

Course Name: Introduction to Microwave and Optical Metamaterials
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Week-1
Lecture-2

Lec 2: Introduction to Microwave and Optical Metamaterials-II



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Hello, students. Welcome to lecture 2 of the online course on Introduction to Microwave and Optical Metamaterials.

Lecture Outline

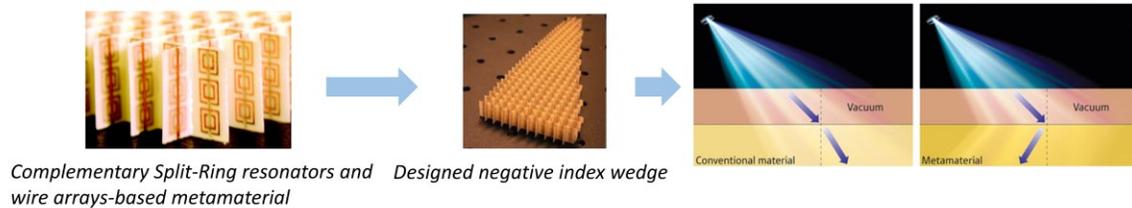
- Microwave Metamaterials: Applications
- Revisiting Metamaterials
- Optical Metamaterials
- Optical Metamaterials: Applications
 - Optical negative index materials
 - Optical magnetism
 - Metalens



So, here is the lecture outline: we will briefly look into the applications of microwave metamaterials that we could not cover in detail in the previous lecture. We will revisit metamaterials and some fundamental concepts again, and then we will move on to optical metamaterials. We will discuss some interesting applications of optical metamaterials, including optical negative index materials, optical magnetism, and metal lenses.

Microwave Metamaterials: Applications

- Therefore, these meta-atoms and their overall arrangements make it possible to achieve medium parameters with extreme values such as:
 - *Zero and Negative*
 - High anisotropies and Inhomogeneities
- Microwave metamaterials: *Working in the range from MHz to 100 GHz*
- Most unusual physical phenomena were first demonstrated at microwave frequencies:
 - **Negative refraction**



So, we have seen that in metamaterials, the meta-atoms play the most critical role.

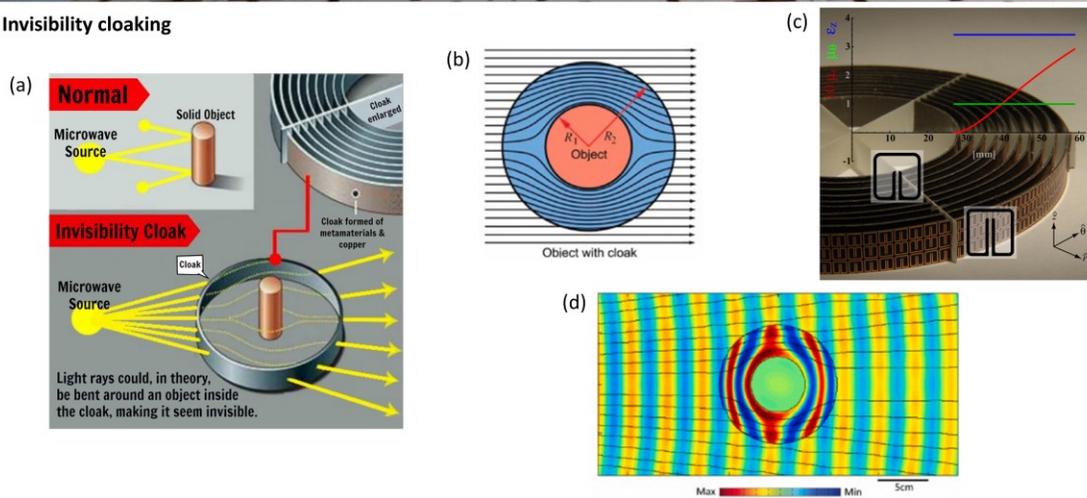
So, the design of the meta-atoms and their overall arrangement in the form of an array can make it possible to achieve medium parameters with extreme values, such as 0 and negative values, whether it is permittivity or permeability. You can also design materials with high anisotropies and inhomogeneities. So when we talk about microwave metamaterials, they are basically working in the range of, you know, megahertz to 100 gigahertz. And the most unusual physical phenomena were first demonstrated at microwave frequencies; as I mentioned, it is easier to perform experiments in this particular frequency range because of the dimensions of the meta-atoms, which are typically in the millimeter range.

So, the effects, like negative refraction, which we discussed briefly in the last lecture, were shown using complementary split-ring resonators along with wire arrays. So, this was a material metamaterial that showed the first negative refractive index. It was also designed in the shape of a wedge. So, this was a negative index wedge and this is what happens when you have a negative index. So, when light falls from a vacuum into this conventional material, it will just bend a little bit, but it will be on the other side of the normal.

