Dielectrics in Metamaterials

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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, LHM

$\varepsilon > 0, \mu > 0$  $\varepsilon < 0, \mu < 0$

Pendry, 1999, simple approach to design

Wires + SRRs

Electric response

Magnetic response

Negative $\varepsilon$ below plasma frequency
Negative $\mu$ above resonance

Negative refraction

1D

Regular Materials  Left-Handed Materials

Metal rings  Slit

Schultz and Smith, PRL, 2000

Boeing Cube

3D

Meta-material

Teflon

Meta-material

Teflon

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

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

Coupled wires with opposite charges

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

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

Coupling with front and back rings

X-coordinates of vertical strips

9.75 GHz 2.15 2.53 2.35 9.45 GHz

9.2 GHz 3.66 2.35 9.75 GHz

9.55 GHz 9.5 GHz

9.45 GHz 2.62 1.7

2.57 10.25 GHz

2.54 10.3 GHz

3.88 10.45 GHz

9.75 GHz 2.54

3.68 9.85 GHz

9.55 GHz 9.5 GHz

2.57 10.25 GHz

2.54 10.3 GHz

3.88 10.45 GHz
Coupling between resonators in the array and redistribution of resonance oscillations with frequency

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

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Magnitude</th>
<th>Phase</th>
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</thead>
<tbody>
<tr>
<td>9.75 GHz</td>
<td>3.57e4</td>
<td></td>
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<td>9.9 GHz</td>
<td>5.05e4</td>
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</tbody>
</table>

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


Forth & Berkeley

After Fontainopoulou, 6th MetaPhD School, 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 $P$

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

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

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

It follows:

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

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

Effective permittivity is a function of individual polarizability

Each scatterer has dipole moment

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

It defines volumetric polarization density $P$

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

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

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

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

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

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

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

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

$$k_0 = \frac{2\pi}{\lambda}$$

$$\varepsilon_r = \varepsilon / \varepsilon_0; \quad \mu_r = \mu / \mu_0$$

(a - radius of sphere)

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

Caused by Mie resonances in spheres

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


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

\[ \varepsilon_{re} \text{ and } \mu_{re} \text{ for } v_f = 0.5, \varepsilon'_{r1} = \mu'_{r1} = 1, \varepsilon'_{r2} = 40, \text{ and } \mu'_{r2} = 200. \]

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

\[ \varepsilon_r \rightarrow \varepsilon_r \left(1 - j \tan \delta \right) \]

At \( \tan \delta > 0.04 \) 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

\[ \varepsilon \sim \text{up to } 1000 \]  
Example: \( \varepsilon = 400, \) \( r_1 = 0.748 \text{ mm}, \) \( r_2 = 1.069 \text{ mm}, \) \( a = 4 \text{ mm} \)

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

Same permittivity for spheres of two sizes: \( \varepsilon \sim 44, \)
\( R_1 = 3.18 \text{ mm}, \) \( R_2 = 2.29 \text{ mm}, \) distance between centers \( \sim 10 \text{ mm} \)
Permittivity of spheres = 44, $R_1 = 3.18 \text{mm}$, $R_2 = 2.29 \text{mm}$

Each sphere alone provided for a negative parameter: large sphere $\varepsilon$, and small sphere $\mu$.

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

Unit cell composed of two different sized spherical DRs.

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

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.
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)
\( \varepsilon = 12.25 \), for Cs- plasma frequency is 0.41 \( \mu m \)

Dispersion diagram

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

When K is small – waves do not see particles
At f=0.1685 – almost isotropic properties

Relatively wide band

Negative refraction appears near TE resonances in dielectric spheres

Phase at the output port becomes advanced in the transmission band – backward wave propagation
Composites for optics can use polaritonon resonances


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

LiTaO₃
**Polaritonic spheres**

\[ \varepsilon(\omega) = \varepsilon_\infty \left( 1 + \frac{\omega_T^2 - \omega_L^2}{\omega_T^2 - \omega^2 - i\omega\gamma_1} \right) \]

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

\[ \omega_L = \omega_T \sqrt{\varepsilon(0)/\varepsilon_\infty} \]

\( \mu < 0 \)

\[ \omega/\omega_T = 0.900 \text{ to } 0.948 \]

\[ \omega_T/2\pi = 26.7 \text{ THz} \]

n-Ge
**Semiconductor spheres**

near bulk plasma frequency

\[ \varepsilon(\omega) = \varepsilon_0 \left( 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma_2} \right) \]

\[ \varepsilon < 0 \]

\( \omega_p = \omega_T \]

\[ \omega_p \approx \sqrt{n_{d,a}} \]

