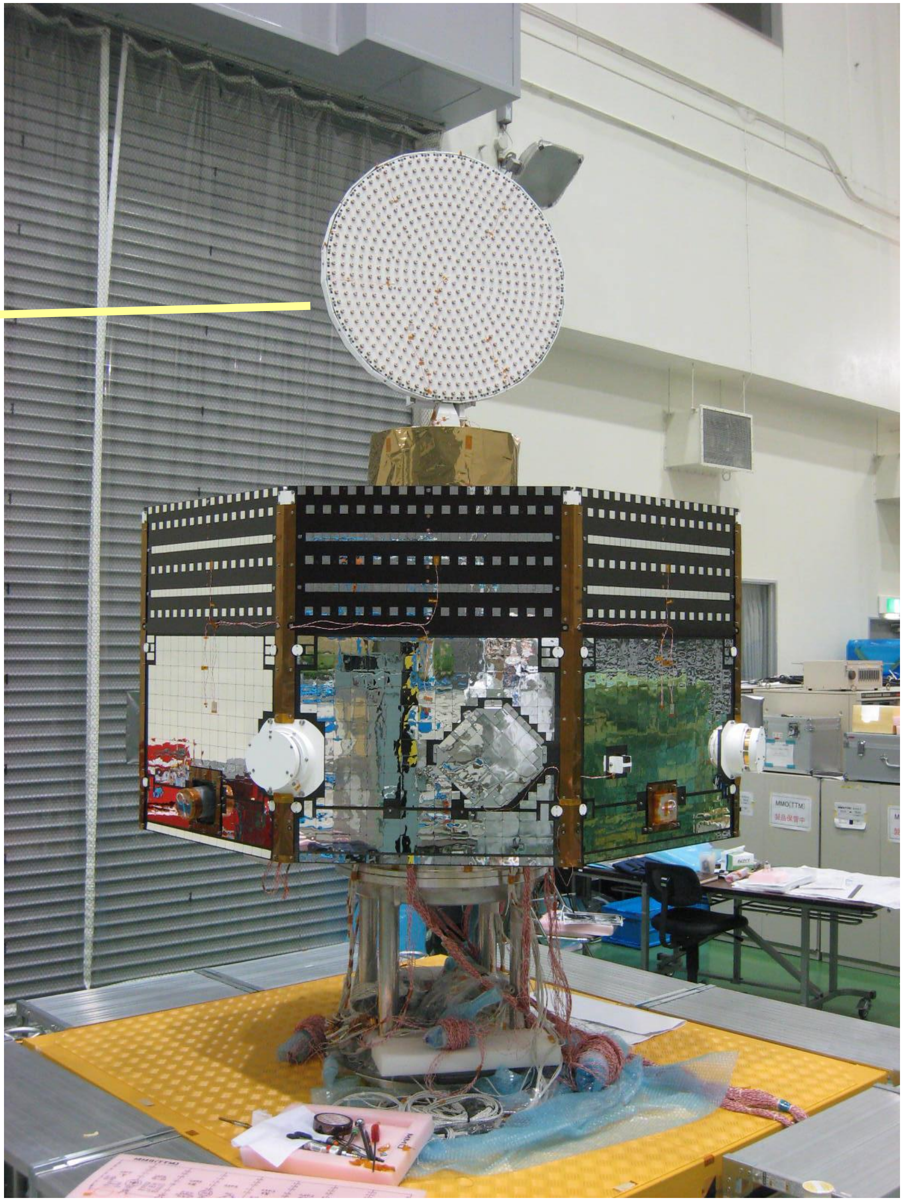
* $\lambda_{8.55}$ ≈ 35.294 mm

The same beam width is realized.

A beam width of 22° for a 7-dB reduced field intensity criterion is realized, meeting the requirement for both of the feed antennas.

*Helical antenna array for a "BepiColombo"





Presented by
JAXA and
NEC-TOSHIBA Space System

Out line

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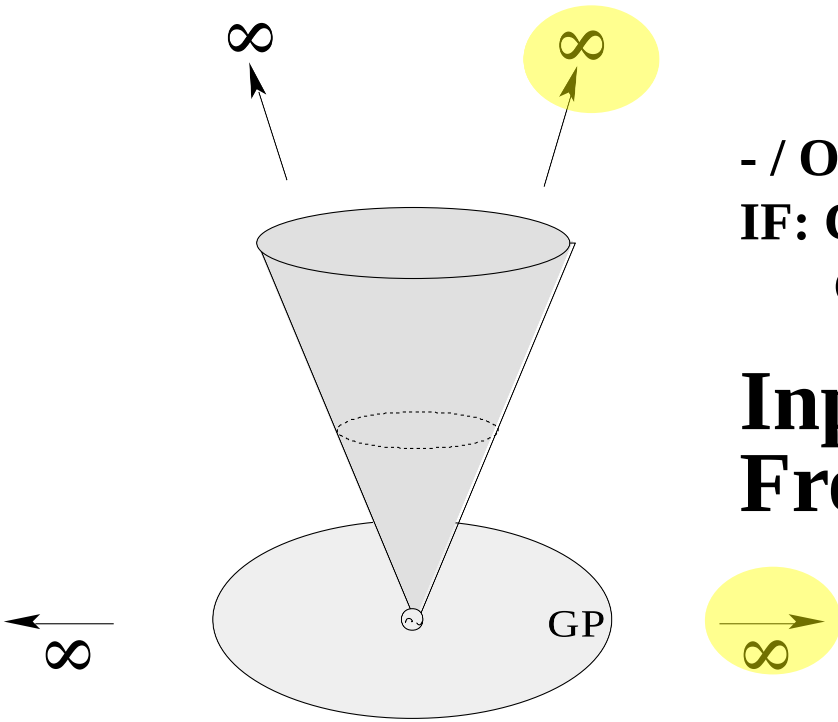
*Conducting Conical Antenna



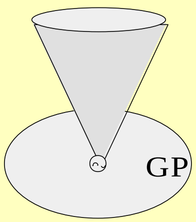
- / Only an Out-going Current
IF: Conical Arm: Infinitely Long &
Ground Plane : of Infinite Extent

Input impedance : Frequency-Independent*

Practical Structure

//The Conical Arm Cannot Be Infinitely Long!

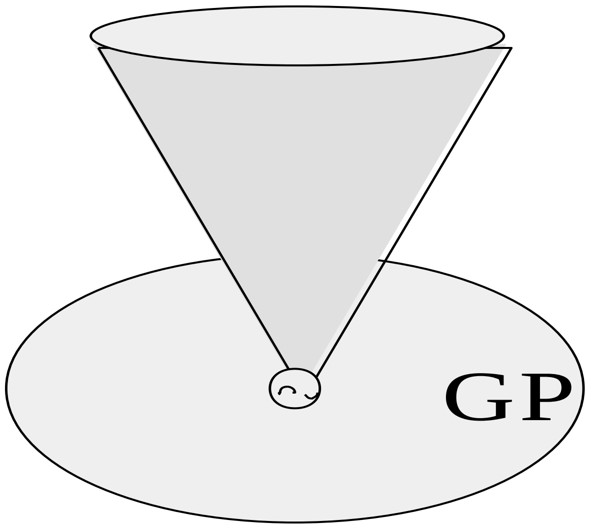
Practical
Truncated
Conical Antenna



No More: Inherent Frequency-Independent Characteristics

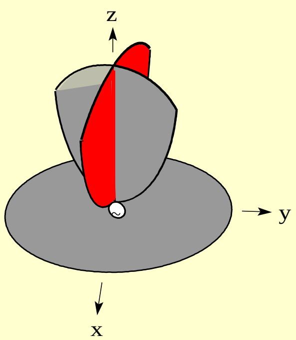
// .. Expect Wideband Characteristics

- Partially Retains the Original Structure



Truncated
Conical Antenna*

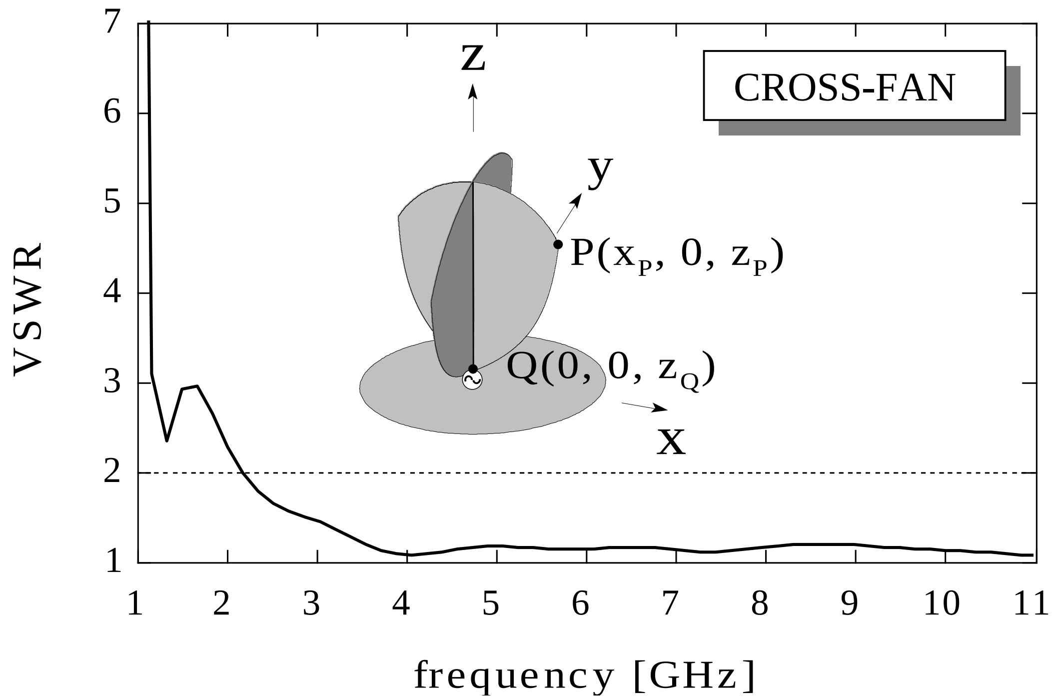
Modification from a Truncated Conical to A CROSS-FAN Antenna



.. FABRICATION
Low-Profile Antenna

- - A Pair of Fan-Shaped Plates
Intersect at Right Angles*

*Frequency Response of the VSWR of the Cross-Fan Antenna

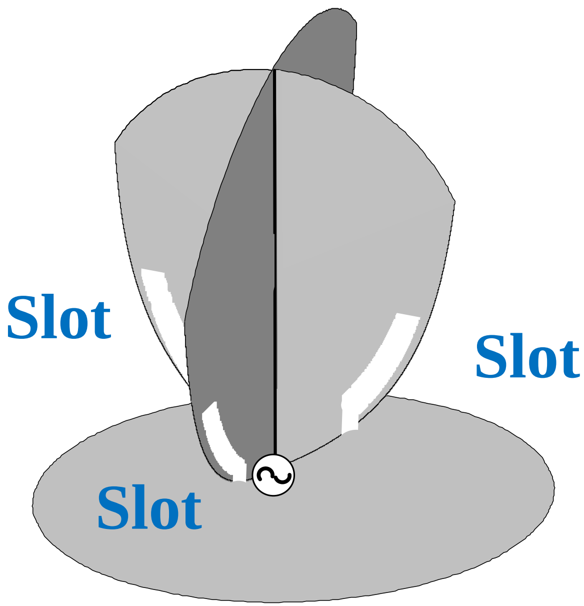


Antenna Height : 0.3 Wavelength at 2.1 GHz

Note: VSWR : less than two at frequencies above 2.1 GHz*.
Antenna Height : 0.3 Wavelength at 2.1 GHz.
Radiation : Omnidirectional around the antenna axis (z-axis).

Technique for Stop-Band Generation

in order to prevent the reception of interference from nearby devices



CROSS-FAN-SLOT

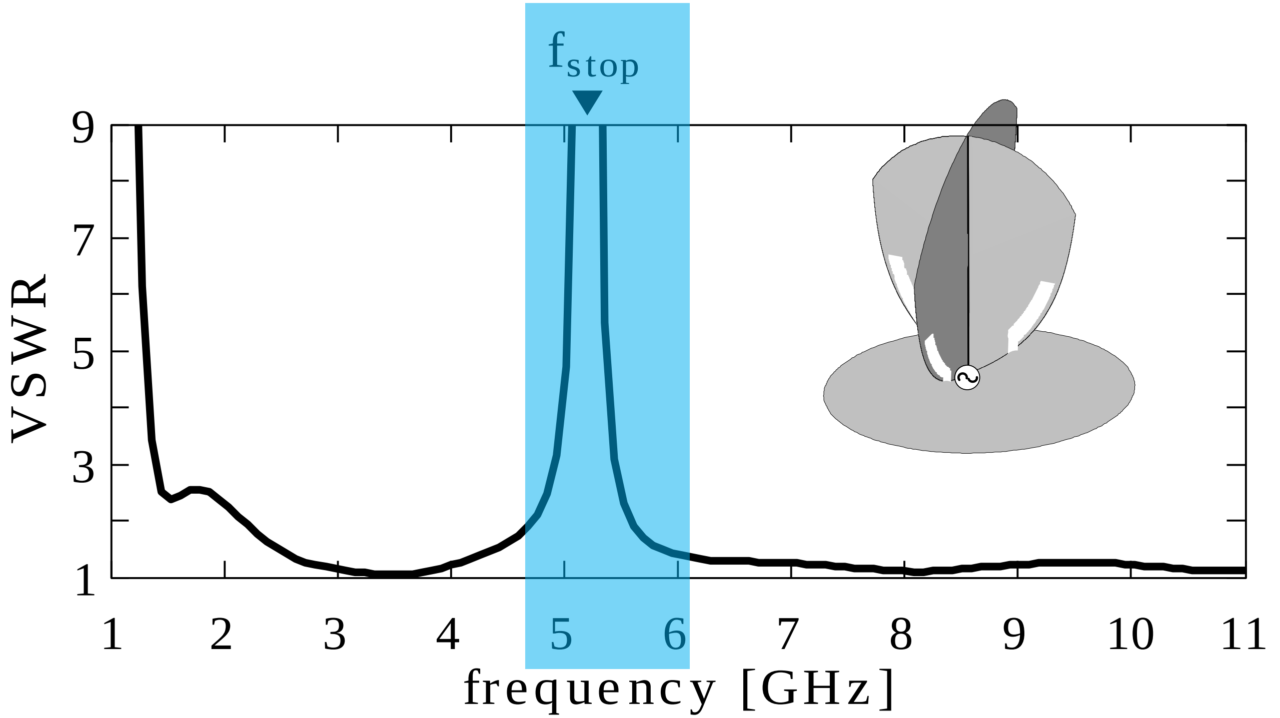
Requirement of Stop Band

Cross-fan : often required to have a stop band within the VSWR band∧

Introducing slots* into the fan-shaped plates : recommended.

This antenna : designated as the CROSS-FAN-SLOT.

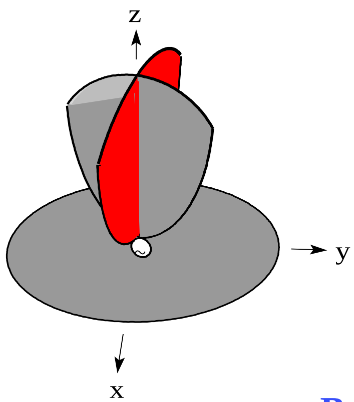
***VSWR of the CROSS-FAN-SLOT**



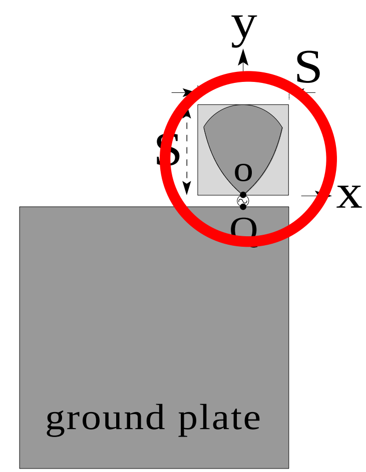
A Stop Band : *   around 5.2 GHz

Slot Length L_{slot} : ~ one-quarter wavelength at f_{stop}.

