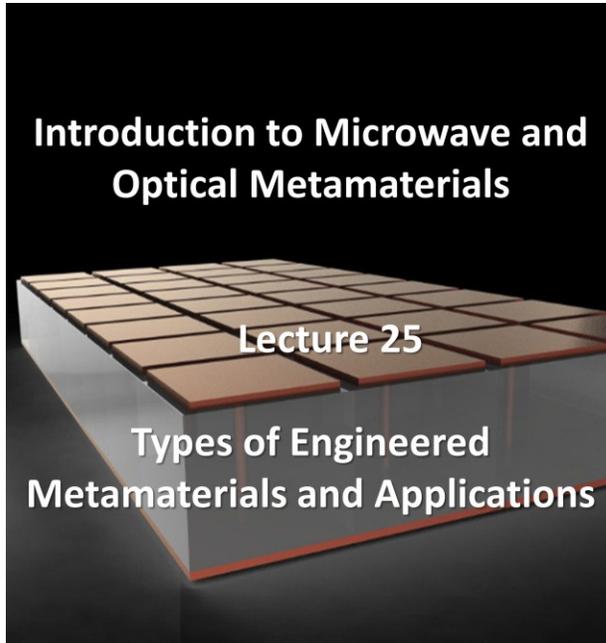**Course Name: Introduction to Microwave and Optical Metamaterials**
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Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-5
Lecture-25

Lec 25: Types of Engineered Metamaterials and Applications

Lecture Outline

- Applications of Chiral Metamaterials

- Bi-isotropic and Bianisotropic Metamaterials

- Non-Resonant Metamaterials and Applications

- Hyperbolic Metamaterials and Applications

Hello everyone, welcome to Lecture 25 of the online course on Introduction to Microwave and Optical

Applications of Chiral Metamaterials

1. Chiral Metamaterial Sensors
- Chiral metamaterial sensors using split ring resonators with double splits (SRDS) have shown sensing capabilities in the X-band range.

- The resonance frequency of the SRDS-based sensor:
  - Varies linearly with the permittivity and thickness of the sensor layer
  - Enables detection of environmental and organic parameters

- When filled with target material, the sensor can detect – Tissue temperature, sand humidity, calcium chloride density

- Other potential sensing applications include – Pressure, temperature, humidity/moisture, density sensing

2. Nonlinear Optics in Chiral Metamaterials

- Chiral applications in biochemical engineering extend beyond the linear regime.

- Chiroptical effects in second-harmonic generation (SHG) are often much stronger than in the linear regime.

- SHG process – two photons at a fundamental frequency annihilate into one photon at double the frequency.

- SHG requires noncentrosymmetric media (lacking inversion symmetry).

- Chiral metamaterials are naturally suitable since they are intrinsically noncentrosymmetric.

- Chirality detection – can be performed with linearly polarized light, regardless of the polarization direction and state of the SHG output.

- Linear optical responses in chiral metamaterials are reciprocal and nonlinear responses like SHG, are nonreciprocal.

3. Chiral Light–Matter Interactions

- Enhancing chiral light–matter interaction is one of the goal in chiral metamaterials.

- Superchiral fields are employed to overcome weak chiroptical signals in nature.

- Nanostructures developed to boost chiroptical signals include:
  - Plasmonic structures
  - Dielectric nanoparticles
  - Negative-index metamaterials

- Quantum emitter and chiral metamaterial interactions have been experimentally studied.
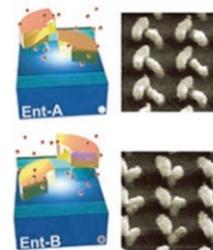

Fig. Chiral light – matter interactions: Enantiomer A and B of the twisted-arc chiral metamaterial.

Metamaterials. Today's lecture will be on different types of engineered metamaterials and their applications. So, here is the lecture outline: we will talk about chiral metamaterials and their applications, and introduce biaxial and bianisotropic metamaterials. We will discuss about non-resonant metamaterials and their applications and briefly we will touch upon hyperbolic metamaterials and also show their different application scenarios. So chiral metamaterials okay we have seen that you know chiral metamaterials sensors using splitting resonators with double splits okay they are also known as SRDS okay splitting with double slit okay or double split they

have shown sensing capabilities in the X band. Now, the resonance frequency of the chiral metamaterials based SRDS sensor is linearly related to the permittivity and the thickness of the sensor layer, which creates a suitable approach for sensing environment and organic parameters.

So, when the sensor layer is filled with related material changes in the tissue temperature, sand humidity, then the calcium chloride, lead density all these things can change the resonance frequency and that can be detected. Other potential sensing

Applications of Chiral Metamaterials

3. Chiral Light–Matter Interactions

▪ The circular dichroism of the arc metamaterials reached as high as 50% at the wavelength of resonance – results in high transmission image contrast.

