



# Dielectrics in Metamaterials

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# Outline

1. Introduction: Conventional metamaterials and the effective medium theory
2. Towards dielectric metamaterials in frames of the effective medium theory. Composite materials
3. Beyond the effective medium theory - arrays of coupled dielectric resonators (DRs)
4. Coupled DR arrays *versus* photonic crystals
5. Latest developments on artificial materials from DRs

## 1. Introduction:

Conventional metamaterials & the  
effective medium theory

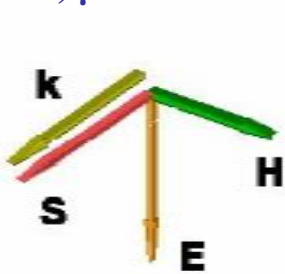
# “Conventional” Metamaterials

Veselago, 1964, LHMs

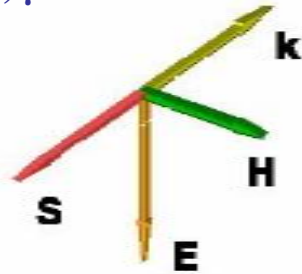
Pendry, 1999, simple approach to design

$$\epsilon > 0, \mu > 0$$

$$\epsilon < 0, \mu < 0$$

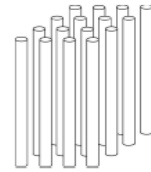


Regular Materials



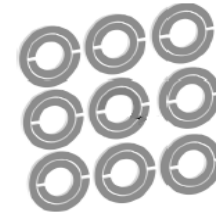
Left-Handed Materials

Wires



Electric response  
Negative  $\epsilon$  below  
plasma frequency

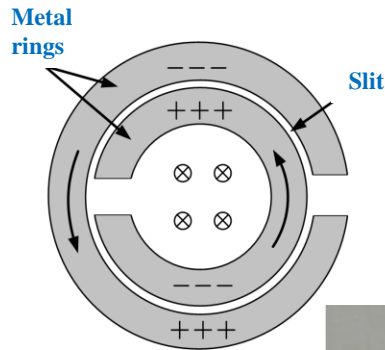
SRRs



Magnetic response  
Negative  $\mu$   
above resonance

Negative  
Refractive  
Index  
Material

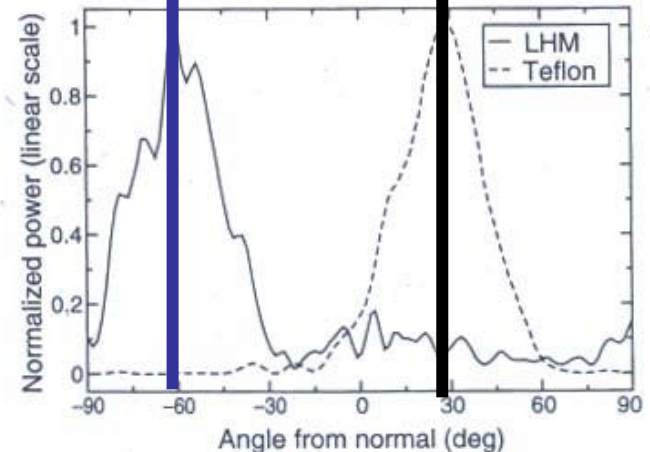
1D



Negative refraction

Meta-material  
 $n = -2.7$

Teflon  
 $n = 1.4$



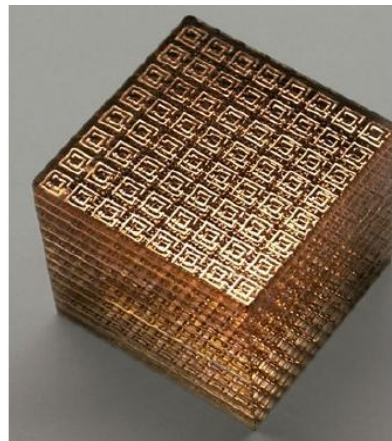
\*R. A. Shelby et al., Science, 2001

2D



Schultz and Smith, PRL, 2000

3D



Boeing Cube

# Concepts used at designing and explaining metamaterials

## Long wave approximation

Dimensions of “atoms” are much smaller than  $\lambda$

## Effective medium theory

Waves do not see “atoms” and pass through the metamaterial as through a uniform medium with effective permittivity and permeability

## No inter-resonator interaction

Resonators do not interact - responses are simply superimposed

## Inconsistencies

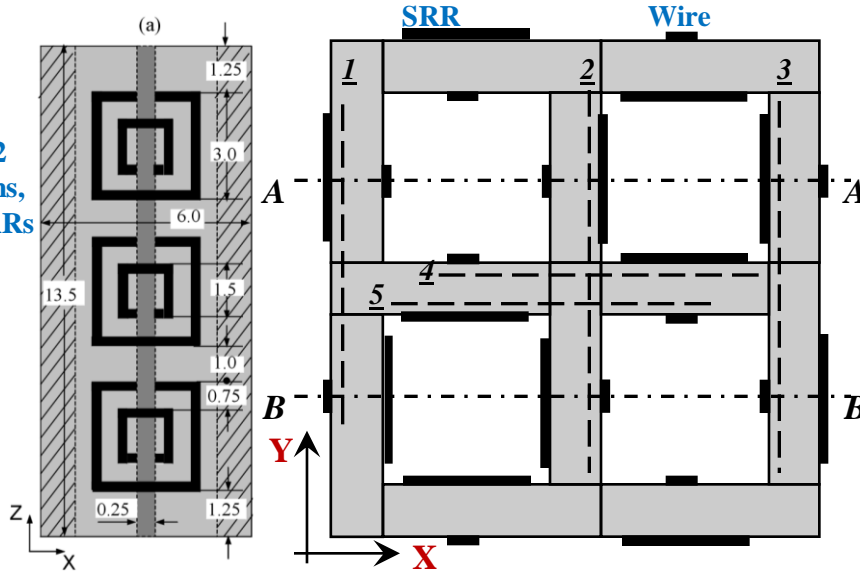
SRRs are only about  $\lambda/6$ , and cut-wires length is about  $\lambda/2$

Cut-wires support  $\lambda/2$  resonance, no plasma-type behavior

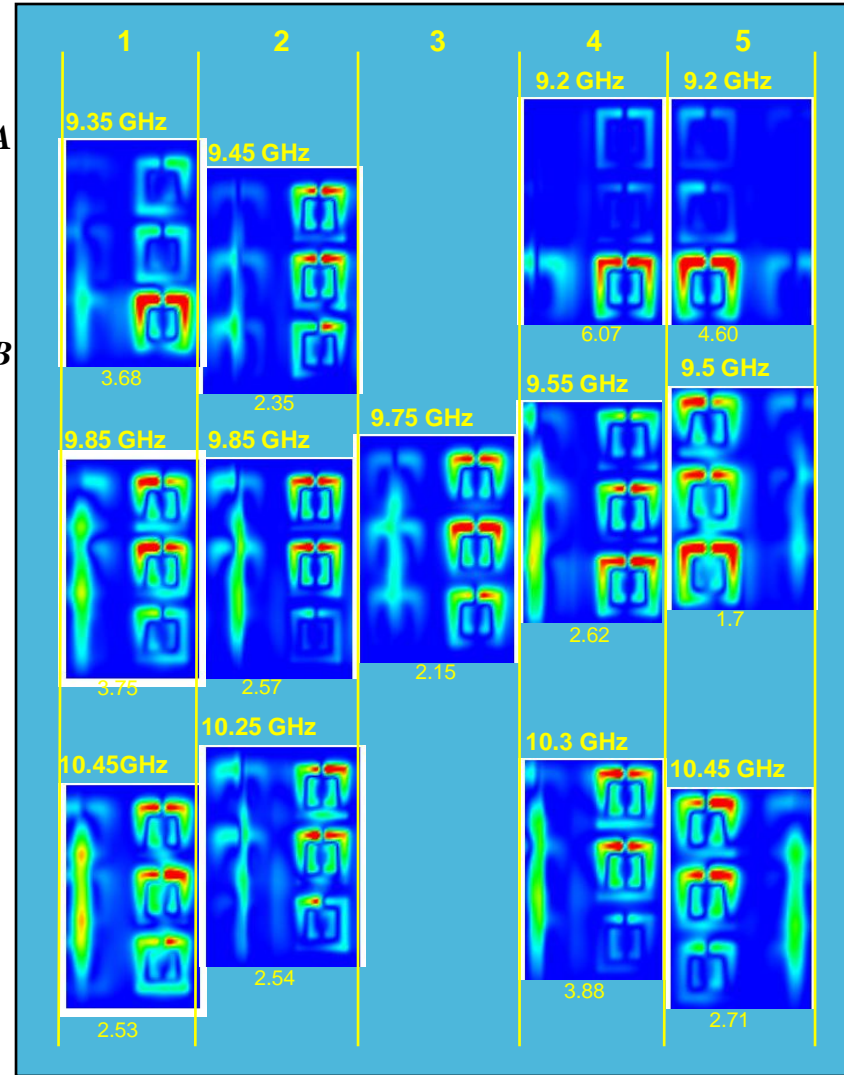
# FDTD modeling of EM response in a “conventional” metamaterial

Semouchkina et al., *IEEE Trans.MTT*, 2005

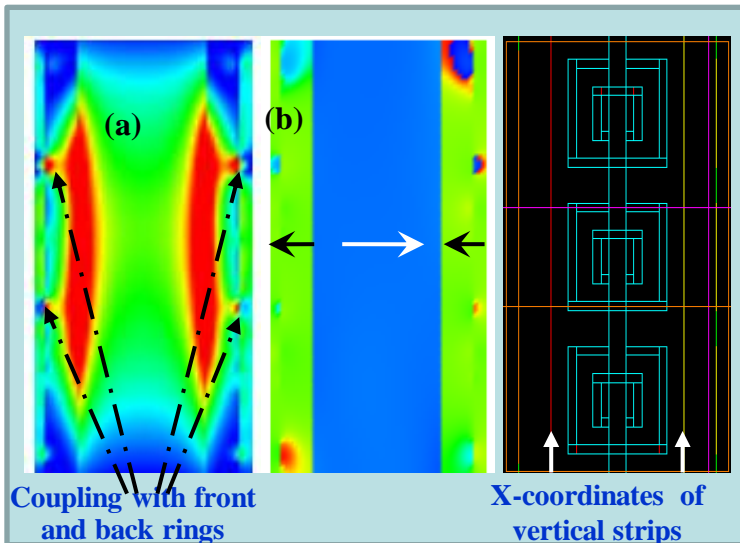
MM part composed of 12 vertical columns, each with 3 SRRs and 1 wire



(a) Amplitude and (b) phase distributions of electric field oscillations in B-B cross-section of the right column



Amplitude distributions of electric field oscillations in cross-sections marked by numbers 1-5 demonstrate irregular flash-like response caused by mode splitting



Coupling with front and back rings

X-coordinates of vertical strips

Coupled wires with opposite charges

# Coupling between resonators in the array and redistribution of resonance oscillations with frequency

Positions of the SRRs (long strips) and wires (short strips)

Patterns of electric field ( $E_y$ ) oscillations in the median XY cross-section of the sample

9.75 GHz

9.9 GHz

10.05 GHz

10.2 GHz

10.35 GHz

$3.57e4$

$5.05e4$

$5.88e4$

$4.65e4$

$3.53e4$

Upper row: magnitudes

Lower row: phases

Sin-phase oscillations in neighboring areas transform in oscillations with opposite phases

**Coupling between resonators and mode splitting contradict the effective medium theory concepts**

It could point out at an alternative mechanism of the left-handedness

# Drawbacks of Conventional Metamaterials

- Anisotropy
- Enhanced losses caused by metal parts
- Low transparency due to high density of discontinuities
- Narrow operating band and too high dispersion
- The problem of combining proper electric and magnetic responses
- Poor compatibility with technologies used for optical materials



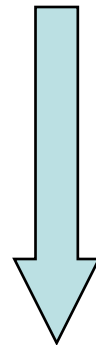
New approaches to metamaterial design



Combining two resonances  
in one resonator



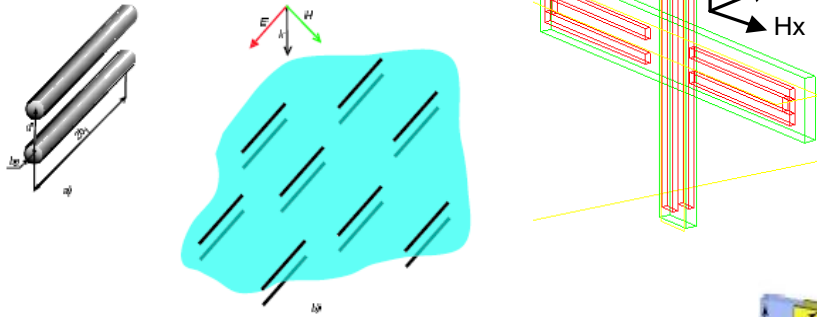
Introducing more suitable  
resonators



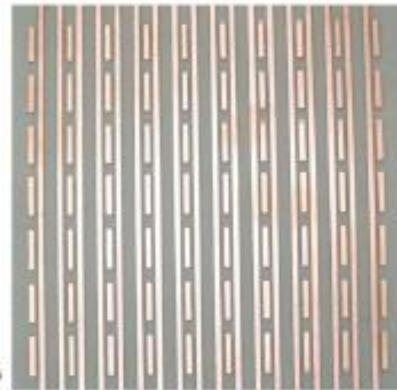
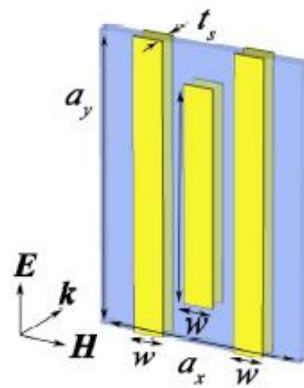
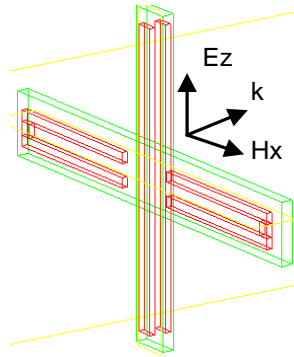
All-dielectric metamaterials

# From SRRs – to U-shape - to Paired Strips – to Fish-Net

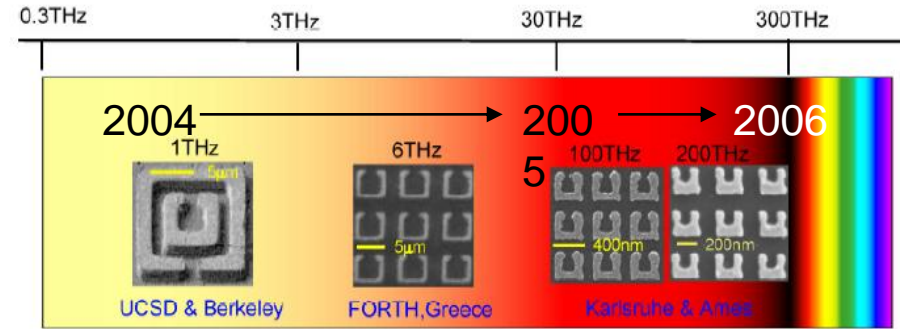
Podolskiy et al.,  
*J. Nonlinear Opt. Phys.*, 2002



Shalaev et al.,  
*Optics Express*, 2005;  
*J. Opt. Soc. Am. B*, 2006

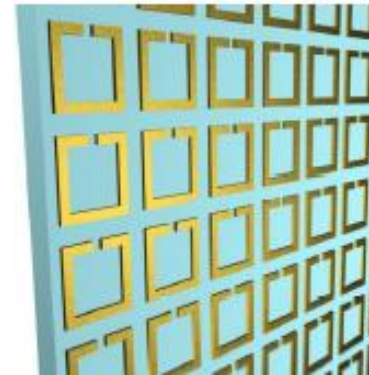


Zhou et al., *Phys. Rev. B*, 2006



After Fontainopoulou, 6<sup>th</sup> MetaPhD School,

2007



Fish-net



Infrared – Zhang et al., *Optics Express*, 2005, Doling et al., *Opt. Lett.*, 2006  
Scaling to microwaves and interpretation – Kafesaki et al., *Phys. Rev. B.*, 2007

Effective medium theory  
is not working

2. Towards dielectric metamaterials in frames of the effective medium theory.

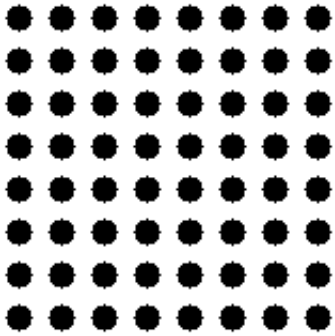
Composite materials

Isotropy and low loss expected

# The basics of a composite medium

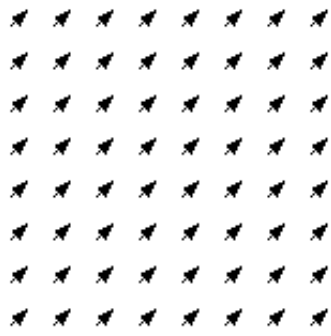
Each object (“atom” or “molecule”) has an electric polarizability  $\alpha_E$  and magnetic polarizability  $\alpha_M$  that lead to bulk (effective)  $\epsilon$  and  $\mu$

## Clausius-Mossotti Model



Array of polarizable scatterers

**Spherical “atoms”  
embedded in host material**



Array of dipoles provides for a continuous polarization density  $P$

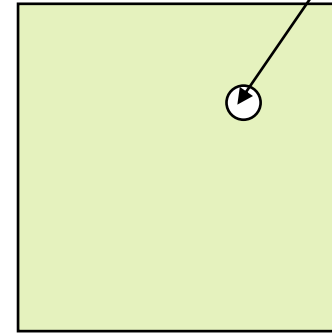
Each scatterer has dipole moment

$$\vec{d} = \epsilon_0 \alpha_E \vec{E}_{act}$$

It defines volumetric polarization density  $P$

$$\vec{P} = N\vec{d} = \epsilon_0 N \alpha_E \vec{E}_{act} = \epsilon_0 N \alpha_E \left( \vec{E} + \vec{P} / 3\epsilon_0 \right)$$

Local field acting on every dipole  $\vec{E}_{act}$  is due to source and fields from all other dipoles



Acting field is the macroscopic field minus that of the removed sphere:

$$\vec{E}_{act} = \vec{E} - \left( -\frac{\vec{P}}{3\epsilon_0} \right) = \vec{E} + \vec{P} / 3\epsilon_0$$

It follows:

$$\vec{P} = \epsilon_0 \frac{N \alpha_E}{1 - N \alpha_E / 3} \vec{E} = \epsilon_0 \chi \vec{E}$$

$$\epsilon_{r,eff} = 1 + \chi = \frac{1 + 2N \alpha_E / 3}{1 - N \alpha_E / 3}$$

Effective permittivity is a function of individual polarizability

# Polarizabilities of Spheres

*Mie resonances in spheres could lead to polarizabilities opposite in phase to  $E$  and negative permittivity behavior*

From the **Mie** scattering solution **Gans and Happel** (1909) and independently **Lewin** (1947) have obtained polarizabilities and then effective parameters of the composite

$$\alpha_E = 4\pi a^3 \frac{\epsilon_r F(\phi) - 1}{\epsilon_r F(\phi) + 2}$$

$$\alpha_M = 4\pi a^3 \frac{\mu_r F(\phi) - 1}{\mu_r F(\phi) + 2}$$

$$F(\phi) = \frac{2(\sin \phi - \phi \cos \phi)}{(\phi^2 - 1)\sin \phi + \phi \cos \phi}$$

$$\phi = k_0 a \sqrt{\mu_r \epsilon_r}$$

$$k_0 = 2\pi / \lambda$$

$$\epsilon_r = \epsilon / \epsilon_0; \quad \mu_r = \mu / \mu_0$$

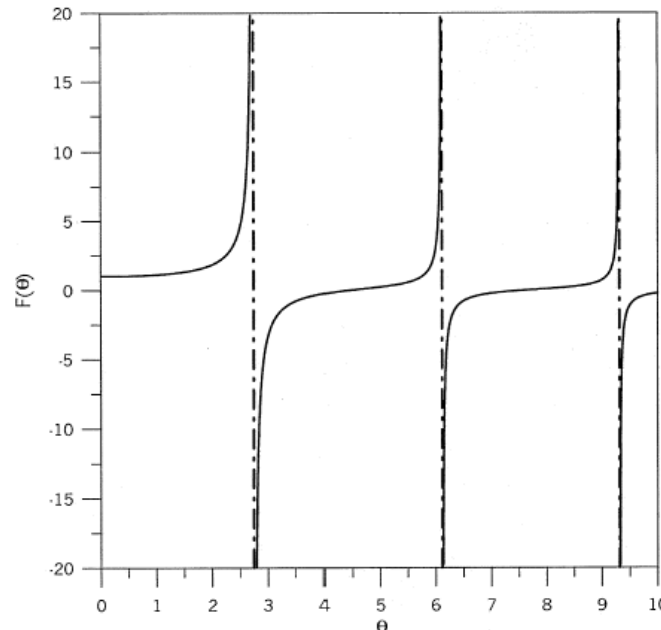
( $a$  - radius of sphere)

**Lewin**'s expressions for effective parameters  
(after **Holloway et al.**, *IEEE Trans. AP*, 2003)

$$\epsilon'_{re} = \epsilon_{r1} \left( 1 + \frac{3v_f}{\frac{F(\theta) + 2b_e}{F(\theta) - b_e} - v_f} \right)$$

$$\mu'_{re} = \mu_{r1} \left( 1 + \frac{3v_f}{\frac{F(\theta) + 2b_m}{F(\theta) - b_m} - v_f} \right)$$

$$v_f = \frac{4\pi a^3}{3p^3} \text{ volume fraction, } b_e = \frac{\epsilon_1}{\epsilon_2}, \quad b_m = \frac{\mu_1}{\mu_2}$$



Resonance dependence of  $F(\phi)$  on frequency

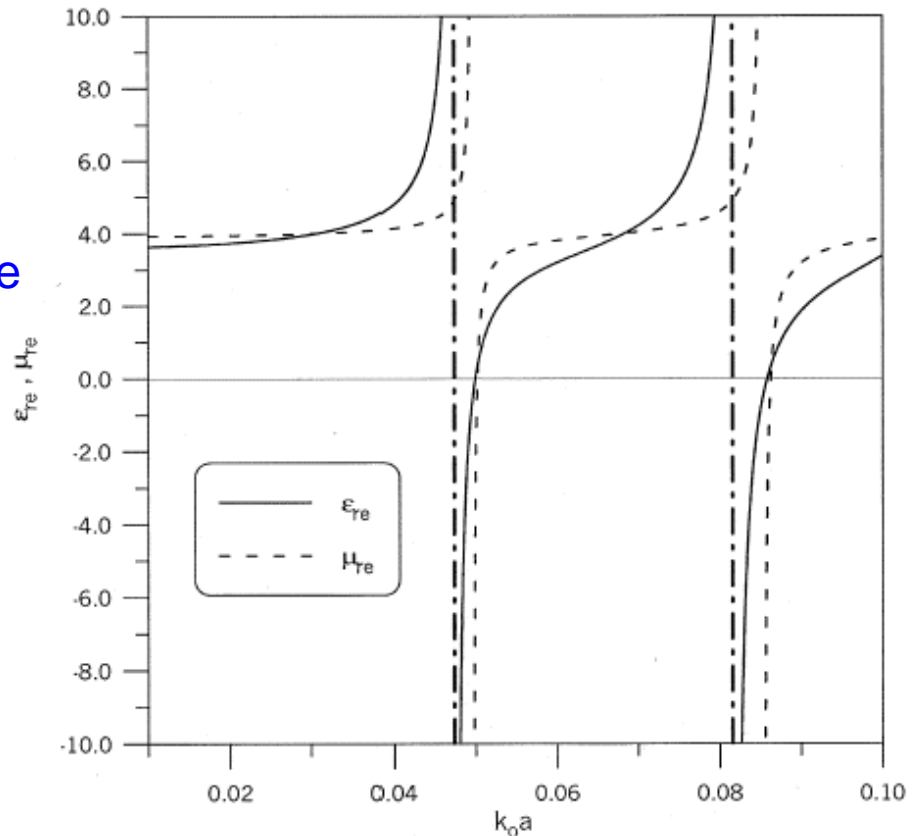
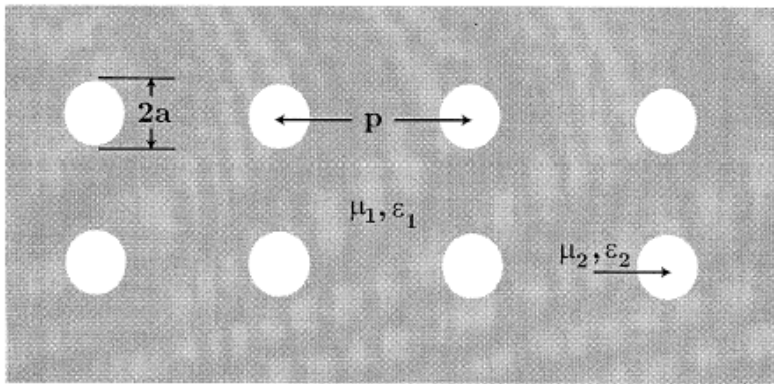
Caused by Mie resonances in spheres

$$\frac{(2n-1)\lambda}{2}$$

# Towards metamaterials

Holloway *et al.*, *IEEE Trans. Antennas & Propag.*, 2003

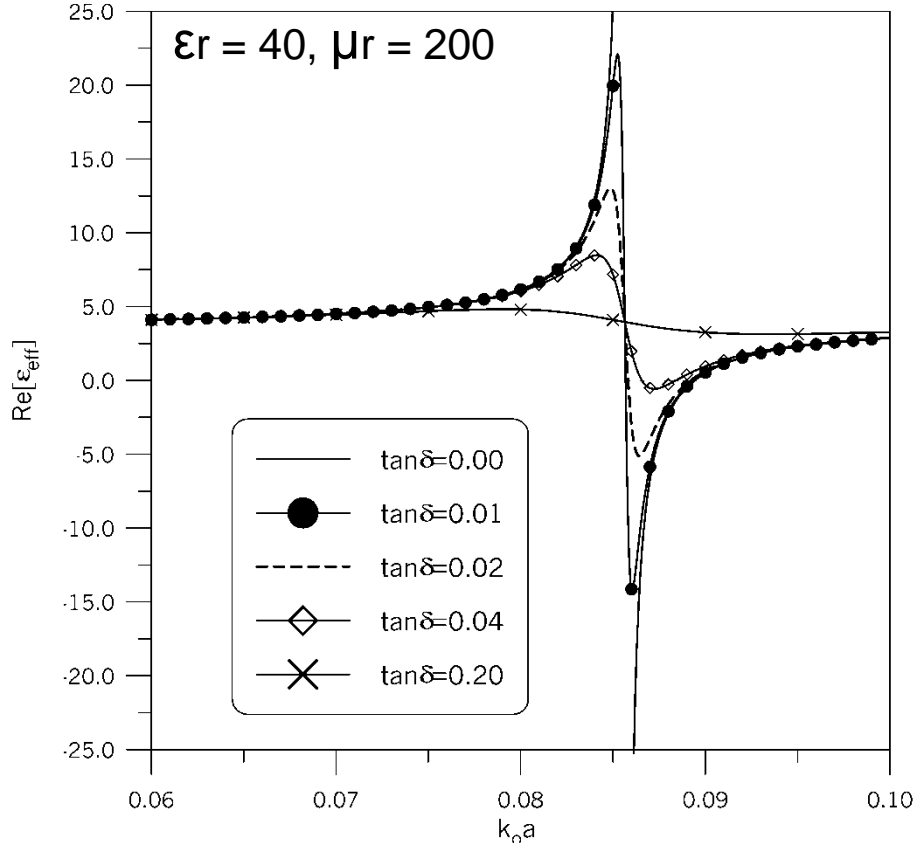
It is supposed that an array of magneto-dielectric spheres could provide a combined electric and magnetic response leading to double negativity



$\epsilon_{re}$  and  $\mu_{re}$  for  $v_f = 0.5$ ,  $\epsilon'_{r1} = \mu'_{r1} = 1$ ,  $\epsilon'_{r2} = 40$ , and  $\mu'_{r2} = 200$ .

