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-3
Lecture-15

Lec 15: Concept Behind Metamaterials

Hello students, welcome to lecture 15 of the online course on the interaction of microwave and optical metamaterials. In this lecture on the concept behind metamaterials, we will be covering the following topics. So, we will look into metamaterials where engineering of the field matter interaction takes place and we will go across metamaterials, how they are built, what are the basic concepts, how do you classify them and also how do you classify engineered materials by size and frequency. So, when we talk about metamaterials, these are basically engineered materials which are allowed to customize your electromagnetic wave and matter interaction right. So, it is basically a structure designed to manipulate how fields you can take electromagnetic fields or even acoustic waves they interact with matter. So you can grasp this concept with a simple analogy.

So you can just imagine standing in a field of tall grass on a breezy day. So you will see that as the wind blows, each blade of grass sways in response to the strength and direction of the wind. So although the wind itself is invisible, a dispersed stream of gas which is the vibrations in the molecules or vibration in the gas molecules you can say, they can exert a force that we all can feel right. Now, a physicist might describe this wind as a vector field which is continuously present throughout space and the motion of grass is a direct consequence of interaction of material with this invisible field.

Lecture Outline

- Metamaterials: Engineering Field–Matter Interactions
- Metamaterials: Basic Homogenization
- The Concept of Metamaterials
- Engineered Materials: Classifications
- Engineered Materials Classifications: By Size and Frequency

Now, this particular image, if you are able to visualize it, can offer a very helpful parallel to many complex phenomena. For example, if you consider a beam of light traveling through glass. So, light here is composed of electric and magnetic fields, okay. And you can consider this as the wind in this particular picture. And the electrons within the glass will act like the blades of grass that you saw in the previous analogy.

Metamaterials: Engineering Field–Matter Interactions

- At its core, a metamaterial is a structure designed to manipulate how fields — such as electromagnetic or acoustic waves — interact with matter.
- To grasp this concept, consider a simple analogy.
- Imagine standing in a field of tall grass on a breezy day.
- As the wind blows, each blade of grass sways in response to its strength and direction.
- Though the wind itself is invisible—a dispersed stream of gas molecules—it exerts a force we can feel.
- A physicist might describe this wind as a vector field, continuously present throughout space.
- The motion of the grass is a direct consequence of this invisible field interacting with matter.

Source: https://people.ee.duke.edu/~drsmith/metamaterials.htm

And these electrons will be oscillating in response to the electromagnetic field. Now, if you could see those electrons, you would be observing them jiggling under the influence of the light. Now, once you understand field matter interaction, it gives you immense opportunities to do useful things with it because now which way you can make your material behave with your incident electromagnetic field to give you a desired response. Just like people have used windmills to extract the energy from the wind by convert it into mechanical motion and then eventually to other forms of energies can be stored and later assist as needed. There are many other types of fields that also can be controlled or harnessed by engineering their interaction with materials.

So, this is where the field of metamaterials will be useful that gives you control over manipulating electromagnetic fields. So, when we take you know materials they are the means by which we can take hold of and manipulate the field which is otherwise invisible right. So, that is where metamaterials belong and they allow you to take things a step further allowing us to create the exact kind of material response we want for a particular application rather than relying randomly on the properties of the conventional materials and compounds which are found in nature. So this is the best thing about metamaterial, it allows you to engineer the material to give you your desired response. Just as we could fashion windmills to produce power from wind rather than trying to use the grass so we can also structure metamaterials to control fields in ways just not possible with conventional materials.

Metamaterials: Engineering Field–Matter Interactions

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So, metamaterials in short you can say that these are basically artificially structured materials that can be used to control and manipulate light, sound and any other you know physical phenomena. When I consider light sound, I am also talking about microwaves and any other electromagnetic radiation, okay? So, all the electromagnetic fields and acoustic fields can be manipulated using metamaterials. So, this particular figure shows you that you can group metamaterials by different professional disciplines. You can classify them as electromagnetic, acoustic, thermal, and mechanical metamaterials.

Ok. Although the first concept of metamaterials appeared in the field of electromagnetism, they were used in forming perfect planes ok. Then some acoustic cloaking, double negative acoustic materials, thermal camouflaging, I am just naming a few we have already discussed the different kind of applications in the initial lectures right. So, here we will try to understand how metamaterials give us a new property which is not a average of its you know structural properties. So the properties of the metamaterials are basically derived from the inherent properties of their constituent materials as well as from the geometrical arrangement of those materials. So what is important here to understand that the physical structure plays the major role in defining how that material is going to behave ok.

