Progress with Metamaterial Research

Prof. Subal Kar

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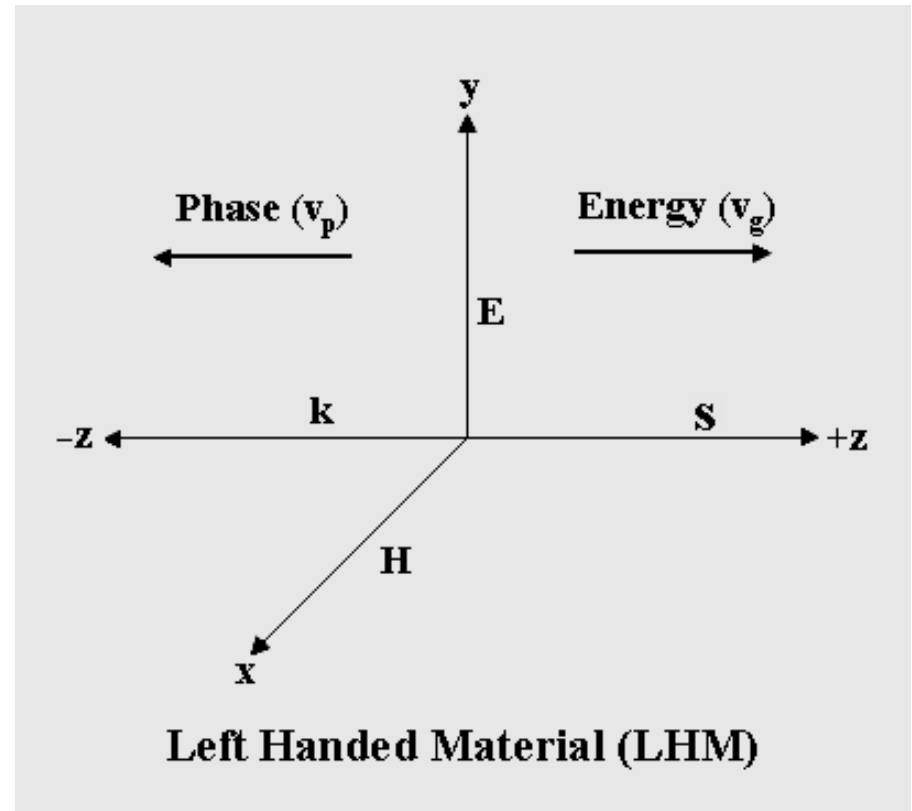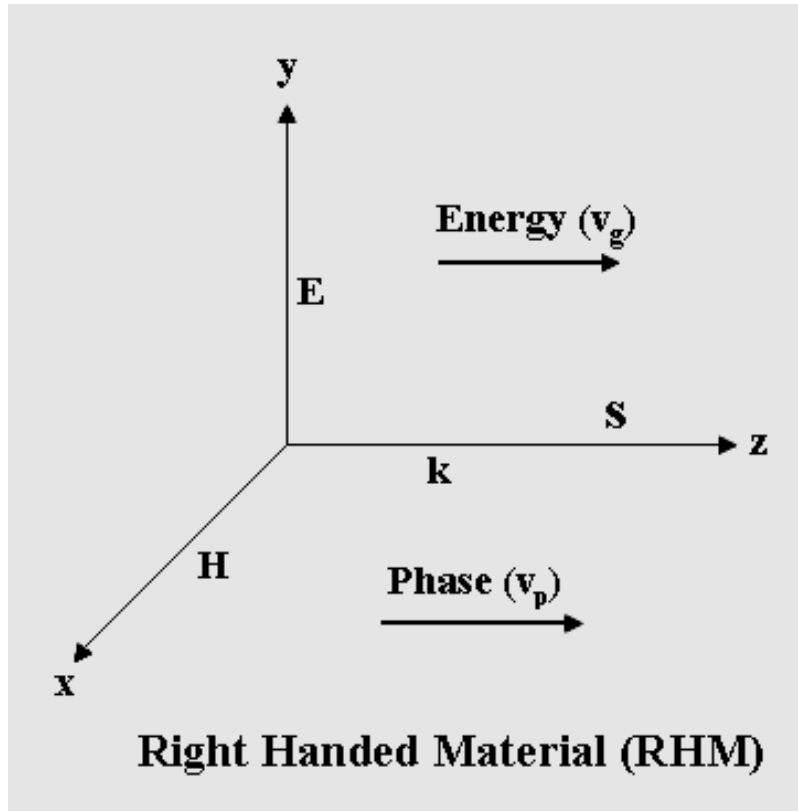
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Introduction

➢ Metamaterial,or phenomenologically the Left-Handed Material (LHM), is popularly known to make things "invisible".

➢ Technically speaking LHM is artificially structured material (commonly metal-dielectric composite) having extrinsic inhomogeneity but to an incident e.m. wave it is effectively homogeneous. The structural properties, rather than the chemistry (of the material with which it is designed), determine the characteristics of LH materials.

➢ LHMs are realized with unit cells in periodic structure having unit cell dimensions commensurate with small-scale physics [$h \ll \lambda$, where h is the characteristic dimension of a unit cell (i.e the elementary motif size) and λ is the operating wavelength].

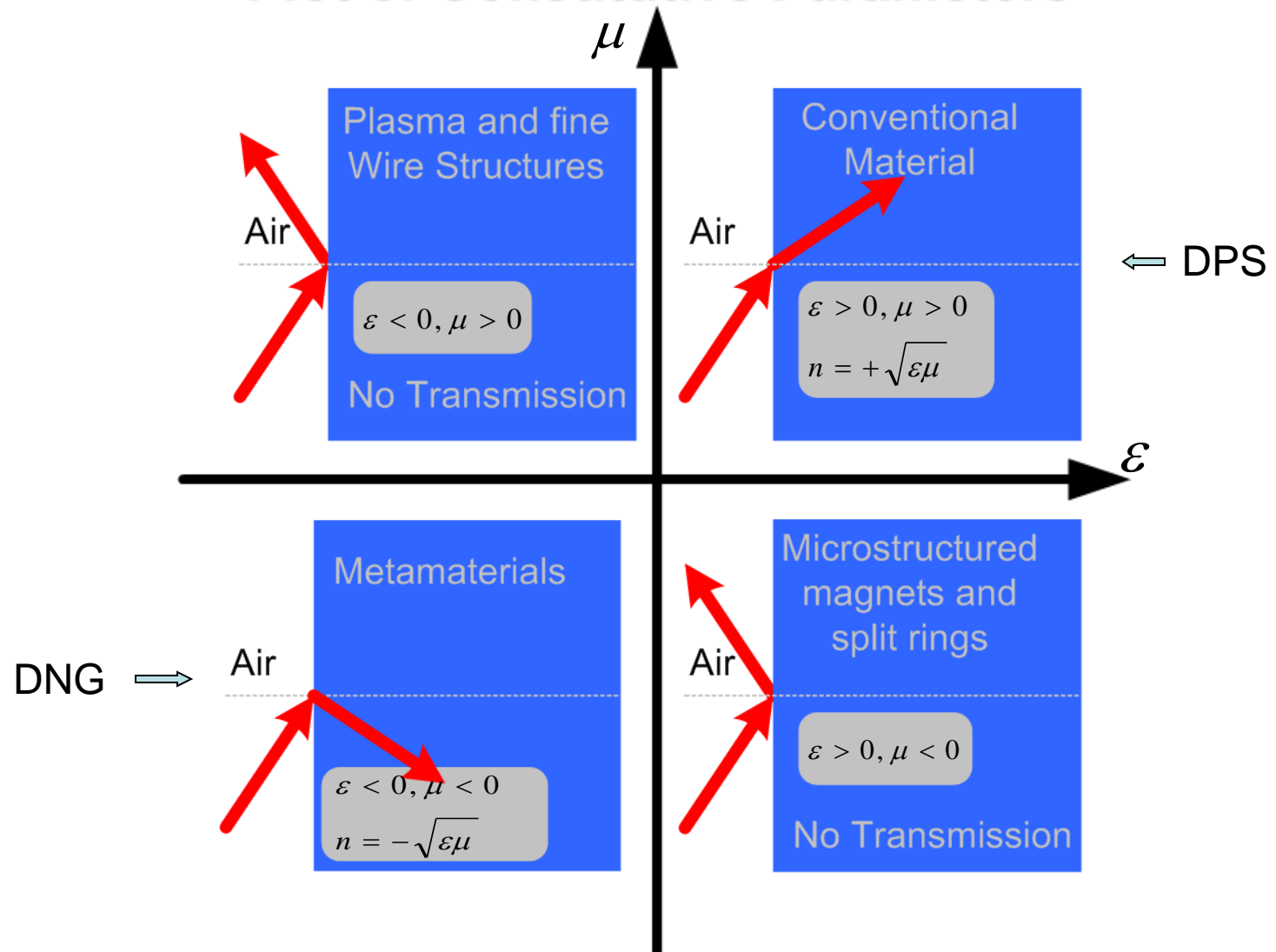➢ In recent years, the R&D in metamaterials is very active in realizing exotic functionalities not available in nature.

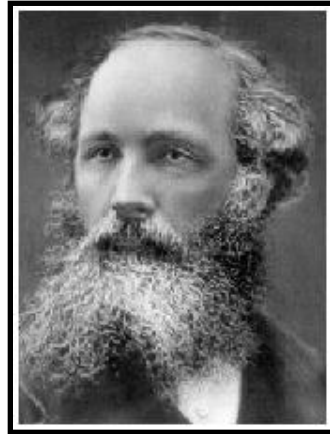# Right Handed vs Left Handed Materials

Right Handed Material (RHM)

Left Handed Material (LHM)

➤ RHM (Natural Materials)

➤ LHM (Metamaterial)

Plot of Constitutive Parameters

μ

ε

Plasma and fine
Wire Structures

Air

$\varepsilon < 0, \mu > 0$

No Transmission

Conventional
Material

Air

$\varepsilon > 0, \mu > 0$

$n = +\sqrt{\varepsilon\mu}$

$\Longleftarrow$ DPS

Metamaterials

Air

DNG $\Longrightarrow$

$\varepsilon < 0, \mu < 0$

$n = -\sqrt{\varepsilon\mu}$

Microstructured
magnets and
split rings
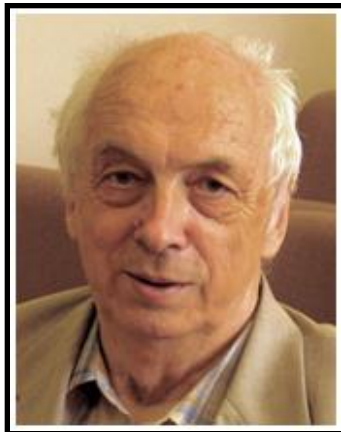
Air

$\varepsilon > 0, \mu < 0$

No Transmission
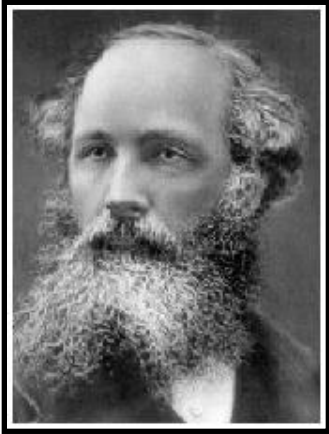
THE VISIONARIES

J. C. Maxwell

J. C. Bose

V. G. Veselago

J. B. Pendry

J. C. Maxwell

➤ **J. C. Maxwell is a father figure in electromagnetism.**

➤ **The two curl equations of Maxwell leads to the wave equation:**

$$\nabla^2 \Psi + n^2 \frac{\omega^2}{c^2} \Psi = 0$$

Where: $n^2 = \varepsilon_r \mu_r$

➤ **For RHM or double positive (DPS) medium when both ε_r and μ_r are positive, $n(= +\sqrt{\varepsilon_r \mu_r})$ is positive while for LHM or double negative (DNG) medium when ε_r and μ_r are simultaneously negative, $n(= -\sqrt{\varepsilon_r \mu_r})$ is negative. However, the *Maxwell's wave equation is equally valid for signal propagation both in case of RHM and LHM*.**

J. C. Bose

❑ *J.C. Bose was an experimental wizard*. **He did some pioneering experimental research on the properties of electromagnetic waves.**

❑ *His research on twisted structures (1898) as polarizer was essentially artificial 'Chiral materials' we know in today's terminology*.

❑ **However, after a short spell of research in e.m. waves he later on shifted to the research on plant physiology, in which he is the pioneer.**
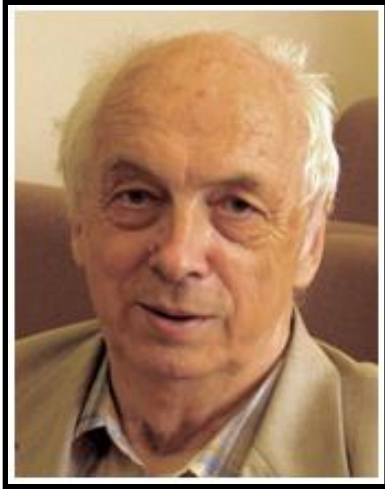
V. G. Veselago

❖ *The seminal paper by V. G. Veselago* **of Lebedev Physics Institute , U.S.S.R, published** *in 1967 is reckoned as the beginning of the LHM vision.* **He investigated theoretically the consequences when both permittivity (ε) and permeability (μ) of a non-magnetic material is negative.**

❖ *His theoretical investigations indicated the* <u>reversibility of Snell's law, reversed Doppler effect, and reversal of Cherenkov radiation</u> *for materials with ε and μ simultaneously negative.*

❖ **He first termed such materials as Left-Handed Material (LHM), which is also known as negative index material (NIM).**
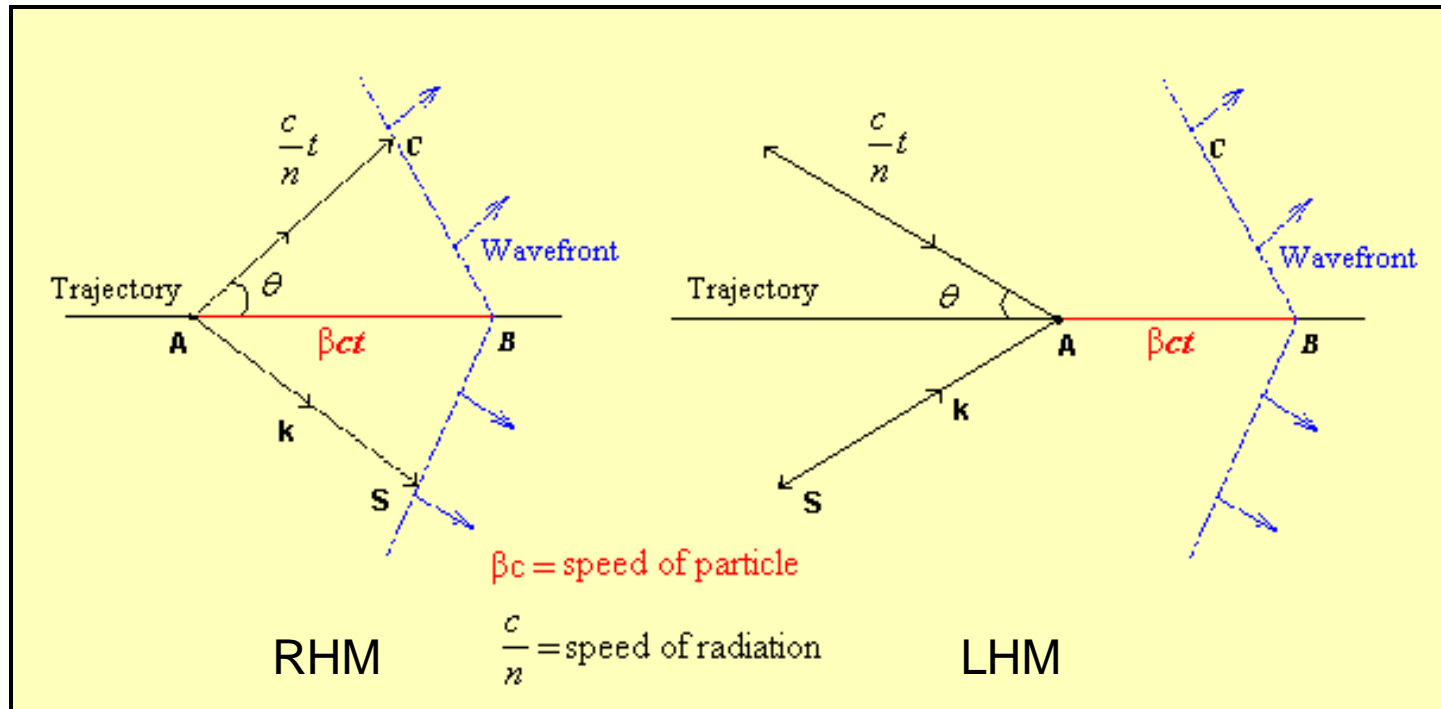
Consequences of LHM

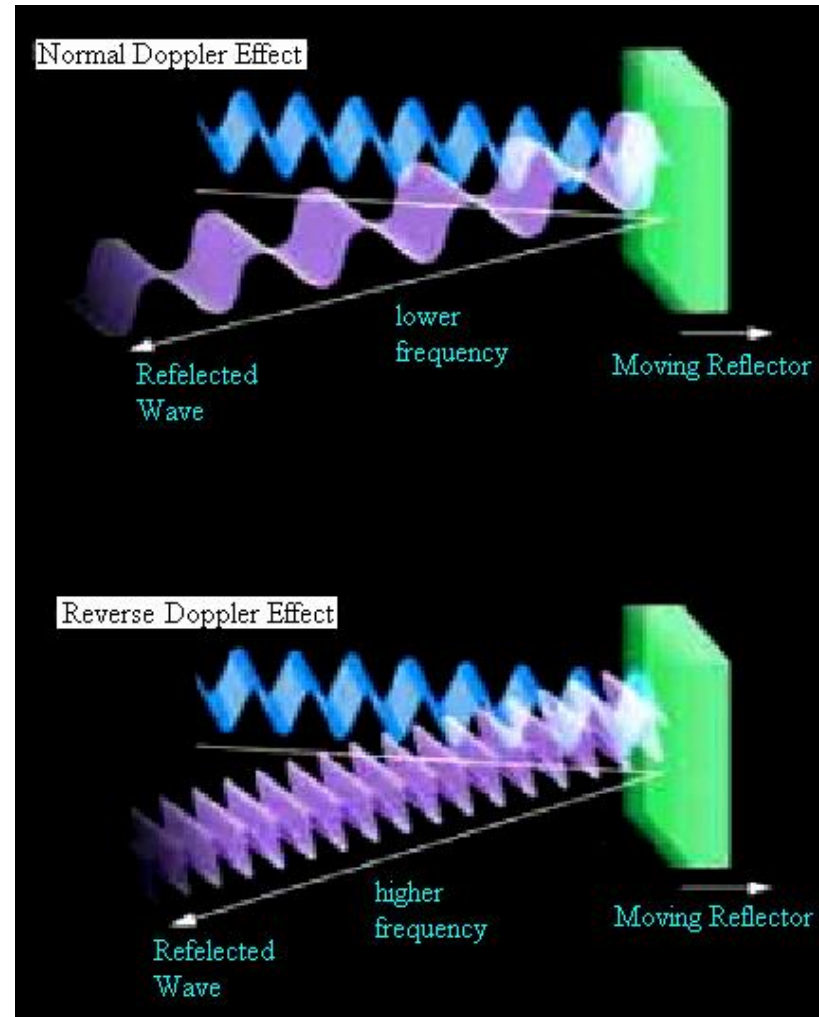$$[n_1 \sin\theta_i = n_2 \sin(-\theta_r) = -n_2 \sin\theta_r]$$
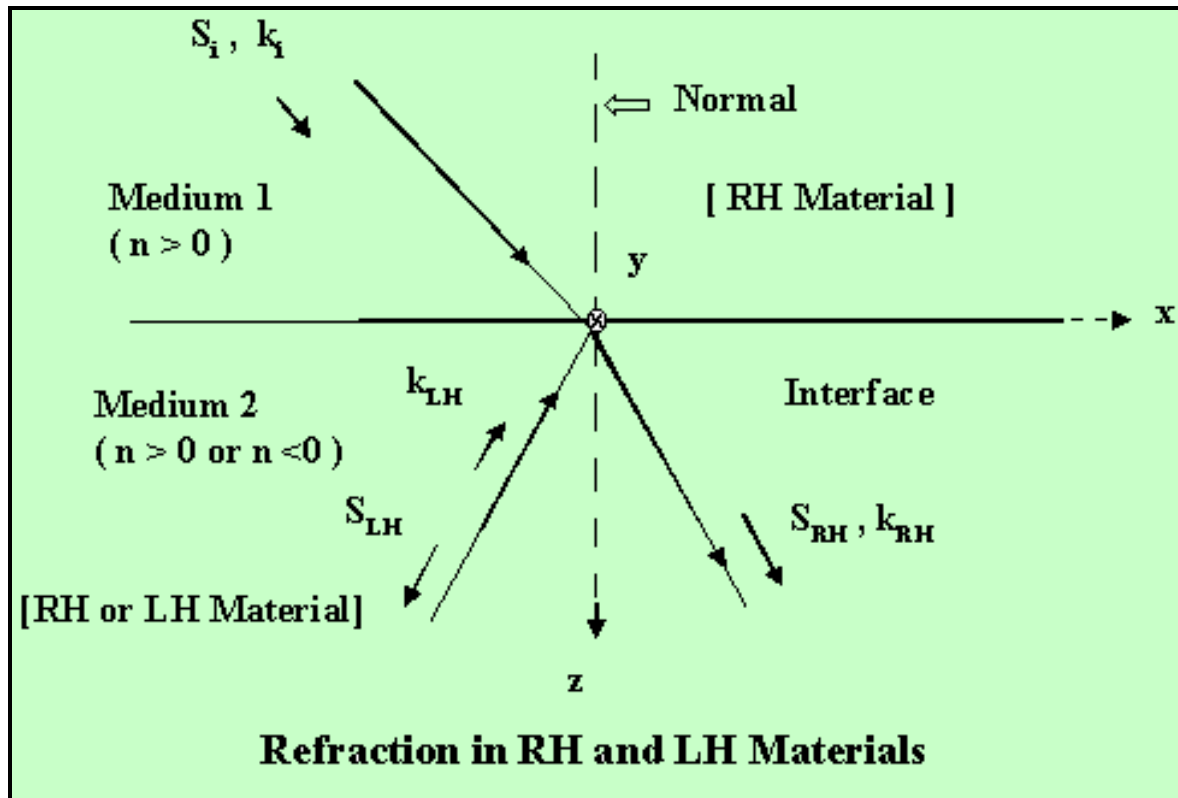
REVERSAL OF SNELL'S LAW

Consequences of LHM (contd.)