*A proper choice of materials parameters formally provides a possibility to have both electric and magnetic resonance responses at the same frequency, however, a physical opportunity to have two modes excited simultaneously is doubtful*

# Magneto-dielectric metamaterial - unrealistic idea



*Most critical problem - losses*

$$\epsilon_r \rightarrow \epsilon_r (1 - j \tan \delta)$$

At  $\text{tg} \delta > 0.04$  permittivity fails to be negative

*Second problem – specifics of magnetic components*

Magnetic materials are unacceptably lossy and do not support high permeability above 3-5 GHz

*Third problem – solutions are suitable only for dipole-like resonance modes*

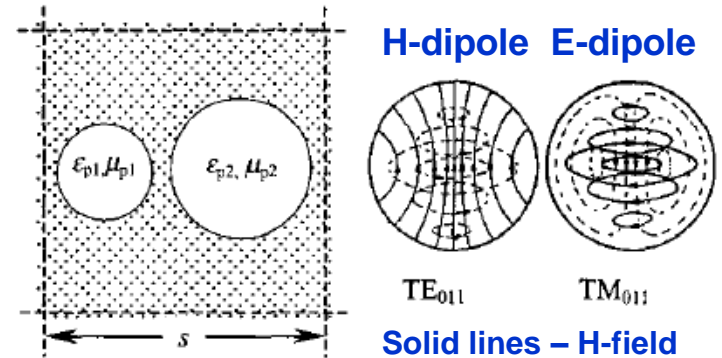
Full-wave ( $n\lambda$ ) resonances and other modes with field distributions are not reducible to linear dipoles cannot be taken into account ?

# An alternative – obtaining negative permeability due to magnetic resonance in additional dielectric spheres

Vendik and Gashinova, *34th EuMC, 2004*

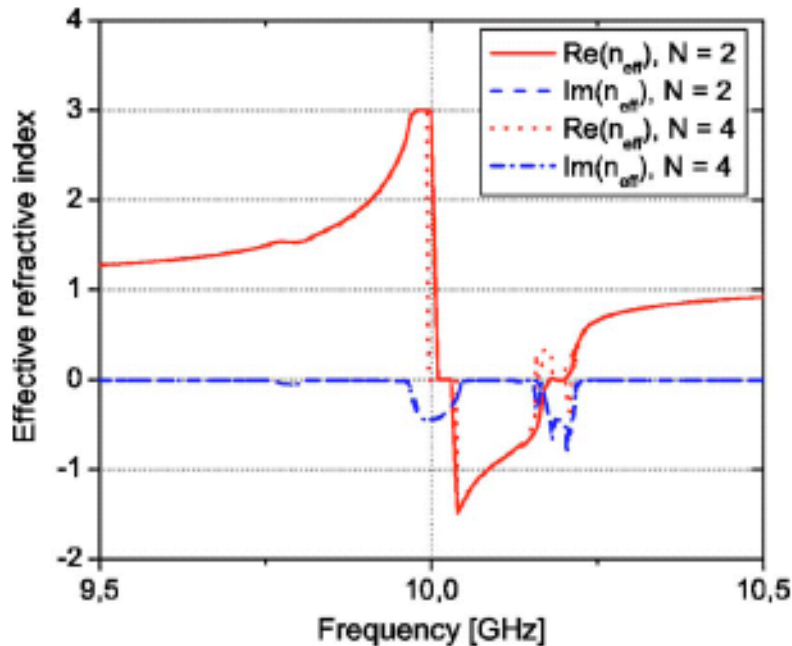
Application of Lewin's expressions to composite including dielectric spheres of two types

$\epsilon \sim$  up to 1000    Example:  $\epsilon = 400$ ,  $r_1 = 0.748$  mm,  $r_2 = 1.069$  mm,  $a = 4$  mm

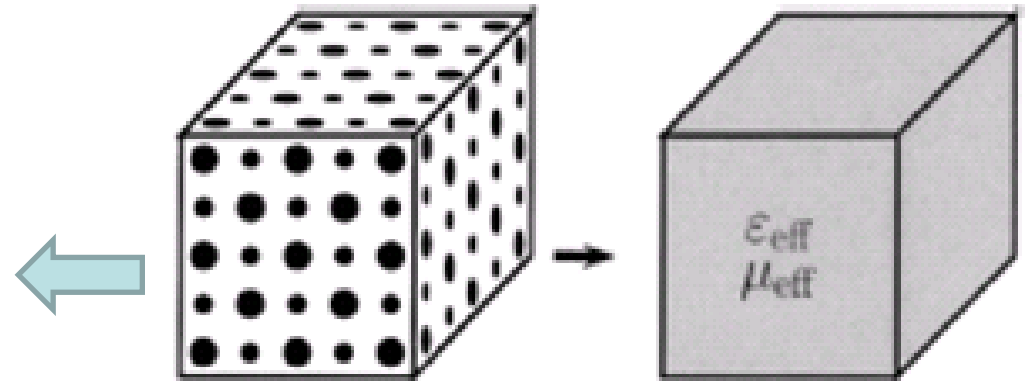


Conventional approach to metamaterial design – two superimposed arrays

*Kolmakov et al., Proc. URSI GA, 2005* – used Lewin-type expressions for a composite of two rod arrays,  
*Jylhä et al., JAP, 2006* – spheres of different size

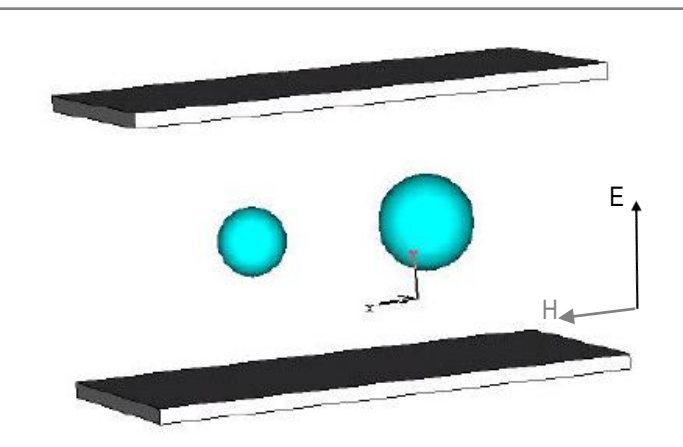


no experimental confirmation

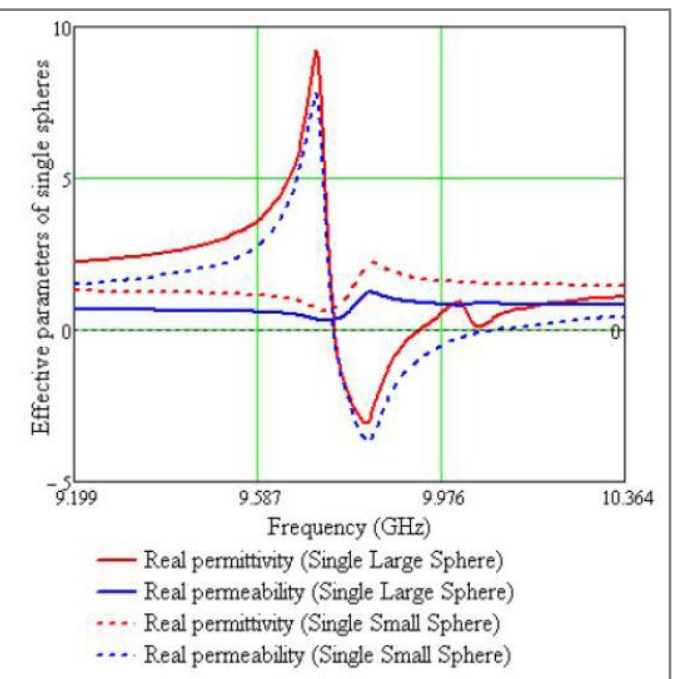


Same permittivity for spheres of two sizes:  $\epsilon \sim 44$ ,  
 $R_1 = 3.18$  mm,  $R_2 = 2.29$  mm, distance between centers  $\sim 10$  mm

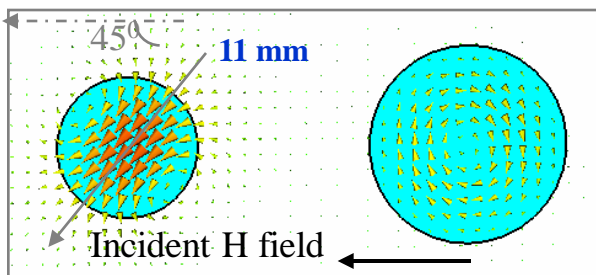
# Unit cell composed of two different sized spherical DRs



Permittivity of spheres =44,  
 $R_1=3.18\text{mm}$ ,  $R_2=2.29\text{ mm}$

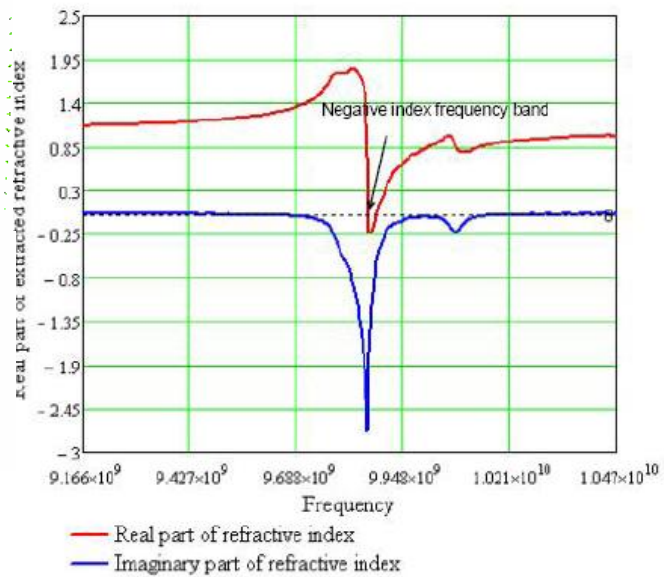
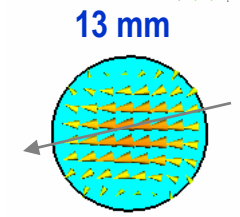
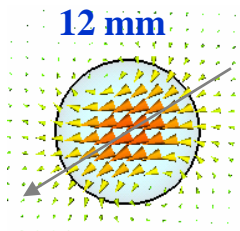


Top view on magnetic field distributions at separation between the spheres:

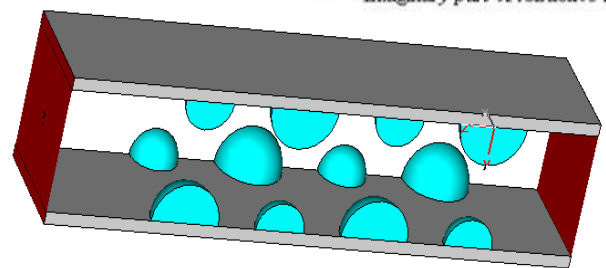


Coupling between spheres changes orientation of magnetic dipole formed in the small sphere

Only at 12 mm distance the index of refraction becomes negative in a very narrow band



These data do not agree with the results by Jylhä *et al.*, where negative index was observed in a wider band



Jylhä *et al.* used PMC and PEC boundary conditions at modeling quarters of spheres that excluded any rotational freedom of the modes

## *Problems of composites from dielectric spheres*

- **coupling between resonators can make effective medium theory inapplicable**
- **adjusting two resonances is a serious challenge for fabrication tolerance because of narrow bands**
- **ceramics technologies are still not ready to process composites of spheres with “optical” dimensions**

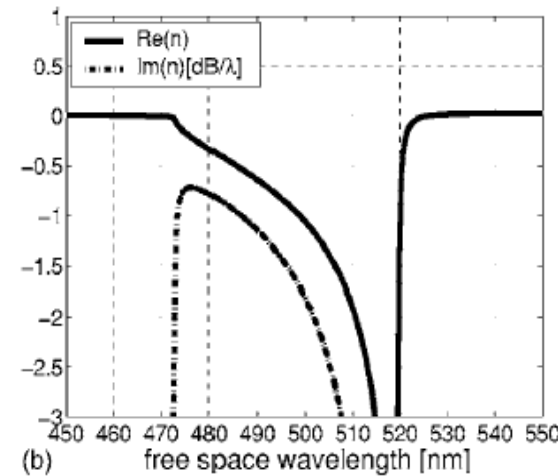
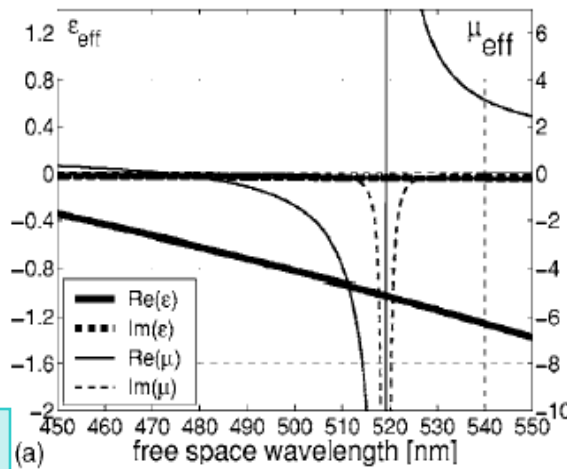
# Potential solution – dielectric spheres embedded in a material with negative permittivity

Seo et al., Appl.Phys.Lett., 2006 - to avoid fabrication tolerance problems

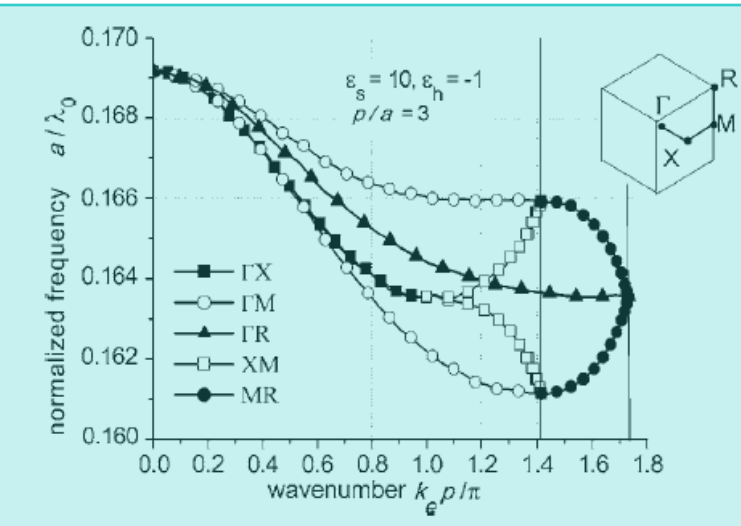
GaP spheres of 72 nm in Cs medium (volume fraction – 0.2)

$\epsilon = 12.25$ , for Cs -plasma frequency is  $0.41 \mu\text{m}$

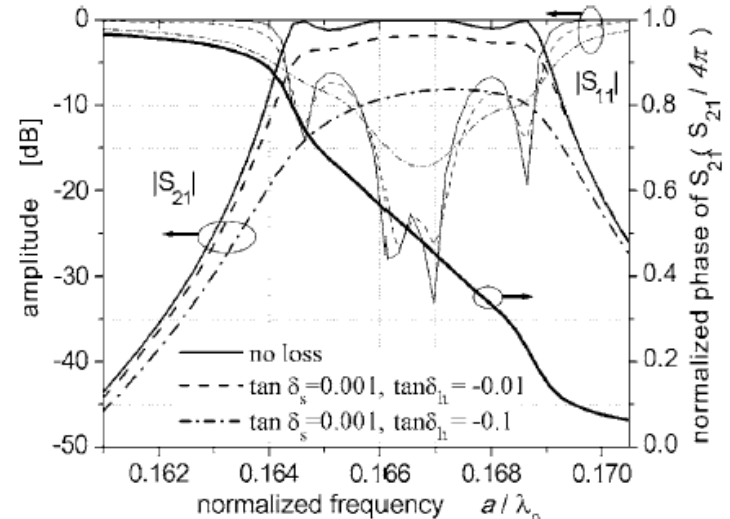
## Dispersion diagram



Negative refraction appears near TE resonances in dielectric spheres



$\frac{\partial \omega}{\partial k} < 0$  -left-handed bands for all propagation directions



Phase at the output port becomes advanced in the transmission band – backward wave propagation

When K is small – waves do not see particles

At  $f=0.1685$  – almost isotropic properties

Relatively wide band

# Composites for optics can use polariton resonances

V. Yannopoulos and A. Moroz, *J. Phys.: Condens. Matter*, 2005

Two arrays of spherical particles  
 one - from polaritonic material  
 another – from Drude-like material

LiTaO<sub>3</sub>

**Polaritonic spheres**

$$\epsilon(\omega) = \epsilon_{\infty} \left( 1 + \frac{\omega_L^2 - \omega_T^2}{\omega_T^2 - \omega^2 - i\omega\gamma_1} \right)$$

$\gamma$  - loss factor,  $\omega_T$  and  $\omega_L$  -  
 transverse and longitudinal  
 optical phonon frequencies

$$\omega_L = \omega_T \sqrt{\epsilon(0)/\epsilon_{\infty}}$$

$$\mu < 0$$

$$\omega/\omega_T = 0.900 \text{ to } 0.948$$

$$\omega_T/2\pi = 26.7 \text{ THz}$$

n-Ge

**Semiconductor spheres**

near bulk plasma frequency

$$\epsilon(\omega) = \epsilon_0 \left( 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma_2} \right)$$

$$\epsilon < 0$$

$$\omega_p = \omega_T \quad \omega_p \approx \sqrt{n_{d,a}}$$

Similar idea and results –

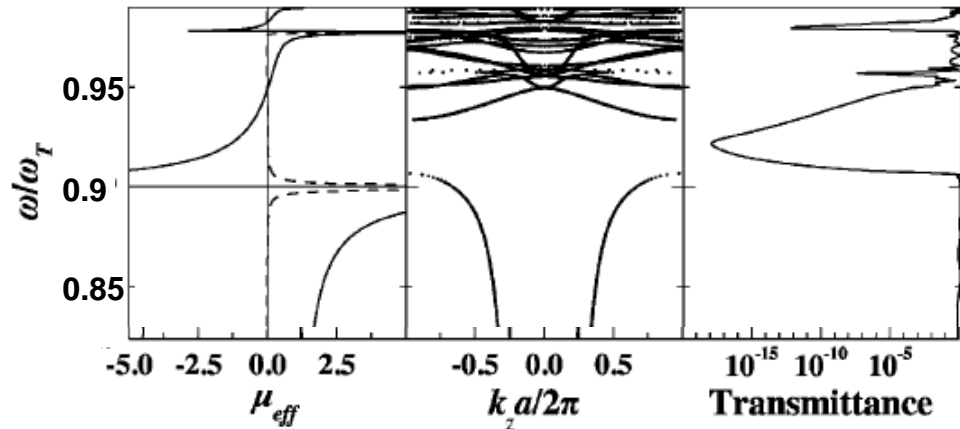
*Wheeler et al. , Phys.Rev.B, 2005*

SiC, TlBr, TlCl could give range 8.1- 149 THz

# Effective parameters

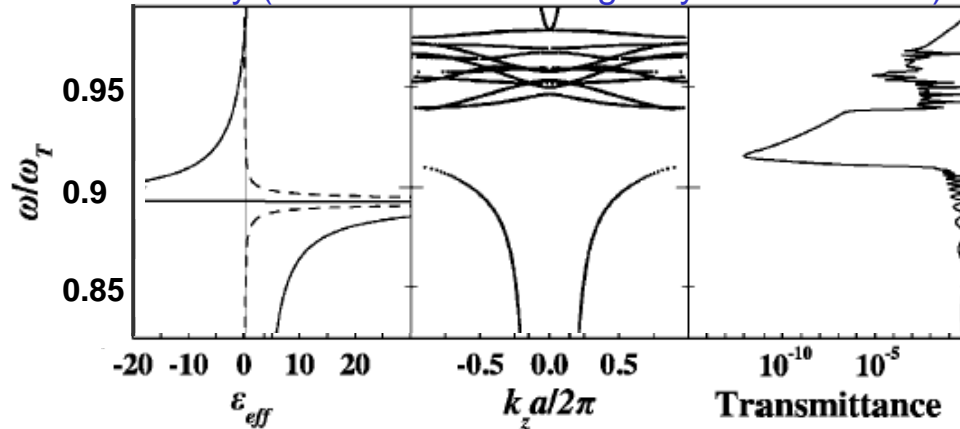
## Array of polaritonic spheres

$\mu_{eff}$  predicted by extended Maxwell–Garnett theory ( real - solid and imaginary - broken lines)

