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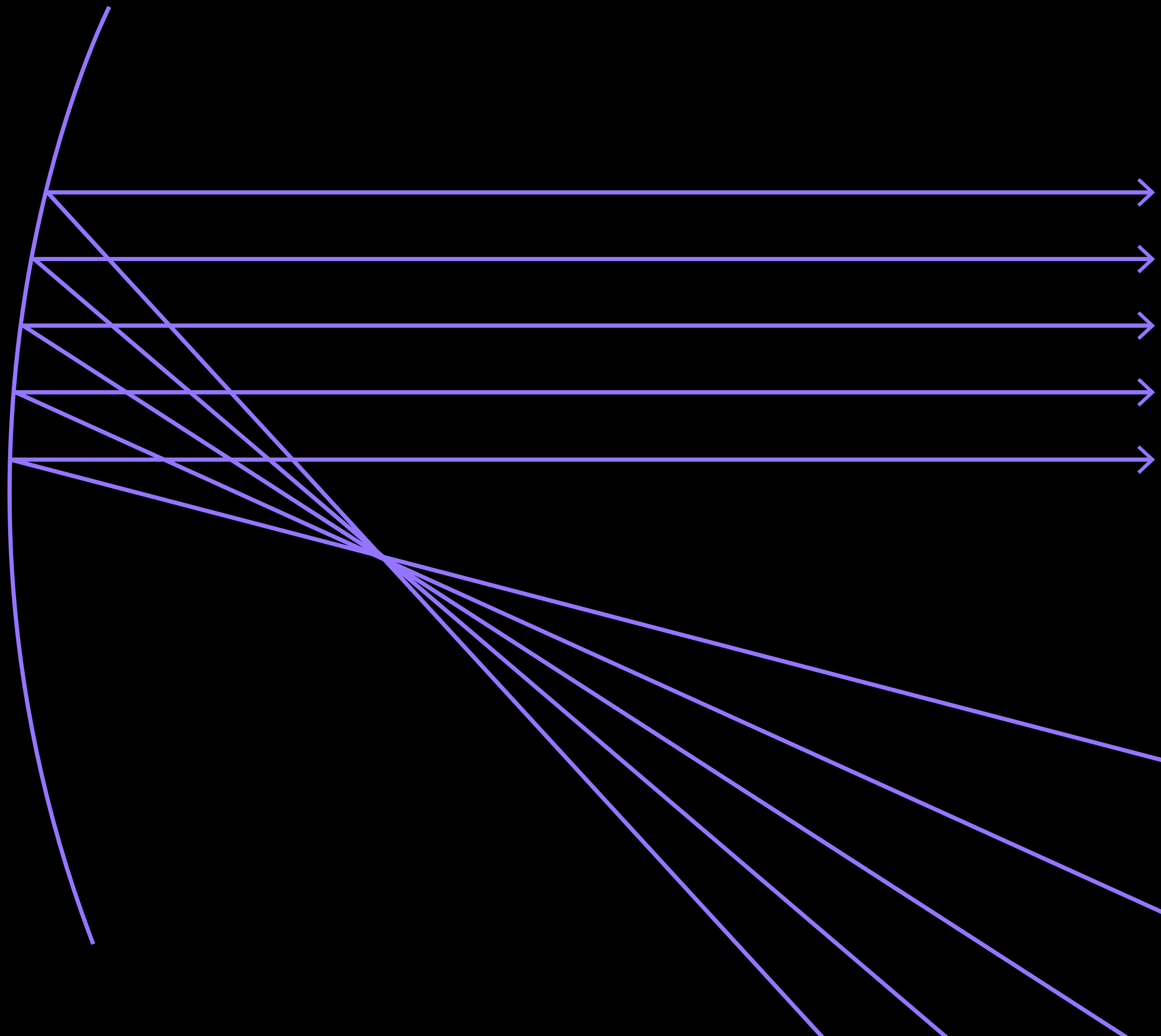
Metamaterial-Inspired Directive Radiators and Scatterers



Featuring
Richard W. Ziolkowski, University of Technology Sydney

04 May 2022

A Quick Zoom Tutorial

- Submit a question by clicking on “Q&A”
- Like a question that’s been submitted?
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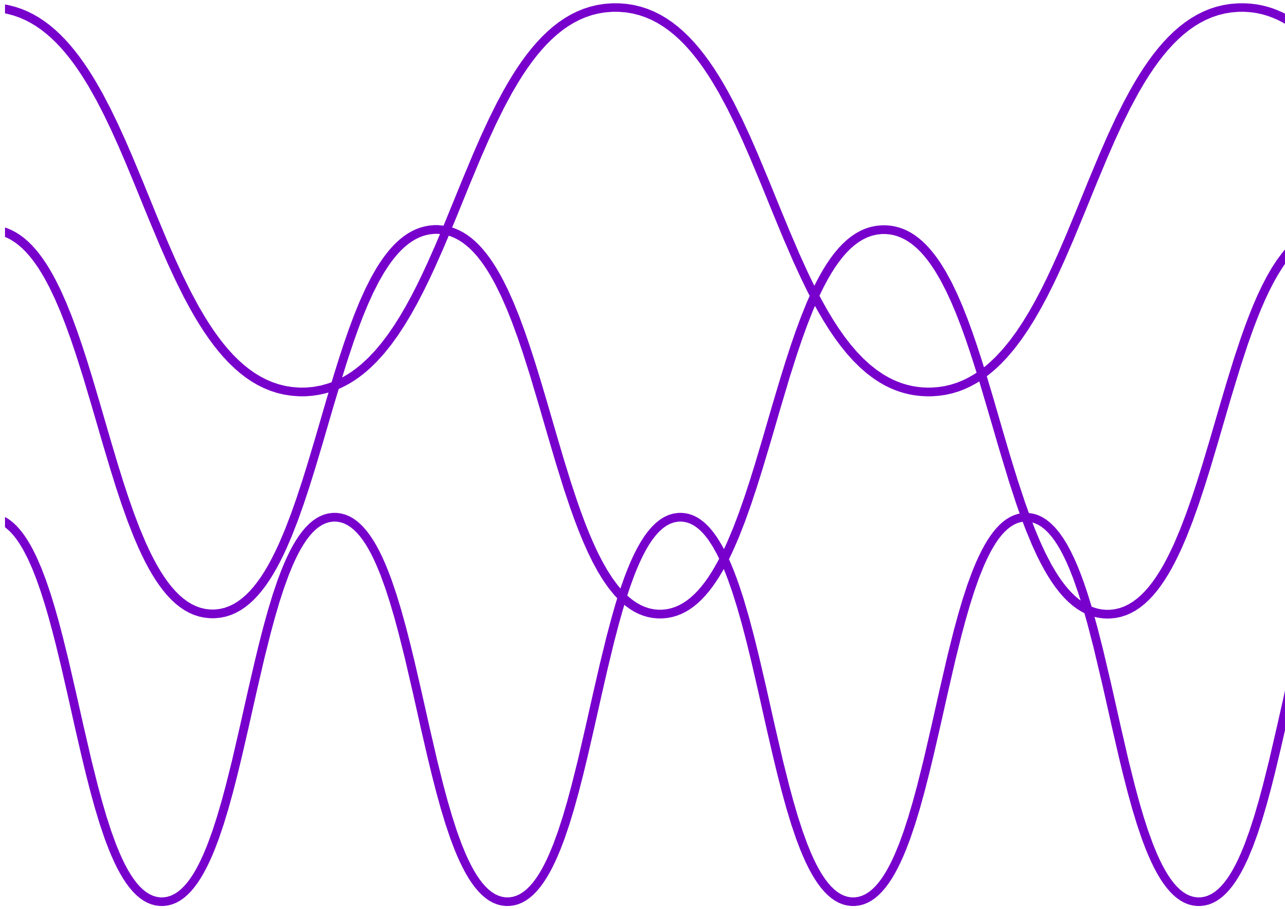
**Photonic Metamaterials
Technical Group**

Metamaterial-Inspired Directive Radiators and Scatterers

Richard W. Ziolkowski,
University of Technology Sydney

4 May 2022



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About the Photonic Metamaterials Technical Group

Our technical group provides a forum for those working on problems related to fundamental and applied aspects of waves in random and periodically nanostructured materials as well as plasmonics.

Our mission is to connect the 2360+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- 12 previous webinars available to view on-demand
- Discussion of seminal papers
- Dialogues on Metamaterials series

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

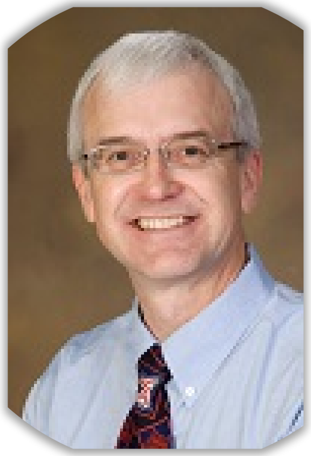
Ways to connect with us:

- Our website at www.optica.org/OP
- On LinkedIn at www.linkedin.com/groups/9017099/
- On Twitter at #MetamaterialsTG
- Email us at TGactivities@optica.org

- **Upcoming Webinars featuring**
  - **Prof. S. Torquato (Princeton)**
  - **Prof. C Kagan (Upenn)**

Stay tuned!

Today's Speaker



Richard W. Ziolkowski

University of Technology Sydney

Richard W. Ziolkowski received the Ph.D. degree in physics from the University of Illinois at Urbana-Champaign, Urbana, IL, USA in 1980. He received an Honorary Doctorate degree from the Technical University of Denmark (DTU) in 2012. He was with the Engineering Research Division of LLNL from 1981 until he joined the University of Arizona in 1990. He is currently a Distinguished Professor in the Global Big Data Technologies Centre in the Faculty of Engineering and Information Technologies (FEIT) at the University of Technology Sydney, Ultimo NSW Australia and is a Professor Emeritus at the University of Arizona, ECE Dept and the COS. Prof. Ziolkowski was the recipient of the 2019 IEEE Electromagnetics Award (IEEE Technical Field Award). He is an IEEE Life Fellow as well as a Fellow of OPTICA and APS. He was the 2014-2015 Australian DSTO Fulbright Distinguished Chair in Advanced Science and Technology. He served as the President of the IEEE Antennas and Propagation Society (AP-S) in 2005.

Metamaterial-inspired Directive Radiators and Scatterers

Richard W. Ziolkowski

University of Technology Sydney
Global Big Data Technologies Centre

OPTICA
8:00-9:00 PDT 04 May 2022

Many special thank you’s

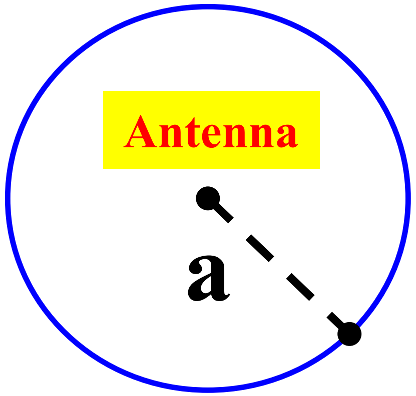
to

Dr. Dimitrios C. Tzarouchis

for his very kind invitation to me to share with you
some of our metamaterial-inspired efforts !!

Useful definitions for my presentation

Smallest
Enclosing Sphere



$$ka = \frac{2\pi}{\lambda}\, a = 2\pi\, \frac{a}{\lambda}$$

Electrically
Small

$$ka \le 1$$

“Gain” = “Efficiency” × Directivity

$$\text{Directivity} = 4\pi\, \frac{r^2\, \hat{r}\cdot\left[\frac{1}{2}\, Re\{\vec{E}\times\vec{H}^*\}\right]}{\oiint_S \vec{S}\cdot\hat{r}\, r^2 \sin\theta\, d\theta\, d\varphi}$$

During my presentation, I will share with you a myriad of metamaterial-inspired radiators and scatterers (R&Ss)

- **Brief review of how we design our electrically small R&Ss**

  Near-Field Resonant Parasitic (NFRP) Paradigm

- **Review the concepts of passive and active electrically small photonic R&Ss**

  Core-shell antennas and nano-antennas

- **Review the concepts of electrically small directive R&Ss**

  Huygens dipole R&Ss

- **Review the *Magic of Multipoles***

  Superdirective R&Ss

- **Review some of the more exotic passive and active core-shell based R&Ss**

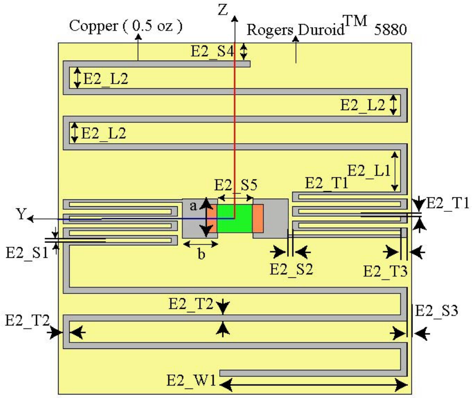
I will emphasize microwave versions and their analogous photonic ones

DARPA Metamaterials Program – Boeing R&D lead: Lumped element-based DNG metamaterial designs and experiments were achieved with very small unit cells

A. Erentok et al,
APL, Nov. 2007
JAP, Aug. 2008

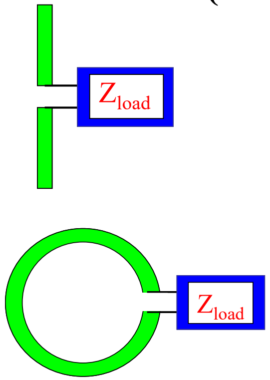
UA Unit Cell meanderline with lumped element inductor
~ λ / 100

ENG
($\varepsilon < 0, \mu > 0$)



μ

DPS
($\varepsilon > 0, \mu > 0$)



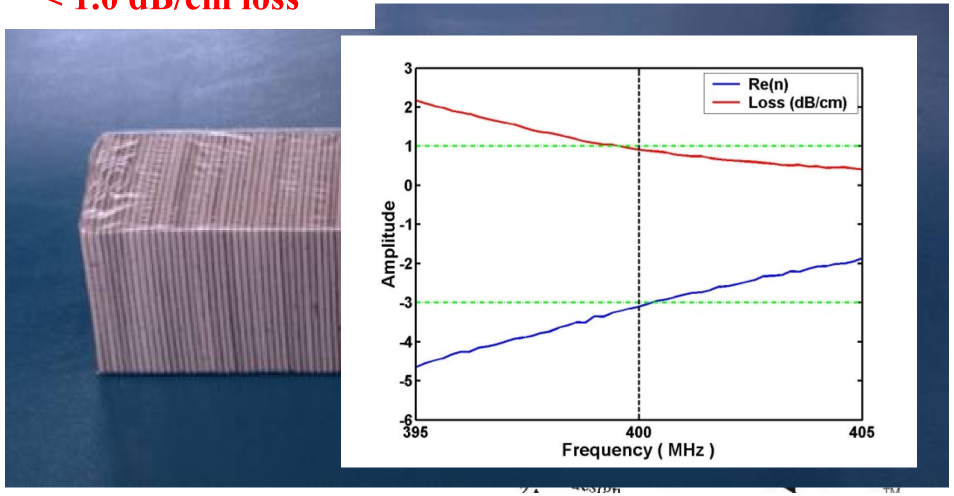
U Arizona
Electric and Magnetic Artificial Molecules
for
RAMs, Smart skins
and
FDTD ABCs
(Physics-based PMLs)

F. Auzanneau (CEA-CESTA, France)
& R. W. Ziolkowski, 1997-1999

ε

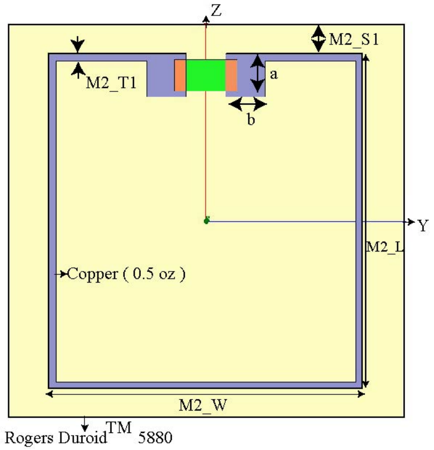
λ / 75 DNG unit cell at 400 MHz with < 1.0 dB/cm loss

DNG



Complete NIM slab (~ 900 Unit Cells)

MNG
($\varepsilon > 0, \mu < 0$)

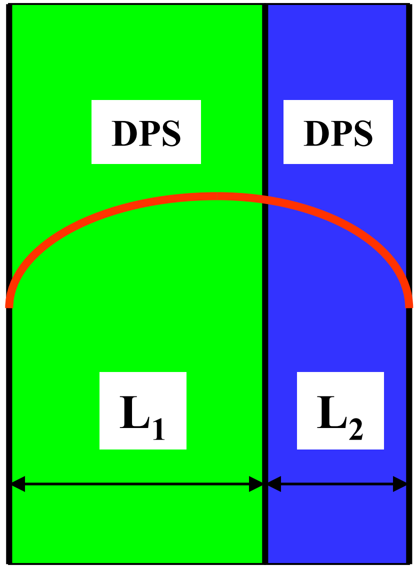


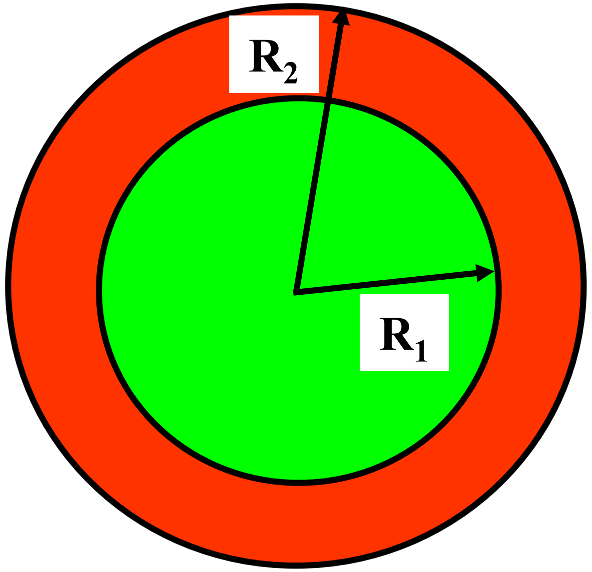
UA Unit Cell
CLL = capacitively loaded loop
+
lumped element capacitor
~ λ / 100

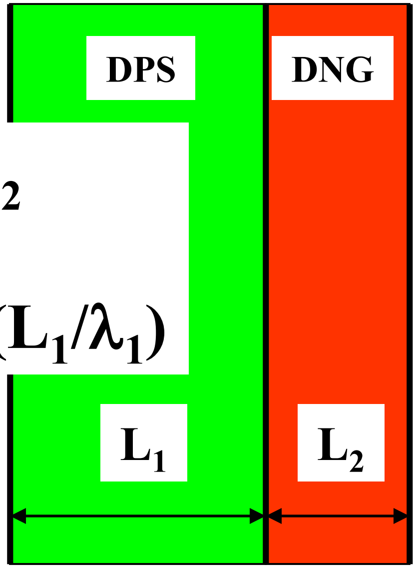
Juxtaposition of positive and negative materials leads to the possibility of electrically small systems

$$2(k_1L_1 + k_2L_2) = m2\pi$$

$$m = 1,2,\ldots$$







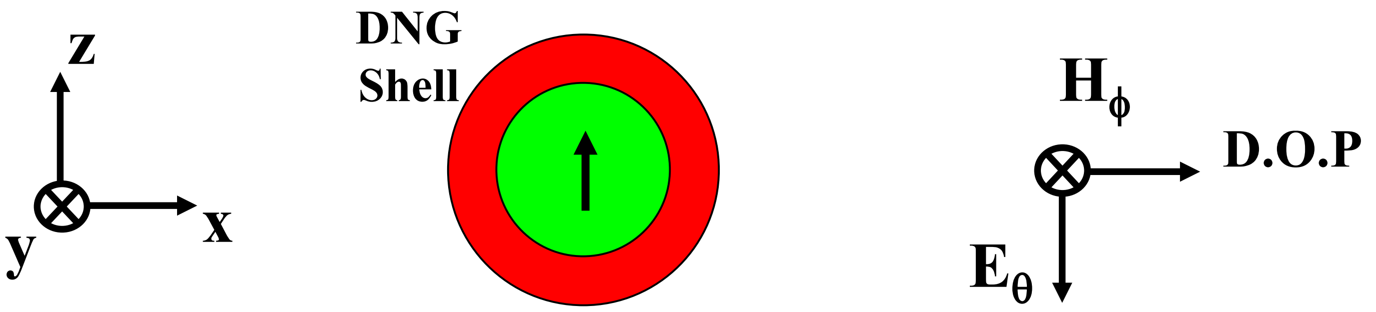
$$k_1L_1 + k_2L_2 = 0$$

$$L_2/\lambda_2 = (n_1/|n_2|)(L_1/\lambda_1)$$

$$E = \Sigma_{mn}\, a_{mn}\, TE_{mn} + b_{mn}\, TM_{mn}$$

$$b_{mn} = \frac{A_{mn} + j\,B_{mn}}{C_{mn} + j\,D_{mn}} \quad \begin{array}{l} \rightarrow 0\text{, Non-radiating} \\ \rightarrow 0\text{, Resonant} \end{array}$$

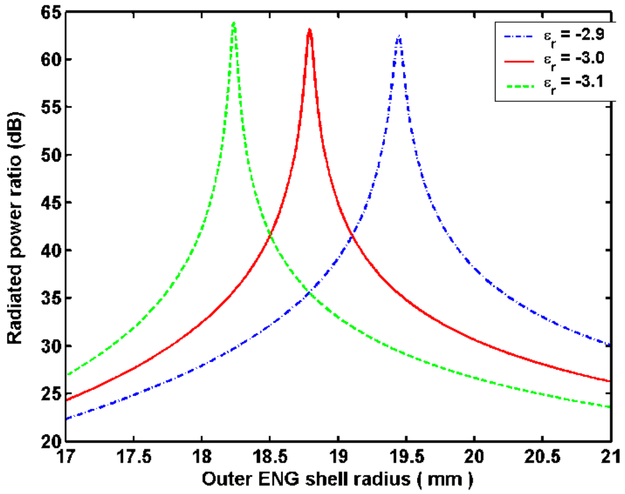
Analytical Solutions Demonstrate the Existence of Electrically Small Radiating and Reciprocal Scattering Systems

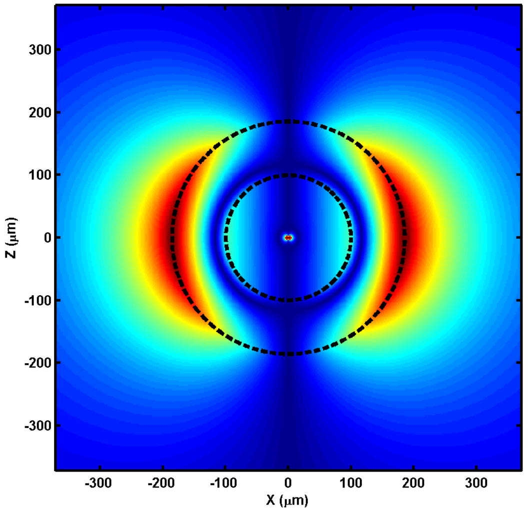


Receiver in far field

Dipole Source

Radiated Power Ratio || Purcell factor





Total Magnetic Field Intensity Source Case

$kr_2 = 0.117$

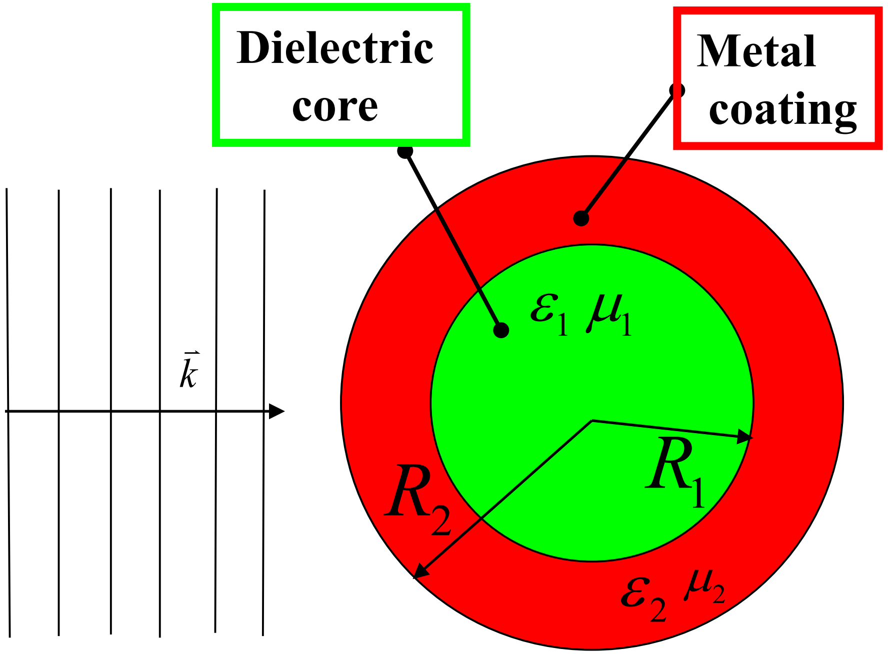
$r_2 \sim \lambda_0 / 53.5$

$r_1 = 10$ mm, $f_0 = 300$ MHz, $\lambda_0 = 1000$mm

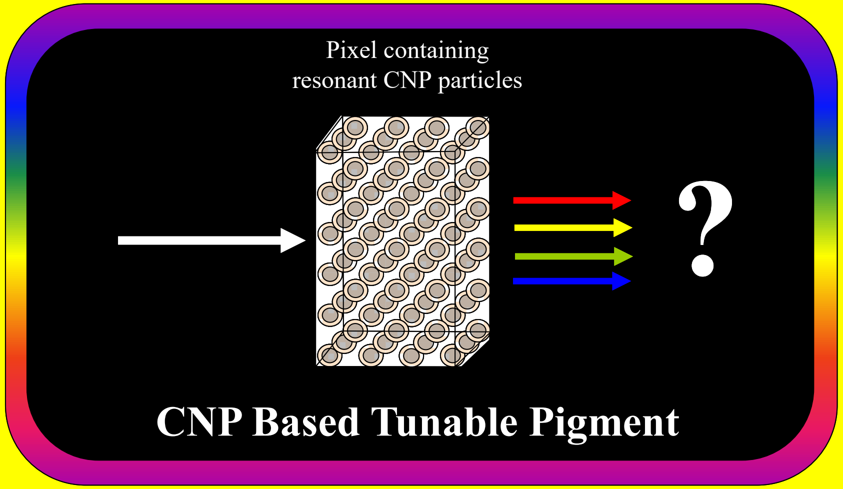
R. W. Ziolkowski and A. D. Kipple, IEEE Trans. AP, vol. 51, no. 10, pp. 2626-2640, October 2003

