

Course Name: Introduction to Microwave and Optical Metamaterials
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Week-1
Lecture-3

Lec 3: Applications of Optical Metamaterials & Classifications of Metamaterials



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Hello students, welcome to Lecture 3 of the online course Introduction to Microwave and Optical Metamaterials. Today's lecture will be on the applications of optical metamaterials and some classifications of metamaterials.

Lecture Outline

- Optical Metamaterials: Applications
 - Artificial Chirality
 - Cloaking
 - Imaging
- Classification of Metamaterials — Based on material properties
- Metamaterials – Classification based on functionalities
 - Electromagnetic Metamaterials
 - Acoustic metamaterials
 - Thermal metamaterials
 - Mechanical Metamaterials

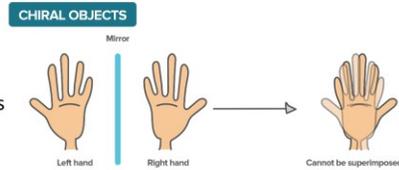


So, here is the lecture outline: we will look into the applications of optical metamaterials such as artificial chirality, cloaking, and imaging. We will revisit some fundamentals on the classification of metamaterials based on the material properties, but this time with a better understanding from the previous lectures, and we will also classify metamaterials based on functionalities. Such as electromagnetic metamaterials, acoustic metamaterials, thermal metamaterials, and mechanical metamaterials. So, this is just to give you an overview that the metamaterial field is really vast and you can use the metamaterial concept for different applications.

Optical Metamaterials: Applications

Artificial Chirality

- Chirality refers to the geometric property of a structure lacking any mirror symmetry plane.
- It exists in many forms in nature, ranging from molecules, to proteins, and to crystals.
- In contrast, a structure is achiral if it is indistinguishable or superimposable on its mirror image.
- Chiral geometries can produce intriguing optical effects.
- E.g. circular birefringence or optical rotation is the rotation of polarization of linearly polarized light as it travels through a chiral material, while circular dichroism is the differential absorption of left-handed polarized (LCP) and right-handed polarized (RCP) light.
- A very strong optical activity may be seen in a metamaterial system consisting of metamolecules that itself are not chiral.



So, let us take this first example of optical metamaterials, which can produce artificial chirality. Now, chirality basically refers to the geometric property of a structure lacking any immediate symmetry plane. So, here is an example. of a chiral object.

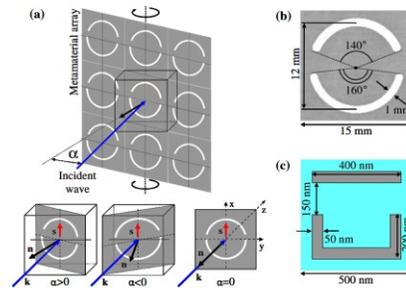
So, if you take your left hand and place it before mirror ok you will see the see your right-hand right. So, if you try to superimpose your left hand and right hand, you will not be able to do that, okay, because of this property called chirality. So, chirality basically exists in many forms in nature, starting from molecules to proteins and to crystals. So, even this particular example shows that we also have chiral objects with us. In contrast, a structure is called chiral if it is indistinguishable or if you can properly superimpose the object on its mirror image.

Now, chiral geometries can produce intriguing optical effects — some really exciting optical effects, such as circular birefringence or optical rotation. Or it is even called polarization rotation, which is basically the rotation of the polarization of linearly polarized light when it travels through a chiral material. And this rotation basically happens because the material has different refractive indices for left and right circularly polarized light. So, birefringence means two different refractive index values, right? It also shows another important property called circular dichroism, which is basically the differential absorption of left and right circularly polarized light. So, very strong optical activity can be seen in the metamaterial system.

Optical Metamaterials: Applications

Artificial Chirality

- Planar metamaterials based on an array of asymmetrically split-rings manifest optical activity and circular dichroism at oblique incidence of light (Fig.(a)).
- The direction of asymmetry is represented by a polar vector s (long to short arc).
- Optical activity is seen when the metamaterial plane is tilted around the x -axis so that the sample normal n and the incident wave vector k form an angle $\alpha \neq 0$.
- Configurations $\pm\alpha$ are enantiomeric arrangements showing optical activity of opposite signs.
- Configuration $\alpha = 0$, i.e., normal incidence, shows no optical activity.
- Unit cell of the metamaterial: an asymmetrically split ring aperture in a 1mm thick aluminum sheet (Fig. (b)).
- Unit cell of the optical metamaterial containing 50nm thick aluminum wires placed on a 500 μm -thick glass substrate (Fig. (c)).