Metamaterials: Engineering Field–Matter Interactions

- Materials are the means by which we can take hold of and manipulate what is otherwise invisible.
- Metamaterials take things a step further, allowing us to create the exact kind of material response we want for some particular application, rather than relying randomly on the properties of conventional materials and compounds.
- Just as we fashion windmills to produce power from wind rather than trying to use grass, we can structure metamaterials to control fields in ways just not possible with conventional materials.
- **Metamaterials** are artificially structured materials used to control and manipulate light, sound, and many other physical phenomena.

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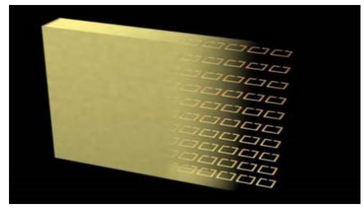
So, for a natural material the atoms decide the overall property in metamaterials you have meta atoms or unit cells which tells you about the overall property. Though there are many structures that qualify as metamaterials, the most common is that of an arrangement of elements or metatoms whose size and spacings are much smaller relative to the scale of the spatial variation of the exciting field. So, this is the main concept, okay? The variation or the size of the spacing of the unit cells should be much smaller than the wavelength of light or any other field it is interacting with. So, in this limit the responses of individual scatterers as well as their interactions can often be incorporated or homogenized into a continuous and effective material parameters. So, you can get epsilon effective and mu effective.

The collection of discrete elements is thus replaced conceptually with a hypothetical continuous material and this is where the concept of metamaterial looks like. So, you basically have a collection of discrete materials, but then conceptually you can think of a homogeneous hypothetical continuous material giving you effective permeability and permittivity. Now, the advantage of this homogenization process. is that sophisticated and complex materials can be engineered sometimes with properties beyond nature, beyond what nature is providing you and it is a simple and intuitive way to do it. So, the metamaterial elements can be thought of as the molecules or atoms of this artificial material that you are designing.

Metamaterials: Engineering Field–Matter Interactions

- The properties of metamaterials are derived both from the inherent properties of their constituent materials, as well as from the geometrical arrangement of those materials.
- Though there are many structures that qualify as metamaterials, the most common is that of an arrangement of elements whose size and spacing is much smaller relative to the scale of spatial variation of the exciting field.
- In this limit, the responses of the individual elements, as well as their interactions, can often be incorporated (or homogenized) into continuous, effective material parameters; the collection of discrete elements is thus replaced conceptually by a hypothetical continuous material.



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and they can be designed and optimized by various kind of numerical methods and simulations and people have developed the skills of making these materials over the years. So, metamaterials provide basically a path to multi-scale design in that the properties of the metamaterial elements will be first determined and an equivalent hypothetical continuous material will be used for subsequent system designs right. So, this fundamental question has generated an enormous amount of discussion in the metamaterial community over the years that how you do the homogenization right. and it has also led to countless arguments and controversies. So, initially a metamaterial was defined simply as an artificial material structured using arrays of macroscopic elements rather than atoms and molecules of conventional material.

Metamaterials: Basic Homogenization

- This fundamental question has generated an enormous amount of discussion in the metamaterials community over the years and led to countless arguments and controversies!
- Initially, a metamaterial was defined simply as an artificial material, structured using arrays of macroscopic elements rather than the atoms and molecules of conventional materials.

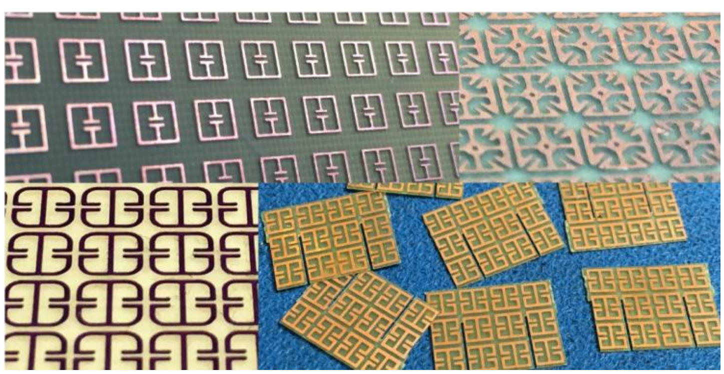

Fig. Different fabricated metamaterials.

