DREL
DEPARTMENT OF RADIO ELECTRONICS

Antennas for Wireless Body Area Networks

The 24th International Traveling Summer School on Microwaves and Lightwaves

Zbynek Raida

OUTLINE

- **Introduction to antennas**
  From Maxwell equations to applications
- **Human body**
  Ways of modeling
- **Antennas**
  On-body versus off-body
- **Conclusions**

Maxwell equations (1)

James Clerk Maxwell

- **1864**: The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.

Maxwell equations (2)

$$\oint_l \mathbf{H} \cdot d\mathbf{l} = I + \frac{d}{dt} \int_S (\varepsilon \mathbf{E}) \cdot d\mathbf{S}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{d}{dt} (\varepsilon \mathbf{E})$$

$$\oint_l \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \int_S (\mu \mathbf{H}) \cdot d\mathbf{S}$$

$$\nabla \times \mathbf{E} = -\frac{d}{dt} (\mu \mathbf{H})$$

$$\oint_S (\varepsilon \mathbf{E}) \cdot d\mathbf{S} = Q$$

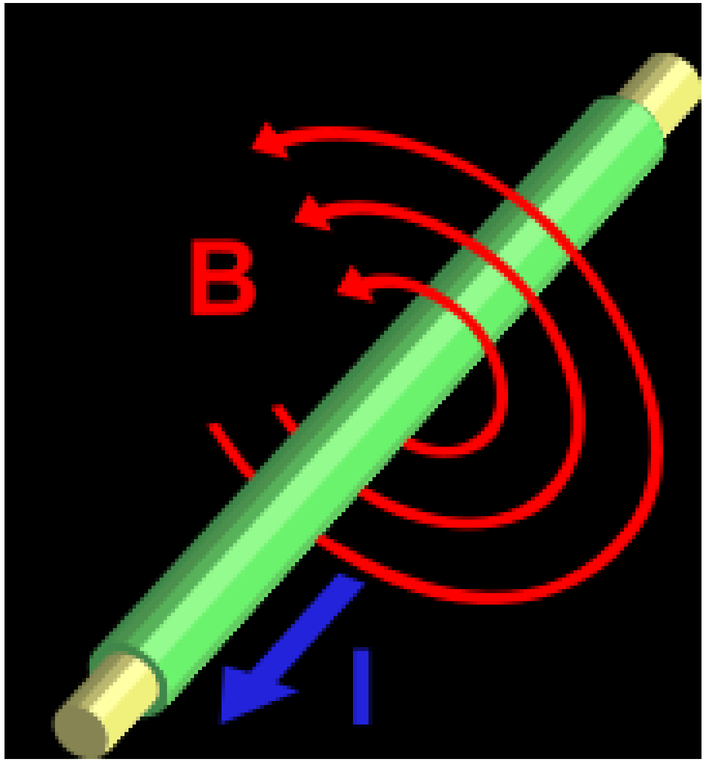
$$\nabla \cdot (\varepsilon \mathbf{E}) = \rho$$

$$\oint_S (\mu \mathbf{H}) \cdot d\mathbf{S} = 0$$

$$\nabla \cdot (\mu \mathbf{H}) = 0$$

Maxwell equations (3)

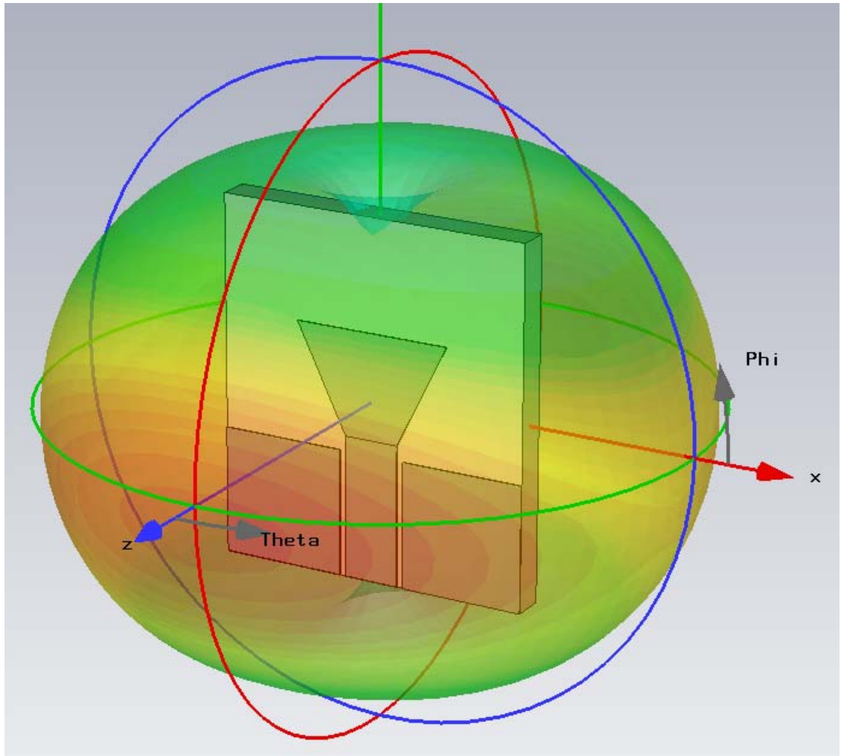
André-Marie Ampére



$$\oint_l \mathbf{H} \cdot d\mathbf{l} = I + \frac{d}{dt} \int_S (\varepsilon \mathbf{E}) \cdot d\mathbf{S}$$

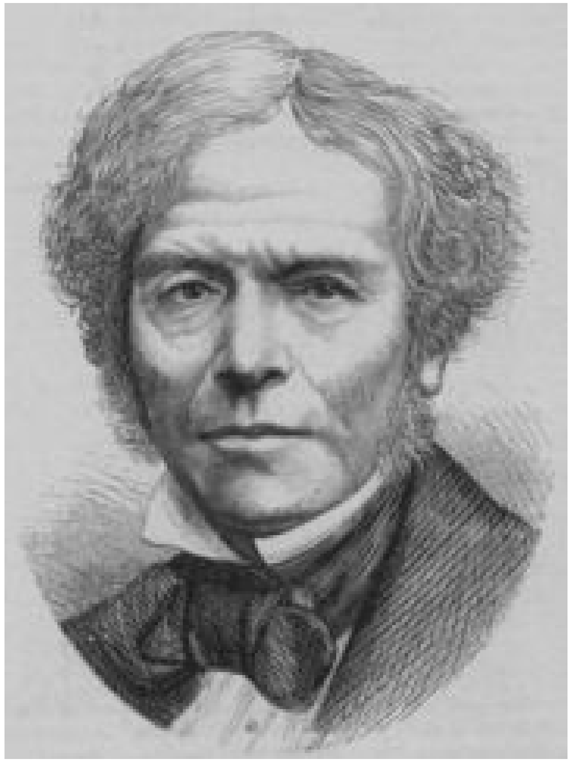
Maxwell equations (4)

André-Marie Ampére

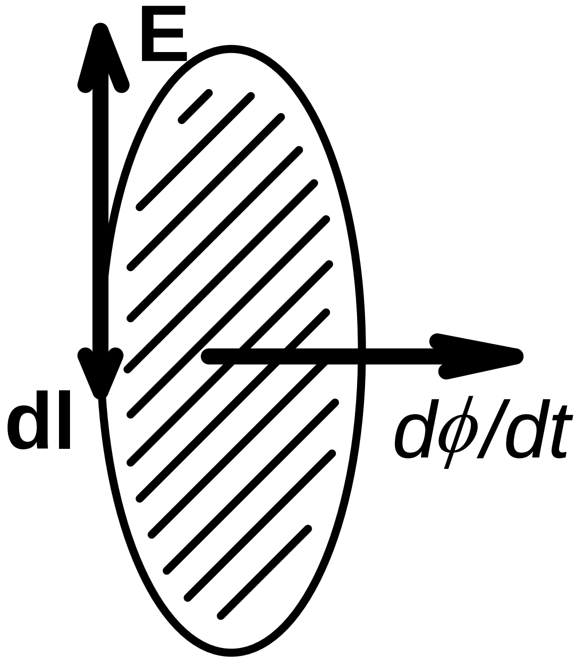


$$\oint_l \mathbf{H} \cdot d\mathbf{l} = I + \frac{d}{dt} \int_S (\varepsilon \mathbf{E}) \cdot d\mathbf{S}$$

Maxwell equations (5)

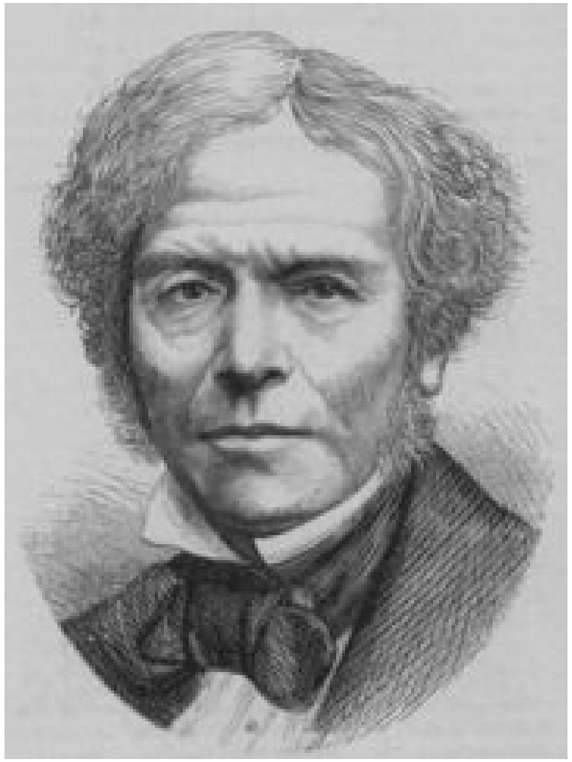


Michael Faraday

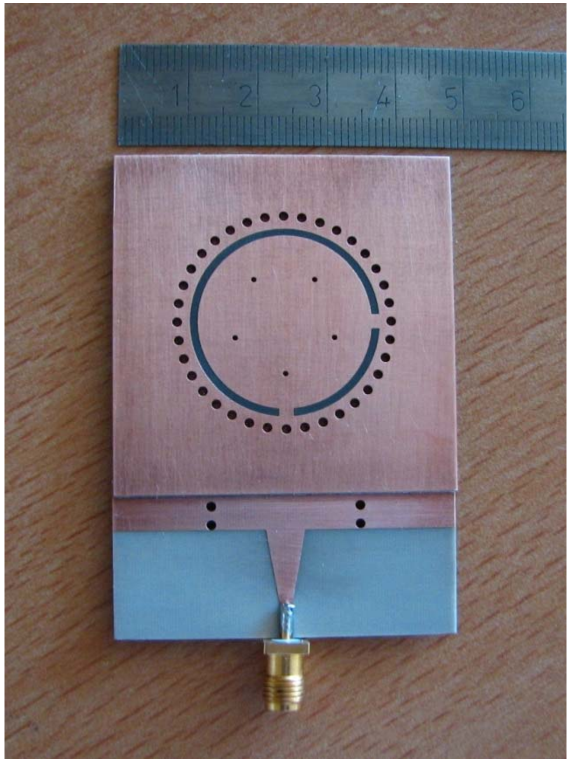


$$\oint_l \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt}\int_S (\mu \mathbf{H}) \cdot d\mathbf{S}$$

Maxwell equations (6)



Michael Faraday



$$\oint_l \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt}\int_S (\mu\,\mathbf{H}) \cdot d\mathbf{S}$$

Wave equation

- Let's assume harmonic fields
- Then, Maxwell equations

$$\nabla \times \mathbf{E} = -j\omega\mu\,\mathbf{H}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + j\omega\varepsilon\,\mathbf{E}$$

- Reducing the number of unknowns $\rightarrow$ potentials

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad \nabla^2\mathbf{A} + k^2\mathbf{A} = -\mu\mathbf{J} \qquad k^2 = \omega^2\varepsilon\,\mu$$

$$\mathbf{E} + j\omega\mu\,\mathbf{A} = -\nabla\varphi \qquad \nabla^2\varphi + k^2\varphi = 0$$

$$\varphi = \left(j\omega/k^2\right)\nabla\cdot\mathbf{A}$$

Potentials

- Currents flowing along antenna wire

$$\mathbf{A}(\mathbf{r}) = \mu_0 \iiint \mathbf{J}(\mathbf{r}') \frac{\exp\left[-j\,\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')\right]}{4\pi\left|\mathbf{r}-\mathbf{r}'\right|}\, d\mathbf{r}'$$

- Charges accumulating at the ends of antenna

$$\varphi(\mathbf{r}) = \frac{1}{\varepsilon_0} \iiint q(\mathbf{r}') \frac{\exp\left[-j\,\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')\right]}{4\pi\left|\mathbf{r}-\mathbf{r}'\right|}\, d\mathbf{r}'$$

- Continuity theorem

$$-j\,\omega\, q(\mathbf{r}) = \nabla \cdot \mathbf{J}$$

- Radiated wave

$$\mathbf{E}(\mathbf{r}) = -\, j\,\omega\,\mathbf{A}(\mathbf{r}) - \nabla\varphi$$

Elementary dipole (1)

- Magnetic vector potential

$$\mathbf{A}(\mathbf{r}) = \mu_0 \iiint \mathbf{J}(\mathbf{r}') \frac{\exp[-j\,\mathbf{k} \cdot (\mathbf{r} - \mathbf{r}')]}{4\pi |\mathbf{r} - \mathbf{r}'|} \, d\mathbf{r}'$$

$$dA_z = \frac{\mu_0}{4\pi} I \, dz \frac{e^{-jkr}}{r}$$

Elementary dipole (2)

- Substituting vector potential to Maxwell equations

$$dE_r = \frac{1}{4\pi\varepsilon}\frac{2I\,dz}{\omega}k^3\cos\vartheta\left[\frac{-j}{(kr)^3}+\frac{1}{(kr)^2}\right]e^{-jkr}$$

$$dE_\vartheta = \frac{1}{4\pi\varepsilon}\frac{I\,dz}{\omega}k^3\sin\vartheta\left[\frac{-j}{(kr)^3}+\frac{1}{(kr)^2}+\frac{j}{(kr)}\right]e^{-jkr}$$

$$dH_\varphi = \frac{1}{4\pi}I\,dz\,k^2\sin\vartheta\left[\frac{1}{(kr)^2}+\frac{j}{(kr)}\right]e^{-jkr}$$

Elementary dipole (3)

- Far field

$$dE_{\vartheta} = 60I \; j\frac{k}{2}\sin\vartheta \, dz \, \frac{e^{-jkr}}{r}$$