Consisting of metamolecules that themselves are not chiral, but still, because of, you know, the orientations, you can create artificial chirality in it. So, here is an example. So, you take a planar metamaterial that is based on an array of asymmetrically split rings, and when I say asymmetrical split rings, you see the two rings are not identical; one is a larger arc and the other is a smaller arc. So, they can manifest optical activity and circular dichroism at an oblique angle of incidence. So, what happens? Let us first define the direction of asymmetry, which is represented by a polar vector S , as you can see here.

Okay, you can see here as well. So, this vector basically goes from the long arc to the short arc. Okay, optical activity is seen when the metamaterial plane is tilted around the x -axis, as you can see here, so that the sample normal n and the incident wave vector k form a non-zero angle, which is shown here and here. So, this is for the case of normal incidence, okay, but these are the two cases where the sample normal and the wave vector are forming an angle, okay. So, in this case, α is so; here also, you can see α defined like this.

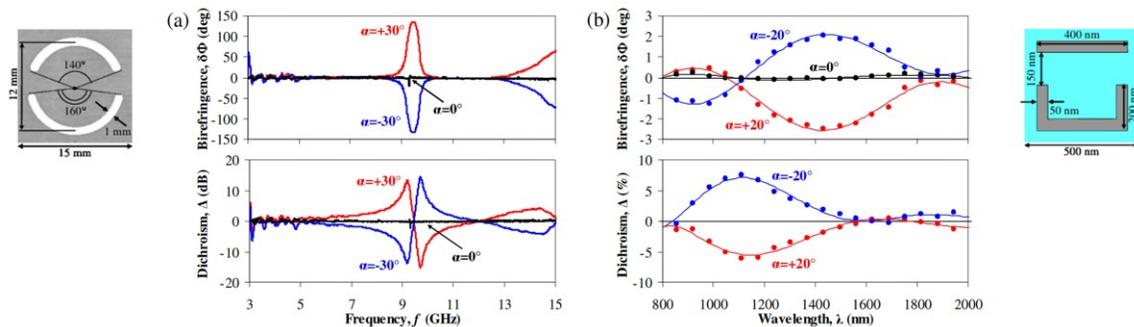
So, here α is positive; here α is negative. So, you are basically getting two configurations, right? So, configurations with plus minus α are called enantiometric arrangements that show optical activity of opposite signs. Right, whereas you take this particular configuration, which is α equals 0, that is for normal incidence, and that will not show any optical activity. Now, this is particularly the unit cell that is used for metamaterials that work in the microwave regime. So, you can see the dimensions are typically in millimeters, okay.

So, this is basically a symmetric split ring structure, which is a complementary structure that means you are basically not making the ring; you are basically removing the portion. So, these are basically complementary structures which are made out of 1 mm thick aluminum sheets. So, you are just making apertures like this, and that is giving you the unit cell. When you want to see the same thing in optics or optical frequency, you are going to make optical metamaterial. So, you

have to work with a glass substrate that is typically 500 microns thick; this is the periodicity, and all the parameters are now on the order of nanometers.

Optical Metamaterials: Applications

Artificial Chirality



Circular birefringence ($\delta\phi$) and circular dichroism (Δ) observed in transmission for different tilt angles : (a) microwave metamaterial (measured in an anechoic chamber using broadband horn antennas and a vector network analyzer) and (b) photonic structure (measured in a microspectrophotometer using linear polarizers and a superachromatic wave plate).

That is where the optical wavelength lies. So, you start with a 50-nanometer-thick aluminum wire, which is placed like this to form your asymmetrical arcs, okay. So, here are the results of this particular structure. So, first we will discuss the left one. So, it shows circular birefringence, which is $\delta\phi$ in degrees, and also the dichroism, which is Δ given in dB, which are observed in the transmission for different tilt angles.

So, we considered here α plus 30 degrees and α minus 30 degrees, and for reference, the non-tilted case of α equals 0 is also shown right. So, this is for the microwave metamaterial, which is measured in an anechoic chamber using broadband horn antennas. You can see the range of frequencies, and this is detected using a vector network analyzer (VNA), right? And on the right side, you see the photonic structure. So everything now is for optical metamaterials. So you are basically looking at a wavelength range starting from, say, 800 to 2000 nanometers.