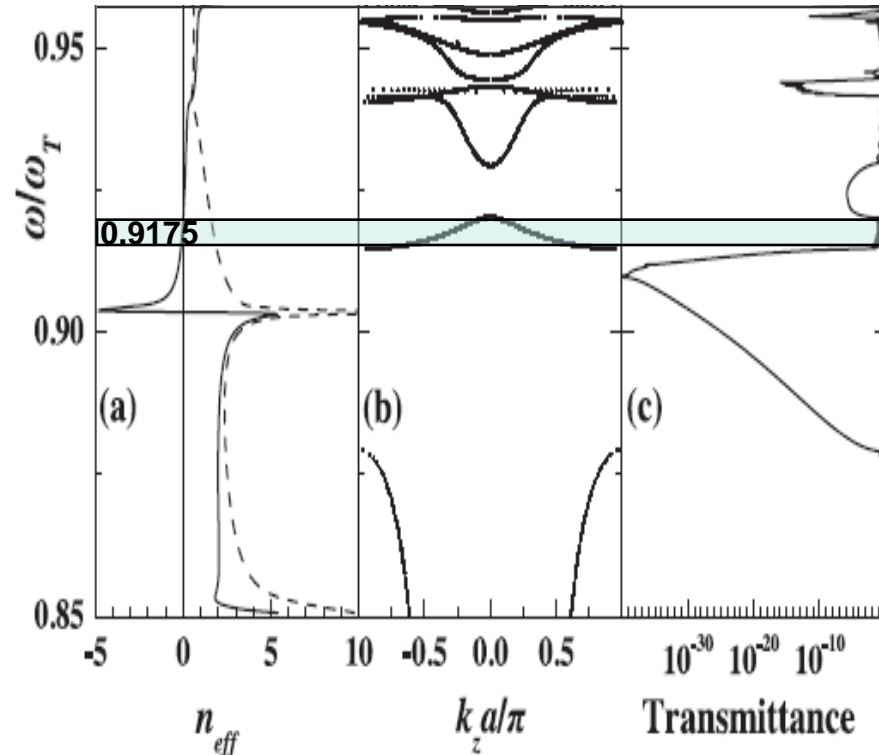


## Array of semiconductor spheres

$\epsilon_{eff}$  predicted by extended Maxwell–Garnett theory ( real - solid and imaginary - broken lines)



## Metamaterial



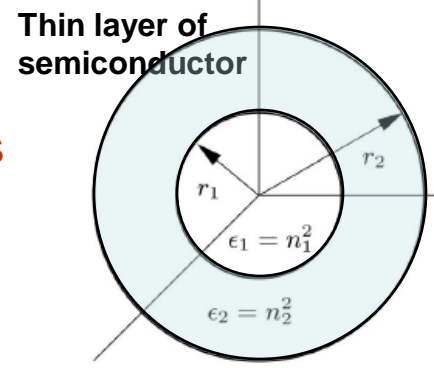
Peak transmission is observed at the area of negative refraction band

*Truly subwavelength structure with  $\lambda/a(r)$  ratio as high as 14:1*

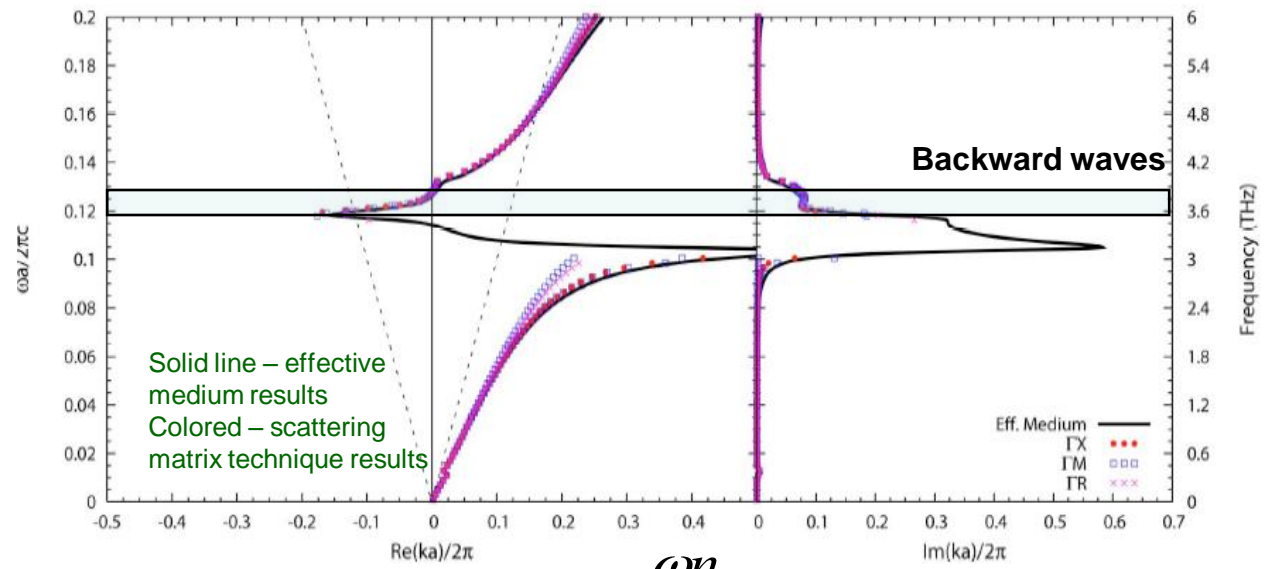
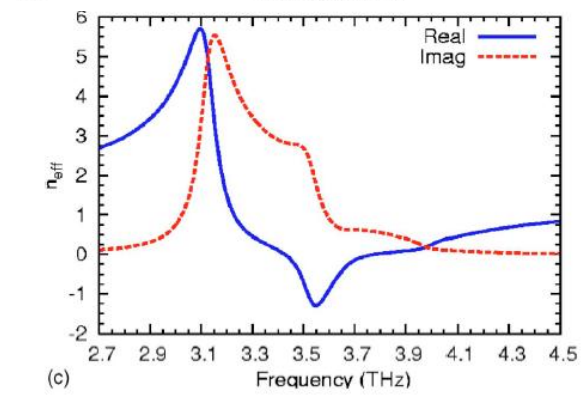
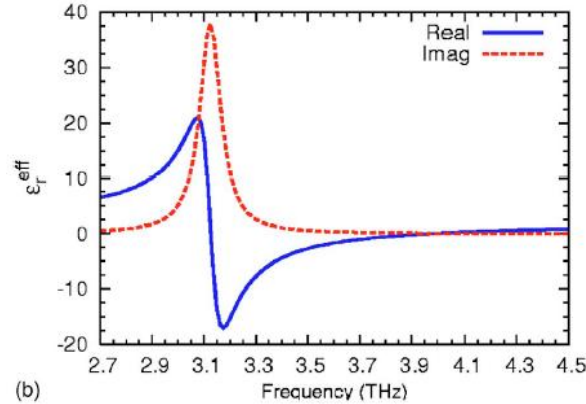
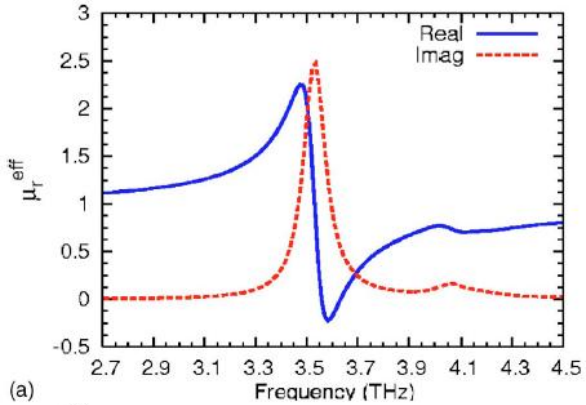
# Step back – “two spheres in one”

Wheeler *et al.*, *Phys.Rev.B*, 2006

LaNbO<sub>3</sub> polaritonic spheres coated with a thin layer of Drude material



To avoid interaction between two resonances they are shifted in frequency



$$k = \frac{\omega n_{eff}}{c} < 0, \text{ if } n_{eff} < 0$$

Backward waves are seen when

$$v_p = \omega / k < 0 \quad v_g = \frac{\partial \omega}{\partial k} > 0$$

Still no experimental confirmation

### 3. Beyond the effective medium theory - arrays of coupled dielectric resonators

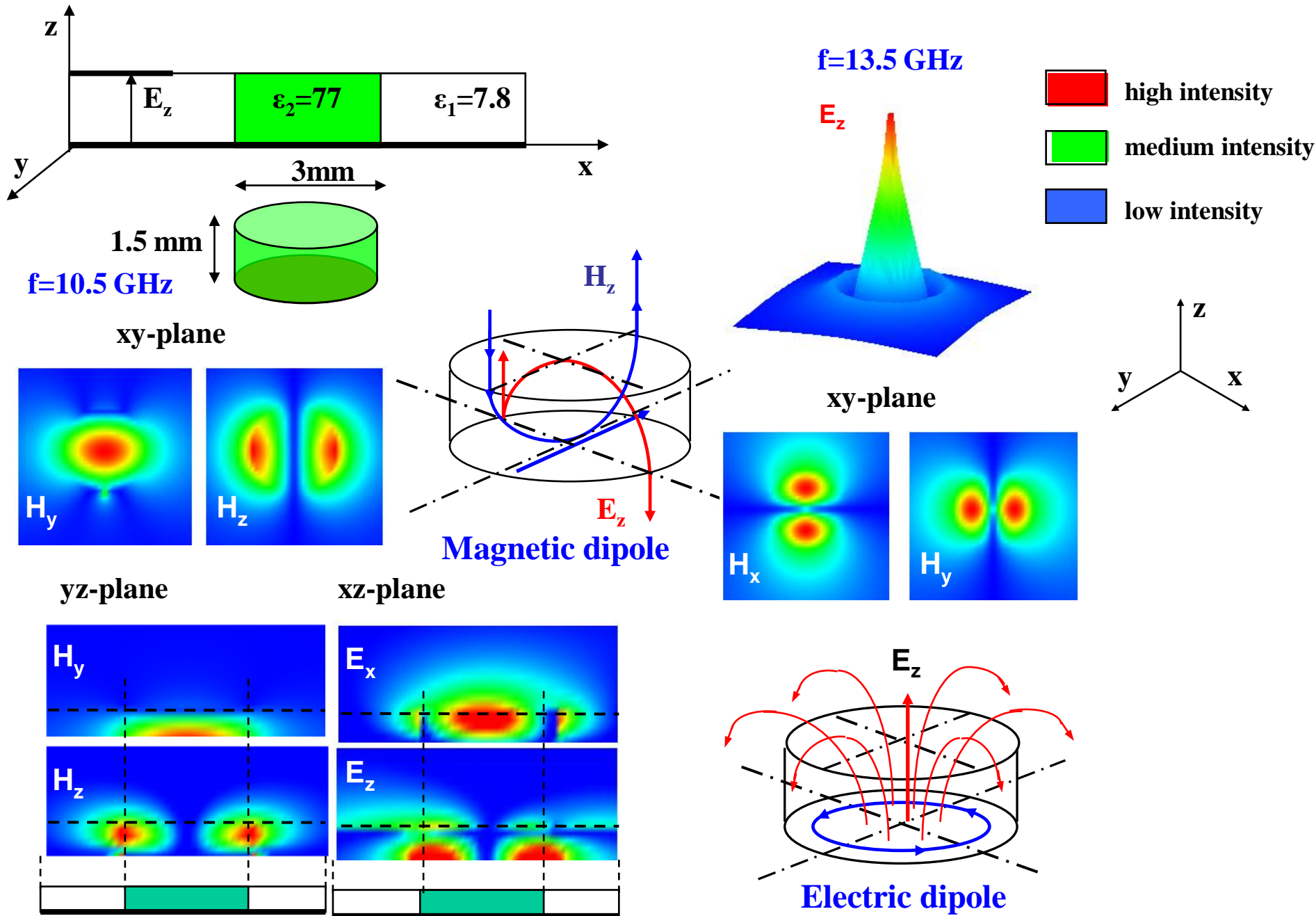
Semouchkina *et al.*, *Proc.IASTED*, 2004

Semouchkina *et al.*, *IEEE Trans.  
Microwave Theory & Techn.*, 2005

Ueda and Itoh, *Digest of Nat.Radio Sci.  
Meeting*, 2006

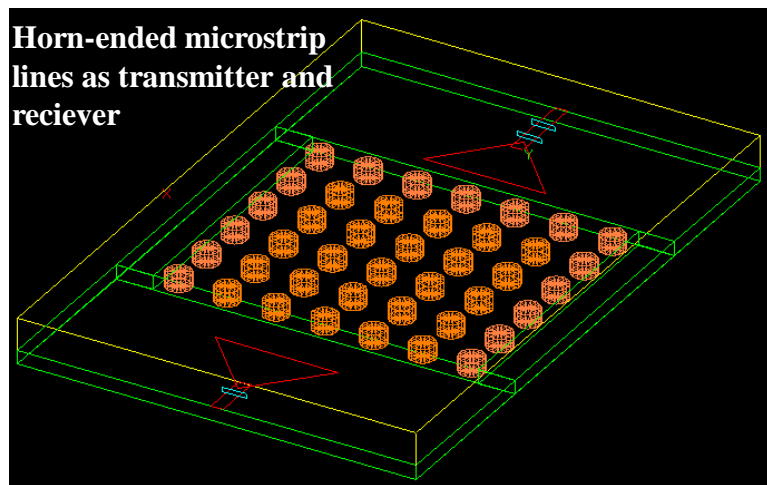
T. Ueda and T. Itoh, *PIERS 2006-Tokyo  
Abstracts*, 2006.

# Resonance modes in a Cylindrical Dielectric Resonator



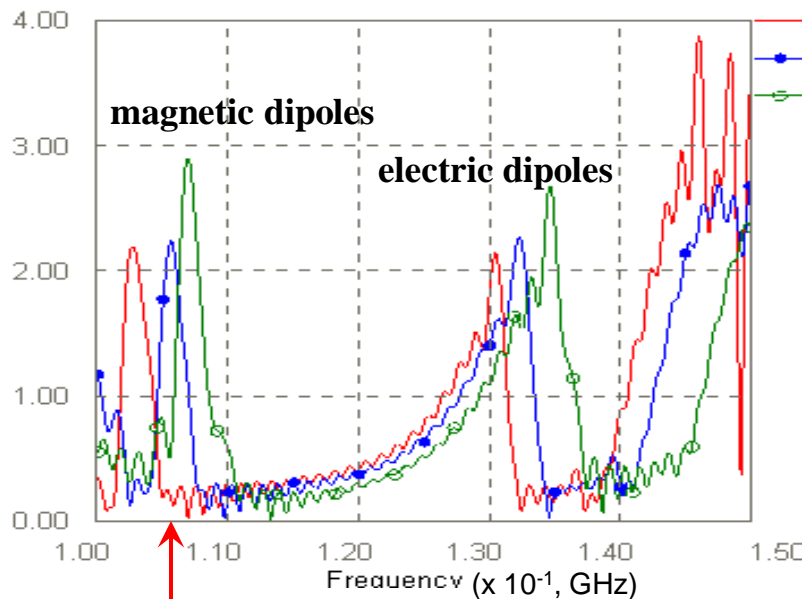
# FDTD modeling of transmission through DR arrays

Schematics of simulation

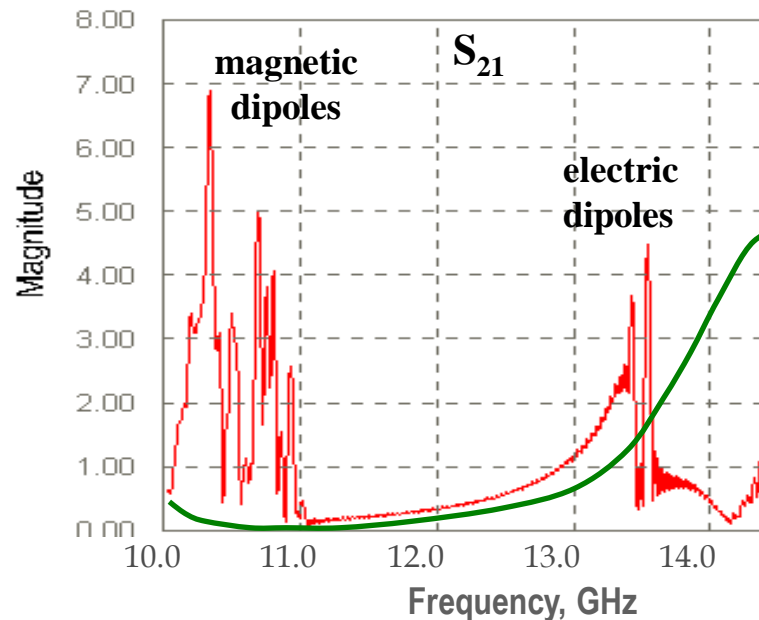
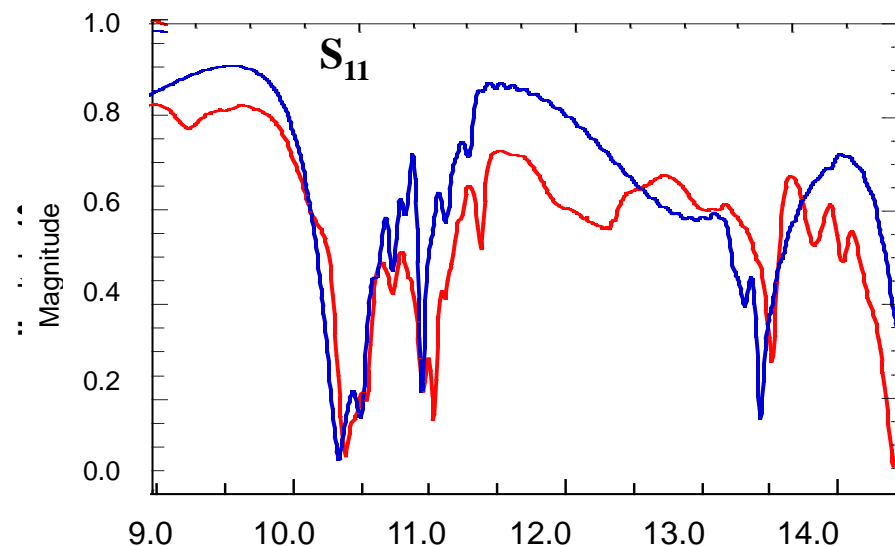


Diameter of DRs  $\Theta = 2.64$  mm,  
lattice parameter  $\alpha = 6.24$  mm,  $\epsilon = 62$

$S_{21}$  ( $\times 10^2$ )

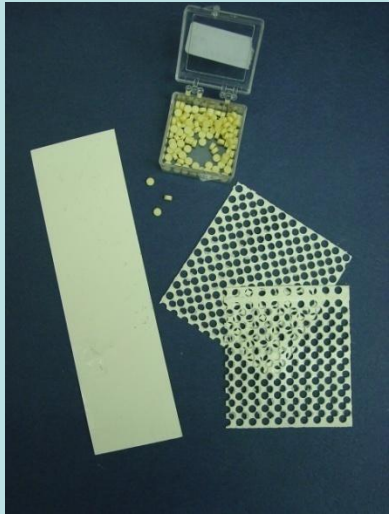


$$\lambda_{air} = 28.6\text{mm} = 10.8\theta = 4.58\alpha$$

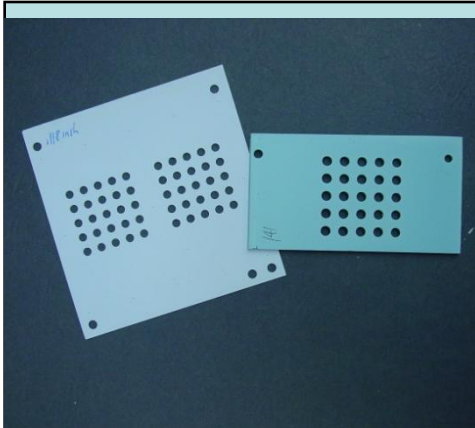


Two split bands of enhanced transmission

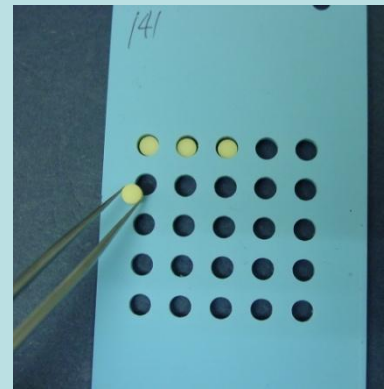
# Overview of the Fabrication process



Cylindrical resonators are punched from a laminated stack of Bismuth-Zinc-Tantalate low temperature cofired ceramic (LTCC) tape). The resonators are fired to 875° C.

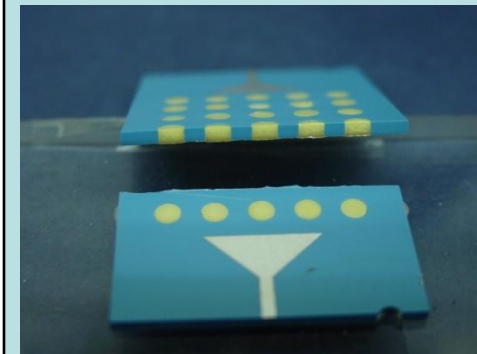


Matrix “trays” are created from a laminated stack of low-K commercial cofired ceramic tape. Holes are punched to allow for precise resonator placement. Hole diameter is larger than one of fired resonators.



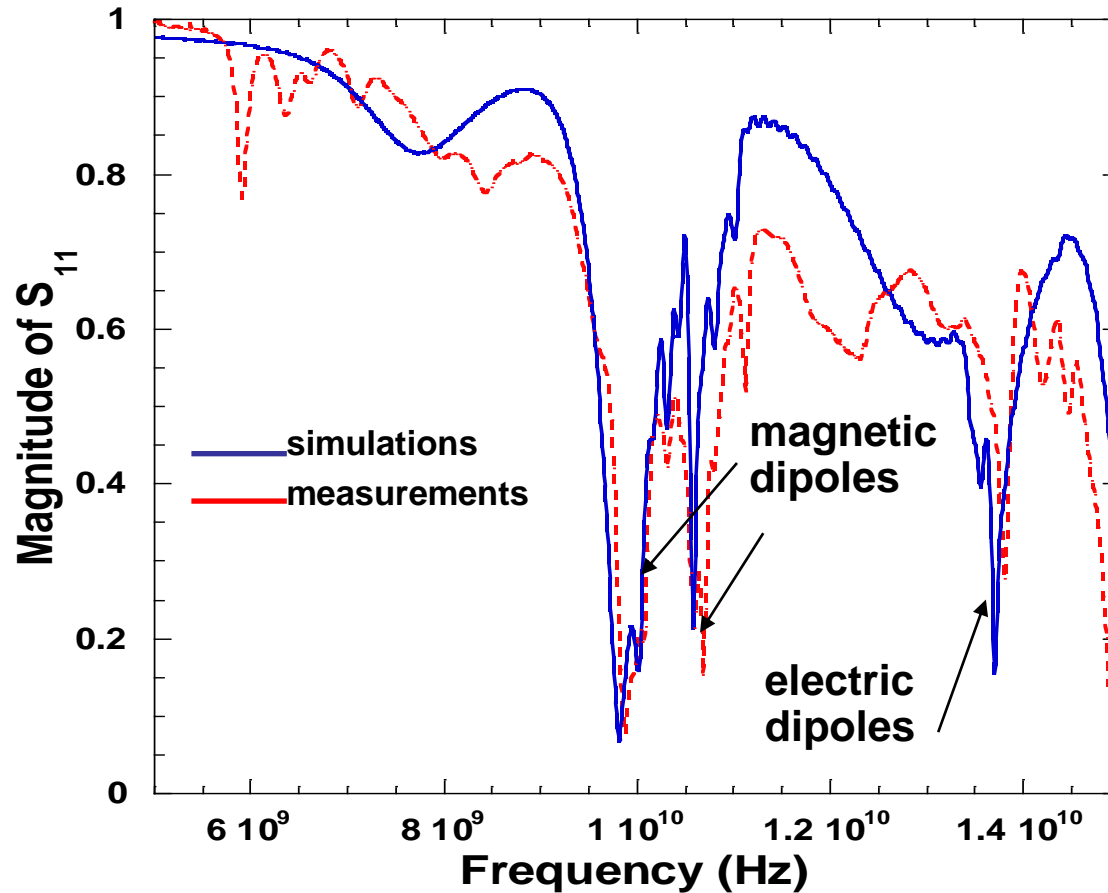
Fired resonators are placed in each hole of the matrix tray and then fired to 850° C. During the firing cycle, the matrix LTCC shrinks around the fired resonators.

Silver ground plane and microstrip horns are printed and fired using a post-fire process.

