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University of Aveiro

25JUN2014

International Summer School on
Wireless Power Transmission for Space Applications

Hybrid FSS and rectenna design for wireless power harvesting

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www.it.pt I www.estg.ipleiria.pt

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Agenda

- **Presentation of our research group**
- Motivation for today's topics
- Wireless Sensor Networks for spacecraft
- FSS for space applications:
  - *Frequency selectivity and site shielding*
  - *Antenna beam steering*
- Ambient RF Energy Harvesting
- Hybrid FSS and rectenna design
- Conclusions

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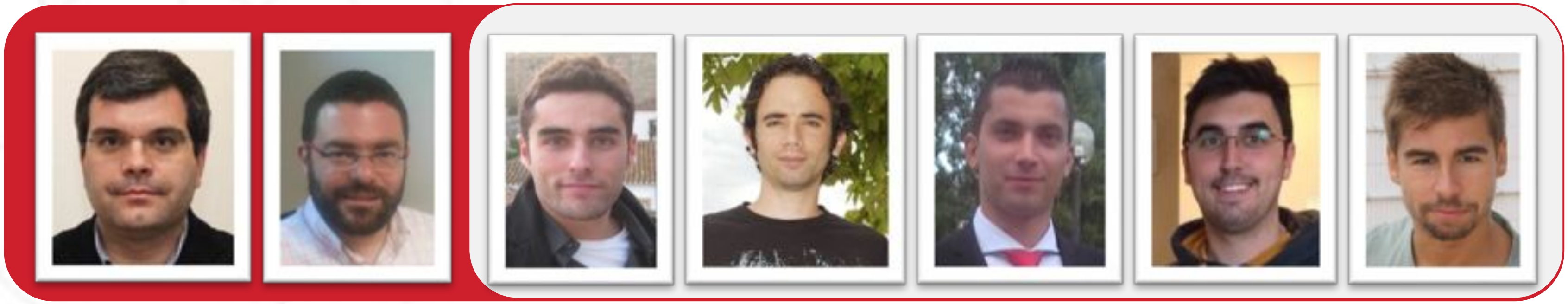
Our team



Rafael Caldeirinha | Telmo Fernandes | Sérgio Morgadinho | David Ferreira | Nuno Leonor | João Reis | Rodolfo Gomes

External collaborators

Miqdad Al-Nuaimi | Jürgen Richter | Manuel Garcia Sanchez | Iñigo Cuiñas | Zaid El-Daher | Akram Hammodeh

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Research lines

- Propagation modelling in vegetation media;
- Measurement and modelling of radiowave propagation on fixed and terrestrial radio networks at frequencies above 1 GHz;
- Ray tracing based models for doubly selective radio channels;
- RF measurement systems, channel sounder topologies and synthetic aperture radars for radio imaging;
- **RF transparency control of building wall structures;**
- **Design and evaluation of novel antenna systems and novel electronic beam forming methodologies;**
- Millimetre Wave Wireless Radio System Prototype for Giga-bit/second Multimedia Application.
- Hybrid FSS and rectenna design for wireless power harvesting
- …

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Laboratory facilities (1/3)

- The Radio Systems Laboratory at IT- Leiria is divided into three different sections:
  - *RF and Microwave circuit and system characterization with measurement capabilities ranging from a few kHz to 26.5 GHz.*
  - *The lab is equipped with the following test and measurement devices:*
    - » Vector Network Analysers (3 GHz and 20 GHz);
    - » CW signal generators (3GHz and 27 GHz);
    - » Spectrum Analysers (3GHz and 26.5GHz) with RF Analysis capability for CDMA 2000, W-CDMA, IS-95, GSM, Bluetooth, Wi-Fi, etc.
    - » Noise Figure measurement device (1.8GHz);
    - » Active High Frequency probe (3GHz);
    - » Power Meter (18GHz);
    - » A complete set of transitions, cables, attenuators and other miscellaneous devices.

Laboratory facilities (2/3)

- The Radio Systems Laboratory at IT- Leiria is divided into three different sections:
  - *(cont.):*
    - » Antenna and Radio Channel Characterization;
    - » Anechoic Chamber (6x5x3 meters) with possibility of small vehicle access;
    - » 4 sets of PC controlled positioning devices with accuracy of 0.01 arc sec;
    - » Calibrated measurement antennas for 20, 40 and 60 GHz;
    - » Channel Sounder with double selective channel measurement capability (multipath and Doppler) for 20, 40 and 60 GHz;
    - » Sounders for CW RF channel measurements at 20, 40 and 60 GHz.
    - » Outdoor (9 m height) pneumatic antenna masts;
    - » Inverter Power Supply to support outdoor measurements;

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Laboratory facilities (3/3)

- The Radio Systems Laboratory at IT- Leiria is divided into three different sections:
  - *DVB-T signal analysis and generation;*
    - » DVB-T/H signal generator with RF transmitter for UHF frequencies;
    - » DVB-T/H and IPTV signal receiver and analyser;
    - » UHF Low Noise Amplifier;
    - » UHF RF power Amplifier;
    - » Various UHF antennas suited for DVB outdoor tests;
  - *HDMI/SDI converters;*

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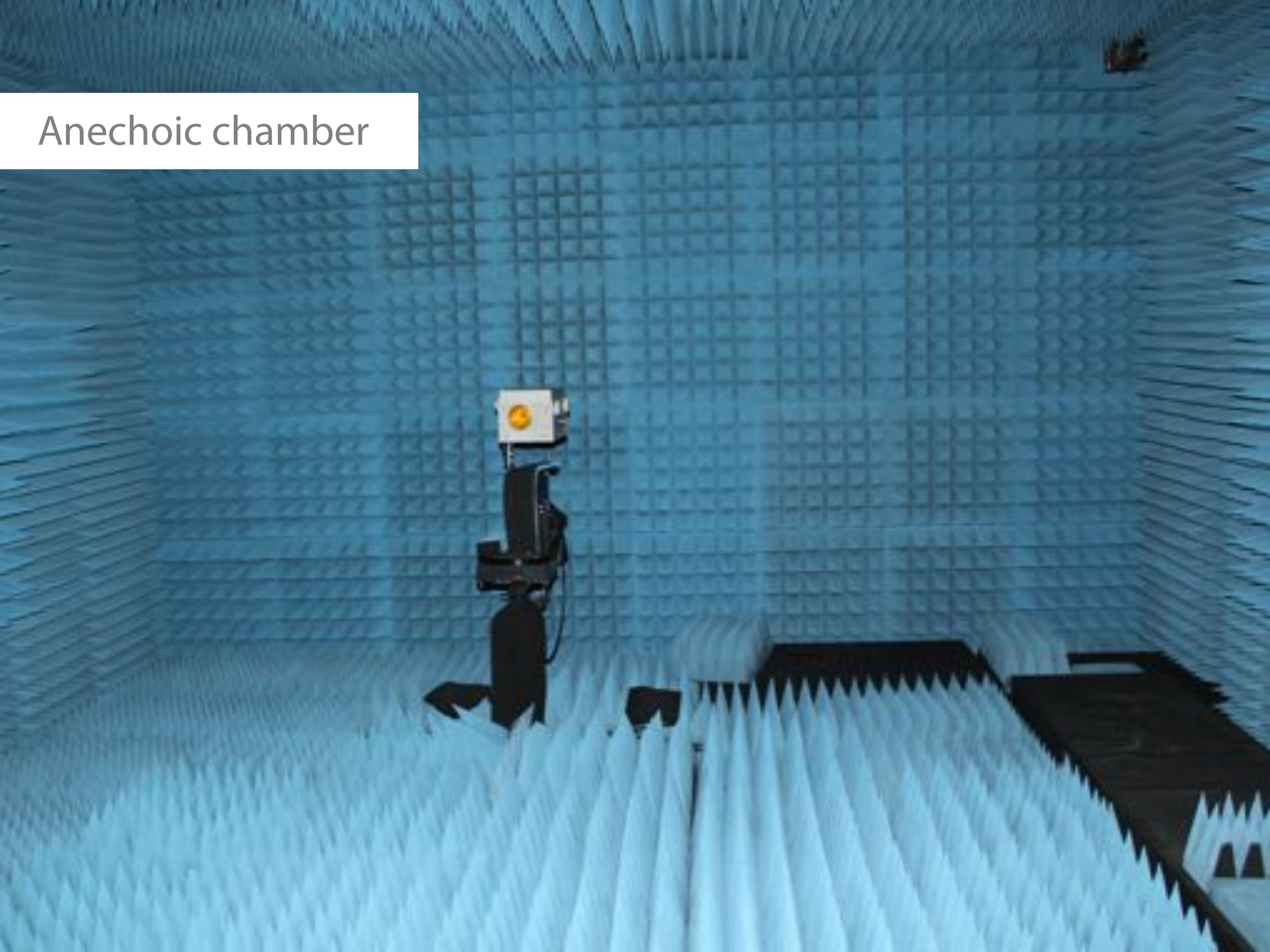
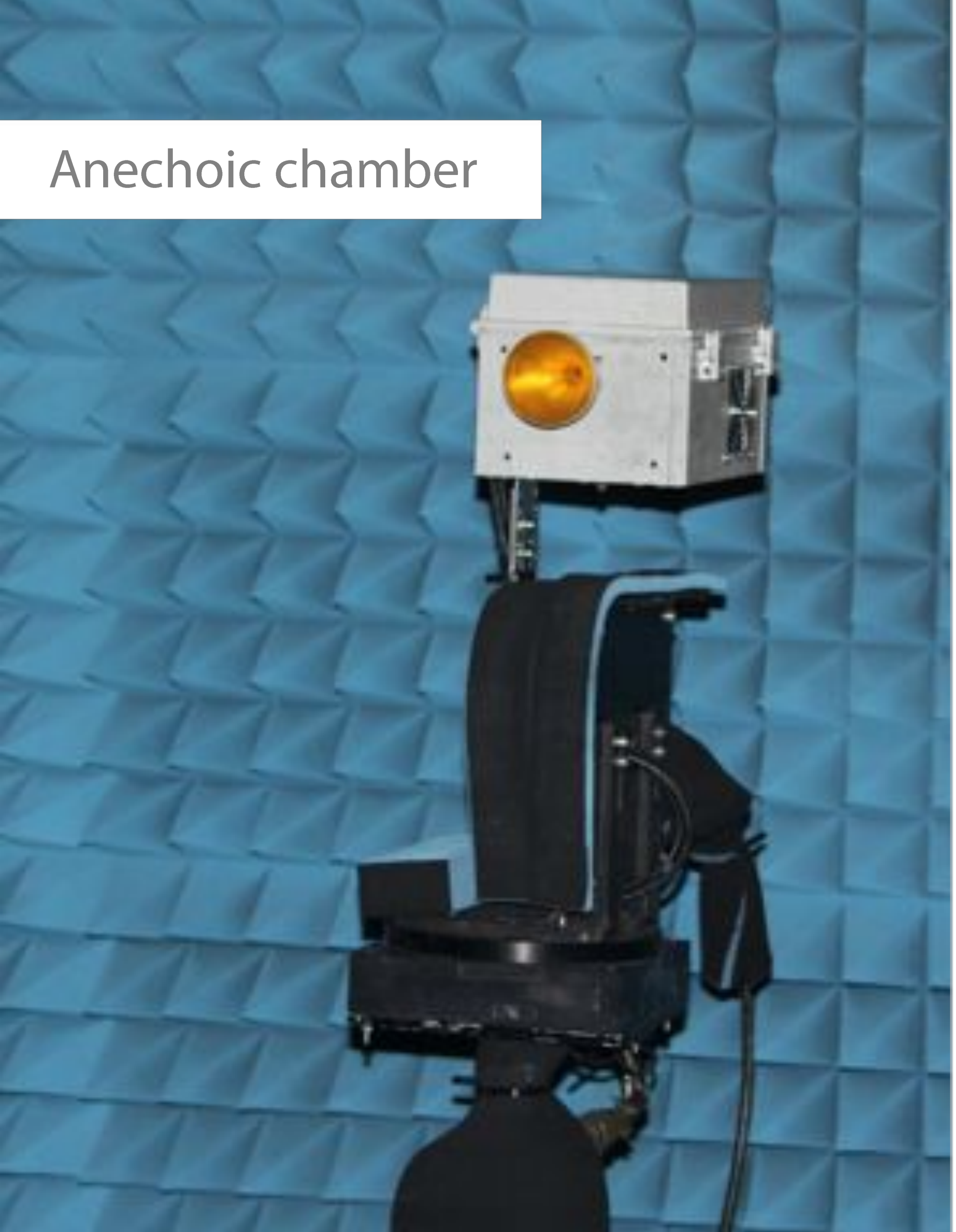
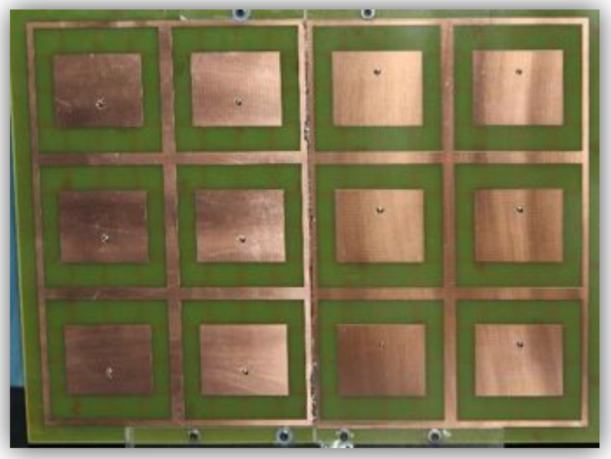
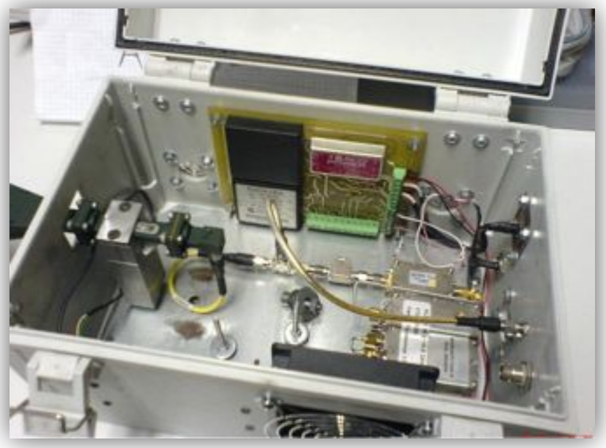

Anechoic chamber

Anechoic chamber

Anechoic chamber



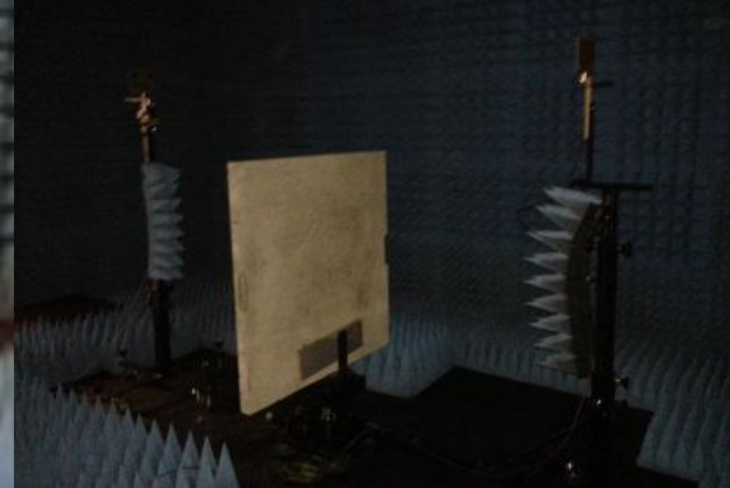




Anechoic chamber

Anechoic chamber

Anechoic chamber



(Past) Collaborating Institutions

- University of South Wales
  (former University of Glamorgan), UK
- Instituto de Telecomunicações(DL- IT), Portugal
- Polytechnic Institute of Leiria, Portugal
- University of Portsmouth, UK
- Qinetiq, UK
- Rutherford Appleton Laboratories, UK
  - *University of Vigo, Spain*
- Main Sponsors:
  - *National Radio Propagation Programme (NRPP), Radiocommunications Agency (RA), UK (2001) (~£250.000);*
  - *FCT (2005) and IT (2009, 2010, 2011).*

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Motivation

- Why Wireless Power?

Cable elimination

[Source: J. Smith,2013]

Battery elimination

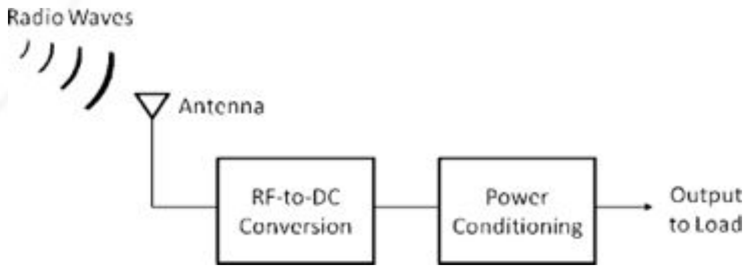
[Source: J. Smith,2013]

Remote exploration rover in space

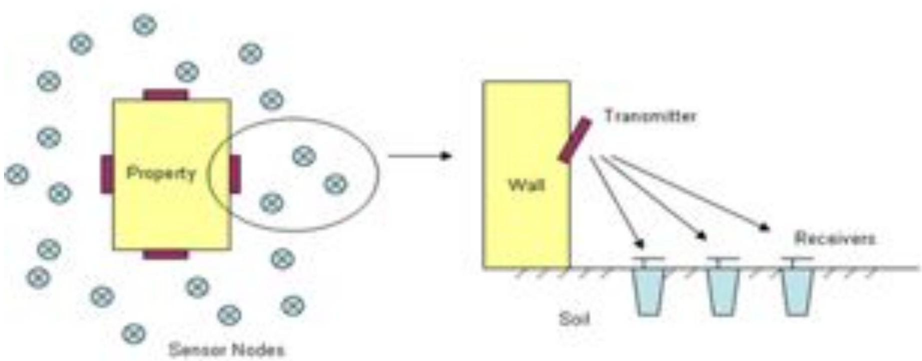
[Source: http://machinedesign.com]

Motivation

- Why Wireless Power?
  - *Wireless Power Harvesting from ambient RF*
    - » Recycling ambient microwave energy with broad-band rectenna arrays
    - » Design of efficient ambient Wi-Fi energy harvesting systems



[Source: http://www.sensorsmag.com]



[Source: http://wikimedia.org/wikipedia]

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Motivation

- Why Wireless Power?
- Why metamaterials?
  - *[Smith and Pendry, in early 2000] have demonstrated the ability to realise metamaterials:*
  - *Artificial materials with exotic properties that cannot be found in the nature.*
  - *Since then, this has become a hot topic:*
    - » Super lens;
    - » Cloaking;
    - » Electromagnetic and antenna domains, new artificial materials allow :
      - to reduce significantly the size of antennas;
      - to emulate the behaviour of a shaped reflector;
      - to realize small and light wave absorbers;
      - etc…
  - *Recently, in the SATCOM domain (i.e. Satellite on the move applications, SOTM), [Kymeta, 2012] launched a new antenna product based on metamaterials surface technology (MSA-T) in Ka band.*

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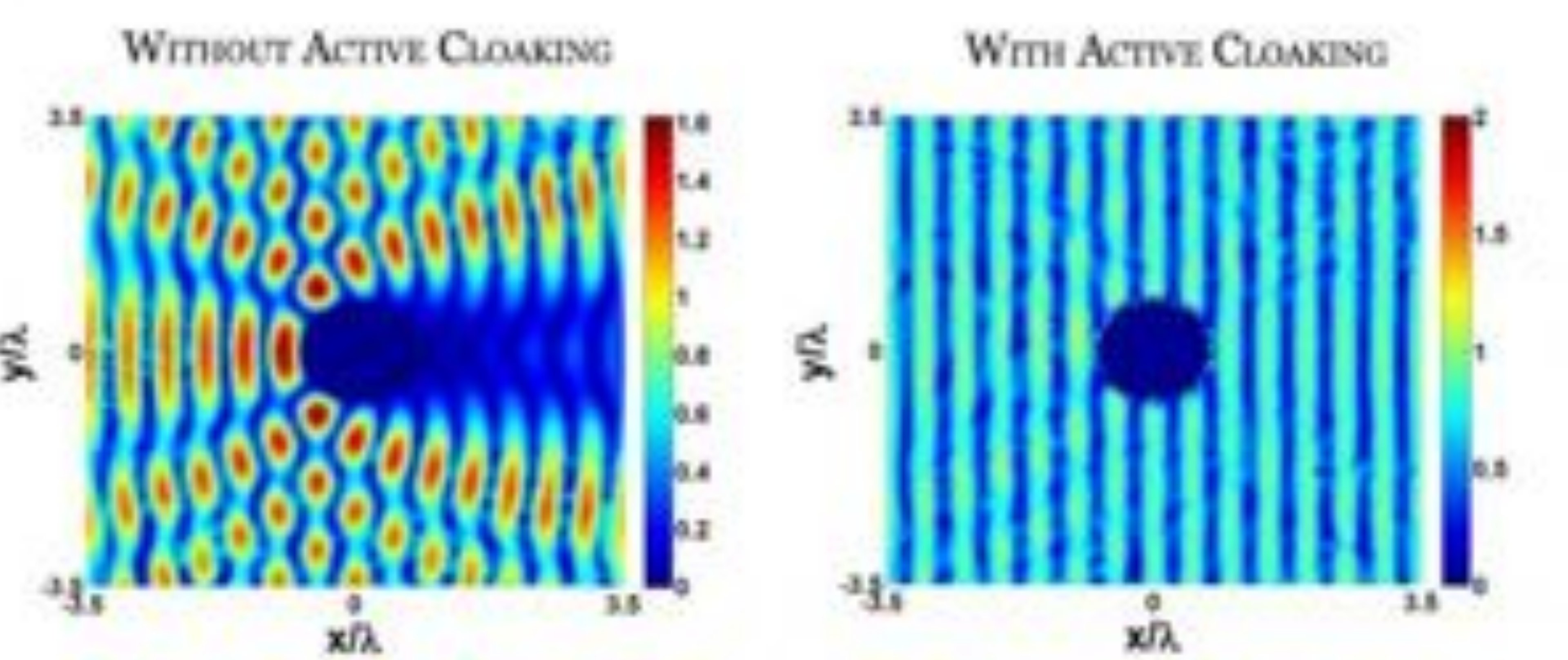
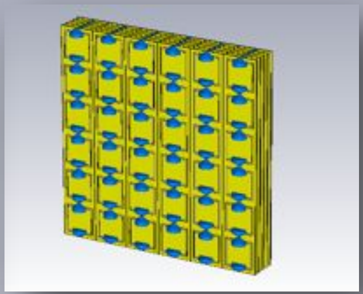
Invisibility cloak

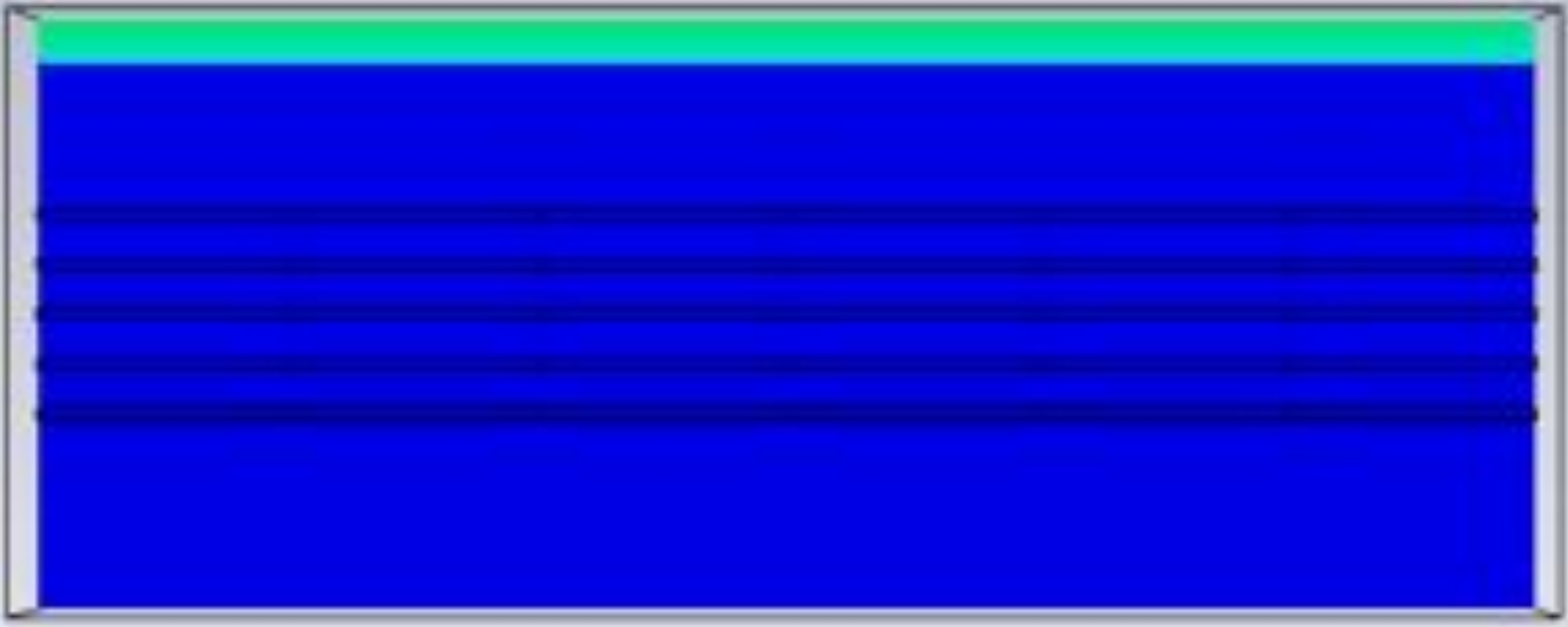


[Source: http://discovermagazine.com]

Invisibility cloak

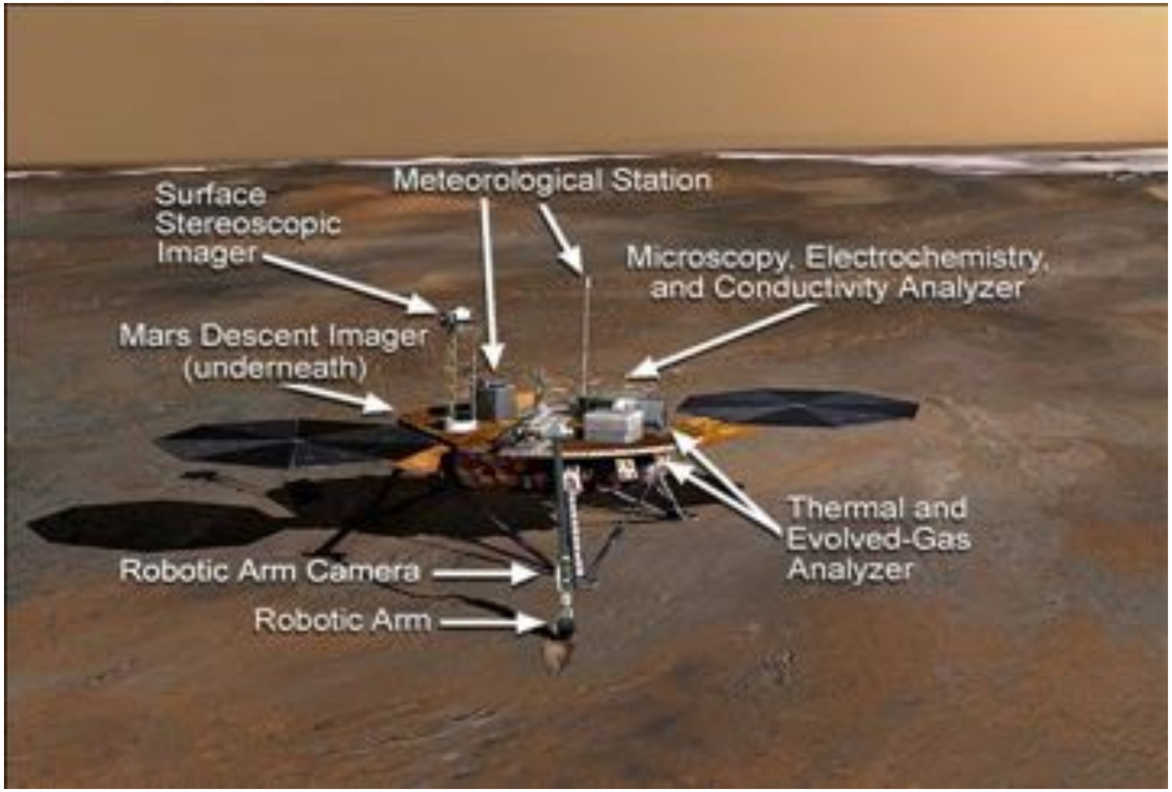
Beam steering 30 deg.





Motivation

- Wireless Power Harvesting for sensors positioned in harsh environments and in difficult access areas



[Source: http://wikimedia.org/wikipedia]

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Wireless Sensor Networks for Spacecraft

- In 2010, Snecma has implemented a comparative benchmarking between BeanAir Wireless acquisition system and a wired acquisition system.