Okay. So this structure is of the unit cell; it is measured in a micro spectrophotometer using linear polarizers and a super achromatic wave plate. So here also you can see that α equals 0 gives you a flat line with no birefringence, but for α plus 20, that is the red ones, and α minus 20, the blue ones, you can see birefringence, and also you can see dichroism happening. So, with that, we move on to the next application of optical metamaterials, which is also very, very exciting, and that is cloaking. So, as I mentioned in the previous lecture, you can make artificially structured metamaterials that have enabled unprecedented flexibility in manipulating electromagnetic waves, and they can produce new functionalities, such as cloak invisibility, based on a concept called coordinate transformation, right? So, this particular figure we have seen

earlier shows you that the first experimental demonstration of a cloak was at the micro frequencies. Now the main idea of invisibility will be in the optical domain.

Optical Metamaterials: Applications

Cloaking

- Artificially structured metamaterials have enabled unprecedented flexibility in manipulating electromagnetic waves and producing new functionalities, including the cloak of invisibility based on coordinate transformation.
- The first experimental demonstration of such a cloak at microwave frequencies.
- However, that design cannot be implemented for an optical cloak, which is certainly of particular interest because optical frequencies are where the word 'invisibility' is conventionally defined.



"An invisibility cloak"



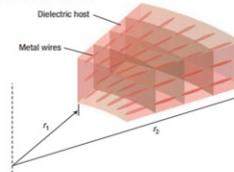
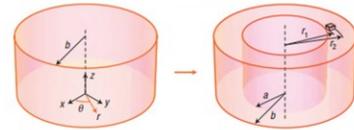
This is also particularly important; the microwave cloaking is also particularly important for stealth applications, which are part of modern warfare. So, here I believe all of you remember that when you keep this solid object within this particular cloak, light rays or microwave radiation are made to go around this object, and they emerge out of the cloak as if there is nothing disturbing in their path. That means this object that you are putting in the cloak is basically becoming invisible. Now, the same design cannot be implemented for an optical cloak. However, optical cloaking and true invisibility cloaking are very, very exciting, and people have been trying this for many, many decades.

So, here is a prediction, or you can say a schematic, of how you want the invisibility cloak to look. So, there is a lady holding a cloak that makes her invisible. In the part where the cloak is covering her body, you can see the tree and the background through it. Okay, so there is nothing blocking the light, and this cloak is very challenging because you need to achieve this cloaking not only at a particular frequency; you have to have it for the entire visible light wavelength range and also for all the angles, okay? So, that makes this invisibility cloak really, really challenging.

Optical Metamaterials: Applications

Cloaking

- The coordinate transformation is used in the proposed optical cloak of cylindrical geometry in which a cylindrical region $r < b$ is compressed into a concentric cylindrical shell $a < r < b$.
- This recipe is similar to the cloak developed in the microwave region.
- A small fraction of the cylindrical cloak where the wires are all perpendicular to the cylinder's inner and outer interfaces, but their spatial positions do not have to be periodic and can be random.
- Also, for large cloaks, the wires can be broken into smaller pieces that are smaller in size than the wavelength.

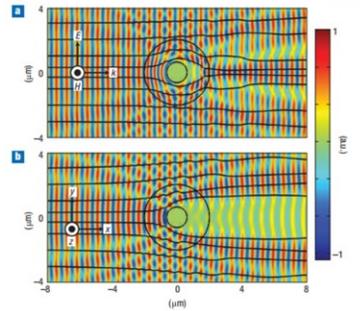
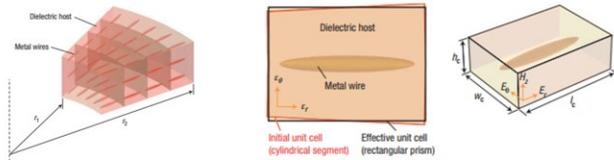


So, if you remember how things were done. So, you need to use the concept of coordinate transformation, which is also part of this transformation optics, and we will go into details later on. But you can see what we are trying to achieve here: the coordinate transformation is basically used in the proposed optical cloak of cylindrical geometry, where the region of the cylinder ranges from $r < b$; that is, this entire thing has to be now mapped within this particular concentric shell, where r is between a and b . Okay, so all these things have to be mapped here, so that means whatever you keep inside will not have any effect on the electromagnetic waves. So, this recipe looks very similar to the cloak that was developed in the microwave regime, right? So, you can also think of it in this particular way: a small fraction of the cylindrical cloak can be thought of where the wires are all perpendicular to the cylinder's inner and outer interfaces, but the spatial positions do not have to be periodic; they can be random. Okay. And for large cloaks, you do not need to have this kind of, you know, continuous wear; you can have the wear broken into small pieces that are smaller in size compared to the wavelength.