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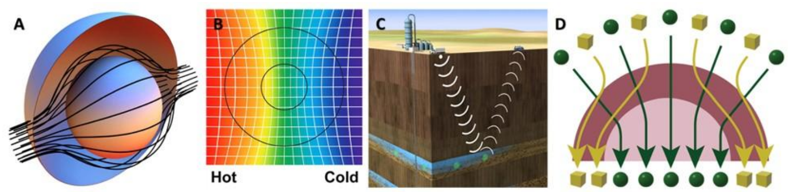
So, these are different pictures of fabricated metamaterials. So, these are the unit cells or meta atoms which are basically having some physical design structur e and this design basically is different from all other designs and they are showing you different property. So, this physical structure is also important; their periodicity is also important, okay. So, they all decide the effective permittivity and permeability of the overall material. So, this is another kind of design.

Metamaterials: Basic Homogenization

- While these macroscopic inclusions are themselves made of conventional matter, their geometric configuration introduces a new layer of influence.
- Unlike natural materials, whose properties arise primarily from atomic-scale interactions, metamaterials derive their unique behavior not only from the base materials used but also from the shape, arrangement, and scale of their structural elements.
- By simply altering the geometry of these inclusions—such as their size, shape, or spatial orientation—researchers can design metamaterials with entirely new functionalities, offering a powerful design lever that transcends the limitations of traditional material science.



IIT Guwahati | NPTEL swayam Source: Smith, D.R. and Pendry, J.B.,Journal of the Optical Society of America B, 23(3), pp.391-403, 2006.

So, you can understand that you can basically change this design change the periodicity and make a material with a effective different effective permittivity and permeability. Now, you must have seen that these macroscopic inclusions are themselves made of conventional matter, right? However, their geometric configuration the way you design it, the way you design the periodicity that introduces a new layer of influence right. So, unlike natural materials whose properties primarily rise from the atomic scale interactions, you will see that in metamaterial devices ok. The unique behavior is basically coming not only from the base material, but mainly from the shape arrangement and the scale of their structural elements. And this is where the physical structure becomes the defining parameter of the overall properties.

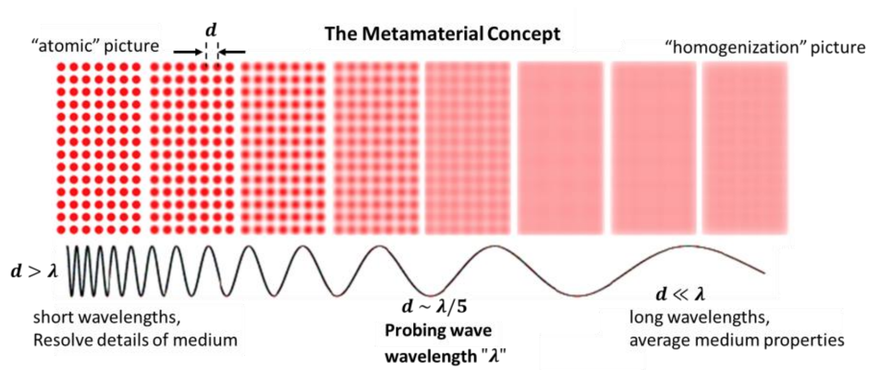
So by simply altering the geometry of these inclusions, such as their shape, size, periodicity, spatial orientation, you can design new-new metamaterials with very unique functionalities and that offers a very powerful design tool that can break all the limitations of conventional material science. So, here I have shown you the figure of four different types of metamaterials. The first one is basically optical cloak which is a three-dimensional cloak that shows you that the light rays can bend around the object and then again converge here in a way that as if this particular object does not exist in the path of the light. So, you will be able to see the things behind this object, and that is how you are cloaking or hiding it. So, this cloak material that the one that you have put which allows the bending of light in a desired direction.

Okay, that is made of metamaterials. In this particular figure, you can see that this is the thermal concentrator. So, it is basically a constant heat source that is applied to the left of the concentrator. The mesh is formed by streamlines of thermal flux vertical and also the isothermal values which are basically the horizontal lines that illustrate the deformation of the transformed thermal space which is squeezed into the central disc over here. Similarly, you can see that there are seismic metamaterials used for sensing.

So, you can have enhanced monitoring of the subsurface fluids and structures something like fractures after injection of some contrast agents that form periodic metastructures. And you can also think of in other field something like mass separation where anisotropic membrane that consists of isotropic cylindrical holes of radius r1 covered by a cylindrical shell anisotropic cylindrical shell which is got a internal radius of r1 and outer radius of r2. So, the two molecules can permeate the membrane where one compound is directed around the core. Okay, and the other one is directed towards the core. So, that way you can actually see that different kinds of metamaterials can be formed.

The Concept of Metamaterials

- An illustration of the metamaterial concept is shown in the figure below, which shows a composite material formed out of some *red dots*.
- The dots might be little plastic spheres, for example, or maybe even molecules, but they are separated from each other by some amount of space.