▪ Resonant light confinement leads to:
  • Chiral-selective enhancement of nonlinear interactions

▪ Applications:
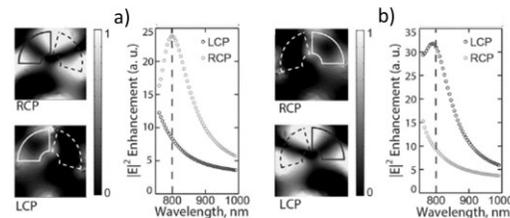 • Chiral-selective imaging
  • Sensing
  • Spectroscopy

Fig. $|E|^2$ field enhancement of a) enantiomer A and b) enantiomer B under LCP and RCP.

applications include the sensing of pressure, temperature, humidity, moisture, and density. So, you can also have a sensor for these

4. Active Chiral Metamaterials

▪ Active control of chirality in metamaterials is crucial for polarization-sensitive imaging and interactive displays

▪ Chirality control involves switching between left- and right-handed enantiomers and vice-versa.

▪ In the terahertz regime:
  • Optical pumping in silicon (Si) is used to switch chirality
  • A pulsed laser at 800 nm excites electron–hole pairs across 1.12 eV bandgap of Si
  • Under 500 mW pump laser, silicon's photoconductivity reaches 50,000 S/m

▪ All-optical tunable chirality achieved using a double-layer metamaterial – Built with nonlinear nano-Au: ITO layer between two L-shaped nanoantennas.

▪ Observed a 45-nm peak shift in circular dichroism spectrum under a 40 kW/cm² pump.
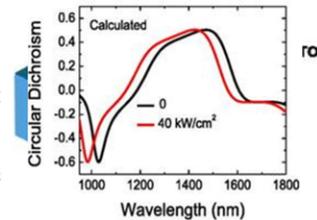
applications or for sensing these parameters. Now, chiral metamaterials are also very useful in nonlinear optics.

So, the chiral optical properties will see that that can give rise to second harmonic generation and typically these are often much stronger than in the linear regime. Now, why we are interested is that in the case of biochemical engineering, the chiral applications can extend beyond the linear regime. So, you can actually have this kind of non-linear effect, like second harmonic generation, happening. Now, in the second harmonic generation process, two photons at the fundamental frequency annihilate into one photon with double the frequency, right? So, the second harmonic generation basically requires a non centrosymmetric media that lacks inversion symmetry and chiral metamaterials are naturally suitable for this kind of application since they are intrinsically non centrosymmetric. Now, the detection of chirality can be achieved by distinguishing it with linearly polarized light.

Regardless of the polarization direction and the state of the second harmonic light output, okay. So, linear optical responses in chiral metamaterials are reciprocal, while non-linear responses like second harmonic generation are basically non-reciprocal. So, this is what we need to keep in mind. Now, with that, we can go ahead and try to see different chiral material interactions with light; you can also call it chiral light-matter interaction. So, the main goal one of the main goals of this chiral metamaterial is to basically enhance this chiral light matter interaction.

So, super chiral fields are basically employed to overcome weak chiro-optical signals in nature. So, you will see various nanostructures are developed to enhance these chiro-optical signals such as plasmonic nanostructures, dielectric nanoparticles and also you know negative index metamaterials. Right. So, the interaction between the quantum emitter and chiral metamaterials has been experimentally investigated. And you can see in this particular figure that here chiral arc metamaterial are basically adapted as two enantiomers enantiomer A and B.

So, there is slight variation one is kind of the mirror image of the other ok. And you can see that you know achiral quantum dots are basically predominantly surrounding the upper arc of the metamaterials. So, these are enantiomers A and B of the twisted arc chiral metamaterial, and they are very useful for chiral light-matter interaction. So, we will see that how the light matter interaction basically changes because of this Now, in the linear regime, you can see that the chiral dichroism of the arc metamaterial reached as high as 50% at the wavelength of resonance that is around 780 nanometer which can lead to very strong contrast of the

Bi-isotropic and Bianisotropic Metamaterials

- Bi-isotropic materials – Isotropic media where electric and magnetic flux densities are linearly coupled to both electric and magnetic fields.

- Pasteur media – can rotate the polarization of light during refraction or transmission.

- Not all materials with a twist effect fall in bi-isotropic class.

- The twist effect in bi-isotropic materials stems from their chirality ($\kappa \neq 0$) and/or non-reciprocity ($\chi \neq 0$).

- The term "bianisotropy" indicates dual polarization mechanisms and anisotropic behavior.

- For more complex materials, such as many metamaterials, the fields are not necessarily parallel.

- When one set of the fields are parallel, and one set are not, the material is called anisotropic.

transmission images that you can see in this figure. And here we are particularly showing the E square enhancement in both the cases, this is for enantiomer A, this is for enantiomer B under LCP and RCP light.