- Long-term main technical aims are:
  - *Positioning this kind of sensors in a harsh environment and in difficult access areas.*
  - *Simplifying the system thanks to the reduction of quantity engine cables; consequently, engine mass will be reduced as well.*
  - *Radio Interference reduction and WPT*

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Wireless Sensor Networks for Spacecraft

- Spacecraft sensors without batteries or cables
  - *It could drastically cut maintenance costs;*
  - *It would transmit data on stress endured during space flights and key maintenance information to cabin crew*

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Wireless Sensor Networks for Spacecraft

- Requirements for **spacecraft** applications [BeanAir, 2014]:
  - *Monitoring and controlling the behavior of a spacecraft*
    - during testing phases on ground or during a space flight;
  - ***Short-range*** *(10m to 30m) & low data-rate wireless sensor networks;*
  - *Hundred of measurement nodes are required*
    - steadily increasing the mass (**acquisition systems & cables**) and the project costs and time;
  - *Two different types of measurement modes:*
    - Static measurement (temperature, humidity)
    - Dynamic measurement (acoustic, vibration)
  - *Fast response time*
  - *Lossless data compression and transmission*
  - *Time- synchronized and rugged wireless sensor network*

Wireless Sensor Networks for Spacecraft

- Benefits & challenges of WSN [BeanAir, 2014]:
  - *Benefits*
    - » Easy to deploy and scalable
    - » Decreasing mass & wires
    - » Building new applications (HUMS - Health and usage monitoring system, moving parts)
  - *Challenges:*
    - » Interferences (multipath fading, radio jamming…) & obstacles
    - » Fast response time & time-synchronization
    - » Power supply & low power considerations

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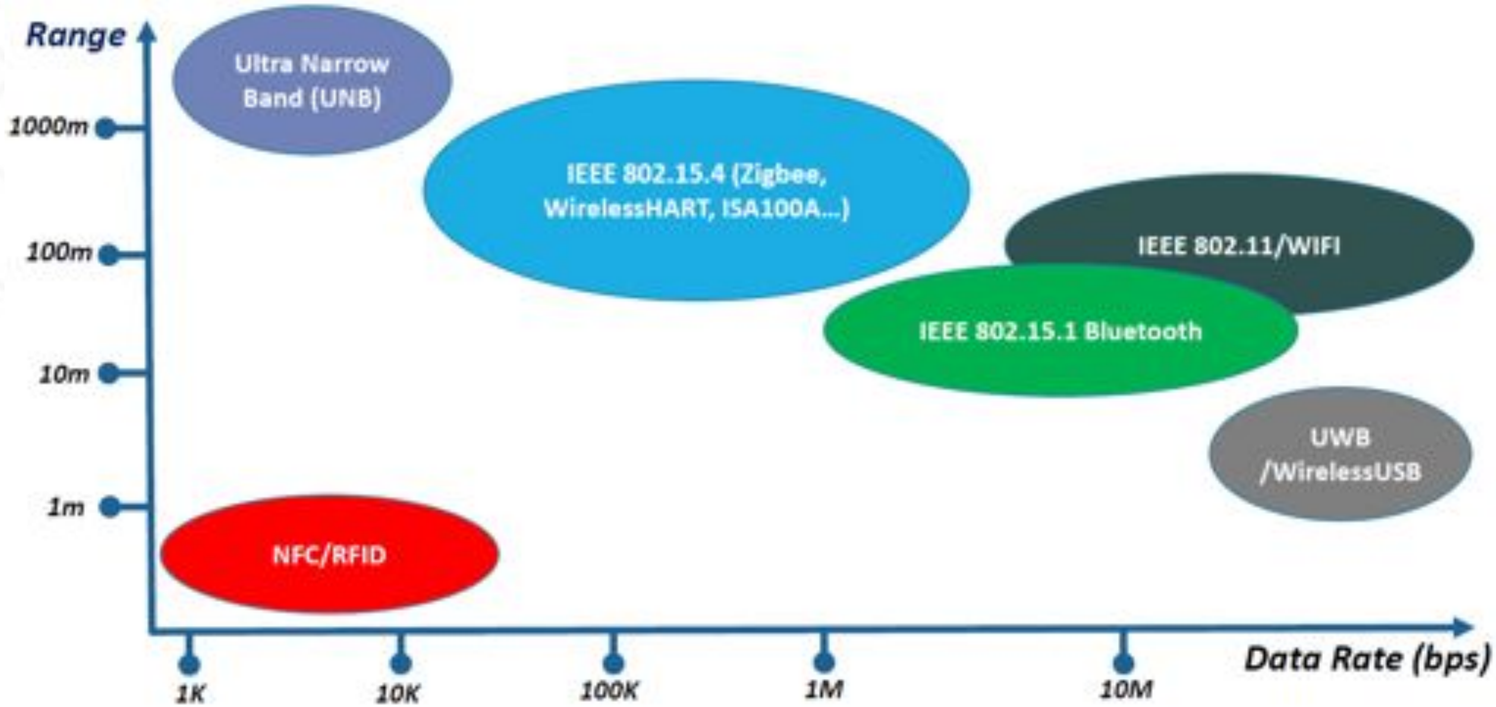
Wireless Sensor Networks for Spacecraft

- Existing wireless protocols on the market [BeanAir, 2014]



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Wireless Sensor Networks for Spacecraft

- Why choosing IEEE 802.15.4 MAC Layer [BeanAir, 2014]:
  - *Lightweight MAC Layer (10 to 20 kbytes of flash memory instead of 4MBytes for the Wi-Fi);*
  - *Comes with a fast response, low data rate (typically: 250 kbps) & lowpower*
  - *Provides a better wireless range than Bluetooth or Wi-Fi*
- But what about the existing standard wireless protocol based on the IEEE 802.15.4 ?
  - *Zigbee wireless protocol is more suitable on Energy Metering and Smartgrid markets but response time is not guaranteed;*
  - *WirelessHART and ISA100A are used on process industry market:*
    - » not easy to deploy and not compatible with dynamic measurement
  - *Mesh network is not needed on a spacecraft!*

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Wireless Sensor Networks for Spacecraft

- *IEEE 802.15.4 TaskGroup*

IEEE 802.15.4 amendment	*Main features*	*Applications*
IEEE 802.15.4-E (2012)	• CSMA-CA Channel access • Data rate: 250 kbps • RF channels: 16 channels in the 2.4GHz	Process Industry
IEEE 802.15.4-A (2007)	• Higher precision ranging (1 meter accuracy) • CSMA-CA Channel access • PHY is based on IR-UWB (Impulse Radio Ultra wide Band) and CSS (Chirp Spread Spectrum) • Data rate: up to 6.8 Mbps • RF channel: 2.4 GHz (CSS), 3GHz to 8GHz (IR-UWB)	Real Time location systems (RTLS)
IEEE 802.15.4-G (2012)	• CSMA-CA Channel access • Data rates: 250 kbps, 40 kbps and 20 kbps • RF channels: 16 channels in the 2.4 GHz ISM band, 10 channels in the 915 MHz, 1 channel in the 868MHz	Smart grid network (large network with millions of fixed endpoints)

[BeanAir, 2014]

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Wireless Sensor Networks for Spacecraft

- *Beanair is working on an innovative wireless sensor networks dedicated to the new generation of spacecraft (Ariane VI)*

BeanAir

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FSS for space applications

- Develop new propagation enhancement (and reduction) techniques using Frequency Selective Surfaces (FSS);
- Control the transparency of spacecraft (fuselage?) at specific radio frequencies;
- Increase radio coverage inside a spacecraft;
- Overcome structural radio path obstructions (invisibility cloaking)
- Shield specific areas from unwanted radio signals;
- …

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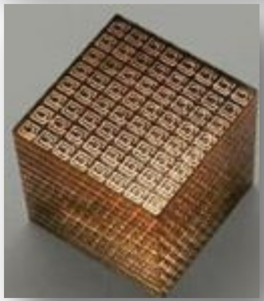
Metamaterials / FSS

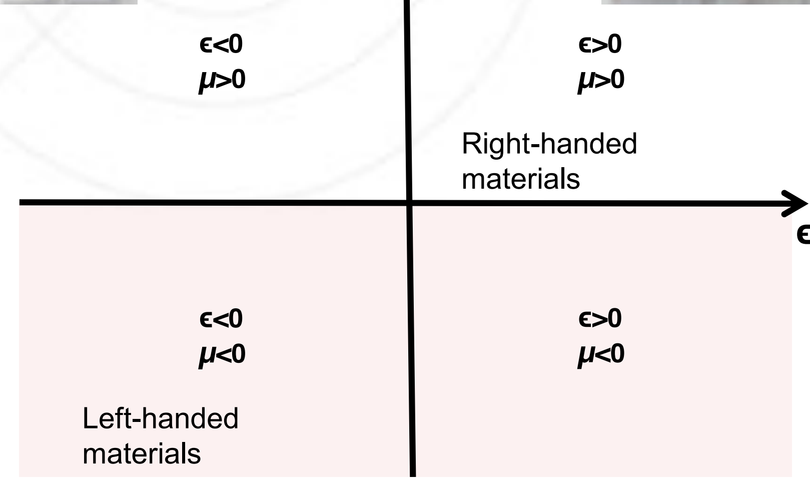
- Artificial materials composed by physical structures instead of atoms and molecules;
- Periodicity smaller than wavelength of incident wave;
- Characterised by unusual electromagnetic properties:

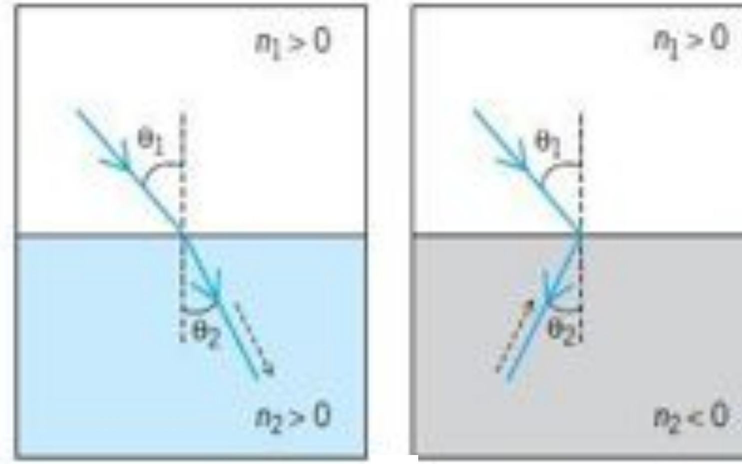
μ - magnetic permeability;
ϵ - electric permittivity;
n - refractive index.

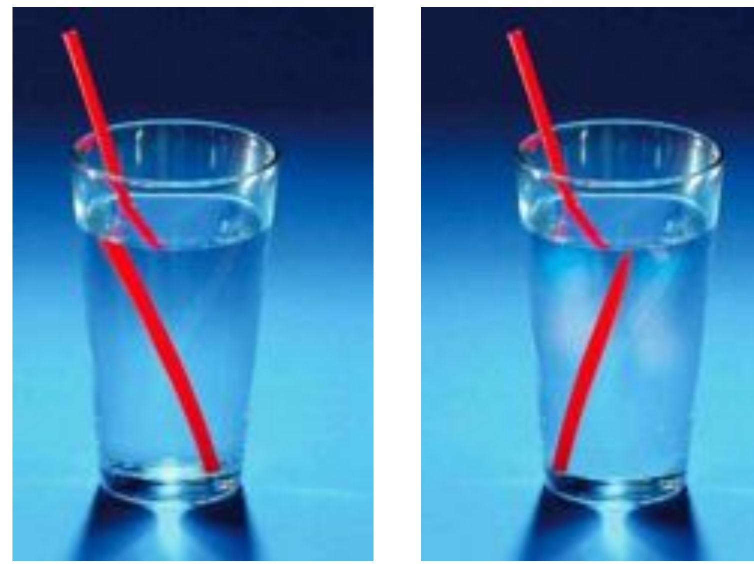


Metamaterials / FSS

- Materials parameter space







Refractive index: $n = \pm\sqrt{\varepsilon.\mu}$

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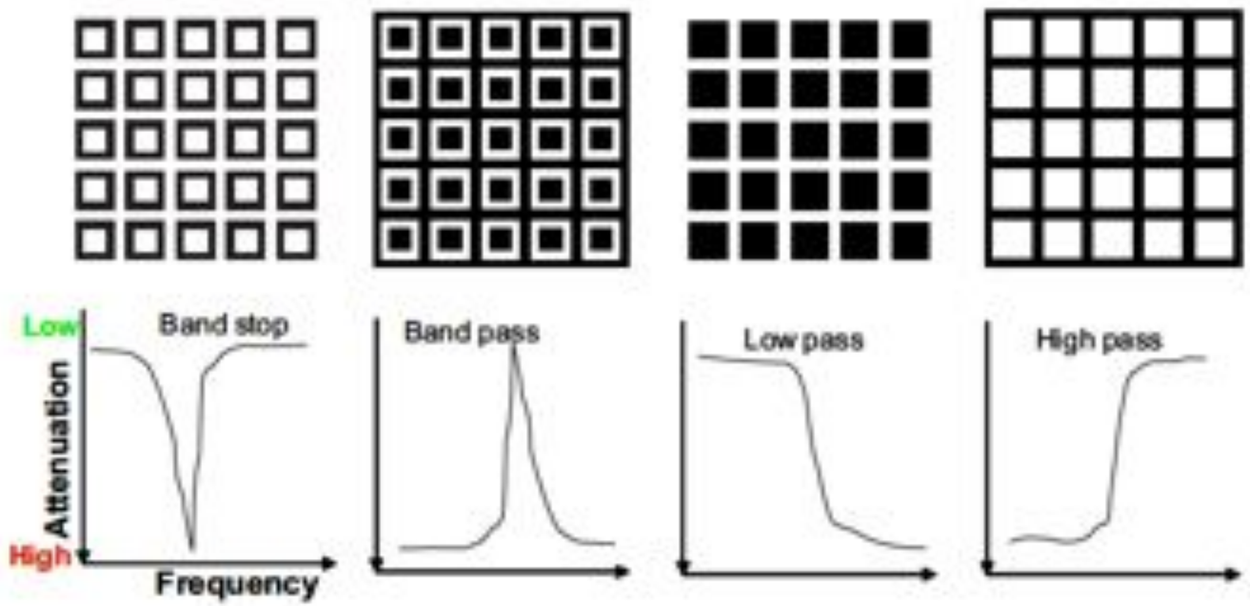
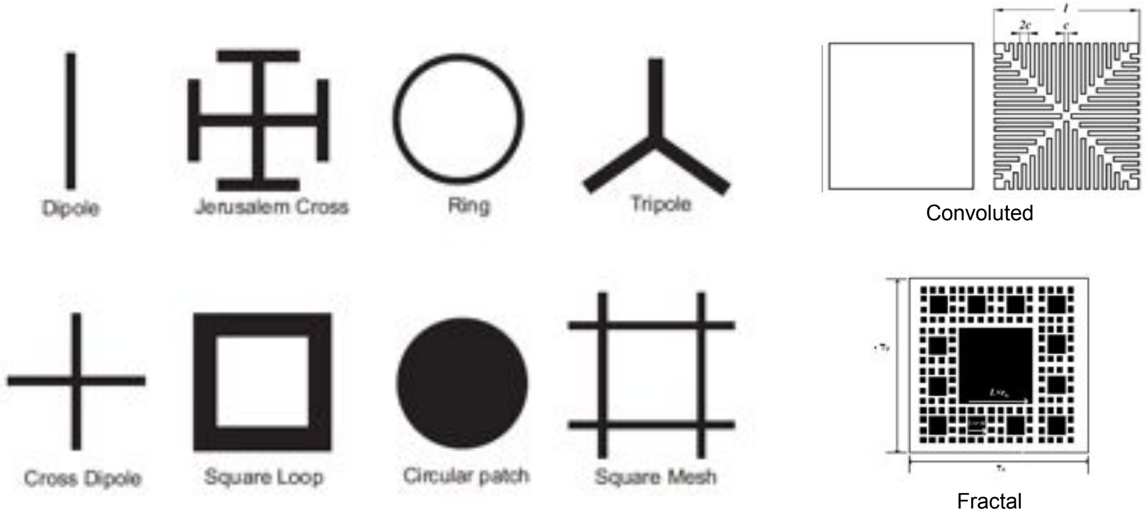
FSS principles

- Generic frequency response of a FSS.



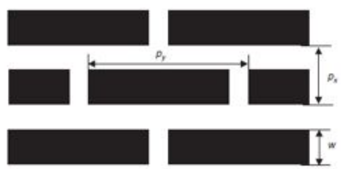
FSS performance influencing factors

- FSS element geometry:
  - *Centre connected: Dipoles, tripoles, Jerusalem crosses and cross dipoles;*
  - *Loop types: Square loops and rings;*
  - *Solid interior types: Patches and apertures fall in this category;*
  - *Combinations: Combination of previous, convolutions, fractals…*

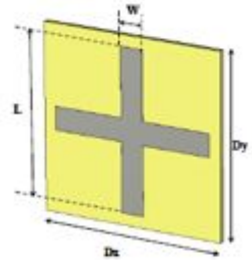


Passive FSS [from literature]

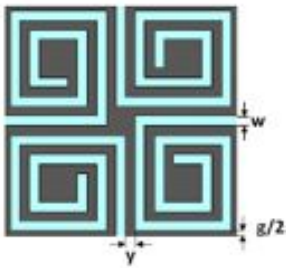
- Single Layer



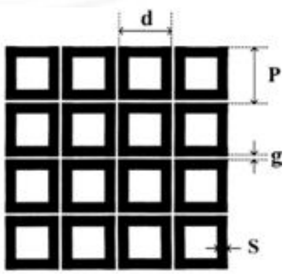
Linear Dipole



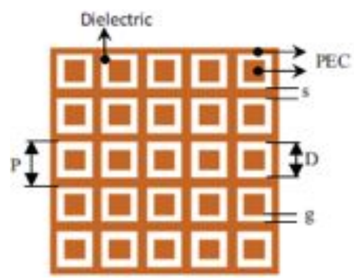
Cross Dipole



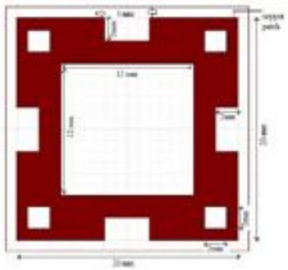
Spiral



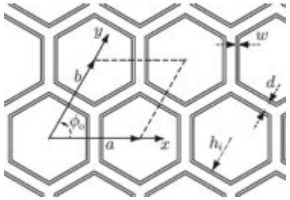
Square



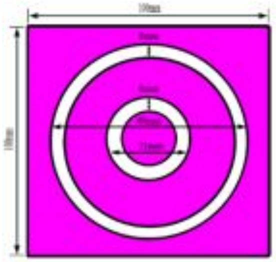
Square



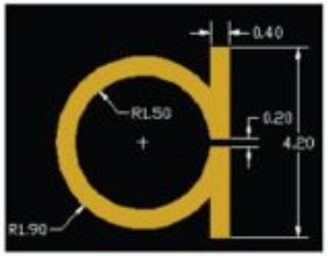
Square



Hexagonal



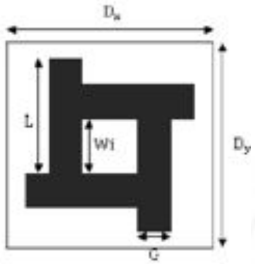
Ring



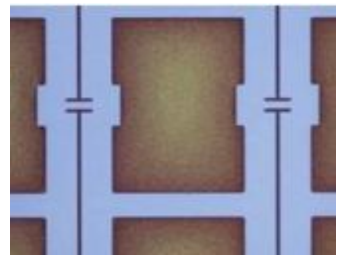
Omega symb. split ring

Passive FSS [from literature]

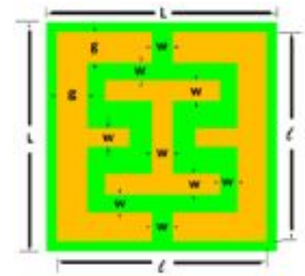
- Single Layer



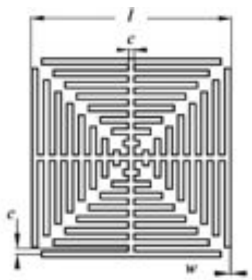
Fan



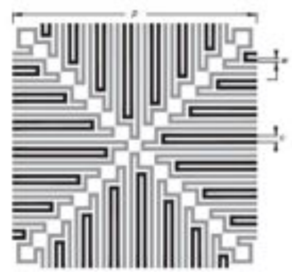
I-shape and Patch combination



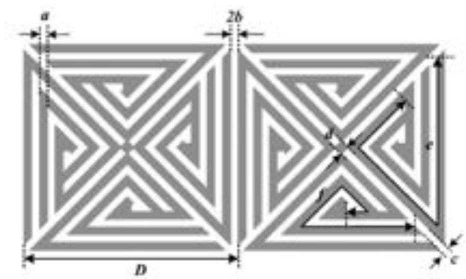
Dual E-shape and I-shape combination



Convoluted

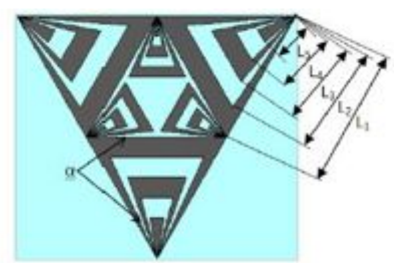


Interwoven



Meander-line

Fractals



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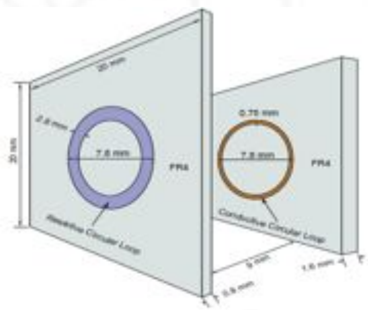
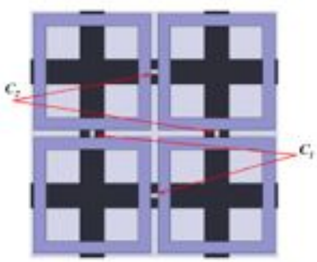
Passive FSS [from literature]

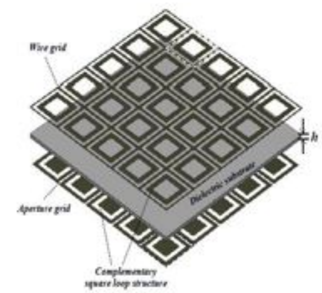
- Multi-layer

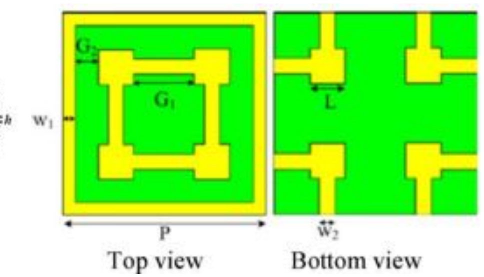


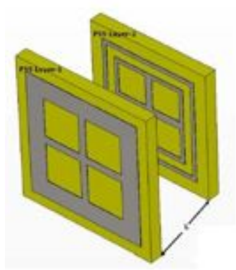
Multi-layer ring



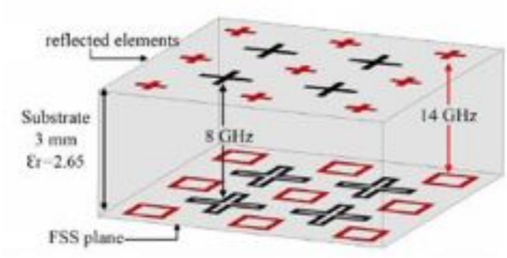
Multi-layer square

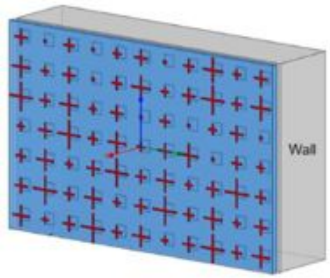


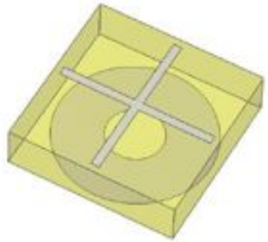




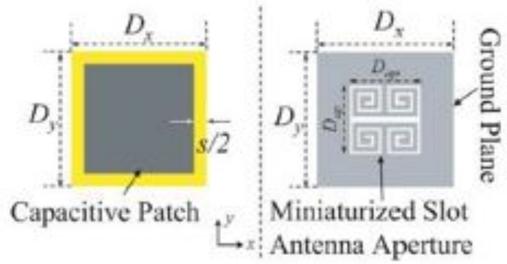
Cross dipole and square







Cross dipole and ring



Square and Convoluted Square

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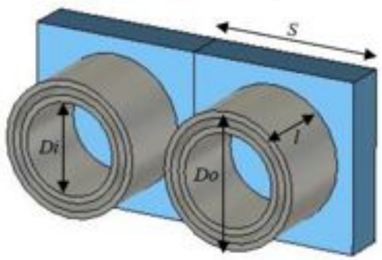
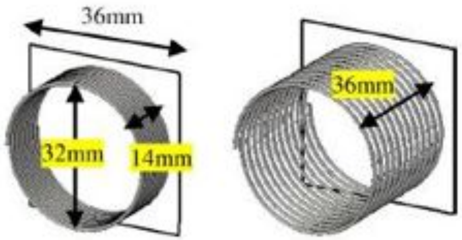
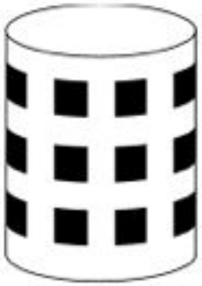
Passive FSS [from literature]

- 3-Dimensional







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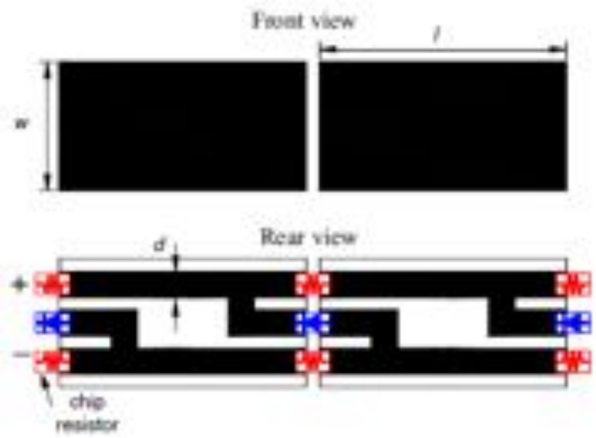
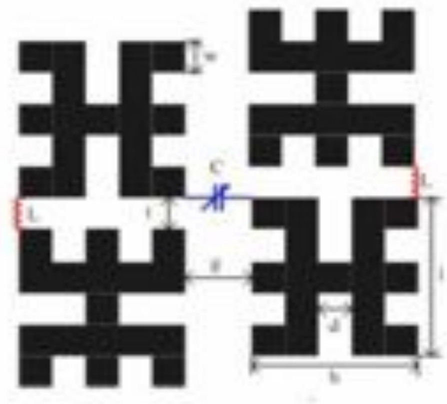
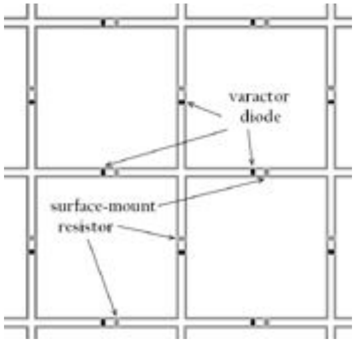
Active FSS [from literature]

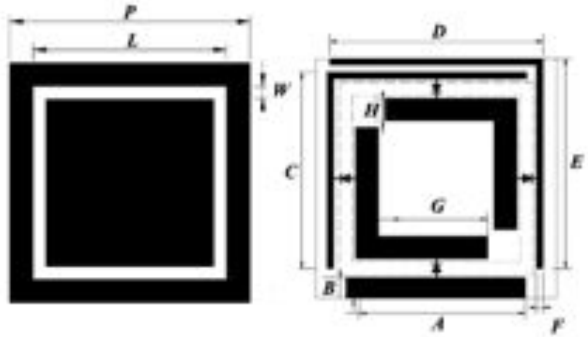
- Linear dipoles





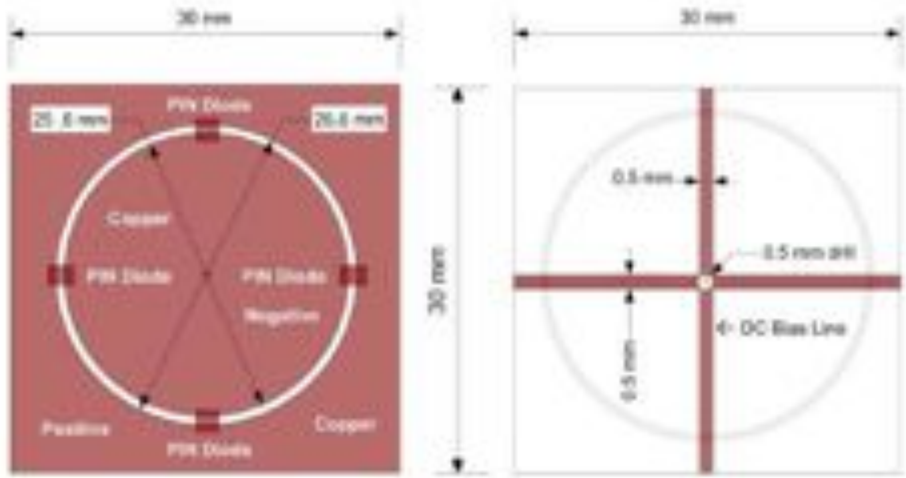
- Square

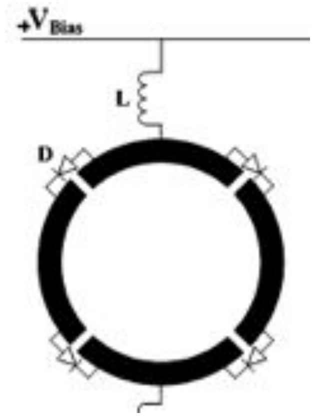


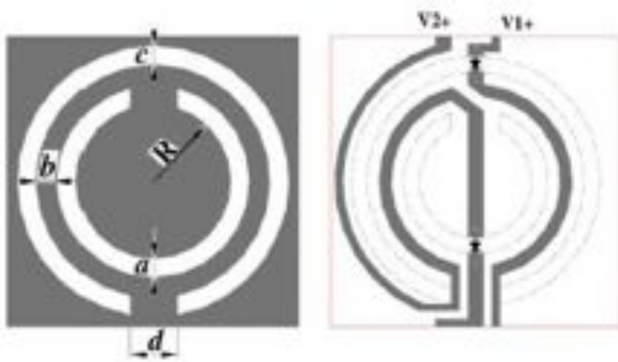


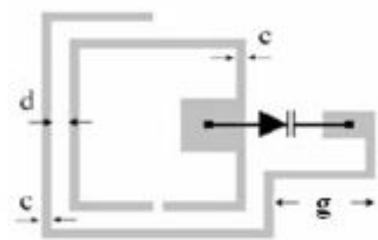
Active FSS [from literature]