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So, this is something very similar to this kind of concept not exactly, but the whole idea here is to tell you that metamaterial concept can be used across different disciplines based on your application and the way to construct this materials remain same. And that is why it is very important to understand the concept behind the metamaterials, okay. So, in this particular slide I will show you an illustration of the metamaterial concept which shows the composite material that is basically formed out of some red dots ok. Now, these dots might be little plastic spheres or they may be even molecules which are separated from each other by some amount of space, okay. So, here d is marked as the inter particle separation.

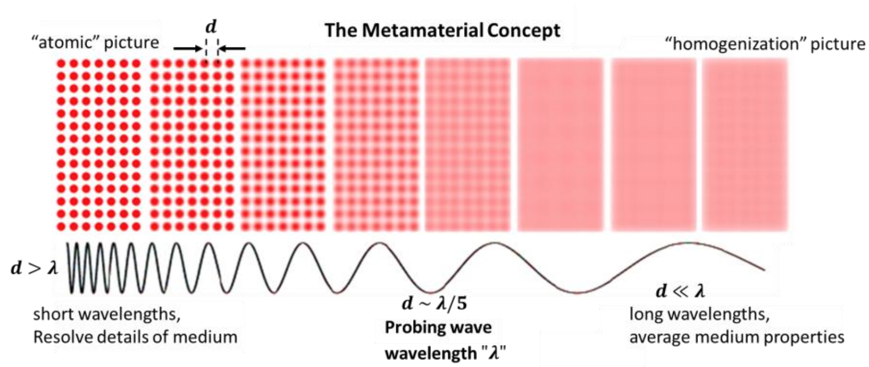
Now, if you have attempt to investigate this material with a wave say light or electromagnetic wave, then the wavelength corresponding to the wave indicates how much of the detailed internal structure we can resolve using that particular wave. So, then comes the wave with which you are going to compare this structure. Now, if the wavelength is on the order of or smaller than the inclusions that is like this, then we do not really see a homogeneous material, we rather see it in this form. We see it in the form of a collection of objects, right? And this is the reason why x-ray which is typically very small to the atomic scale ok or you can say it is comparable the wavelength of x-ray is comparable to the atomic scale ok. You basically see individual atoms and that is why x-ray is used to study the internal structure of materials.

And again, this is because X-ray wavelengths can be smaller than the distances between the atoms, okay. That is there in a solid, and that is why X-rays can see individual atoms. Now, on the other hand, if you go to the other extreme, say where the wavelength is much larger than this periodicity. In that case, what is happening is that the wave cannot resolve the internal structure of the material. Rather, it will see a homogenized picture by assuming an effectively average property of the material.

The Concept of Metamaterials

- If we attempt to investigate this material with a wave (like light or electromagnetic waves), then the wavelength corresponding to the wave indicates how much of the detailed internal structure we can resolve.

- If the wavelength is on the order of or smaller than the inclusions, then we don't really see a homogeneous material but rather a collection of objects.



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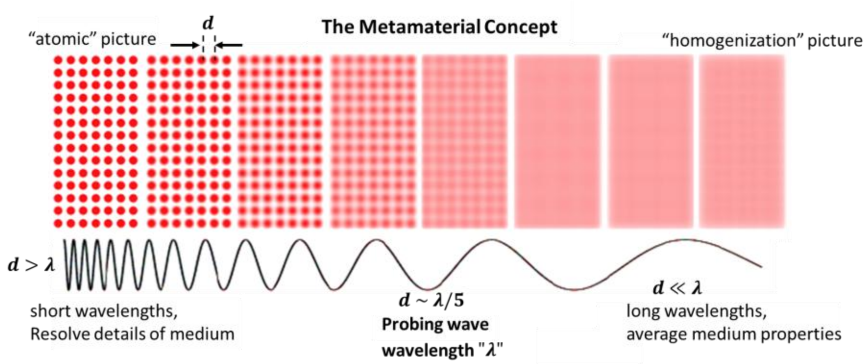
So, clearly you can see the material properties of the inclusions will play some important role in determining the property of this effective medium, but not only the material property their shape and arrangement will also play a important role. So, in this particular illustration, our atoms are represented by red dots, as we mentioned. For electromagnetic waves the red colour must be like indication of say some index of refraction or maybe some other property something like polarizability. And when you see the white region in the figure, that is basically the property of the space; right there are gaps in between. So, to illustrate how the property of the collection of this inclusions get averaged out you will see that what we have done here is to just blur those red dots.

