Course Name- Nanophotonics, Plasmonics and Metamaterials

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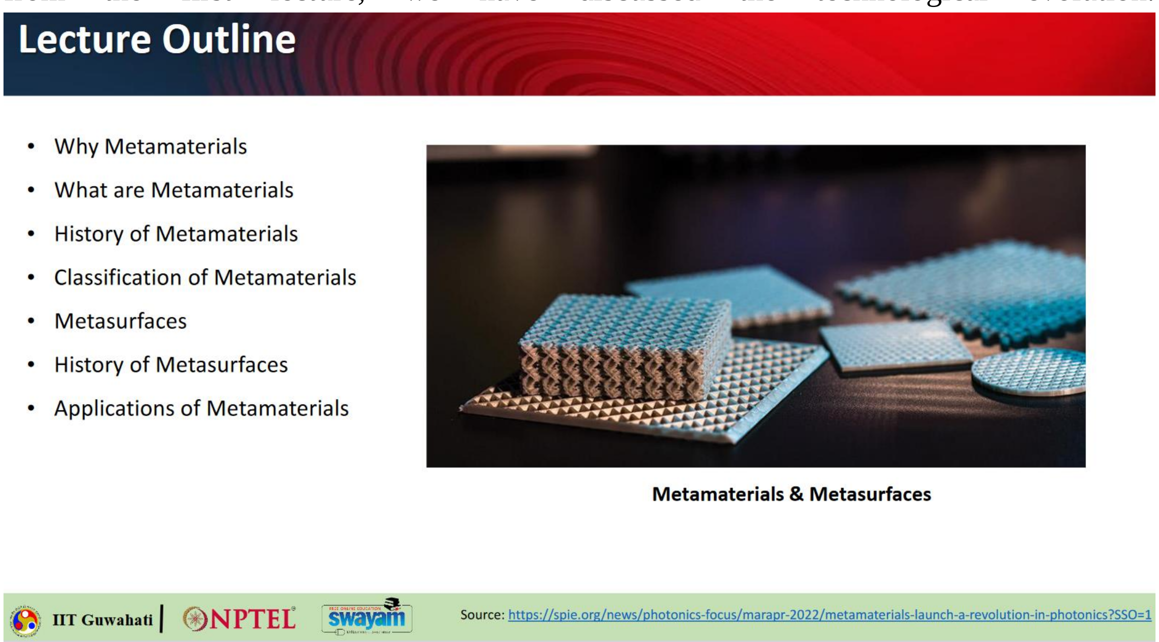
Week-01

Lecture -02

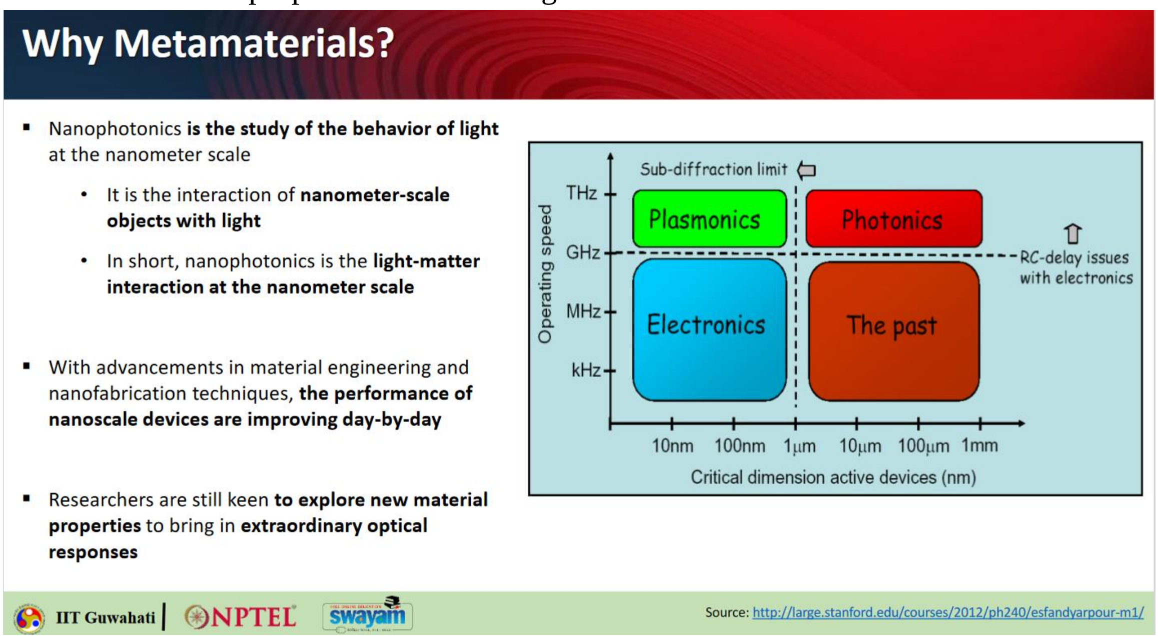
Hello students, welcome to the second lecture of the online course on Nanophotonics, Plasmonics and Metamaterials. In the second lecture, we will cover the introduction to metamaterials and metasurface. So the lecture outline is shown here. We will discuss why metamaterials, what are metamaterials, history of metamaterials, then the classifications, then we will introduce metasurfaces, history of metasurfaces and we will discuss some applications of metamaterials and also if time permits, we will cover some applications of metasurfaces. So this picture shows some typical example of metamaterials and metasurfaces. Why we are studying metamaterials? If you recollect from the first lecture, we have discussed the technological evolution.



We have seen that electronics have done extremely well towards miniaturization of the device dimensions and it can bring down the critical device dimension below 10 nm and that is perfectly fine. That is why the electronic devices are becoming compact and lightweight day by day. But there is a problem with the speed. The maximum speed electronic circuits can go up to is restricted to GHz because of the RC delay related issues with electronics.

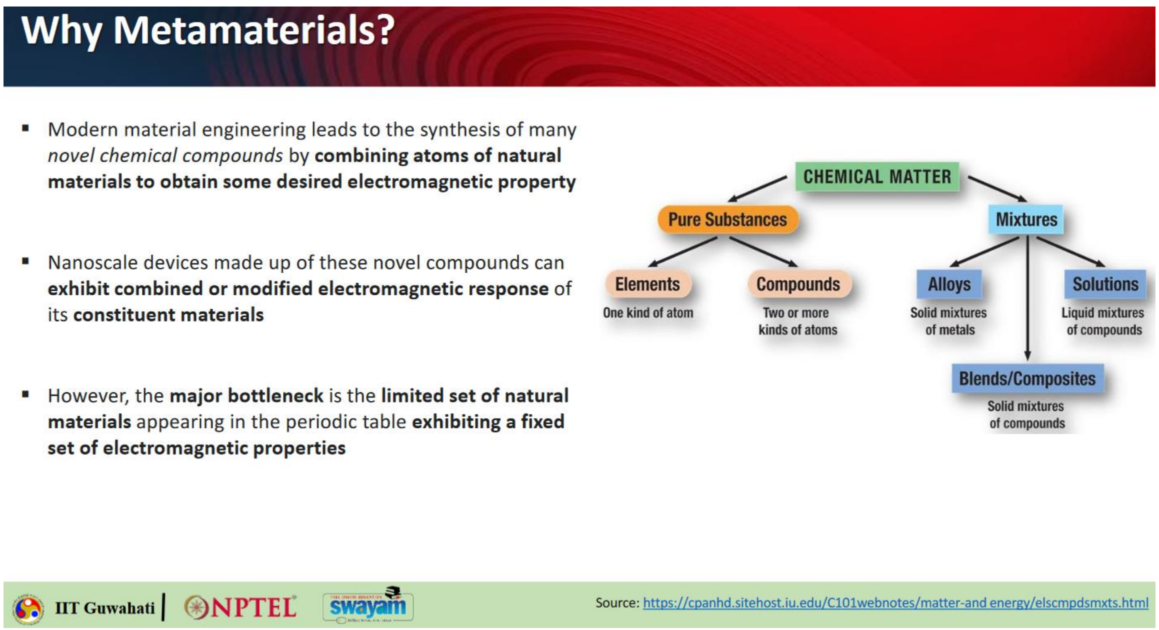
Dielectric photonics have very well, you know, can break this speed barrier and bring terahertz speed on the bench. But then there are problems with dielectric photonics towards the miniaturization of the circuit and that is a fundamental limit called diffraction limit of light. So that restricts the photonic circuits to be miniaturized beyond or below micrometer scale. And that is where Plasmonics actually came into the picture where Plasmonics is a perfect blend of both the electronics and photonics world. And Plasmonics is nothing but a branch of nanophotonics that we have discussed.

So nanophotonics is basically the study of the behavior of light in the nanometer scale. It is the interaction of nanoscale objects with light. In short nanophotonics is basically the light matter interaction at the nanoscale. Now with the advancements in material engineering and also in the nanofabrication techniques, the performance of the nanoscale devices are improving day by day. So, researchers across the world are keen in exploring new material properties to bring in new features on the bench.