As Slot Length L_{slot} ↑
Stop-Band Center Freq. f_{stop}* ↓



Base Station Antenna >>> Portable Handset Antenna



CROSS-FAN /: Used as a Base Station Antenna

Fan-shaped plate antenna

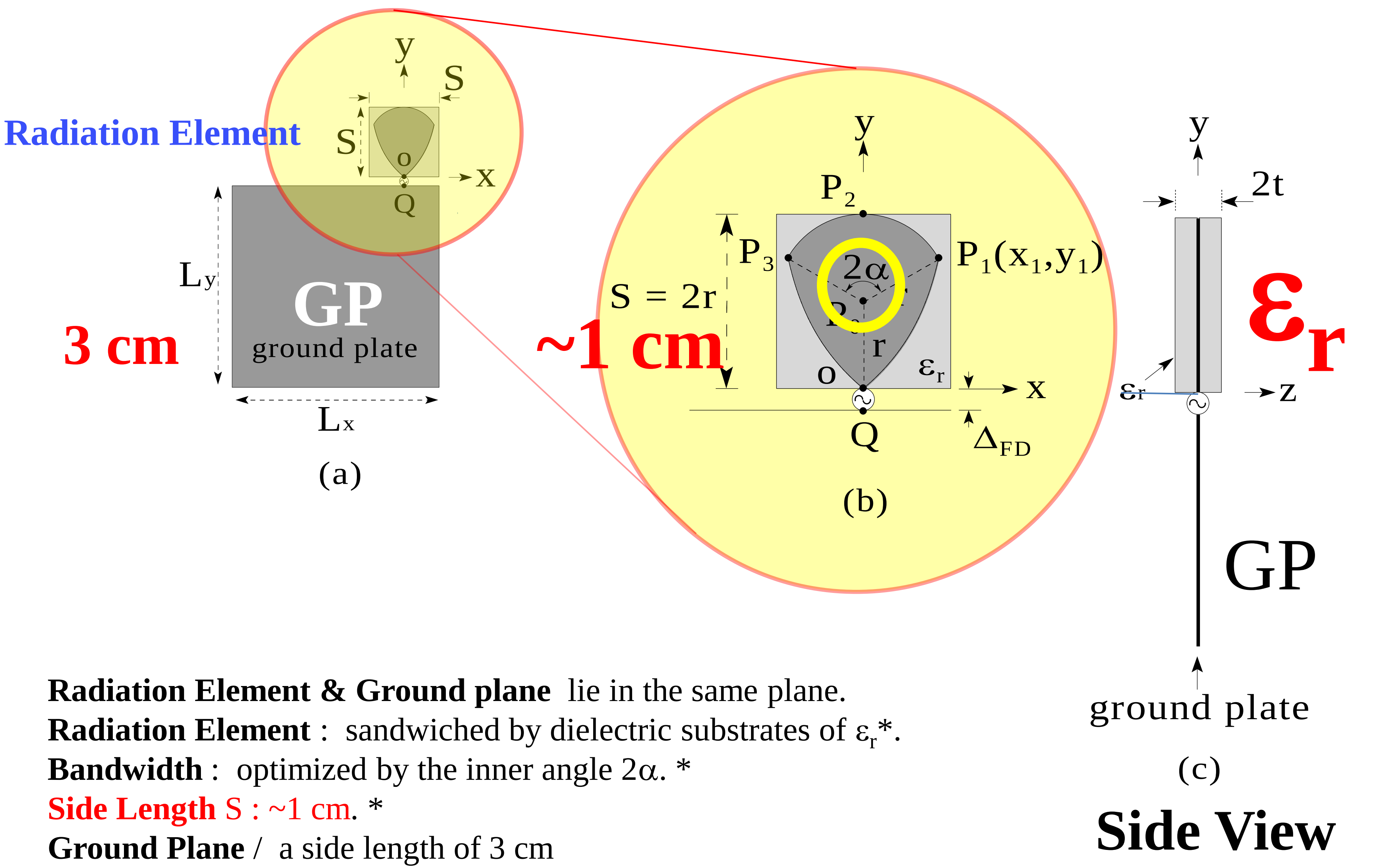
.. MODIIFICATION CROSS-FAN for a Portable Handset

- REQUIREMENT **Card-type Structure**

.. REDUCTION **Two fan-shaped plates to one plate ** &**

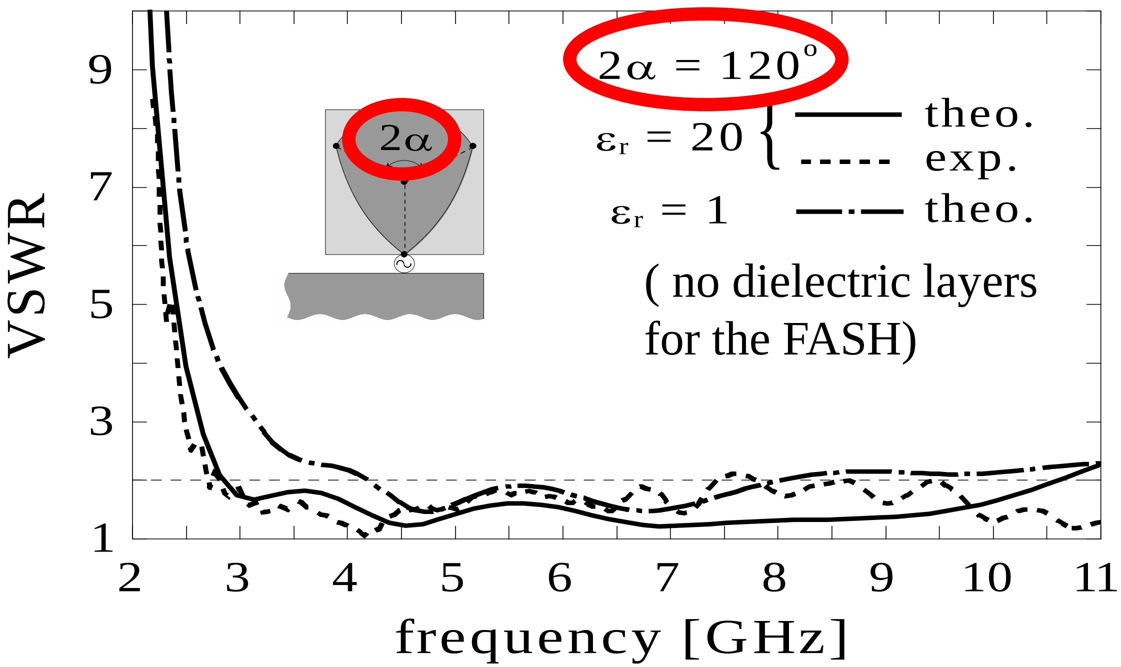
.. MAKE **Antenna Height Small - : Fan-shaped plate antenna**

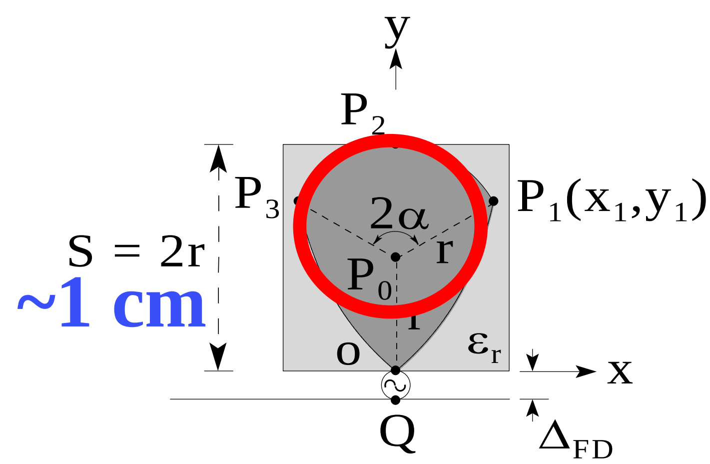
* Detail of fan-shaped plate Antenna



Radiation Element & Ground plane lie in the same plane.
Radiation Element : sandwiched by dielectric substrates of ε_r*.
Bandwidth : optimized by the inner angle 2α. *
Side Length S : ~1 cm. *
Ground Plane / a side length of 3 cm

*Frequency response of the VSWR





(b)

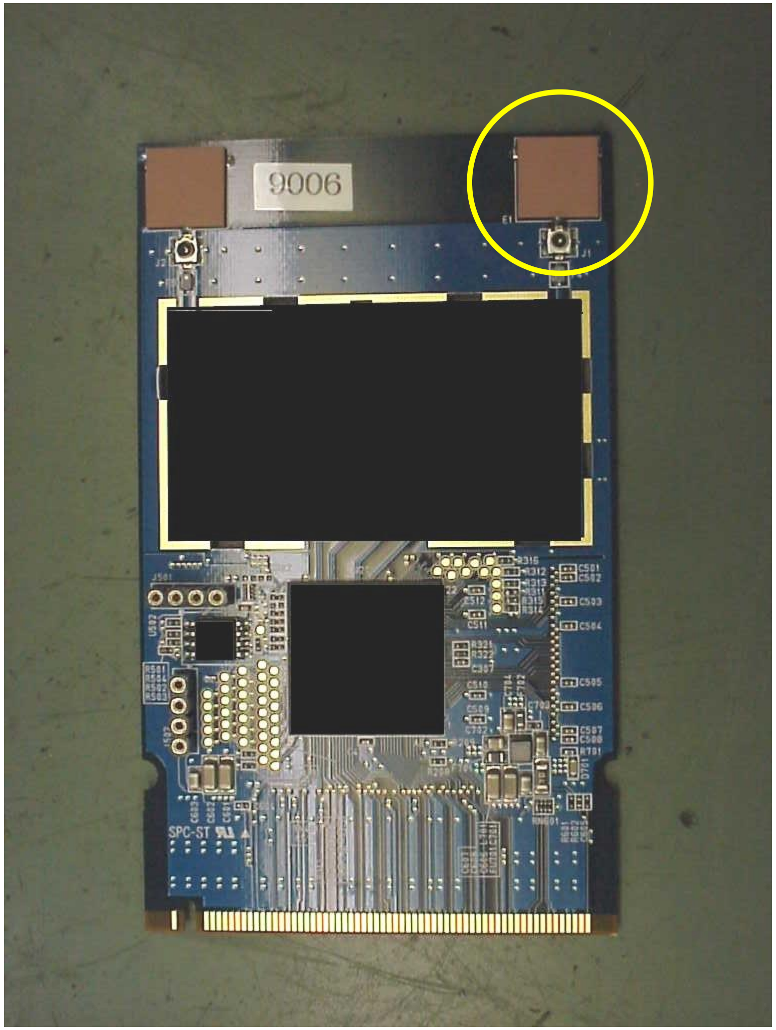
2α = 120 degrees.
(ε_r, 2t, S) = (20, 1 mm, 10.87 mm),
(L_x, L_y) = (30 mm, 30 mm),
r = 5.44 mm

Note: **VSWR < 2 above 2.75 GHz**.

Antenna Height : **0.09λ at 2.75 GHz**.

Ground Plane / a side length of 3 cm

Installation of a <u>Fan-Shaped Antenna</u> *



- : Installed in a handset device. *
- : Sandwiched by dielectric substrates

Substrate /
an area of ~1 cm x 1 cm.

Designed by Nakano Lab.
Produced by Mitsumi Co.

The substrate has an area of 1 cm by 1 cm.
The antennas installed inside a handset device.

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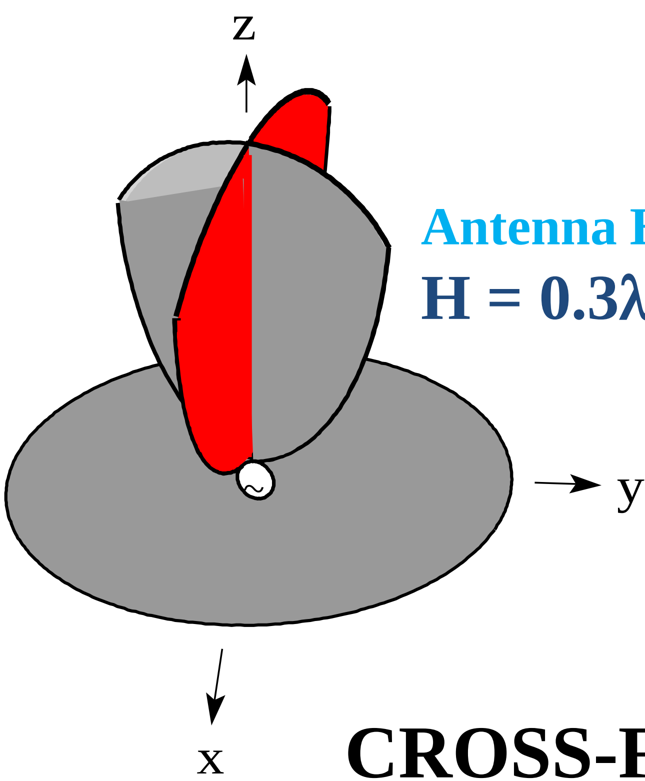
BASE STATION ANTENNA II



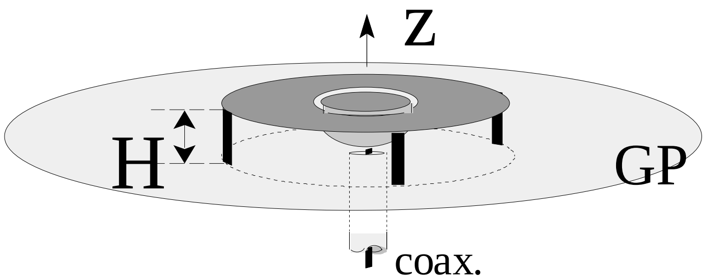
Antenna Height

H = 0.3λ

→

Lower Base Station Antenna

H = 0.07λ



CROSS-FAN

BOR-SPR

Body of Revolution with
a Shorted Parasitic Ring

BOR-SPR Base-station Antenna

*****BOR-SPR Antenna** : composed of

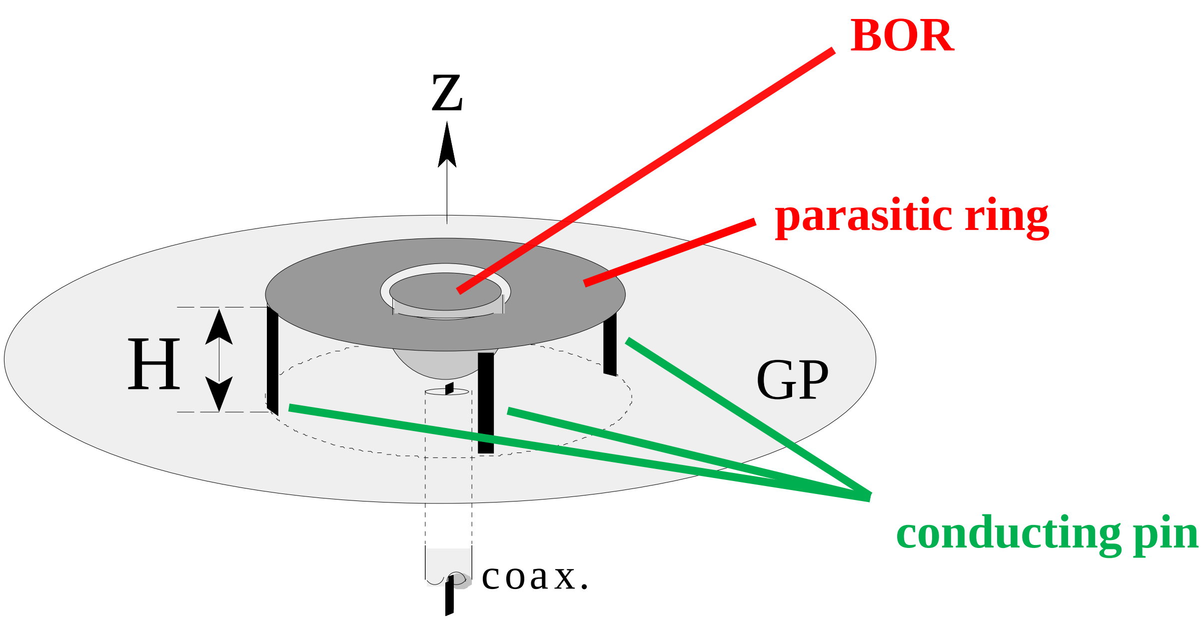
a conducting body of revolution (feed section) *

& a parasitic conducting ring* :

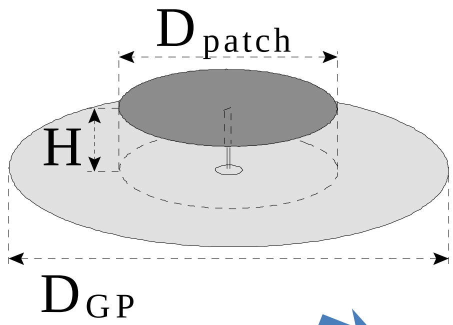
shorted to the ground plane through conducting pins *.