And then eventually you get it mixed with the background, which is white, until you achieve a uniform light red color. So, this is where the homogenization takes place. Right. So, now we understand how you know things are moving on that scale. So, here distinct properties are there every individual atoms are seen here things are getting averaged out.

So, let us analyze this more precisely. So, if we attempt to investigate this material with a wave let us consider the wavelength lambda okay and as we discussed earlier that if the wavelength is smaller than the inclusion that is d is larger than lambda. In that case, the wave is able to see a collection of objects, and here you can also call this an atomic picture. The atoms are represented by the little red dots that you see here. Now, if the interatomic spacing which is d in this case okay, no not d, d is basically the periodicity okay, interatomic space will be this space okay.

The Concept of Metamaterials

- On the other hand, if the wavelength is much larger than the inclusions and their spacing, then the wave cannot resolve the internal structure of the material and effectively averages the properties.
- Clearly, the material properties of the inclusions play a role in determining the properties of the effective medium, but so do their shapes and arrangement.



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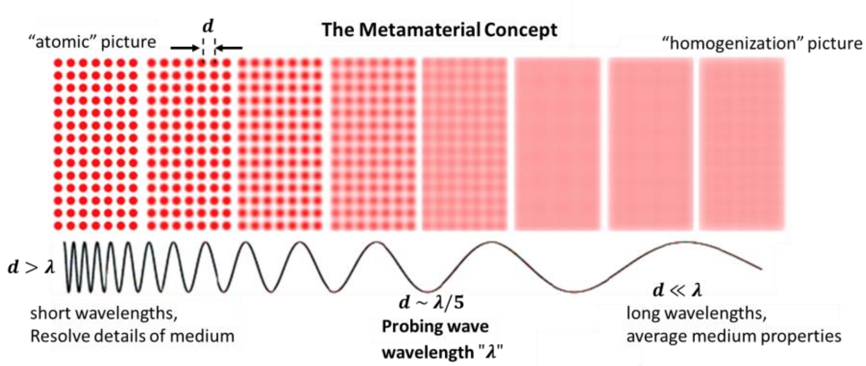
So, this is nothing but d is basically the diameter of the atoms plus the periodicity ok. So, if the inter atomic spacing is again found to be in the order of the incident wavelength, you will see that the resonate the unit cells will start resonating and you will get the concept of resonating metamaterial. Now, on the other hand, if you look from this side, we just saw that if lambda is much larger than D. The wave is unable to resolve any internal structure of this material, and rather it will give you an effectively average property right. So, what happens in between? So, this is where the homogenization picture takes place, this is where the atomic picture is ok, then there is something in between ok.

The Concept of Metamaterials

- On the other hand, if the wavelength is much larger than the inclusions and their spacing, then the wave cannot resolve the internal structure of the material and effectively averages the properties.
- Clearly, the material properties of the inclusions play a role in determining the properties of the effective medium, but so do their shapes and arrangement.



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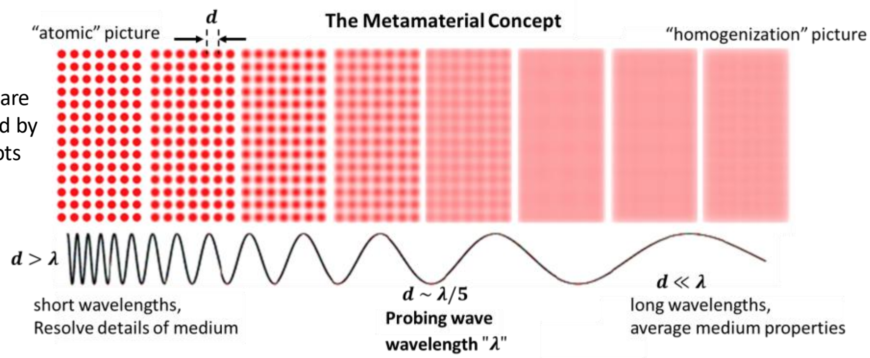
So, what is this in between? If the spacing between the atoms is found to be on the order of the

The Concept of Metamaterials

- Let's analyze more precisely. If we attempt to investigate this material with a wave, then the wavelength 'λ' corresponding to the wave indicates how much of the detailed internal structure we can resolve.

- If the wavelength is smaller than the inclusions i.e. $d > \lambda$, what is seen is a collection of objects *i.e.* an "atomic" picture.