- Ring



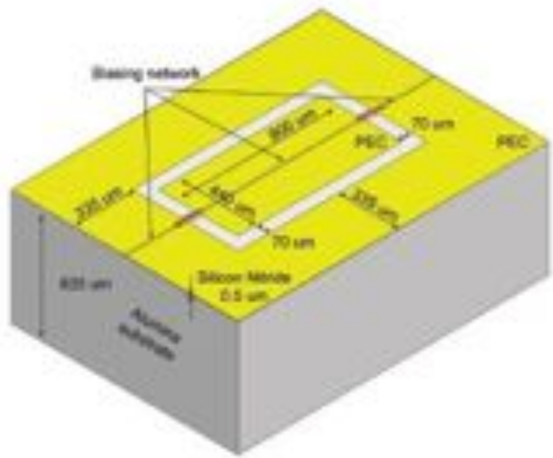




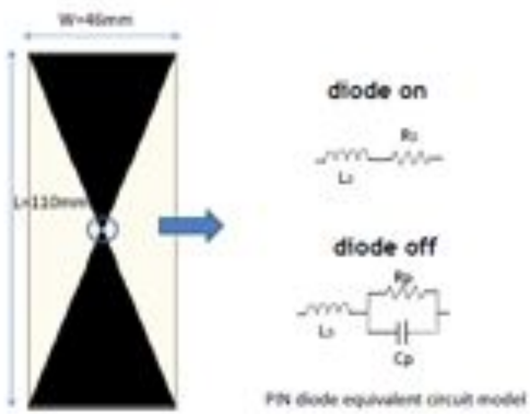


Active FSS [from literature]

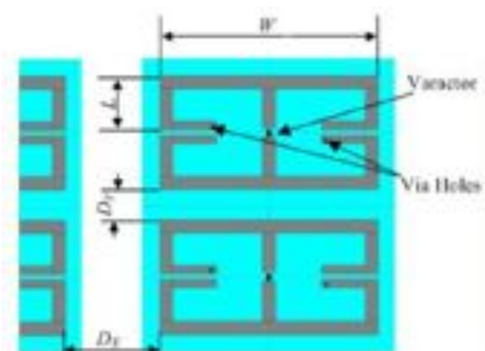
- Rectangular



- Bowtie



- Anchor shape



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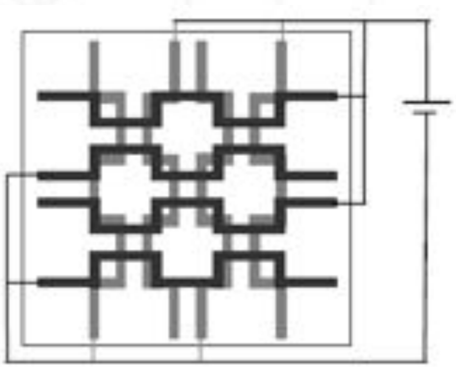
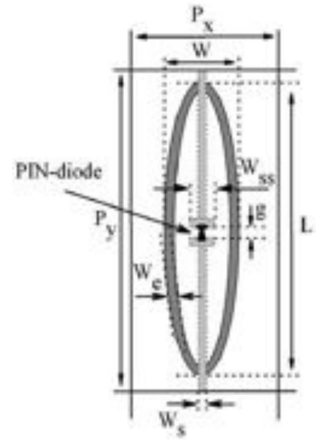
Active FSS [from literature]

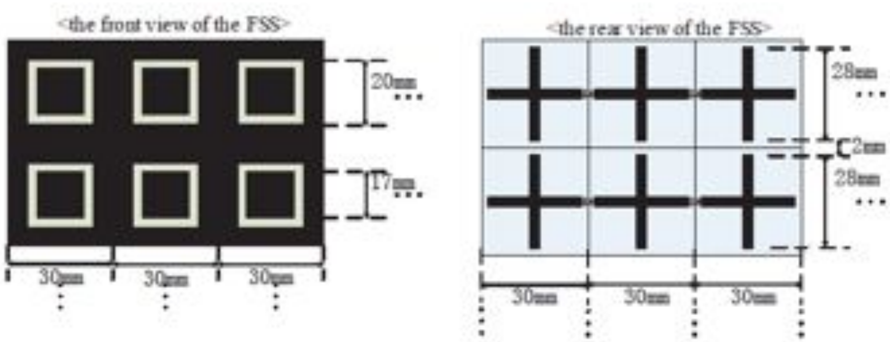
- Meander line



- Strip dipole and elliptical loop



- Square loop and cross dipoles



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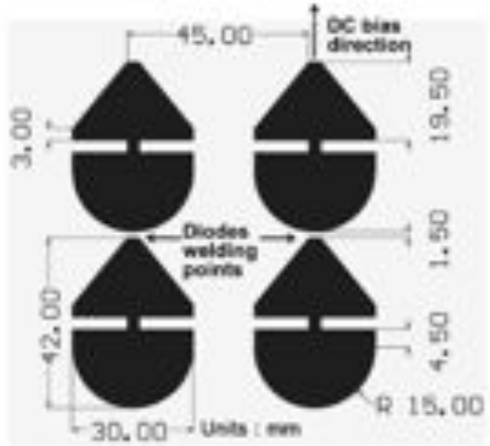
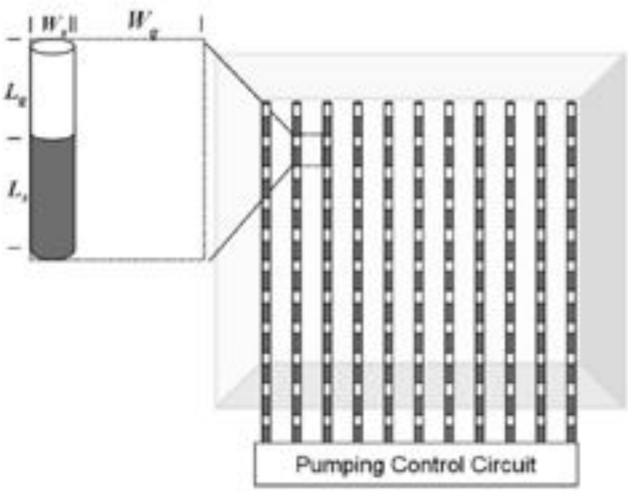
Active FSS [from literature]

- Raindrop



- Tubes filled with Liquid



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W. D. Burnside and K. W. Burgener, "High frequency scattering by a thin lossless dielectric slab," IEEE Trans. Antennas Propag., vol. AP-31, no. 1, pp. 104–110, Jan. 1983.

M. Yang, A. K. Brown, and S. Stavrou, "Resonant Behavior of Radio-Transmission Loss Due to Periodic Building Structures", IEEE Trans. Antennas and Prop., vol. 53, no. 5, pp. 98–105, Oct. 2011.

H. H. Sung, "Frequency Selective Wallpaper for Mitigating Indoor Wireless Interference", PhD thesis, University of Auckland, 2006.

F. Bayatpur, "Metamaterial-Inspired Frequency-Selective Surfaces", PhD thesis, University of Michigan, 2009.

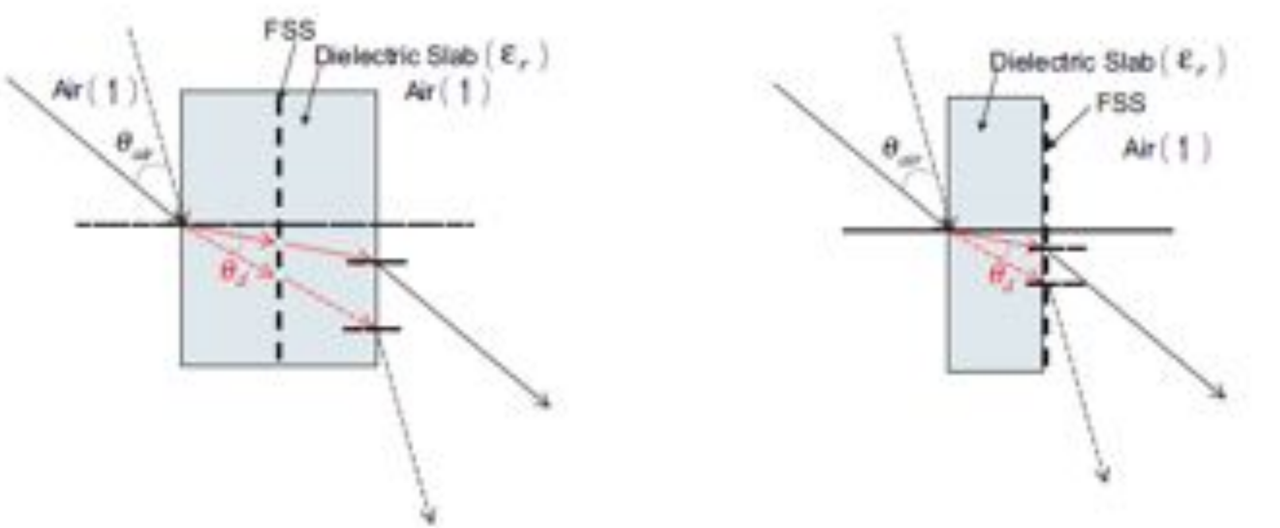
FSS performance influencing factors

- FSS element geometry:
  - *FSS performance for different element shapes (1 = Good, 4 = Bad)*

Element shape	Angular stability	Cross-polariaation level	Larger bandwidth	Small band separation
Dipole	4	1	4	1
Jerusalem Cross	2	3	2	2
Ring	1	2	1	1
Tripole	3	3	3	2
Cross Dipole	3	3	3	3
Square Loop	**1**	**1**	**1**	**1**

FSS performance influencing factors

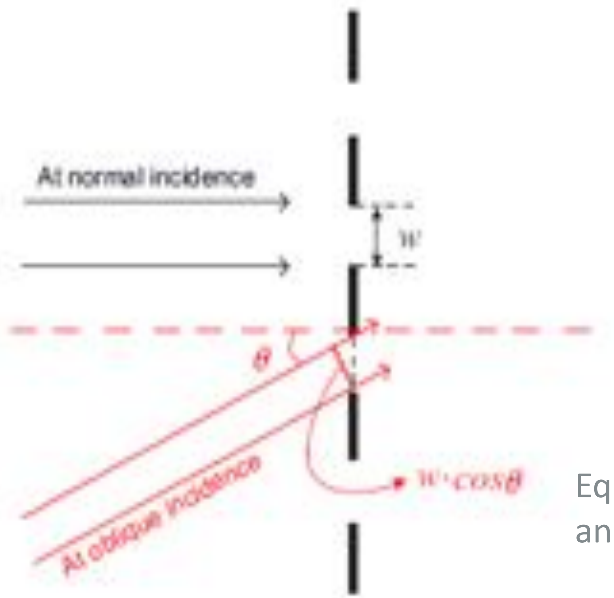
- FSS element conductivity
  - *Power dissipation, production costs…*
- FSS dielectric substrate
  - *used to provide a structural support*
  - *The choice of dielectric substrates and their arrangement influences the resonant frequency of the FSS by a factor of* $\sqrt{\varepsilon_{eff}}$



(a) FSS in dielectric substrates, $\varepsilon_{eff} = \varepsilon_r$. (b) FSS on a dielectric substrate, $\varepsilon_{eff} = (\varepsilon_r + 1)/2$.

FSS performance influencing factors

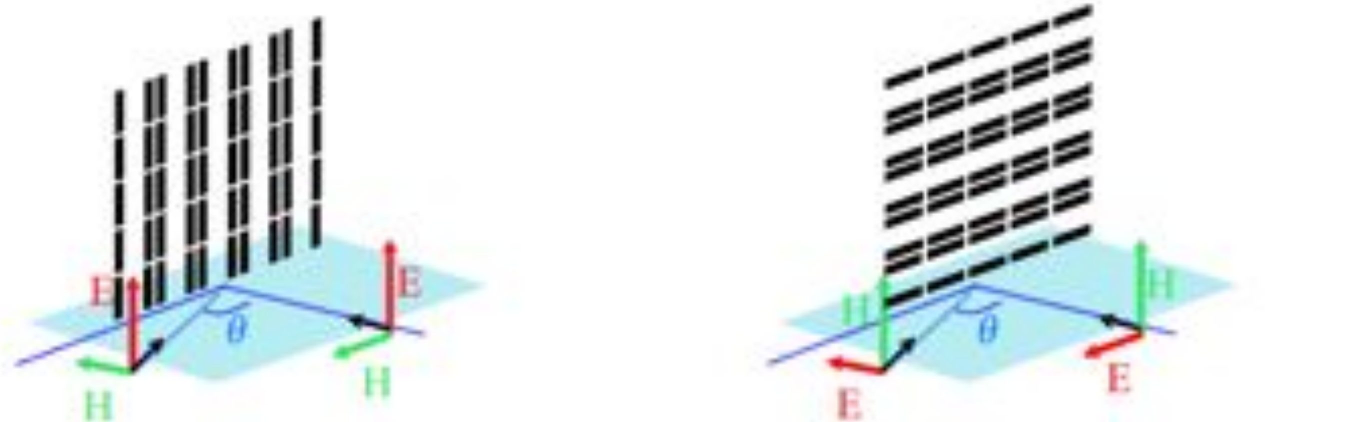
- Signal incidence angle



Equivalent separation between elements at an oblique angle

FSS performance influencing factors

- Signal incidence polarisation



(a) The inductive component with TE-wave incidence (b) The inductive component with TM-wave incidence

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Simulation methods for FSS studies

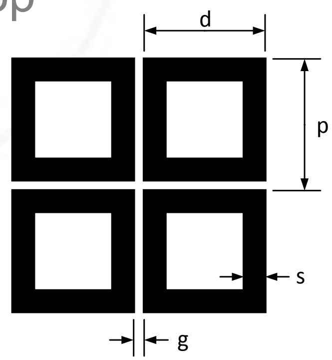
- For complex FSS structures with inhomogeneous substrates:
  - *Finite Element Method (FEM);*
  - *Finite Difference Time Domain (FDTD);*
  - *Mutual Impedance Method (MIM);*
  - *Equivalent Circuit Models (ECM);*

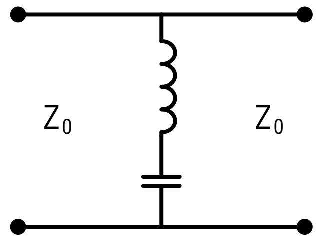
- For periodic screens supported by homogenous dielectric slabs:
  - *Method of Moments (MoM).*

FSS design – equivalent circuit modelling

- Current work - development of an improved equivalent circuit (EC) model to estimate the frequency response of a square loop/slot FSS;
- Square loop

Assume a vertically polarised incident signal





$$\frac{X_L}{Z_0} = \omega L = \frac{d}{p}\cos\theta\, F(p, 2s, \lambda, \theta)$$

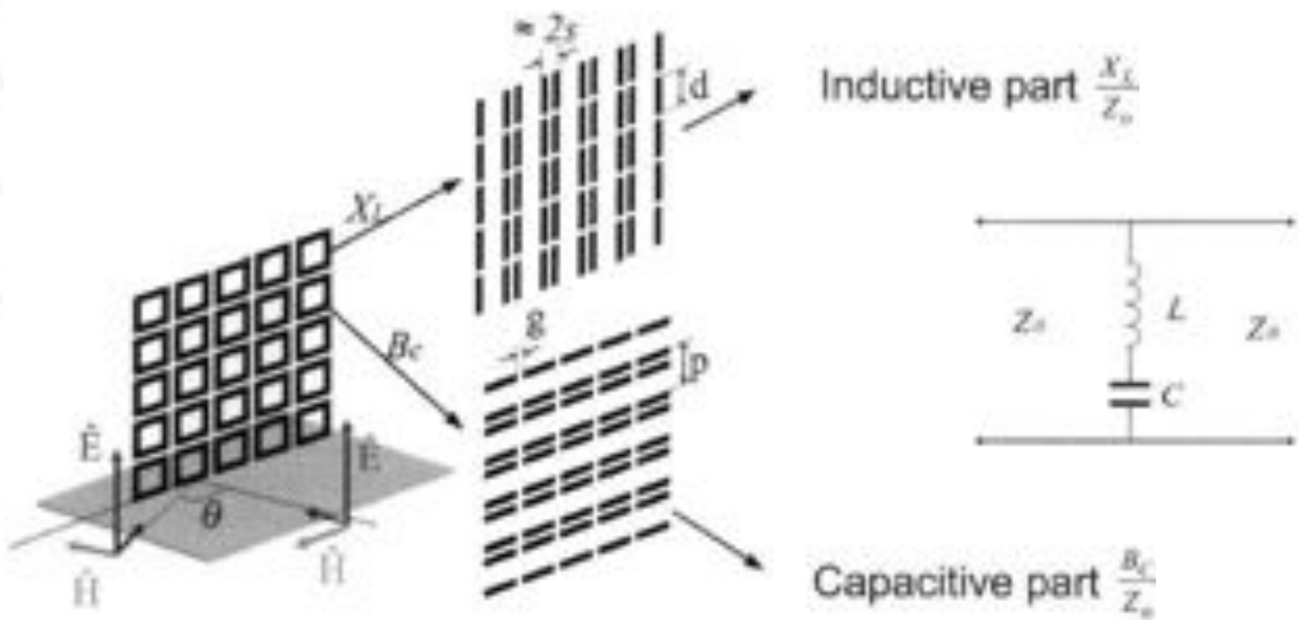
Shunt inductive reactance

$$\frac{B_C}{Z_0} = \omega C = 4\frac{d}{p}\sec\theta\, F(p, g, \lambda, \theta)\varepsilon_{Corr}$$

Shunt inductive susceptance

FSS design – equivalent circuit modelling

- Square loop



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FSS design – equivalent circuit modelling

- Optimisation factor for square loop EC equations:

$$\frac{X_L}{Z_0} = \omega L = \frac{d}{p}\cos\theta\, F(p, 2s, \lambda, \theta)$$

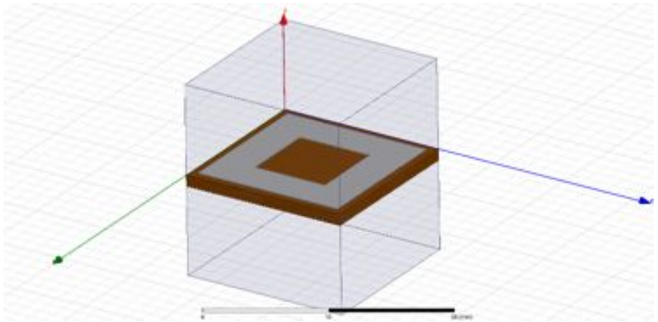
$$\frac{B_C}{Z_0} = \omega C = 4\frac{d}{p}\sec\theta\, F(p, g, \lambda, \theta)\varepsilon_{eff}$$

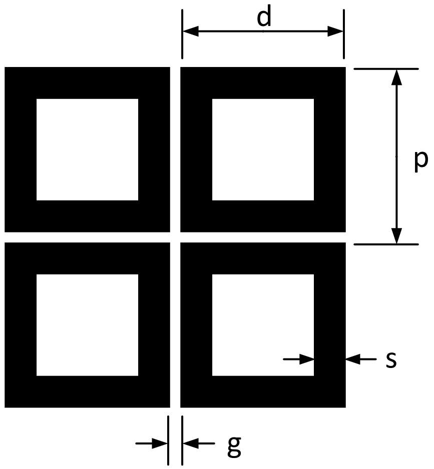
$$F(p, w, \lambda, \theta) = \frac{p}{\lambda}\left[\ln\left(csc\frac{\pi w}{2p}\right) + G(p, w, \lambda)\right]$$

$$G(p, w, \lambda) = \frac{1}{2}\frac{(1-\beta^2)^2\left[\left(1-\frac{\beta^2}{4}\right)(A_+ + A_-) + 4\beta^2 A_+ A_-\right]}{\left(1-\frac{\beta^2}{4}\right) + \beta^2\left(1+\frac{\beta^2}{2}-\frac{\beta^4}{8}\right)(A_+ + A_-) + 2\beta^6 A_+ A_-}$$

$$A_\pm = \frac{1}{\sqrt{\left[1 \pm \frac{2p\sin\theta}{\lambda} - \left(\frac{p\cos\theta}{\lambda}\right)^2\right]}} - 1$$

$$\beta = \frac{\sin \pi w}{2p}$$





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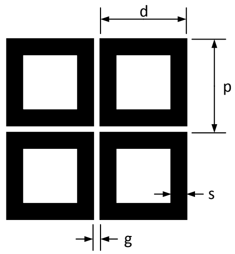
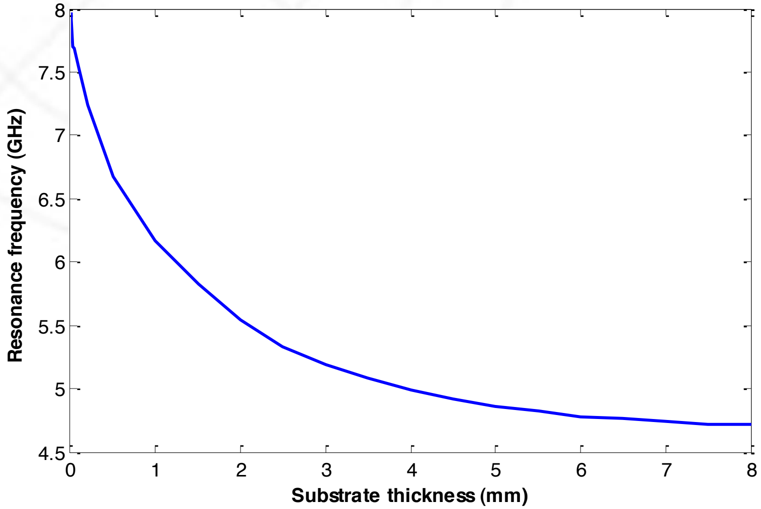
FSS design – equivalent circuit modelling

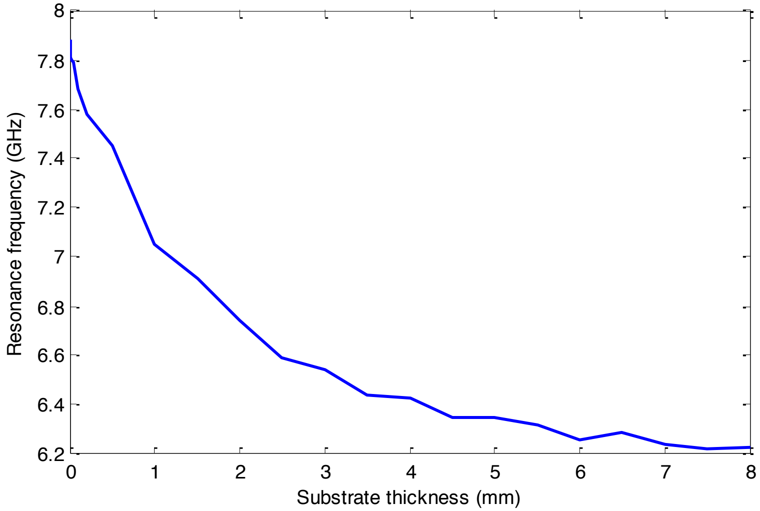
- Optimisation factor for square loop EC equations:



d = 20 mm;
s = 5 mm;
g = 2 mm



(a)



(b)

Parametric simulation of FSS with (a) FR4 substrate and (b) Duroid

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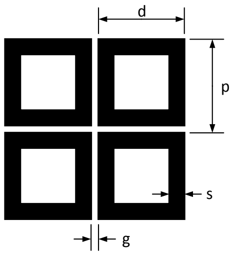
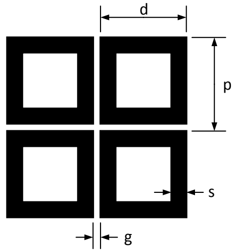
FSS design – equivalent circuit modelling



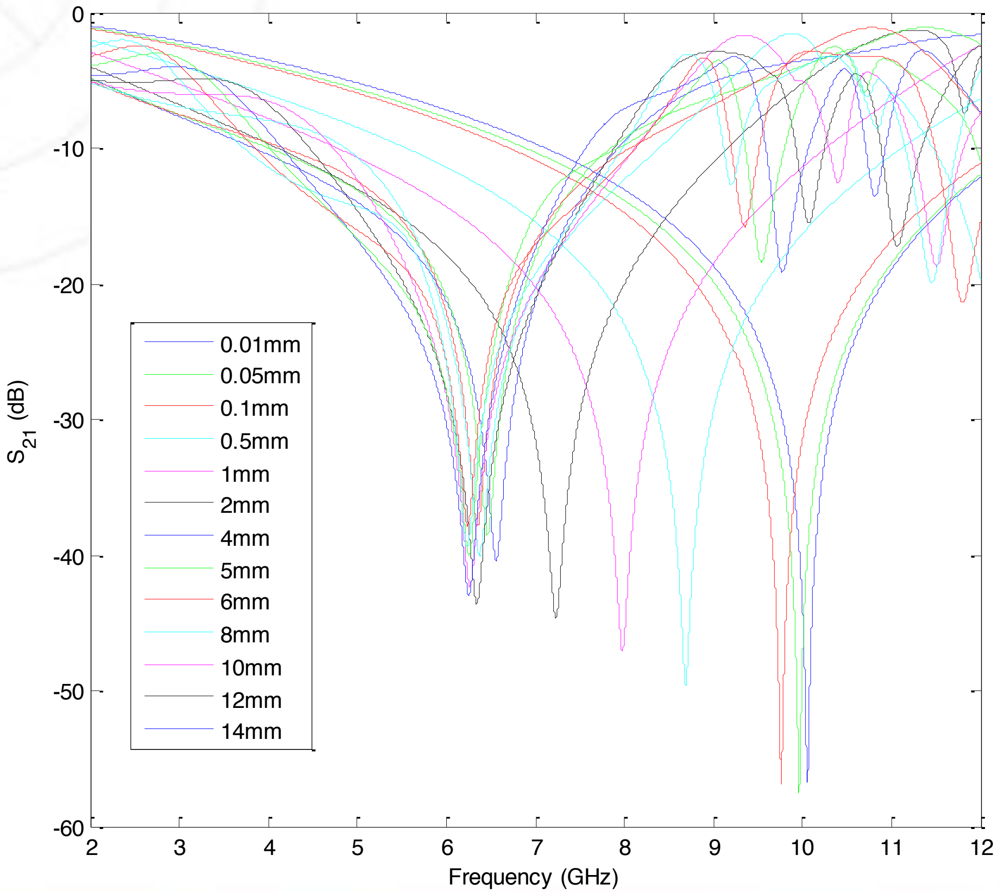
- Optimisation factor for square loop EC equations:

FSS unit cell size (d – s – g)	Simulation tool	Resonance frequency (GHz) for incidence angle theta		
		0°	30°	60°
16-2-2	**HFSS**	**4.67**	**4.62**	**4.56**
	Classic EC	6.49	6.32	6.01
	E.C. with ε_{eff}	4.08	4.05	3.98
	E.C. with ε_{Corr}	4.44	4.39	4.3
16-2-4	**HFSS**	**5.29**	**5.16**	**4.97**
	Classic EC	7.26	6.91	6.36
	E.C. with ε_{eff}	4.69	4.61	4.47
	E.C. with ε_{Corr}	5.26	5.15	4.95
20-4-2	**HFSS**	**4.93**	**4.75**	**4.49**
	Classic EC	6.32	6.12	5.75
	E.C. with ε_{eff}	4.04	4	3.92
	E.C. with ε_{Corr}	4.78	4.71	4.57
20-2-4	**HFSS**	**3.85**	**3.84**	**3.76**
	Classic EC	5.21	5.04	4.75
	E.C. with ε_{eff}	3.3	3.26	3.19
	E.C. with ε_{Corr}	3.7	3.65	3.55
24-4-4	**HFSS**	**4**	**3.87**	**3.68**
	Classic EC	5.1	4.88	4.52
	E.C. with ε_{eff}	3.28	3.23	3.15
	E.C. with ε_{Corr}	3.94	3.85	3.7

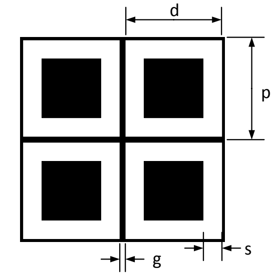
FSS design – equivalent circuit modelling



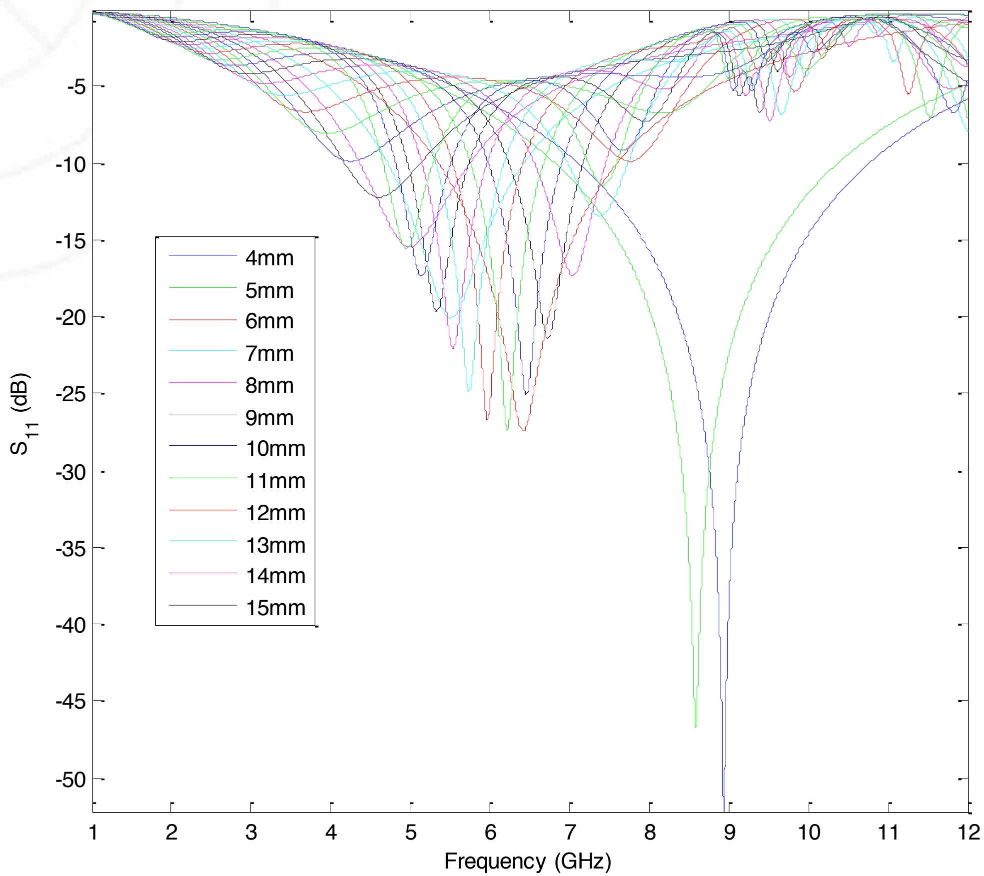
- Frequency response for square loop with varying substrate thickness



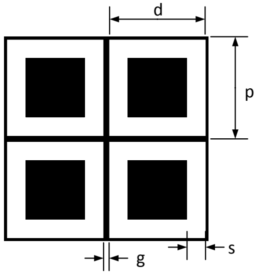
FSS design – equivalent circuit modelling