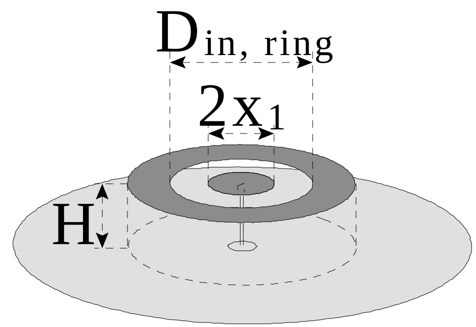
Antenna Height : extremely small*: 0.07 wavelength.

$H = 0.07\lambda$

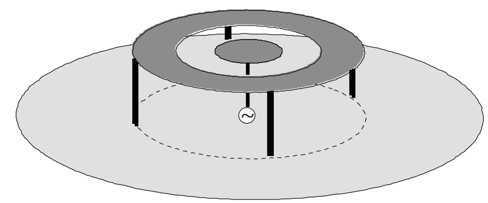


Design of BOR-SPA





.. Add four conducting pins.



$H = 0.07\lambda$

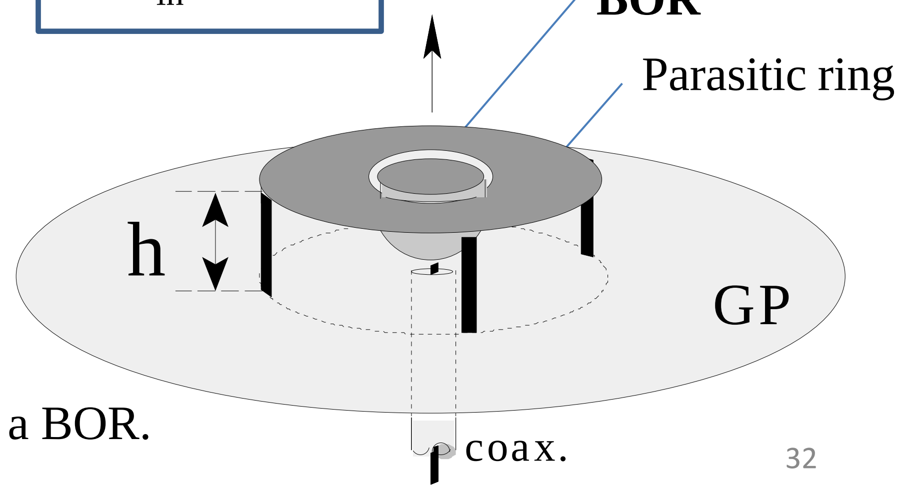
.. Cut a ring slot

Microstrip patch

R_{in} : low < 50
X_{in} : inductive

R_{in} : low < 50
X_{in} : **0**

R_{in} : **50**
X_{in} : 0

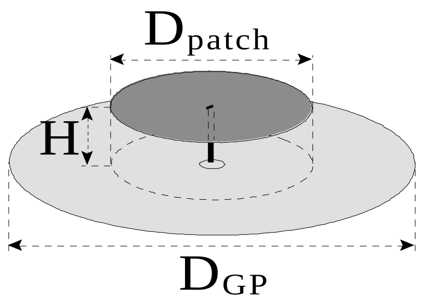


.. Replace the feed section by a BOR.

Design Process

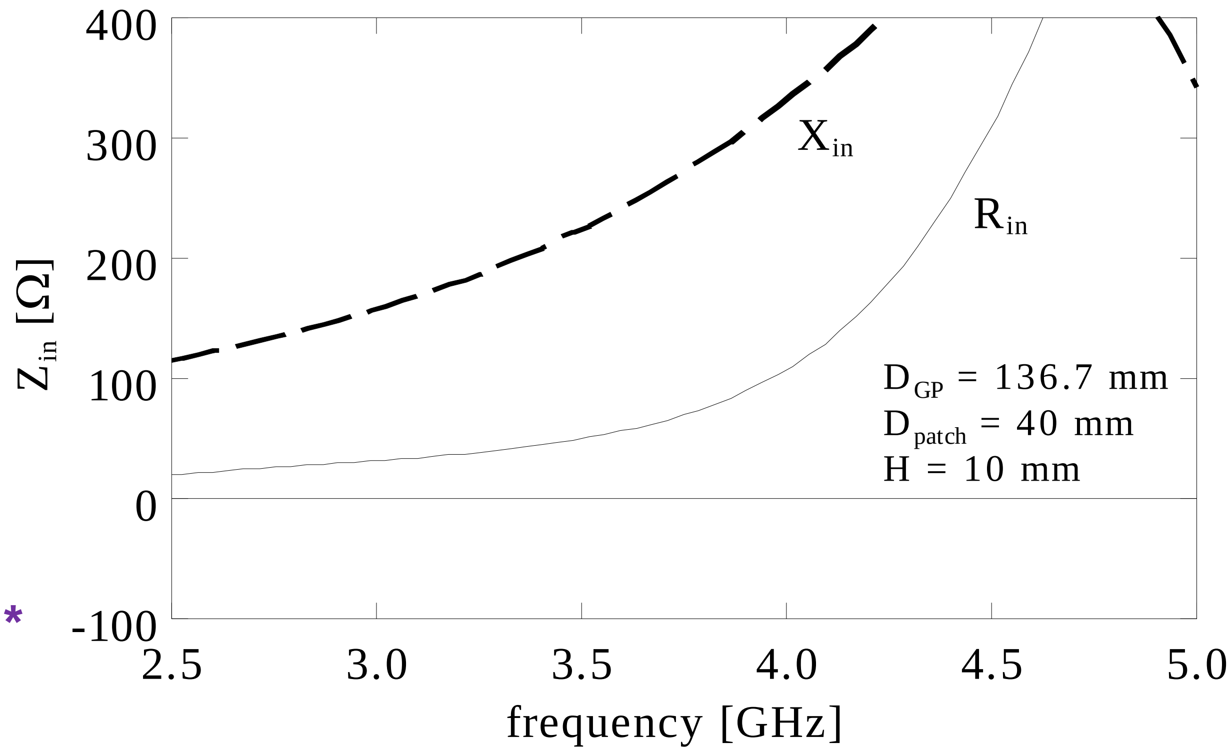
First Step : to analyze the input impedance for a low-profile patch

Patch dia. ~ 4 cm



GP dia. ~ 14 cm

Antenna height H = 1 cm *

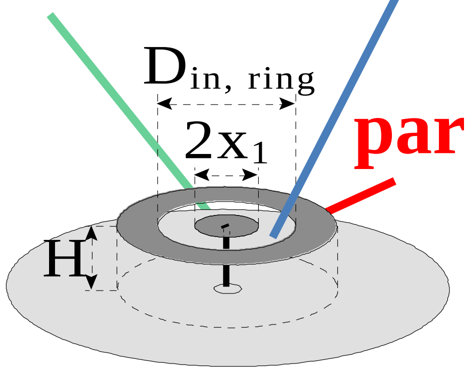


R_{in} < 50 ohms

X_{in} : inductive

Note:
There is a frequency region where the input reactance X_{in} is highly inductive.

Second step : To make the input reactance X_{in} zero by adding a **capacitive component**.

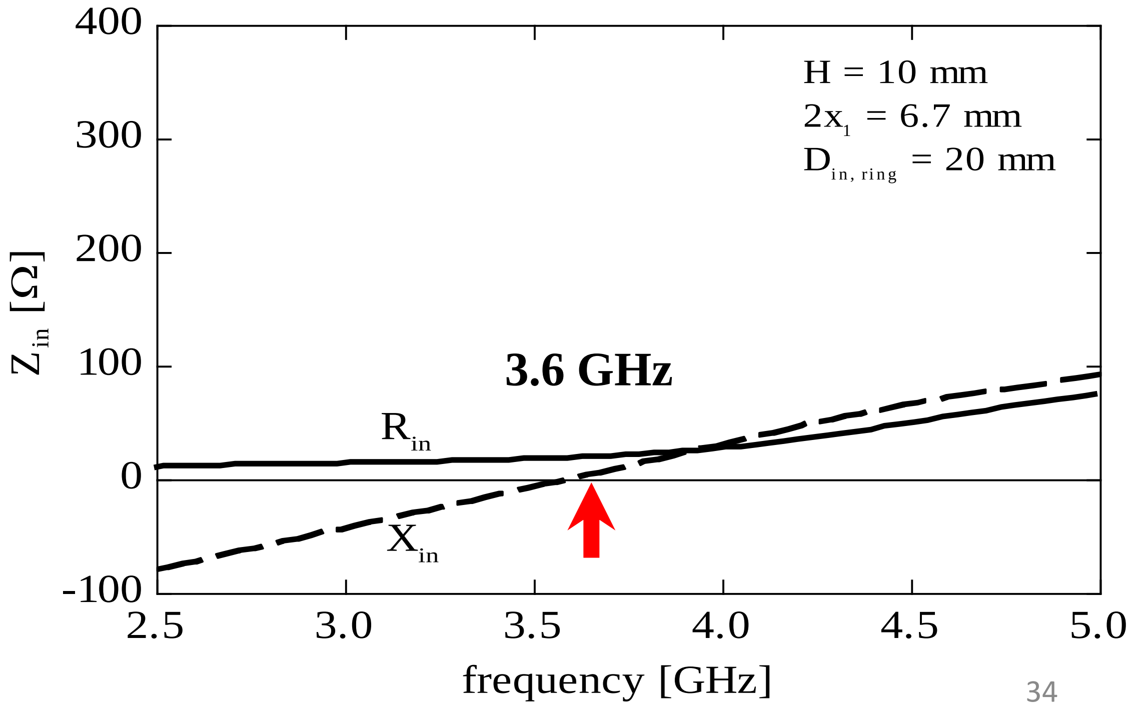


R_{in} : low < 50

X_{in} : **0**

: performed by cutting a ring slot into the original patch.* The slot forms a capacitance.

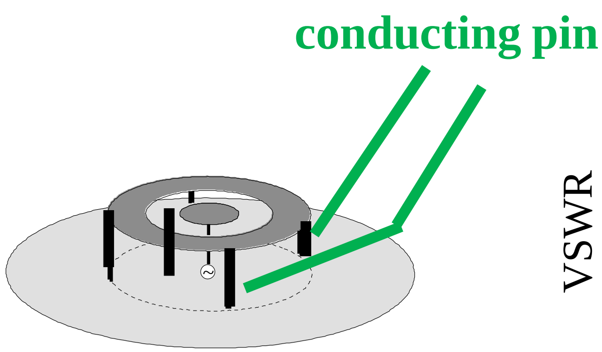
The original patch : divided into two regions, parasitic ring region* & small patch island*

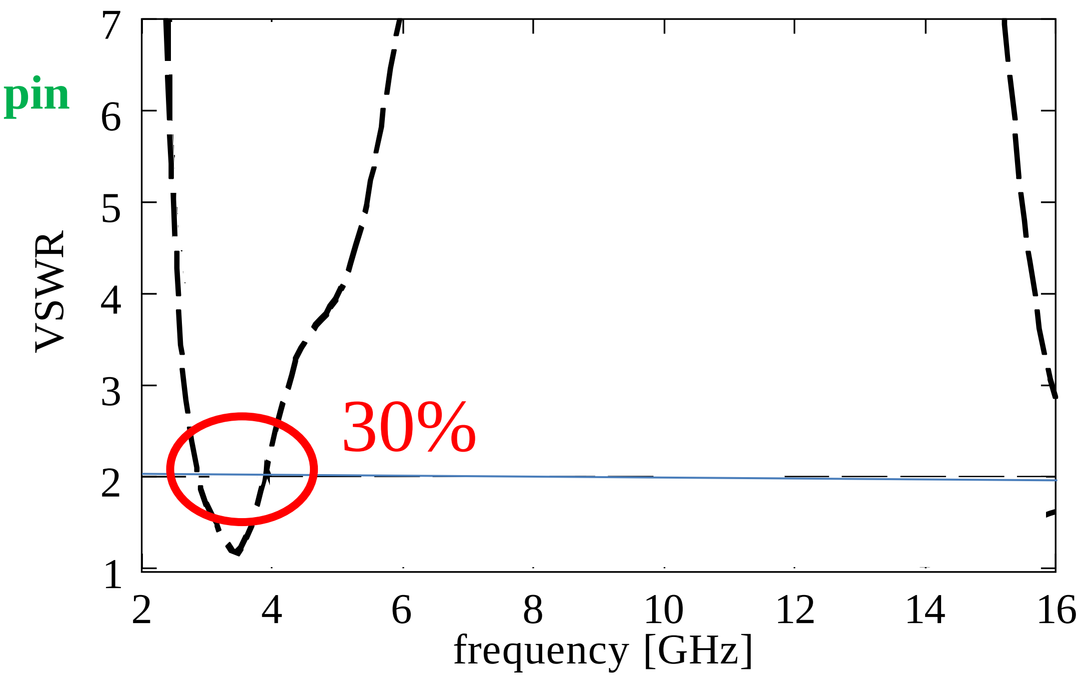


Third Step : To increase the input resistance R_{in}.

: achieved by increasing the antenna volume.

: performed by adding conducting pins & short them to the ground plane*.





