A PRACTICAL VIEW OF METAMATERIAL-ENGINEERED RADIATING AND SCATTERING SYSTEMS

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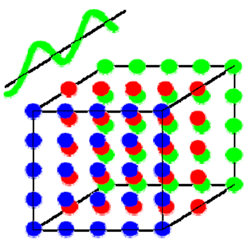
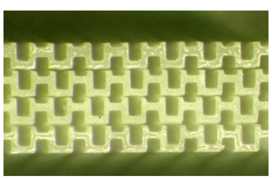
There are different types of artificial materials (metamaterials)

EBG

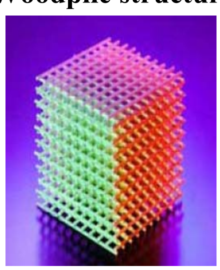


- Bulk material in 1D, 2D, 3D
- Period ≈ λ
- Bragg effect

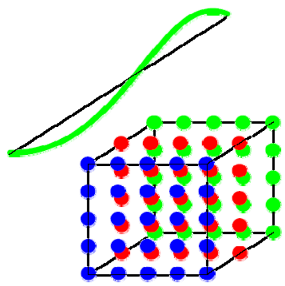
Fan structure



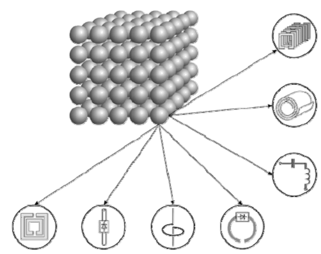
Woodpile structure

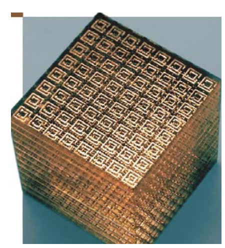


DNG

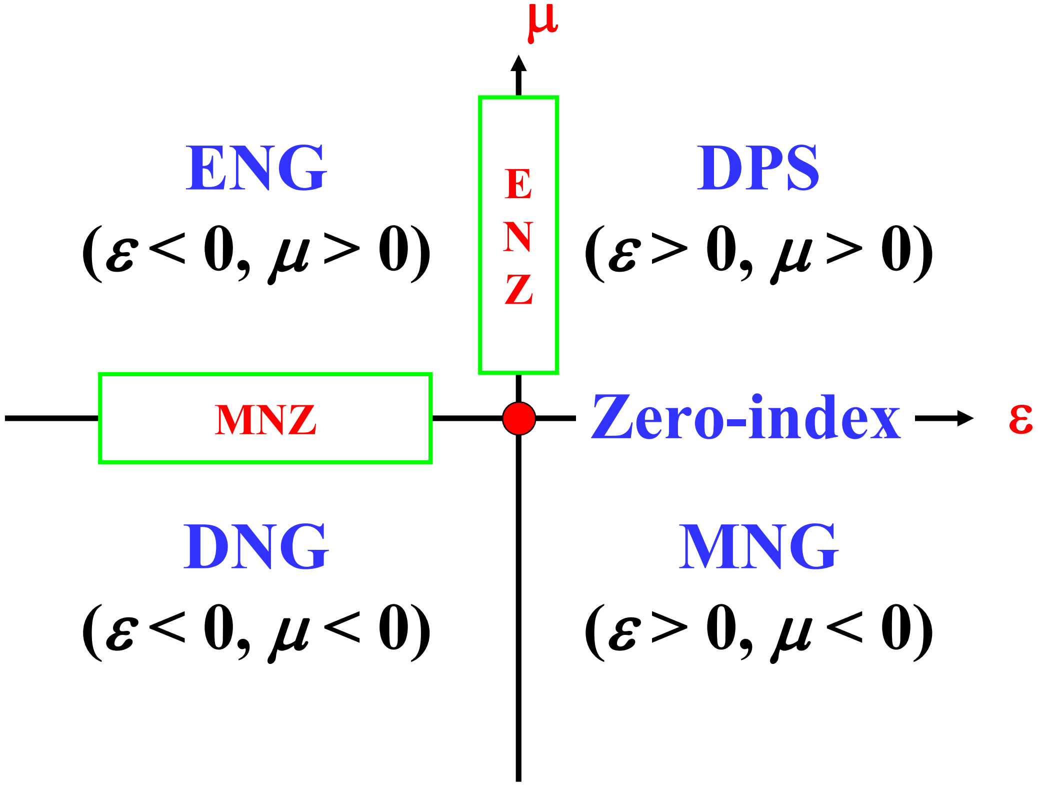


- Bulk material in 1D, 2D, 3D
- Period « λ
- Effective medium theory - homogenization





Metamaterials (MTMs) have exotic properties that may have a high impact on a wide variety of practical applications



The Debye, Lorentz, and Drude linear polarization models produce well-known material responses

Lorentz: Standard 1TD-LM 2TD-LM

$$\partial_t^2 P + \Gamma_e \partial_t P + \omega_0^2 P = \varepsilon_0 \omega_p^2 \chi_\alpha E + \varepsilon_0 \omega_p \chi_\beta \partial_t E + \varepsilon_0 \chi_\gamma \partial_t^2 E$$

$$\chi(\omega) = \frac{\omega_p^2 \chi_\alpha}{-\omega^2 + j\Gamma_e \omega + \omega_0^2} + \frac{j\omega_p \chi_\beta}{-\omega^2 + j\Gamma_e \omega + \omega_0^2} + \frac{-\omega^2 \chi_\gamma}{-\omega^2 + j\Gamma_e \omega + \omega_0^2}$$

Drude:

$$\partial_t^2 P + \Gamma_e \partial_t P = \varepsilon_0 \omega_p^2 \chi_\alpha E$$

$$\chi(\omega) = \frac{\omega_p^2 \chi_\alpha}{-\omega^2 + j\Gamma_e \omega} = \frac{\omega_p^2 \chi_\alpha}{-\omega(\omega - j\Gamma_e)}$$

Debye:

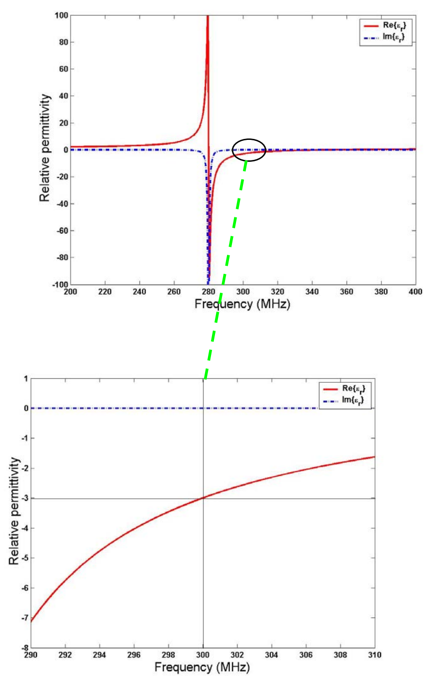
$$\partial_t P + \Gamma_e P = \varepsilon_0 \omega_p \chi_\alpha E$$

$$\chi(\omega) = \frac{\omega_p \chi_\alpha}{j\omega + \Gamma_e}$$

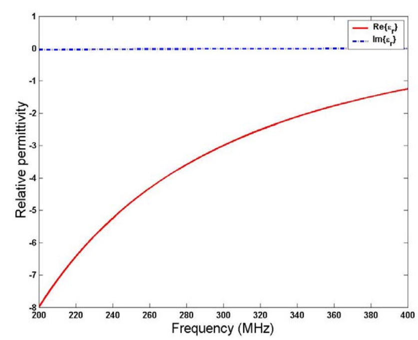
$$\chi(\omega) = \frac{\tilde{P}(\omega)}{\varepsilon_0 \tilde{E}(\omega)}$$

Where do the negative values appear?

Lorentz real part is negative just above the resonance



Drude real part is negative for all frequencies below the plasma frequency



Lorentz behavior = narrow bandwidth
Drude behavior = broad bandwidth

REAL MTMs ARE DISPERSIVE AND LOSSY

Metamaterials (MTMs) realizations

Typical DNG realizations: most well-known - Wire and SRRs

Sizes ~ $\lambda/3$-$\lambda/8$
Not always well matched to free space

Losses are always an issue: need to be minimized for practical applications

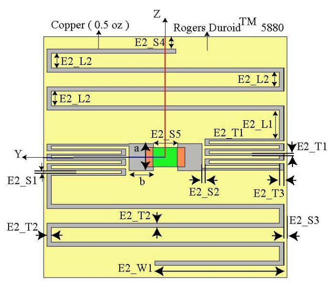
Fabrication issues

Size constraints: gaps, traces, material types
Layer registration (alignment)

Recent lumped element-based DNG metamaterial designs and experiments have achieved very small (λ/75) unit cells

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

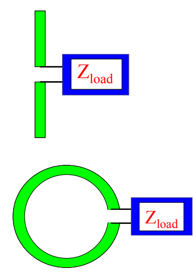
ENG
($\varepsilon < 0, \mu > 0$)



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

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

μ

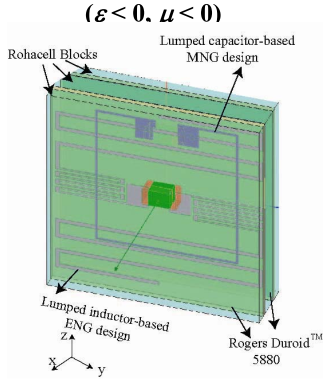


UA
Electric and Magnetic Molecules
for
RAMs, Smart skins
and
FDTD ABCs
(Physics-based PMLs)

● Zero-index

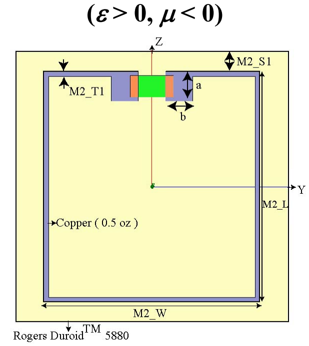
ε

DNG
($\varepsilon < 0, \mu < 0$)



10×10×2.54mm^3
λ /75 unit cell

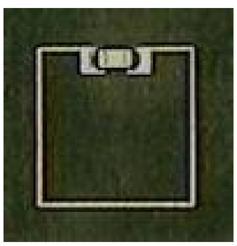
MNG
($\varepsilon > 0, \mu < 0$)



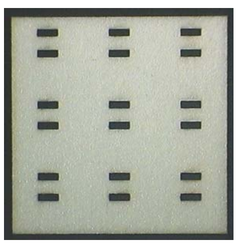
UA Unit Cell CLL with lumped element capacitor
~ λ / 100

Lumped-element based unit cells have achieved the smallest, lowest frequency ENG, MNG, DNG (NIM) materials to date

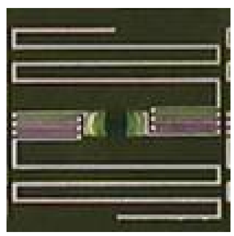
$n_{real} = -3.11$ with a loss of 0.91 dB/*cm* at 400 MHz for **λ /75** unit cell with Z ~ 0.76 Z_0



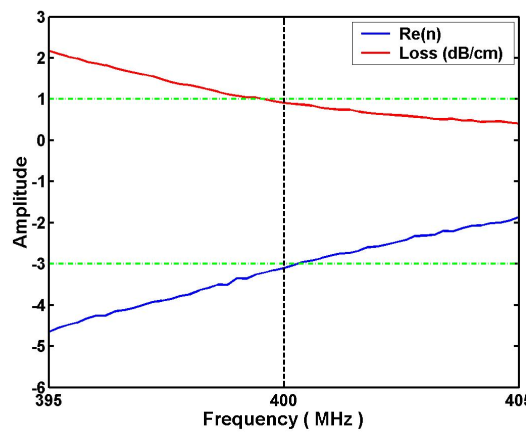
MNG portion



Rohacell™ spacer



ENG portion



Complete NIM slab (~ 900 Unit Cells)