Optical Metamaterials: Applications

Cloaking

- The actual unit cell (cylindrical sector) encapsulating a spheroidal silver wire is substituted by a cell made of a right rectangular prism.
- The geometry of the three-dimensional rectangular unit cell. The parameters h_c and l_c are fixed, and w_c changes in proportion to the radius of each layer.



Magnetic-field mapping around the cloaked object with TM illumination at $\lambda = 632.8 \text{ nm}$.

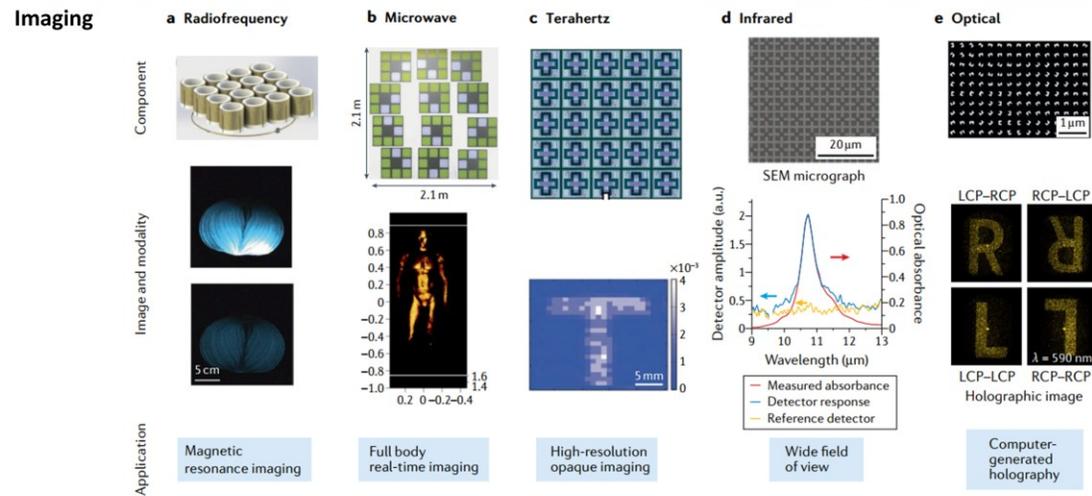
- Fig. (a). The object is inside the designed metal-wire composite cloak where H is the magnetic field, E is the electric field and k is the wave vector.
- Fig. (b). The object is surrounded by vacuum without the cloak. The concentric circles represent the two boundaries of the cloak at $r = a$ and $r = b$, respectively. The hidden object is an ideal metallic cylinder with radius $r = a$.

Okay, so the actual unit cell is the cylindrical sector encapsulating a spheroidal silver wire. Okay, so this is a silver wire in a dielectric host. Okay, so you can look at the geometry like this. So, it is a three-dimensional rectangular unit cell. So, you have the parameters like h_c and l_c , and w_c is basically the width that will change in proportion to the radius in each layer, right? And if you see, the red one shows the initial unit cell, which is basically the cylindrical segment. And from that, you can actually find out what the effective unit cell will be that will give a rectangular prism kind of shape, right? So, here are the results of the electromagnetic simulation that show magnetic field mapping around the cloaked object. So, this is the object that is cloaked.

So, this is basically that cylindrical cloak that has been applied. So, this is under TM illumination, and you see the way the waves are propagating after this cloak; also, the waves propagate in a similar fashion. However, without the cloak that is shown in figure b, you can see that this hidden object, which was actually in a metallic cylinder of radius a , the cloak is not working here. So, it is basically blocking the electromagnetic wave in its path, and it will get automatically detected, right?

So, to illustrate the performance of the proposed optical cloak, These field mapping simulations were performed using the commercial simulation package of COMSOL. So, what it shows is that when you have the cloak, the wave front flows around the cloak and the object, but without the cloak, the waves basically get severely distorted in these regions, and that is why it basically casts a shadow behind the cylinder, right? So, when you put the cloak on, it basically shows the capability of reducing the scattering from the object hidden inside the cloaked region.

Optical Metamaterials: Applications



The next important application is in the field of imaging. So, metamaterials and metasurfaces, which are basically the two-dimensional counterparts of metamaterials, are very useful in imaging applications, and this spans across the electromagnetic spectrum. So, we can start with the first one: the first column. Where you can see radio frequency, okay? So, these are basically metamaterials for enhanced magnetic resonance imaging applications. The upper panel here shows a larger splitting resonator array combined with a varactor diode that is inserted in the gap that serves as a non-linear element to turn on and turn off the resonance of this array.

