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

- Antenna Height from $\lambda/4$ to $\lambda/100$ -

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.
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

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   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

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*Body of Revolution with a Shorted Parasitic Ring*

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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**
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

Backward Radiation

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

Helical Antenna

Axial Mode

C-current

S-current

I = I_r + jI_i

arm length

Feed point F

7.36\lambda
.. Remove the S-current region & use only the C-current region for CP radiation

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

~ an antenna height of 0.19 wavelength above the GP

Feed point F

arm length

2 turns

7.36 λ
*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%.

**Aperture Efficiency ~ 90%**

**Phase**:
controlled by rotating the element around its axis.

**Amplitude**:
controlled by the vertical length inserted into the cavity.
ARRAY /: 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 $\eta = 88\%$

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)
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
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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
Modification from a Truncated Conical to A CROSS-FAN 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: 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 $L_{\text{slot}}$: ~ one-quarter wavelength at $f_{\text{stop}}$.

As Slot Length $L_{\text{slot}}$
Stop-Band Center Freq. $f_{\text{stop}}$
CROSS-FAN /: Used as a Base Station Antenna

.. MODIFICATION  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 $\varepsilon_r$.*
Bandwidth : optimized by the inner angle $2\alpha$. *
Side Length S : $\sim 1$ cm. *
Ground Plane / a side length of 3 cm

Side View
*Frequency response of the VSWR*

Note: \( VSWR < 2 \) above 2.75 GHz.

Antenna Height: \( 0.09\lambda \) at 2.75 GHz.

Ground Plane / a side length of 3 cm
Installation of a **Fan-Shaped Antenna**

- 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.**
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Antenna Height $H = 0.3\lambda$

Lower Base Station Antenna
$H = 0.07\lambda$

CROSS-FAN

BOR-SPR
Body of Revolution with a Shorted Parasitic Ring
*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

- Replace the feed section by a BOR.

\[ H = 0.07\lambda \]

Microstrip patch

- \( R_{\text{in}} : \text{low} < 50 \)
- \( X_{\text{in}} : \text{inductive} \)

.. Cut a ring slot

.. Add four conducting pins.

\( D_{\text{GP}} \)

\( D_{\text{patch}} \)

\( D_{\text{in. ring}} \)

\( 2x_1 \)

\( h \)

\( \text{coax.} \)

\( \text{GP} \)

\( \text{BOR} \)

\( \text{Parasitic ring} \)

\( \text{.. Replace the feed section by a BOR.} \)
Design Process

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

Patch dia. ~ 4 cm
GP dia. ~ 14 cm
Antenna height \(H = 1\text{ cm}\)*

\[R_{\text{in}} < 50 \text{ ohms}\]
\[X_{\text{in}}: \text{inductive}\]

Note:
There is a frequency region where the input reactance \(X_{\text{in}}\) is highly inductive.
Second step: To make the input reactance $X_{in}$ zero by adding a capacitive component.

- 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*

$R_{in}$: low < 50

$X_{in}$: 0

$H = 10$ mm
$2x_1 = 6.7$ mm
$D_{in, ring} = 20$ mm
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.

\[ H = 0.07\lambda \]

- Parasitic ring
- Conducting pin

Excited by a Central Feed Pin
* Frequency response of the VSWR for the BOR-SPR.

An extremely-wide frequency-band of 147% *

Note: The radiation: omnidirectional around the z-axis.

\[ H = 0.07\lambda \]

\[ r_{\text{patch}} = 0.13\lambda \]

**BOR-SPR**

Body of Revolution with Shorted Parasitic Ring

147% BW
BOR-CROSS is installed on the ceiling of a building.
Out line

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*Conventional Grid Array Antenna (GAA)

Antenna height $H = 2.5 \text{ mm}$

$= 0.05\lambda_6$

GAA: excited from its edge*
- creates a tilted beam*  *Beam direction*  / a frequency-scanning function.

*Beam Direction as a function of frequency.
The gain should be constant across the wide frequency band to be used for beam scanning.

?? Desirable Gain Behavior??
As one solution to this issue*,

.. Propose a **New Grid Array Antenna***

Conventional

Proposed

-: Rhombic GAA
Proposed RGAA:

An extension of the conventional GAA.

Radiation Elements :: bent with bend angle $2\alpha$ *
forming numerous rhombic cells.*

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

Conventional GAA

$2\alpha = 180^\circ$
*Gain for a **RGAA**  -- bend angle of $2\alpha = 120^\circ$.*

**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 $2\alpha = 120^\circ$.

Note: the beam direction increases linearly with an increasing frequency.

Representative radiation patterns at 6 GHz* and 7.7 GHz *

GAA: $\sim2.28\lambda_6 \times 5.2\lambda_6$
GP : 150 mm $\times$ 325 mm
$= 3\lambda_6 \times 6.5\lambda_6$

Details of this work
H. Nakano, Y.Iitsuka, J. Yamauchi, “Rhombic grid array antenna,”
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Bidirectional
Circularly polarized (CP) wave

Unidirectional CP wave

Conducting plate
~:: Two Techniques to overcome ::~

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

: to replace the conducting plate by an EBG reflector *

Antenna Height $\lambda/10$
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 $\frac{\lambda}{10}$?
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Section IV  Remarks
s ~ conduction reflector

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

- 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.
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]*

\[ \beta \]: phase constant along the arms
\[ k_0 \]: phase constant in free space
\[ f_{\text{balance}} \]: *balanced frequency : chosen to be 3 GHz
\( f_L \): 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

![Diagram showing LH-CP and RH-CP Radiation](image-url)
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.

The gain has a moderately wideband characteristic — meets one of the requirement 2.
Radiation Pattern

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 $\lambda/4$ to $\lambda/100$

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

Some natural antennas, specified by a positive-$\beta$ 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-$\beta$ current.