REVERSED CHERENKOV RADIATION

# Consequences of LHM (contd.)

**REVERSAL OF DOPPLER EFFECT**

> *John Pendry made the real breakthrough* **who showed the possibility for practically realizing the electric and magnetic plasma at microwave frequency using an array of thin metallic wires (1996) and an array of split-ring resonators (1999) respectively to realize negative ε_{reff} and negative μ_{reff} below the plasma frequency.**
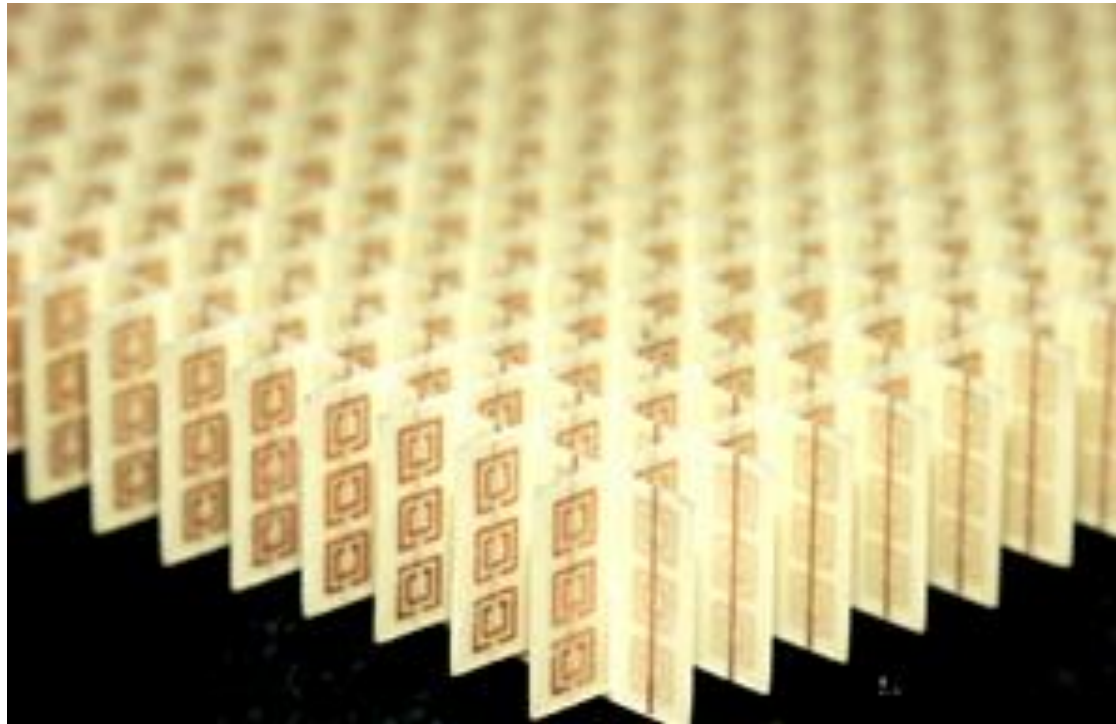
J. B. Pendry

TW Array
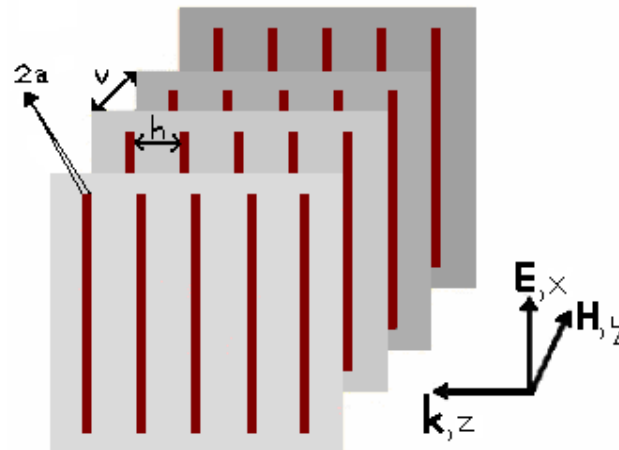
SRR Array
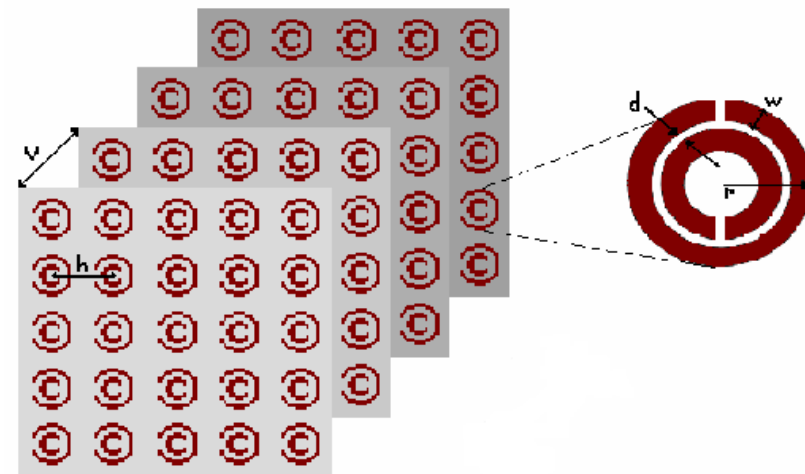
❑ *The first experimental realization of negative refractive index* using a composite structure of thin wire (TW) and split-ring resonator (SRR) *was reported by UCSD, U.S scientists under the leadership of D. R. Smith (2001)*
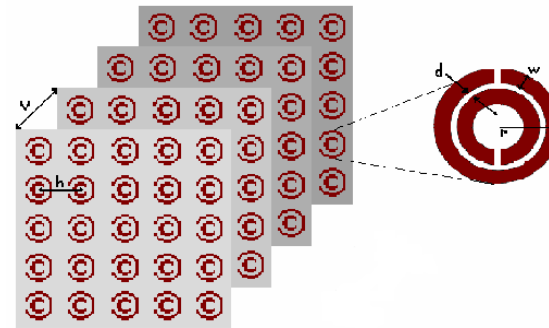

2D Plasmonic Metamaterial

Plasmonic Metamaterial

➢ The first metamaterial was thus of plasmonic type.

➢ Negative permittivity realized with an array of metallic thin wires (TW), below its electric plasma frequency, and negative permeability with a matrix of C-shaped split-ring resonators (SRR), below its magnetic plasma frequency.
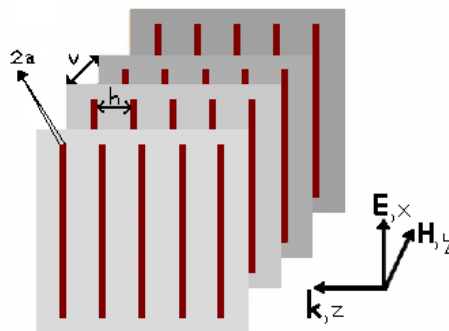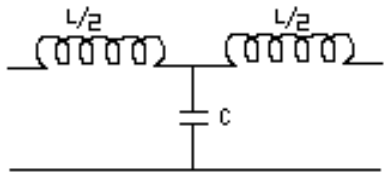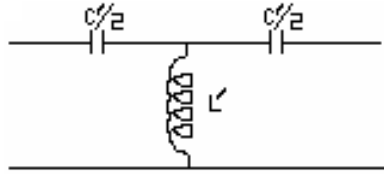

TW Array

SRR Matrix

➢ *Each unit cell* in such periodic array of TW and SRR when irradiated with an e.m. signal *acts respectively as an 'electric atom' and 'magnetic atom' mimicking the atomic arrangements as in the lattice of natural material*.

Transmission Line Metamaterial

➢ Recognizing the analogy between the LH waves possible with the dual of the normal transmission line and similar backward wave already known to exist in periodic structures, Eleftheriades et. al, Olnier, and Caloz et. al almost simultaneously proposed in 2002 an alternative way to realize LHM property using transmission lines.

➢ The practical implementation ***is done by periodically loading a host transmission line with series capacitance and shunt inductance***. Effective metamaterial property is realizable only when the ***unit cell dimension (d) satisfies the condition***: $d << \lambda$
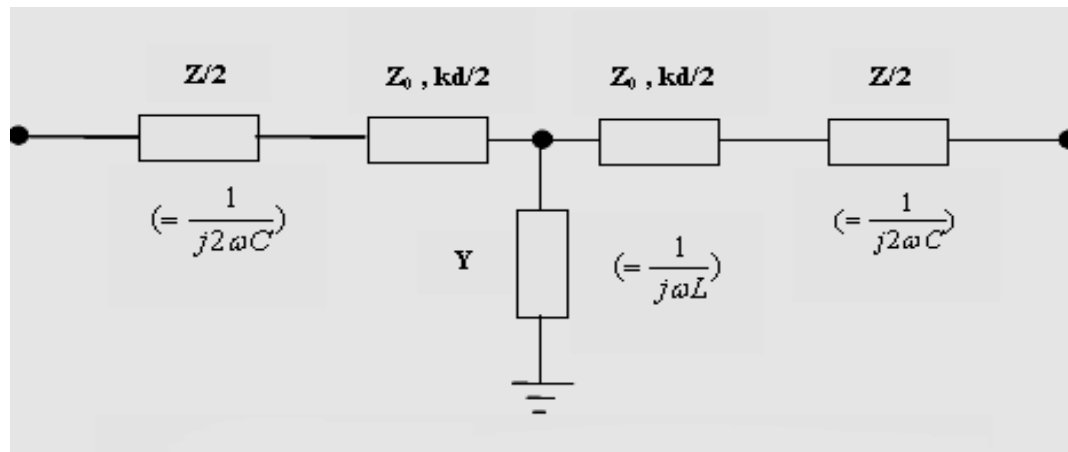
Transmission Line Metamaterial (contd)

| Parameters	β	Z_C	v_p	v_g	n
RHM	$\omega\sqrt{LC}$	$\sqrt{\dfrac{L}{C}}$	$\dfrac{1}{\sqrt{LC}}$	$\dfrac{1}{\sqrt{LC}}$	$\dfrac{\sqrt{LC}}{\sqrt{\mu_0\varepsilon_0}}$
LHM	$-\dfrac{1}{\omega\sqrt{L'C'}}$	$\sqrt{\dfrac{L'}{C'}}$	$-\omega^2\sqrt{L'C'}$	$+\omega^2\sqrt{L'C'}$	$-\dfrac{1}{\omega^2\sqrt{L'C'\mu_0\varepsilon_0}}$

➢**For frequency dispersive ε and μ, from Poynting's theorem the expression for energy:**

$$W = \frac{\partial(\varepsilon\omega)}{\partial\omega}|E|^2 + \frac{\partial(\mu\omega)}{\partial\omega}|H|^2$$

➢**Even when ε, μ < 0, their spectral derivatives remain positive. Hence, causality is not violated.**

Transmission Line Metamaterial (contd)

➢ Negative refraction at microwave frequency with PLTL was reported by G. V. Eleftheriades *et. al.* of the   University of Toronto, Canada (2002).
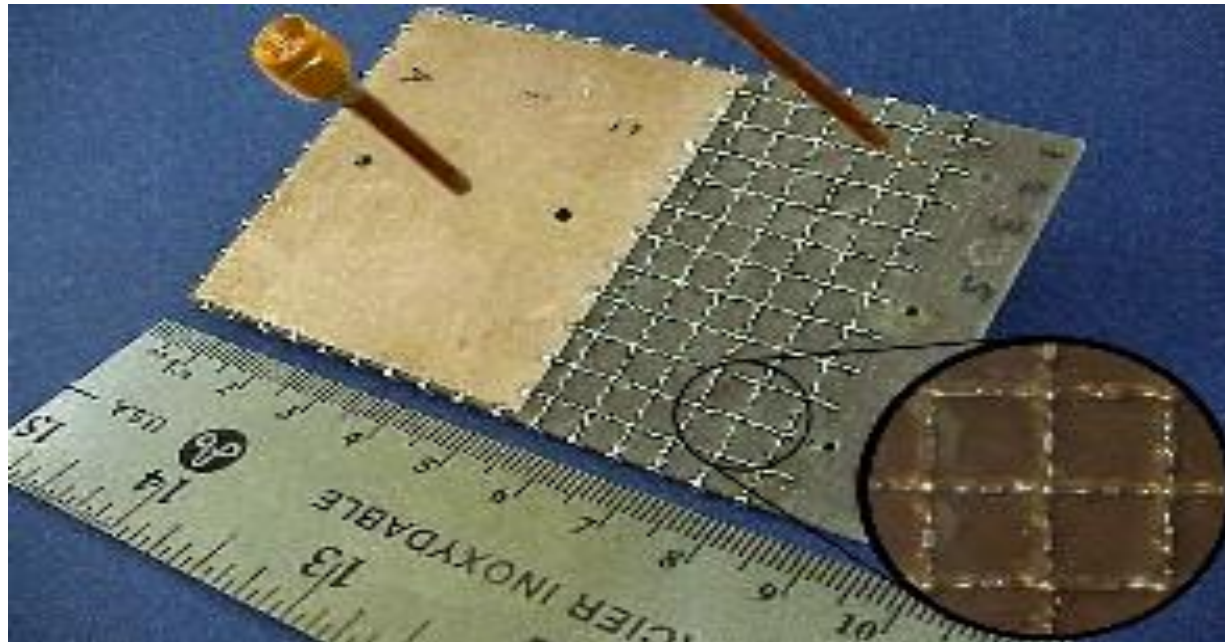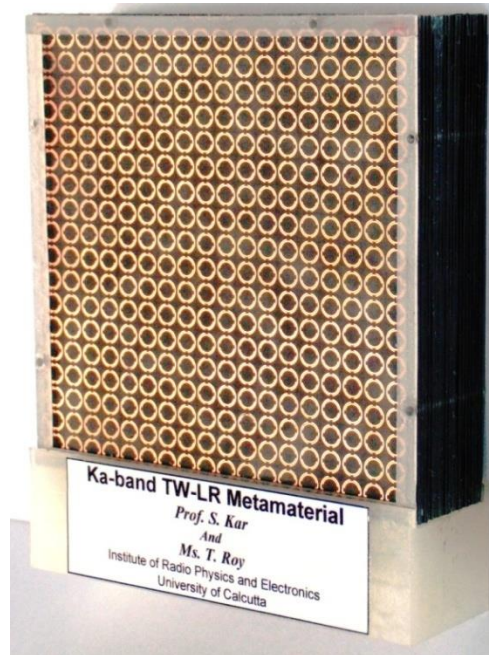

PLTL Metamaterial

➢ Being non-resonant , PLTL exhibit simultaneously low loss and broad bandwidth and are thus well suited for r.f and microwave circuit applications.

Our Metamaterial Research [A Glimpse]

Plasmonic Metamaterial

In this design, it is possible to realize negative refractive index (n) over a bandwidth ($f_{ep} - f_{m0}$) of 3.5 GHz, with
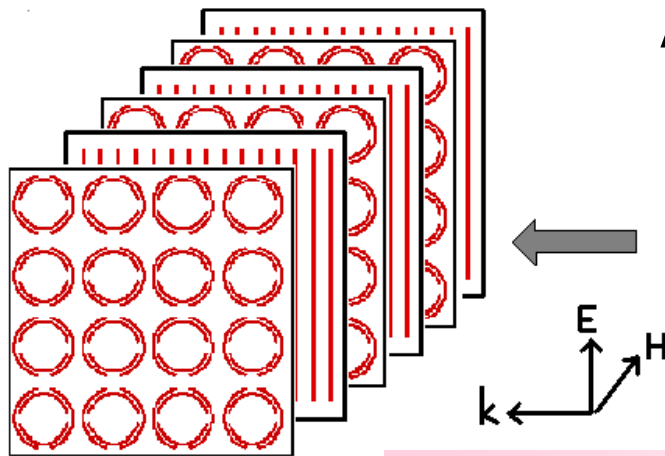n = - 1.84
at 31.25 GHz.