Okay. So, the middle panel here shows that when you keep an onion sample for MRI (magnetic resonance imaging) on top of these things, the signal-to-noise ratio gets enhanced, whereas if you remove this array, the metamaterial array, the signal is like that. So, you can see the signal-to-noise ratio enhances multiple times. Moving to the next one, you can see a metamaterial aperture for millimeter-wave computational imaging. So, the upper portion of the figure shows a metasurface transceiver panel tilted with both transmitting and receiving metamaterial components. The lower portion shows an image of a mannequin observed using the metamaterial panel in conjunction with computational imaging methods.

So, this is useful for full-body real-time imaging. The next column shows you the complementary metal oxide semiconductor terahertz imager at room temperature, which uses a metamaterial absorber. So, this particular upper panel displays a portion of the imaging array. So, the pixel pitch here is roughly 30 microns, and the lower panel basically shows the image of the letter T, as you can see, that is obtained through an opaque envelope. So, this is used for high-resolution opaque imaging.

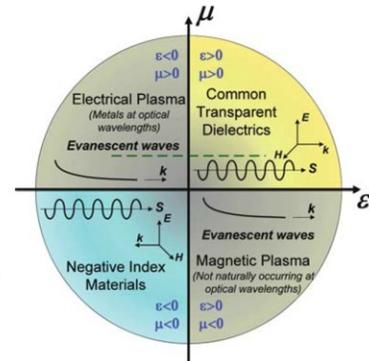
So, you do not need to open up the parcel; you can actually imagine the object inside, okay. The fourth column here shows a metamaterial-enhanced pyroelectric infrared detector. So, the upper panel is basically a scanning electron microscope image of a portion of the detector. Here you can

see the bar that represents 20 microns. So, this is an absorber that comprises a ground plane, lithium niobate, and a metasurface layer.

And this lower panel here shows that the enhanced detector response coincides with the enhanced metasurface absorption. So, with the metasurface, you can have much better detection, and you can also get a wide field of view. Okay, and the last panel here shows multiplexed non-linear metamaterial holography. So, the upper panel shows a region of the metamaterial that encodes the hologram, and the lower panel shows images obtained for different combinations of helicity of the incident light and the detected second harmonic light. So, here you can see left circular polarized and right circular polarized; this one is for RCP LCP, this is LCP LCP, and this is RCP RCP, okay. So, all these different computer-generated holographies with the aid of metamaterials are possible. So, with that, we move on to the classification of metamaterials, which we have already seen in the first lecture, but now, with a better understanding, we will go into a little bit more detail. So, the classification of this epsilon mu diagram is very popular in this field of metamaterials. They represent permittivity and permeability, and the electromagnetic responses of any material can be represented in this particular space.

Classification of Metamaterials — Based on material properties

- The response of a material to external fields is largely determined only by the two material parameters permittivity ϵ and permeability μ .
- An electromagnetic parameter space can be used to classify materials based on these two values.
- The real part of permittivity ϵ_r is plotted to the horizontal axis of the parameter space, while the vertical axis corresponds to the real part of permeability μ_r .
- Therefore materials with all possible combinations of ϵ_r and μ_r can be placed in the parameter space.
- Conventional materials known to be transparent are found in the first quadrant, where both ϵ_r and μ_r have positive values.

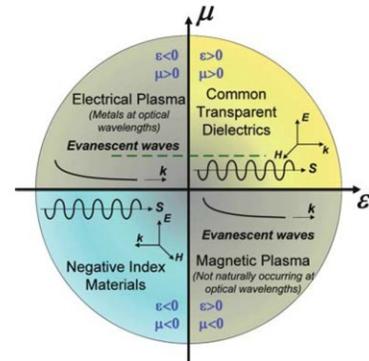


So, we are basically plotting the real part of the permittivity ϵ_r and the real part of the permeability μ_r , okay. So, all the combinations of ϵ_r and μ_r can be placed in this parameter space. The conventional dielectric material typically falls in the first quadrant where both epsilon r and mu r are positive, and we have seen that noble metals like gold, silver, and aluminum are okay. They are the noble metals at optical frequencies, and they are good examples of materials with negative permittivity. They are basically here, and the ones with negative mu can be found in the ferromagnetic medium near the resonance, but there is nothing in this particular regime.

