New Considerations for Antenna Near-Field Theory and Impact on Antennas and Other Applications

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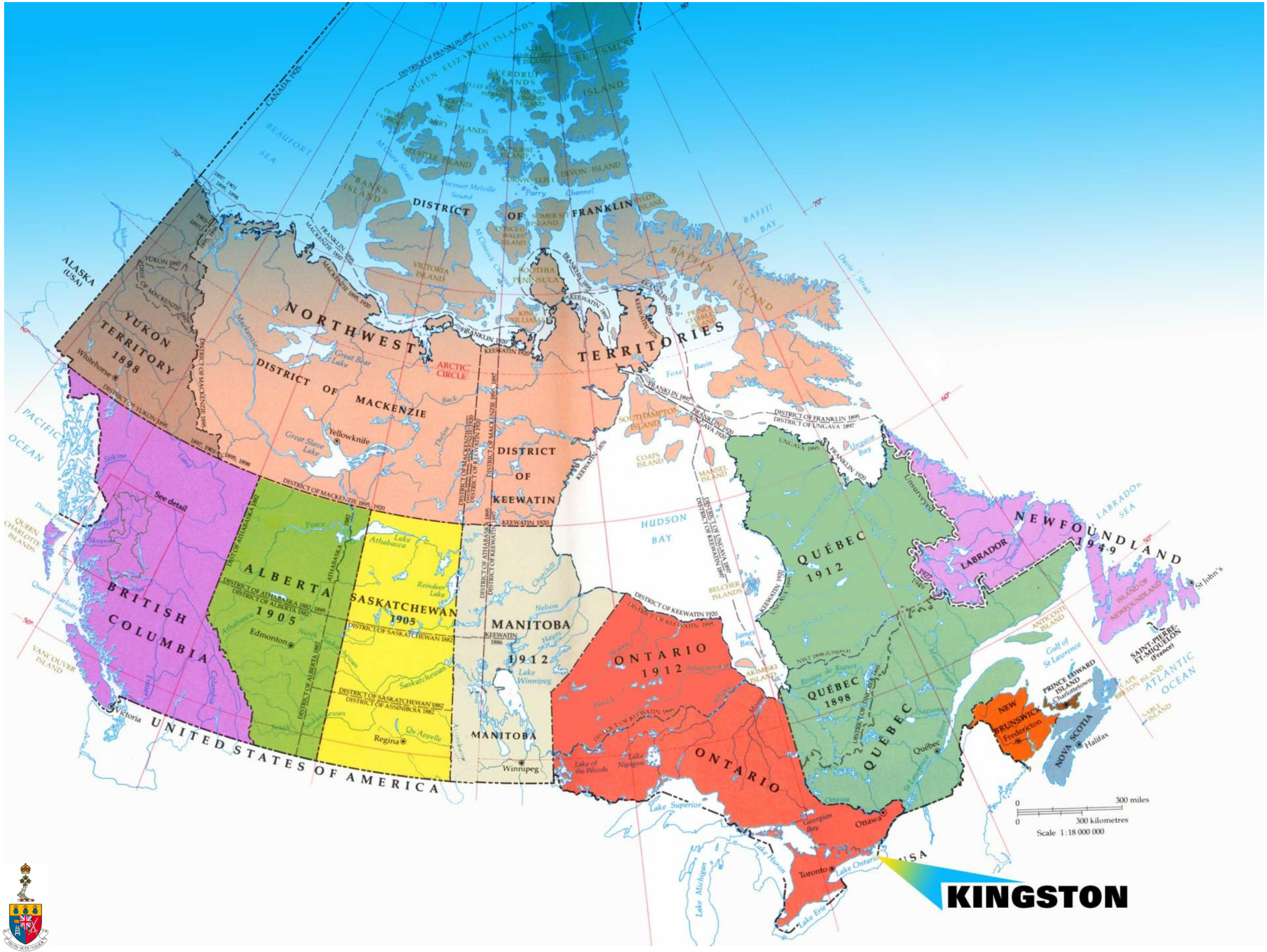


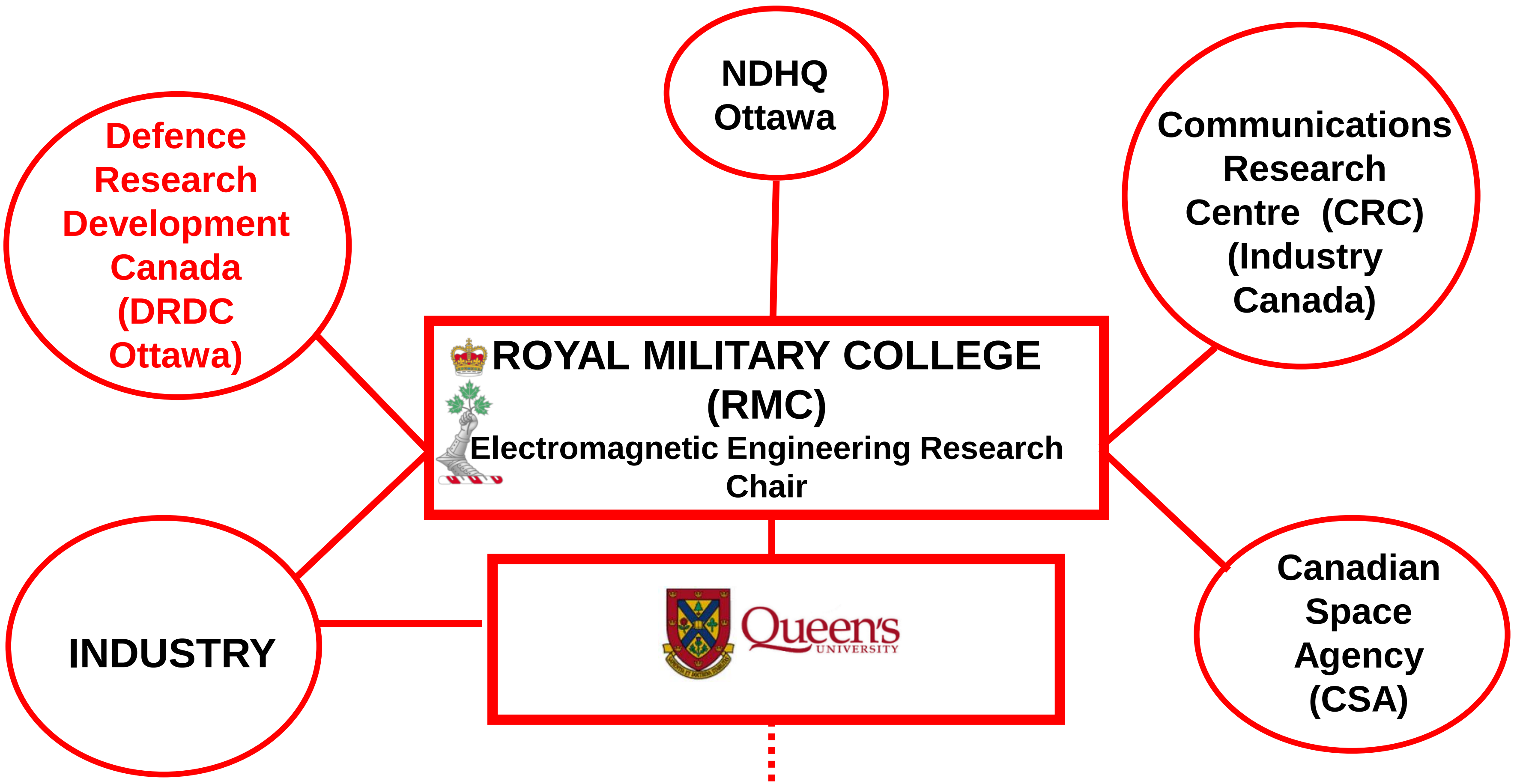
NORTHWEST TERRITORIES
DISTRICT OF FRANKLIN
DISTRICT OF MACKENZIE
DISTRICT OF KEEWATIN
YUKON TERRITORY 1898
ALASKA (USA)
BRITISH COLUMBIA
ALBERTA 1905
SASKATCHEWAN 1905
MANITOBA 1912
MANITOBA
ONTARIO 1912
ONTARIO
QUÉBEC 1912
QUÉBEC 1898
QUÉBEC
NEWFOUNDLAND 1949
LABRADOR
NEW BRUNSWICK
NOVA SCOTIA
PRINCE EDWARD ISLAND
SAINT-PIERRE-ET-MIQUELON (France)
UNITED STATES OF AMERICA
USA
HUDSON BAY
PACIFIC OCEAN
ATLANTIC OCEAN
BEAUFORT SEA
BAFFIN BAY
LABRADOR SEA
ARCTIC CIRCLE
Whitehorse
Yellowknife
Edmonton
Regina
Winnipeg
Victoria
Toronto
Ottawa
Québec
Fredericton
Halifax
Charlottetown
St John's
300 miles
300 kilometres
Scale 1:18 000 000
KINGSTON


Queen's
UNIVERSITY

Canada, 1964

RMC, 1874

Collaborators



At Universities: Canada, U.S.A., Egypt, France and India...

At RMC: Dr. S. Mikki (now with Univ. of New Haven, CT, USA)
Dr. S. Podilchak (now with Univ. of Edinburgh)
Dr. S. Clauzier, Dr. A. Chaloux, Mr. A. Alzahed,
Other graduate students and visiting professors

Current Research Projects at RMC

- Leaky wave Antennas
- Fundamentals of Antenna Near Fields
- DRA (wireless, high gain, UWB, GNSS, SoC (mm-wave))
- UWB Antennas for communication and radar applications
- Phased Arrays for UWB RDA applications
- Direction finding Antennas and techniques
- Printed Antennas and Feeding Circuits (differentially fed, hybrid, tapered slot ...)
- Reconfigurable Antennas
- Antennas for Cognitive Radios and Software Defined Radios
- EBG Structures
- EMC/EMI modeling for complex structures (ships, planes etc.), RCS modeling

Outline and Description

- Introduce new fundamental aspects in Electromagnetics.
- Deal with some outstanding and emerging challenges in applications.
- Introduce new views on
  - Near Field Structure around antennas.
  - New concepts for characterizing antennas and antenna-antenna interactions, antennas embedded in complex environments.

How new theoretical considerations can guide us towards devising new measurements

Progression of Electromagnetics Research

- Early days: Solution of boundary value problems: Analytical solutions
- GTD (geometric theory of diffraction
- 60s, 70s, UTD... Numerical methods. Harrington's method of Moments
- Commercial software tools

......New emerging applications

? Need to look back and research the fundamentals.

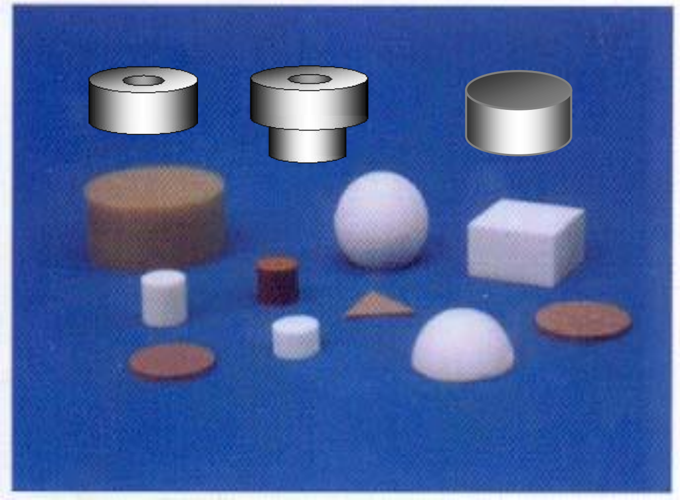
IEEE
Antennas and Propagation Society

- IEEE Antennas and Propagation Society publications (included in membership)

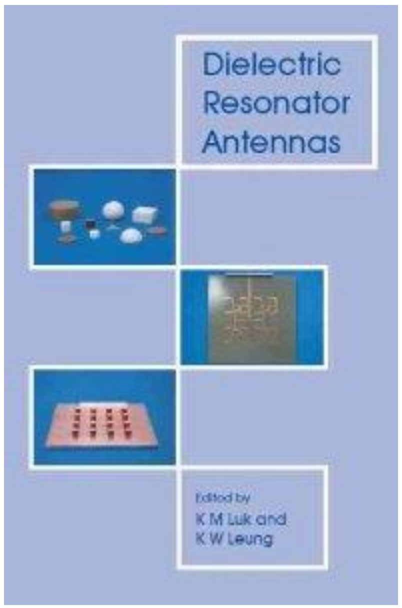
- IEEE Antennas and Propagation Magazine
- IEEE Transactions on Antennas and Propagation
- IEEE Antennas and Wireless Propagation Letters
- ……..

Dielectric Resonator Antennas

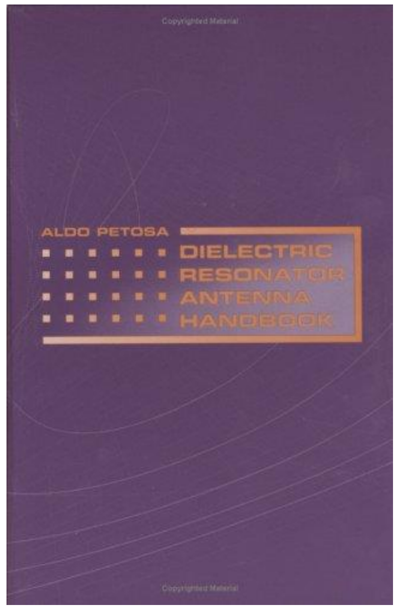
- First proposed in 1983 (S. A. Long, M.N. McAllsiter and L. Shen, *IEEE Trans. Antennas and Propagat.*, May 1983)
- Majority of work has been reported since 1990
- Material is fed energy so that it acts as a resonator
- Energy *leaks* from the resonator
- *Leakage* can be controlled through design thus can be used as an antenna
- Impetus for increased interest was potential for high frequency operation



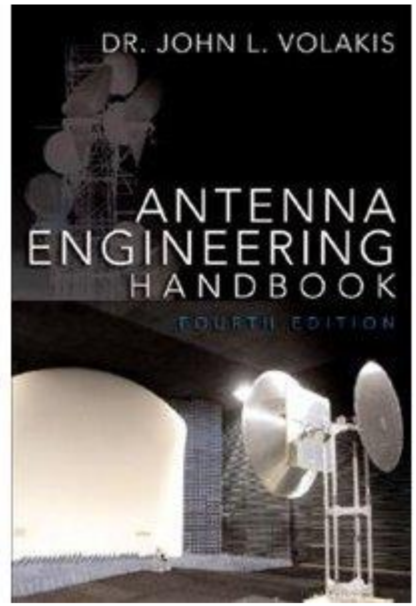
Related Recent Books



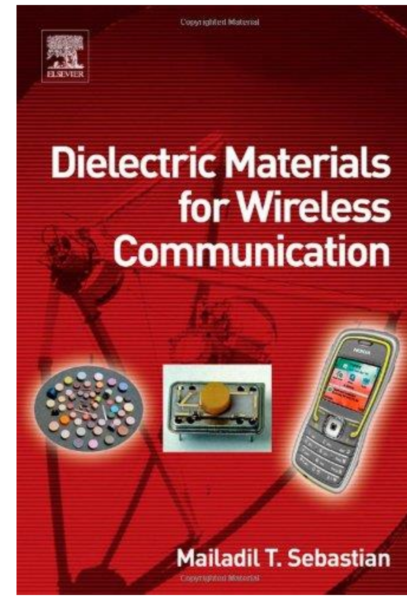
Dielectric Resonator Antennas*, Eds. Luk & Leung, Res. Studies, 2002*



Dielectric Resonator Antenna Handbook*, Ed. Petosa, Artech House, 2007*



'Dielectric Resonator Antenna' (Eds. Kishk & Antar), ***Antenna Engg. Handbook*** *(Ed. Volakis), McGraw Hill, 2007*



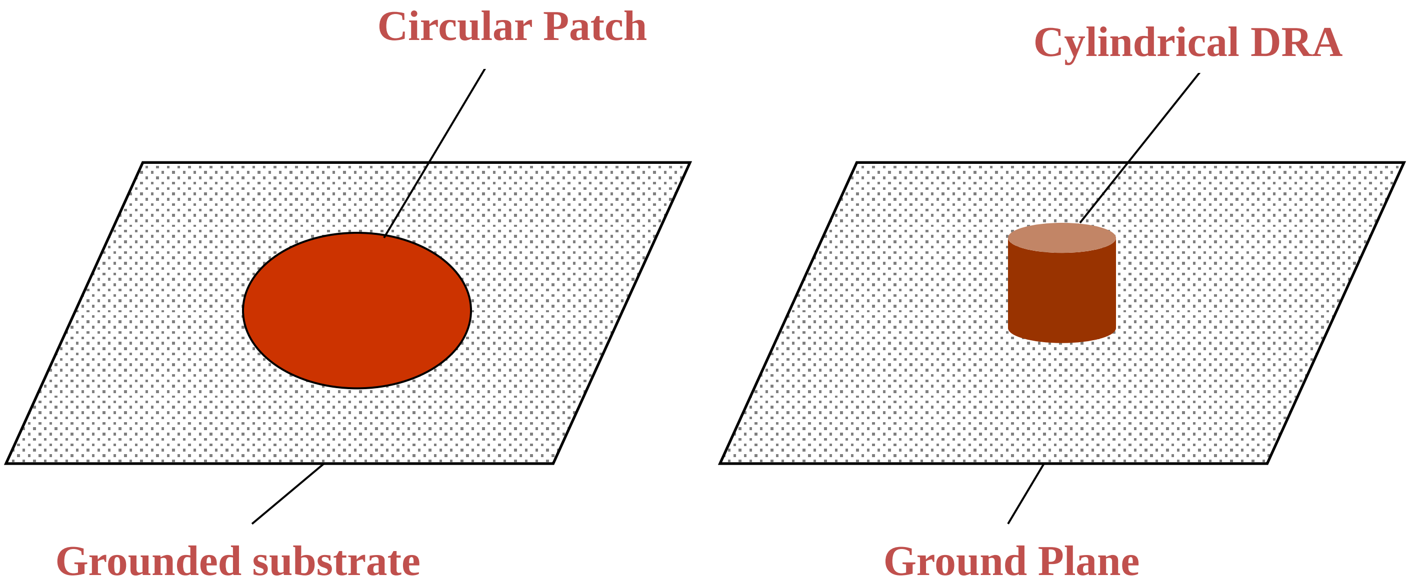
Dielectric Materials for Wireless Communication, *Ed. M.T. Sebastian, Elsevier, 2008*

- **About 3000 New materials developed**
- **More than 5000 papers have been published**
- **About 1000 patents filed in related technologies**

Main Advantages

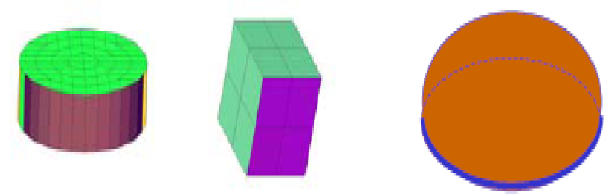
- **Low dissipation loss - High Radiation efficiency (> 98%)**
- **Low radiation Q-factor - Wide bandwidth**
- **Wide frequency range of operation (55MHz – 135 GHz)**
- **No surface waves - Low mutual coupling, no scan blind & wider scanning range**
- **Design flexibility - different shapes**
- **Size control – Wide range of materials**
- **Easily integratable with other devices**
- **Different radiation characteristics**
- **Mechanical Simplicity**
- **Less susceptible to tolerance errors**
- **Dielectric strength (> 200V/mil) - High power capability**
- **Wide temperature range (-65°C to +110°C)**

Comparison between Dielectric Resonator Antenna and Circular Microstrip Patch Antenna

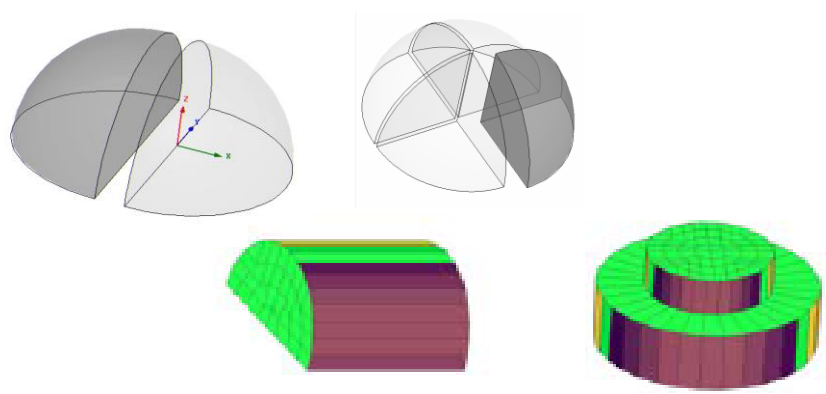


DRA Geometries

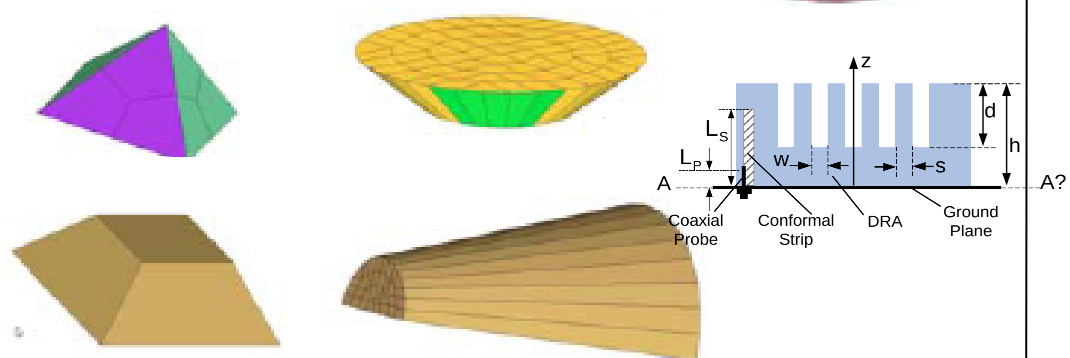
Basic Shapes



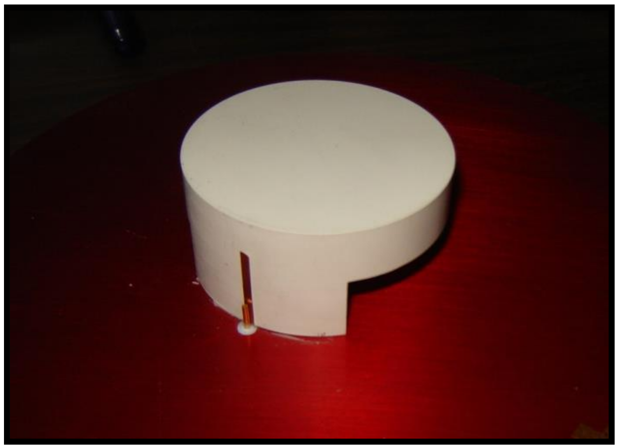
Originated from basic Shapes



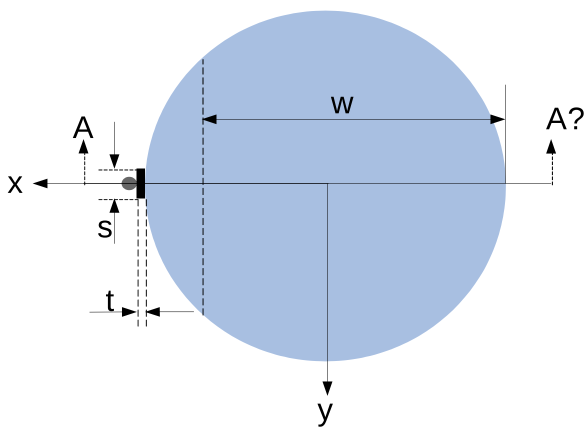
Shaped geometries

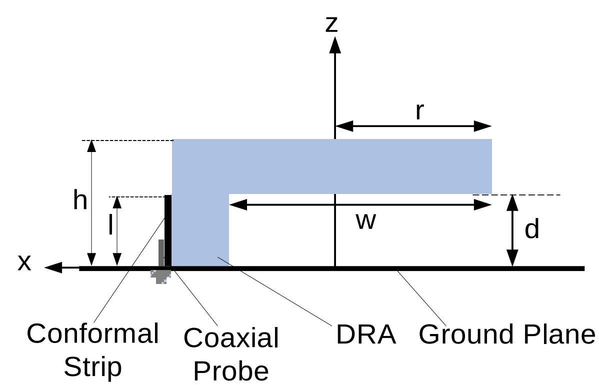


Shaped DRA - cont'd



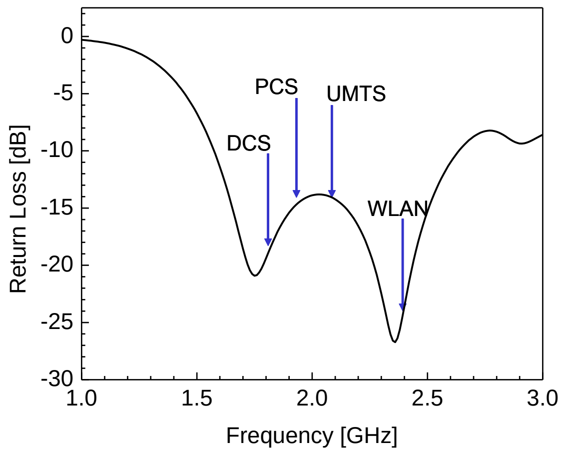
- Simple Geometry
- Easy to Fabricate from a single piece
- About 50 % bandwidth covering four wireless bands
- About 8 dBi peak gain in all the bands

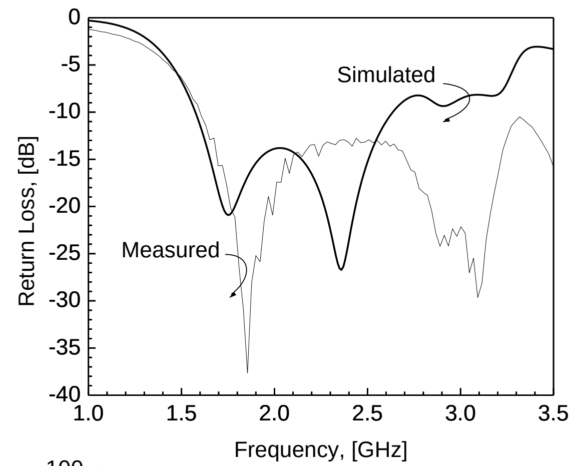


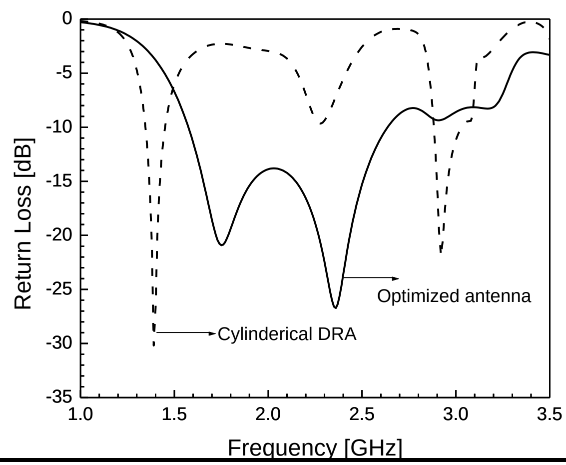


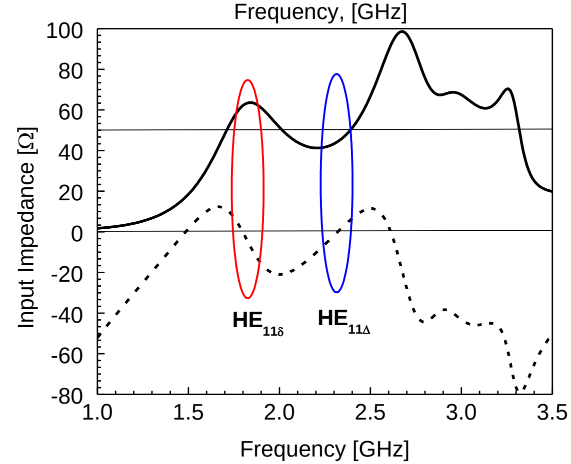
*Chu, Guha, Antar: IEEE AWPL,*Vol. 8, 2009