So, that is the typical refraction that we know. But when you replace this conventional material with this metamaterial, which has a negative refractive index. So, the light or the electromagnetic wave will bend on the same side of the normal, and it will go in this direction rather than going this way. So, this completely unusual physical property of any material. Other applications include invisibility cloaking.

Microwave Metamaterials: Applications

▪ Invisibility cloaking



So, here you can see that in normal propagation, you have a microwave source and there is a solid object that is visible because of the reflections from the object, okay? But if you want to keep this object hidden from the microwave source, you have to think of a cloak that is made of metamaterial. So, here you can think of a cloak that is basically made of rings of split ring resonators, okay. So, here at least you can see theoretically that light rays can bend around the solid object inside the cloak, and this is how you can make the light rays appear as if there were no object standing here. So, this is another illustration of the ray tracing program that has been used to calculate the ray trajectories when you have an object that is being surrounded by this particular cloak. So, here you have to remember that this R_2 is much greater than the wavelength of the light we are discussing.

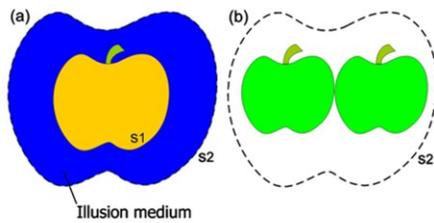
Then, when you realize this using metamaterials, this is typically how a two-dimensional microwave cloaking structure looks. So, here you have the plot, okay. You can see that μ_r , which is basically shown in red, is multiplied by 10 for clarity, whereas you have μ_θ , okay? So, μ_θ is basically the green one, which has a constant value of 1, and ϵ_z is the blue one, which also has a constant value of 3.423, okay. So, what is shown here is that you basically have rings of split ring resonators lined up.

So, this is the structure of the split ring resonator in the inner array, and this is how it looks in the outer array. So, what it does is it basically, you know, guides your rays like this around the object. So, whatever you are putting here in the center is basically getting hidden, right? So this is another snapshot from the time-dependent study. So here you can see these are the electric field patterns with streamlines indicating the power flow, which is the Poynting vector. So here is the object that is being hidden by the cloak. So what was the line, you know, the way the wave was propagating? Because of the cloak, after that, it also propagates in the same way. So, you will not be able to see this object, right? So, it is basically an invisibility cloak. So, invisibility cloaking is possible because of the metamaterials, which require some extreme or exotic values of

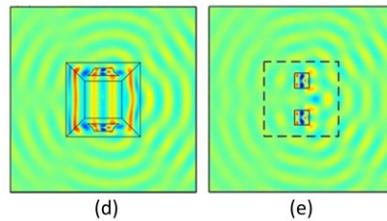
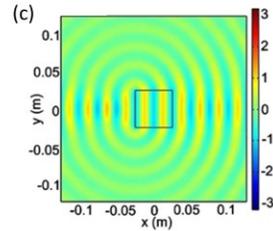
permittivity and permeability. So, in this particular course, we will go into the depth of understanding transformation optics and other concepts relevant to invisibility cloaking, and I will show you how to design those kinds of metamaterials, okay.

Microwave Metamaterials: Applications

Optical Illusion



A simple scheme of an illusion medium layer that transforms the image of an object a golden apple into that of the illusion two green apples .

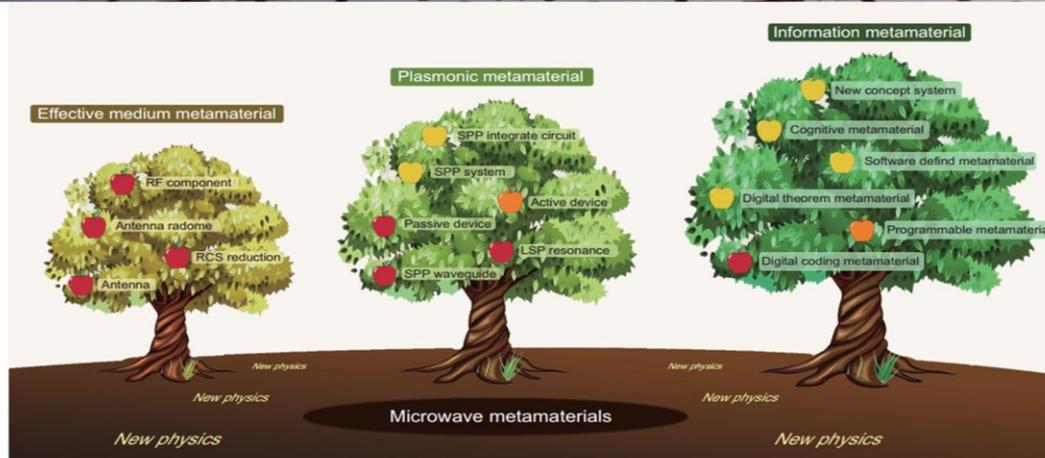


Now, moving forward, there are other applications, like optical illusions. So, here you can see a golden apple, which is the actual object enclosed within an illusion medium, the blue one. And in the physical space. So, what happens is that it will behave as if there are two green apples in the virtual space. So, if you think in other words, the tangential components of the electromagnetic fields of the whole virtual boundary that is S2 will be exactly the same in the physical and the virtual space. So here and here, the overall effect will be similar, and that is how you can match it.