So, this one is LCP, and this is RCP. Okay, you can see the dark one, LCP and RCP. So, there is a difference, and that is shown here; these are basically simulation data, okay. So, this is for enantiomer A that shows substantial enhancement of the intensity Within the surrounding region of the chiral arc okay you can see from this field plots as well at 800 nanometer under RCP you have more field enhancement / here okay which is basically seen here also okay. The same thing is shown here, but here you can see the enhancement is basically seen in the case of LCP which you can also see from the electric field plot.

So, what we understand that the light confinement at the resonant wavelength was largely boosted yeah and thereby you have got this chiral selective enhancement in the non-linear light matter interaction. So, in this case for the case of enantiomer A, RCP is showing the enhancement, in the case of enantiomer B, LCP is showing the enhancement. So, this basically manifests the potential for the application of this kind of chiral metamaterials in chiral selective imaging, sensing, spectroscopy, etc. So, now let us look at active chiral metamaterials. Now,

active control / the chirality of metamaterial has the potential of serving as one of the key element for the future optical systems such as polarization, sensitive imaging and say interactive display and so on, right.

So, achieving active control / chiral metamaterials involves the reconfiguration of the metamolecule from a left hand enantiomer to a right hand counterpart and vice versa right. So, you have to involve that switching right. So, in the terahertz regime, the generation of charge carriers via optical pumping in silicon is basically used to switch this chirality. You can also think of a laser pulse working at 800 nanometer is utilized to excite the electron hole pair across 1.1 to electron volt band gap that is of the electrons, okay.

And then, under the illumination of a 500-milliwatt pump laser, the silicon's photoconductivity can reach as high as 50,000 siemens per meter. So, this feature basically enables all optical switching of the handedness in chiral metamaterials in terahertz regime ok. So, an all optical tunable chirality has also been realized in a double layer metamaterial which basically consists of a non-linear nano auto AU, nano AU colon ITO that is basically this structure okay. So, the you can see the structure here okay that is having a ITO layer in between two L shaped gold nano antennas okay. So, these are the two L-shaped golden antennas, and you have ITO here, and this is your silica substrate, right? So, what happens in this case one can observe a 45 nanometer shift in the peak when you are looking at the circular dichroism spectrum ok under 40 kilowatt per meter square 40 kilowatt per centimeter square kind of pump.

So, that is typically a weak pump, and this work basically opens up the possibility for ultra-low power as well as ultra-fast. All optical tunable chirality is at optical frequency. So you can see the wavelength range here. So, you are basically tuning the chirality in the visible range. Now, we move on to another type of metamaterial, which is biisotropic and

Bi-isotropic and Bianisotropic Metamaterials

- Historical context:
  - First bi-isotropic study: François Arago (1811)—observed polarization rotation in quartz
  - General field properties in bianisotropic media were recognized in the 1970s
  - Wave propagation in such media was studied thoroughly in the 1990s

- Recent interest (last decade) in bianisotropy is due to its potential in — Optical activity, asymmetric absorption/reflection, one-way transparency, anomalous refraction, etc.

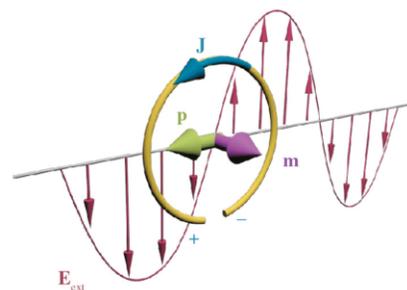- Example: Split-ring resonators – show electric, magnetic, and bianisotropic responses.

Fig. A metal split-ring resonator positioned in the electric field distribution E_{ext} of a standing wave.

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bianisotropic.

So, what are these? In physics, engineering, and materials science, a biisotropic material is basically an isotropic material. where electric and magnetic flux densities are linearly coupled to both the electric and the magnetic fields via scalar constitutive relations ok, including magneto electric coupling terms ok. So, a major subset of this kind of material also known as Pasteur media they can rotate the polarization of the light in either refraction that is like transmission right. So, not all materials with a twist effect basically fall into this biaxotropic class. The twist effect of the class of biaisotropic materials is basically caused by the chirality okay that is kappa non-zero okay and or their non-reciprocity which is given as non-zero chi okay.

So, that all depends this non-reciprocity of the structure right of the media in which the electric and the magnetic field of an electromagnetic wave or you can say simply light interact in a very unusual way. Now, if you move on to the next term that is bianisotropy that are a type of electromagnetic material where electric and magnetic fields are basically coupled. And an electric field here can induce a magnetic response, and a magnetic field can induce an electric response, right? And this coupling is basically described by constitutive relations that include magneto-optic coupling terms, making them distinct from simpler materials like isotropic or anisotropic materials. So, when we talk about, you know, bianisotropy, that basically implies a dual polarization mechanism, and there is also an inbuilt anisotropic behavior, right? So, for most materials, the electric field E and the electric displacement field D are okay, as well as when you talk in terms of magnetism. So, you have a magnetic field B and the inductive magnetic field H; they are basically parallel to one another.