R. W. Ziolkowski and A. D. Kipple, Phys. Rev. E., vol. 72, 036602, September 2005

Optical Metamaterials and Applications Based on Passive Resonant Core-shell Nano-Particles (CNPs)



Excited by 500nm visible light
10nm, 30nm radius CNPs



Three CNP layers generate the entire NTSC and RGB Gamuts

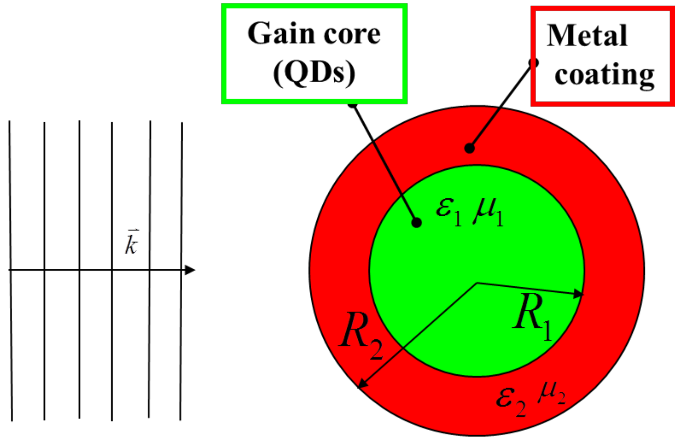
J. A. Gordon and R. W. Ziolkowski
Colors generated by tunable plasmon resonances and their potential applications to ambiently illuminated color displays
***Solid State Comm.*, vol. 146, pp. 228-238, April 2008**

Optical Metamaterials and Applications Based on Active Resonant Core-shell Nano-Particles (CNPs)

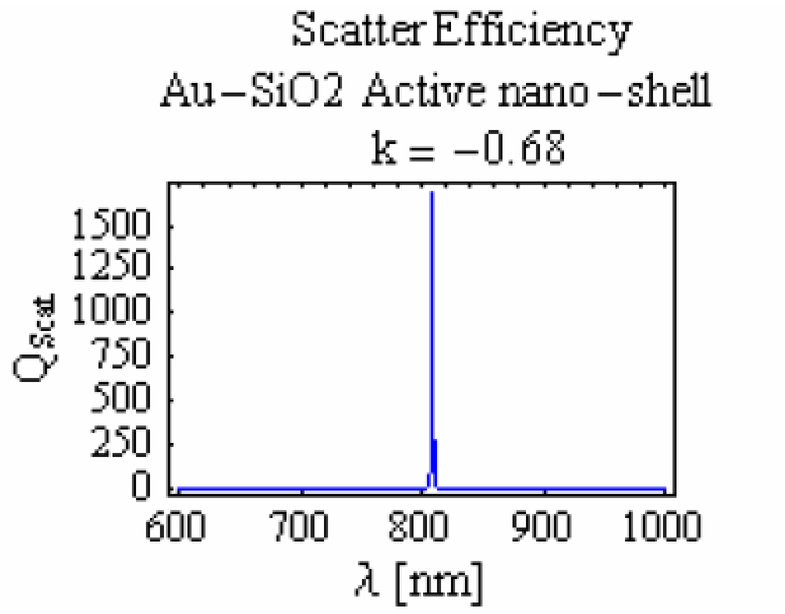
Joshua A. Gordon & Richard W. Ziolkowski

The design and simulated performance of a coated nano-particle laser
Opt. Express., vol. 15, 2622-2653, Mar. 2007

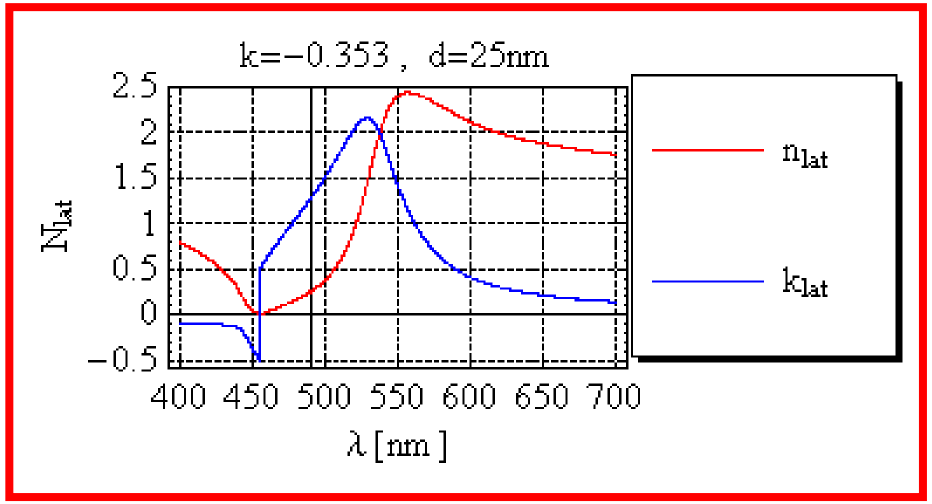
CNP optical metamaterials
Opt. Express, vol. 16, 6692-6716, Feb. 2008



Excited by 500nm visible light
10nm, 30nm radius CNPs



8 nm gain SiO$_2$ core, 2 nm Ag shell, d = 25 nm period

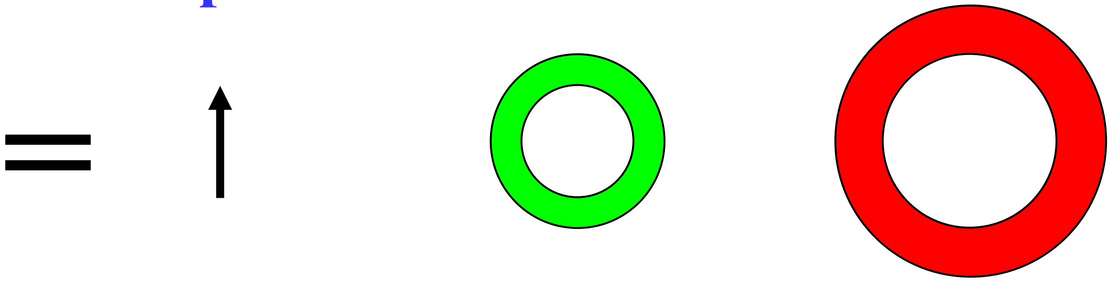


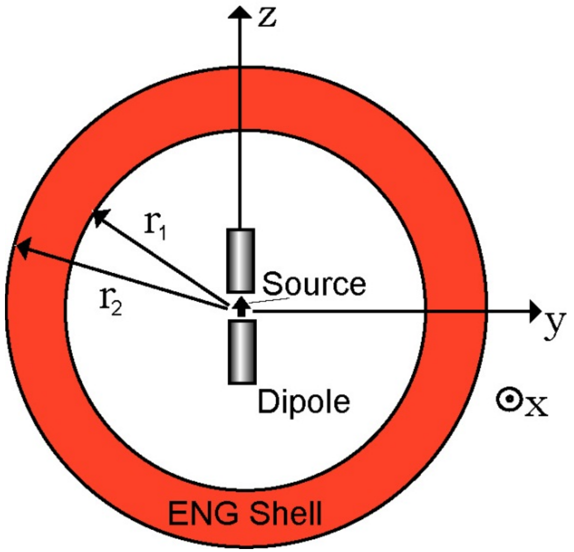
Active ENZ MTM in the visible with low loss

Efficient Electrically Small Antennas:
Metamaterial-based

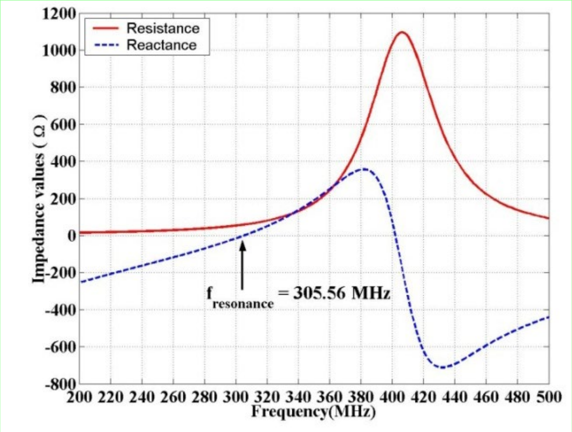
Center-fed dipole - ENG shell Antenna

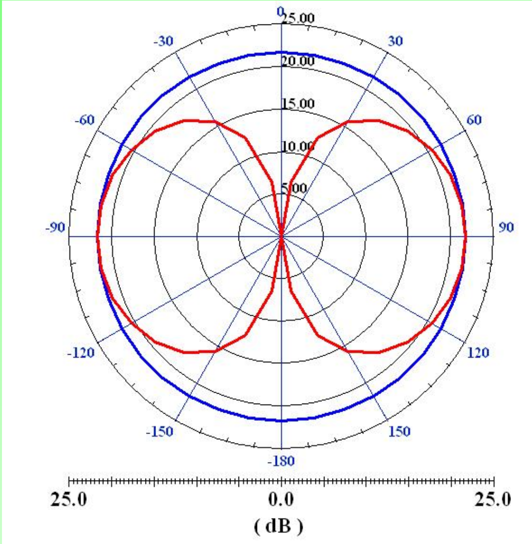
Small Dipole **DPS (air) Shell** **ENG Shell**





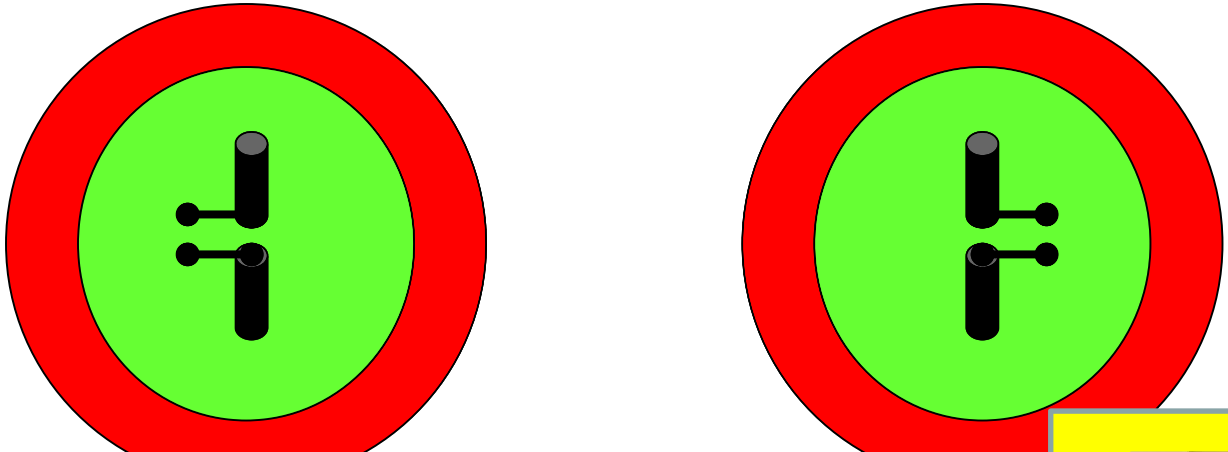
R. W. Ziolkowski and A. Erentok, "Metamaterial-based efficient electrically small antennas," *IEEE Trans. Antennas Propagat.*, vol. 54, pp. 2113-2130, July 2006

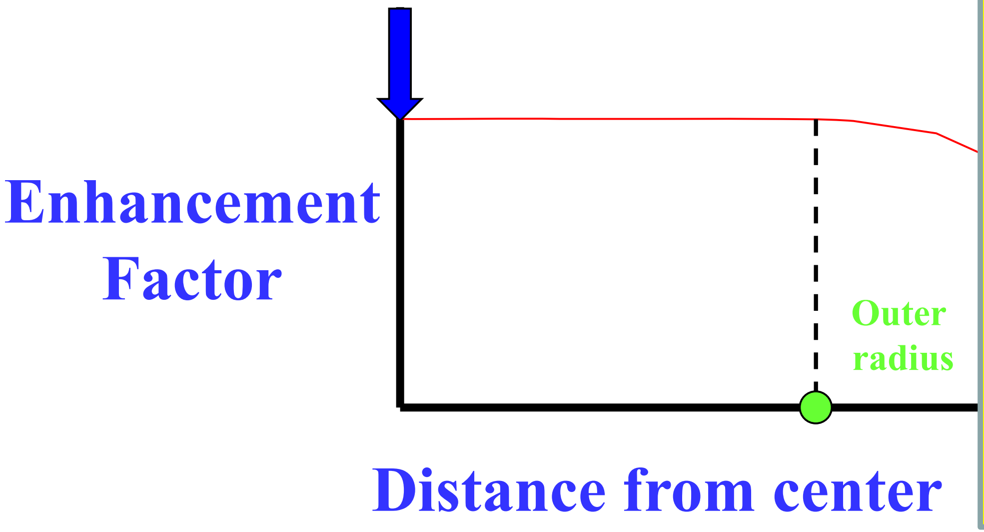




radius ~ λ/52
ka ~ 0.12
OE ~ 100%

We found that the location of the dipole is not a critical issue
⇨ The MTM shell is an electrically small resonator excited by the driven dipole

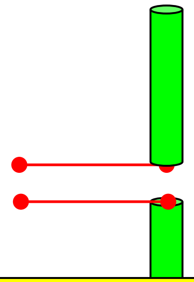


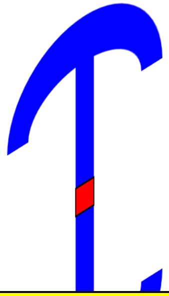


DTU
2021 H. C. Ørsted
silver medal

S. Arslanagić, R. W. Ziolkowski, and O. Breinbjerg, “Radiation properties of an electric Hertzian dipole located near-by concentric metamaterial spheres” ***Radio Science*****, 42, RS6S16,** doi:10.1029/2007RS003663, November **2007**

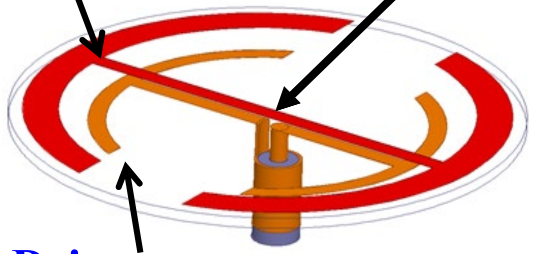
Metamaterial-inspired Near-Field Resonant Parasitic (NFRP) Approach



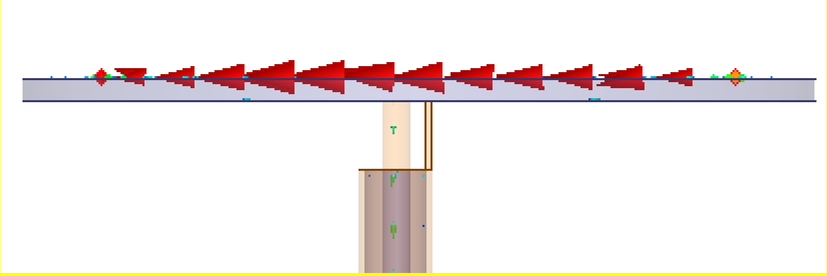


Curved
I structure
= Egyptian
Axe

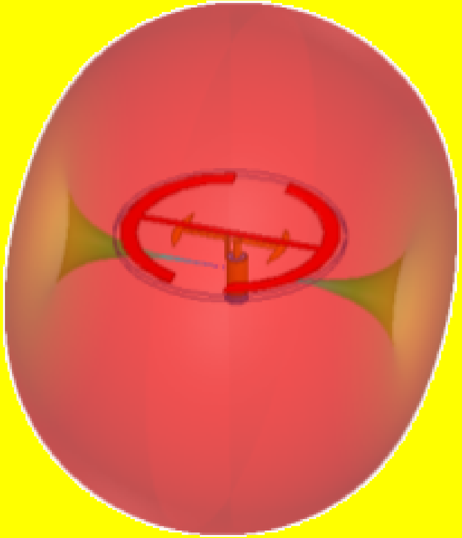
Loaded with



Radiation Efficiency > 90 %



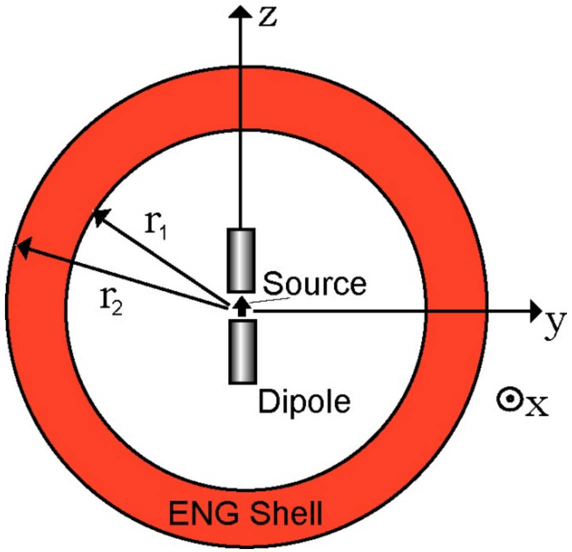
At resonance,
current is mainly on NFRP element



Electric Dipole Pattern

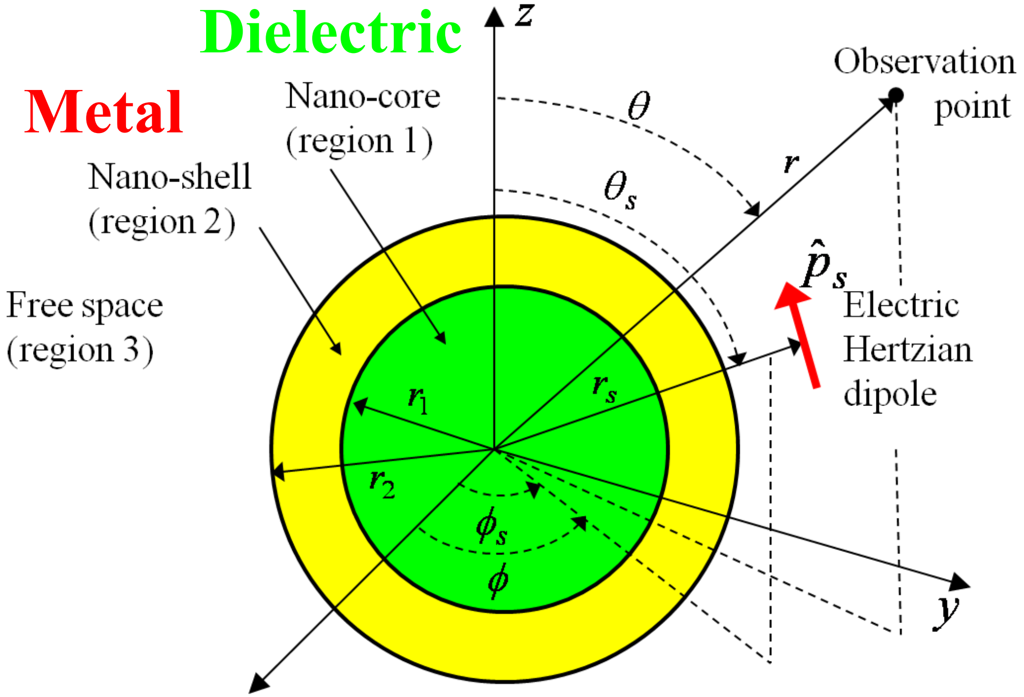
The metamaterial-based antenna paradigm works at microwave frequencies AND for nano-antenna applications

Center-fed dipole - ENG shell Antenna



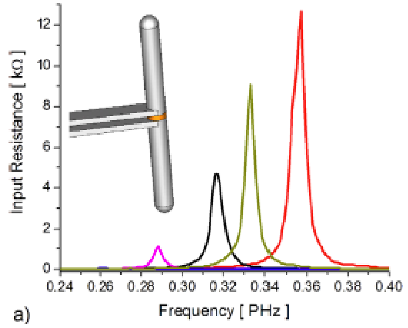
A. Erentok & **R. W. Ziolkowski**
***IEEE Trans. Antennas Propag.* 2006**

Metamaterial-engineered Nano-antenna approach



S. Arslanagić & **R. W. Ziolkowski**
***J. Opt.* 2010**

Metamaterial-engineered nano-antenna approach: Passive & Active NFRP elements



Traditional Approach

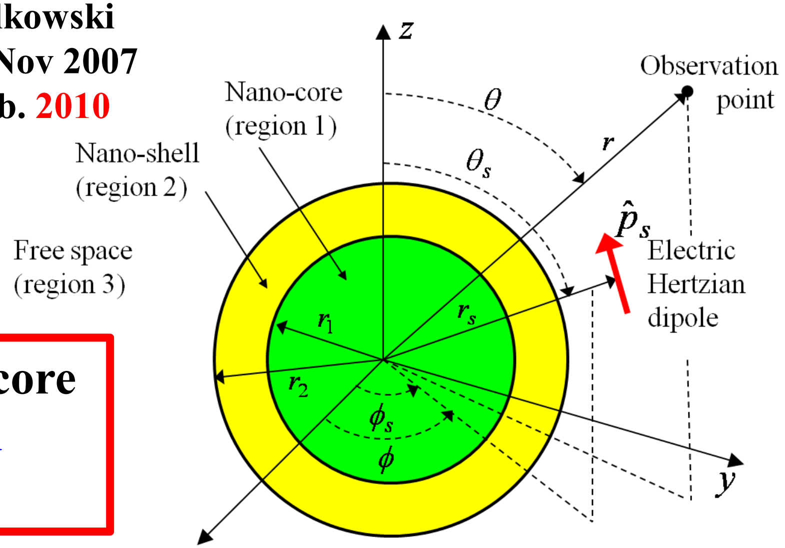
Change reactance at feedpoint to get a "resonance"

Alu & Engheta, PRL, 2008

S. Arslanagić & R. W. Ziolkowski
Radio Science, 42, RS6S16, Nov 2007
J. Opt., vol. 12, 024014, Feb. 2010

Gain-impregnated core

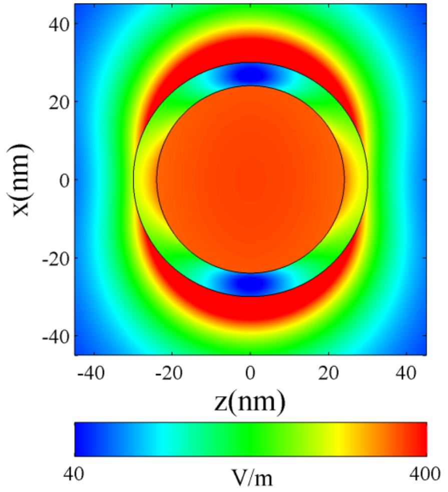
highly localized nano-amplifier



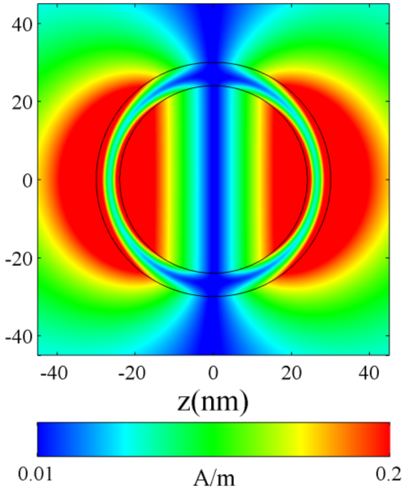
Dipole Resonance

Plasmon-assisted electrically small cavity ⇨ Feedback Mechanism

Ag-SiO$_2$ CNP
|E$_{Tot}$|, κ = -0.25



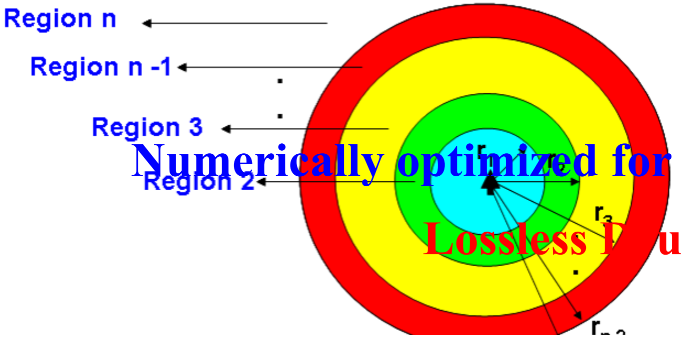
Ag-SiO$_2$ CNP
|H$_{Tot}$|, κ = -0.25



EHD(s) fluorescing atom(s) or molecule(s)

