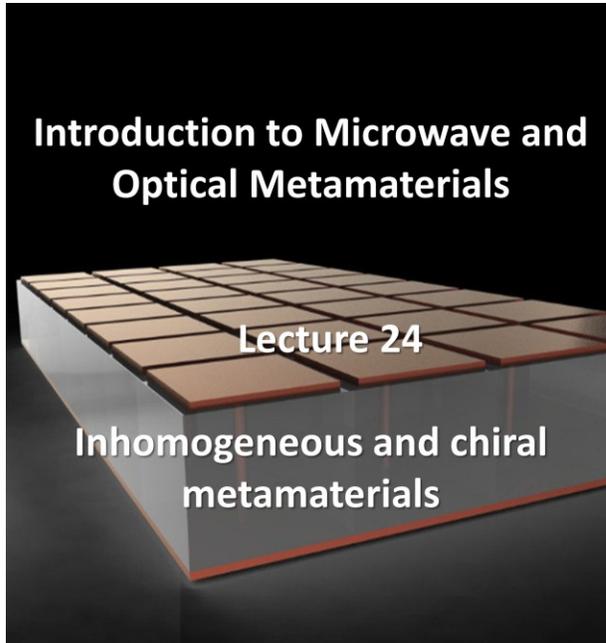**Course Name: Introduction to Microwave and Optical Metamaterials**
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-5
Lecture-24

Lec 24: Inhomogeneous and Chiral Metamaterials

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Lecture Outline

- Inhomogeneous Metamaterial

- Types of Engineered Metamaterials

- Chiral Metamaterials

 Hello everyone, welcome to Lecture 24 of the online course on Introduction to Microwave and Optical

Inhomogeneous Metamaterial

- Metamaterials are artificial media designed to control light propagation via tailored unit cells (meta-atoms).

- By adjusting geometry and material dispersion of the meta-atom, novel phenomena can be achieved:
  - Negative refraction
  - Optical cloaking
  - Optical analogues of effects from other physics domains

    Inhomogeneous Metamaterials:

- Inhomogeneous metamaterials differ from homogeneous ones:
  - Their constituent properties vary spatially across the material.
  - This variation enables different regions to have distinct refractive indices, permittivity, etc.
  - Result: tunable and unique electromagnetic behavior

Inhomogeneous Metamaterial

- Homogeneous, isotropic materials are often preferred for simplicity in:
  - Analysis
  - Design

- At the same time, these simplifications exclude attractive effects that needs to be explored.

- Recent metamaterial research has emphasized (which rely on inhomogeneous metamaterials):
  - Transformation optics
  - Cloaking applications

- Inhomogeneous metamaterials can be created by varying meta-atom size and geometry with spatial position.

- <u>Example application</u>: Magnetic field shielding

Inhomogeneous Metamaterial

- Inhomogeneous metamaterials can outperform traditional shielding methods, including:
  - High-permeability (μ) materials
  - Active magnetic field shielding

- Relative permeability values used to illustrate material behavior:
  - $\mu_r = 100$: represents a high-permeability material
  - $\mu_r = 0.01$: represents a low-permeability material

- Magnetic shielding mechanisms differ based on permeability:
  - High-permeability materials: trap or guide magnetic fields within the shield.
  - Low-permeability materials: repel magnetic fields, preventing entry.
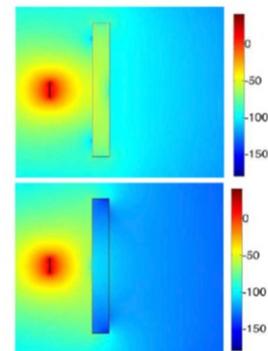
Fig. Shielding with different materials. Isotropic case with (a) low μ and (b) high μ.

Metamaterials. So, today's lecture will be on inhomogeneous and chiral metamaterials. Here is the lecture outline, we will discuss about

- For homogeneous and inhomogeneous metamaterial study – Unit elements are capacitor loaded conductor loops (inductors).

- To improve shielding – introducing inhomogeneity additionally in the metamaterial to enhance shielding effectiveness even more.

- Inhomogeneity in metamaterials can be engineered by tuning the resonance frequencies of individual elements.

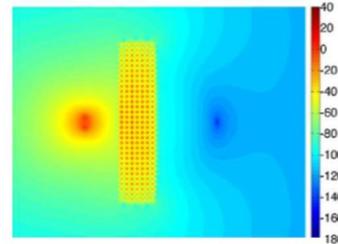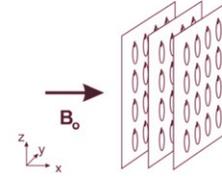- This tuning allows control over desired current values.