(not to scale)

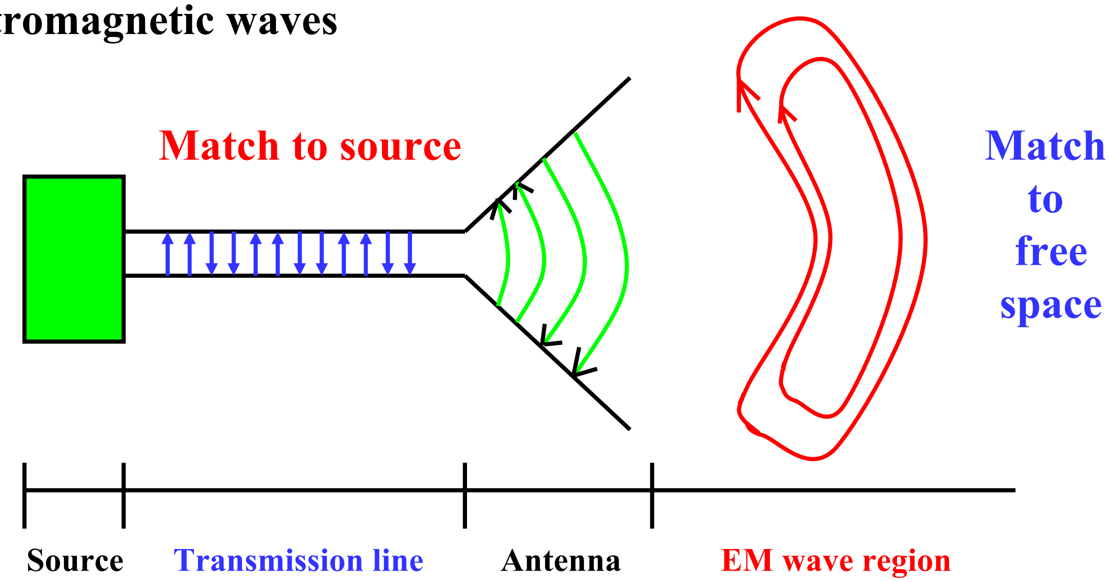
This work was supported in part by **DARPA** Contract number HR0011-05-C-0068.

Metamaterials provide a means to enhance various performance characteristics of a variety of antenna systems

- ☺ **Electrically small antennas – ENG, MNG, DNG MTMs and the corresponding inspired near-field resonant parasitics**
- ☺ **Multi-functional antennas – multi-frequency NFRPs, LP vs CP**
- ☺ **Low profile antennas –** ***AMCs via MNG (high impedance) substrates***
- ☺ **Directive antennas –** ***Zero-index ($\varepsilon = \mu = 0, Z = Z_0$) substrates***
- ☺ **Dispersion-compensated antennas – all MTMs are dispersive**
- ☺ **Ultrawide Band (UWB) antennas – NFRPs as filters, add-on functionality**

What is an antenna??

Antennas are transducers: **They take voltages and currents (charges and their motions) and transform them into electromagnetic waves**



Designs: tailor currents to achieve desired performance characteristics

Computational Electromagnetics Modeling (CEM) Applied to Antennas

- **Method of Moments (MoM)**

  NEC (numerical electromagnetics code, Gerry Burke), Mini-NEC, ADS Momentum

- **Finite Element Method (FEM)**

  ANSYS/ANSOFT High Frequency Structure Simulator HFSS (Zolton Cendes)

- **Finite Difference Time Domain (FDTD)**

  Remcom XFDTD (Luebbers), SEMCAD (Nik Chavannes, ETH-Z), GEM (Raj Mittra)

- **Finite Integration Technique (FIT)**

  CST Microwave Studio (Thomas Weiland, old MAFIA code)

Computational Electromagnetics Modeling (CEM) Applied to Antennas

- **NEC**

  Wire antennas, circuit loads

- **HFSS**

  General 2D and 3D structures, CAD draw, localized mesh refinement, optimizer, multi-processor
  Co-design (circuits + radiating structures) with HFSS Designer (equivalent two-ports)

- **FDTD, FIT**

  Time behavior, dispersive material models nonlinear models

Small Dipole Antenna:
Fields and Wave Impedance

$$\vec{E} = -ik\eta I\ell \frac{e^{ikr}}{4\pi r}\left\{\hat{r}\left[\left(\frac{i}{kr}\right)^2 + \frac{i}{kr}\right]2\cos\theta + \hat{\theta}\left[\left(\frac{i}{kr}\right)^2 + \frac{i}{kr} + 1\right]\sin\theta\right\}$$

$$\vec{H} = -ik\, I\ell \frac{e^{ikr}}{4\pi r}\left\{\hat{\phi}\left[\frac{i}{kr} + 1\right]\sin\theta\right\}$$

$$Z = \frac{E_\theta}{H_\phi} = \eta\frac{\left(\frac{i}{kr}\right)^2 + \frac{i}{kr} + 1}{\frac{i}{kr} + 1}$$

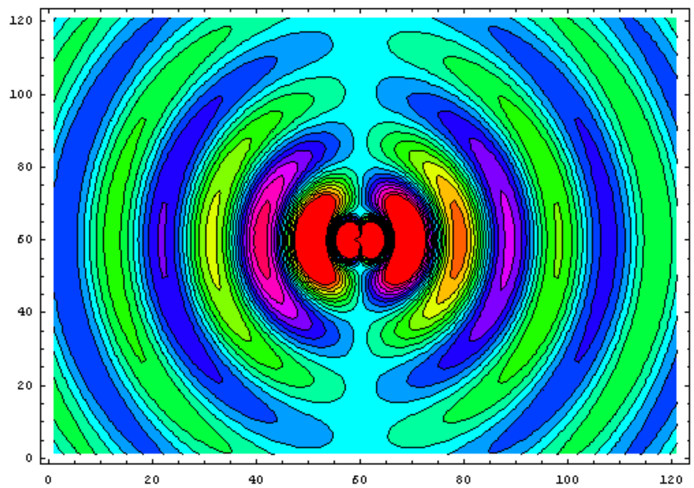
$$\lim_{r\to 0} Z = -i\eta\left(\frac{1}{kr}\right)^3$$

Near field is very capacitive

$$\lim_{r\to\infty} Z = \eta$$

Resistive in free space $= 376.7 \sim 120\pi$ ohms

Small Dipole Antenna:
Field Regions

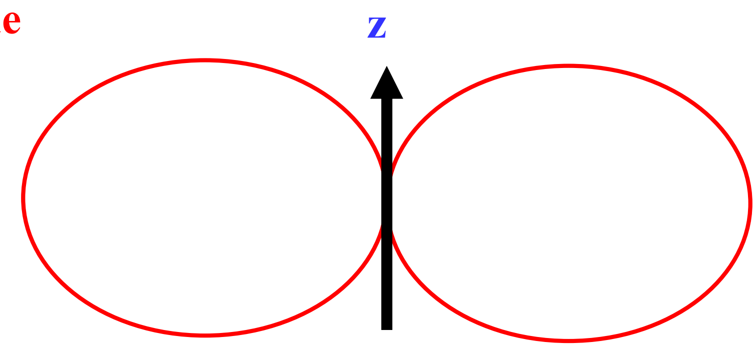


$$Field = \frac{1}{r}\{\bullet\} + \frac{1}{r^2}\{\bullet\bullet\} + \frac{1}{r^3}\{\bullet\bullet\bullet\}$$

Far field | **Induction field** | **Near field**

Small antennas radiate primarily in a dipole mode

Small
Electric Dipole
TM_{10} mode



Power Pattern = $\sin^2 \theta$
Directivity = $1.5 \sin^2 \theta$
Max Directivity = 1.5 = 1.76 dB

Small Dipole Antenna:
Radiated Power

Complex power for a very small electric dipole of length ℓ in a medium with wave impedance η and wave number k = n ω/c

Total power = integrate Poyntings' vector over sphere

$$P = \int_0^{2\pi}\int_0^{\pi} \frac{1}{2} E_\theta H_\phi^* \, r^2 \sin\theta \, d\theta \, d\phi = \eta \frac{\pi}{3}\left|\frac{I_0 l}{\lambda}\right|^2 \left[1 - \frac{j}{(kr)^3}\right]$$

$$P_{\text{total radiated}} = \eta \frac{\pi}{3}\left|\frac{I_0 l}{\lambda}\right|^2 = \frac{1}{2} R_{rad} I_0^2$$

← **RADIATION RESISTANCE**

$$P_{\text{reactive}} = -j\,\eta \frac{\pi}{3}\left|\frac{I_0 l}{\lambda}\right|^2 \frac{1}{(ka)^3}$$

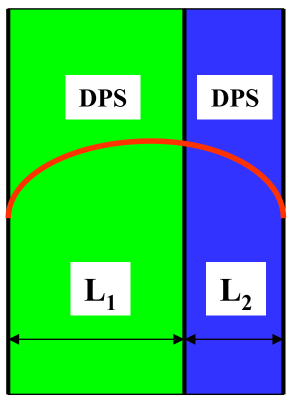
← **CAPACITIVE REACTANCE in Radiansphere**

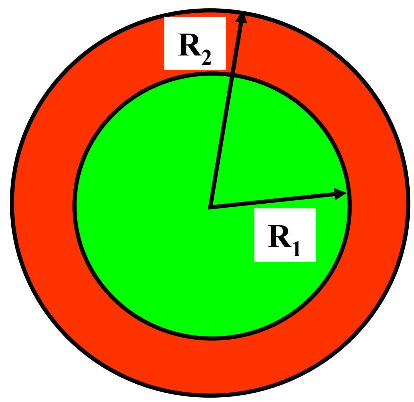
$$R_{rad} = 80\pi^2 \left|\frac{l}{\lambda}\right|^2$$

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

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

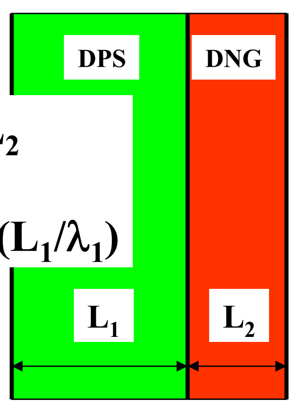
$$m = 1,2,\ldots$$





$$k_1L_1 + k_2L_2 = 0$$

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



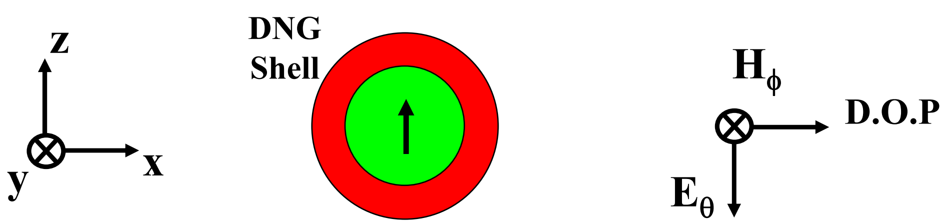
$$E = \Sigma_{mn}\, a_{mn}\, TE_{mn} + b_{mn}\, TM_{mn}$$

$$b_{mn} = \frac{A_{mn} + j\,B_{mn}}{C_{mn} + j\,D_{mn}}$$

$A_{mn} + j\,B_{mn} \rightarrow 0$, Non-radiating

$C_{mn} + j\,D_{mn} \rightarrow 0$, Resonant

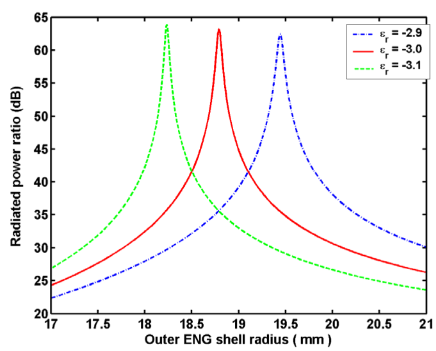
Analytical Solutions Demonstrate the Existence of Electrically Small Radiating and Reciprocal Scattering Systems