So, what is happening in the second and fourth quadrants? Okay, because you have an imaginary refractive index coming up. So, the waves are basically not allowed to propagate. So, you get evanescent waves, right? So, I believe all of you understand how the refractive index is calculated for epsilon and mu. So, n equals plus or minus the square root of epsilon and mu.

Classification of Metamaterials — Based on material properties

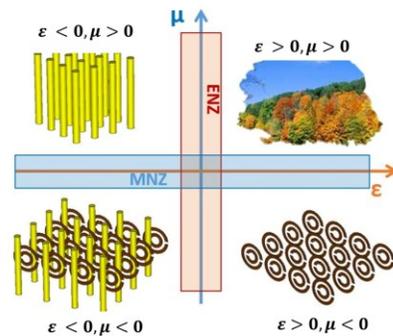
- Noble metals at optical frequencies are good examples for materials with negative ϵ , and negative μ can be found in ferromagnetic media near a resonance.
- No propagating waves can be supported in materials represented by the second and fourth quadrants.
- One of the two parameters is negative and the index of refraction becomes purely imaginary (in second and fourth quadrants).
- In the domain of optics, all conventional materials are confined to an extremely narrow zone around a horizontal line at $\mu = 1$ in the space, as represented by the green dashed line.



Right. So, depending on whether the product inside the square root is positive or negative, you take the positive or the negative square root, right? So, that is what is happening in these two cases. So, when one of the parameters is negative, the index of refraction becomes purely imaginary, and that is the case where you will have only evanescent waves. And in the domain of optics, all conventional materials are confined to an extremely narrow zone that is given by this horizontal line that marks μ equals 1, and that is the case that an optical metamaterial will just work in this particular area. So, once again we have seen this diagram, but just for a quick recap, the top right quadrant where both are positive is called double positive metamaterials or double positive materials. So, these are the most occurring media, such as dielectric, that fall in this category.

Classification of Metamaterials — Based on material properties

- **Top Right Quadrant:** $\epsilon > 0, \mu > 0$ called as double positive materials.
 - Most occurring media (e.g. dielectrics) fall under this designation.
- **Top Left Quadrant:** $\epsilon < 0, \mu > 0$ called as epsilon negative material.
 - In certain frequency regimes ,many plasmas exhibit these characteristics.
- **Bottom Right Quadrant:** $\epsilon > 0, \mu < 0$ called as mu negative material.
 - In certain frequency regimes, some gyromagnetic material exhibits these characteristics
- **Bottom Left Quadrant:** $\epsilon < 0, \mu < 0$ termed as double negative material.
 - This class of materials can only been produced artificially.



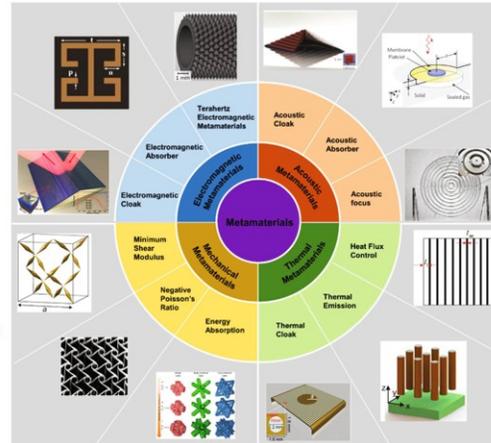
This one has these kind of, you know, quadrants where epsilon is negative. So, you can call it epsilon-negative material. So, in certain frequency regimes, many plasmas exhibit these characteristics; you can think of an array of metallic wires giving you this. But the bottom right quadrant is where permittivity is positive and permeability is negative.

So, if you call it mu negative material. So, in a certain frequency range, some gyro magnetic materials exhibit these properties. And the third quadrant, which is where both epsilon and mu are simultaneously negative. So, you can also call them double negative materials, and this class of material has to be produced artificially. So, this is the true metamaterial section, right? Now, you can also classify metamaterials based on their functionalities.