Shaped DRA - cont'd



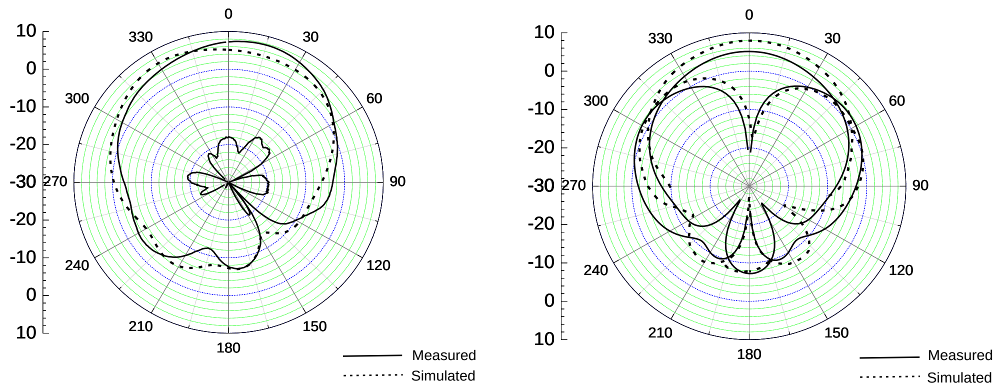




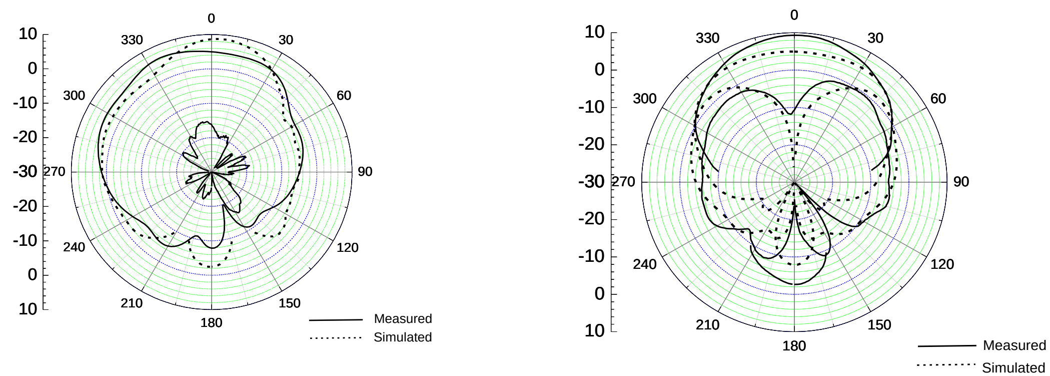


Radiation Characteristics

Band	Gain
DCS	7.25dBi
PCS	8.45dBi
UMTS	8.30dBi
WLAN	8.61dBi



DCS: 1.78 GHz



WLAN: 2.4 GHz

Hybrid antennas
(DRA + Monopole)

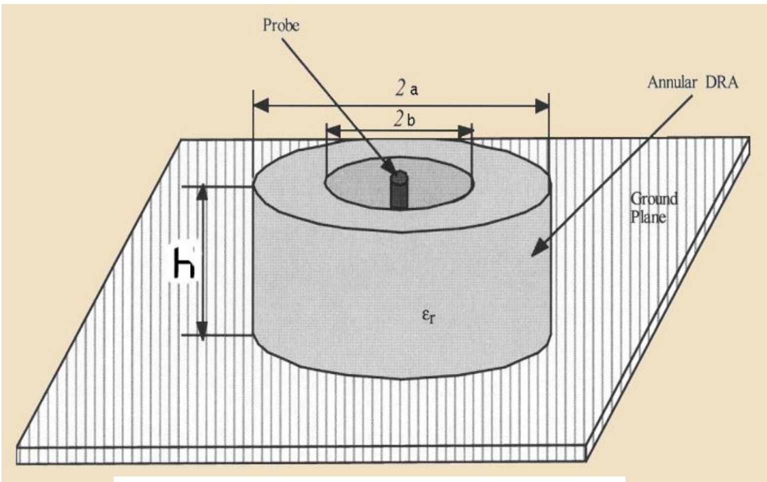
The monopole antenna is one of the oldest, simplest, and most widely used antenna in wireless communication systems.

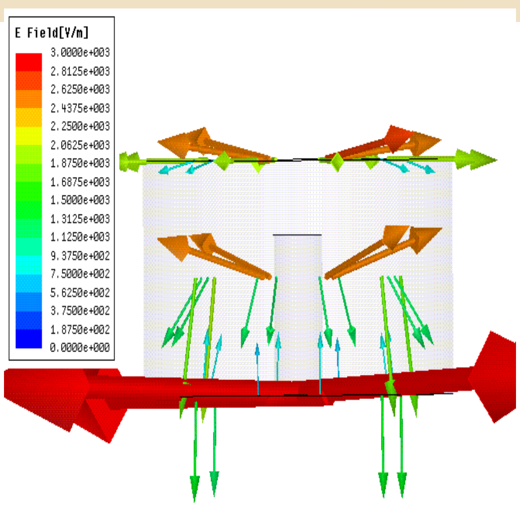
However, this antenna might just '<u>not</u>' be able to survive the increases in <u>bandwidth demand</u> imposed by today's emerging new wireless services, e.g. UWB [3.1 – 10 GHz].

Monopole Antenna

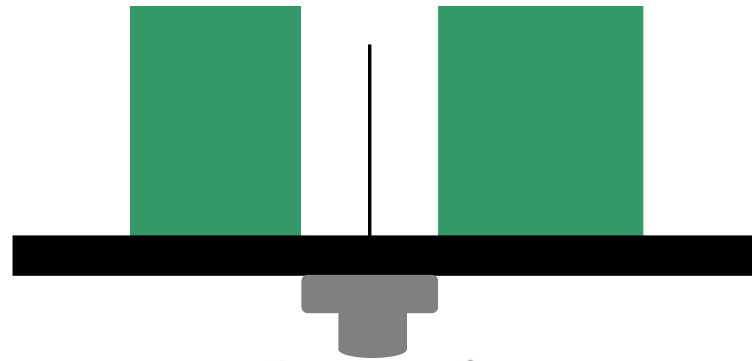
This means we would need several antennas each operating at its own frequency.

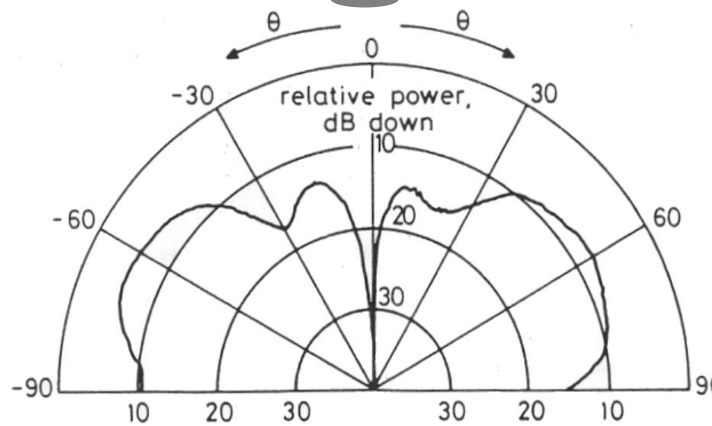
Dielectric Ring Resonator (DRR) with $TM_{01\delta}$ mode





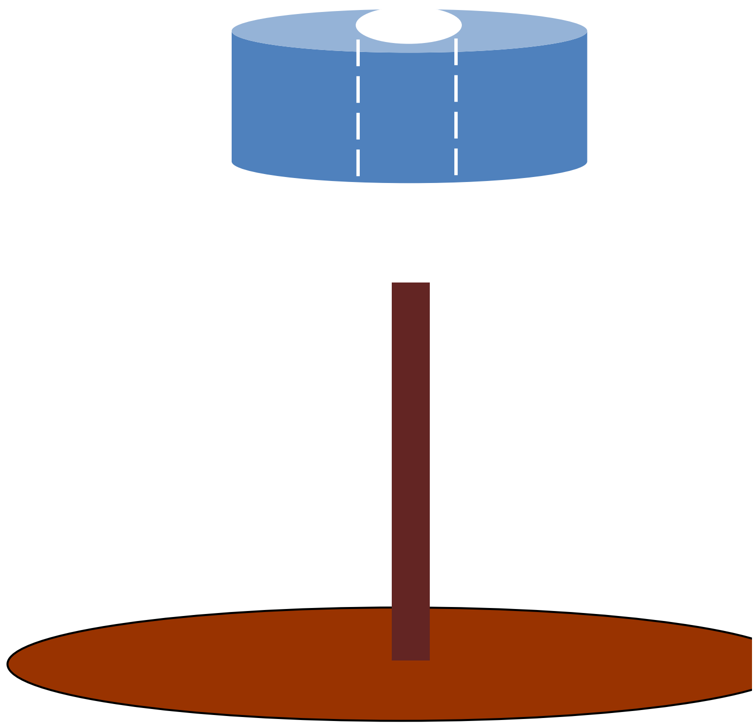
Mongia et al *Elect. Lett.* 29(17) 1530-1531, 1993.

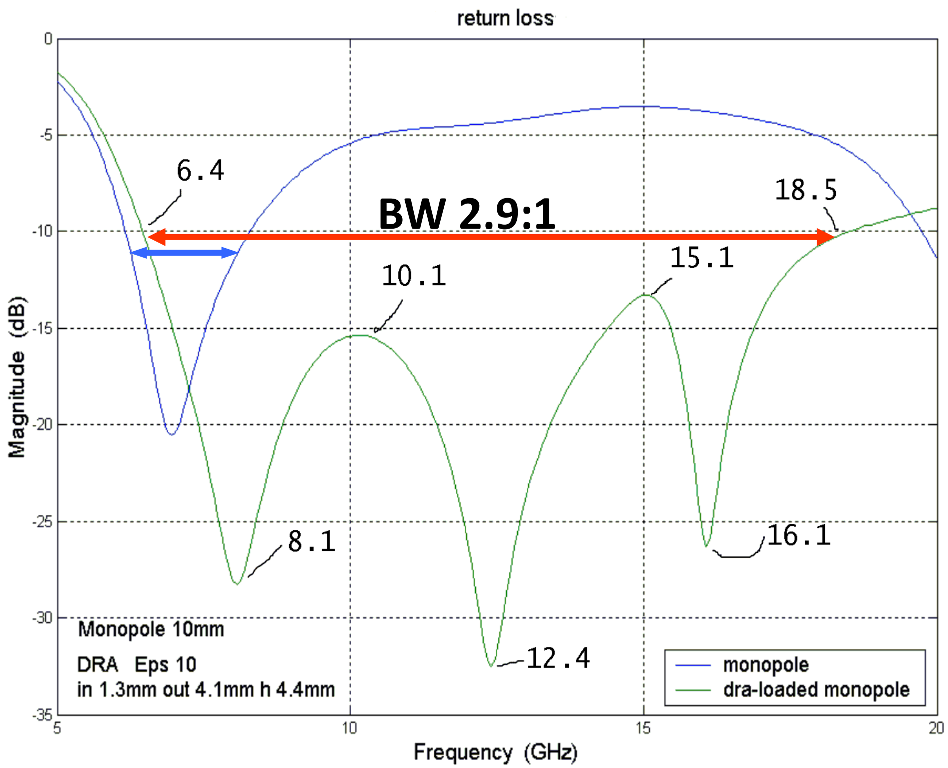




Q: What happens if a monopole designed for resonance at f_1 and DRR at f_2 are brought together?

Electric monopole + DRR





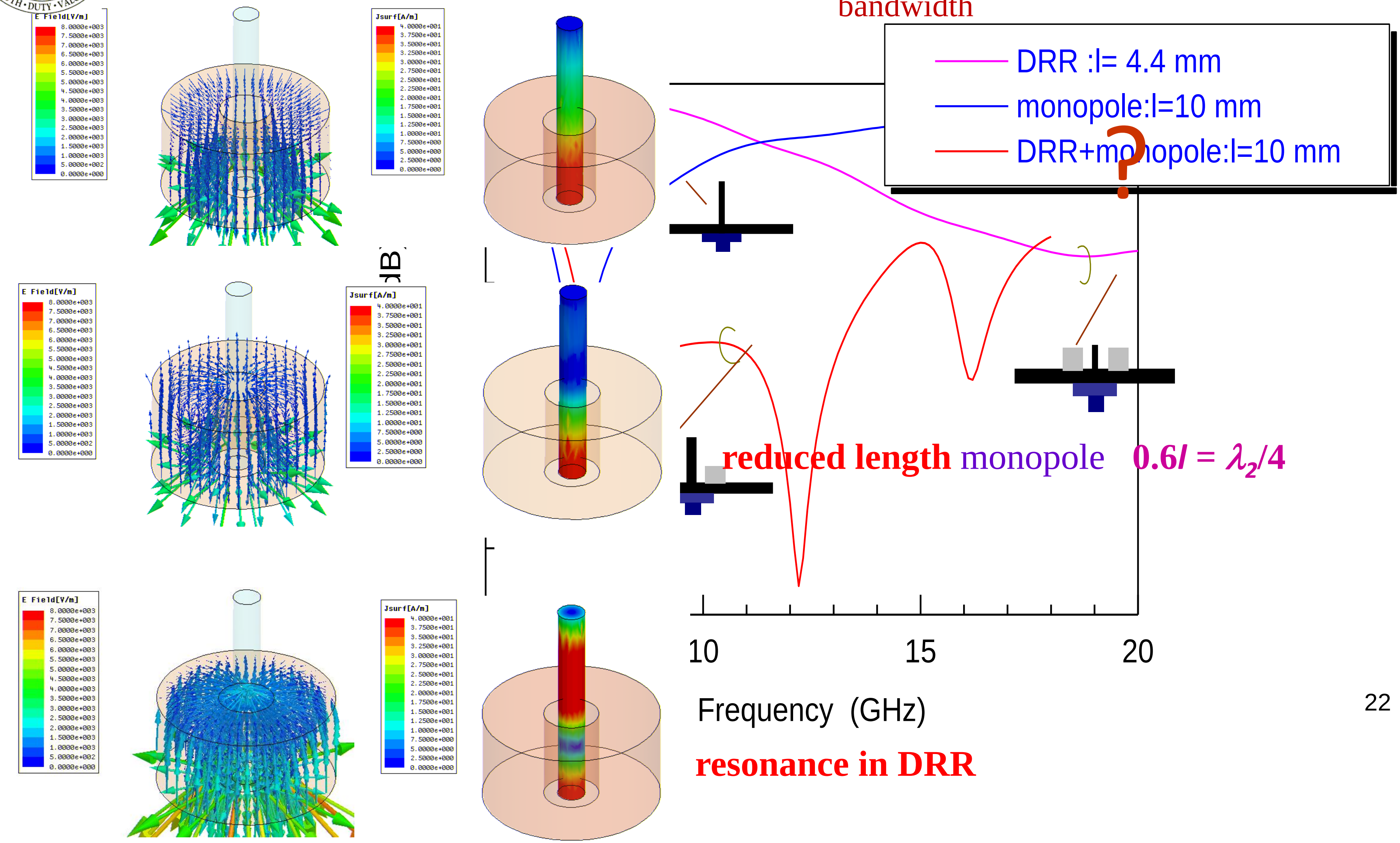
Ittipiboon, Petosa, Thirakoune, "Bandwidth enhancement of a monopole using dielectric antenna resonator loading," *ANTEM*, Canada, Aug. 2002

US patent no.6940463 Sept. 2005

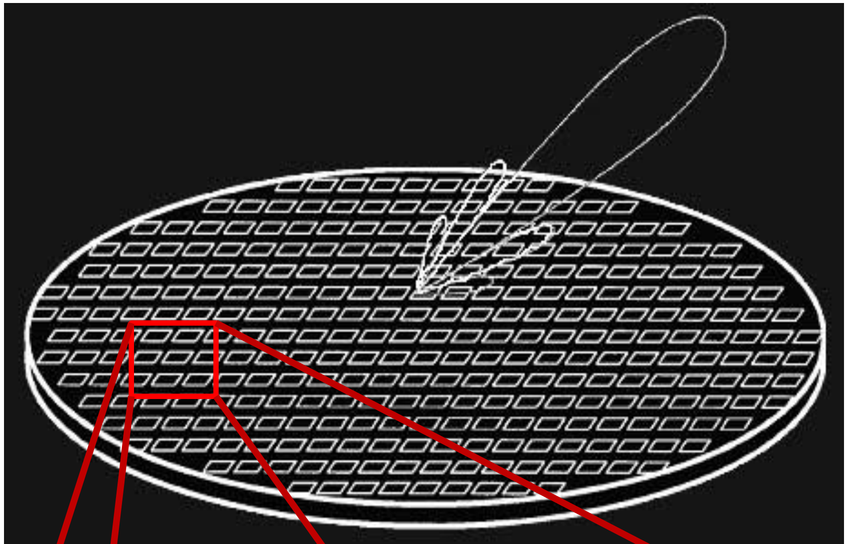
Lapierre, Antar, Ittipiboon, Petosa, IEEE MWCL, Jan. 2005.

Why?

Dielectric bodies surrounding the monopole effectively reduces the length of monopole and resonates at higher freq. and the collective frequencies offer a wider bandwidth

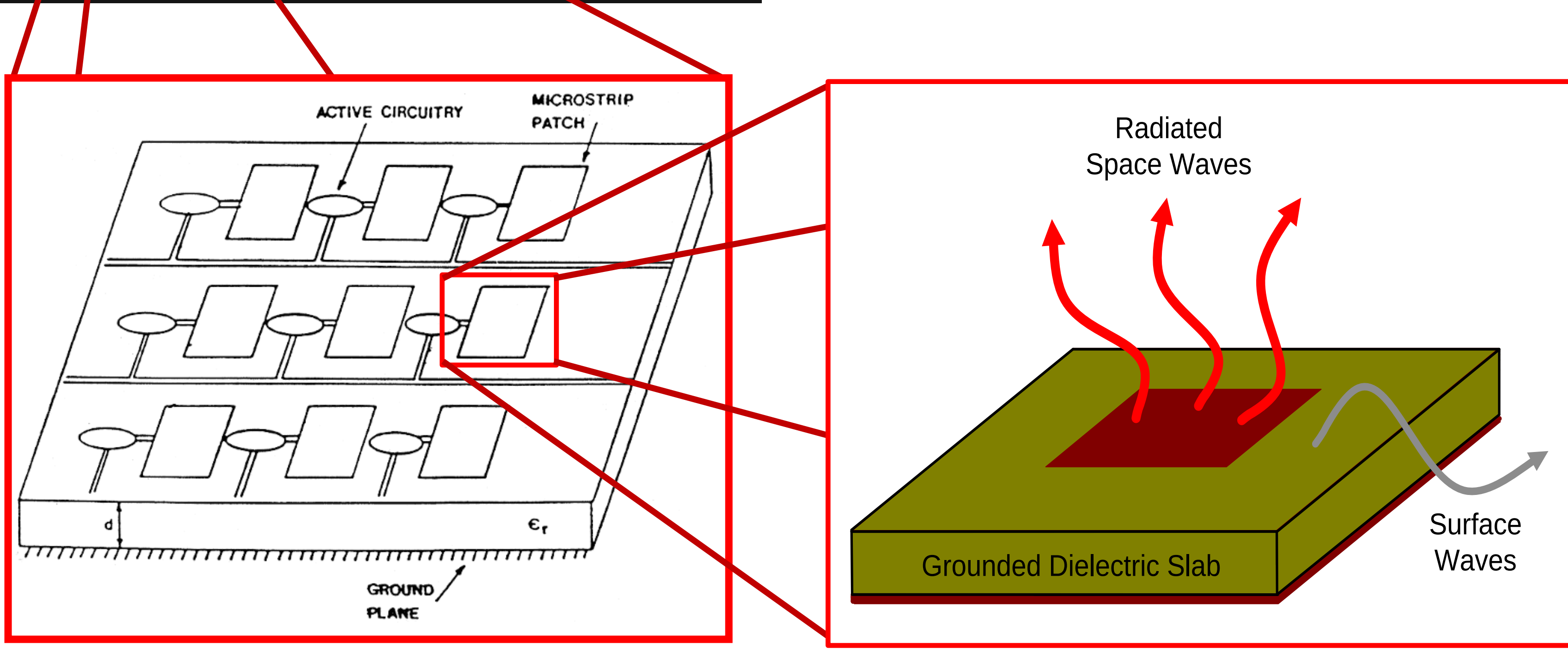


A Class of Printed Leaky Wave Antennas



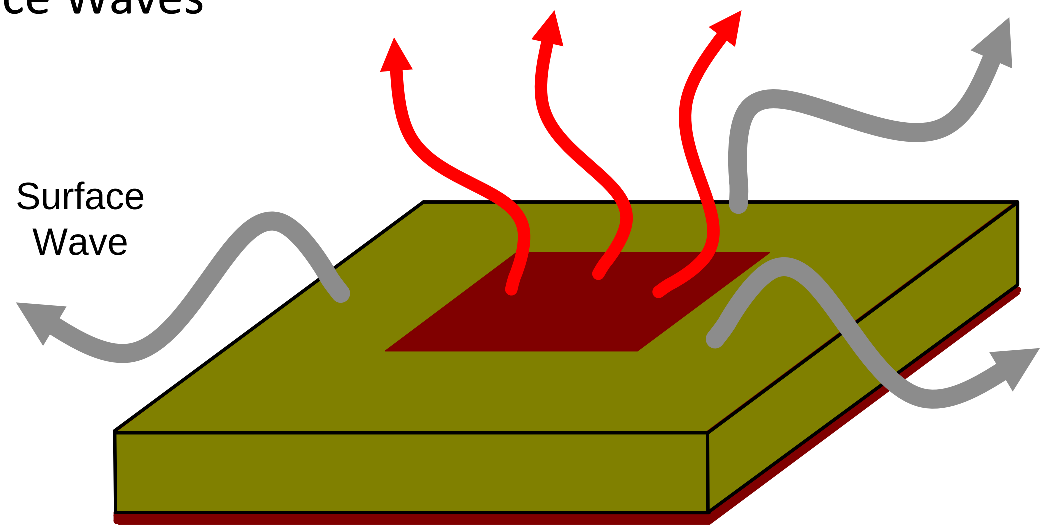
X Surface-Wave (SW) excitation can be an **adverse** and **undesired** effect at high frequencies.

- Element Coupling,
- Power Losses,
- Unwanted Radiation, and
- Typically Reduced Efficiencies.



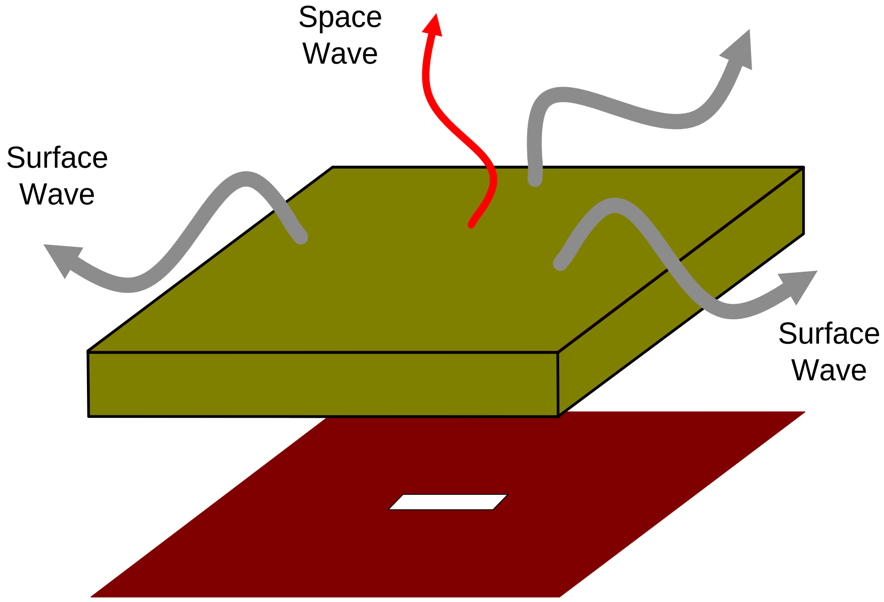
What type of <u>Waves</u> can Exist on Planar Circuits and Devices?

- Complex Waves:
  - Surface Waves (SWs)
  - Leaky Waves (LWs)
- Radiated Space Waves



Surface Waves Are Not Desirable !!

- Potential Advantages: Make use of Surface Waves by efficiently exciting & guiding them
- **Turned into a useful tool for realizing**
  - **(a) new antenna design and**
  - **(b) new way of making microwave circuit designs**



- Excite SWs using slot arrangement.
- Make use of the natural and unwanted effects that are considered parasitic.
- Structure defined by a grounded dielectric slab (GDS).

S. Mahmoud, Y. M. M. Antar, H. Hammad, and A. Freundorfer, "Theoretical considerations in the optimization of surface waves on a planar structure," *IEEE Trans. Antennas Propag., vol. 52, no. 8, pp.* 2057–2063, Aug. 2004.