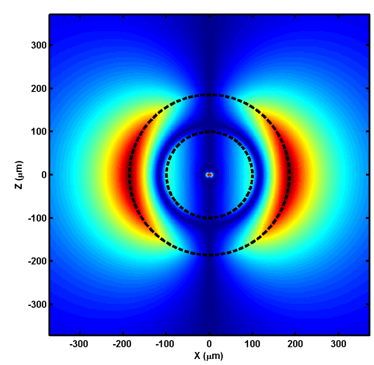


Receiver in far field

Dipole Source

Radiated Power Ratio





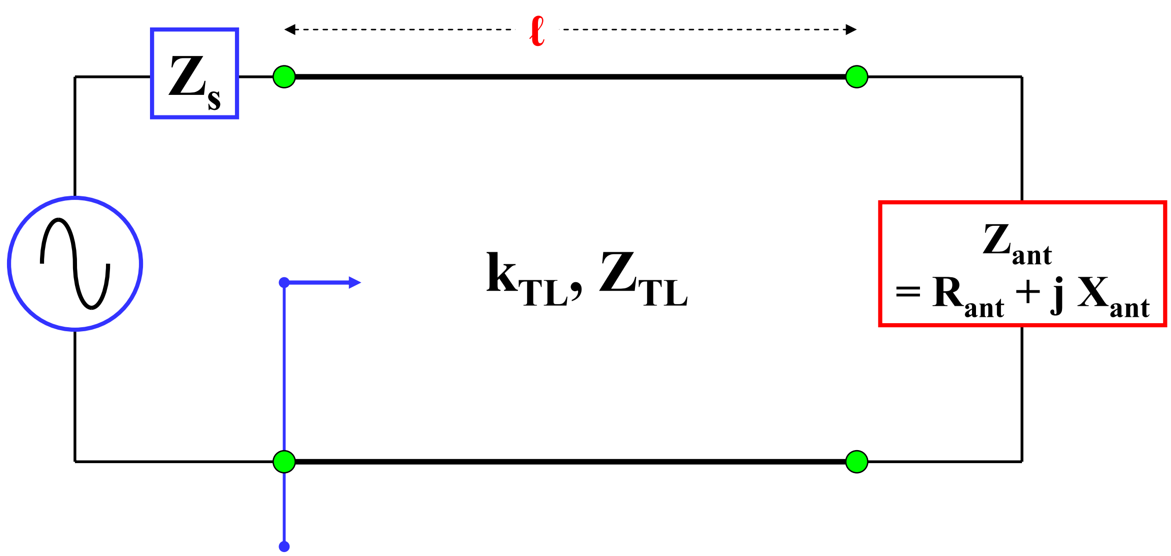
Total Magnetic Field Intensity Source Case

r_1 = 10 mm, f_0 = 300 MHz, λ_0 = 1000mm

kr_2 = 0.117
$r_2 \sim \lambda_0$ / 53.5

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

Basic circuit representation of an antenna



$$Z_{in}(\omega) = Z_{TL}\,\frac{Z_{ant} + jZ_{TL}\tan k_{TL}\ell}{Z_{TL} + jZ_{ant}\tan k_{TL}\ell}$$

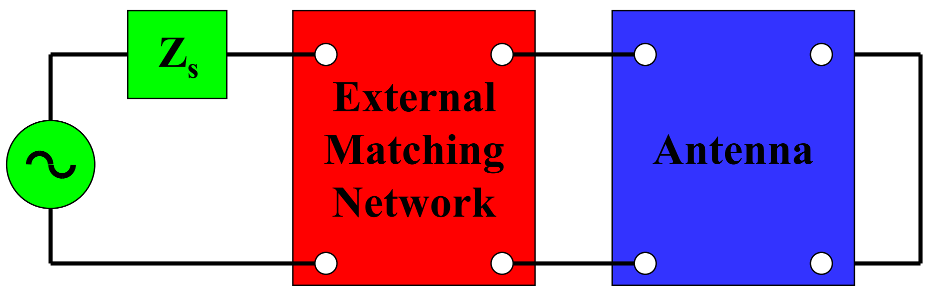
$$|\Gamma| = \left|\frac{Z_{in}(\omega) - Z_{TL}}{Z_{in}(\omega) + Z_{TL}}\right| \sim 1$$

$$R_{dipole} \ll 1$$

$$X_{dipole} < 0,\ |X_{dipole}| \gg 1$$

External Matching Networks

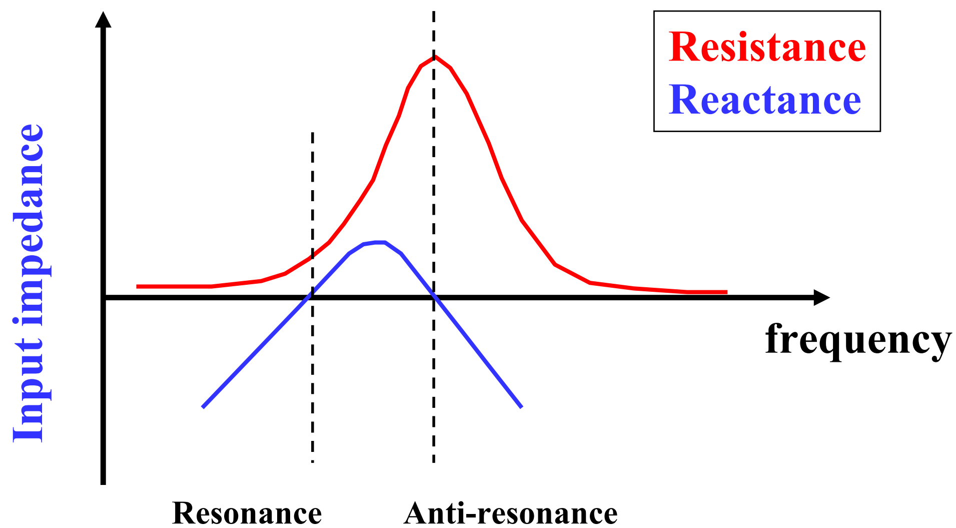
Traditional



EMN provides both *resistive* AND *reactance* matching

Passive: Even narrower bandwidth
Active: Can increase bandwidth – but real components generally limit result

Antenna resonances



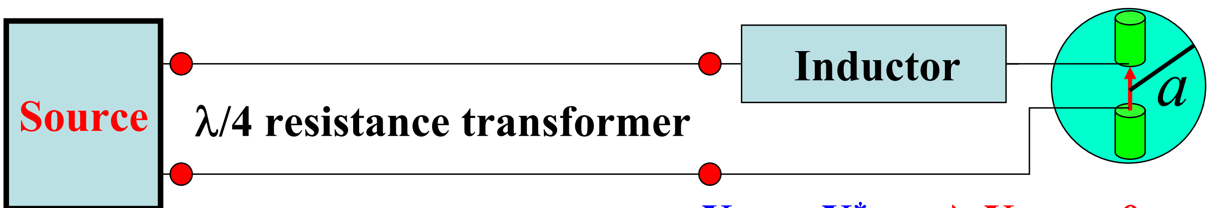
$$Z_{input}(f_0) \sim 50\Omega$$
$$R_{input}(f_0) \sim 50\Omega,\ X_{input}(f_0) \sim 0$$

$$Q_{YB} \approx \frac{f_0}{2R(f_0)} \left|\partial_f Z_{input}(f_0)\right|$$

$$FBW_{3\,\mathrm{dB}} = 1 / Q_{YB}$$

Metamaterial-engineered ESAs

Electrically small electric dipole = highly capacitive element

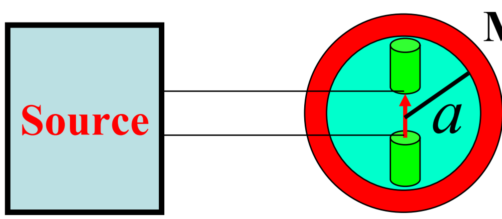


$X_{ind} = X^*_{ant} \Rightarrow X_{total} = 0$

Input impedance matched to the source $\Rightarrow \Gamma = 0$

Max Accepted Power

Desire:

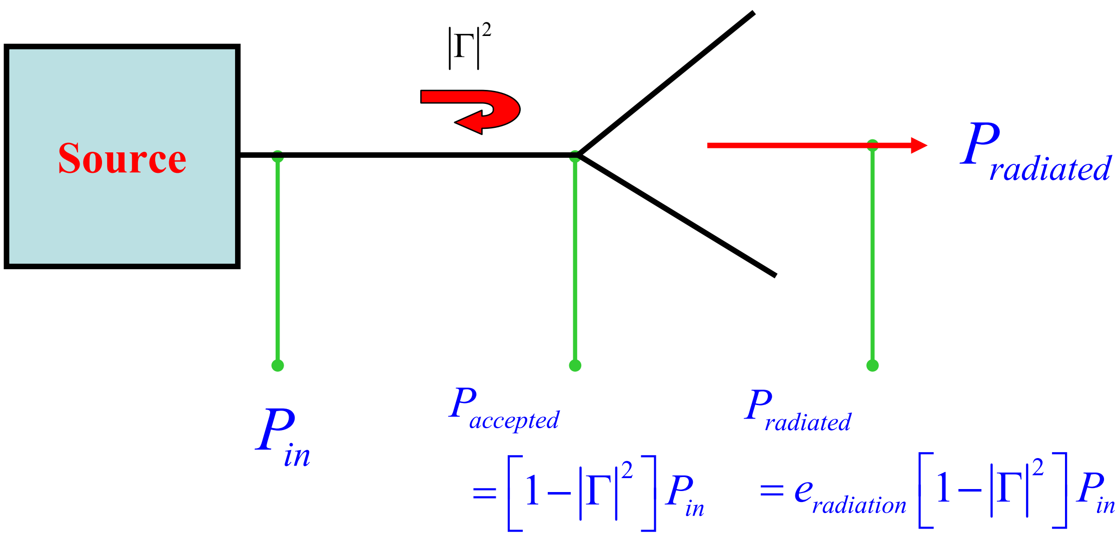


MTM "thing-a-ma-jigger"