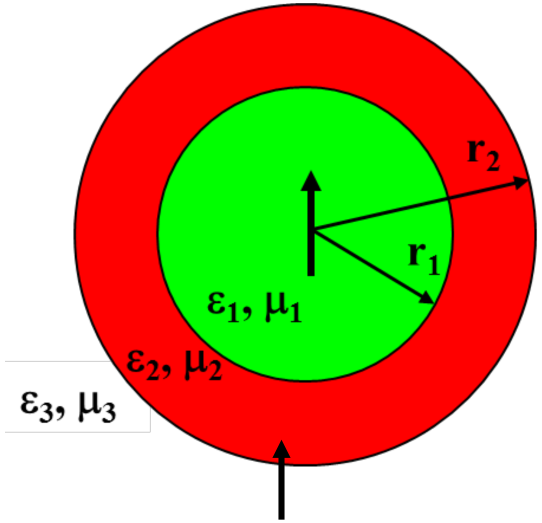
Quantum Transition from an Excited state

Single (Multi)-band radiating & non-radiating ENG-based ESA designs using one (many) metamaterial shell(s)

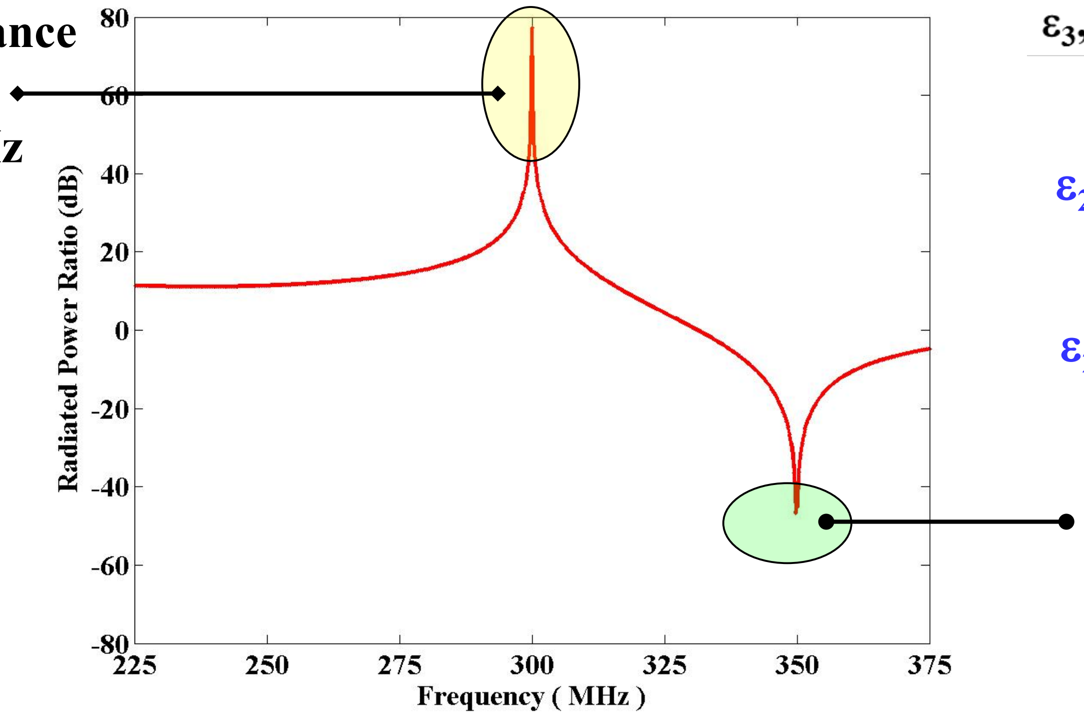


Numerically optimized for r_1 = 10 mm, r_2 = 20 mm

Lossless Drude Model



Super-resonance Mode @ 300MHz



ε_2 (300 MHz) = - 0.3606

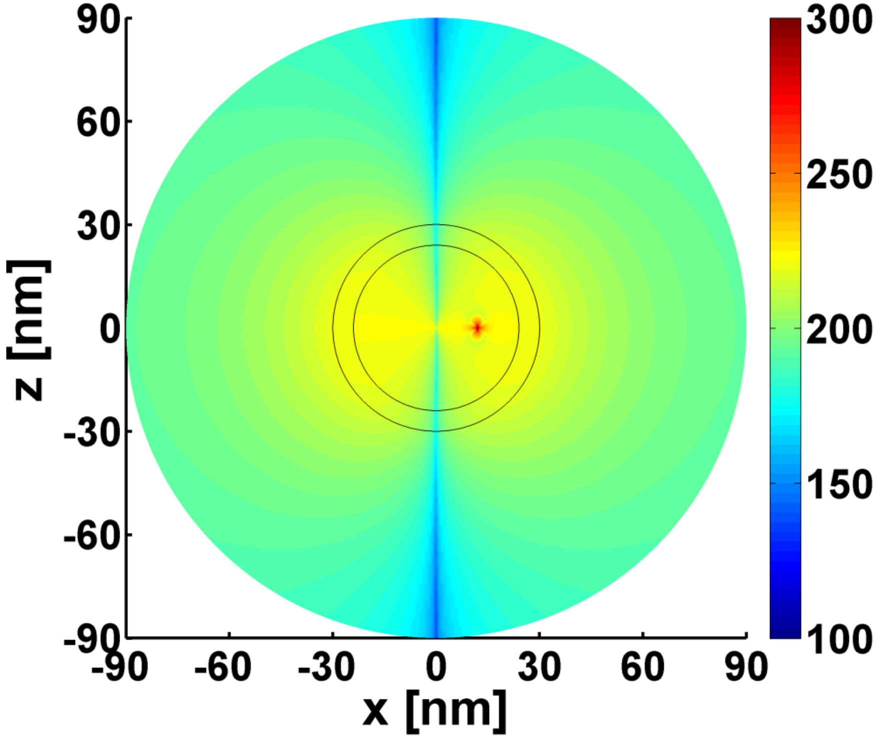
ε_2 (350.23 MHz) ≈ 0

Non-radiating Mode @ 350.23 MHz

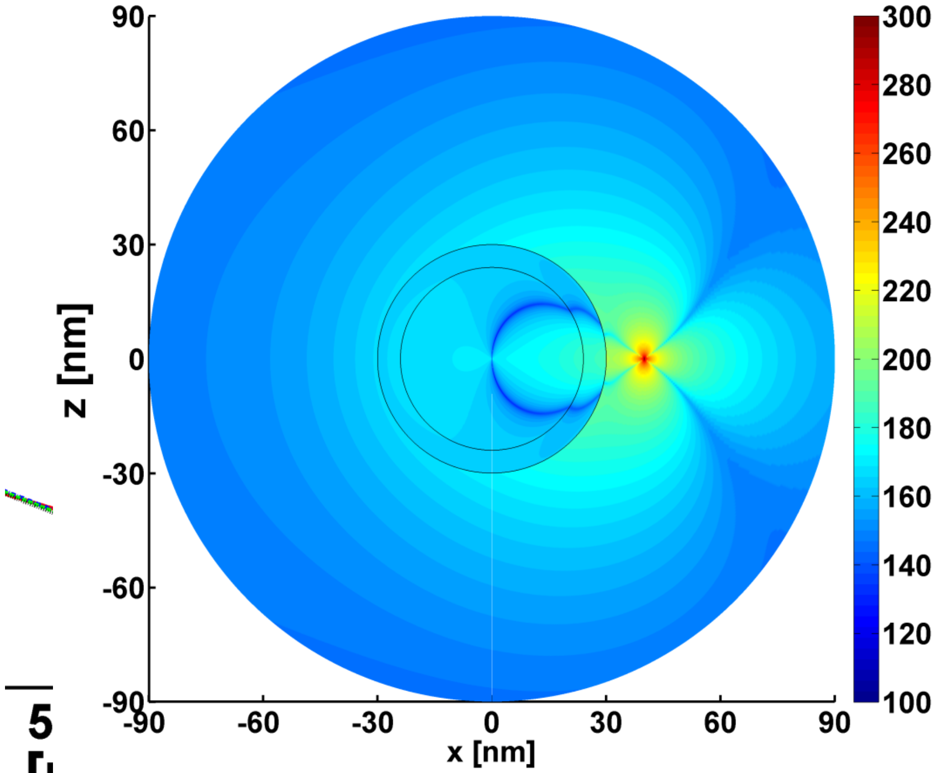
A. Erentok and R. W. Ziolkowski, A hybrid optimization method to analyze metamaterial-based electrically small antennas, *IEEE Trans. Antennas Propag.*, vol. 55, no. 3, pp. 731-741, March 2007

When the EHD is inside or outside of the active CNP, both super-resonant (enhancement) and non-radiating states (jamming) exist

R_s = 12nm



R_s = 40nm

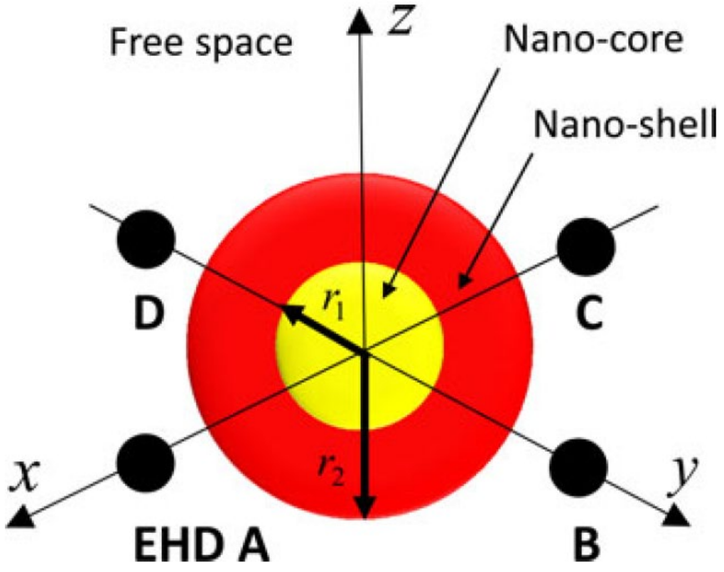


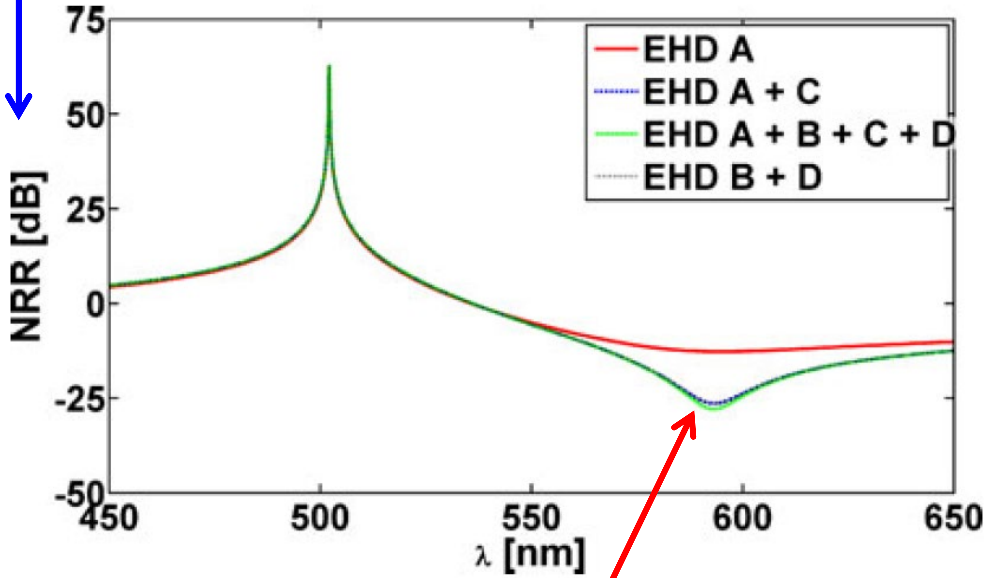
EHD radiating in presence of active CNP

Non-radiating state (jammed EHD)

Active cancellation of fields radiated by quantum emitters

Normalized radiation resistance = Purcell Factor





EHD = electric Hertzian dipole

Significant reduction of total radiated power

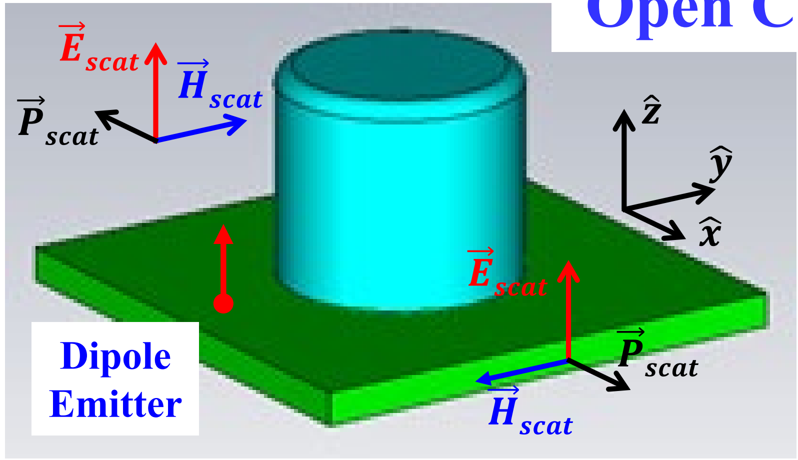
S. Arslanagić and R. W. Ziolkowski,
Jamming of quantum emitters by active coated nano-particles
IEEE J. Sel. Topics Quantum Electron., vol. 19, no. 3, 4800506, May/June 2013

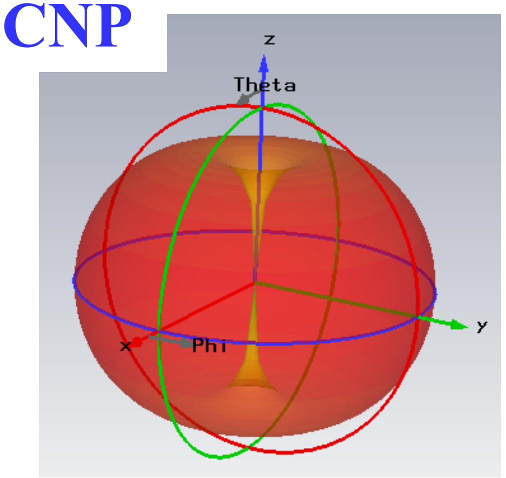
Active Open and Closed Cylindrical Coated Nano-Particles driven by a dipole emitter (molecule)

J. Geng, R. W. Ziolkowski,
R. Jin and X. Liang,
"Numerical study of
active
open cylindrical coated
nano-particle antennas,"
IEEE Photon., vol. 3, issue 6,
1093-1110, Dec. 2011

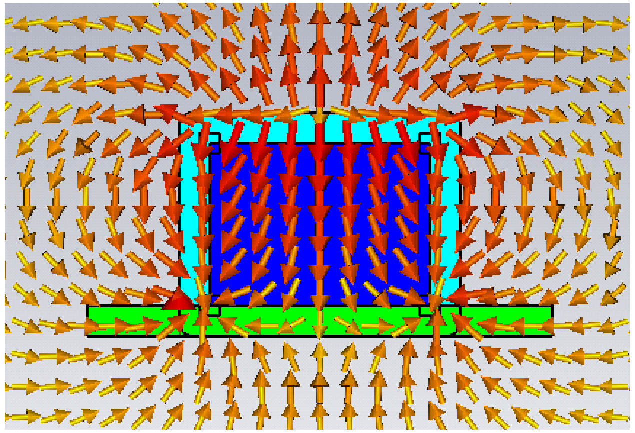
Height = 31.5 nm
Core radius = 21.3 nm
Silver thickness = 6.0 nm
Silica slab: 90 nm × 90 nm × 6 nm

Open C-CNP

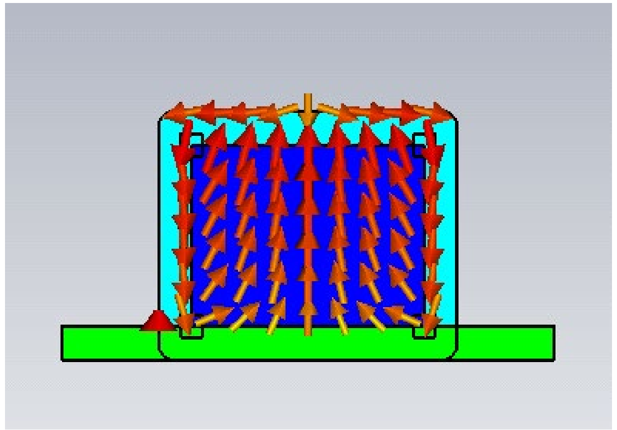




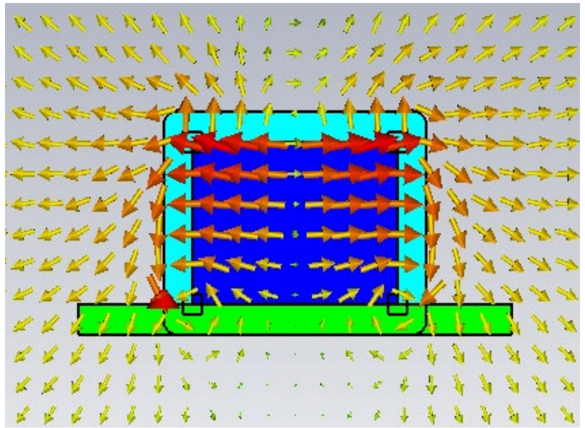
E-field



Current density



Ponyting flux



At resonance 500 nm = 600 THz: 65 dBi enhancement of Total Radiated Power

A plasma realization of the ENG shell-based ESA:
Operate antenna at frequency below the plasma frequency

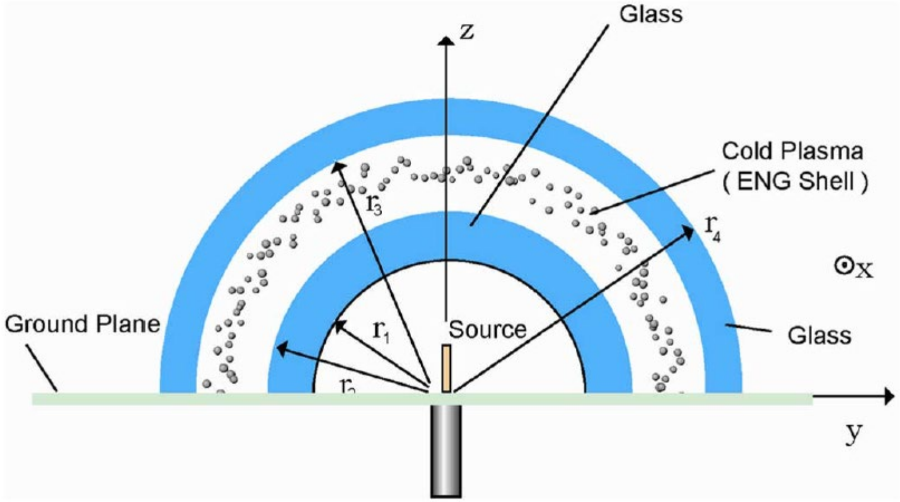
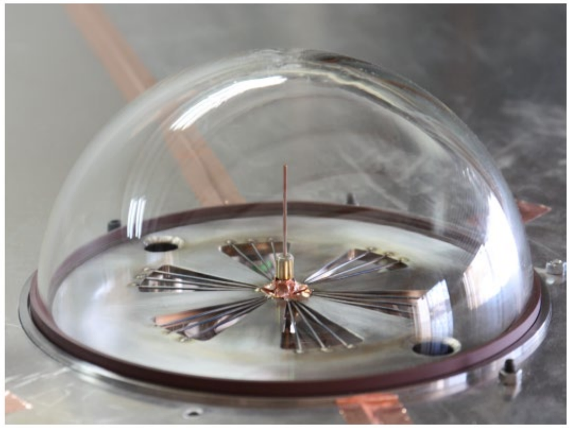
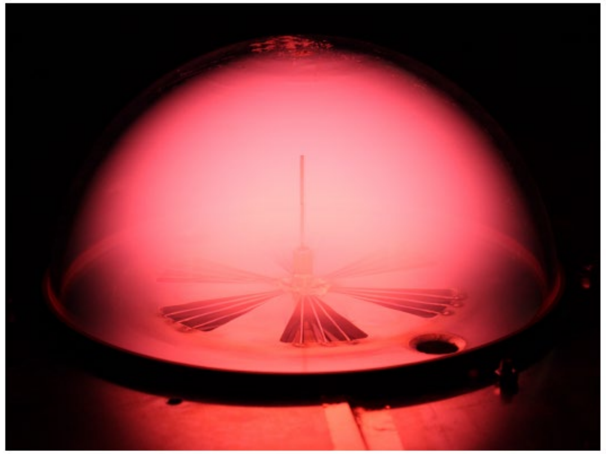


Fig. 4. Geometry of the coax-fed monopole-(glass-ENG-glass) shell system.

A. Erentok and R. W. Ziolkowski, A hybrid optimization method to analyze metamaterial-based electrically small antennas, *IET Microwaves, Antennas Propag.*, vol. 1, pp. 116-128, February 2007



(a) ESA w/o plasma discharge

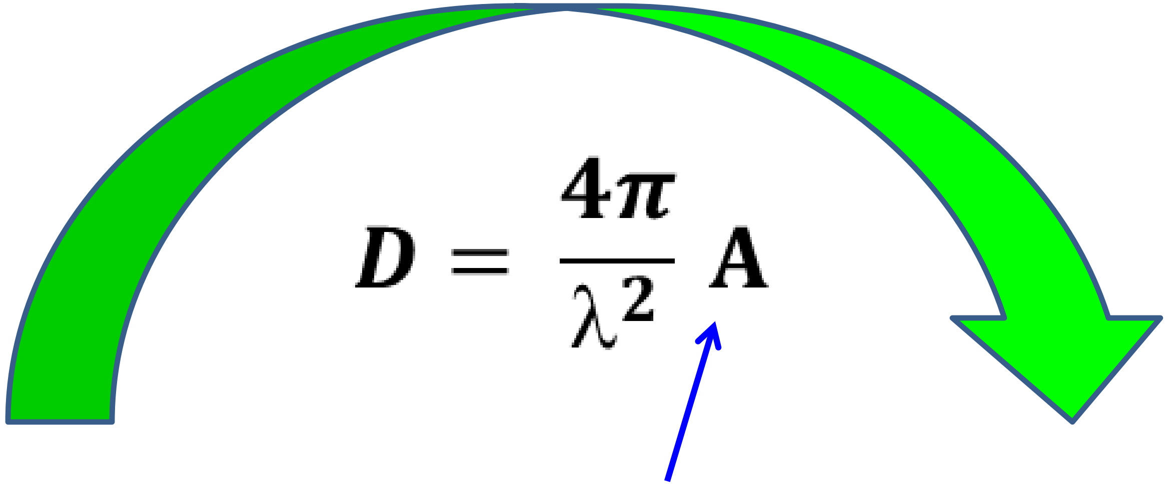


(b) ESA with plasma discharge

V. Laquerbe, R. Pascaud, T. Callegari, L. Liard, and O. Pascal, Universite de Toulouse, Towards antenna miniaturization using plasma, 13th European Conference on Antennas and Propagation (EuCAP 2019)

Physical Bounds – How does one engineer around them ??