Subal Kar and T. Roy

Showcased at the National Theme Meeting at BARC, Mumbai, on 17th August 2009.
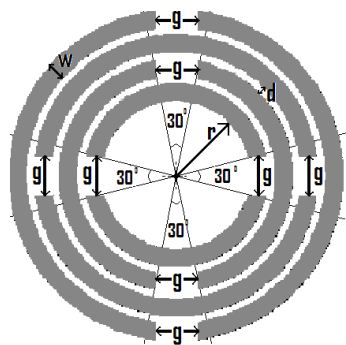
The First Metamaterial of India

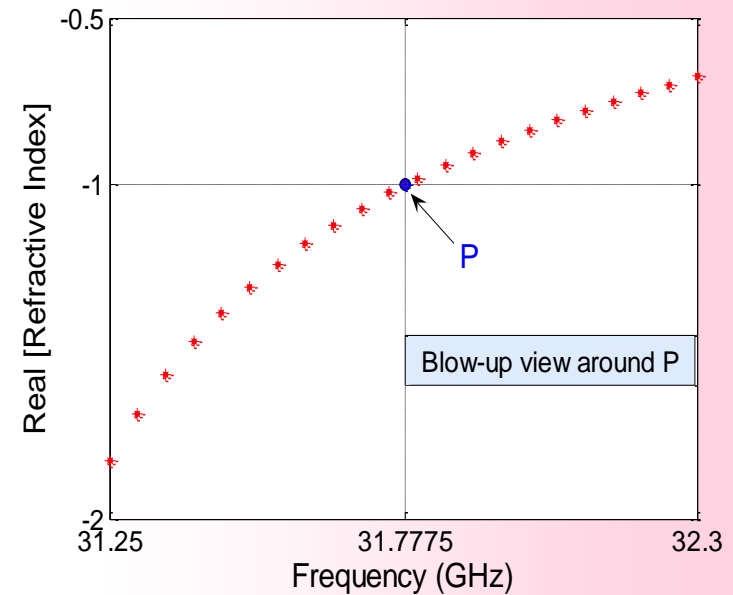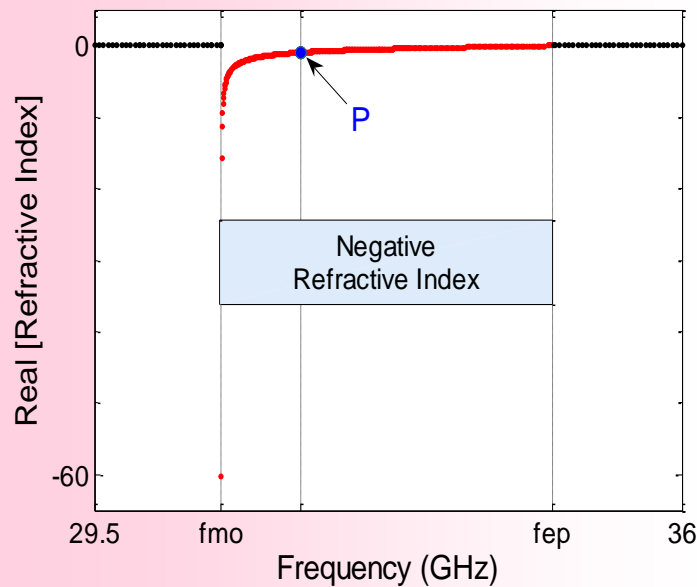**Documented as on-line news article in *Nature* (India) on 20th August 2009**

[http://www.nature.com/nindia/2009/090820/full/nindia.2009.273.html]

Analytical Modelling Result

LR-TW

LR Unit Cell

Real [Refractive Index]

Negative Refractive Index

Frequency (GHz)

Real [Refractive Index]

Blow-up view around P

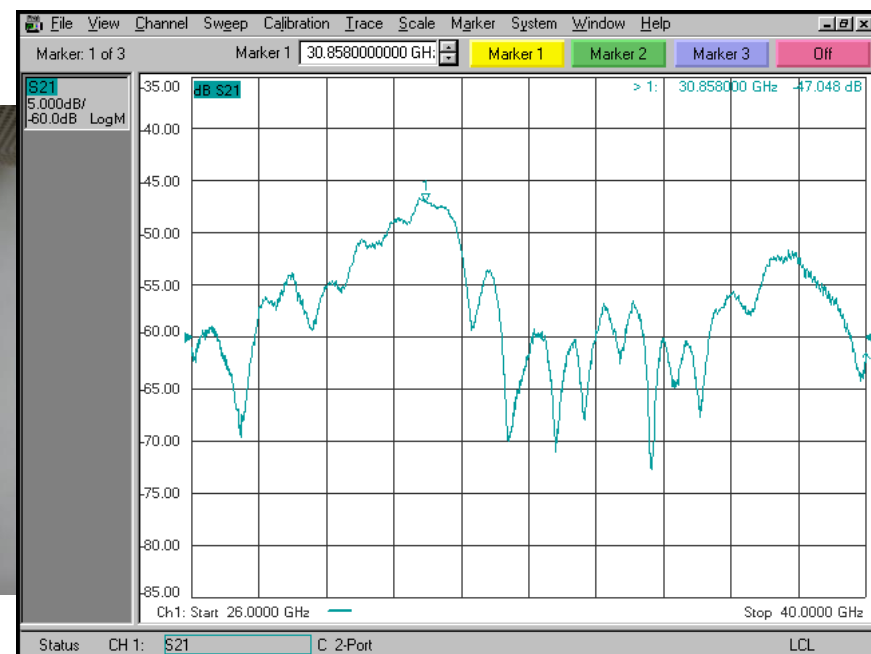Frequency (GHz)

T. Roy and Subal Kar

Experimental Result
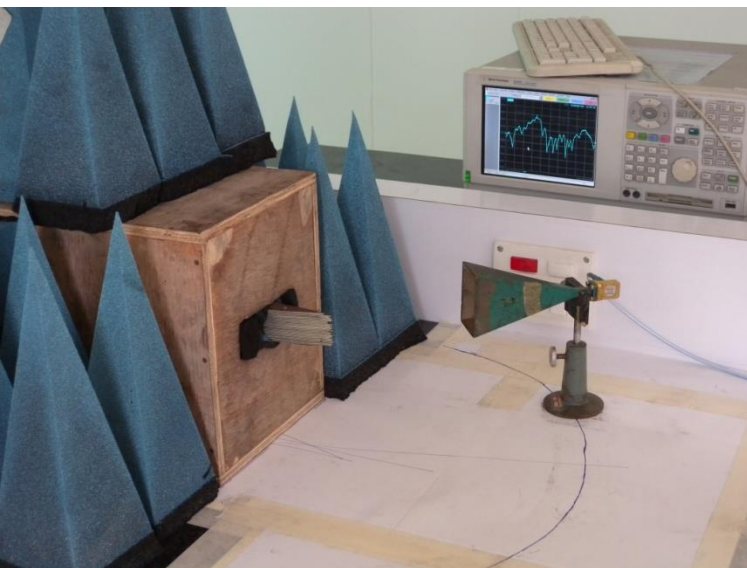
Experimental Set-up

15^0 Prism Metamaterial $\implies$

n = − 1.89 at 30.858 GHz
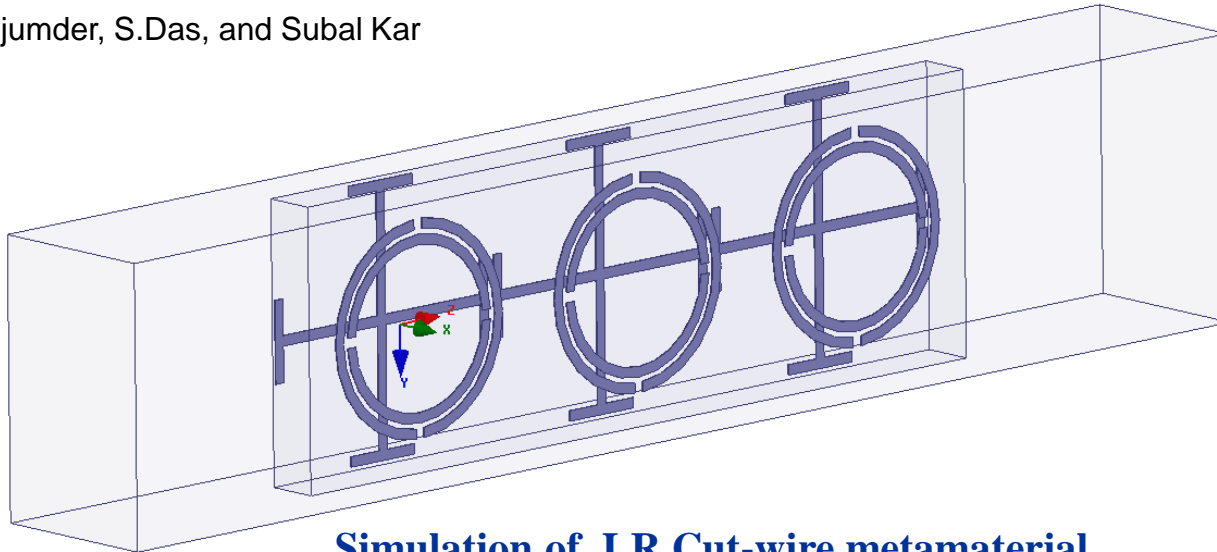
[Analytical: n = - 1.84 at 31.25 GHz]

A.Kumar, S.Chatterjee, A. Majumder, S.Das, and Subal Kar

Negative Refraction Frequency Pass-band

LR Cut-wire based two dimensional Metamaterial

A.Kumar, A.Majumder, S.Das, and Subal Kar

Simulation of LR Cut-wire metamaterial

Dimensions of LR	Dimensions of Cut-wire
Inner radius = 1.6mm	Lc = 1.6mm
Width of strip = 0.2mm	Width of strip = 0.2mm
Gap between strips = 0.1mm	Gap between end strips = 0.15mm
Unit cell dimensions = 5.5mm x 5.5mm x 2.5mm	Unit cell dimensions = 5.5mm x 5.5mm x 2.5mm
Substrate name : Arlon Diclad 880	Substrate name : Arlon Diclad 880
Substrate thickness : 0.508mm	Substrate thickness : 0.508mm
Substrate dielectric constant : 2.2, 0.0009	Substrate dielectric constant : 2.2, 0.0009

LR Cut-wire based Metamaterial : Negative Refraction

$$n = \frac{\sin(\delta)}{\sin(A)}$$

RHM Region

A = angle of incidence

δ = angle of refraction

A = 18.44 degrees for sample

LHM Region

Normal vector

Incident Gaussian Beam
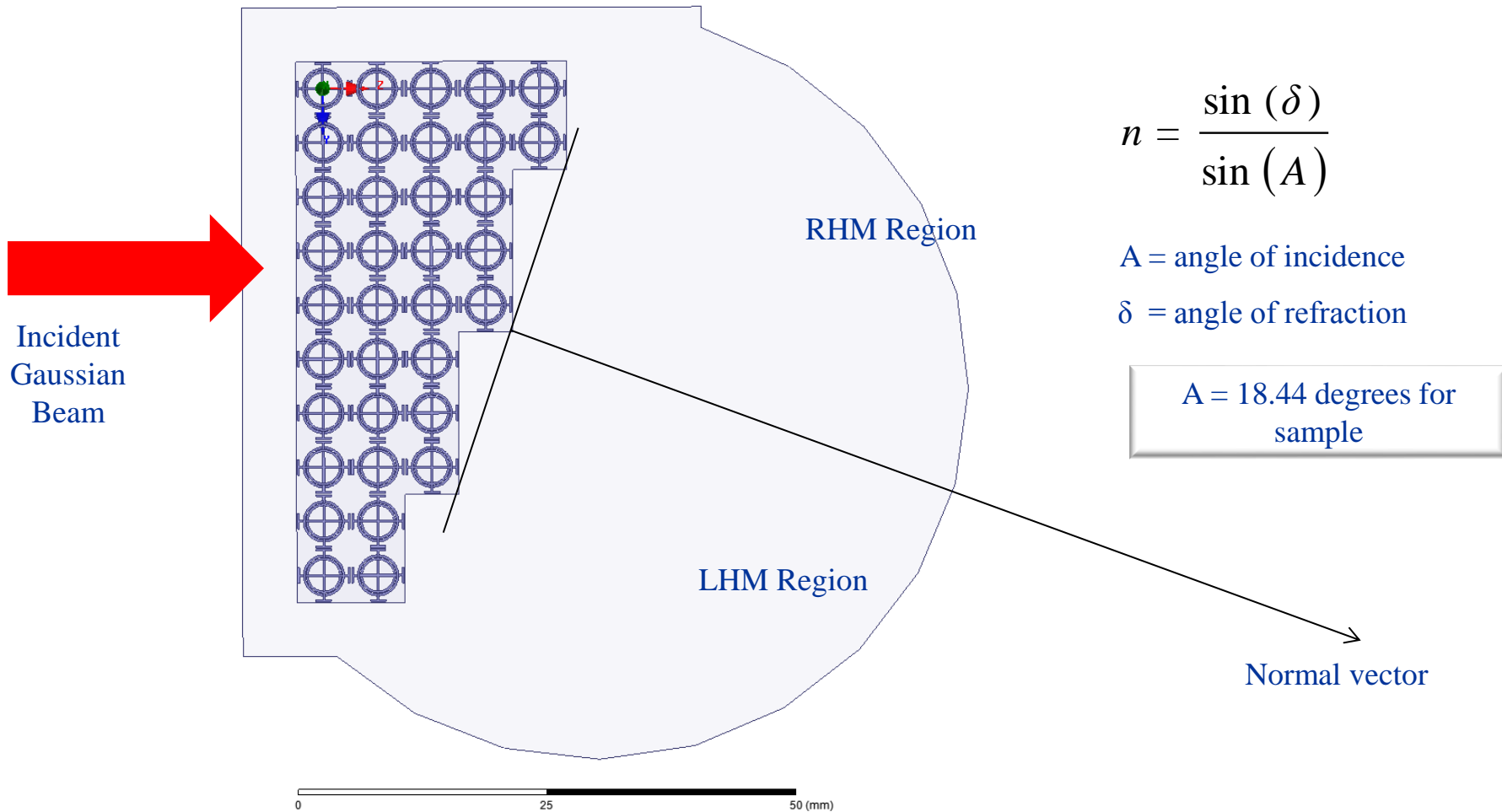
Simulation of LR Cut-wire based Metamaterial wedge

LR Cut-wire based Metamaterial : Negative Refraction

$$n = \frac{\sin(\delta)}{\sin(A)}$$

A = angle of incidence

δ = angle of refraction

A = 18.44 degrees

δ = 34 degree

RHM Region

n = -1.76

LHM Region

Normal vector

Incident Gaussian Beam
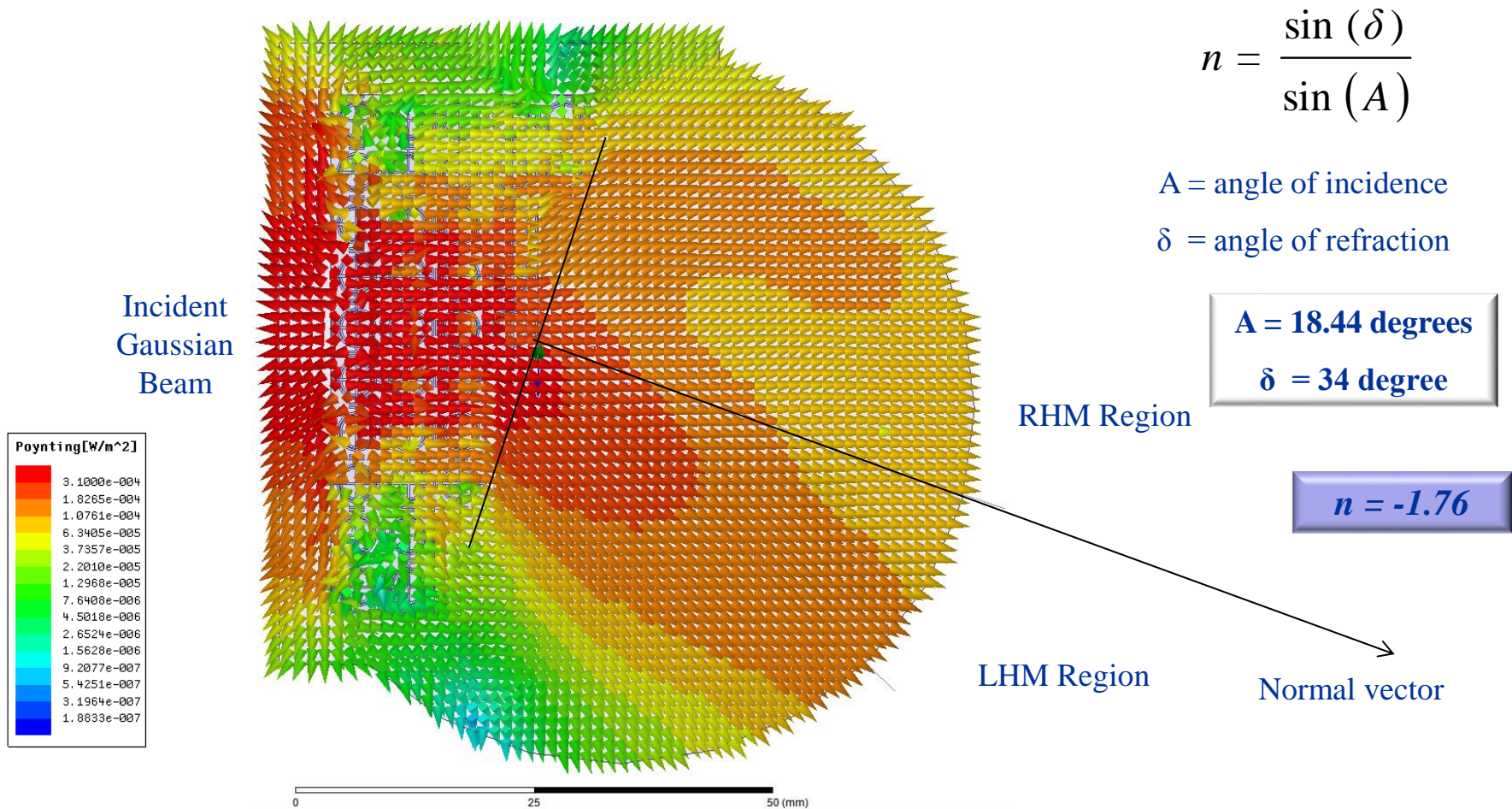
Simulation of LR Cut-wire based Metamaterial wedge at 10.5GHz

Testing of LR Cut-wire based Metamaterial wedge at X band
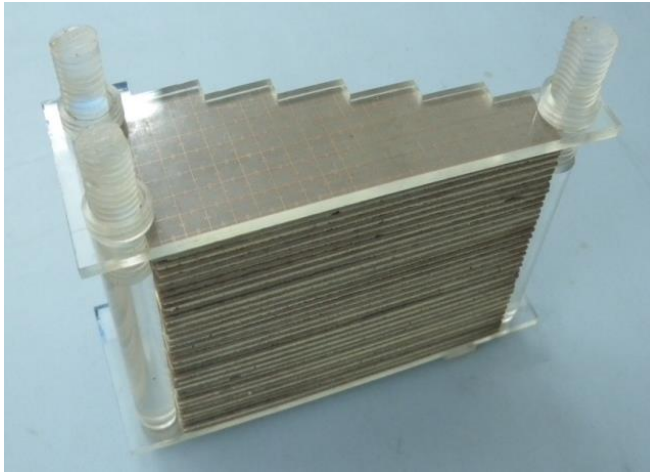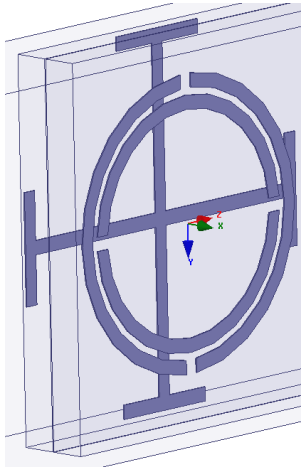
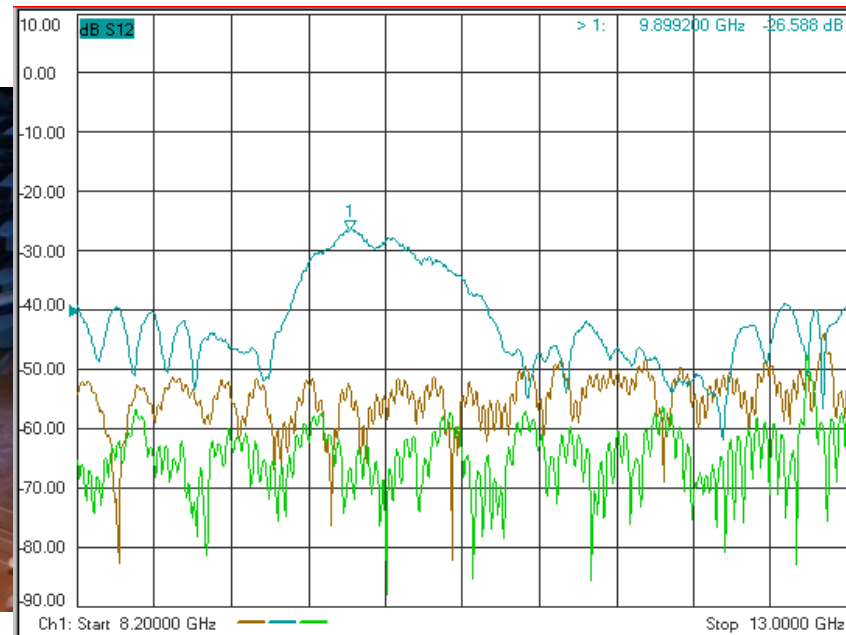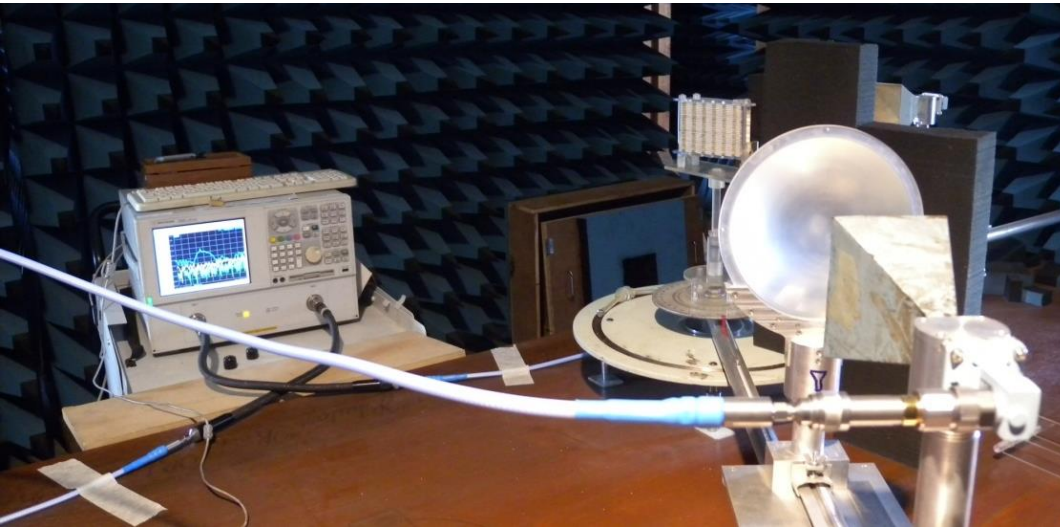**The way cut-wire and LR is combined is very critical**