- **No matching circuit**
- **Efficient ESA**

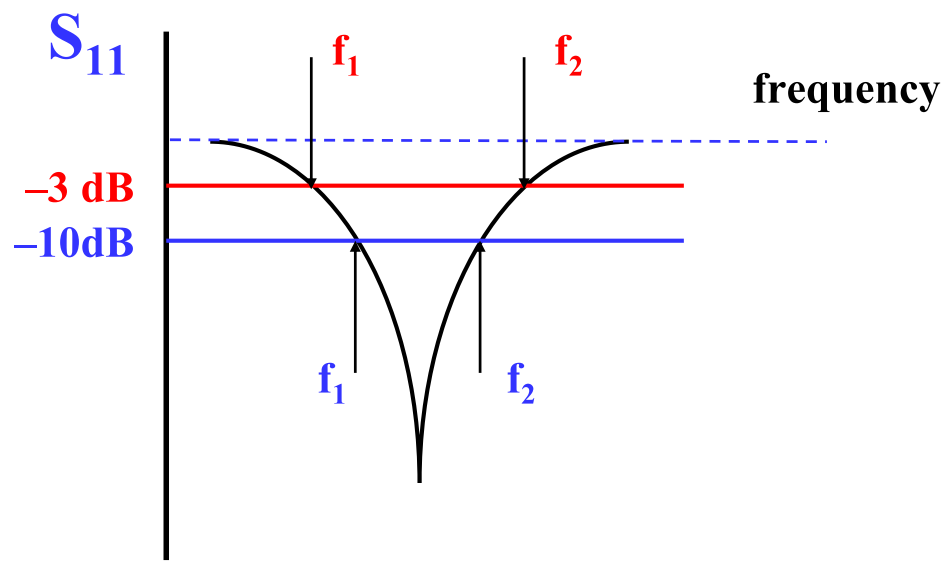
Electrically Small Antenna Terminology

Efficiencies



RE = P_{rad} / P_{acc}
OE = P_{rad} / P_{in}

Frequency bandwidth



Narrowband antenna: **VSWR half-power bandwidth (–3dB)** **BW = f_2-f_1**

Broadband antenna: **10dB bandwidth (VSWR < 2)** **BW = f_2-f_1**

Electrically Small Antenna Terminology

Quality factors and bandwidths of antenna under test (AUT)

$$FBW_{Half\ Power\ VSWR} = \frac{f_{+3dB} - f_{-3dB}}{f_{resonant}}$$

$$Q = \frac{2}{FBW_{Half\ Power\ VSWR}}$$

Electrically small:
$k_0 a \leq 0.5$

Quality factor and bandwidth limits

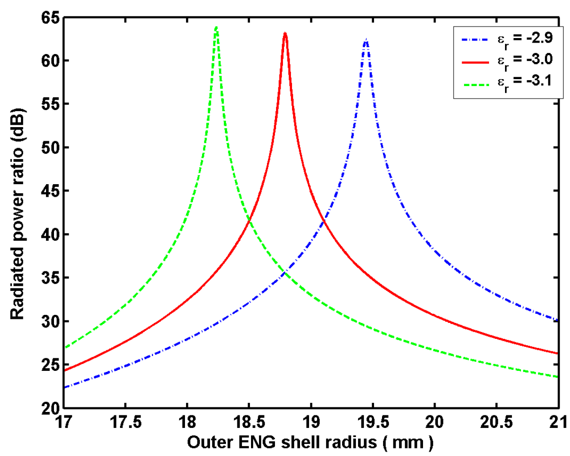
$$Q_{\text{Chu}} = \frac{1}{(k_0 a)^3} + \frac{1}{k_0 a} \sim (k_0 a)^{-3}$$

$$FBW_{\text{Chu}} = 1/Q_{\text{Chu}} \sim (k_0 a)^3$$

$$Q_{\text{ratio}} = \frac{Q}{Q_{\text{lower bound}}}$$

$$Q_{\text{lower bound}} = RE \times Q_{\text{Chu}}$$

We were told: "It can not be done"



Radiated Power Ratio

Ideal analytical solution:
Constant current on the dipole

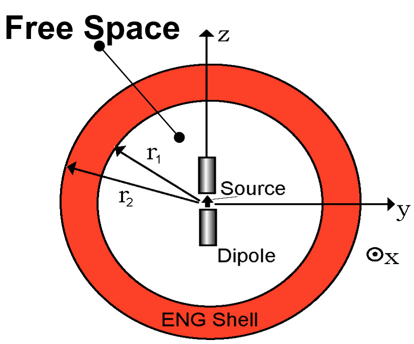
RPR ⟶ Radiation resistance ratio

This would imply that the radiation resistance would be Mega-ohms in size
→ it could not be
coupled (matched) to a real source (50Ω)

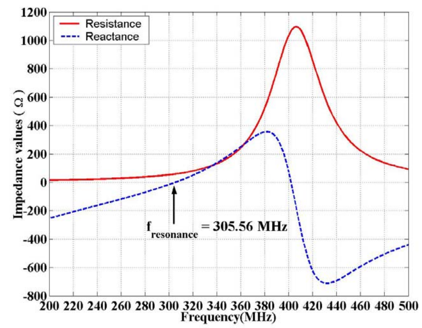
$r_1 = 10$ mm, $f_0 = 300$ MHz, $\lambda_0 = 1000$mm $\rightarrow r_2 \sim \lambda/50$, $ka \sim 0.12$

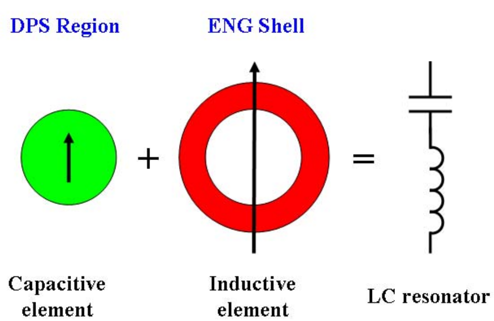
R. W. Ziolkowski and A. D. Kipple, Phys. Rev. E., vol. 72, 036602, September 2005

Center-fed dipole-ENG shell example: Using a highly subwavelength resonator to achieve a metamaterial-based *efficient* electrically-small antenna *(ESA)*

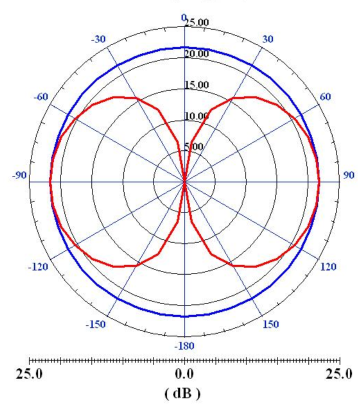


radius ~ λ/52
ka ~ 0.12
OE ~ 100%



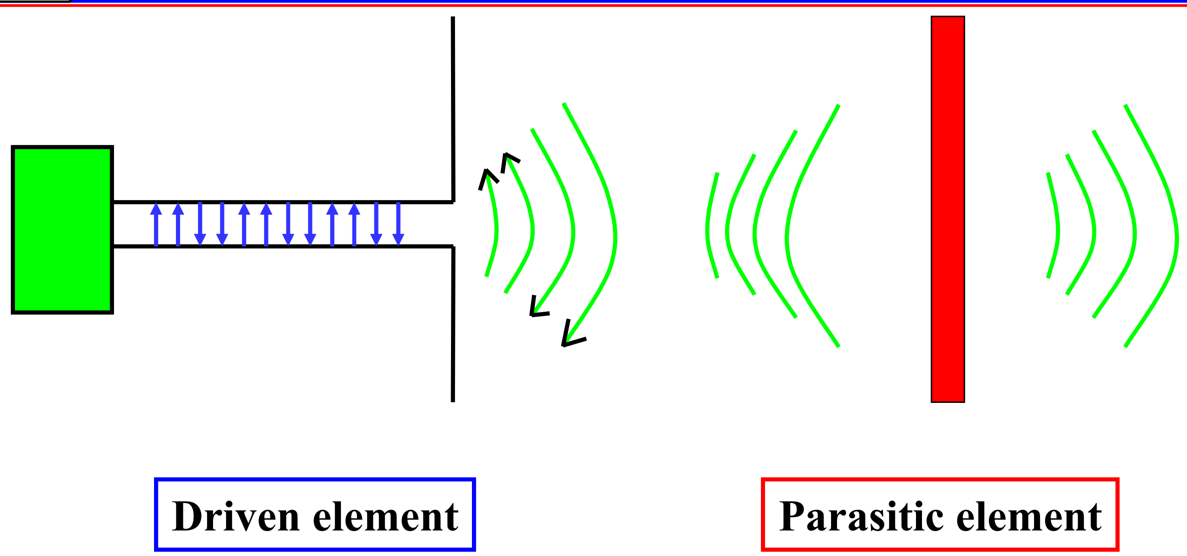


E-plane and H-plane patterns



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

The resonant metamaterial shell acts as a parasitic element



Parasitic:

- **Impacts the load the source sees (changes the input impedance)**
- **Impacts the radiation efficiency**
- **Impacts the pattern**
- **Allows feed/source to remain the same**
- **Flexible multi-function designs**

Source coupled to a NFRP element, i.e., a lossy, electrically small resonator

Lossy resonator:

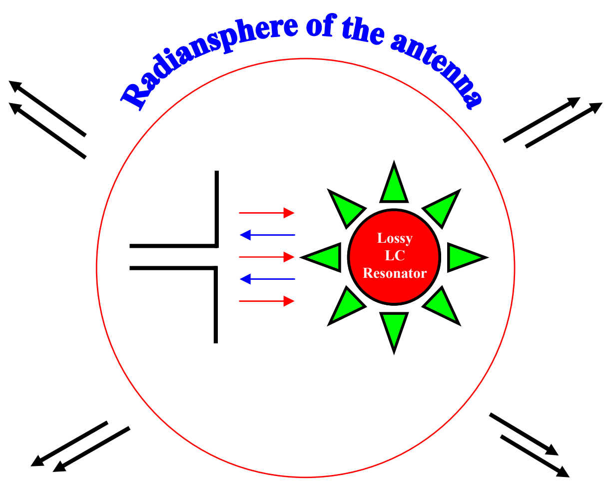
- **Peak of resistance and zero crossing of the reactance are no longer coincident**
- **The zero crossing and the resistance values can be tuned separately**

Near-field:

- **Large field values**
- **Allows simultaneous matching to source and to free space**

Match resonator type to source type based on MTM behaviors

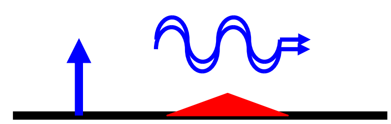
Near-Field Resonant Parasitic (NFRP) Antenna



Radiated power

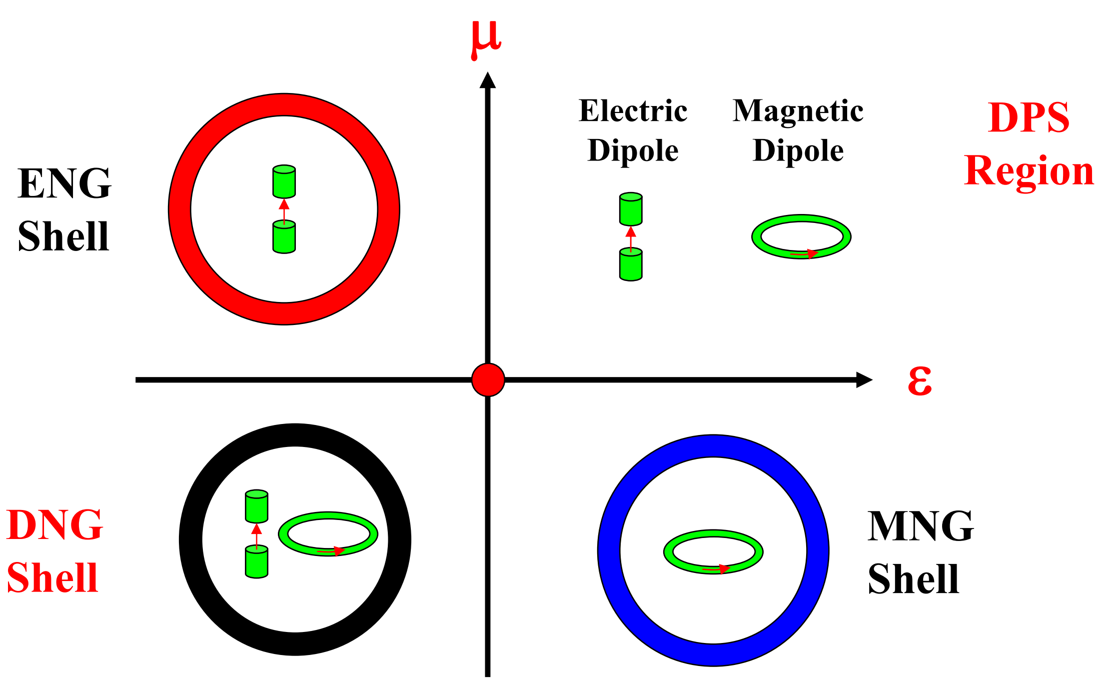
NFRP provides means for the antenna to be nearly perfectly matched to the source AND to free space