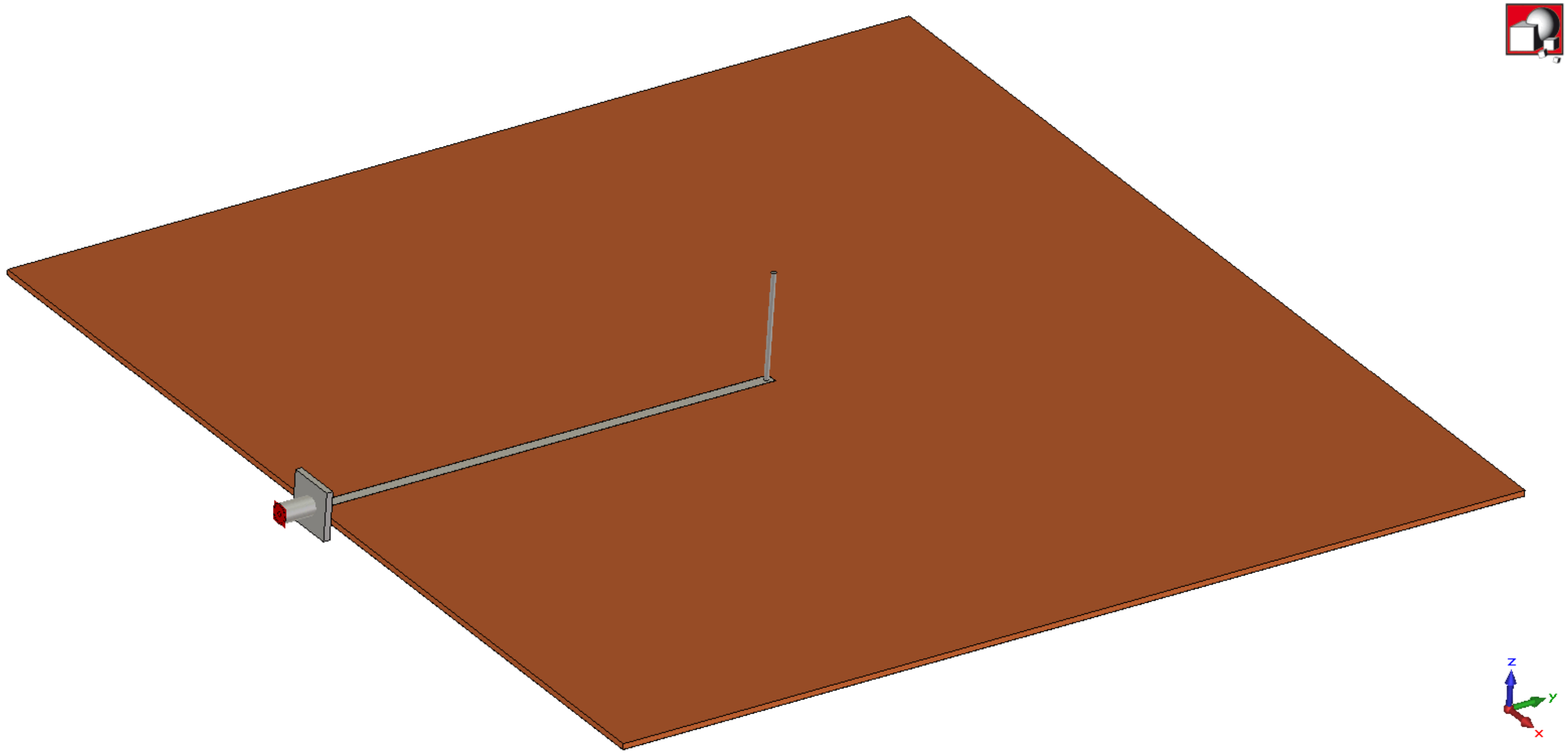
$$dH_{\varphi} = \frac{dE_{\vartheta}}{120\pi}$$

- Radiation pattern

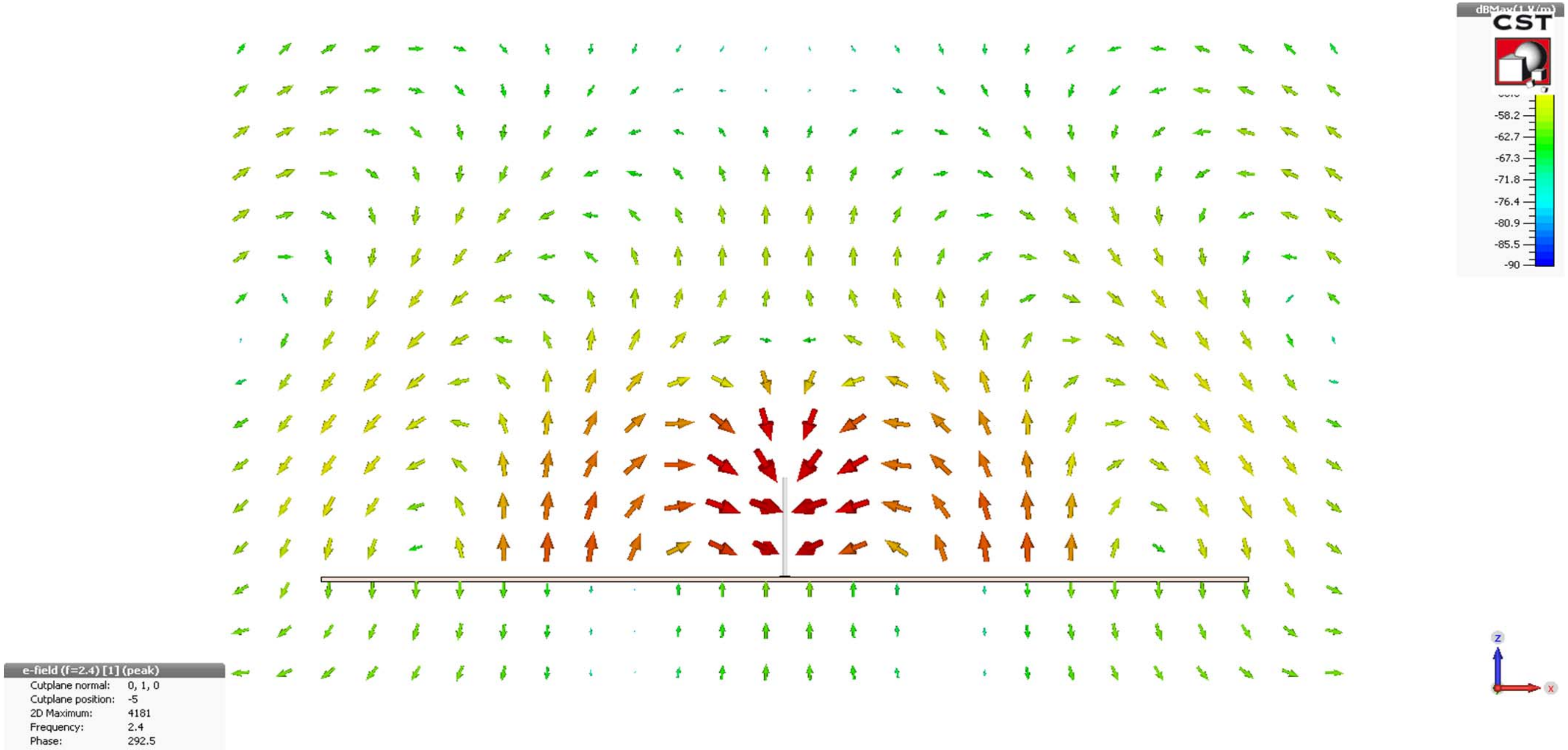
$$E = 60I \; F(\varphi,\vartheta)\,\frac{e^{-jkr}}{r}$$

$$F(\varphi,\vartheta) = j\,\frac{k}{2}\sin\vartheta \; dz$$

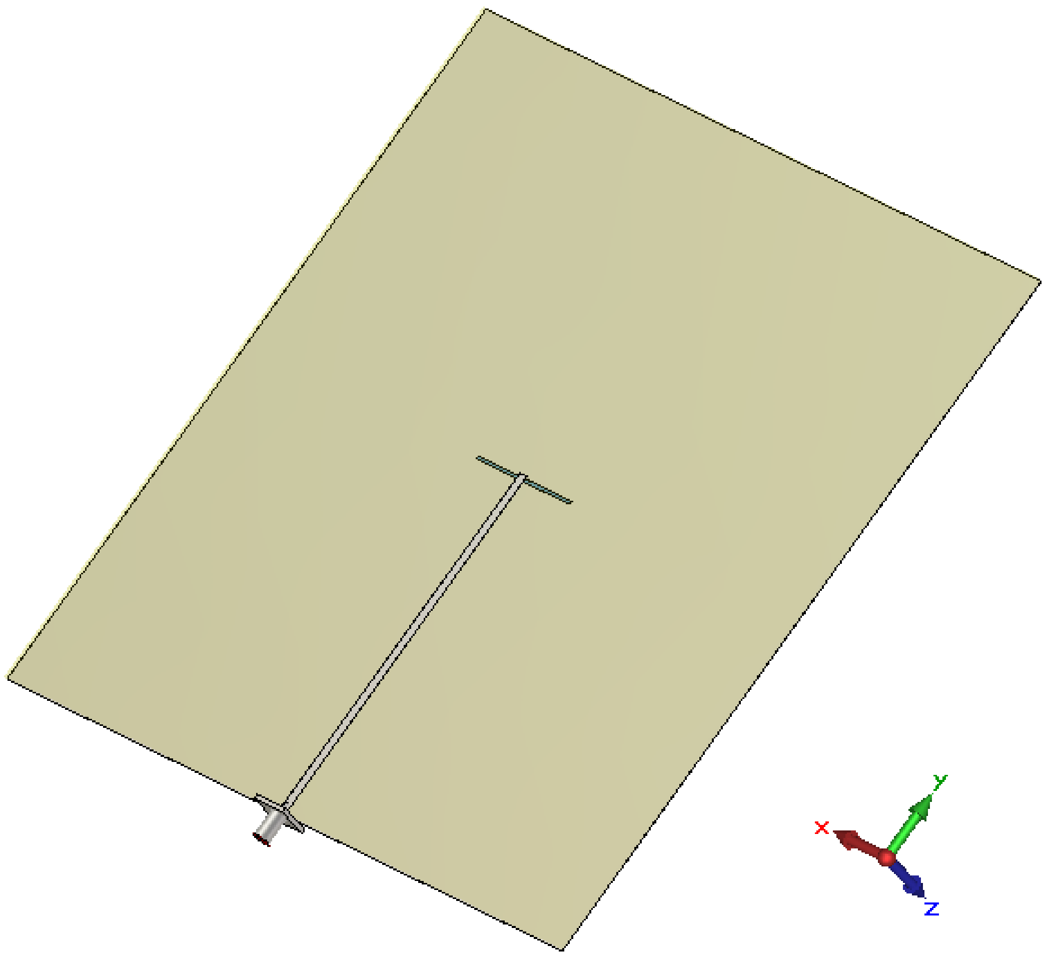
Elementary dipole (4)



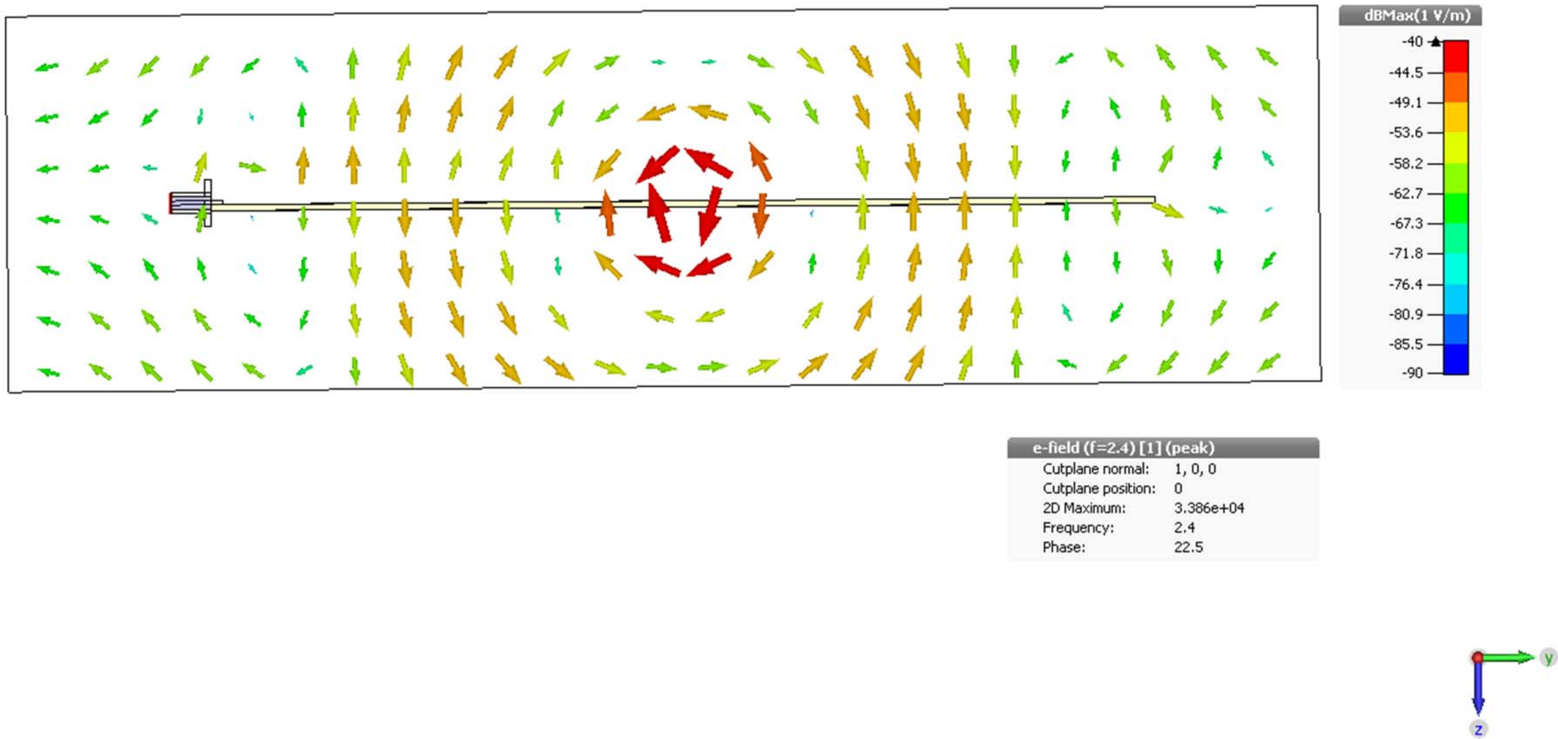
Elementary dipole (5)



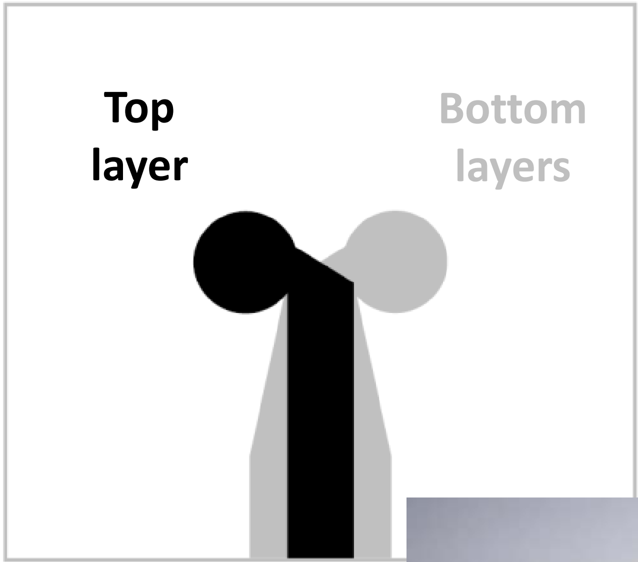
Elementary dipole (6)