SIZE MATTERS: Gain vs Effective Area of Antenna



$$D = \frac{4\pi}{\lambda^2} A$$

Electrically Small Dipole
D = 1.5 (1.76 dB)

Increase
Aperture area

More Directivity

Alternatives: Arrays, Zero-Index Superstrates, AMCs, EBGs, Huygens Sources

Directive Antennas: $D = 4\pi A / \lambda^2$ $= (ka)^2$ for circular aperture

Reflector antennas are high gain antennas

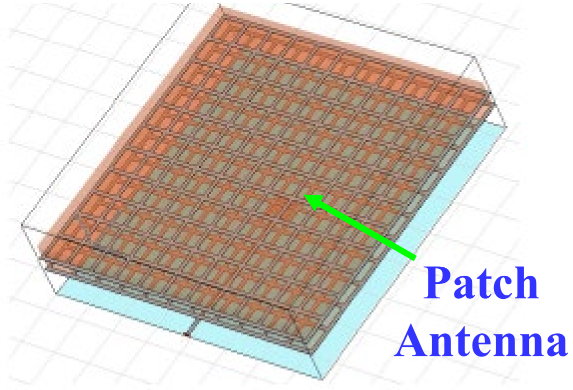
Large area = Very high directivity

> 50 dBi (10^5)

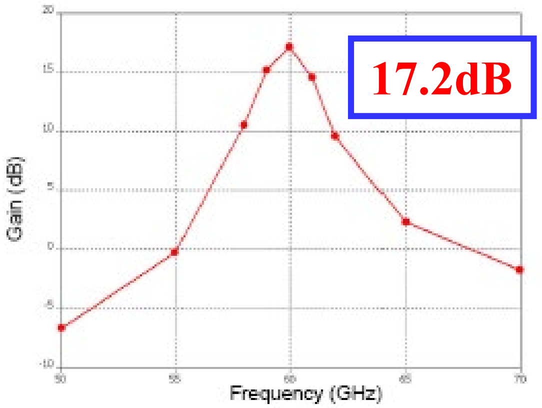
We achieved higher directivity with several metamaterial techniques – these were not electrically small

Zero-Index Superstrates

Zero-n effects give best directivity for given area

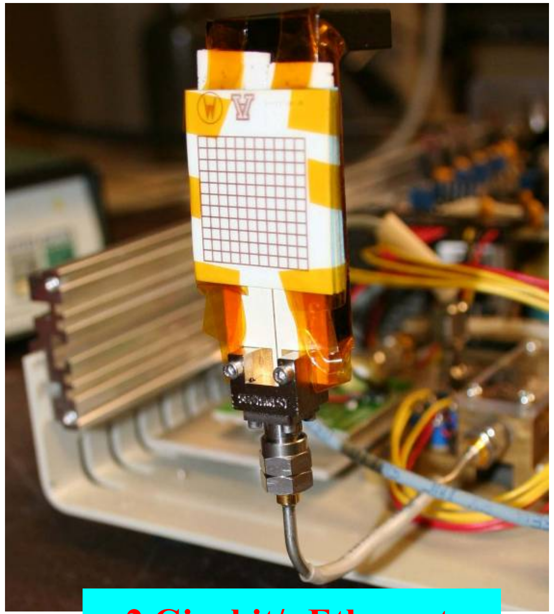


(a) Structure



Bare Patch ~ 3.2dB

60 GHz Experimental verification



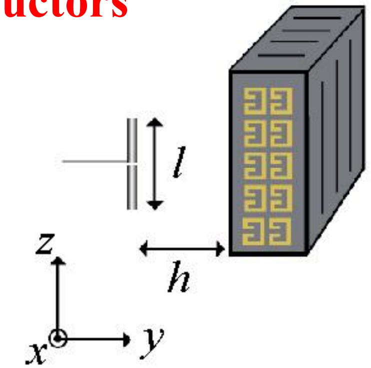
2 Gigabit/s Ethernet data exchange achieved

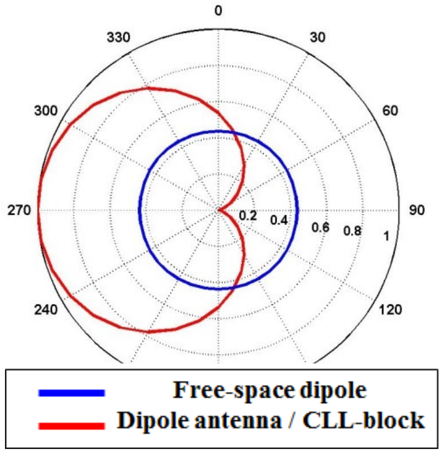
S. J. Franson and R. W. Ziolkowski, "Gigabit per second data transfer in high gain metamaterials structures at 60GHz," *IEEE Trans. Antennas Propag.*, vol. 57, pp. 2913-2925, Oct. 2009

We have achieved higher directivity with several other Metamaterial-based techniques:

Artificial Magnetic Conductors (AMCs)

MNG unit cells = CLLs
***NO* ground plane**

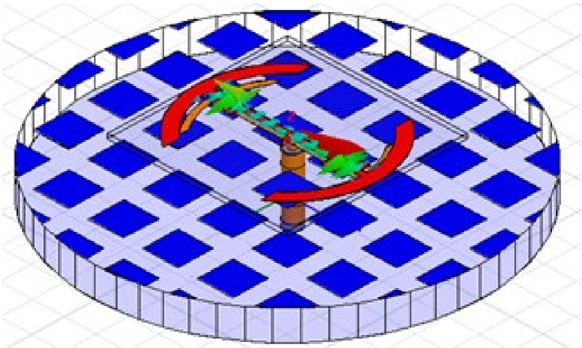




A. Erentok, **P. Luljak, and R. W. Ziolkowski, "Antenna performance near a volumetric metamaterial realization of an artificial magnetic conductor,"** ***IEEE Trans. Antennas and Propagat.*****, vol. 53, pp. 160-172, Jan 2005**

Electromagnetic Bandgap (EBG) Structures

EAD +
Mushroom
Structured
Ground plane
HIS = High
Impedance Surface

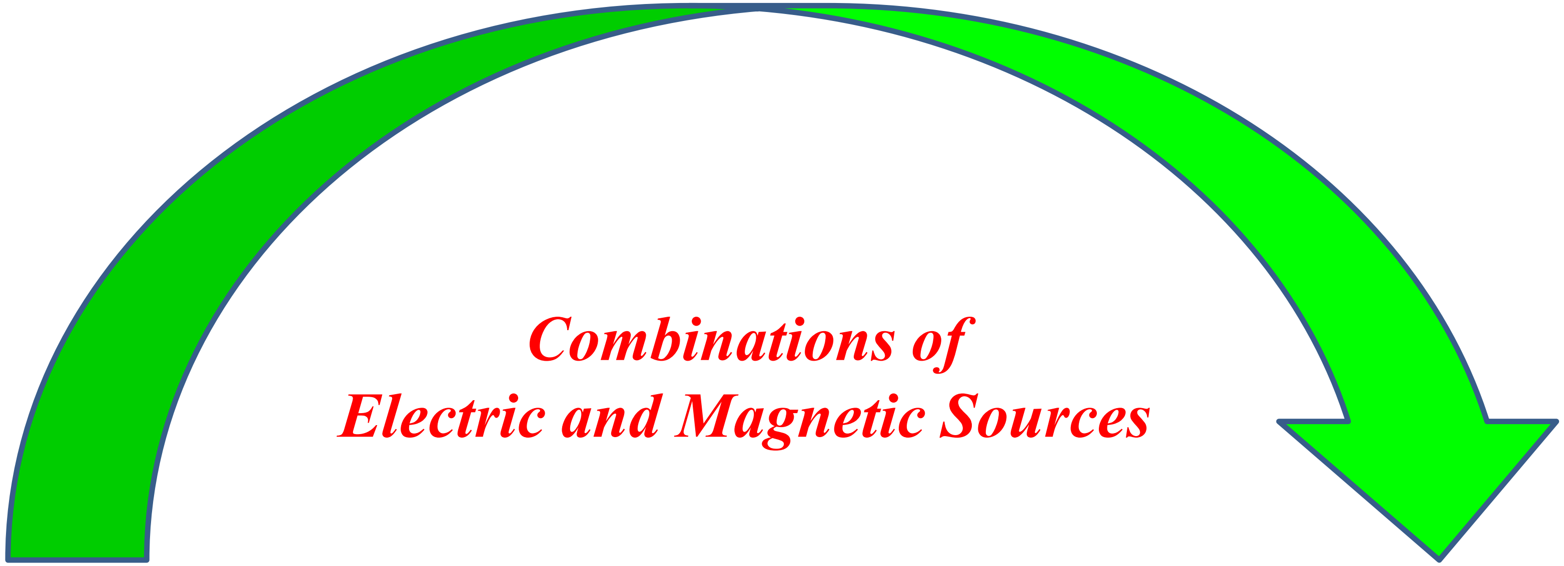


EBG substrate: TransTech MCT-40
$\varepsilon_r = 40$, $\tan \phi \leq 0.0015$

Results:
ka ~ 1 @ 1575.42 MHz
Peak Gain = 4.36 dB
FTBR = 4.88 dB
OE = 87.82%

P. Jin and R. W. Ziolkowski, "High directivity, electrically small, low-profile, near-field resonant parasitic antennas," ***IEEE Antennas Wireless Propag. Lett.*****, vol. 11, pp. 305-309, 2012**

Can one achieve an *electrically small source* with more directivity than a dipole, i.e., > 1.5 (1.76 dB) ??



Combinations of
Electric and Magnetic Sources

Electrically Small Dipole
G = 1.5 (1.76 dB)

More Directivity

High directivity from small R&Ss is possible – in theory *AND* in practice ☺

Superposition of a large number, N, of higher order multipoles leads to super-directivity

Oseen's "Einstein needle radiation"

C. W. Oseen, *Ann. Phys. (Leipzig)*, vol. 69, 202 (1922)

100 yr Anniversary 🎉

R. F. Harrington, "On the gain and beamwidth of directional antennas," *IRE Trans. Antennas Propag.*, vol. 6, no. 3, pp. 219–225, Jul. 1958

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

Antenna, Scatterer

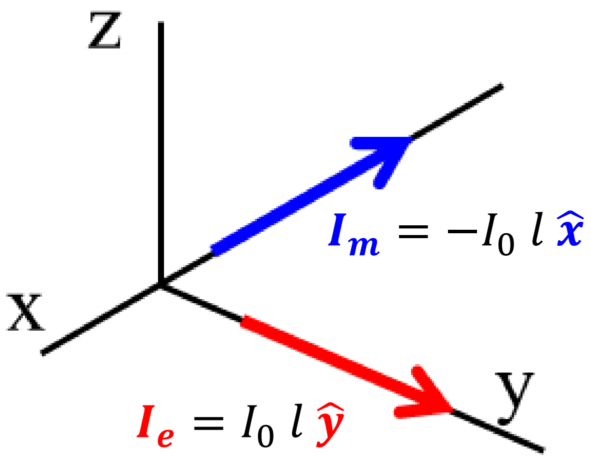
Presence of both electric and magnetic multipoles (order N)

Huygens Dipole R&Ss: **N = 1** $D_{max} = 3$ **(4.77 dB)**

Ideal Broadside Radiating Huygens Dipole Source

The electric fields radiated into the far field of a combination of balanced, in-phase pair of electric and magnetic sources

an elemental electric current source $\vec{J}$ along the y-axis
and
an elemental magnetic current source $\vec{K}$ along the -x-axis



$$\vec{E}^{ff}_{\omega,J}(\vec{r}) = j\,\omega\,\mu\,I_0\ell\frac{e^{-jkr}}{4\,\pi\,r}\;(\,\hat{r}\times\hat{r}\times\hat{y}\,)$$

$$\vec{E}^{ff}_{\omega,K}(\vec{r}) = -j\,\omega\,\mu\,I_0\ell\;\frac{e^{-jkr}}{4\,\pi\,r}\;(\,\hat{r}\times\hat{x}\,)$$

$$\boxed{\overrightarrow{ED}\times\overrightarrow{MD}\propto\hat{z}}$$

Superposition:

$$\vec{E}^{ff}_{\omega,\text{total}}(\vec{r}) = j\,\omega\,\mu\,I_0\ell\;\frac{e^{-jkr}}{4\,\pi\,r}\;\vec{\mathcal{P}}(\theta,\phi)$$

$$\vec{H}^{ff}_{\omega,\text{total}}(\vec{r}) = \frac{1}{\eta}\;\hat{r}\times\vec{E}^{ff}_{\omega,\text{total}}(\vec{r})$$

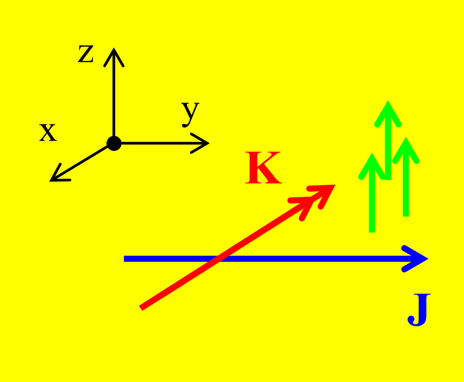
Vector Pattern:

$$\begin{aligned}\vec{\mathcal{P}}(\theta,\phi) = \Big[\;(\,\hat{r}\times\hat{r}\times\hat{y}-\hat{r}\times\hat{x}\,)\;\Big] &= \sin^2\theta\sin\phi\cos\phi\,\hat{x}\\ &-(\cos^2\theta+\sin^2\theta\cos^2\phi+\cos\theta)\,\hat{y}\\ &+[\sin\theta\sin\phi+\sin\theta\cos\theta\sin\phi]\;\hat{z}\end{aligned}$$

The combination of balanced, in-phase electric and magnetic dipole current moments yields a *CARDIOID* pattern

Huygens Dipole Antenna (**HDA**)

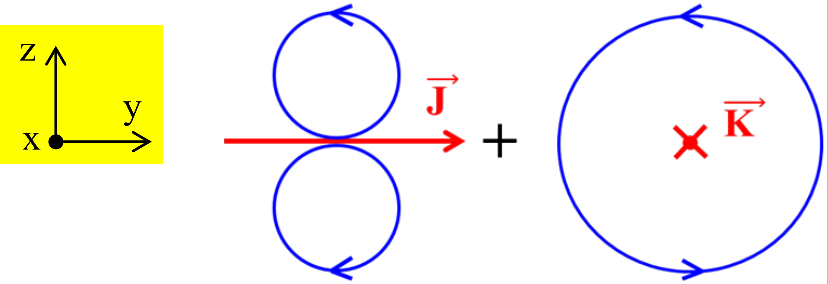
Electric dipole



Magnetic dipole

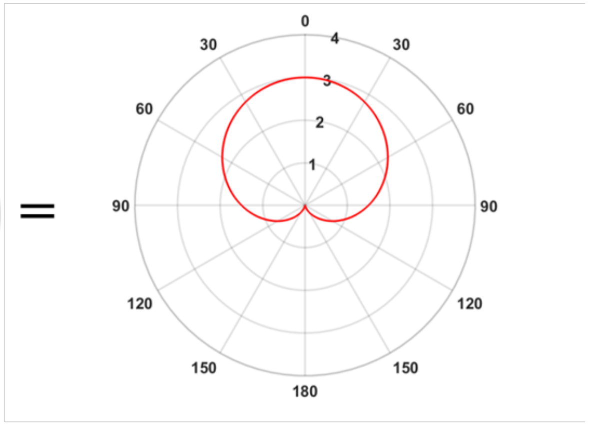
Note equal cardioids in both principal planes

Electric Field



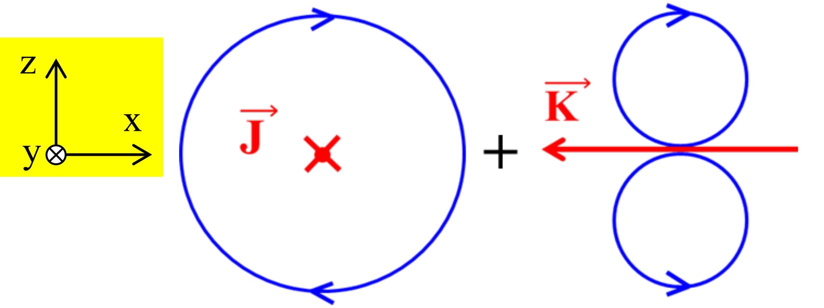
$\varphi = 90°$

=



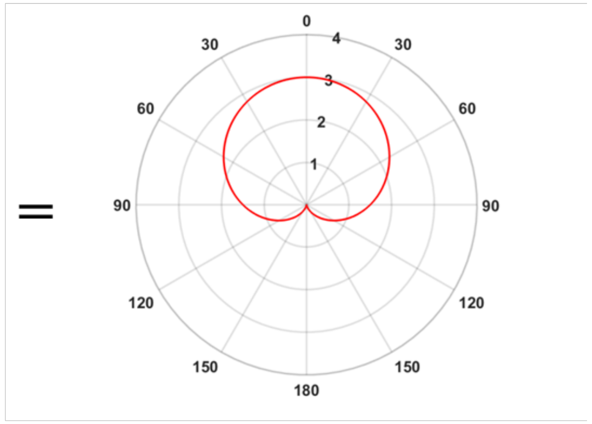
Cardioid Directivity

Magnetic Field



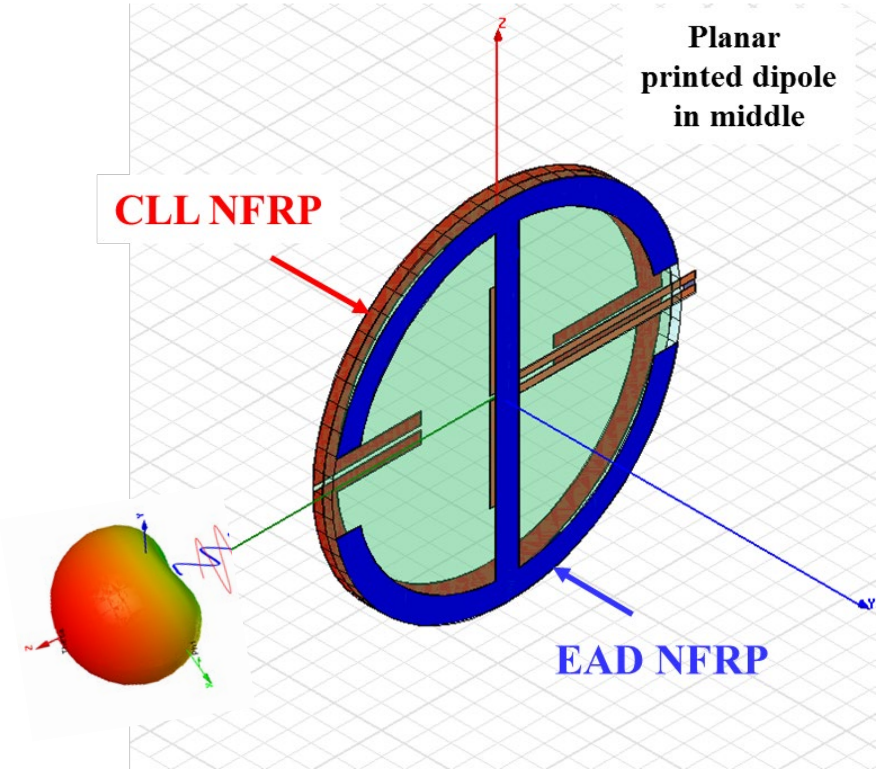
$\varphi = 0°$

=



Both endfire and broadside Huygens near-field resonant parasitic (NFRP) antennas have been designed and confirmed experimentally

Endfire



Planar printed dipole in middle

CLL NFRP

EAD NFRP

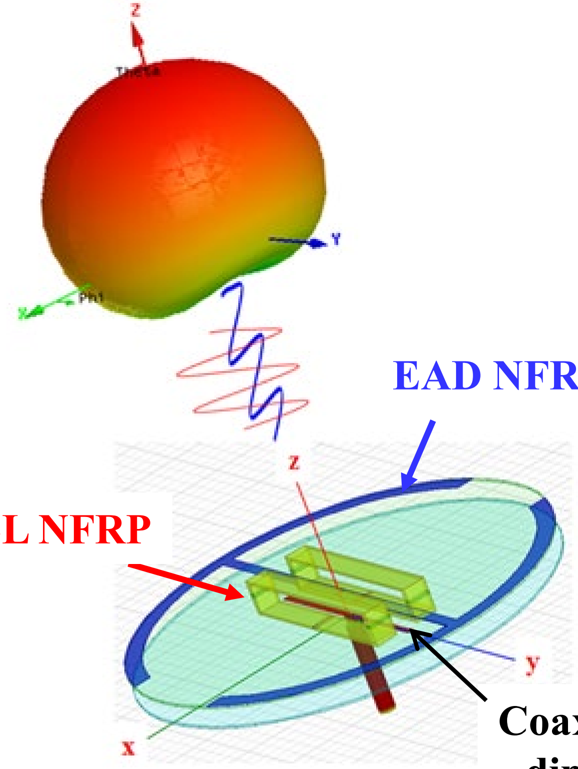
P. Jin and R. W. Ziolkowski

“Metamaterial-inspired, electrically small, Huygens sources,”

IEEE Antennas Wirel. Propag. Lett., vol. 9, pp. 501-505

May 2010

Broadside



EAD NFRP

CLL NFRP

Coax-fed dipole

R. W. Ziolkowski

“Low profile,
broadside radiating, electrically small
Huygens source antennas,”

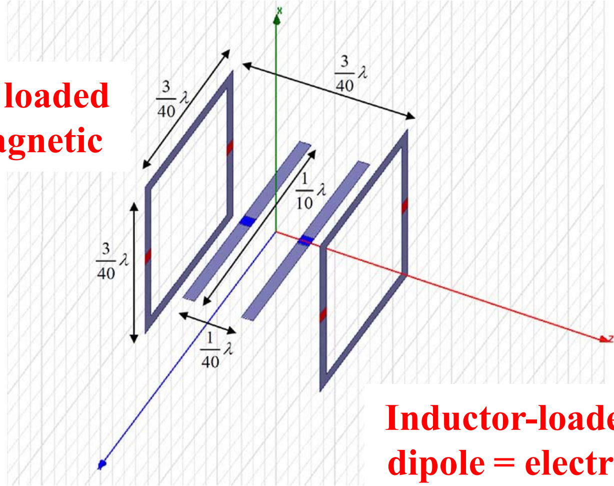
IEEE Access, vol. 3, pp. 2644-2651

Dec. 2015

Huygens metasurface analogue

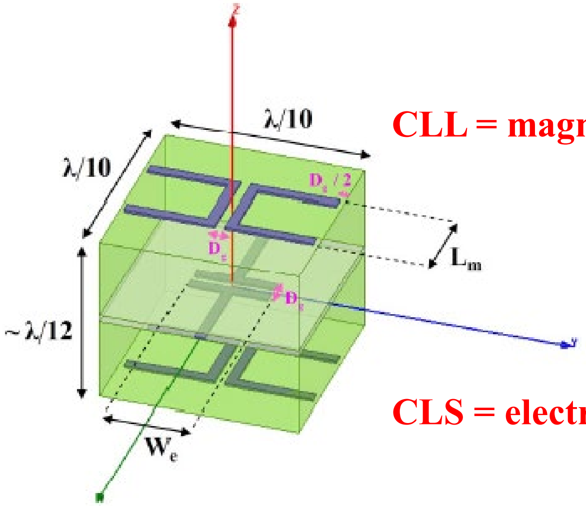
A. Eptein and G. V. Eleftheriades
Passive lossless Huygens metasurfaces for conversion of arbitrary source field to directive radiation
IEEE Antennas Propag., vol. 62, no. 11, pp. 5680-5695, Nov. 2014

A. Eptein and G. V. Eleftheriades
Huygens' metasurfaces via the equivalence principle: Design and applications
J. Opt. Soc. Am. B, vol. 33, no. 2, A31-A50, Feb. 2016



Capacitor loaded
CLL = magnetic

Inductor-loaded
dipole = electric

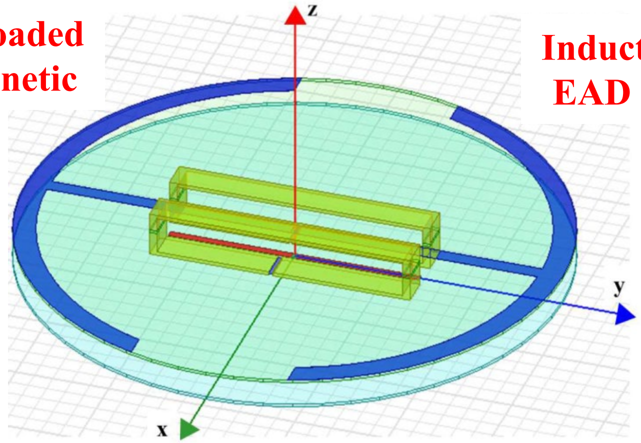


CLL = magnetic

CLS = electric

Capacitor loaded
CLL = magnetic

Inductor-loaded
EAD = electric

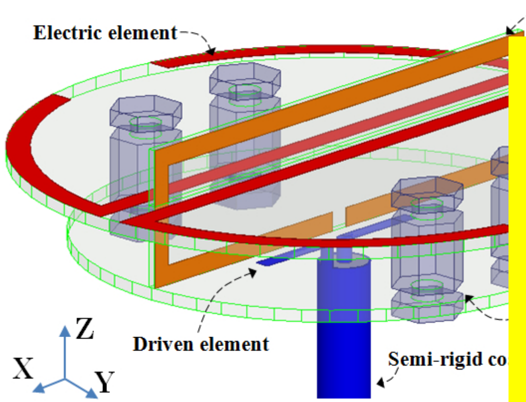


R. W. Ziolkowski
Low profile, broadside radiating, electrically small Huygens source antennas
IEEE Access, vol. 3, pp. 2644-2651, Dec. 2015

$ka = 0.45$

$h \sim \lambda_0 / 80$

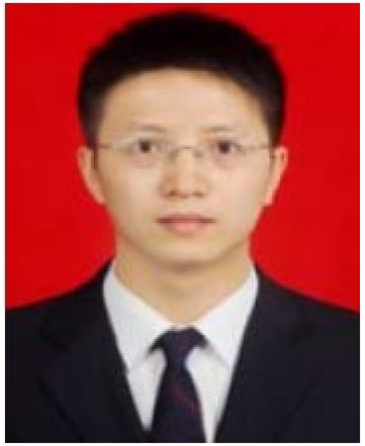
Original experimentally verified, *broadside radiating* electrically small, NFRP LP HDA