Potential barrier greatly reduced



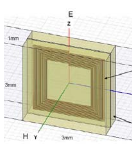
Engineer the parasitic to get $X_{total} = 0, R_{in}=50\Omega, R_{out}=377\Omega$

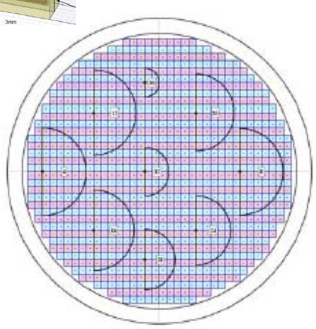
Metamaterial-based efficient ESAs
Both electric and magnetic versions have been developed



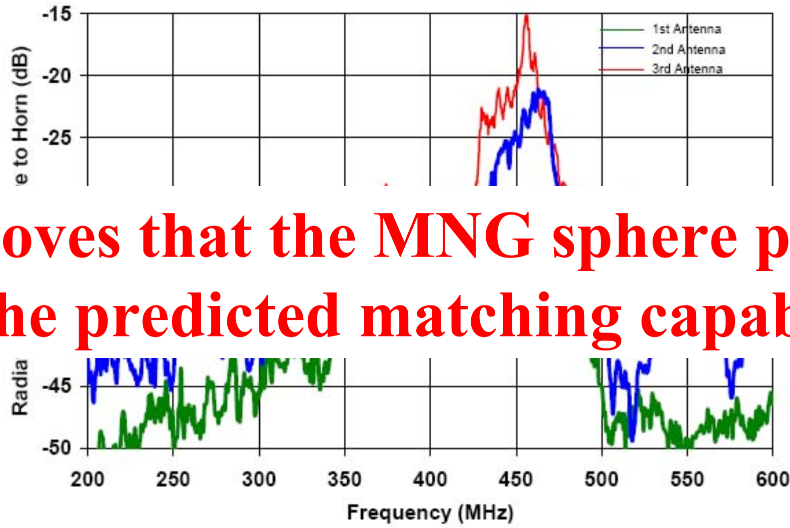
Adjust antenna and shell to achieve complete impedance matching
⇨ 100% OE for lossless MTMs, perfect metals

Assembled Hemispherical Antenna





Radiated Power Relative to Horn for 3 Versions of Antenna



Proves that the MNG sphere provides the predicted matching capabilities

1st ANTENNA : Higher loss spiral unit cell on quartz, amorphous arrangement, R_L=5.0cm, R_S=3.5cm

2nd ANTENNA: Lower loss sprial unit cell on alumina, crystalline arrangement, R_L=5.0cm, R_S=1.8cm

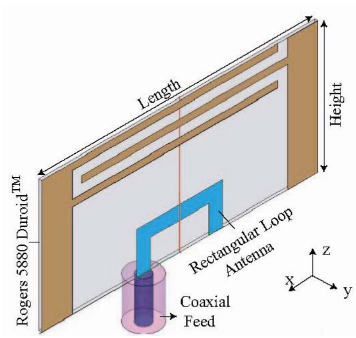
3rd ANTENNA: Lower loss sprial unit cell on alumina, crystalline arrangement, R_L=9.0cm, R_S=1.8cm

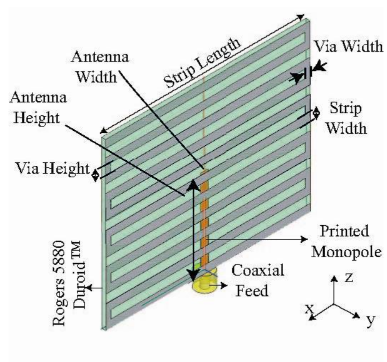
UA has successfully developed several *metamaterial-inspired* efficient electrically-small antennas

EZ Magnetic

EZ Electric

2D



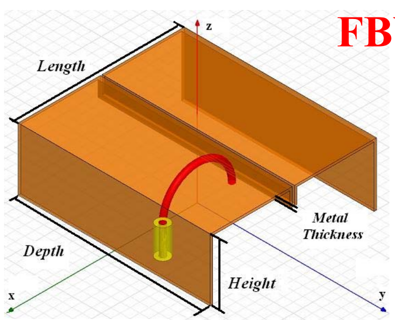


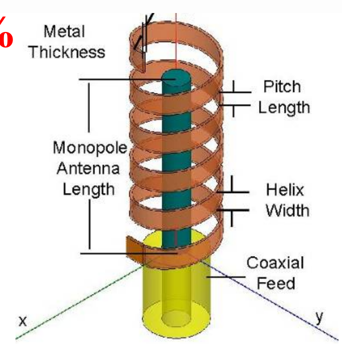
ka ~ 0.5

OE > 90%

FBW_{VSWR} ~ 1-4%

3D

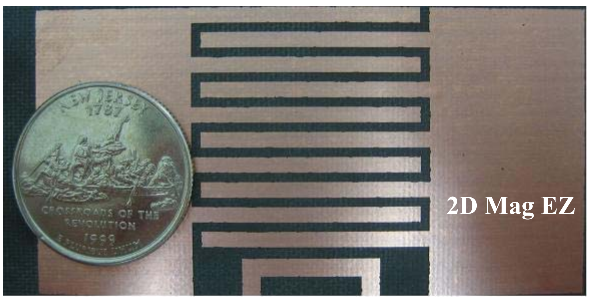


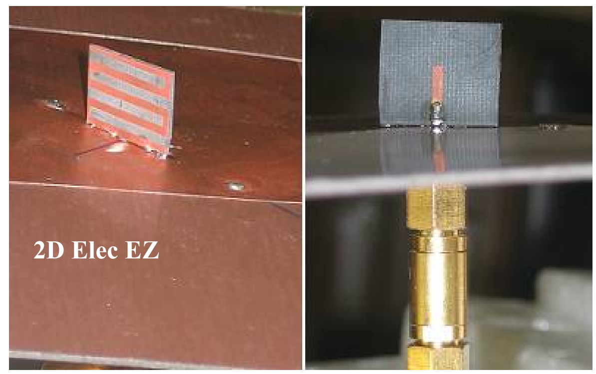


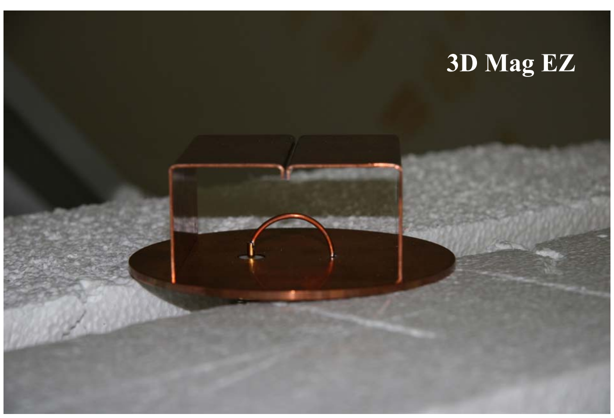
A. Erentok and R. W. Ziolkowski
IEEE Trans. Antennas Propagat.
vol. 56 , pp. 691-707, Mar 2008

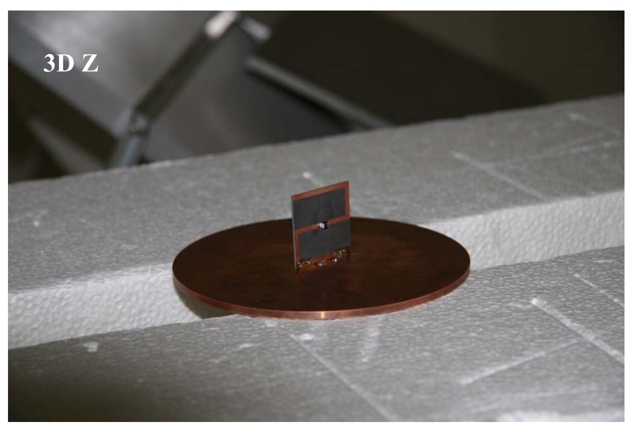
Resonant near-field parasitic designs

Several metamaterial-inspired antennas have been fabricated and tested successfully

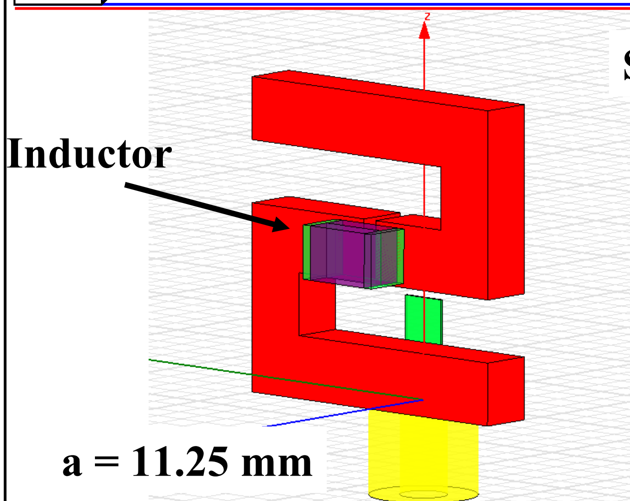


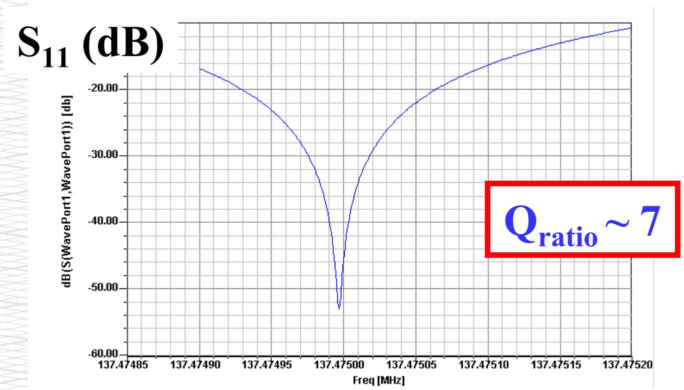




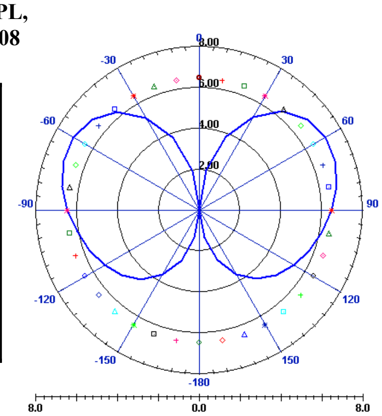


The Z antenna has been shown to achieve very good performance for a very electrically small antenna