So in this particular diagram, you can see that if you have an object like this in the path of your electric field distribution, you can see this, but when you put this within this particular illusion medium. So, what is inside this is basically a metallic square cylinder, and you are putting it within this illusion, ah, medium layer. So, it behaves as if there are two objects. So, it is creating the same effect as if there were two dielectric square cylinders. So that is also how you can create an optical illusion.

So instead of having a golden apple, you can think of having two green apples, or something like that.

Microwave Metamaterials: Applications Tree



So here are the application areas of metamaterials. So you can see that discovering the new physics has undoubtedly become the most necessary requirement for developing all these new metamaterials. So if you think of effective medium metamaterials, you can design RF components, antenna radomes, RCS reduction, and different new antennas based on that, right? These are some key devices and components that are typically unavailable with traditional techniques, but by using effective media metamaterials, you will be able to design them. When it comes to plasmonic metamaterials, a new surface plasmon-based framework for microwave technology can be set up from the basic transmission lines to systems and also in integrated circuits, which not only compensates for traditional microwave technology but also produces new and irreducible irreplaceable applications.

So, here you can think of creating different active and passive devices, localized surface plasmon resonance, different types of waveguides, and integrated circuits based on plasmonic metamaterials. There are metamaterials that can also be used for digital coding. So, those are also called information metamaterials. So, they have huge potential, as you can expect. So, naturally, the digital coding metamaterials will evolve to be software-defined and cognitive from being reprogrammable, leading to information metamaterials, such as all these different types of tunable structures.

So, information metamaterials will represent a link between the physical sciences and new information science, which will result in many new concepts in information systems. So, in the future, all this belongs to microwave metamaterials; they not only represent a material or a device, but also an overall intelligent system or real-time information processor. So what we have seen till now is that almost all electromagnetic phenomena and devices basically result from the interaction of electromagnetic waves and materials, and in this particular sense, the realization of the electromagnetic functionality—that is, the desired epsilon and mu permittivity and permeability—is meant to manipulate the way waves behave with your structure. the interaction,

right. So, with the myriad of delicate structures proposed and produced by the scientists and engineers over the last decade or one and a half decades or so, the eventual capacity and diversity of the electromagnetic devices, okay.

Revisiting Metamaterials

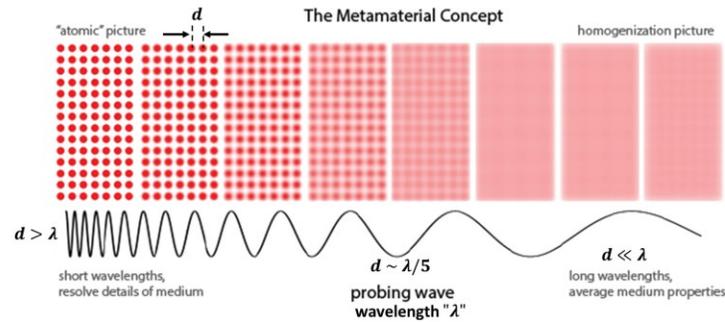
- Almost all electromagnetic phenomena and devices result from interactions between waves and materials.
- In this sense, the realization of an electromagnetic functionality is meant to manipulate the waves in a desired manner by elaborating structures and geometries with available materials.
- With the myriad of delicate structures proposed and produced by scientists and engineers around the world, the eventual capability and diversity of electromagnetic devices are largely limited only by the scope of available materials used to build them.
- Some fundamental constraints do exist that may make a desired property absolutely impossible.
- For example, no medium allows a chain of optical pulses traveling inside it to travel faster than the free space speed of light because of the causality requirement.
- However, many desired electromagnetic properties, similar to the case of monopole magnets, seem to be lacking in nature even though there are no physical laws preventing the existence of such phenomena.

have largely increased because they are not only restricted by the available materials, as we have seen in the previous lecture. So, some fundamental constraints do exist that may make some desired properties absolutely impossible. But then, more or less, you know that without those extreme features, you can right now achieve a good amount of desired properties using a metamaterial concept. So, a few things are not possible, as I mentioned; no medium can allow a chain of optical pulses to travel at a speed faster than, you know, the speed of light in a vacuum because of the causality requirement, okay. However, there are many other desired electromagnetic properties, something similar to the case of monopole magnets, that seem to be lacking in nature, but there are no physical laws that basically prevent such phenomena from existing.