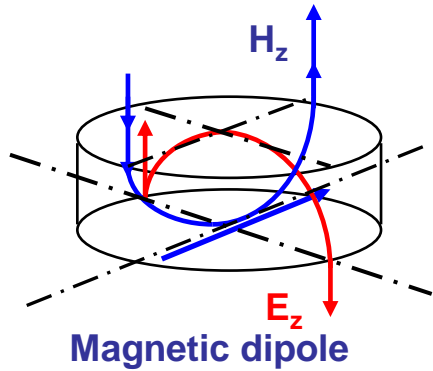


Above: cross-sectional view of finished metamaterial structure: resonator diameter-3 mm, height-1.5 mm, lattice constant-5.6 mm

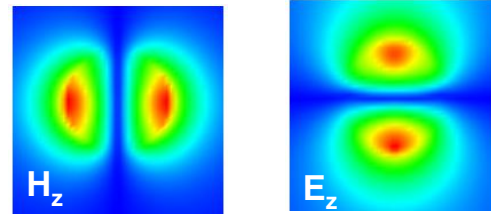
# Comparison of Simulated and Experimental Data



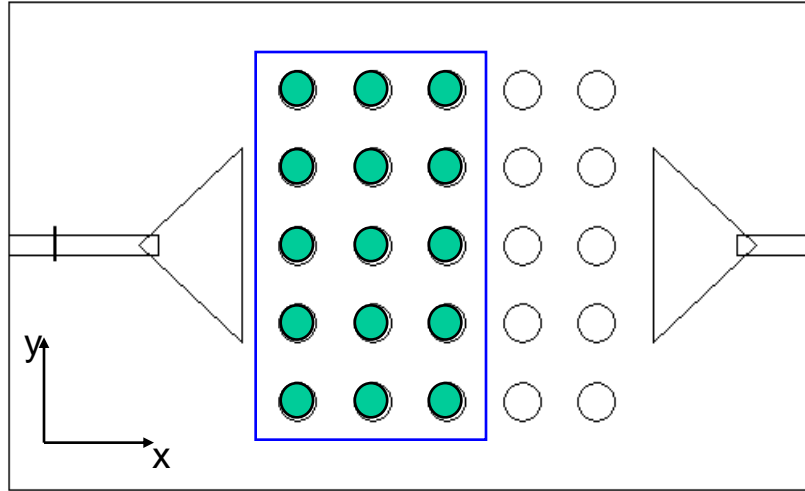
# Resonant Coupling in array of DRs



Median xy-cross-section

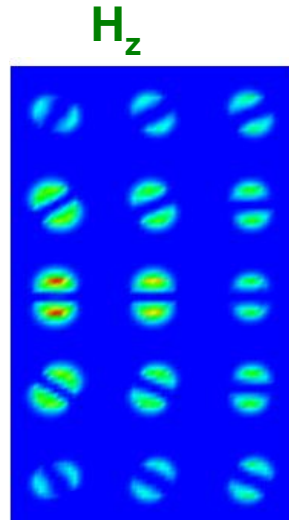


Amplitude distributions of magnetic and electric field oscillations

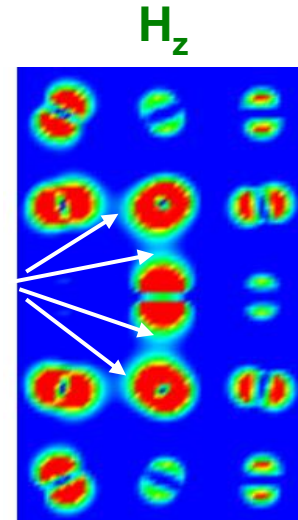


Area of field control

Magnetic dipoles turn to be codirected with magnetic field of incident wave



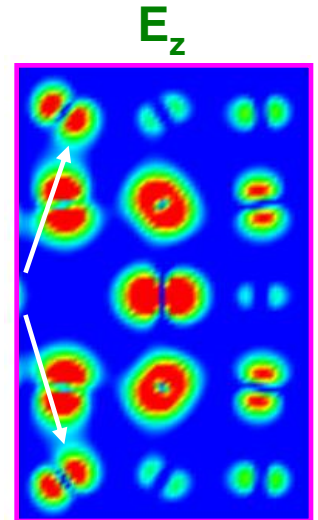
9.75 GHz  
below resonance



10.5 GHz

Magnetic Coupling

Rotational invariance of modes leads to their re-orientation at resonance coupling between DRs



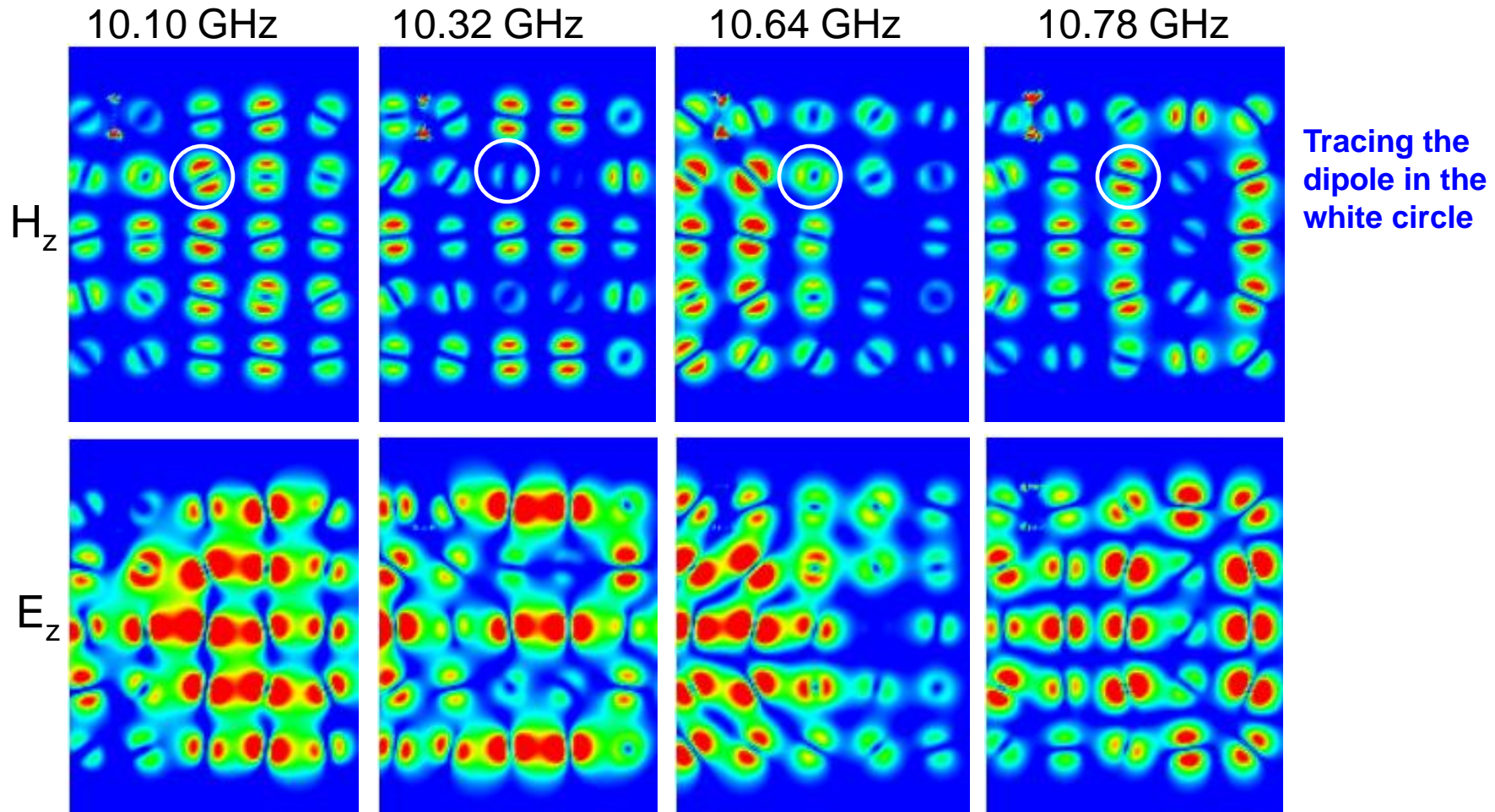
10.5 GHz

Electric Coupling

Coupling can contribute to enhanced wave propagation

# Change of Resonance Patterns with Frequency

## Square Lattice, Magnetic resonance



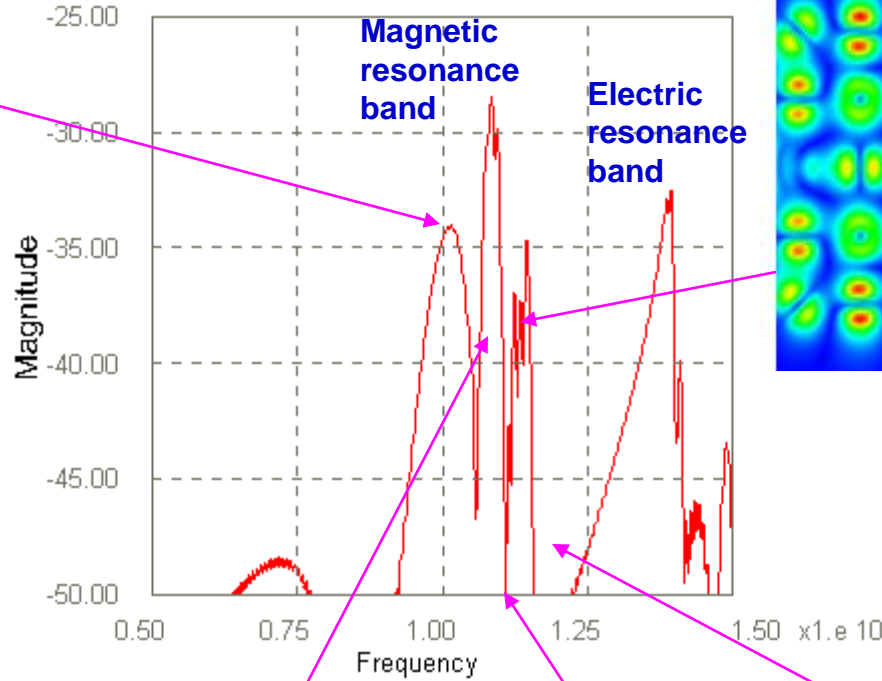
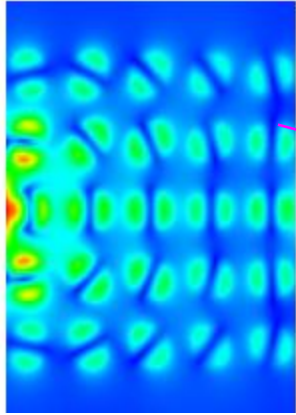
Chains of coupled fields – mostly transverse for magnetic field and longitudinal – for electric fields

Flash-like resonances and rotation of dipoles to couple with proper neighbors

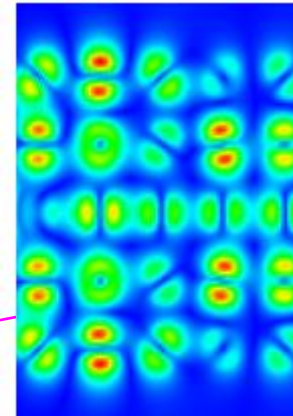
*Similar to resonances in conventional metamaterials*

# Resonant Coupling of Magnetic Dipoles

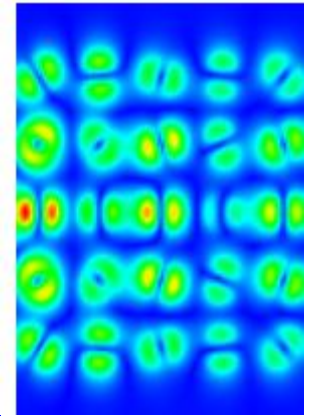
10.0 GHz



11.35 GHz



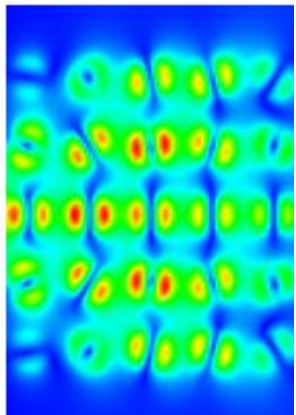
11.4 GHz



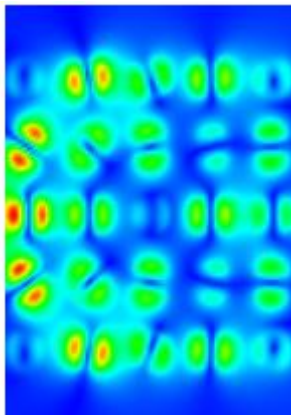
$E_z$  in XY-plane

Band Gap

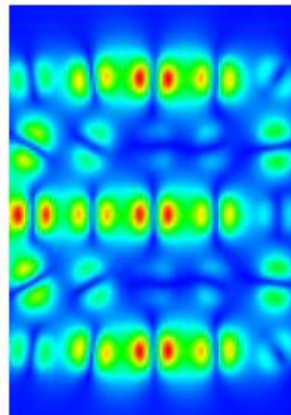
10.7 GHz



10.8 GHz

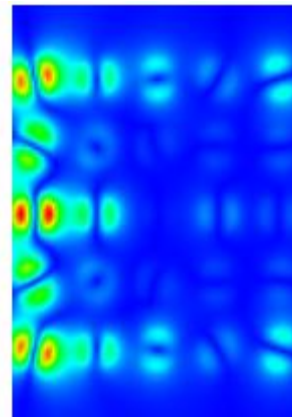


10.95 GHz

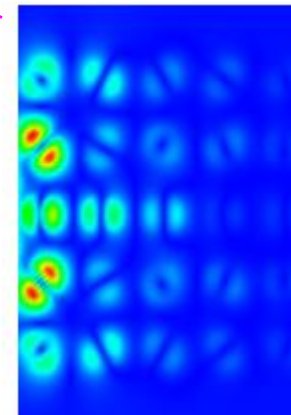


-50 dB

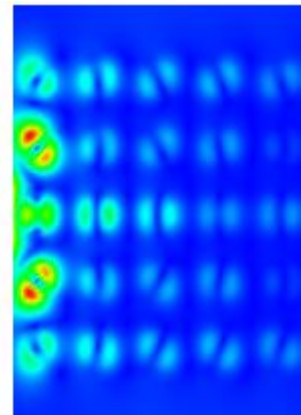
11.05 GHz



11.65 GHz

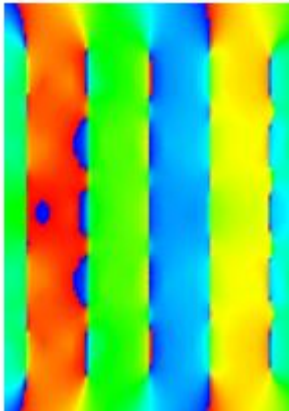
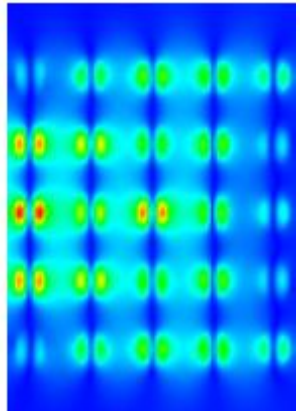


12.0 GHz

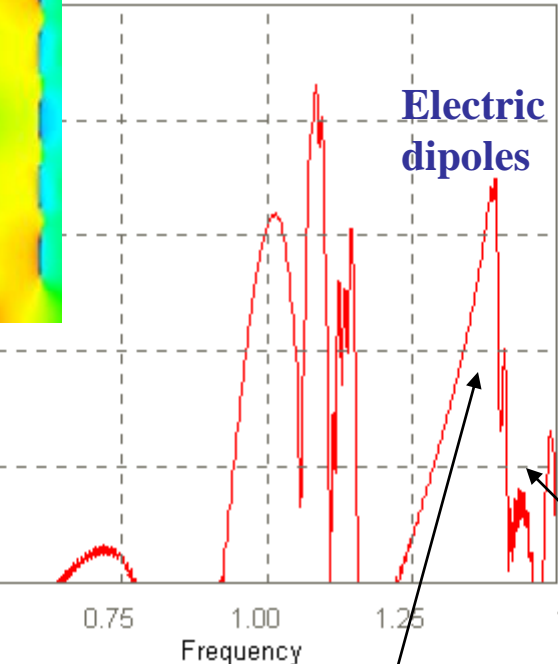


# Resonant Coupling of Electric Dipoles

$H_y$  in XY-plane,  
13.95 GHz

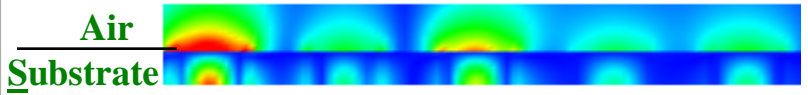


**Magnetic coupling**

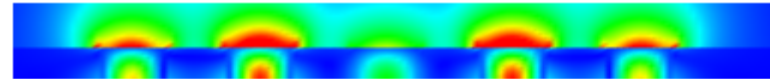


$E_z$

XZ-median cross-section, 14.0 GHz



YZ-cross-section through second row, 14.0 GHz



$E_z$  in XY-plane

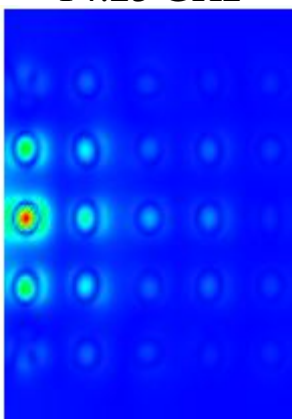
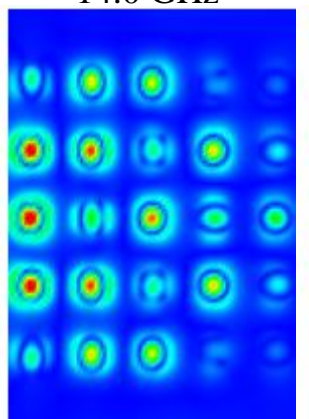
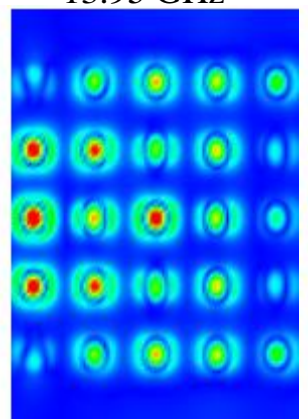
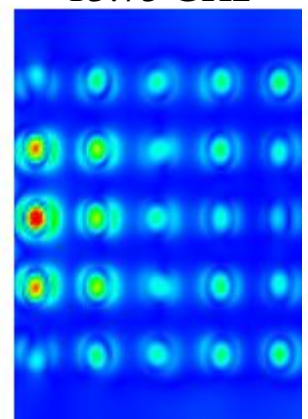
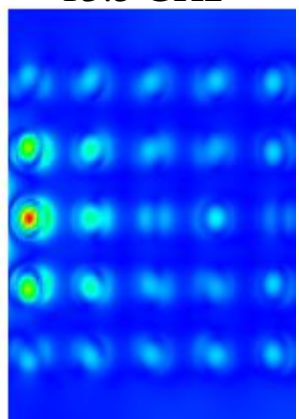
13.5 GHz

13.75 GHz

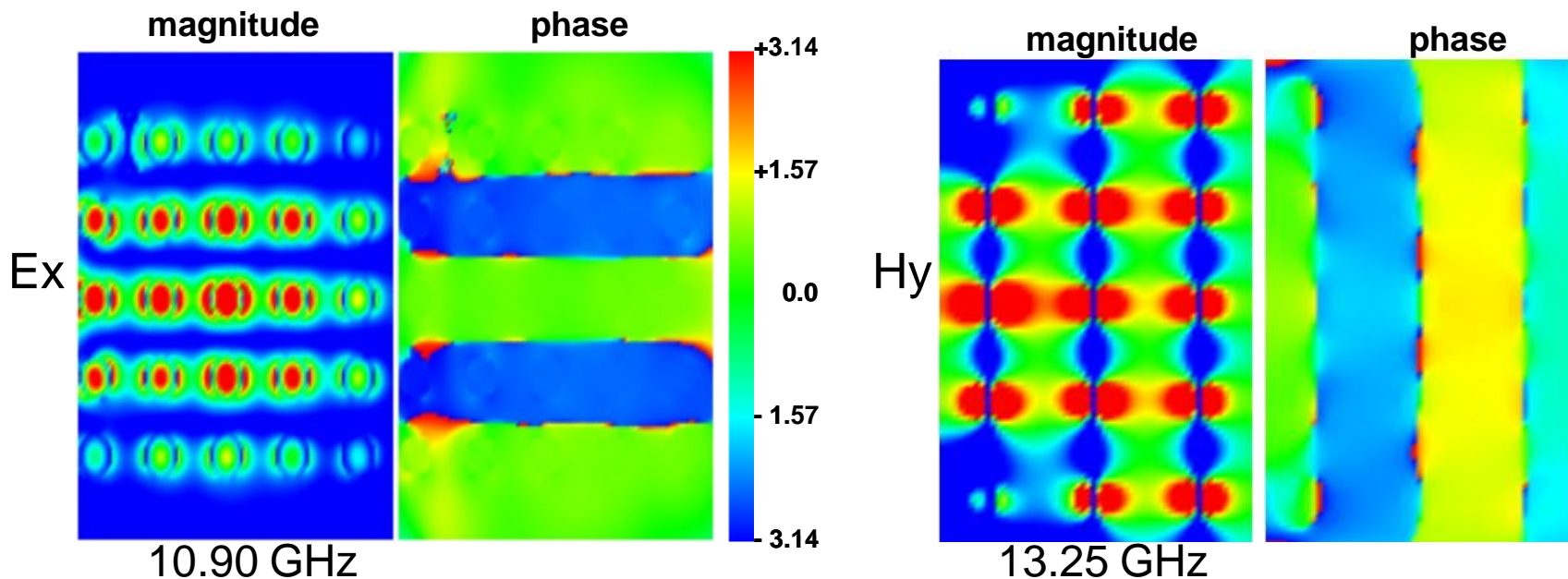
13.95 GHz

14.0 GHz

14.25 GHz

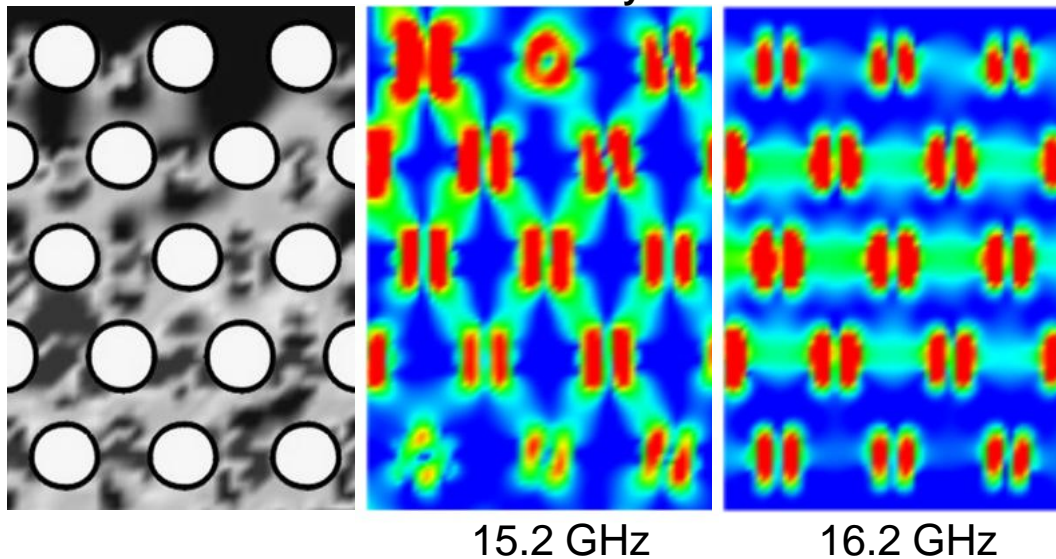


# Formation of Electric and Magnetic Laminar Superstructures



## Specifics of Coupling Patterns in DR arrays at higher frequencies

$H_y$  amplitude



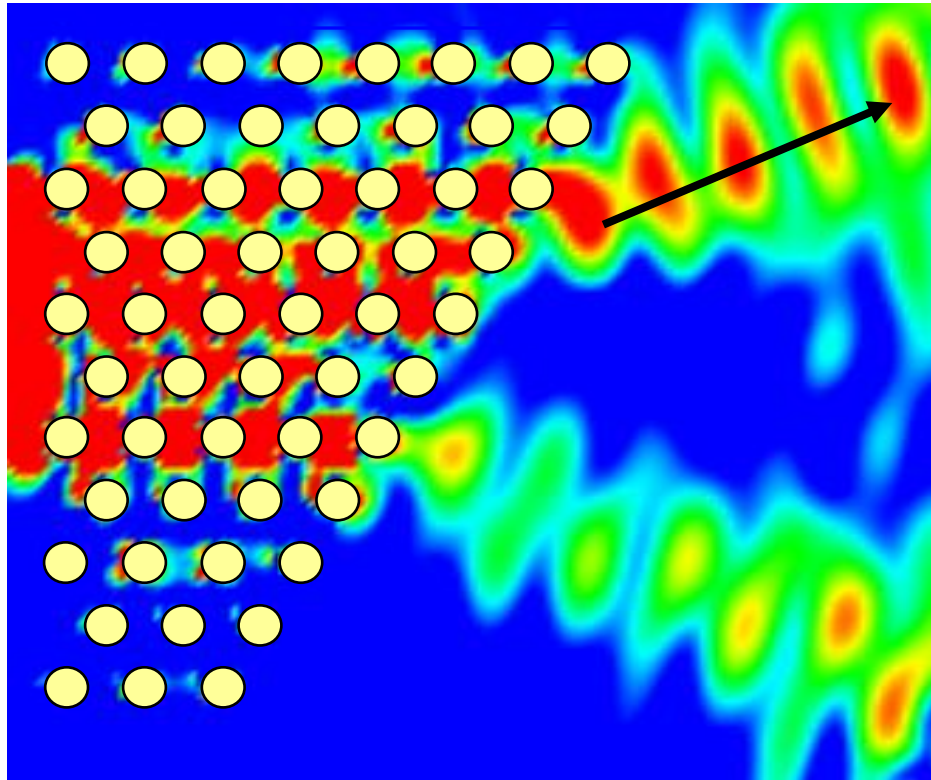
$$\lambda_{air} = 19 - 20 \text{ mm} \approx 7.5\theta \approx 3\alpha$$