- The atoms are represented by little red dots



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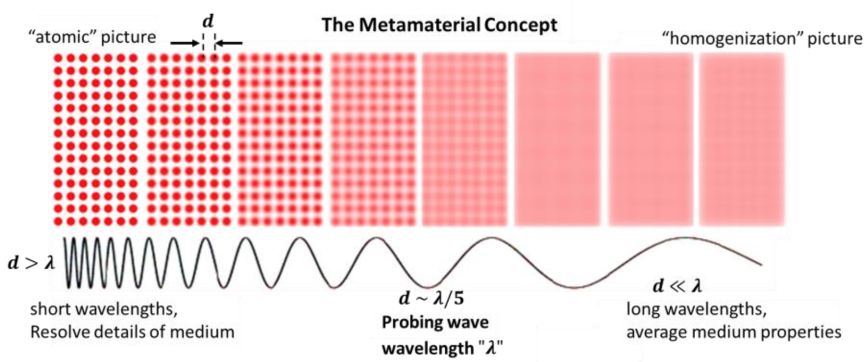
wavelength, then you can say d. is order of lambda by 5, then the properties of the collection of the inclusions will average as we did was to blur the red spot okay. All those red dots were made blurred and then they were basically getting mixed to give you that uniform light red color right. So, it does not look very simple, but it is essentially not very simple, okay. So, the question is can you just average the property of the molecules or some collection of objects, the way an artist can simply blend the colours.

The Concept of Metamaterials

- On the other hand, if the wavelength is much larger than the inclusions and their spacing i.e. $d \ll \lambda$, then the wave cannot resolve the internal structure of the material and effectively averages the properties.

- If the spacing between the atoms is in order of wavelength i.e. $d{\sim}\lambda/5$, the properties of the collection of inclusions average, all we did was to blur the red dots, eventually mixing with the white region until we have a uniform light red color.



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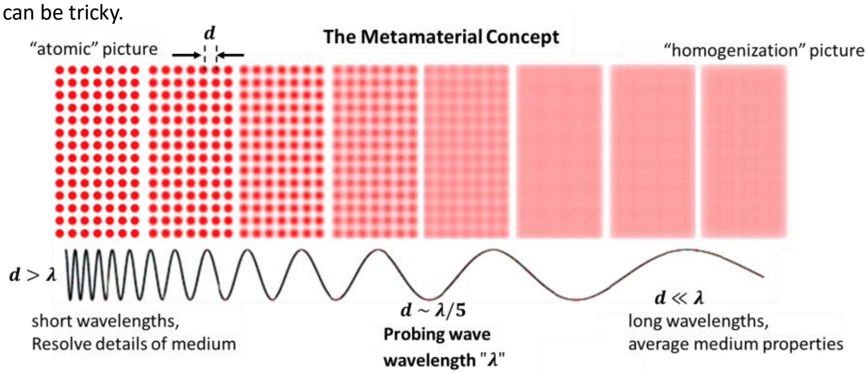
In fact, if you will be wondering that sometimes things become very easy, it is that simple. However, in general, obtaining a homogeneous property from microscopic properties could be a little tricky as well. So, in such cases many researchers have considered this problem which is also known as an effective medium theory or homogenization and that is discussed in different areas of physics. Now, this theories often will take the form of mathematical formulas that apply to fairly specific arrangement of objects such as say a cubic array of dielectric or metallic spheres for example, right. Effective medium theory, you can always try to approximate a periodic array of meta atoms which is nothing but your metamaterials to be represented with effective permittivity and permeability.

The Concept of Metamaterials

- So, is it as simple as that?
- Can we just average the properties of molecules or other collections of objects, the way an artist might blend colors?
- Sometimes, in fact, it's nearly that easy. But, in general, obtaining the homogenized properties from the microscopic properties can be tricky.