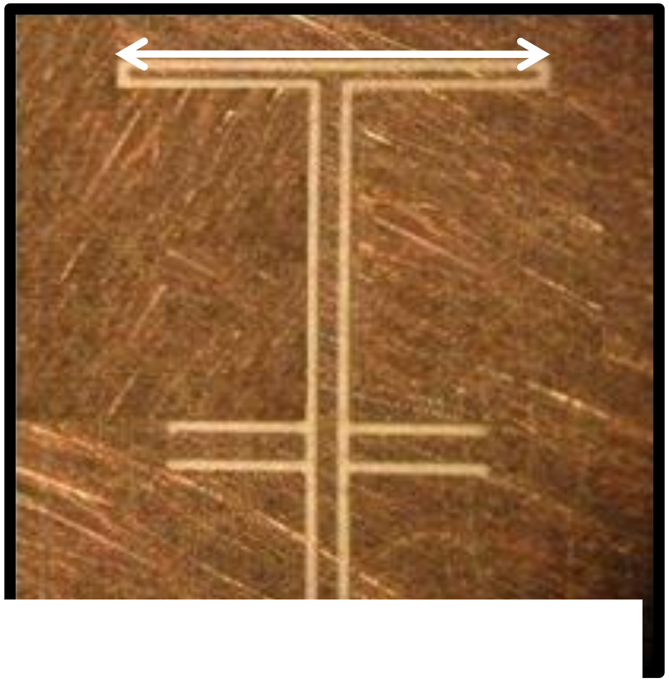
Guide the Surface Waves to New Potentials & Applications

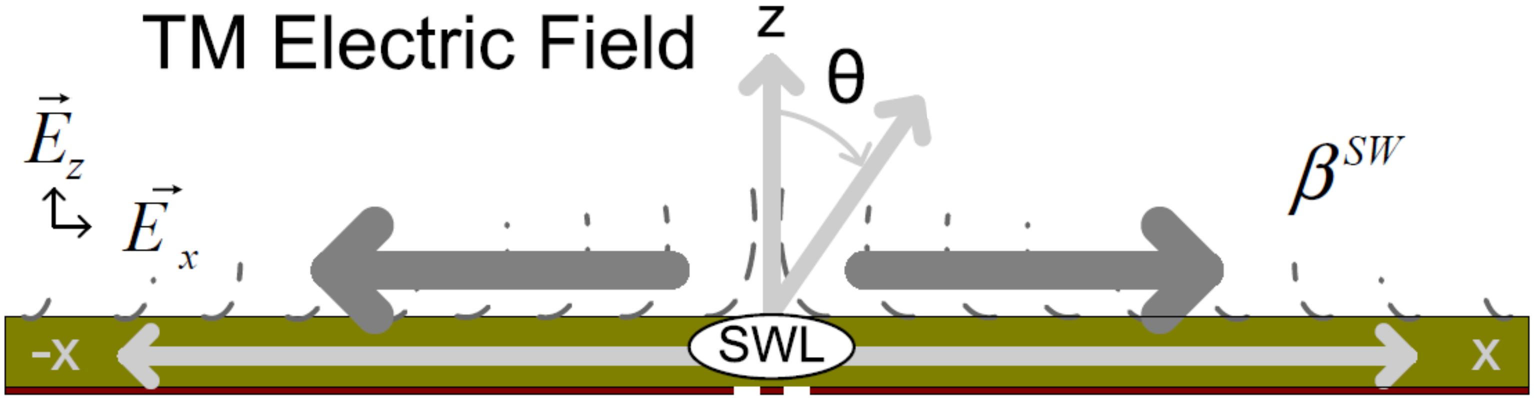
- ✓ High Gain Leaky-Wave Antennas,
- ✓ Directive Radiation at End-Fire & Broadside,
- ✓ Beam Steering,
- ✓ Broad bandwidths (BWs) of Operation,
- ✓ Low Cost Designs,
- ✓ Planar Surface-Wave Lenses,
- ✓ Slab Power Combining,
- ✓ Power Routing, and
- ✓ Guidance Techniques

A Review of The Planar Surface-Wave Launcher (SWL)

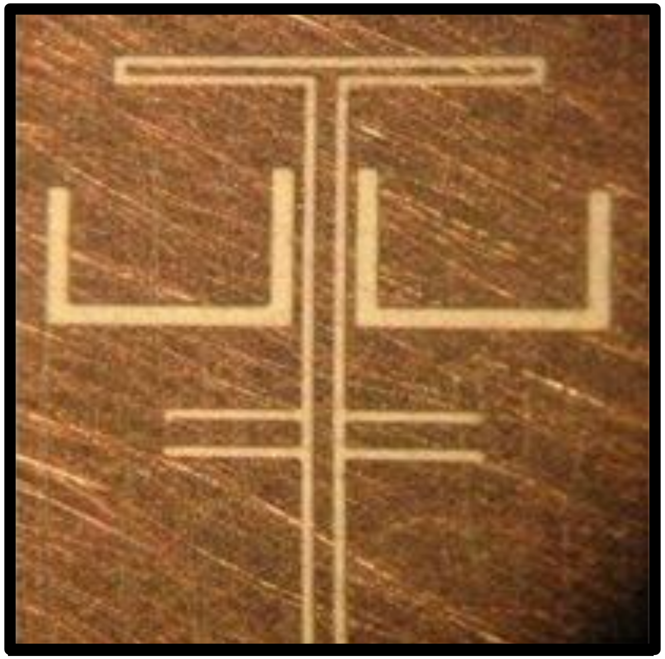
- Main slot acts as a printed antenna for generation of surface waves (SWs).
- Tuning stubs improve matching.
- Coplanar waveguide feed line.
- Bi-directional SW field distribution generated on the air-dielectric interface.
- Slot arrangement defines a non-directive surface-wave launcher (SWL).

$$l \approx \lambda^{SW} / 2$$





How to Efficiently Excite and Maintain SWs



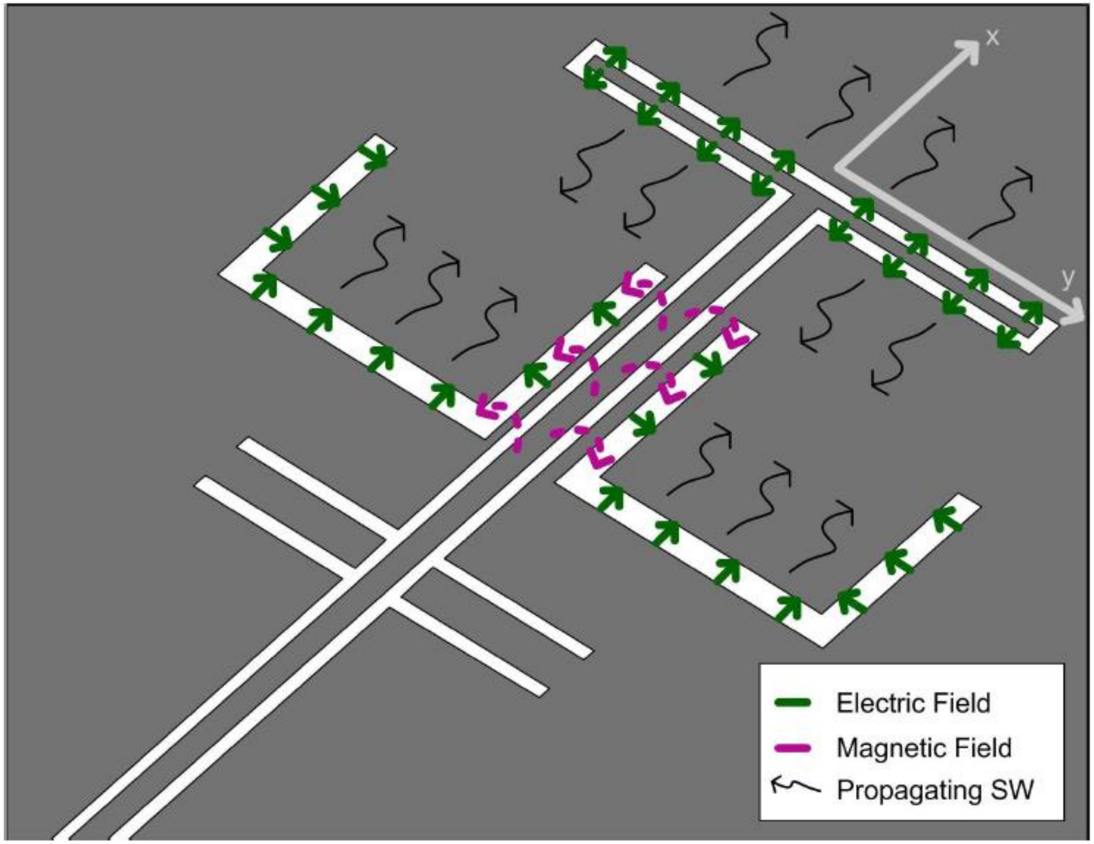
Non-Directive Surface-Wave Launcher

- Field propagation in **both the backward** and **forward** directions.

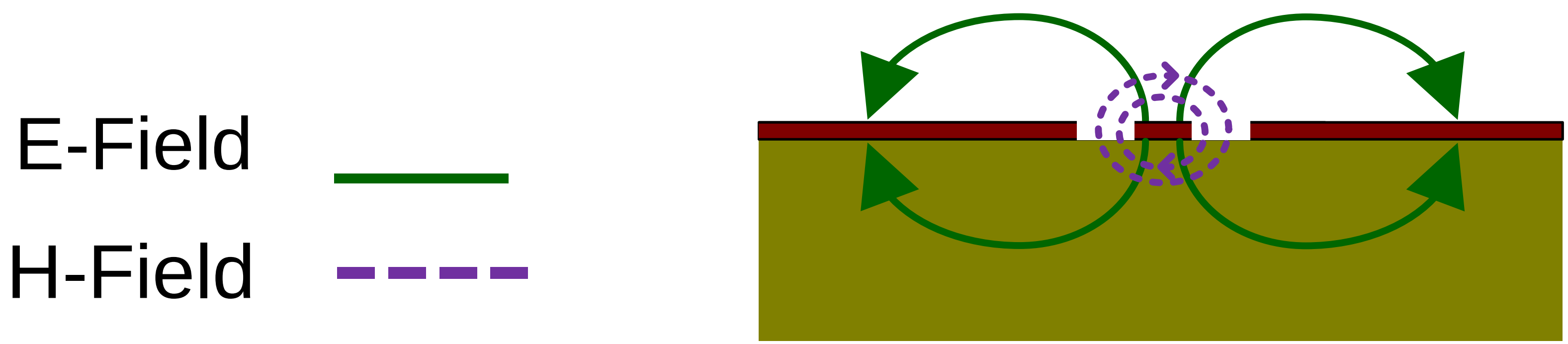
Directive Surface-Wave Launcher

- Secondary reflector slot causes fields to **add in the forward direction** and **cancel in the backward direction**.

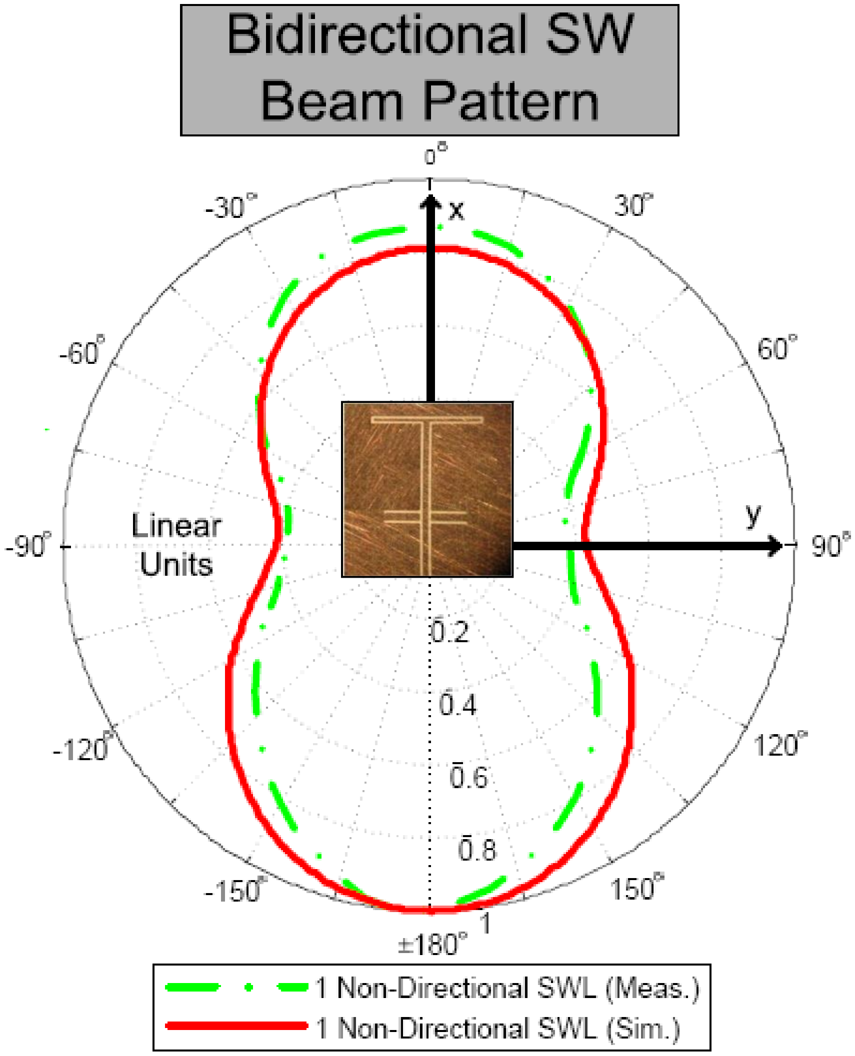
How does the SWL Direct the Fields?

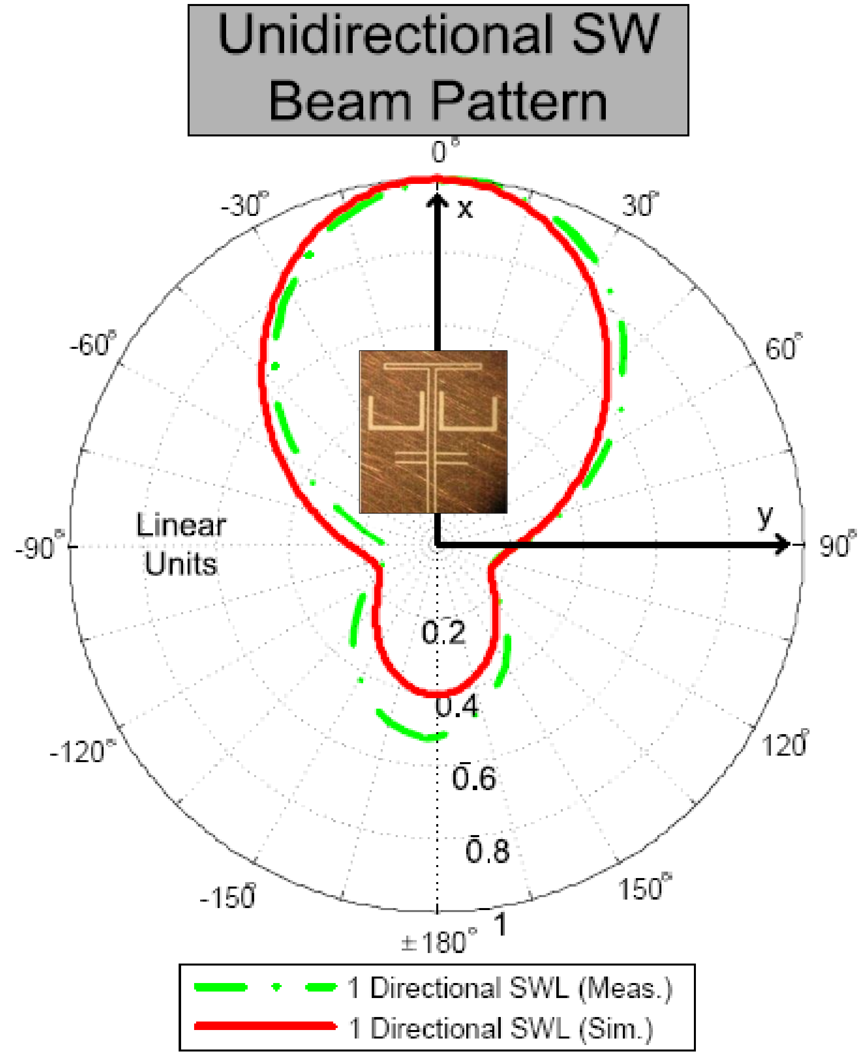


- Main slot coupling by the E-field.
- Coupling into secondary slots occurs by the H-field.
- Slot configurations act as an integrated ground plane antenna for SW excitation.



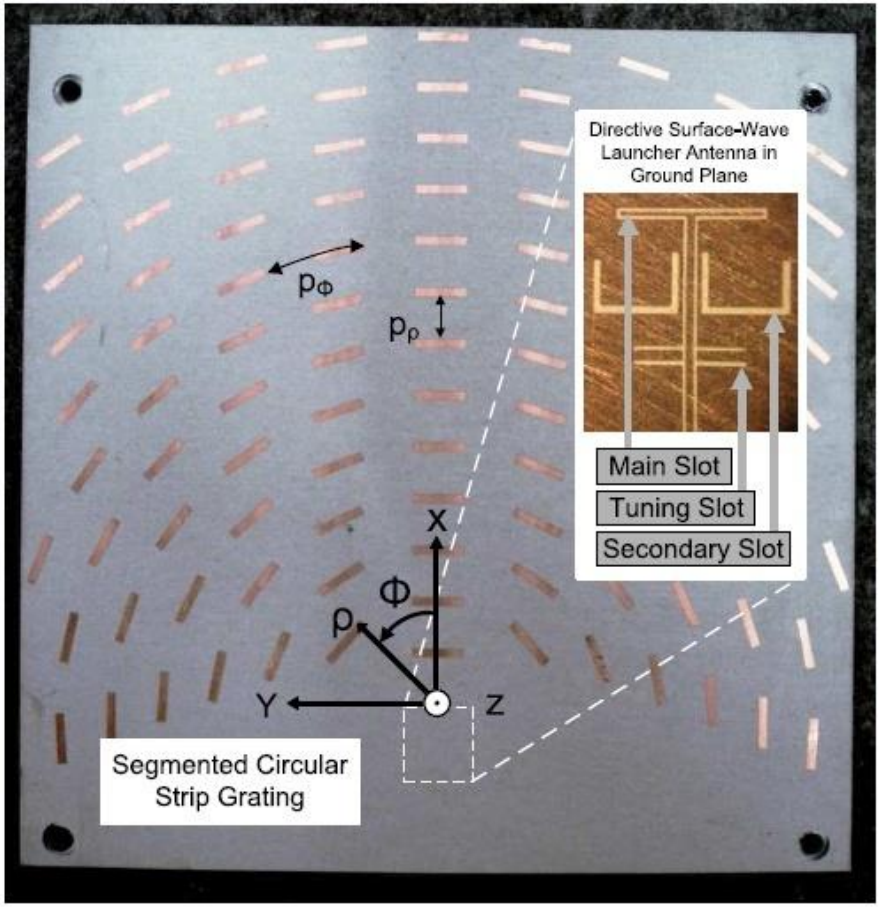
Radial Near-Field Distribution



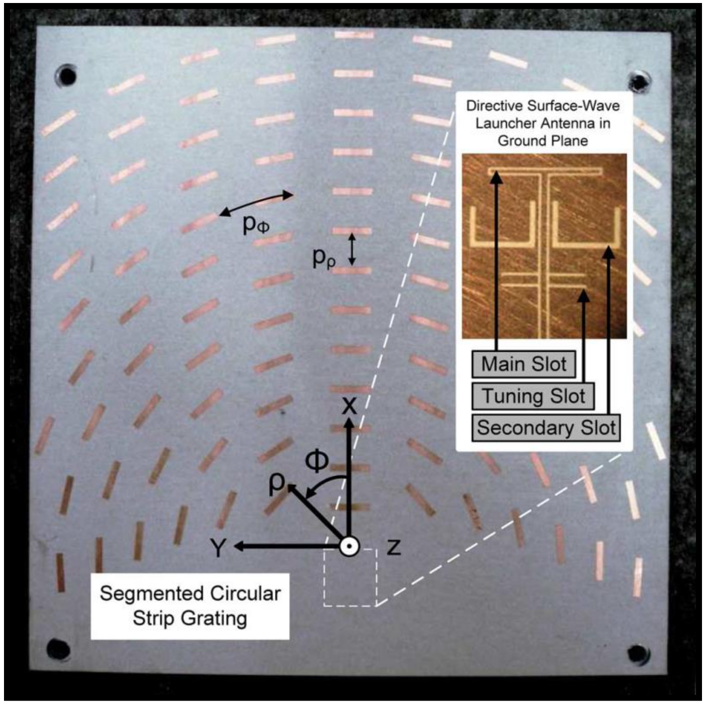


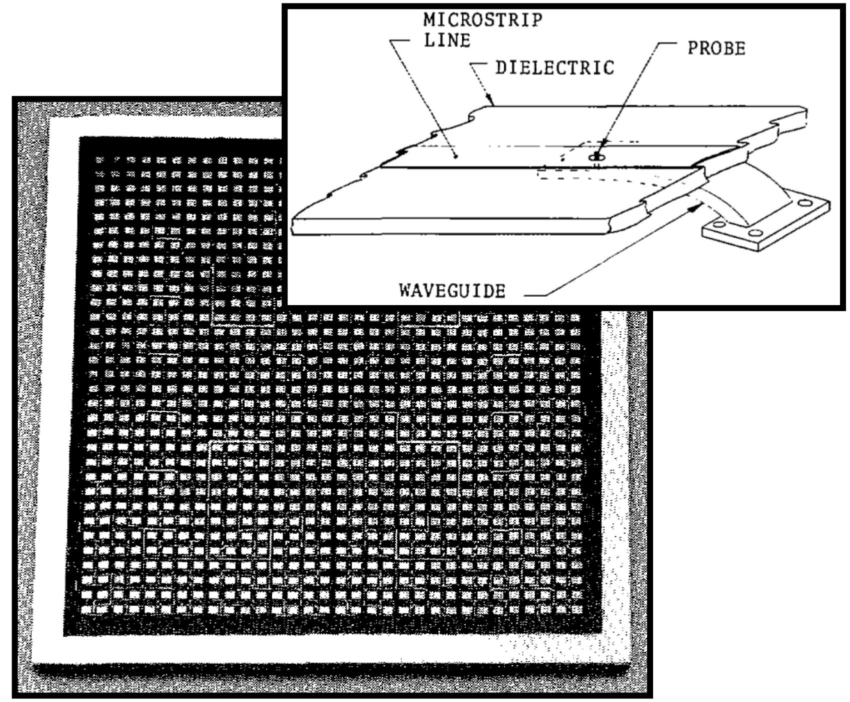
Design for Broadside Radiation and One-Sided Beam Scanning

- The radially orientated strips act as a feedless array of radiating elements.
- If the strip placement is designed correctly, maximum radiation at broadside is possible or continuous beam scanning through broadside as a function of frequency.
- It is important to note that the directive SWL generates both TM and TE fields and the combination of these wave types on the aperture can assist in achieving broadside radiation.



S.K. Podilchak, A.P. Freundorfer and Y.M.M. Antar, "Broadside Radiation From a Planar 2-D Leaky-Wave Antenna by Practical Surface-Wave Launching," IEEE Antennas and Wireless Propag. Lett., vol. 7,pp.516-519, 2008.





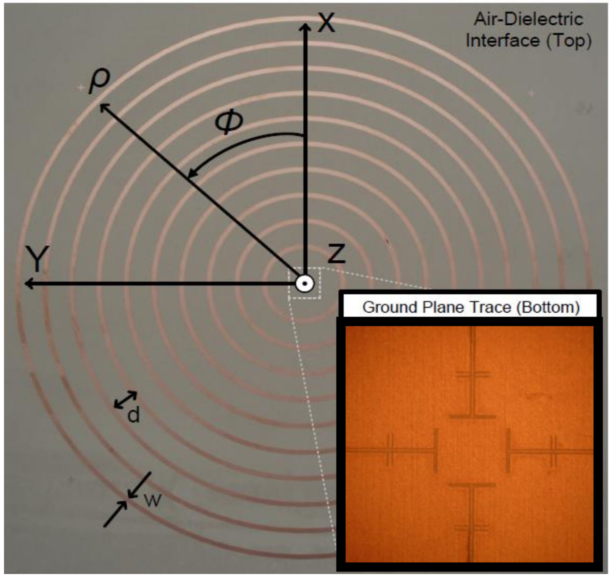
Weiss, M.; , "Microstrip antennas for millimeter waves," *Antennas and Propagation, IEEE Transactions on* , vol.29, no.1, pp. 171- 174, Jan 1981.