EM coupling resembles  
chemical bonds

# Wave Propagation through Prism of DRs

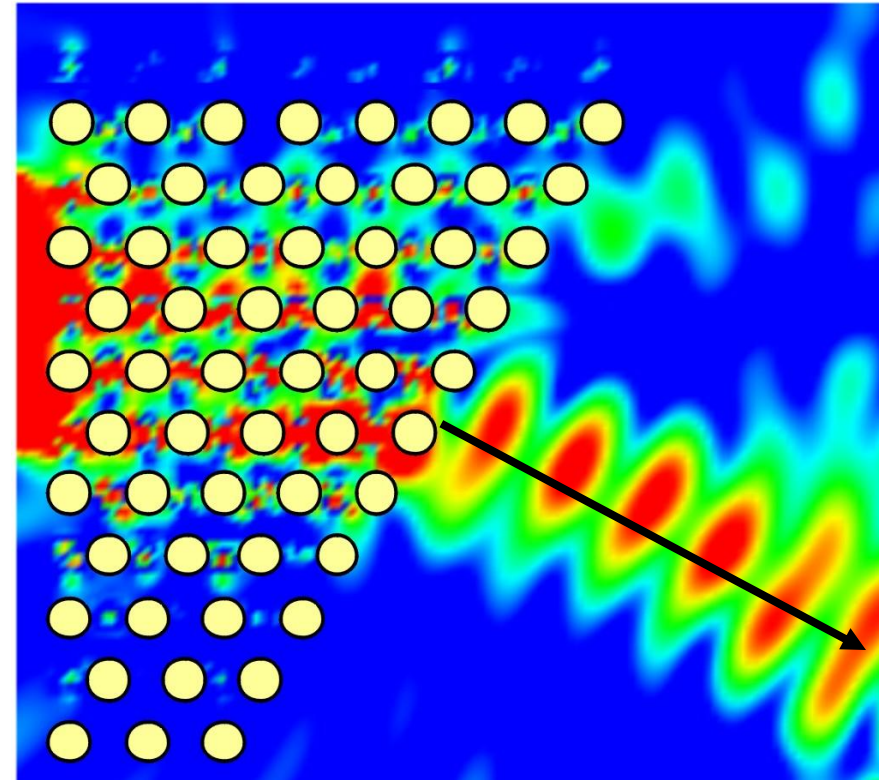
Rhomboid lattice

$f=16.0$  GHz



Positive beam refraction

$f=16.9$  GHz



Negative beam refraction

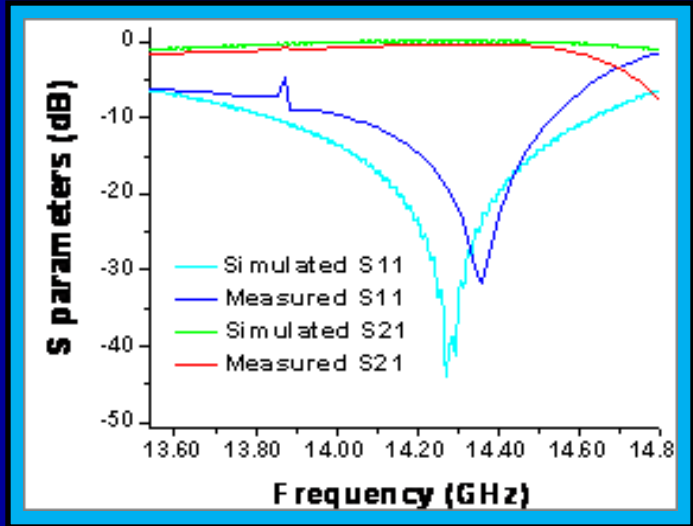
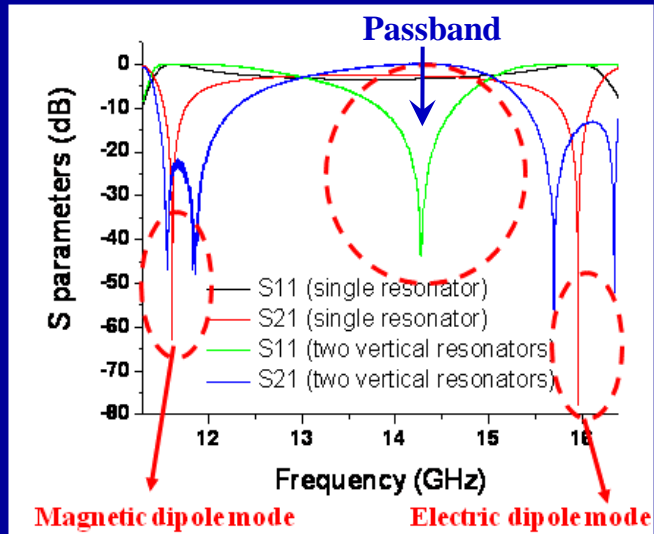
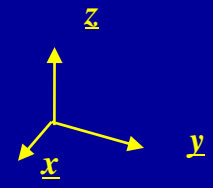
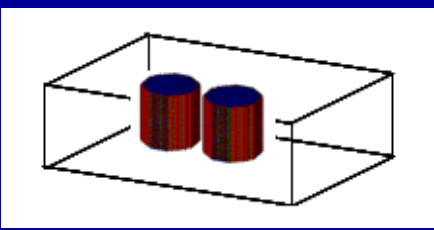
Substrate:  $K=77$ , DRs:  $K=7.8$

# Unit cell composed of two similar sized cylindrical DRs

Diameter and height ~ 4 mm,  $\epsilon = 35.5$

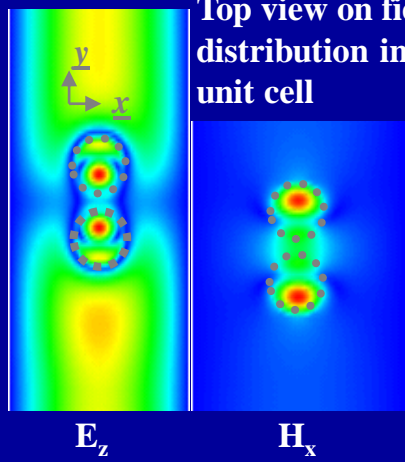
TE<sub>10</sub> mode wave propagation in y-direction, spacing between resonators is 5 mm

EM responses of single resonators and of a unit cell

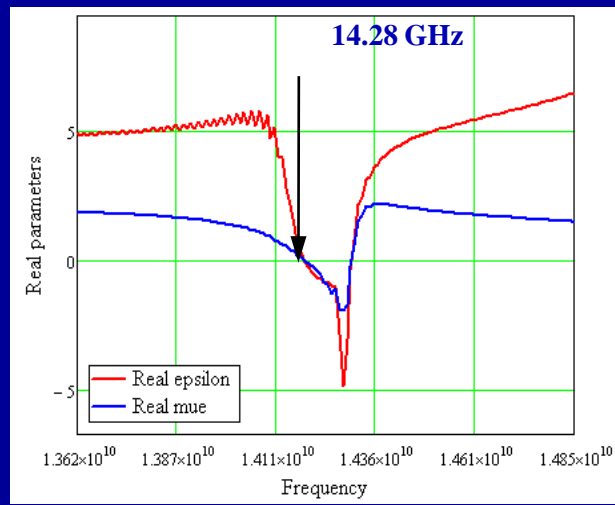


Experiments confirm enhanced transmission and drop in reflections at inter-resonance frequency

Passband revealed between two resonance frequencies

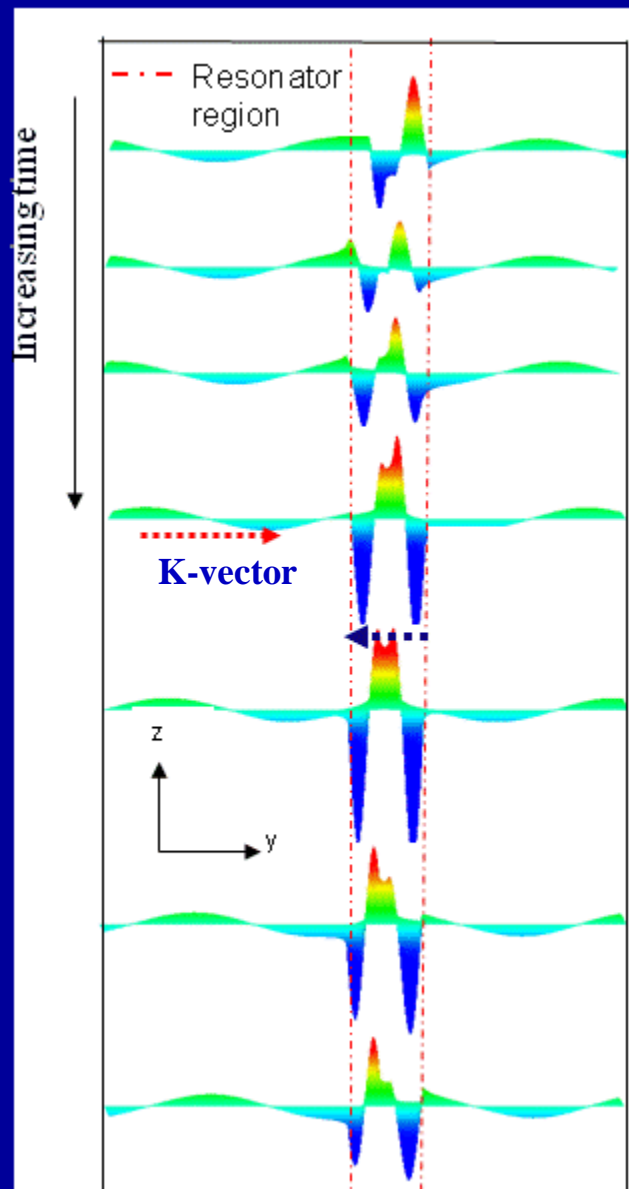


Field distributions at the passband show strong inter-resonator coupling and formation of a combined mode

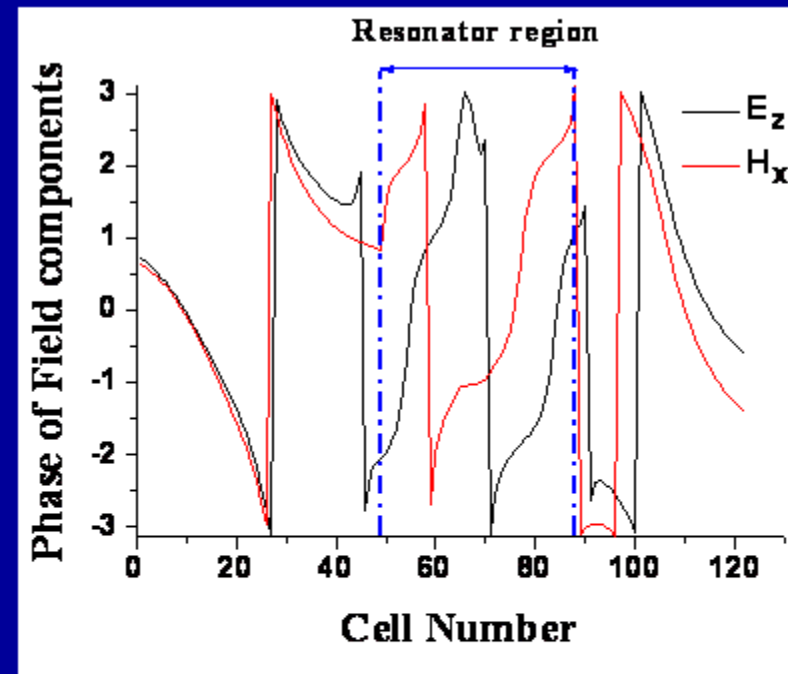


Both parameters become negative in the passband

# “Backward wave” behavior in unit cell of two similar DRs



Time-domain  $E_z$  component animation at 14.27 GHz (within the passband)



- Phase of  $E_x$  and  $H_x$  components increases along the waveguide within the resonator region
- Consistent with backward-wave behavior

## 4. Coupled DR arrays *versus* Photonic Crystals

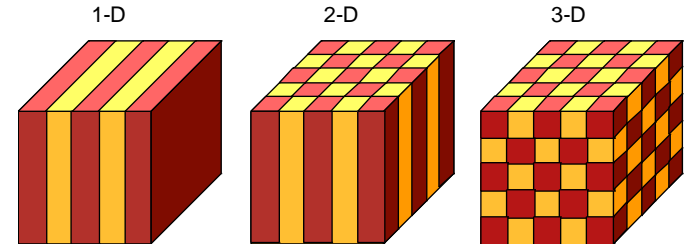
# Evolution of photonic crystals from 1D metal to 3D dielectric structures



1D Photonic Crystal  
(Bragg grating and thin film stack)



After Joannopoulos et al.



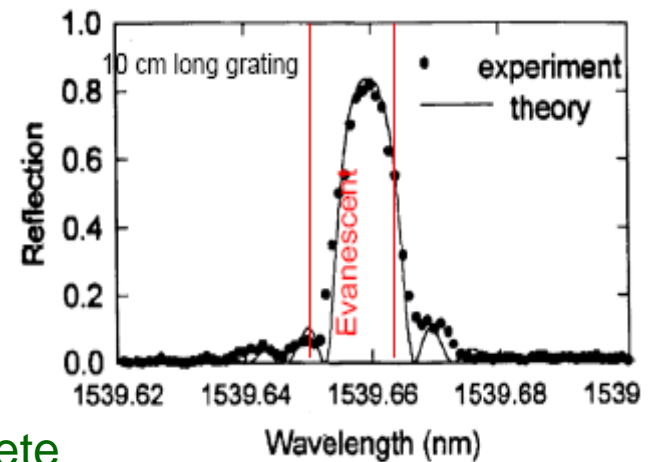
1-D  
periodic in one direction

2-D  
periodic in two directions

3-D  
periodic in three directions



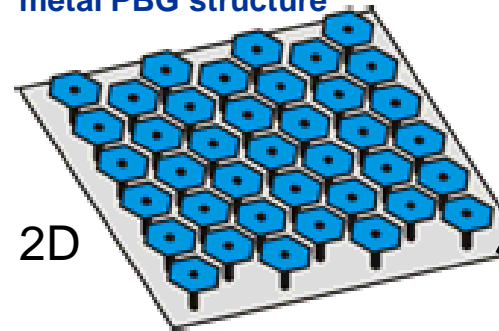
Bragg condition  $2L = n\lambda$ ,  $\lambda = 2L/n$



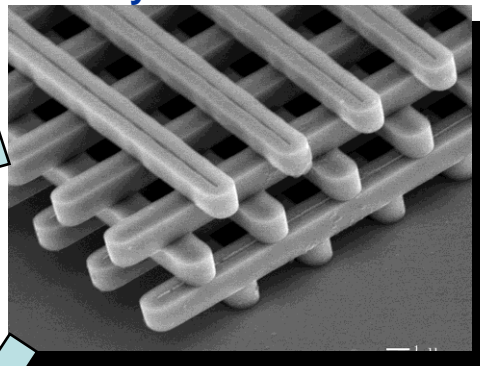
Complete band-gap



Mushroom-like metal PBG structure

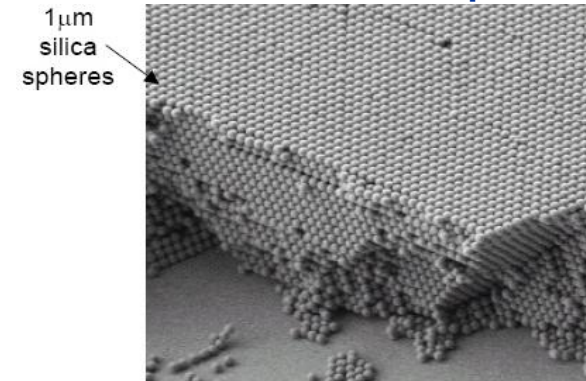


PBG crystal of alumina rods

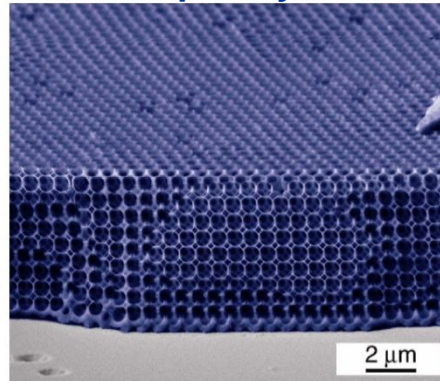


Lin et al., Nature 1998

Dielectric PBG opal and inverted opal crystals



Norris et al., Nature, 2004



Vlasov et al., Nature, 2001

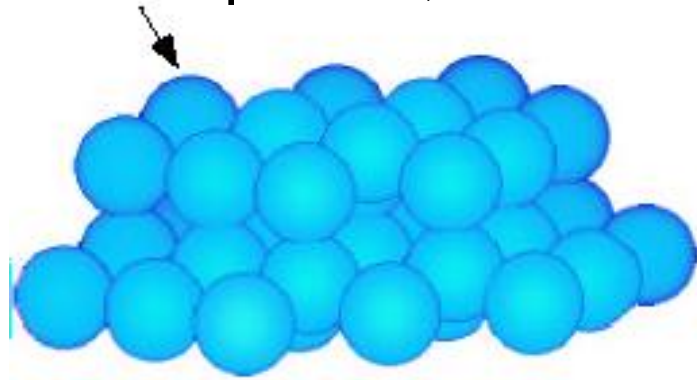
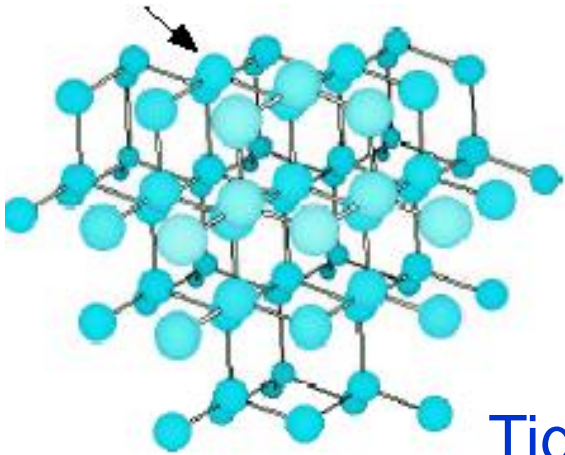
D. Sievenpiper, HRL Laboratories LLC

# Electronic and Photonic Crystals

atoms in diamond structure

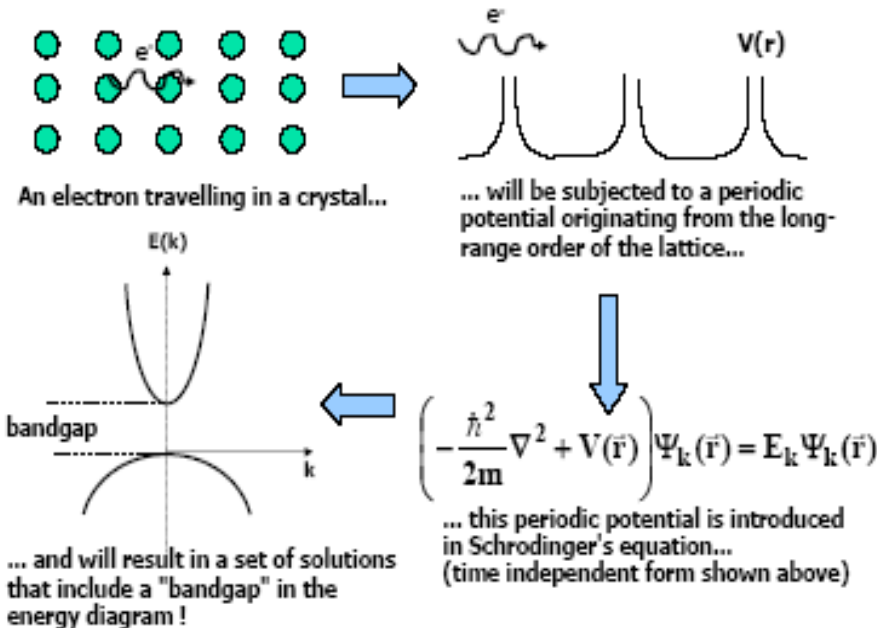
dielectric spheres, diamond lattice

Periodic Medium

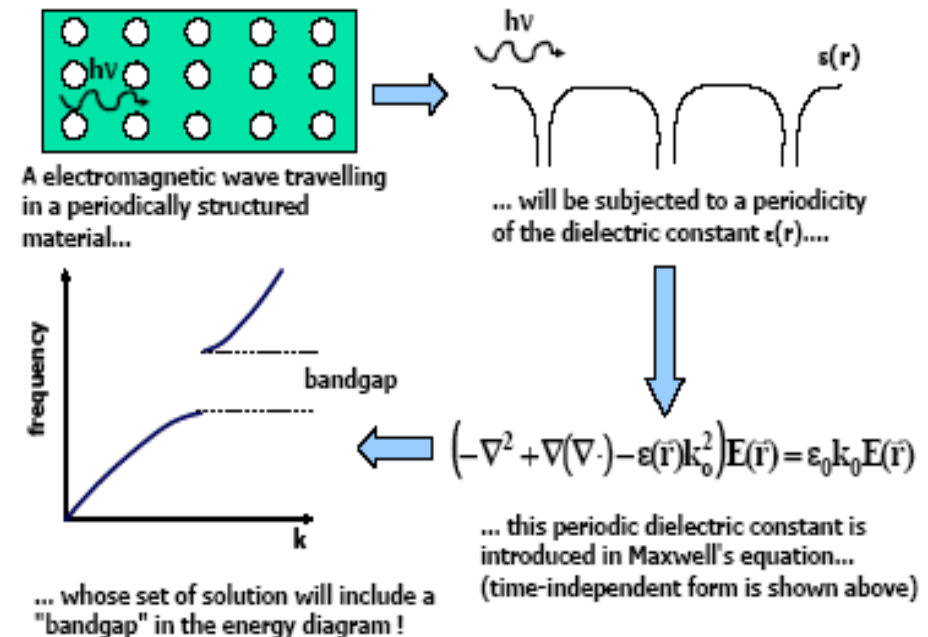


Tight binding approximation

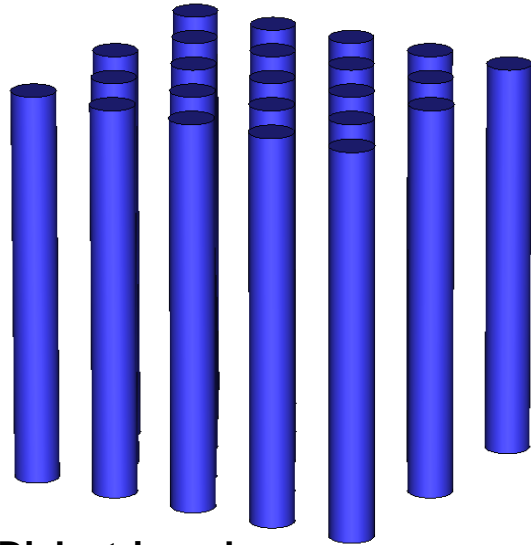
Electronic bandgap....



