Rete di Eccellenza "MASTRI" (MAteriali e STRutture Intelligenti) - POR Campania FSE 2007/2013

Metamateriali alle microonde

Scattering da Superfici Selettive in Frequenza (FSS)

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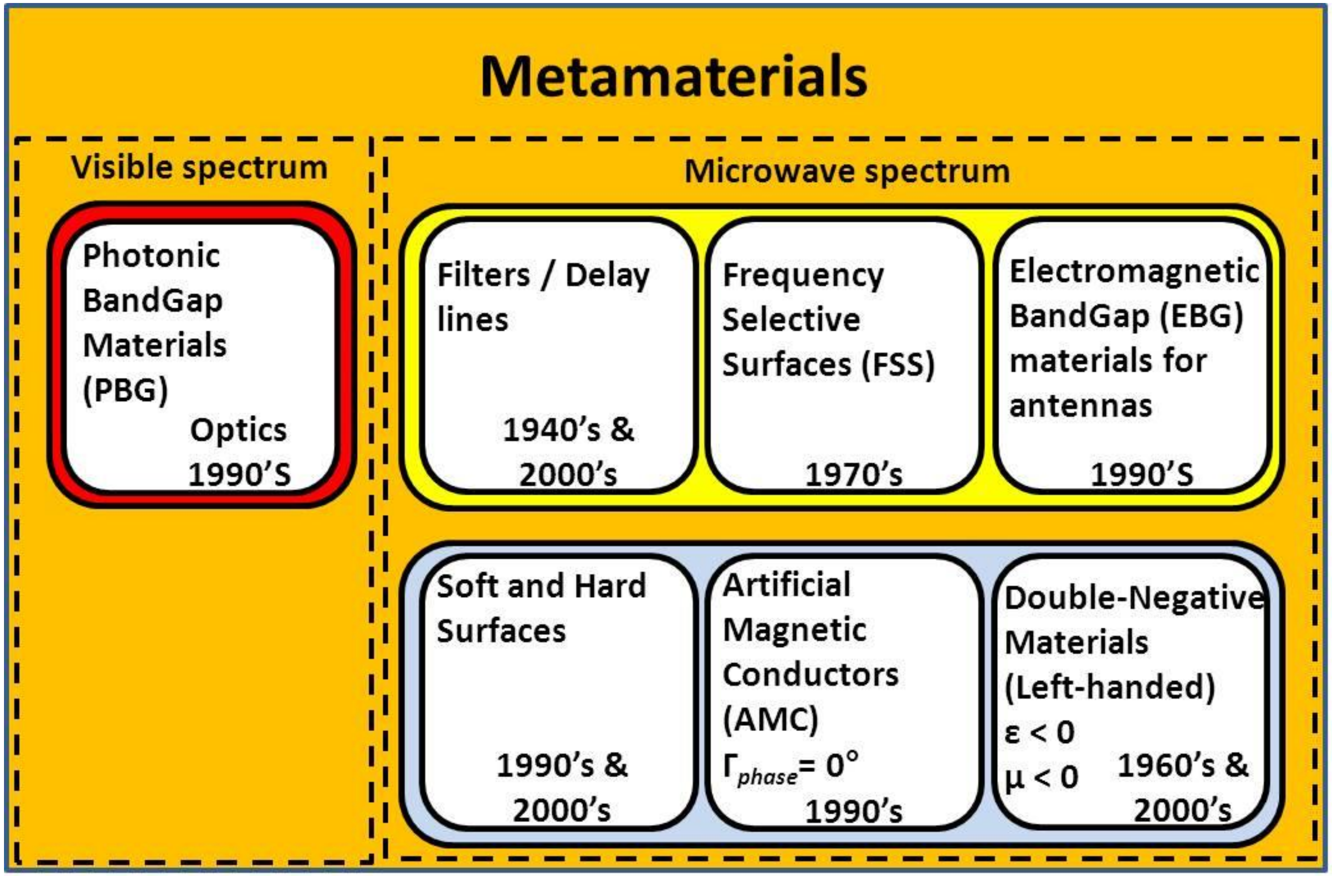
Outline Metamateriali

Metamateriali:

- Overview storica
- Classificazione in termini di impedenza superficiale
- Determinazione delle caratteristiche stop-band
- Materiali double-negative
- Onde backwards
- Rifrazione negativa
- Possibili applicazioni

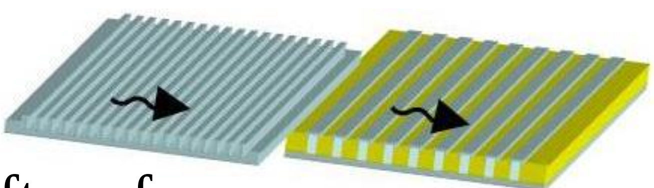
Metamaterials

Metamaterials are a big family of composite materials with unique features that do not exist in nature



Classificazione in termini di impedenza superficiale

	Surface impedances		Boundary conditions Transverse E-field components		Wave propagation at surface	GO-reflection coefficients
	$Z_l = -\frac{E_l}{H_t}$	$Z_t = \frac{E_t}{H_l}$	Normal E_n	Tangential E_t		
PEC	0	0	$\frac{\partial E_n}{\partial n} = 0$	$E_t = 0$	No (E_t) Yes (E_n)	R_p=1 R_o= -1
PMC	∞	∞	$E_n = 0$	$\frac{\partial E_t}{\partial n} = 0$	No (E_n) Yes (E_t)	R_p= -1 R_o=1
Soft Surface	∞	0	$E_n = 0$	$E_t = 0$	No, polarization-independent	R_p= -1 R_o= -1
Hard Surface	0	∞	$\frac{\partial E_n}{\partial n} = 0$	$\frac{\partial E_t}{\partial n} = 0$	Yes, polarization-independent	R_p=1 R_o=1



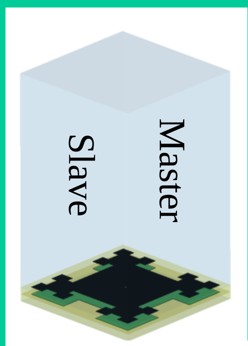
Soft surfaces

Hard surface

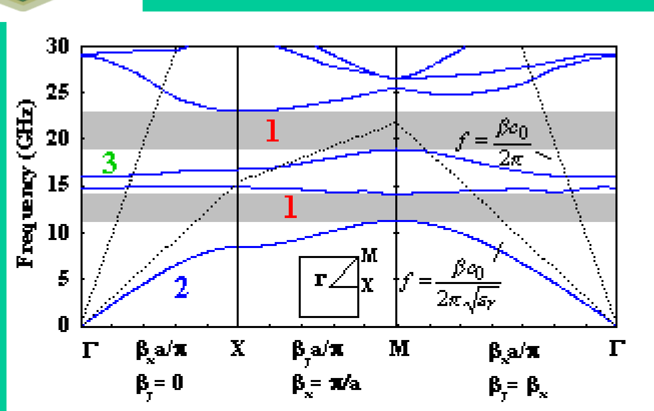
Determinazione delle caratteristiche stop-band (1/2)

In order to determinate the band gap of an EBG structure, different methods exist. Each one suits the particular application the structure is designed for.