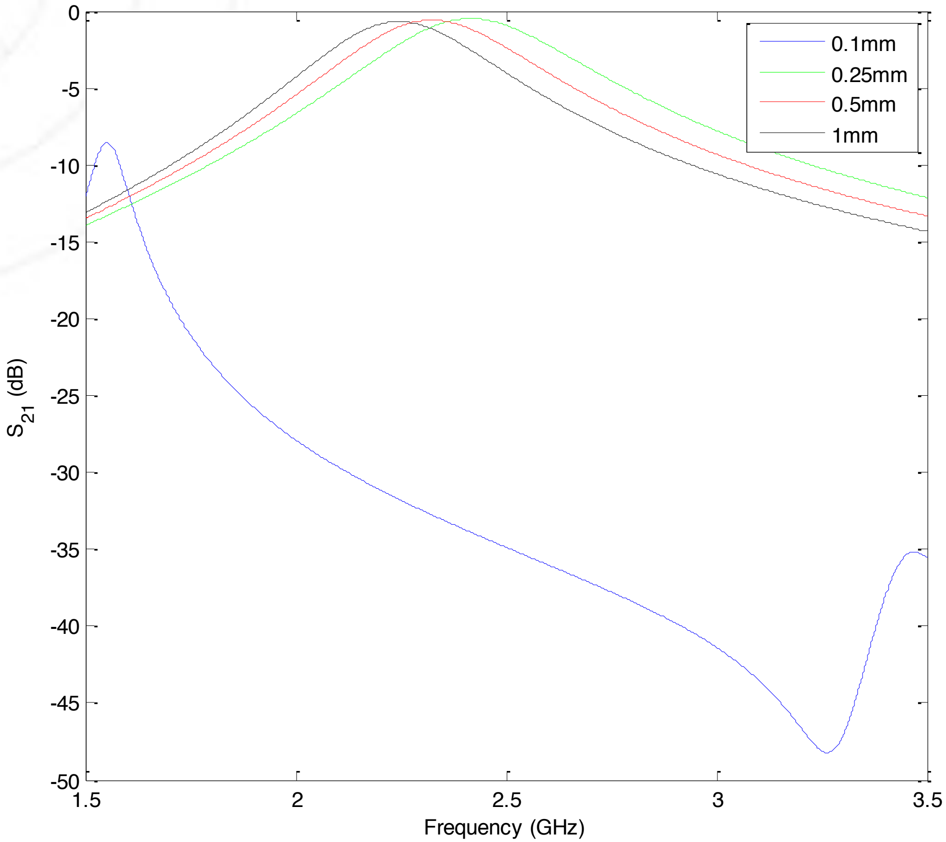
- Frequency response for square slot with varying substrate thickness



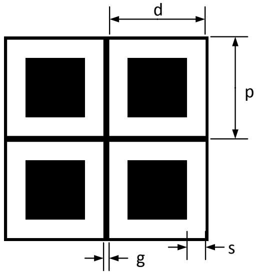
FSS design – equivalent circuit modelling



- Frequency response for square slot with varying substrate thickness



FSS design – equivalent circuit modelling



- Frequency response for square slot with varying incident angle

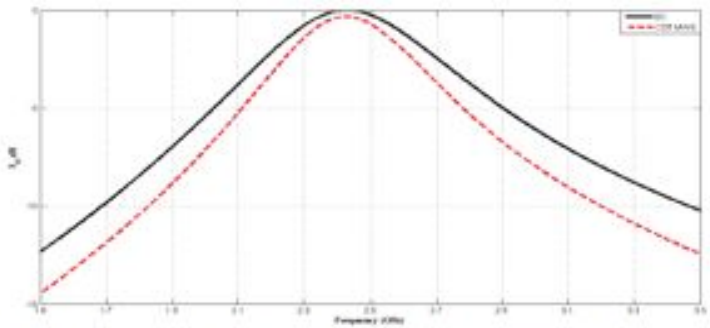


Fig. 2 The TE-wave incidence theoretical angular response calculated based on the EC model for square mesh-patch array FSS, with $\varepsilon_r = 3$, $\theta = 0^o$ *to* 50^o

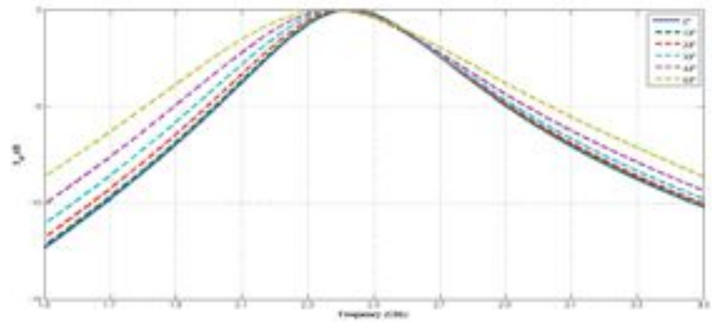


Fig. 3 The TE-wave incidence EC vs. CST for a unit cell consisting of square mesh-patch array, $\theta = 0^o$

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Reference

N. Qasem, R. Seager, "Indoor Band Pass Frequency Selective Wall Paper Equivalent Circuit & Ways to Enhance Wireless Signal", Loughborough Antennas & Propagation Conference, 2011.

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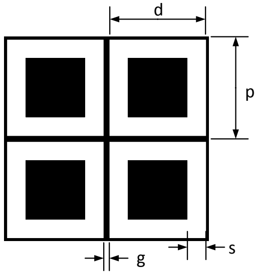
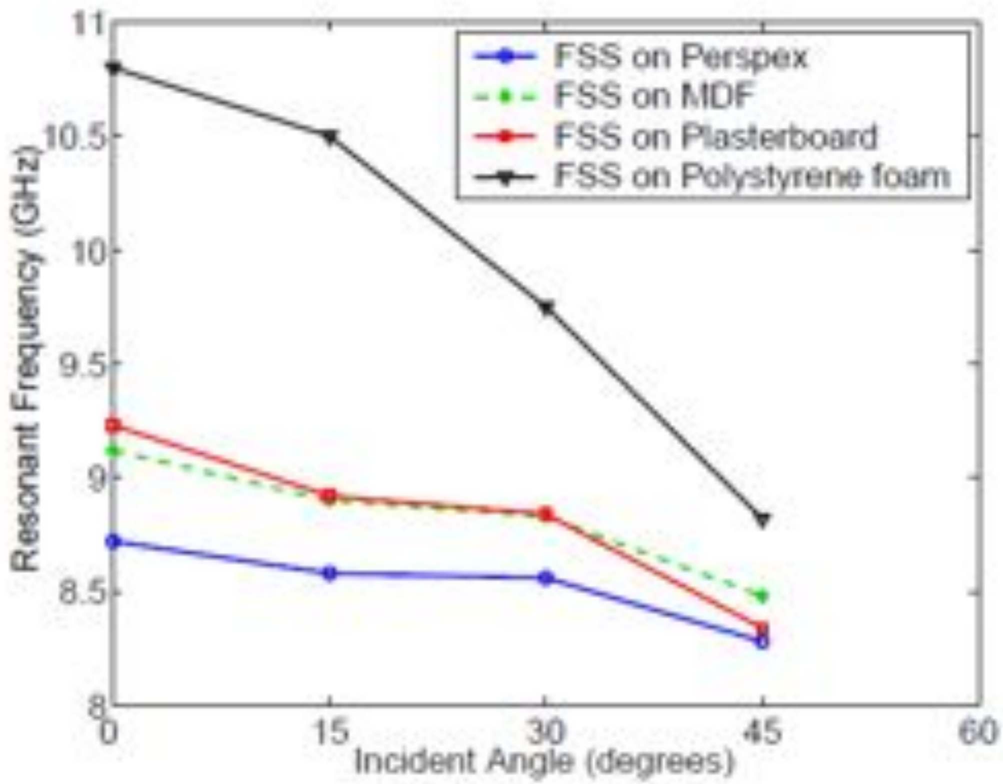


- Resonance variations with incident angle



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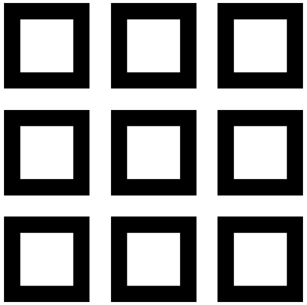
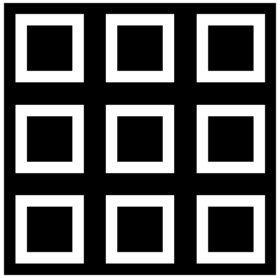
FSS design – equivalent circuit modelling

- On-going work
  - *Measurement of a 6GHz square loop FSS prototype (reject-band):*



  - *Measurement of a 6GHz square slot FSS prototype (pass-band):*

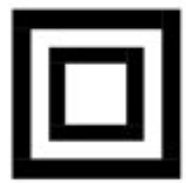


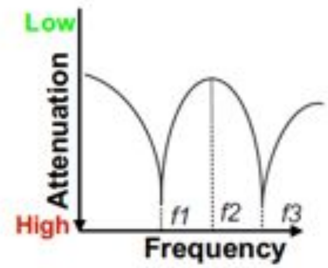
  - *Validation of EC model.*

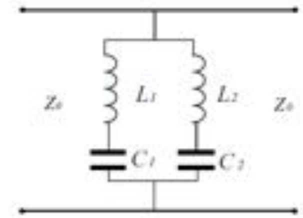
Future work

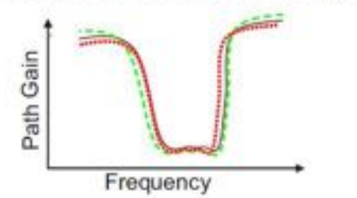
- Implementation of an active FSS based on the square design:
  - *Switching / Tuning capabilities.*
- Development of a new complex FSS structure for multiple frequencies of interest.
- Integration of a FSS prototype in a realistic (ideally) spacecraft structure:
  - *Development of a Multilayer model to predict behavior of “sandwiched” complex structure.*

Parameter	Action	Change in resonant frequency	Variation in resonant frequency at different incident angles
p	Reduce	Higher	Same
g	Reduce	Lower	Less
s	Reduce	Lower	Less









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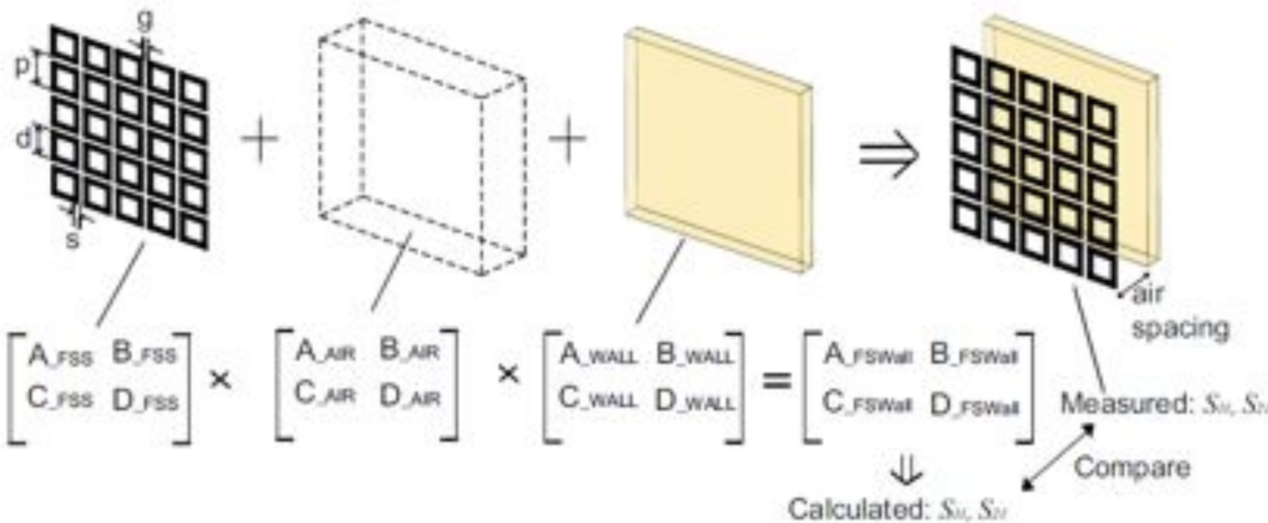
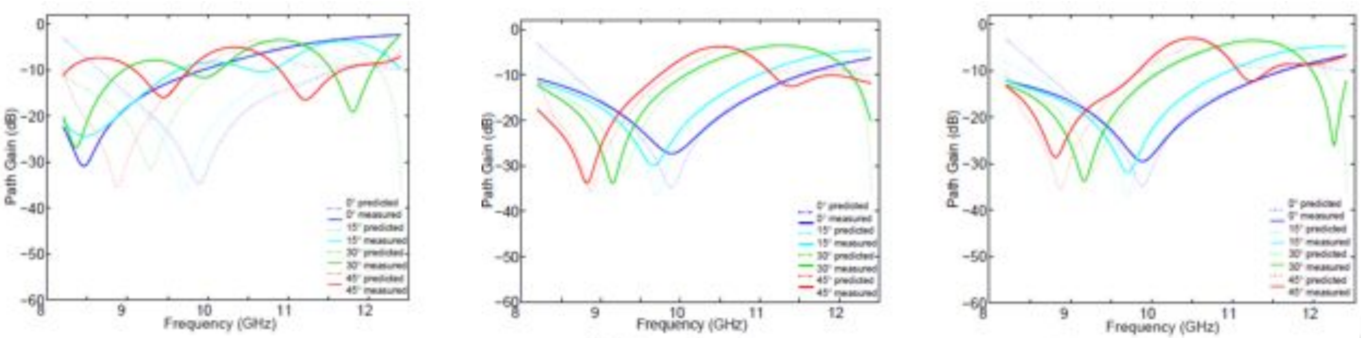
Future work

- *(Cont.) Development of a Multilayer model to predict behavior of "sandwiched" complex structure.*





(b) 10mm air spacing

(c) 20mm air spacing

Agenda

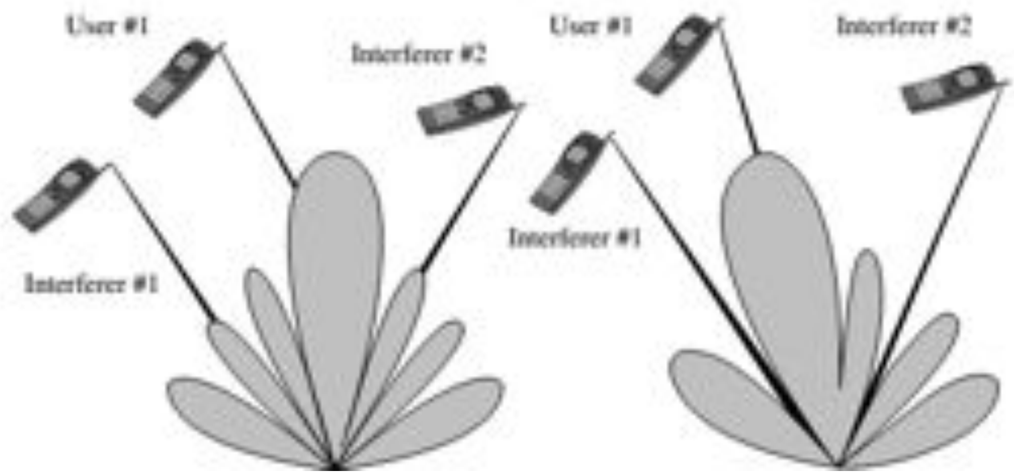
- Presentation of our research group
- Motivation for today's topics
- Wireless Sensor Networks for Spacecraft
- **FSS for space applications:**
  - *Frequency selectivity and site shielding*
  - ***Antenna beam steering***
- Ambient RF Energy Harvesting
- Hybrid FSS and rectenna design
- Conclusions

Antenna Beam steering

- The beam steering concept;
- Beam steering applications;
- Technology overview for beam steering applications;
- Metamaterials for beam steering applications:
  - *Metamaterials overview;*
  - *Transmitarray technique;*
  - *Metamaterial unit-cell;*
  - *Transmitarray elements;*
  - *Beam steering with a MM Transmitarray;*
- Gain enhancement with MM at 60GHz ;
- Beam steering with Fabry-Perot antenna;
- Challenges & Further work.

The beam steering concept

- **Beam steering** – the ability of changing the direction of the radiation pattern main lobe aiming to focus their energy towards the intended users, instead of directing it unnecessary directions.



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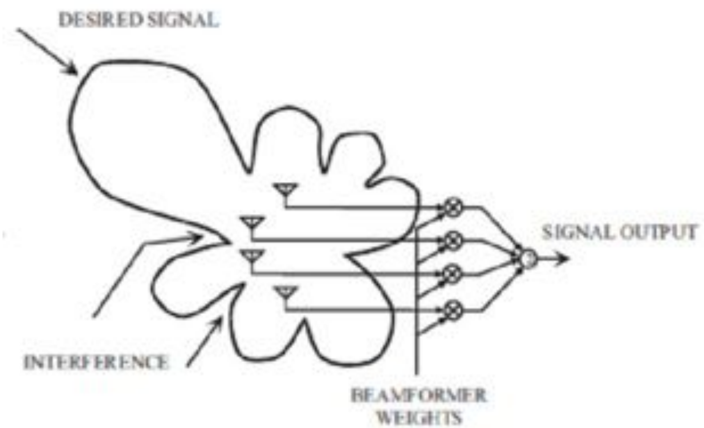
The beam steering concept

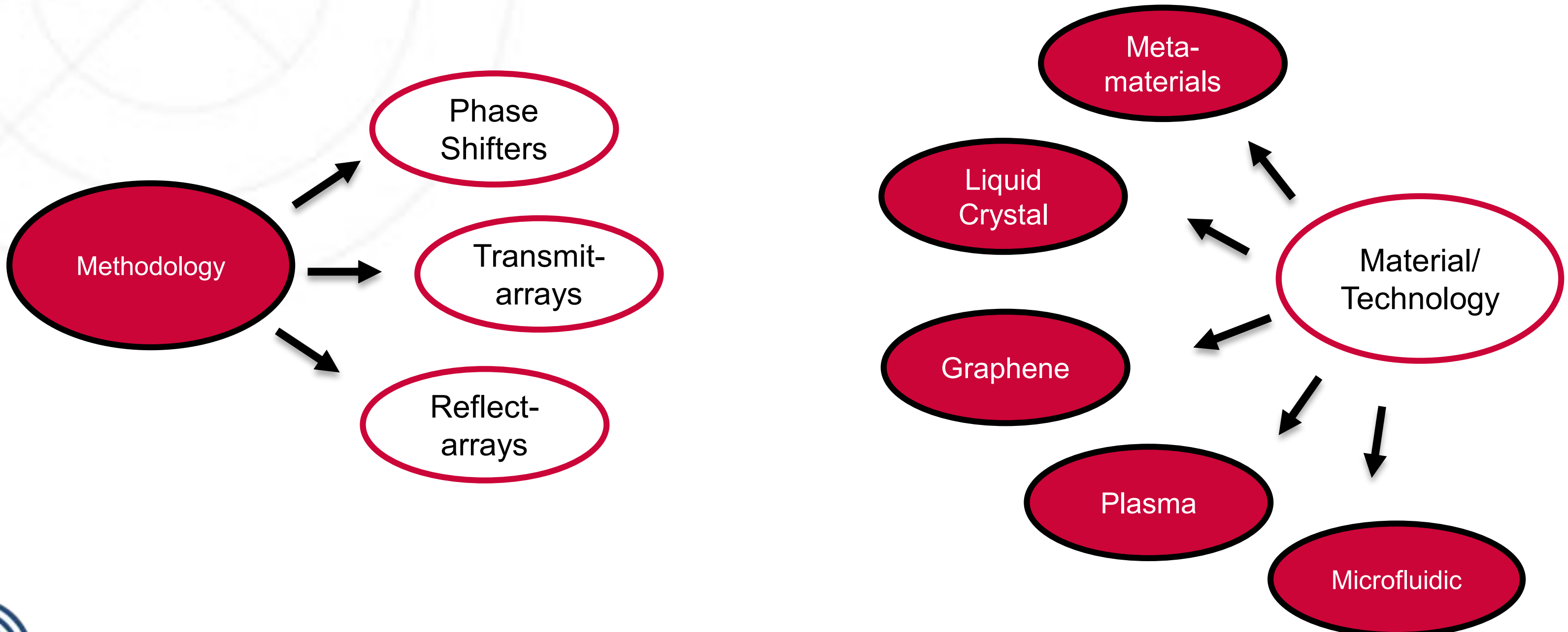
- Common antenna array based on RF phase shifters:
  - *Use of 1 PS per antenna, in an antenna array;*
  - *Extremely high cost (precision PS);*
  - *Electronically complex;*
  - *Complex calibration;*
  - *Bulky and heavy.*



Adapted from Jack H. Winters, "Smart Antennas", chapter 6 .

Novel beam steering applications emerging

Technology overview for beam steering applications



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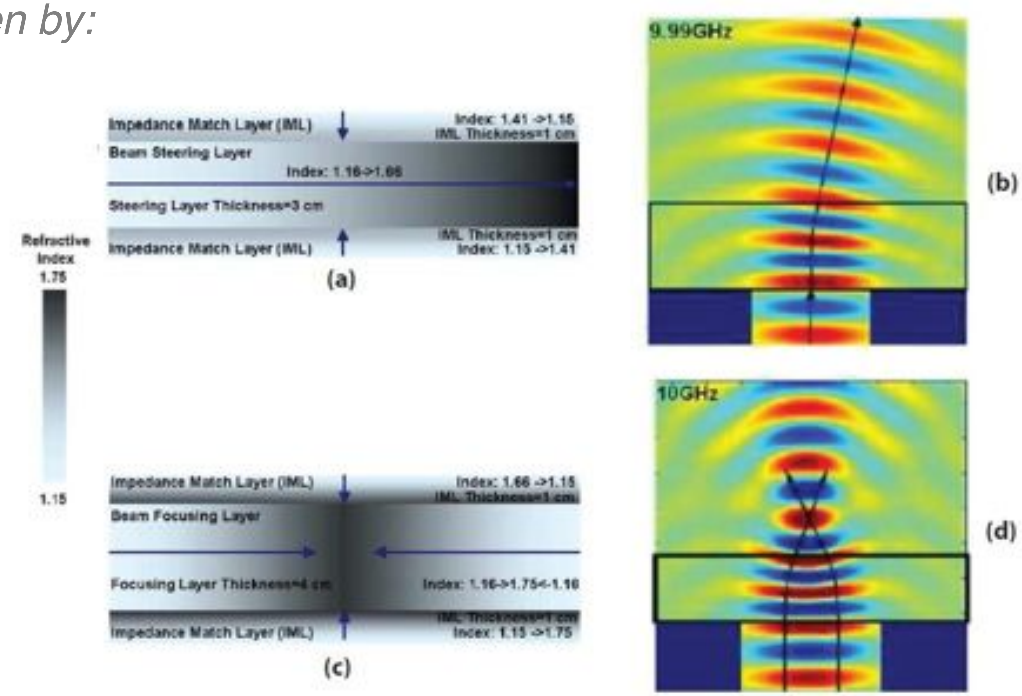
Metamaterials for beam steering applications

- Gradient Index Metamaterials
  - *Refractive index varying between positive values;*
  - *Phase delay is given by:*

$$\alpha = n.k_o.t$$

$$k_o = \omega\sqrt{\varepsilon_o.\mu_o}$$



α- phase delay;
t - slab thickness;
n - refractive index;
k_0 - propagation constant

Beam steering (a) and focusing (b) slab, with gradient-index distribution. Image adapted from A. Sajuyigbe, Electromagnetic Metamaterials for Antenna", 2010.

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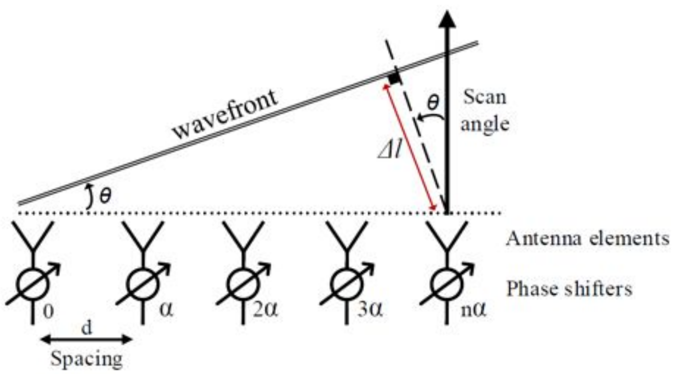
Transmitarray technique

Linear antenna array

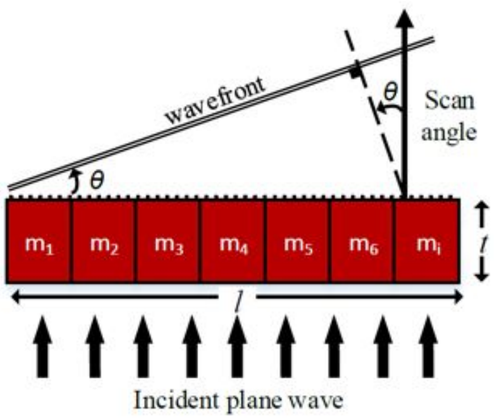


$$\alpha = \frac{2\pi . d . sin\theta}{\lambda}$$

$$\theta = arcsin\left(\frac{\alpha.\lambda}{2\pi.d}\right)$$

Transmitarray topology

Gradient refractive index



$$\alpha_i = \frac{2\pi}{\lambda_o}.t.n_i = k_o.t.n_i$$

$$n = \sqrt{\epsilon_r.\mu_r}$$

$$\epsilon_{r_i} = [n_1 + (m_i - 1).\Delta n]^2$$

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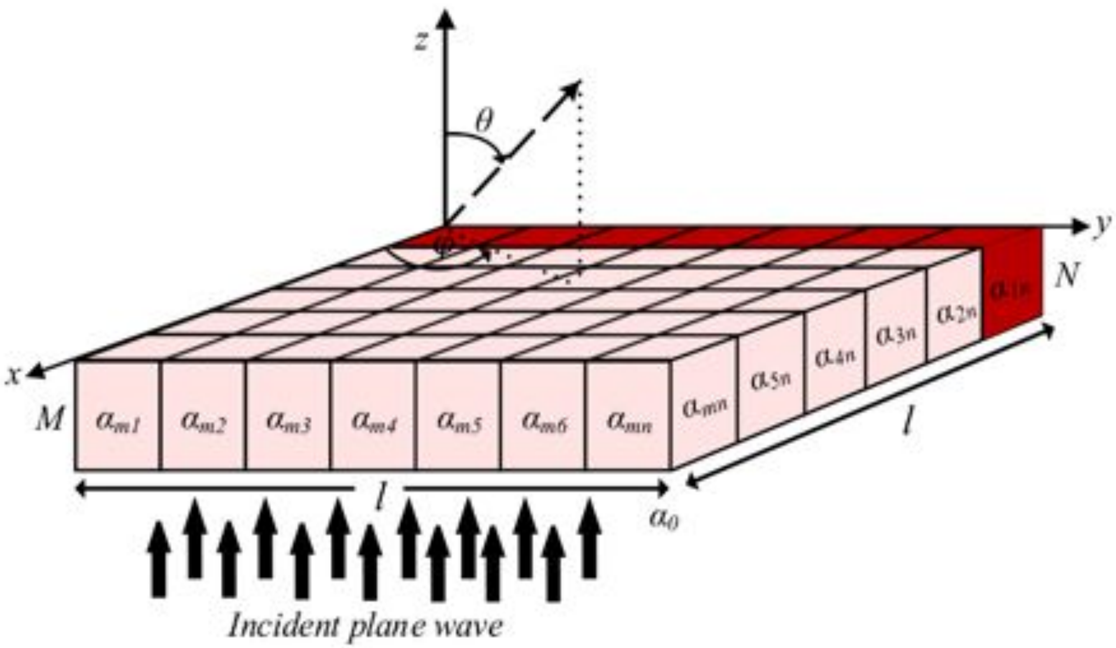
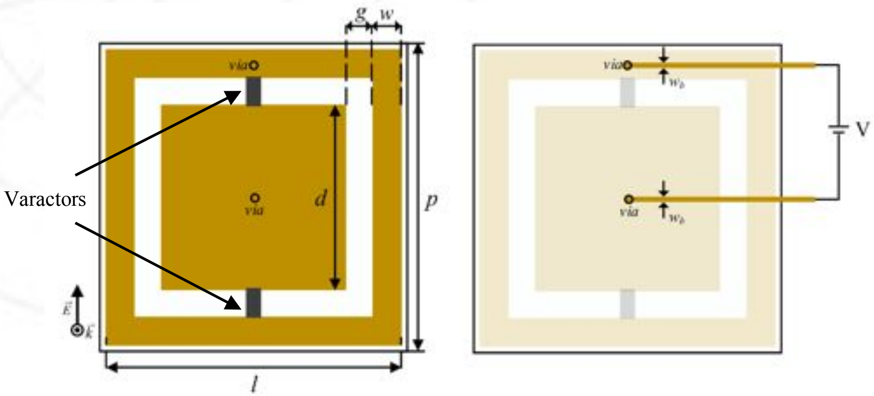
Transmitarray technique

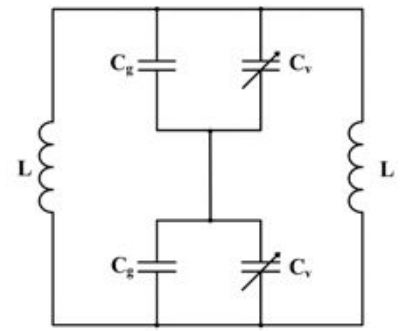
- 2D Transmitarray topology
  - *Gradient refractive index*



Metamaterial unit-cell



Top and bottom unit cell layout .

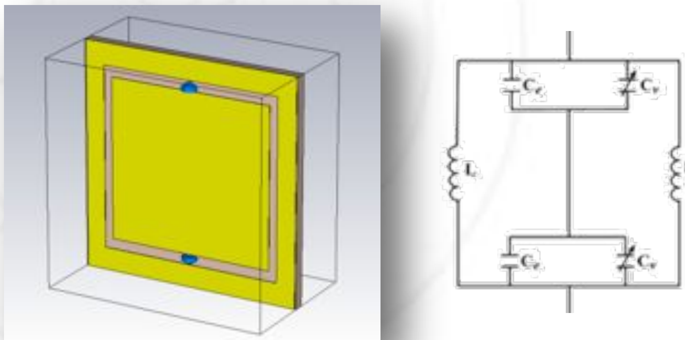


Unit cell equivalent circuit.