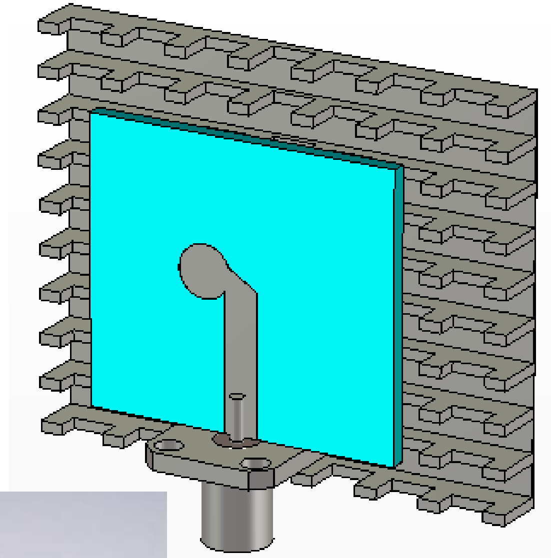


Elementary dipole (7)

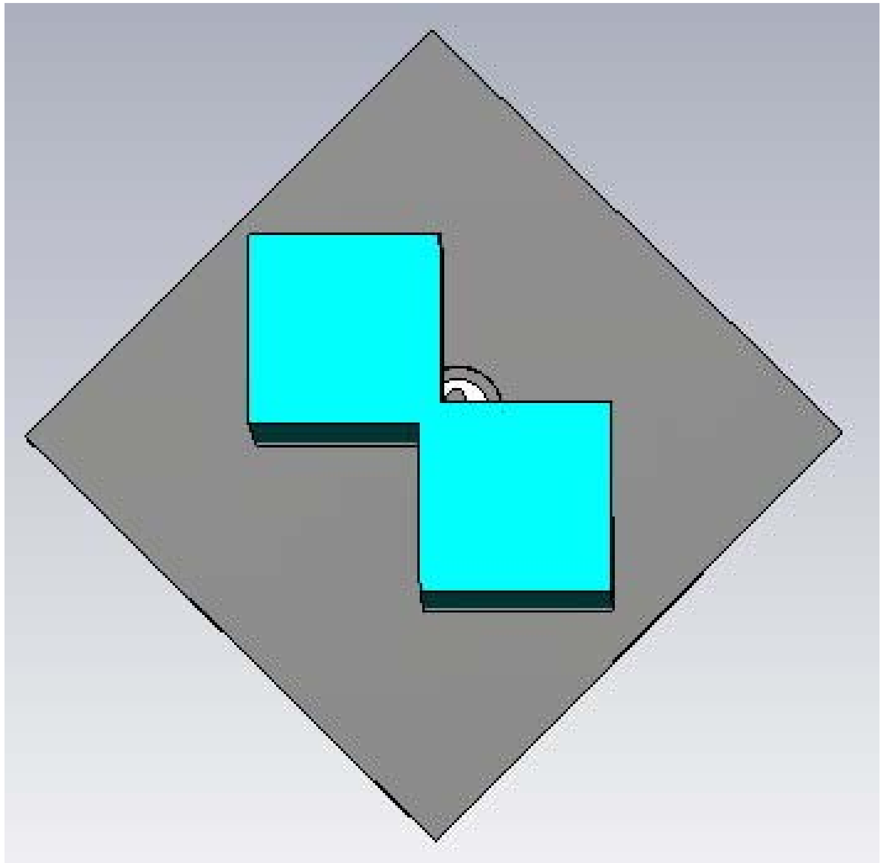


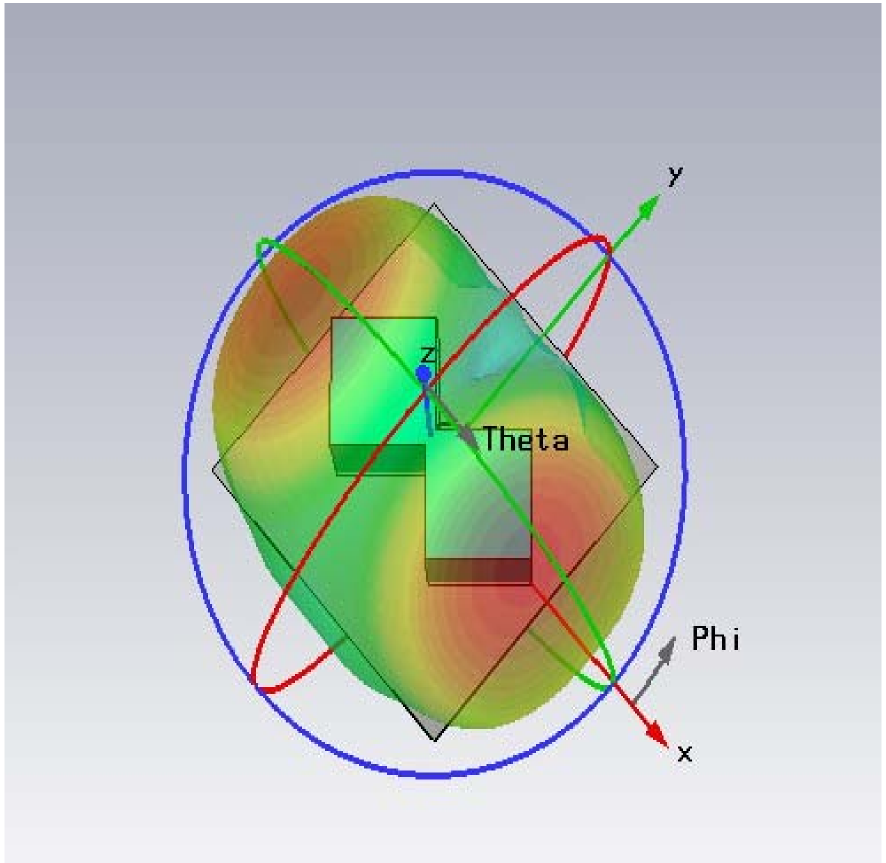
Practical dipoles (1)



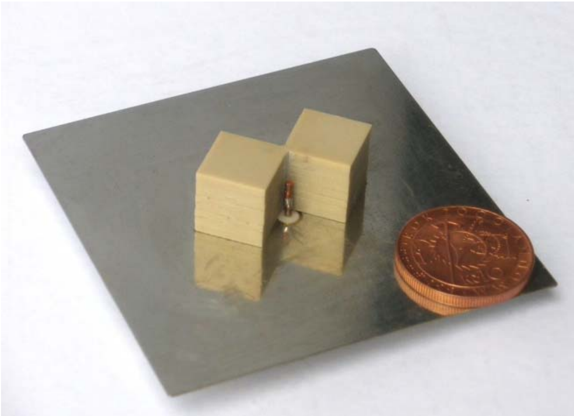


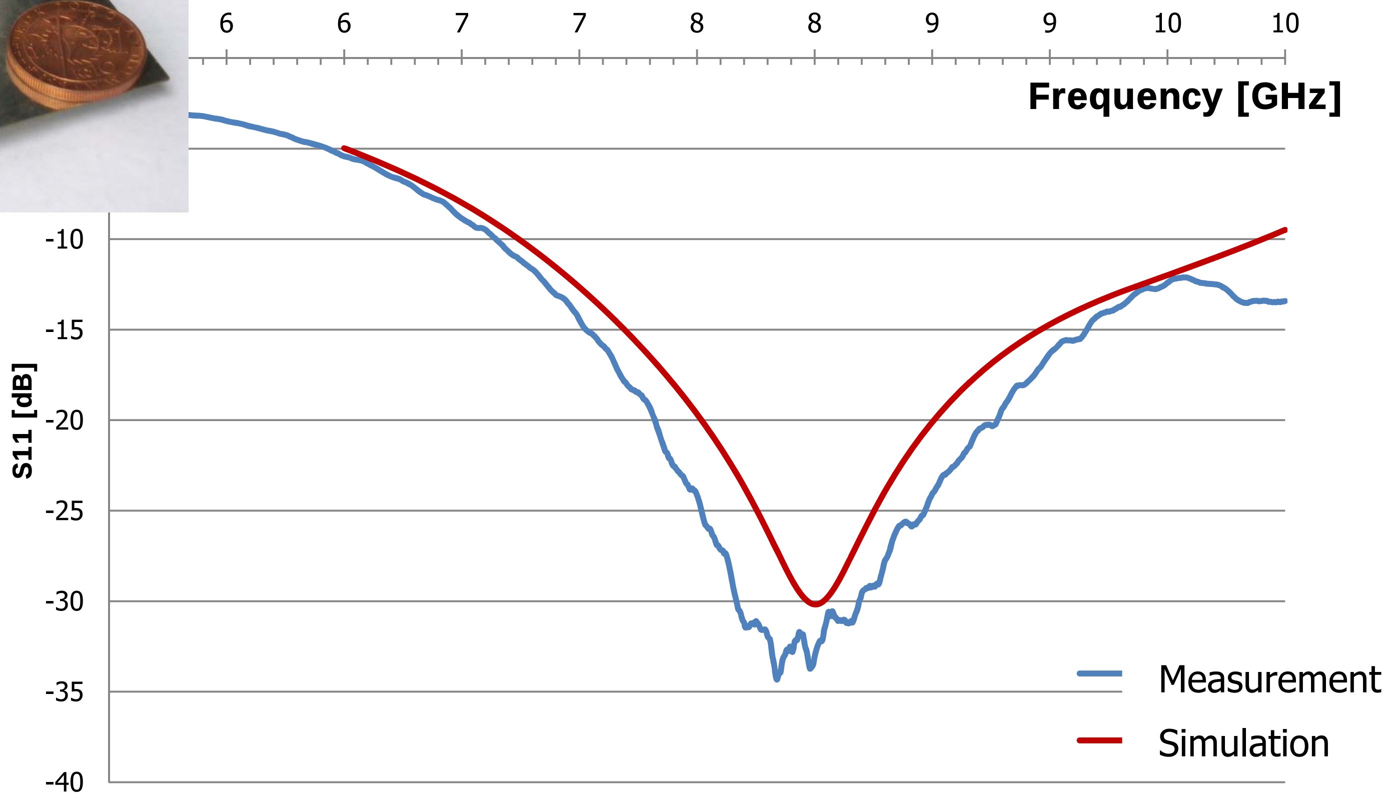
Practical dipoles (2)





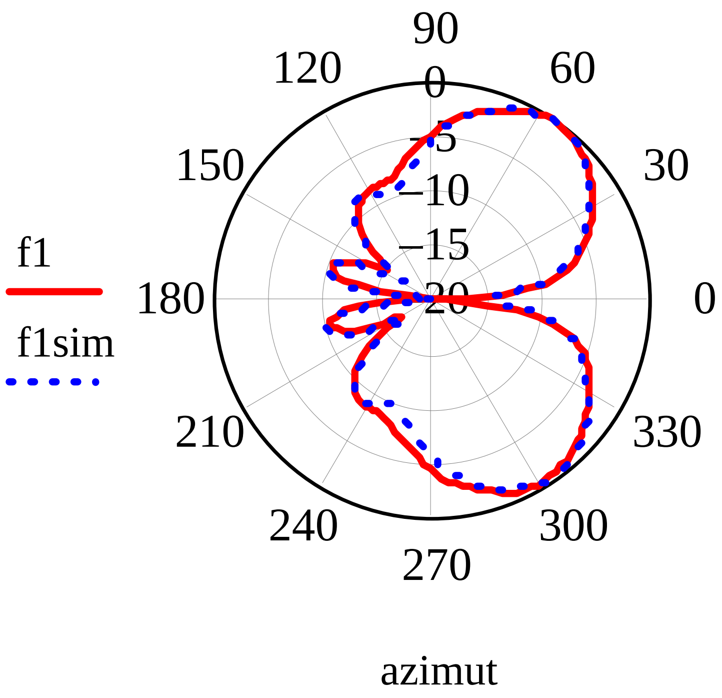
Practical dipoles (3)

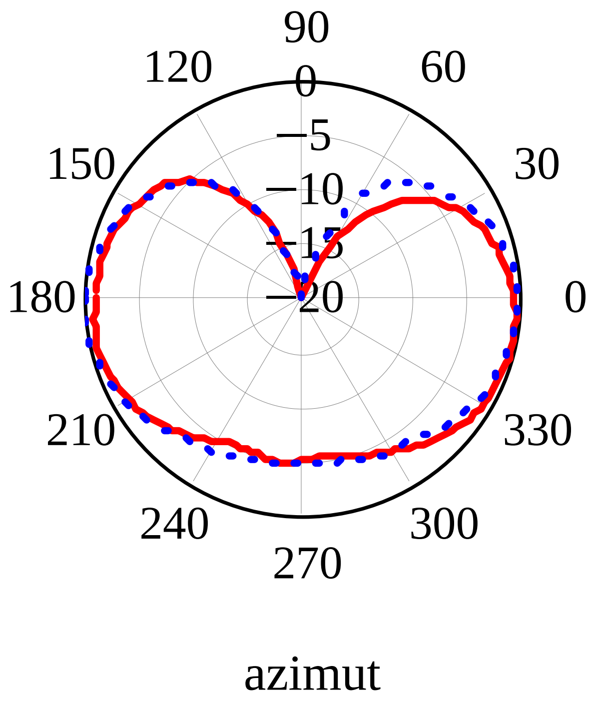




Practical dipoles (4)

f = 7.30 GHz **E plane** **H plane**





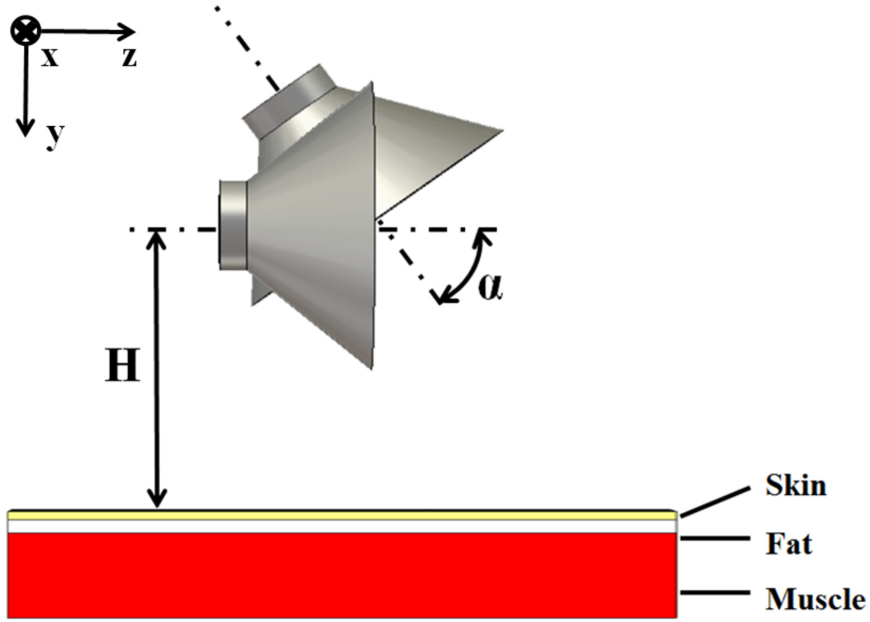
Towards tissue

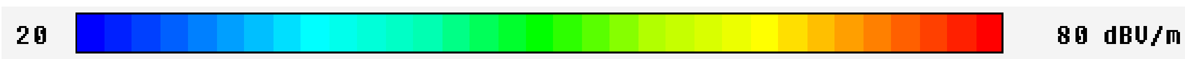
- Surface and creeping waves:
  tangential electric field intensity attenuated
- Monopoles exciting vertical polarization versus slot antennas → in parallel to skin
- Sensors → directional antennas
- Central unit → omnidirectional antenna
- Testing → phantoms