A = 18.44 degrees

δ = 32 degree

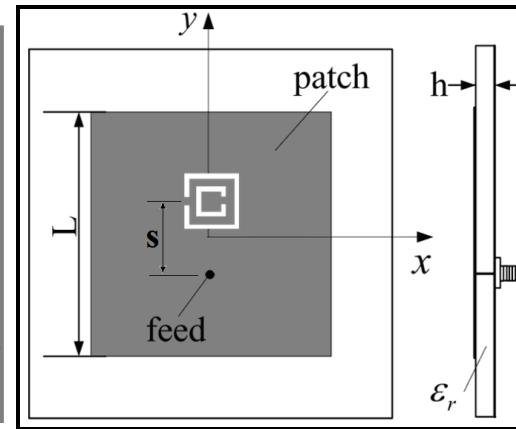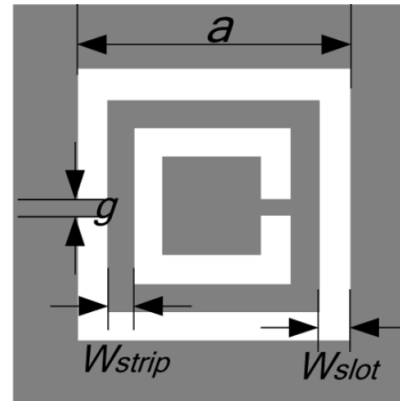**n = -1.68**

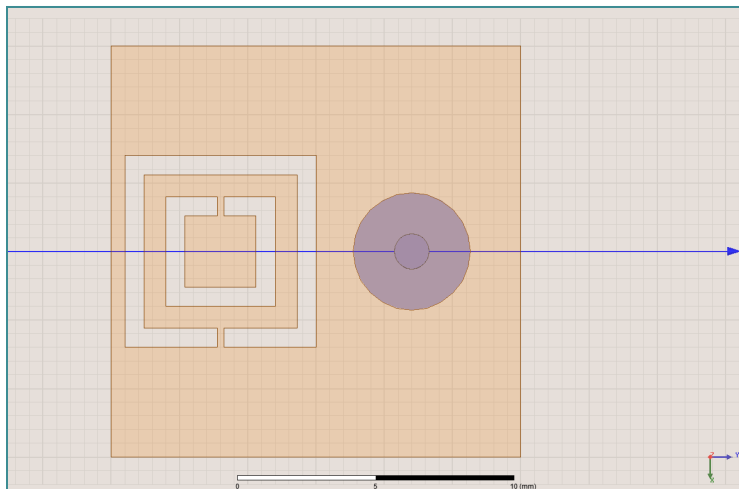# CSRR loaded Coaxial probe-fed Patch Antenna

M.Ghosh, A.Kumar, A. Majumder, and Subal Kar

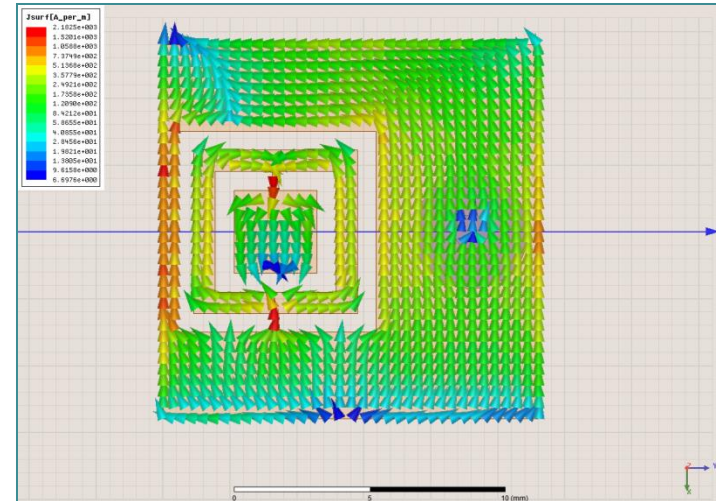| Parameters	Dimensions (in mm)
L	14
a	7.5
W_strip	0.8
W_slot	0.7
s	5.8
g	0.25
p	26.7

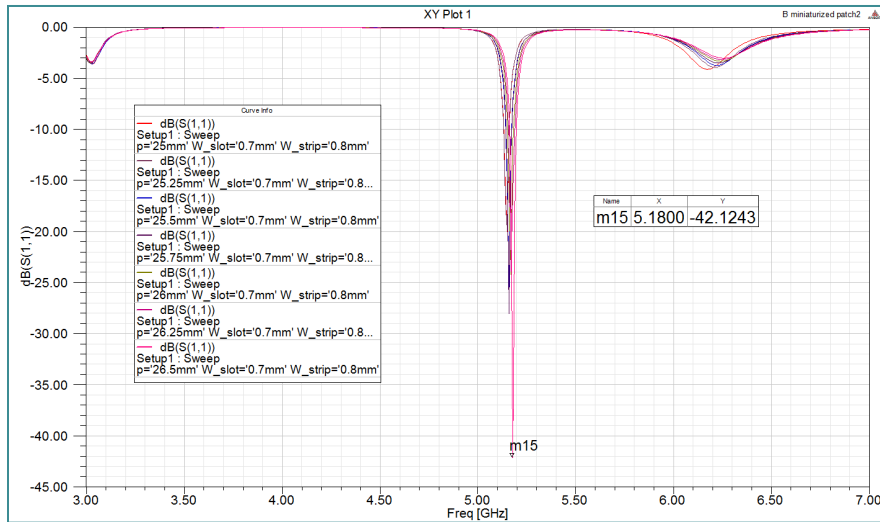| ε_r	2.2
h	0.5 mm

Schematic

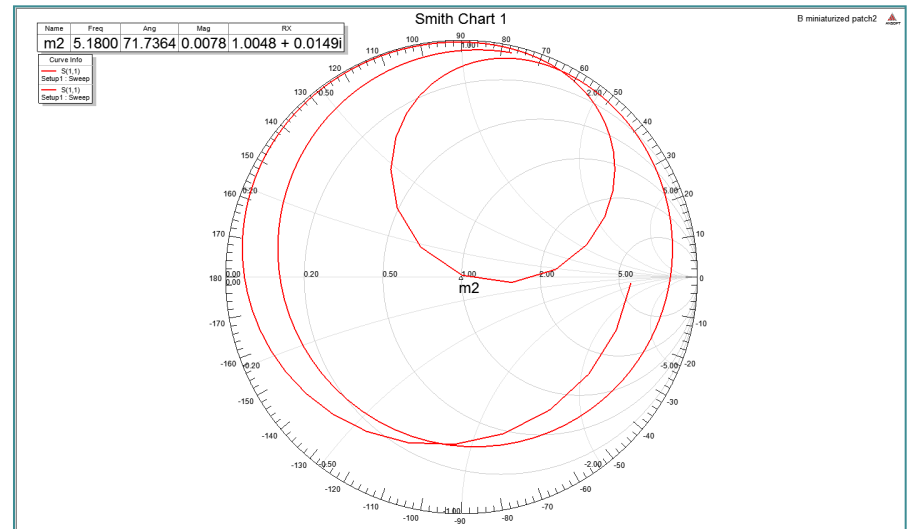Surface Current lines in the CSRR loaded patch

Results for CSRR loaded patch antenna at 5.2 GHz

⟸ Return Loss vs. Frequency

Smith Chart Plot indicating impedance matching between the patch and the coaxial line feed ⟹

Smith Chart Plot: impedance matching between the patch and the coaxial line feed
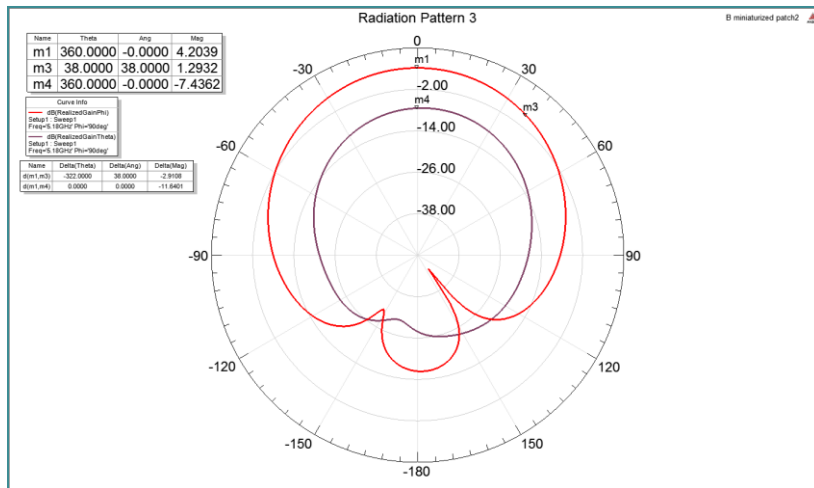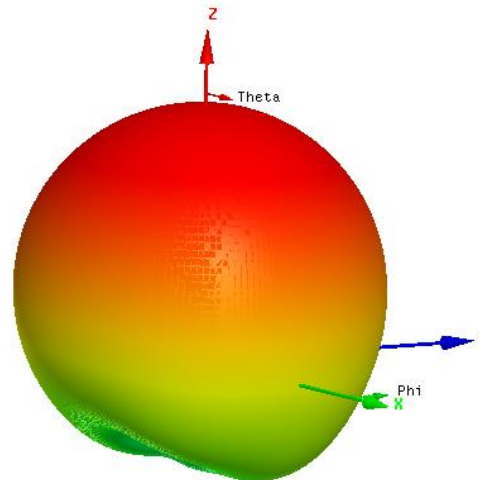

Co-and Cross pol. pattern in E-plane
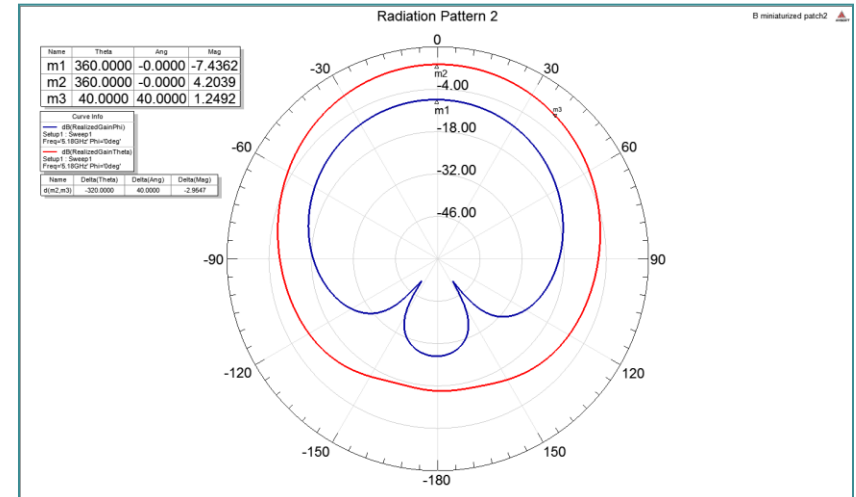
Co-and Cross pol. pattern in H-plane

3-D radiation pattern ⟹
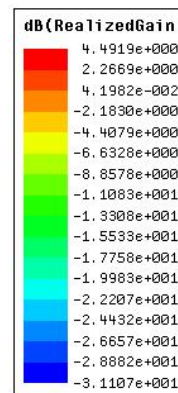
Experimental studies on fabricated structure
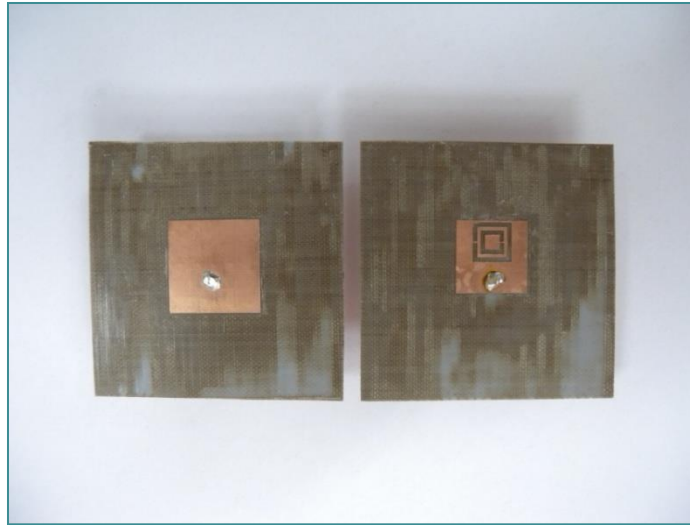
Comparative view of the fabricated antennas showing size reduction
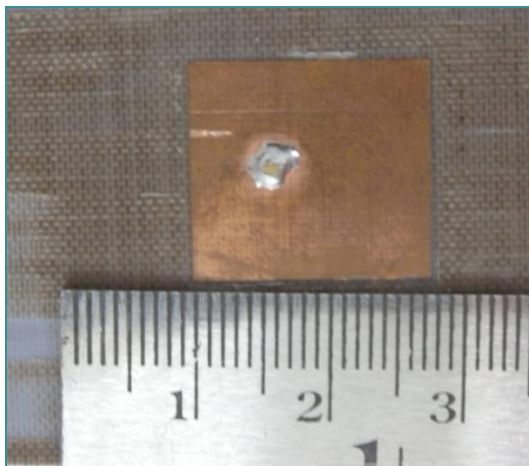
CSRR loaded patch ⟹

[24% size reduction]
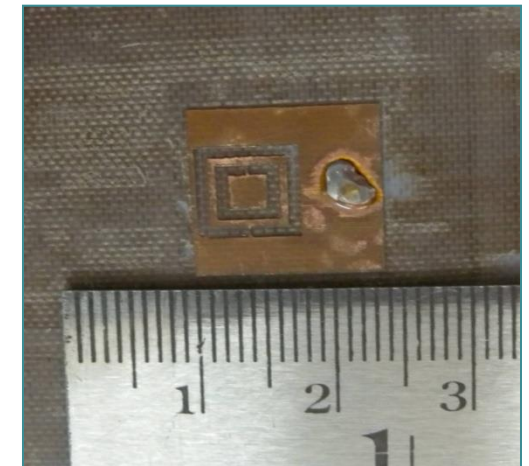
⟸ Conventional patch

Comparative (Measurement vs. Simulation) Radiation Characteristics of Conventional and CSRR loaded patch antenna

E-Plane Pattern (Co-Pol.) for Simple Patch

— **Measurement** — **Simulation**
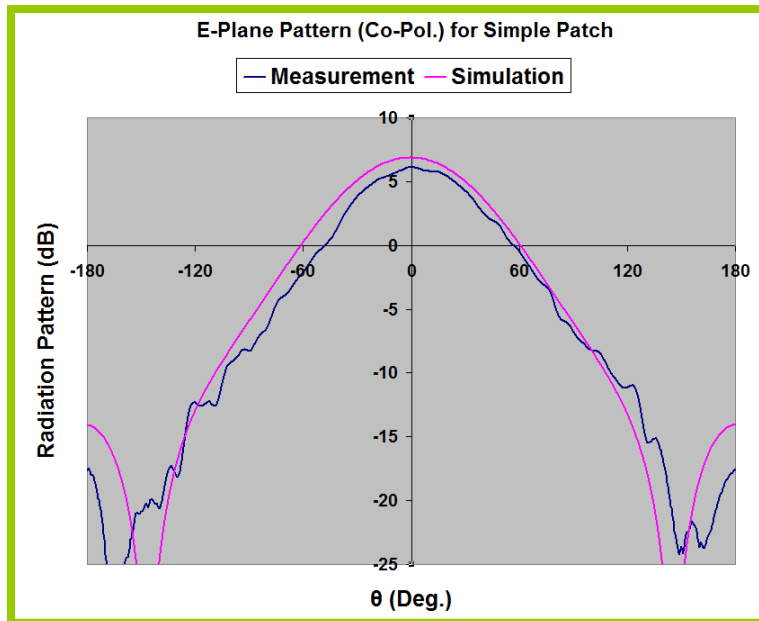
Measured gain : 6.11 dB
Simulation gain : 6.86 dB

E-Plane pattern (Cross-Pol.) for Simple Patch

— **Measurement** — **Simulation**

Measurement: 31.10 dB down
Simulation: 56.35 dB down

Comparative (Measurement vs. Simulation) Radiation Characteristics of Conventional and CSRR loaded patch antenna (Contd…)
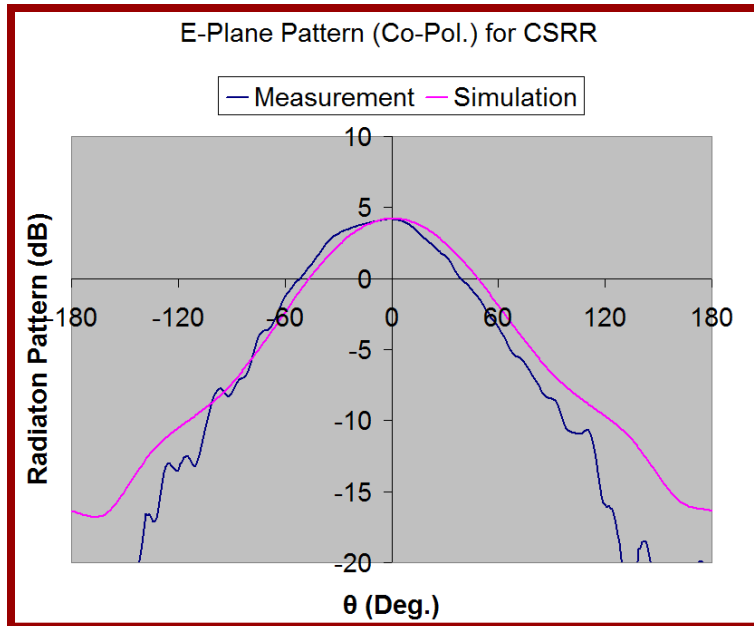
Measured gain : 4.18 dB
Simulation gain : 4.20 dB

Measurement : 10.36 dB down
Simulation: 7.43 dB down
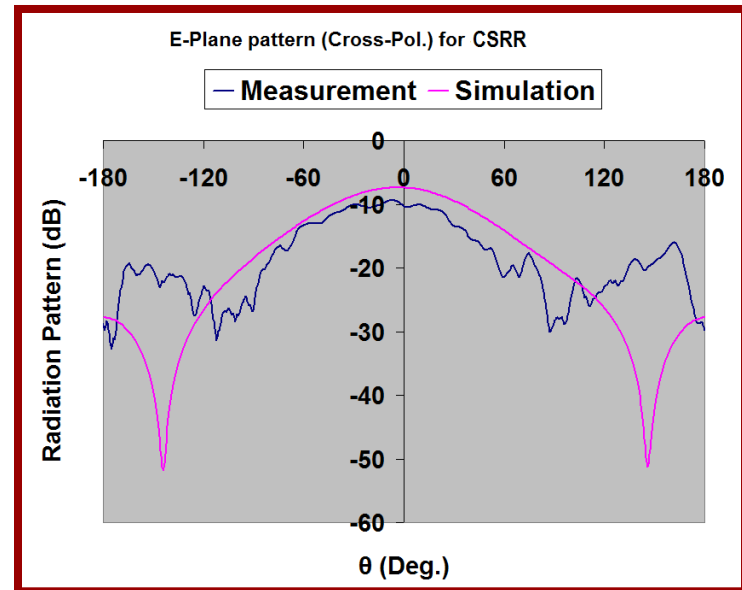
Exotic Application Potential of Metamaterial

➢ 'Superlens/Sub-wavelength imaging' overcoming the *diffraction limit* of conventional optics supposed to be possible due to *evanescent wave amplification* in LH media is gaining enough enthusiasm which might one day make it possible to image individual strands of DNA.
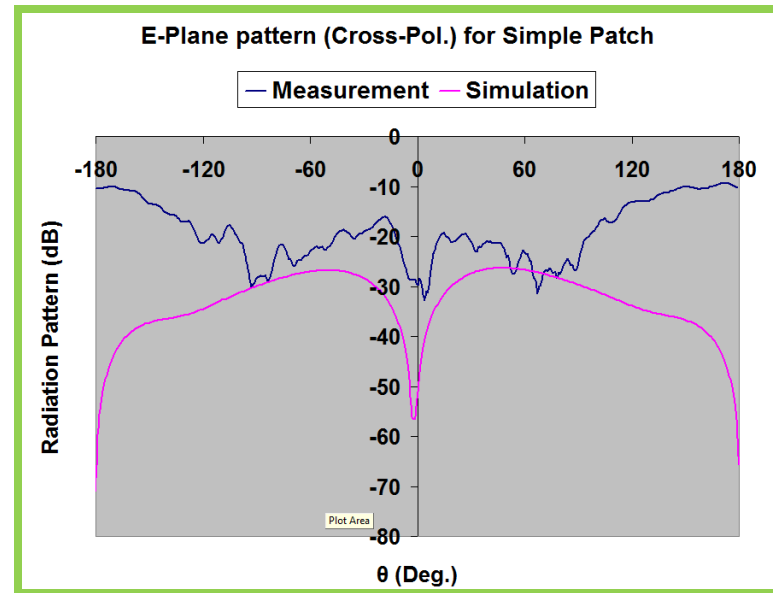
➢ 'Cloaking' of objects (may not be of the Harry Potter type at the moment) opening up the possibility of making reliable optical memories for new generation computers and showing new avenues for stealth technology.