Fig. Shielding effect of homogeneous metamaterial.

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Source: Mustafa B et al., "Molding the Flow of Magnetic Field with Metamaterials: Magnetic Field Shielding," Progress In Electromagnetics Research, Vol. 126, 303-316, 2012.

inhomogeneous metamaterials, introduce different types of engineered metamaterials in this category and then focus on chiral metamaterials. Now, what are metamaterials? We have seen that these are basically artificial media which are designed to control light propagation via tailored unit cells which are also called meta atoms. Now by controlling the geometry and the material dispersion at the meta atom, novel effects such as negative refraction, optical cloaking as well as a series of you know optical analogues to the phenomena known in other physics domain can be observed. Now,

- Methods to achieve this include:
  - Changing capacitance values
  - Altering inductors
  - Using two inductors in series and modifying mutual inductance between these two by changing the distance between the inductors.

- Figure depicts an inhomogeneous metamaterial obtained by changing capacitance values

- The new inhomogeneous metamaterial thus improve the shielding effect.
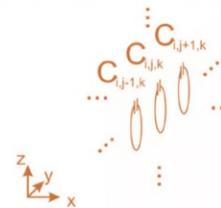
Fig. An illustration of an inhomogeneous metamaterial built by capacitance values that depend on the location $C_{i,j,k}$

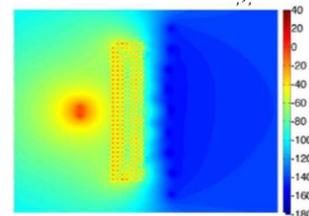**Fig.** Shielding effect of inhomogeneous metamaterial.

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Source: Mustafa B et al., "Molding the Flow of Magnetic Field with Metamaterials: Magnetic Field Shielding," Progress In Electromagnetics Research, Vol. 126, 303-316, 2012.

inhomogeneous metamaterials are those artificial metamaterials where the arrangement and the properties of their constituent elements will not remain same throughout the material rather they will vary throughout the material and that is where they are different from the homogeneous metamaterials where the properties remain consistent throughout.

Now, this variation basically enables different regions of distinct refractive indices and permittivities, and that leads to unique and tunable electromagnetic behavior. So, you have different regions having different material properties, right? So, in general, homogeneous isotropic material properties simplify the analysis and the overall design. However, one can try to work on these kinds of parameters that allow for some attractive effects, okay. So, you can, like, if you give away this kind of simplification, you will have more control / the electromagnetic properties within the material.

So, you will see that in last few years, metamaterial research has basically focused on those directions mainly towards an interesting field of cloaking which is based on transformation optics. okay and there you basically require inhomogeneous materials or inhomogeneous metamaterials okay and this inhomogeneous metamaterials can be treated by varying the meta atom size and geometry with spatial position so throughout the metamaterial things are not going to remain same okay So, what are examples of this kind of thing? So, the first example you can think of is magnetic field shielding, okay. It is an important application of a lot of practical interest. So, let us look into some examples here. So, we will see that shielding by means of inhomogeneous metamaterials will have some added advantages / traditional shielding.

So, that we achieve using you know high permeability material and typically the active magnetic field shielding which is known as ok. So, here the relative permeability values that are used to illustrate material behavior is considered to be you know $\mu r = 100$ in this case this is the high permeability one and this is the one with low permeability that is you know 0.01 ok. So, both are the relative permeabilities. Now, what is interesting here is that the magnetic field shielding mechanism basically differs based on the permittivities involved, okay.

So, in the first case, which is the high permeability material, you can see that it basically traps or guides the magnetic field within the shield. So, this is the shield ok and this basically traps the field within and in the case of low permeability material, this basically does not allow any magnetic field to enter ok and that basically repels the magnetic field. So, that is also another kind of shielding, right? So, you can actually have magnetic field shielding by materials with different permeability working on different principles. Now, for homogeneous and inhomogeneous materials okay you can understand that you can for the case of inhomogeneous we are now considering you know unit cells which are capacitor loaded conductor loops as you can see here this conductor loops are nothing but inductors right. So, you will see the shielding performance of an array of such loops.

So, the magnetic field source again in this case is a current loop with a radius of 8 centimeter and you see the unit elements of the metamaterial are also current loops which are having radii of 0.8 centimeter and the distance between the elements is maintained to be 7 centimeter. So, what is

done here to improve the shielding? You can additionally introduce inhomogeneity in this metamaterial, and that basically improves the effectiveness of the shielding even more. So, what is happening? So, the inhomogeneity in this metamaterial can be engineered by tuning the resonance behavior or resonance frequencies of each individual element. So, this tuning basically allows you a control / desired current values right.