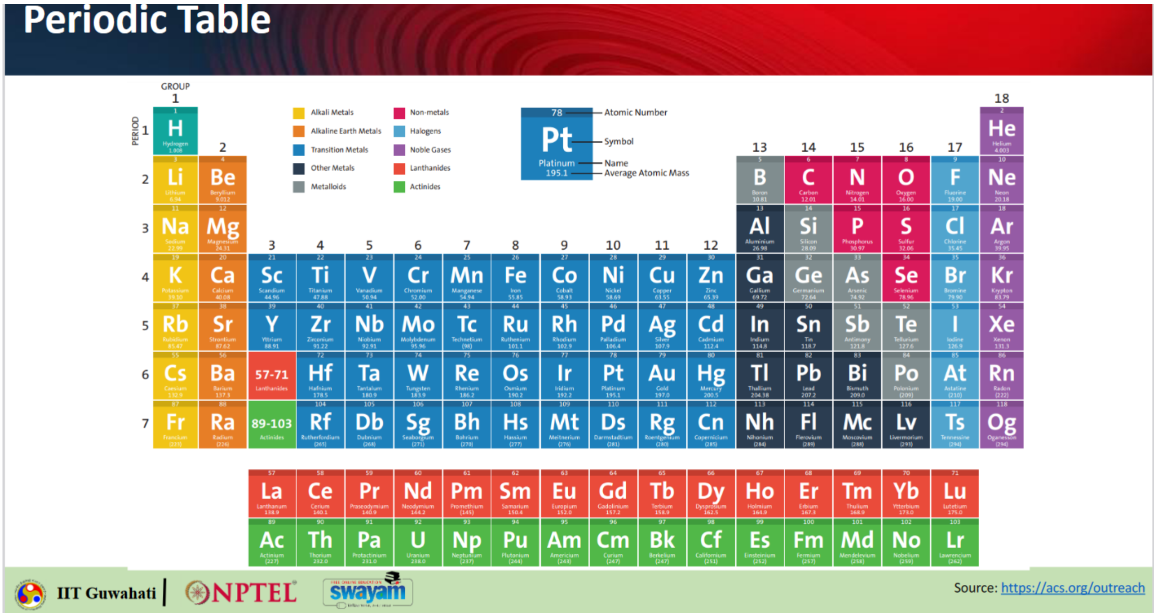


So that is what has asked or tempted people to look for different kinds of combinations of materials. So if you look for modern material engineering, they actually believe in different chemical matters which are made of either pure substances such as pure elements or compounds which are like two or different kinds of atoms or different mixtures such as alloys which are mixtures of metals, solid mixtures of metals, solutions which are basically liquid mixtures of compounds and blends and composites which are solid mixtures of different kinds of compounds. So all in all these are different permutations and combinations of natural materials which are available. And why people have explored all this? They want to get some desired electromagnetic properties from those compounds and that will help them to achieve some exotic applications. Now nanoscale devices made up of all these kind of compounds that we see here, they basically exhibit a combination of the electromagnetic properties or we can say these are like modified electromagnetic properties of their constituent materials.

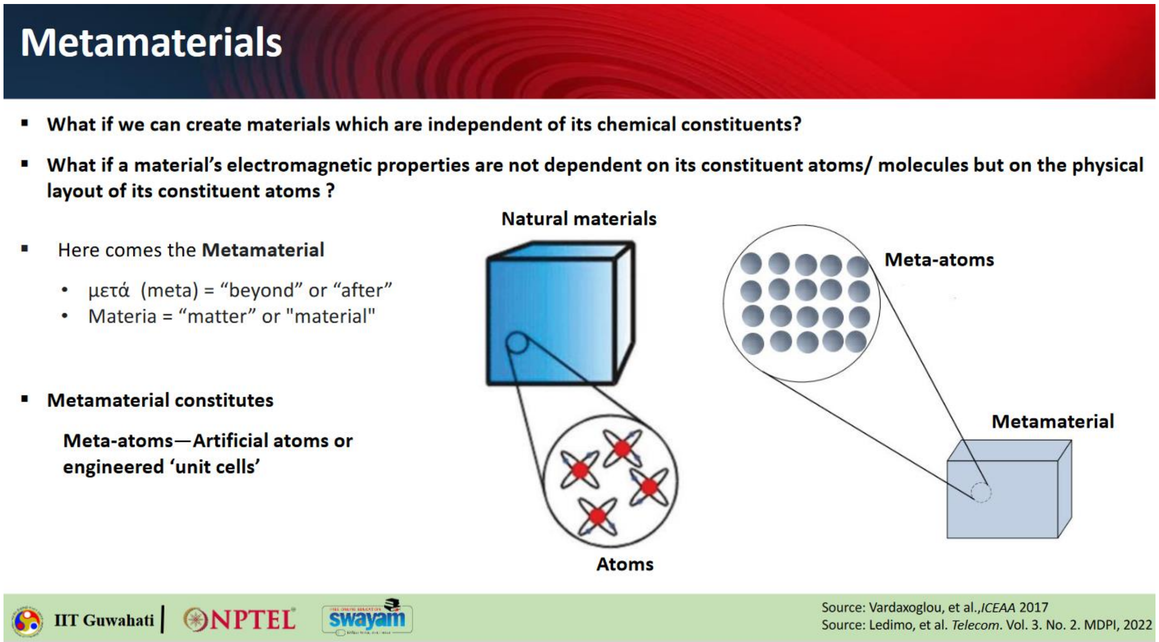
So the chemical composition of the material plays an important role. And in doing so, the main bottleneck or I would say the limiting factor becomes that the set of limited number of materials available to play with. So if you look into the periodic table which you have seen in your school days, out of this only a certain number of materials and their compounds or composites have properties or electromagnetic properties in that particular frequency range of interest. So the set is very limited, not more than 500 or 600 combinations you can try. So, one material can be good at something, not good at another thing and so on.



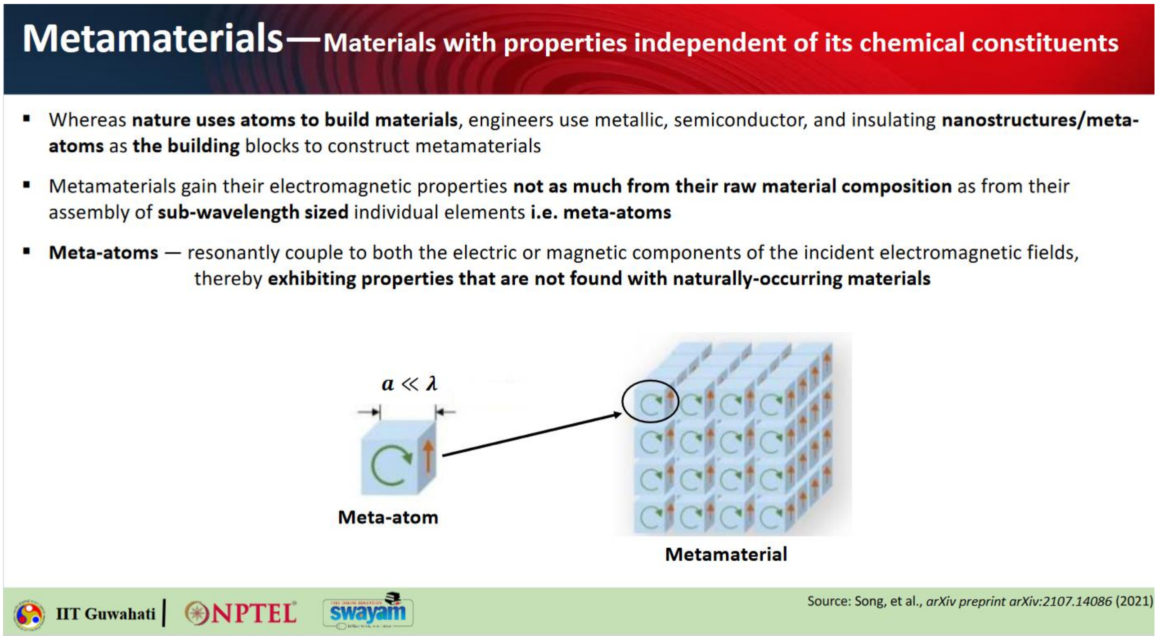
So, property wise there are restrictions and that you cannot overcome. So that is what has actually tempted people to look into metamaterials. Now what are metamaterials? These are like materials we can create on our own, we can design. And their properties are independent of their chemical constituents. So that gives us a lot of opportunity.