➢ 'Reversed Cherencov radiation' possible with metamaterial based accelerator might revolutionize future accelerator research, especially in the design of sensitive detectors.

Super-lens/Sub-wavelength Imaging

❑ At the image plane object details are not obtainable when focusing is done by RH media due to the 'diffraction limit': $\Delta x \sim 2\pi / k = \lambda$, where *Δx* is the minimum resolvable feature. The diffraction limit manifests itself as an image smeared over an area approximately one wavelength in diameter.

❑ This happens because the evanescent waves which contain the sub-wavelength details of the object decays rapidly in a RH media.

❑ However LH media is found to be capable of amplifying the evanescent waves, possible with surface plasmon polaritons coupling between the z = 0 and z = d faces of LHM slab, thus overcoming the diffraction limit. Sub-wavelength details of the object is thus obtainable at the image plane with LH media focusing.

❑ The counter-intuitive LHM plane slab focusing is thus said to perform as a 'super-lens'.

Super-lens/Sub-wavelength Imaging (cont..)

- *Hyper lens based on the diffraction free superlens capability, designed by UC Berkeley team (2007)* to magnify sub-diffraction limited objects and project the magnified images to the far field with conventional lens.

- Hyperlens consists of a metamaterial formed out of curved periodic stack of Ag and Al_2O_3 deposited on a half cylindrical cavity fabricated on a quartz substrate.

- Experimental results demonstrated far field imaging with resolution down to 125nm *at 365nm working wavelength*.

- *May have possible application in nanotechnology photolithography*.

HYPERLENS
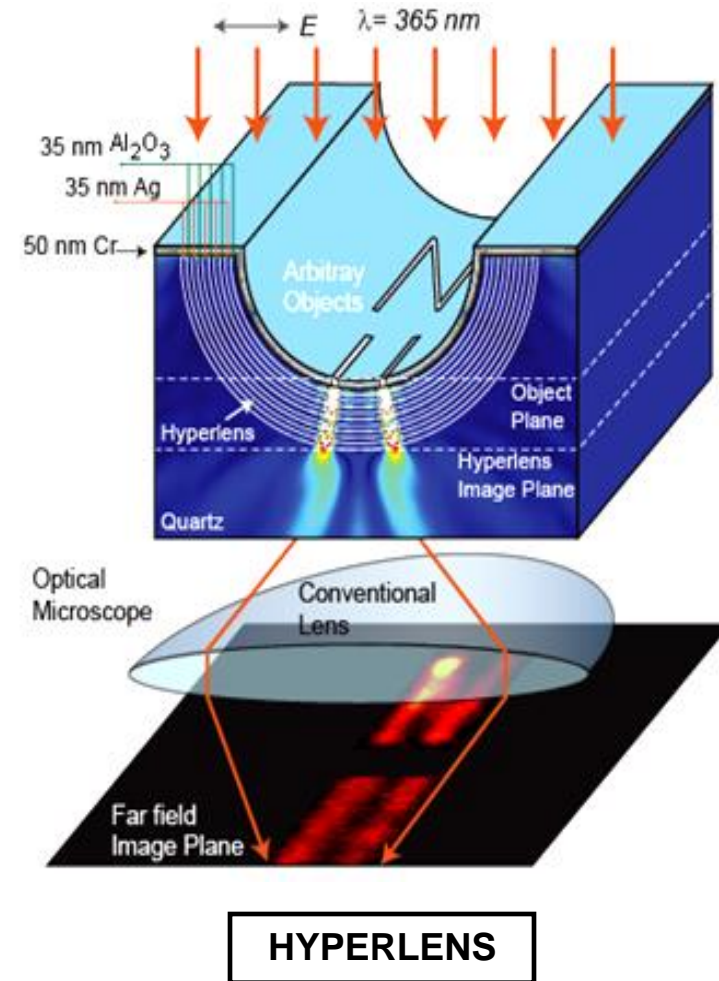
Refraction and Transmission in LHM
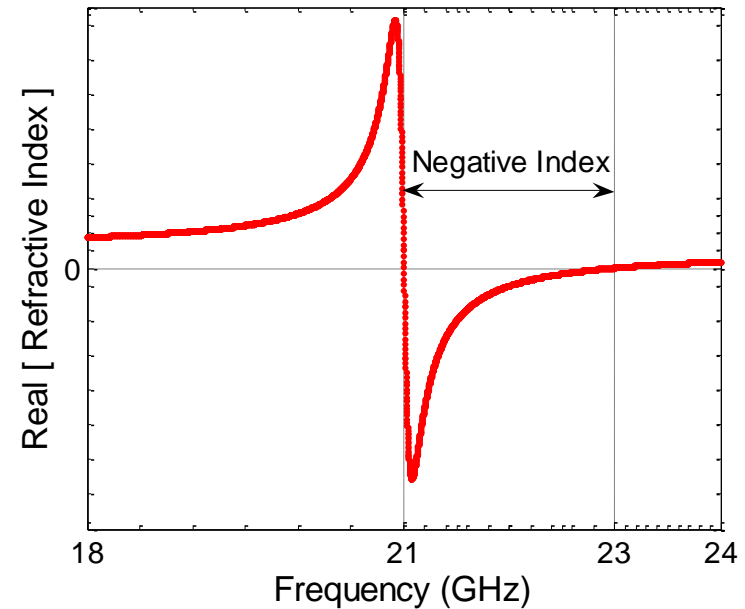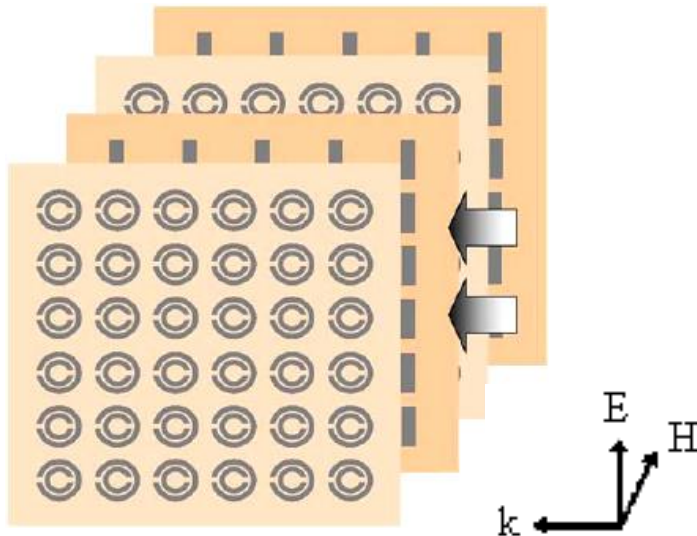
$$\varepsilon_{reff}(\omega) = 1 - \frac{\omega_{ep}^2 - \omega_{e0}^2}{\omega^2 - \omega_{e0}^2 - j\gamma_e\omega}$$

$$\mu_{reff}(\omega) = 1 - \frac{\omega_{mp}^2 - \omega_{m0}^2}{\omega^2 - \omega_{m0}^2 - j\gamma_m\omega}$$

$$n(\omega) = \pm\sqrt{\varepsilon_{reff}\,\mu_{reff}}$$

where, ω_{ep} **is the electric plasma frequency**

ω_{e0} **is the electric resonant frequency**

ω_{mp} **is the magnetic plasma frequency**

ω_{m0} **is the magnetic resonant frequency**

γ_e **and** γ_m **are the respective damping factors due to metal loss**

[T. Roy, D. Banerjee, and Subal Kar]

Refraction and Transmission in LHM (contd)

$$\text{Transmission Function} = T = \left| Tmag \right| e^{i\left| Tpha \right|}$$
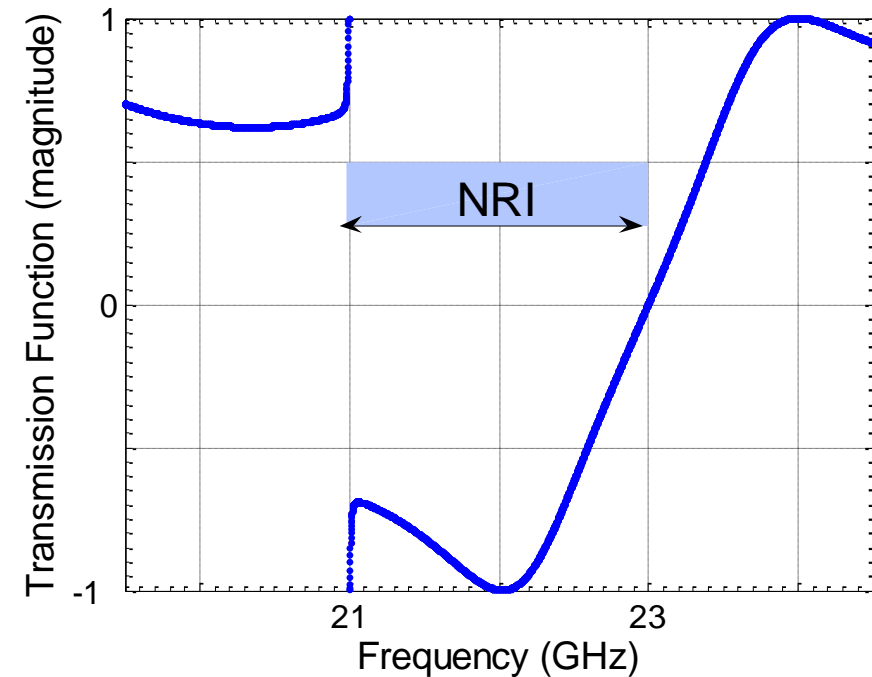
$$Tmag = \frac{tt'}{\sqrt{1 + r'^4 - 2r'^2 \cos\left(2k_z' d\right)}}$$
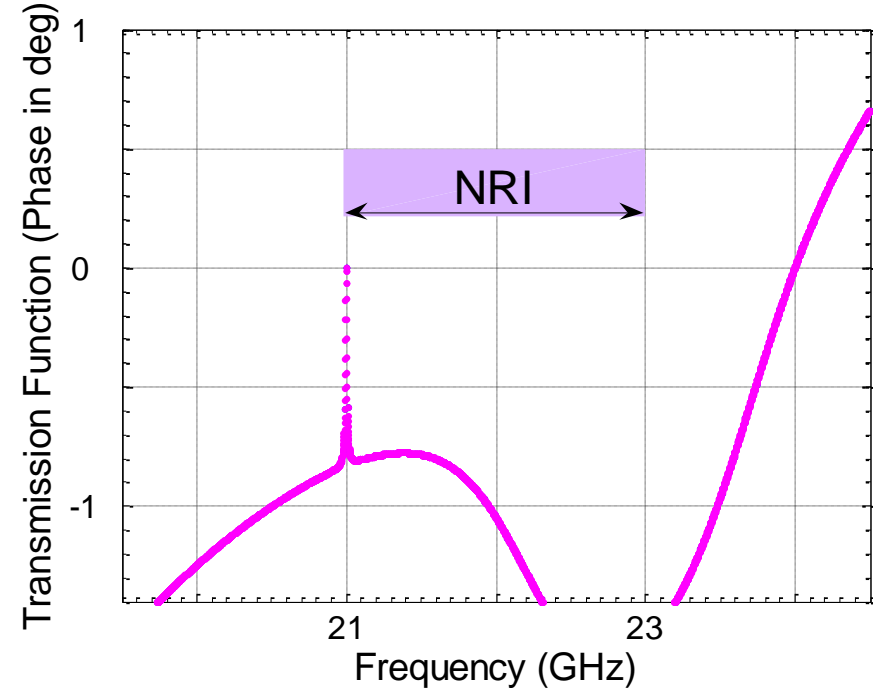
$$Tpha = \tan^{-1}\left[\frac{1 + r'^2}{1 - r'^2} \tan\left(k_z' d\right) \right]$$

[T. Roy and Subal Kar]

Refraction and Transmission in LHM (contd)

$$v_p = c_0 \big/ n = L \big/ \tau_p$$

$$v_g = c_0 \big/ n_g = L \big/ \tau_g$$

Where,

$$n_g = (n + \omega \, dn \big/ d\omega)$$

[T. Roy and Subal Kar]

Evanescent Wave Amplification

Evanescent wave growth with slab thickness *d* as parameter
(A: 15cm, B: 1.5cm, C: 0.15cm)

[T. Roy and Subal Kar]

Evanescent Wave Amplification (contd)

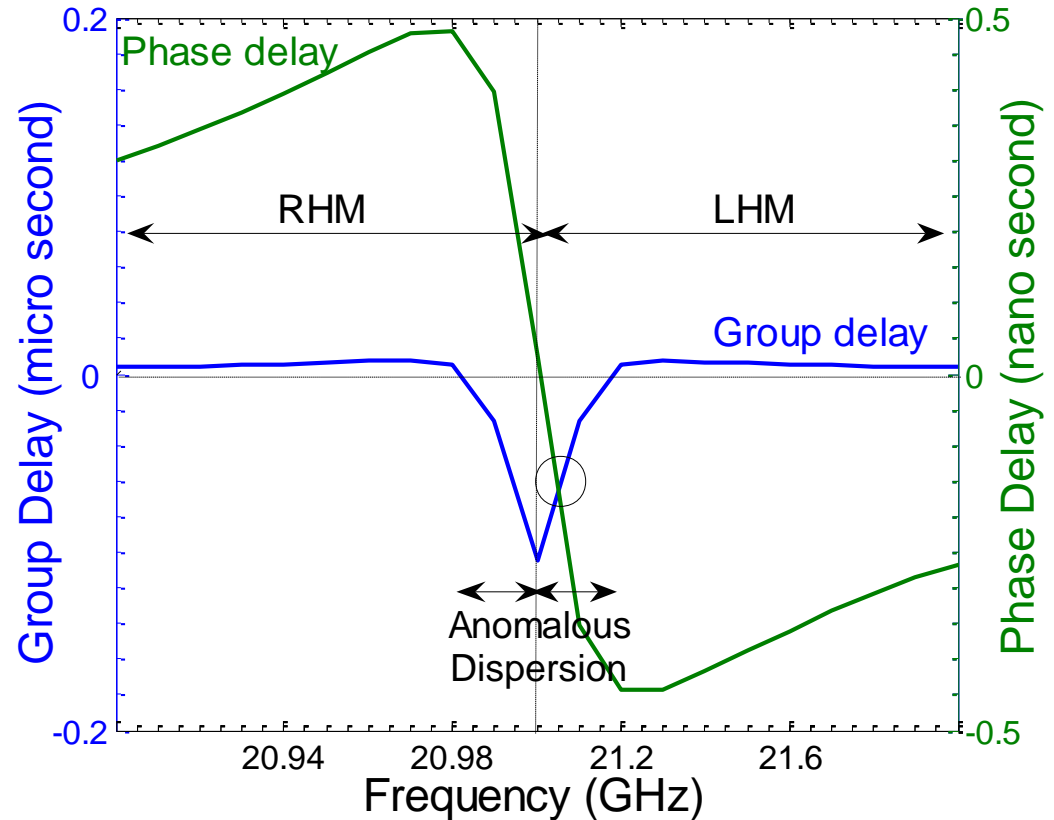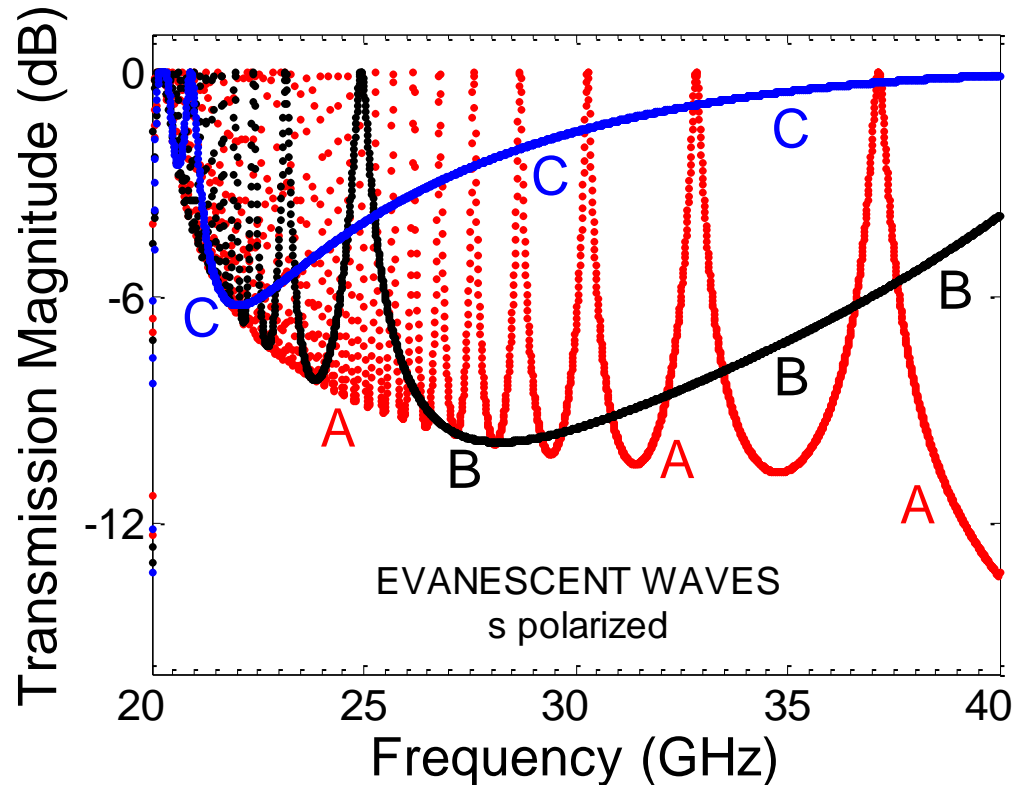❑ Evanescent wave amplification in LH media is found to be possible with surface plasmon polaritons coupling between the z = 0 and z = d faces of LHM slab.

❑ However, studies show that *losses in LH media has significant deleterious effect in realization of evanescent wave amplification which is crucial for sub-wavelength focusing with LH media*.

Transfer Function of LHM slab:

$$H\left(k_x\right) = t_1\, P\, t_2\, P'$$

t_1, t_2 → effective transmission coefficients at z = 0 and z = d.