- Band pass spatial filter;
- Tunable resonant response.

$$\omega_0 = \frac{2}{\sqrt{L(C_v + C_e)}}$$

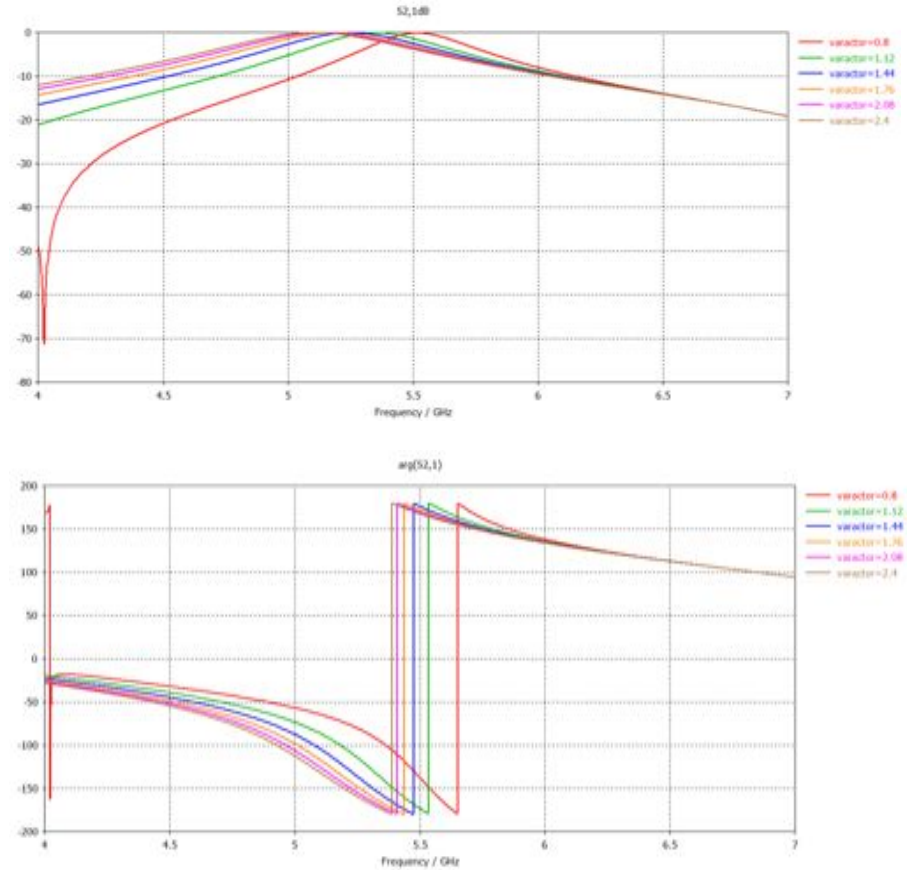
Metamaterial unit-cell



Unit cell and equivalent circuit.

$$\omega_0 = \frac{2}{\sqrt{L(C_v + C_e)}}$$

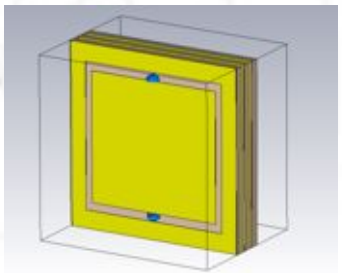
Δf~500MHz → **Cv:** 0.8 to 2.4pF

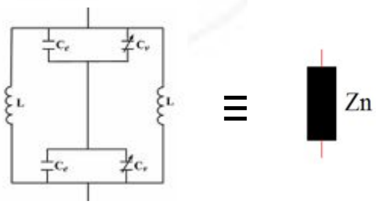


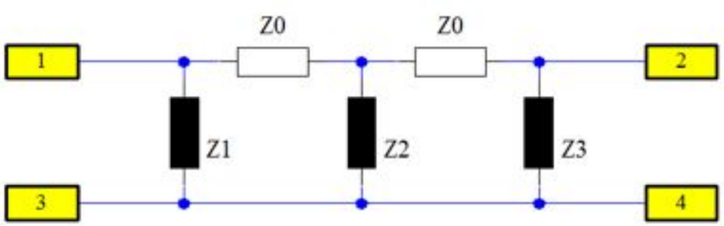
S_{21} transmission loss - magnitude[dB] II phase[deg] – Unit cell model.

W. Pan, C. Huang, P. Chen, M. Pu, X. Ma, and X. Luo. A beam steering horn antenna using active frequency selective surface. Antennas and Propagation, IEEE Transactions on, PP(99):1-1, 2013

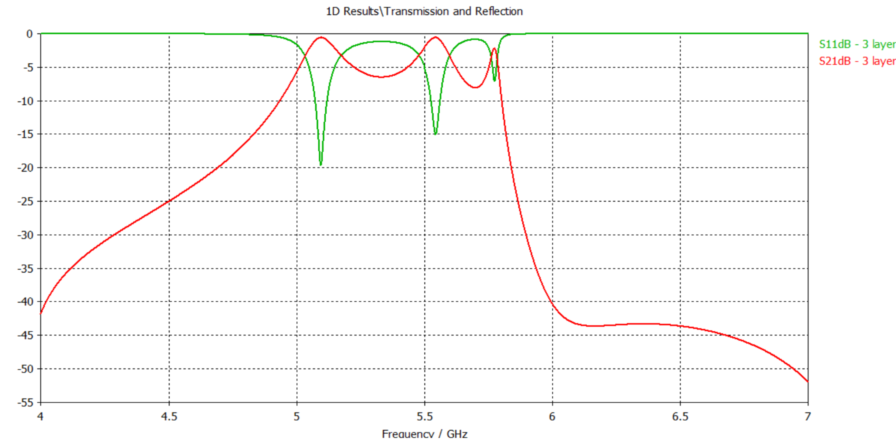
Metamaterial unit-cell

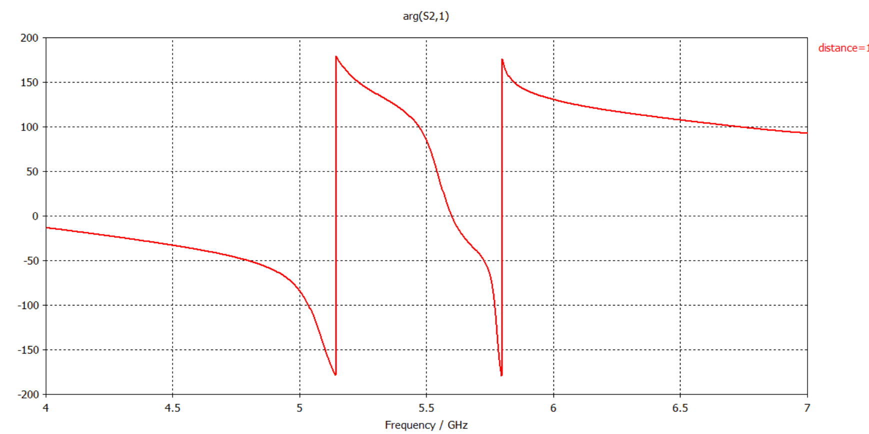






Equivalent circuit model for 3 layer stacked cell.





S_{11} and S_{21} magnitude[dB] II S_{21} phase[deg] – 3layers unit cell spaced 1mm.

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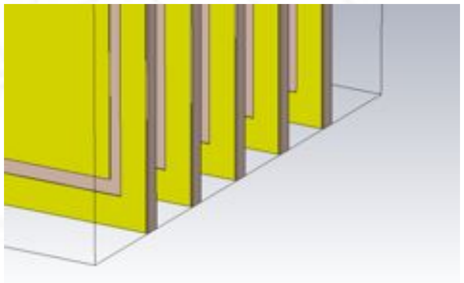
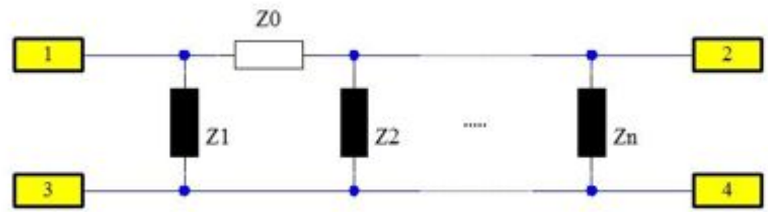
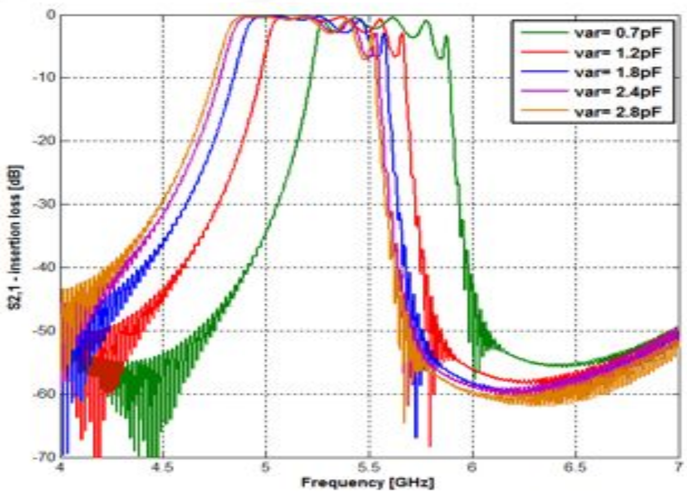
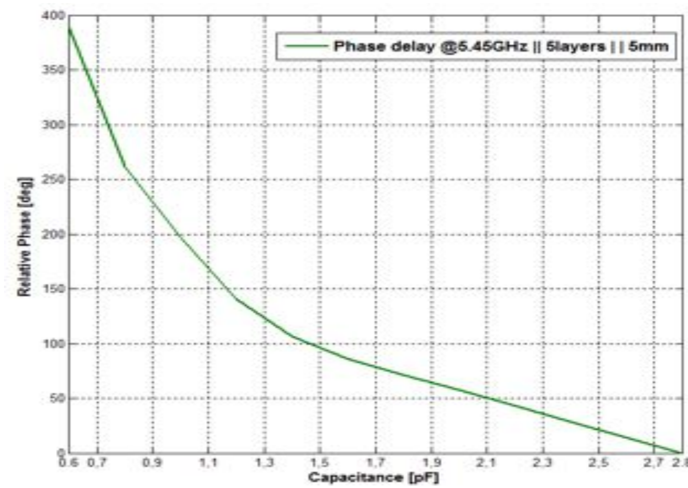
Transmitarray elements









S_{21} insertion loss[dB] II S_{21} phase[deg] for best case scenario: 5 layers unit cell spaced 5mm. Capacitance varying from 0.7 to 2.8pF. f_0 = 5.45GHz; BW~250MHz.

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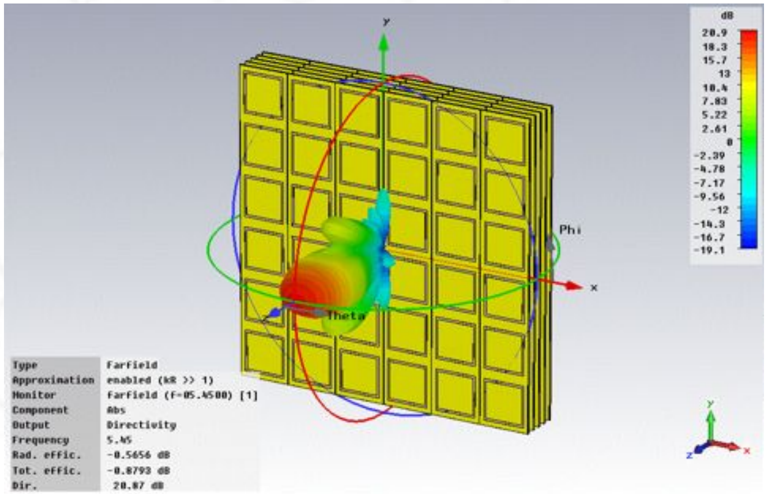
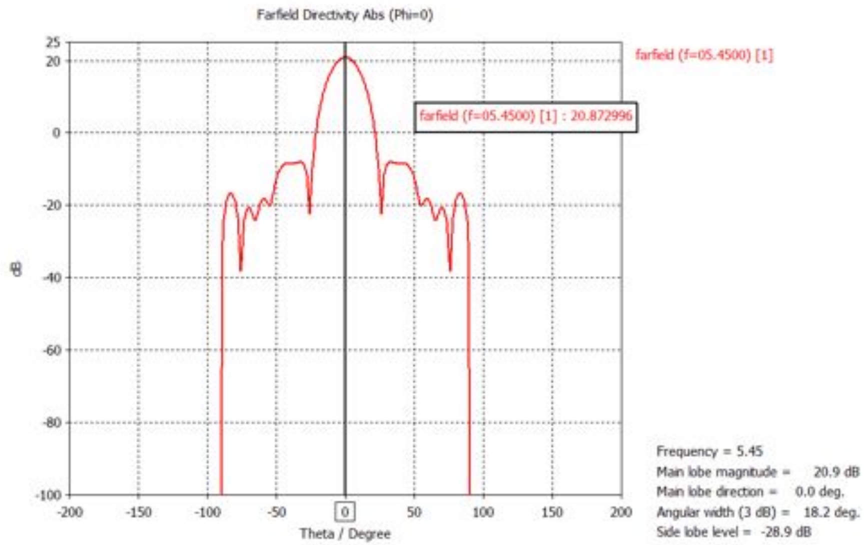
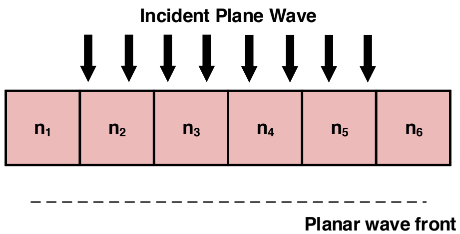
Beam steering with a MM transmitarray







Refractive index distribution

Scan angle – 0 deg.

TEM incident plane wave with Gaussian signal excitation

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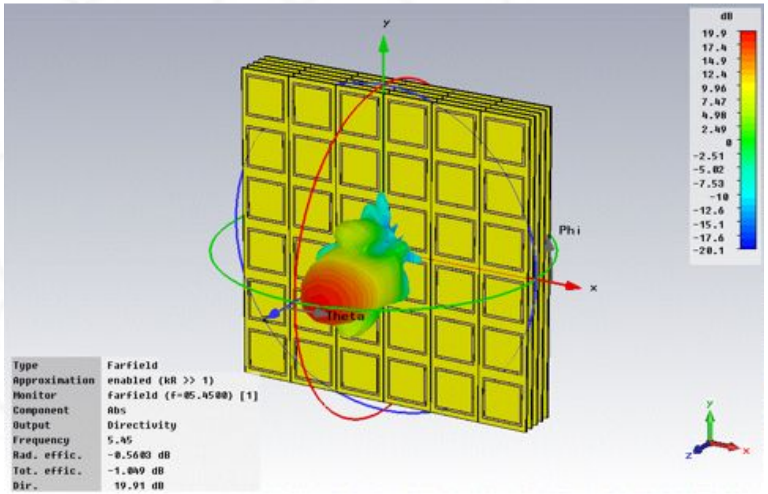
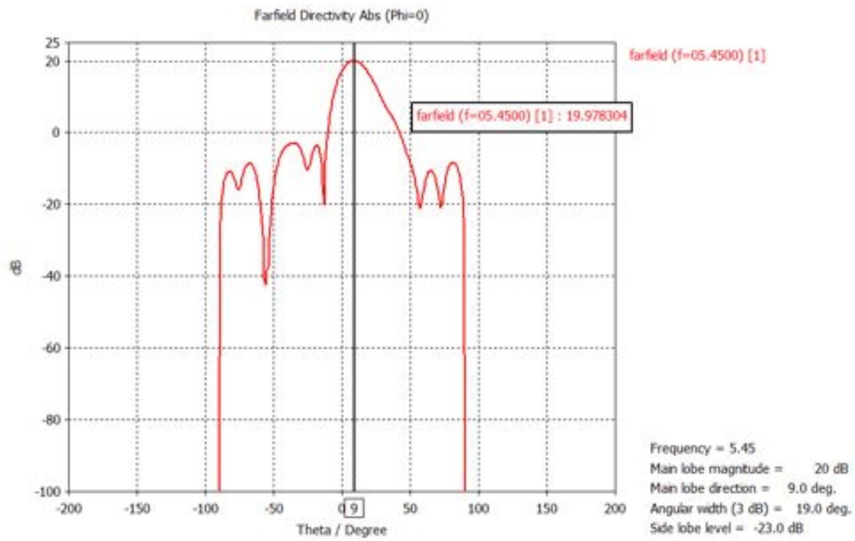
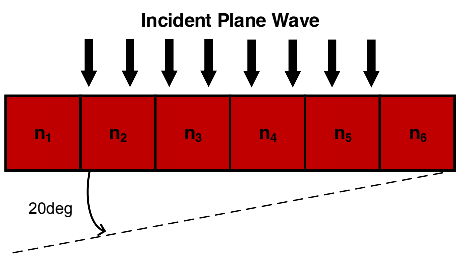
Beam steering with a MM transmitarray







Refractive index distribution

Scan angle – 10 deg.

TEM incident plane wave with Gaussian signal excitation

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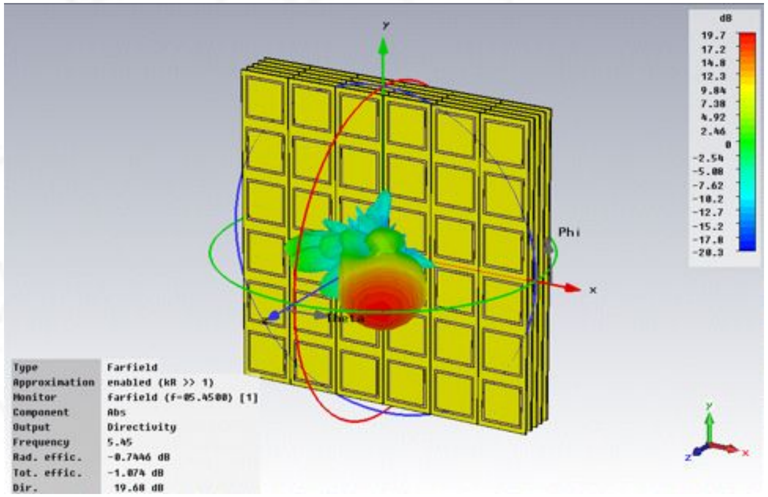
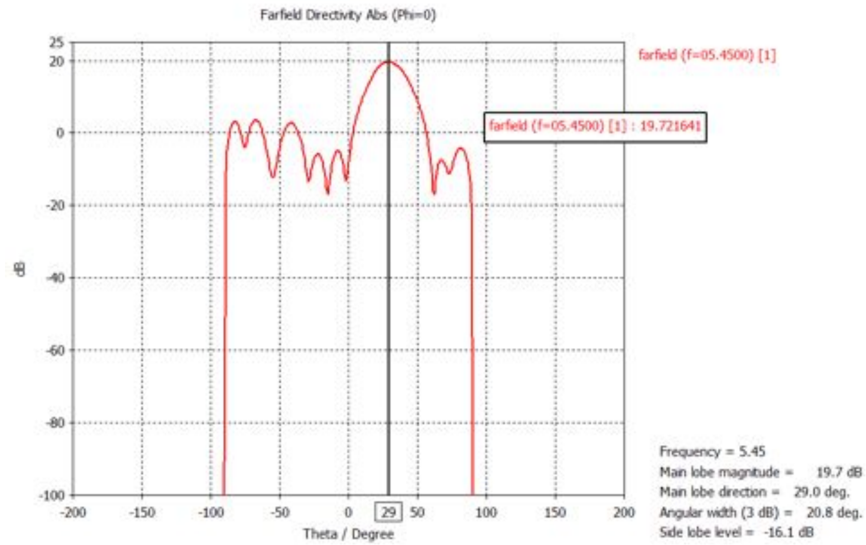
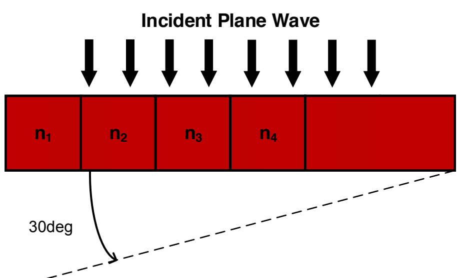
Beam steering with a MM transmitarray







Refractive index distribution

Scan angle – 30 deg.

TEM incident plane wave with Gaussian signal excitation

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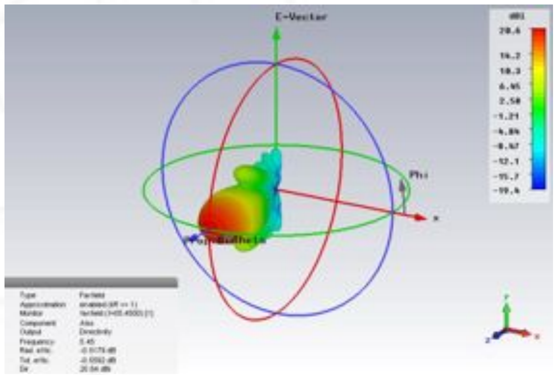
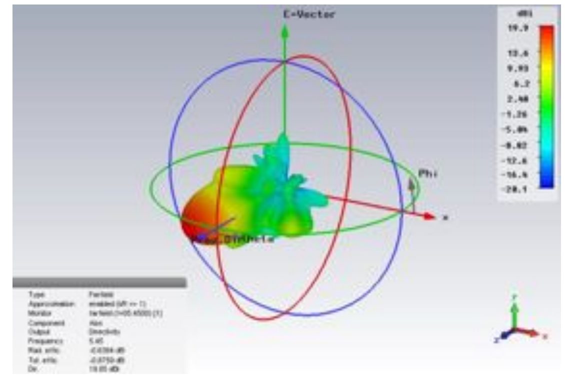
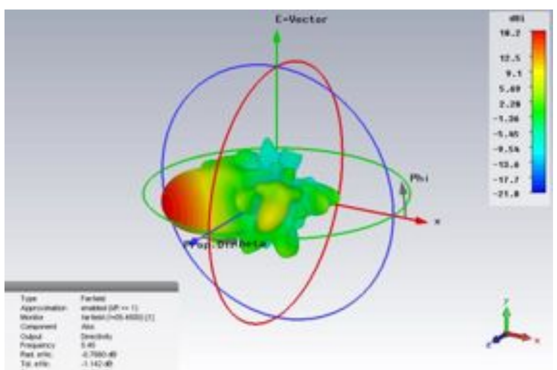
Beam steering with a MM transmitarray



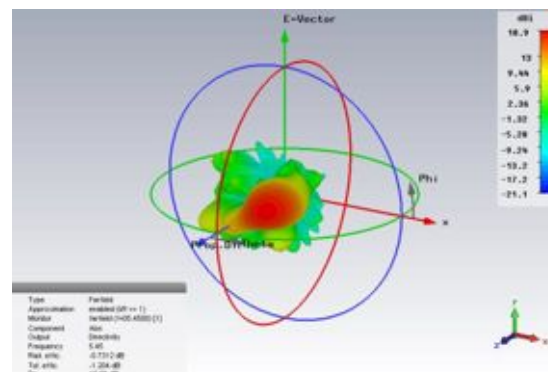
THE:0deg and PHI:0deg.



THE:20deg and PHI:195deg.



THE:30deg and PHI:170deg.



THE:30deg and PHI:30deg.

al excitation

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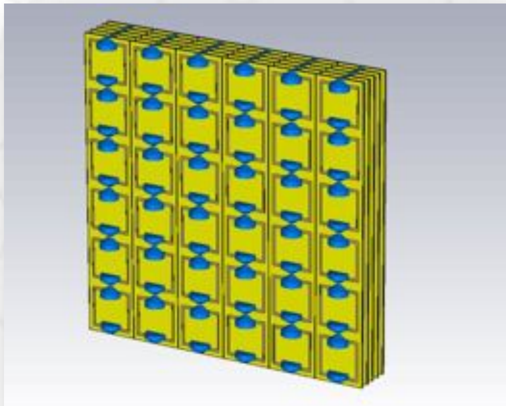
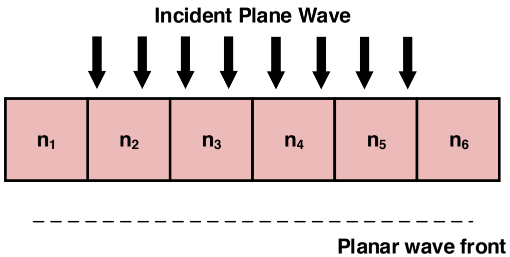
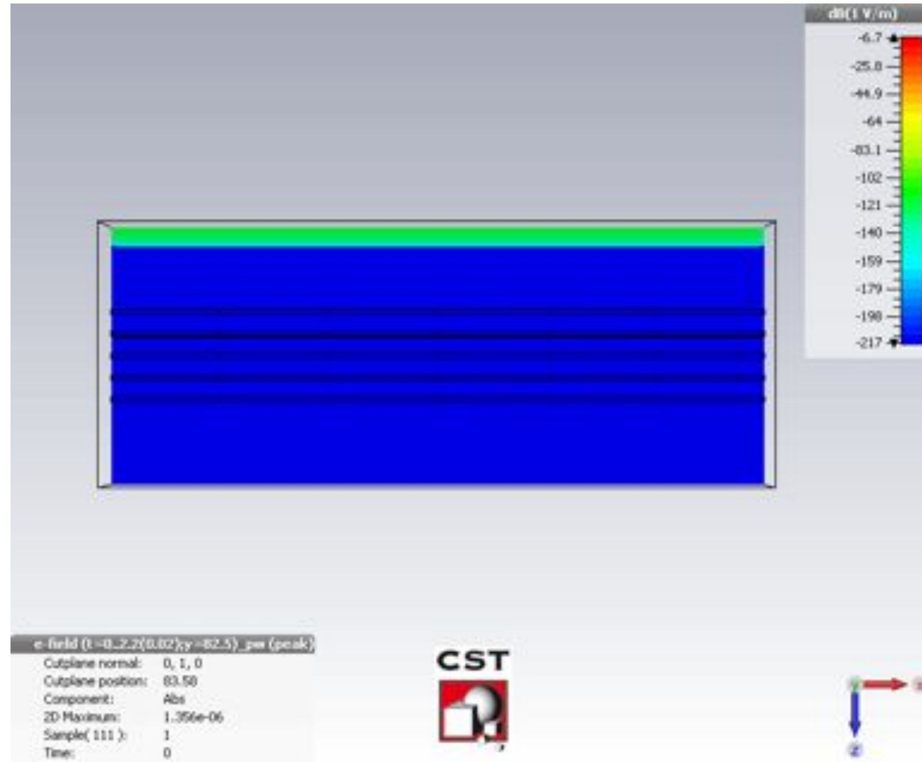
Metamaterial active transmitarray – simulation results



TEM incident plane wave with Gaussian signal excitation.



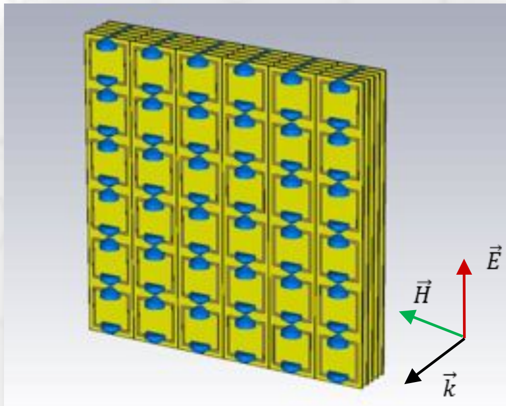
Metamaterial slab Top view.



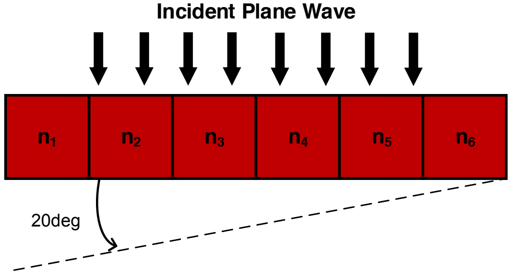
Top view of the propagation of the electric field through a grandient metamaterial slab.

Metamaterial active transmitarray – simulation results

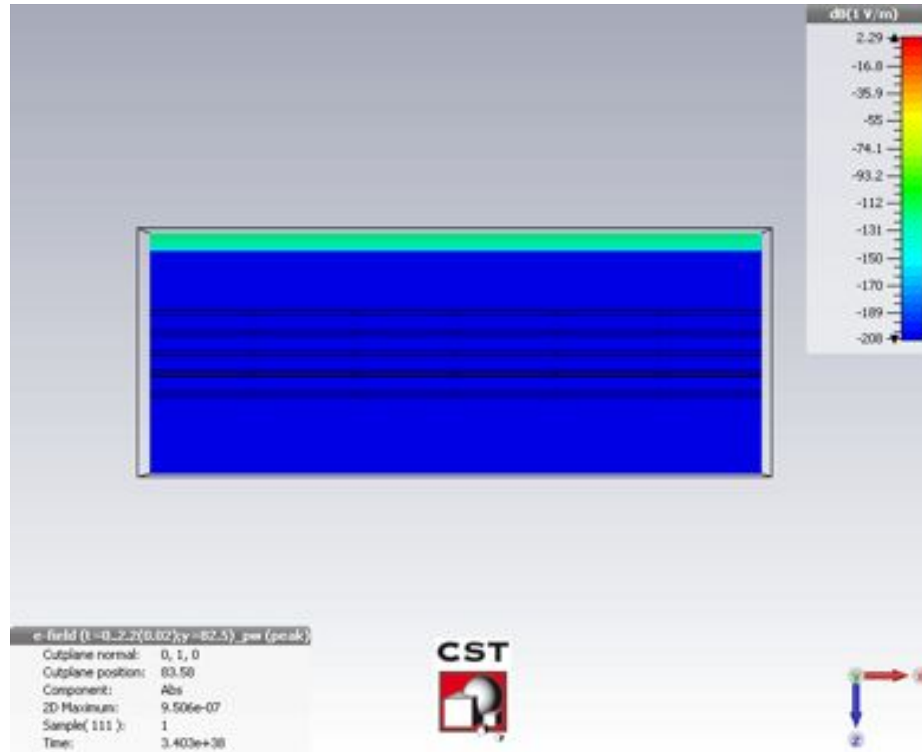
Beam steering – 20 deg.



TEM incident plane wave with Gaussian signal excitation.



Metamaterial slab Top view.



Top view of the propagation of the electric field through a grandient metamaterial slab.