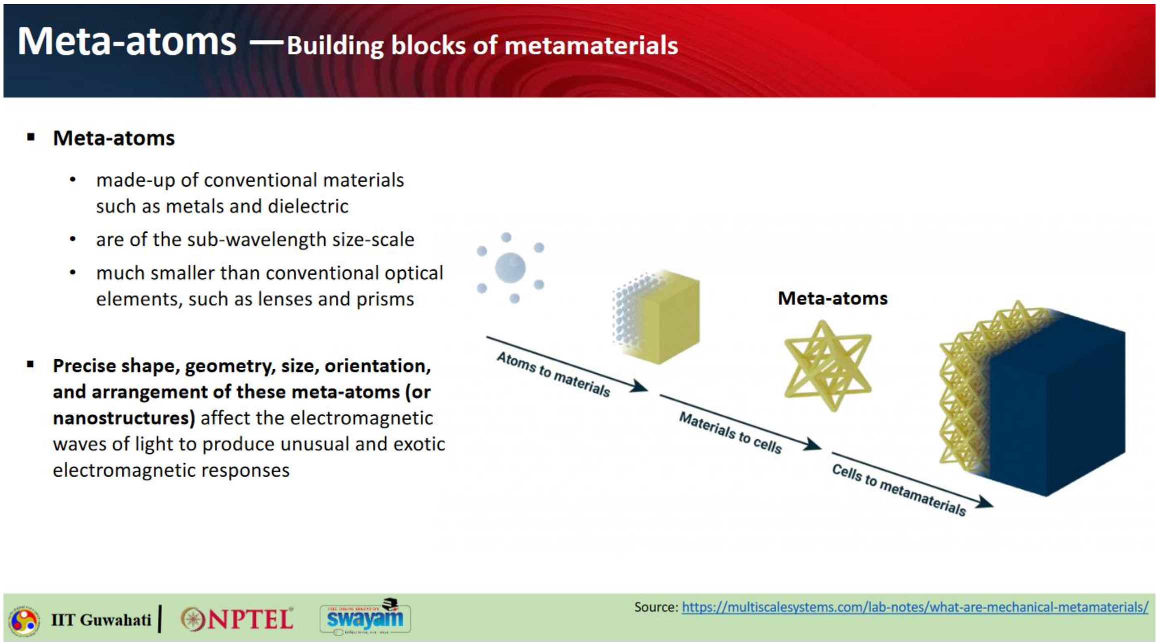
So this is what is interesting in metamaterials that the electromagnetic properties are not dependent on its constituent atoms or molecules but they are dependent on the physical layout of the constituent atoms. So the physical design defines the property of the material. So if you break the name metamaterial in two parts, meta and material, so they have basically come from a Greek word meta which means beyond or later or after and material means, materia means material. So, it is like beyond materials, beyond natural materials. That is metamaterials. So, in short we can say that metamaterials constitutes of meta atoms which are basically artificial atoms or engineered unit cells. Just like the figure shown here, natural materials are made of atoms, metamaterials are made of meta atoms. And you can actually decide what should be the design of these meta atoms. So nature builds materials using atoms, engineers can build metamaterials using metallic semiconductor or insulating nanostructures as meta atoms. So, metamaterials gain their properties not as much as from their raw material composition but mainly from their sub wavelength sized individual elements which are meta atoms.



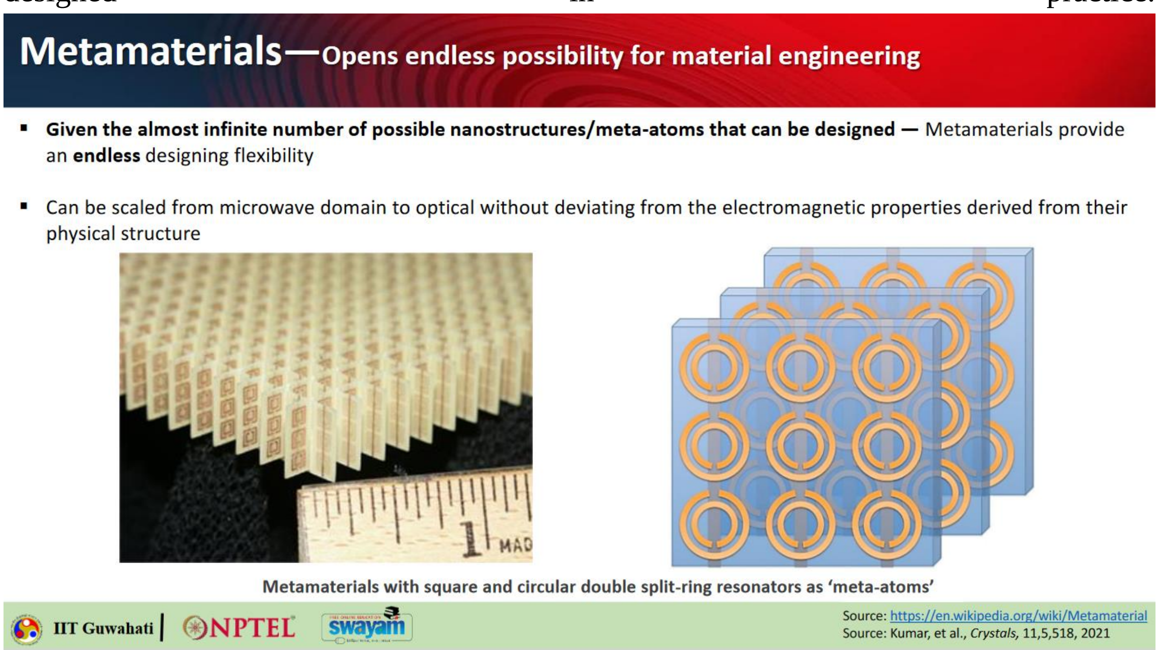
And these meta atoms they can resonantly couple to both electric and magnetic components of the incident electromagnetic field and that is how they are able to bring out some extraordinary properties, electromagnetic properties which are not found in natural materials. So this is a schematic that shows a 3D metamaterial and each of these elements, the building block as you can see which is periodically repeated in three dimension, so each of these building block is having a electric response as well as a magnetic response. And what is the important thing here is the size of this metamaterial is much much smaller than the wavelength of the light that are electromagnetic wave they are interacting with, so that makes them metamaterial. So let us one more time because we understood the properties of a metamaterials are derived from meta atoms. So meta atoms become the most important part.



So what are these meta atoms made of? They are made of the conventional materials such as metal and dielectric which we find in nature that is fine. But then like this you know you have the atoms in from the periodic table you bring them to make your meta atom but the design of meta atom is done in such a way that their assembly which is the metamaterial can bring out some extraordinary properties which are not seen in natural materials and that is how you know you can go from atoms to metamaterials. So remember that these meta atoms are sub wavelength in size scale. They are much smaller than the conventional optical elements such as lenses and prisms. And the precise shape, geometry, size, orientation and arrangement of these meta atoms or nanostructures you can call them as nanostructures as well.



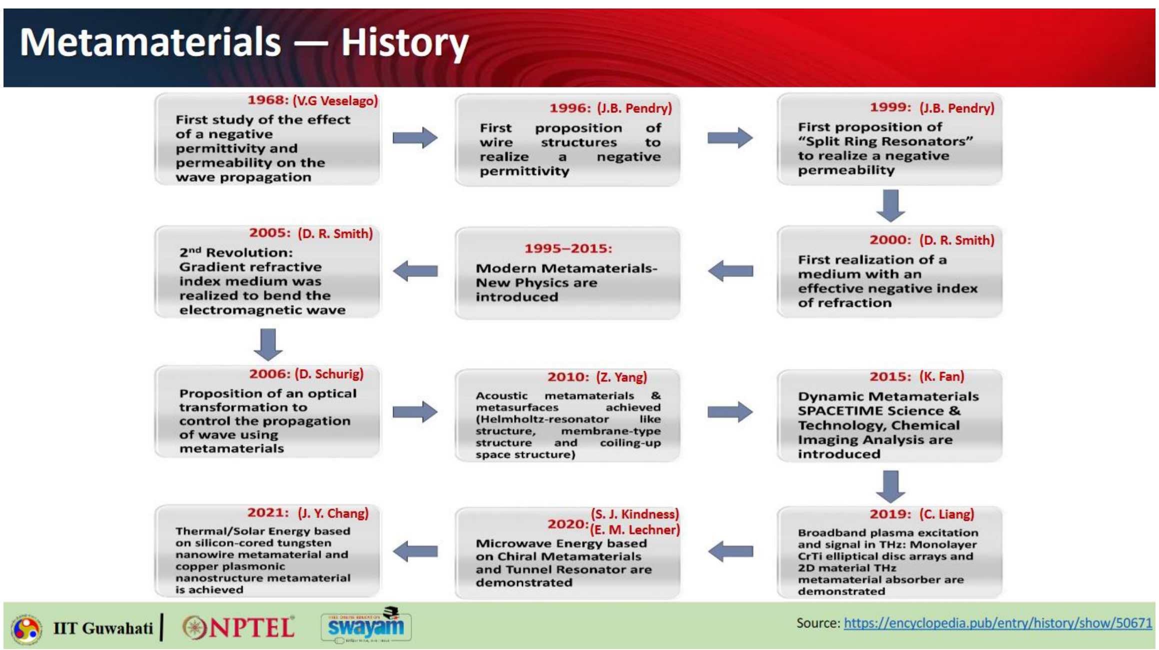
They basically affect the electromagnetic properties of light and give out some unusual and exotic responses. So how many possibilities now we have? How many constituent meta atoms you can think of? 500, 1000, 1 lakh, it is infinite. So you can design using like the normal materials you can design any shape, any structure, any nanostructure that can actually work as a meta atom. So you can think of almost infinite possibilities of nanostructures or meta atoms that can be designed. So that many metamaterials can be designed in practice.



So here are some examples of metamaterials where you can see this one uses a square shape double splitting resonator as its meta atom which is periodically repeated and this one uses a circular shape double splitting resonators as its meta atoms. So each of these will have different properties, different scale depending on the frequency range they are supposed to work on. Frequency range or wavelength scale they are supposed to work on. And this metamaterial concept is same for all the domains. So starting from microwave domain to optical domain.

So you can design metamaterials without deviating from their electromagnetic properties. So one more time the properties of metamaterials are derived from their meta atoms. So whatever you will design that design will decide the electromagnetic properties not the constituent atoms in that design. Because that design say you want to make this kind of split ring. Now if you are making it based on copper so it does not mean that the properties of copper will actually play a major role here.

No the major role will be decided by this circular split rings. But then if you change the material from copper to some other material say gold or silver there will be slight variation. That is why I mentioned that the property of the metamaterial depends mainly on the physical structure not as much on the constituent material. There will be slight deviation if you change this ring from one material to another. But mainly the property that you are seeing of this metamaterial is coming from this double circular split ring kind of structure.