So, those kinds of things you can try, you know, to build in this metamaterial world.

Revisiting Metamaterials

- An approach to realize a novel electromagnetic property is to create an artificially structured composite consisting of well-arranged functional inclusions of subwavelength dimensions.
- Although the unit size of such inclusions is usually several orders beyond the atomic or molecular level of a conventional material, the inhomogeneity scale of these composite structures is still much smaller than the wavelength of interest and their electromagnetic responses can be expressed in terms of homogenized “effective” material parameters.



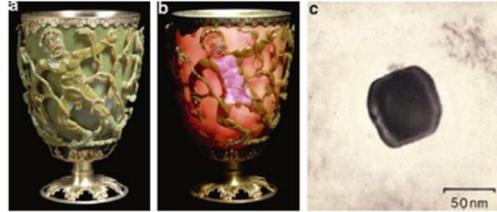
So if you revisit the metamaterial concept, we will see that it is an approach to realize a novel electromagnetic property from the artificially structured composite. And for that, what is important is that you are basically making some functional inclusions in a properly arranged manner. And those inclusions are typically sub-wavelength in dimension. So, although the unit cell size is several orders of magnitude lower than the wavelength, they are beyond the atomic and molecular level of a conventional material.

The inhomogeneity scale of this kind of composite structure is still much smaller than the wavelength. of interest and their electromagnetic responses can be. Although the unit cell of such inclusions is usually several orders beyond the atomic or molecular level of a conventional material, it is still relevant to study. The homogeneity scale of these composite structures is still much smaller than the wavelength of light. The electromagnetic wave of interest and its electromagnetic response can be expressed in terms of homogenized effective material parameters.

So, here you can see that the red dots show the inclusions. So this is where the diameter is much larger than λ . So as you go to this side, your wavelength is increasing, or you can say the inclusions are getting much, much smaller compared to λ . So, in that case, when it goes like that, your wave is not able to resolve the internal structure of the material. So, from here, things are getting just diluted, right, because the feature size of the inclusions is much, much smaller than the wavelength. So, wavelength cannot resolve them. So, you will start seeing a more or less average homogenized property. So, that is why, from the initial red colors, which show some properties of the inclusions, if you keep moving towards the right, you are seeing that you are basically getting a light red color because things are just getting mixed up somewhere. Mixing the red and the white, and you will see that for D greater than λ by 5, you are getting more of a homogenization picture. So, these artificial and functional materials are engineered to fulfill the prescribed electromagnetic properties, and they are called metamaterials.

Optical Metamaterials

- Such artificial, functional materials engineered to fulfill the prescribed electromagnetic properties, usually referred to as “metamaterials.”
- Let us focus our attention on the carefully fashioned structures exhibiting exotic properties at optical frequencies – we will consider optical metamaterials.
- When tracing the history, people started using optical metamaterials deliberately in art pieces without a full understanding of the physics behind the results they achieved.
- A famous example is the Lycurgus Cup exhibited in the British Museum; the Roman glass chalice dates from the fourth century AD.
- The cup was made from probably the first known metamaterial – ruby glass with gold nanoparticles embedded.

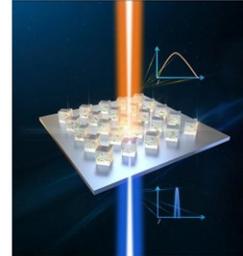


So, with the platform being set up right now, let us introduce and focus on another aspect of metamaterials, which are carefully fashioned structures that exhibit exotic properties in the optical frequency domain and are typically called optical metamaterials. So, when tracing the history, people started using optical metamaterials deliberately in art pieces without even having a full understanding of the physics that resulted in those exciting features. A famous example is the Lycurgus Cup that is still on display in the British Museum. So there, the Roman, it's basically Roman glass from the 4th century AD. So you can see that this cup was made from probably the first known metamaterial, which is ruby glass with gold nanoparticles embedded.

So when you shine light from the outside, the nanoparticles scatter the green light. So you can basically say the cup appears green, but if the light source is inside, those nanoparticles absorb the blue-green light, and what is coming out to you is basically the red light, and that is why the cup appears red. So the same cup looks different because of these nanoparticles being embedded in the glass.

Optical Metamaterials

- The idea of metamaterials has been quickly adopted in the optics community.
- Among all the branches of today's metamaterial research, those materials exhibiting tailored electromagnetic responses at light frequencies, known as optical metamaterials, are by far the most fascinating and most challenging topic.
- *Light is the ultimate means of sending information to and from the interior structure of materials – it packages data in a signal of zero mass and unmatched speed.*
- The burgeoning optical metamaterial research activities are a result of the combination of a wealth of nanofabrication techniques with advances in nanoscale imaging and computational electromagnetic design and simulations.