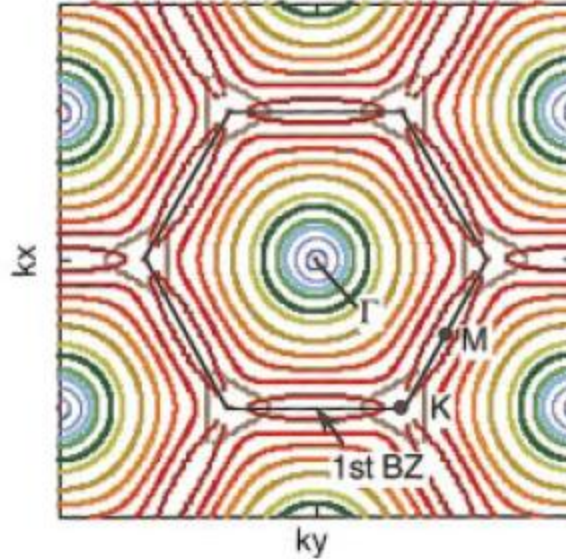
... vs optical bandgap



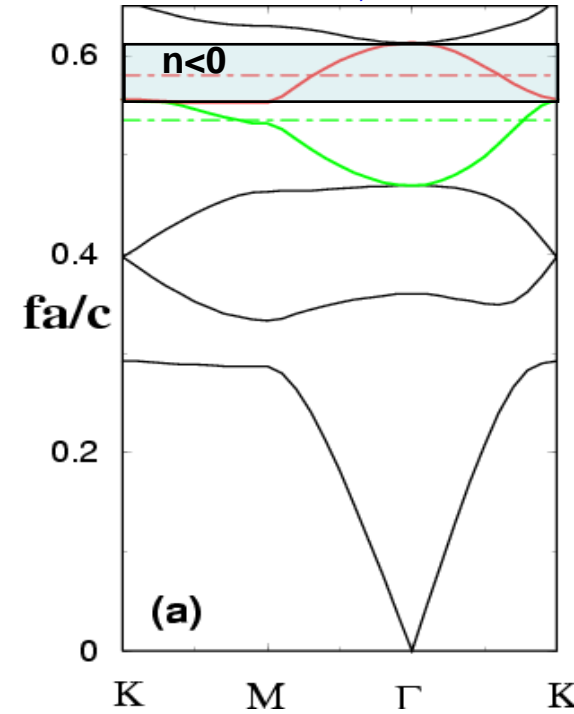
# Negative refraction in photonic crystals



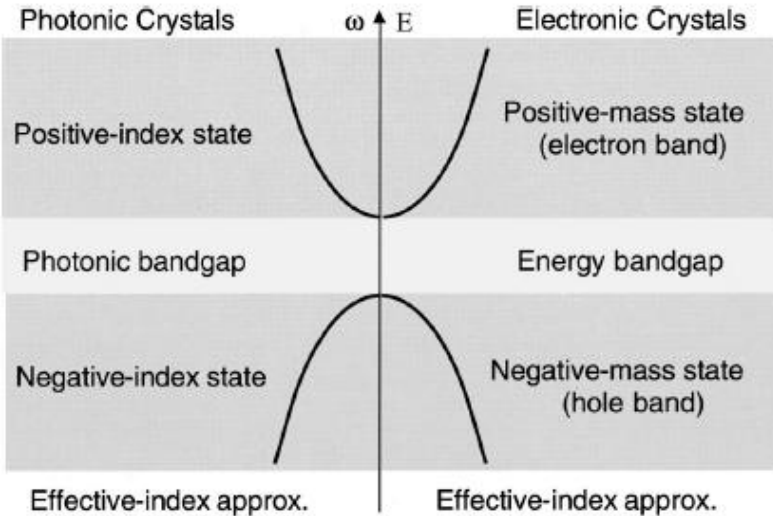
A plot of allowed k values at a given f  
Equi-Frequency Surface (EFS)



Notomi, Opt.&Quant.  
Electronics, 2002

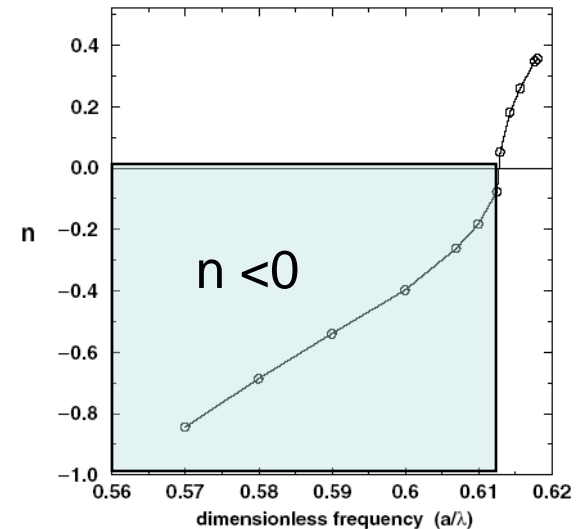


Dielectric rods  
 $\epsilon = 12.96$   $r = 0.35a$



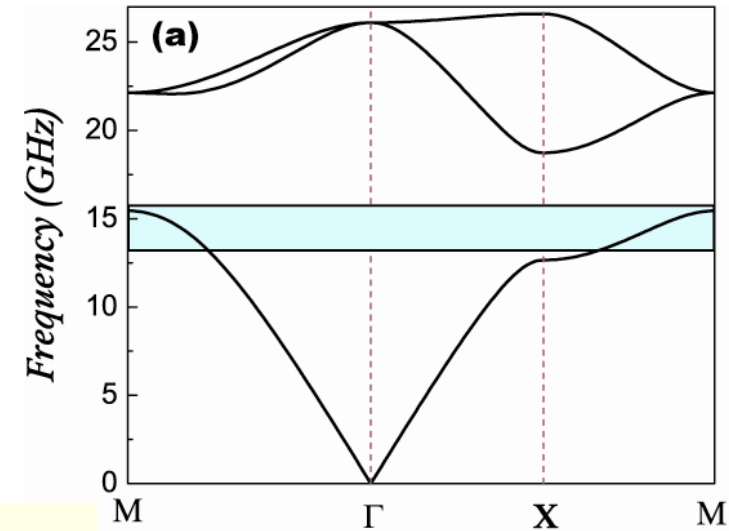
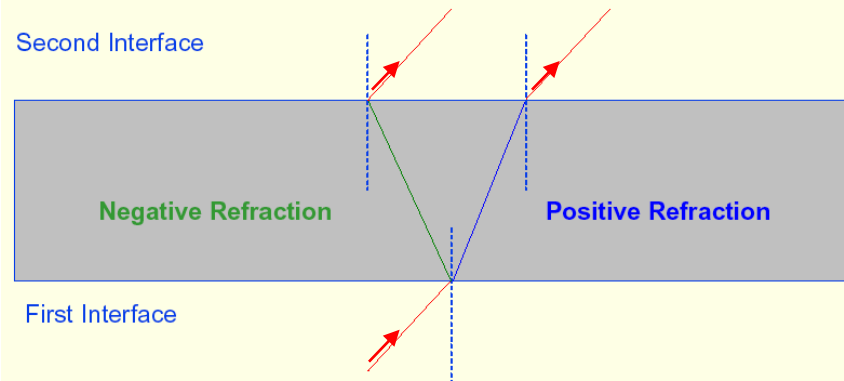
$$v_{en} = v_g = \frac{\partial \omega}{\partial k}$$

thus is perpendicular to  
the equi-frequency  
dispersion diagram



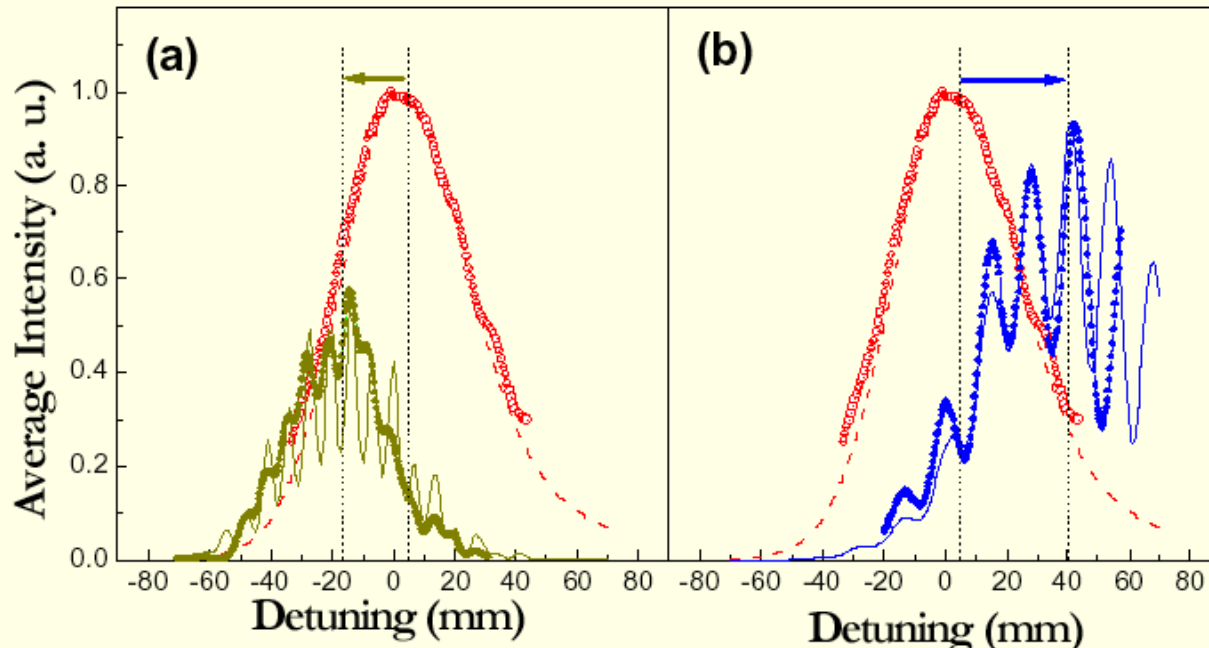
# Experiment

Cubukcu et al., Nature, 2003



Photonic Crystal

Polystyrene Pellets



Foteinopoulou and Soukoulis, Phys.Rev.B, 2003

Left-handedness ( $n < 0$ )

demands :  $n_p < 0$

$$\vec{v}_g \cdot \vec{k} = \vec{S} \cdot \vec{k} < 0$$

Negative refraction is also possible at  $n > 0$

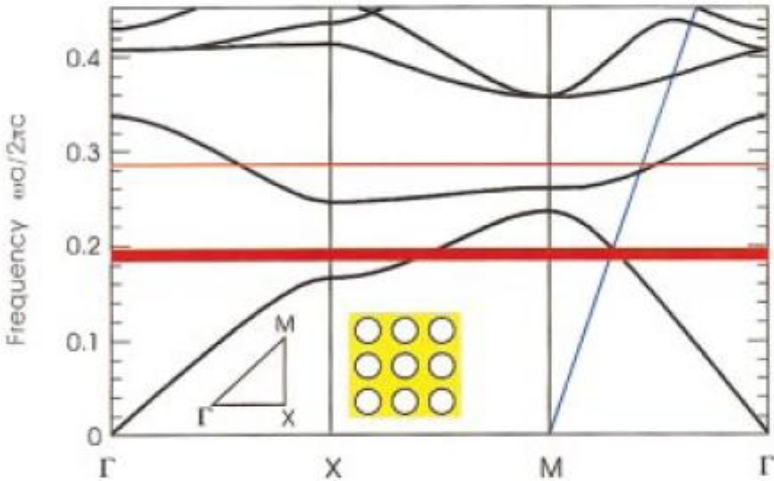
# Negative refraction without negative effective index

All-angle negative refraction - AANR!

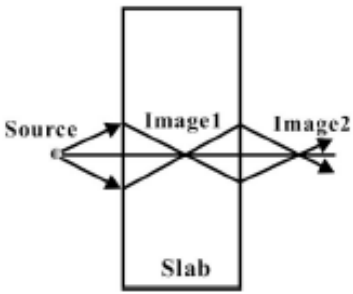
C. Luo, S.G. Johnson, J. D. Joannopoulos, J. B. Pendry, Phys. Rev. B65, 201104, 2002

H.-T.Chien, H.-T.Tang, C.-H.Kuo, C.-C.Chen, and Z.Ye, Phys.Rev. B 70, 113101, 2004

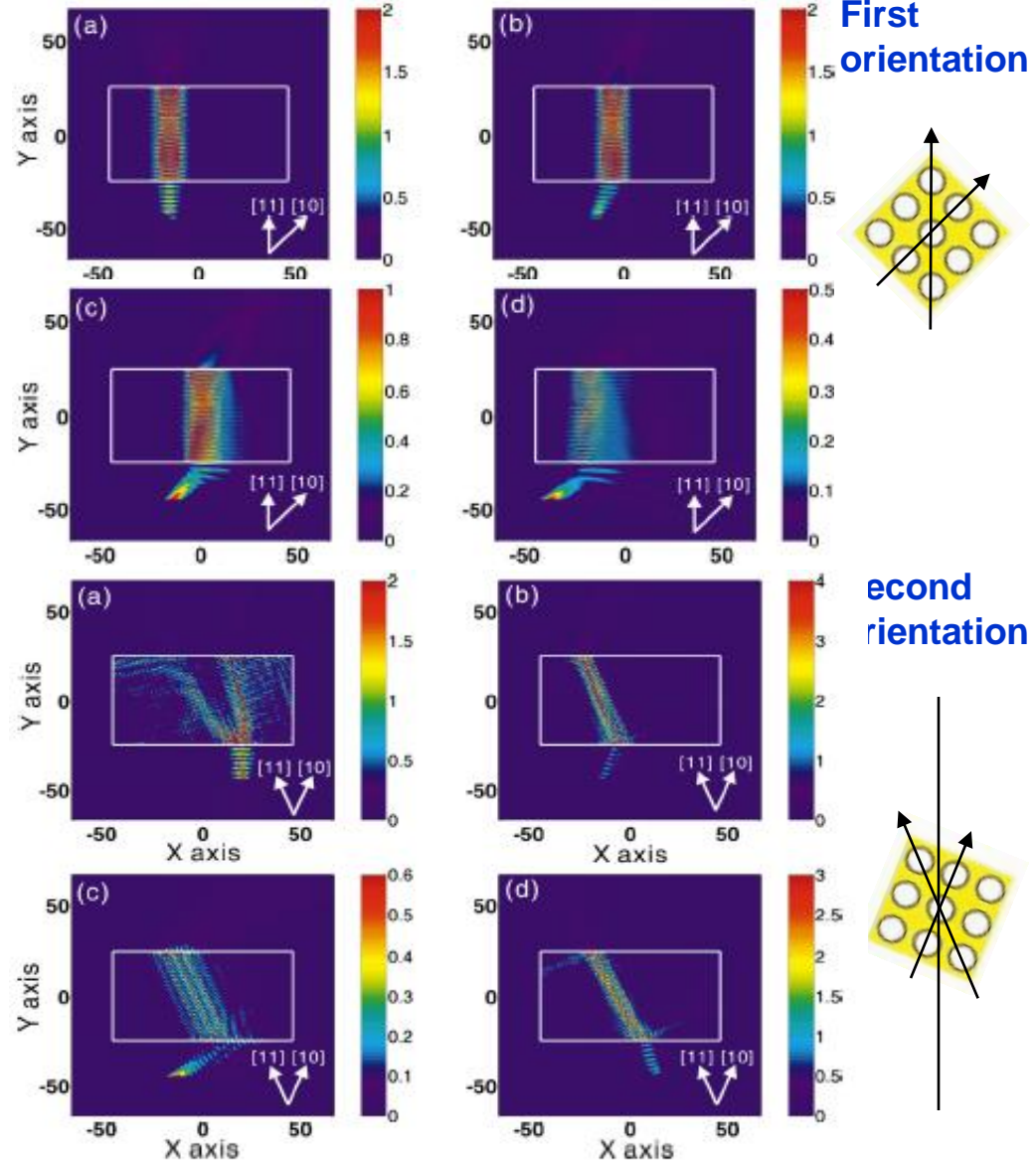
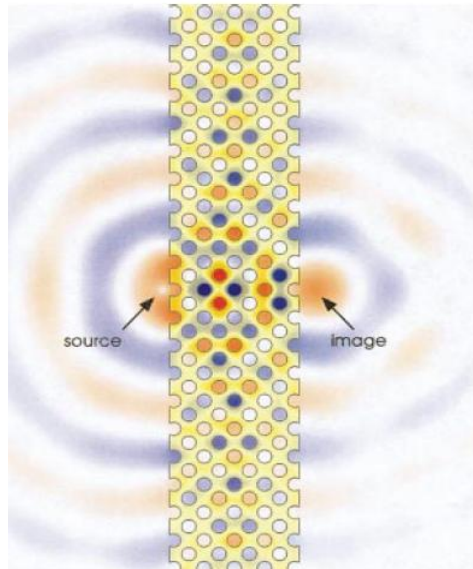
Air cylinders in Si,  $\epsilon = 12$ ,  $r = 0.35 a$



Superlensing typical for LHMs



Supposed possible only for  $n < 0$



Beam is propagating along [11] at all angles – no NR

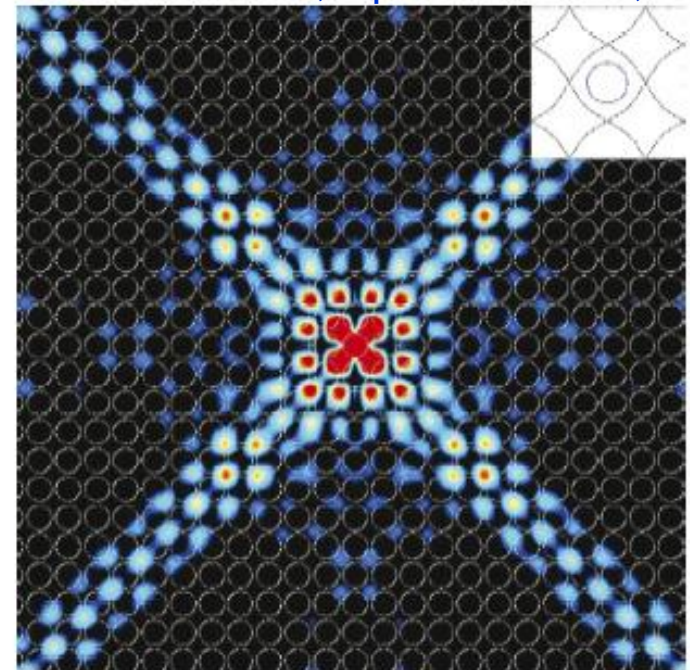
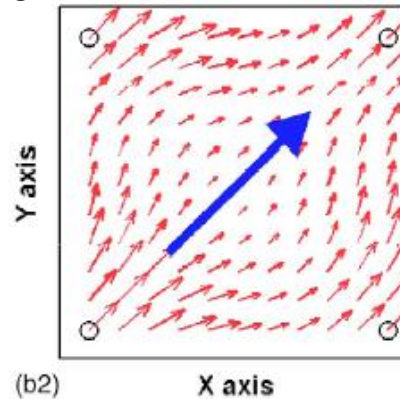
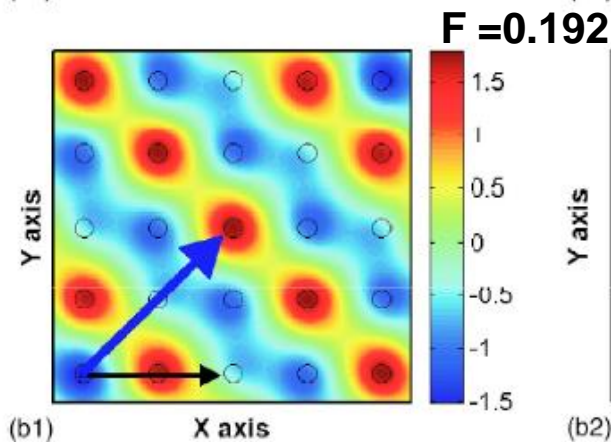
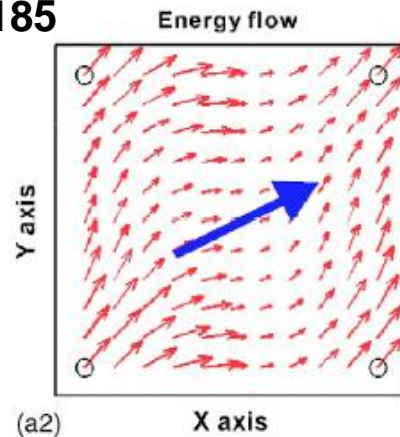
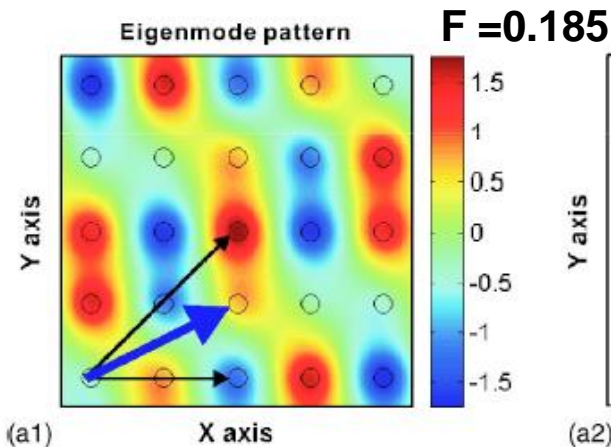
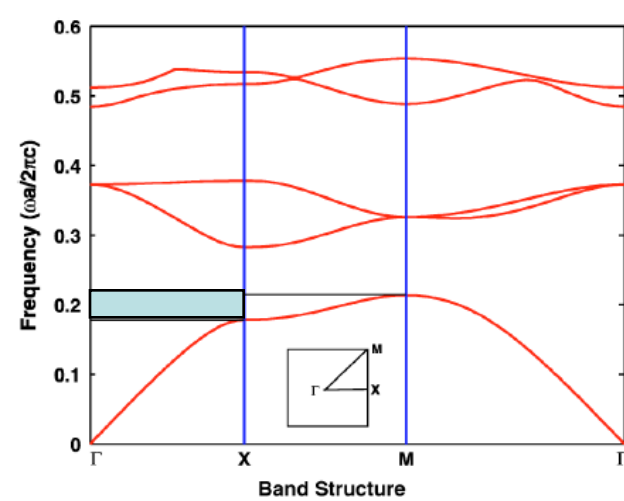
# Self-collimation and coupling

L.-S.Chen, C.-H. Kuo, and Z.Ye, Phys.Rev.E 69, 066612, 2004

Partial band gaps provides efficient channel for light transmission along permitted direction ( $\Gamma M$ ).