R_{in} : increased to **50 ohms**

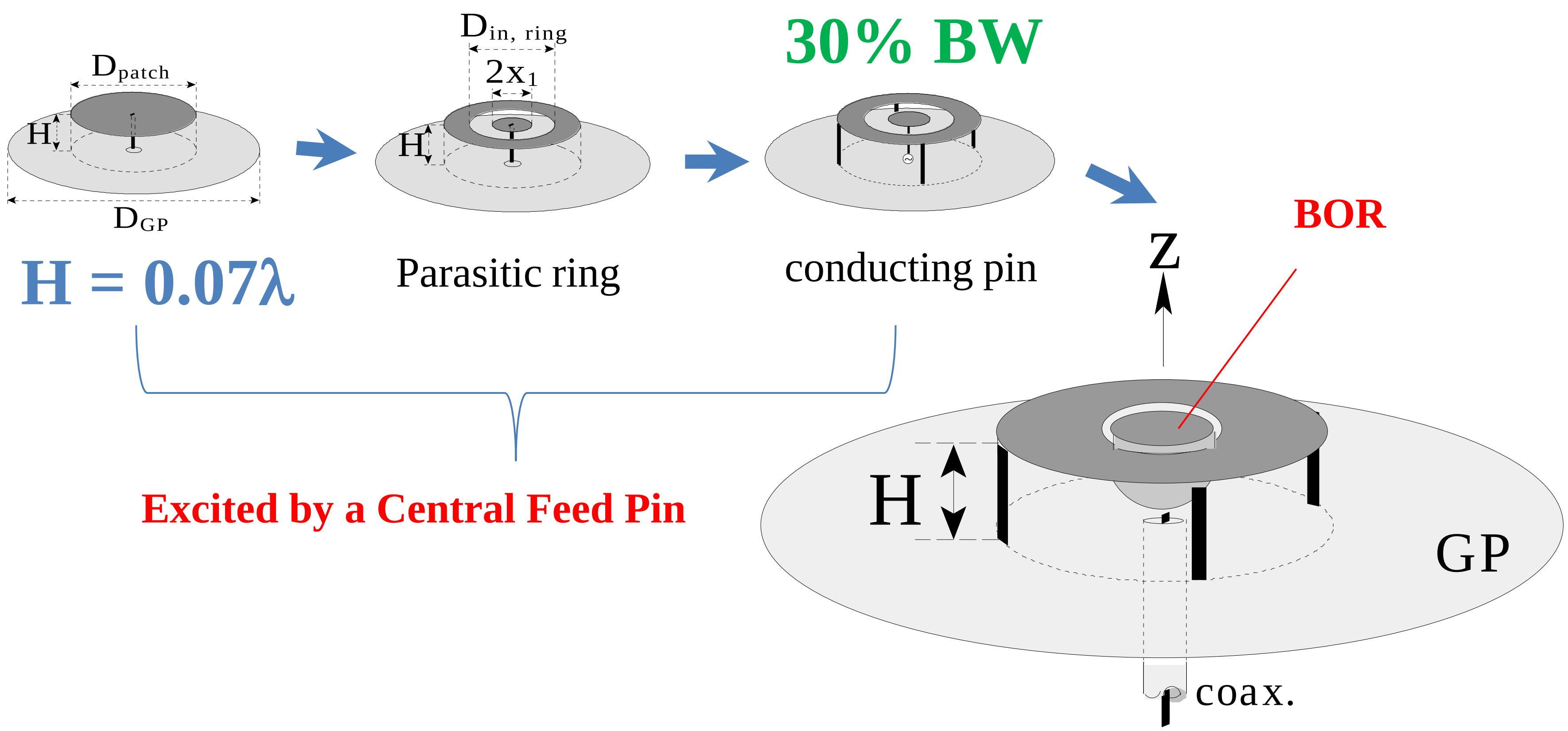
X_{in} : 0

Final Step : To further increase the frequency BW.

Antenna: excited by a central feed pin *

Central feed pin : replaced by a **conducting body of revolution.***

Generating line of the BOR : defined by an exponential function.



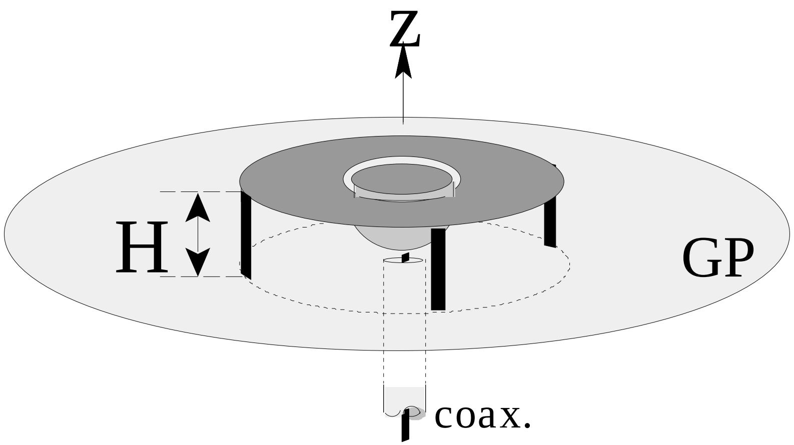
H = 0.07λ

Parasitic ring

conducting pin

Excited by a Central Feed Pin

* **Frequency response** of the VSWR for the BOR-SPR.



$H = 0.07\lambda$

$r_{patch} = 0.13\lambda$

BOR-SPR

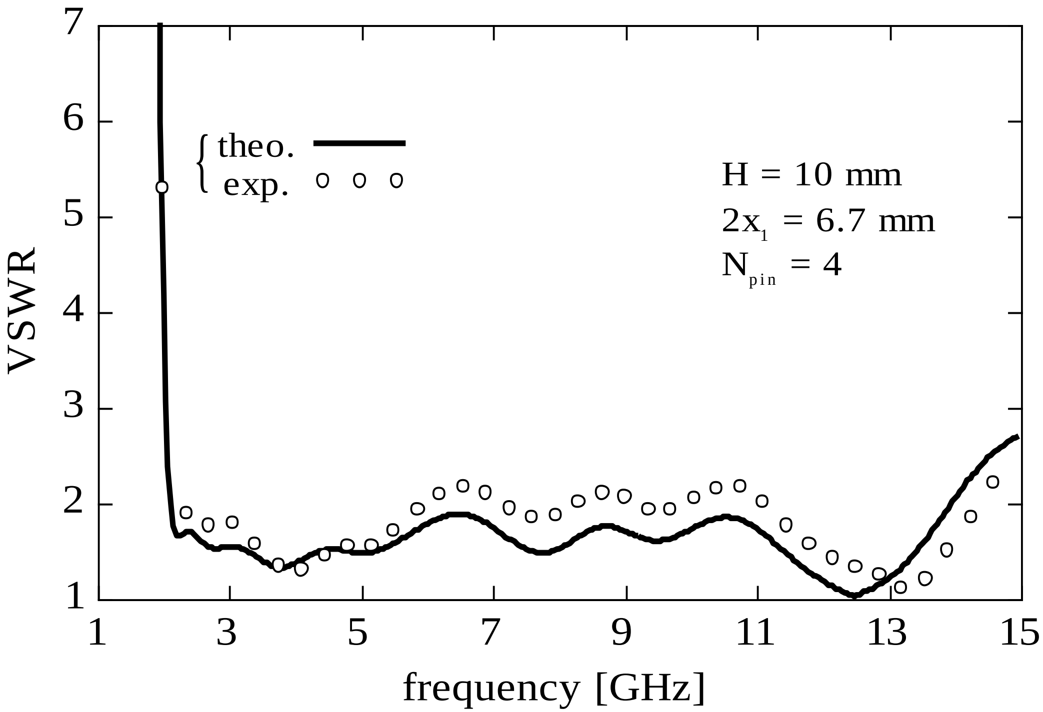
Body of Revolution with
Shorted Parasitic Ring

An extremely-wide frequency-band of

147% *

Note: The radiation :

omnidirectional around the z-axis.



147% BW

Installation example of BOR-CROSS

Designed by Nakano Lab.
Produced by Yagi Antenna Co.

BOR-CROSS is installed on the ceiling of a building.

Out line

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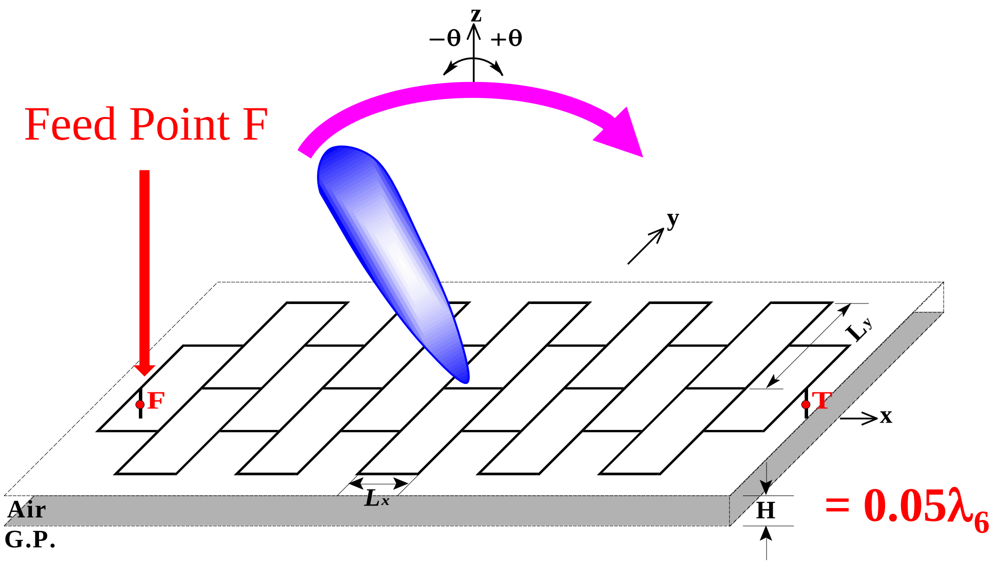
Section IV Remarks

*Conventional Grid Array Antenna (GAA)



Antenna height H = 2.5 mm

= 0.05λ_6

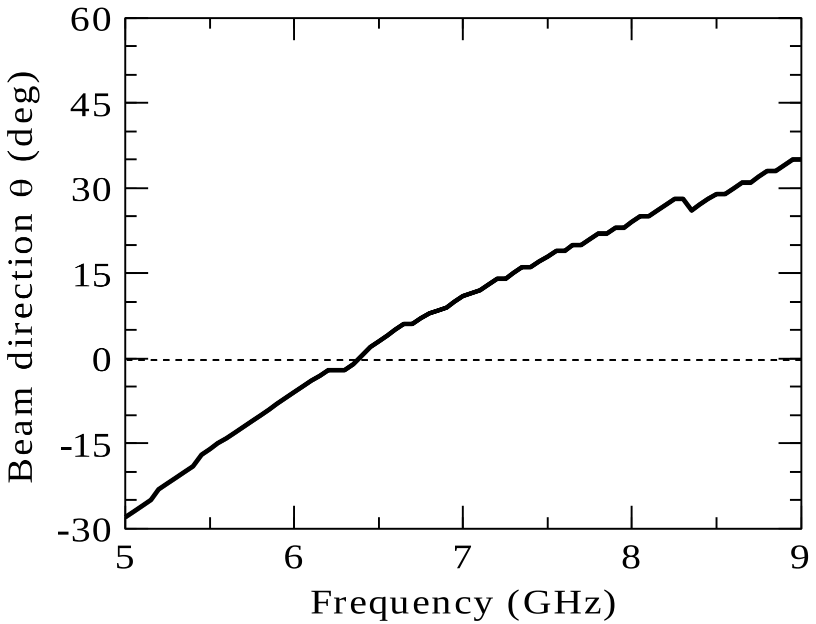
GAA : excited from its edge*

- creates a tilted beam* *Beam direction*

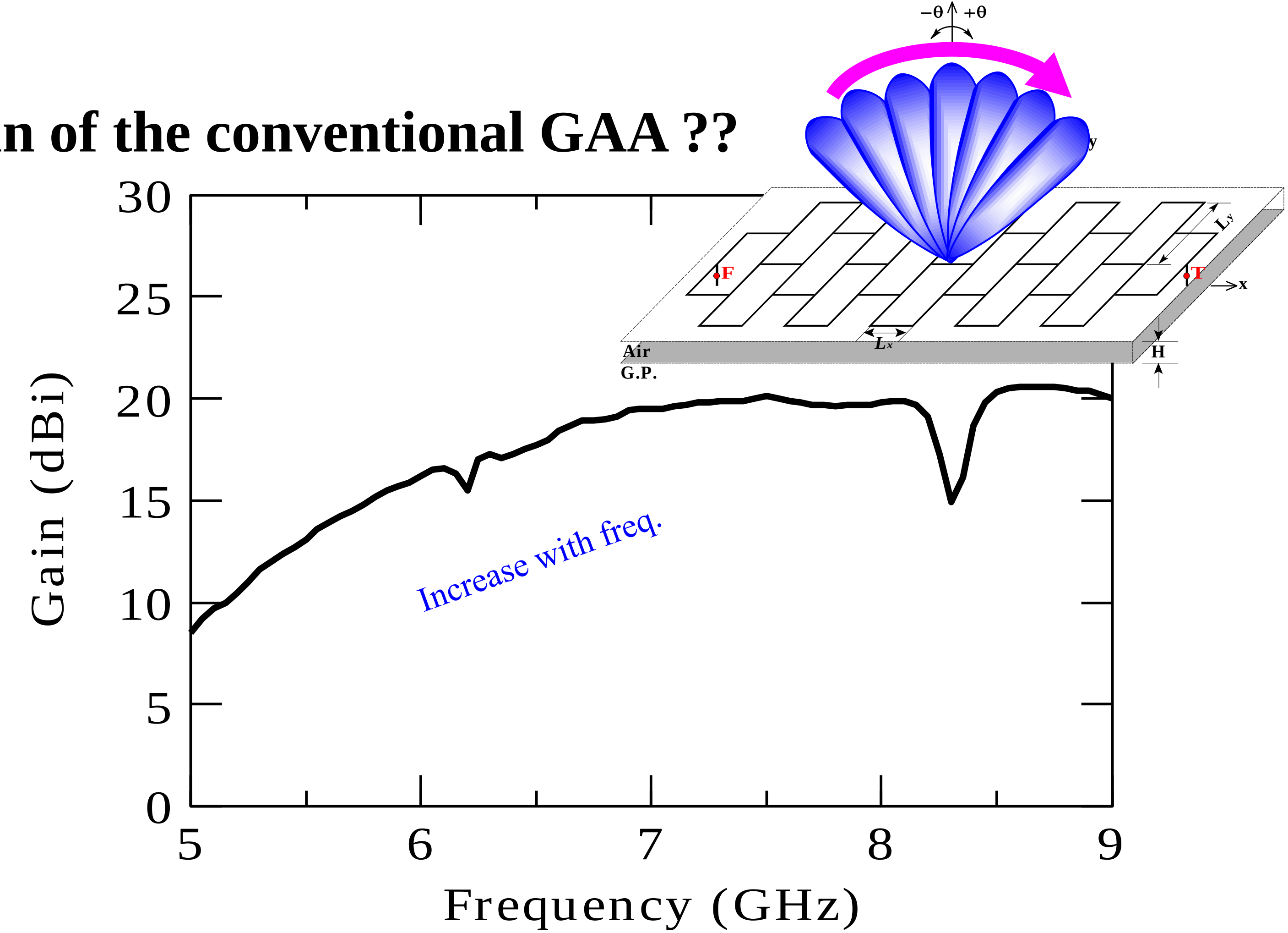
/ a frequency-scanning function.

*Beam Direction

as a function of frequency.



?? Gain of the conventional GAA ??



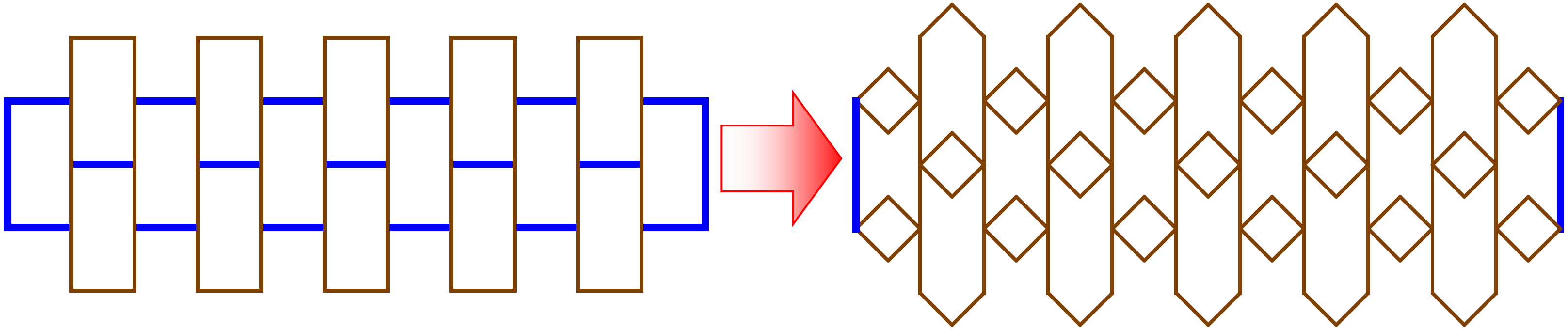
?Desirable Gain Behavior?