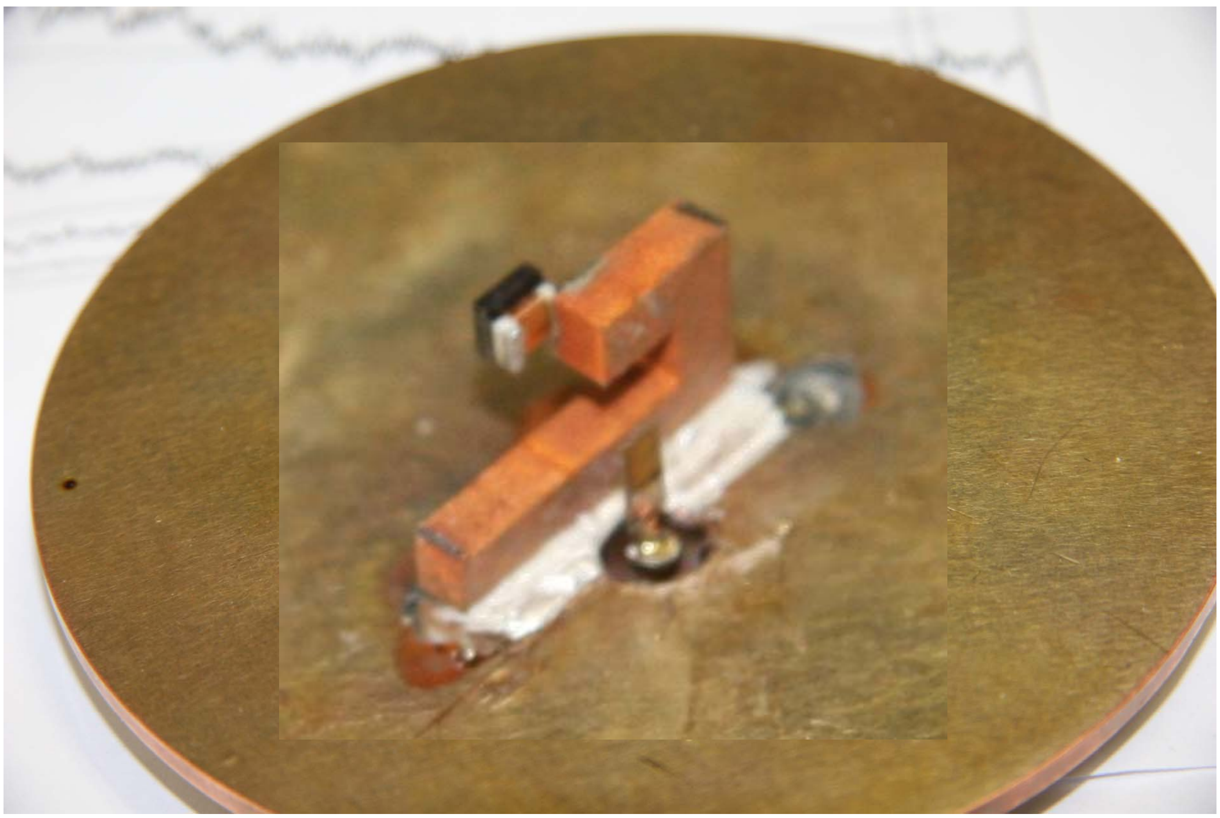
R. W. Ziolkowski, AWPL, vol. 7, pp. 217-220, 2008



Inductor	100 nH	1000 nH	2000 nH	8000 nH
Res. Freq. (MHz)	611.1	193.7	137.5	67.4
ka	0.114	0.046	0.032	0.016
size	λ / 44	λ / 138	λ / 194	λ / 396
OE	93.4%	71.2%	60.5%	34.4%

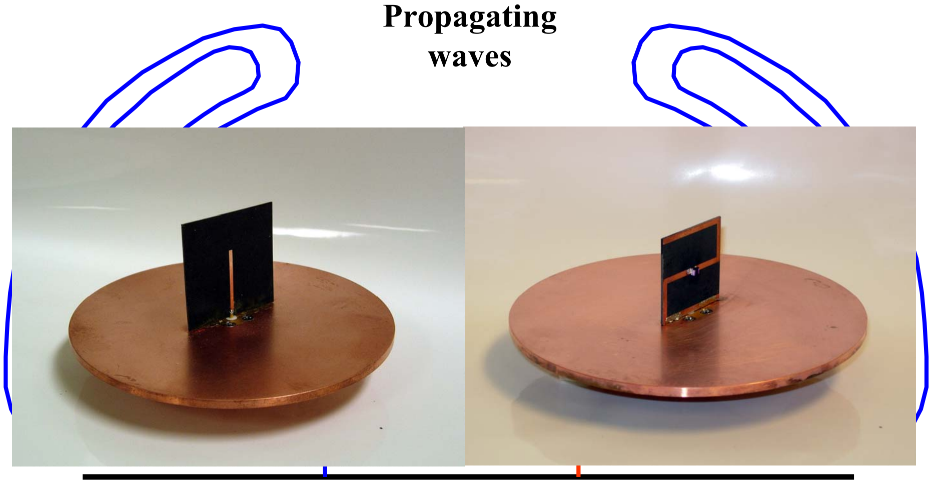
Only height of monopole was varied to achieve complete matching

First fabrication/measurement attempt of Z antenna
Catastrophic structural failure during shipping



What is the essence of the MTM-inspired antennas?? Resonant Near-Field Parasitic

Far-field
Propagating
waves

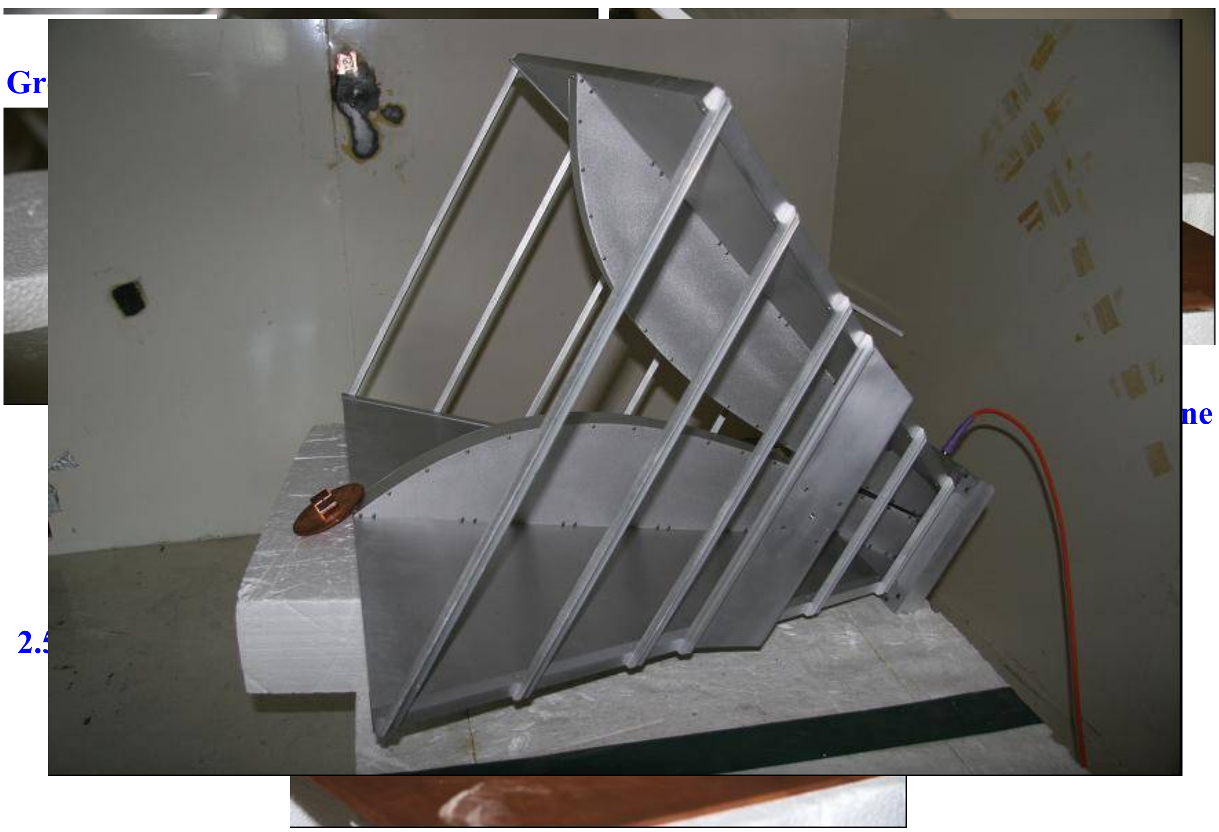


Analogous to dielectric resonator antenna
But resonator is very electrically small

Strong resonator that leaks (lossy) – reactance matched AND resistance matched to source and to free space