Concepts of refraction index becomes not applicable

Matthews et al., Optics Comms., 2007



Spatial width of a light beam inside photonic crystal freezes

Transmission without diffraction  
No effective medium theory

Energy flows along  $\Gamma M$  no matter how the Bloch vector is directed

# Are coupled DR arrays related to photonic crystals?

Photonic crystals

Arrays of coupled DRs

**Negative refraction with or without negative index**

**Effective medium theory – not applicable**

Weak coupling between “atoms”

Strong coupling and splitting of resonance modes

Uniform network of bonds

Stochastic network of bonds

Identical resonance responses in “atoms”-scatterers

Different angular orientation of dipole-like resonance modes

Tight-binding approximation

Not applicable

Efficient transmission channels provided by partial band-gaps

Efficient transmission along chains of coupled fields

Self-collimation of light

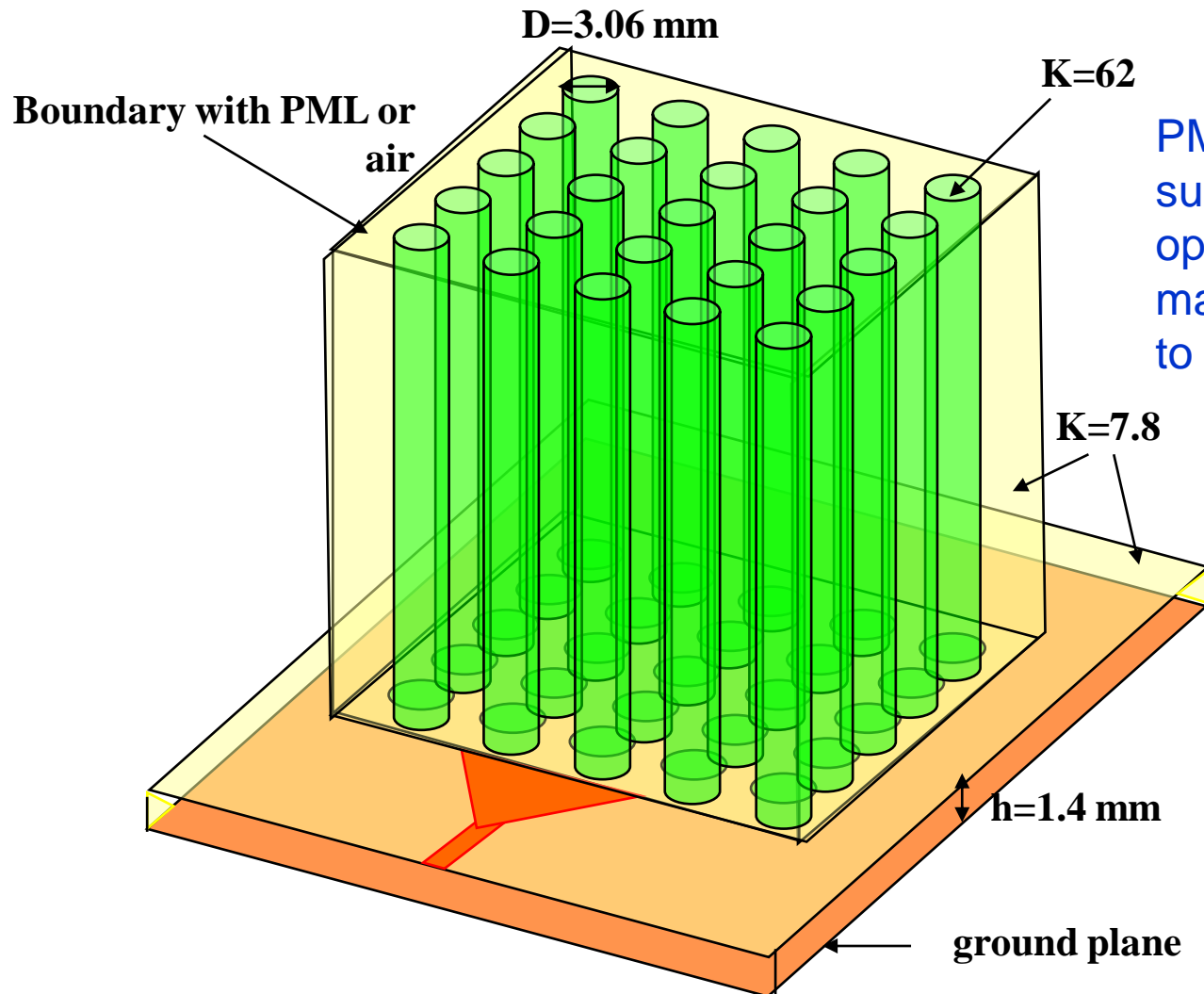
**They perform differently**

To verify the differences between the arrays of 2D PCs and DRs:

**FDTD study of PCs comprised of rods**

**Dielectric and diameter – similar to DRs**

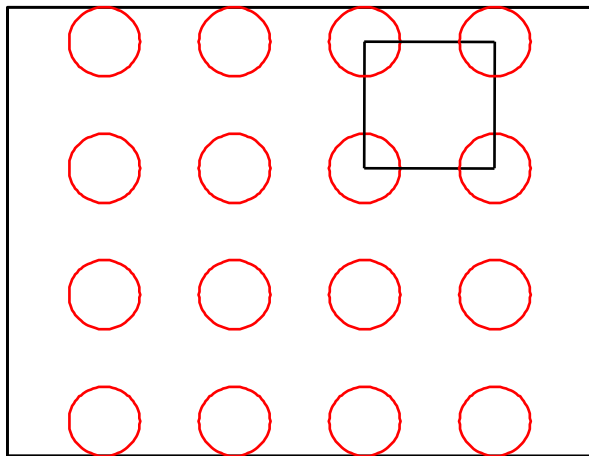
**Excitation – horn-like microstrip ends used for DR arrays**



PML boundary conditions suppress reflections from open ends of the rods and make the problem equivalent to an infinite one

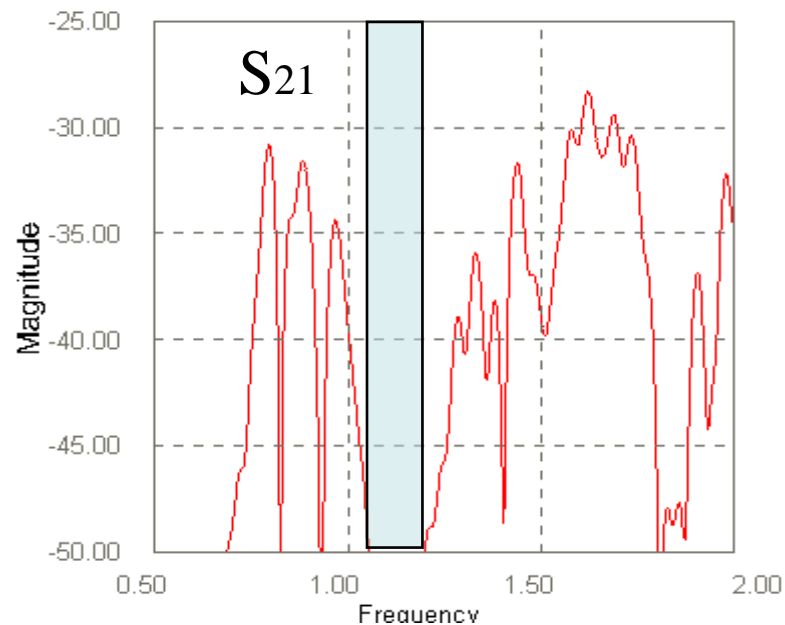
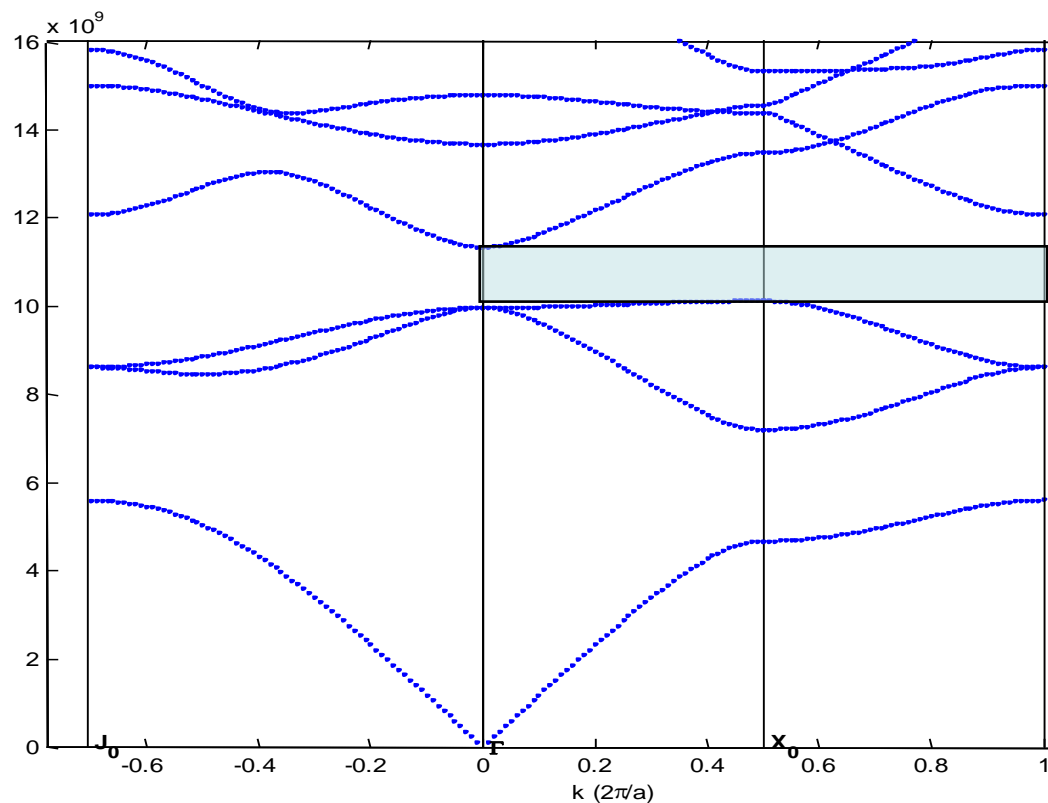
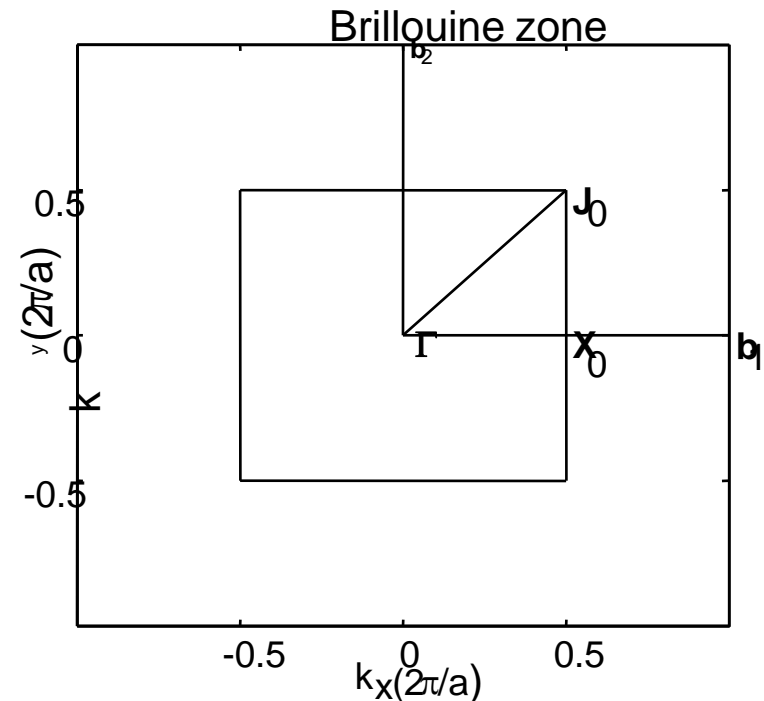
# Band Structure Simulation

Lattice in the real space



$K = 62,$   
 $D = 3.06 \text{ mm}$

Calculations by plane-wave expansion method  
(N. Malkova, NASA Ames Research Center)



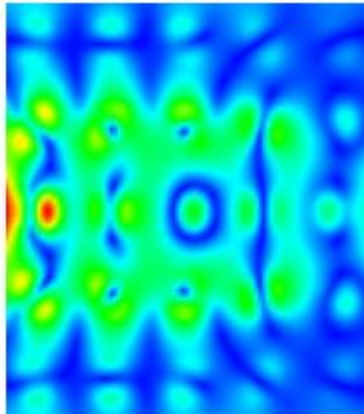
**Gap: 10.4 – 11.9 GHz**

# Fields in photonic crystal

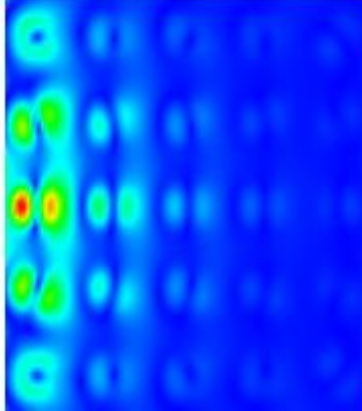
Gap

Transmission

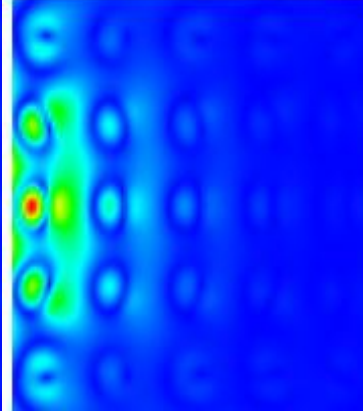
9.0 GHz



10.6 GHz

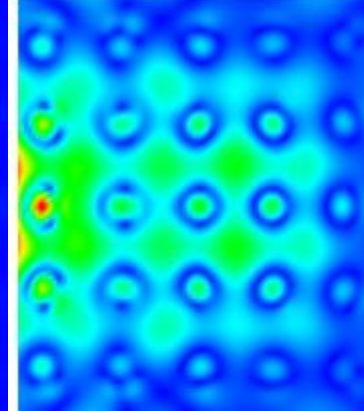


11.5 GHz

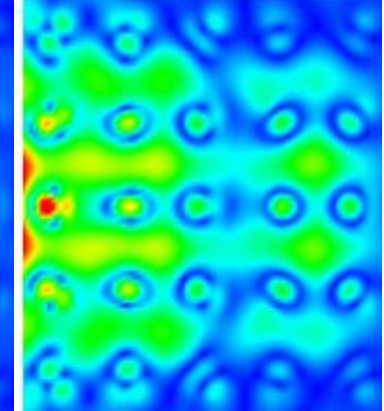


Transmission

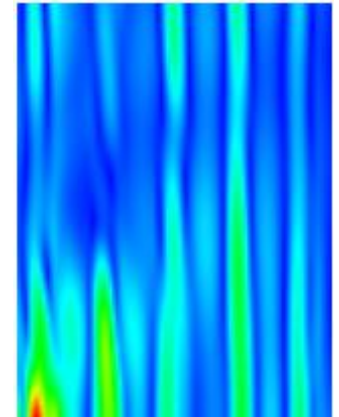
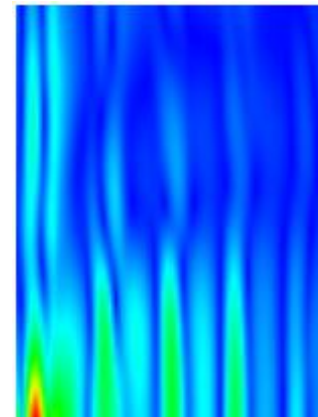
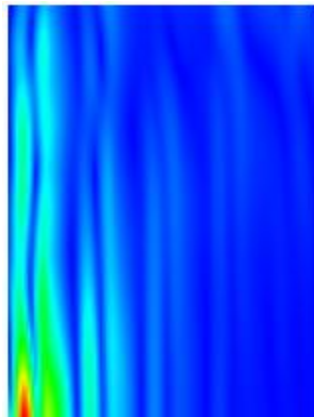
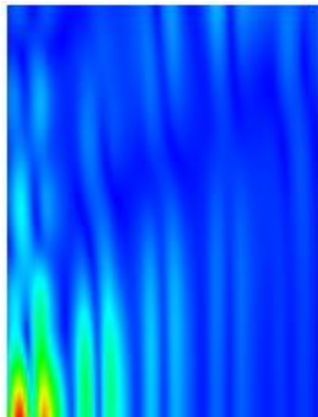
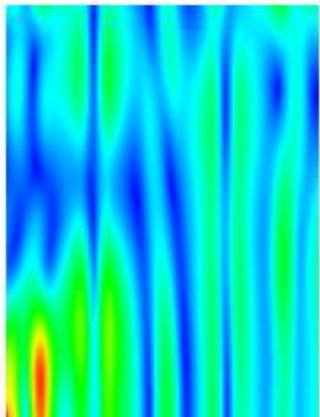
12.5 GHz



13.0 GHz



$E_z$  in XY plane (0.9 mm from ground plane)



$E_z$  in median XZ-cross-section

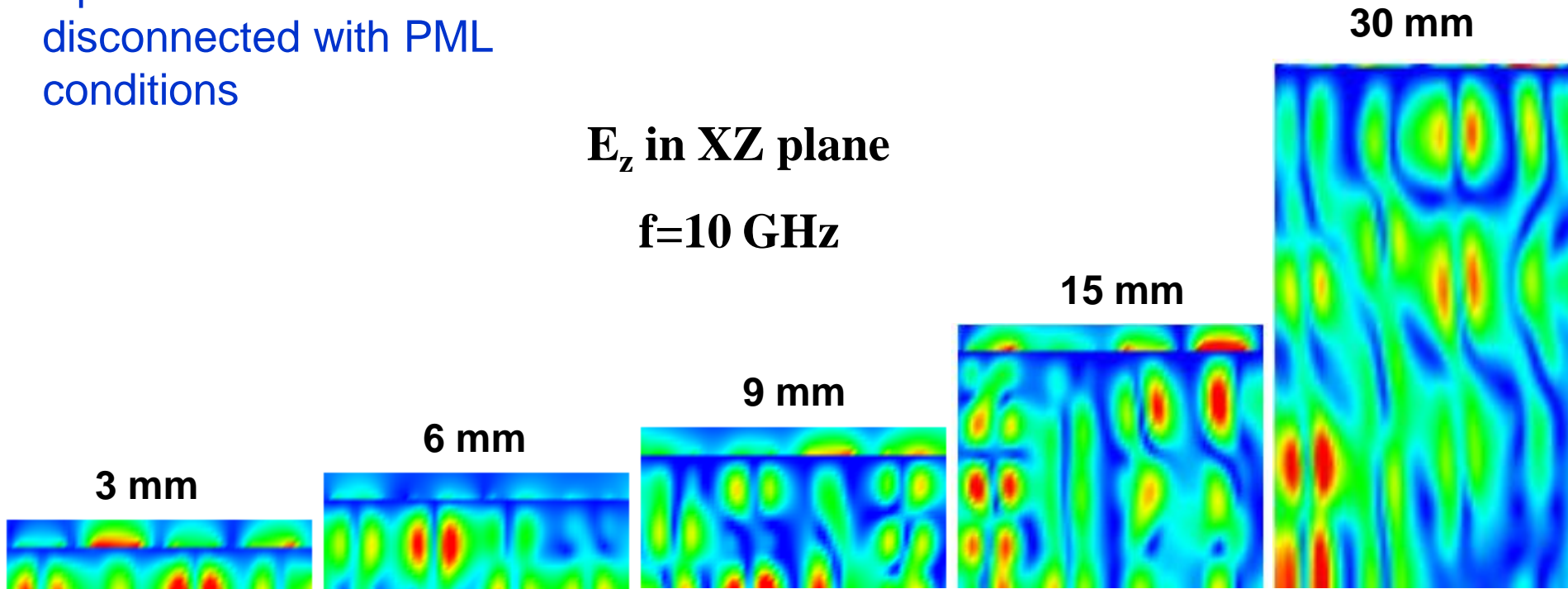
**Propagation between the rods,  
diffraction, no resonance patterns**