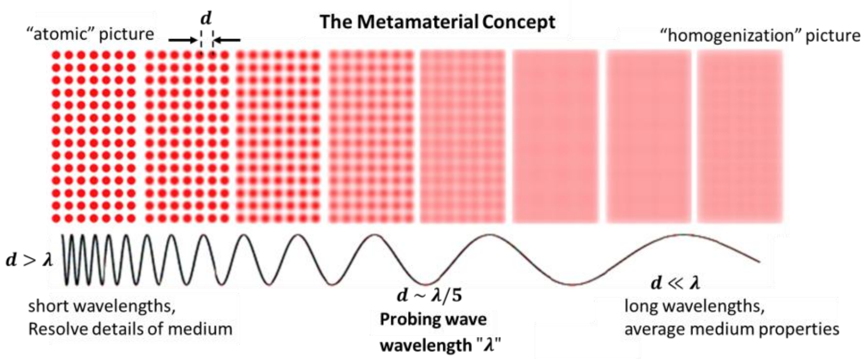


Okay, and that is where the concept of metamaterials will be useful, right? So, what do we require to make this metamaterial concept more useful and usable as an engineering tool? We basically require a technique that allows one to determine the homogeneous properties of any collection of objects or unit cells regardless of their shape and the material composition And we will use this kind of and discuss this kind of engineering tools in the upcoming lectures in this course and we will see how we can use this simple theory to get this kind of homogenization or equivalent homogeneous medium properties from a layer of matter atoms periodically repeated that is basically the matter materials. So, now let us also look into a bigger picture of all types of engineered materials and we will see when we do the classification where exactly metamaterials fit in there. So, engineered materials as you all know are basically materials which are purposely tailored to exhibit some useful and enabling electromagnetic properties. So, you start with ordinary materials which are basically the pure materials found in nature or you can synthesize them in lab okay. Now, based on solely the atomic scale phenomena, you can break them in different sub categories something like conductor, dielectrics, magnetics, absorbers and so on.

You can also take this ordinary materials and mix them up in different proportions and that will be mixtures where the properties are also getting mixed ok. So, you can come you can combine and can get some average properties for the dielectrics, magnetics, absorbers and magnetodielectrics. Now, these two are kind of you can correlate because of average properties are kind of mix match of the ordinary materials properties. But then comes the metamaterial which are basically the composite materials decide to provide some properties which are not at all supported by this two class. So, you can think of resonant type of metamaterial or non resonant type of metamaterials giving you resonant type can give you double positive single negative it can be negative mu or negative epsilon material it can have both negative.

The Concept of Metamaterials

- In fact, many researchers have considered this problem, which is often called "effective medium theories," or homogenization, in many different areas of physics.
- These theories often take the form of mathematical formulas that apply to fairly specific arrangements of objects—a cubic array of dielectric or metal spheres, for example.



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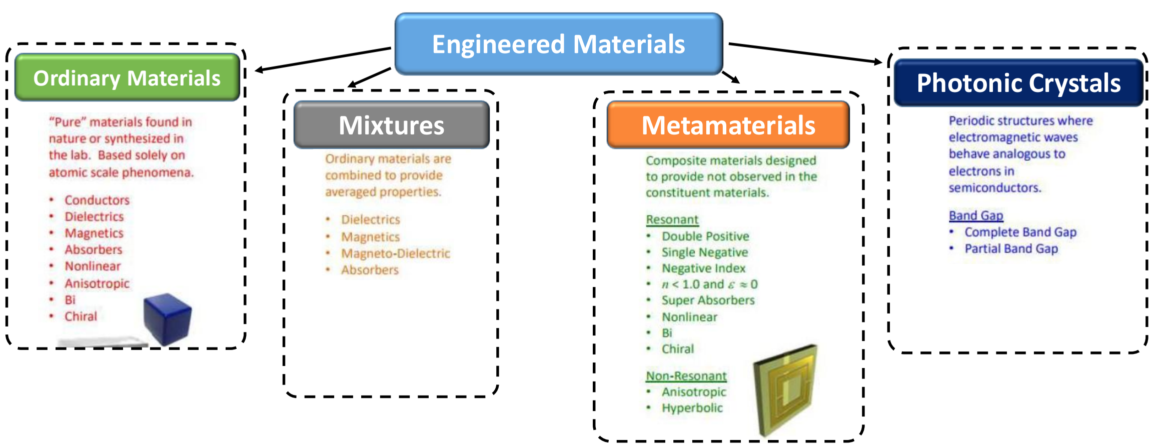
So, you will get negative index material you can have epsilon near 0 material super absorber non-linear bi and chiral kind of material. For the non-resonant type, you can have anisotropic and hyperbolic kinds of materials. So, this is the classification of metamaterials. Again, you can think of photonic crystals. Few people also consider them as a part of metamaterials because these are also periodic structures that, you know, can fine-tune the light-matter interaction, okay.