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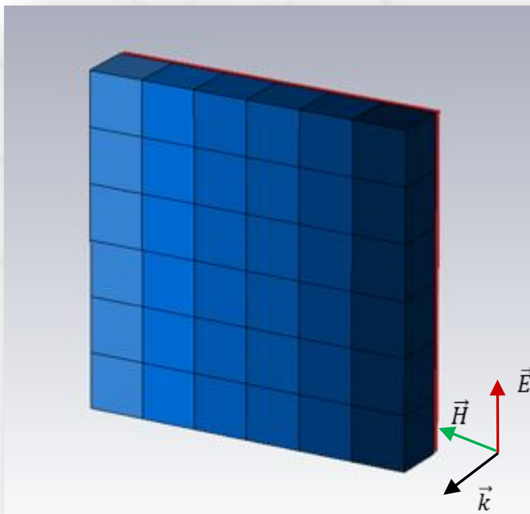
Metamaterial active transmitarray – simulation results

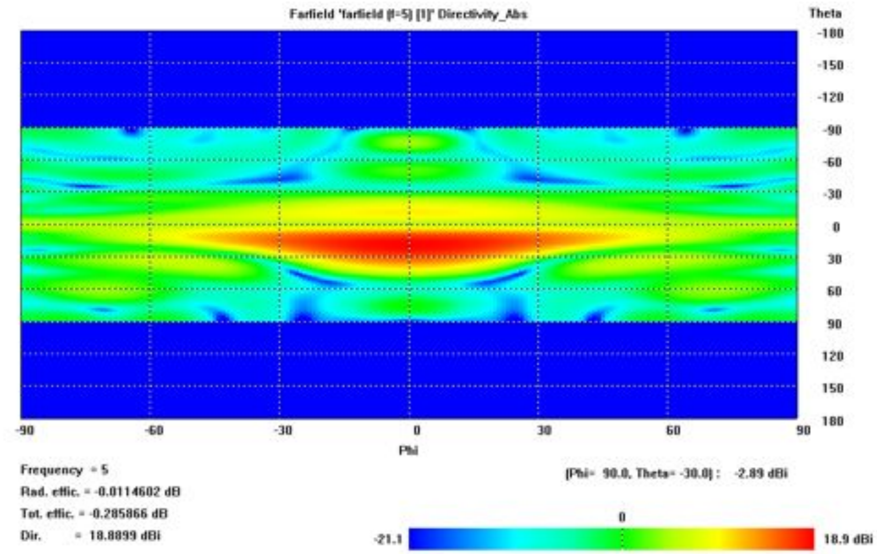
Beam steering – 20 deg.

Gradient refractive index MM

Proof-of-concept : 20deg in theta direction



Slab composed by 6x6 cubes of dielectric material whose permittivity is distributed in a gradient manner. Excited by an TEM incident plane wave.



2D radiation pattern – Maximum directivity[dB] for Theta=10º and Phi=0º @5GHz

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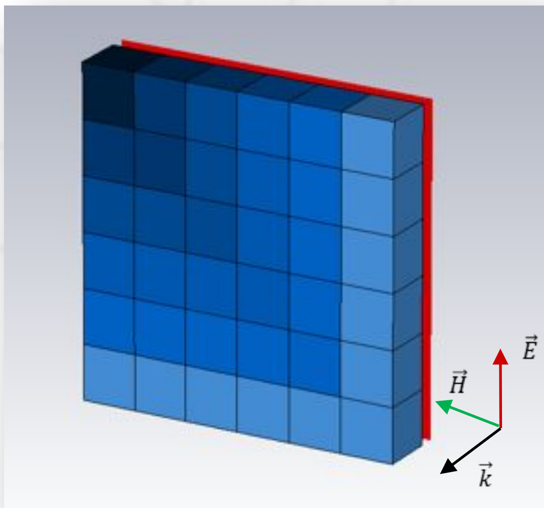
Metamaterial active transmitarray – simulation results

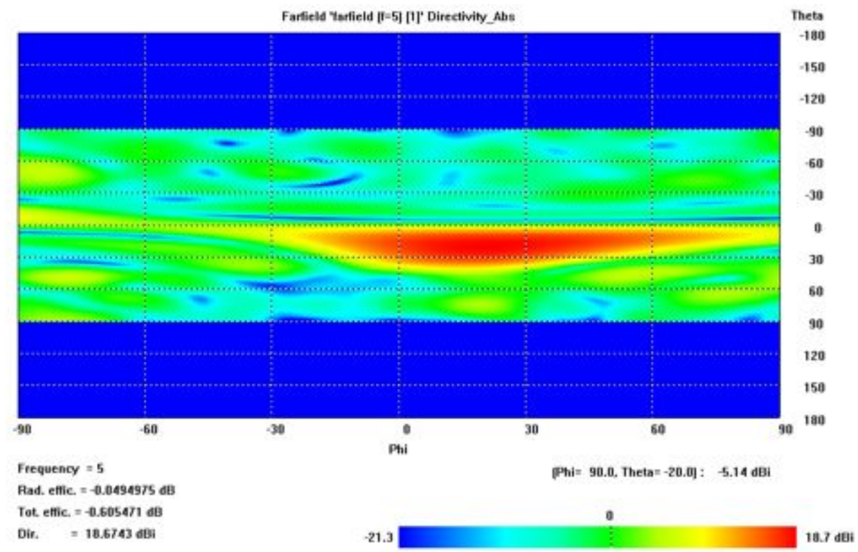
Beam steering – 20 deg.

Gradient refractive index MM

Proof-of-concept : 20deg in theta and Phi direction



Slab composed by 6x6 cubes of dielectric material whose permittivity is distributed in a gradient manner. Excited by an TEM incident plane wave.



2D radiation pattern – Maximum directivity[dB] for Theta=20º and Phi=20º @5GHz

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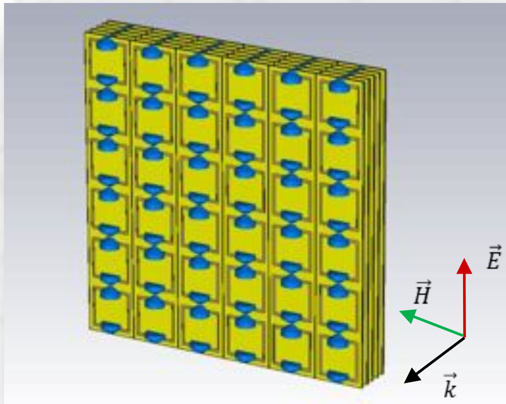
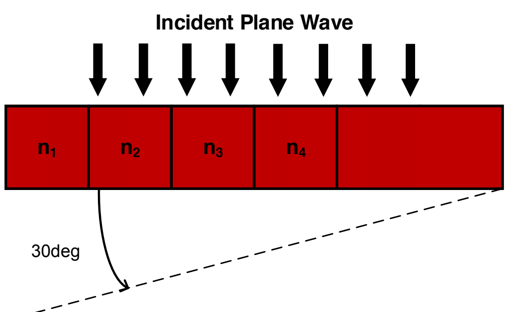
Metamaterial active transmitarray – simulation results

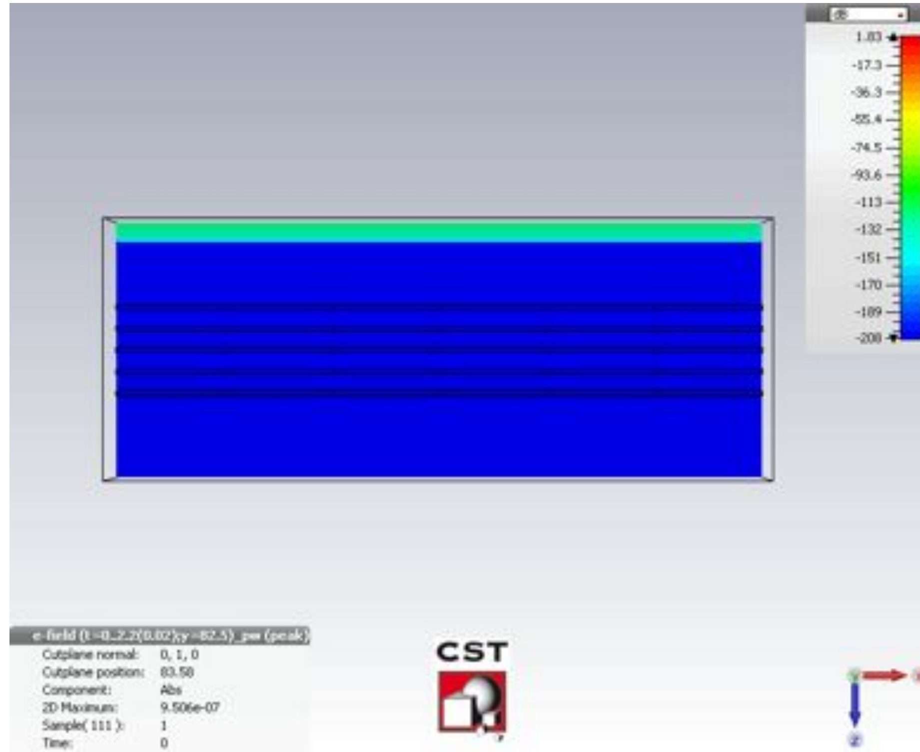
Beam steering – 30 deg.



TEM incident plane wave with Gaussian signal excitation.



Metamaterial slab Top view.



Top view of the propagation of the electric field through a grandient metamaterial slab.

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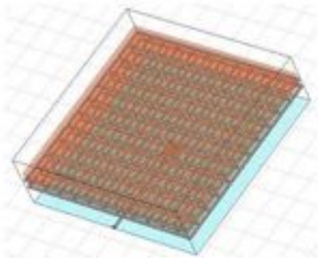
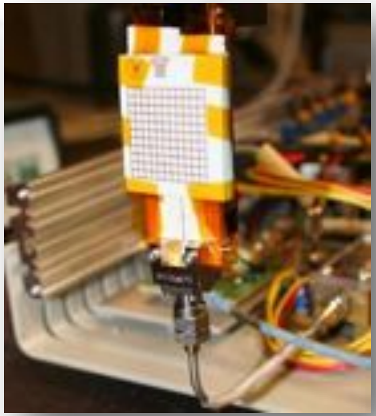
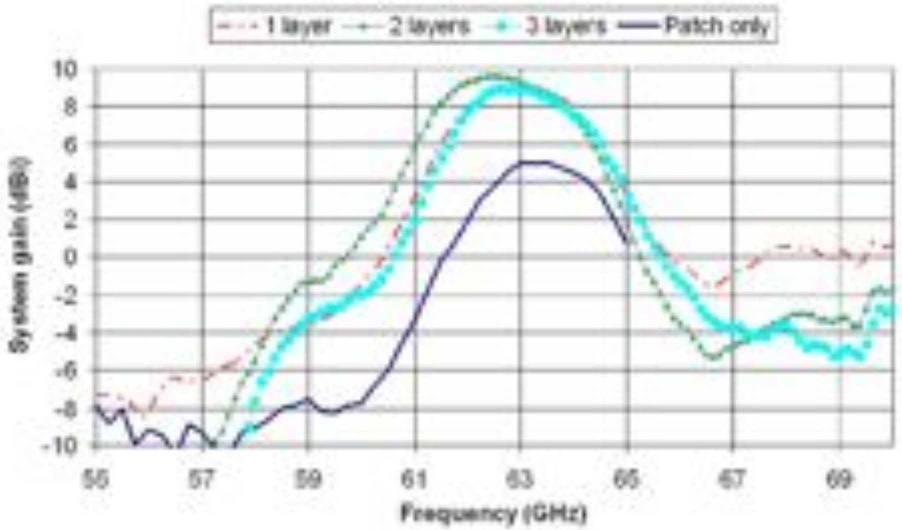
Beam steering with a MM transmitarray

- Gain enhancement with MM at 60GHz







- Metamaterial structure used as supertrate;
- Substrate (foam) adapted to air.
- Structure with near-zero refractive index;

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Steven J Franson, "Gigabit per Second data Transfer in High-Gain Metamaterial Structures at 60GHz". IEEE Transactions on Antennas, Vol.57, October 2009.

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Challenges & Further work

- Challenges
  - *Operation frequency limits vs. cells dimension;*
  - *Phase shift variation depending on discrete elements (varactors/PIN diodes / MEMS);*
  - *Radiation pattern dependent on the millimetre separation between layers;*
  - *Unit cell synthesis and electromagnetic analysis;*
  - *Radome thickness vs. index of refraction;*
  - *Near field effects in radome.*

- Further work
  - *Low cost and low losses prototype realization to prof the concept.*

Agenda

- Presentation of our research group;
- Motivation for today's topics
- Wireless Sensor Networks for Spacecraft
- FSS for space applications:
  - *Frequency selectivity and site shielding*
  - *Antenna beam steering*
- **Ambient RF Energy Harvesting**
- Hybrid FSS and rectenna design
- Conclusions

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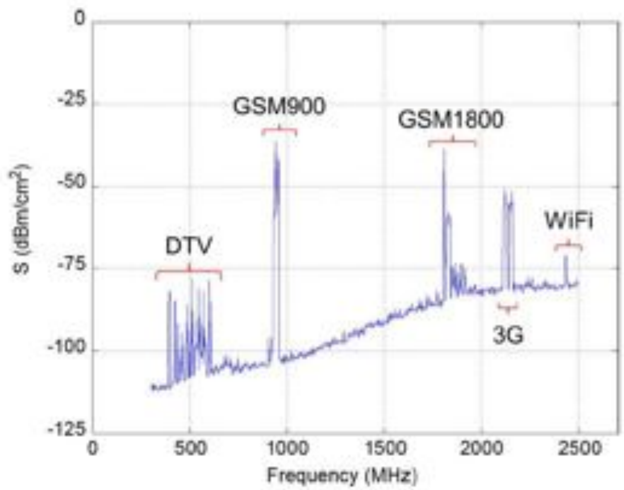
Ambient RF Energy

- Input RF power density measurements in an urban environment…



SUMMARY OF LONDON RF SURVEY MEASUREMENTS

Band	Frequencies (MHz)	Average S_{BA} (nW/cm²)	Maximum S_{BA} (nW/cm²)
DTV (during switch over)	470-610	0.89	460
GSM900 (MTx)	880-915	0.45	39
GSM900 (BTx)	925-960	36	1,930
GSM1800 (MTx)	1710-1785	0.5	20
GSM1800 (BTx)	1805-1880	84	6,390
3G (MTx)	1920-1980	0.46	66
3G (BTx)	2110-2170	12	240
WiFi	2400-2500	0.18	6

[Source: Piñuela *et al* , "Ambient RF Energy Harvesting in Urban and Semi-Ûrban Environments", IEEE Trans. Micro. Theory and Techn., Vol. 61, No.7, July 2013]

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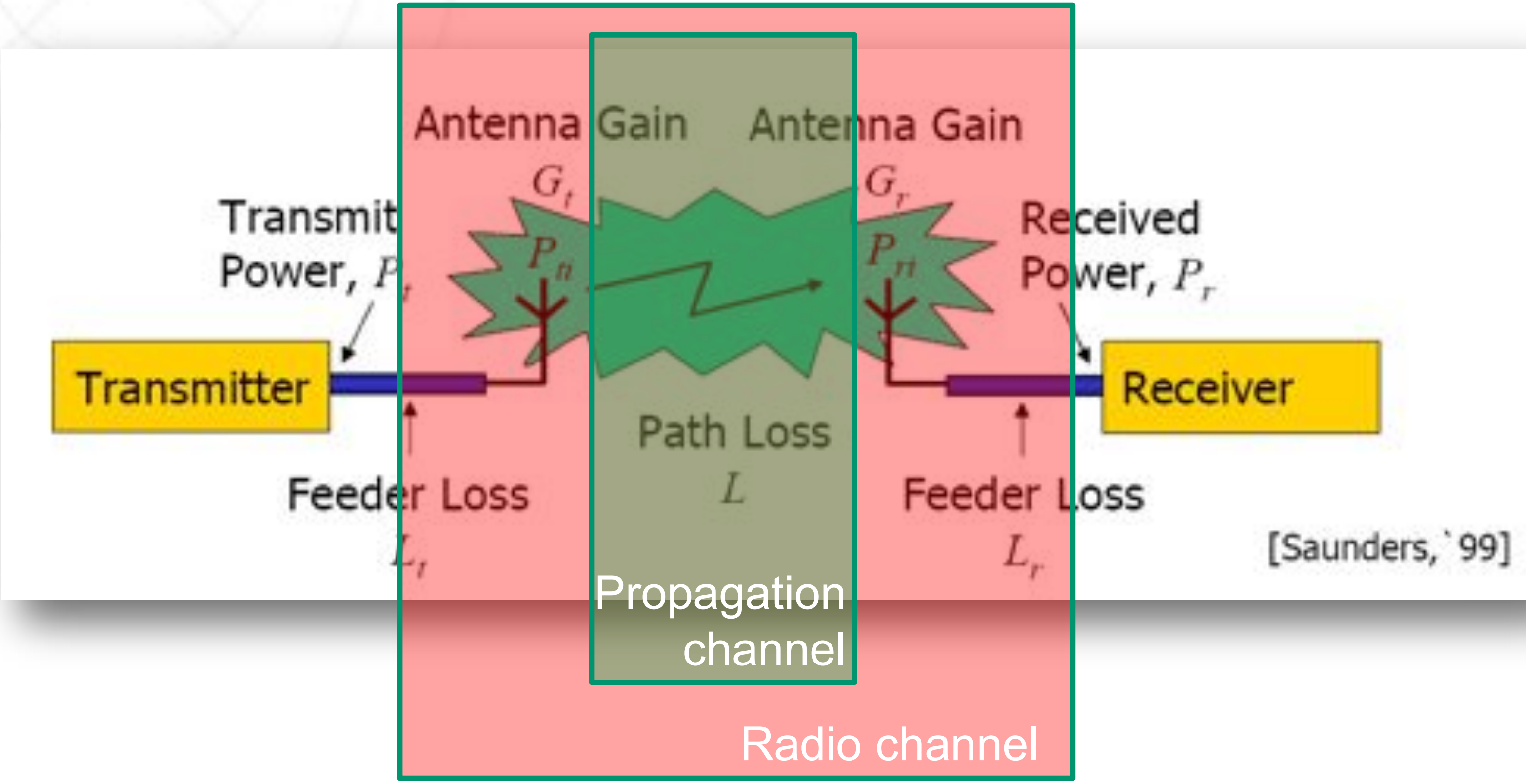
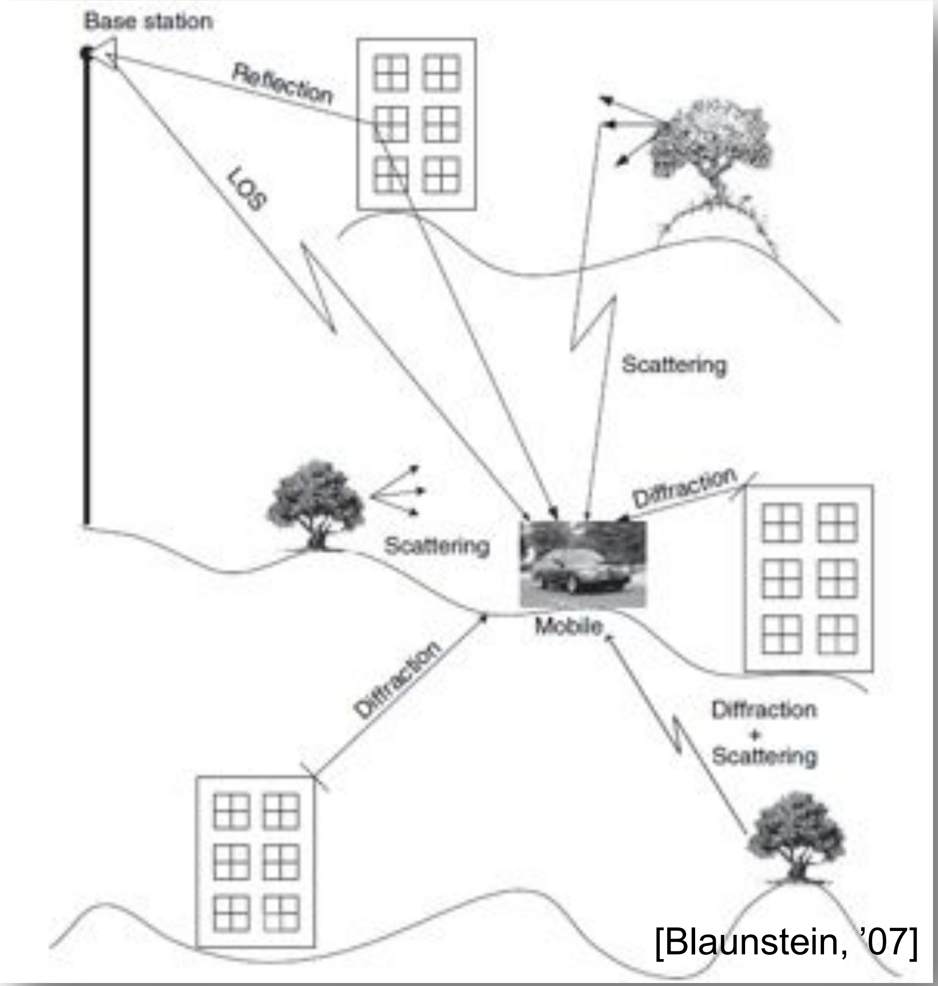
Modelling of the radio propagation channel

- Definition of Path Loss:



Modelling of the radio propagation channel

- Multipath effects:



[Blaunstein, '07]

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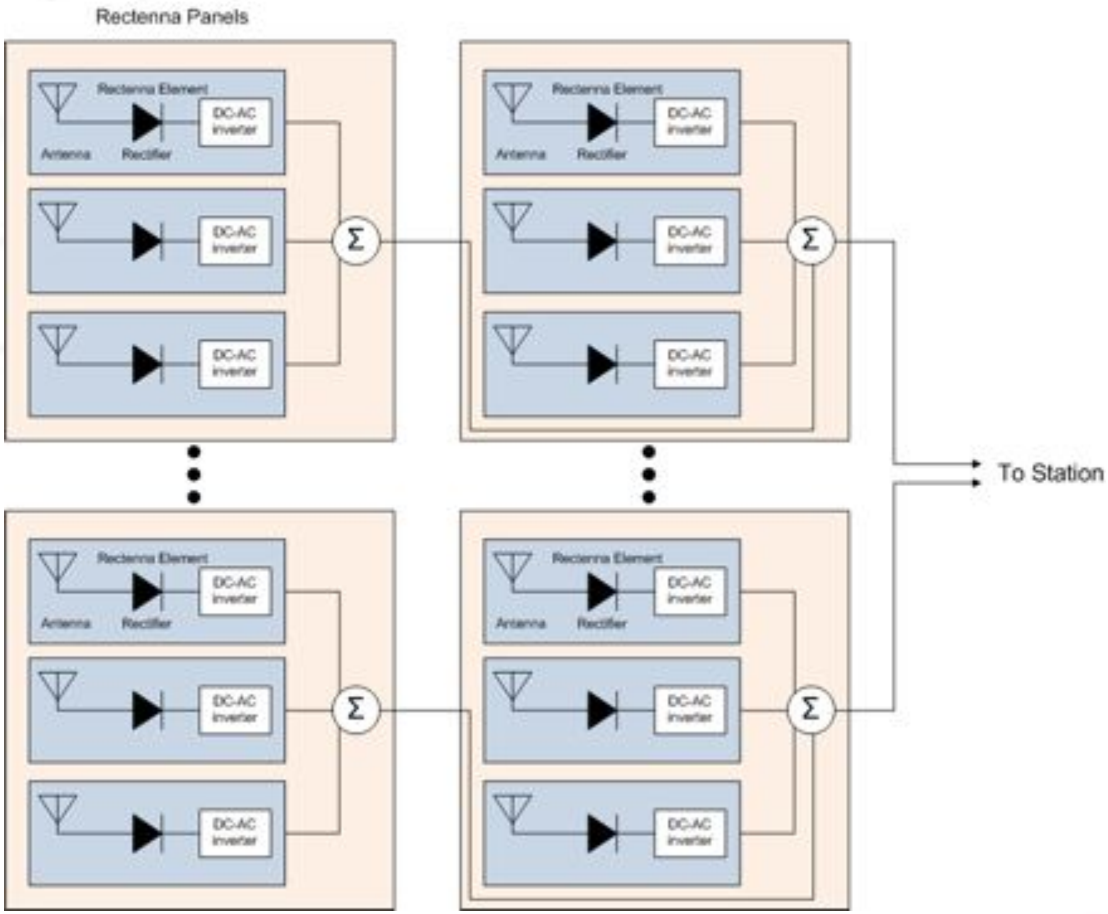
Analogy to solar panels…

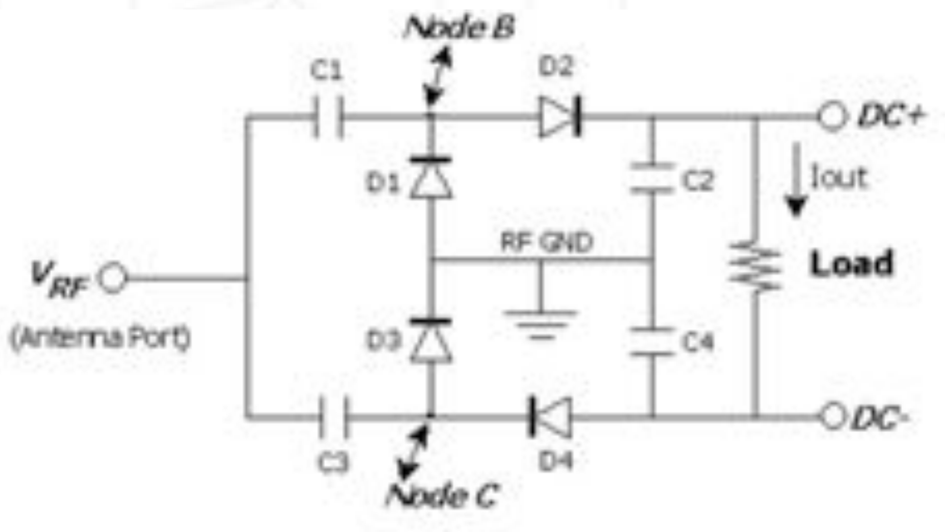
- On flat surfaces…

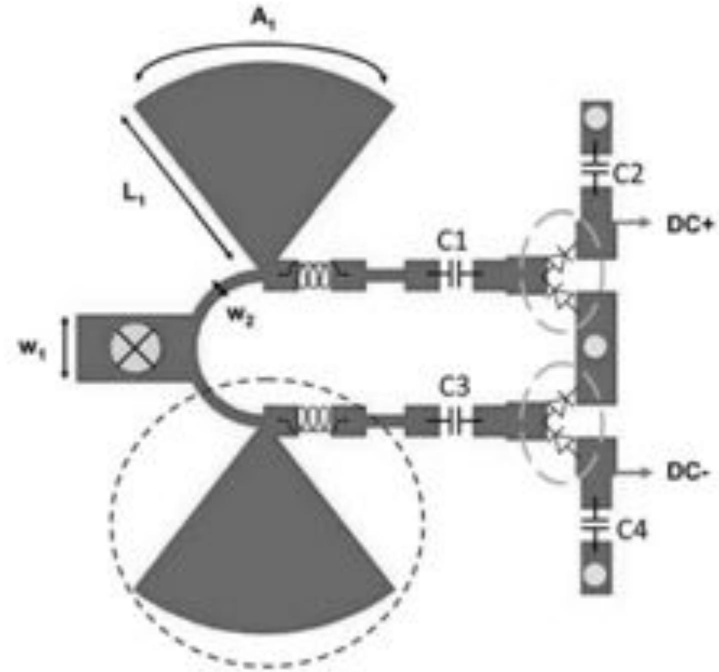


[Source: http://www.propagation.gatech.edu]

Rectifier element design

- A single-stage full-wave Greinacher rectifier [Curty *et al*, 2000]





-----: Matching network, ——: Zero-bias diodes,
●: Shorting vias, ▒: Antenna excitation

$w_1 = 1.83$ mm, $w_2 = 0.30$ mm, $L_1 = 5.72$ mm, and $A_1 = 75°$. Diodes: SMS7630, Capacitors: 100 nF

U. Olgun C.-C. Chen J.L. Volakis, ´Design of an efficient ambient WiFi energy harvesting system, IET Microwave Antennas Propagation, 2012, Vol. 6, Iss 11, pp 1200-1206

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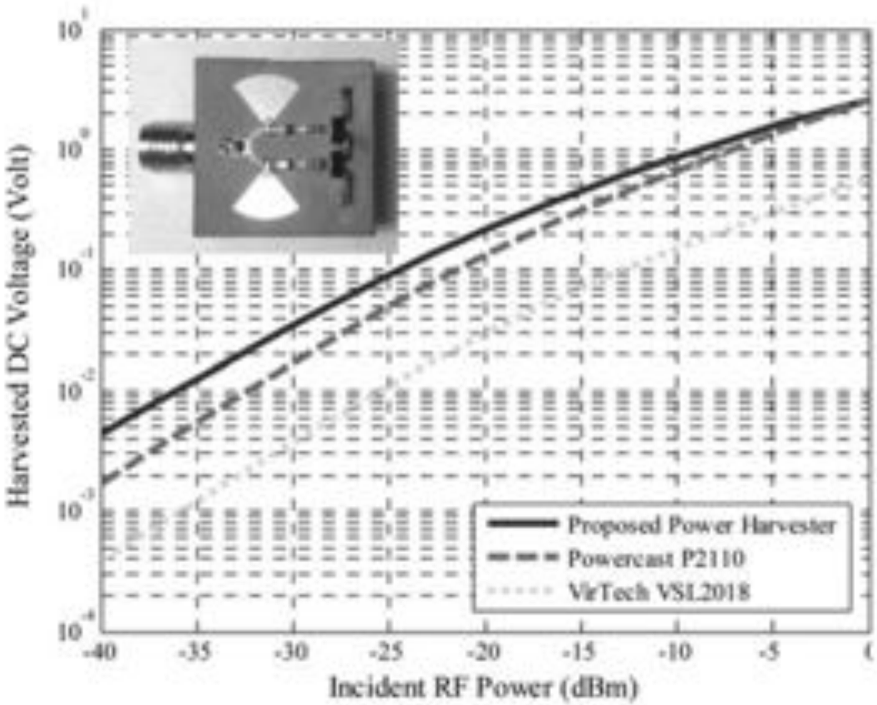
Rectifier element design