But like those kind of materials are known as isotropic medium, but for some complex materials such as in many

Bi-isotropic and Bianisotropic Metamaterials

- Magnetoelectric cross-coupling introduces:
  - Chirality parameter (κ): Measures strength of chirality and affects wave phase
  - Tellegen parameter (χ): Measures non-reciprocal magnetoelectric coupling, also affects wave phase
- Figure: Isotropic media categorized by the signs of ε and μ.
- Wave propagation requires ε and μ to be of the same sign.
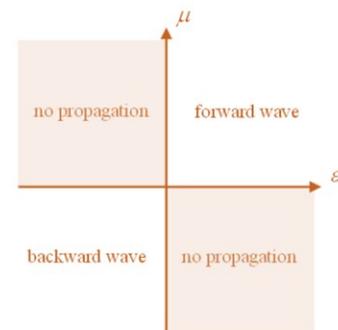- Double-negative media support backward waves.

Fig. The effect of chirality on the backward-wave characteristics of bi-isotropic media in isotropic media.

metamaterial you will see that these fields are not necessarily parallel ok. So, that is the case when you can call them like these materials are anisotropic. So, when they are parallel you call them isotropic, when they are not parallel this kind of materials you call them as anisotropic fine. So now let us look into the historical context of this kind of material. So, although the first known study on the bioisotropic materials dates back to 1811 when Frankes Arago observed the rotation of polarization or you can say the polarization plane of linearly polarized light in quartz.

The general properties for the fields in bioisotropic media were recognized much later, only in the 1970s. So, you can see the gap between these two studies, okay. The wave propagation in such media was studied thoroughly only in the 1990s. So, during the last decade the interest in this bi-anisotropy has resumed thanks to the unique opportunities it provides for the design of matter surfaces where You can control the optical activity, asymmetric absorption, reflection, one-way transparency, anomalous refraction, etc. So, when you want to do more peculiar stuff in terms of the electromagnetic response of your material, you can use this kind of bianisotropic metamaterials.

So, you can take a simple example of a split-ring resonator. You can see this is the split ring. So, here is what you can see in addition to the electric and magnetic polarization. So, this is the incident external electric field; this is the way it is polarized. So, you get a polarization like this; there is a polarization current.

So, there is a current density that gives you a magnetic dipole moment in this direction, right? So, this is how the magnetic metal splintering resonator is positioned in an external electric field distribution, right? Now, what you see here is that in addition to the electric and magnetic polarization, this splitting resonator also possesses an isotropic response. How much do you have to understand that the electric field E external here is basically exciting the magnetic dipole moment M, isn't it? Because of this current flowing through the loop. Now, since the resonator size is comparable to the wavelength, the induced polarization current J is nonlocal. That means it depends on the external field in the entire volume occupied by the resonator. Okay, and due to the geometry of the split ring, the electric field also excites both; you know, you also get a polarization because of the charge splitting.

So, you get both electric and magnetic dipoles, right? So, it becomes very interesting, and a simple split ring resonator has, you know, electric and magnetic, as well as bianisotropic, responses. Now the magnetoelectric cross coupling means that in addition to the permittivity ε and permeability μ, you got to now study a parameter that measures the strength of the chirality kappa and then you also need to study the Telegon parameter chi, okay. That measures the non-reciprocal magnetoelectric coupling, which also affects the wave phase. So, here you can see on the figure that shows the division of isotropic media into 4 classes depending on whether you know ε or μ are positive or negative. So, this is the effect of chirality on the backward wave characteristics.

So, you can see this is the ε axis, and this vertical axis is μ. So, here both are positive. So, you get a forward wave. Here, you get negative ε and positive μ. So, you do not get any propagation.

Here, you also get positive ε and negative μ. So, you do not get any propagation, but here both ε and μ are negative. So, you get a propagation, but that is backward in the backward direction. So, you get a backward wave. So, what you understand is that wave propagation requires ε and μ to be of the same sign.

So the double negative media basically support backward waves. Now, however, when the chirality parameter is allowed to be non-zero, that is, kappa is non-zero, the situation is basically characterized as shown in this particular figure. where we are, for simplicity, considering that the telegram parameter chi is 0, ok. So, what is this figure telling us? It shows the effect of chirality on the backward wave

Bi-isotropic and Bianisotropic Metamaterials

- Figure: Allows nonzero chirality ($\kappa \neq 0$), assuming $\chi = 0$.