1) Eigenvalues



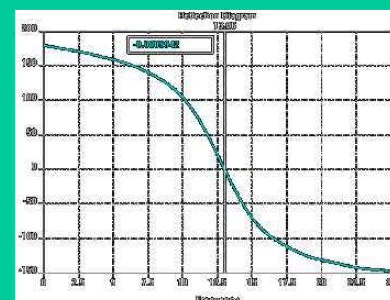
Searching for propagating surface modes on infinite EBG plane.



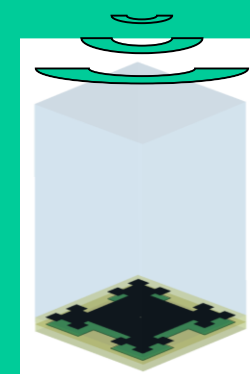
2) Arg (S11)

Measuring the phase of the reflection coefficient.

Particular boundary conditions make the EBG plane infinite.



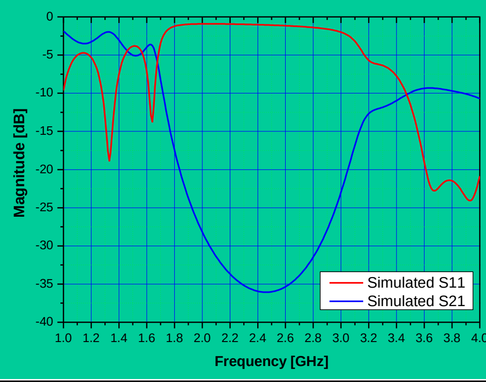
Plane wave

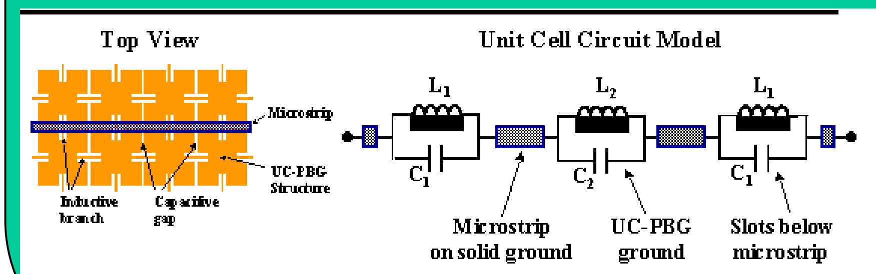


Determinazione delle caratteristiche stop-band (2/2)

3) Strip-line

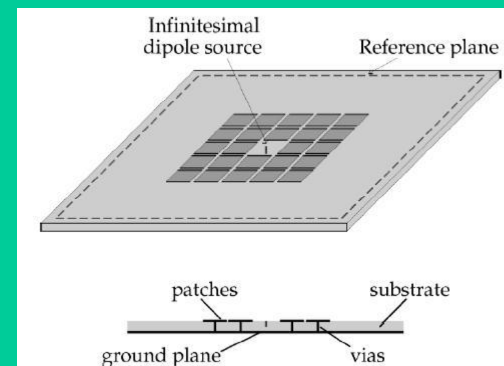
Measuring the Transmission Coefficient between the two ports at the endings of the strip-line.

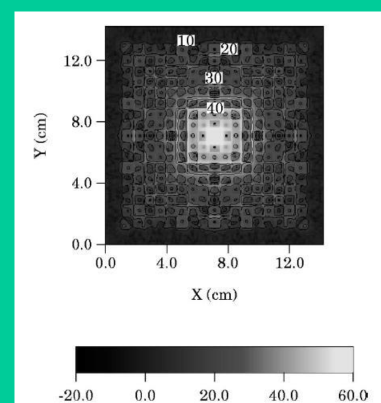


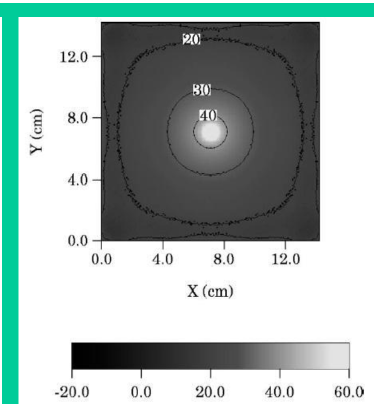


4) Infinitesimal dipole

Comparing the surface waves distribution on the ground plane and comparing it with a normal ground plane





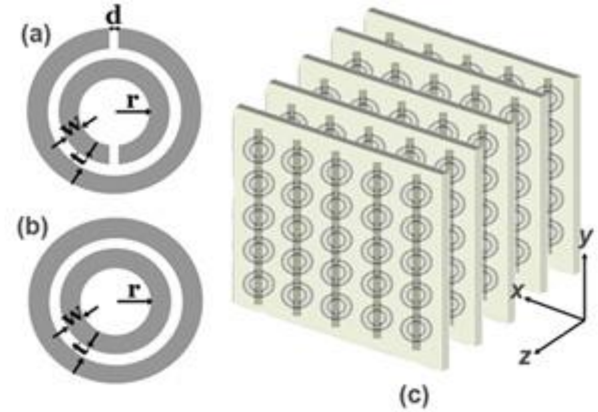


Metamateriali double-negative

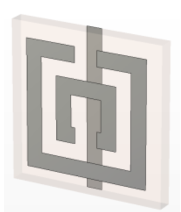
$\varepsilon_{eff}<0$ ⟷ $n<0$ ⟷ Direction of propagation is reversed with respect to the direction of energy flow!

$\mu_{eff}<0$

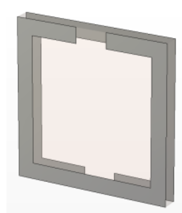
Thin metallic periodic wires can realize negative permittivity materials. The combination with a split ring resonator gives negative permeability.