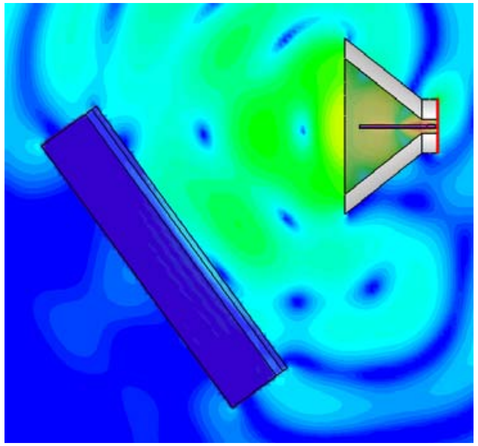
Parameters of tissues

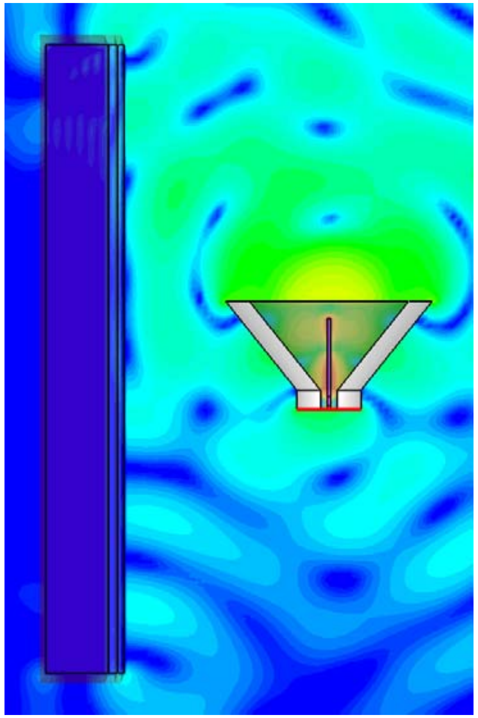
	ε_r [-]	ε_r [-]	σ [S/m]	σ [S/m]
Tissue	2.40 GHz	5.80 GHz	2.40 GHz	5.80 GHz
Skin	38.063	35.114	1.441	3.717
Fat	5.285	4.955	0.102	0.293
Muscle	52.791	48.485	1.705	4.962

Numerical phantoms (1)

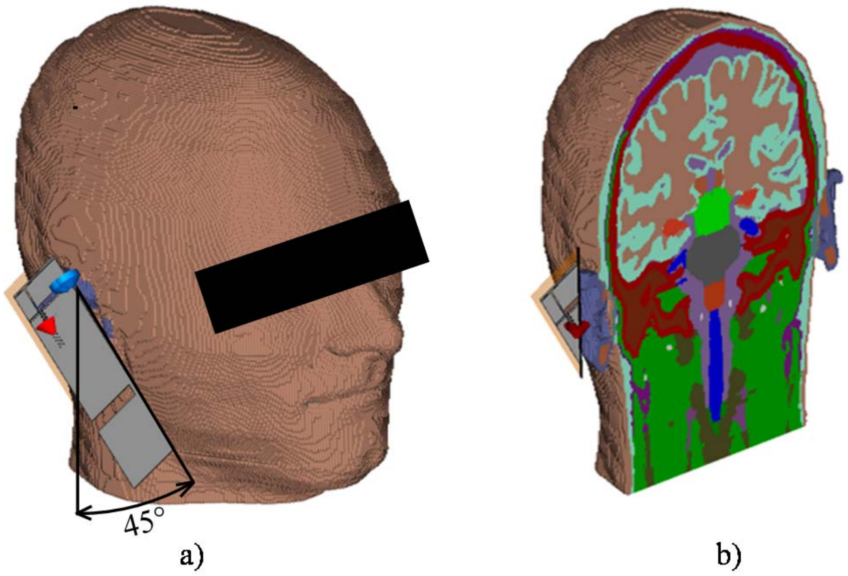






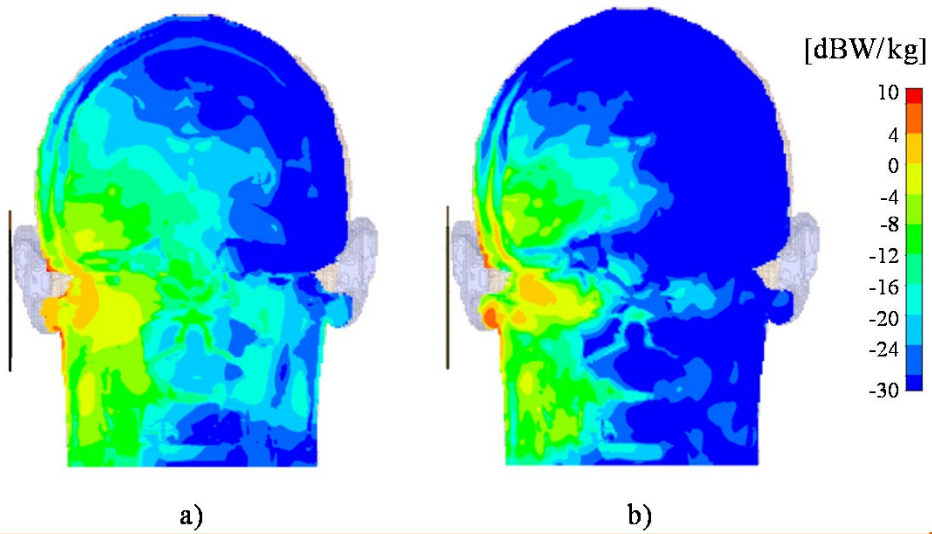


Numerical phantoms (2)



Detailed anatomical models of the human body provided by the ITIS foundation

A. Christ, W. Kainz, E. G. Hahn, K. Honegger, M. Zefferer, E. Neufeld, W. Rascher, R. Janka, W. Bautz, J. Chen, B. Kiefer, P. Schmitt, H. P. Hollenbach, J. X. Shen, M. Oberle, N. Kuster, The virtual family—Development of anatomical CAD models of two adults and two children for dosimetric simulations, Phys. Med. Biol., vol. 55, no. 2, pp. 23-38, Jan. 2010

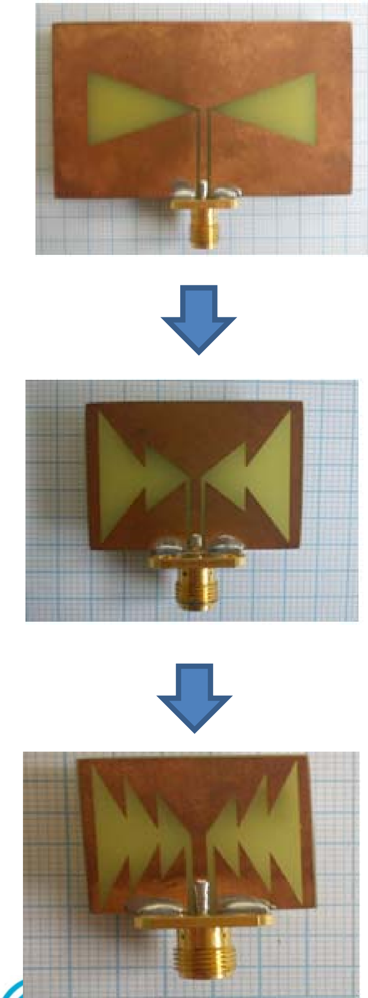


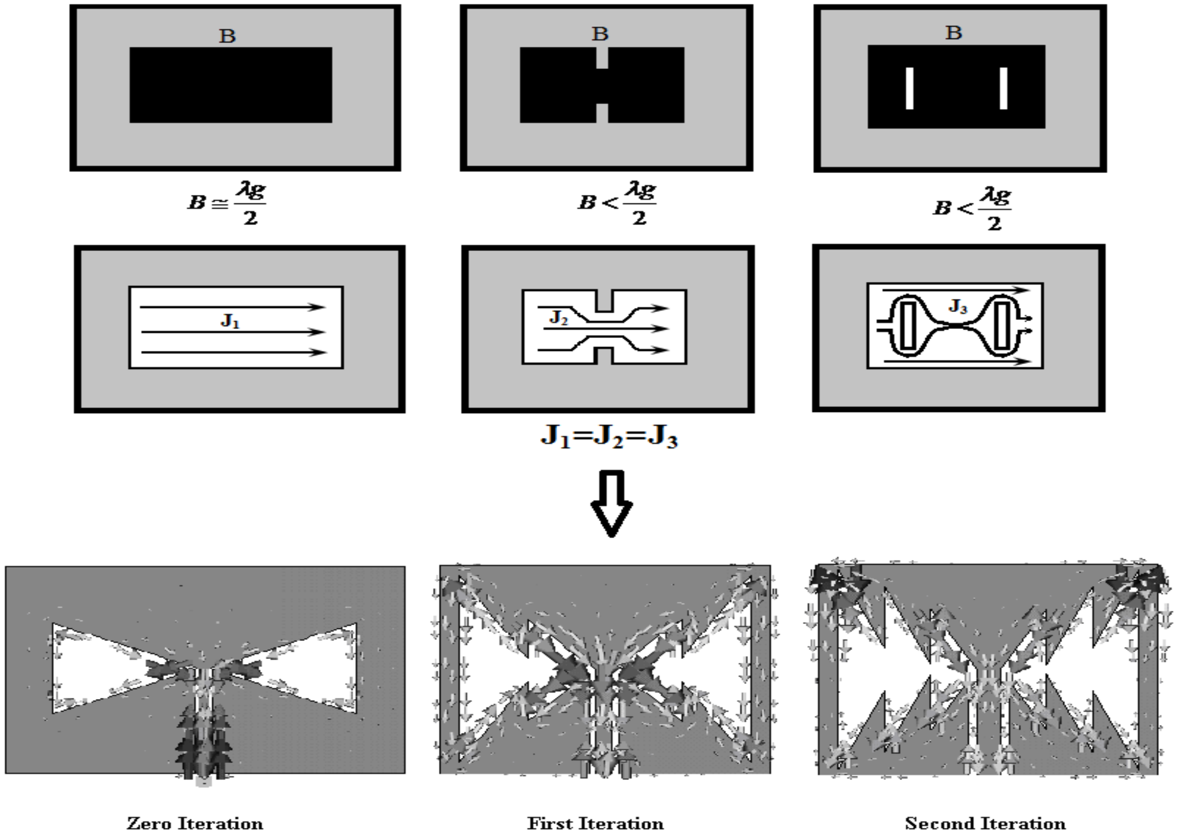
Physical phantoms

- Block of the basis 200 mm × 200 mm and the height 20 mm
- Modified agar gelatin (ε_r = 48)
- Agar: 66%
  Water: 33%

Fractal slot dipole (1)

Notches: the same current length in reduced area

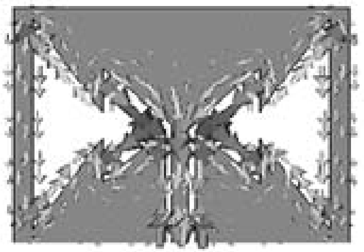


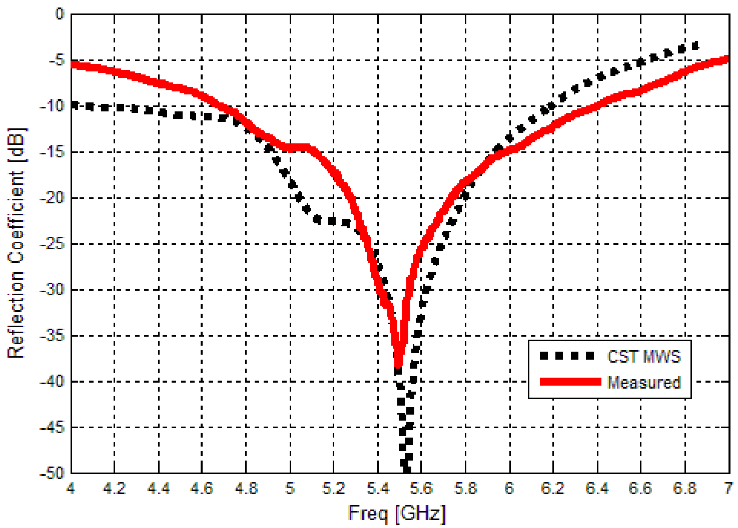


Optimum ratio:

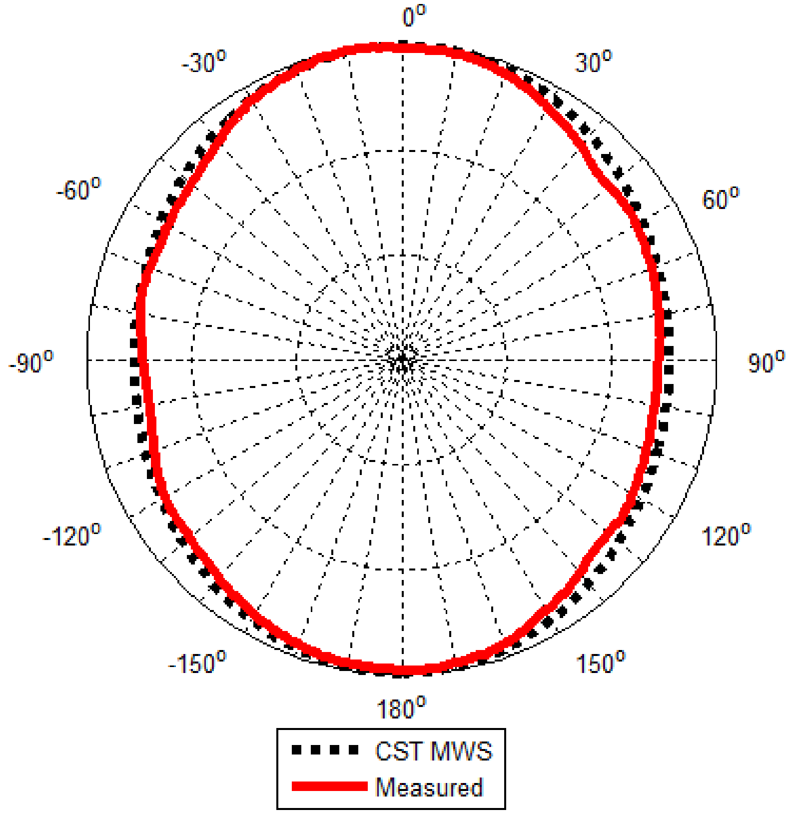
1.00 : 0.58 : 0.43

Fractal slot dipole (2)