- The permittivity and permeability are assumed to be of the same sign, and the square root of their product is assumed to have the same sign as ε and μ.

- Depending on κ, the medium may support:
  - Two forward waves
  - Two backward waves
  - One forward and one backward wave

- Key implication:
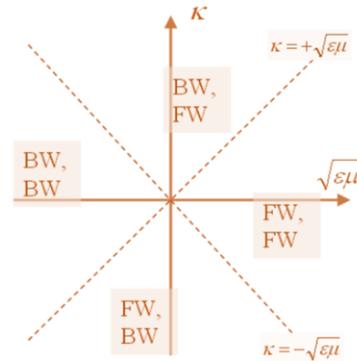 - Negative-index media can exist without double-negative ε and μ

Fig. The effect of chirality on the backward-wave characteristics of bi-isotropic media when ε and μ have the same sign and tellegen parameter as zero.

characteristics of the bi-isotropic media when you are considering ε and μ to have the same sign and we are considering a special case where kappa = 0.

So, this is important. So, we are considering ε and μ to be of the same sign. So, the square root will basically take the sign of these two parameters. So, kappa is calculated as the square root of ε μ. So, if both are positive, kappa is also positive. If both are negative, then kappa will also be negative, right? So, depending on this kappa, the medium can then support two forward waves, okay.
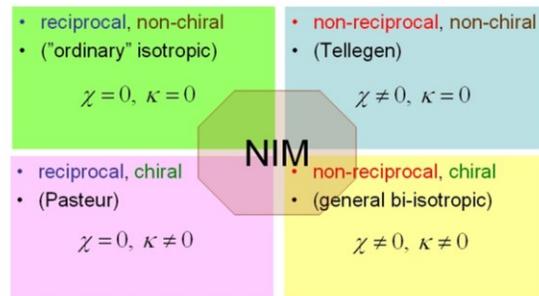
So, here you can see you get forward waves here ok, here you can get backward and forward, here you can get forward and backward, here you can get backward backward right. So, these two waves basically depend on the magnitude of the chirality parameter, which is kappa. So you are getting two eigenwaves, which can be forward. In that case, the wave vector amplitudes are both positive, or you can have both backward. So in that case, both wave vector amplitudes will be negative.

Or you can even have waves with one positive and one negative, right? So, all these possibilities are available. So, what are the key implication here is that a negative index media can exist without double negative ε and μ ok. So, that is the understanding here. So, you can say a corollary is that in order to create a negative index medium, that means a medium that supports backward waves. So, it is not a necessary condition to have a double negative.

Material, right? So, we can see that a

## Bi-isotropic and Bianisotropic Metamaterials

- A sufficiently large chirality parameter ($\kappa > \sqrt{\mu\varepsilon}$) can induce backward-wave behavior

- Chiral nihility: A special case where $\mu\varepsilon = 0$ but $\kappa \neq 0$, enabling wave propagation solely due to chirality.

- The interrelation of the domains of backward-wave media and the four subclasses of bi-isotropic materials (Figure).

- Negative-index media (NIM) – A plane eigenwave can exhibit backward propagation (i.e., negative phase velocity).

- NIM are possible across all subfields of bi-isotropic materials including chiral (handed), non-chiral, reciprocal and non-reciprocal.

- reciprocal, non-chiral
- ("ordinary" isotropic)

  $\chi = 0, \ \kappa = 0$

- non-reciprocal, non-chiral
- (Tellegen)

  $\chi \neq 0, \ \kappa = 0$

NIM

- reciprocal, chiral
- (Pasteur)

  $\chi = 0, \ \kappa \neq 0$

- non-reciprocal, chiral
- (general bi-isotropic)

  $\chi \neq 0, \ \kappa \neq 0$

sufficiently large chirality parameter when your kappa is much larger than square root of ε and μ that can also induce backward wave behavior. So, this is something very new and you can see that you know if you have very small absolute values of

- Anisotropy refers to the variation of a material's properties based on direction.

- It can be classified into:
  - Uniaxial anisotropy – Involves one unique direction, known as the optic axis, which affects material properties
  - Biaxial anisotropy – Involves two distinct directions influencing the material's behavior

- Effective permittivity ($\varepsilon_\parallel$ or $\varepsilon_\perp$) for two principal polarizations
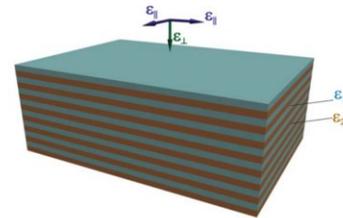
$$\varepsilon_\perp = \frac{\varepsilon_1 \varepsilon_2}{f_2 \varepsilon_1 + f_1 \varepsilon_2} \text{ and } \varepsilon_\parallel = f_1 \varepsilon_1 + f_2 \varepsilon_2$$

permittivity and permeability that can give you some interesting possibilities in the connection of chirality where you can also see backward wave. So, you need to understand that the extreme case in this respect is the so-called chiral nihility, which means where the chirality will disappear. So, that is the special case where you know ε μ becomes 0, but your kappa is nonzero. That means you know the medium will still possess a nonzero chirality parameter.