The gain should be constant

across the wide frequency band to be used for beam scanning.

As one solution to this issue*,

.. Propose a <u>New Grid Array Antenna</u>*



Conventional

Proposed

-: Rhombic GAA

Proposed RGAA :

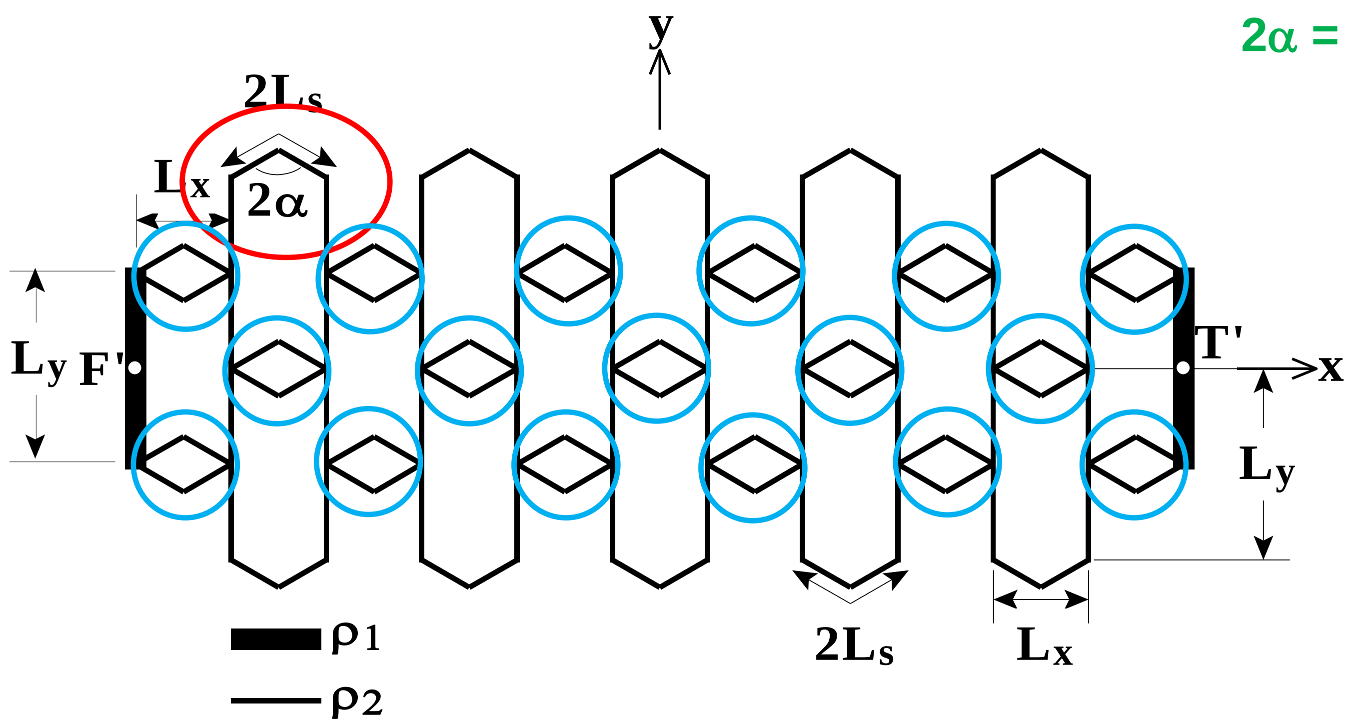
An extension of the conventional GAA.

Radiation Elements :: bent with bend angle 2α *

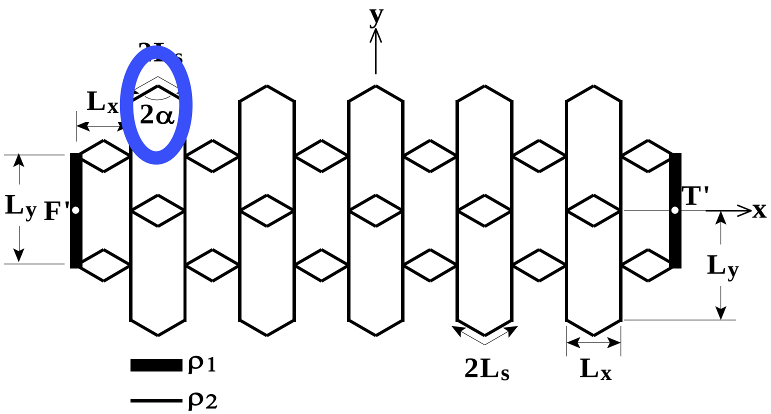
forming numerous rhombic cells.*

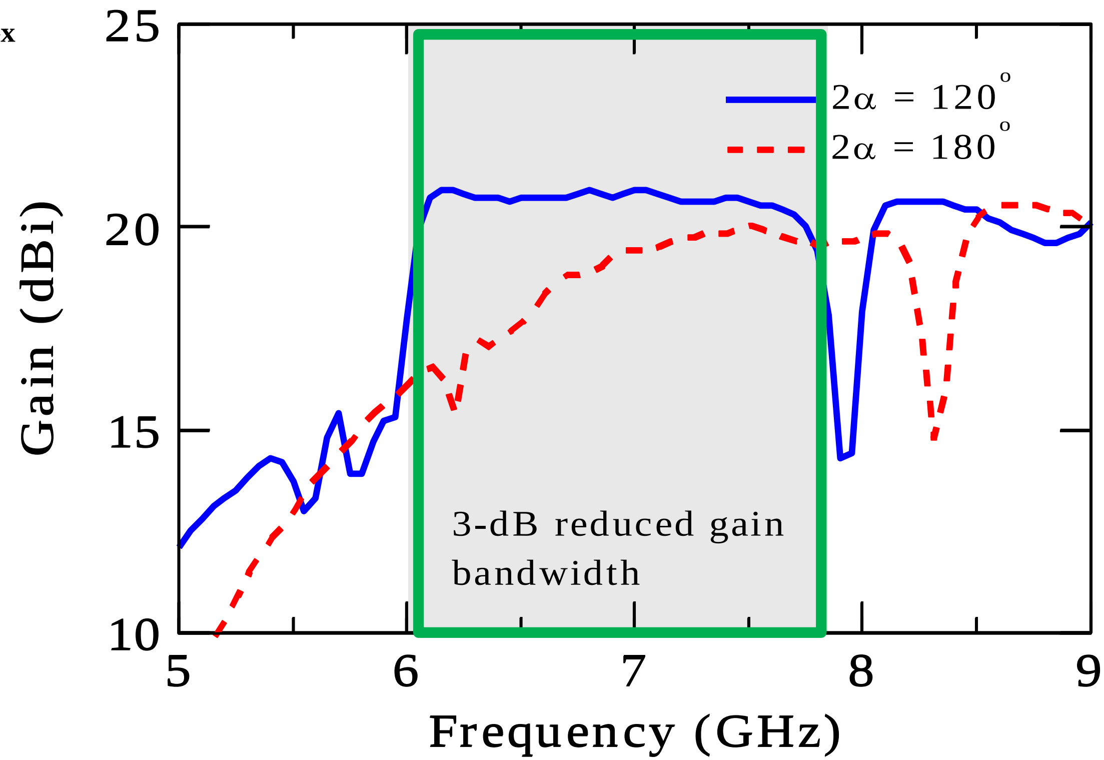
The conventional GAA : a special case , - - the bend angle : 180 degs.

Conventional GAA
$2\alpha = 180^o$



Gain for a RGAA -- bend angle of $2\alpha = 120^o$.



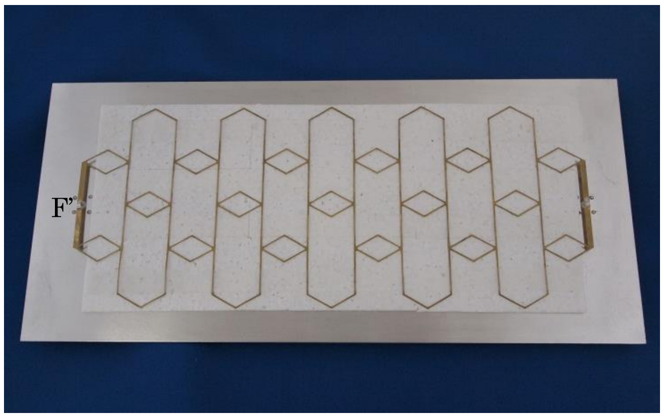


Constant Gain
across a wide frequency band

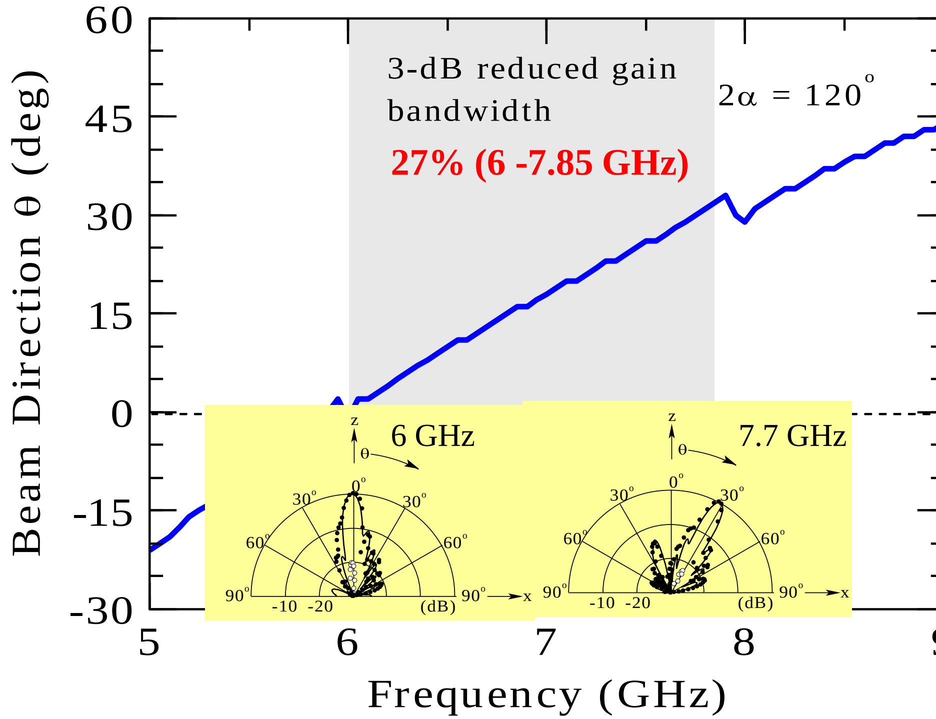
Note: -/ a constant gain across a wide frequency-band. *
the gain for the conventional GAA using a red dotted line*
: clear that the gain for beam scanning is improved.

* Beam Direction for Bend Angle 2α = 120°.

Note: the beam direction increases linearly with an increasing frequency.
.. Representative radiation patterns at 6 GHz* and 7.7 GHz *



GAA: ~2.28λ_6 x 5.2λ_6
GP : 150 mm × 325 mm
= 3λ_6 × 6.5λ_6



Details of this work

H. Nakano, Y.Iitsuka, J. Yamauchi, "Rhombic grid array antenna,"
in IEEE Trans. AP, No.5, 2013 (in press)

Out line

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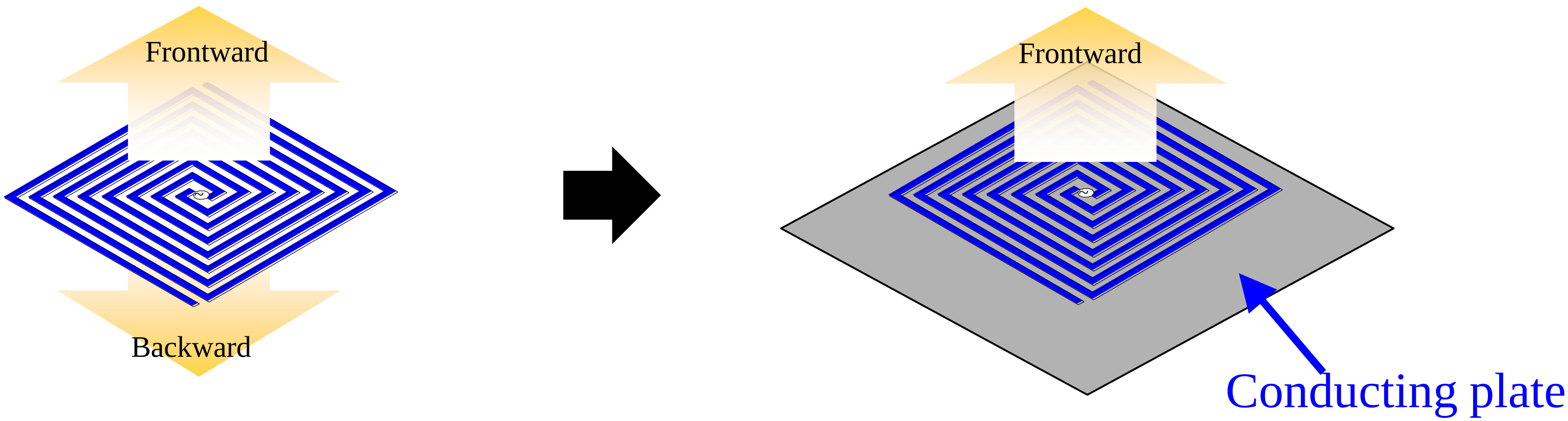
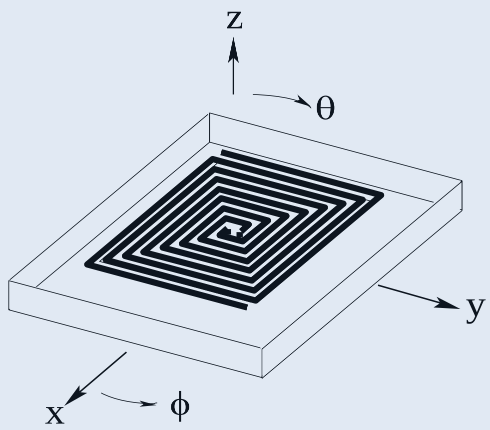
Spiral Antenna