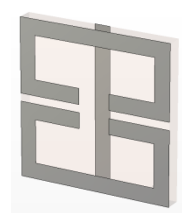
Overview of Split-Ring Resonators



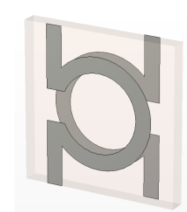
Edge-coupled



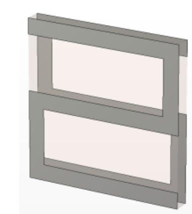
Broadside



Axially symmetric



Omega



S-ring

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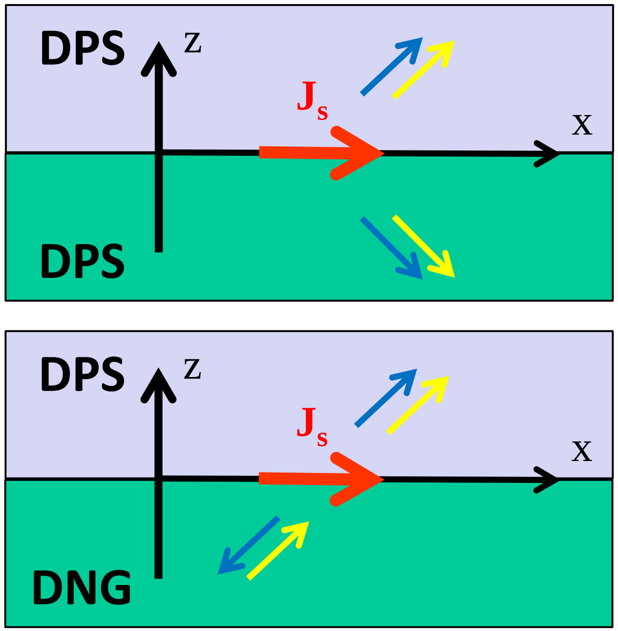
Onde backwards (1/2)



Frecce blu = Poynting vectors
Frecce gialle = Wave vectors

J_s=$I_0 e^{-jk_{0x}x}\delta(z)\hat{x}$ current sheet on the interface between two semi-infinite media!

The wavenumbers in each medium must satisfy the dispersion relation: ${k_{i,x}}^2 + {k_{i,z}}^2 = {k_i}^2 = \omega^2\varepsilon_i\mu_i$

Boundary conditions require the wavenumbers tangential to the interface to be the same in each medium $k_{1,x} = k_{2,x} = k_{0,x}$

$$k^{DPS}{}_z = +\sqrt{\omega^2\varepsilon_{DPS}\mu_{DPS} - k^2{}_{0x}}$$

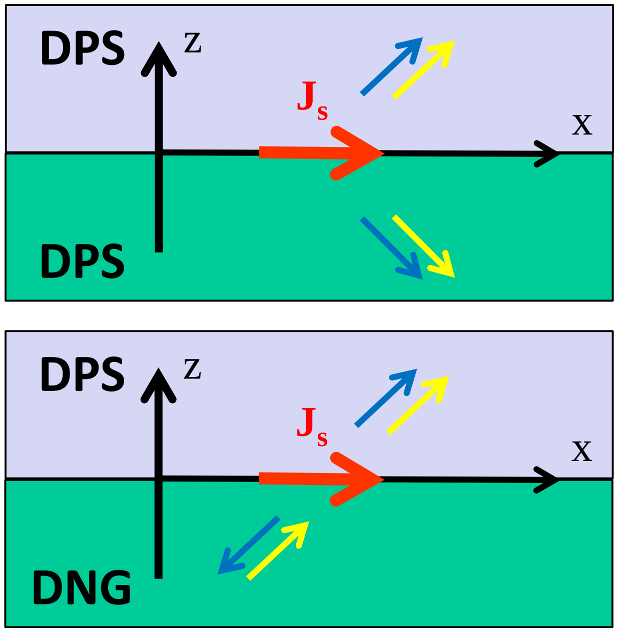
Propagation constants normal to the interface

$$k^{DNG}{}_z = -\sqrt{\omega^2\varepsilon_{DNG}\mu_{DNG} - k^2{}_{0x}}$$

Wave vectors in each region:

$\boldsymbol{k}_1 = k_{0,x}\hat{x} + k_{1,z}\hat{z}$ $\quad \boldsymbol{k}_{2,DPS} = k_{0,x}\hat{x} - k_{2,z}\hat{z}$ $\quad \boldsymbol{k}_{2,DNG} = k_{0,x}\hat{x} + |k_{2,z}|\hat{z}$

Onde backwards (2/2)



Frecce blu = Poynting vectors
Frecce gialle = Wave vectors

Poynting vectors in each region:

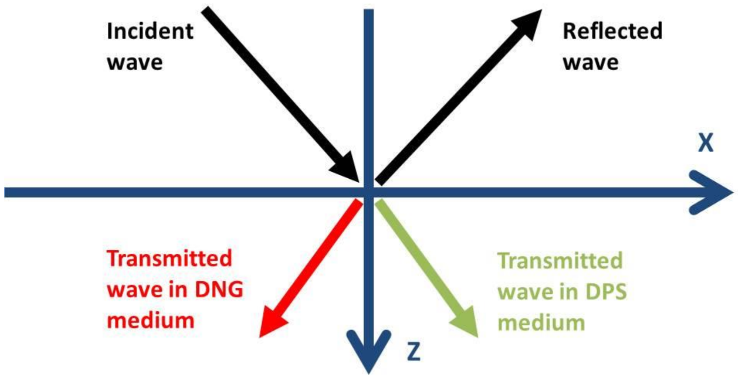
$$\langle \mathbf{S}_1 \rangle (x,y,z,\omega) = \frac{1}{2\omega\varepsilon_1}\left|\frac{k_{2,z}}{\varepsilon_2}\frac{I_0}{k_{1,z}/\varepsilon_1 + k_{2,z}/\varepsilon_2}\right|^2 \left(k_{0,x}\hat{x} + k_{1,z}\hat{z}\right)$$

$$\langle \mathbf{S}_{2,DPS} \rangle (x,y,z,\omega) = \frac{1}{2\omega\varepsilon_2}\left|\frac{k_{1,z}}{\varepsilon_1}\frac{I_0}{k_{1,z}/\varepsilon_1 + k_{2,z}/\varepsilon_2}\right|^2 \left(k_{0,x}\hat{x} - k_{2,z}\hat{z}\right)$$

$$\langle \mathbf{S}_{2,DNG} \rangle (x,y,z,\omega) = \frac{1}{2\omega|\varepsilon_2|}\left|\frac{k_{1,z}}{\varepsilon_1}\frac{I_0}{k_{1,z}/\varepsilon_1 + |k_{2,z}|/|\varepsilon_2|}\right|^2 \left(-k_{0,x}\hat{x} - |k_{2,z}|\hat{z}\right)$$

The power flow of the wave generated in the DNG medium is opposite to the positive phase direction of the source!