So, how can you achieve this? The methods to achieve this will include first you can change the capacitance values ok. Then you can also think of changing the inductors ok and you can think of using inductors or two inductors in series that will modify and you can also think of modifying their mutual inductance between these two by changing the distance between the So, there are different ways you can you know change this resonance of individual elements and you can create inhomogeneity right. So, once you change, you create some inhomogeneity; you can see it. So, this is for a homogeneous metamaterial of the same size, and everything you see here shows the magnetic field strength is around, say, - 80 to - 100 dB. But when you introduce this kind of you know inhomogeneity by altering the capacitance or the inductance or the mutual inductance effect for different layers you can see that you are actually able to get almost - 180 dB you know.

Filled means it is almost negligible here. So, you are getting very good shielding in this particular case, and that is obtained by changing the capacitance values, right? So, what we learn from here is that inhomogeneous metamaterial can give better shielding as compared to the homogeneous metamaterial and the regular material of high or low permeability. Right, okay. So, now if you recall you will remember that we have discussed this several * in our earlier lectures that engineered materials and the materials we are interested in in this particular course is basically the metamaterials right. So, what are the key characteristics? The first thing you have to remember is that the periodicity we are discussing here is of the order of λ by 10.

That is, you know, typically the size of the unit cell of the meta atom will be one-tenth of the wavelength that is interacting, okay. So, that is very important for achieving the desired resonance. The second thing is that you know the oscillating currents that are there in each meta atom. So, they basically emulate atomic resonances ok and this behavior of the electrons within the conductive elements of the metamaterials mimics the kind of resonance happens in atoms and that leads to a very strong interaction with the electromagnetic field. So, finally, your you know light matter interaction improves right.

So, we have seen that the resonant metamaterials basically achieve their unique properties through their resonating unit cells. And these structures are designed in a way that interacts strongly with the electromagnetic field at a specific frequency. So, you basically try to match the resonance of the structures with the incident field's frequency, okay. An important parameter to remember here is that we are talking in terms of a length scale which is $\lambda / 10$, right? And this we have already discussed that the oscillating currents in this ah meta atoms basically emulate the atomic resonances and because of which people have been able to demonstrate left hand metamaterials where both permittivity and permeability can be achieved negative / a particular frequency range. You can also have a refractive index less than 1, and so on.

Now there is another type of metamaterial called non-resonant metamaterial. So, here the meta-atoms are not basically of the resonant type, right? So, non-resonant metamaterials rely on a very different mechanism as compared to the resonant metamaterials to achieve their properties. So, you can see that they are not dependent on resonances, right? So, what are the key characteristics of this kind of nonresonant metamaterials? The first thing is that here also the period should be much much smaller than λ and there are no current oscillations or wave scattering happening in this case. So, the overall structure is behaving like a So, here you have greater tolerance okay to any kind of structural deformity okay. And because there are no kind oscillations or wave scattering, they do not rely on oscillating currents or strong scattering properties for their functionality, right? So, what are the examples of this kind of metamaterial? They are anisotropic metamaterials, they are hyperbolic metamaterials and these metamaterials exhibit different properties depending on the direction of propagation of the electromagnetic waves.

So, another important metamaterial that we will encounter today is chiral metamaterials. Now, what is chiral, or you can say, what is chirality? So, chirality basically refers to a geometric property of a structure that lacks any mirror symmetry plane, right? So, a chiral medium is basically composed of particles that cannot be superimposed on their mirror images. So, you can take an example of this. So, you take your right hand and bring it in front of a mirror; you get the reflection that looks like your left hand. If you bring them together, you will see that they will not be superimposed correctly.

So, due to this kind of chiral asymmetry any medium that has got unit cells ok or meta atoms made of this kind of chiral structure, they will basically exhibit different responses to a left circularly polarized right to a right circularly polarized right. So, these two different polarizations will see different kinds of responses, right? So, in the 1910s ok Lindemann extended the concept of optical activity from visible light to radio waves ok. So, he used helical coils as artificial chiral molecules and since then you know the chiral media in the microwave region has been applied in various technologies such as antennas, polarizer, waveguides etcetera. So, in 2003 Tretyakov and his group they proposed the idea to fabricate a metamaterial that is composed of chiral particles such as you know helical wires to get negative refraction for one of the circular polarizations with kappa much larger than square root of ε Now, what is this kappa that is called the chiral parameter? So, it is a key parameter that basically describe the optical property of the chiral materials particularly in the context of metamaterials and chiral media right. So, it basically quantifies the degree of chirality, which refers to the handedness or non-superimposability of an object with its mirror image, right? So, in essence, you can say that a non-zero chiral parameter indicates that this material interacts differently with left circular and right circular polarized light.