So, that enables web propagation solely because of the chirality right. So, here you can see the interrelation of the domains of backward wave media and the four subclasses of biaxotropic materials, right? So, what we are considering is basically a negative index medium here. So, you can think of four categories, something like reciprocal. So, when it is reciprocal so kappa sorry chi = 0 and then so this one is reciprocal and non chiral.

So, you have an ordinary isotropic medium. So, you can write them as kappa, sorry, chi = 0, kappa = 0. So, there can be a reciprocal chiral medium, which is basically the Pasteur medium. So, the chiral chirality parameter is non-zero. So, you have kappa non-zero, but the reciprocal of chi = 0. On the other hand, you can have non-chiral, but also non-reciprocal, which is the telogen medium.

So, that is typically chi not equal to 0, but kappa = 0, and then you can have non-reciprocal and chiral. So, this is the general bioisotropic media where both are basically nonzero. So, negative index media are possible across all these subfields of bioisotropic materials, including the chiral, which are handed mediums. Something here we have seen: these two are the non-chiral mediums. So, there is no handedness; then you can also have this in reciprocal and non-reciprocal kinds of media.
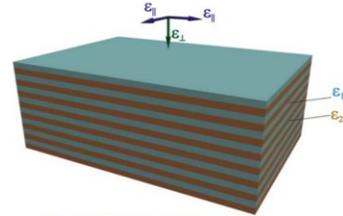
So, negative index medium is possible in all these different categories. So, negative index media is the media where a plane eigen wave can exhibit you know backward propagation that means it

has got a negative phase velocity and that can be possible across all these different sub fields. So, now let us look at non-resonant

metamaterials and their applications. So anisotropy basically refers to the variation of material properties based on direction and you can classify this into uniaxial anisotropy that involves one unit direction which is also known as optic axis that affects the material properties. It can also be classified into biaxial anisotropy that involves two distinct directions influencing the material's behavior.

So, uniaxial will have only one optic axis; biaxial will have two, okay. So, we have seen this particular geometry before. So, why are we showing it again? Because this is a stratified metal-dielectric composite. If you recall this figure, this is nothing but a layered metal dielectric structure where the permittivities of the two constituents are given as ε_1 and ε_2. Now, for the two components in this multilayer stack if we consider the volume fraction of material 1 is F_1 and for material 2 it is F_2, F_2 is nothing but $1 - F_1$.

In that case you can say that the effective permittivity along the two principle polarization that is when the electric field is polarized along the plane of the interface that is ε parallel it can be this direction or this direction this or this that can be given as $\varepsilon_1 \varepsilon_2$ / oh sorry ε parallel can be simply written as $f_1 \varepsilon_1 + f_2 \varepsilon_2$. And ε perpendicular is when the electric field is polarized normal to the interface. You can write ε perpendicular $= \varepsilon_1 \varepsilon_2$ / $f_2 \varepsilon_1 + f_1 \varepsilon_2$. Now, the extraordinary axis is basically aligned perpendicular to the plane, and the ordinary axis, as you can see in these two directions, the permittivity is the same. So, you can consider them as ordinary axes; they are basically aligned parallel to the interface, right? So, this is basically a uniaxial stack.

Now, for this kind of uniaxial stack made of nanolayered metamaterials, the effective permittivity tensor is basically a diagonal matrix that can be written as follows. So, you can write

ε effective, which will have you know ε parallel, ε parallel in the two directions, and then you have ε. Perpendicular in the other direction, right? So, this is the extraordinary refractive index or permittivity; this is along with the ordinary ones. So, you can also write them as ε o, ε o that is ordinary, and ε e that is extraordinary. Now this we have also seen earlier that if there are more materials, so you can actually still find out the ε parallel based on the summation of i / fi, fi is the volume fraction of each material.

ah that has got a permittivity of ε i. And you can find out the perpendicular component as 1 by ε perpendicular will be summation / i f i / ε i right. So, for some

Non-Resonant Metamaterials and Applications

- Arrays of dielectric rods in air consistently produced stronger anisotropy than arrays of air holes in dielectric.

- Hexagonal arrays produced stronger anisotropy than square arrays due to the greater packing density of the rods.