- Continuous Beam Scanning Through Broadside: **-55° to +47°**
- Operation: 18 to 26 GHz
- Gain: **17.2 dBi,** App. Eff.: **5%**
- Rad. Eff.: **57%**
- **105 Radiating Elements**
- No Complicated Corporate Feed

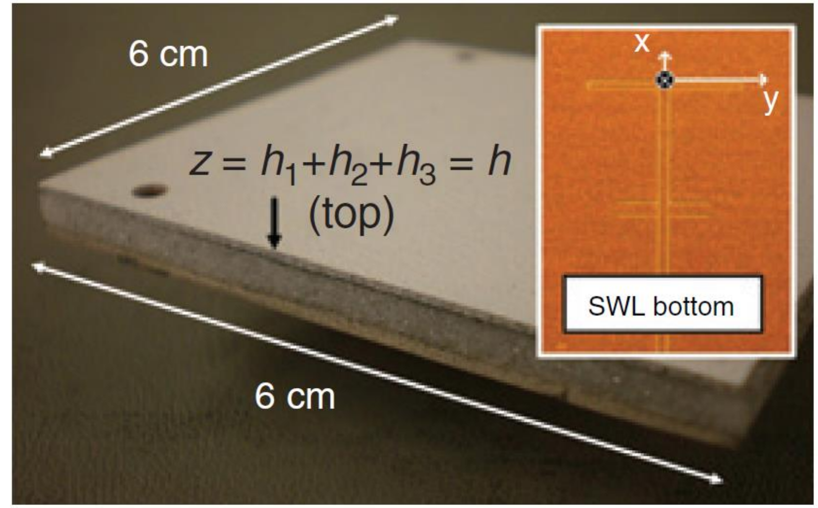
- Broadside Radiation Only: 38 GHz
- Gain: 19.0 dBi, App. Eff.: **~5%**
- Rad. Eff.: **~ 3%**
- **1024 (32 x 32) Radiating Elements**
- **Element Feeding Losses Problematic**

(waveguide/microstrip transition and corporate feed network)

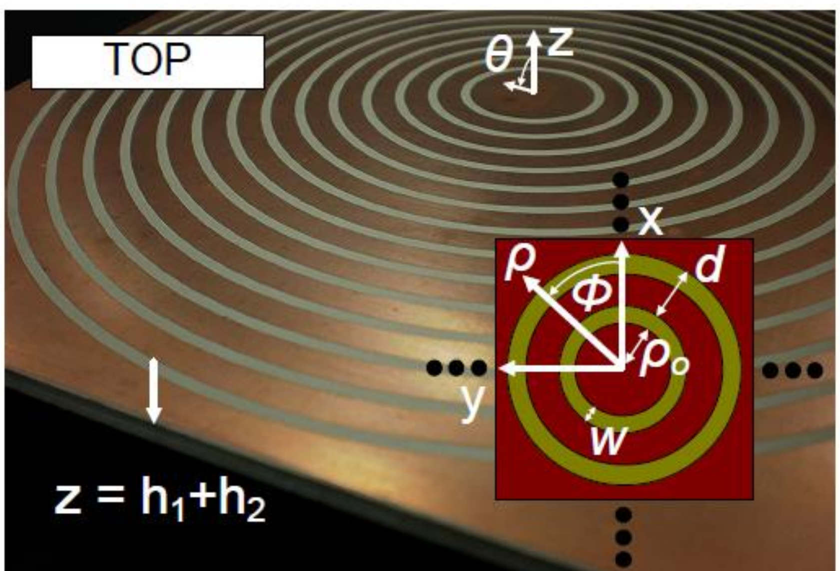
Single-Layer ‘Bull-Eye’ LWA



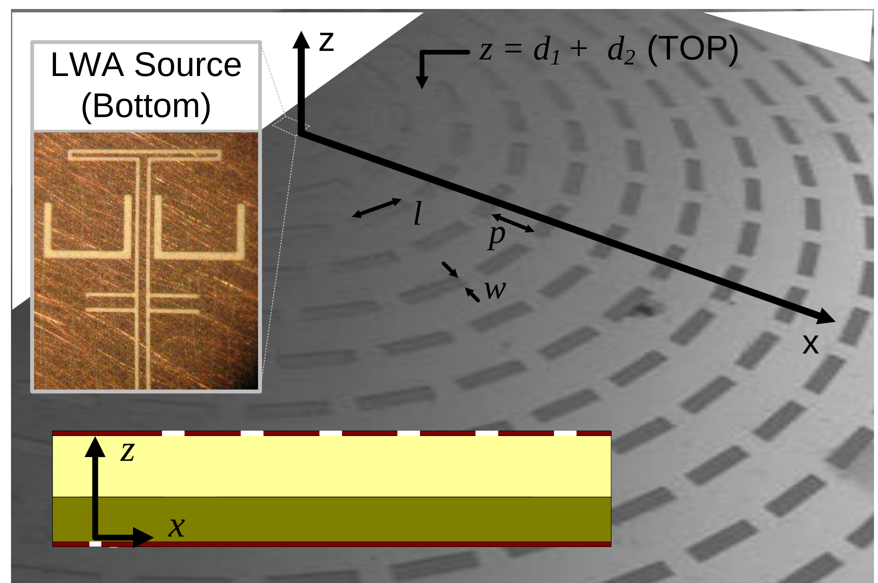
Dielectric-Based SW-Fed LWA



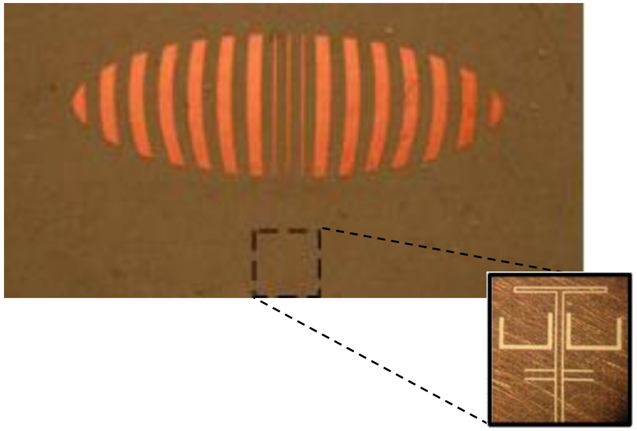
Two-Layer Cavity-Based ‘Bull-Eye’



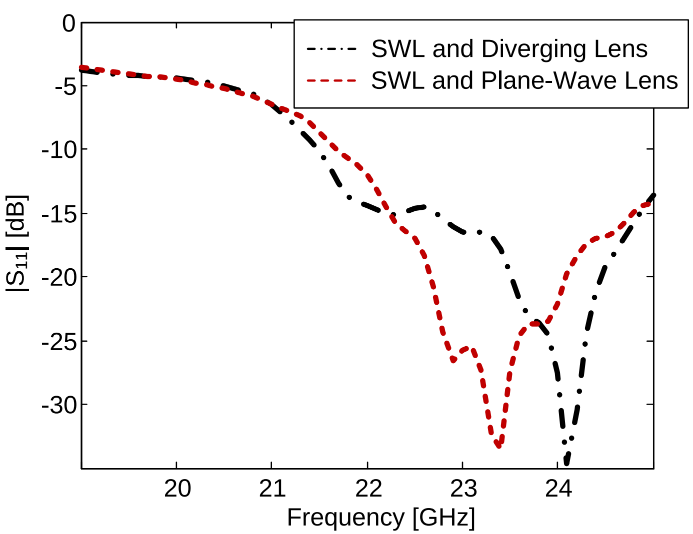
Two-Layer Cavity-Based Guide and Slots

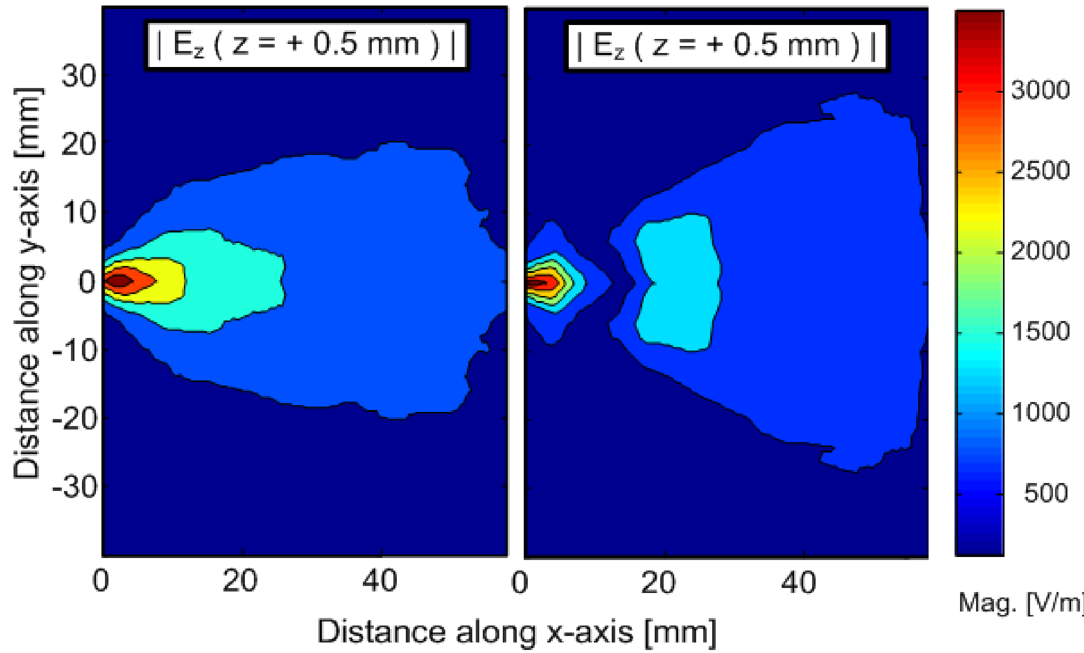


Double-Convex Lens Design for Field Divergence



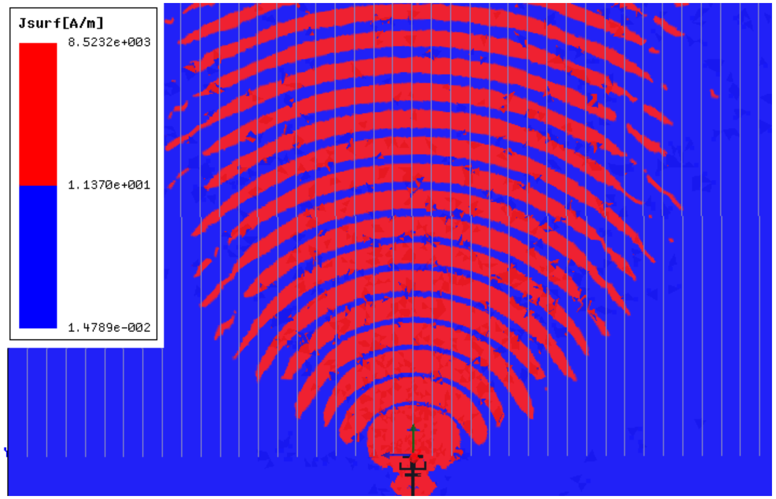
Diverging SW Lens



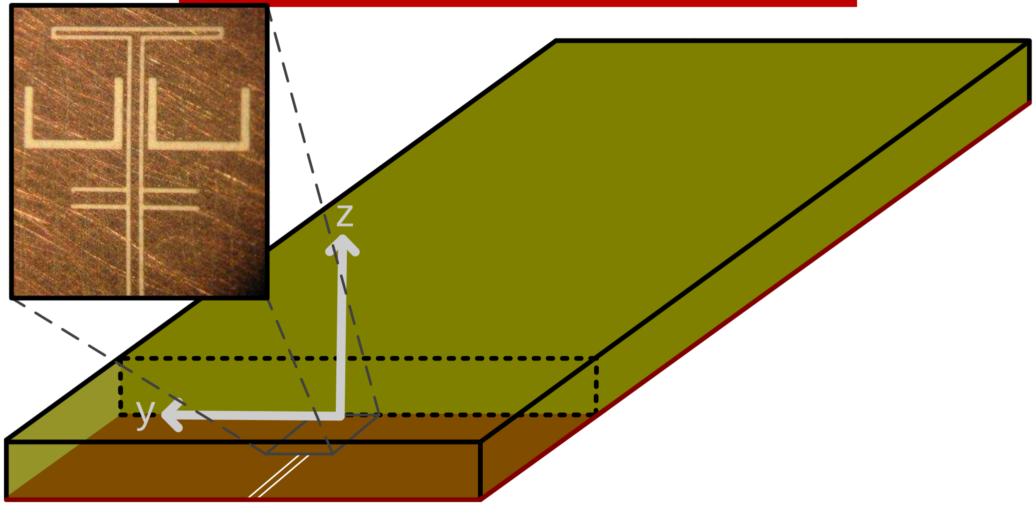


No Lens **With Lens**

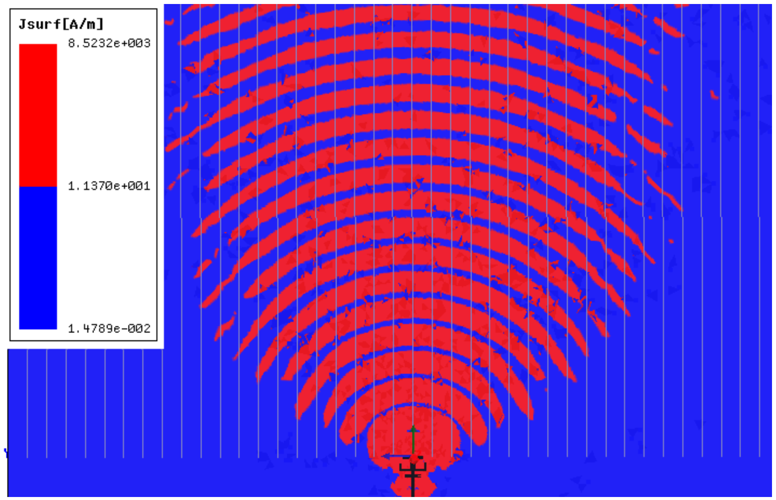
New Guide for Surface Wave Power Routing and Field Channeling

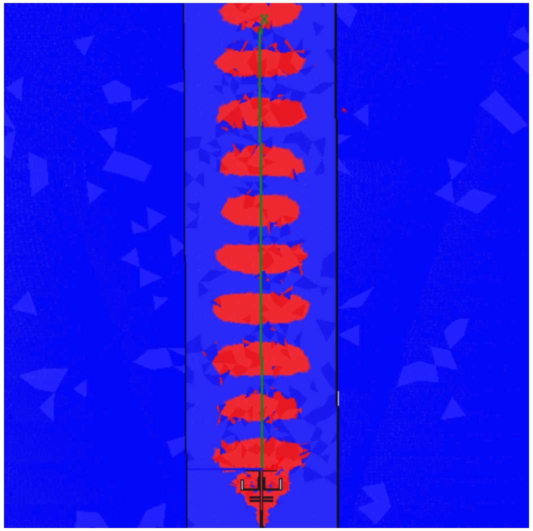


Cylindrical SW Propagation



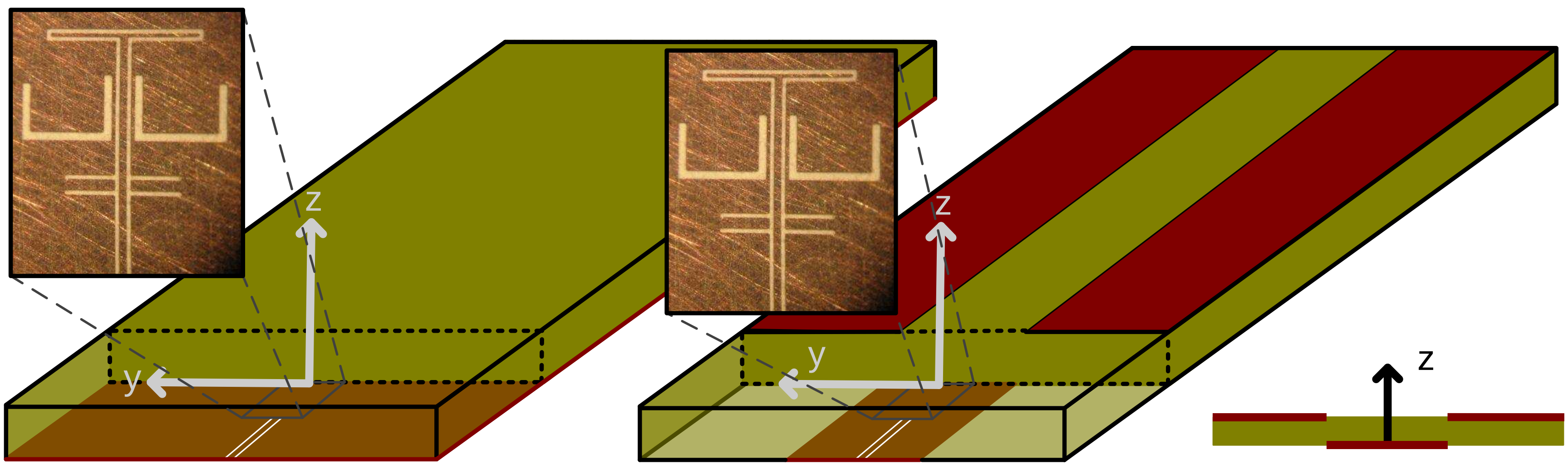
New Guide for Surface Wave Power Routing and Field Channeling





Cylindrical SW Propagation

Channeled SW Propagation



Topics for IEEE AP Distinguished Lectures

Dielectric Resonator Antenna for Wireless and Other Applications

This presentation will address the basic fundamentals of DRAs, the most recent developments and research directions……….

New Considerations for Antenna Electromagnetic Near Fields

This presentation focuses on a new fundamental approach to some electromagnetic phenomena with particular focus on *near-field zone* of electromagnetic radiation…………

A Class of Printed Leaky Wave Antennas

Leaky wave antennas form one type of traveling wave antennas in which an aperture is illuminated by the fields of a traveling wave. We present practical designs of 1Dl and 2D leaky wave antennas that radiate fan-shaped beams and conical or pencil beams respectively, along with some planar feeding schemes.

Main Scientific Objectives

We are eventually considering questions about:

1. How the far field radiation pattern is created as we move gradually away from the source.

2. How the energy is stored in EM systems (can we improve energy handling in devices, questions related to efficiency, etc.)

3. **EM interaction is one of the main goals, arrays, NF and Far field shaping, etc.**

4. **The questions of measurement and how theory can guide the invention and development of new generations of experiments.**

New Developments in Electromagnetic Fundamentals

Fundamental Electromagnetic Theory and Components

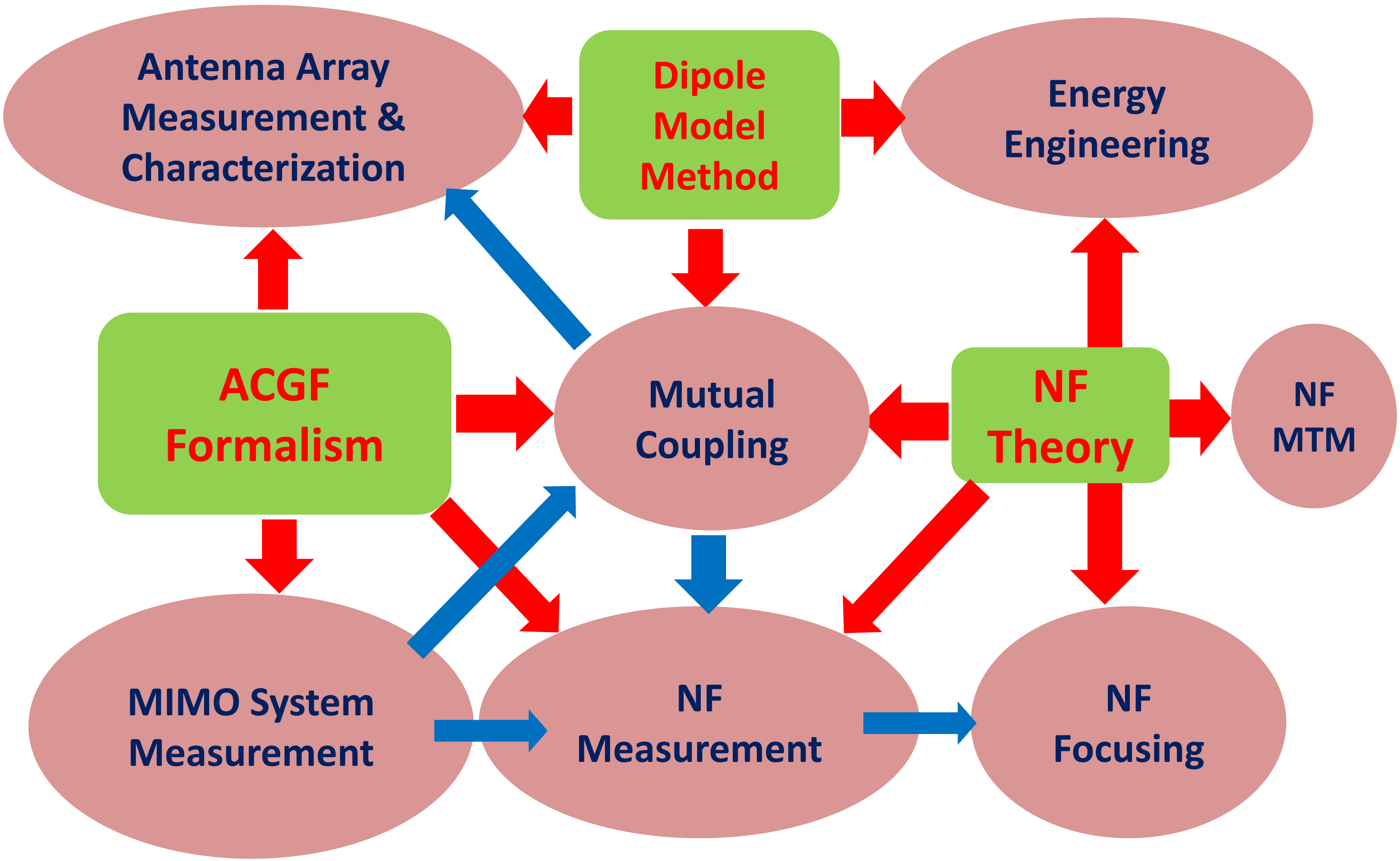
Analysis of Electromagnetic Problems Based on Measurement

1. The Infinitesimal Dipole Model (IDM) Method.
2. The Antenna Current Green's Function (ACGF) Method.

Near-Field Theory

- A new general approach to EM foundations.
- Re-examination of EM energy concepts.
- Development of near-field engineering and devices exploiting near field potentials.
- Development of near-field metamaterials.

Overall View on Recent Progress




Three major developments, and


How they interconnect with Current and Emerging applications

To Probe Further

- Main reference is the following comprehensive book about the new foundations of applied EM theory and their applications

Spatial Structures of Electromagnetic Fields

Said Mikki and Yahia Antar

Artech House, 2015

Impact on Energy Engineering

- Energy storage and energy localization are now fundamental for developing new generations of applications, such as
  1. Wireless energy transfer.
  2. Energy retrieval and manipulation.
  3. System miniaturization.

- Proper understanding of some of these energy applications cannot be done within the traditional perspective of reactive energy.

- New theoretical foundations are needed to develop the concept of electromagnetic energy beyond reactive energy to incorporate
  1. Localized energy.
  2. Stored energy.

Impact on Mutual Coupling Engineering

- Mutual coupling is becoming fundamental for all applications because of the need to
    1. Minimize the size of the system, and
    2. The need to run systems in dense and crowded environments.
- Conventional methods don't provide a proper understanding since they tend to focus only on what happens at the ports or the far field.
- It was found that electromagnetic mutual coupling cannot be reduced to mutual impedance, but require
    1. A deeper understanding of localized interaction energy.
    2. A general method to represent mutual coupling mathematically in terms of a proper system or transfer function.
- A key to this topic is a good understanding of the near field in the interaction process, which goes beyond port coupling.
- New techniques to compute mutual coupling in large and complex antenna arrays that avoid inverting the full coupled EM operator are proposed [1,2].

[1] Said Mikki and Yahia Antar, "The Antenna Current Green's Function Formalism (Parts I and II)," *IEEE TAP*, Sept 2013.

[2] Said Mikki and Yahia Antar, "A Rigorous Approach to Mutual Coupling in General Antenna Systems Through Perturbation Theory," (to appear *in IEEE AWPL*).

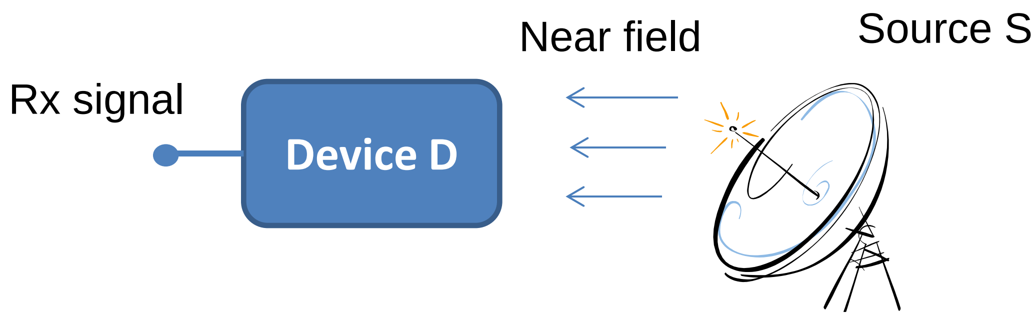
Impact on MIMO Systems Engineering

- In MIMO systems, there is a need to examine near-field interactions in light of their impact on mutual coupling and the system performance.
- It is found that complete description of MIMO systems cannot be done in terms of conventional circuit parameters.
- Moreover, it is found that far field characterization is not enough where near field aspects and energy localization issue are becoming increasingly important for applications.
- MIMO and mobile devices operate in typical heavily populated urban environments where near field coupling with other devices and nearby scatterers are fundamental for maintaining high performance.

[1] S. Clauzier, Said Mikki and Yahia Antar, "A generalized methodology for obtaining optimum current distributions on antennas for MIMO applications," submitted to *IEEE AWPL*.

[2] Said Mikki and Yahia Antar, "On cross correlation in general antenna systems with applications to spatial diversity and MIMO systems," submitted to *IEEE TAP*.

Case I. Practical Scenarios for NF Interactions in EM Systems: Near Field Incidence



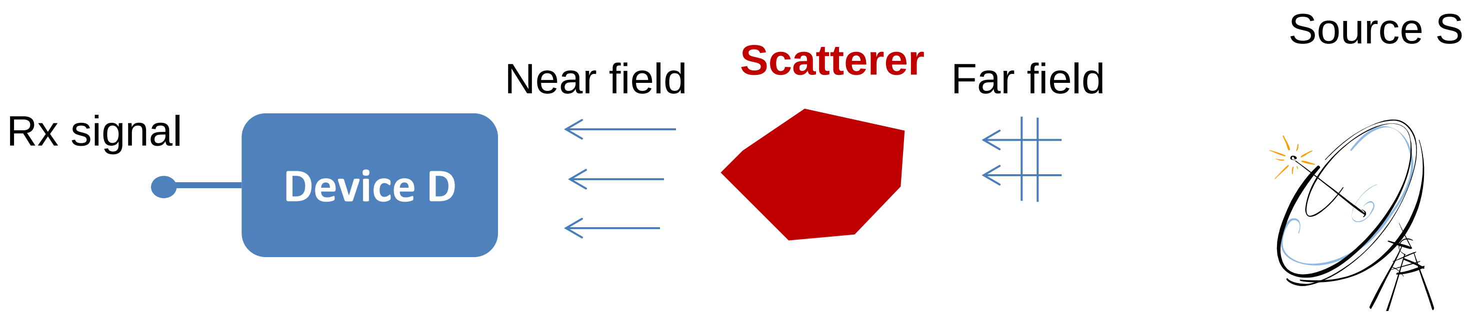
In dense and compact systems, various parts of the radiation and circuit elements are placed in close proximity to each other.

Do we know how to characterize the response of a generic device to generic NEAR field illumination?

The generic Device D is described using its <u>exact transfer function (new)</u> in space, the antenna current Green's function (ACGF).

<u>The ACGF allows us to describe the problem for arbitrary near-field excitation without the need to solve Maxwell's equations for every new near field.</u>

Case II. Practical Scenarios for NF interactions in EM Systems: Far Field Incidence (near field effects!)



- Although the entire system is illuminated by plane wave, and since scattered fields at close distance are near fields, the device D is effectively bombarded by **near field**.

This situation is typical in

- Complex environments (such as dense and populated urban spaces).
- Compact systems where mutual coupling is significant
- MIMO systems where the existence of multiple paths caused by close scatters is essential.

Characterization of mobile devices and communication systems are currently moving toward measurement of systems in near-field environments.

1. **NF chambers.**
2. **NF Diagnostic imaging.**
3. **NF testing.**

The Near Field Theory

General Introduction

Fundamental Electromagnetic Theory and Applications

Analysis of Electromagnetic Problems Based on Measurement

1. The Infinitesimal Dipole Model (IDM) Method.
2. The Antenna Current Green's Function (ACGF) Method.

- A new general approach to EM foundations.
- Re-examination of EM energy concepts.
- Development of near-field engineering and devices exploiting near field potentials.
- Development of near-field metamaterials.