Optical cuboid resonators

So, the idea of metamaterials has been quickly adopted by the optics community. Among all the branches of today's metamaterial research, you will see that the materials which can exhibit tailored electromagnetic responses at optical frequencies are very fascinating and most challenging as well; this is the domain of optical metamaterials.

Light is the ultimate means of sending information that we have learned. So, anything you can send with light because it can package data in a signal of zero mass and unmatched speed. So, people are always fascinated by what they can do with light. So, with the amount of optical metamaterial research activities going on and with the combination of continuous improvement in nanofabrication technology, a lot of advancements have been made in nanoscale imaging and computational electromagnetic design and simulations. All these things together have made this field very attractive.

So, this is one example of a broken symmetry metasurface that is made of cuboid-type resonators. So, you see the incoming light has a broad spectrum here, but after passing through this metasurface, the beam becomes very spectrally narrow; you can see the sharp blue resonance, okay. So, here is what is happening: the swirling patterns that you can see. The swirling patterns of the arrows show the electric field distribution of the light trapped in these dielectric resonators, and that is what is giving this kind of sharp narrowband transmission. So, these are new features that can be designed based on the metacell, which was the cubic resonator in the previous case, and their arrangement.

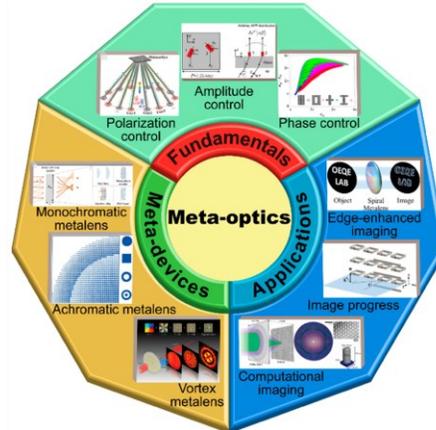
You can put them in a square lattice or any other lattice, and accordingly, their spacing can be controlled so that the properties can be controlled. So, within this rapidly developing and highly multidisciplinary field of optical metamaterials, there are several interesting research directions, such as optical negative index materials, optical magnetism, and meta-lenses. Giant artificial chirality, electromagnetic clocks for invisibility, and imaging. These are gaining a lot of attention,

aren't they? So here is a bird's-eye view of this entire field. Optical metamaterials, which are also known as meta-optics.

Optical Metamaterials: Applications

Within the rapidly developing and highly, multidisciplinary field of optical metamaterials, several key research directions have been emerging, including:

- Optical negative index materials
- Optical magnetism
- Metalens
- Giant artificial chirality
- Electromagnetic cloaks of invisibility
- Imaging



So, the fundamentals tell you that you can have control over the polarization amplitude and the phase of the reflected or the transmitted light, okay. You can make devices such as monochromatic or achromatic metalenses. So, they can be flat lenses with, you know, perfect resolution; we will discuss how they look. You can also think of vortex metalenses, and they can be used in applications like edge-enhanced imaging. Image progress, computational imaging, and so on.

So let us pick them up one by one. So if you think of optical negative index material, you can use a double periodic array of pairs of parallel gold nanorods. Here you can see the operation kind goes in this direction and the opposite in the other gold nanorod. So this can give you a negative refractive index in the optical range. So, you know light normally incident with the electric field polarized along the length of these rods, and you can maintain the magnetic field to be perpendicular, okay. You can see that the electric and magnetic resonances both experience resonant behavior at certain frequencies, right? So, this is how the schematic looks for this array of nanorod pairs.

This B shows the FEM, or the field emission scanning electron microscope, image. So, this is the length scale of 5 microns, and this is the length scale here when you zoom in further, okay, and this is what the elementary cell looks like. Such behavior, which involves electric and magnetic resonances from the plasmon resonance in the pair of nanorods, can give both electric and magnetic components, or this behavior results from plasmon resonance in the pair of nanorods for both electric and magnetic components of light.

Optical Metamaterials: Applications

Optical negative index materials

- A double-periodic array of pairs of parallel gold nanorods has a negative refractive index in the optical range.
- For normal incident light with the electric field polarized along the rods and the magnetic field perpendicular to the pair [Fig.(a)], the electric and magnetic responses can both experience resonant behavior at certain frequencies.
- Such behavior results from the plasmon resonance in the pairs of nanorods for both the electric and magnetic components of light.

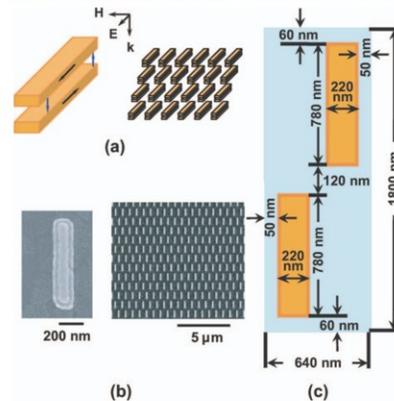


Fig. (a) Schematic for the array of nanorod pairs. (b) Field-emission scanning electron microscope images. (c) Elementary cell.