Bidirectional

Circularly polarized (CP) wave

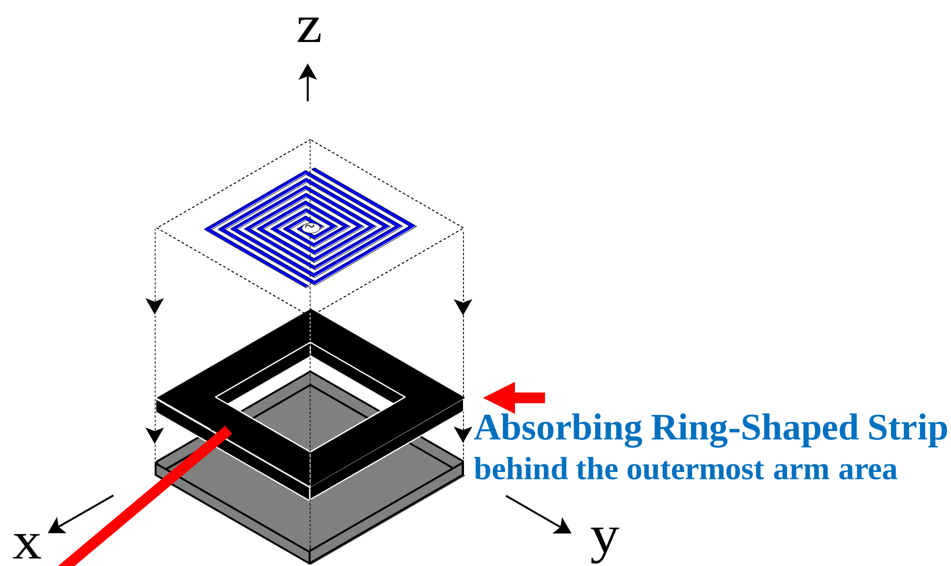


Unidirectional CP wave

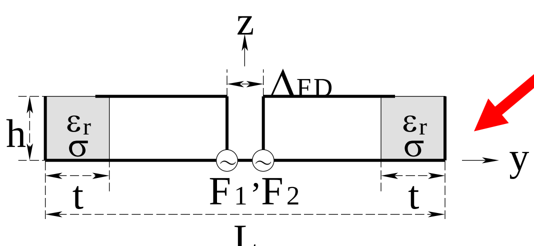


Perspective view

First Technique



Exploded view



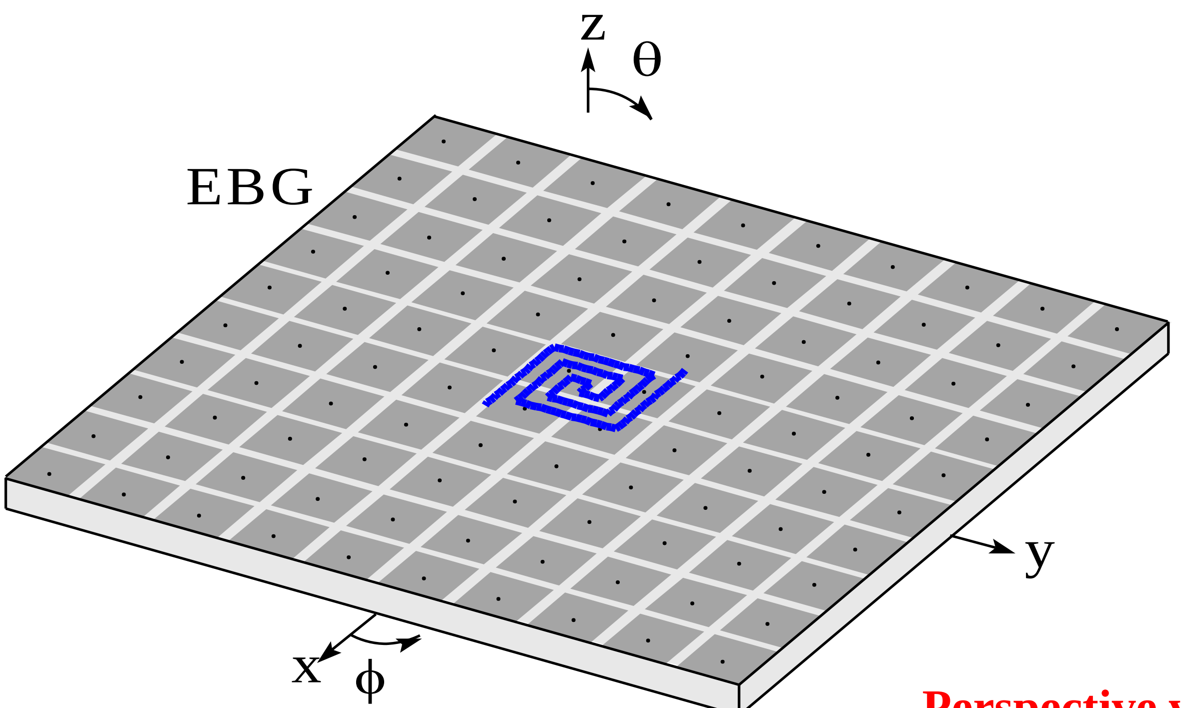
Side view

~:: Two Techniques to overcome ::~

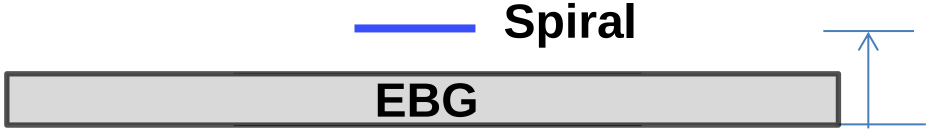
1st technique_ to place an absorbing ring-shaped strip*

Second Technique

: to replace the conducting plate by an EBG reflector *



Perspective view

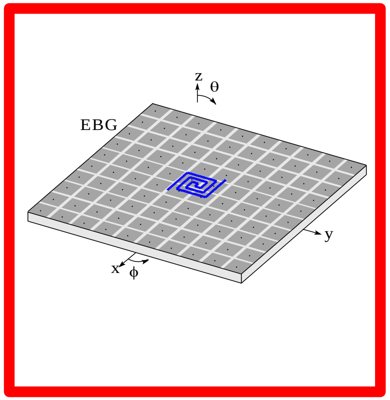


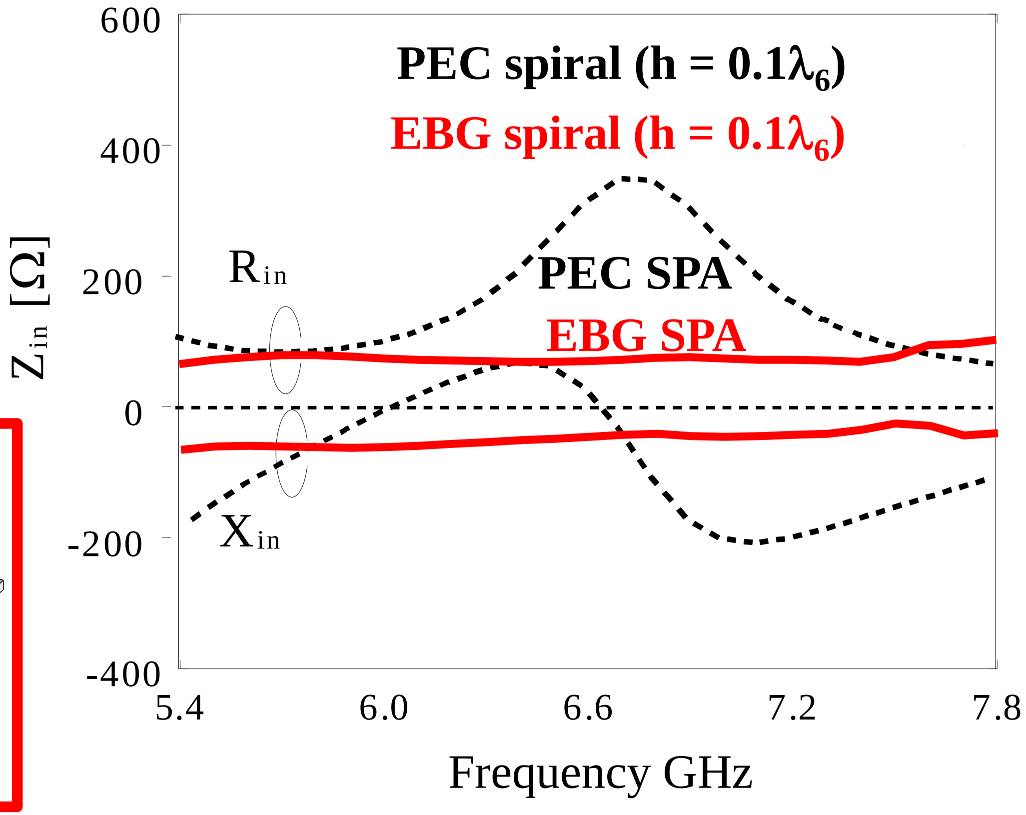
Side view

Antenna Height

$\lambda/10$

.. / Effect of an EBG-Reflector on Z_{in}





Zin becomes constant when the conducting plate is replaced by an EBG reflector.

Q
Antenna Height

Is it possible to
further reduce the height of
a spiral antenna from $\lambda/10$?

Out line

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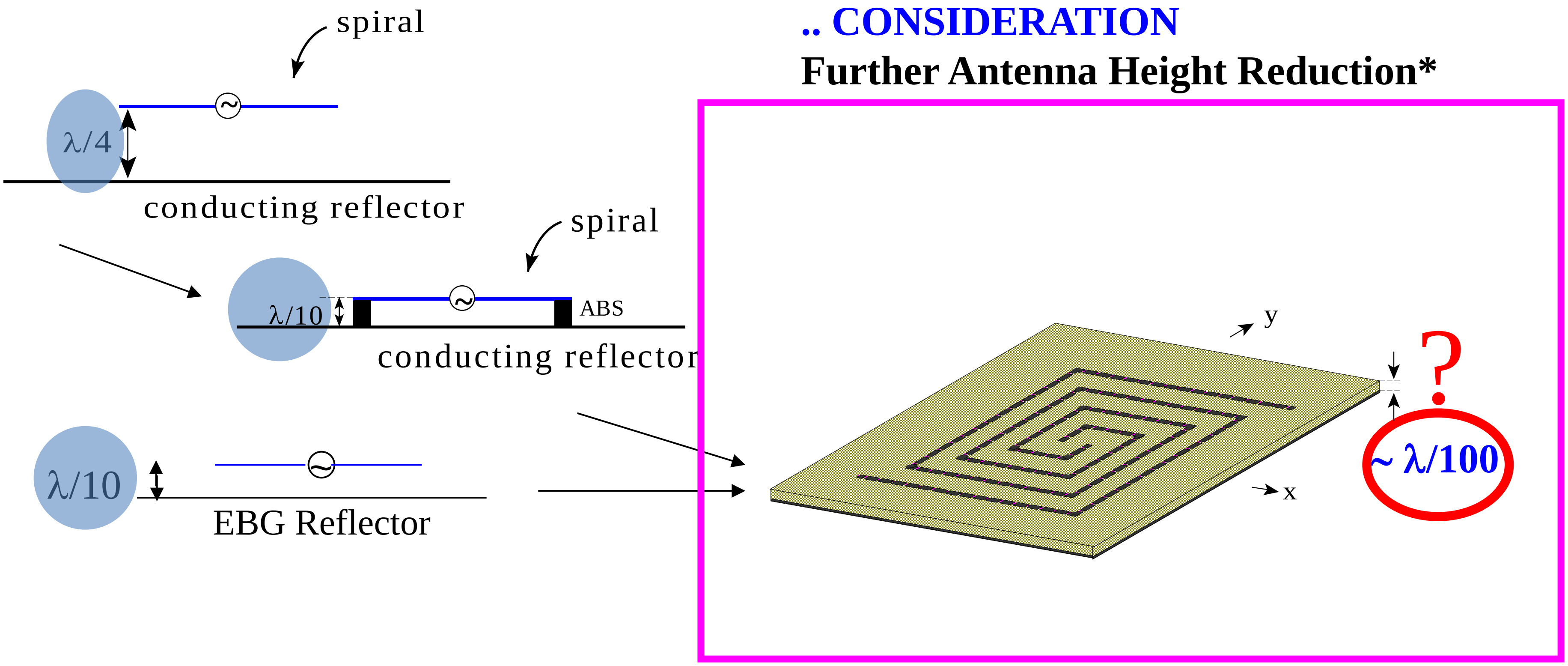
.. CONSIDERATION

Further Antenna Height Reduction*



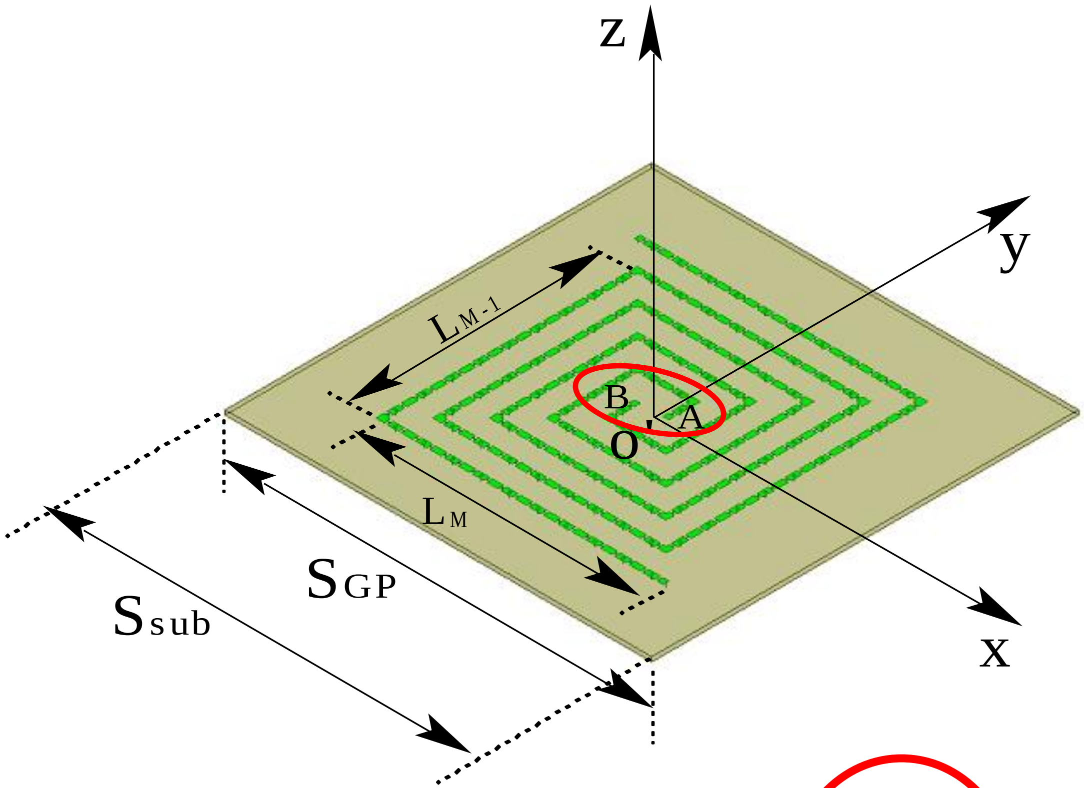
- - An antenna height of approximately λ/100

*Proposed Two-arm Spiral Antenna

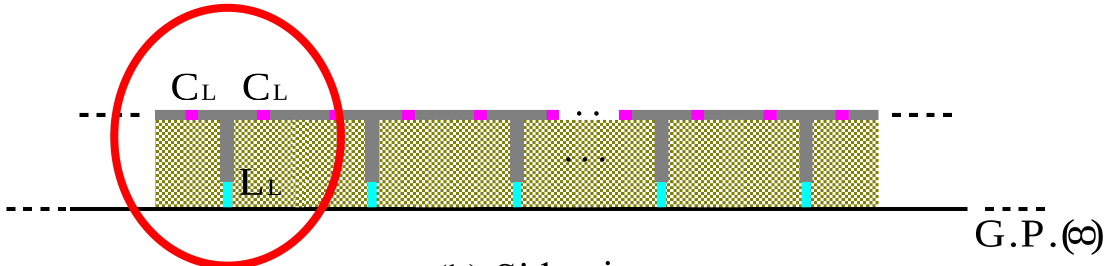
– will be designed to meet two requirements.

1. Symmetrical Radiation Pattern

2. Extremely Low-profile Structure



(a) Perspective view.