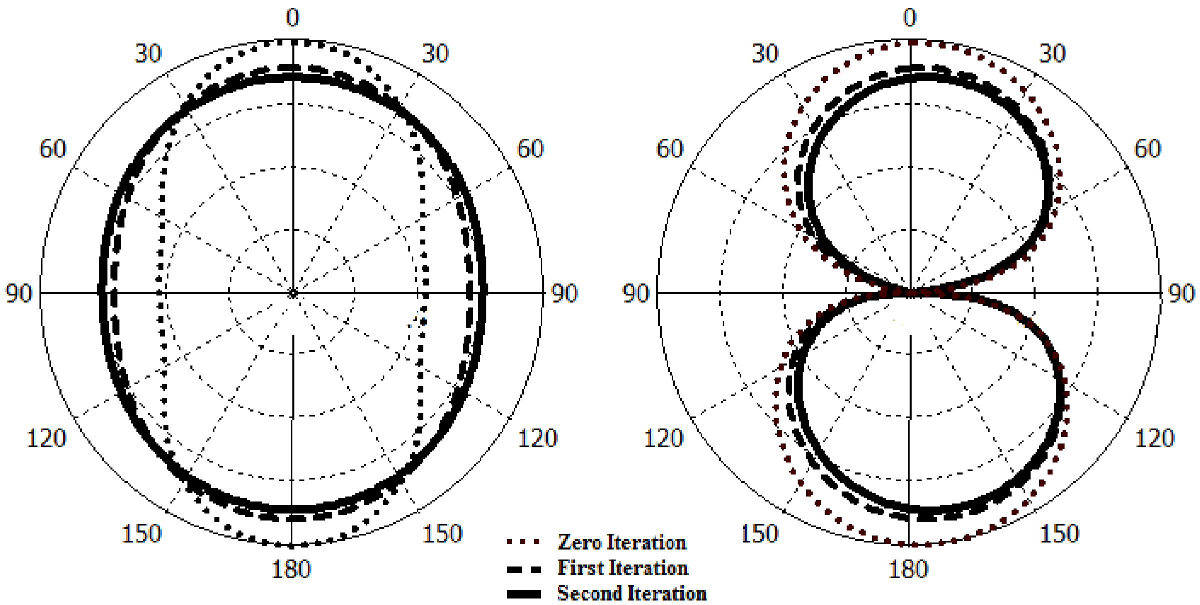
BW = 39.64%



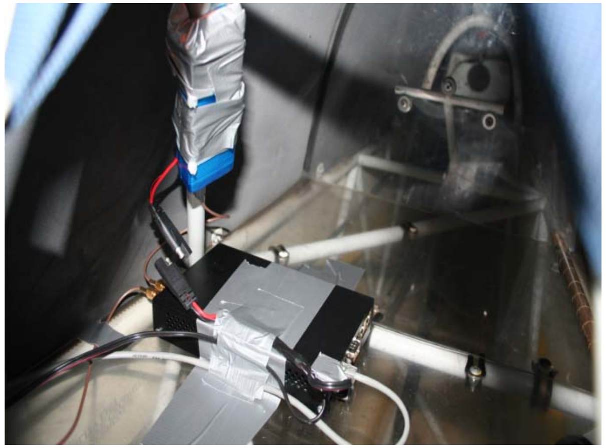
H – Plane
G = 4.1 dBi@5.5GHz

Fractal slot dipole (3)

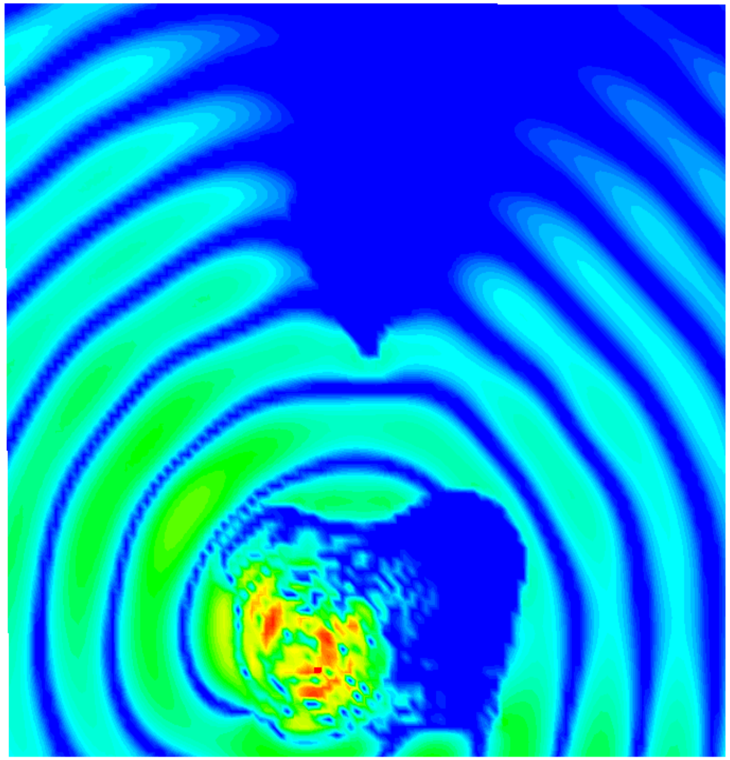
Iteration	Dimensions [mm]	Bandwidth [%]	VSWR in band
0	60 x 35	25.73	1.35
1	30 x 25	39.64	1.20
2	22 x 23	42.28	1.23

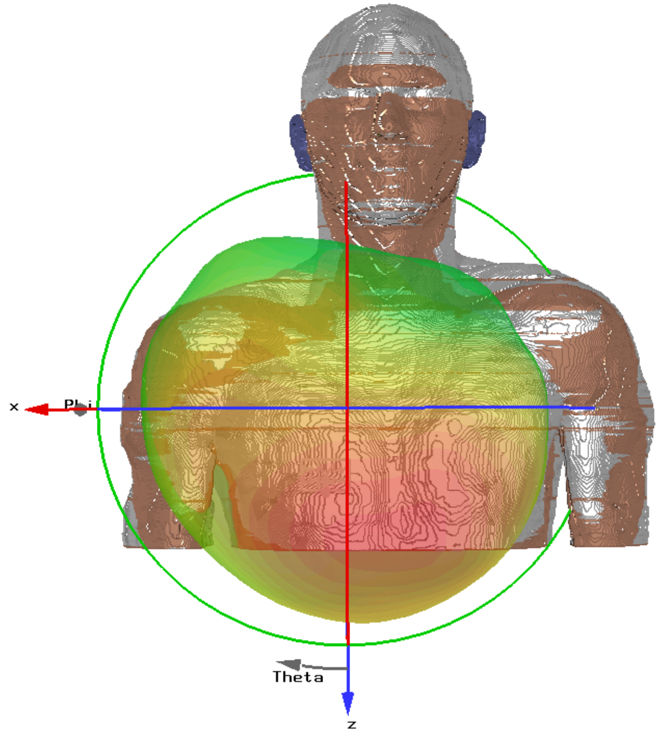


Fractal slot dipole (4)



Fractal slot antenna (5)





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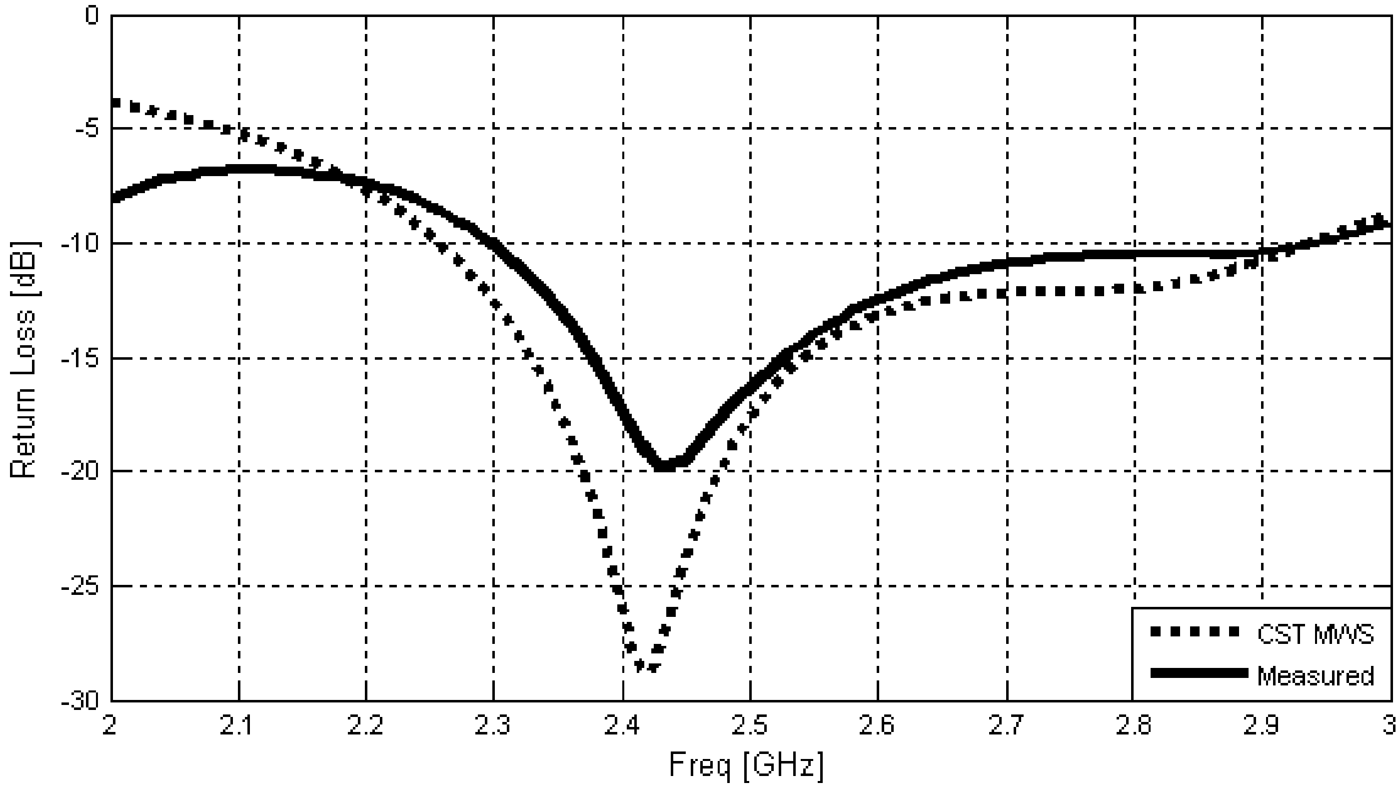
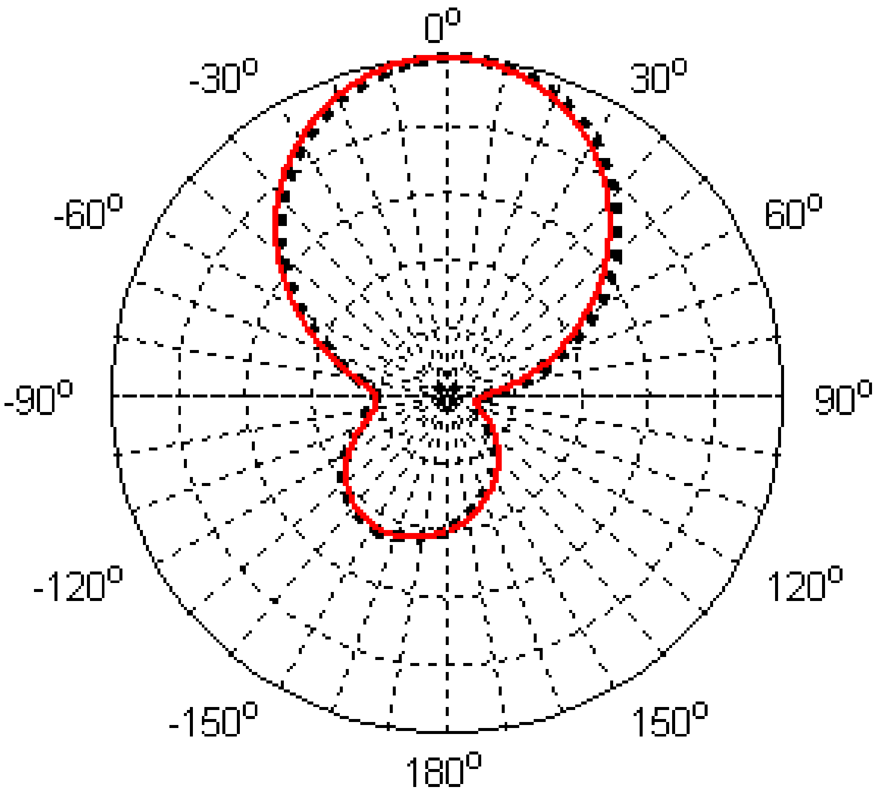
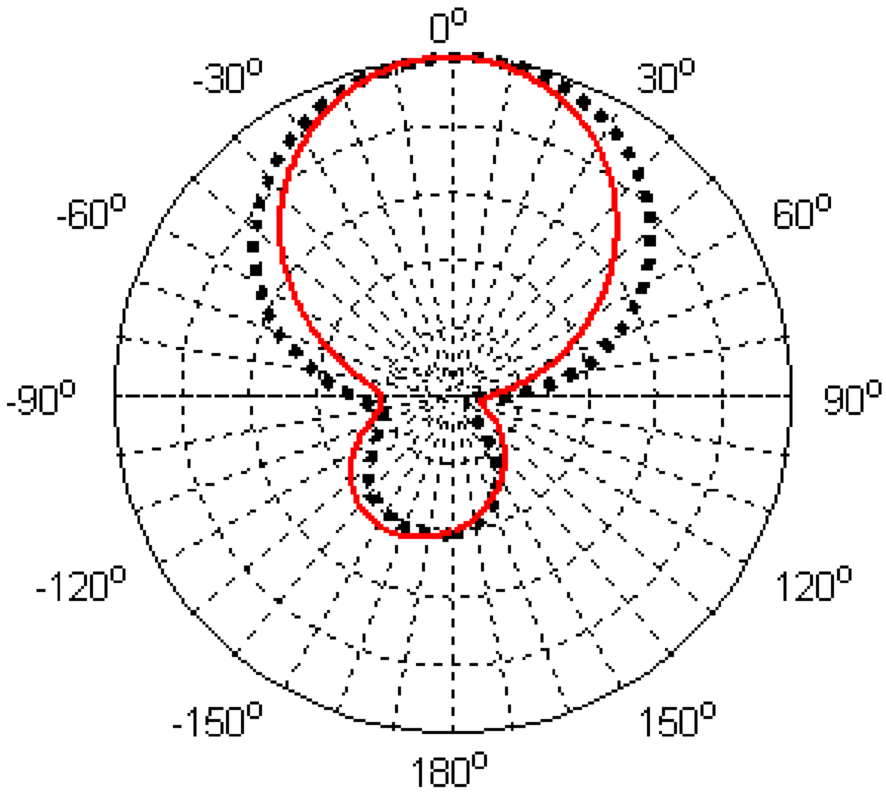
Fractal slot antenna (6)