Metamaterials – Classification based on functionalities

According to their functionalities, currently developed metamaterials can be roughly classified into four categories:

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| <ul style="list-style-type: none"> • Electromagnetic metamaterials <ul style="list-style-type: none"> ✓ Cloaking ✓ Absorbers ✓ Terahertz Application • Thermal metamaterials <ul style="list-style-type: none"> ✓ Heat Flux Control ✓ Thermal Emissions ✓ Cloaking | <ul style="list-style-type: none"> • Acoustic metamaterials <ul style="list-style-type: none"> ✓ Cloaking ✓ Absorber ✓ Focusing • Mechanical metamaterials <ul style="list-style-type: none"> ✓ Energy Absorption ✓ Negative Poisson's Ratio ✓ Minimum Shear Modulus |
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So, you can typically put them in four categories: the electromagnetic metamaterials, as we have described. They can have applications in cloaking and as absorbers in terahertz applications. You can think of acoustic metamaterials. There you can also make acoustic cloaks, absorbers, and devices for focusing acoustic waves. You can think of thermal metamaterials that can control the heat flux distribution, control the thermal emissions, and also perform cloaking. So, you can hide an object's thermal signature or mimic another object's signature, which is also used for thermal camouflage applications that are very important in modern warfare. Finally, you have mechanical metamaterials, which are very useful for impact reduction or energy absorption with a negative Poisson ratio and minimum shear modulus, so a lot of classifications can be done based on the range. In or based on the domain or functionalities where metamaterials are functioning. So, this is called classification based on its functionality. But in this course, we will be focusing only on electromagnetic metamaterials that are particularly working in the microwave and optical frequency range.

Electromagnetic Metamaterials

- The classical behavior and features of electromagnetic metamaterials: negative index, imaging, and cloaking, etc.
- Let's briefly explore some emerging classes of metamaterials—**information metamaterials**, **intelligent metamaterials**, and **quantum metamaterials**—which are paving the way for next-generation applications in advanced communication systems, sensing technologies, and beyond.

Information metamaterials:

- In the classical regime, traditional electromagnetic metamaterials have limitations of fixed functionalities and an inability to control EM waves in real-time.
- To overcome these restrictions, information metamaterials, including digital coding and field-programmable metamaterials, have recently been proposed to enable real-time manipulation of EM waves.
- Information metamaterials enable real-time manipulation of EM waves and direct digital information processing and further realize information perception, understanding, memory, learning, and even cognition.
- At the same time, they also provide a new physical platform to achieve more flexible, real-time, and intelligent EM wave manipulation.

Right. So the classical behavior and features of electromagnetic metamaterials have been seen already. They are giving us a negative refractive index. They are useful for imaging and cloaking. So, other than these classical ones, there are some emerging classes of metamaterials that are called information metamaterials, intelligent metamaterials, and quantum metamaterials. which are basically paving the way for the next generation applications in modern advanced communication systems sensing technologies and beyond.

So, let us look into information about metamaterials. So, in the classical regime, traditional electromagnetic metamaterials have limitations of fixed functionalities; once they are made, they just perform in the same way. And there is no way to control the electromagnetic wave in real time; you cannot change the behavior of the metamaterial. So, to overcome this restrictions information metamaterials which includes digital coding and field programmable metamaterials have been recently proposed that could enable real time manipulation of electromagnetic waves. So, information metamaterials will enable real-time manipulation of electromagnetic waves and direct digital information processing. And further, they will help you to realize information perception, understanding, memory, learning, and even cognition.

Electromagnetic Metamaterials

Information metamaterials:

Digital coding metamaterials:

- Coding metamaterials generally contain a finite number of elements and manipulate EM waves by virtue of discrete coding sequences.
- The initial coding metamaterial consisted of two basic elements with different structural dimensions, corresponding to the coding states "0" and "1" with a 180° phase difference.

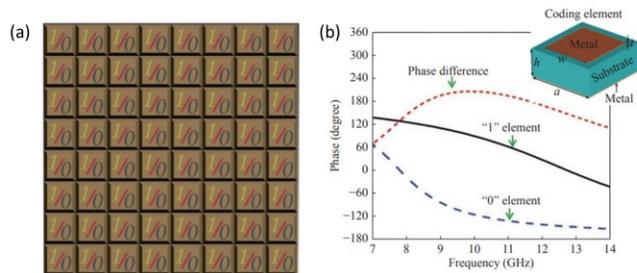


Fig. (a) Schematic of the coding metamaterials containing two types of elements, "0" and "1".
(b) Geometry of the coding element and corresponding 1-bit reflection phases.

So, at the same time, they also provide a physical platform to achieve more flexible, real-time, and intelligent electromagnetic wave manipulation, and that is very important. So, if you take the example of digital coding metamaterials. So, coding metamaterials basically contain a finite number of elements and manipulate electromagnetic waves by virtue of discrete coding sequences. So, the initial coding metamaterials consisted of two basic elements of different structural dimensions corresponding to the coding states of 0 and 1, which means a 180-degree phase difference.