Some Critical 'Open' Questions

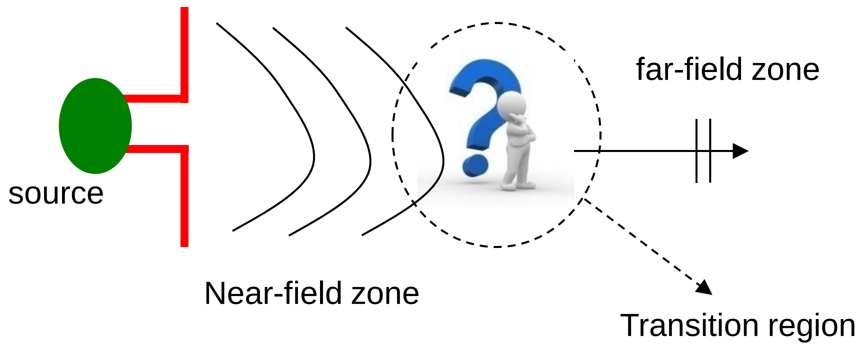
Although there has been enormous progress in the last seven decades in all areas of applied electromagnetics, many major issues remain open.

There seems to be no conclusive answers to questions such as:

1. **How does a given antenna radiate?**
2. **How does the radiation field emerge into being starting from the near field?**

These questions can be put compactly into one major query:

1. **What is electromagnetic energy?**
2. **What is the stored energy in antenna systems?**
3. **What is the nature of electromagnetic interactions between coupled objects?**



The road to the far field must be traversed through the **near field zone**. Nothing much is known about the physics of this **transition**, which clearly is essential in the working of any antenna system.

Relevance of the New NF Theory to Emerging Applications

Some emerging applications involve the following consideration

1. Devices and systems exists in dense environment.
2. Objects in these environments tend to interact strongly in the NF Zone.

Examples of such recent applications

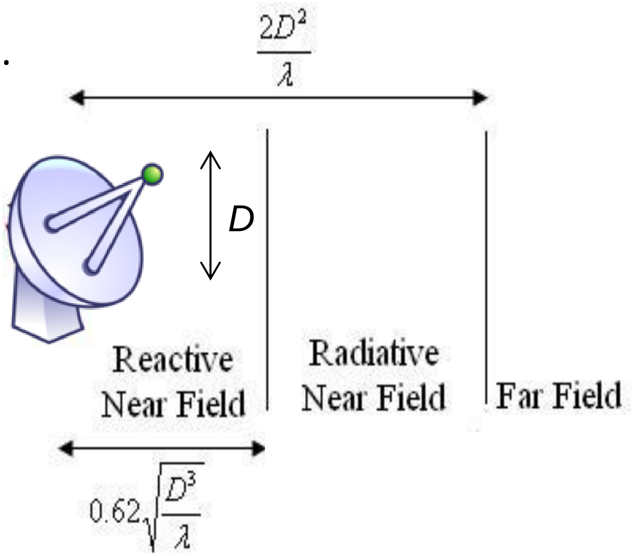
1. Near-Field Communications (NFC)
2. Near-field focusing and matching.
3. Energy transfer and harvesting.
4. Metamaterials.
5. Nano-scale EM System.
6. MIMO systems.
7. Tera-Hertz Applications.

<u>Knowing the structure of the NF could provide more physical insight towards how we handle such new and emerging applications.</u>

What do we know about the antenna NF?

There exists in the antenna community the following understanding of the topic of the NF

1. Far Field (Fraunhofer) region.
2. Radiating or intermediate Near Field or Fresnel Region.
3. Reactive Near Field



"Reactive" Near Field Region:

The boundary of this region is commonly given as

$$R < 0.62\sqrt{\frac{D^3}{\lambda}}$$

Radiating Near Field (Fresnel) Region

The radiating near field or Fresnel region is the region between the near and far fields. In this region, the reactive fields are not dominant; the radiating fields begin to emerge.

The region is commonly given by:

$$0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda}$$

Foundations of the Common View About the NF

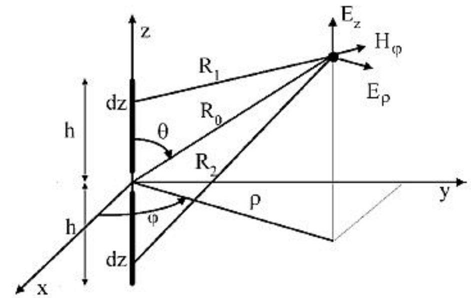
Consider the radiation expressions of small dipole

$$\boldsymbol{H} = \frac{1}{4\pi} IL \sin\theta \, e^{-j\beta_0 r} \left(\frac{j\beta_0}{r} + \frac{1}{r^2} \right) \boldsymbol{\phi}$$

$$\boldsymbol{E} = \frac{j\eta_0 IL}{2\pi\beta_0} \cos\theta \left(\frac{j\beta_0}{r^2} + \frac{1}{r^3} \right) e^{-j\beta_0 r} \boldsymbol{r}$$

$$- \frac{j\eta_0 IL}{4\pi\beta_0} \sin\theta \left(-\frac{\beta_0^2}{r} + \frac{j\beta_0}{r^2} + \frac{1}{r^3} \right) e^{-j\beta_0 r} \boldsymbol{\theta}$$

Far field　　Intermediate NF　　reactive NF



We notice the bifurcation into three types of terms:

The traditional view on NF is therefore based on an extrapolation of the 1/r series dependence of the simple small dipole antenna.

1. This extrapolation is at best heuristic.

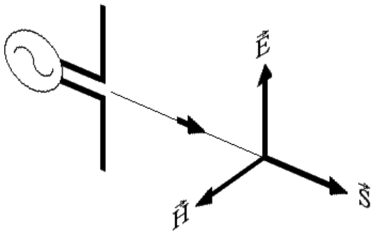
2. There exists no rigorous theory in which the structure of the NF is studied systematically for arbitrary antennas.

3. <u>Our work starts by generalizing the spatial approach using the Wilcox expansion in which all higher powers of 1/r are included systematically to understand the NF of arbitrary antennas.</u>

The Near Field vs the Far Field

- The form of the far field is well known. It is given by the formula (here A is the far field amplitude) [1]

$$\mathbf{E}(\mathbf{r}) = \frac{e^{ikr}}{r}\left[\hat{\varphi}\, A_{\varphi}(\theta,\varphi) + \hat{\theta}\, A_{\varphi}(\theta,\varphi)\right]$$



1. That is, the field is transverse to the radial direction. It takes the form of a **spherical outgoing wave**.

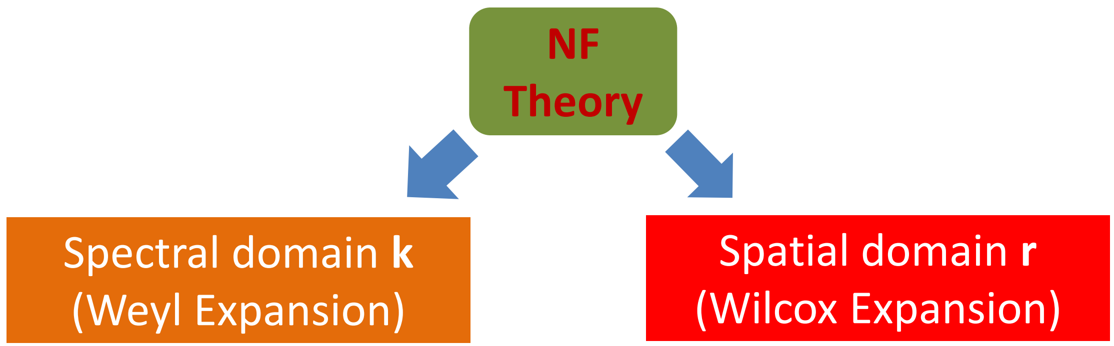
2. No such simple mathematical structures exist in the case of the NF.

3. The present work is an attempt to develop <u>a general theory of the mathematical structure of the NF</u>.

[1] C. Balanis, *Antenna Theory: Analysis and Design*, Wiley, 2005.

Two-Level Approach to the NF

We approach the problem at two levels:



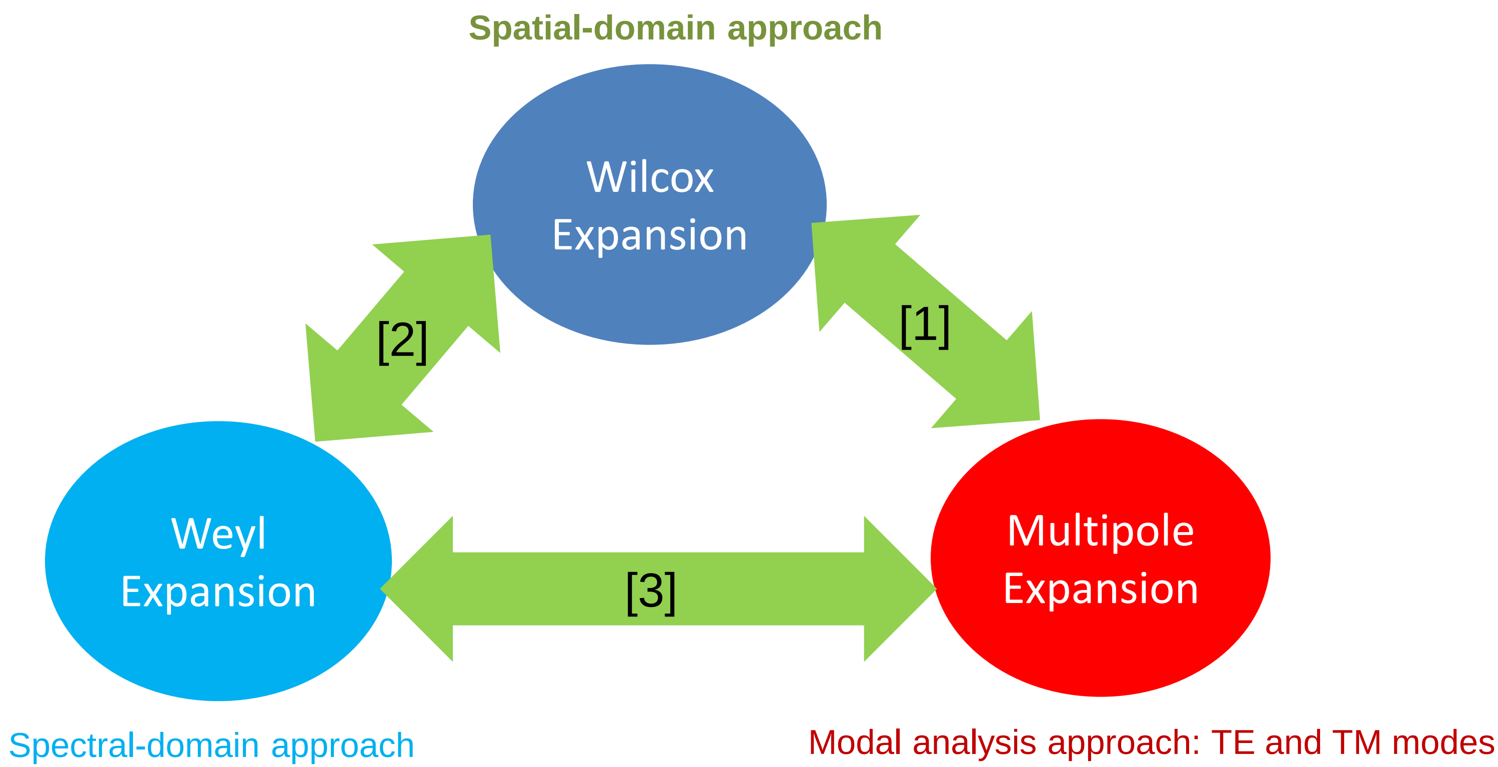
Spatial domain: How the NF varies with the position **r** $\rightarrow$ **infinite summation**

Spectral domain: How the NF varies with the wave vector **k**.

Relation between the spatial and spectral domain is given by the Fourier integral

$$\mathbf{E}(\mathbf{r}) = \int \mathbf{E}(\mathbf{k}) e^{ikr} d^3 r$$

Overall Theoretical Structure of the Electromagnetic NF



While the three Weyl, Wilcox, and multipole expansions are well known in literature, little has been said about the subtle mode of their mutual interrelation among each other. This has been investigated in our work [1], [2].

[1] Said Mikki and Yahia Antar, "A theory of antenna near field-Part I," *IEEE TAP*, December 2011.

[2] Said Mikki and Yahia Antar, "A theory of antenna near field-Part II," *IEEE TAP*, December 2011.

[3] A. J. Davaney and E. Wolff, "Multipole expansions and plane wave representations of the electromagnetic fields," *J. Math. Phys*., vol. 15, no. 2, Feb 1974.

The interplay between the three major elements of our NF theory

1. Wilcox expansion: This is the approach to the antenna problem in the spatial domain. The main goal is to study the distribution of EM energy in spatial regions surrounding the antenna. The signature of the method is the power of 1/r terms.
2. Multipole expansion: This is the approach to the antenna problem in terms of operating modes familiar to engineers. The main goal is the understanding of the NF structure in terms of special well-known functions (eigenfunctions of mathematical physics). The signature of this method is working with antenna spherical TE and TM modes.
3. Weyl expansion: Here we work in the spectral domain. The main goal is to understand the NF as a process in space and time by decomposing the field into a sum (spectrum) of propagating and evanescent modes. The signature of our approach is the use of rotation of coordinate systems to generate the dynamic change in the propagating part according to the direction along with the antenna field is being observed.

Wilcox Expansion

Total field in the exterior region [1]

$$\mathbf{E}(\mathbf{r}) = \frac{e^{ikr}}{r}\sum_{n=0}^{\infty}\frac{\mathbf{A}_n(\theta,\varphi)}{r^n}, \quad \mathbf{H}(\mathbf{r}) = \frac{e^{ikr}}{r}\sum_{n=0}^{\infty}\frac{\mathbf{B}_n(\theta,\varphi)}{r^n}$$

Here the complex angular functions A_n and B_n vary from one antenna to another. They can be computed from the far field.

Far field $$\mathbf{E}(r\to\infty) = \frac{e^{ikr}}{r}\mathbf{A}_0(\theta,\varphi), \quad \mathbf{H}(r\to\infty) = \frac{e^{ikr}}{r}\mathbf{B}_0(\theta,\varphi)$$

Far field amplitudes are related as $$\mathbf{B}_0(\theta,\varphi) = \frac{1}{\eta}\hat{r}\times\mathbf{A}_0(\theta,\varphi)$$

- The Wilcox expansion is the natural mathematical tool for studying the structure of the NF in the spatial domain.
- It expands the radiated fields into the sum of partial parts, each consisting of term that depends on the radial distance in the simple form $1/r^n$ for some integer *n.*
- We combined the Wilcox expansion with the classical spherical harmonics series, i.e., we effectively performed modal analysis of the EM field into spherical TM and TE modes.

[1] C. H. Wilcox, “An expansion theorem for electromagnetic fields,” *Communications on Pure Mathematics*, 1956.

Multipole Expansion

1) Multipole expansion: This is the approach to the antenna problem in terms of operating modes familiar to engineers [1].

2) The main goal is the understanding of the NF structure in terms of special well-known functions (eigenfunctions of mathematical physics). The signature of this method is working with antenna spherical TE and TM modes.

$$\mathbf{H}(\mathbf{r}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \left[a_M(l,m)\, h_l^{(1)}(kr)\, \mathbf{X}_{lm} - \frac{i}{k} a_E(l,m)\, \nabla \times h_l^{(1)}(kr)\, \mathbf{X}_{lm} \right]$$

$$\mathbf{E}(\mathbf{r}) = \eta \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \left[a_E(l,m)\, h_l^{(1)}(kr)\, \mathbf{X}_{lm} + \frac{i}{k} a_M(l,m)\, \nabla \times h_l^{(1)}(kr)\, \mathbf{X}_{lm} \right]$$

[1] David Jackson, *Classical Electrodynamics*, 1975.

Weyl Expansion

1) Here we work in the spectral domain. The main goal is to understand the NF as a process in space and time by decomposing the field into a sum (spectrum) of propagating and evanescent modes.

2) The signature of our approach is the use of rotation of coordinate systems to generate the dynamic change in the propagating part according to the direction along which the antenna field is being observed.

$$g(\mathbf{r}) = \frac{e^{ikr}}{r} = \frac{ik}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dpdq\,\frac{1}{m}\,e^{ik\left(px+qy+m|z|\right)},$$
$$m = \sqrt{1-p^2-q^2}.$$

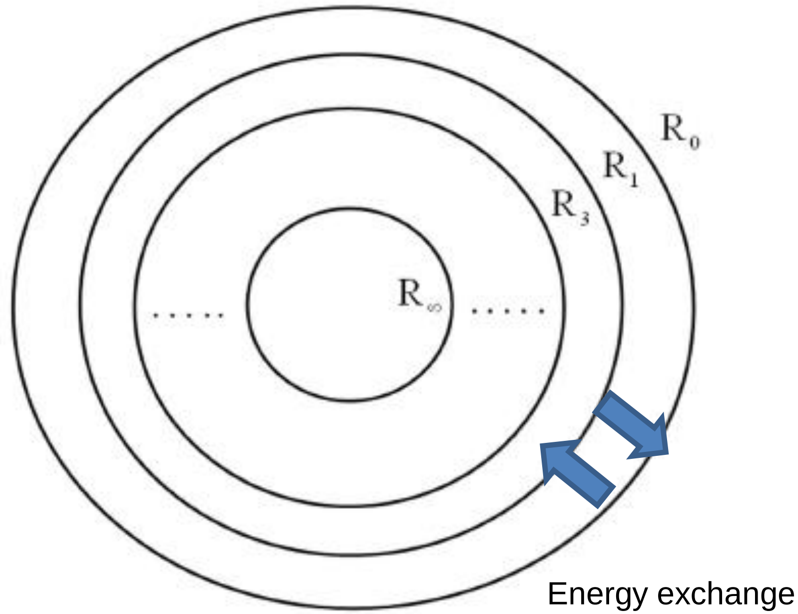
[1] Born and Wolf, *Principles of Optics*, 1964.

Spherical Layering of the Near Zone Using the Wilcox Expansion

• Based on the Wilcox expansion, we divide the entire exterior region into an infinite number of "asymptotic layers" each consisting of one term in the expansion and should be understood in an asymptotic sense.

• The Wilcox expansion is used to compute the total energy densities, which is related to the imaginary part of the input impedance.

• The details of modal analysis of this spatial picture of the near field is quite complex and interested researchers are referred to the references.



General description of antenna near-field spatial structure.

R_0 = Far-Field Zone

R_∞ = Smallest sphere enclosing the antenna

Energy Expression from the Wilcox Expansion

From the Wilcox expansion, we derive the expressions of the electric and magnetic energy densities starting from classical EM theory (lengthy details are omitted)

$$w_e(r) = \frac{\varepsilon}{4}\sum_{n=0}^{\infty}\frac{\langle \mathbf{A}_n, \mathbf{A}_n\rangle}{r^{2n+2}} + \frac{\varepsilon}{2}\sum_{\substack{n,n'=0\\ n>n'}}^{\infty}\frac{\langle \mathbf{A}_n, \mathbf{A}_{n'}\rangle}{r^{n+n'+2}},$$

Total energy density

Self interaction

Mutual interaction

$$w_h(r) = \frac{\mu}{4}\sum_{n=0}^{\infty}\frac{\langle \mathbf{B}_n, \mathbf{B}_n\rangle}{r^{2n+2}} + \frac{\mu}{2}\sum_{\substack{n,n'=0\\ n>n'}}^{\infty}\frac{\langle \mathbf{B}_n, \mathbf{B}_{n'}\rangle}{r^{n+n'+2}}$$

Total energy density

Self interaction

Mutual interaction

A new quantity is identified and emphasized: The interaction or total energy exchange integral

$$\langle \mathbf{F}(\theta,\varphi), \mathbf{G}(\theta,\varphi)\rangle \equiv \int_{4\pi} d\Omega\, \mathrm{Re}\left\{\mathbf{F}(\theta,\varphi)\cdot\mathbf{G}^*(\theta,\varphi)\right\}$$

Exchange energy between two fields **F** and **G**

It can be proven that the following decomposition of the total energy density into "reactive" and radiation densities is possible

$$w_e \equiv w_e^1 + w_{\mathrm{rad}}, \quad w_h \equiv w_h^1 + w_{\mathrm{rad}}. \qquad w_{rad} = \text{far-field radiation density}$$

Reactive energy density

$$\left.\begin{aligned} w_e^1(r) &= \frac{\varepsilon}{4}\sum_{n=1}^{\infty}\frac{\langle \mathbf{A}_n, \mathbf{A}_n\rangle}{r^{2n+2}} + \frac{\varepsilon}{2}\sum_{\substack{n,n'=1\\ n>n'}}^{\infty}\frac{\langle \mathbf{A}_n, \mathbf{A}_{n'}\rangle}{r^{n+n'+2}}, \\ w_h^1(r) &= \frac{\mu}{4}\sum_{n=1}^{\infty}\frac{\langle \mathbf{B}_n, \mathbf{B}_n\rangle}{r^{2n+2}} + \frac{\mu}{2}\sum_{\substack{n,n'=1\\ n>n'}}^{\infty}\frac{\langle \mathbf{B}_n, \mathbf{B}_{n'}\rangle}{r^{n+n'+2}}. \end{aligned}\right\} \text{Reactive energy expansions}$$

Multipole Expansion: Modal Analysis of the Antenna Field

The multipole series is the expansion of the EM fields into the eigenfunction of the Laplacian operator in spherical coordinates.

Vector spherical wavefunctions

Spherical Bessel functions

$$\mathbf{H}(\mathbf{r}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \Big[a_M(l,m)\, h_l^{(1)}(kr)\, \mathbf{X}_{lm} - \frac{i}{k} a_E(l,m)\, \nabla \times h_l^{(1)}(kr)\, \mathbf{X}_{lm} \Big]$$

$$\mathbf{E}(\mathbf{r}) = \eta \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \Big[a_E(l,m)\, h_l^{(1)}(kr)\, \mathbf{X}_{lm} + \frac{i}{k} a_M(l,m)\, \nabla \times h_l^{(1)}(kr)\, \mathbf{X}_{lm} \Big]$$

$$\mathrm{TM}_{lm}\ \mathrm{mode} \equiv \begin{cases} \mathbf{r} \cdot \mathbf{E}_{lm}^{\mathrm{TE}} \\ = a_M(l,m)\, \frac{l(l+1)}{k} h_l^{(1)}(kr)\, Y_{lm}(\theta,\varphi) \\ \mathbf{r} \cdot \mathbf{H}_{lm}^{\mathrm{TE}} = 0. \end{cases}$$

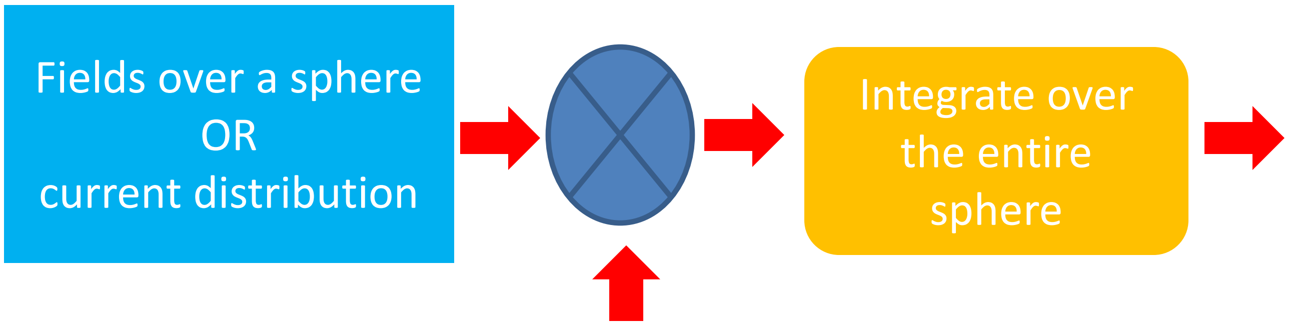
$$\mathrm{TE}_{lm}\ \mathrm{mode} \equiv \begin{cases} \mathbf{r} \cdot \mathbf{H}_{lm}^{\mathrm{TE}} \\ = a_E(l,m)\, \frac{l(l+1)}{k} h_l^{(1)}(kr)\, Y_{lm}(\theta,\varphi) \\ \mathbf{r} \cdot \mathbf{E}_{lm}^{\mathrm{TE}} = 0, \end{cases}$$

- We employ the multipole series to describe the antenna NF in terms of its TE and TM modes.
- The coefficients of the expansions provide the starting data for our subsequent computation of the reactive energy in general antenna systems.
- The definitions of the vector spherical harmonics used here can be found in standard literature of EM theory or special functions in mathematical physics.

* For reference, see David Jackson's *Classical Electrodynamics*.

How to Obtain the TE and TM Modes of Arbitrary Antennas (Spectral or Modal Analysis)

$$\langle \mathbf{A}_n, \mathbf{A}_m \rangle = \text{Function}\left[a_{lm}^{TE}, a_{lm}^{TM} \right]$$



$$a_{lm}^{TE,TM}$$

Modal Expansion Coefficients

$$Y_{lm}(\theta, \varphi)$$

Spherical harmonics

A modal analysis of a given antenna described by either far or near fields can be obtained in a straightforward manner through integrations over **finite regions** with **well-behaved integrands** [1].

[1] David Jackson, *Classical Electrodynamics*, 1975.

How to Use the NF Theory

- The NF theory still needs to be further developed in order to make it directly available to future and current applications.
- The most important use of the NF theory is to construct the new definitions of EM energy and the detailed structures of the NF for simple practical antennas.
- We suggest the need for future research to go into the construction of NF maps for electrically-small antennas (Hertzian dipoles), wire antennas, and patch antennas, just to mention few.
- The new NF maps will rely on the general mathematical expression developed in Part II of the NF theory and aim at providing new insights into the known operation of these basic antennas in light of the new theory.
- Recent examples of applications based on the NF theory (Part I) is [1] for near field synthesis and for Part II is [2], which develops new numerical methods for the characterization of energy localization in mutually coupled antenna systems.

[1] Clauzier, S.; Mikki, S.M.; Antar, Y.M.M., "Design of Near-Field Synthesis Arrays Through Global Optimization," *IEEE Trans. Antennas and Propagation*, vol.63, no.1, pp.151,165, Jan. 2015.
[2] Mikki, S.M.; Antar, Y.M.M., "A New Technique for the Analysis of Energy Coupling and Exchange in General Antenna Systems," *IEEE Trans. Antennas and Propagation*, no.12, December 2015.