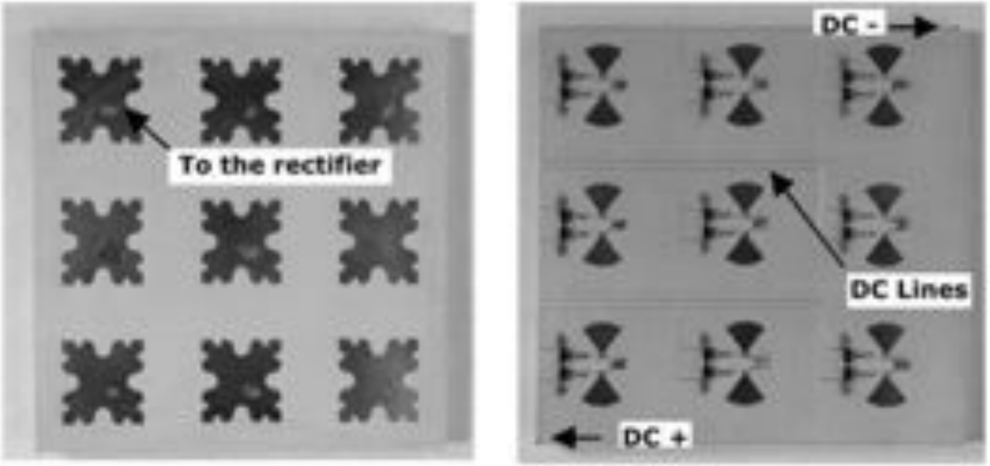
- A single-stage full-wave Greinacher rectifier [Olgun, 2012]



U. Olgun C.-C. Chen J.L. Volakis, ´Design of an efficient ambient WiFi energy harvesting system, IET Microwave Antennas Propagation, 2012, Vol. 6, Iss 11, pp 1200-1206

Rectenna design

- RF power harvester



	Minimum	Typical	Maximum
Output voltage [V]	1.764	1.8	1.836
Output current	0	10 μA	Ambient: 50 μA; dedicated: 780 μA
RF power sensitivity [dBm]	-40	-30	0

U. Olgun C.-C. Chen J.L. Volakis, ´Design of an efficient ambient WiFi energy harvesting system, IET Microwave Antennas Propagation, 2012, Vol. 6, Iss 11, pp 1200-1206

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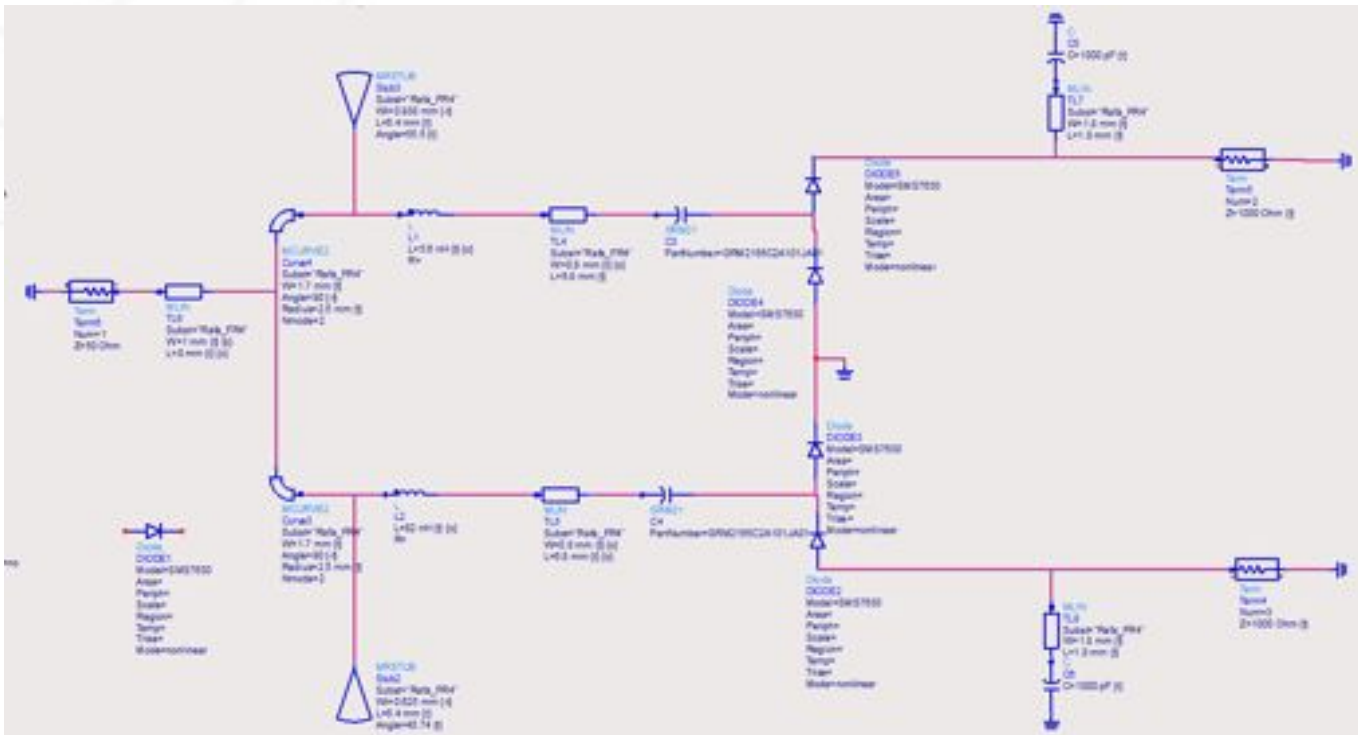
Implementation at 2.4 GHz

- Implementation of a single-stage full-wave Greinacher rectifier [adapted from Olgun *et al*, 2012]
- Rectenna = Antenna + Rectifier (RF to DC);



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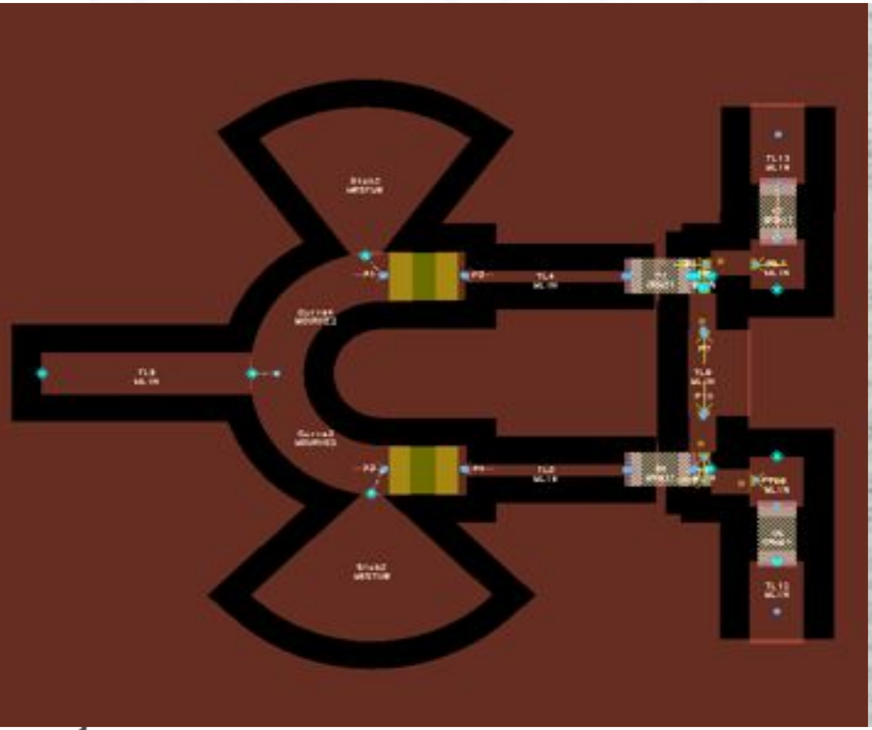
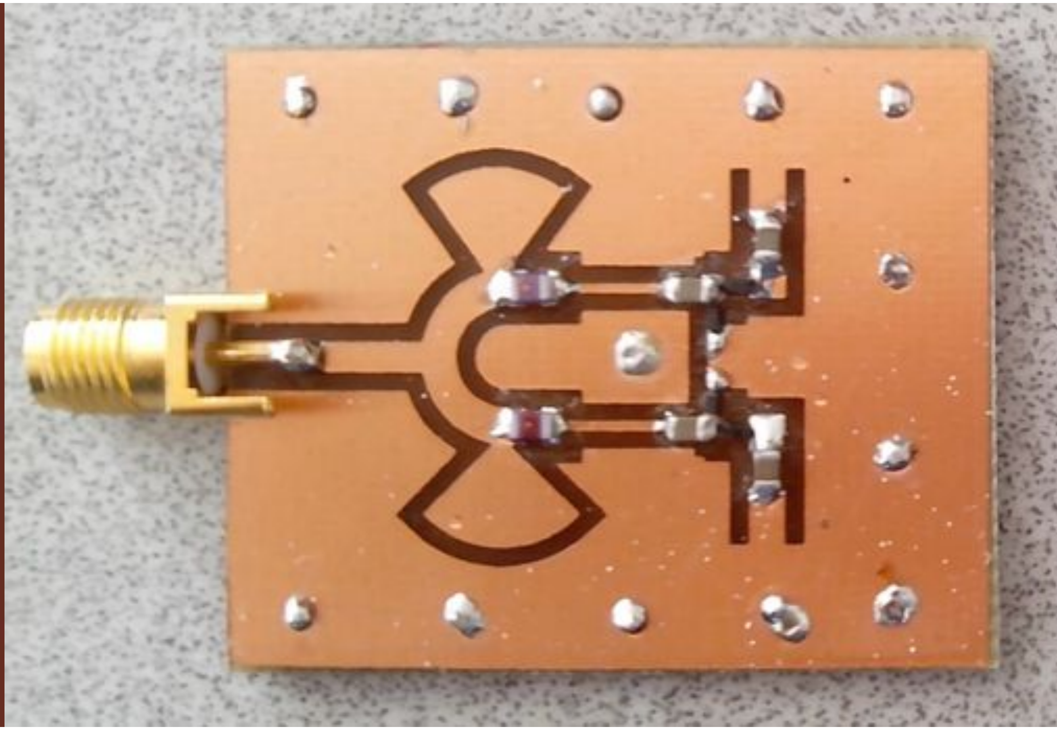
Implementation at 2.4 GHz

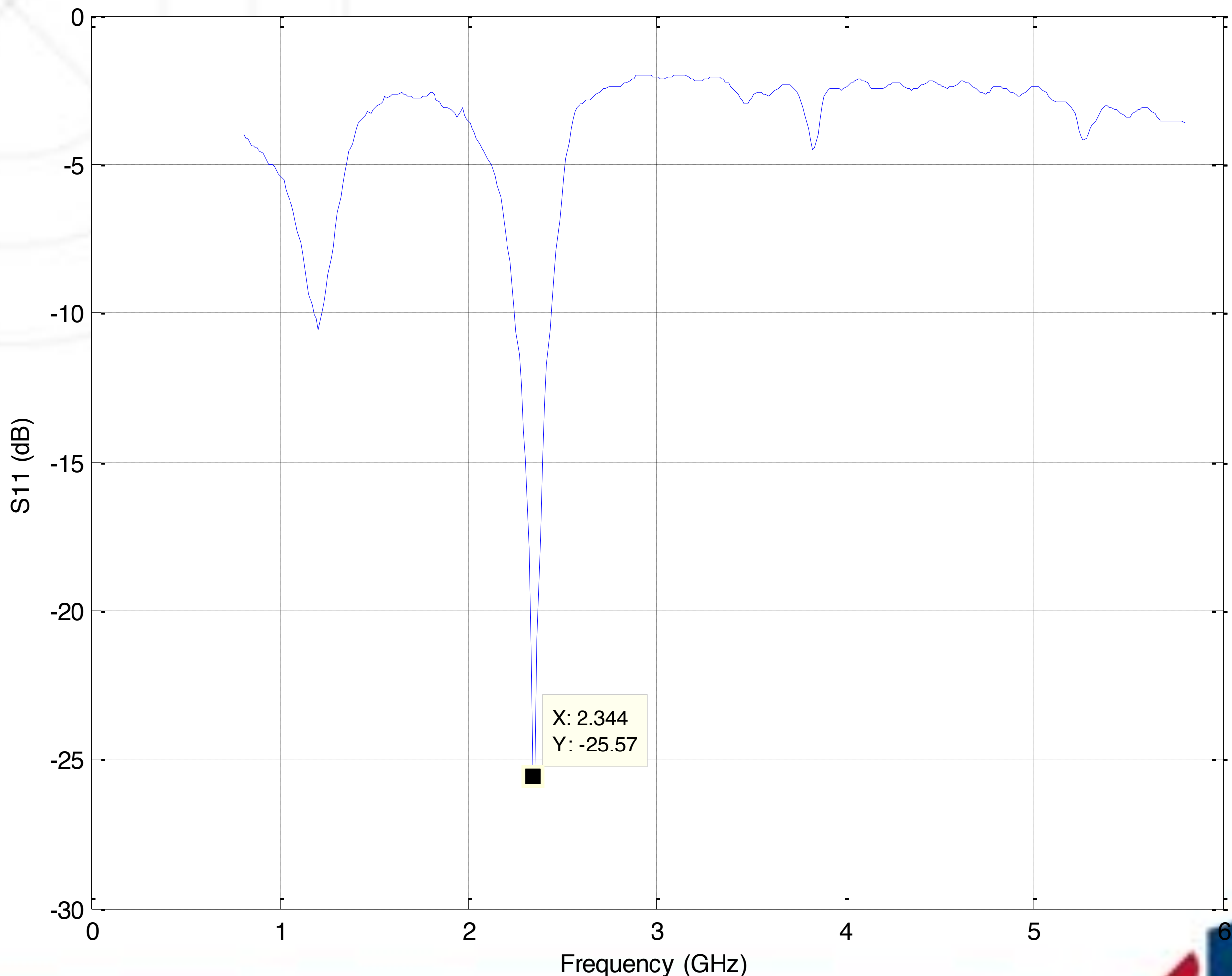
- Rectenna = Antenna + Rectifier (RF to DC);





Implementation at 2.4 GHz

- Input matching of a single RF-DC element



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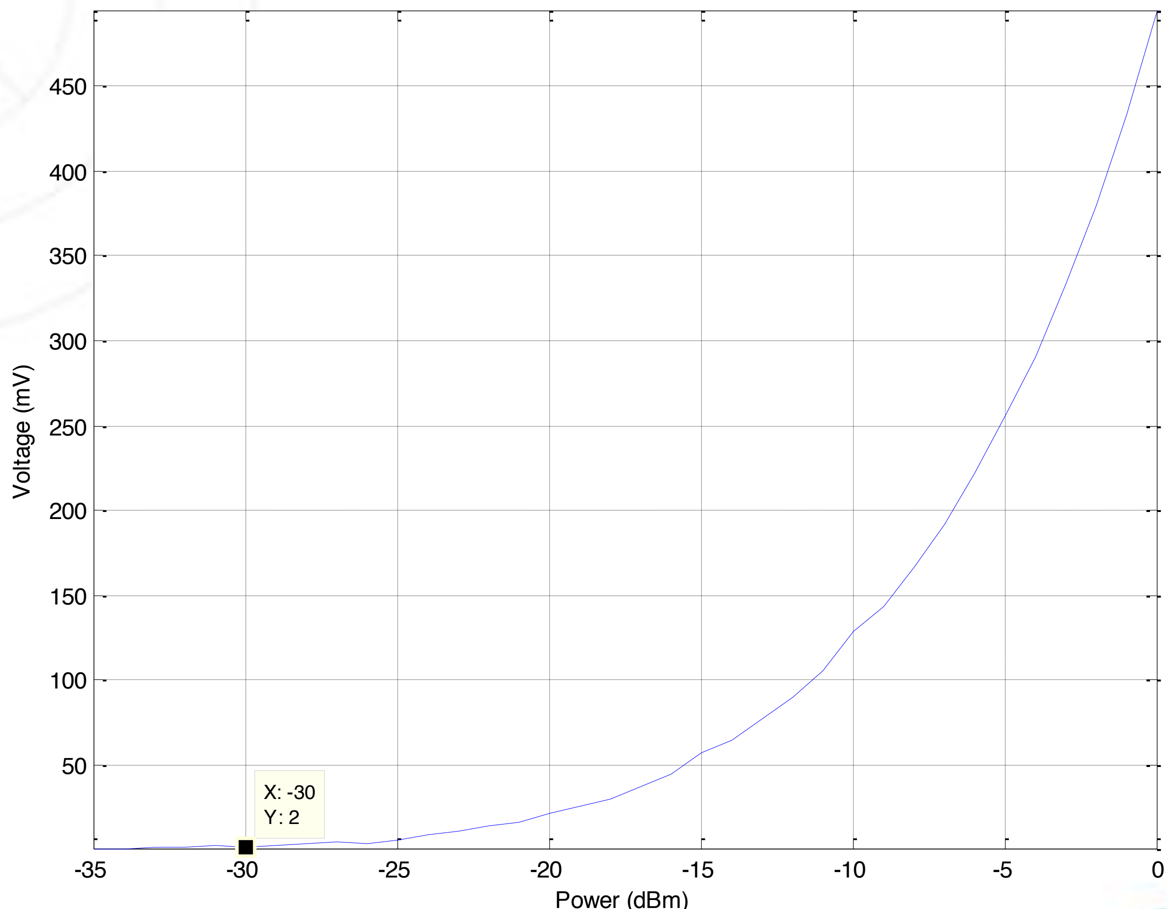
Implementation at 2.4 GHz

- RF-DC response of a single element



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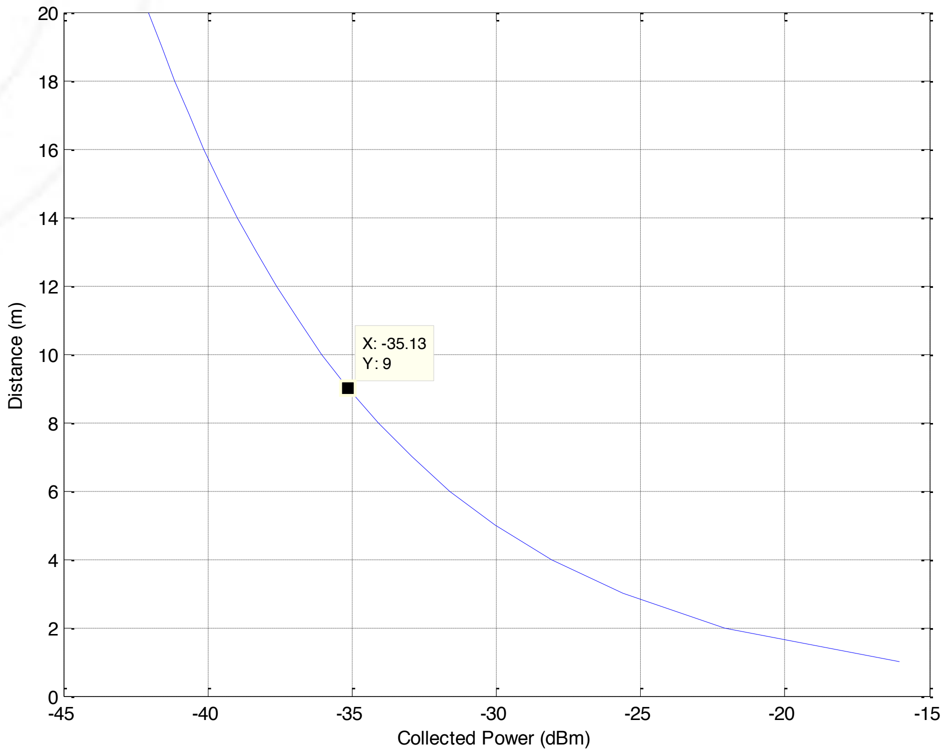
Maximum range for an unit cell

- Link budget, assuming single tone @ 2.4GHz EIRP=20dBm (Wi-Fi), G_rx = 4dBi, FSL



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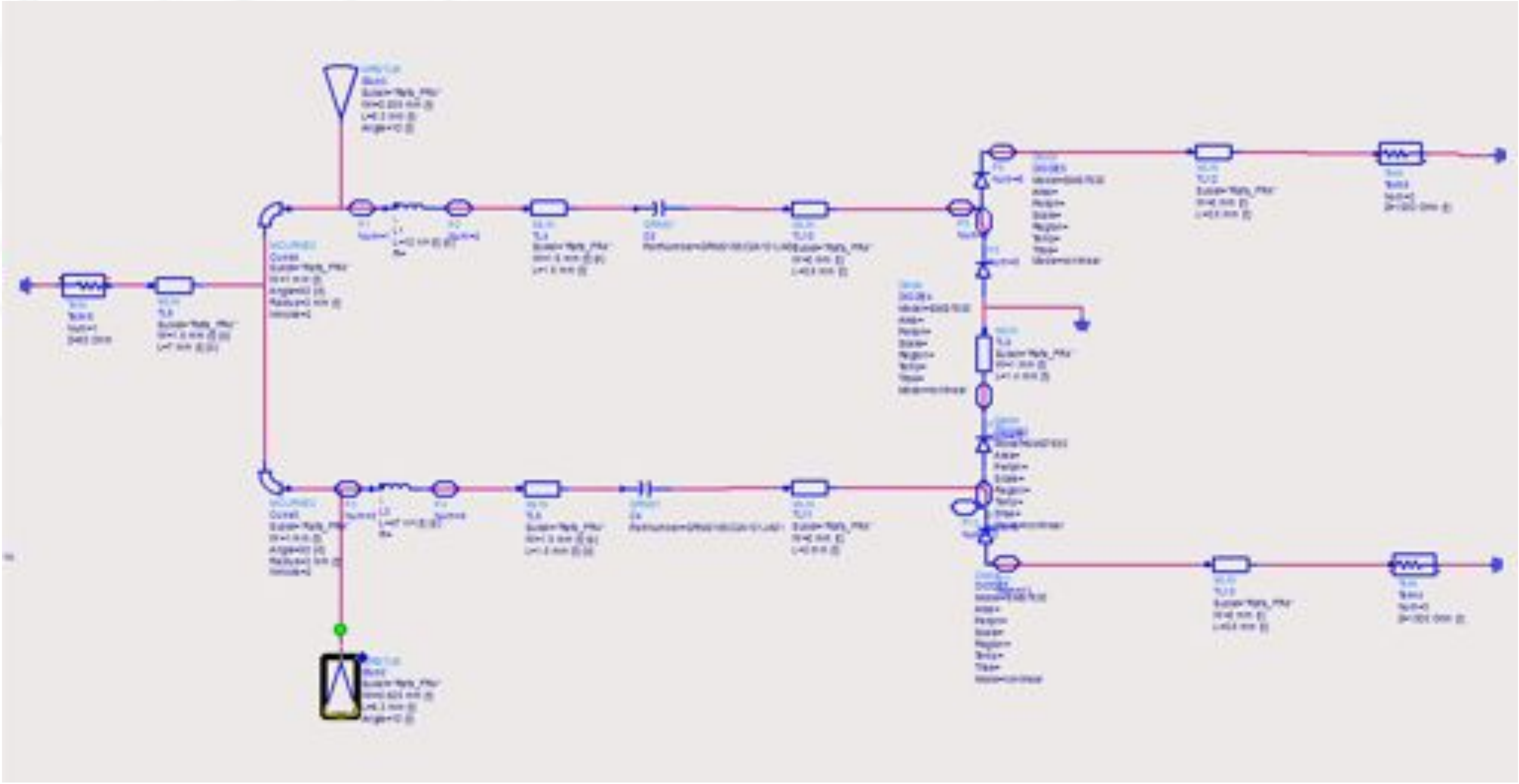
Dual band RF-DC converter



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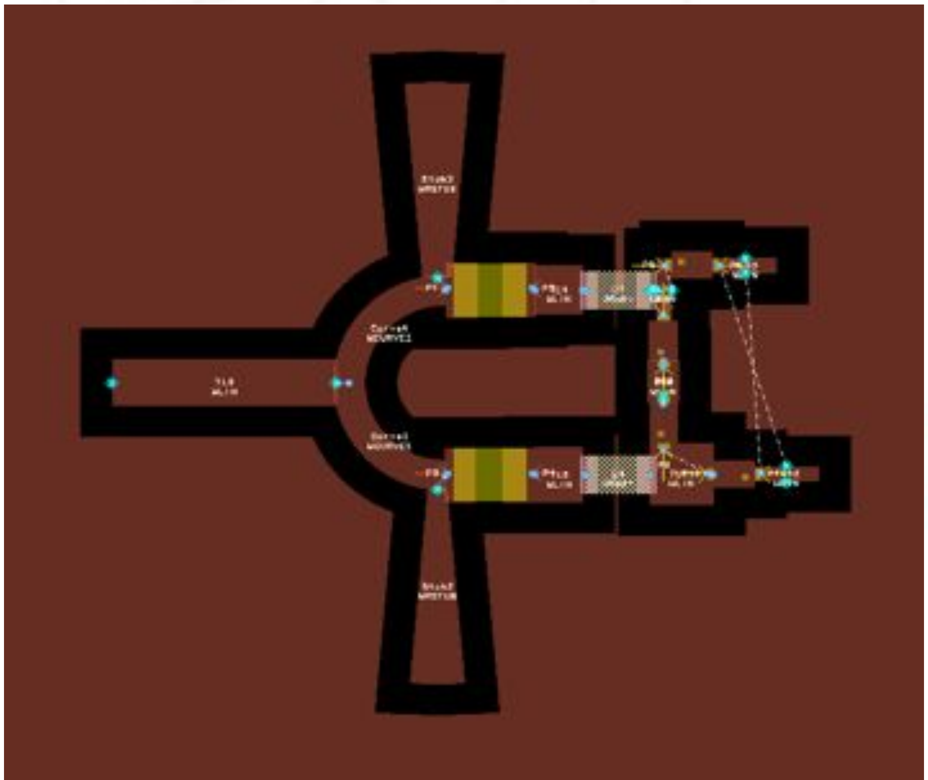
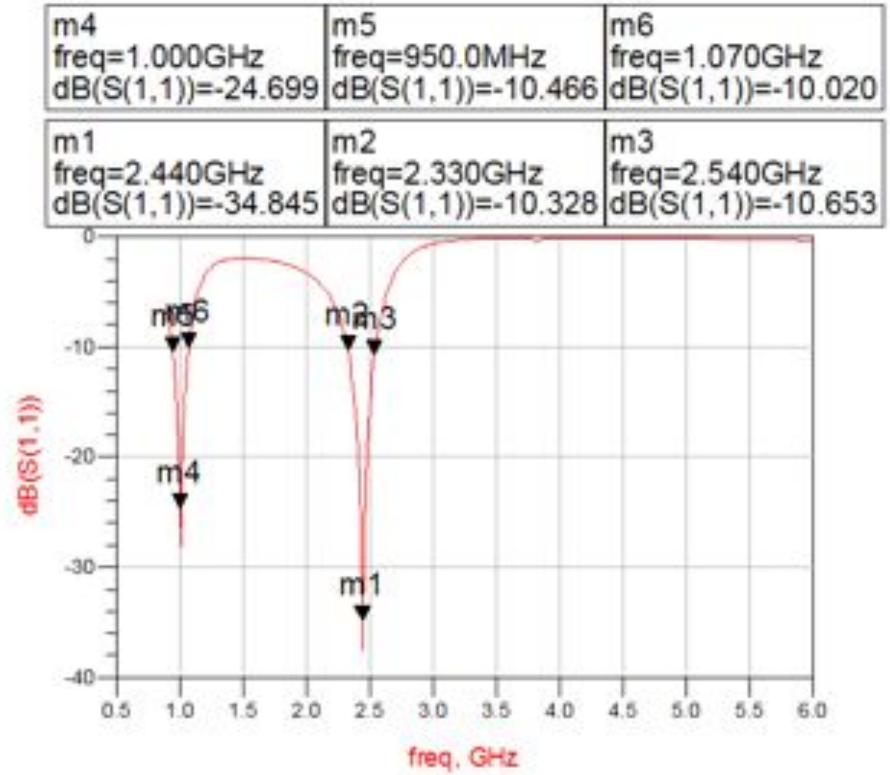
Dual band RF-DC converter