Rifrazione negativa



Geometry of the scattering of a wave obliquely incident upon a DPS-DNG interface

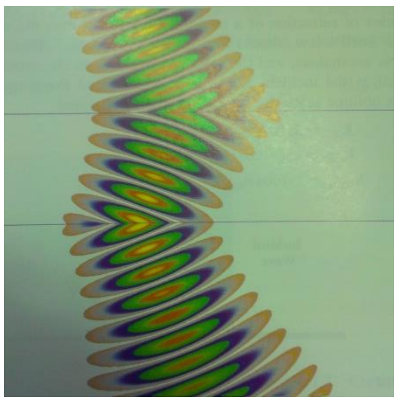
Enforcing the boundary conditions at the interface we obtain the law of reflection and Snell's law from phase matching:

$$\theta_{refl} = \theta_{inc}$$

$$\theta_{trans} = sgn(n_2) sin^{-1}\left(\frac{n_1}{|n_2|} sin\theta_{inc}\right)$$

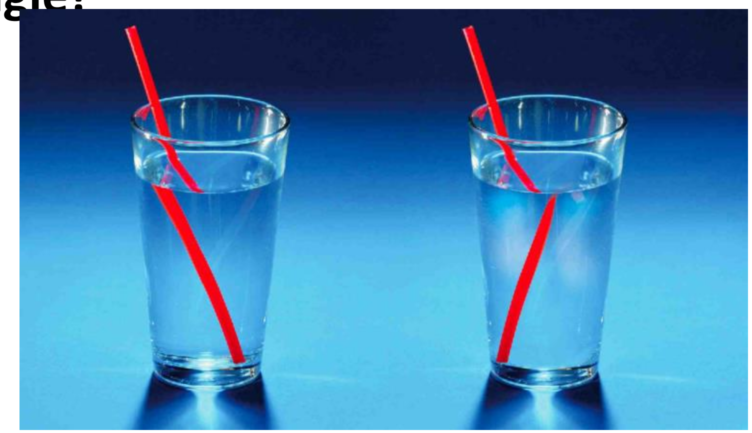
In case of a DPS-DNG interface, the refraction is anomalous!

The refracted angle is on the same side of the interface normal as the incident angle!



Simulazione FDTD di propagazione attraverso interfaccia DPS-DNG

Esempio equivalente in ottica



Rifrazione negativa

Conclusioni

Metamateriali:

- Metamaterials are a large family of metallo-dielectric structures with specific electromagnetic properties. By varying periodicity and/or LC contribution in each elementary cell, different combinations of electric properties can be derived (ENG, MNG and DNG).
- Such versatility is exploited in several conventional applications (antennas, filters, delay-lines, etc.) but it also suggested new ones like cloaking.
- Several features make manufactured metamaterials limited or different than ideal references. These are mostly due to the truncation of the periodicity and a non-omnidirectional behavior.

Outline

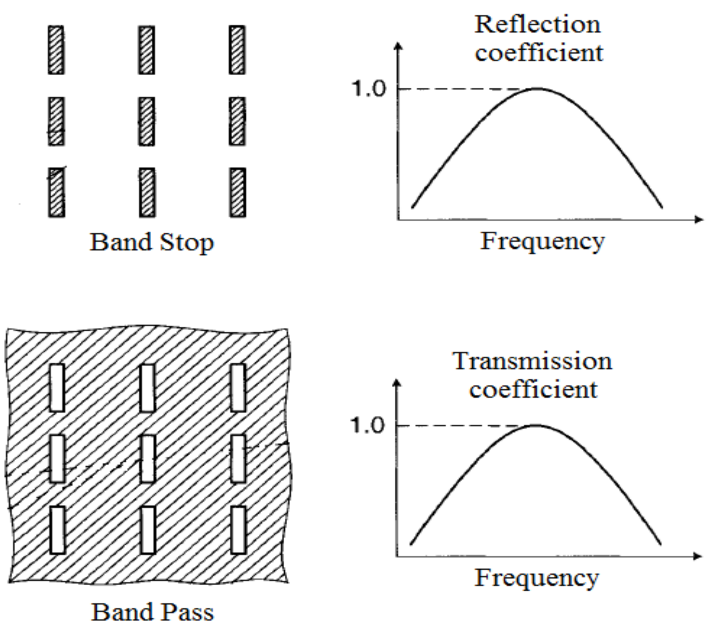
Frequency Selective Surfaces (FSS):

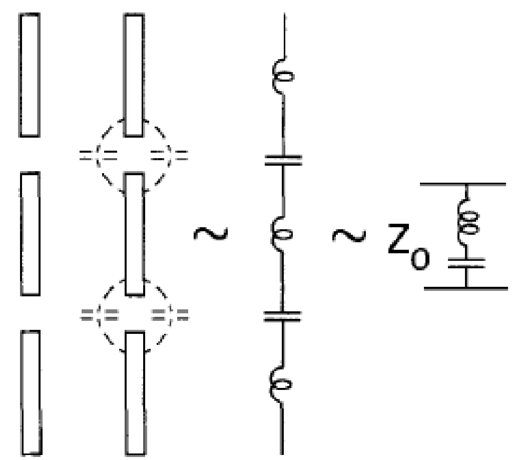
- Introduction
- Types of FSS
- Applications
- Grating lobes issues
- Structure Analysis
- Basic principles investigations
- Numerical techniques analysis
- Numerical analysis of a conical structure

Conclusions

Frequency Selective Surfaces: Intro

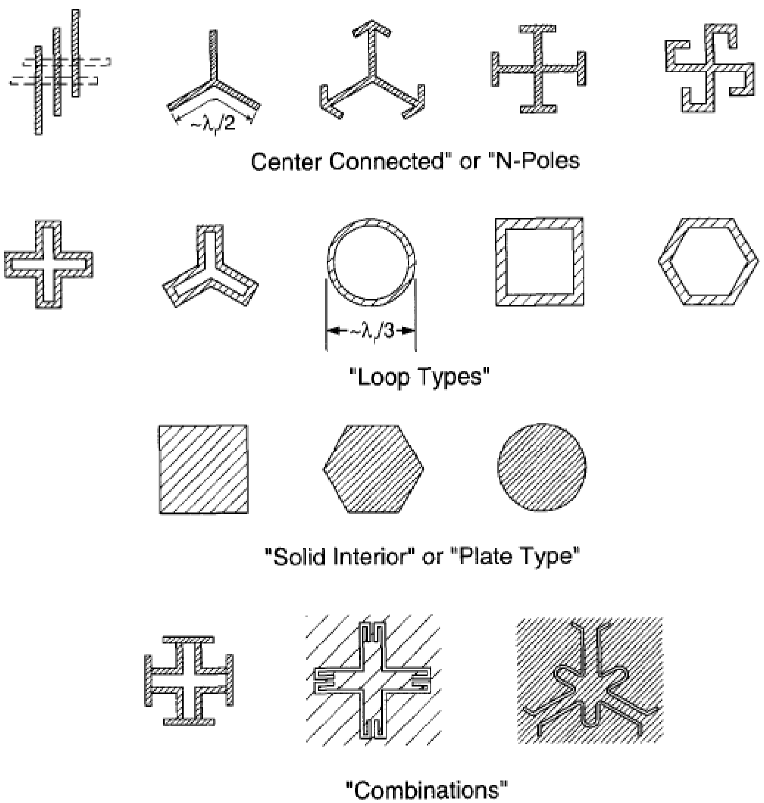
- Periodic structures filtering Electromagnetic Waves in space and frequency
- Two main categories: Active FSS and Passive FSS
- Two types of filtering behaviour: Band stop (strips) and Band pass (slots)
- Works like a circuital filter (LC) that resonate at specific frequency