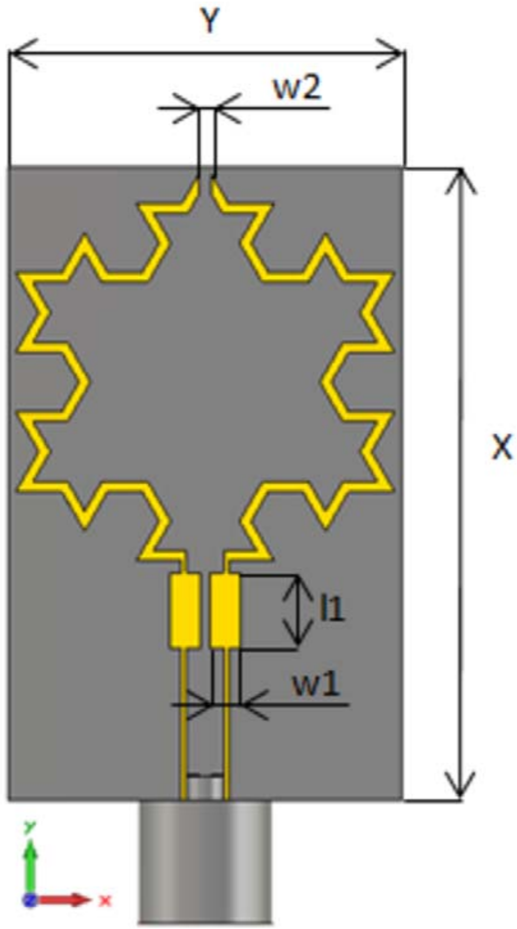


Fractal slot antenna (7)

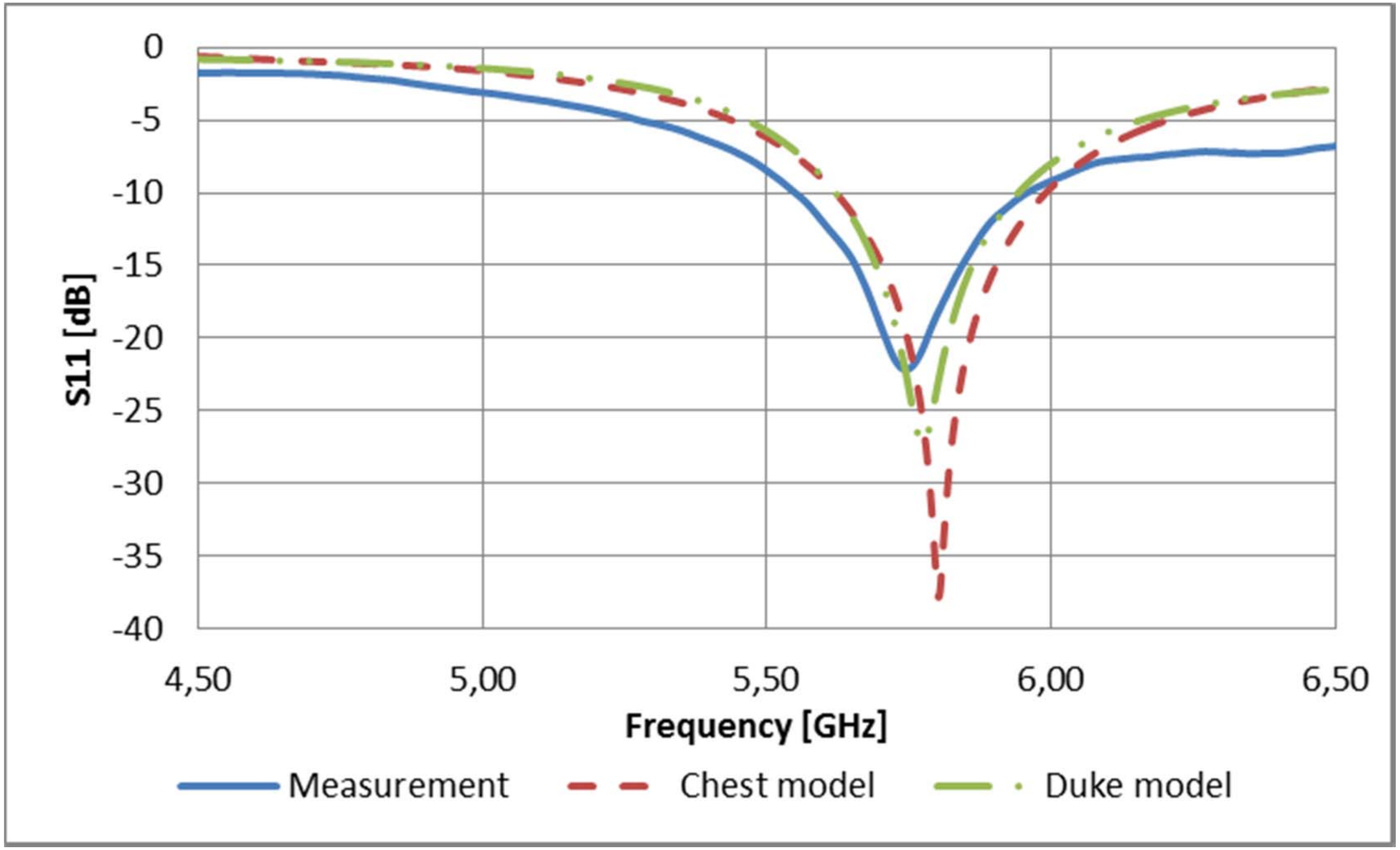




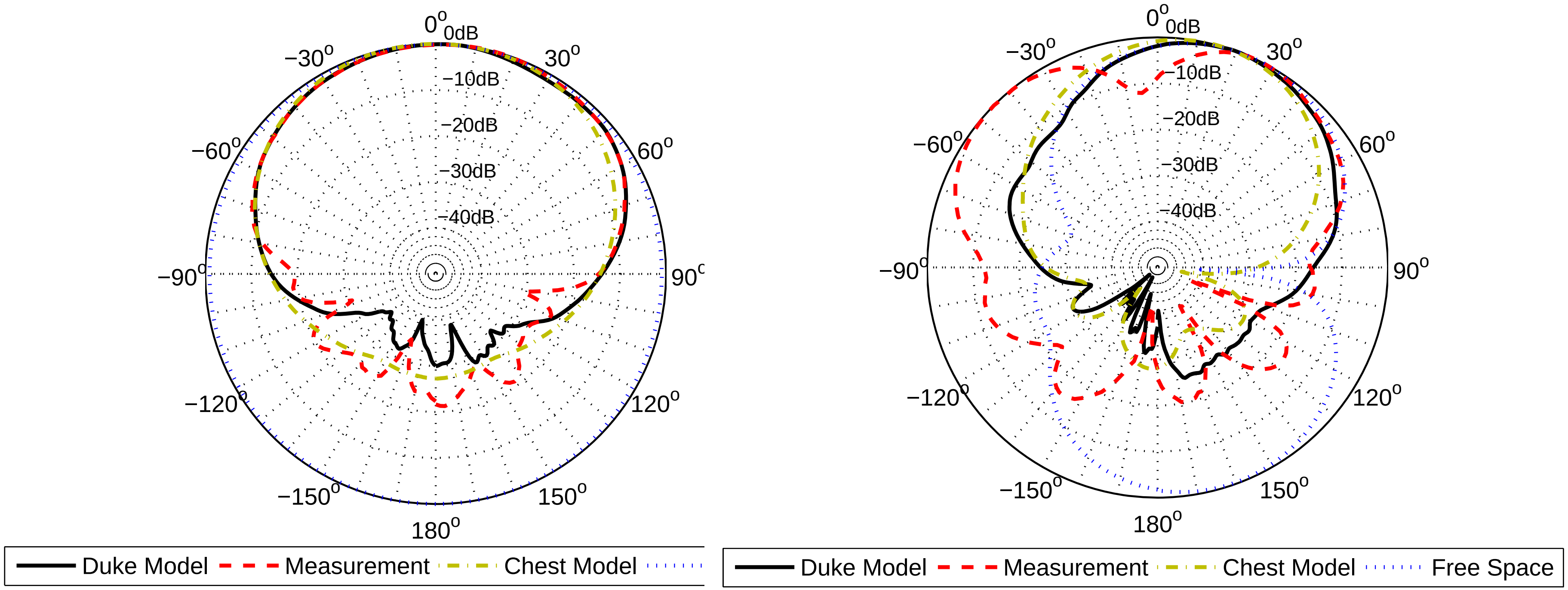
Koch loop antenna (1)



Koch loop antenna (2)



Koch loop antenna (3)



Slot loop antenna (1)

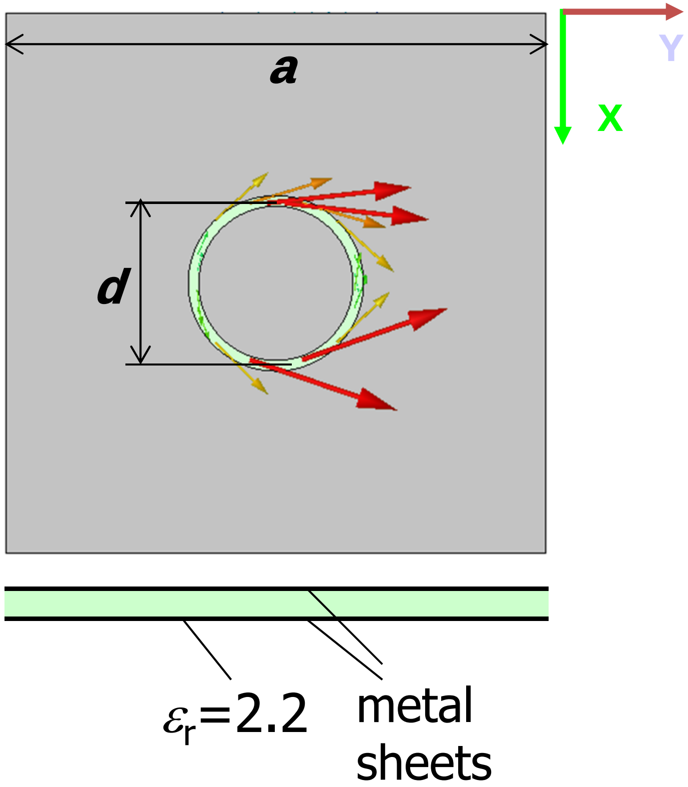
Parameters to be met:

- Frequency: 5.725 GHz to 5.875 GHz (ISM band)
- Input impedance: 50 Ω
- Radiation: omnidirectional in antenna plane
- Polarization: linear
- Impedance bandwidth: 2.6%
- Tested: on muscle-equivalent phantom

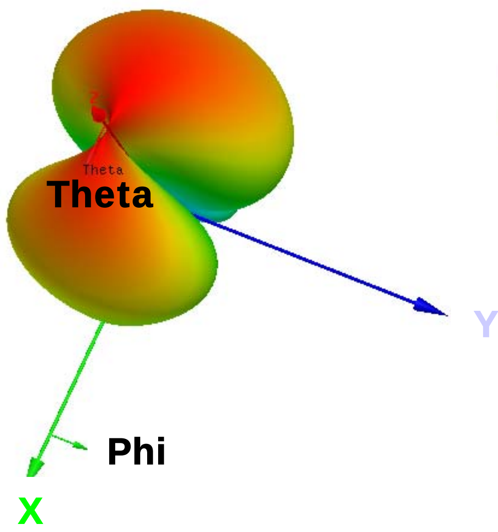
Slot loop antenna (2)

- Circular loop antenna: first operating mode

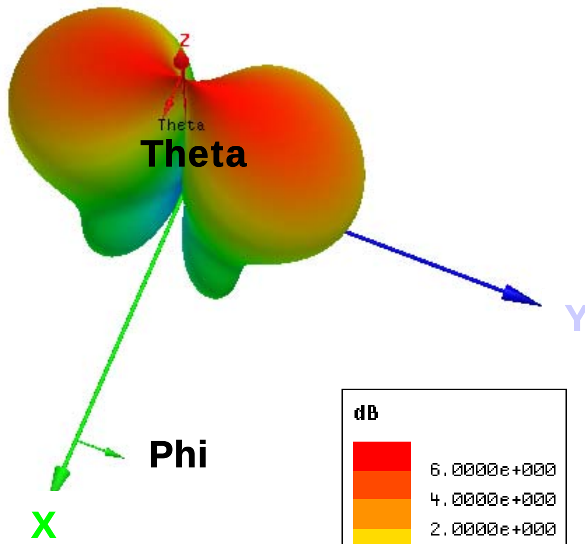
Equivalent magnetic current

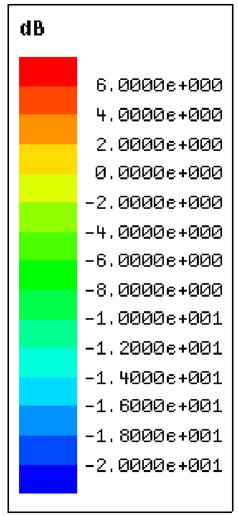


Gain Theta



Gain Phi



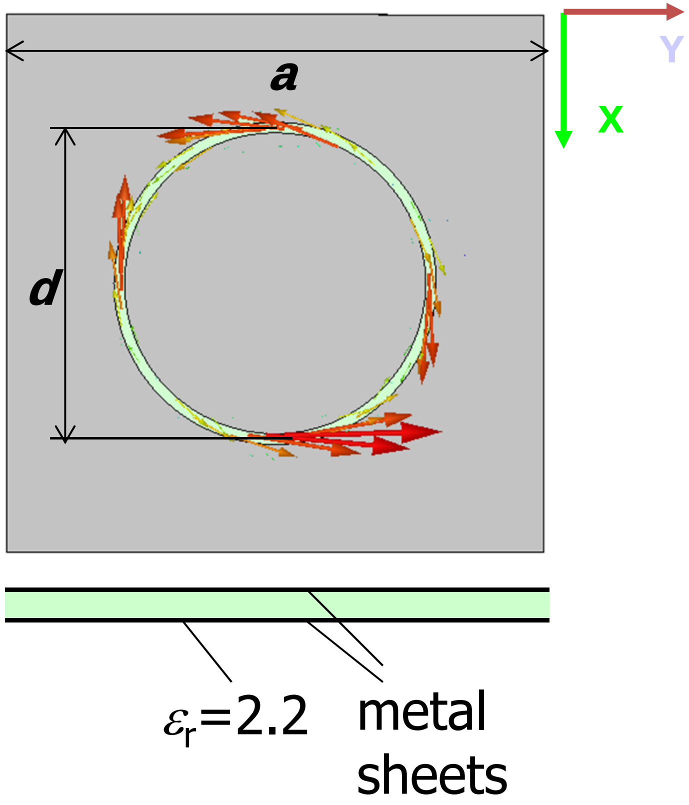


f = 5.8 GHz
$d \approx$ 16 mm; a = 56 mm

Slot loop antenna (3)