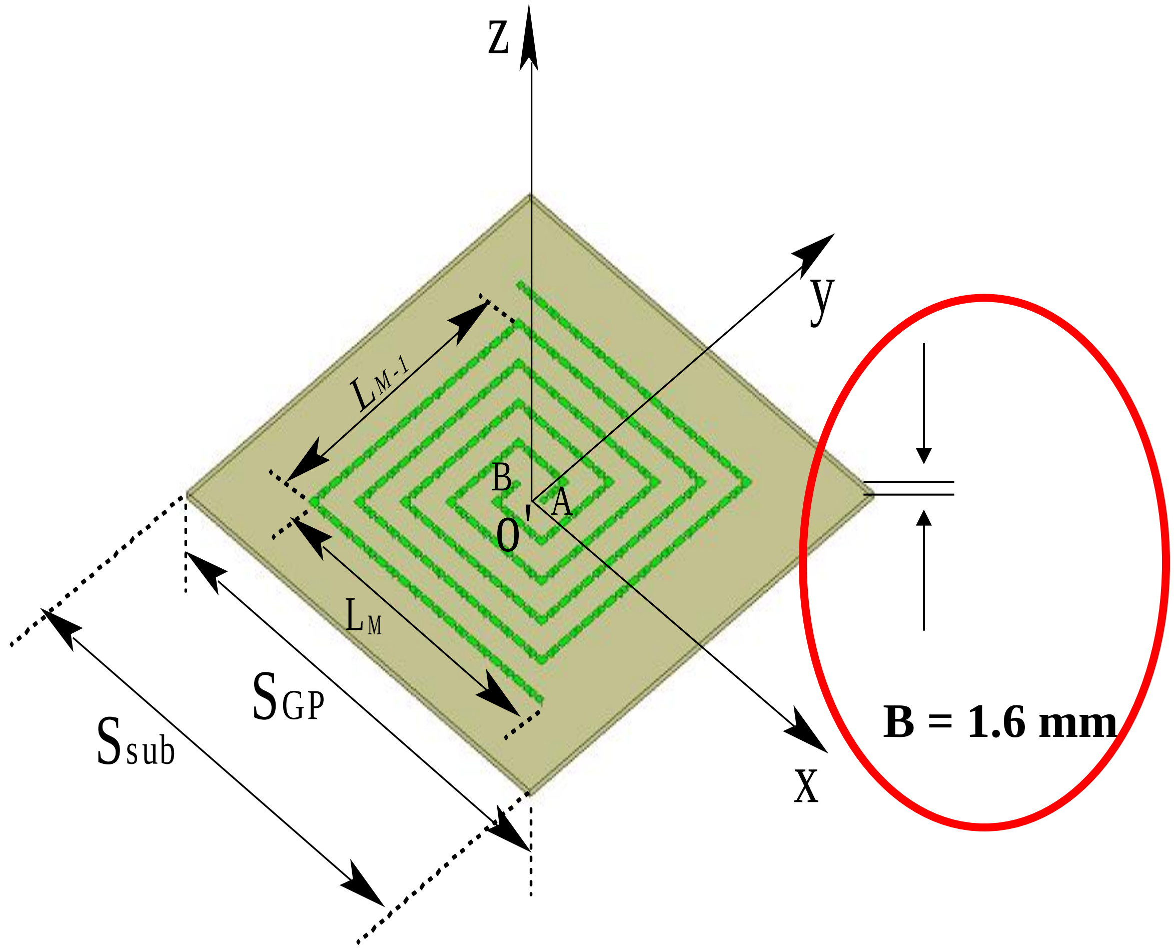


(b) Side view

- two feed points A and B *
- excited in balanced mode.
- **Antenna arms**: composed of numerous cells,

Cell * / two capacitors & one inductor.

Capacitors and inductor : : periodically added to the antenna arm.



1. Symmetrical Radiation Pattern

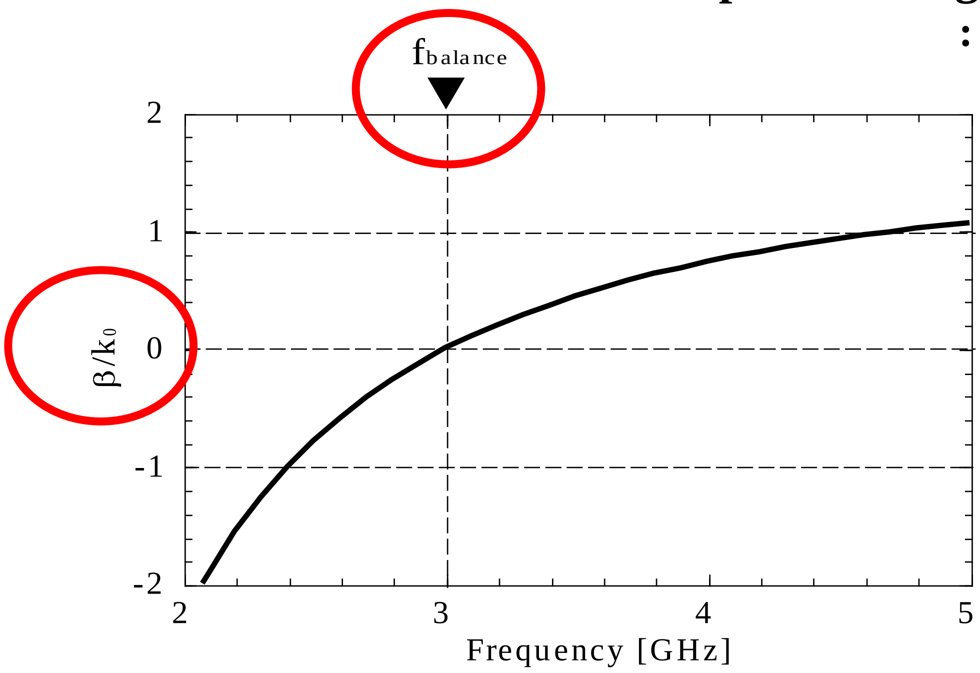
2. Extremely Low-profile Structure

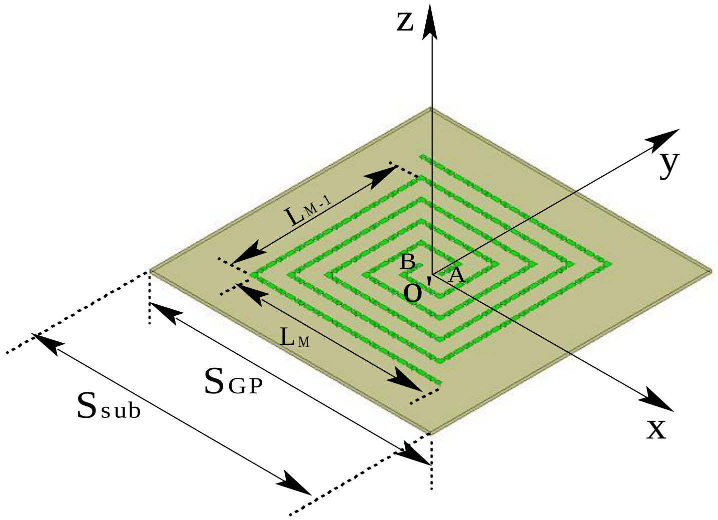
Perspective view.

.. An Antenna Height of 1.6 mm*

~ 0.013 wavelength at 2.5 GHz

*Dispersion Diagram from 2 GHz to 5 GHz
: Calculated Using Scattering Parameters [S]*





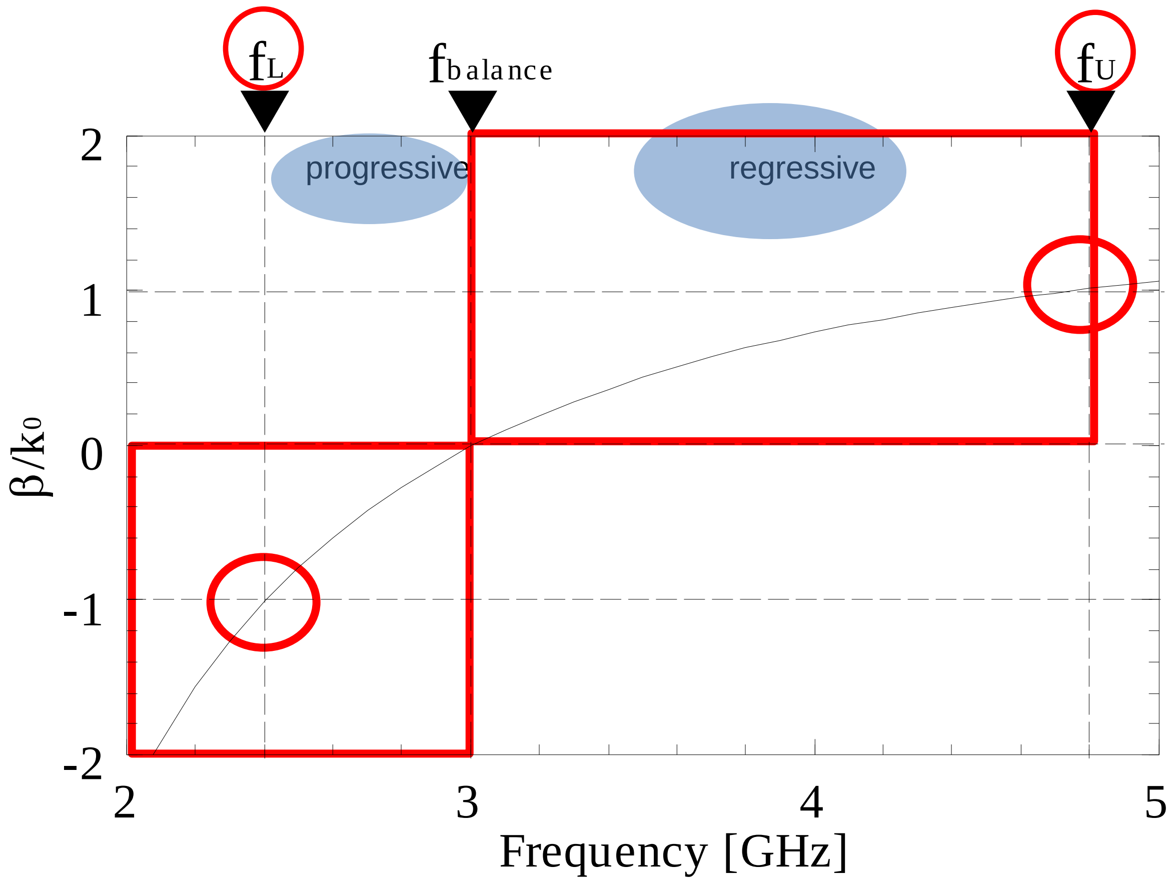
β : phase constant along the arms

k_0: phase constant in free space

$f_{balance}$: *balanced frequency : chosen to be 3 GHz

Dispersion Diagram

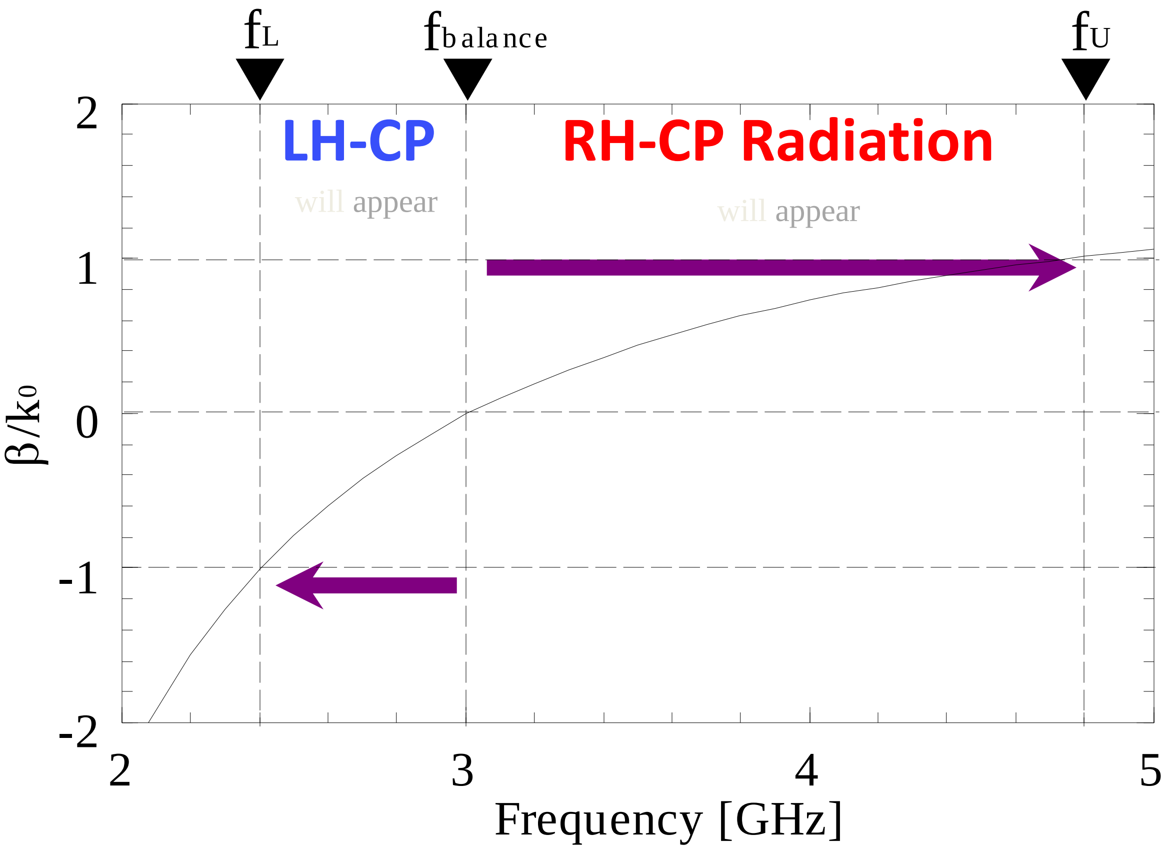
f_L : lower bound for a fast wave* **f_U : upper bound for a fast wave***



@ f_L^*, $\beta/k_0 = -1$

@ f_U^*, $\beta/k_0 = +1$

// Dual-band Counter-CP Radiation//
If the antenna size is appropriately chosen

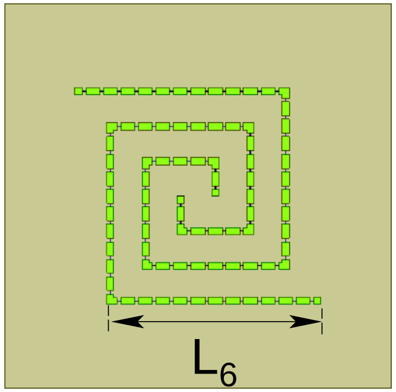


Design

.. An MTM Spiral having 6 Filaments.

~ The MTM spiral operates in the first mode.