So this is the history of the metamaterials. So it dates back to 1968 when Russian scientist Vesel ago did the first study of the effect of negative permittivity and permeability on wave propagation. And this was followed by Sargent Pendry in 1996 where he proposed first the wire structures that could realize a negative permittivity. So that was kind of artificial material structure where the material structure is deciding the negative permittivity. Then three years later in 1999 Professor Pendry again designed split ring resonator based structure to realize negative permeability.

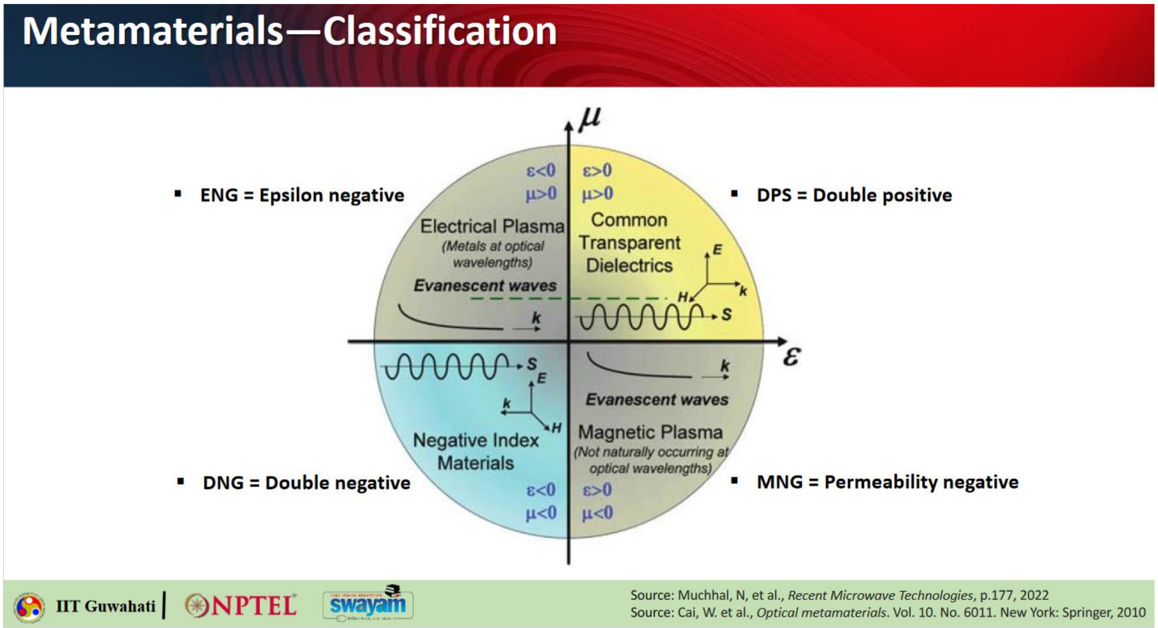
Now when you have negative permittivity and negative permeability both are negative you can actually develop materials which have negative refractive index. Now how these are related refractive index n is square root of mu and epsilon. So when both mu and epsilon are negative you will have negative refractive index. So the first experimental demonstration was done by David Smith's group and they were able to make metamaterials with negative refractive index. So 1995 to 2015 was the golden era or the first revolutionary phase for metamaterials and modern metamaterials, new physics, all these things, metamaterial physics were introduced.

In 2005 David Smith brought in the second revolution in this metamaterial field by realizing gradient refractive index medium. So the refractive index is now changing with space. So there is a gradient and that allowed him to bend electromagnetic waves. So any gradient in the material would allow you to bend the waves. So bending can actually help you explore many new interesting applications.

In 2006 proposition of an optical transformation to control the propagation wave using metamaterial was proposed and demonstrated by Dr. Schurig. So till date things were done mainly in RF and microwave domain and then it entered the optical domain. In 2010 Dr. Yang actually introduced metamaterials to acoustic field or acoustic domain where acoustic metamaterials and metasurfaces were achieved.

In 2015 dynamic metamaterials, space time, science and technology and chemical imaging analyses were introduced by Professor Fan. In 2019 broadband plasma excitation and signal in terahertz were introduced. So that actually brought 2D metamaterials, terahertz metamaterial absorbers. These things were demonstrated by Professor Liang. In 2020 microwave energy based chiral metamaterials and tunnel resonators were demonstrated by Professor Kindness and Lechner.

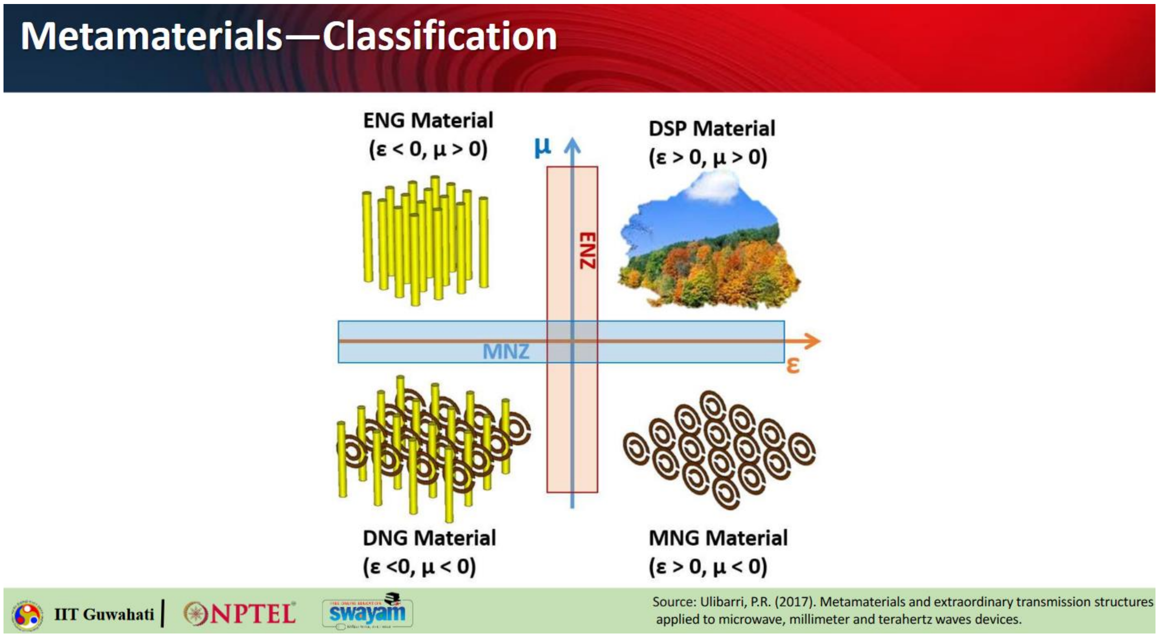
And in 2021 thermal solar energy based silicon core tungsten nanowire metamaterial and copper plasmonic nanostructure metamaterial were achieved. So as you can see starting from 1968 to 2023 a lot has changed in this metamaterial field. From theory, from speculation to experimental demonstration all these things have been possible over the years. Now if you want to understand metamaterials more we got to classify metamaterials. So, the classification of metamaterial depends on permittivity and permeability of a structure.



Now I hope all of you remember from your school days what is permittivity and permeability. So briefly permittivity is the property of the material that measures the opposition offered against formation of electric field. So it is given by this epsilon, Greek alphabet. And it tells the number of charges required to generate one unit of electric flux in a given medium. And on the other hand permeability is related to magnetic field.

So it actually measures the ability of the material to allow formation of magnetic lines of force or you can say magnetic field within the material. So it speaks about the ability of magnetization that material possesses for any applied magnetic field. So once you understand that these are the two properties, now let us actually draw this axis and divide them into four quadrants. So this is the quadrant where both permittivity and permeability are positive.

So these are called DPS materials. So double positive because both permittivity and epsilon and mu are positive. So which materials fall in this category? The common transparent dielectrics can fall in this category. And if you do E cross H you will see the wave propagation happening in this particular direction. So this is the propagation or the energy propagation for the wave that is possible for double positive materials. Now let us move on to this second quadrant where permittivity is negative and permeability is positive.



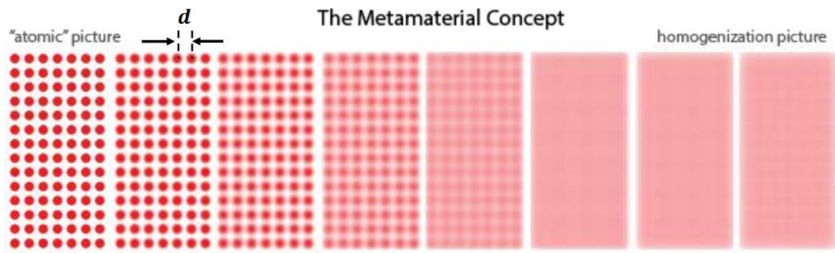
So this is called epsilon negative or ENG material, epsilon negative material. So examples such as metals in optical wavelength, they actually have negative permittivity. So what does it mean? Wave propagation is not possible. So light cannot actually enter a metal, it is reflected back. So it is only evanescent wave that propagates.