- Of all the combinations, a hexagonal array of hexagonal shaped rods suspended in air provided the highest birefringence.
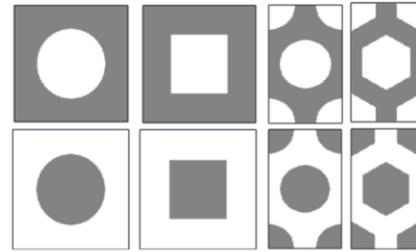

- Hexagonal array of circular rods
- Can be manufactured easily

- Hexagonal array of hexagonal shaped rods.
- However, hexagonal shaped rods are difficult to manufacture

- Double parameter sweep is performed to determine the rod radius and thickness of the supports that maximize the anisotropy.

- The dielectric is chosen to be polycarbonate (PC) which has a dielectric constant of ε_r = 2.57.

- It is concluded from this data that the support features should be made as small as possible while still being mechanically robust.

- The radius of the dielectric rods that optimizes the anisotropy was found to be $0.42a$.

- Under these conditions, the dielectric tensor was calculated to be:

$$\varepsilon_{simulated} = \begin{bmatrix} 1.8533 & 0 & 0 \\ 0 & 1.9535 & 0 \\ 0 & 0 & 2.0525 \end{bmatrix}$$
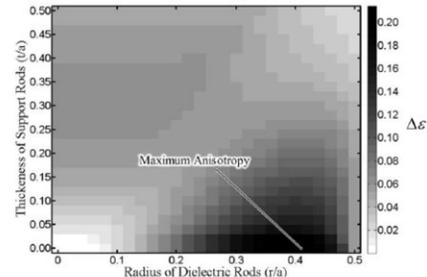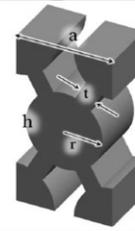
applications you can see that you know you can actually make artificial wave plates ok that can be made in this kind of geometry. You will see that the wave plates basically rely on the difference between the values of these two permittivities: extraordinary and ordinary. Now, the strength of anisotropy is also called birefringence because you see two different refractive index values in two different directions.

So, you call it birefringence by means of 2, okay. So, the strength of anisotropy can be calculated as δ ε which is basically the difference between ε E and ε O. Now, if the difference is positive you call it as the positive uniaxial metamaterial, if the difference is negative you call it as a negative uniaxial metamaterial. So, usually a stack of dielectric alternative layers is used to design negative uniaxial metamaterials, because in this case you will get ε O larger than ε E. So, there are different geometries people have tried. So, here lot of these geometries are shown always remember the dark color shows the material with higher refractive index and lighter color shows the lower refractive index.

So, here it is like dielectric material and air, okay. So, you can see that you know people have made a lot of positive uniaxial materials using array of blocks, which can be either cylindrical or of square cross-section. So these are square cross-sections, and these are of a cylindrical unit cell. There are other designs. So these are actually the real blocks.

So these are dielectric rods, the top you are seeing. So it looks like a circle. This is a square rod. So you are looking down from the top. These two are square arrays, and these two are basically hexagonal arrays. So, this is a hexagonal lattice or you can say hexagonal array of circular rods, dielectric rods in air, this is a hexagonal rod hexagonal array of hexagonal rods in air and these are the complementary structure.

That means, in a dielectric slab you are making a circular hole or a square hole or you are

making you know holes in the form of rectangular lattice or so on. Now, why people have tried so many different structures is to see where they get higher anisotropy. So, it is found that hexagonal arrays produced stronger anisotropy than square arrays due to their greater packing density. That makes sense, okay, and of all these combinations, you will see the hexagonal array of hexagonally shaped rods.

So, this one is suspended in air. So, this is the one that has given the highest birefringence. So, this is a clear winner, okay. Now, there are some challenges that hexagonally shaped rods are not easy to manufacture. So, people usually go with the hexagonal area of circular rods because these are easy to manufacture. Now, considering the ease of fabrication and design, The final design that people go with is the hexagonal array of circular rods.

So, people do a double parameter sweep to determine what should be the radius of the rod and the thickness of their support because you cannot have all the rods suspended in air then the entire structure will fall down. So, you need this kind of supporting structures that will connect one circular rod to another circular rod, but obviously it is clear that you want this to be as thin as possible. So, this kind of a study that plots the thickness of the supporting rod T/A, A is basically the latest period and then here you have R/A. So, this is the normalized plot shows you that the maximum anisotropy can be achieved here when the radius is 40% of the lattice period, but you need to go for thickness of the support rod as minimal as possible. So, in this case, the dielectric was chosen to be polycarbonate, which has a dielectric constant of 2.

57. Ok, and the whole idea is that you need to keep the supporting rod as small as possible while it is still mechanically robust. So, the final the optimal value was found to be 0.42 a exactly here And these are the values of the dielectric tensor that was calculated. So, you actually get three different values in three different directions, right? Ideally these two should have been same, but because of the rod they show up some kind of different values ok, but this is the constituent material, but you can see here you are getting anisotropy ok because of this. So, these are the final

Non-Resonant Metamaterials and Applications

- The final design dimensions were $a = 8.0$ mm, $r = 6.4$ mm, $h = 13.86$ mm, and $t = 1.8$ mm.