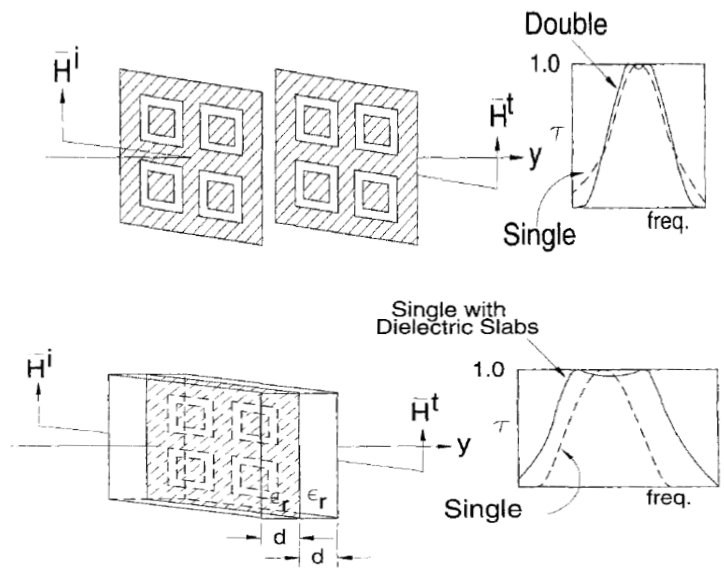


Frequency Selective Surfaces: Types

- Unlike a circuital filter, the structure must work for different incidences and polarizations
  - Many types of geometries are made to achieve this goal



- Using many layers can enhance the frequency behavior



Frequency Selective Surfaces: Applications

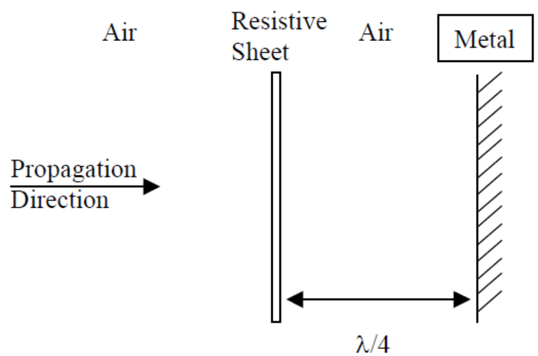
Hybrid Radome

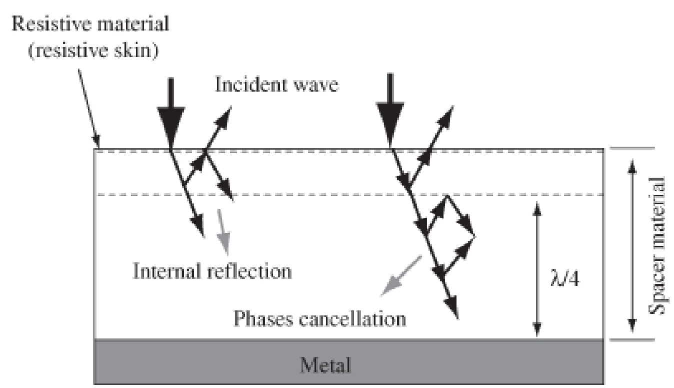
Ground Based Radome

Aircraft Radome

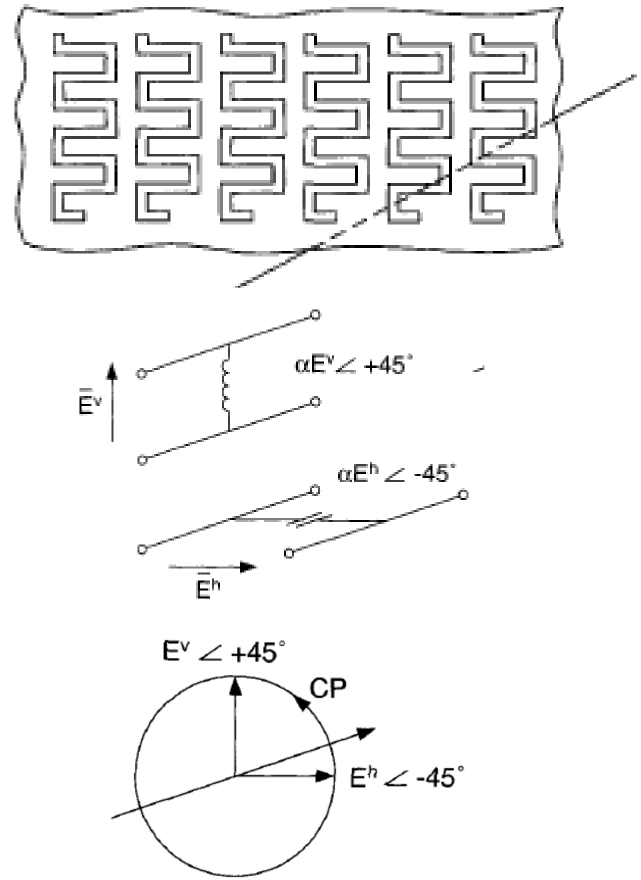
Radar Absorbing Materials

Salisbury Screen





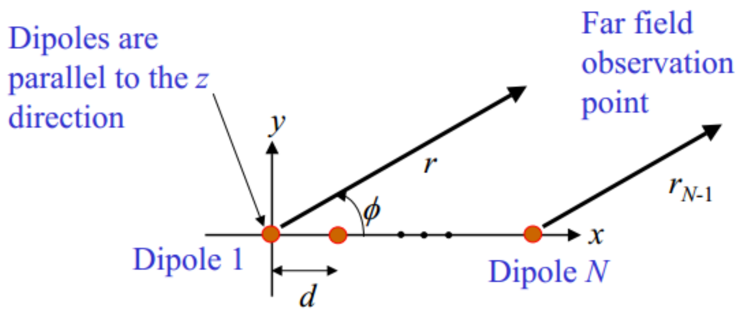
Meanderline Polarizer



Frequency Selective Surfaces: Grating lobes issue

- Grating lobes: spatial replication of main lobe

- Assuming that the excitation currents (Active Array) have the same amplitude (for example I=1) and the difference in phase is β, we can define the Array Factor as:



$$AF = \frac{\sin\left(N\left(\frac{kd\cos\phi + \beta}{2}\right)\right)}{\sin\left(\frac{kd\cos\phi + \beta}{2}\right)}$$

The maximum values of AF occour when: $\left(\frac{kd\cos\phi+\beta}{2}\right) = \pm m\pi, \quad m=0,1,2,\ldots..$