So, here you can see that each element can be either 1 or 0. So, this is the schematic of the coding metamaterial, which has two types of elements, 0 and 1, and this particular B shows the geometry of the coding element and the corresponding 1-bit reflection phases. So, this is the phase of the 1 element over the frequency range, and this is the phase of the 0 element for this frequency range, and this is their phase difference. Okay, so this particular inset shows the coding element, which is mainly a square metallic patch on the top layer, and it has a dielectric substrate in the middle layer; again, there is a metal ground plane on the bottom layer. So, just for information, the substrate has a thickness of around 1.964 millimeters with a dielectric constant of 2.65, and it has a loss tangent of 0.001. The metallic patch has a thickness of 0.018 mm, a width of W , and a periodicity that is typically A , which is 5 millimeters; this patch is designed with widths of 4.8 mm and 3.75 mm, and that is where the phase difference of approximately 180 degrees is obtained in the broadband. So, here the frequency range of interest is from 8.1 gigahertz to 12.7 gigahertz, where you can have around this. around 180 degrees. So, there is exactly a 180-degree phase difference at 8.7 and also at 11.5 gigahertz, right? So, you can use the patch particle with a width of, say, 4.8 millimeters as the zeroth element, and when you change the width to 3.75 millimeters, that can be used as the one element, okay. So, they can be easily fabricated on a single-layer dielectric board, and you can construct this particular metasurface.

Electromagnetic Metamaterials

Information metamaterials:

Digital coding metamaterials:

- For example, when the coding pattern is all "0" or all "1", a single reflected beam will be generated at the broadside.
- If the coding pattern is set as "010101.../ 010101...", then two symmetrically reflected beams will be generated, as conceptually shown in Fig. (a).
- Four symmetrically reflected beams will be generated if the coding pattern is set as the checkerboard-type distribution "010101 .../101010 ...", as conceptually shown in Fig. (b).

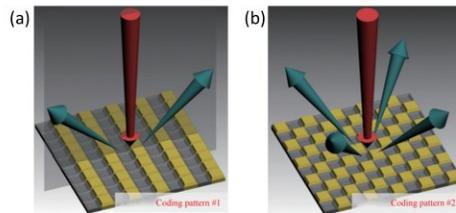


Fig. Schematic of beam scattering under different coding patterns.

So, you can take this further by saying that when you take the coding pattern to be all 0s or all 1s. So, in that case, you can get only one single reflected beam from the board, okay? But if you change the coding pattern to 0, 1, 0, 1. Like that, okay. So, that means you are basically having, you know, this kind of design, okay? So, 0 and then 1, 0 and then 1. So, you are basically getting 2 symmetrically reflected beams generated, and if you change a coding pattern to a checkerboard kind of distribution, in that case, you will be able to generate 4 symmetrically reflected beams. So, the same surface can give you a different optical response in real time based on the coding that you are doing.

Electromagnetic Metamaterials

Information metamaterials:

Digital coding metamaterials:

- One-bit metamaterial structures with periodic coding sequences, and corresponding analytical and full-wave simulation results.
- The coding sequences are (a) 000000.../000000..., (b) 010101.../010101.... and (c) 010101.../101010
- The first row of Fig. shows the near-field distributions on the observation plane normal to the metamaterial.

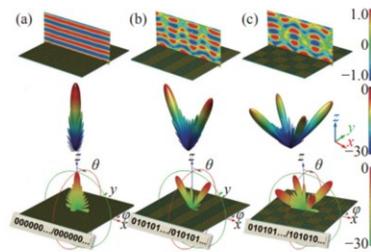


Fig. Near-field distributions and far-field scattering beams for coding metamaterials with different coding patterns.

So, this kind of 0 and 1 possibility is also called a 1-bit metamaterial structure. With periodic coding sequences, they are verified using analytical and full-wave simulations. So if you choose the coding sequence to be all 0, it is like a planar metamaterial of the same element, which is just giving the reflected beams in this direction, okay.

So, this is the near-field distribution in the top row, and these are basically the far-field scattering patterns for different coding sequences. So, when you have 0 and 1 grating, you get 2 beams, and then when you go for a checkerboard kind of design, which is basically periodicity in both the x and y directions, you will get 4 symmetrical beams. Right. So, this is how you can make digitally encoded metamaterial surfaces.



Thank You

So, with that, we will conclude this lecture. We will start the discussion of classification and metamaterials and an overview of the metamaterial technology in the next lecture. Regarding this lecture, if you have any queries, you can email this particular email address, mentioning the course name and the lecture number in the subject line. Thank you.