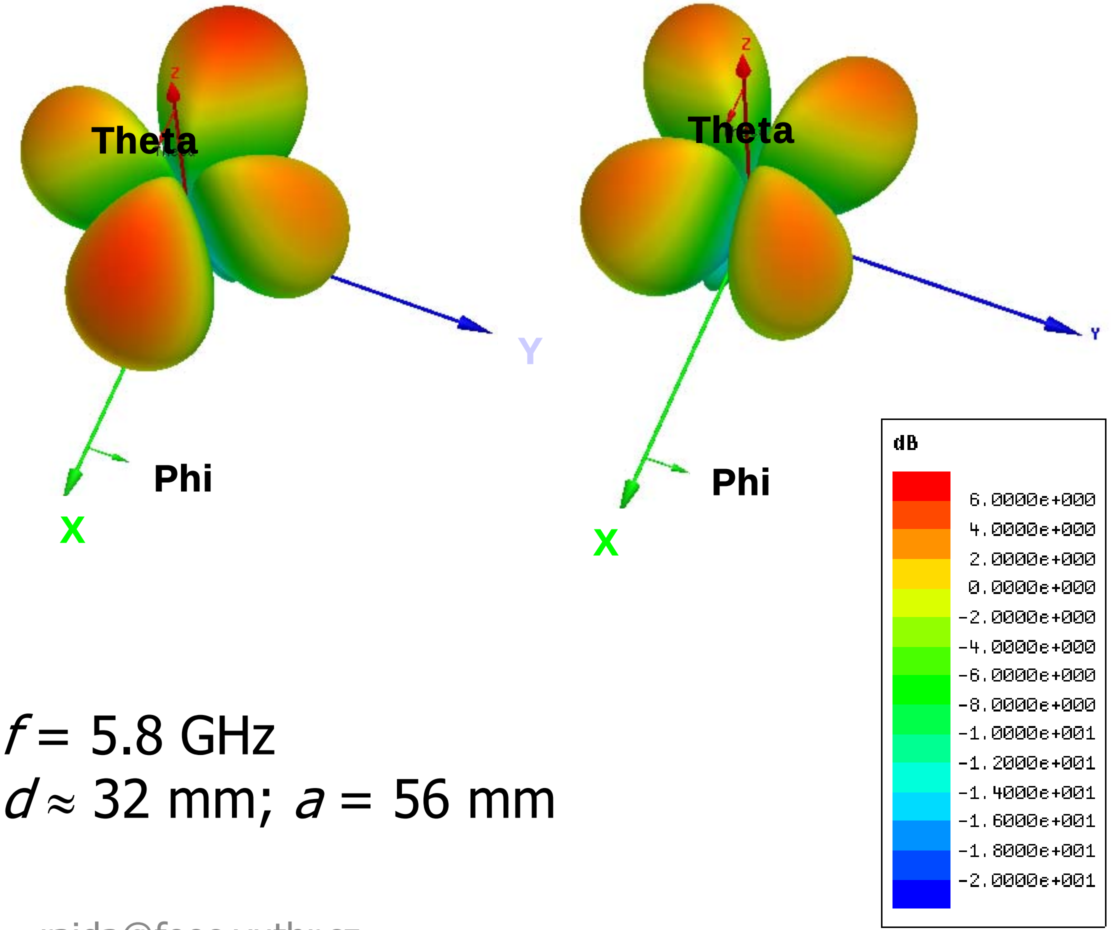
- Circular loop antenna: second operating mode

Equivalent magnetic



Gain Theta

Gain Phi



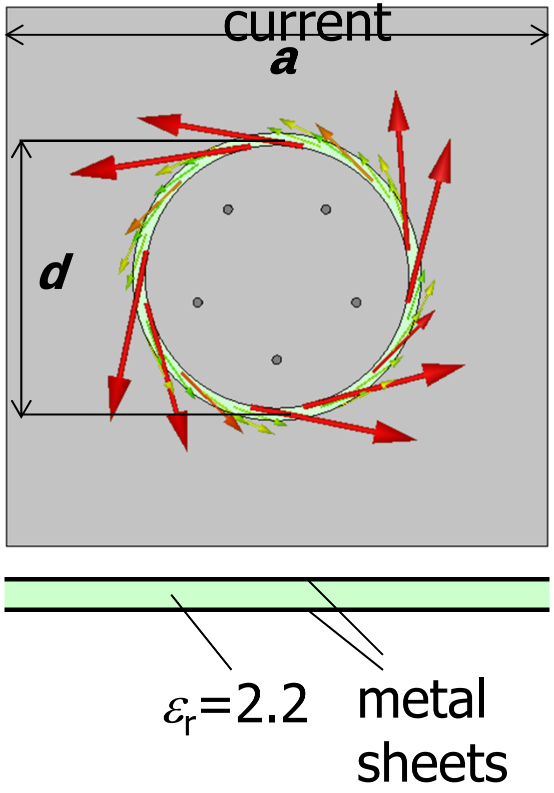
f = 5.8 GHz

$d \approx$ 32 mm; a = 56 mm

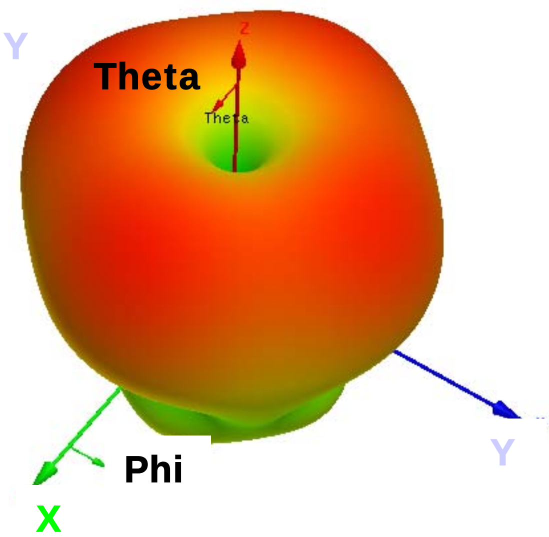
Slot loop antenna (4)

- Circular loop antenna with 5 shorting vias

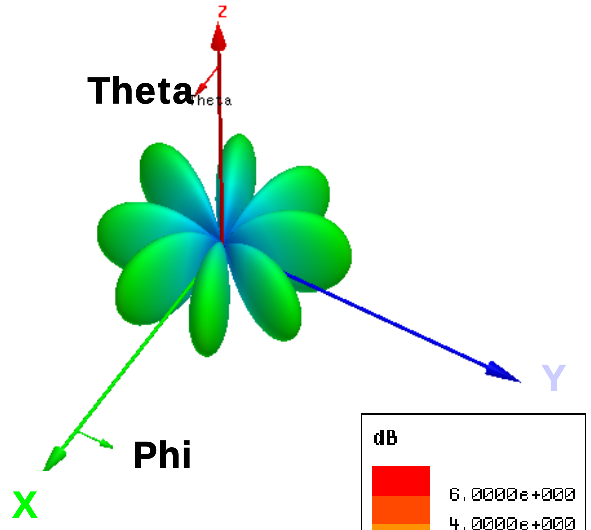
Equivalent magnetic current

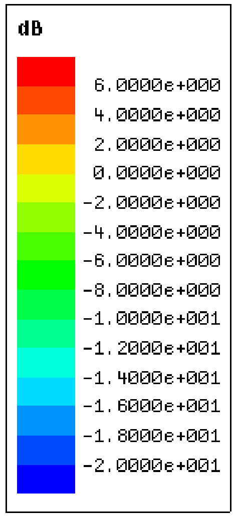


Gain Theta



Gain Phi



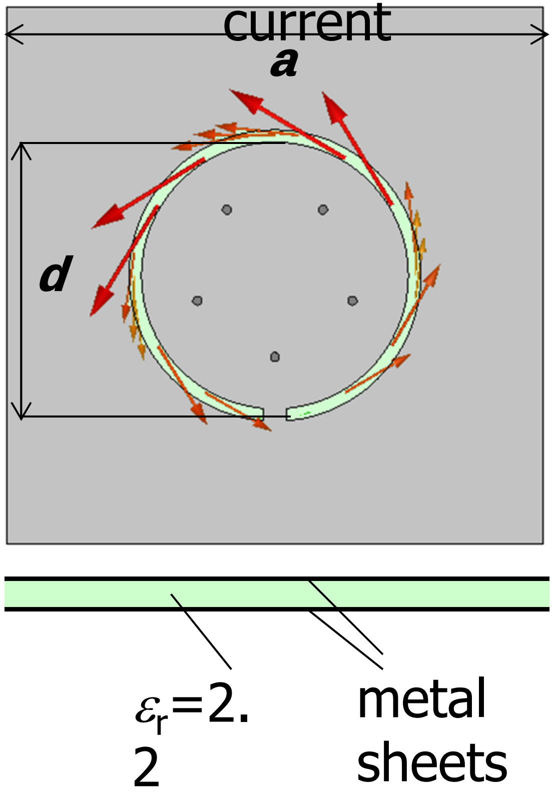


f = 5.8 GHz
d = 24.5 mm; *a* = 48 mm

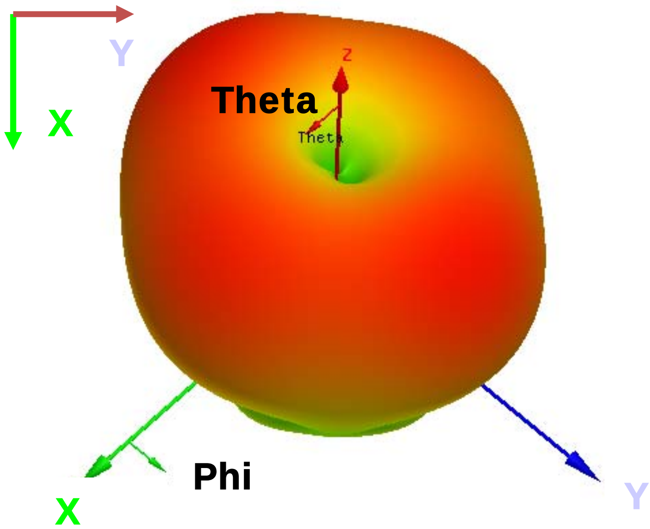
Slot loop antenna (5)

- Circular loop antenna with 5 shorting vias and 1 shorting strip

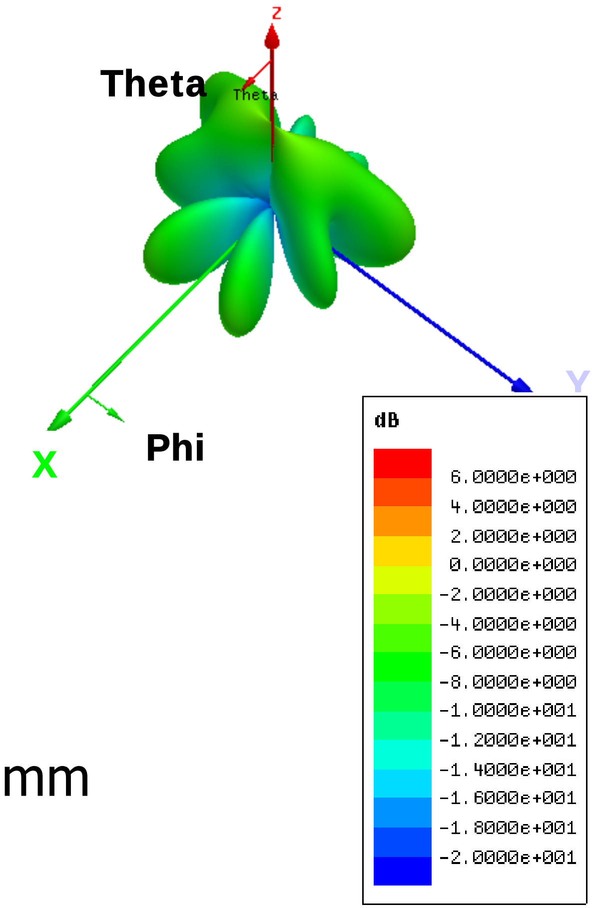
Equivalent magnetic current



Gain Theta



Gain Phi



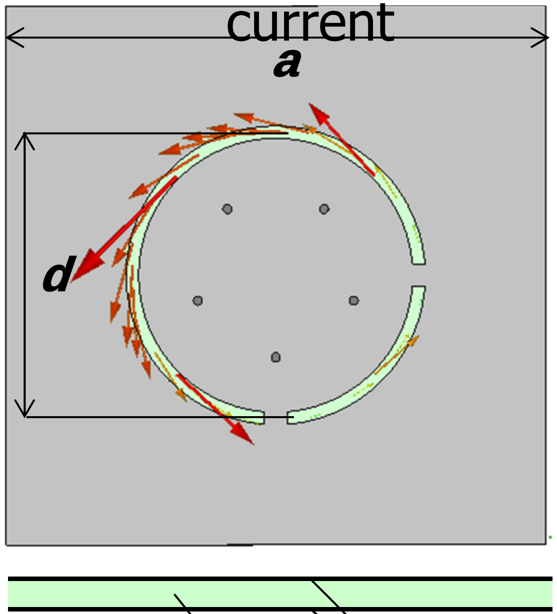
f = 5.8 GHz

d = 25.0 mm; a = 48 mm

Slot loop antenna (6)