So, in natural chiral metamaterials sorry materials such as quartz or sugar solution, you will see the chiral parameter kappa which can also be calculated as you know the difference between the two refractive index by 2. So, that is n RCP (right circular polarization) - n LCP (left circular polarized light), okay, the refractive index that you see. For these two different polarizations, divide by 2. So, that chiral parameter is much, much smaller than 1 in the case of natural chiral molecules, and you will see that the square root of $\varepsilon \mu$ is much larger than 1. That means that, in such a material, negative refraction is not possible.

Now, in chiral metamaterials kappa this chiral parameter can also be a complex number where you will see that the real part basically relates to optical rotation that is basically the rotatory power and the imaginary part will cater to ah circular dichroism that is basically the difference in the absorption between the two circular polarized lights LCP and RCP right. So, now in the case of chiral metamaterials, you also have a concept called chiral nihility, right? So, that happens when ε and μ are close to 0. So, in that case, even small kappa chirality can also lead to a negative refractive index for one circular polarization. So, in 2004 Sargent Pendry basically proposed a microwave chiral metamaterial which was using this kind of twisted Swiss rolls ok as meta atoms and as long as the chiral parameter kappa was large enough a negative refraction could be obtained in chiral metamaterials. So, this was shown in 2000, after 2004.

So, what happens to chiral metamaterials with a negative refractive index? You can see that the negative refractive index can be achieved by ensuring optical activity in chiral metamaterials or nanoplasmic structures. So, this enhancement can be done by rapidly rotating the electric field direction of a linearly polarized wave / a short distance in a chiral medium. So, I will show you some figures for that. So, in figure A you can see this is a bilayer chiral structure which is a twisted double rosettes kind of structure that can be used to achieve giant polarization rotation. Figure B shows a double-layer array of twisted crosses.
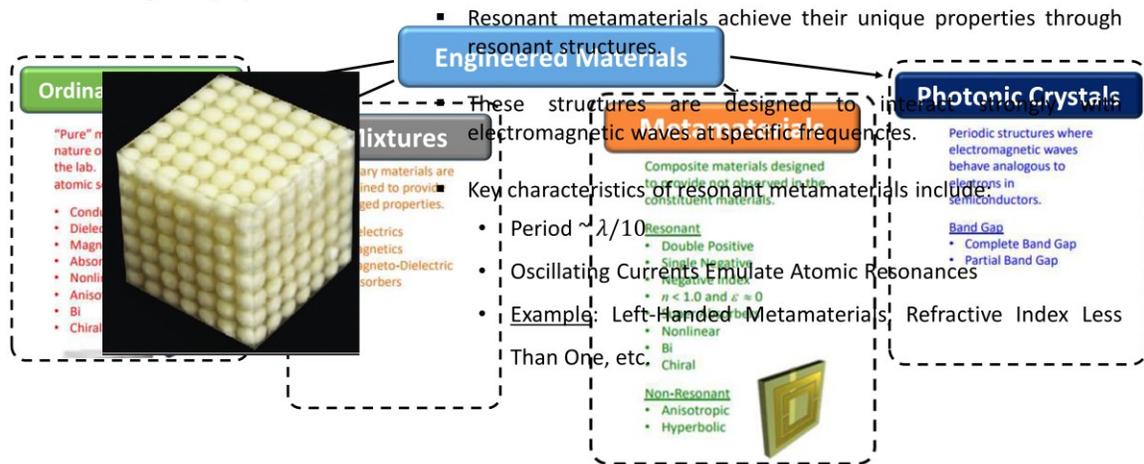
Okay, and this is the structure. So, this can also give an negative refractive index from an effective bilayer design. This figure actually shows a conjugated bilayer γ dn array. So, this kind of a swastik symbol ok the conjugated one ok. That is like you have two on opposite sides of a dielectric slab, and then you have a metamaterial made from that, okay.

So, what do you see that this kind of structure breaks the mirror symmetry along the normal plane that enhances the chirality and strong chiral metamaterial can have negative refractive index for one circular polarization around the resonant frequencies. So, figure D shows another kind of structure, which is basically a chiral resonator array made of gold and that also demonstrates a negative refractive index. Okay. Figure E shows a conjugated double Z or Z-type structure. So, that also enhances the optical activity through local field enhancement between the nanogaps present here, and these are all made of metal.