H = λ / 20.45

Si ed

TANG, Ming-Chun
Chongqing University

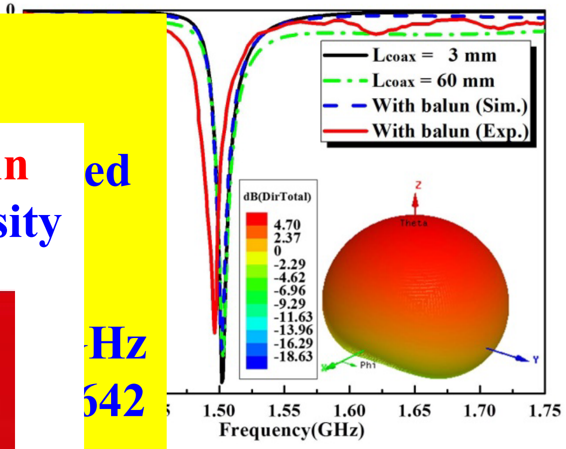


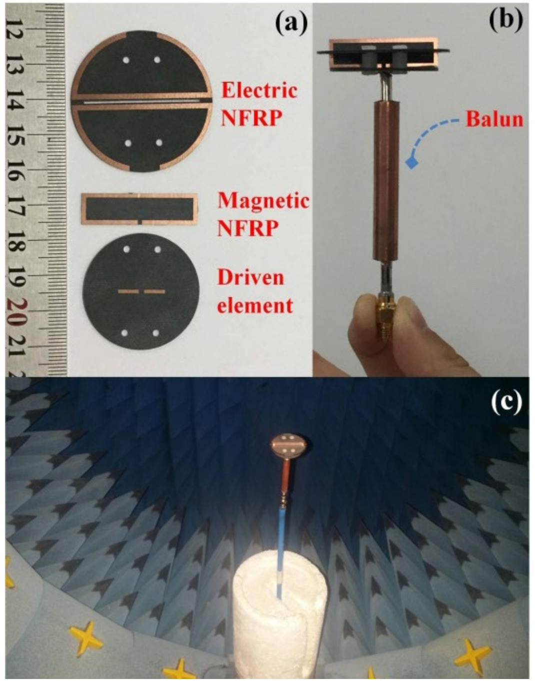
1.5 Hz
ka 642

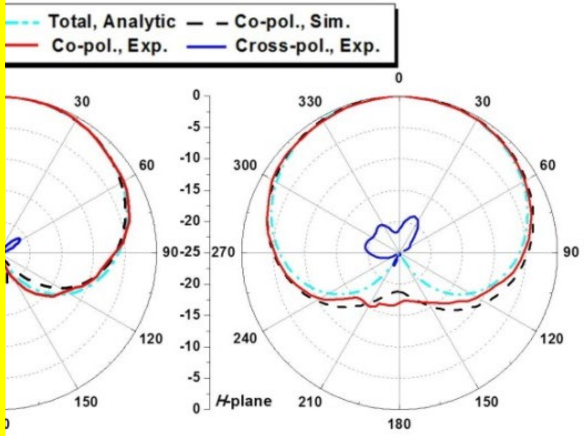
3. Bi

18 B

-10 dB Impedance Bandwidth
8.1 MHz 9.3 MHz

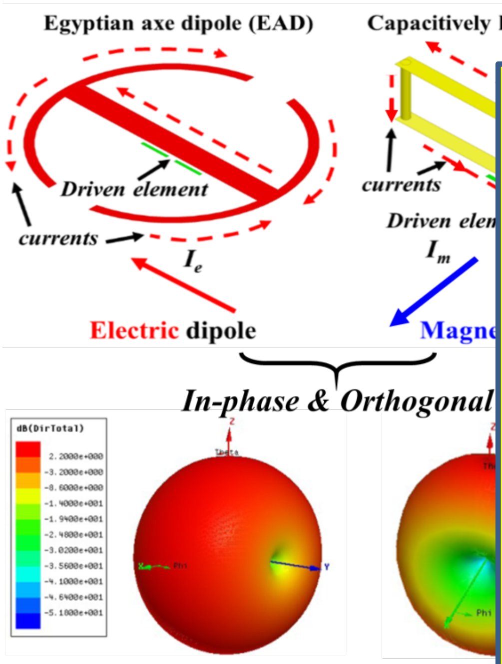






M.-C. Tang, H. Wang, and R. W. Ziolkowski, “Design and testing of simple, electrically small, low-profile, Huygens source antennas with broadside radiation performance,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 11, pp. 4607-4617, Nov. 2016

“Modern version” of a LP HDA, termed an HLP



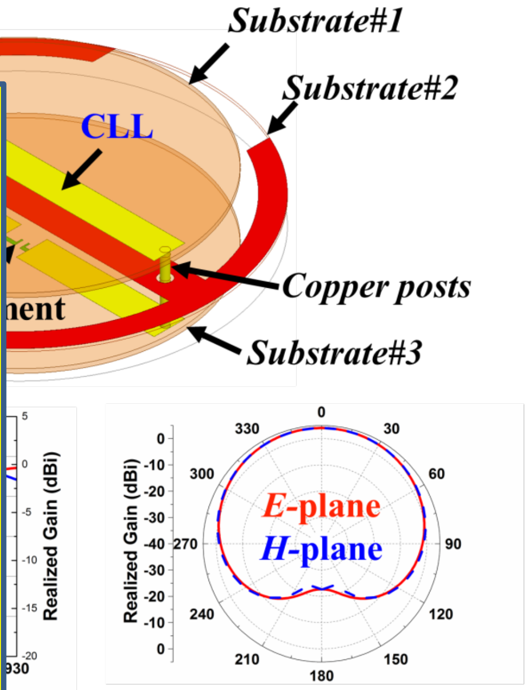
Dipole length: 0.5 Wavelength –

EAD diameter: 0.2 Wavelength -

LIN, Wei

University of Technology Sydney

ARC DECRA Fellow



B

3.8 dBi

HPBW: ± 67°

Identical at φ = 0 ° and 90 °

W. Lin, R. W. Ziolkowski, and J. Huang, Electrically small, low-profile, highly efficient, Huygens dipole rectennas for wirelessly powering Internet-of-Things devices, IEEE Trans. Antennas Propag., vol. 67, no. 6, pp. 3670-3679, Jun. 2019

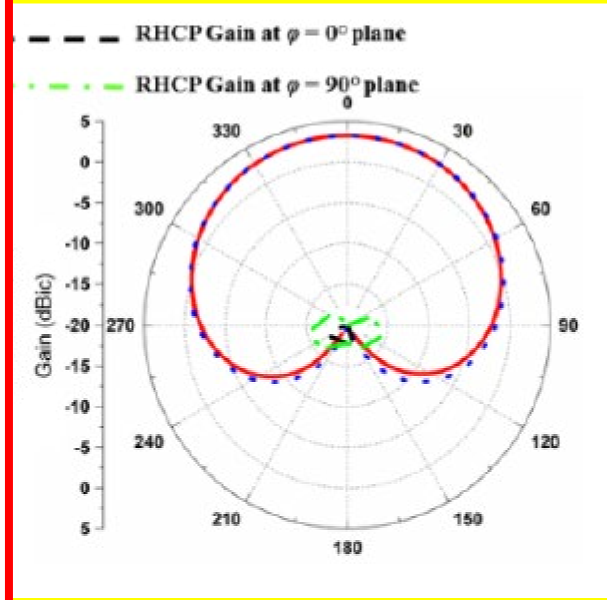
Multi-functional and Reconfigurable

HDAs have been achieved with

combinations of multiple NFRP elements

Electrically-Small Huygens CP antenna – 1.575 GHz version
Two pairs of EAD and CLL NFRP elements with 90° phase differences

Measured Results	
Polarization	LHCP
Profile	λ / 25
ka	0.73
Efficiency	70 %
FTBR	17.7 dB
Peak directivity	3.07 dBic



Realized gain pattern at 1.575 GHz

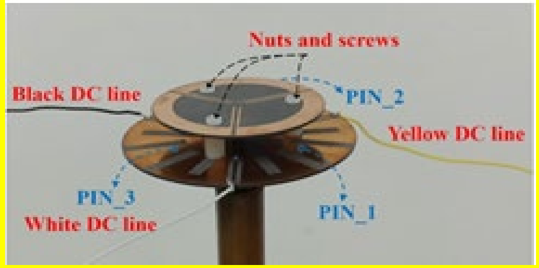
W. Lin and R. W. Ziolkowski, “Electrically-small, low-profile, Huygens circularly polarized antenna,” IEEE Trans. Antennas Propag., vol. 66, no. 2, pp. 636-643, Feb. 2018

We have successfully demonstrated a variety of *Reconfigurable* Huygens Dipole Antennas (HDAs)

☺ Pattern reconfigurable HDA covering entire azimuthal plane

M.-C. Tang, B. Zhou, and R. W. Ziolkowski

Low-profile, electrically small, Huygens source antenna
with pattern-reconfigurability that covers the entire azimuthal plane
IEEE Trans. Antennas Propag., vol. 65, no. 3, pp. 1063-107, Mar. 2017



☺ Polarization reconfigurable HDA

2 LP, LHCP, RHCP states

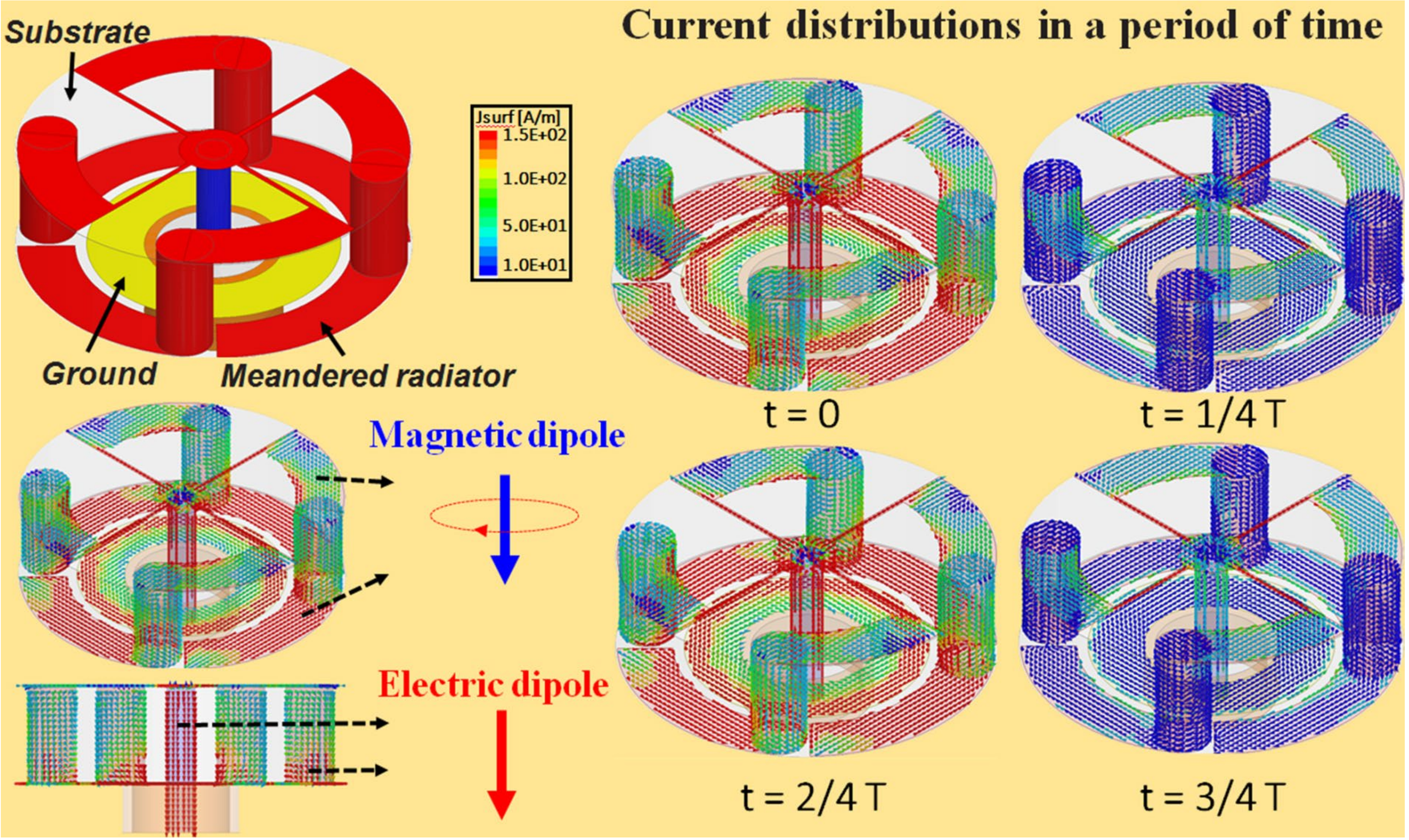
M.-C. Tang, Z. Wu, T. Shi, and R. W. Ziolkowski
Electrically small, low-profile, planar, Huygens dipole antenna with
quad-polarization diversity
IEEE Trans. Antennas Propag., vol. 66, no. 12, pp. 6772-6780, Dec. 2018.

☺ Ultrathin (λ_0 / 385) reconfigurable

Left-Right unidirectional and
Combined bi-directional in azimuthal plane

Z. Wu, M.-C. Tang, M. Li, and R. W. Ziolkowski
Ultra-low-profile, electrically small, pattern-reconfigurable
metamaterial-inspired Huygens dipole antenna
IEEE Trans. Antennas Propag., 04 Jul. 2019

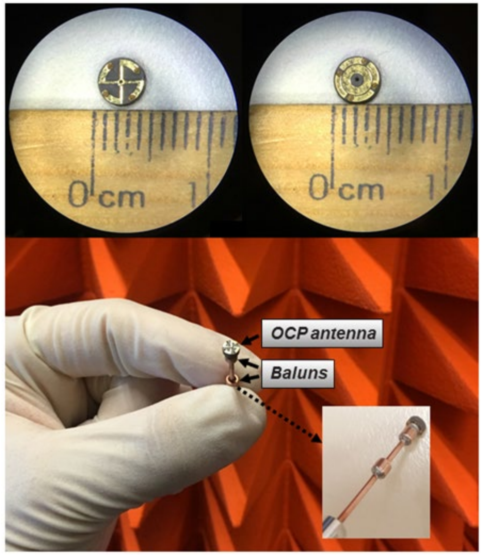
Combining Electric and Magnetic Dipoles Oriented in Parallel Produces an Omni-directional CP Antenna

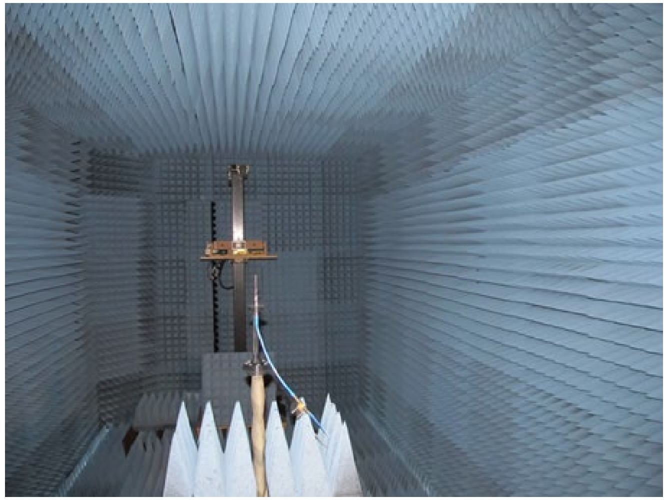


W. Lin, R. W. Ziolkowski, and T. C. Baum, "28GHz compact omni-directional circularly polarized antenna for device-to-device (D2D) communications in future 5G systems," *IEEE Trans. Antennas Propag*., vol. 65, no. 12, pp. 6904-6914, Dec. 2017

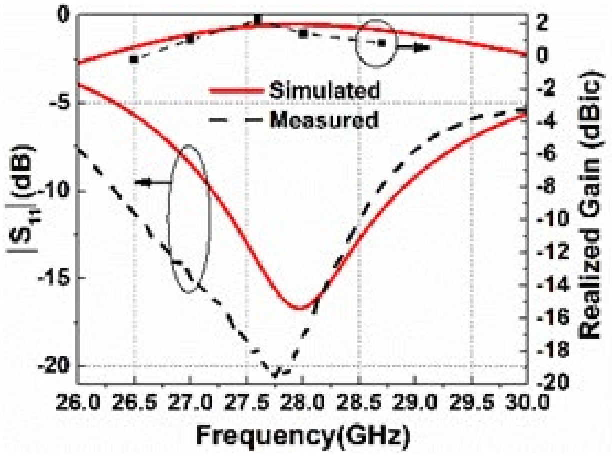
OCP prototype measured over 5G 28 GHz Band

Confirmation of simulated performance characteristics

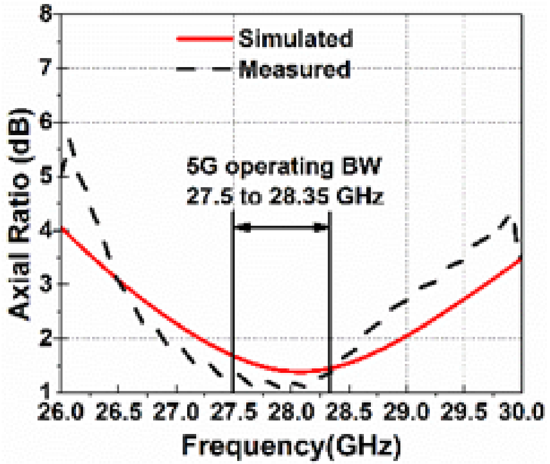




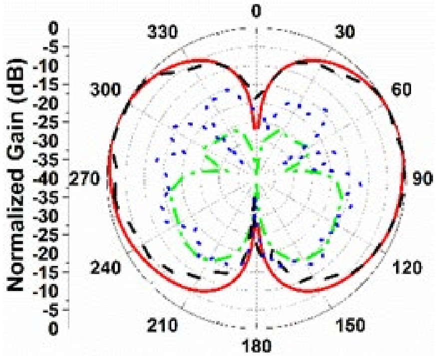
$|S_{11}|$ and Realized Gain



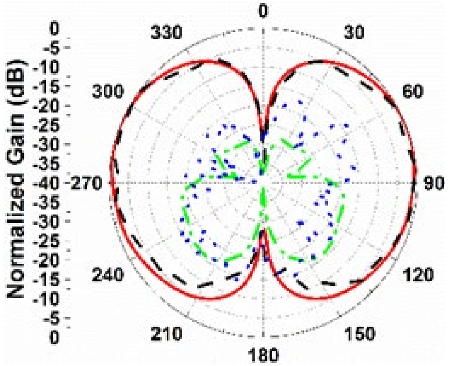
AR



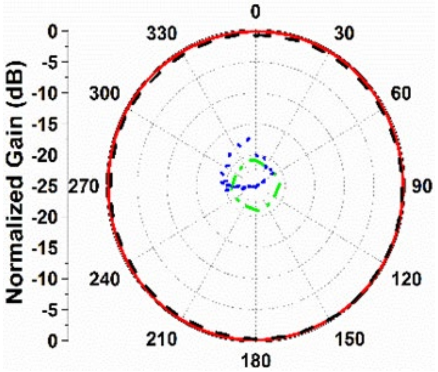
$\phi = 0°$



$\phi = 90°$

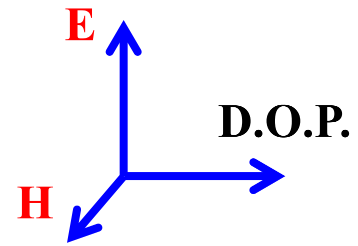


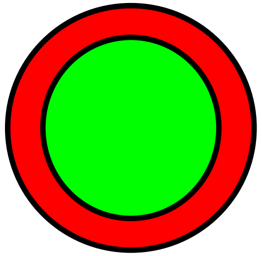
$\theta = 90°$



Realized Gain

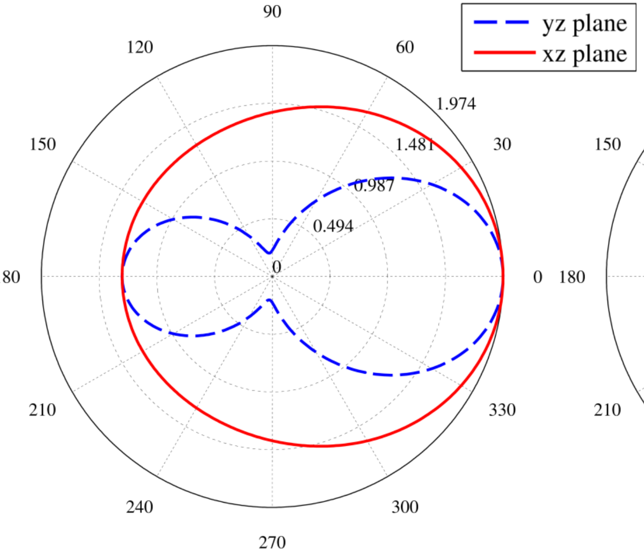
At IR frequencies, polaritonic materials exhibit large permittivity values
Simultaneously excite electric and magnetic dipoles
→ Huygens source properties



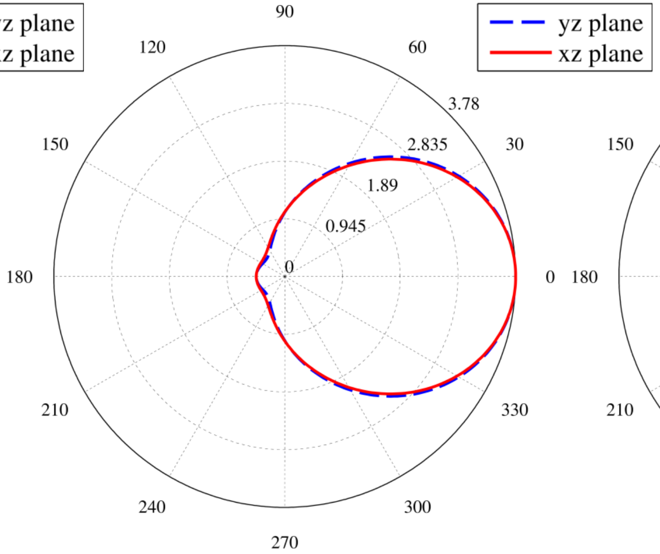


1 μm PbTe spherical core
Magnetic dipole response near 11μm

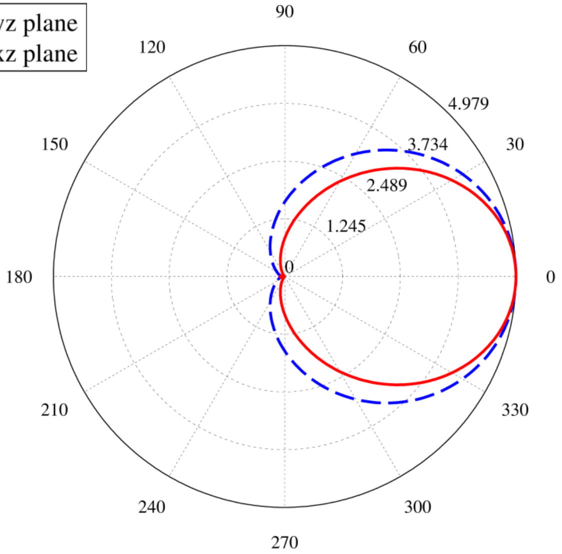
SiC (ENG) spherical shell
Tunable electric dipole response



1.2 core/shell ratio



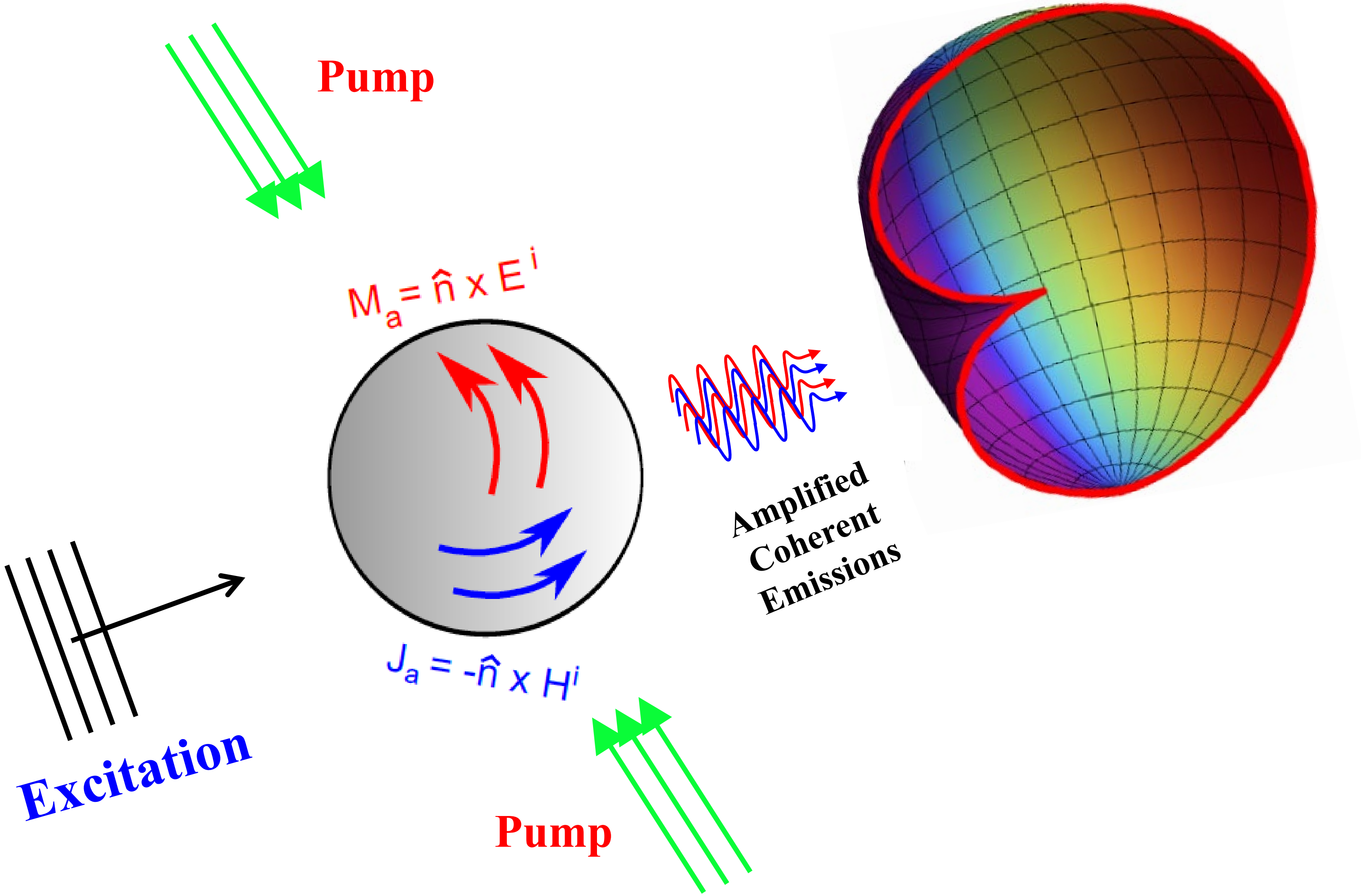
1.4 core/shell ratio



1.575 core/shell ratio

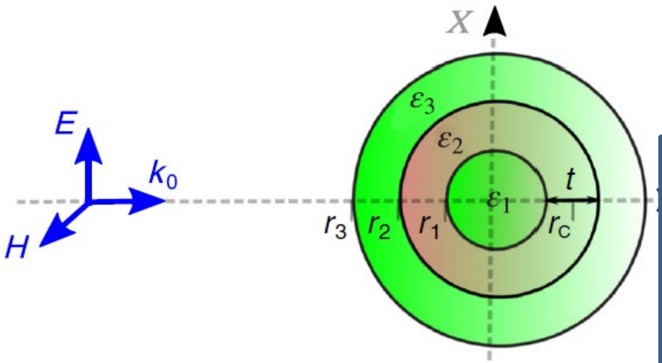
S. D. Campbell and R. W. Ziolkowski, Simultaneous excitation of electric and magnetic dipole modes in a resonant core-shell particle at infrared frequencies to achieve minimal backscattering, *IEEE J. Sel. Topics Quantum Electron.*, vol. 19, no. 3, 4700209, May/June 2013

Can we combine the Huygens source concepts, basic antenna theory, and our active CNP experiences to achieve a Huygens source nanolaser ??