# Fields in the Structures with Different Rod Height

Open ends of the rods  
disconnected with PML  
conditions

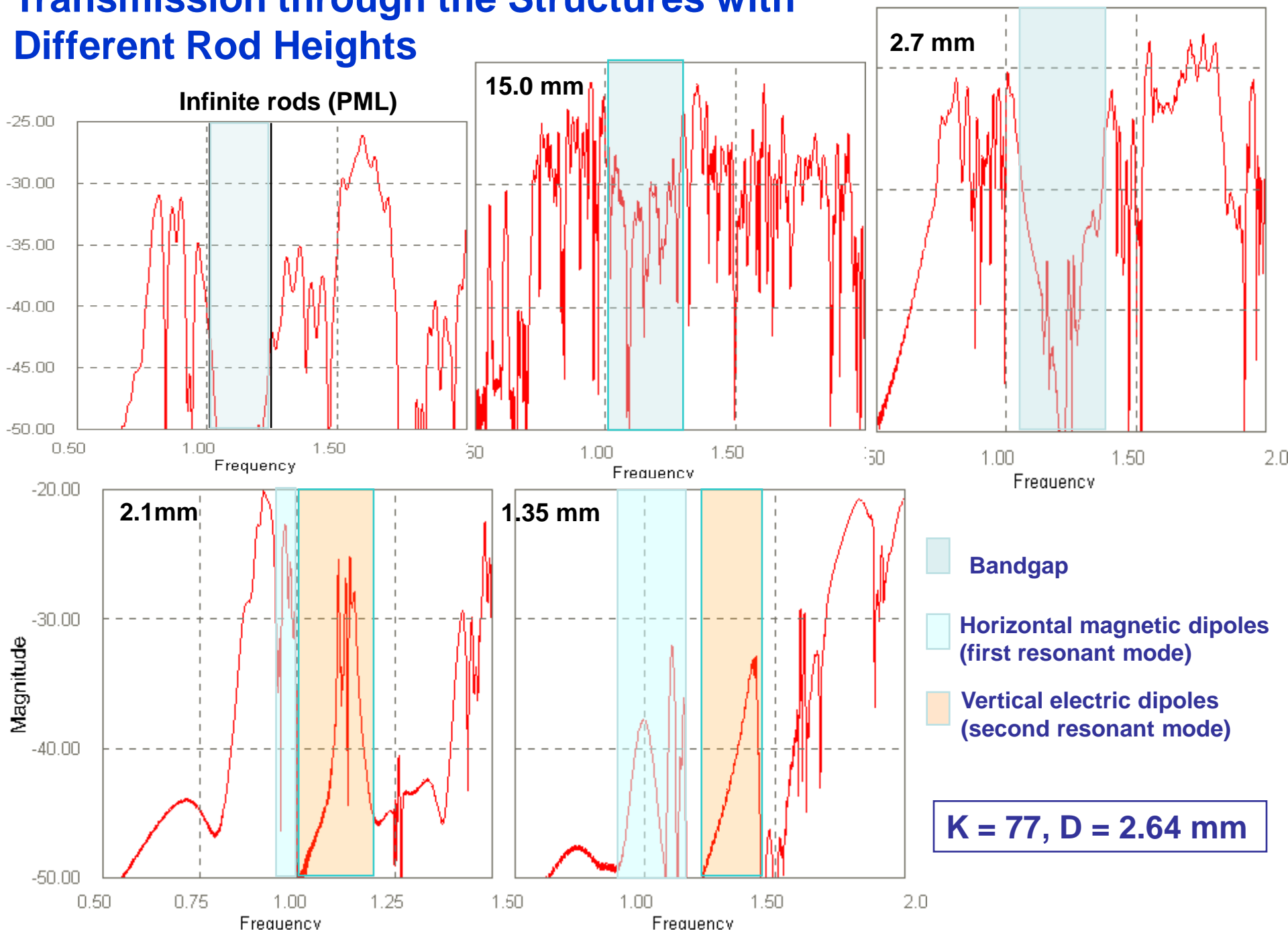
$E_z$  in XZ plane

$f=10$  GHz



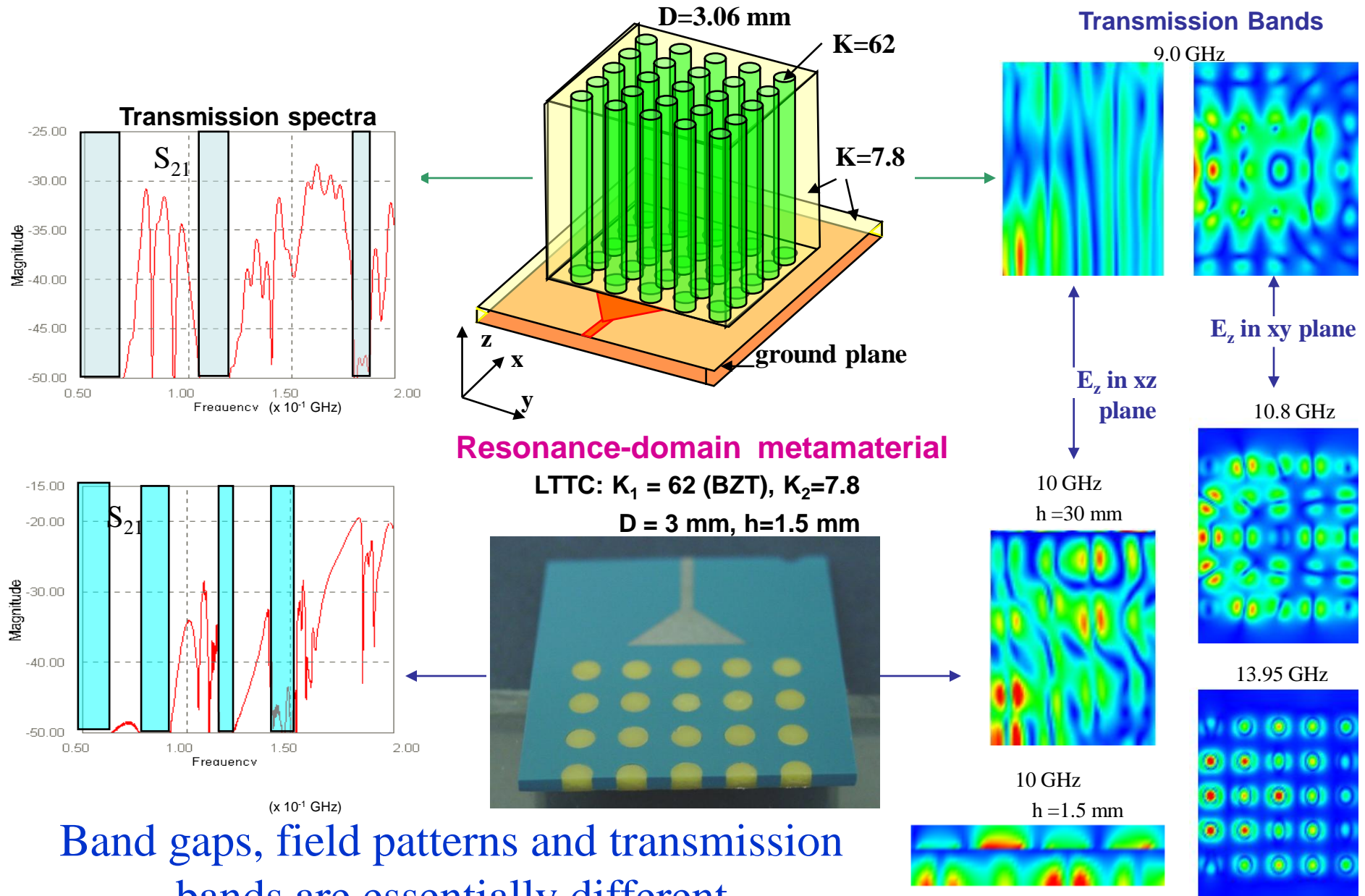
Resonances are well seen

# Transmission through the Structures with Different Rod Heights



# Coupled DR arrays vs. Photonic Crystals

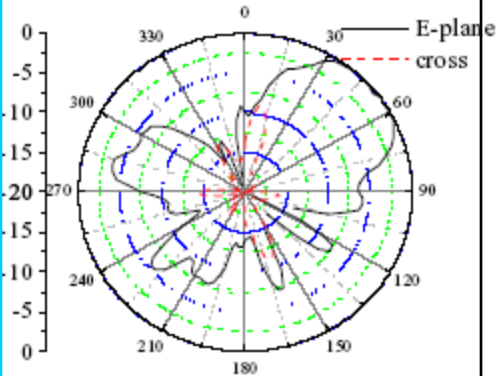
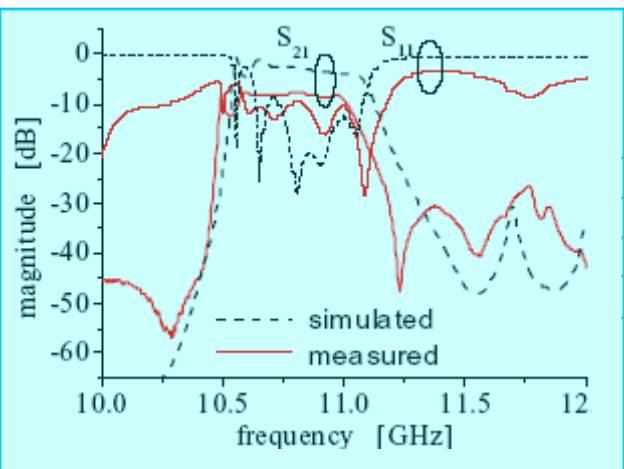
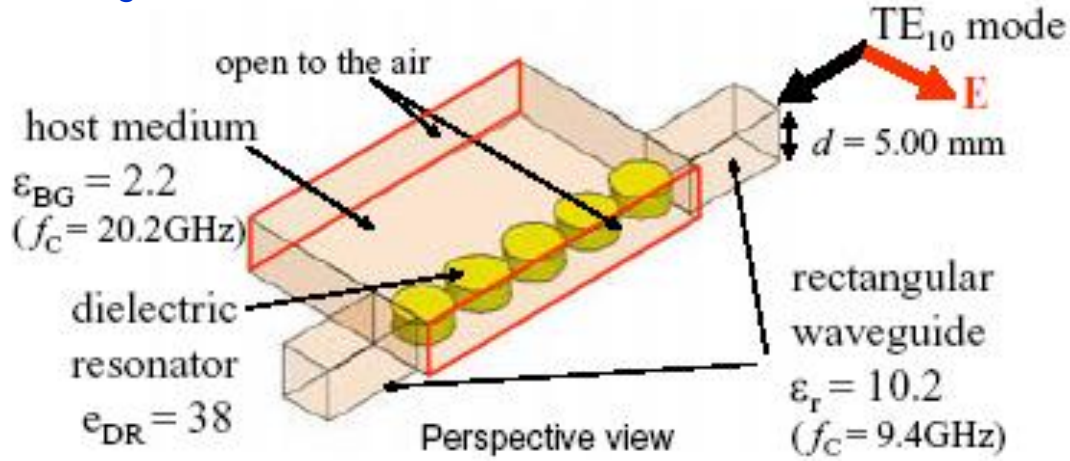
PBG structure (infinite rods): Bragg-scattering of EM wave



## 5. Latest developments on artificial materials from DRs

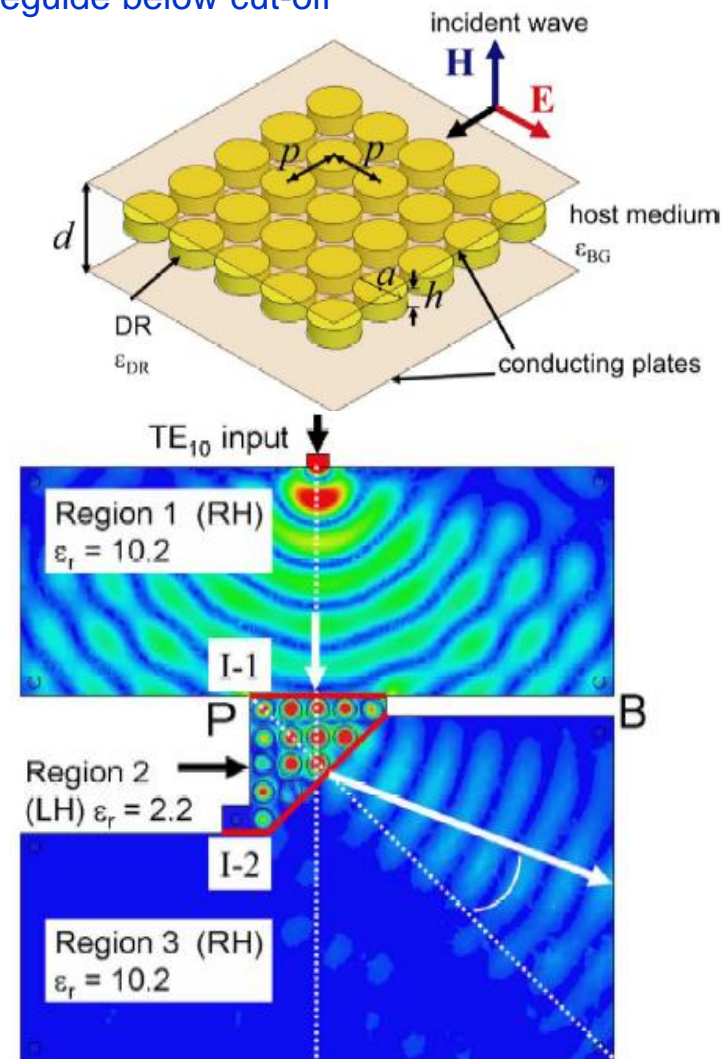
# One-DR scheme in a negative-epsilon background

Ueda *et al.*, *Proc. Asia-Pacific Microw. Conf.*, 2006  
 Transmission lines of cylinder DRs  
 in waveguide below cut-off



Backward leaky-wave radiation confirms  
 backward wave propagation in the DR line

Ueda *et al.*, *IEEE Trans. MTT*, 2007  
 2D lattices of cylinder DRs in  
 waveguide below cut-off



Negative refraction was also  
 experimentally confirmed

# Negative epsilon background is questionable

No evidences that evanescent waveguide modes are retained in the presence of a “second” waveguide” consisting of coupled resonators, which compress the wave and launch it through the chain

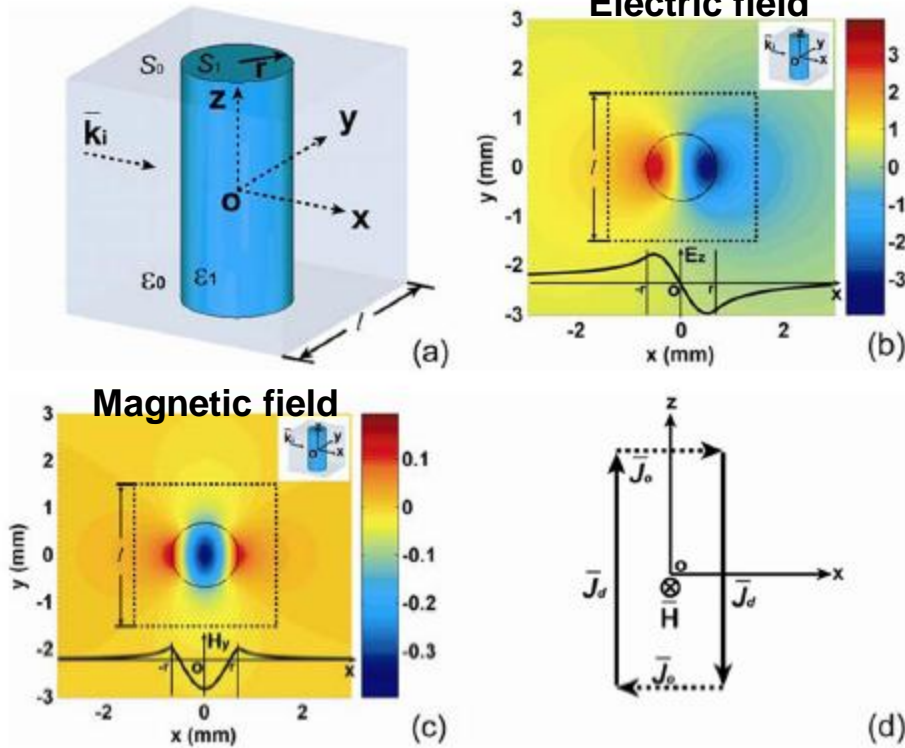
Wave tunneling through the waveguide below cut-off was observed for the chains of BS-SRRs although no negative permeability was provided by the SRRs and, so, no double negativity of the whole medium existed

[Semouchkina *et al.*, *Proceedings of IEEE IMS 2007*]

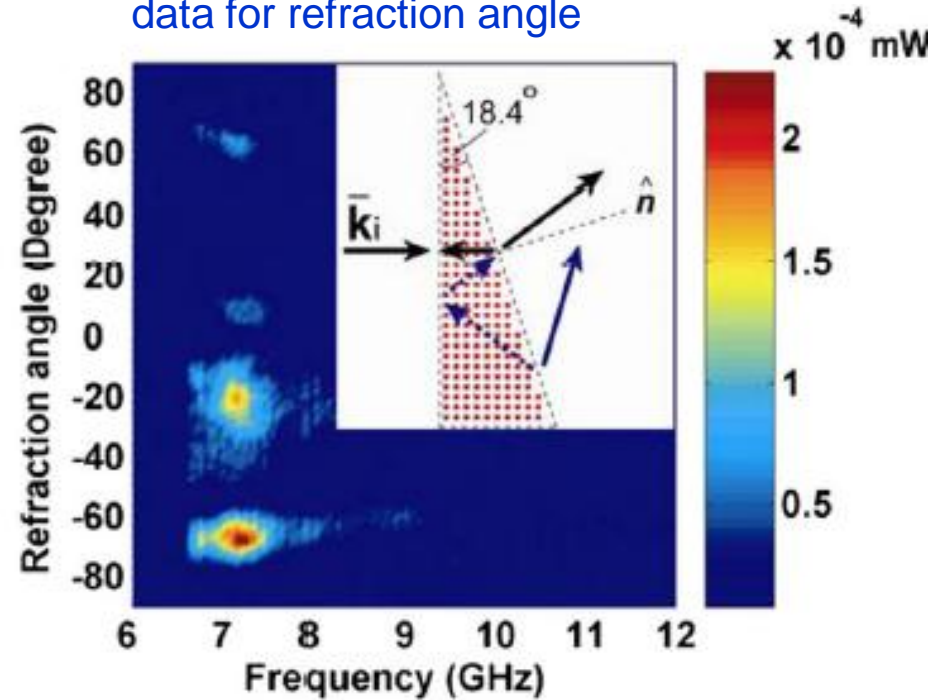
# Can one-resonator scheme provide for two responses as a two resonator scheme?

Peng, Grzegorzczyk *et al.*, *Phys.Rev.Lett.*, 2007 – array of DR rods

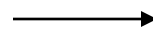
Magnetic resonance



Red spots on the left show experimental data for refraction angle

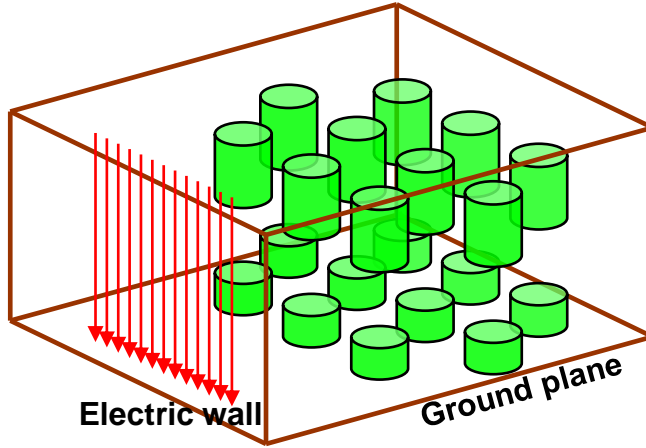
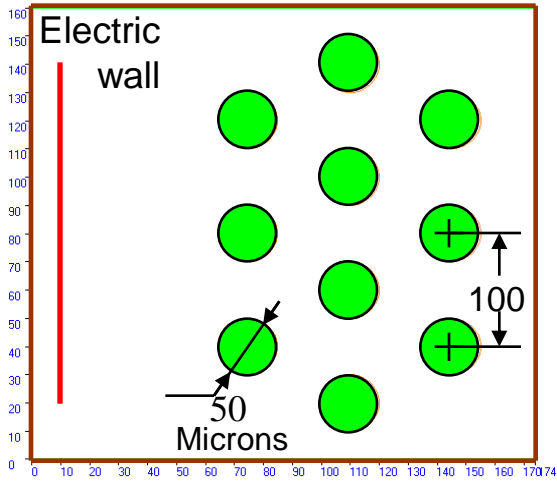


Displacement currents along the rod surface were supposed to provide for electric response, while magnetic dipoles along the diameters of the rods– for magnetic response

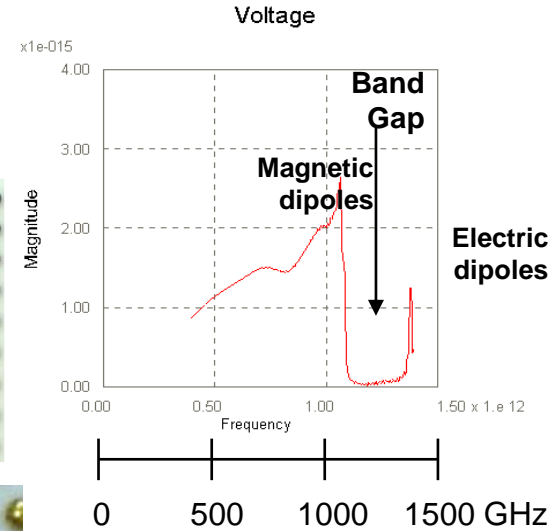


Displacement currents are oppositely directed and so their total electric response is zero

# 2D and 3D Metamaterials for THz-Range



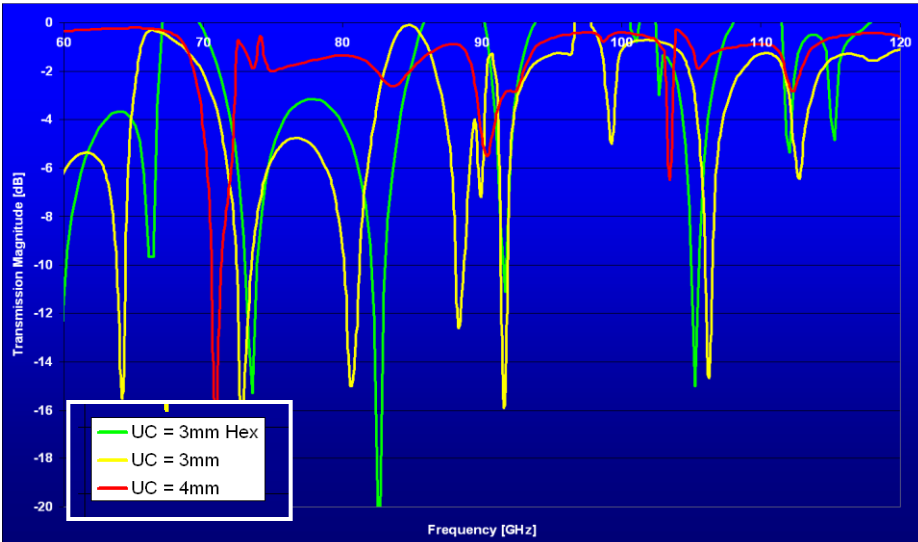
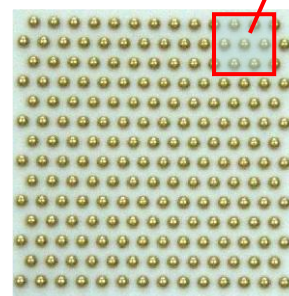
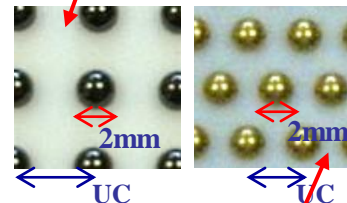
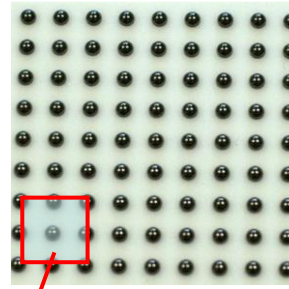
Field simulations have shown rotation of dipoles in 3D space and coupling between layers



## Measurements using THz time-domain spectroscopy

Silicon Nitride,  $\text{Si}_3\text{N}_4$   $\epsilon_r \approx 8.9$  and brass spheres, square and hexagonal lattices

Holes were punched in a PTFE substrate ( $\epsilon_r = 2$ ) and spheres were held in place with a tape backing transparent at THz

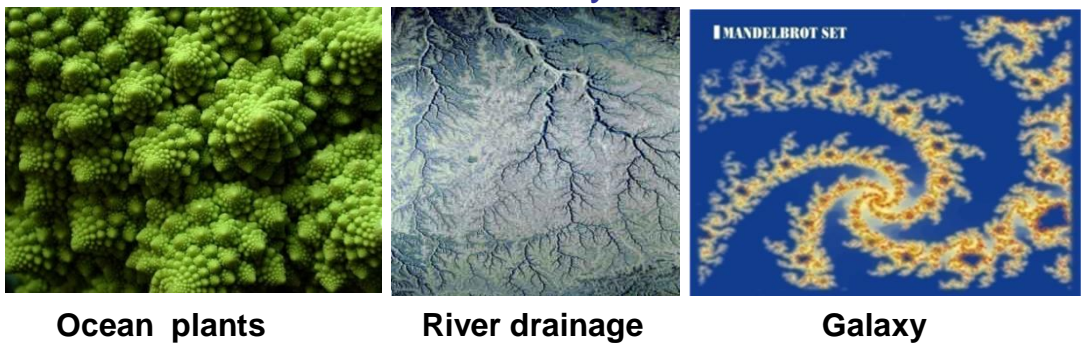


Transmission bands related to wave propagation through network of coupled magnetic dipoles and coupled electric dipoles are similar to those at microwaves

# 3D Photonic Fractals for Electromagnetic Wave Confinement

Fractals — The Geometry of Nature

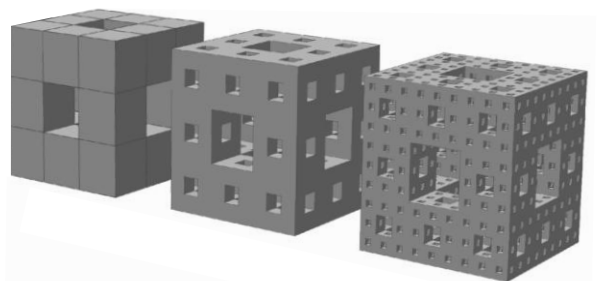
In collaboration with the *Smart Processing Research Center, Osaka University, Japan*  
 Acknowledgements: Y. Miyamoto, S. Kirihara



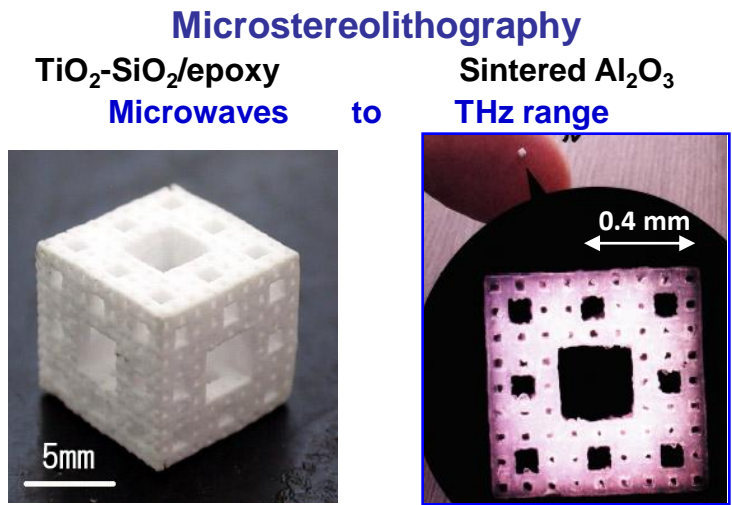
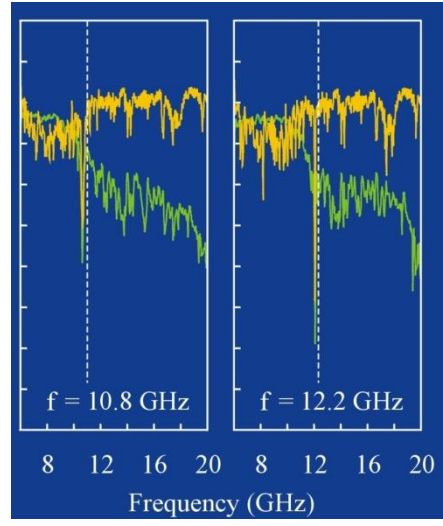
Ocean plants

River drainage

Galaxy



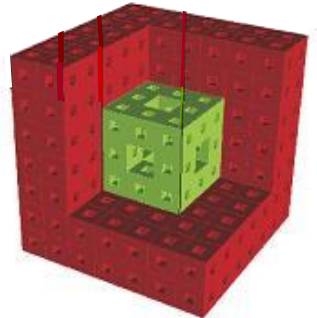
3D fractals are expected to provide for much more efficient EM confinement than light localization in photonic crystals, and promise dramatic shrinkage of the devices for integrated optics and microwaves



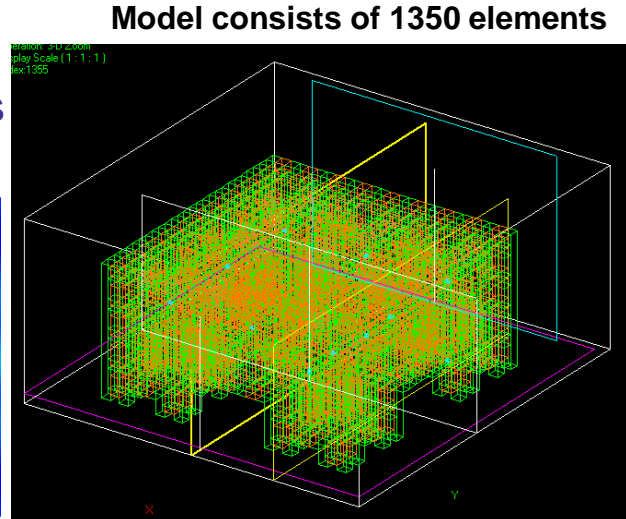
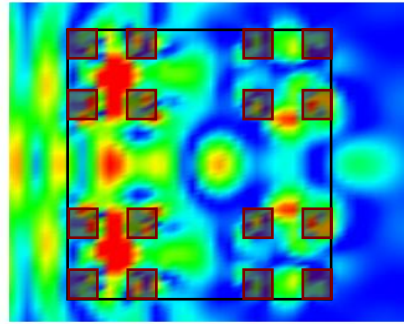
Electromagnetic Field Analysis

Increased image of sub-millimeter 3<sup>d</sup> stage fractal

Potential Applications:  
 High-performance Antenna,  
 Perfect Absorber,  
 Efficient Filter,  
 Fractal Oven,  
 Solar Cell Window,  
 EM and Light Battery



Menger sponge buried inside photonic crystal for enhanced EM confinement



# Conclusions

- Application of the effective medium theory to metamaterials cannot be justified when there is coupling between resonators
- Development of dielectric metamaterials in frames of the effective medium theory has not yet provided experimental results
- Arrays of coupled DRs present an alternative demonstrating metamaterials properties: enhanced transmission, negative refraction and backward wave propagation, although they cannot be described by the effective medium theory
- Coupled DR arrays demonstrate properties different from those typical for photonic crystals and present a different class of perspective artificial materials
- FDTD simulations of extended metamaterials samples can provide for correct interpretation of the results

Acknowledgements: Michael Lanagan, Clive Randall, George Semouchkin, and Raj Mittra