So, you will see that they also have you know lot of optical activity and to strengthen the intermolecular capacitive coupling, you can actually use a conventional conjugated γ dn kind of structure that can be morphologically you know transformed into this kind of conjugated double z metasurface kind of structure right. So, the very small gaps that you see between the adjacent metallic elements basically increase the inter

Types of Engineered Metamaterials

- As discussed earlier, Engineered materials are materials that are purposely tailored to exhibit useful and enabling electromagnetic properties.

Resonant Metamaterials

- Resonant metamaterials achieve their unique properties through resonant structures.
- These structures are designed to interact strongly with electromagnetic waves at specific frequencies.

Key characteristics of resonant metamaterials include:

- Period ~ $\lambda/10$
- Oscillating Currents Emulate Atomic Resonances
- Example: Left-Handed Metamaterials, Refractive Index Less Than One, etc.

Engineered Materials

Ordinary Materials

"Pure" materials found in nature or synthesized in the lab. ... atomic s...

- Cond...
- Diele...
- Magn...
- Abso...
- Nonli...
- Aniso...
- Bi
- Chiral

Mixtures

...ary materials are ...ined to provide ...ged properties.

- ...electrics
- ...gnetics
- ...gneto-Dielectric
- ...sorbers

Metamaterials

Composite materials designed to provide not observed in the constituent materials.

Resonant
- Double Positive
- Single Negative
- $n < 1.0$ and $\varepsilon \approx 0$
- Nonlinear
- Bi
- Chiral

Non-Resonant
- Anisotropic
- Hyperbolic

Photonic Crystals

Periodic structures where electromagnetic waves behave analogous to electrons in semiconductors.

Band Gap
- Complete Band Gap
- Partial Band Gap

molecular coupling, right? That can be characterized by electrical capacitance. Here, you can also see the same thing. So, here you are basically using this conjugated double-Z metamaterial composed of copper wire. So, these are copper wires on a Teflon substrate.

So, we can also see 3D chiral metamaterials that are especially effective for optical frequencies. They consist of building blocks with feature sizes at the nanoscale level, and they have much more complex geometries. So, they are more intricate than chiral metamaterials. So, the fabrication processes typically involves top down methods something like cuts and shapes of the materials using ion beam lithography or electron beam lithography or even direct laser writing. If you think of bottom up assembly, they they will basically deal about you know assemblies of small components that that add up to give you complex shapes ok.

So, here you can see one such 3D chiral metamaterial which is basically a 3D array of chiral splittering resonators ok that that forms a isotropic chiral metamaterial right. Here is another example that displays a 3D gold helices like this that can be used as a broadband circular polarizer in the mid IR range ok. So, this particular device can also be used or metamaterial can also be used for circular transmission conversion from LCP to RCP and vice versa that depends on the length of this helix their pitch and the radius of this helix ok. Also, the wear radius okay all these parameters play important role and the fabrication process here basically involves direct laser writing of the helical pores and that is followed by electrochemical deposition of gold and you can finally get this kind of gold helix 3D gold helix array. Next, we move on to some sort of, you know, self-assembled chiral metamaterials.

So, when you compare with top down fabrication methods, this self assembly technology provides an alternative bottom up approach for realizing structures at the nanometer scale which are cost effective and yet highly cost effective. tunable, and they also work in a fast manner. So, we will see that there are certain challenges with nanoscale structures. when they self assemble

because you have to play between a balance of different kind of forces acting at the nano scale something like you know Van der Waals force, capillary forces, then you have static or transient electromagnetic forces, you have different kind of convective and friction forces and so on. So, this basically allows precise control / the metallic nanoparticles with varying chemical compositions, geometries, and sizes.

So, they result in plasmonic

Types of Engineered Metamaterials

<u>Non-Resonant Metamaterials</u>

- Non-resonant metamaterials, in contrast, rely on different mechanisms to achieve their properties.

- They don't depend on strong resonances in the same way as their resonant counterparts.

- Key characteristics of non-resonant metamaterials include:
  - Period Can Be Much Less Than λ
  - No Current Oscillations or Wave Scattering
  - Greater Tolerance to Structural Deformations
  - <u>Examples</u>: Anisotropic Metamaterials, Hyperbolic Metamaterials
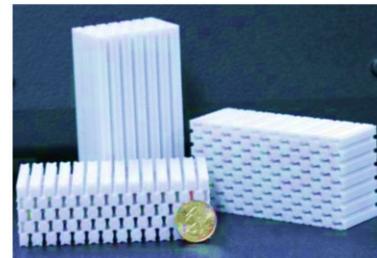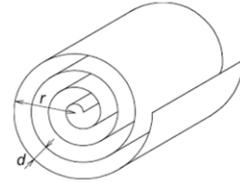
Chiral Metamaterials

- Chirality refers to the geometric property of a structure lacking any mirror symmetry plane.