Engineered Materials: Classifications

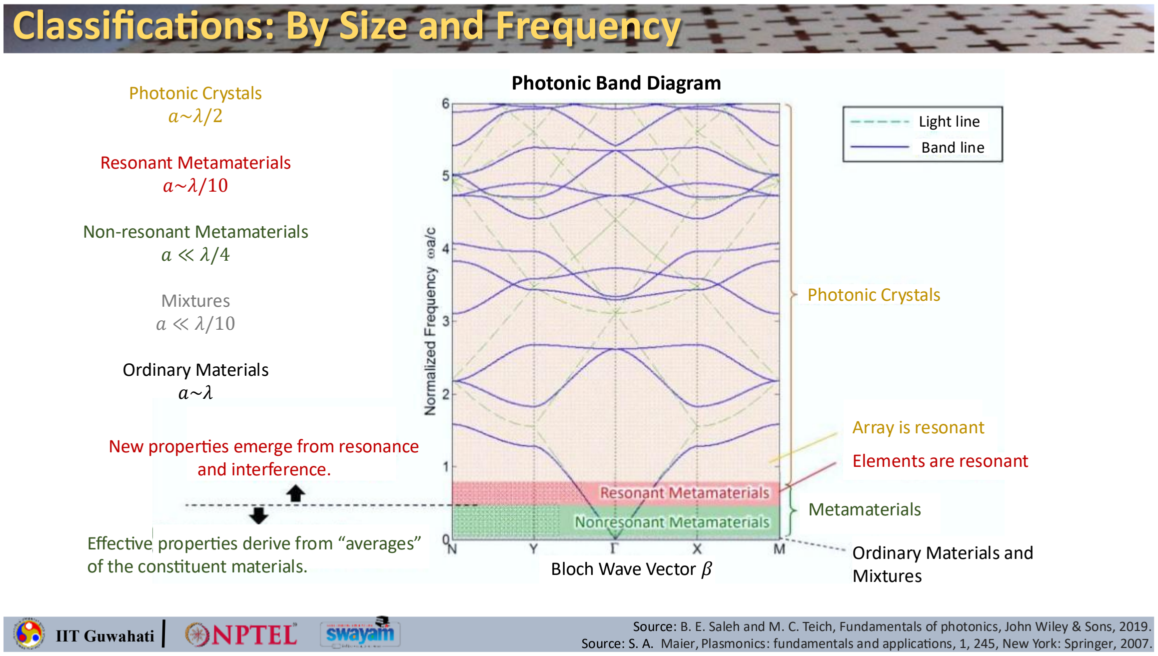
- As discussed earlier, Engineered materials are materials that are purposely tailored to exhibit useful and enabling electromagnetic properties.



IIT Guwahati | NPTEL swayam Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: S. A. Maier, Plasmonics: fundamentals and applications, 1, 245, New York: Springer, 2007.

Here, the electromagnetic waves basically behave in a periodic photonic structure in the same manner electrons behave in semiconductors. So, here you can engineer the complete band gap or partial band gap of this material, okay. So, you are actually able to tune or tailor some properties. So, we can also see the classification by size and frequency, yeah. This particular slide shows you a photonic band diagram in which you have the normalized frequency.

Omega a by c on the y-axis and you have block wave vector b on the x-axis. So, this is typical band diagram ok, but why we are interested here is to see that in the case of photonic crystals, the lattice periodicity a is basically of the order of lambda by 2 ok. So, this is the case of photonic crystals. So, photonic crystals are basically from here to here, okay. Now, when we talk about resonant metamaterials, the periodicity a is of the order of lambda by 10.



So, you can see the resonant wavelengths are kind of here. So, in these particular resonant metamaterials, the unit cells or elements are basically resonating. In the case of photonic crystals, the array is resonating right. So, in the case of resonant metamaterials, what is happening is that the elements or the unit cells are resonating. So, the new properties basically emerge from the resonance and interference between the unit cells.

you also have non-resonant metamaterials where the periodicity is much much smaller than lambda by 4 and that is basically in this region ok. So, here the effective property is derived from the averages of the constituent materials, right? So, this is where your non-resonant metamaterials lie and then you have mixtures where the periodicity is much much smaller than lambda by 10 ok. So, you just mix up the materials, and in ordinary material, you have a periodicity of the order of the unit cell dimensions, right? So, this is where, in this particular diagram, the ordinary materials and the mixtures lie. So, this I believe all of you have seen this earlier that the blue lines that basically tell you about the band diagram. okay and this dashed lines tell you the light line that is if that periodic crystal would have been replaced by a homogeneous medium how you know the bands would have behaved.

So, you can see that the gap in the blue lines is basically telling us about the band gap and so on. But here why I have put everything together just tell you that what is the scale comparable to the wavelength that tells you whether the the the thing that you have made is a photonic crystal or is it a resonant matter material or a non-resonant matter material or it is a mixture or ordinary material okay so this particular relation of the size on the periodicity of the unit cell with The lambda or the wavelength of the interacting light or electromagnetic wave is very important. So, with that, we will conclude this lecture. We will discuss the optical properties of metals and dielectrics in the next lecture. So, if you have got any queries on this lecture, you can drop an email to this email address mentioning the lecture title and the course number on the subject line. Thank you.