- Circular loop antenna with 5 shorting vias and 2 shorting strips

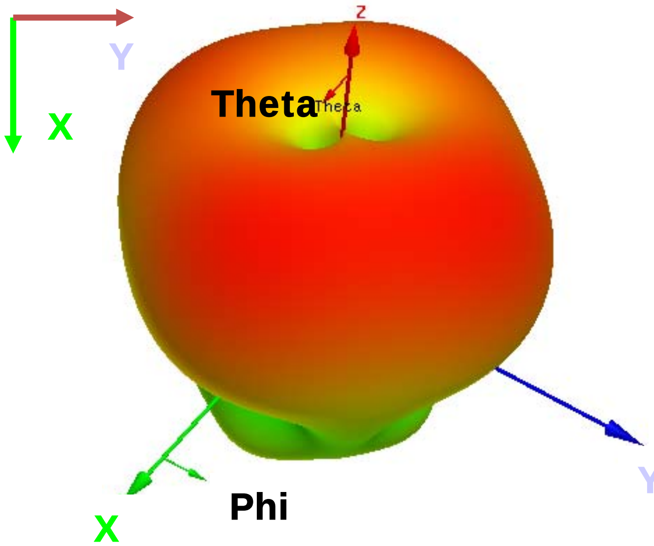
Equivalent magnetic current



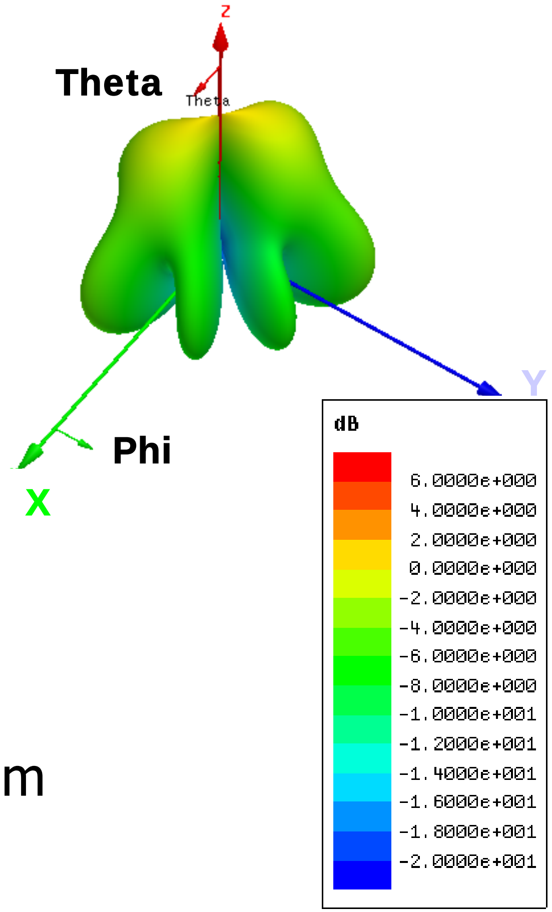
ε_r=2.2

metal sheets

Gain Theta



Gain Phi

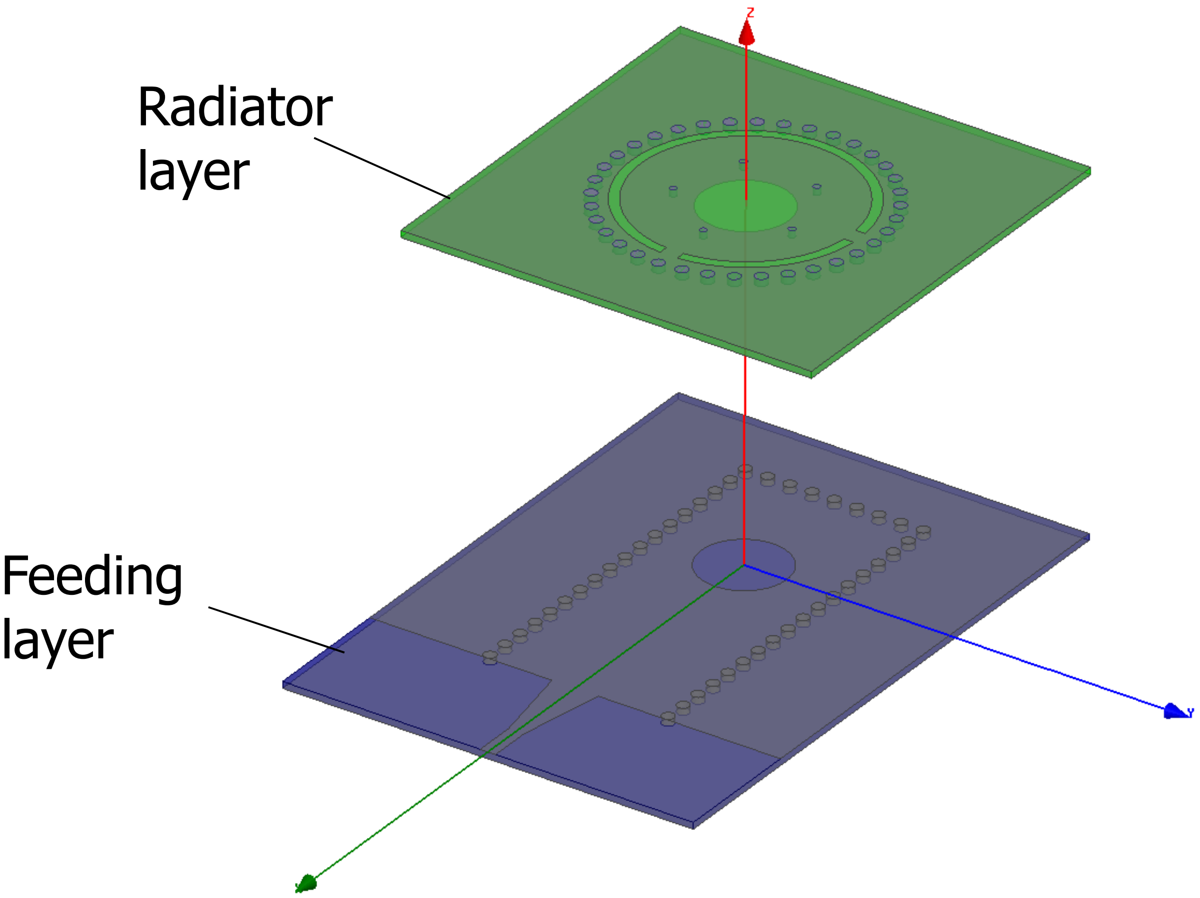


f = 5.8 GHz

d = 25.5 mm; a = 48 mm

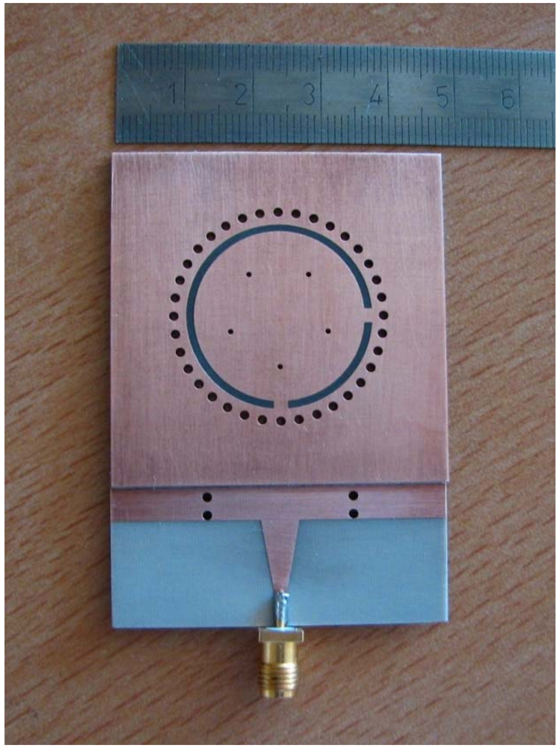
Slot loop antenna (7)

- Antenna configuration

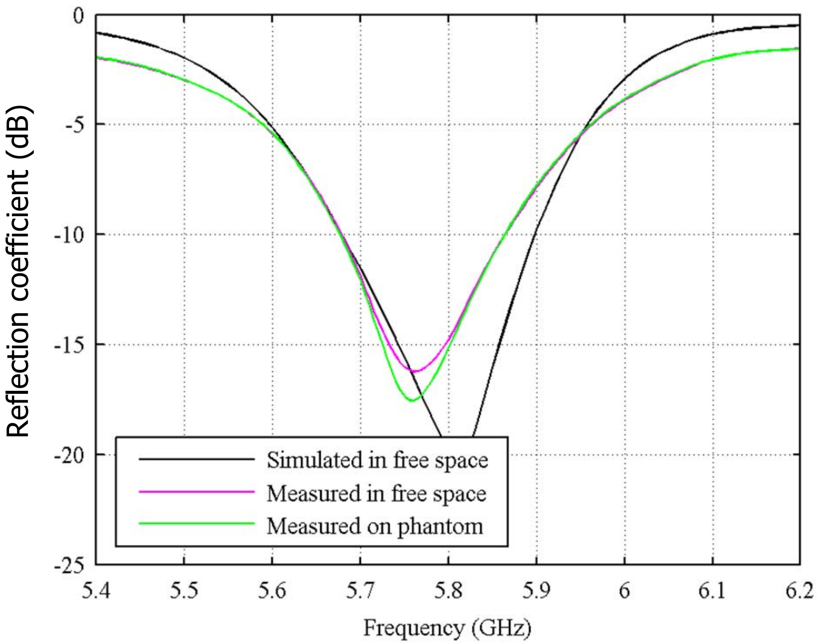


Slot loop antenna (8)

Fabricated antenna



Reflection coefficient



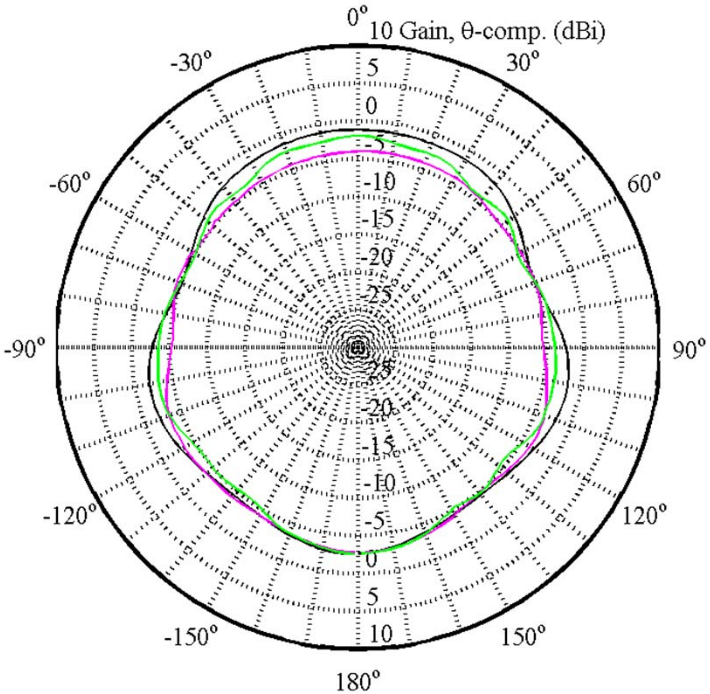
IEEE 802.11a frequency band 5.725 – 5.825 GHz

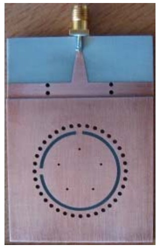
ISM band 5.725 – 5.875 GHz

Slot loop antenna (9)

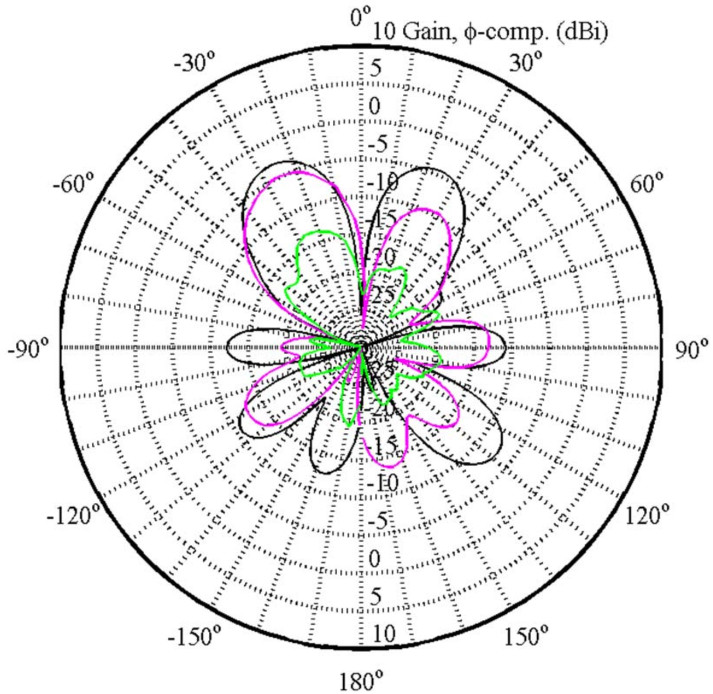
- Comparing radiation in horizontal plane

Gain Theta





Gain Phi



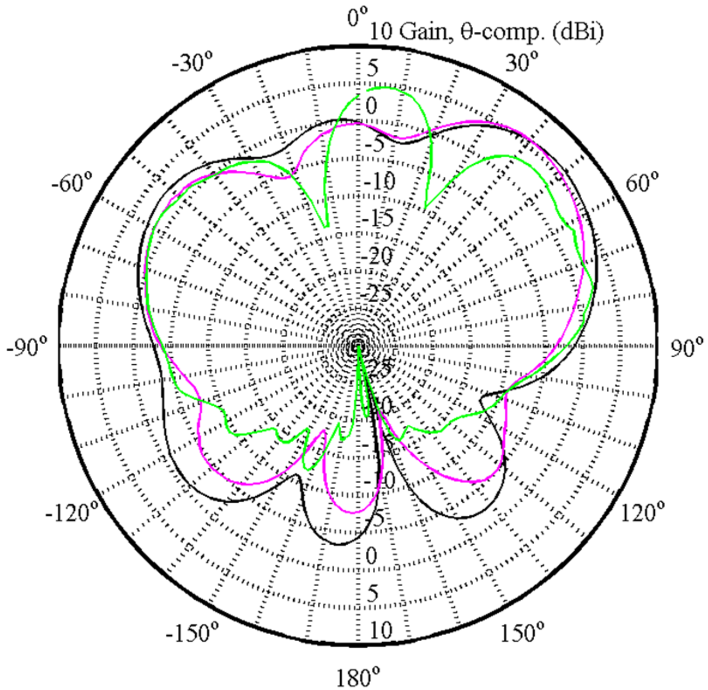
Simulated in free space
Measured in free space
Measured on phantom

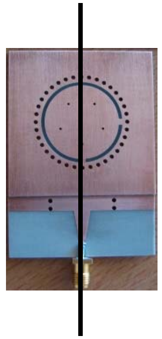
f=5.8 GHz

Slot loop antenna (10)

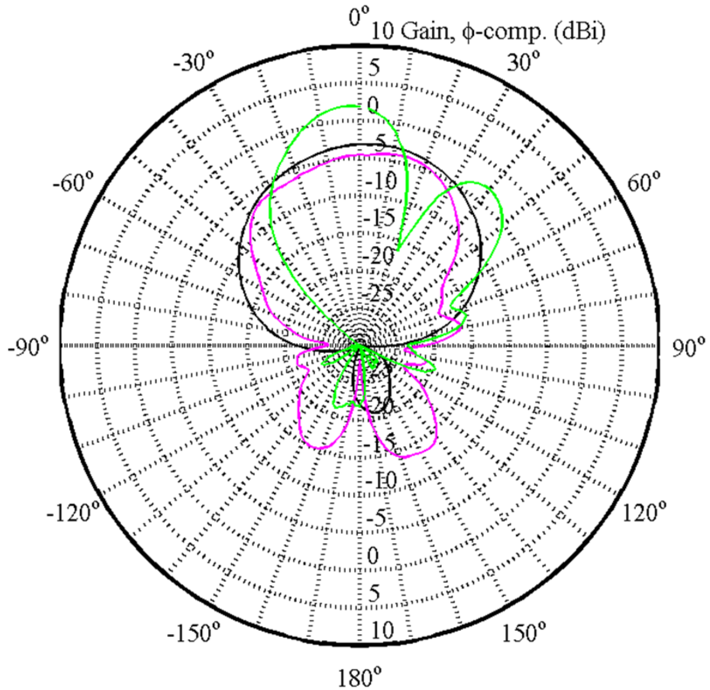
- Comparing radiation in vertical plane

Gain Theta





Gain Phi



Simulated in free space
Measured in free space
Measured on phantom

f=5.8 GHz

Summary

- Planar slot-line antennas suitable
  for wireless body area networks presented
- Slot dipoles: directional
- Slot loops: omnidirectional
- Testing
  - Good agreement of chest model and voxel phantom
  - Good agreement of simulation and measurement

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TR instruments

ROHDE&SCHWARZ

HKE


WORKIN'

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sensor, information and communication systems

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Thank you
for your attention

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