Complete Analytical Evaluation of the Reactive Energy in the Near Field Shell

Using the modal expansion (previous slide) of the antenna fields into spherical TE and TM modes, we managed to express the total reactive energy of general antenna systems into complete analytical form

Self interaction terms

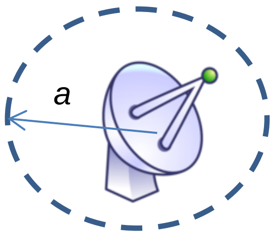
Mutual interaction terms

Total reactive energies

$$W_e^1 = \sum_{n=1}^{\infty} \frac{(\varepsilon/4)\langle \mathbf{A}_n, \mathbf{A}_n \rangle}{(2n-1)\, a^{2n-1}} + \sum_{\substack{n,n'=1 \\ n>n'}}^{\infty} \frac{(\varepsilon/2)\langle \mathbf{A}_n, \mathbf{A}_{n'} \rangle}{(n+n'-1)\, a^{n+n'-1}},$$

$$W_h^1 = \sum_{n=1}^{\infty} \frac{(\mu/4)\langle \mathbf{B}_n, \mathbf{B}_n \rangle}{(2n-1)\, a^{2n-1}} + \sum_{\substack{n,n'=1 \\ n>n'}}^{\infty} \frac{(\mu/2)\langle \mathbf{B}_n, \mathbf{B}_{n'} \rangle}{(n+n'-1)\, a^{n+n'-1}}.$$

a= maximum antenna size

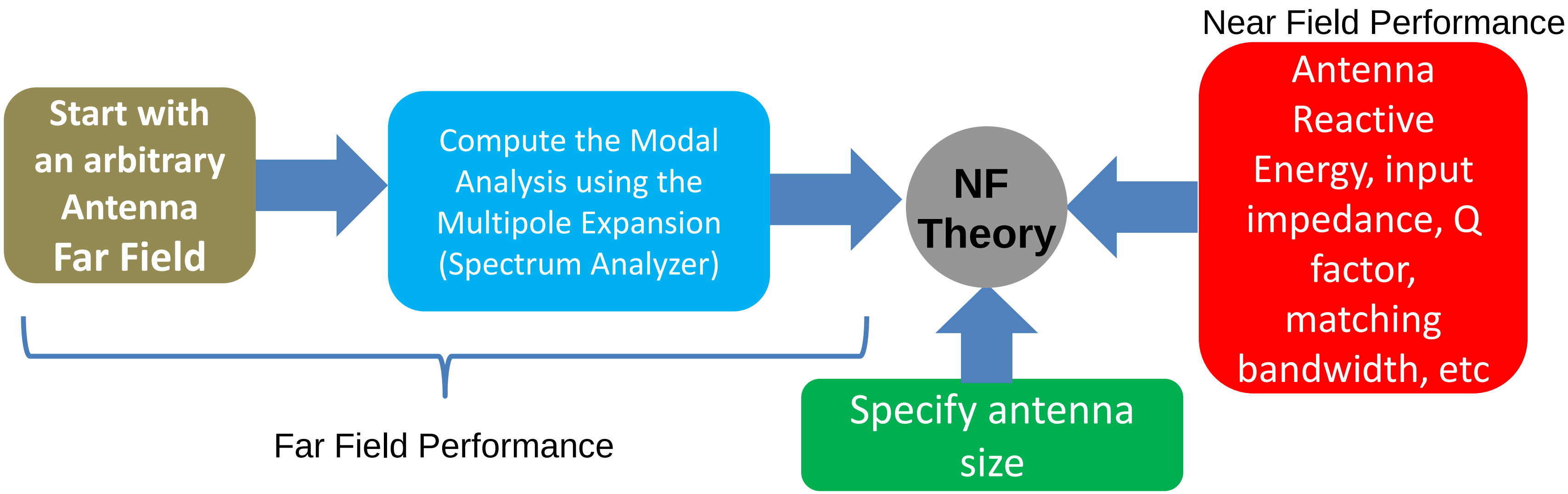


The expressions above provide in one formula the original interplay between:

1. Far field (through the multipole expansion)
2. Near field (e.g., input impedance, mutual coupling, etc.)
3. Antenna size (the minimum radius a)

- The results above provide the general formulation of the topic of antenna fundamental limitations.
- The connections between the far field from one side, and the antenna size and input impedance on the other side, appears here for the first time (see next slide).

Generalized Scheme for the Analysis of the Interrelation between Impedance, Far Field, and Size for Arbitrary Antennas



- We require only the expansion coefficients of the far field in terms of TE and TM modes (see Jackson's *Classical Electrodynamics*.)

- The rest of the procedure is analytical and complete expressions can be found in Part I of the main work.

- The new analytical evaluation opens the door for fresh reconsideration of the topic of fundamental antenna limitations.

Methodology

1. Start the antenna Far Field.
2. Analyze this field into TE and TM modes.
3. Specify the antenna size a.
4. Plug the modal amplitude (Step 2) into the expression of the reactive energy.
5. Study the behaviour of impedance, Q, BW, as we vary far field and size parameters of interest.

How Does the NF Theory Contribute to the Understanding of Electromagnetic Energy?

The new NF theory provided a critical examination of an already well-established genre of EM energy, the traditional reactive energy.

In the theoretical literature, there is in general a confusion about the rigorous definition of EM energy. Many authors confuse

1. Reactive energy
2. Evanescent (localized) Energy
3. Stored energy.

The new NF theory clarifies the essential aspects of these terms.

1. For example, it can be shown <u>that reactive energy and stored energy are not identical.</u>
2. Moreover, the concept of evanescent energy needs to be re-examined more closely.
3. The neglected phenomena of coupling between propagating and nonpropagating modes is studied in detail for the first time.

The Stored Field Energy: Proposed Experiment

- We define the stored field energy as **the energy of that part of the antenna field that is not propagating**.
- It is obvious then that this definition is much more complex than the definition of the reactive energy since it involves the concept of "non-propagating field".
- This concept being a field concept, must then be examined throughout the whole space comprising the exterior region surrounding the antenna system under consideration.
- **<u>More precisely, we define the stored system as the capacity of an antenna system to do work when the power supply is switched off.</u>**
- After turning off the source, part of the energy will escape into the far zone while the rest will couple into the feed circuit. The stored energy is then the sum of these two parts.
- We conclude that a <u>time-dependent near field theory</u> is needed to compute the stored energy. This is beyond the work attempted here which is mainly a frequency-domain theory.

The Concept of Localized Energy

We define tentatively the general localized energy as the energy of the non-propagating part of the total field, i.e., the self energy of the evanescent part

$$W_{\mathrm{ev}}^{e}\left(\hat{u}\right)=\frac{\varepsilon}{4}\int_{V_{\mathrm{ext}}}d^{3}r\,\left|\mathbf{E}_{\mathrm{ev}}\left[\mathbf{r};\hat{u}\left(\mathbf{r}\right)\right]\right|^{2},$$

- The vector field **u**(**r**) specifies how we choose the orientation of the local coordinate frame.

  1. It turns out that not all choices of the orientation of local frame will lead to finite total localized energy.

  2. It turns out that a very natural choice, the **radial** one, will lead to well-defined total localized energy.

  3. This definition also has several technical advantages.

- In conclusion, we suggest that <u>the **radial localized energy** is the best approximation of the energy process in the near field when dealing with single antenna systems.</u>

Analysis of Electromagnetic Problems Based on New Developments

Fundamental Electromagnetic Theory and Applications

Analysis of Electromagnetic Problems Based on Measurement

1. The Infinitesimal Dipole Model (IDM) Method.
2. The Antenna Current Green's Function (ACGF) Method.

Near-Field Theory

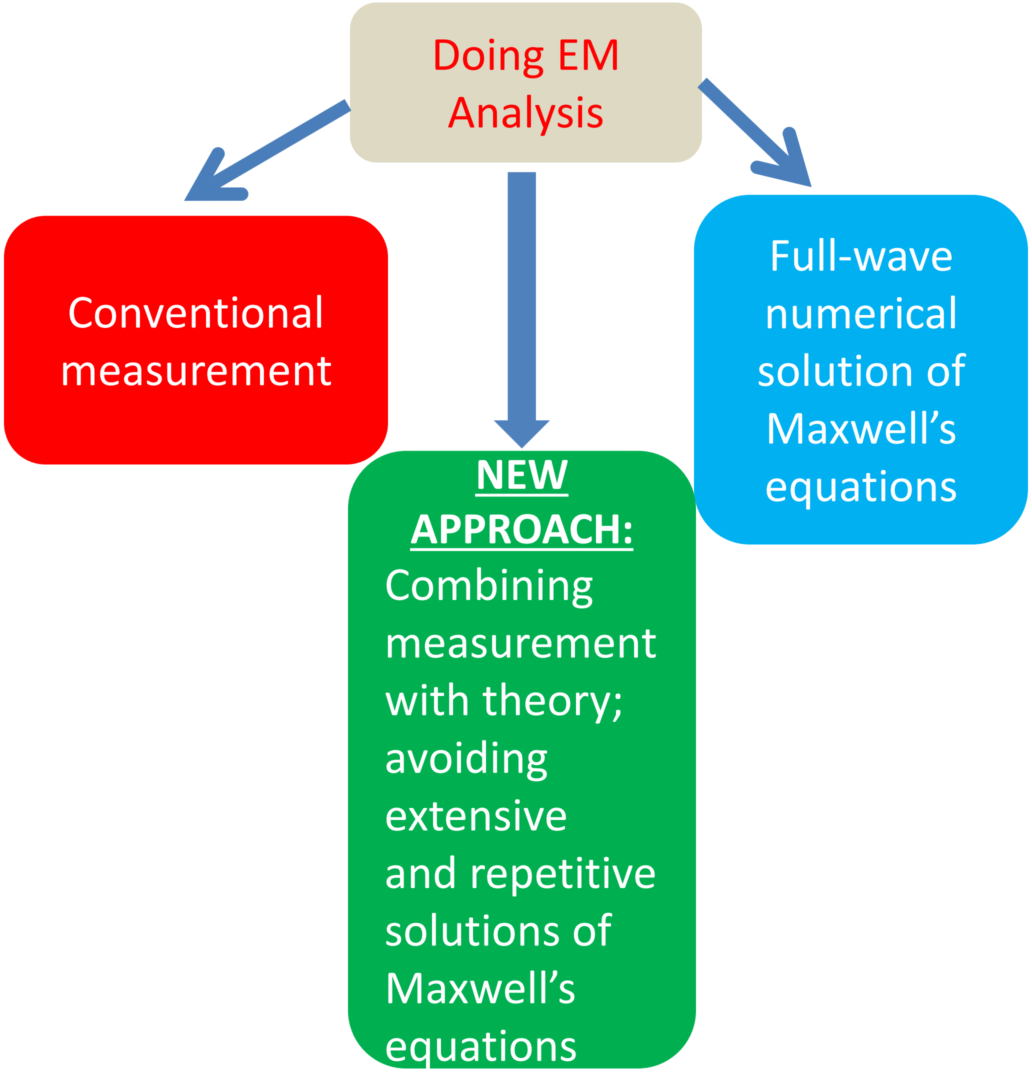
- **A new general approach to EM foundations.**
- **Re-examination of EM energy concepts.**
- **Development of near-field engineering and devices exploiting near field potentials.**
- **Development of near-field metamaterials.**

Analysis of Electromagnetic Problems: New Perspectives

Traditionally, prediction and estimation of electromagnetic problems is done by solving boundary-value problems based on Maxwell's equations.

Full-wave numerical solution of Maxwell's equations requires the use of complex numerical methods, such as Finite-Element Method (FEM), Finite Difference Time Domain (FDTD), and Method of Moment (MoM).

It is now possible, however, to rely on and develop new tools and methods in electromagnetic theory that allows prediction and estimation of major quantities without actually repeatedly solving Maxwell's equations.

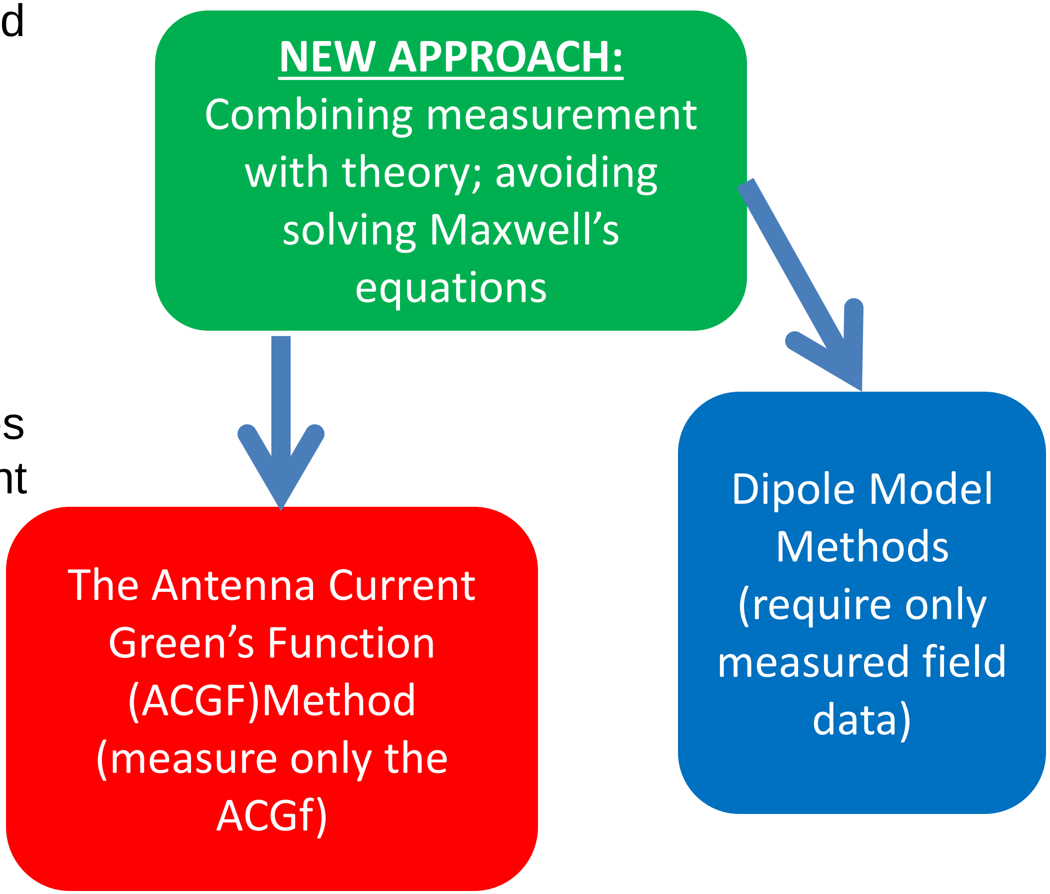


The Structure of a New Approach

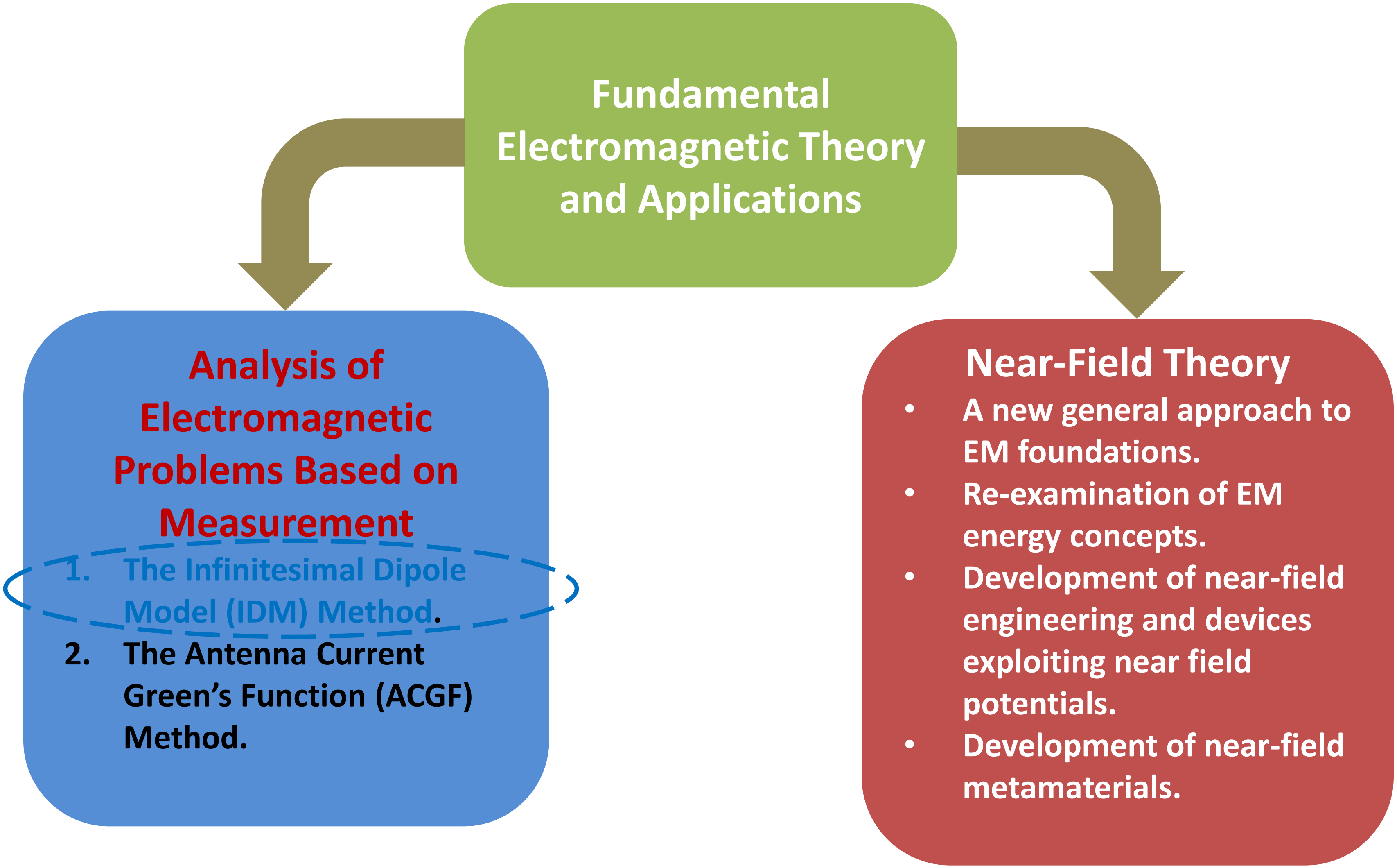
- In the new approach, instead of performing repeated measurement for each EM quantity of interest, we measure or determine one special quantity.

- The new approach combines theory with the measurement of this special quantity to produce an extensive prediction of EM behavior.

- We propose two examples:
  1. The Infinitesimal Dipole Method (IDM)
  2. The Antenna current Green's Function (ACGF) Method



The Infinitesimal Dipole Model (IDM) Method


Fundamental Electromagnetic Theory and Applications
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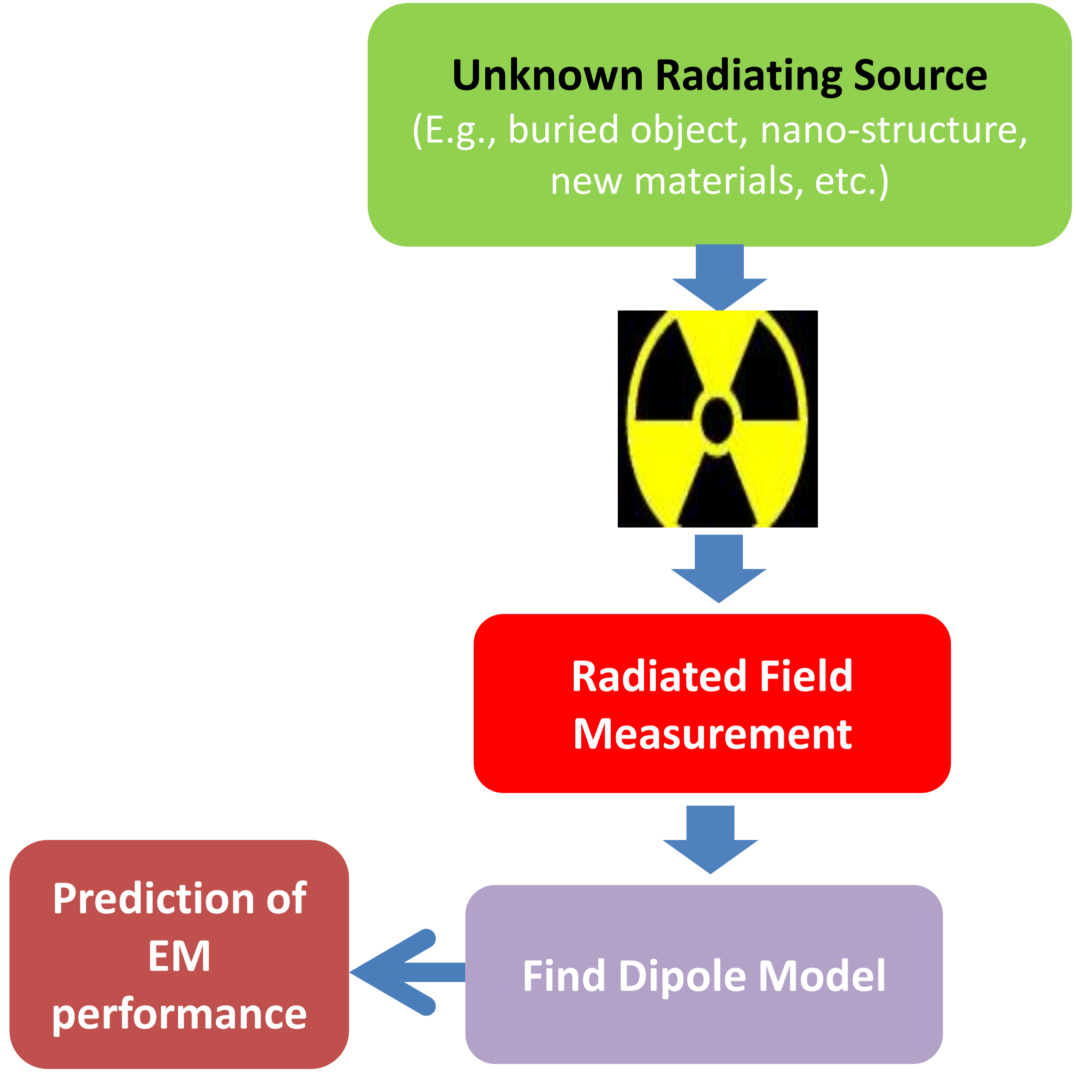
Near-Field Theory
• A new general approach to EM foundations.
• Re-examination of EM energy concepts.
• Development of near-field engineering and devices exploiting near field potentials.
• Development of near-field metamaterials.

The Infinitesimal Dipole Model (IDM Approach)

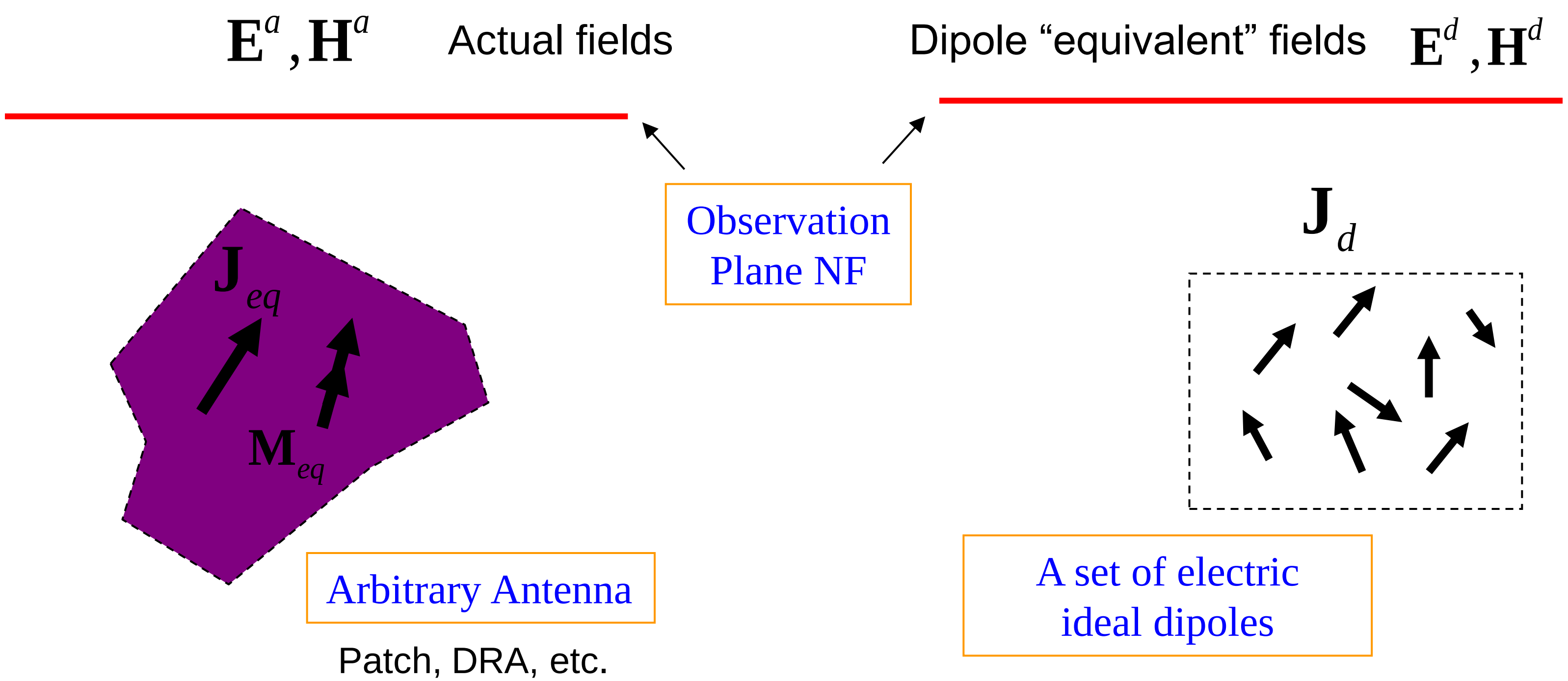
1. In the IDM approach, we measure or determine fields in a small spatial region.
2. Based on this measurement, we use theory to construct a <u>model</u> composed of a <u>small number of infinitesimal dipoles</u>.
3. These dipoles excite the major modes of the radiated field in the unknown source.
4. The IDM can predict <u>the field everywhere in the exterior region of the unknown source</u>.



Basic Ideas

- Start with some NF data of the device under consideration.
- Use global optimization algorithm (Genetic Algorithm, Particle Swarm Optimization, etc) to search for the locations, moments, and orientations of small dipoles producing the same NF.
- Verify that the obtained distribution of small number of dipoles can re-radiate the same NF of the original device.

A set of infinitesimal electric dipoles is optimized to produce the same near field of the original arbitrary antenna.



Applications of the IDM Method

Radiating sources with unknown electromagnetic boundary conditions [1]

Examples:

1. Nanostructures
2. Burid objects
3. Target detection

Near-Field Synthesis [2]

Example:

Use the IDM method to design near-field focusing antenna arrays

Large-and-Complex Antenna Arrays [3]

Example:

Apply the IDM to single antenna type then using mutual coupling methods to correct the model for large arrays with arbitrary topologies

[1] Said Mikki and Ahmed Kishk, “Theory and applications of infinitesimal dipole models for computational electromagnetics,” *IEEE TAP*, May 2007.

[2] S. Clauzier, S. Mikki and Y. M.M. Antar, ‘ Design of Near-field Synthesis Arrays through Global Optimization’, *IEEE Transactions in Antennas and Propagation*, January 2015.