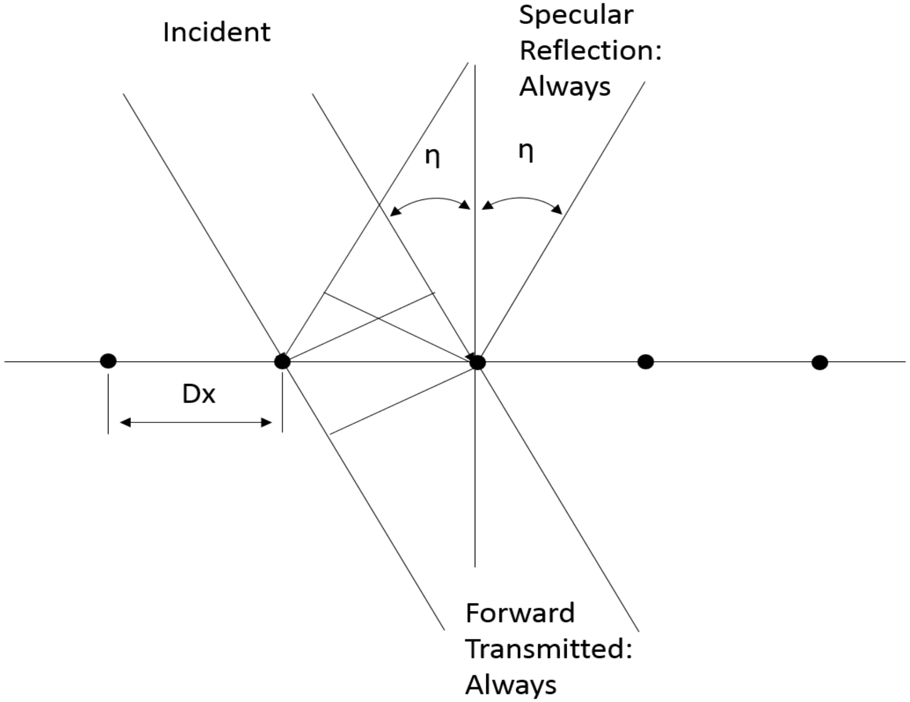
$$\phi_{max} = \cos^{-1}\left[\frac{\lambda}{2\pi d}(-\beta \pm 2m\pi)\right]$$

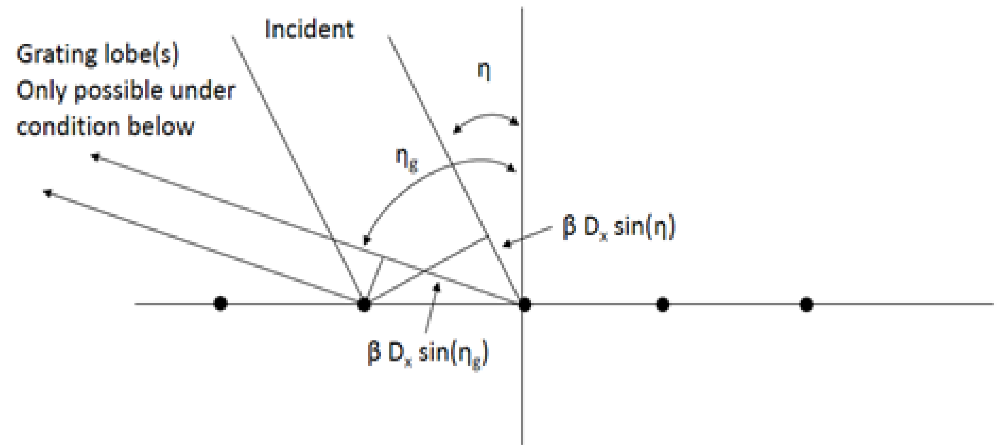
There are more than one maximum angles ϕ_{max}, that gave the grating lobes

<u>The condition for grating lobes to occour is that d ≥ λ</u>

Frequency Selective Surfaces: Grating lobes issue

- Grating lobes for a passive array

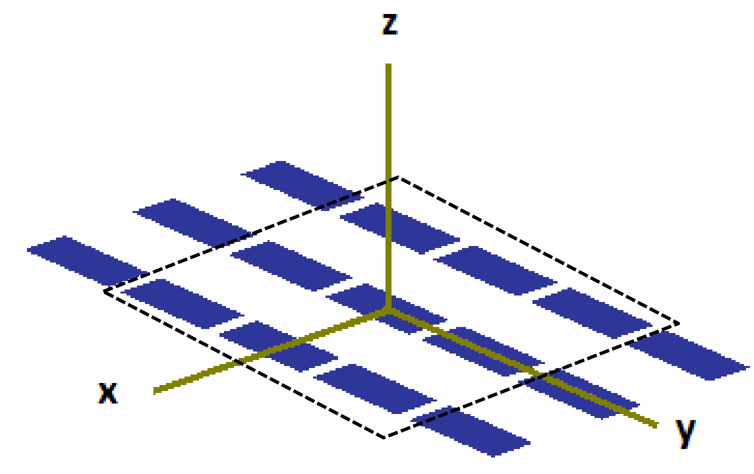




Grating lobes condition:

$$\beta Dx\,(\sin\eta + \sin\eta_g) = 2\pi n$$

Frequency Selective Surfaces: Numerical analysis



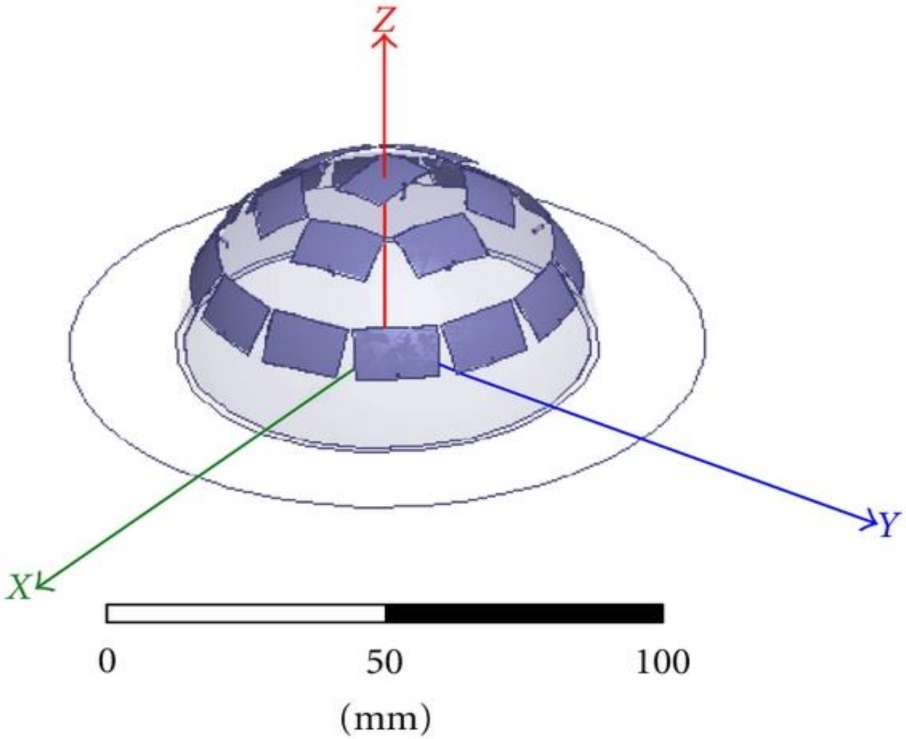
Planar FSS

- Numerical analysis simplyfied
- It is necessary to analyse only one unit cell

- Doubly infinite structure
- The interaction with an incident plane wave is dictated by the spatial period between the elements and the size of the single element in presence of the others
- The interaction (scattering) is related to the input impedance of the element that depends by dimension and the shape and the proximity of the other elements
- The input impedance is varying with the frequency and determinates the bandwidth
- To understand the behaviour it is sufficient to study the interaction of one element with with some elements adjacent to it.