Moderately wide-band characteristics:: Expected



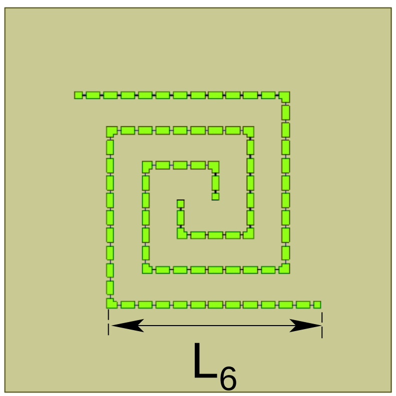
$L_6 = 6\text{ cm} = 0.5\lambda_{2.5}$

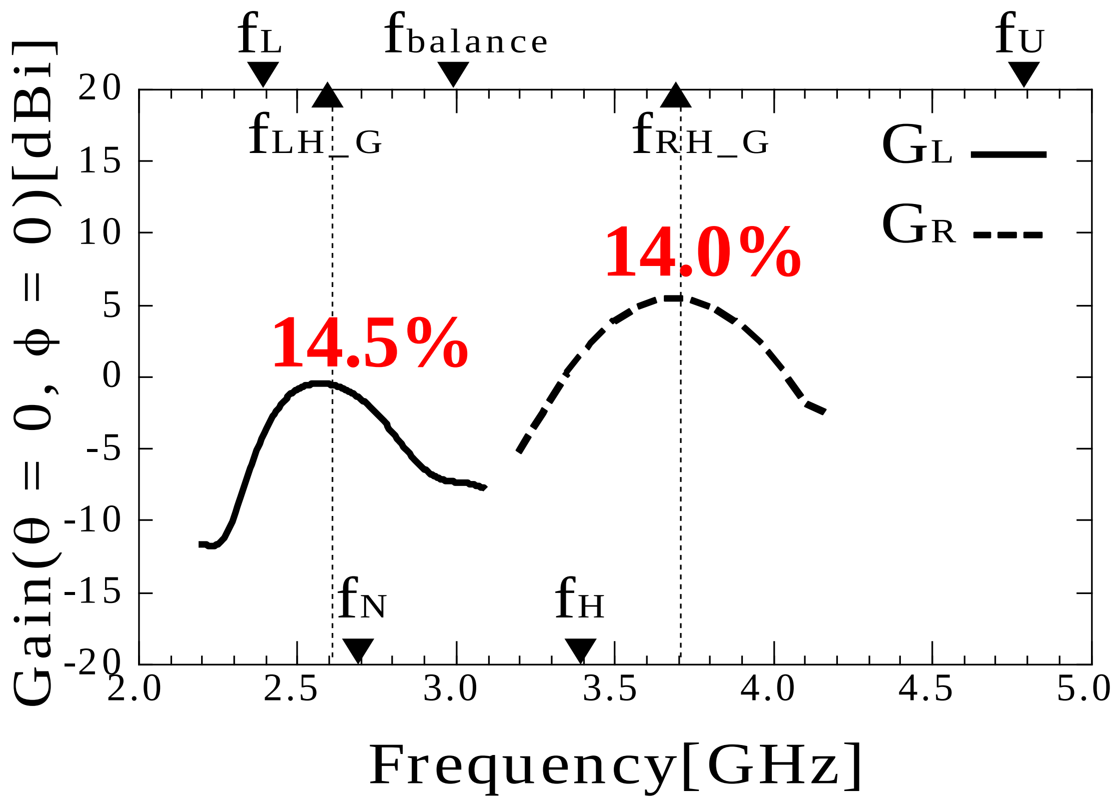
* Frequency response of the gain

The maximum **LH CP gain** appears near the N-frequency.

The maximum **RH CP gain** appears near the H-frequency.

M = 6



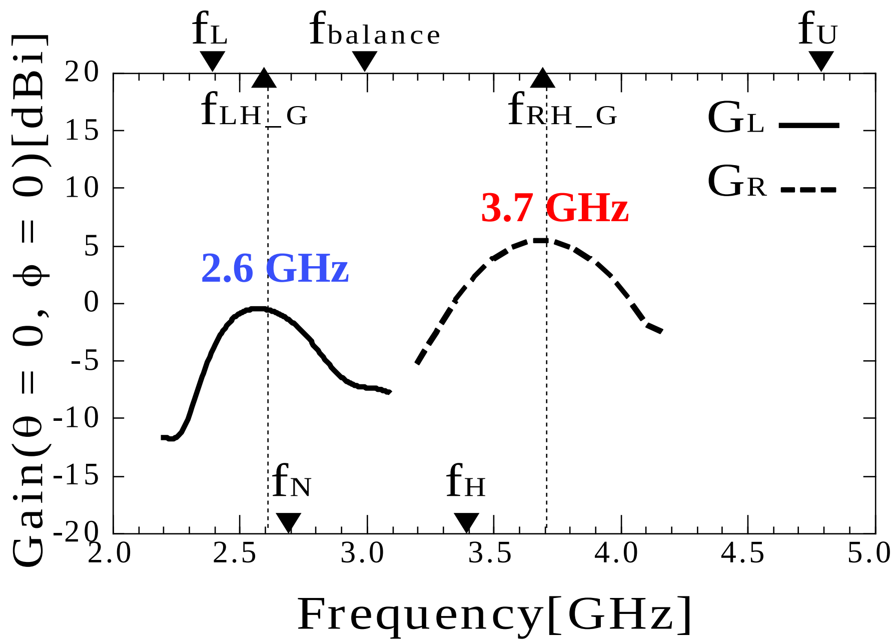


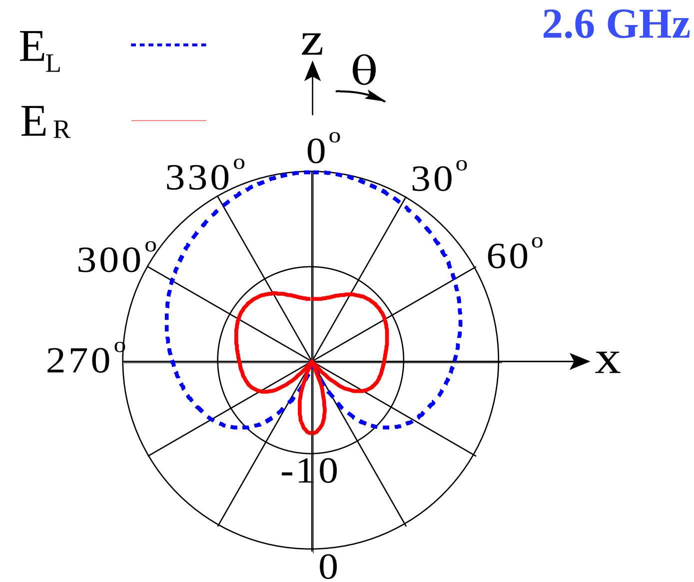
The gain has a moderately wideband characteristic

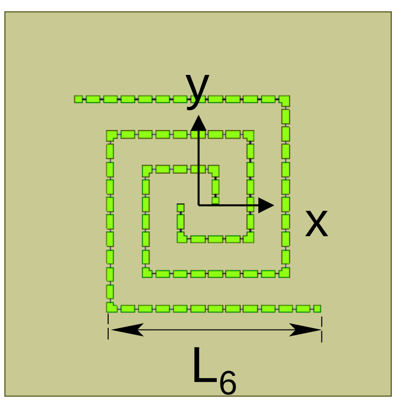
~ meets one of the requirement 2.

Purposes
1. Symmetrical Radiation Pattern
2. Moderately Wideband Characteristics

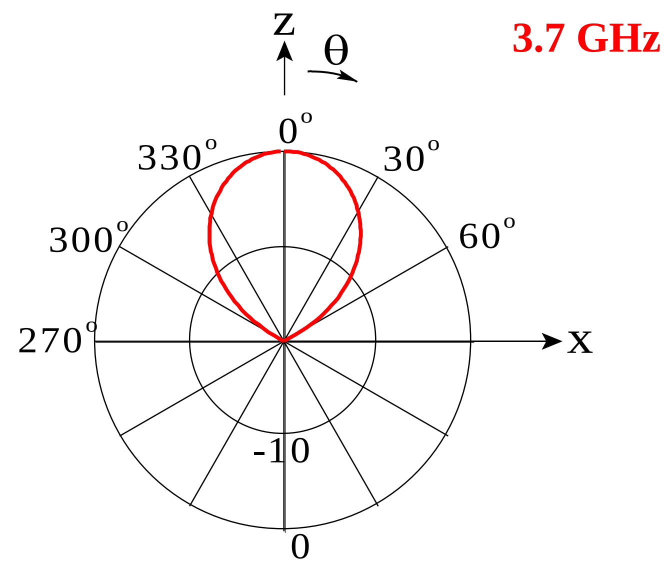
Radiation Pattern







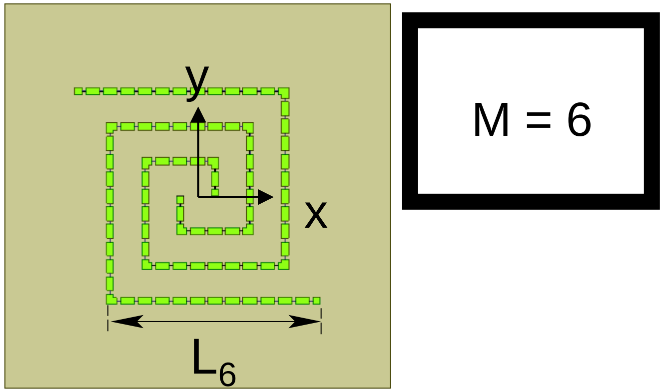
M = 6

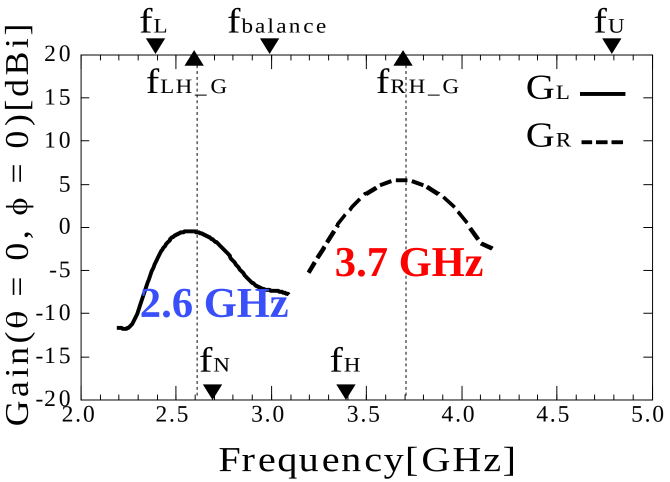


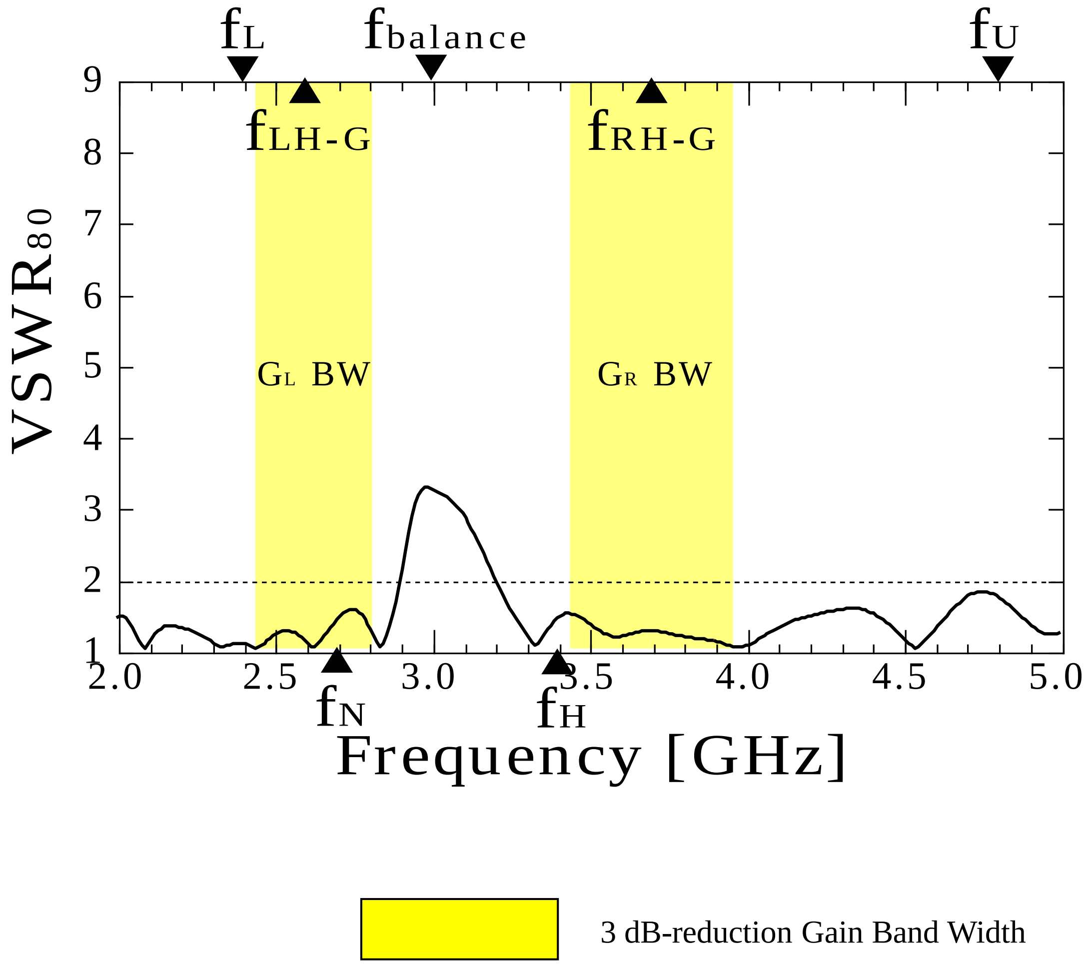
Purposes
1. Symmetrical Radiation Pattern
2. Moderately Wideband Characteristics

- : symmetrical with respect to the z-axis

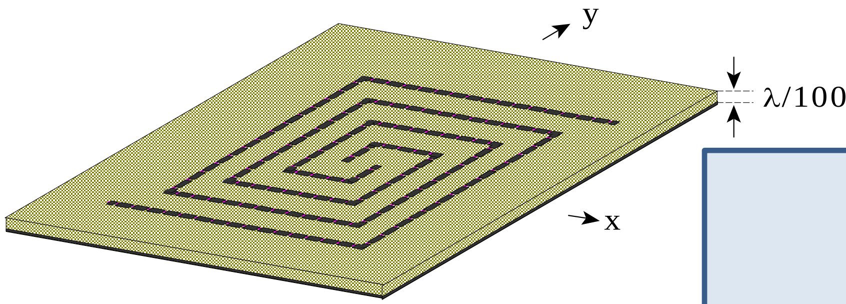
Frequency response of the VSWR for M = 6 *

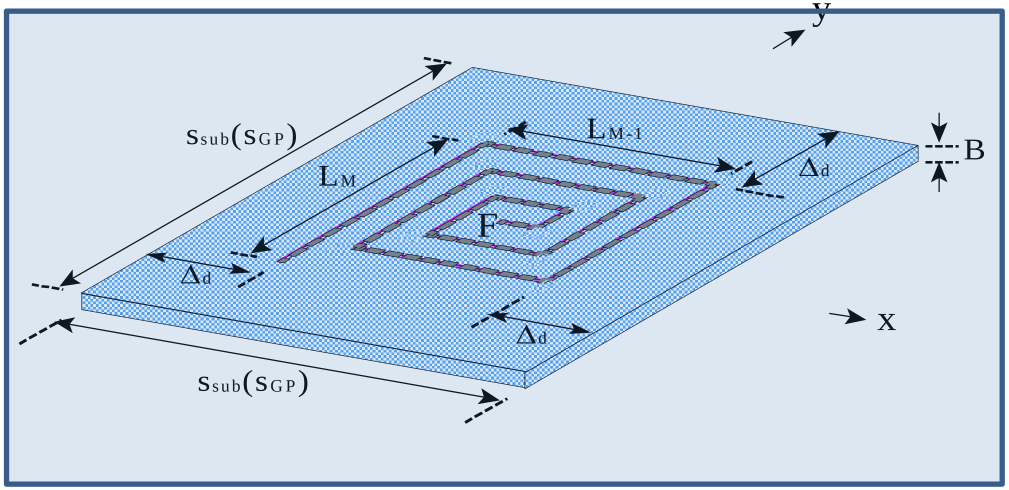






The VSWR : less than 2 within the gain bandwidth





Two-Arm MTM Spiral*

Current Work

A Monofilar MTM Spiral

- does not require a balun circuit

- -

Effects of the pitch and ground plane on the antenna characteristics :: *

Details of this work

Dual-band Counter Circularly Polarized Radiation from a Single-arm Metamaterial-based Spiral Antenna

in IEEE Trans AP, June, 2013 (accepted for publication)

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REMARKS

Antenna Height from λ/4 to λ/100

An incoming current should be reduced to realize a wideband antenna.

Some natural antennas, specified by a positive-β current, realize wideband characteristics, having a low profile structure.

The antenna height can be reduced using a metamaterial property, which is featured by a negative-β current.