So, when we talk about plus bond resonance, we are basically referring to surface plus bond resonance, which is a phenomenon that occurs when electrons in a thin metal sheet become excited by light directed at the sheet at a particular angle of incidence and then travel parallel to the sheet. So, when the experiments were done, they could see that a negative refractive index, basically the real part n' , was found to be minus 0.3, and this was achieved at the optical communication wavelength of 1.5 microns, right? So, here is the real n' , which is the real part, and n'' , which is the imaginary part of the refractive index, which is obtained from the simulations, and this is what you see from the experiments. The ones are the simulation, and the circles are basically the experiments. The zoomed version shows that you are actually getting a negative refractive index at a particular wavelength range. So, at 1500 nanometers, n' was recorded to be close to minus 0.3, right? So you are actually able to create a negative refractive index at a particular wavelength based on the design of a unit cell that looks like this. The next important or interesting application is optical magnetism. Normally, all the magnetic materials are non-magnetic at optical frequencies. So, μ_r equals 1, but you can actually have optical magnetism, right? So, optical negative index metamaterials or NIMs, which are also known as left-handed materials, are basically artificially engineered metal-dielectric composites that give you n' negative over a certain range of frequencies, right? In addition, a magnetic resonant behavior should also be observed for these negative index materials at this range. So, the magnetic resonance in any optical negative-index material is always required to make the real part of the effective refractive index negative.

Optical Metamaterials: Applications

Optical negative index materials

- A negative refractive index (real part) $n' = -0.3$ is achieved at the optical communication wavelength of $1.5 \mu\text{m}$ (200 THz).

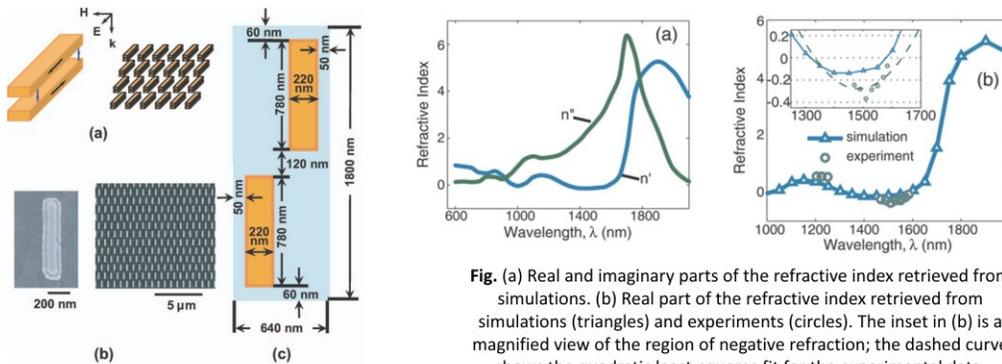


Fig. (a) Real and imaginary parts of the refractive index retrieved from simulations. **(b)** Real part of the refractive index retrieved from simulations (triangles) and experiments (circles). The inset in (b) is a magnified view of the region of negative refraction; the dashed curve shows the quadratic least-squares fit for the experimental data.

So, for that, either you have to have this condition that your μ' is negative, or your ϵ' is negative, or you can follow a more, you know, general necessary condition, which is this one. So, $\epsilon' \mu'' + \mu' \epsilon''$ should be negative. So, this is valid for a passive medium. So, always remember that a single prime denotes the real part of the permittivity or permeability, and the double prime tells you about the imaginary parts. So, how people have actually realized optical magnetism can be seen from this figure.

So, they have taken pairs of thin silver strips this time. So, these are the two silver strips that are separated by a dielectric spacer of alumina. Okay. This offers an easy way to achieve negative magnetism by coupling the near-field modes. So, here you can see the thickness and the width of this, and the strips are separated by a luminal layer of thickness D .

Optical Metamaterials: Applications

Optical magnetism

- Optical negative index metamaterials (NIMs), also known as left-handed materials, are artificially engineered metal-dielectric composites that exhibit $n' < 0$ within a certain range of wavelengths.
- In addition, a magnetic resonant behavior should be observed in NIMs at this range.
- The magnetic resonance in any optical NIM is always required to make the real part of the effective refractive index negative, either through the strong (sufficient) condition $\mu' < 0$ and $\varepsilon' < 0$, or through a more general necessary condition $\varepsilon'\mu'' + \mu'\varepsilon'' < 0$, which is valid for a passive medium.
- Pairs of thin silver strips separated by a dielectric spacer could offer an easy way of achieving negative magnetism by coupling near-field modes.

Which is the width again w , and the refractive index is 1.62, and there is one complex part you might consider, ok, you might 1.62. And you can consider this in the form of a subweb length lattice constant or a grating; you can consider this as a unit cell in a periodic 1D grating.