And if you think of this quadrant, the fourth quadrant where you can see the permittivity is positive but permeability is negative. So this typically happens in magnetic plasma and it does not occur at the optical wavelength. So you do not have any natural material over here. You can have natural material over here which are the dielectric, you can have natural materials over here like metal but nothing in optical frequency comes to this region. And then comes the most interesting part of metamaterials which is DNG means double negative.

That means permittivity and permeability both are negative. So in this case, you know, E cross H when you do, you can see that the propagation, so the pointing vector is in this direction left to right but the wave will propagate in the opposite direction. So that is the negative index materials and initially only this particular domain materials were called metamaterials. But now the definition of metamaterial is much more relaxed and whenever you are able to make any kind of artificial structure that can give you a property which is customizable or you can change everything at your will, we can call it metamaterial. So, we can see here that this region as we discussed, these are all-natural materials.

The Metamaterial Concept

- 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 dielectric/ metal spheres, e.g., or maybe even molecules, but they are separated from each other by some distance ***'d'***



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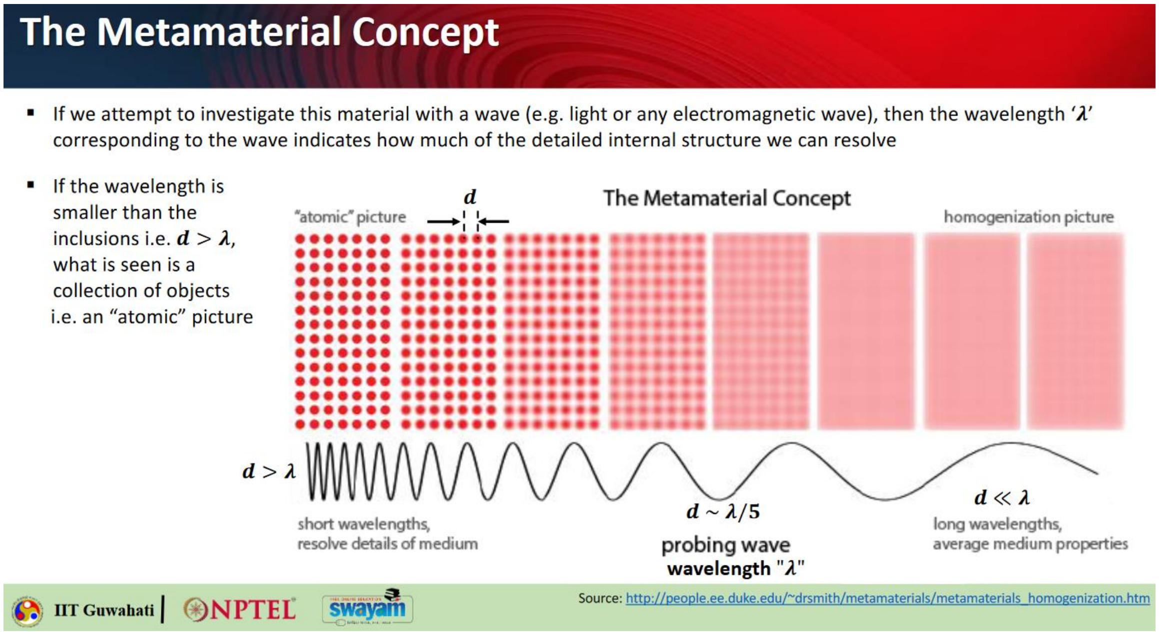
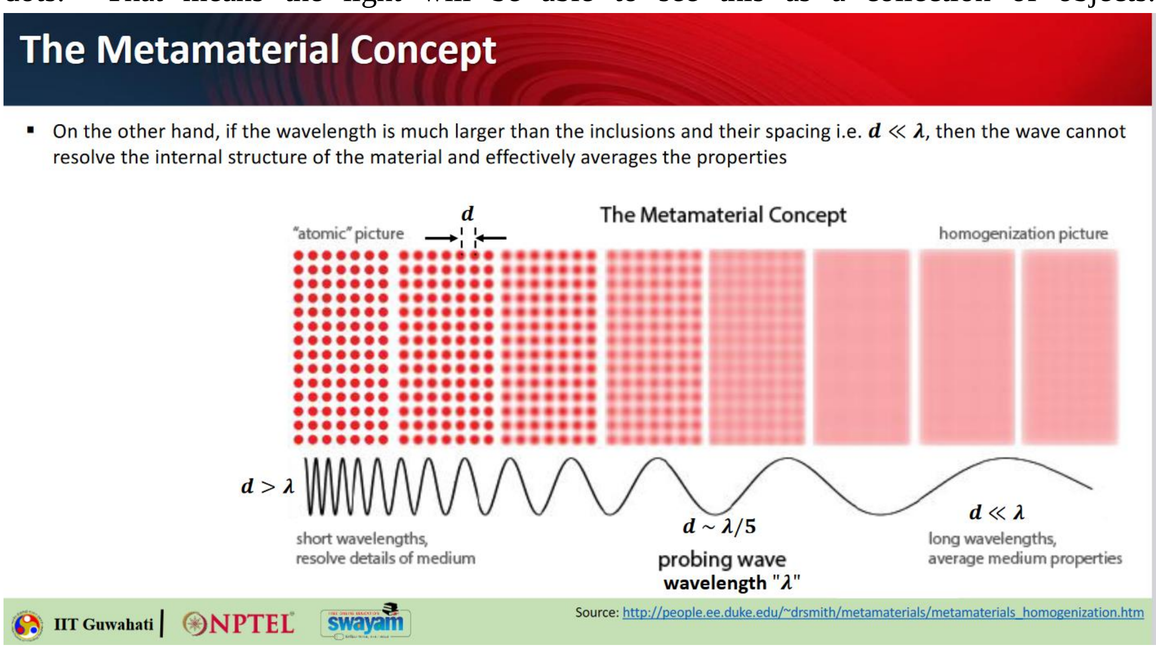
Source: http://people.ee.duke.edu/~drsmith/metamaterials/metamaterials_homogenization.htm

So we have shown a picture of nature. Here you can see, you can actually have an array of metallic rods and that can actually give you a customizable property, negative permittivity but then that property is customizable which depends on the size of this rod and the period of this rod array. So that way you can actually also call this a metamaterial. Similarly, you can have an array of double splittering or double circular splittering resonators and they actually define the negative permeability. So this is also not a natural material but using this kind of structures you can obtain negative permeability. So these things people have shown mostly in microwave region because the size of the constituent materials like this and meta atoms, they are easy to handle.

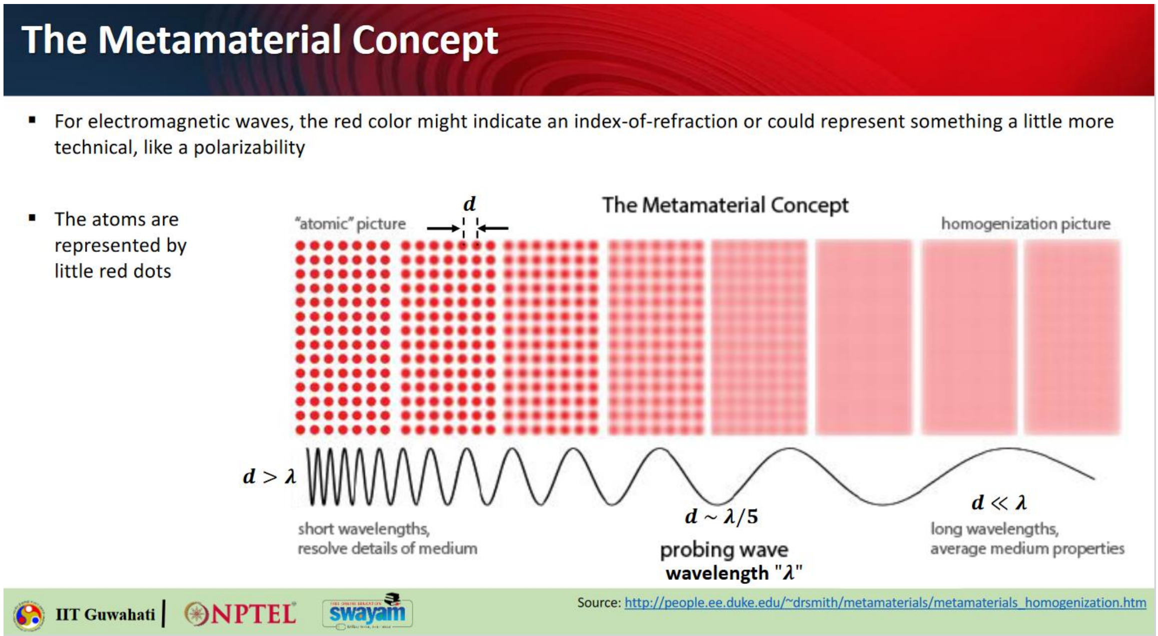
They are in say millimeter or centimeter scale. And when you combine these two together, so this one has got negative permittivity and this one has got negative permeability and when you bring them together as you can see, this is a metallic array of metallic rods with the splittering resonators associated with each of these rods, you can actually get a double negative material. So let us focus on the metamaterial concept, how it works. What is the relationship of the structure or the meta atom with the wavelength of light or electromagnetic wavelength it is interacting with? Now this is an illustration of the metamaterial concept as you can see here. So let us assume that a material is made out of some red dots like this. Now what are these dots? These dots could be little dielectric or metallic spheres or cylinders if you see them from the top view and even molecules and let us assume they are separated by a distance d.