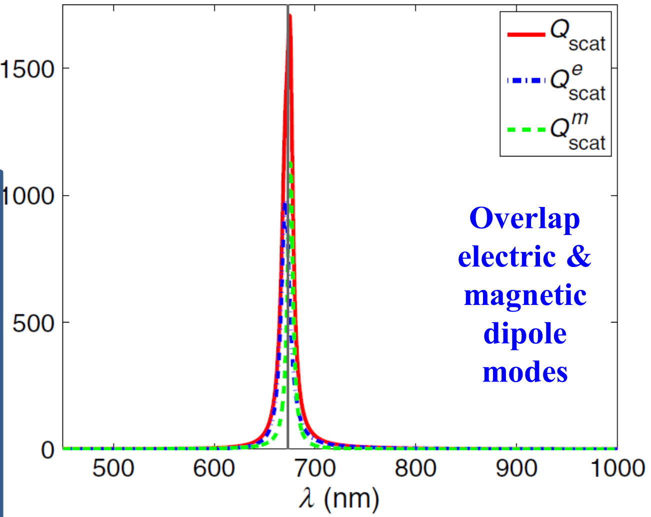


Can the *BALANCED* electric and magnetic dipoles responses be enhanced by the same gain constant at the same optical frequency?

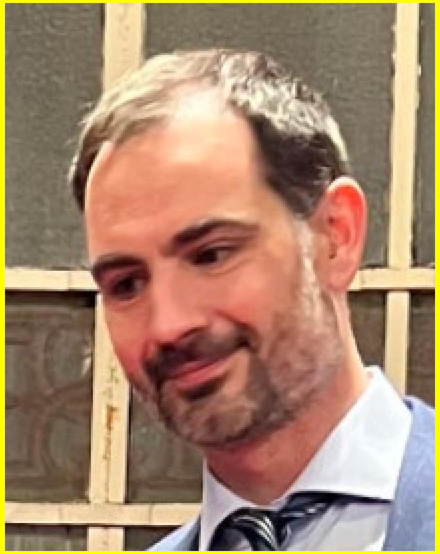
With high eps material to obtain both electric and magnetic dipole modes, we designed a Huygens source nanoparticle laser



Gain in Si core
120 nm outer radius
Si-Ag-Si

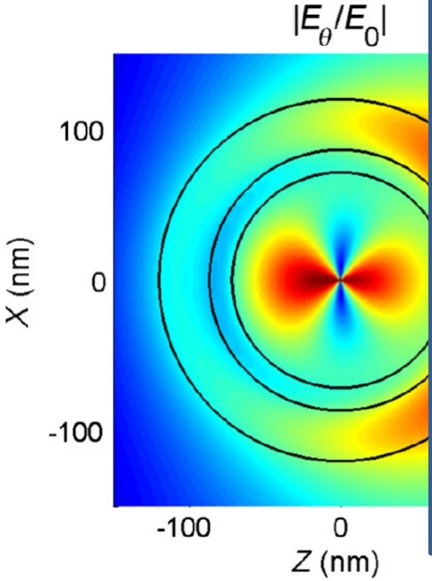


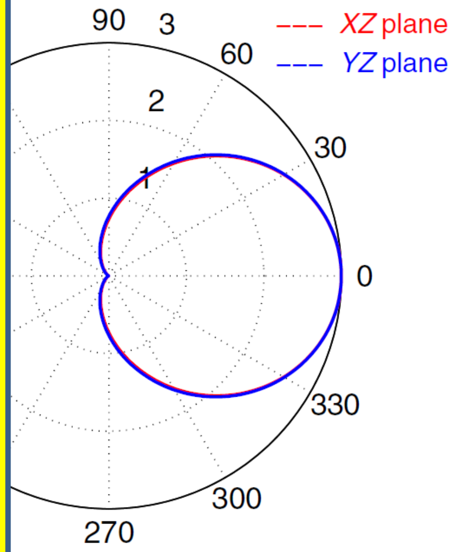
Overlap electric & magnetic dipole modes



Inigo Liberal
UPNA
Leo Felsen Award
EuCAP 2022

Tune electric and magnetic dipol
overlap in the presence of





I. Liberal, I. Ederra, R. Gonzalo, and R. W. Ziolkowski, **Induction theorem analysis of resonant nanoparticles: Design of a Huygens source nanoparticle laser,** *Phys. Rev. Applied*, vol. 1, 044002, May 2014.

Additional Degrees of Freedom with the NFRP Paradigm

Magic of Multipoles ☺

Employ a

Mixture of Multipoles

to achieve

Unidirectional,

even Higher Directivity

R&Ss

Determined the currents on a small sphere that would produce needle radiation

Far-field:

$$E_{\theta}^{J,ff}(r,\theta,\phi,\omega) = i\,\omega\,\mu\,\frac{e^{ikr}}{4\,\pi\,r}\,J_0\,a^2\,\mathcal{FJ}_{\theta}(\theta,\phi,\omega)$$

$$\mathcal{FJ}_{\theta}(\theta,\phi,\omega) = 4\pi \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell}(-i)^{\ell}\,c_{\ell\,m}\,j_{\ell}(ka)\,Y_{\ell\,m}(\theta,\phi)$$

Define:

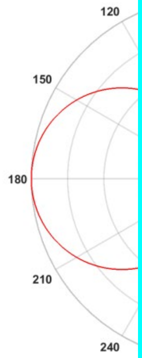
$$c_{\ell\,m} = \frac{1}{4\pi}\sqrt{\frac{2\ell+1}{4\pi}}\,\frac{i^{\ell}}{j_{\ell}(ka)}\,\delta_{m\,0}$$

Pattern:

$$\begin{aligned}\mathcal{FJ}_{\theta}(\theta,\phi,\omega) &= \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell}\sqrt{\frac{2\ell+1}{4\pi}}\,Y_{\ell\,m}(\theta,\phi)\,\delta_{m\,0}\\ &= \sum_{\ell=0}^{\infty}\left[\frac{2\ell+1}{4\pi}\right]P_{\ell}(\cos\theta)\,\delta(\phi)\ \equiv\delta(\hat{r}-\hat{z})\end{aligned}$$

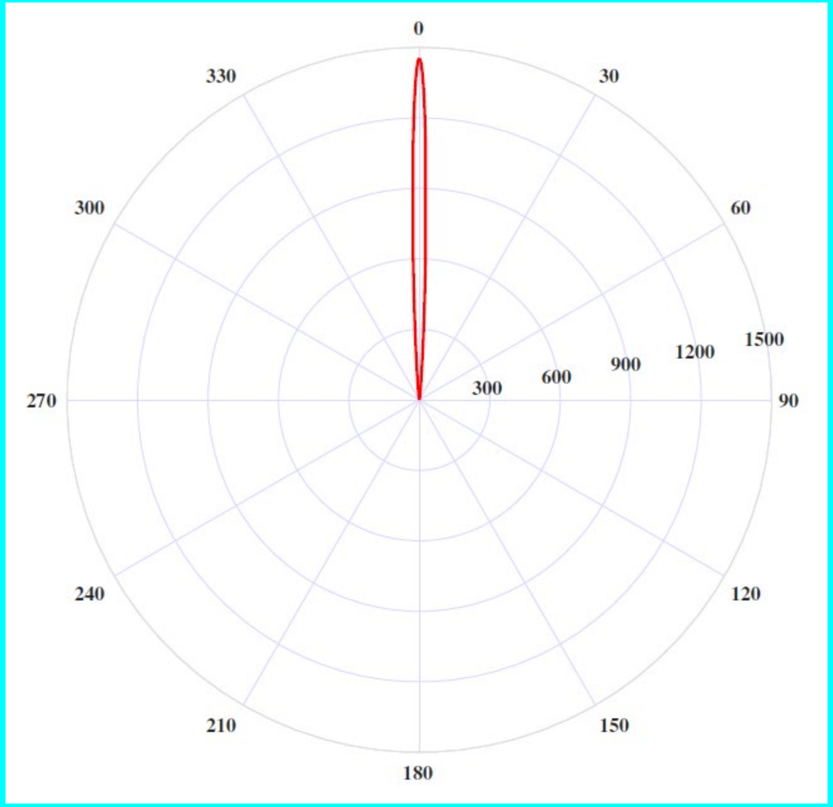
R. W. Ziolkowski, “Huygens multipole arrays to realize unidirectional needle-like radiation,” *Phys. Rev. X*, vol. 7, 031017, Jul. 2017

Higher-order Mode Patterns: N = 1, 2, 3, 4, 5



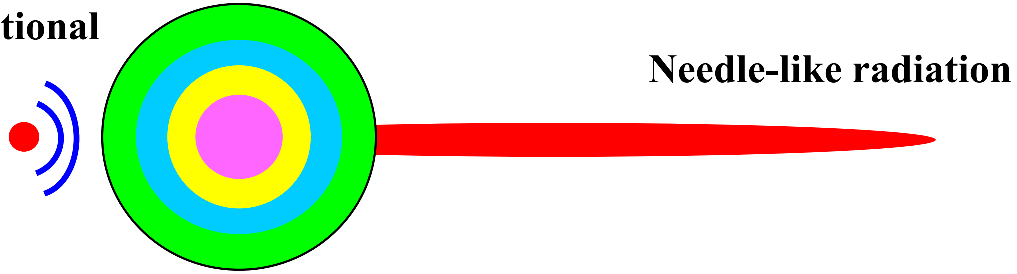
N = 1000 Huygens multipoles

Unidirectional Needle-like radiation



$N \to \infty$ $P_N(\theta) \to \delta(\theta)$

A multilayered cylinder can convert an isotropic source field into a superposition of higher order multipoles and produce needle-like radiation



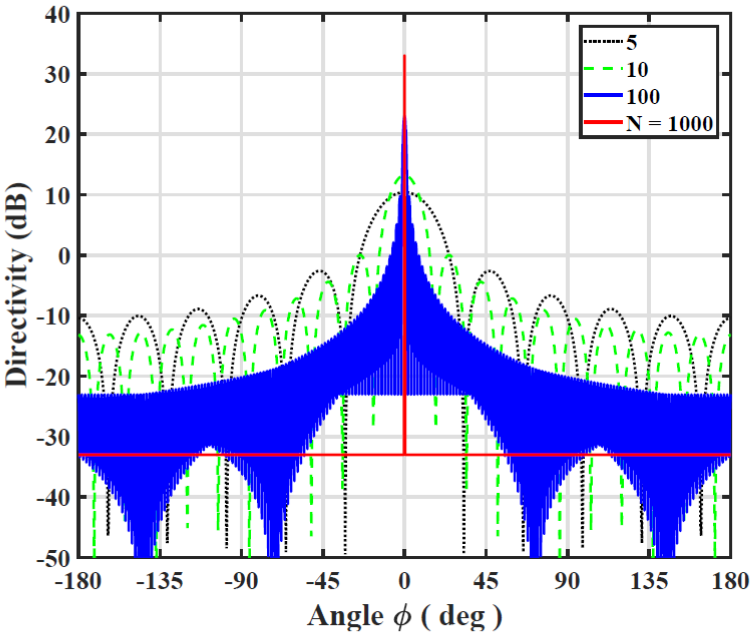
Omnidirectional Source

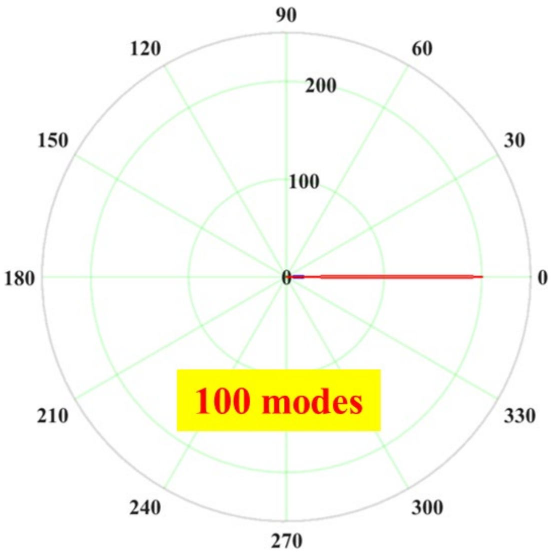
Needle-like radiation

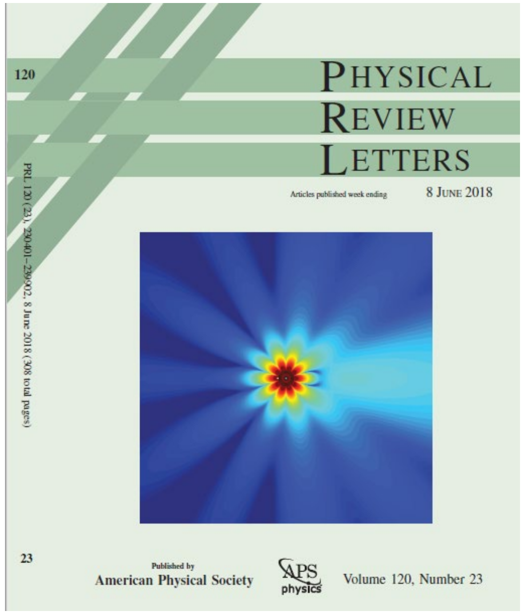
Multilayered Metamaterial-inspired Transformer

N-layered Cylinder
Canonical Scattering Problem

2D bound $D_{N,\max} \approx 2N+1$







PHYSICAL REVIEW LETTERS

Articles published week ending 8 JUNE 2018

Published by American Physical Society

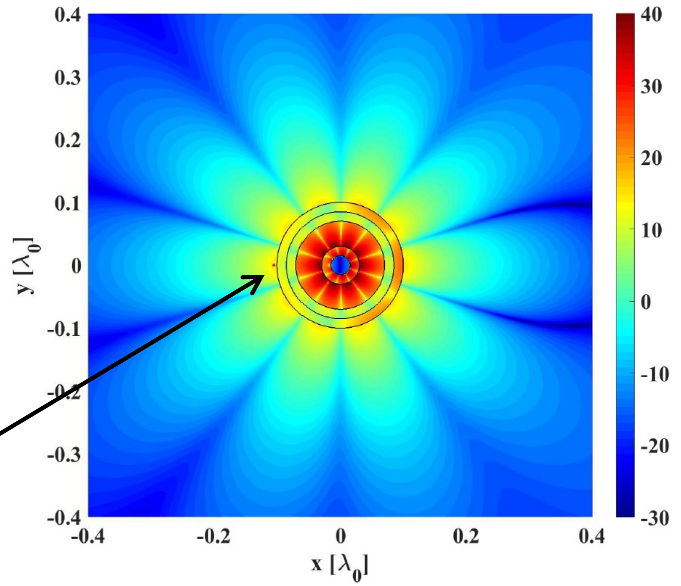
Volume 120, Number 23

S. Arslanagić and R. W. Ziolkowski, "Highly subwavelength, superdirective cylindrical nanoantenna," *Phys. Rev. Lett.*, vol. 120, 237401, Jun. 2018

Simulated results 5 layer (ENG, DPS values)

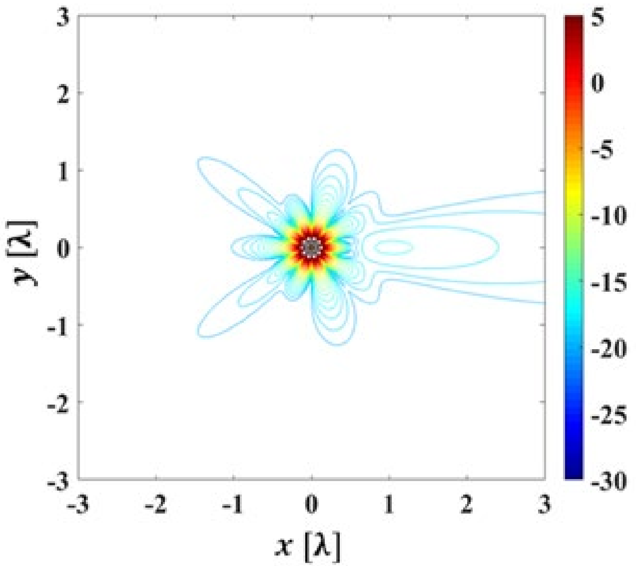
Size: λ / 10 total radius at 500 nm

Near field



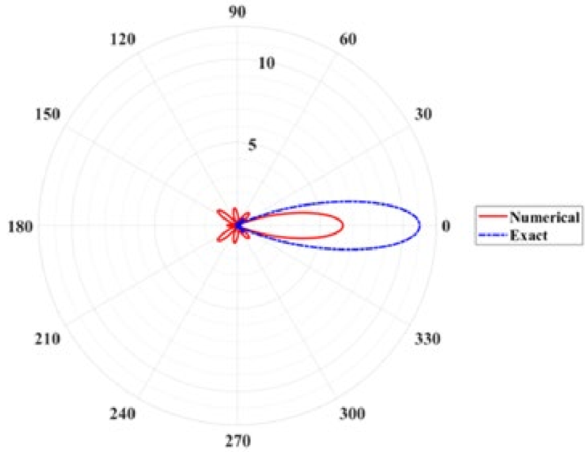
Source just outside cylinders

Mid range



Directivity Pattern

linear scale



Directivity $= 6.37 = 8.04$ dB

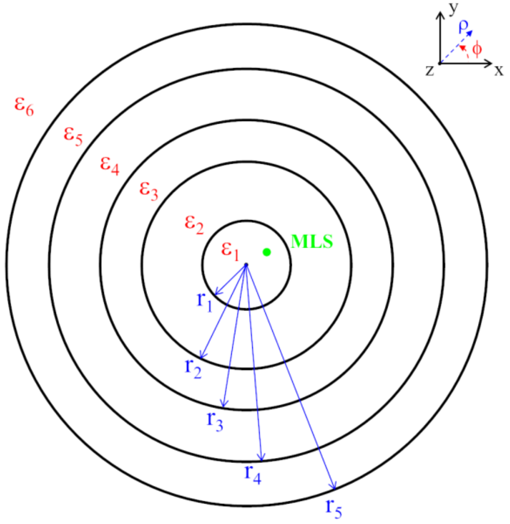
$= 5.07\, D_{2\mathrm{D,max}}$

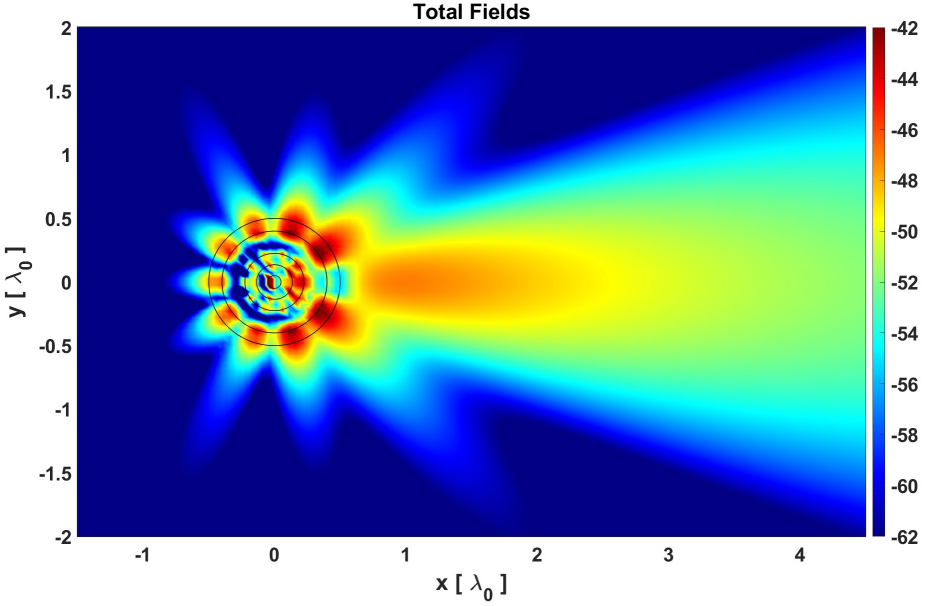
→ **Super-directive system**

S. Arslanagić and R. W. Ziolkowski, "Highly subwavelength, superdirective cylindrical nanoantenna," *Phys. Rev. Lett.*, vol. 120, 237401, Jun. 2018

R. W. Ziolkowski, Mixtures of multipoles – Should they be in your EM toolbox?,
IEEE Open J. Antennas Propag., vol. 3, pp. 154–188, 2022

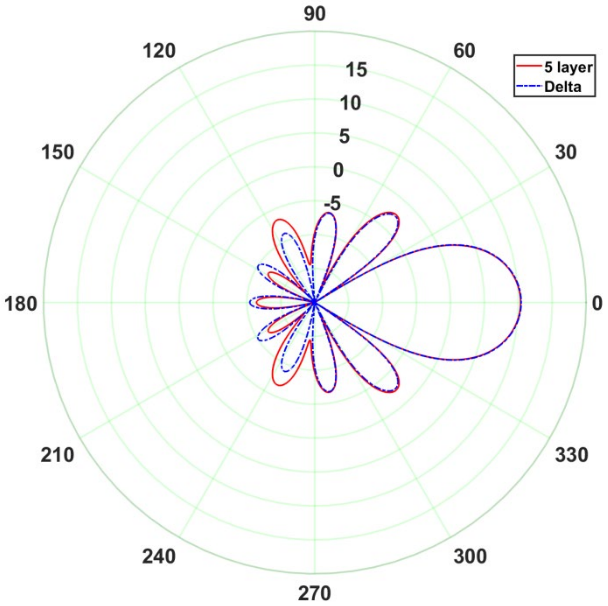
Antenna Version





Superdirective Performance

dB scale



Ideal coefficients Modes 0, 1, …, 5

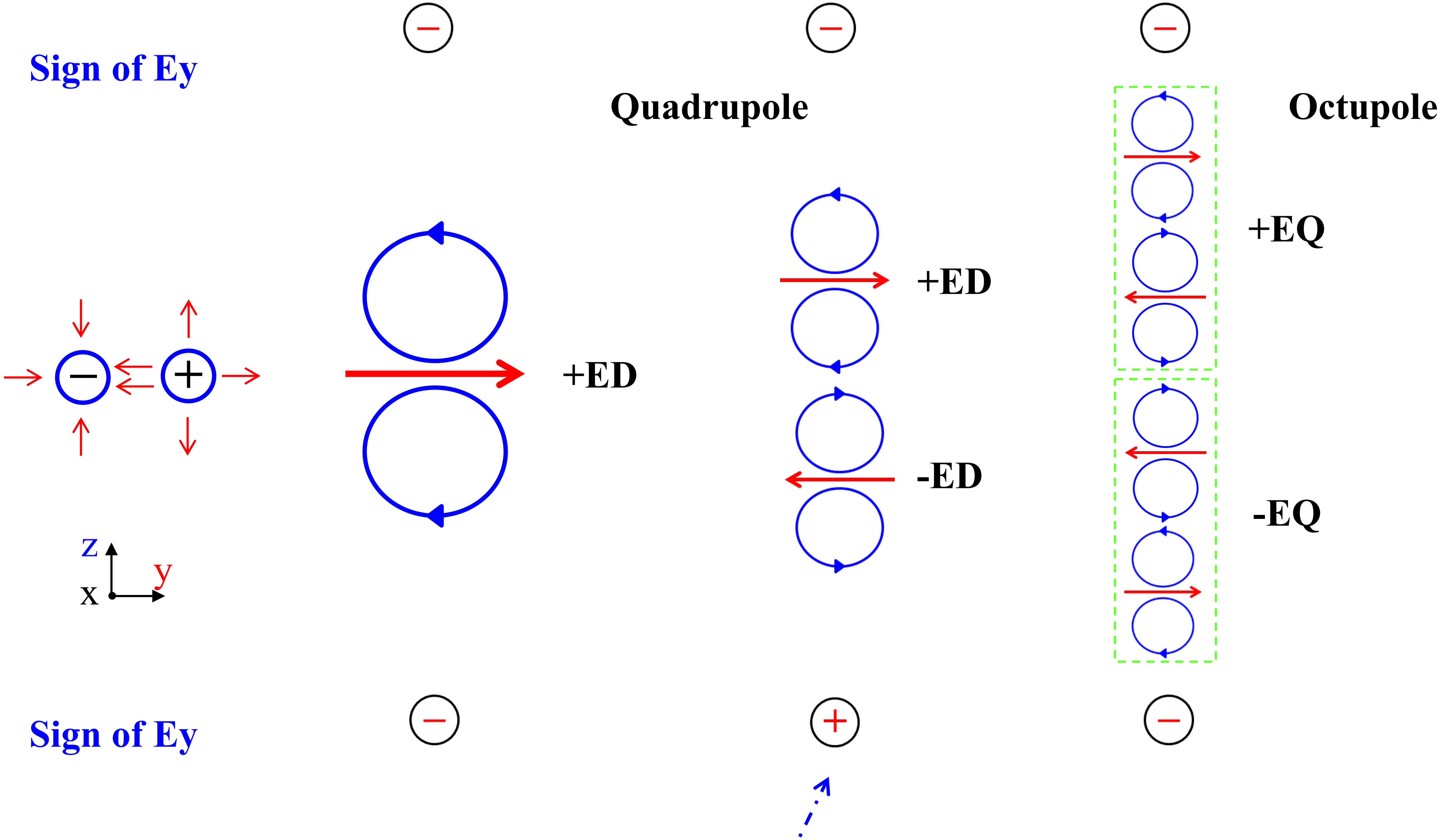
$D_{\max}$ = 10.41 dB

Theoretical maximum directivity for width of structure = 7.98 dB

With $r_5 = \lambda / 2$, 5 layers, realized:

$D_{\max}$ = 10.34 dB

How does one construct multipoles with dipole elements?