P, P' → Phase change or amplitude amplification/decay factor within and outside the LHM slab
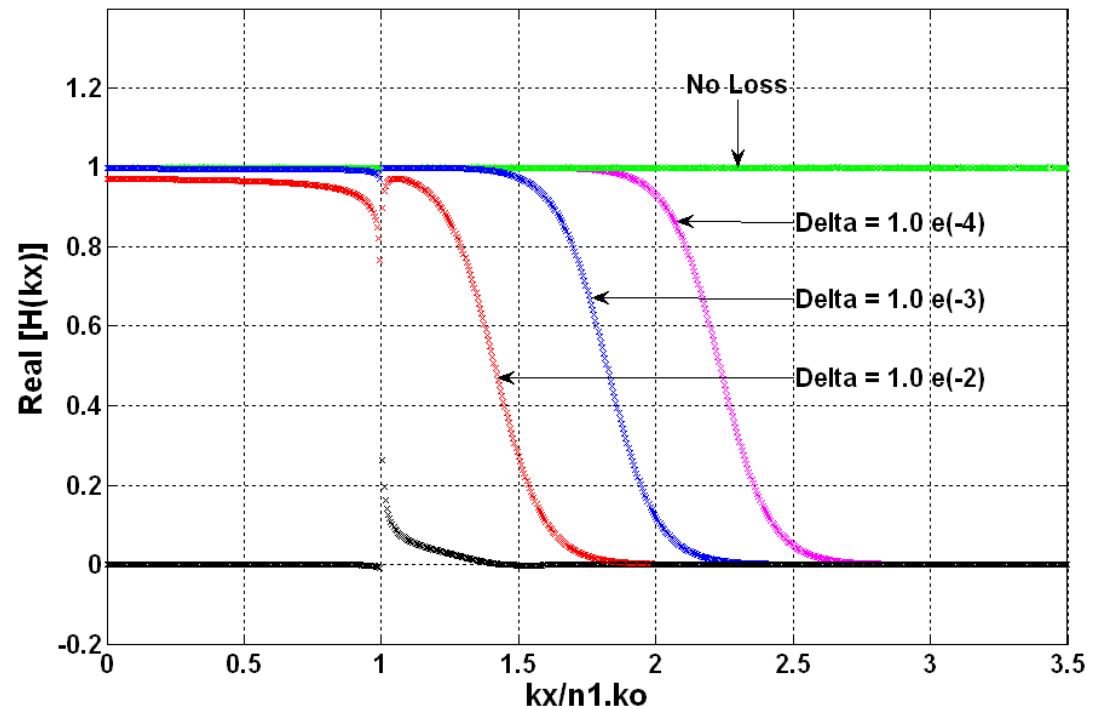
[M.Ghosh and Subal Kar]

Evanescent Wave Amplification (contd)
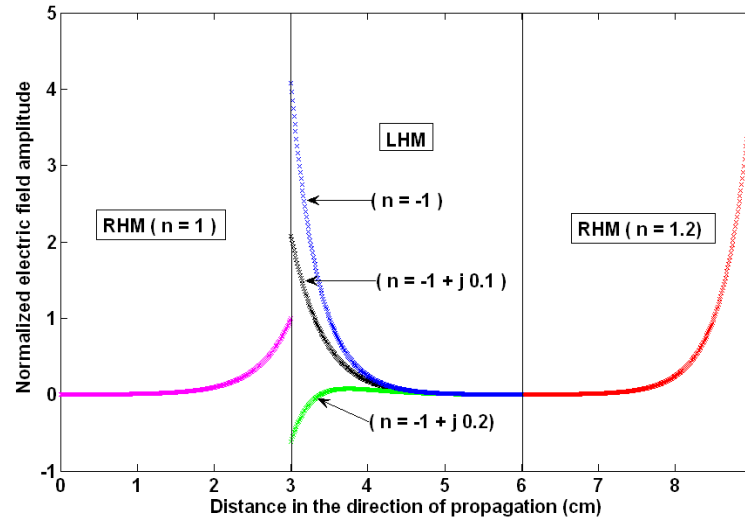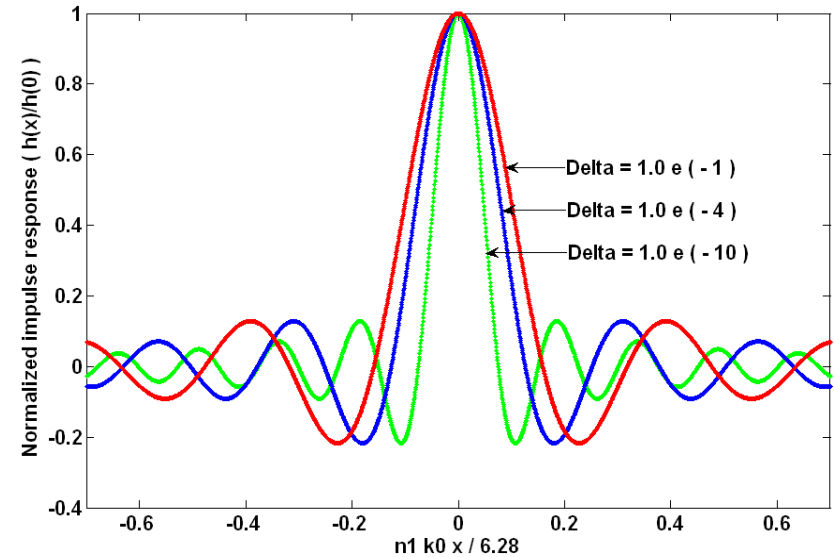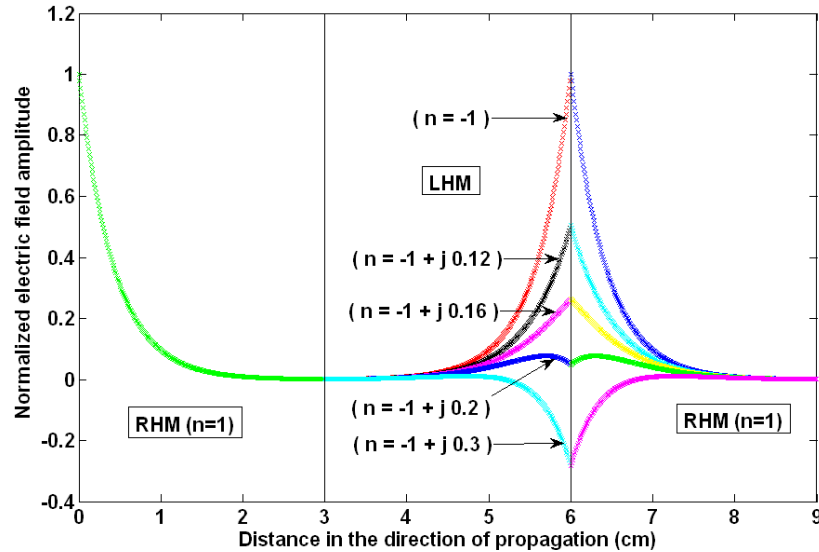
[M.Ghosh and Subal Kar]

Variants of Split Ring Resonators (SRR)

- *MULTIPLE SPLIT RING RESONATORS (MSRR)*
- *SPIRAL RESONATORS (SR)*
- *LABYRINTH RESONATORS (LR)*
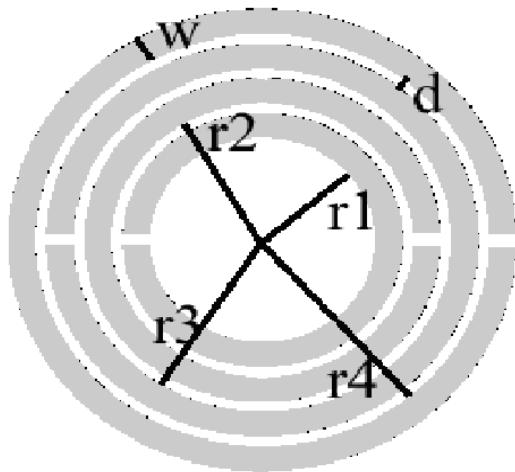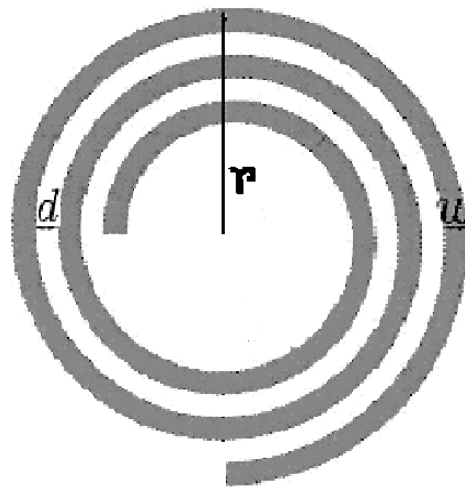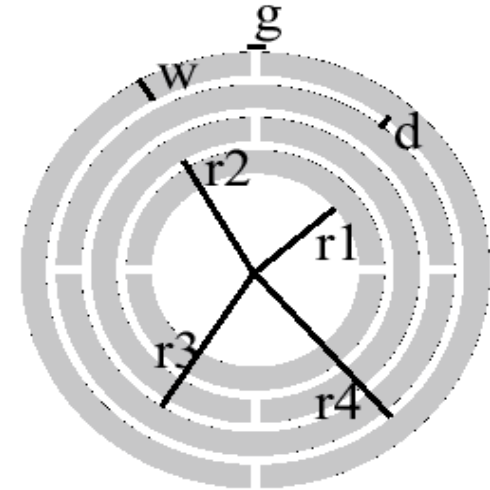
MSRR   **SR**   **LR**

[T. Roy and Subal Kar]

Variants of Split Ring Resonators (SRR) (contd)

❖ Suitability of LR Over other Variants of SRR

➢ Structural parameters remaining the same, each of f_{m0}, Δf (=f_{mp}-f_{m0}), Re[μ_{reff}] follows: LR > MSRR > SR.
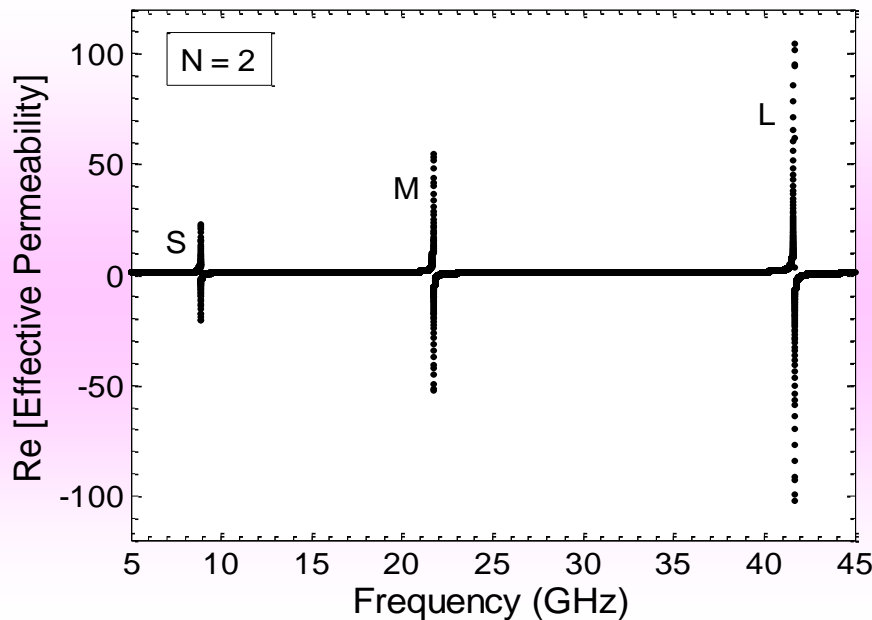
r and Δf at f_{m0} = 41.649 GHz		
Structure type	**r (mm)**	**Δf (GHz)**
LR	1.000	0.670
MSRR	0.648	0.278
SR	0.357	0.081

[T. Roy and Subal Kar]

Variants of SR: TTSR and NBSR
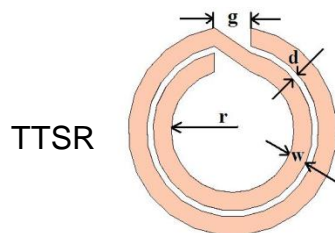
TTSR
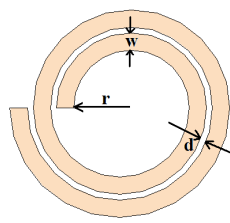
SR
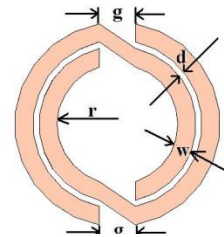
NBSR

Analytical Result →
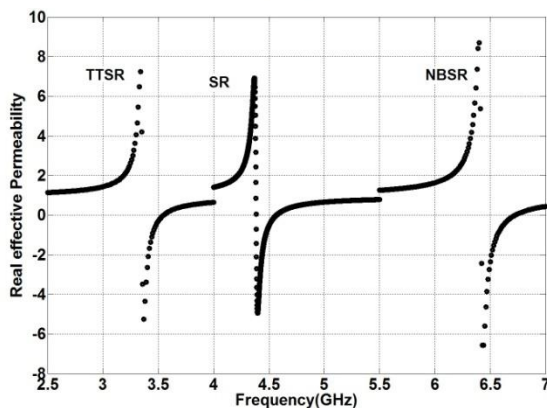
HFSS Simulation Result
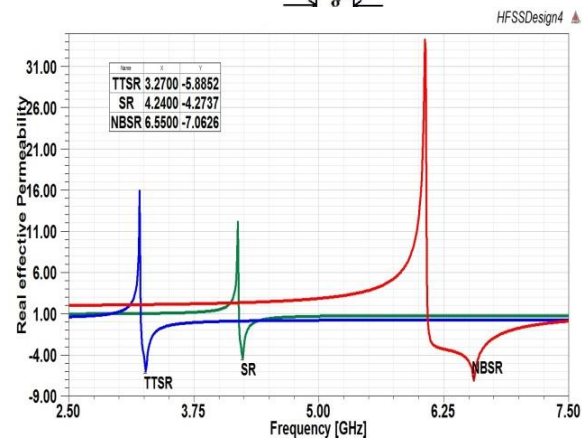
TTSR →
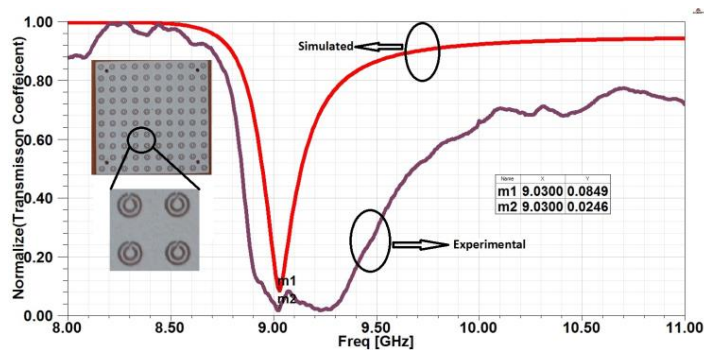
NBSR
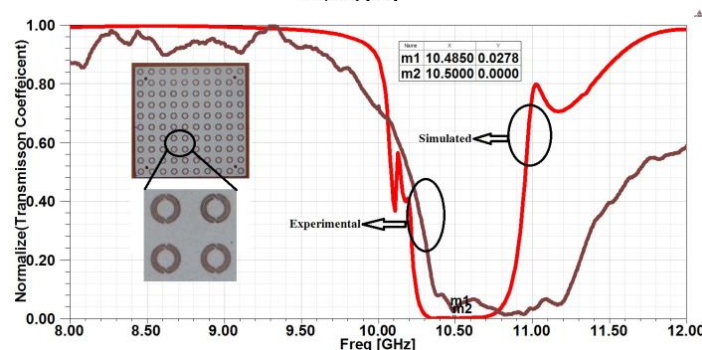
S. Chatterjee, A. Kumar, A. Majumder, S. Das, and Subal Kar

Plasma Frequency of wire media

<u>Analytical Method</u>

$$f_p{}^2 = \cfrac{c_0{}^2}{2\pi sa \left[\cfrac{\int_0^{\frac{a}{2}} ln\left[\frac{\frac{s}{2}^2+y^2}{r_0(2\sqrt{\frac{s}{2}^2+y^2}-r_0)} \right] dy}{a} + \cfrac{\int_0^{\frac{s}{2}} ln\left[\frac{\frac{a}{2}^2+y^2}{r_0(2\sqrt{\frac{a}{2}^2+y^2}-r_0)} \right] dy}{s} \right]}$$

$$\epsilon_{eff} = 1 - \frac{f_p{}^2}{f^2 + 2i\gamma f}$$

<u>Loss factor Method</u>

$$k = \frac{Power\,Lost}{Power\,Entered} = \frac{1 - |S_{11}|^2 - |S_{21}|^2}{1 - |S_{11}|^2}$$
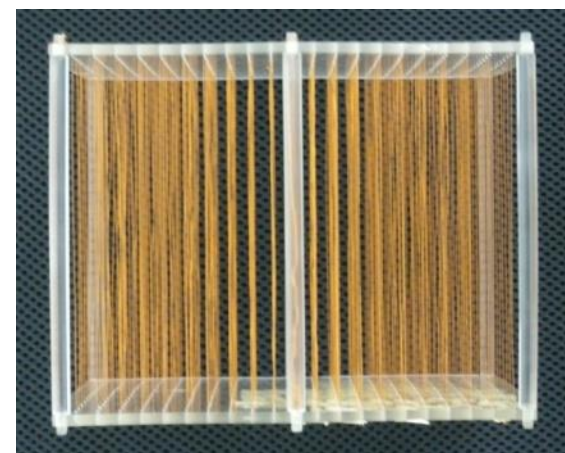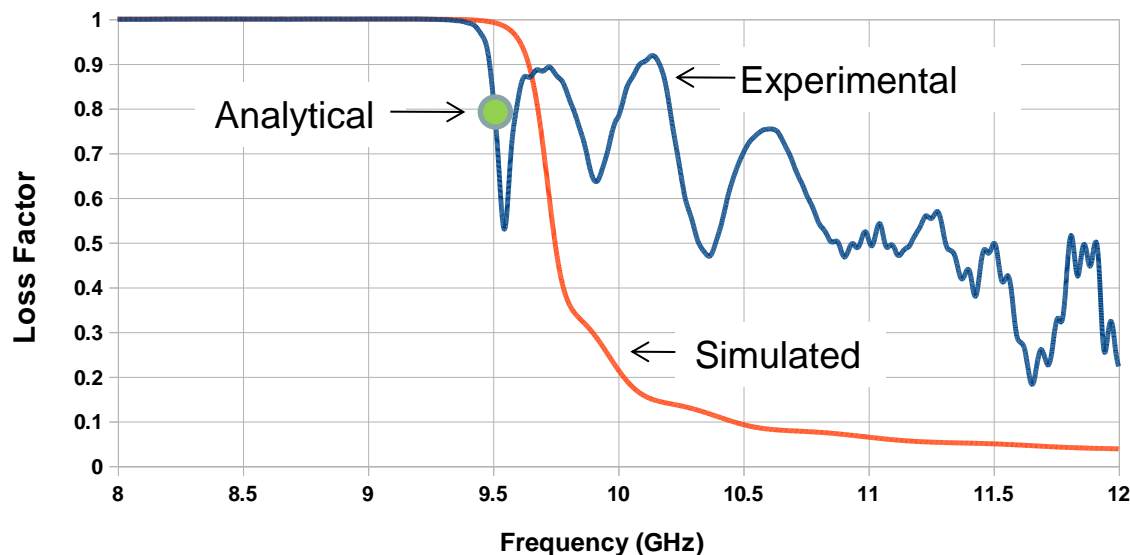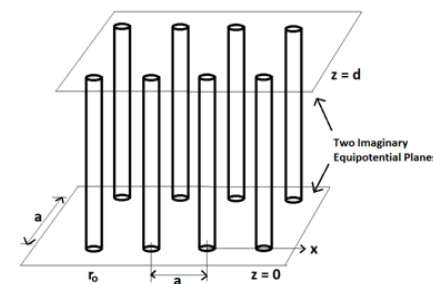
Fabricated Wire Media

A. Kumar, A. Majumder, S. Chatterjee, S. Das, and Subal Kar

Metamaterial Cloaking Devices

➢ Among the many tropes found in science-fiction and fantasy, few are more popular than the cloaking device. We are familiar with the Harry Potter's invisibility cloak or the Star Trek technology that can make whole Romulan warships disappear.

➢ *Since 2006, the development of metamaterial based cloaking device is gaining pace with extreme enthusiasm*. However, it must be noted that the science-fiction movie type invisibility cloak is still a distant possibility – though not impossible.

➢ The first 2D cloaking device was developed in 2006 by D. R. Smith et.al of Duke University, US.

Metamaterial Cloaking Devices (contd.)

➤ Their cloaking device ***at microwave frequency*** consisted of a group of concentric circles made of metamaterial (loops of copper wire stamped on fiber glass) with a cylindrical gap in the middle where the object to be cloaked was placed.

➤ Their device could mask or make the object invisible from only one wavelength of the incident microwave signal. ***The device was not perfect causing shadowing of microwaves, i.e., distortions***

Metamaterial Cloaking Devices (contd.)

➢ The metamaterial for cloaking was designed to have graded refractive index (n), having n = 1 on the outside of the device and decreasing to zero in the center.

➢ Eventually when microwave is directed at the device, *the wave split bending subtly around the device and able to reform on the other side: the effect can be compared to river water flow around a smooth rock, when no wakes are formed*. The trick is not a simple job as one has to make sure that waves from all angles are bend smoothly without scattering.
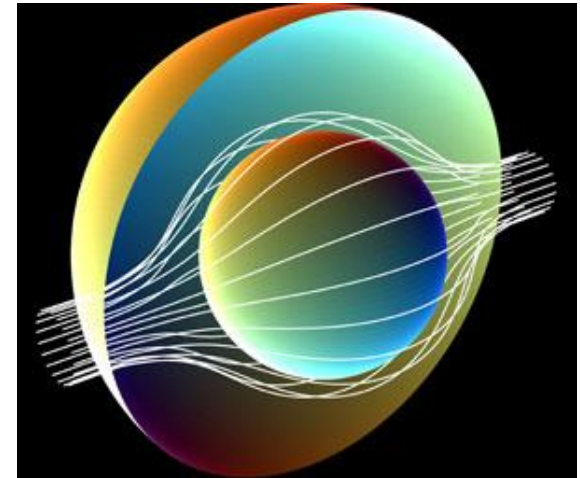
Metamaterial Cloaking Devices (contd.)