SiC, TiBr, TiCl could give range 8.1 - 149 THz

Effective parameters

Array of polaritonic spheres
\( \mu_{\text{eff}} \) predicted by extended Maxwell–Garnett theory (real - solid and imaginary - broken lines)

Array of semiconductor spheres
\( \varepsilon_{\text{eff}} \) 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”


LaNbO$_3$ polaritonic spheres coated with a thin layer of Drude material

To avoid interaction between two resonances they are shifted in frequency

\[ k = \frac{\omega n_{\text{eff}}}{c} < 0, \quad \text{if} \quad n_{\text{eff}} < 0 \]

Backward waves are seen when

\[ \nu_p = \frac{\omega}{k} < 0 \quad \nu_g = \frac{\partial \omega}{\partial k} > 0 \]

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
Resonance modes in a Cylindrical Dielectric Resonator

Magnetic dipole

Electric dipole

f=13.5 GHz

ε₂=77
ε₁=7.8

1.5 mm

3mm

xy-plane

yz-plane

xz-plane

f=10.5 GHz

ε₂=77
ε₁=7.8

1.5 mm

3mm

high intensity
medium intensity
low intensity

Electric dipole
FDTD modeling of transmission through DR arrays

Schematic of simulation:

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

$S_{21} \times 10^2$

Two split bands of enhanced transmission

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

- Magnitude of $S_{11}$
- Frequency (Hz)

- Simulations
- Measurements

- Magnetic dipoles
- Electric dipoles
Resonant Coupling in array of DRs

Magnetic dipole

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

10.5 GHz

Electric Coupling

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

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

**Magnetic Resonance Band**

10.0 GHz

10.7 GHz

10.8 GHz

10.95 GHz

10.4 GHz

-50 dB

E_z in XY-plane

**Electric Resonance Band**

10.8 GHz

10.95 GHz

11.05 GHz

11.35 GHz

11.4 GHz

11.5 GHz

11.65 GHz

12.0 GHz

Band Gap
Resonant Coupling of Electric Dipoles

Electric dipoles

Magnetic coupling

$E_z$

XZ-median cross-section, 14.0 GHz

$E_z$ in XY-plane

13.5 GHz 13.75 GHz 13.95 GHz 14.0 GHz 14.25 GHz

Gap

YZ-cross-section through second row, 14.0 GHz

$H_y$ in XY-plane, 13.95 GHz

Substrate
Formation of Electric and Magnetic Laminar Superstructures

Specifics of Coupling Patterns in DR arrays at higher frequencies

$H_y$ amplitude

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

EM coupling resembles chemical bonds
Wave Propagation through Prism of DRs

Rhomboid lattice

Positive beam refraction

f=16.0 GHz

Negative beam refraction

f=16.9 GHz

Substrate: K=77, DRs: K=7.8
Unit cell composed of two similar sized cylindrical DRs

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

TE10 mode wave propagation in y-direction, spacing between resonators is 5 mm

**Passband revealed between two resonance frequencies**

**EM responses of single resonators and of a unit cell**

Top view on field distribution in the unit cell

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

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

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

D. Sievenpiper, HRL Laboratories LLC

Mushroom-like metal PBG structure

PBG crystal of alumina rods

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

1-D periodic in one direction

2-D periodic in two directions

3-D periodic in three directions

Lin et al., Nature 1998

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

Norris et al., Nature, 2004

Vlasov et al., Nature, 2001

Complete band-gap
Electronic and Photonic Crystals

Atoms in diamond structure dielectric spheres, diamond lattice

Periodic Medium

Tight binding approximation

Electronic bandgap....

An electron travelling in a crystal...

... will be subjected to a periodic potential originating from the long-range order of the lattice...

\[ \left( -\frac{\hbar^2}{2m} \nabla^2 + V(\mathbf{r}) \right) \psi_k(\mathbf{r}) = E_k \psi_k(\mathbf{r}) \]

... this periodic potential is introduced in Schrodinger's equation... (time independent form shown above)

... and will result in a set of solutions that include a "bandgap" in the energy diagram!

... vs optical bandgap

A electromagnetic wave travelling in a periodically structured material...