Z antenna size comparisons

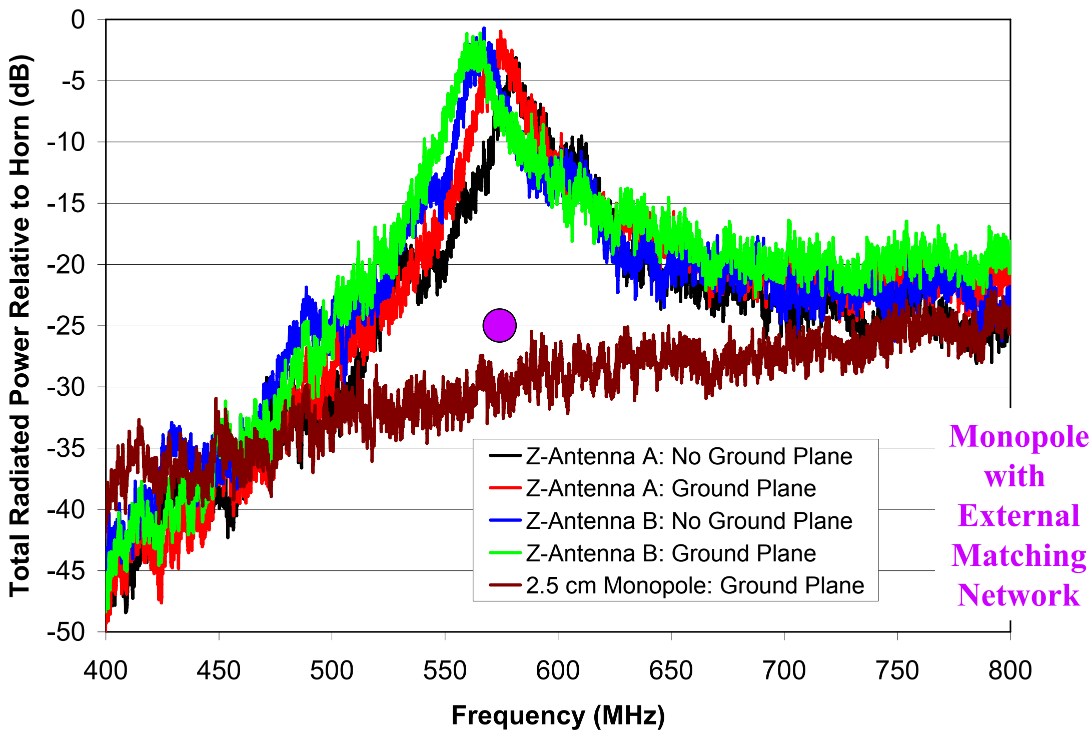
Gr



ne

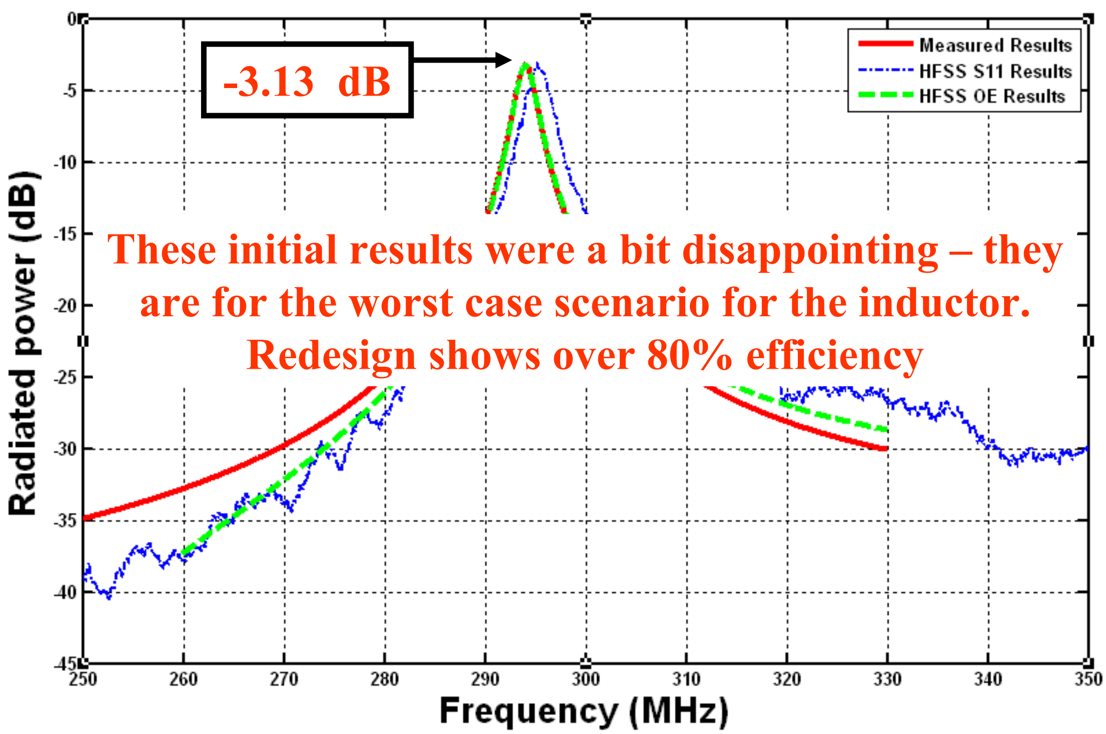
2.5

Very good agreement has been obtained between HFSS predictions and measured results for the 40mm×40mm, 47nH case at 560 MHz



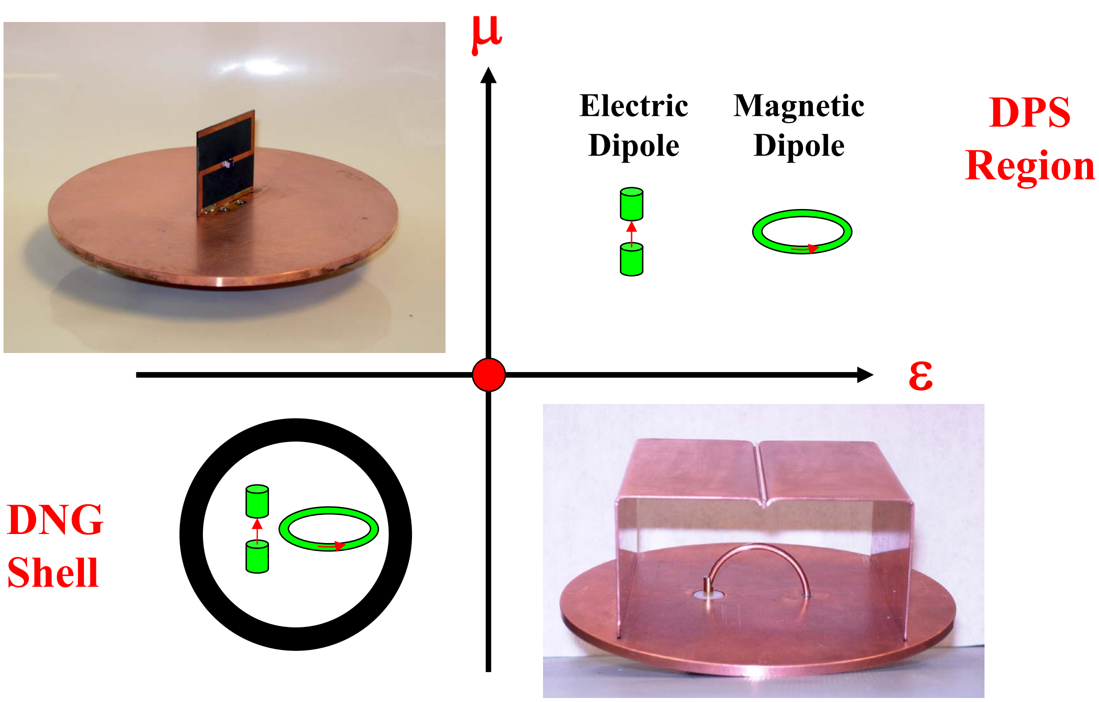
Best: ~ –0.7dB (OE ~ 80%), FBW ~ 3%, Q_{ratio} ~ 4

Very good agreement has been obtained between HFSS predictions and measured results for the 169nH case



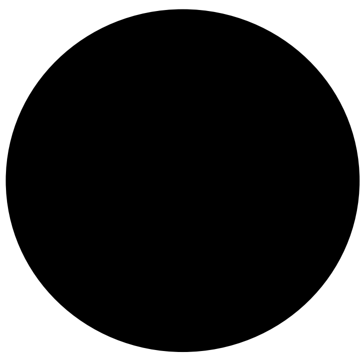
These initial results were a bit disappointing – they are for the worst case scenario for the inductor. Redesign shows over 80% efficiency

Metamaterial-inspired efficient ESAs
Both electric and magnetic versions have been developed

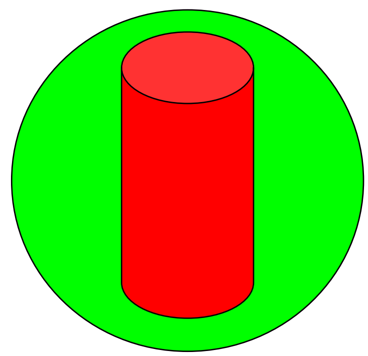


Adjust antenna and NFRP to achieve complete impedance matching AND resistive matching to free space ⇨ > 90% OE

What is the minimum Q (FBW~ 2/Q) for an ESA ??



ONLY reactive energy outside of radiansphere



INCLUDES reactive energy inside of radiansphere

Chu limit

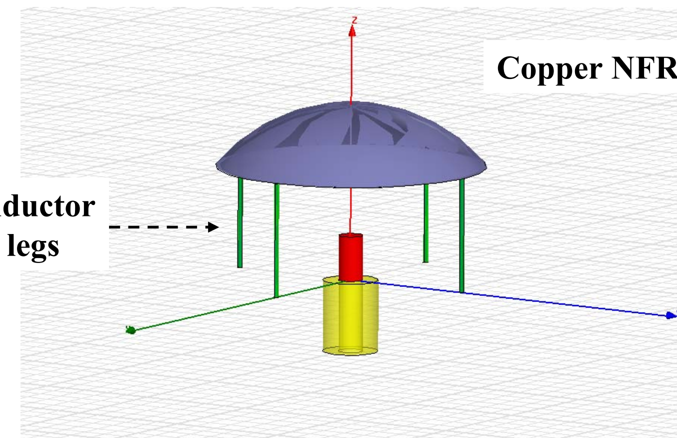
$$Q_{\text{Chu lower bound}} = \eta_{\text{rad}} \left[\frac{1}{ka} + \frac{1}{(ka)^3} \right]$$

Thal limit

$$Q_{\text{Thal l.b.}} = 1.5\; Q_{\text{Chu lb}}$$ electric type

$$= 3.0\; Q_{\text{Chu lb}}$$ magnetic type

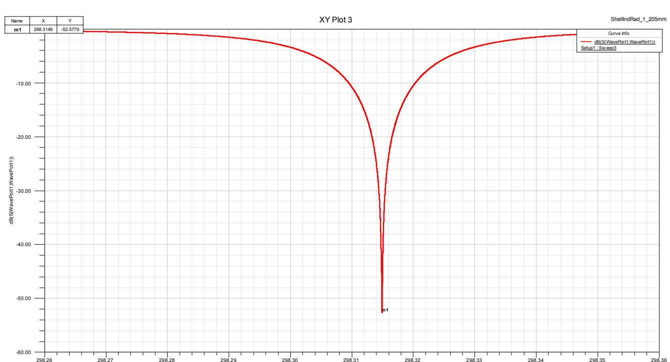
Canopy antenna was developed to explore reaching the Chu/Thal limit passively and beyond actively

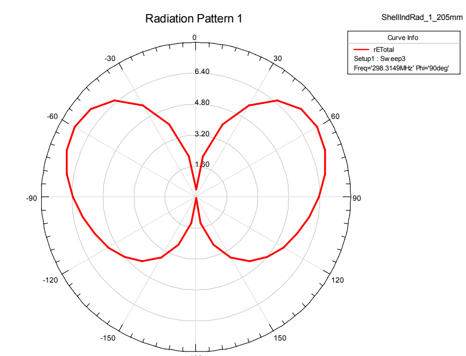


Copper NFRP *morphed* to "fill" radiansphere

Inductor legs

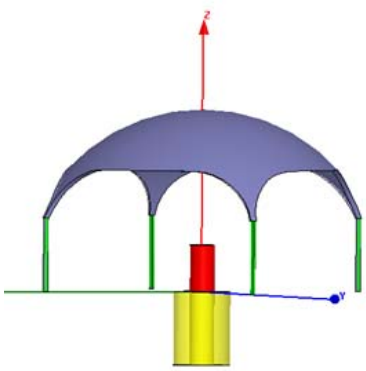
f_{res} ~ 300 MHz
ka ~ 0.047
OE ~ 97%
$Q_{Chu\ ratio}$ = 1.75
$Q_{Thal\ ratio}$ = 1.17





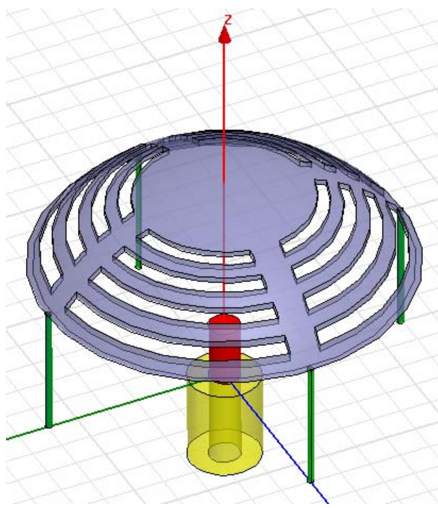
We tried to push the Q ratio results below: $Q_{ratio} \sim 1.75$

LAX antenna



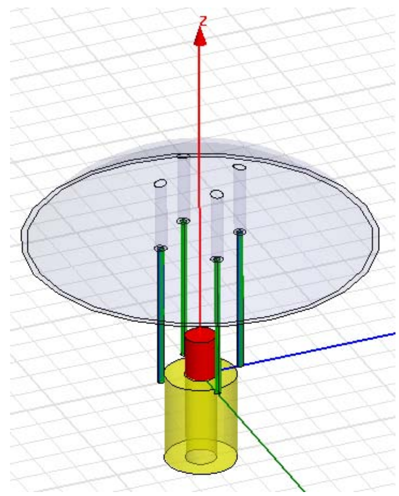
f_{res} = 297.7784 MHz
ka = 0.0463
OE= 94.642 %
Q_{ratio} = 1.81