Frequency Selective Surfaces: Numerical analysis

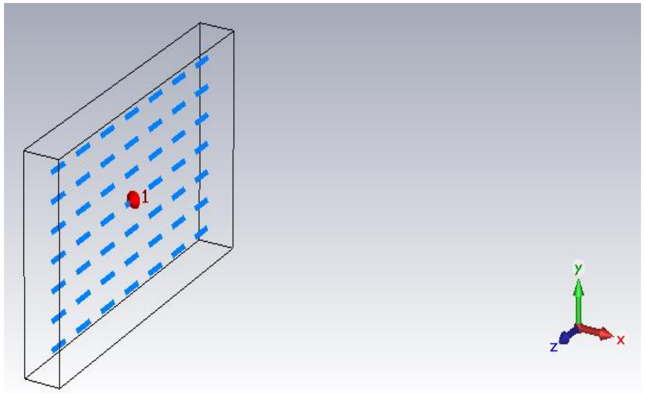
- Conformal or not periodic structure



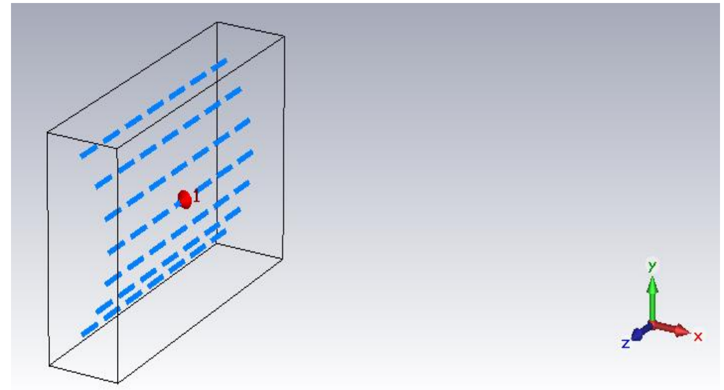
- Periodicity is lost
- There are truncation effects due to the finite size of the structure
- For a conformal structure there are curvature effects also
- It is not possible to study only few elements of the structure, but it is necessary to take in account all the elements of the structure
- Time consuming
- Memory consuming
- An approximate analysis of the input impedance of the single element (in presence of the others) can predict the frequency behaviour of the structure

Frequency Selective Surfaces: Basic principle investigation

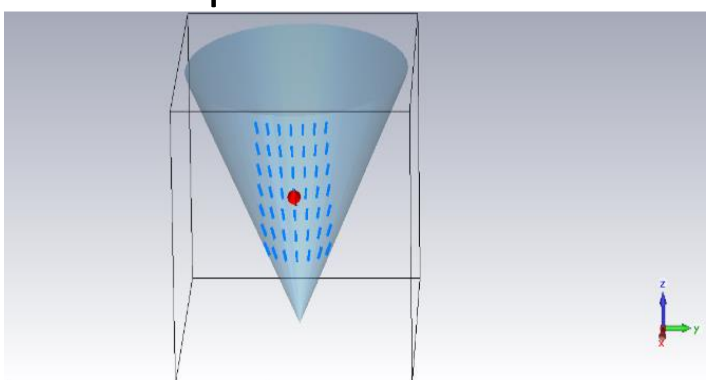
Planar structure 7x7



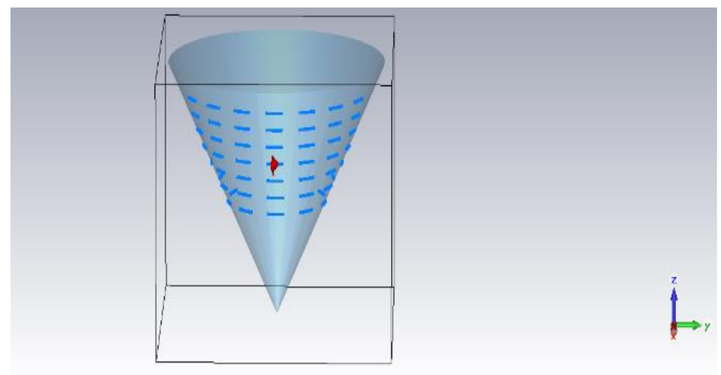
Cylindrical structure 7x7



Conical structure with radial strips 7x7



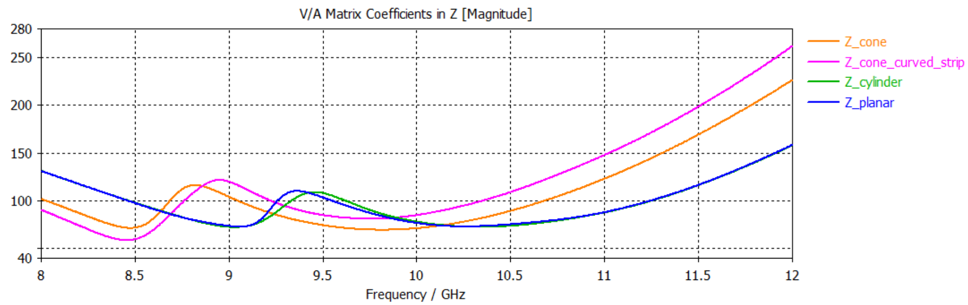
Conical structure with circumferential strips 7x7