Optical Metamaterials: Applications

Optical magnetism

- Figure shows a pair of thin silver strips with thickness t and width w .
- The strips are separated by an alumina spacer with thickness d , width w , and a refractive index of $1.62 + 0i$.
- The sub-wavelength lattice constant of the grating is p to be 300 nm with $t = 35$ nm, $d = 40$ nm, and $w = 140$ nm.
- In the resonant (TM) polarization, the magnetic field is aligned with the largest dimension – the infinite length of the strips.

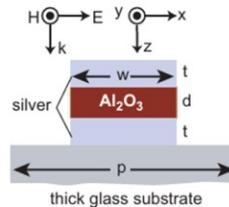


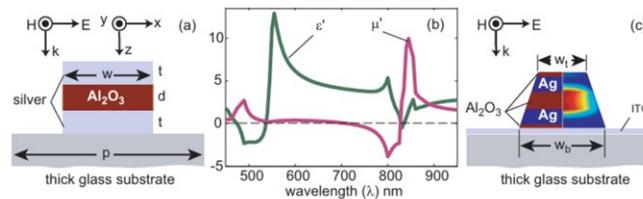
Fig. Unit cell for the array of coupled silver nano-strips.

So, this P is given as 300 nanometers. And these are the other parameters: T equals 35, D , 40, and W equals 140 nanometers, right? And they have considered resonant TM polarizations. So, in that case, the magnetic field is aligned with the largest dimension that is along the infinite length of the strips.

Optical Metamaterials: Applications

Optical magnetism

- In such an ideal sub-wavelength grating Fig. (a), a relatively wide negative magnetic response exists in the TM regime and extends from a wavelength of 720 nm to 825 nm, as shown in Fig. (b).
- Fig. (c) shows a cross-section of the structure adjusted relative to the ideal structure of Fig. (a) in order to reflect fabrication realities.



So, in such a case when you study the response, you can plot the epsilon prime and mu prime for this particular structure, and you see that mu prime gives you a negative magnetic response in the TM regime, extending from typically 720 to 825 nanometers. And this particular figure shows

you the cross section of the structure adjusted in relation to the actual structure when you try to fabricate it. So, it gets a bit tapered, but more or less you get a similar kind of response.

Optical Metamaterials: Applications

Metalens

- Making a perfect lens that produces flawless images has been a dream of lens makers for centuries.
- In 1873, Ernst Abbe discovered a fundamental '*diffraction limit*' in optics: whenever an object is imaged by an optical system, such as the lens of a camera, fine features — *those smaller than half the wavelength of the light* — are permanently lost in the image.
- The loss of information arises because light emerging from the object's fine features carries components with high spatial frequency — that is, evanescent waves that exponentially decay, resulting in an imperfect image.
- The 'lost treasures', as the subwavelength details could be called, are the fundamental reason for Abbe's diffraction limit, which determines the smallest features that one can see through even the best of lenses.
- Practically speaking, this limits the resolution of all the imaging and lithography systems that are the cornerstones of modern biology and electronics.

So, the last important application that we will be discussing today will be metal lenses. So, what is a metal lens? First you have to understand that making a perfect lens that produces flawless images has always been the dream for lens makers for centuries. So, in 1873, Ernst Abbe could discover the fundamental diffraction limit in objects. So, that tells us that whenever an object is imaged by an optical system such as a lens of a camera, fine features that are smaller than half of the wavelength of light, $\lambda/2$, will be permanently lost in the image. So this loss of information arises from the object's fine features because they carry high spatial frequencies.

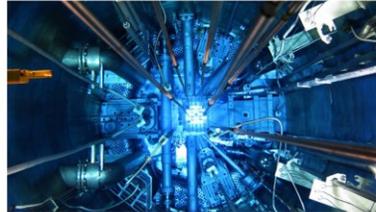
That is, their evanescent waves basically decay exponentially, and that is why you get an imperfect image: because those waves cannot be captured. So the lost treasures, such as these sub-wavelength details, are the fundamental reason for Abbe's diffraction limit, which determines the smallest feature that one can see through the best of the lenses. So, practically speaking, this limits the resolution of all the imaging and lithography systems, which are the cornerstones of modern biology and electronics. So that was the big challenge, and metamaterials helped us overcome this hurdle. So for more than a century, many events and attempts have been made to overcome the diffraction limit.

Optical Metamaterials: Applications

Metallens

- For more than a century, attempts have been made to overcome the diffraction limit.
- In 1967, Veselago raised the question of the physical meaning and feasibility of hypothetical materials with a negative index of refraction.
- He found that in such negative index media (NIM) a number of surprising phenomena occur, such as the reverse equivalents of Snell's law, Doppler shift and **Cherenkov** radiation.

Cherenkov radiation is present, among others, in the water that surrounds the fuel in nuclear reactors. Electrically charged particles moving at very high speeds are a by-product of the reaction inside the reactor.