➢ Interesting developments on cloaking devices have been reported in 2009 at microwave, optical, even at sonic frequencies.

➢ In January 2009, Duke University group under the leadership of *D. R. Smith has developed cloaking device at microwave frequency that is capable of cloaking over a broad range of frequencies*.

➢ To guide the design and fabrication of the metamaterial –> a new series of complex mathematical commands (i.e., algorithms) were developed. *This powerful new algorithm made it possible to custom design unique metamaterial with specific cloaking characteristics*.

Metamaterial Cloaking Devices (contd.)

➤ In the new cloaking device, a beam of microwave aimed through the cloaking device at a 'bump' on a flat mirror surface bounced off the surface at the same angle as if the bump were not present. Additionally, the device prevented the formation of scattered beams that would normally be expected from such a perturbation.
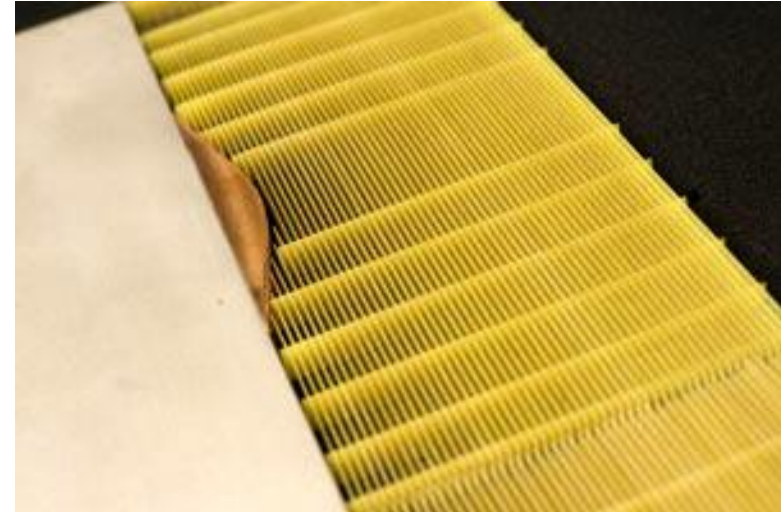
➤ The cloak, which measures 20" X 4" and less than 1" high is actually made from more than 10,000 individual pieces arranged in parallel rows. Each piece is made of the same fiber glass materials used in circuit boards and etched with copper. The algorithm determine the shape and placement of each piece.

Metamaterial Cloaking Devices (contd.)

➤ *In April 2009, a team led by Xiang Zhang at UC Berkeley achieved 'carpet cloaking'* (an object covered with a piece of cloth would normally be detectable based on its telltale bump, but with the new metamaterial even the bump seems to vanish).
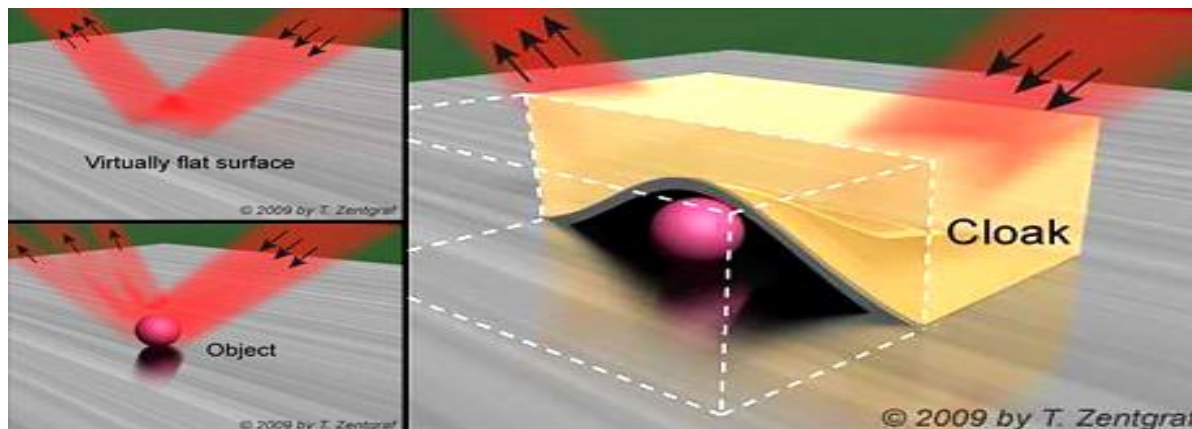
➤ They achieved the effect by drilling tiny nano-holes into the cloaking material, a silicon based metamaterial. *The cloaking system was operated in near infrared frequency and scalable to visible light. Carpet cloaking is capable of hiding microscopic objects*.

Metamaterial Cloaking Devices (contd.)

Application View Points

➢ D.R. Smith commented that their 2009 cloaking device may be used to make obstacles that impede communication signals 'disappear', thus possibly can dramatically improve the performance of mobile antennas by reducing interference.

➢ Xiang Zhang's carpet cloaking device may have potential use in optical computing, for example, such cloaks may be used to allow light to move more efficiently, by hiding the parts of a computer chip that get in the way of the beam. Also expensive dielectric mirrors—special mirrors used to make printed circuits for electronics—can be ruined by tiny defects in their surfaces, which may be cloaked making it to look like perfect mirror again.

➢ However, cloaking devices to make objects invisible to people is still a distant concept, but not impossible—as commented by Smith

Reversed Cherenkov Radiation

❑ Cherenkov Radiation (CR) is seen in nuclear reactors as a characteristic 'blue glow' which results when a charged particle (such as an electron) travels through a dielectric (electrically insulating) medium with a phase velocity (v_p) greater than the speed of light (c) in that medium.

❑ CR is commonly used in experimental particle physics for particle identification.

❑ Particle identification can be done in terms of its mass evaluated from its measured momentum and the threshold velocity , the later being the velocity above which the particle motion in the medium emits Cherenkov radiation. The CR light cone is detected on a position sensitive photon detector.

❑ Most advanced type of such CR detector is the ring imaging Cherenkov (RICH) detector. The Large Hadron Collider (LHC) has used proximity gap RICH detector for its ALICE (A Large Ion Collider Experiment) program.

Reversed Cherenkov Radiation (contd.)

❑ In RHM the charged particle and the Cherenkov Radiation (CR) cone travel along the same direction, while in case of LHM (when the refractive index n is negative) they are counter directed, i.e., reversed CR is expected.

[*Radiation coupling condition*: $\omega = k.v_p$; thus $\cos\theta = 1/(n\beta)$, where $\beta = v_p/c$]

❑ The reversed CR has a distinct advantage that the detectors for particle and the reverse CR are naturally separated as they are in forward and backward regions respectively, so their physical interaction is minimized, resulting in clear CR measurement and hence the sensitivity of detection is improved.

❑ Optical metamaterial would be perfect for CR detectors. Though some success has been realized with optical metamaterials, still a long way to go for their application in CR detection.

Reversed Cherenkov Radiation (contd.)

❑ In 2007 Argonne Wakefield Accelerator Group, Argonne, Illinois Institute of Technology, Chicago, has made experimental studies on metamaterial loaded waveguides for possible accelerator applications at X-band.
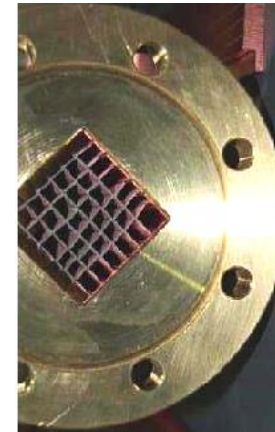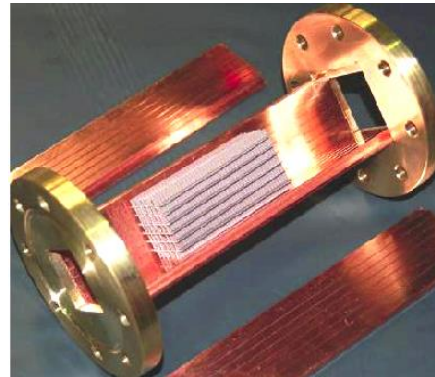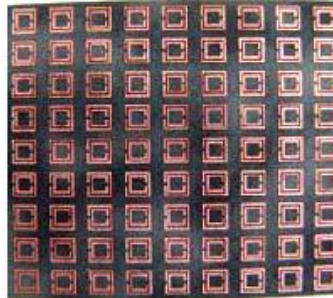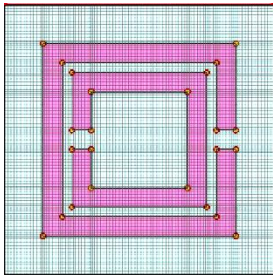
❑ In 2009, the same group has studied that the radiation pattern of CR in dispersive metamaterials presents lobes at very large angles with respect to particle motion and found that the frequency and particle velocity dependence of the radiated energy can differ significantly from CR in a conventional (RHM) detector media.

Other Application Potential of Metamaterial

➢ Apart from those exotic applications, active and advanced research is going on with new ideas emerging every new morning for the developments of metamaterial based microwave and higher frequency passive components and antennas with improved performance along with size miniaturization.

➢ Peoples are even talking of quasi-crystal metamaterial and many more fashionable yet promising terms for meta-material.

➢Transmission line LHM property is used in the design of highly efficient and miniaturized antennas, filters and directional couplers etc.

Low Profile Omnidirectional Antenna

Broadband Bandstop Filter
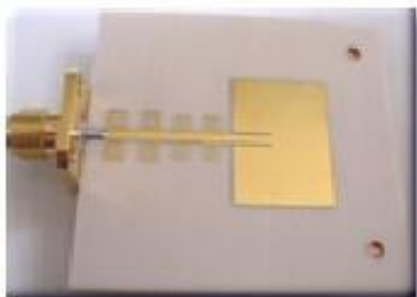
Patch Antennas using SRRs
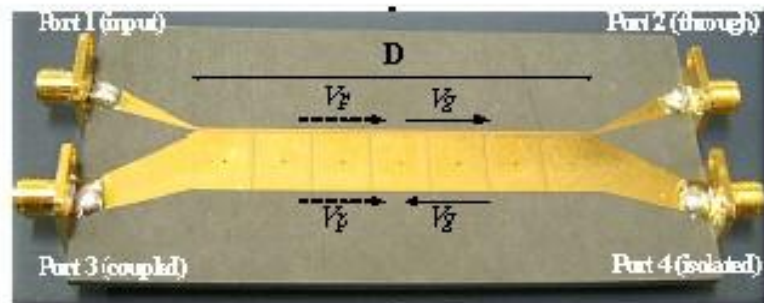
Backward-wave Directional Coupler

CPW-SRR Filter
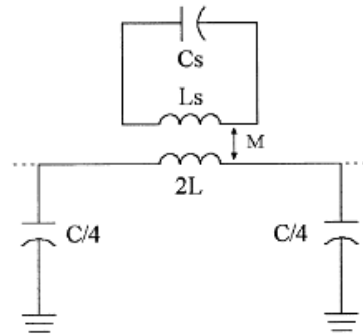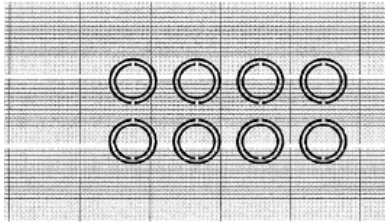
$$\cos(\beta l) = 1 - \frac{LC\omega^2}{2} + \frac{\frac{C}{C_s'}}{4(1 - \frac{\omega_o^2}{\omega^2})}$$

where, $C_s' = \dfrac{L_s}{(M^2\omega_o^2)}$ $\qquad L_s' = C_s M^2 \omega_o^2$

$$\omega_o^2 = \frac{1}{L_s C_s} = \frac{1}{L_s' C_s'}$$
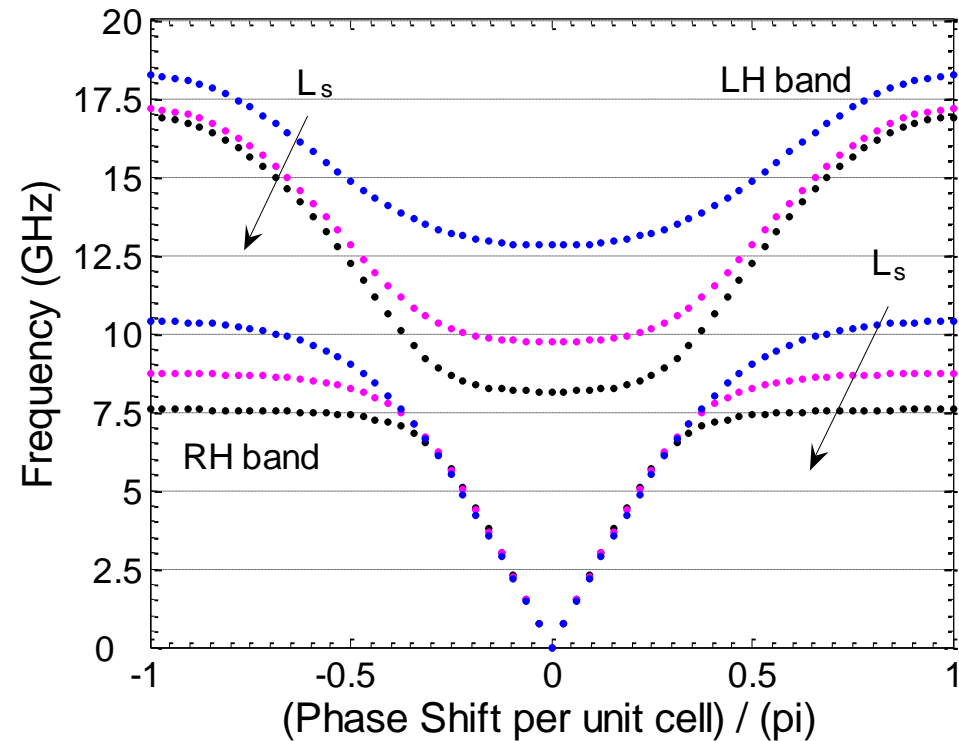
[T. Roy and S. Kar]

SRR Array Loaded Waveguide Filter
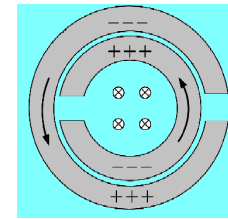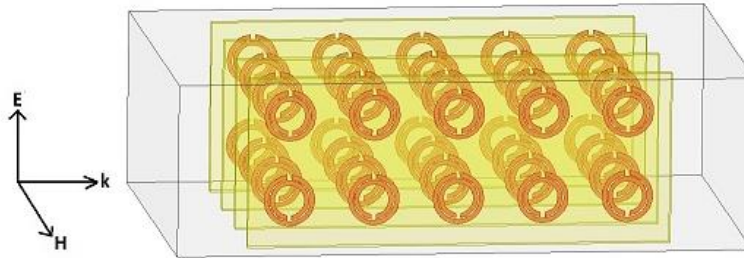
SRR
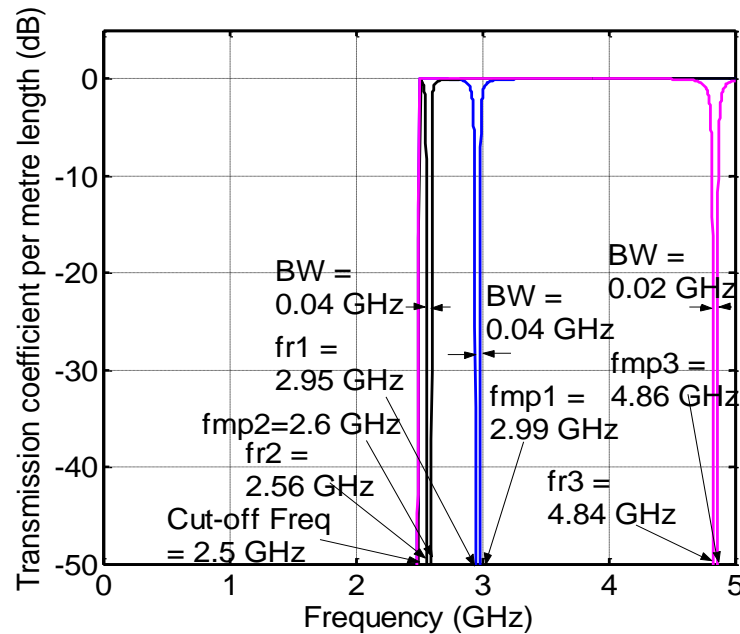
LHM stop-band
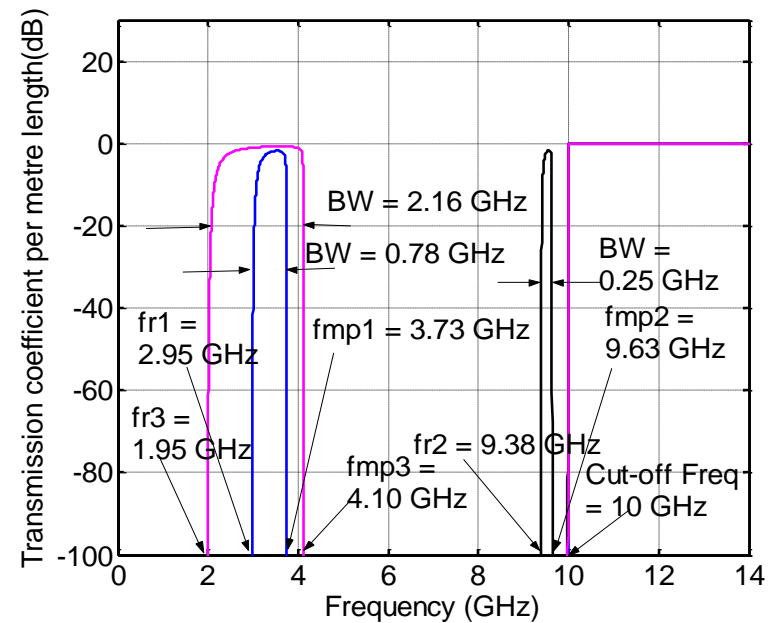
LHM pass-band

[S. S. Sikdar, T. K. Saha, and S. Kar]

THz and Optical Metamaterial

➢ Initial metamaterial developments were in the microwave frequency domain, being limited by the available fabrication technology in those days for such sub-wavelength structures.

➢ However, real benefit of metamaterial developments will be practical with optical or at least terahertz (THz) metamaterial.

➢ The ubiquitous Split-Ring metmolecule can be scaled down in size up to about 200 THz, but this scaling breaks down at higher frequencies as the metal does not behave any more as a conductor and becomes transparent to the radiation for wavelengths shorter than 1.5 μm i.e beyond 200 THz range.

➢ This scaling limit combined with the fabrication difficulties of making nano-meter scale SRRs along with metal wires (SRR-TW combination) led to the development of alternative designs that are more suitable for THz and optical regimes.