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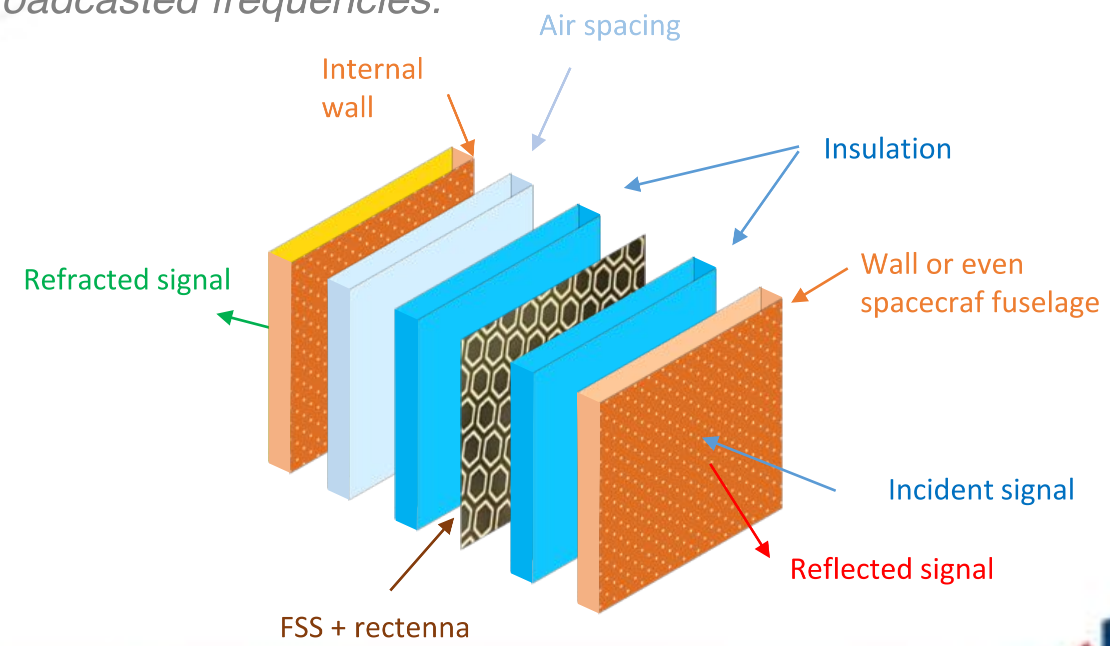
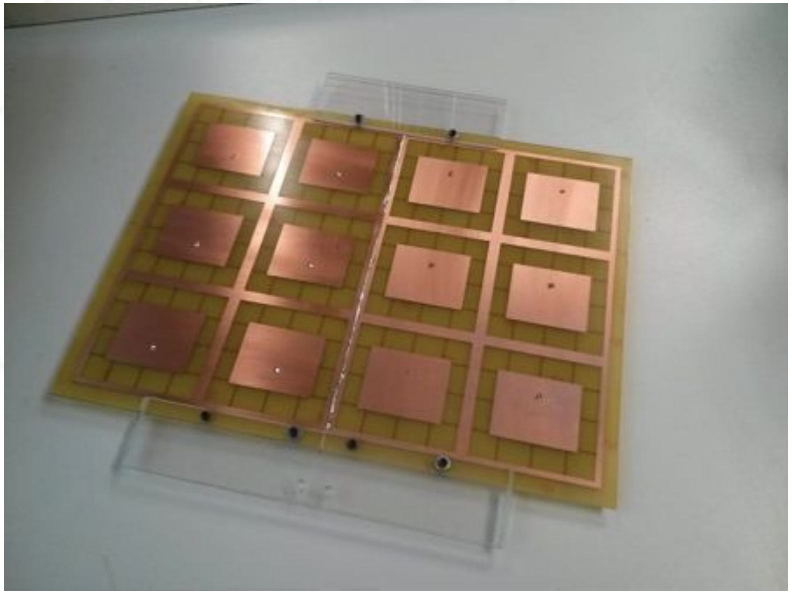
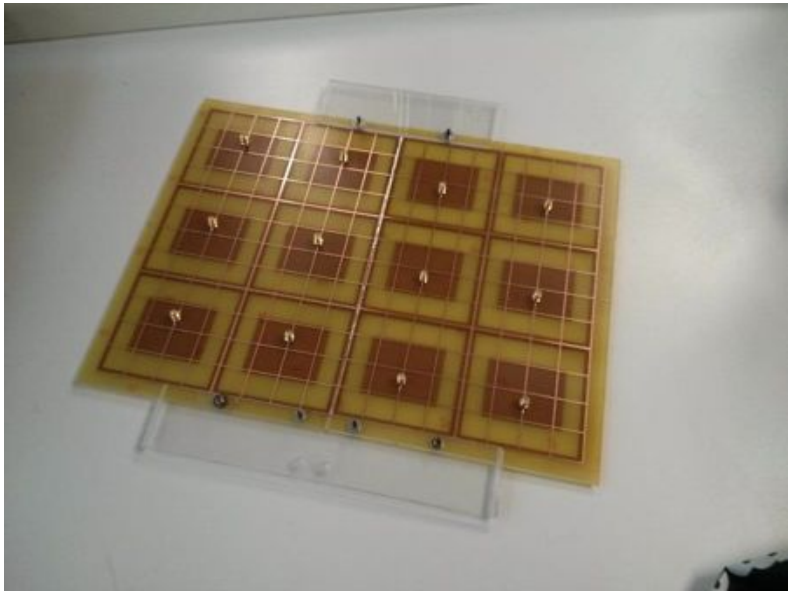
Hybrid FSS + Rectenna

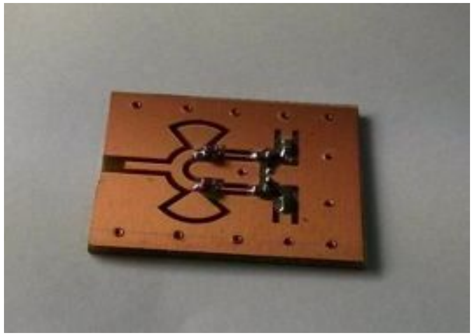
- FSS structure adapted to allow RF energy harvesting;
- Single-band RF energy harvesting:
  - *Reject-band FSS, e.g. harvest Wi-Fi signal energy that one desires to block with the FSS*
- Multi-band simultaneous RF energy harvesting:
  - *Pass-band FSS, e.g. allow Wi-Fi to pass, and harvest all other broadcasted frequencies.*



Hybrid FSS + rectenna prototype







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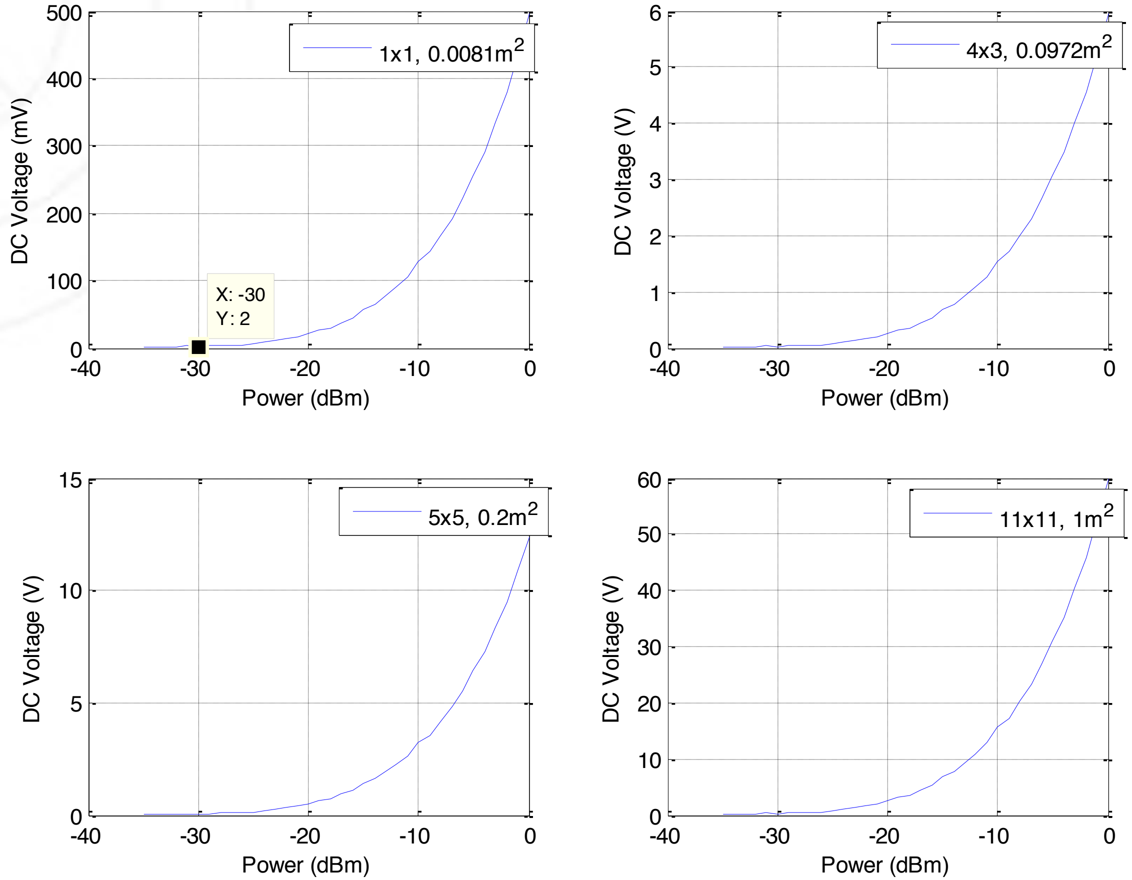
Implementation at 2.4 GHz

- RF-DC response of the array (unit cell: 9cm x 9cm)



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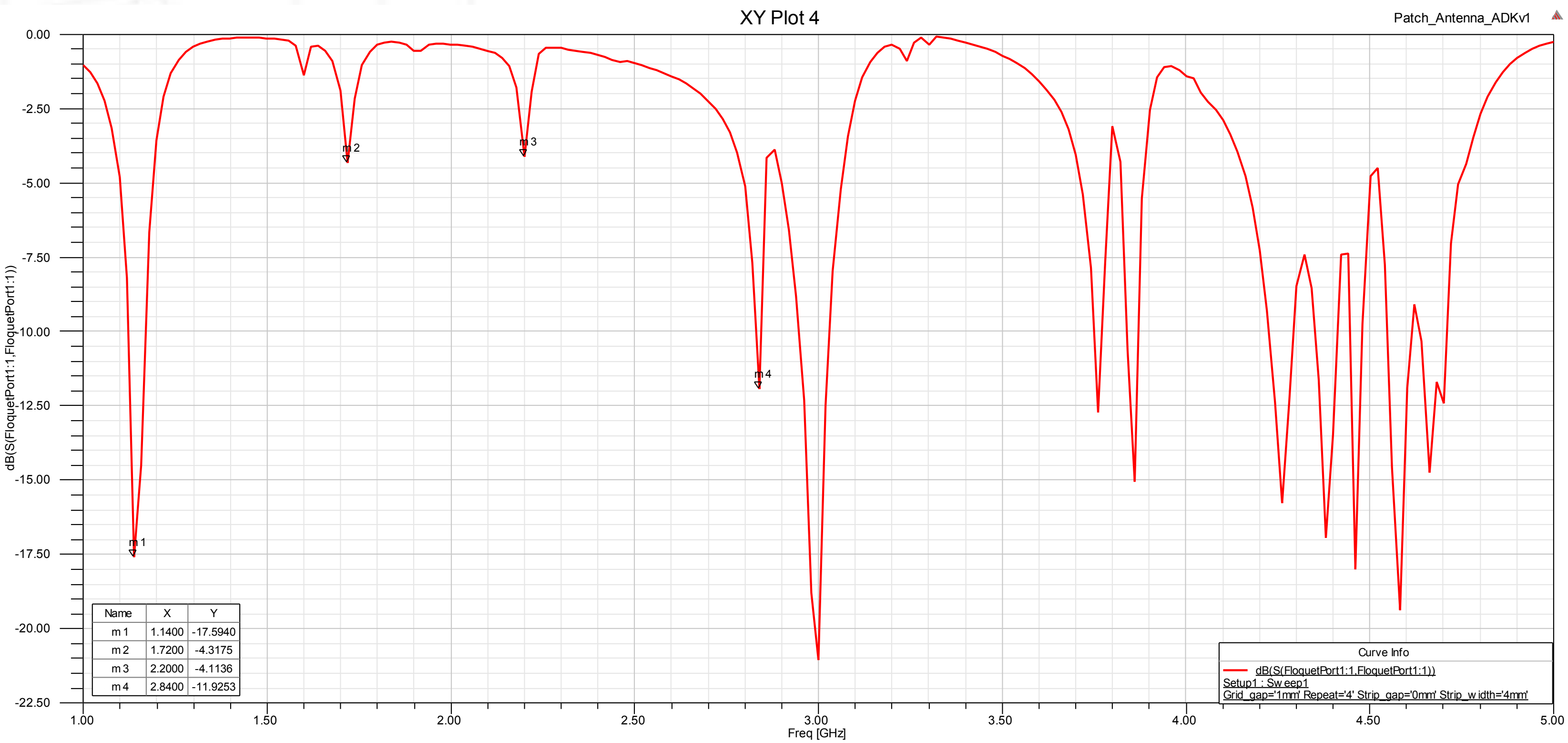
Hybrid FSS + Rectenna - Simulations

- S_{11} from the “FSS-side” of the hybrid structure.



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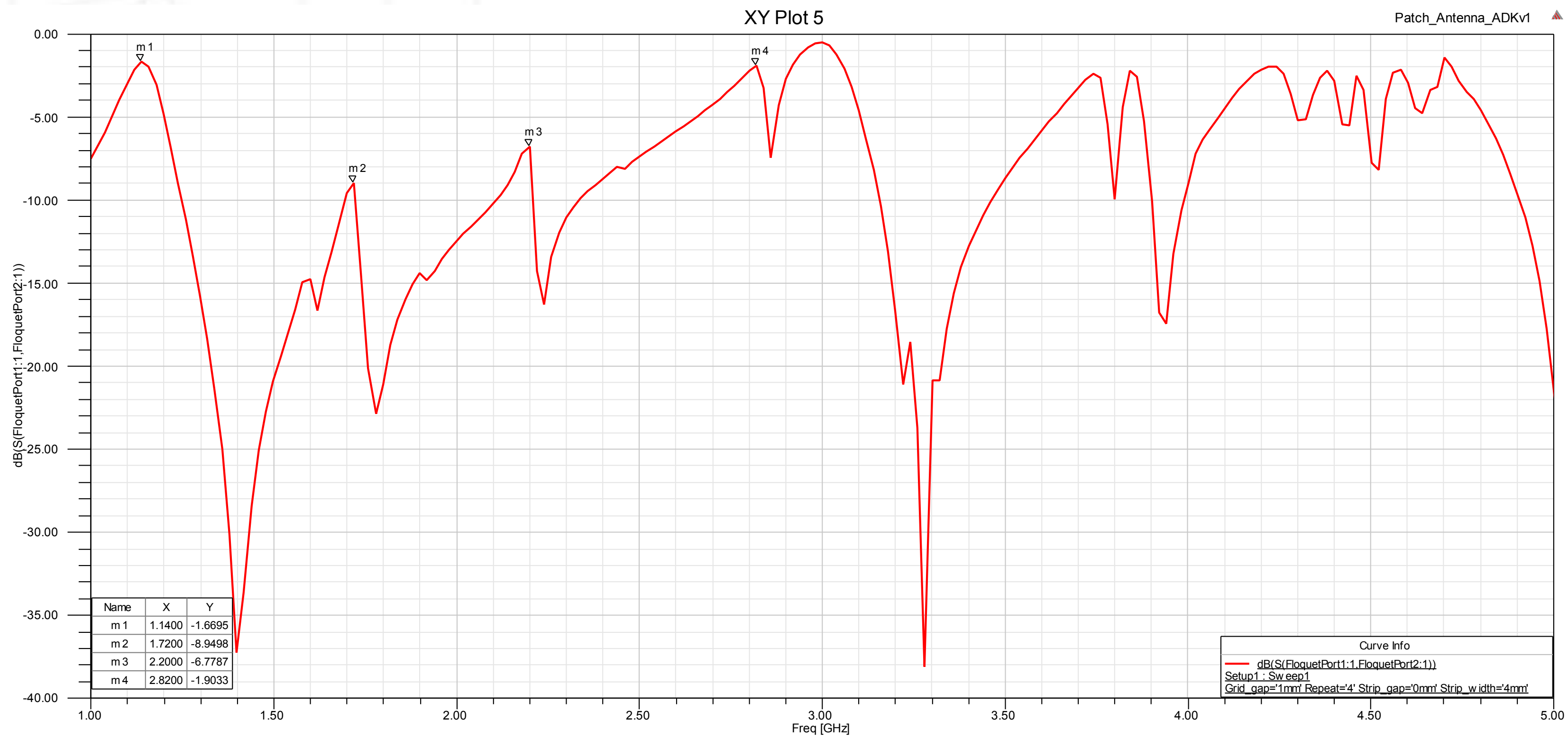
Hybrid FSS + Rectenna - Simulations

- S_{21} from the “FSS-side” of the hybrid structure.



Name	X	Y
m 1	1.1400	-1.6695
m 2	1.7200	-8.9498
m 3	2.2000	-6.7787
m 4	2.8200	-1.9033

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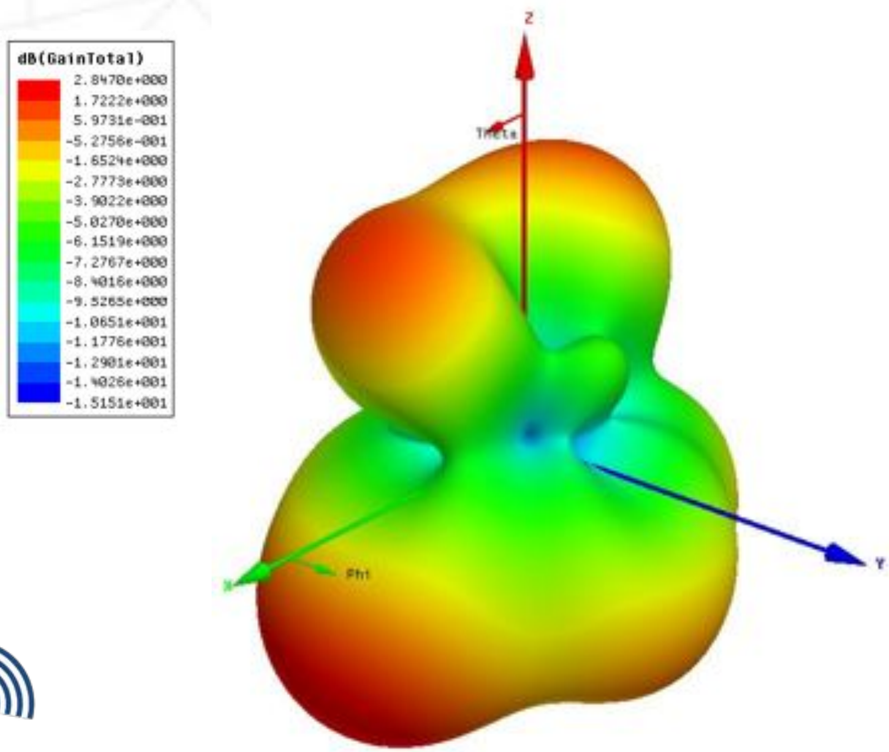
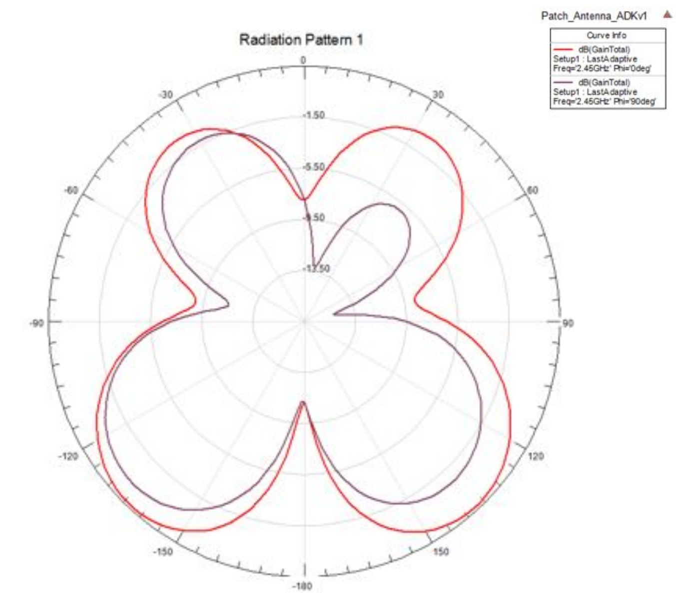
Hybrid FSS + Rectenna - Simulations

- Radiation pattern from the “antenna-side” of the hybrid structure.





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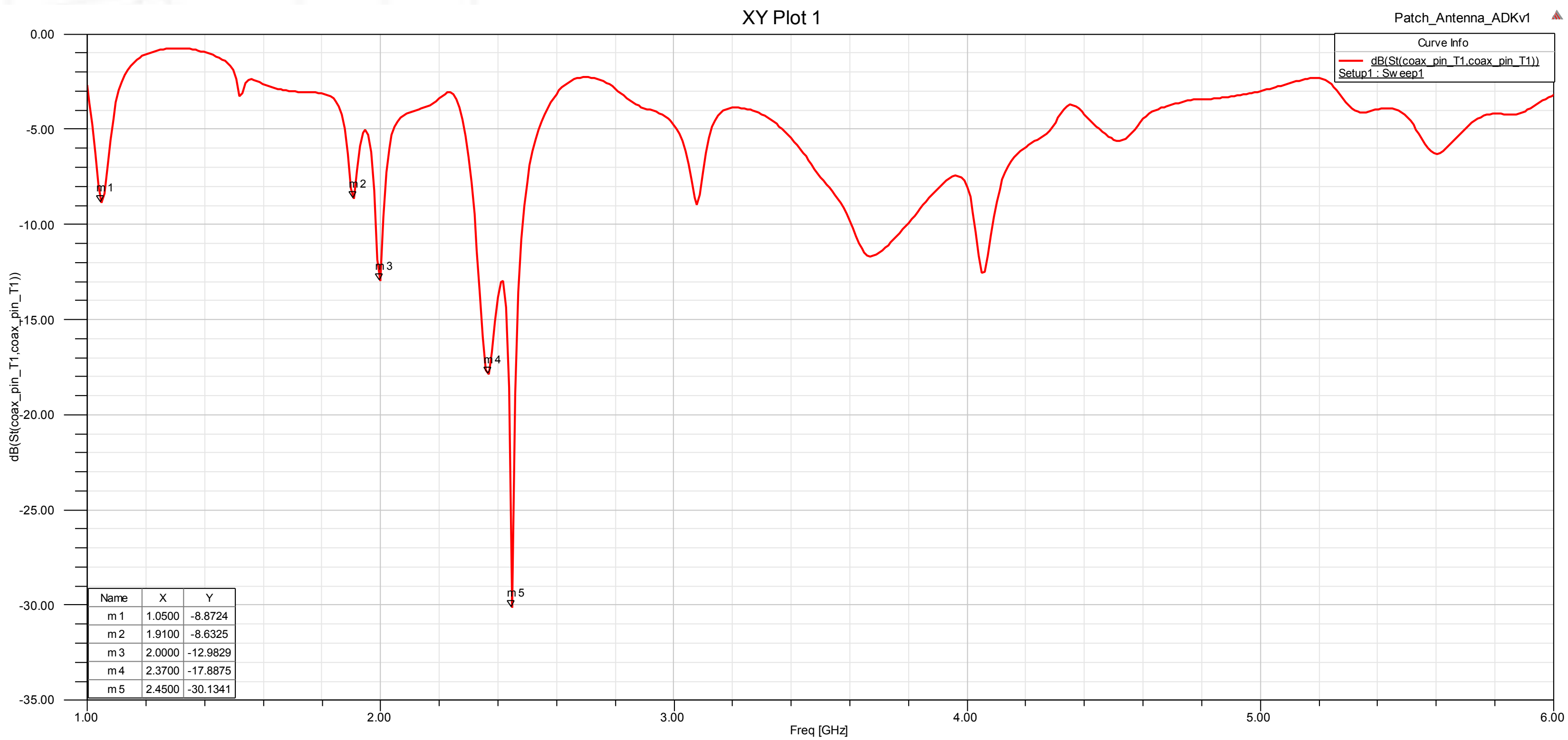
Hybrid FSS + Rectenna - Simulations

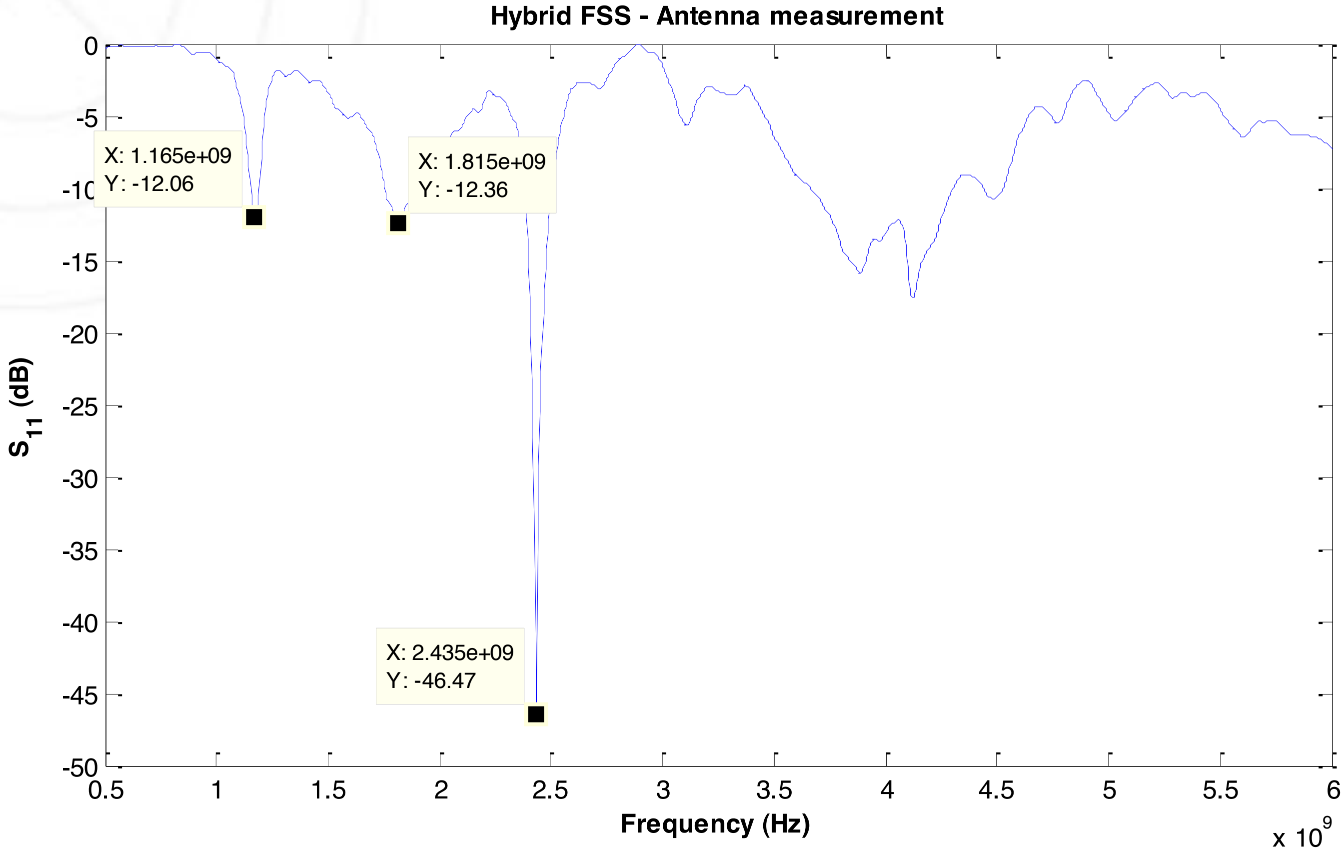
- S_{11} from the “antenna-side” of the hybrid structure.



Name	X	Y
m1	1.0500	-8.8724
m2	1.9100	-8.6325
m3	2.0000	-12.9829
m4	2.3700	-17.8875
m5	2.4500	-30.1341

Hybrid FSS - Measurements

- S_{11} from the "antenna-side" of the hybrid structure.



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Future work

- Improve hybrid FSS structure;
  - *Triple-Band energy harvesting:*
    - E.g. ~1GHz (2G) + 1.8-2 GHz (3G/LTE) + 2.4GHz (Wi-Fi).
  - *Pass-Band FSS:*
    - E.g. 800-900MHz (2G/LTE) + 2.6GHz (LTE) + 5GHz (Wi-Fi).

- Improve rectifiers by minimising RF-DC conversion losses;

- Integration with sensing devices and other low-power electronics.

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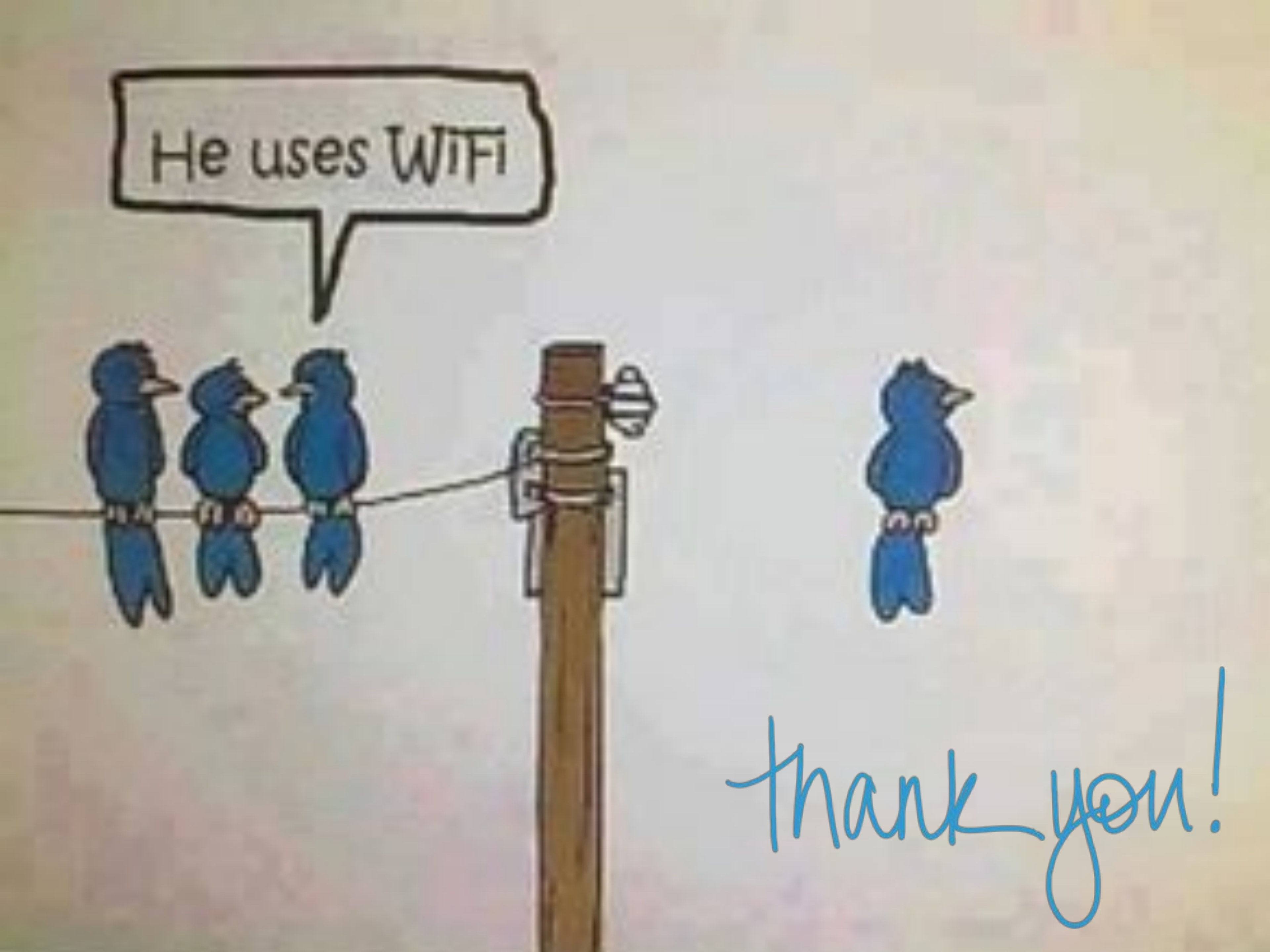
Conclusions

- Potential of Metamaterial / frequency selective surfaces and structures for space applications:
  - *Antenna Beam steering;*
  - *Invisibility cloaking;*
  - *WPT for cable replacing;*
  - *Frequency selectivity;*
  - *Site shielding.*


He uses WiFi
thank you!