Slotted canopy antenna



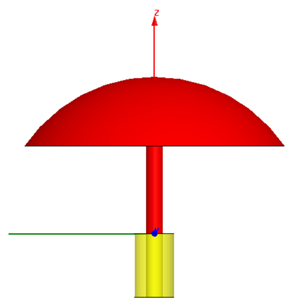
f_{res} = 299.0767 MHz
ka = 0.0465
OE= 96.032 %
Q_{ratio} = 1.75

Modified canopy antenna

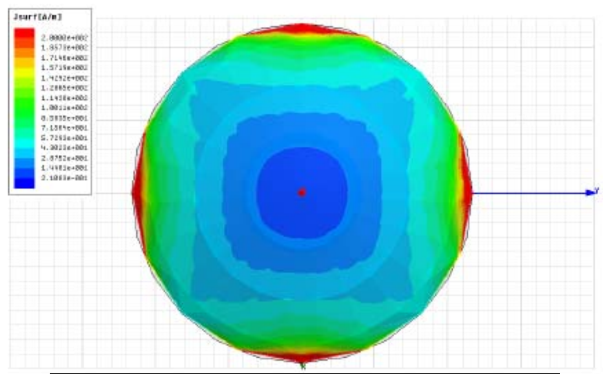


f_{res} = 299.1150 MHz
ka = 0.0465
OE= 92.927 %
Q_{ratio} = 1.78

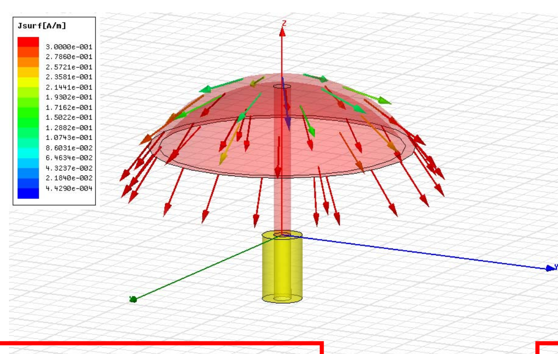
Lower bound reached with pure $J_{\theta} = \sin\theta$ currents



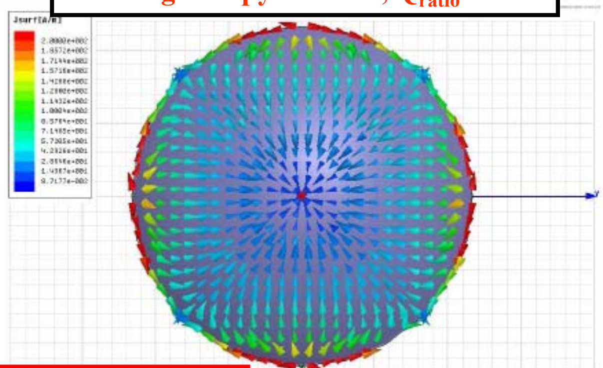
Spherical cap monopole, $Q_{ratio} = 1.5$



Four-leg canopy antenna, $Q_{ratio} = 1.75$

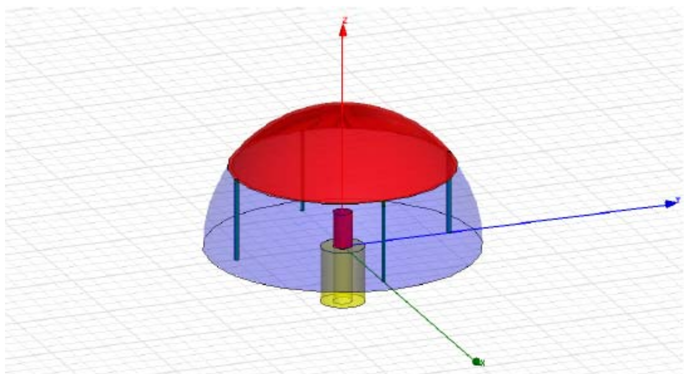


$Z_{in} = 5\Omega$, Not matched

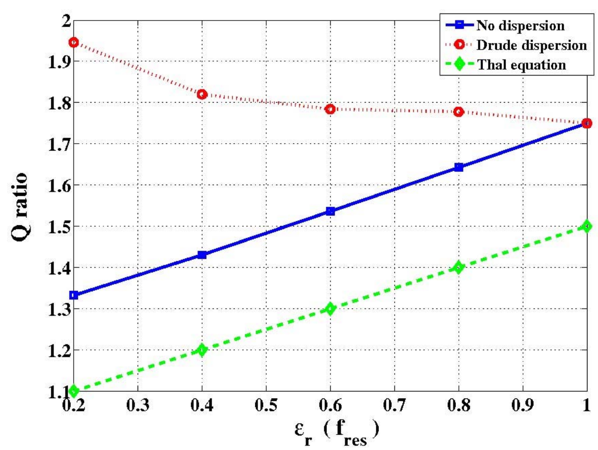


Matched $Z_{in} = 50\Omega$

Reaching the Chu lower bound with electric type ESA with ε → 0 filling



Drude model, Dispersive Metamaterial Filling



MTM
0 < ε < 1
Hemisphere

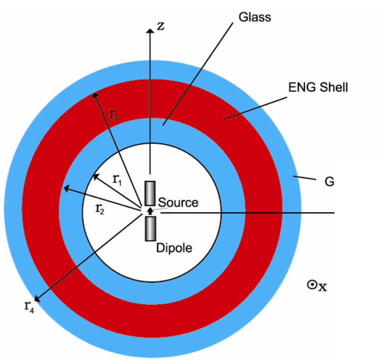
Approaching the Q lower bound

Practically speaking – how useful is a ka = 0.047 antenna whose fractional bandwidth is

0.021%

??????????

Dispersion Engineering provides a means to recover bandwidth advantages



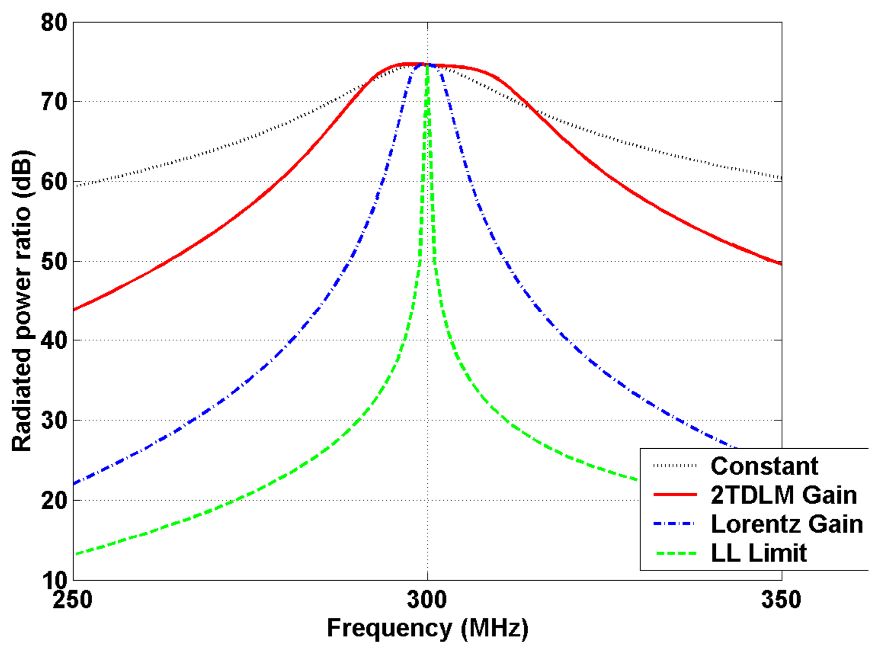
$\partial_f \, \varepsilon$

controls the bandwidth

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

Active metamaterials

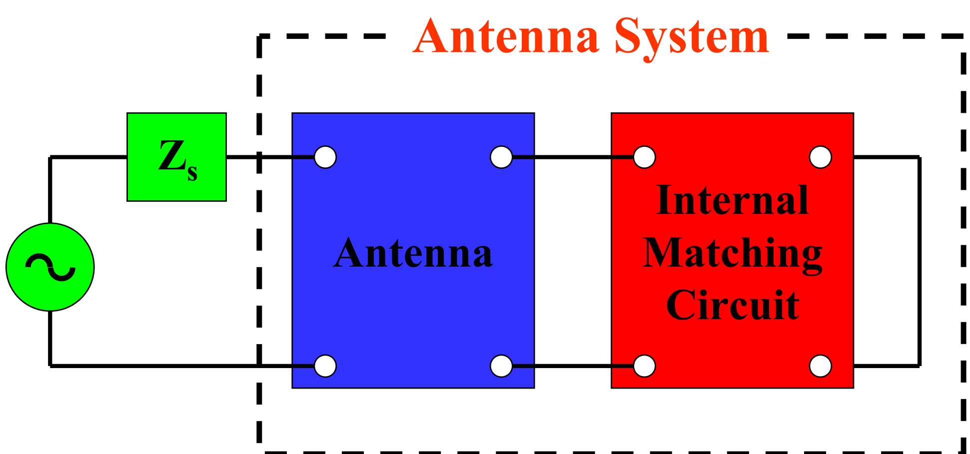
Achieve bandwidths similar to constant ENG values



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

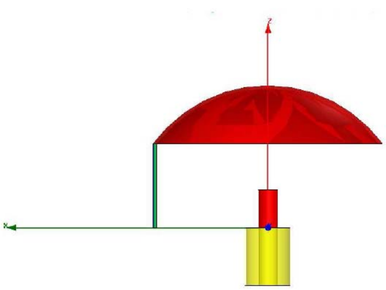
External versus Internal Matching Networks

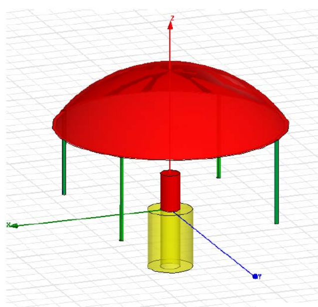
Different Paradigm



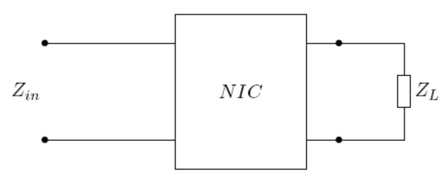
IMN provides ONLY *reactance* matching

Active internal matching element (NIC = Negative Impedance Convertor) leads to interesting bandwidths

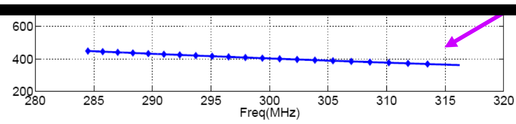




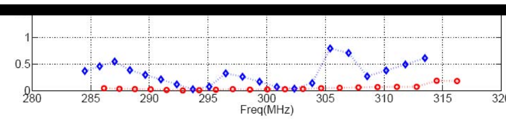
$$\partial_\omega (\omega L) < 0$$



Active design: ka = 0.047 antenna with >10% bandwidth



Curve fitting to HFSS-predicted resonance frequencies when *only* inductor values are varied



With the curve fit inductor values, i.e., the active circuit, HFSS predicts essentially the same performance

Thank you for listening ☺

Any questions ??