Frequency Selective Surfaces: Basic principle investigation

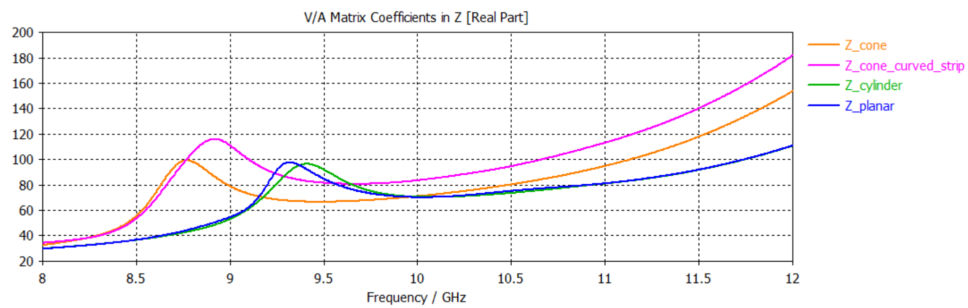
Input impedance of active element

Z Magnitude



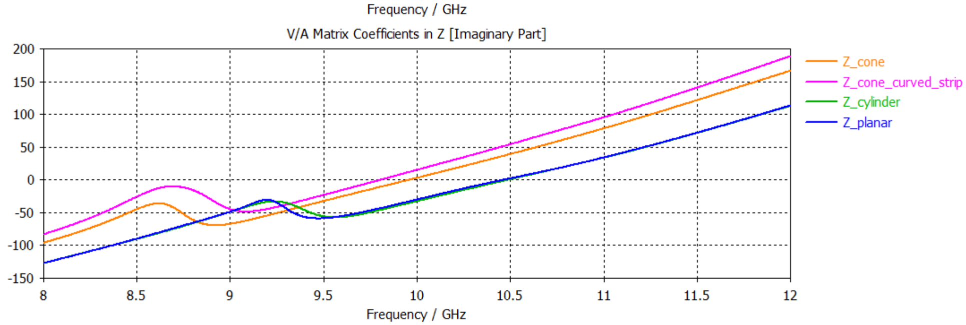
Z_cone_radial_strip
Z_cone_curved_strip
Z_cylinder_surface
Z_planar_surface

Z Real Part



Z_cone_radial_strip
Z_cone_curved_strip
Z_cylinder_surface
Z_planar_surface

Z Imaginary Part



Z_cone_radial_strip
Z_cone_curved_strip
Z_cylinder_surface
Z_planar_surface

Frequency Selective Surfaces: Numerical analysis techniques

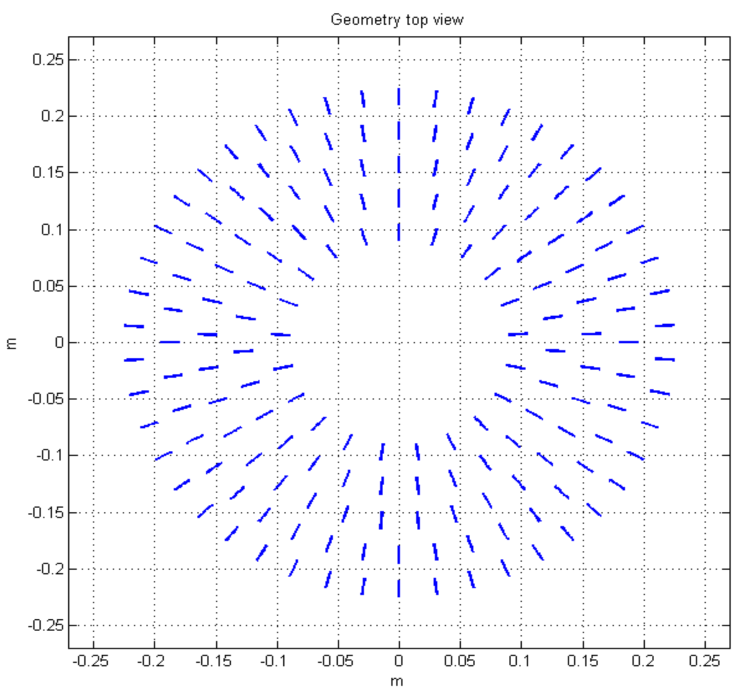
Table I

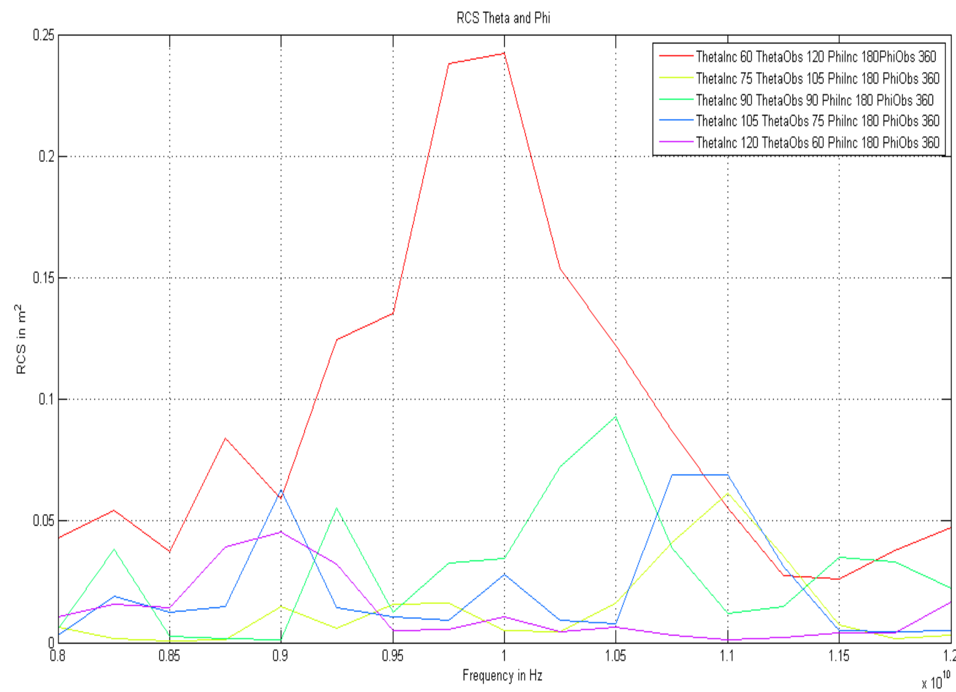
Summary of notable numerical techniques for FSS simulation

Numerical technique	Description	Pros	Cons
Finite Element Model	Most general, handles complex material and geometries, volume mesh and field equation, numerically exact solution	Can handle complex geometries and inhomogeneus medium	It is necessary to discretize (mesh) the entire volume under investigation
Integral Equation (Method of Moments)	Efficient solution for open radiation and scattering problems, currents solved on surface mesh, efficient with structures are primarily metallic	It is necessary to discretize only the regions where the metal objects are present. Good for electrically large objects.	Not possible to simulate complex geometries and inhomogeneus medium and broadband analysis

Frequency Selective Surfaces: BackScattered Field

- Analysis on a conformal conic structure with 5 crown of strips with λ/2 gaps (vertical and horizontal)
- There are 5 incident waves with different angles (θ and ϕ)
- Radar Cross Section evaluation in a «specular direction»





Conclusions

Resonant frequency of the structure:

- It is related to the size of the single element, the shape of the object and the surface geometry, because it changes the input impedance

Conformal surfaces:

- There is no analytical formulations to analyze conformal FSS
- The literature dedicated to this particular aspect of FSS theory is sparse and lacks of a unified approach
- The basic principles of the FSS are also valid in the case of the conformal structures, but more analysis are required

Grazie per l’attenzione.
Domande?