- To measure the three tensor components of the metamaterial, three samples were printed in three orientations.

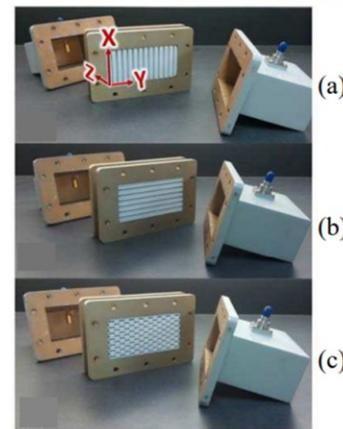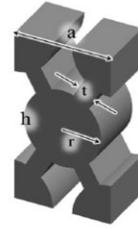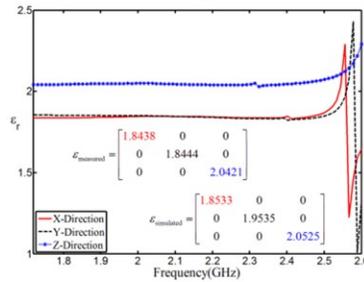- Measured result shows good matching with the simulated results.

$$\varepsilon_{measured} = \begin{bmatrix} 1.8438 & 0 & 0 \\ 0 & 1.8444 & 0 \\ 0 & 0 & 2.0421 \end{bmatrix}$$

$$\varepsilon_{simulated} = \begin{bmatrix} 1.8533 & 0 & 0 \\ 0 & 1.9535 & 0 \\ 0 & 0 & 2.0525 \end{bmatrix}$$

X-Direction
Y-Direction
Z-Direction

Fig. Materials under test when rods are (a) in the x-direction; (b) in the y-direction; (c) in the z-direction.

dimensions that has been used and people have fabricated this in different directions and 3 in 3 different orientation it has been printed for testing.

And you can see that they show how much better results you know. So, the simulated value actually showed very different result, but when they measure it they could see that that rod has got very minimal effect and these two values are very close to each other and that is what was expected right. So, they show very good results with this uniaxial

Hyperbolic Metamaterials and Applications

- Hyperbolic metamaterials: highly anisotropic, uniaxial materials having hyperbolic dispersion.
  - Act like a metal in one direction and a dielectric in the orthogonal direction

- The material's dispersion relation in wavevector space, forms a hyperboloid and therefore it is called a hyperbolic metamaterial.

- Applications – sensing, reflection modulator, all-optical ultra-fast switching for integrated photonics and imaging.
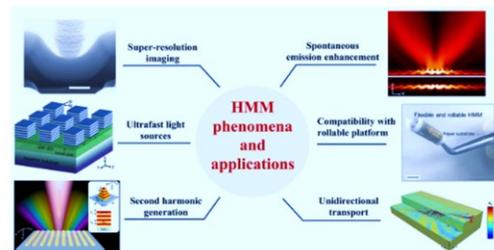
Fig. Phenomena and applications of hyperbolic Metamaterials.

metamaterial. So, the final thing we will discuss today is this hyperbolic metamaterial. Why are we considering this? Because hyperbolic metamaterials are known to have very high anisotropy, These are also uniaxial materials that have hyperbolic dispersion. So, here it is basically you have you know hyperbolic metamaterials which act like a metal for certain polarization or you can say direction of light propagation and they behave like dielectric for the other right.

Because you have got negative and positive permittivity tensor components that give you extreme anisotropy. So, here the figure basically highlights various phenomena and applications of this hyperbolic metamaterials something like super resolution imaging, ultra first light sources, second harmonic generation, spontaneous emission enhancement, compatibility with rollable platforms and also unidirectional transport right. So, as you can see that you know it hyperbolic metamaterials have got you know some peculiar characteristics because here the dispersion relation in the wave vector space actually forms a hyperboloid ok. And that is why they are known as hyperbolic metamaterials, and there you can have a lot of interesting applications. We will take up this later on I am just mentioning about them here because in the context of anisotropic metamaterial they are also a very their promising candidate because they have applications in sensing, reflection modulation or all optical ultra first switching ok.

You can also use them for integrated photonics and imaging, right? So, we will be discussing hyperbolic metamaterials in detail in this course later on. So, for this lecture, we will stop here, and we will continue our discussion with a magnetic metamaterial that is based on a splitting resonator in the next lecture. So, if you have any queries regarding this lecture, drop an email to the address mentioned in the course title and include the lecture number in the subject line.

Slides inserted by fallback (review if needed):

Thank You

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