- A chiral medium is composed of particles that cannot be superimposed on their mirror images.

- Due to this chiral asymmetry, the medium exhibits different responses to:
  - Left circularly polarized (LCP) waves
  - Right circularly polarized (RCP) waves

- In the 1910s, Lindeman extended the concept of optical activity from visible light to radio waves.

- Since then, chiral media in the microwave region have been applied in various technologies, including: Antennas, Polarizers, Waveguides, etc.

CHIRAL OBJECTS

Mirror

Left hand   Right hand   Cannot be superimposed
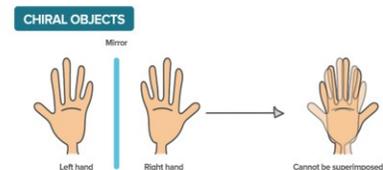
Chiral Metamaterials

- In 2003, Tretyakov *et al.* proposed the idea to fabricate a metamaterial composed of chiral particles, such as helical wires to get negative refraction for one of the circular polarizations with $\kappa \gg \sqrt{\varepsilon\mu}$

- In natural chiral materials (e.g., quartz, sugar solutions):

  - Chiral parameter $\kappa = \dfrac{(n_{\text{RCP}} - n_{\text{LCP}})}{2} \ll 1$ and $\sqrt{\varepsilon\mu} > 1$

  - Thus, negative refraction is not possible.

- Chiral nihility concept:

  - When ε and μ are near zero, even small κ can result in negative refractive index for one circular polarization.

- In 2004, Pendry proposed a microwave chiral metamaterial using twisted swiss rolls as meta-atoms.

- As long as the chiral parameter κ is large enough, negative refraction can be obtained in chiral metamaterials.

Chiral Metamaterials

Chiral Metamaterials with Negative Refractive Index

- Negative refractive index can be achieved by enhancing optical activity in chiral metamaterials or nanoplasmonic structures

- Enhancement done – rapidly rotating the electric field direction of a linearly polarized wave over a short distance in a chiral medium.

- Figure a: Uses bilayer chiral structure (double twisted rosettes) to achieve giant polarization rotation.

- Figure b: Shows a double-layer array of twisted crosses – an effective bilayer design yielding a negative refractive index.

- Figure c: Describes a conjugated gammadion array, made by – placing two conjugated gammadion structures on opposite sides of a dielectric slab.
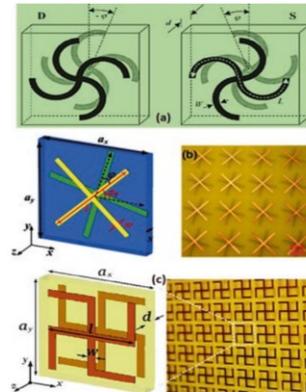

Fig. Chiral metamaterials with negative refractive index due to strong optical activity: (a) bilayer twisted Rosette structures; (b) an array of left-handed twisted gold crosses; (c) a conjugated bilayer gammadion structure

Chiral Metamaterials

Chiral Metamaterials with Negative Refractive Index

- Figure d: A chiral resonator array made of gold demonstrates a negative refractive index.

- Figure e: Shows a Conjugated Double Z Metasurface (CDZM) – enhances optical activity through local field enhancement in nanogaps between metals.

- To strengthen intermolecular capacitive coupling – A conventional conjugated gammadion structure is morphologically transformed into a CDZM.

- The very small gaps between adjacent metallic elements – Increase intermolecular coupling.
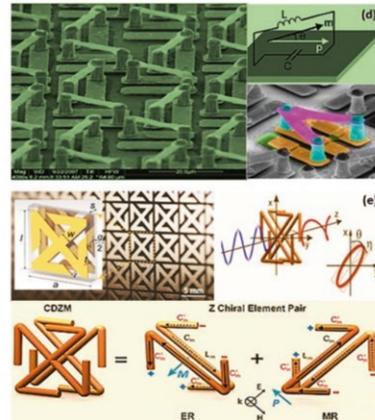
Fig. (d) chiral resonator array made of gold; and (e) a conjugated double-Z metamaterial (CDZM) composed of copper wire on Teflon substrate