MHz – THz Metamaterial

21 MHz

Wiltshire et. al., UK, 2001

5 GHz
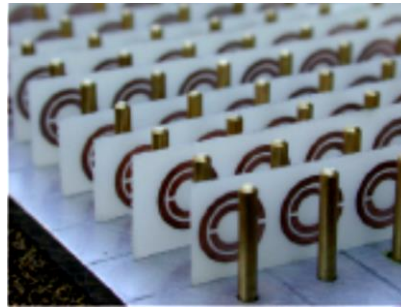
Shelby et. al., USA, 2000

100 GHz

Gokkavas et. al., Turkey, 2006

1 THz
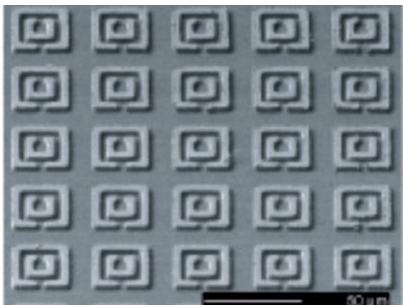
Yen et. al., USA, 2004

100 THz

200 nm
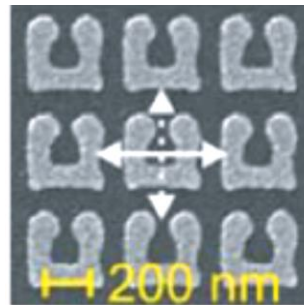
Linden et. al., Germany, 2004

200 THz

Enkrich et. al., Germany, 2005

Alternative Designs for Optical NIM
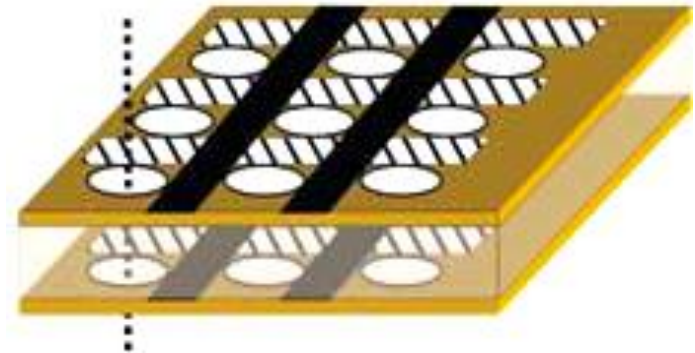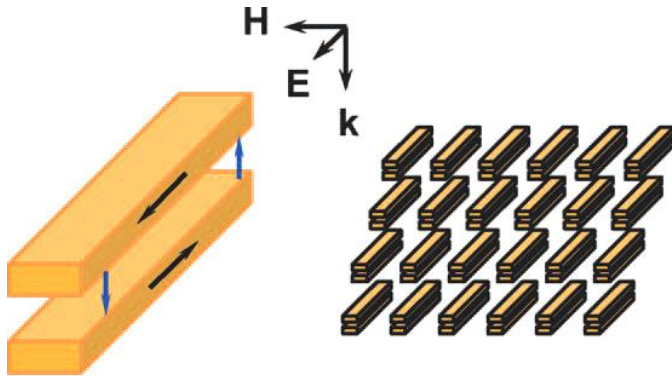
Cut-Wires: Pairs of metal nano-strips separated by dielectric spacer. Anti-parallel current flow in the pair results in magnetic resonance. Parallel current flow in the same strip causes electric resonance. Difficult to get overlapping ε<0 and µ<0 zones.

Fishnet: Combines magnetic coupled strips (to provide µ<0) with continuous electric strips (to provide ε<0) over a broad spectrum. Hence overlapping frequency zone for simultaneously negative ε and µ is easily obtained at optical frequency.

[Shalaev et. al., USA, 2005]

[S. Zhang et. al., USA, 2005]

Optical NIM Design: Cut-wires

[Shalaev et. al., Indiana, USA, December 2005]
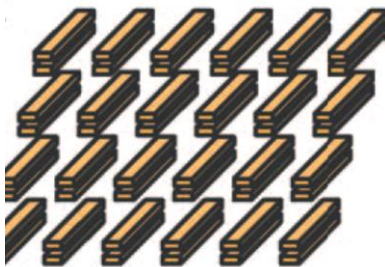
Schematic for array of nanorod pairs

200 nm   5 µm

2 mm x 2 mm array of nanorods imprinted on a glass substrate using electron-beam lithography
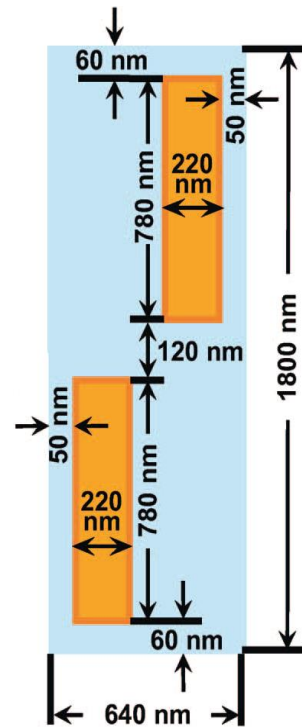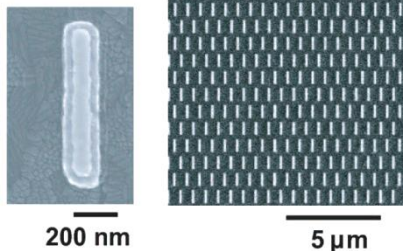
Bottom rods & Elementary cell

✓ The sandwich structure, of gold nanorods (50nm) with SiO_2 (50nm) filling deposited serially in an electron-beam vacuum evaporator.

✓ The top rods are designed smaller (670 nm X 120 nm) than the bottom rods (780 nm X 120 nm).

✓ A negative refractive index of $n' \approx -0.3$ at the optical wavelength of 1.5 µm was reported.

Optical NIM Design: Fishnet

[S. Zhang et. al., New Mexico, USA, September 2005]
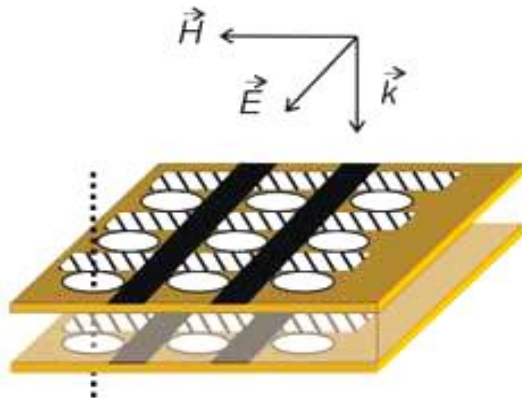
Schematic representation
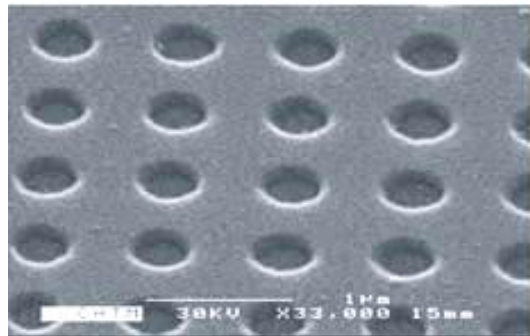
Scanning electron microscopy picture of the fabricated structure

- ✓ The multilayer structure consist of an Al_2O_3 dielectric layer between two gold films perforated with a square array of holes (838nm pitch; 360nm diameter) on a glass substrate

- ✓ The active regions for the electric (dark regions) and magnetic (hatched regions) responses are indicated.

- ✓ A minimum negative refractive index of   *n'* ≈ −2 was obtained around 2μm

Review of Fishnet NIM
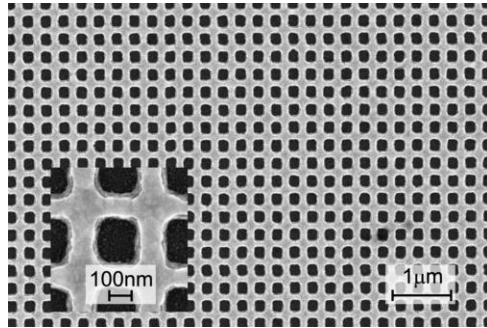
Top-view electron micrograph of the sample
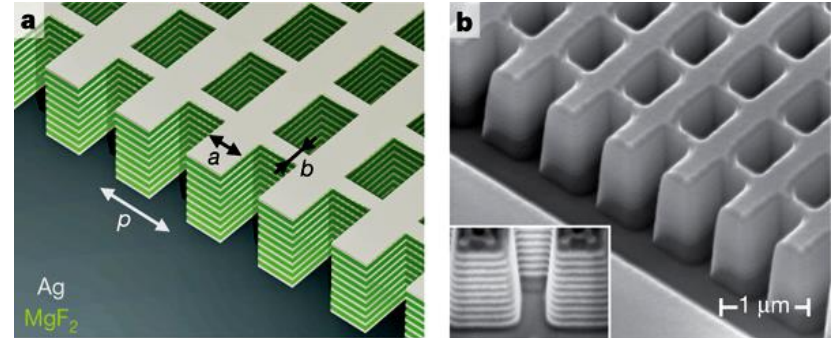
(a)Schematic (b) SEM image of 3D fishnet structure

✓ <u>January 2007</u>, the U.S. Department of Energy's Ames Laboratory with Karlsruhe University, Germany, designed a Ag-based, mesh-like NIM with <u>n' = - 0.6 at 780 nm</u> using *electron-beam lithography* (EBL)

✓ It was made by etching an array of holes (100 nm wide) into layers of Ag and MgF_2 on a glass substrate.

✓ <u>August 2008</u> the University of California, Berkeley engineered <u>3-D optical fishnet</u> metamaterial by using *focused ion-beam* (FIB) milling.The RI varies from $n \approx 0.63$ at 1,200 nm to $n \approx -1.23$ at 1,775 nm.

✓ Alternating layers of 30 nm Ag and 50 nm MgF_2 were stacked together nanoscale-sized fishnet patterns were cut into the layers.

3-D Metamaterial

➢ Though appears to be most challenging yet the *demand of the day is three-dimensional (3-D) metamaterial*.

➢ Initial 3D LHM were made by creating *multilayer structures* (involves challenging lift-off process) and also by using a *layer-by-layer technique* (requires careful alignment).

➢ Complex 3D structures *may be fabricated by electron-beam writing, focused-ion beam chemical vapor deposition*, etc. but the methods are too complex and time consuming for mass production purpose.

➢ Fabrication methods based on **two-photon photopolymerization TPP is considered the most promising for future manufacturing of large area true 3D metamaterials**. Direct single beam laser writing, multiple-beam TPP technique are the methods offering sub-diffraction resolution down to 100nm.

➢ *Nanoimprint lithography also may be a successful method for fabricating 3D metamaterial*.

Fruit for the Picking

➢ The <u>Metamaterial Tree of Knowledge</u> shows the progression and future of metamaterial research or in other words the 'road ahead for metamaterials'.

Science 328, 582 (2010)

The Metamaterial Tree of Knowledge — labels: Quantum Metamaterial, Sensor Metamaterial, Switchable metamaterials, Non-linear metamaterials, Gain-assisted Metamaterials, Transformation Optics Metamaterials, High/low epsilon metamaterials, Designer dispersion, Chiral metamaterials, Negative index, Artificial Magnetism, Electromagnetic and Microwave Technology
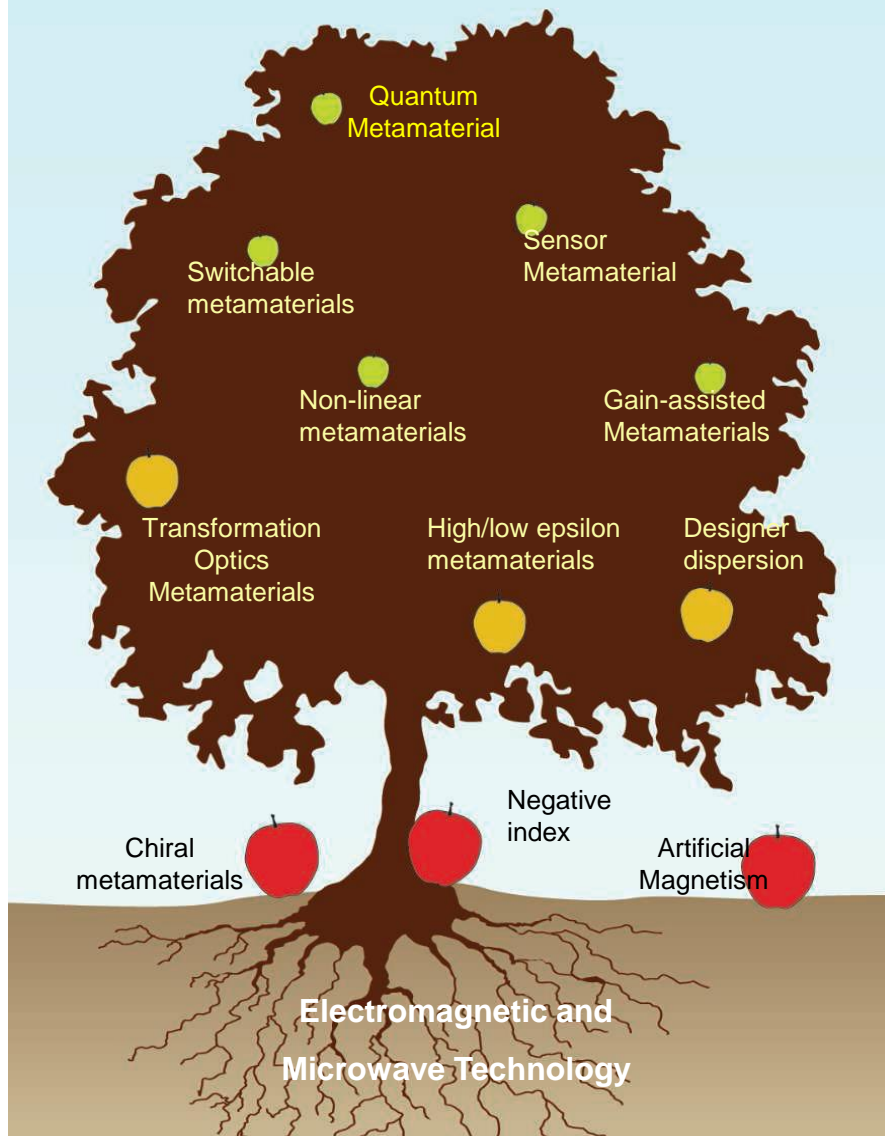
The Metamaterial Tree of Knowledge

❖ Negative index material is ripe, moving into domain of applications.

❖ Chiral materials and artificial magnetism well researched.

❖ Control of e.m response and dispersion characteristics are currently flourishing.

❖ Emerging directions of investigations are gain-assisted, switchable, sensor and quantum metamaterials.

Emerging Directions of Research

➢ Hybridizing a gain medium (semiconductor quantum dots or quantum well structures) with a plasmonic metamaterial can lead to a multifold intensity increase and a narrowing of their photoluminescence spectra.
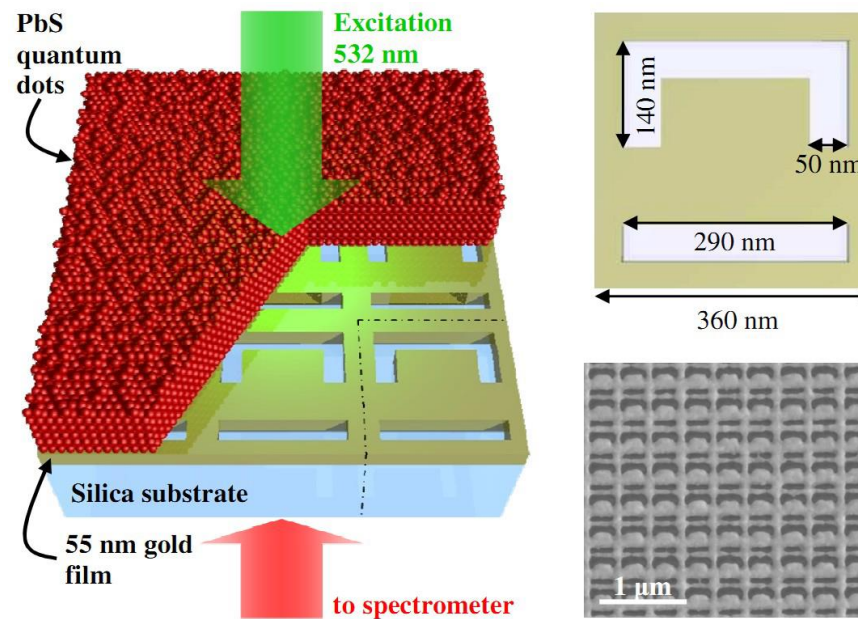
Photonic metamaterial hybridized with semiconductor quantum dots

➢ The luminescence enhancement is a clear manifestation of the quantum Purcell effect, and it can be controlled by a metamaterial's design.

Emerging Directions of Research (contd ….)
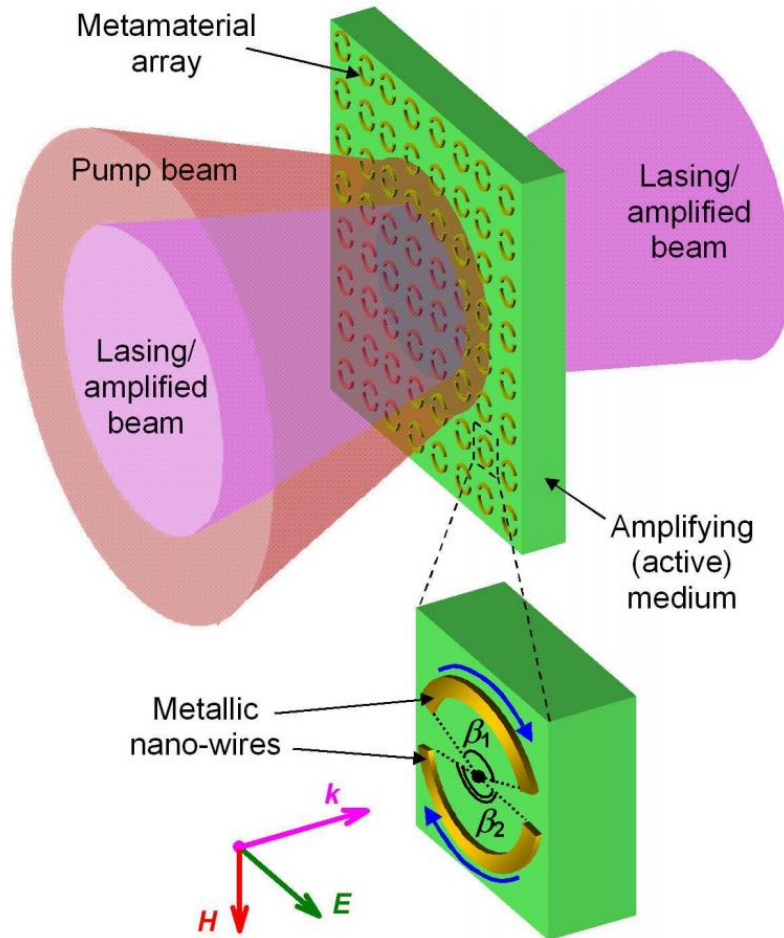
Lasing Spaser

➢ This is an essential step towards the development of "lasing spaser", which is a laser whose emission is fueled by plasmonic excitation in an array of coherently emitting meta-molecules.

➢ In contrast to conventional lasers that operate at wavelengths of suitable natural atomic or molecular transitions, the lasing spaser's emission wavelength can be controlled by metamolecule design.

Emerging Directions of Research (contd..)

➢ Switchable metamaterials is a rapidly expanding area of research.

➢ Indeed, the development of nanophotonic all-optical data processing circuits depends on the availability of fast and highly responsive nonlinear media that react to light by changing their refractive index and absorption.

➢ This is difficult to deliver in nanoscale size devices using electronic or molecular nonlinearities, where stronger responses often come at the expense of longer reaction times and where the optical path through the nonlinear medium is shorter than the wavelength of light.

➢ Recent experiments show that the ultra-fast nonlinear response of silicon can be strongly enhanced by adding a metamaterial layer. Single-wall semiconductor carbon nanotubes deposited on metamaterials exhibit an order-of-magnitude higher nonlinearity than the already extremely strong response of the nanotubes themselves, due to a resonant plasmon-exciton interaction making high speed switching possible.

Emerging Directions of Research (contd..)

➢ Superconducting metamaterials offer an incredibly fertile arena for research as losses there are extremely small.

➢ The classical object of metamaterials research—the ubiquitous split-ring metamolecule—has much in common with the fundamental unit of superconductivity, the Josephson junction ring.

➢ An array of superconducting Josephson rings could be a truly quantum metamaterial, where each metamolecule is a multilevel quantum system supporting phase qubits. However, applications of superconducting metamaterials will be limited to the microwave domain for niobium-based metamaterials, and to the terahertz spectral domain if high-temperature superconductors are used. This is because higher frequencies destroy the superconducting phase.

➢ In natural solids, optical response is determined by the quantum energy-level structure of the constituent atoms or molecules. By contrast, the electromagnetic properties of metamaterials are derived from the resonant characteristics of the subwavelength plasmonic resonators (SRR etc.) from which they are constructed. *Thus 'quantum metamaterials' would provide a much closer analogy to natural crystals which the metamatrial mimics.*

A Few Comments

➢ No progress in metamaterial research will be possible without further developments in fabrication technology.

➢ New techniques will have to achieve perfection of nanostructures at close to the molecular level, and at low cost.

➢ We need to go beyond electron beam lithography, focused ion beam milling, and nano-imprint. However, the new techniques must be able to build metamaterials to almost any blue print.

➢ Real challenge is to create truly volume (i.e 3 D) metamaterials, and a great deal of innovative efforts are now being concentrated on that.

➢ Metamaterials were considered to be 'material like' during initial developments but shifting paradigms now can consider metamaterial as 'device': where the structuring of metal and the hybridization with functional agents brings new functionality and the response becomes non-linear, gain-assisted, switchable and so forth. *In near future, we might be able to enter the field of quantum metamaterials*.

MILES TO GO , MILES TO GO BEFORE I SLEEP

Thank You