Now you are using some kind of electromagnetic wave to see this. Now depending on the wavelength of light and what is the relationship between this d and the wavelength of light lambda, you will see a different picture. If you assume that the wavelength is much smaller than the inclusions that is d, in that case you will see each of these particular red dots. That means the light will be able to see this as a collection of objects.

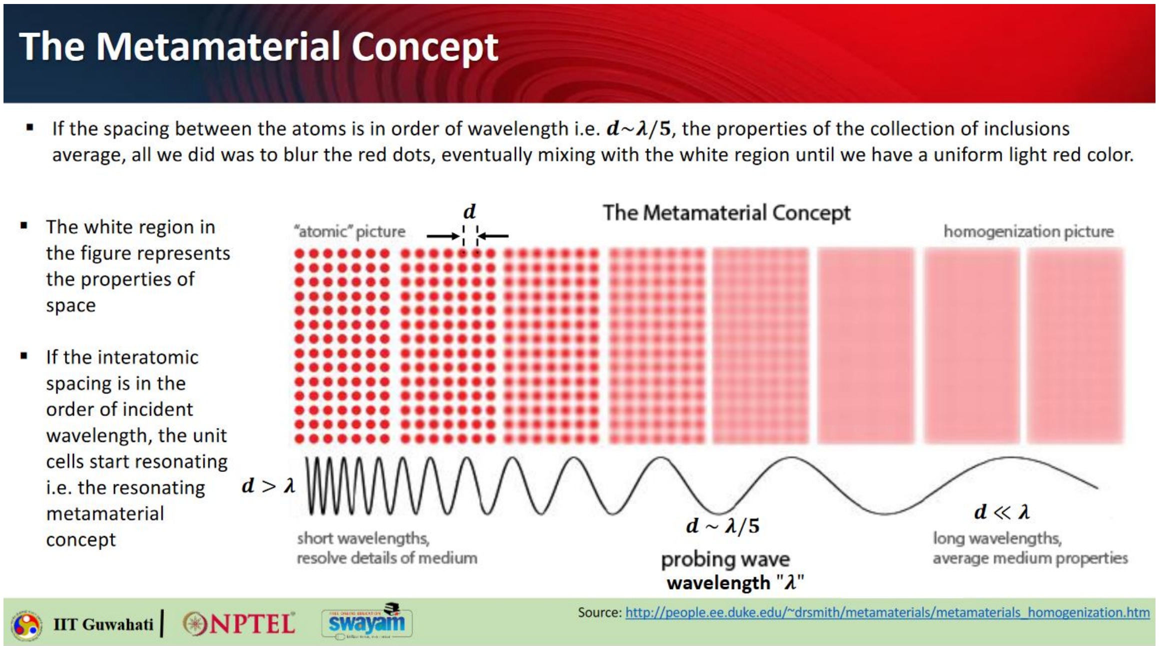


It means you will be able to see the atomic picture. On the other hand if you take the other extreme where say the wavelength is much much longer than this inter-particle or inter-atomic separation, in that case the wave will not be able to resolve any of this internal structure and it will more or less effectively average out the property. So these are the two extremes. So here you will see a homogeneous picture, here you will see an atomic picture. Now what are these red dots? So these red dots can represent you know say for a material it can represent the index of refraction or it can be something more technical, something like the polarizability of a material. And as you see that in this scale each of these can be individually seen but when the wavelength is much much larger things get averaged out.

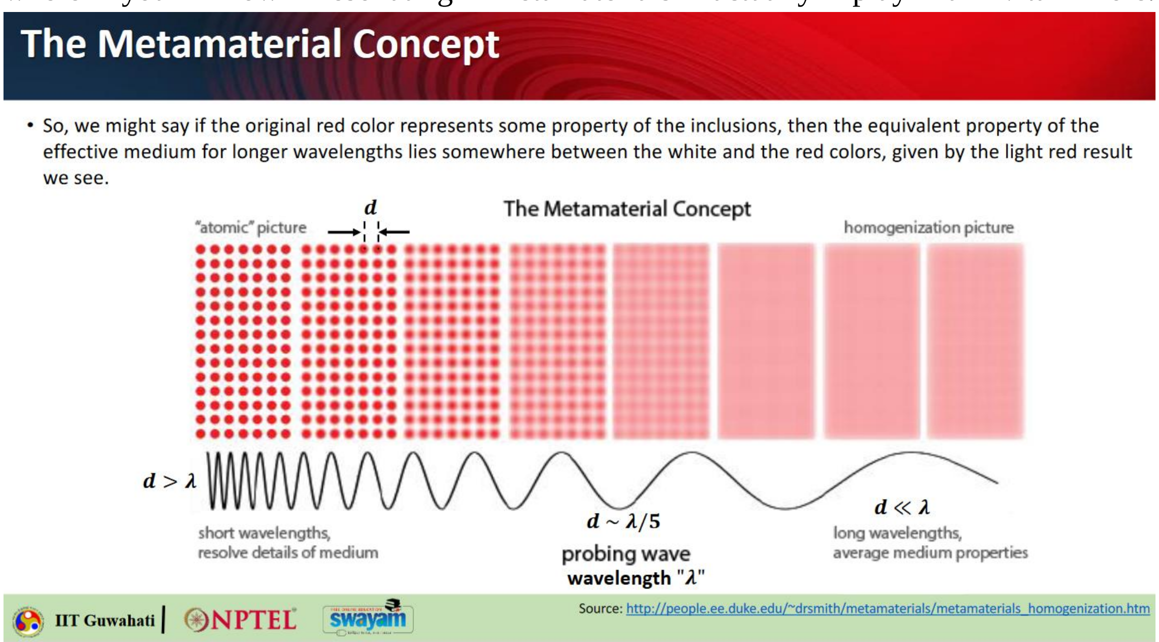


Now what happens in between here? So this is the case where the spacing between the atoms that is d is basically of the order of the wavelength. It is comparable. So when d is say comparable to lambda by 4 or lambda by 5 then you actually get a collection of the properties that is more or less averaged out. So here you see these are red dots having some white spaces and slowly towards the wavelength when the wavelength is becoming very very large it is getting a uniform light red color.

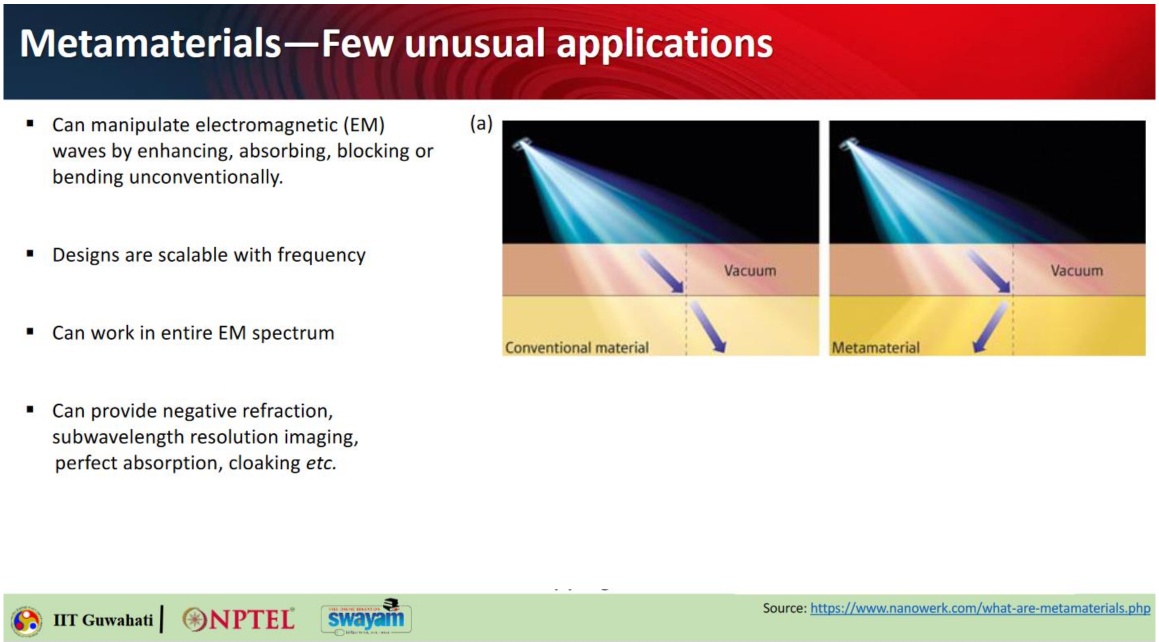
So metamaterials somewhere concept comes from this. So you are actually having some kind of property which is decided by this individual red dots and also their spacing and depending on the wavelength that is interacting with your material you will finally have the properties seen. So if the inter-atomic spacing that is d is in the order of the wavelength of light the unit cells will start resonating. So that is the concept of resonating metamaterial. That means each of these meta atoms will be a resonating structure. So, whatever we have seen so far is more or less examples of resonating metamaterials.



There are also concepts towards this range where individual meta atoms do not have much identity and in that case, we can actually go for non-resonant metamaterials. We will come into those concepts when we go into metamaterials in more details. So more or less this is how the metamaterial concept has come into picture. So, this is the range where you know resonating metamaterials actually play a vital role.