... will be subjected to a periodicity of the dielectric constant \( \varepsilon(\mathbf{r}) \)...

\[ -\nabla^2 + \nabla(\nabla \cdot \varepsilon(\mathbf{r})) \right) \mathbf{k}_0^2 = \varepsilon_0 \mathbf{k}_0^2 \mathbf{E}(\mathbf{r}) \]

... this periodic dielectric constant is introduced in Maxwell's equation... (time-independent form is shown above)

... whose set of solution will include a "bandgap" in the energy diagram!
Negative refraction in photonic crystals

Dielectric rods
$\varepsilon = 12.96 \quad r = 0.35a$

Thus is perpendicular to the equi-frequency dispersion diagram

\[ n < 0 \]

A plot of allowed $k$ values at a given $f$

Equi-Frequency Surface (EFS)

\[ \nu_{en} = \nu_{g} = \frac{\partial \omega}{\partial k} \]

Thus is perpendicular to the equi-frequency dispersion diagram

Notomi, Opt.&Quant. Electronics, 2002
Negative refraction is also possible at $n > 0$ left-handedness ($n < 0$) demands:

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


Negative refraction is also possible at $n > 0$.
Negative refraction without negative effective index

All-angle negative refraction - AANR!


Air cylinders in Si, ε = 12, r = 0.35 a


Superlensing typical for LHMs

Supposed possible only for n<0

First orientation

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

Second orientation
Partial band gaps provides efficient channel for light transmission along permitted direction ($\Gamma \text{M}$).

Concepts of refraction index becomes not applicable.

Energy flows along $\Gamma \text{M}$ no matter how the Bloch vector is directed.

Spatial width of a light beam inside photonic crystal freezes.

Transmission without diffraction.

No effective medium theory.
### Are coupled DR arrays related to photonic crystals?

<table>
<thead>
<tr>
<th>Photonic crystals</th>
<th>Arrays of coupled DRs</th>
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</thead>
<tbody>
<tr>
<td><strong>Negative refraction with or without negative index</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Effective medium theory</strong> – not applicable</td>
<td></td>
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<tr>
<td>Weak coupling between “atoms”</td>
<td>Strong coupling and splitting of resonance modes</td>
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<td>Uniform network of bonds</td>
<td>Stochastic network of bonds</td>
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<td>Identical resonance responses in “atoms”-scatterers</td>
<td>Different angular orientation of dipole-like resonance modes</td>
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<tr>
<td>Tight-binding approximation</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Efficient transmission channels provided by partial band-gaps</td>
<td>Efficient transmission along chains of coupled fields</td>
</tr>
<tr>
<td>Self-collimation of light</td>
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</tbody>
</table>

**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

**Diagram:**

- Boundary with PML or air
- $D = 3.06\text{ mm}$
- $K = 62$
- $K = 7.8$
- $h = 1.4\text{ mm}$
- Ground plane

**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

\[ k = 62, \quad D = 3.06 \text{ mm} \]

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

Brillouine zone

\[ G \times 10^9 \]

\[ J_0 \]

\[ S_{21} \]

Gap: 10.4 – 11.9 GHz
Propagation between the rods, diffraction, no resonance patterns

Fields in photonic crystal

Transmission

9.0 GHz

10.6 GHz

11.5 GHz

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

Infinite rods (PML)

Transmission through the Structures with Different Rod Heights

$K = 77, D = 2.64$ mm

Vertical electric dipoles (second resonant mode)

Horizontal magnetic dipoles (first resonant mode)

Bandgap

$K = 77, D = 2.64$ mm
Coupled DR arrays vs. Photonic Crystals

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

Transmission spectra

Resonance-domain metamaterial

LTTC: \(K_1 = 62 \text{ (BZT)}, \quad K_2 = 7.8\)

\(D = 3 \text{ mm}, \quad h = 1.5 \text{ mm}\)

Transmission bands

Band gaps, field patterns and transmission bands are essentially different
5. Latest developments on artificial materials from DRs
One-DR scheme in a negative-epsilon background


Transmission lines of cylinder DRs in waveguide below cut-off

![Diagram of DR scheme](image1)

- Host medium: \( \varepsilon_{BG} = 2.2 \) (\( f_c = 20.2 \text{GHz} \))
- Dielectric resonator: \( \varepsilon_{DR} = 38 \)
- Rectangular waveguide: \( \varepsilon_r = 10.2 \) (\( f_c = 9.4 \text{GHz} \))
- Perspective view

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

![Diagram of 2D lattice](image2)

- Incident wave
- Rectangular waveguide
- Dielectric resonator (DR)
- Conducting plates

Negative refraction was also experimentally confirmed
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?


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

Red spots on the left show experimental data for refraction angle

Magnetic resonance

Electric field

Magnetic field

Frequency (GHz)
Measurements using THz time-domain spectroscopy

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

Holes were punched in a PTFE substrate ($\varepsilon_r = 2$) 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.

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

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

Microstereolithography

Model consists of 1350 elements

Increased image of sub-millimeter 3rd stage fractal

Electromagnetic Field Analysis

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.
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