[3] Said M. Mikki and Yahia M. M. Antar,``Near field analysis of electromagnetic interactions in antenna arrays through eqvuilant dipole models,'' *IEEE Trans. Antennas Propagat.,* vol. 60, no. 3, pp. 1381--1389, March 2012.

Applications based on Infinitesimal Dipole Model (IDM)

New challenges in the design of antennas [1]

- Evolution in the antenna technologies (small antennas for example) with design constraints (size, performances,…).
- A need of numerical modeling to be able to predict the antenna performances before realization and measurement.
- A need for antenna designer to keep a sight of the basic concept principle of antennas.

Based on an Infinitesimal dipole model (IDM) for antennas, we can overcome these new challenges

The IDM can bring a comprehensive study of the near-field and its relation with the far-field.

The IDM can be used as a tool for an antenna surface current optimization process. With applications for example to MIMO or superdirective antenna array.

[1] Balanis, C.A., "Antenna technology: Past, present and future," in *Antenna Technology (iWAT), 2012 IEEE International Workshop on* , vol., no., pp.5-7, 5-7 March 2012

Application of the IDM to a comprehensive study of the near-field

- The basis idea is to analyze the relation between the near-field and the far-field by answering this question:
  - *Is it possible to reconstruct the entire near-field from far-field information ?*
- To answer this question, we have considered the following methodology

CONSIDER A STANDARD ANTENNA → **FIND AN EQUIVALENT ARRAY OF ID WHICH REPRODUCING THE SAME FAR-FIELD** → **COMPARE THE OPTIMIZED NEAR-FIELD WITH THE DESIRED NEAR-FIELD**

Extract the near-field and the far-field

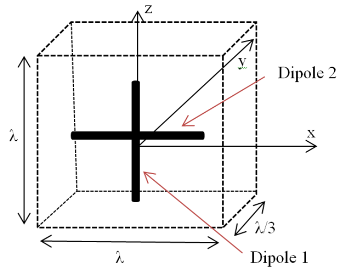
Optimization of an infinitesimal dipoles array which gives the same far-field than the example antenna

→ The array of ID reproduces correctly the near-field

Application of the IDM to a comprehensive study of the near-field

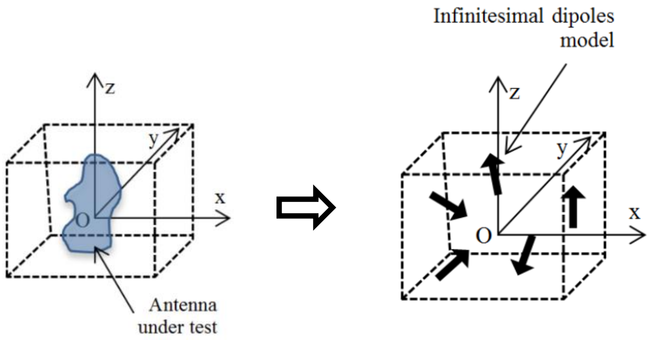
One example will be considered:

Two crossed dipoles

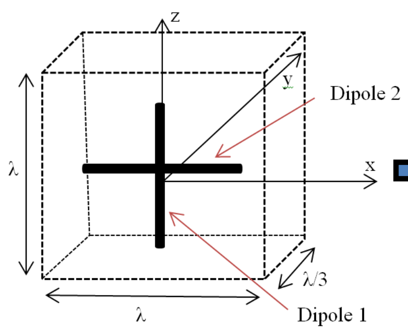


Reference antenna

The far-field will be synthesized by an array of 5 ID

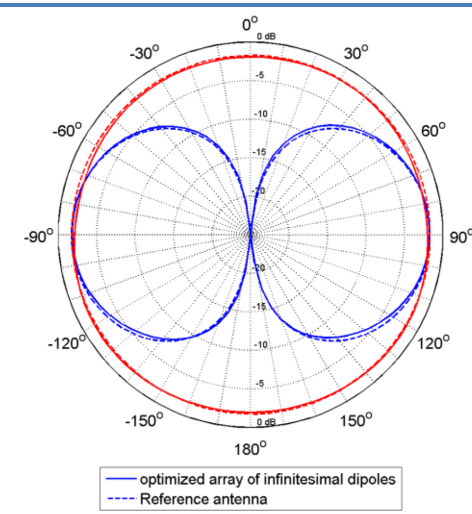


The NF will be compared

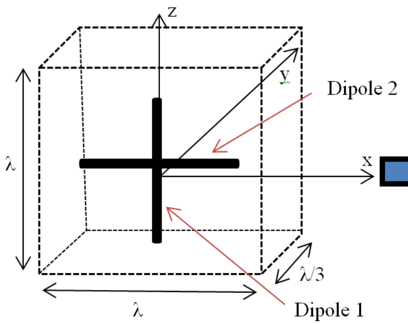


Step 1: Optimization of an array of ID which gives the same far-field than the reference antenna

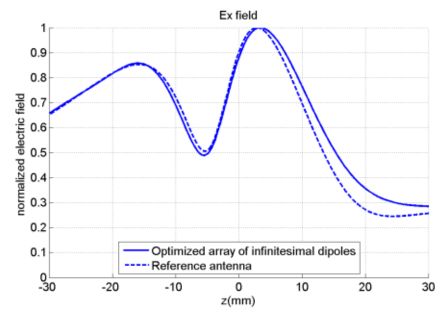
Genetic algorithm

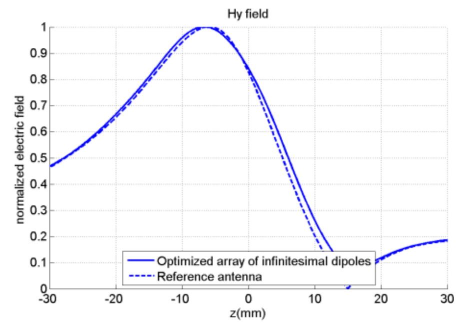


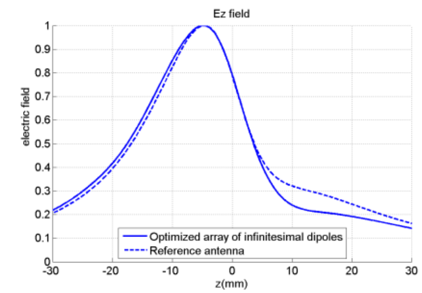
Application to a comprehensive study of the near-field



Step 2: Comparison of the near-field between the optimized ID array and the reference antenna



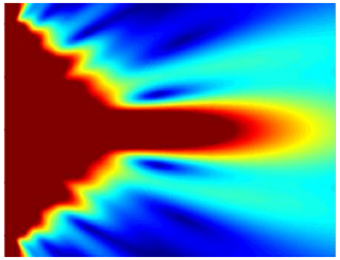




Comparison of the near-field at 15mm (λ/2) from the antenna

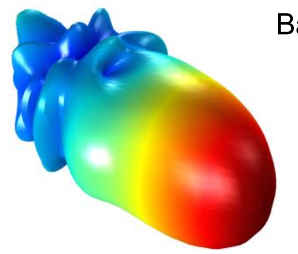
Application for the design of a Near-field focusing antenna

- Based on the previous work, we can design a NFF antenna by working only with the far-field information.



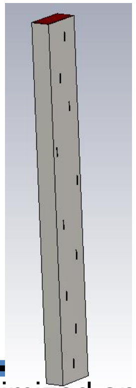
Desired Near-field radiation

Fourier Transform



Corresponding far-field

Based on the "Antenna Current Engineering Program"



Optimized antenna

Based on the present work, the slotted waveguide will have the desired near-field

Application to the current optimization: MIMO system

Objective: Synthesize a surface or volume MIMO antenna array with optimum cross-correlation.

Step 1 : Define a shape (2D or 3D) and a number of ID

Antenna conformal to an air craft nose shape will be considered

Step 2 : Optimize the amplitude, phase, orientation and position of the ID array to minimize the cross-correlation coefficient (or diversity gain)

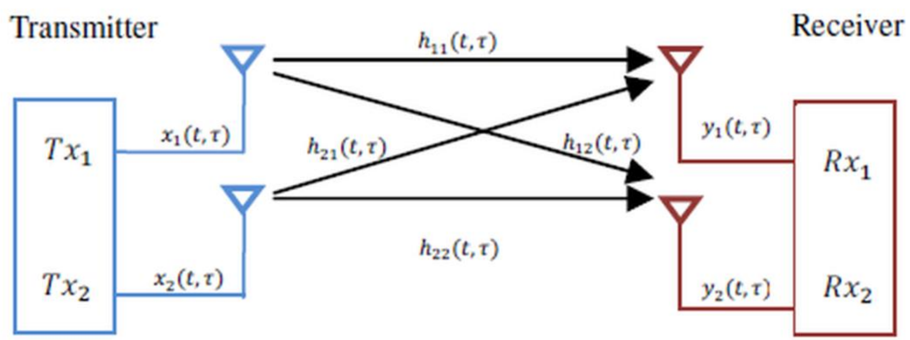
The Genetic Algorithm will be used

Step 3 : Realize the physical layout based on the optimized current

- The effect of the ground plane will be evaluated
- the critical MIMO density will be studied
- The physical implementation will be discussed

Application to the current optimization: <u>MIMO system</u>

Definition of the cross-correlation coefficient [1]:



"*The correlation coefficient is a measure that describes how the communication channels are isolated from each other […].*"

➡ Measure the correlation between signal $x_1(t,\tau)$ and $x_2(t,\tau)$ (resp. $y_1(t,\tau)$ and $y_2(t,\tau)$ for the transmitter (resp. receiver)

In an isotropic communication channel, the cross-correlation coefficient can be calculated using,"

$$\rho = \frac{\left|\int_{4\pi} d\Omega \boldsymbol{E}_1(\theta,\varphi).\boldsymbol{E}_2^*(\theta,\varphi)\right|}{\sqrt{\int_{4\pi} d\Omega |\boldsymbol{E}_1(\theta,\varphi)|^2}\sqrt{\int_{4\pi} d\Omega |\boldsymbol{E}_2(\theta,\varphi)|^2}}$$

➡ Computationally difficult to evaluate

E1 and E2 are the far-field radiation pattern of the two antennas (Tx1, Tx2)

[1] M. Sharawi *Printed MIMO Antenna Engineering*, 2014, Artech House

Application to the current optimization: MIMO system

A new expression using current surface expression has been developed in [1]

$$\rho = \frac{\left|\int_{4\pi} d\Omega\, \mathbf{E}_1(\theta,\varphi)\cdot\mathbf{E}_2^*(\theta,\varphi)\right|}{\sqrt{\int_{4\pi} d\Omega\, \left|\mathbf{E}_1(\theta,\varphi)\right|^2}\sqrt{\int_{4\pi} d\Omega\, \left|\mathbf{E}_2(\theta,\varphi)\right|^2}},$$

With,

$$\boxed{\begin{aligned}&\int_{4\pi} d\Omega\ \mathbf{E}_1(\hat{\mathbf{r}})\cdot\mathbf{E}_2^*(\hat{\mathbf{r}})\\ &\quad = \int_{V_1} d^3r' \int_{V_2} d^3r''\ \mathbf{J}_1(\mathbf{r}')\cdot\bar{\mathbf{C}}(\mathbf{r}',\mathbf{r}'')\ \cdot\mathbf{J}_2^*(\mathbf{r}'')\ ,\end{aligned}}$$

$\mathbf{J}_1(\mathbf{r}')$ and $\mathbf{J}_2(\mathbf{r}'')$ are respectively the current on antenna 1 and antenna 2

Where $\bar{C}(r',r'')$ is called "*The Cross-correlation Green Function*"

$$\bar{C}(r',r'') = \int_{4\pi} d\Omega[\bar{\mathbf{I}} - \hat{r}\,\hat{r}]e^{ik(r',r'').\hat{r}}$$

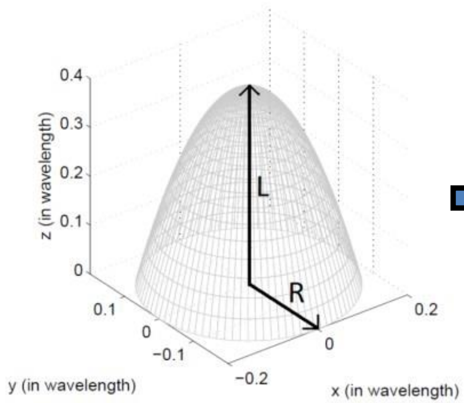
This new formulation is easy to implement and valid in all cases

With this expression we can directly optimize the surface currents on the antenna in order to minimize the cross correlation coefficient.

[1] Mikki, S.M.; Antar, Y.M.M., "On Cross Correlation in Antenna Arrays With Applications to Spatial Diversity and MIMO Systems," in *Antennas and Propagation, IEEE Transactions on* , vol.63, no.4, pp.1798-1810, April 2015

Application to the current optimization: MIMO system

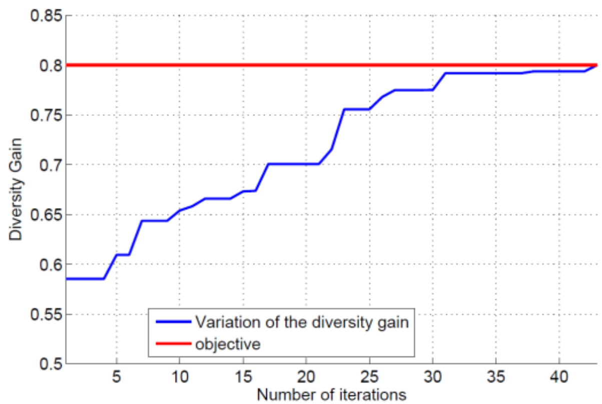
Example : Conformal array (Air craft nose shape)



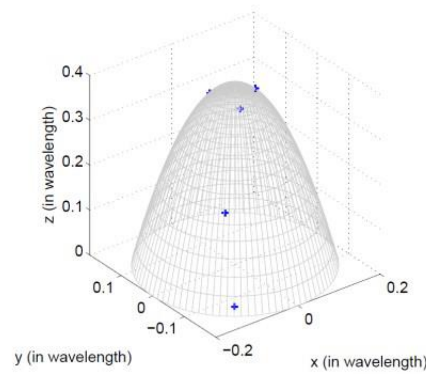
- An array of 8ID has been considered.
- For each ID the orientation $(\theta_{ID}, \varphi_{ID})$ will depend on its location as its tangent to the supporting structure.

R=0.2λ L=0.4λ

Genetic algorithm



Variation of the diversity gain during the optimization process



Optimized position of the infinitesimal dipole array on the surface

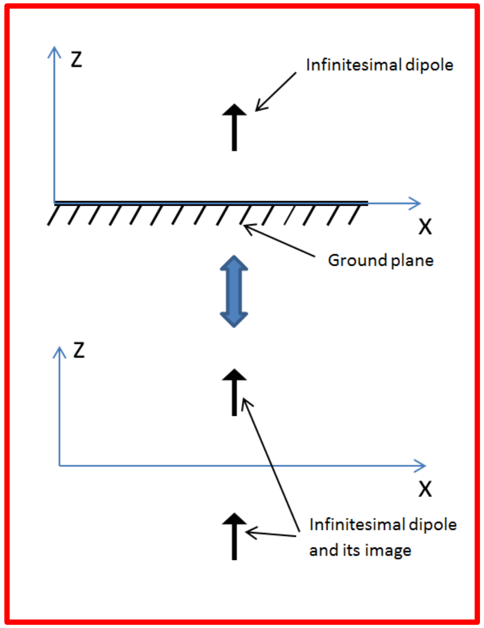
Application to the current optimization: MIMO system

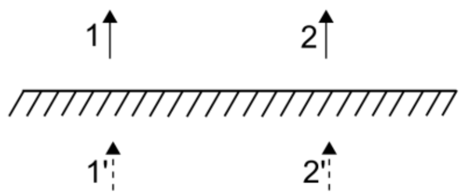
Ground plane consideration

For many applications, antenna are located over a ground plane surface.

How to include the ground plane effect in the antenna current optimization ?

- By considering the image theory



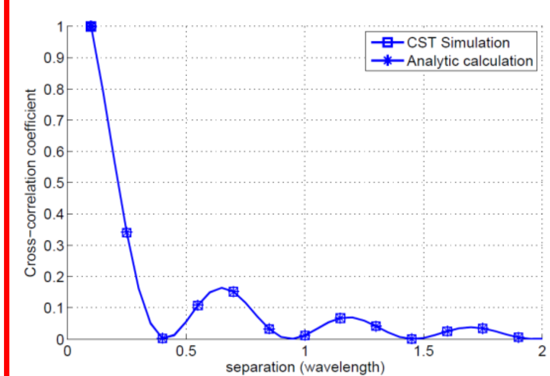


Calculation of the cross-correlation matrix

$$R = \begin{pmatrix} \rho_{11}^{p} & \rho_{12}^{p} \\ \rho_{21}^{p} & \rho_{22}^{p} \end{pmatrix}$$

with

$$\rho_{11}^{p} = \rho_{11} + \rho_{11'} + \rho_{1'1} + \rho_{1'1'}$$
$$\rho_{12}^{p} = \rho_{12} + \rho_{12'} + \rho_{1'2} + \rho_{1'2'}$$
$$\rho_{21}^{p} = \rho_{21} + \rho_{21'} + \rho_{2'1} + \rho_{2'1'}$$
$$\rho_{22}^{p} = \rho_{22} + \rho_{22'} + \rho_{2'2} + \rho_{2'2'}$$



Variation of the cross-correlation as a function of the inter-element distance

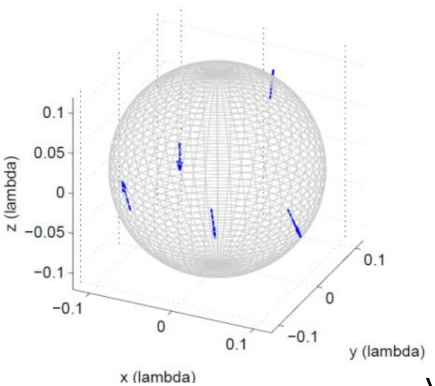
Application to the current optimization: ESA (Electrically Small Antenna)

➡ Calculation of the maximum of directivity

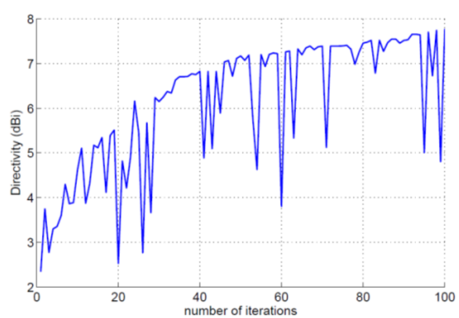
Optimization	*Theory*

Dedicated area : Sphere with a radius of 0.12λ

Optimization



Optimized array of infinitesimal dipoles



Variation of the directivity during the optimization process

Dmax=7.8dBi

Theory

Harrington limit [1,2]- *Determine the maximum of directivity reachable by a small antenna*

$$D_{max} = N^2 + 2N$$

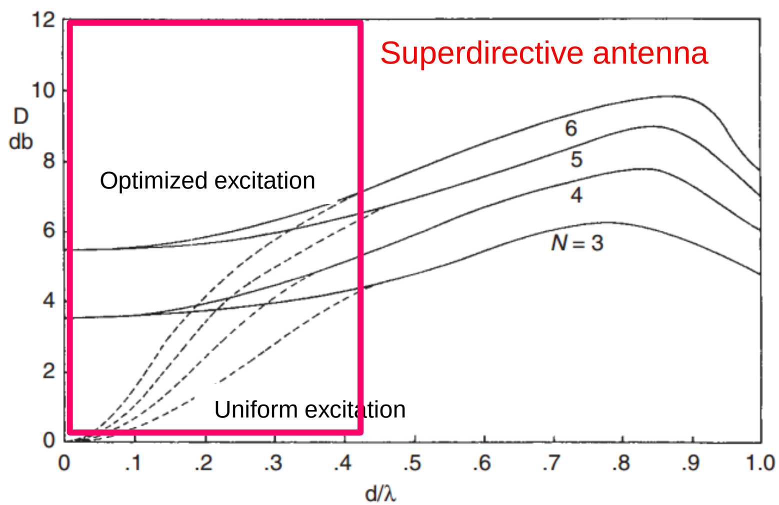
with $N = k(r + \frac{\lambda}{2\pi})$

Dmax=8.12dBi

[1] R.F. Harrington, “Effect of antenna size on gain, bandwidth and efficiency”, *Journal of Research of the National Bureau of Standard*, vol.64D, No. 1, pp 1-12, Jan/Feb. 1960.
[2] M. Pigeon, A. Clemente, C. Delaveaud, L. Rudant, “Analysis of Harrington Limit for Electrically Small Antenna Directivity”, EuCap 2014.

Application to the current optimization: Superdirective antenna array

Usually, we design a superdirective array by optimizing the amplitude and phase coefficient of an antenna array.



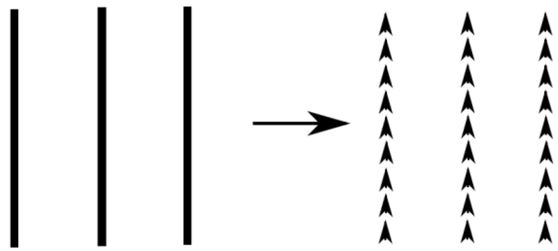
Maximum directivity in function of the inter-element distance [1]

Instead of optimizing only the port excitation, we can optimize the current on the entire antenna in order to reach a higher directivity.

[1] R.C. Hansen, “Electrically Small, Superdirective, and Superconducting Antennas”, John Wiley & Sons, Inc, 2006

Application to the current optimization: Superdirective antenna array

Example on a array of three dipole antennas

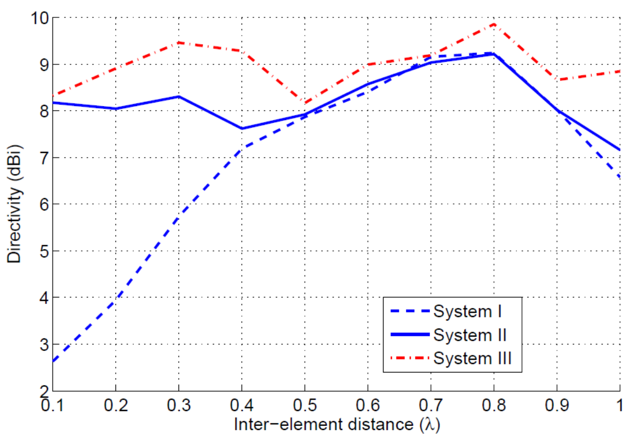


Half-wave dipoles | Infinitesimal dipole model

Discretization of each wire antenna by an array of infinitesimal dipoles.

Comparison of 3 systems:

- **System I:** A classic array of three dipoles with uniform excitation
- **System II:** An optimized array excitation (classic superdirective array system)
- **System III:** A complete current optimization



On average, the complete current optimization attains directivity higher by 1.5dB [1]

[1] S. Clauzier, S. Mikki and Y. M.M. Antar, ‘Generalized Superdirective Antenna Arrays’, submitted to AGU Radioscience.

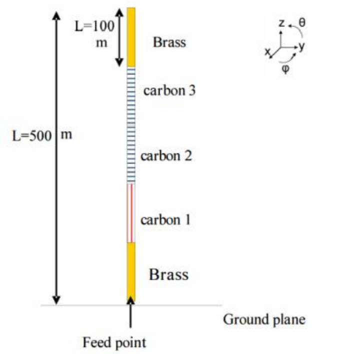
Physical Implementation of the optimized current distribution

An important part of this study is to find a <u>physical implementation solutions:</u>

How to implement an optimized array of infinitesimal dipoles into a <u>physical layout</u> ?

Different solutions are under investigation:

- Consider each infinitesimal dipole as an actual antenna by designing an electrically small antenna [1].
- If applied to a wire antenna, we can consider a wire with different conductivities in order to shape the current distribution [2].



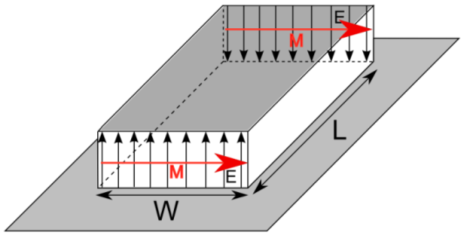
- Consider a printed antenna or a slotted waveguide architecture where each slot is equivalent to a (or an array) of infinitesimal dipole(s) [3].

[1] Wahib, M; Clauzier, S., Mikki, S.; Antar, Y., “A 2.45 GHz Novel Electrically Small Planar Dipole Antenna”, submitted to iWAT 2016
[2] Boucher, S.; Sharaiha, A.; Potier, P., "Broadband loaded cylindrical monopole antenna," *Antennas & Propagation (ISAP), 2013 Proceedings of the International Symposium on* , vol.01, no., pp.104,106, 23-25 Oct. 2013.
[3] Clauzier, S., Mikki, S.; Antar, Y., “Modelization of a slotted waveguide by an Infinitesimal Dipol model and application to far-field synthesis," , submitted to Eucap 2016.

Physical Implementation of the optimized current distribution (using a printed antenna)

➡ How to model a printed antenna by an array of infinitesimal dipoles ?

According to cavity model



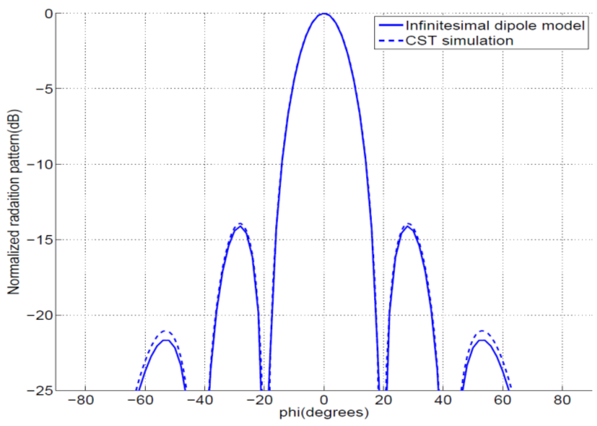
➡ A patch antenna is equivalent to two radiating slots with the same magnetic current density M.

$$\vec{M} = -2\vec{n} \times \vec{E}$$

↳ We can model each slot by an array of infinitesimal magnetic dipoles

➡ Verification for an array of 6 patch antennas

Each patch has been modeled by an array of 10 ID



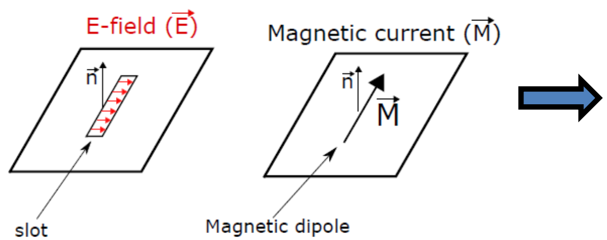
➡

ID model	CST model
13.32dBi	13.4dBi

Directivity

Physical Implementation of the optimized current distribution (using a slotted waveguide)

We can easily model an infinitesimal dipole by a slot.