Sign of Ey

Quadrupole

Octupole

+EQ

+ED

+ED

-ED

-EQ

z

y

x

Sign of Ey

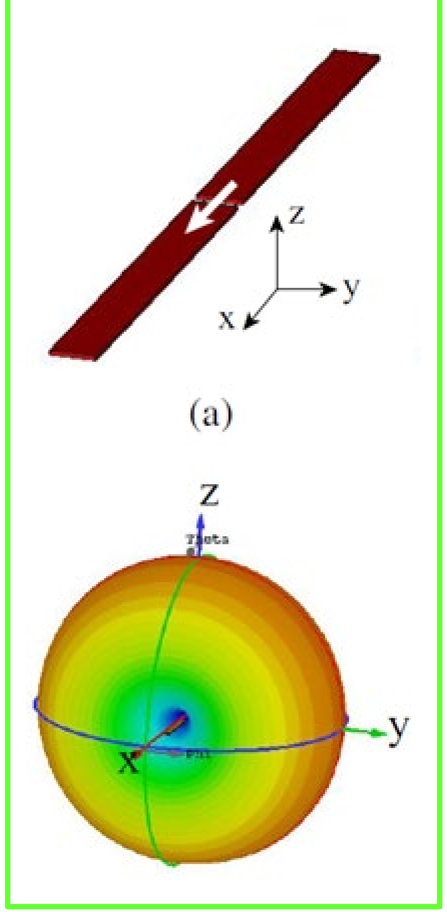
Like magnetic dipole!

Planar Quadrupole Antenna for 28 GHz

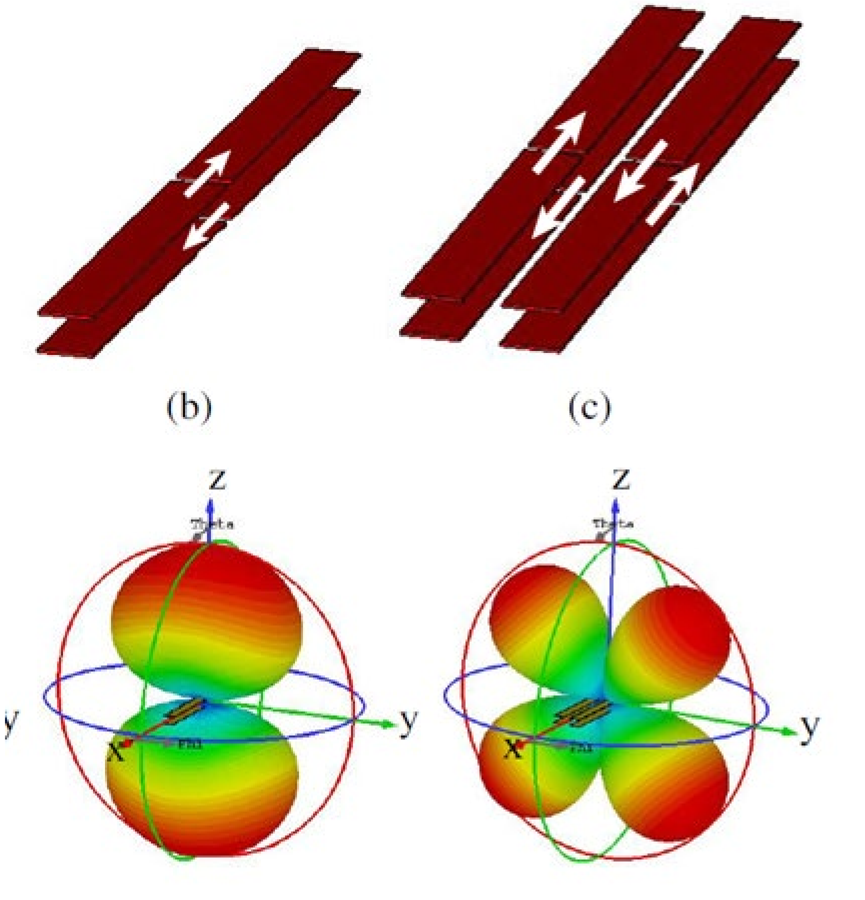
Active
λ/2 strips

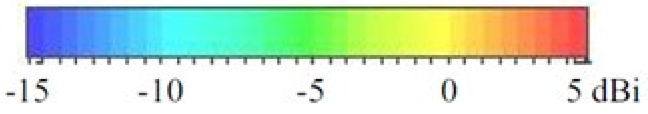
HFSS Sims

Dipole



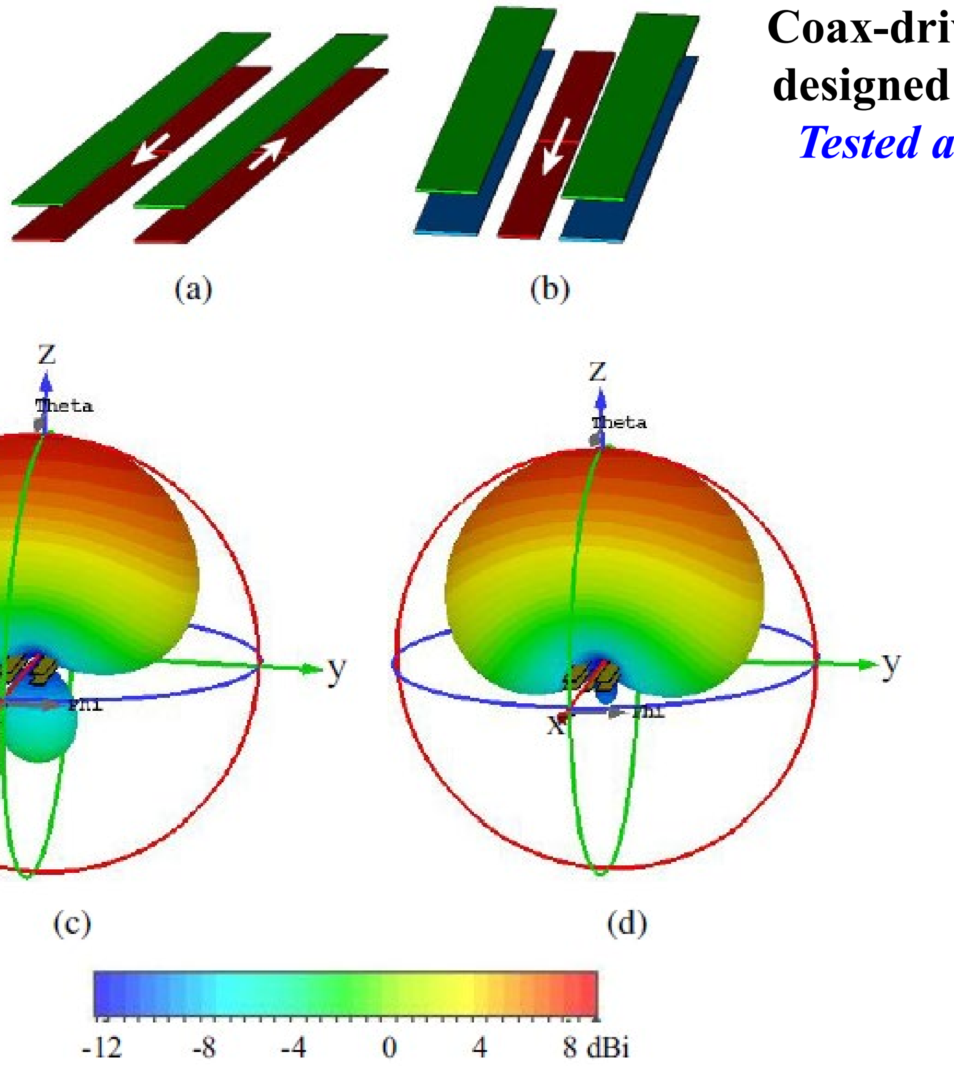
Quadrupoles





Planar NFRP Dipole-Quadrupole Antenna

Red – active
Green – passive
Blue – passive



(a) (b)

(c) (d)

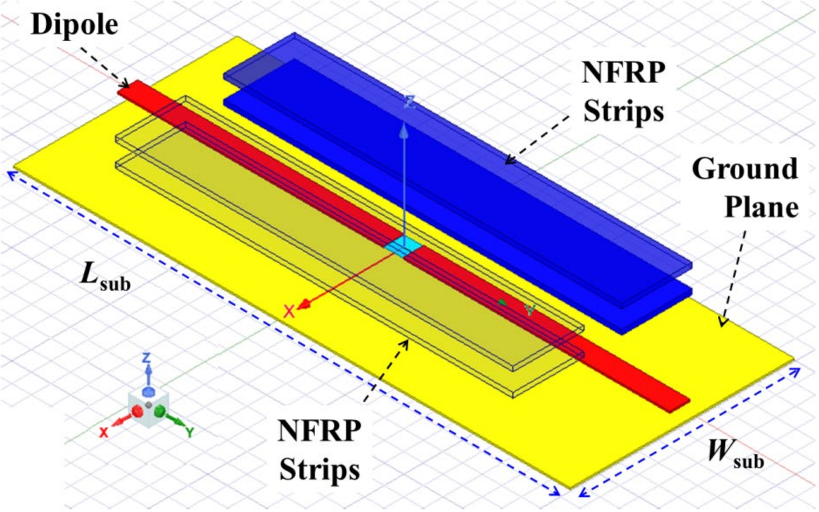
Coax-driven version
designed for 28 GHz
Tested at 1.57 GHz

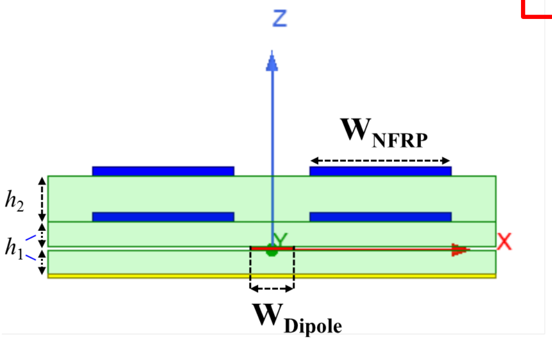
Rocio Rodriguez-Cano
GBDTC Visit
Aalborg Uni, Denmark
Post-doc PennState

R. Rodriguez-Cano and R. W. Ziolkowski, "**Single-layered, unidirectional, broadside-radiating planar quadrupole antenna for 5G IoT applications**," *IEEE Trans. Antennas Propag.*, vol. 69, no. 9, pp. 5524-5533, **Sep. 2021**.

Because the quadrupoles have a E-field symmetry like a magnetic dipole, can introduce a ground plane to remove the backlobe, yielding higher FTBR

OJAP 2022

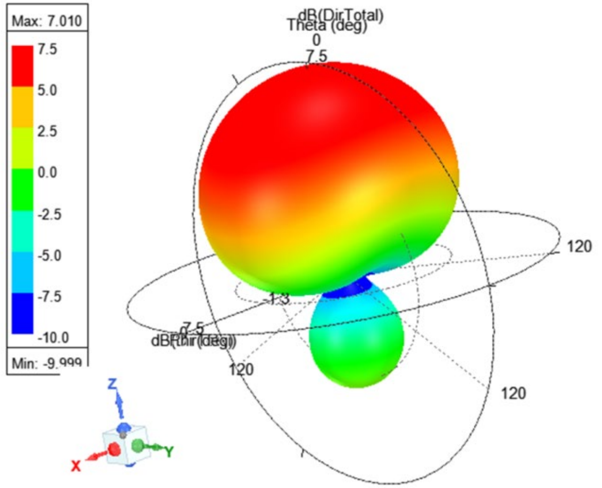




λ_{res} / 19

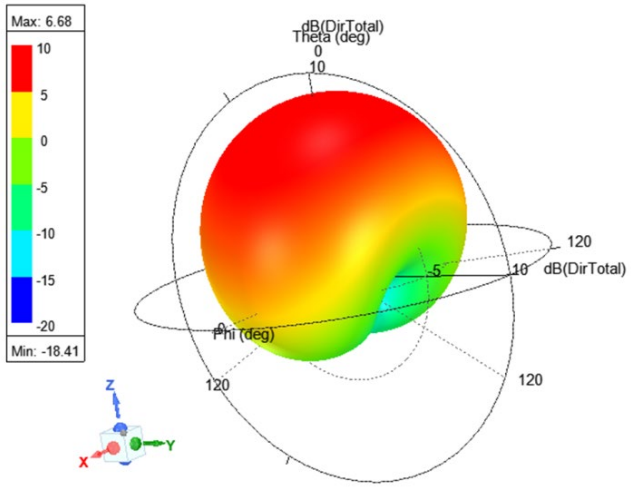
Low profile: horizontal dipoles in presence of ground plane

No Ground Plane



3-metal, 2 rohacell layers @ 28 GHz

Peak Dir = 7.01 dB, FTBR = 7.57 dB, Rad Eff = 97.1%

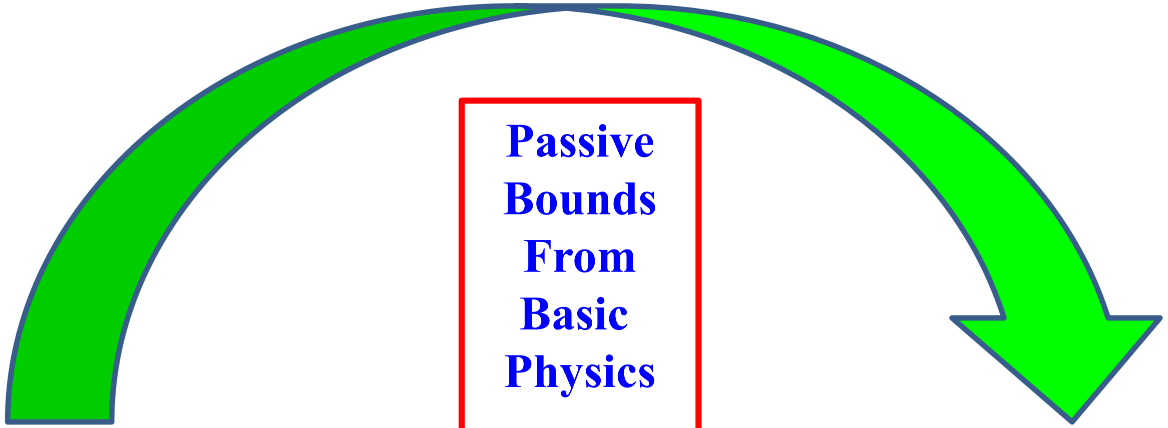


5-metal, 3 rohacell layers @ 28.04 GHz

Peak Dir = 6.68 dB, FTBR = 18 dB, Rad Eff = 95%

Physical Bounds on *Bandwidth* – How does one engineer around them ??

Introduce active elements



Not so useful

Passive Bounds From Basic Physics

e.g.

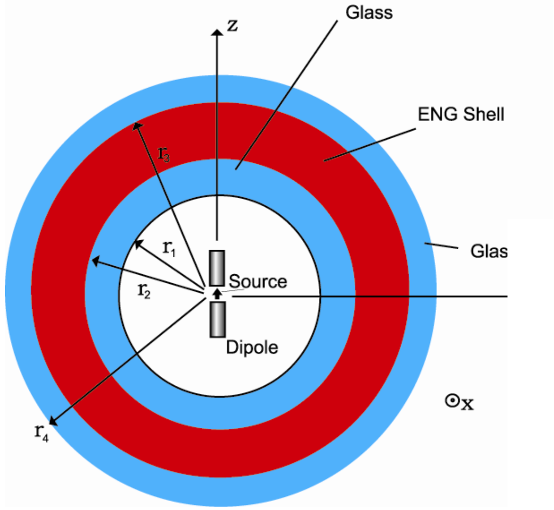
Chu limit

USEFUL

$$Q = \frac{1}{ka} + \frac{1}{(ka)^3}$$

$$FBW_{3\,\mathrm{dB}} = 3\,FBW_{10\,\mathrm{dB}} = \frac{2}{Q} \approx 2(ka)^3$$

Dispersion Engineering provides a means to recover bandwidth advantages



$\partial_f \varepsilon$

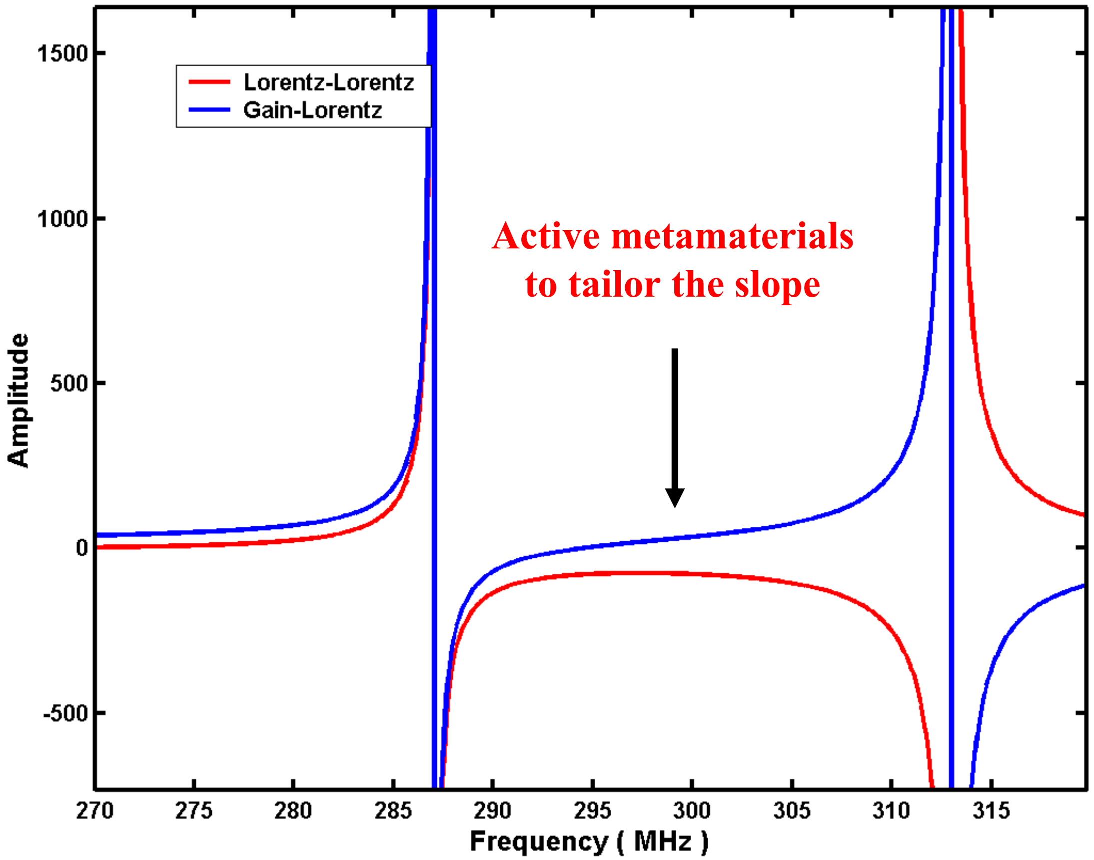
controls the

bandwidth

Infinitesimal dipole-multi-layered spherical shell system with geometry and material optimizations

Combine two resonance lines:

one passive, one active



R. W. Ziolkowski and A. Erentok, *IET Microwaves, Antennas Propag.*, vol. 1, pp. 116-128, February 2007

Additional Degrees of Freedom with NFRP HDAs

Augment either the
Driven dipole
or the
NFRP elements
with complex circuits to
achieve active radiating systems

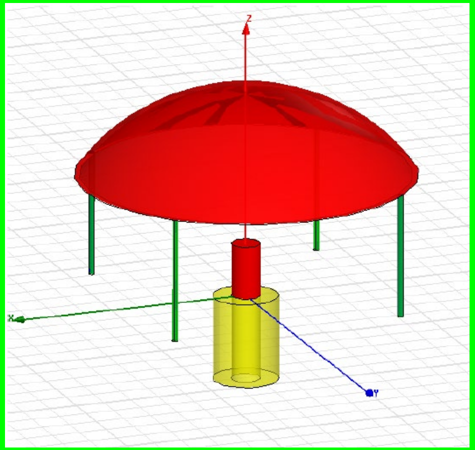
Methods to Overcome Fundamental Bandwidth Limits

- **Active non-Foster element (negative impedance converter - NIC)**

  First introduced by Linvill in 1953! The resistance, capacitance, and/or inductance can be made to decrease with increasing frequency.