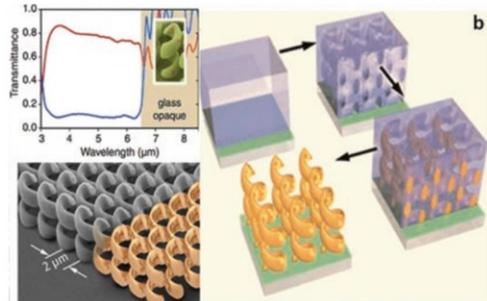# Chiral Metamaterials

3D Chiral Metamaterials

- 3D chiral metamaterials for optical wavelengths:
  - Built from nanoscale structures with complex geometries
  - More intricate than achiral metamaterials

- Fabrication approaches:
  - Top-down: Cuts and shapes materials using: Ion beam lithography, Electron beam lithography, Direct laser writing
  - Bottom-up: Assembles small components into complex assemblies

- Fig. a: Shows a 3D array of chiral split ring resonators (SRRs) for isotropic chiral metamaterials
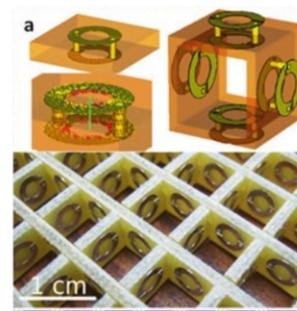
Chiral Metamaterials

3D Chiral Metamaterials

- Fig. b: Displays 3D gold helices used as broadband circular polarizers in the mid-IR range

- Circular transmission conversion (LCP ↔ RCP) depends on:
  - Helix length, pitch and radius
  - Wire radius

- Fabrication involves direct laser writing of helical pores followed by electrochemical gold deposition.

Chiral Metamaterials

Self-assembled Chiral Metamaterials

- Self-assembly offers alternative to bottom-up fabrication method that is:
  - Cost-efficient, fast and highly tunable

- Nanometer-scale structures self-assemble via a balance of forces:
  - Van der Waals, capillary, electromagnetic, convective, and friction forces

- Enables precise control over:
  - Metallic nanoparticles with varying chemical compositions, geometries, and sizes

- Results in plasmonic metamaterials with:
  - Tunable dimensions
  - Programmable nanoscale precision

Chiral Metamaterials

Self-assembled Chiral Metamaterials

- DNA base-pair interactions are commonly used in assembling plasmonic chiral nanostructures:
  - Example: DNA is used as a scaffold to assemble gold nanoparticles into pyramidal geometries (Fig. a)

- Pyramid structure is composed of two pairs of nanoparticles with different sizes:
  - Allow tuning of intensity, spectral response and handedness of Circular dichroism (CD)
  - By adjusting separation along the symmetry-breaking axis

- This method is not limited to gold—other metallic and semiconductor particles can be used.
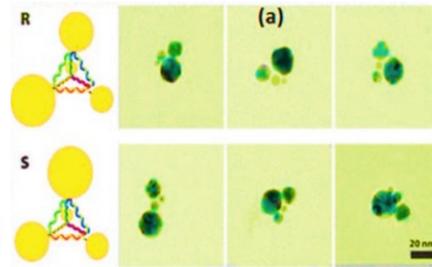

Fig. a) Chiral pyramids of gold nanocrystals obtained with DNA scaffolds

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Chiral Metamaterials

Self-assembled Chiral Metamaterials

- Bifacial DNA origami templates can also be used to assemble chiral nanostructures with metallic nanoparticles.

- Example: Fabrication of 3D chiral metamaterials using four gold nanoparticles.

- Figure shows a rectangular DNA origami template with:
  - Three binding sites on the top surface
  - One binding site on the bottom, aligned below the top binding site

- Chirality control — Left-handed or right-handed geometries achieved by positioning the fourth binding site accordingly.
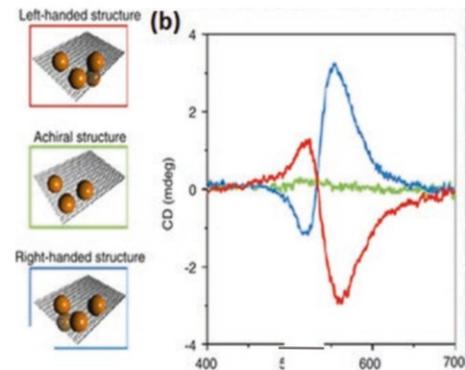

Fig. b) Four gold nanoparticles assembled with bifacial DNA template in left-handed, right-handed, and achiral structures and the corresponding CD spectra of these structures

Chiral Metamaterials

Self-assembled Chiral Metamaterials

- A characteristic bisignate circular dichroism spectrum is observed for left-handed and right-handed chiral nanostructures, compared with achiral nanostructures.

- Chiral plasmonic films can be made by embedding gold nanorods in self-assembled cellulose nanocrystals with chiral arrangement (Fig. a).