- A slot can be modeled by a magnetic dipole
- This magnetic dipole can be discretized by an array of infinitesimal dipoles

We have applied this ‘slot modeling’ to a slotted waveguide combined with a far-field synthesis.

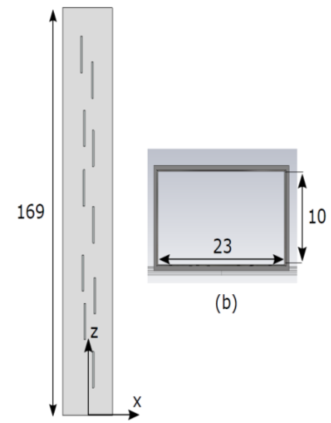
Step 1 : Define a desired radiation pattern → Step 2 : Optimize the position of the slots on the waveguide based on the ID model and the waveguide theory → Step 3 : Realize the slotted waveguide

Step 1 ↓ Define a HPBW, a Side Lobe Level and a beam steering

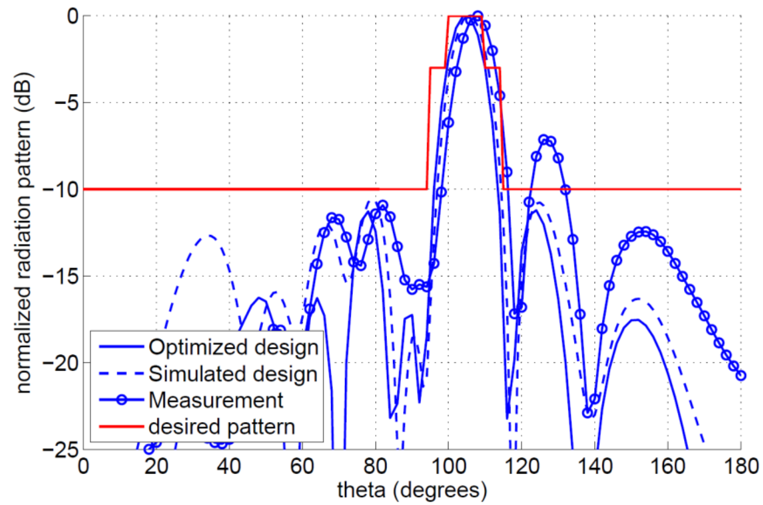
Step 2 ↓ The Genetic Algorithm is used

Physical Implementation of the optimized current distribution (using a slotted waveguide)

Optimization of a infinitesimal dipole array to obtain a certain radiation pattern



Implementation on a slotted waveguide



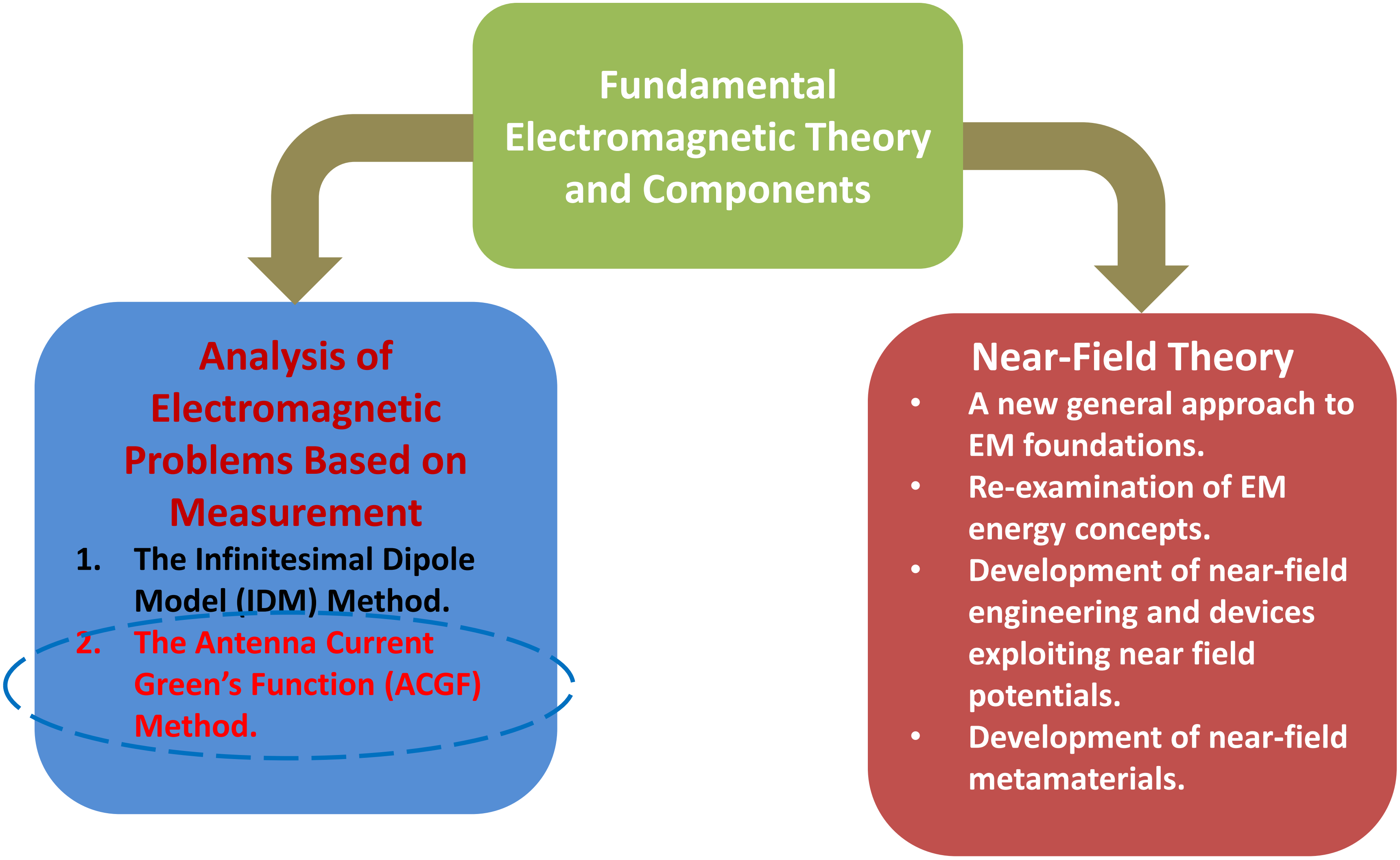
Comparison: ID array, waveguide simulation and waveguide measurement

Realization of a prototype using 3D printing

(a)

(b)

The Antenna Current Green's Function (ACGF) Method


Fundamental Electromagnetic Theory and Components
Analysis of Electromagnetic Problems Based on Measurement
1. The Infinitesimal Dipole Model (IDM) Method.
2. The Antenna Current Green's Function (ACGF) Method.
Near-Field Theory
• A new general approach to EM foundations.
• Re-examination of EM energy concepts.
• Development of near-field engineering and devices exploiting near field potentials.
• Development of near-field metamaterials.

Background to the ACGF Formalism

- Schelkunoff introduced the concept of transfer admittance, which is a forerunner of our ACGF.
- This transfer admittance idea is the following: You consider the antenna as a “continuous circuit”. Here, each point on the antenna surface is considered a circuit port. Next, this “continuous circuit” is replaced by a finite discrete approximation, which can be described mathematically as a matrix.
- Therefore, in Schelkunoffès work, the continuous transfer admittance (the forerunner to our ACGF) *is immediately replaced by a matrix*.
- This concept, however, is merely a circuit concept.
- Schelkunoff’s works is also based on the unproved assumption that by dividing any antenna into smaller and smaller parts, the net contribution of the total parts (superposition) will converge to the actually observed values.

[1] S. A. Schelkunoff, *Electromagnetic Waves*. Princeton, NJ, USA: Van Nostrand, 1943.
[2] S. A. Schelkunoff and H. T. Friis, *Antennas: Theory and Practice*. New York, NY, USA: Wiley, 1952.

The Background to the ACGF formalism

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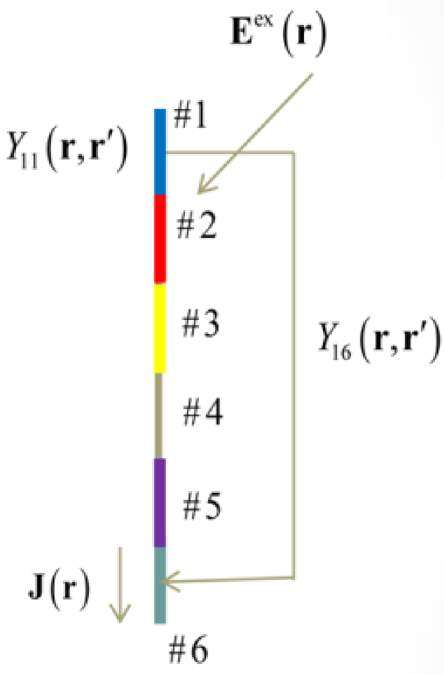


[1] S. A. Schelkunoff, *Electromagnetic Waves*. Princeton, NJ, USA: Van Nostrand, 1943.
[2] S. A. Schelkunoff and H. T. Friis, *Antennas: Theory and Practice*. New York, NY, USA: Wiley, 1952.

Problems with the Original Proposal

- There are many outstanding questions regarding this classic approach:
  - How do we know that the antenna, which is described ultimately by differential equations (Maxwell's equations) can be always approximated in terms of finite number of algebraic equations (matrix representation of a circuit model)?
  - How do we know that this procedure applies to arbitrary antenna shapes? (Schelkunoff studied only wire antennas.)
  - How can we quantify convergence of the results if the number of the composing parts of the antenna (each treated as an infinitesimal circuit) are increased? We need a theory of convergence.
  - A theory and proof of convergence is fundamental for the PRACTICAL issue of how to develop numerical and experimental methods to study reaction of EM devices to arbitrary NF excitation.

The New Formulation

- Can we salvage the original correct initiation of Schelkunoff by developing in a rigorous fashion and by working on a Maxwellian framework of antenna theory and without assuming that the antenna is a circuit represented by a finite matrix (which is strictly speaking, wrong)?

- We have found that the key to bringing Schelkunoff's concept of superposition in antennas (system theory) into the most general level (arbitrary antennas excited by arbitrary field) is the concept of antenna current Green's function.

- Here, no assumption of circuits and point-ports is used, but we work rigorously with the exact mathematical representation of the antenna through EM operators derived from Maxwell's equations (e.g., as is done in full-wave numerical solution before discretization).

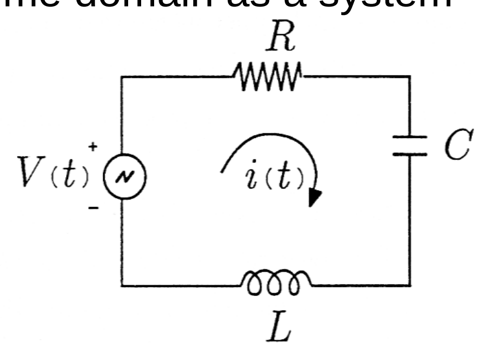
[1] Said Mikki and Yahia Antar, "The Antenna Current Green's Function Formalism – Part I," *IEEE TAP*, September 2013.

[2] Said Mikki and Yahia Antar, "The Antenna Current Green's Function Formalism – Part II," *IEEE TAP*, September 2013.

Previous Work in Electrical Engineering

Engineers tend to describe and work with EM devices using the language of systems and block diagrams.

Basic Example: an RLC circuit is treated in the time domain as a system



The relation between the input and the output is captured by the concept of transfer function

$$H(\omega) = \text{spectral domain (transfer function)}$$

$$h(t) = \text{temporal domain (impulse function)}$$

<u>In the time domain, engineers characterize systems using the idea of system or transfer function</u>

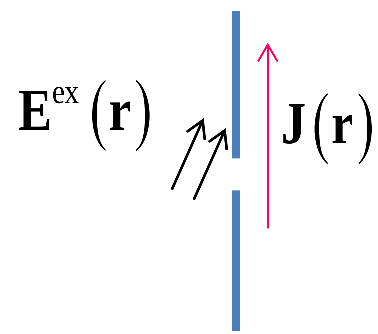
What is the Idea of Antenna Current Green's function?

For EM systems, can we find a suitable generalization of the concept of 'transfer function'?

Input (function in space) → System → Output (function in space)

Basic Example: consider a dipole antenna

$$\mathbf{E}^{\text{ex}}(\mathbf{r}) \rightarrow \text{System} \rightarrow \mathbf{J}(\mathbf{r})$$



The input now is a function of space, a field excitation. The output is the current on the antenna, another function of space.

The Antenna current Green's function:

$$\overline{\mathbf{F}}(\mathbf{r},\mathbf{r}') = \text{spatial domain (impulse function)}$$

$$\overline{\mathbf{F}}(\mathbf{k},\mathbf{k}') = \text{spectral domain (transfer function)}$$

We propose to characterize antennas in the spatial domain using the antenna current Green's function.

The ACGF Formalism

NF Theory → The ACGF Formalism

The internal developmental logic of the NF led to the problem of how to describe EM interactions in general system using the concept of the antenna current Green's function (ACGF).

$$\text{Excitation: } \hat{a}\delta(\mathbf{r}-\mathbf{r}') \rightarrow \boxed{\text{Antenna}} \rightarrow \text{Current: } \overline{\mathbf{F}}(\mathbf{r},\mathbf{r}')\cdot\hat{a}$$

Special Dirac surface delta function [1]

$$\mathbf{E}^{\mathrm{ex}}(\mathbf{r}) \rightarrow \underset{\overline{\mathbf{F}}(\mathbf{r},\mathbf{r}')}{\boxed{\text{ACGF}}} \rightarrow \mathbf{J}(\mathbf{r})$$

$$\mathbf{J}(\mathbf{r}) = \int_S ds\overline{\mathbf{F}}(\mathbf{r},\mathbf{r}')\cdot\mathbf{E}^{\mathrm{ex}}(\mathbf{r}').$$

[1] Said Mikki and Yahia Antar, Appendix of "The Antenna Current Green's Function Formalism – Part I," *IEEE TAP*, September 2013.

The ACGF connects

1. Input FIELD excitation
2. Output Current distribution

How Do We Obtain the ACGF? A Proposed Measurement

We have proven the existence of the ACGF for arbitrary EM problems based on first principles by actually constructing it in terms of the exact EM operators [1].

The ACGF can be obtained through:

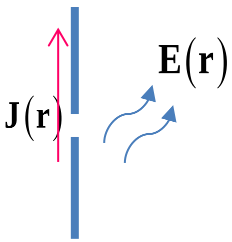
- Conventional full-wave methods (MoM, FDTD, FEM, etc) using distribution theory.
- New numerical methods designed specially for the ACGF (not developed yet.)
- Through direct measurement of the current distribution when the antenna is excited by a very concentrated field pulse.

<u>**Therefore, through measurement one may bypass the expensive approach of solving Maxwell's equations for each new near field scenario. The ACGF can be computed and measured only once. Afterwords, it is stored and used for repeated studies and synthesis involving the antenna under consideration.**</u>

$$\text{Excitation: } \hat{a}\delta(\mathbf{r}-\mathbf{r}') \longrightarrow \boxed{\text{Antenna}} \longrightarrow \text{Current: } \overline{\mathbf{F}}(\mathbf{r},\mathbf{r}')\cdot\hat{a}$$

Special Dirac surface delta function [1]

The ACGF vs the Classic Green's Function of EM Theory



Conventional Green's function

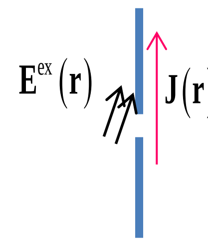
$$\mathbf{E}(\mathbf{r}) = \int_S ds \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}(\mathbf{r}).$$

$$\bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') = \left(\bar{\mathbf{I}} + \frac{1}{k^2} \nabla\nabla \cdot \right) \frac{e^{ikr}}{r}$$

The antenna current Green's function

$$\mathbf{J}(\mathbf{r}) = \int_S ds \bar{\mathbf{F}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{E}^{\mathrm{ex}}(\mathbf{r}').$$

$$\bar{\mathbf{F}}(\mathbf{r}, \mathbf{r}') = \text{numerical model OR measurement}$$



Similarities:

1. Both involve convolution-like integrals.
2. Both are expression of the principle of linear superposition.
3. Both are dyadic tensors.

Differences:

1. The classic EM GF is known in closed-form analytical form.
2. The ACGF can be obtained only by numerical solution or measurement.
3. The ACGF is conceptually and mathematically much more complicated than classic EM GFs.

Applications of the ACGF Method

MIMO Systems

Examples:

1. The channel matrix of MIMO system is given in terms of the measured ACGFs of the Tx and Rx terminals.
2. New design methods to synthesize special MIMO antenna arrays.
3. Deeper physical insight into the spatial structure of the electromagnetic link.

Near-Fields

Example:

1. The ACGF provides a systematic method to characterize EM devices in near-field illumination scenarios.
2. New methods to deal with dense and crowded environments.

Large-and-Complex Antenna Arrays

Example:

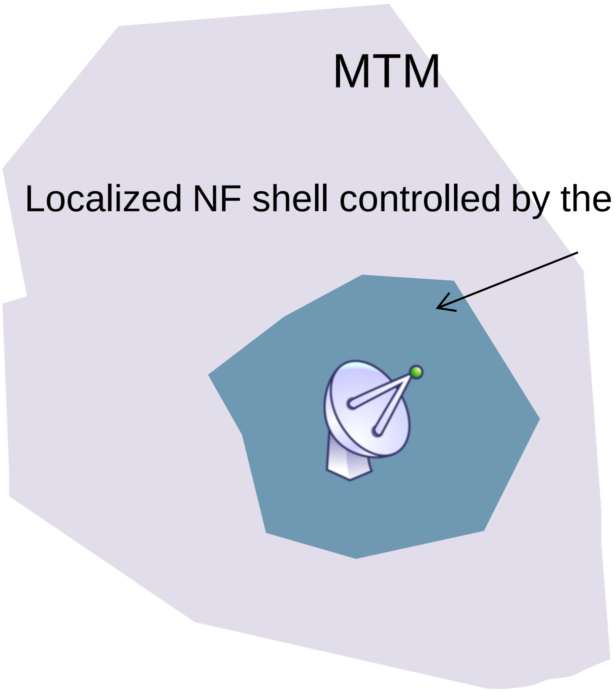
1. Expressing the full mutual coupling effect in terms of special mutual coupling ACGF.
2. Using perturbation theory, new algorithm methods to compute mutual coupling without inverting the full EM operator.

Advantages of ACGF in Terms of Analysis

1. Provides a way to characterize antennas in terms of characteristic modes.
2. These are physically meaningful basic solutions that shed light on the behavior and performance of the antenna system in general.
3. All antennas exhibit a phenomenon of spatial bandwidth similar to the familiar temporal bandwidth w in EM theory.
4. It is possible now to use ACGF to synthesize special antenna systems capable of performing complex spatial filtering functions needed for spatial diversity applications such as mobile, MIMO, and DoA.
5. The ACGF may join with traditional full-wave solvers and measurement as one of the basic methods used in EM to obtain accurate quantitative description of systems and devices.
6. The ACGF provides through the recently proposed mutual coupling ACGF the most general description of EM mutual coupling. Methods to compute this new ACGF using perturbation series not involving inverting the full EM operator of the problem has been proposed.
7. The ACGF is the right tool to develop new understanding of
   - NF communications
   - NF radar, and
   - NF matching.

The New NF Theory and Metamaterials

- We utilize the new NF theory in order to envision new genera of metamaterials (MTMs) for electromagnetic applications (see below).
- Understanding the NF in terms of its spatial structure suggests naturally considering classes of new materials that are sensitive to the spatial distribution of the field.
- Such a class is called nonlocal media. They exhibit spatial dispersion.
- The authors are currently working on understanding the physics of the near field of antennas embedded in such potentially novel materials.
- Preliminary results strongly suggest that a new type of EM behaviour is expected, leading to the potentials of NF engineering at a wider scale than what is available with conventional (temporally dispersive) materials.



A MTM is used to engineer the NF of an antenna embedded inside

The ACGF and the SEM Method

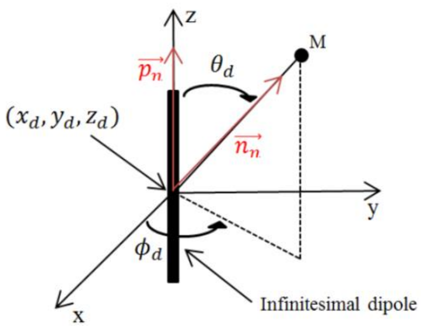
- The authors proposed in [1] a connection between the ACGF and the classic singularity expansion method (SEM.)
- The basic idea is to apply the SEM in the frequency domain instead of the time domain (as it has been used in the latter throughout the last five decades.)
- The key innovation in the new ACGF-SEM method is that the SEM is applied to spatial EM data (here the ACGF itself) in order to provide new physical and computational insights into the performance of EM systems.
- Using the ACGF-SEM, it is possible for example, to find new "characteristic modes" in the current distribution.
- The new "characteristic modes" obtained using the ACGF-SEM have different physical interpretation from Harrington's characteristic modes.
- The new ACGF-SEM "characteristic modes" are currently being investigated for various new applications involving mutual coupling analysis and compensation and novel methods for radar detection [2].

[1] Said Mikki and Yahia Antar, "The Antenna Current Green's Function Formalism (Parts II)," *IEEE TAP*, pp. 4505-4519, September 2013.
[2] Mikki, S.M.; Antar, Y.M.M., Spatial Structures of Electromagnetic Fields, Artech House, 2015.

Application to an Electrically Small Antenna

The Infinitesimal Dipole Model (IDM):

➡ The use of a set of point sources is an easy way to represent complex antenna.



➡ An infinitesimal dipole is defined by:

- A position (x_{ID}, y_{ID}, z_{ID})
- A orientation (θ_{ID}, ϕ_{ID})
- An Amplitude (A_{ID})
- A Phase (φ_{ID})

For an array of N infinitesimal dipoles ➡

$$\mathbf{E}_{\mathbf{array}}(\mathbf{x},\mathbf{y},\mathbf{z}) = \sum_{n=1}^{N} \frac{1}{4\pi\varepsilon_0}(k_0^2.(\mathbf{n_n} \times \mathbf{p_n}) \times \mathbf{n_n}).\frac{e^{-jk_0 r_n}}{r_n} \quad \text{(Far-field)}$$

$$\mathbf{n_n} = \left(\frac{x - x_{ID}(n)}{r_n}, \frac{y - y_{ID}(n)}{r_n}, \frac{z - z_{ID}(n)}{r_n}\right)^T \quad \mathbf{p_n} = A_{ID}(n).e^{j\varphi_{ID}}.\begin{pmatrix} cos(\phi_{ID}(n)).sin(\theta_{ID}(n)) \\ sin(\theta_{ID}(n)).sin(\phi_{ID}(n)) \\ cos(\theta_{ID}(n)) \end{pmatrix}$$

Potential Impact

Some of the possible implications of the research, besides the scientific merits of attaining knowledge for the sake of knowledge itself are the following.

1. Understanding the near-field (NF) helps motivate methods for improving performance measures of existing devices
2. New and fresh theoretical examinations may lead to the discovery of new potentials in the NF that have not been exploited to date in industrial and applications-oriented research, e.g. studying localization (energy confinement and focussing) in general and are suggested here as a way to launch NF focussing and engineering applications.
3. The NF theory may provide a new way for managing and controlling interactions between devices at close range, e.g., mutual coupling in antenna arrays and antennas and circuits embedded in complex EM environments.

Potential Impact (cont’d)

4. Key applications: Near-field communications, nano-scale devices where the EM environment is complex and not well understood yet and **metamaterials where the NF performance of MTMs** has not attracted enough attention to date.
5. The present work is a beginning and although it provides a general insight that has been mathematically verified for arbitrary antennas, the application of this theory to concrete antennas will require further work in line with the nature of the applications, the interest of the device research under consideration and the technological domain of use, etc.
6. Some fully developed applications and computational techniques for combining the generally rigorous mathematical and physical insights (the new NF theory) and existing applications will be described.

Impact on MIMO Systems Engineering

- In MIMO systems, there is a need to examine near-field interactions in light of their impact on mutual coupling and system performance.
- It is found that complete descriptions of MIMO systems cannot be done in terms of conventional circuit parameters.
- Moreover, it is found that far field characterization is not enough where near field aspect and energy localization issues are becoming increasingly important for applications.
- **MIMO and mobile devices operate in typically heavy populated urban environments where near field coupling with other devices and nearby scatterers are fundamental for maintaining high performance**.

Impact on MIMO Systems Engineering (cont'd)

- Here the use of several antennas placed in close proximity to each other may raise the issue of mutual coupling and interactions.
- Coupling between two nearby antennas is most likely to be understood as an NF phenomenon
- Therefore a general theory of NF is essential to understand and manage mutual coupling in complex systems such as MIMO and large phased arrays.
- Furthermore, the merging of pure EM aspects with the communication and signal processing dimension requires a system approach (the antenna current Green's function recently developed by Mikki and Antar*) which rely on the NF theory.

Conclusions

- This talk presents an overall view on recent progress in fundamental research in Applied Electromagnetics.
- We presented a general outline of the new theory of near fields and discussed some of its possible applications.
- In light of the near field theory, there is a possibility of envisioning a new range of experiments aiming at characterizing the structure of antennas in terms of energy localization and propagation.
- The antenna current Green's function as a general method to study the response of antennas to near field illumination was outlined. Its many applications were discussed .
- There is a possibility of building special methods to measure the ACGF and then use the measured data to analyze the performance of EM systems in complex and dense environments by including the effects of near field interactions.
- We hope that theory and new experiments will mutually illuminate each other in the immediate future, especially in light of the increasing complexity of electromagnetic environments.

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[3] Said Mikki and Ahmed Kishk, "Theory and applications of infinitesimal dipole models for computational electromagnetics," *IEEE TAP*, May 2007.

[4] Said Mikki and Yahia Antar, "Near-field analysis of electromagnetic interactions in antenna arrays using infinitesimal dipoles," *IEEE TAP*, March 2012.

[5] Said Mikki and Yahia Antar, "On the fundamental relationship between the transmitting and receiving modes of general antenna systems: A new approach," *IEEE AWPL*, vol. 11, 2012.

[6] Said Mikki and Yahia Antar, "The Antenna Current Green's Function Formalism (Parts I)," *IEEE TAP*, pp. 4493-4504, September 2013.

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[8] S. Henault, S. K. Podilchak, S. Mikki, Y. M. M. Antar, "A general methodology for mutual coupling estimation and compensation," *IEEE TAP*, March 2013.

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[11] Said Mikki and Yahia Antar, "Near Field Engineering via Metamaterials" (under preparation).

[12] Said Mikki and Yahia Antar, *Spatial Structures of Electromagnetic Fields*, Artech House, 2015.