- **Non-Foster (NF) matching networks:**

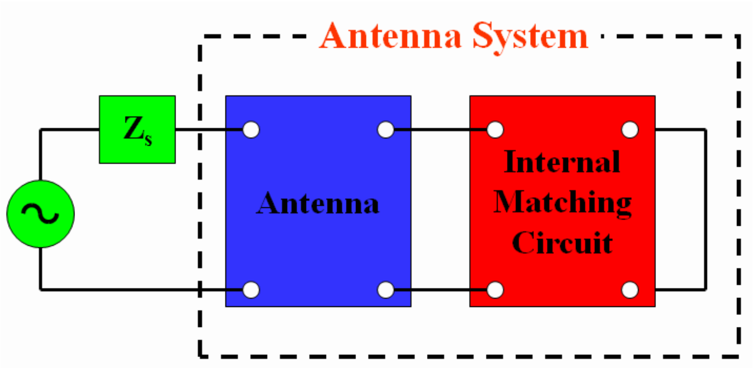
Canopy Antenna



non-Foster inductors as the legs

$ka = 0.047 = \lambda / 134$

FWB > 10%

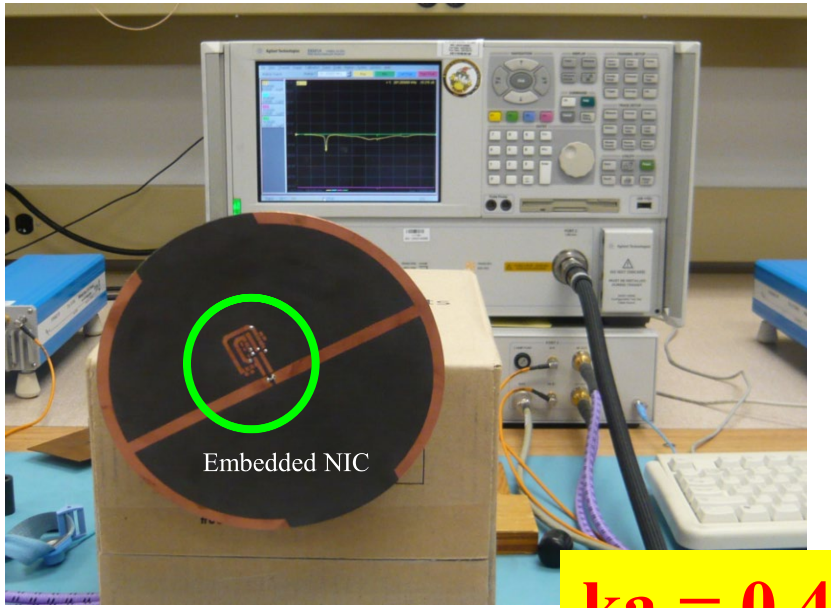


Our method: internal NF matching element

P. Jin and R. W. Ziolkowski,
IEEE Trans. Antennas Propag., Feb. 2010

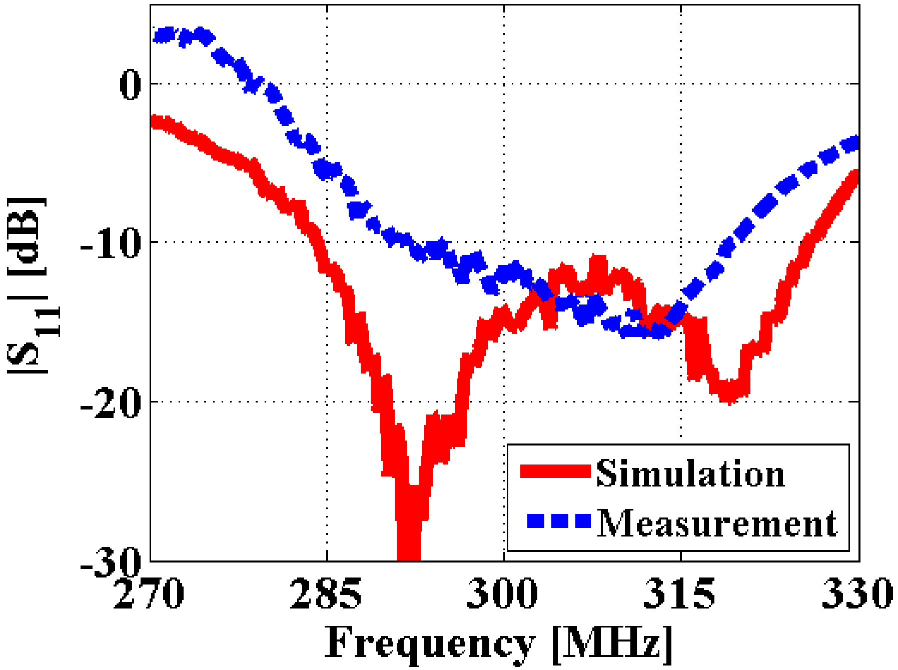
N. Zhu and R. W. Ziolkowski,
IEEE Antennas Wireless Propag. Lett., Dec. 2011

Enhanced Bandwidth Electrically Small EAD Antenna
NFRP element augmented with L-NIC



ka = 0.49

Fabricated NIC-augmented ESA
Measurement setup



L-NIC augmented

Passive EAD

BW_{10dB} = 4.2 MHz
FBW_{10dB} = 1.41%
Q_{ratio} = 1.26

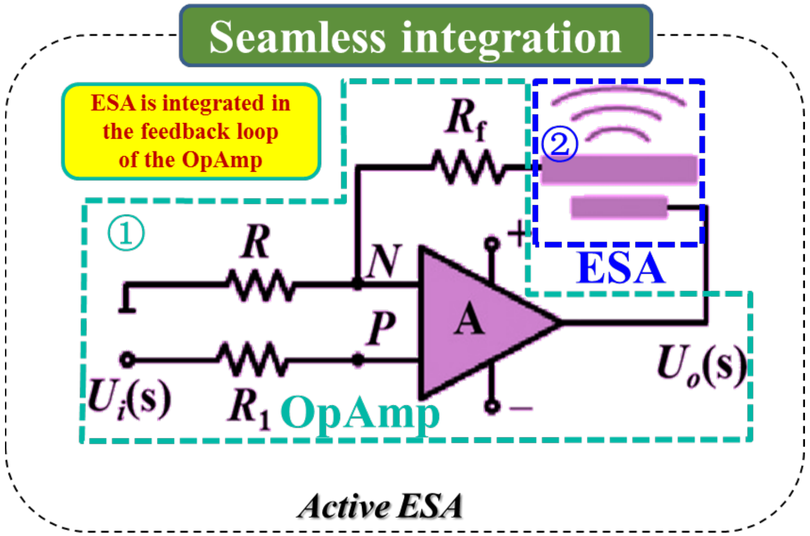
$$5.77 \times (D/Q)_{\text{passive, ub}}$$

NIC-augmented EAD

BW_{10dB} = 25.3 MHz
FBW_{10dB} = 8.49%

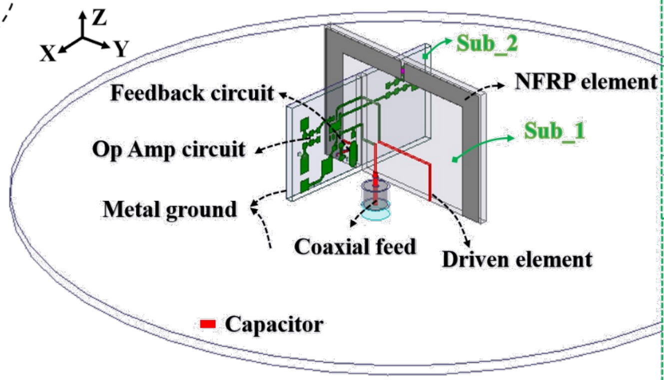
N. Zhu and R. W. Ziolkowski, *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1116-1120, 2012
IEICE Transactions on Communications, vol. E96-B, no.10, pp. 2399-2409, Oct. 2013

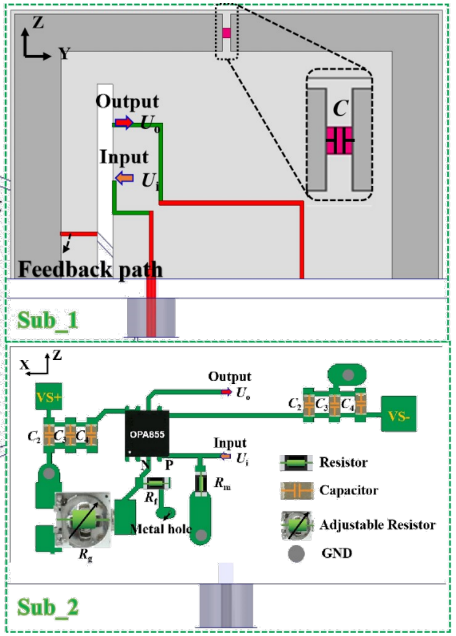
Seamless integration of a passive ESA with an active element enhances its gain without adding any additional space ☺ !!

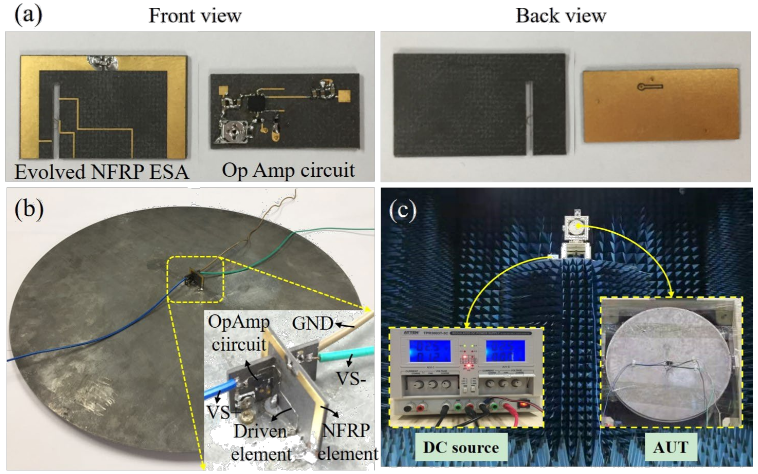


Y. Yu, M.-C. Tang, D. Yi, D. Hong, T. Shi, and R. W. Ziolkowski, "Electrically small antenna with a significantly enhanced gain-bandwidth product," early access *IEEE Trans. Antennas Propag.*, Dec. 29, 2021

ka = 0.15 2D Magnetic EZ antenna integrated into the feedback loop of the OpAmp







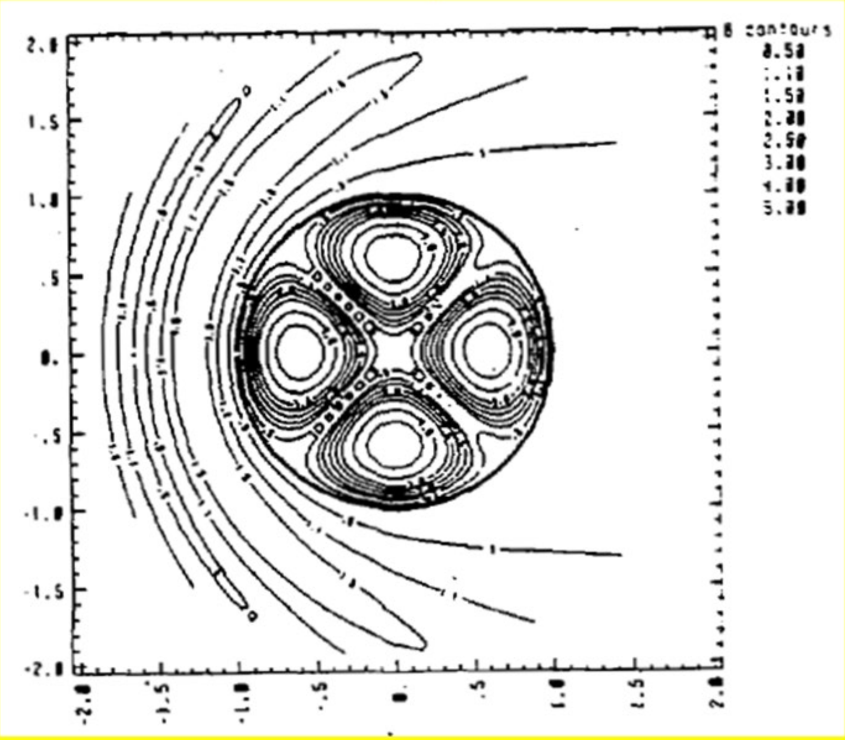
Adjustable gain
Peak = 7.49 dBi

Enhances the Gain-Bandwidth Product of the passive antenna by factor of 15.2
Result SURPASSES the Passive Upper Bound !!

Bound States in the Continuum (BIC) related R&Ss
Aperture Coupling (Dual-Series) problems from 1980's ☺

2D Slit Cylinders

2° full aperture

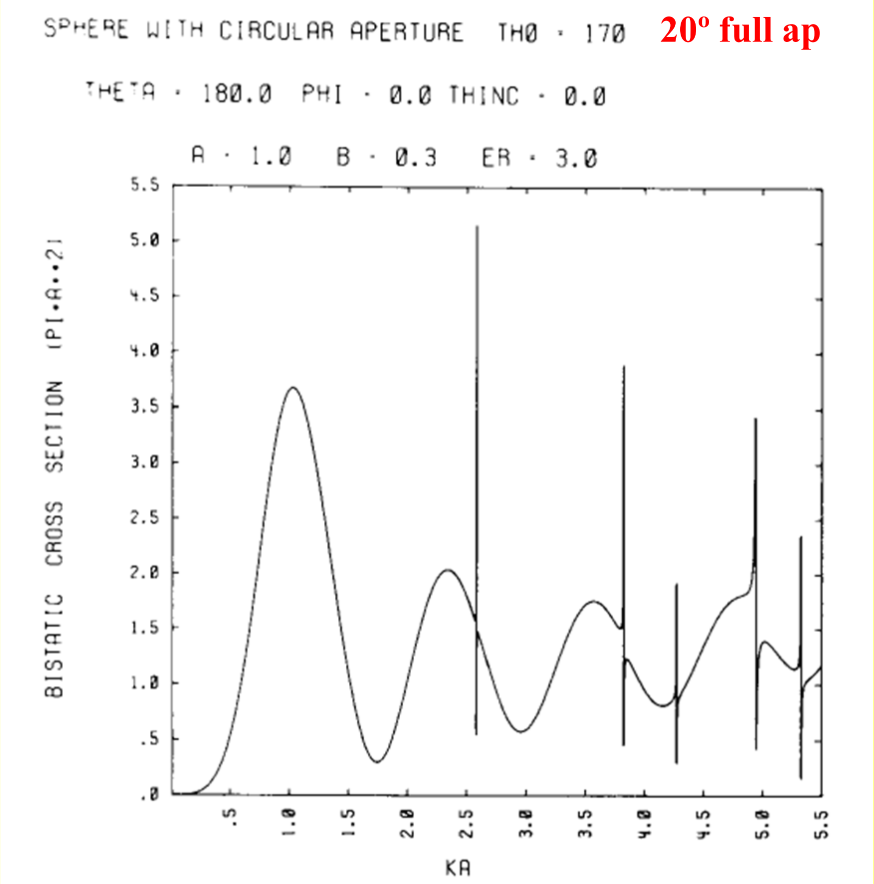


Applications of Riemann-Hilbert problem techniques to electromagnetic coupling through apertures

Radio Sci., **vol. 19(12), pp. 1425-1431, 1984**

3D Holey Spheres

20º full ap



Electromagnetic scattering of an arbitrary plane wave from a spherical shell with a circular aperture

J. Math. Phys., **vol. 26(6), pp. 1293-1314, 1987**

More exotic nano-structured passive and active R&Ss
Primarily full multipole analytical solutions

UTS
UNIVERSITY OF TECHNOLOGY SYDNEY

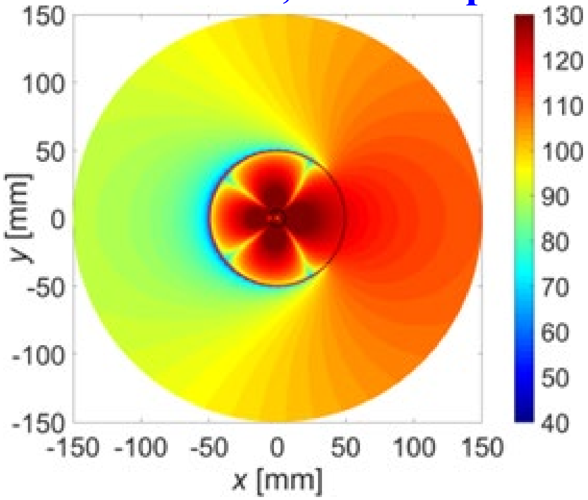
P. M. Kamiński, R. W. Ziolkowski, and S. Arslanagić
Riemann-Hilbert technique scattering analysis of metamaterial-based asymmetric 2D open resonators
***EPJ Applied Metamaterials*, vol. 4, 10, 2017**

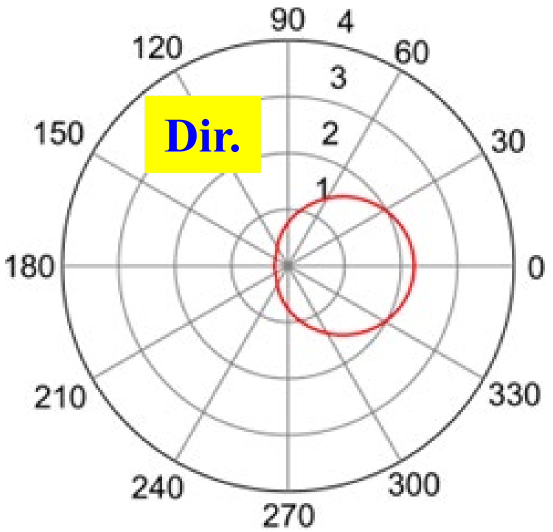
S. Arslanagić and R. W. Ziolkowski
Cylindrical and spherical active coated nano-particles as nano-antennas
***IEEE Antennas Propag. Mag*., vol. 59, no. 6, pp. 14-29, Dec. 2017**

S. Arslanagić and R. W. Ziolkowski
Passive and active nano cylinders for enhanced and directive radiation and scattering phenomena
in *Nanoantennas and Plasmonics: Modelling, Design and Fabrication*
IET - Institution of Engineering and Technology, Stevenage UK, 2020
Chap. 2, pp. 53-102

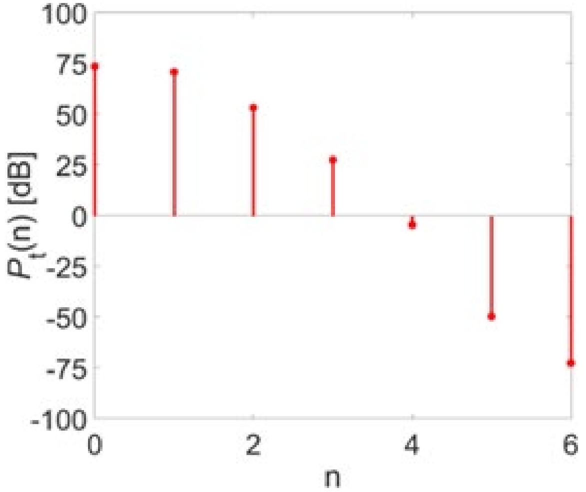
A variety of effects of the offset and open CNP geometries have been investigated

R ~ 50 mm, 90º full ap.



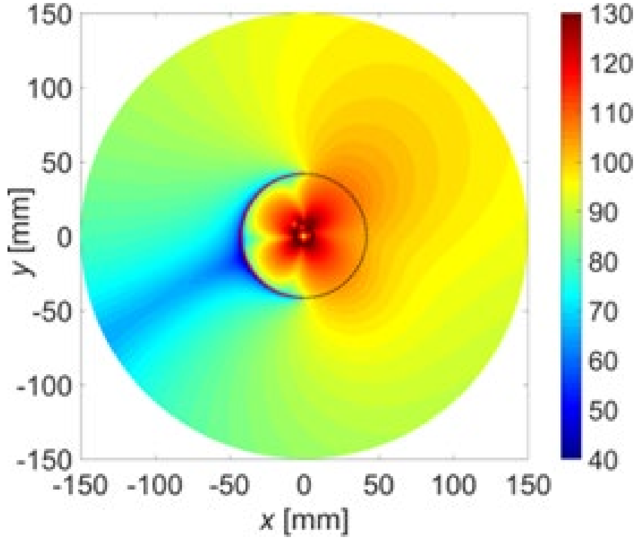


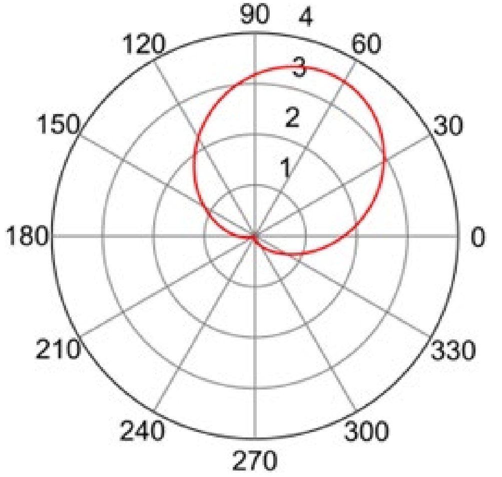
Power Spectrum



Higher order modes are naturally excited by the singularities of the fields at the aperture edges

R ~ 42 mm, 180º full ap.





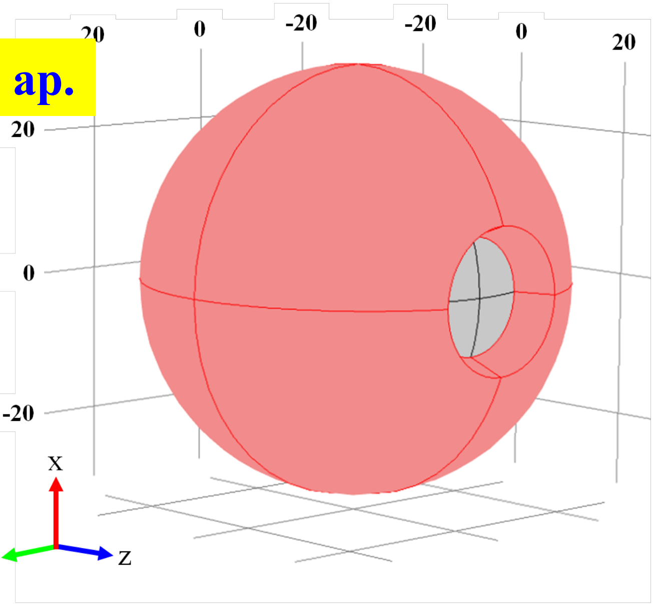
Line source location can steer the radiated beam

S. D. Campbell and R. W. Ziolkowski

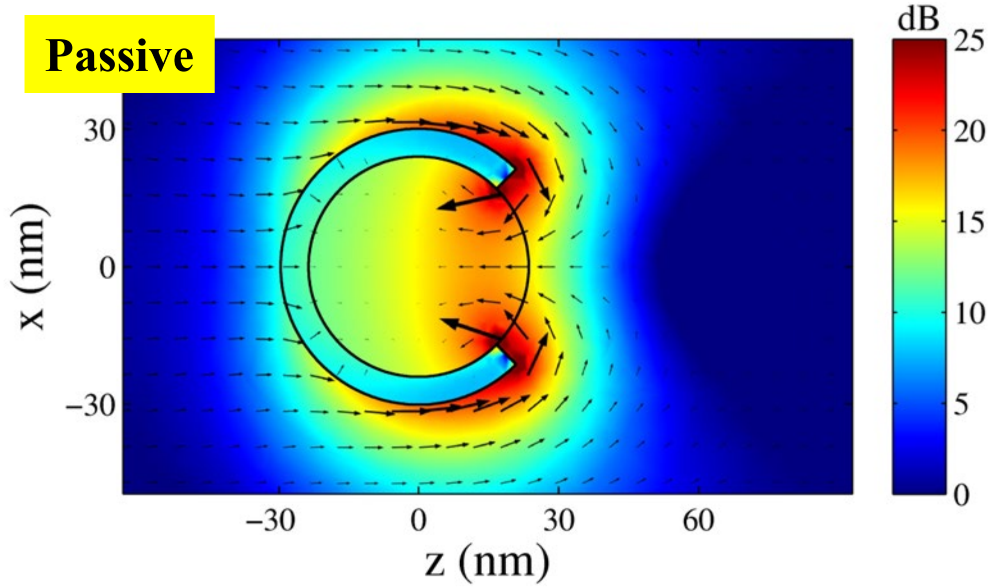
Near-field directive beams from passive and active asymmetric optical nano-antennas

IEEE J. Sel. Topics Quantum Electron., vol. 21, no. 4, 4800112, Jul./Aug. 2014

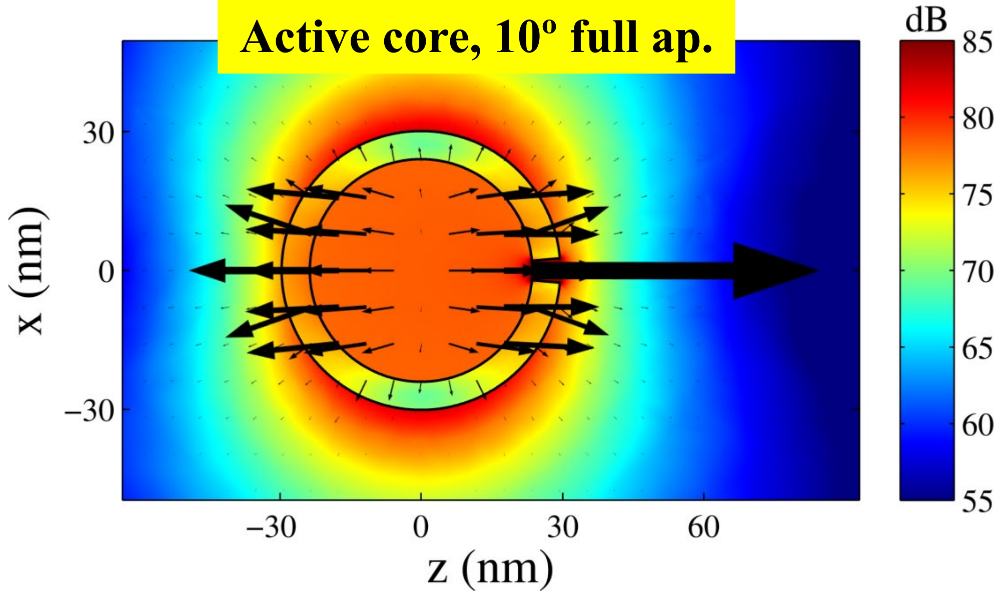
90º full ap.



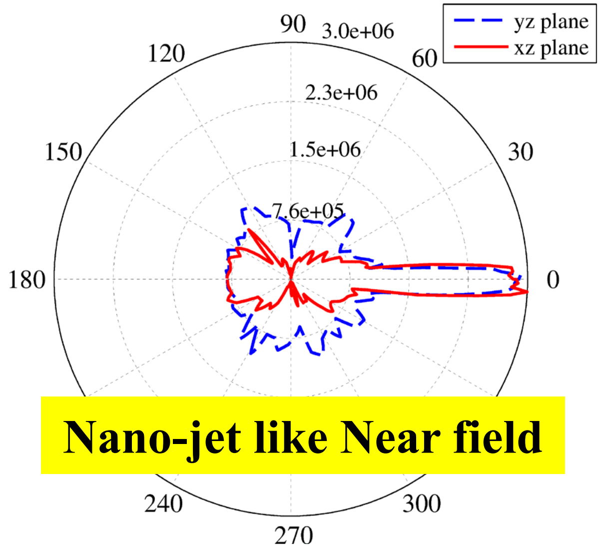
Passive



Active core, 10º full ap.



Nano-jet like Near field



During my presentation, I have shared with you a myriad of metamaterial-inspired radiators and scatterers (R&Ss)

- Briefly reviewed how we design our electrically small R&Ss

  Near-Field Resonant Parasitic (NFRP) Paradigm

- Reviewed concepts of passive and active electrically small photonic R&Ss

  Core-shell antennas and nano-antennas

- Reviewed the concepts of electrically small directive R&Ss

  Huygens dipole R&Ss

- Reviewed the *Magic of Multipoles*

  Superdirective R&Ss

- Reviewed some of the more exotic passive and active core-shell based R&Ss

I emphasized the special electromagnetic scaling property:
the physics and engineering of microwave and photonic systems are analogous

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THANK YOU FOR WATCHING ☺

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Question & Answer