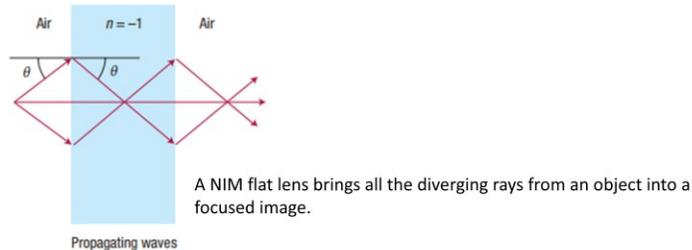


In 1967, Vesela Gord raised the question of the physical meaning and feasibility of these hypothetical materials with a negative index of refraction. So, he could see that in a negative index medium, a number of surprising phenomena occur, such as, you know, the reversal of Snell's law or the Doppler shift. Doppler shift is nothing but a change in the frequency of a wave in relation to an observer who is moving relative to the source of the wave; I believe all of you know this. So, this new phenomenon, this reversal, does not violate the laws of physics, but they are pretty challenging to, you know, realize, and they are counterintuitive, right? Physical perception is also a bit difficult. But if you want to see negative refraction at the interface between a positive and a negative index medium, you should put a negative refraction, okay? So, that can be done by just putting a negative index material here, and you have air on both sides.

Optical Metamaterials: Applications

Metalens

- These new phenomena do not violate the laws of physics, yet they challenge our physical perception and intuition.
- Negative refraction at the interface of a negative and a positive index medium allows a flat slab of NIM to focus all the diverging light rays from an object into two images: one inside the slab and one outside.

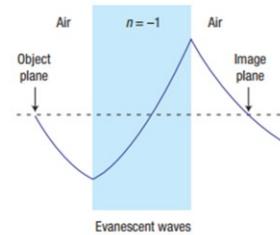


So, you see light enters, and because of the negative index, it comes this way, and you can focus all the diverging light beams. So, these two beams are basically diverging, but because of this negative index medium, you are basically converging them here. So, you can actually form two images: one inside the slab and one outside the slab, right? So, all the beams can now be captured, and that can give you a perfect image, right? So, the light emitted or scattered from an object includes not only the propagating waves, but also the evanescent waves that carry the sub-wavelength details of the object, namely the high spatial frequency components. Now that is what our main problem was: the evanescent waves decay exponentially in any medium that has a positive refractive index. So, they were not being collected by the conventional lens, and that is what was resulting in the diffraction-limited images, right? But if you think of a lens that is basically made of this negative index medium and is placed close to an object.

Optical Metamaterials: Applications

Metalens

- The light emitted or scattered from an object includes not only propagating waves but also evanescent waves, which carry the subwavelength detail of the object.
- The evanescent waves decay exponentially in any medium with a positive refractive index so that they cannot be collected at the image plane by a conventional lens, and this results in a diffraction-limited image.
- But if a lens made of NIM is placed close to an object, the near-field evanescent waves can be strongly enhanced across the lens.
- The NIM can also enhance the evanescent waves across the lens.
- The amplitude of the evanescent waves are identical at the object and the image plane.



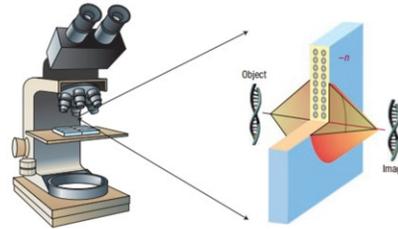
So, what happens to the near field evanescent waves, which were basically decaying, now gets, you know, enhanced. Okay, it was exponentially decaying. So, now they are enhanced, and then further, when they decay, they basically come to the same level as they were in the object plane, right? So, the amplitude of the evanescent wave is found to be identical at the object and the image plane, and that is what is amazing because when that happens, you are basically because of this NIM lens.

Optical Metamaterials: Applications

Metalens

- After emerging from the NIM lens, the evanescent waves decay again until their amplitudes reach their original level at the image plane.
- On the other hand, the propagating waves pass through the NIM lens with both negative refraction and a reversed phase front, leading to zero phase change at the image plane.
- By completely recovering both propagating and evanescent waves in phase and amplitude, a perfect image is created.

A microscope based on an ideal NIM lens should focus both propagating and evanescent waves into an image with arbitrarily high resolution.



The evanescent waves come at the same level, and you can capture that. So, the propagating waves will also pass through this, and when you have both negative refraction and reversed phase front, you are basically leading to a 0 phase change at the image plane, right? So, by completely recovering both the propagating and the evanescent waves in phase and amplitude, you can create a perfect image, and this is a schematic of a microscope based on an ideal negative index medium lens that should focus both propagating and evanescent waves into an image with arbitrary high resolution.



Thank You

So, thank you; that is all for this lecture. If you have any queries, you can always drop an email to this particular email address.