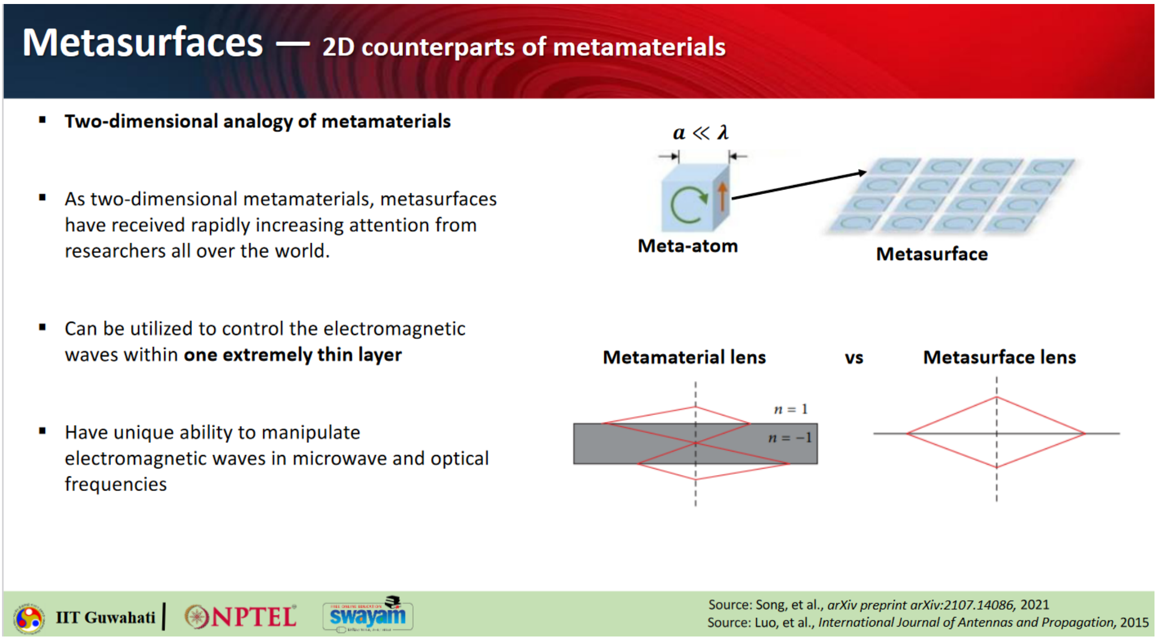
So we have already seen this. So what are the applications? First of all if you see any natural material when light is falling from say vacuum or air into any conventional material this is the path of light. Depending on the refractive index this is slightly bent towards you know the normal or slightly away from the normal but more or less the path remains same. But in metamaterials what happens? Assume that the light is coming from vacuum but from the normal instead of going to this side it will bend on the opposite side and this is what is the feature of you know negative refractive index metamaterial. So this allows you to manipulate the electromagnetic waves in a different way. So, they will allow to enhance or absorb or block or bend unconventionally.



So that is what this field of metamaterial is all about. It can do a lot of unconventional things just like here. So this is the typical law of refraction that you have studied in your school days but this is something completely opposite to that. The other good thing is that the designs of metamaterials are scalable with frequency. So when the frequency increases you just need to scale down your meta-atom size and it will work, the design works.

And you can actually make it work over the entire EM spectrum. So that gives an amazing flexibility that you can actually adopt a design of metamaterial from another field and make it work for you. Like you can take it from a microwave field and to the optical field because the structure defines the main property not the constituent materials. And as you see that negative refraction, sub-wavelength imaging, all these interesting applications are possible with metamaterials. Other applications like perfect absorption, cloaking, etc. So when I say cloaking what is cloaking? Cloaking means hiding an object.

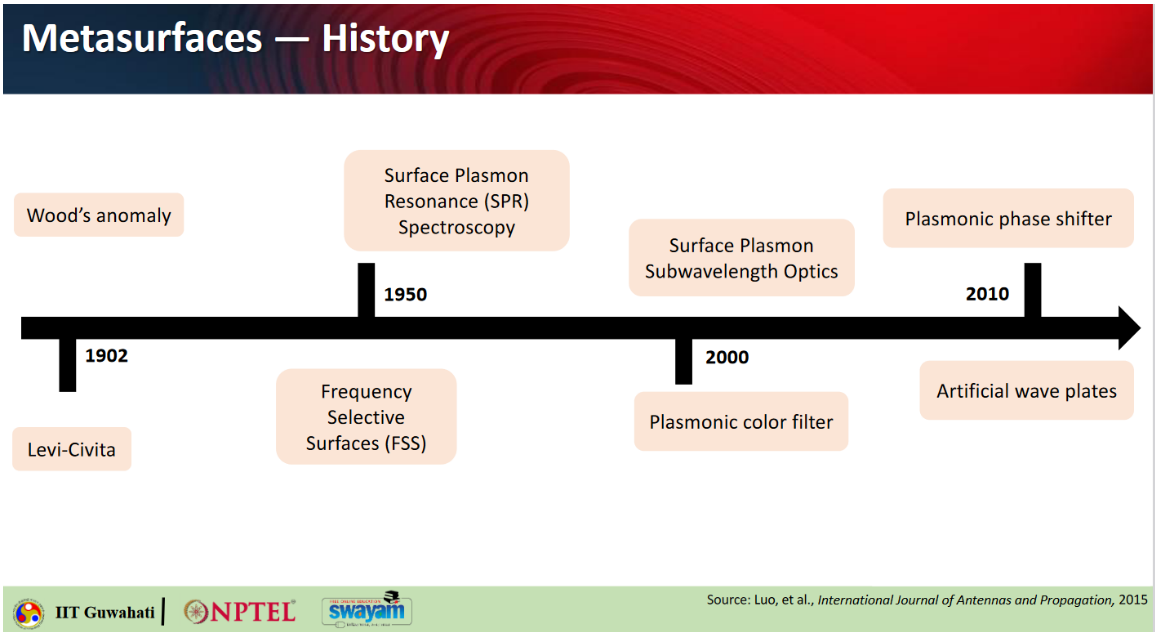
So it can only happen when you are able to bend the light around a particular object so that when you see it from here you see as if the light rays are coming from the source undisturbed because you are actually getting the same kind of beam over here. Sorry, this is the light source so you can actually assume that the detector over here is able to see the source undisturbed. But light rays are actually getting bent around the object. So this is the fundamental of cloaking. In this case you are able to hide this particular object from getting detected.



Now when you discuss about metamaterials there is also a possibility of metamaterials to be in 2D or two dimension. So that we call as metasurface. So in short you can say that metasurfaces are basically 2D counterparts of metamaterials. As you can see here the meta atoms in case of metasurfaces are also 2D elements.

So it is basically a two dimensional analogy of metamaterials. And metasurfaces have received lot of attention over the recent times and you can actually control electromagnetic property of light interacting with this extremely thin layer. And that makes it very interesting because you are able to manipulate microwave and optical frequencies using metasurface. And if you compare metamaterials and metasurface this is how they are different. Like a metamaterial lens will have a finite thickness whereas a metasurface lens will be very very very thin. So you can obviously think of the application areas where metasurface can actually beat the metamaterials.

So if you look into the metasurface history, it all dates back to 1902 when Robert Wood actually found some anomaly in the reflection spectra of metallic grating. And this phenomena is called Wood's anomaly. And from that there was another phenomena called identified by Levi-Civita which is also known as Levi-Civita relation. And that states that a sub wavelength thick film can result in a dramatic change in electromagnetic boundary conditions. So generally speaking, metasurfaces could include some traditional concepts in microwave domain such as frequency selective surfaces, impedance sheets and even ohmic sheets.



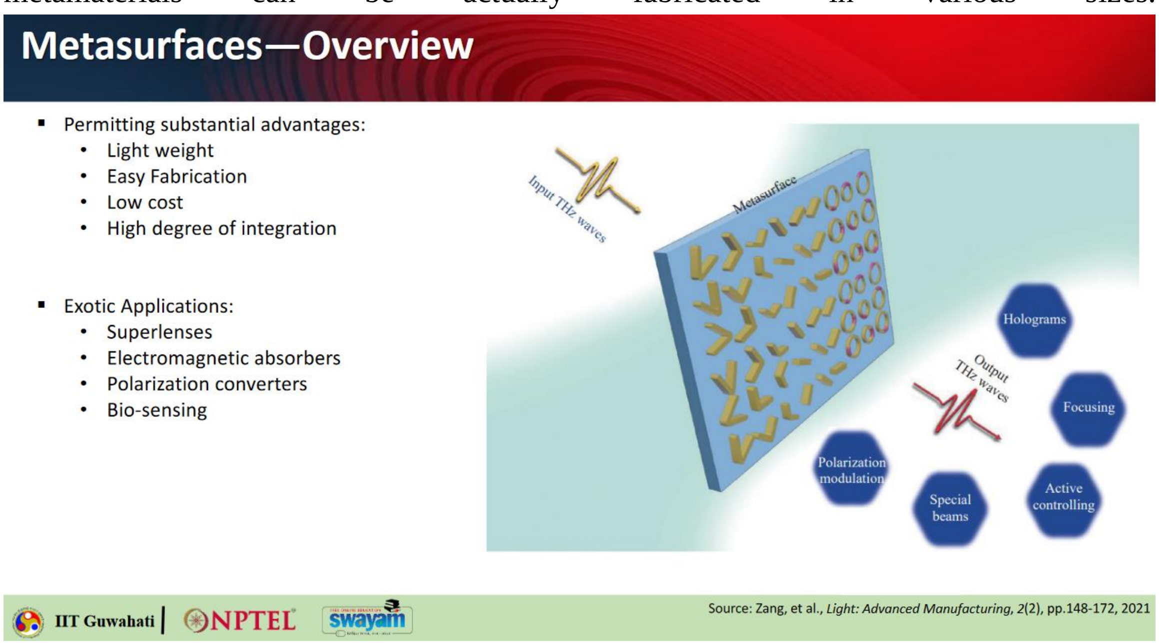
And in the microwave region we have seen that the thickness of these metasurfaces can be much smaller than the wavelength of operation. For example, thousand times smaller than the wavelength they are interacting with because the skin depth can be extremely small for highly conductive surfaces. So people have already demonstrated 0.3 nanometer thick film as metasurfaces which are actually able to absorb all electromagnetic waves in RF microwave and terahertz frequencies.