- Besides, plasmonic chiral nanostructures can be realized by binding chiral molecules with metallic nanoparticles.

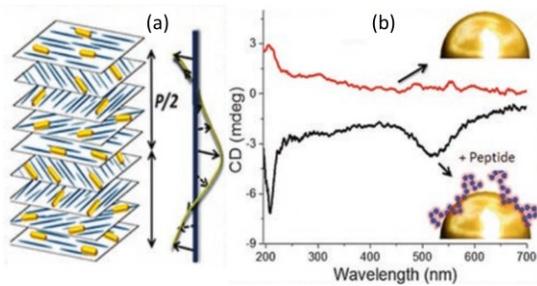- Example (Fig. b): Peptide molecules bound to gold nanoparticles induce chiral dichroism.

Fig. (a) Chiral plasmonic nanostructures assembled with gold nanorods and cellulose nanocrystals; (b) enhanced chiral dichroism after binding gold nanoparticles with peptide molecules that have chiral properties

metamaterials that have tunable dimensions, programmable nanoscale precision, and so on. So, one such method to make self-assembled chiral metamaterials is to use DNA base pair interactions that help in assembling these plasmonic chiral nanoparticles. The plasmonic nanoparticles are typically gold and silver nanoparticles. Here we are talking about gold nanoparticles. So, how do they work? You know that DNA is basically used as a scaffold.

 To assemble the gold nanoparticles into this kind of pyramidal geometry. So, you can see how it works, okay. So, this pyramid structure is basically composed of two pairs of nanoparticles with different size ok as you can see that allows tuning of intensity spectral response and handedness of the circular dichroism. So, once again circular dichroism is nothing but you know ah is a type of absorption spectroscopy that basically measures the difference in the absorption ah between left handed ah and the right handed circularly polarized light. So, this is typically a feature that is offered by chiral molecules.

 So, here the chiral metamolecule, you can say, basically offers this kind of feature. So, by adjusting the separation along the symmetry-breaking axis, you can also get this kind of chiral response. So, as I mentioned, this method is not only limited to gold; you can use any other metallic or semiconductor particles for this purpose. Now, you can also think about using bifacial DNA origami templates to assemble chiral nanostructures involving metallic nanoparticles that you can see here. The fabrication in this case you are talking about involves 3D chiral metamaterials that use four gold nanoparticles.

 So, the figure particularly shows a rectangular DNA origami template which has got three binding sites on the top surface and then you have one binding site on the bottom which is aligned below the top binding site. So, if you see, this is the achiral structure. So, there is no chirality in this; there are just three binding sites on the top surface, but when you put one nanoparticle on the bottom. So, that gives you one kind of handiness. So, this will kind of give you left handedness

structure if you do on the other ah binding site that will give you another kind of handedness you will see that you are able to have a get a control / the chirality of this kind of ah 4 particle nanoparticle system which are assembled using bifacial DNA template.

So, you can get both left-handed structure or right-handed structure and you know you can see their response the circular dichroism ok and they show different chiral properties. So, you can also see another type of self-assembled chiral metamaterial in this particular slide. So, you can understand that a characteristic bisignate circular dichroism spectrum can be observed in the cases of left- and right-handed chiral nanostructures. When you compare them with the achiral ones, okay. So, here what is shown is basically a chiral nanoplasmamine chiral plasmonic film that is basically made by embedding gold nanorods.

So, the yellow ones are basically the gold nanorods that you can see they are embedded in a self assembled cellulose nanocrystals ok and they have some chiral arrangement. So, these plasmonic chiral structures can be realized by binding chiral molecules with these metallic nanoparticles. So, what you see here is that you know you can also use some sort of you know peptide molecules. With your gold nanoparticles, they can also give you some sort of chiral activity. So, this particular graph highlights that chiral dichroism can be enhanced.

So, there is a clear difference between the properties of, you know, bare gold particles and gold particles, you know, bonded with peptide molecules, and you can see they have chiral responses. So, what you understood is that you can introduce chirality in different manners; you can either embed gold nanorods in self-assembled cellulose nanocrystals with some chiral arrangement like this, or you can have peptide molecules bound to gold nanoparticles that can also induce chiral dichroism. So, these are different ways you can realize chiral metamaterials, and they will show different responses to left-handed circularly polarized light and right-handed circularly polarized light. So, with that, we will stop here. We will discuss different types of engineered metamaterials and their applications in the next lecture.

If you have any doubts regarding this lecture, you can drop an email to this email address mentioning the course name and the lecture number in the subject line. Thank you.

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