So that is amazing. Now if you think of optical applications and anti-reflective coating could also be regarded as a very simple metasurface as it was first observed by Lord Rayleigh. The discoveries of Wood and Levi-Civita promoted the development of the two areas which are long-treated independent of each other. One research area of metasurface is about the surface plasmon polariton which is a particular solution of surface wave at metal dielectric interface. And the other one includes FSS, impedance sheet and various other planar antenna arrays.

In optical domain the two areas began to somehow overlap with each other. Most of the metals in the metasurfaces become plasmonic at this particular frequency range. So that is where in optical field this metamaterial concept has boomed a lot. Indeed it will be also shown that SPP and ordinary electromagnetic waves in metasurfaces can be deduced to form a unified theory. So it is basically difficult to separate FSS and metasurface from the perspective of electromagnetic interactions since both of them can be well described by effective medium theory, effective impedance and all these things although FSS is only intended to do some frequency dependent transmission and reflection. In 2000 there are many categories of applications that has come up something like sub-wave length optics, plasmonic filters, modulators, plasmonic components for near-field optics, then amplitude modulation devices, absorbers, anti-reflection coatings, phase shifters, the artificial wave circuits, perfect absorbers and all these things, antennas and many other electromagnetic devices.

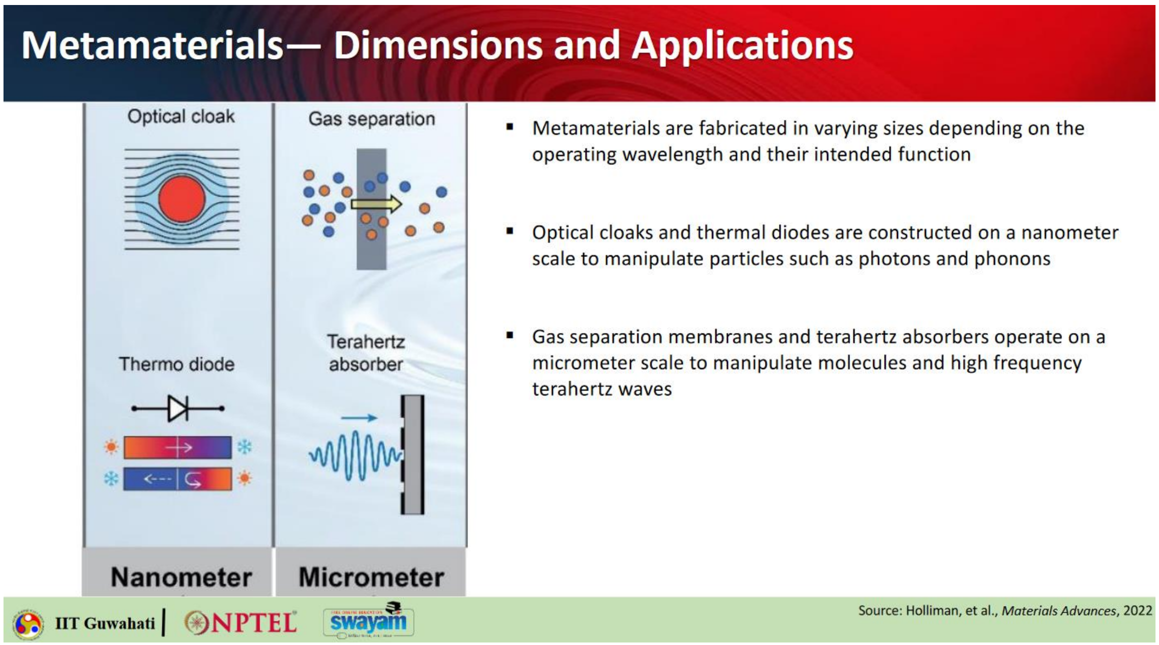
So the field of flat optics has also come up with the advent of this field of metasurfaces. Now what are the main advantages? Unlike the three-dimensional metamaterials, metasurfaces can control the properties of electromagnetic waves within one infinitely thin layer. So that actually provides a couple of advantages, something like they are very lightweight, they are easy to fabricate, low cost and they have high degree of integration. Anything thin is easy to integrate. So metasurfaces can be, as seen here, metasurfaces can be used in various applications due to their abilities to manipulate electromagnetic waves in microwave and optical frequencies.

This artificial sheet of materials, as you see here, they are basically composed of metallic patches in planar or in multi-layer configuration with sub-wave length thickness and as I mentioned they have advantages of being lightweight, ease of fabrication and they can control the propagation on both sides and the surrounding free space. So all these properties allow you to achieve polarization modulation, beamforming, active controlling, focusing, generating holograms using metasurfaces. So there are different exotic applications possible like superlenses which are able to focus in infinitely small volume, electromagnetic absorbers, polarization converters, biosensing and so on. So, metamaterials can be actually fabricated in various sizes.



So these are the concept of metamaterials and metasurfaces. I hope these are clear.

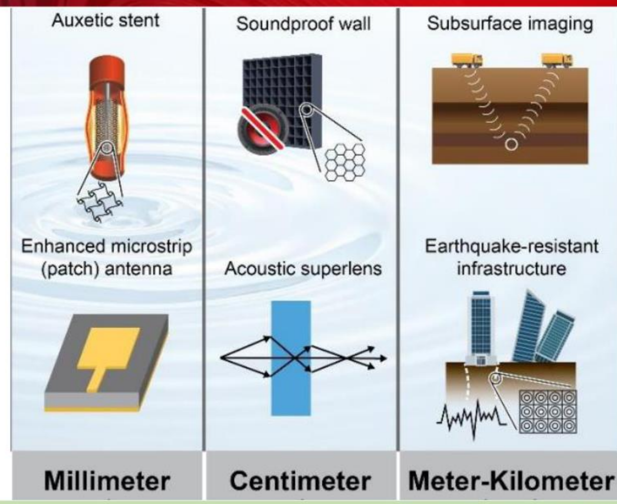
Now let us actually look into some applications of metamaterials and then we will conclude and we will try to cover the metasurface applications in the next lecture. So metamaterials are fabricated in various sizes depending on the operating wavelength and their intended application. So here you can see nanometer scale you can actually create metamaterials for optical clocking or you can actually create thermodiodes which are able to block heat in one particular direction and allow in another. In micrometer scale you can think of gas separation membranes and terahertz absorber which operate in micrometer scale and they could manipulate molecules and high frequency terahertz waves.



So these are the two scales: nanometer, micrometer scale. Even you can also find metamaterials in millimeter scale, centimeter scale and even kilometer scale something like. In millimeter scale you have auxetic stands and microstrip patches, patch antennas. They are constructed with millimeter dimension to manipulate mechanical motion and electromagnetic waves. Now what is auxetic stents? These are basically structures made of materials.

Metamaterials— Dimensions and Applications

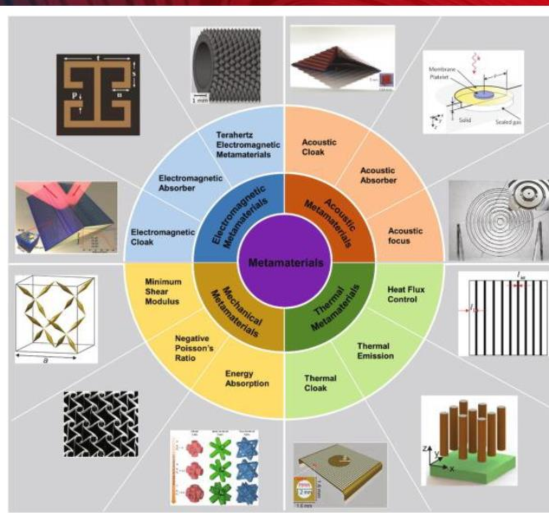
- Auxetic stents and microstrip (patch) antennas are constructed with millimeter dimensions to manipulate mechanical motion and electromagnetic waves
- The soundproof wall and acoustic superlens have periodic structures on the centimeter scale to manipulate sound waves
- Subsurface imaging and earthquake-resistant infrastructure are constructed on the meter to kilometer scale to manipulate seismic waves



Source: Holliman, et al., *Materials Advances*, 2022

They have negative Poisson ratio. So when they are stretched they become thicker perpendicular to the plate force. And this occurs due to their particular internal structure and the way they deforms when the sample is uniaxially loaded. And a stand here as you can see is basically a small mesh tube typically used to hold open passages in the body such as weak or narrowed arteries. You can also build in centimeter scale you can bring metamaterials that can provide soundproof wall and you can also have acoustic super lenses that can manipulate sound waves. So, as you can understand like with the different scale you are actually looking also for different different domain of waves in the electromagnetic spectrum where metamaterials will be interacting.

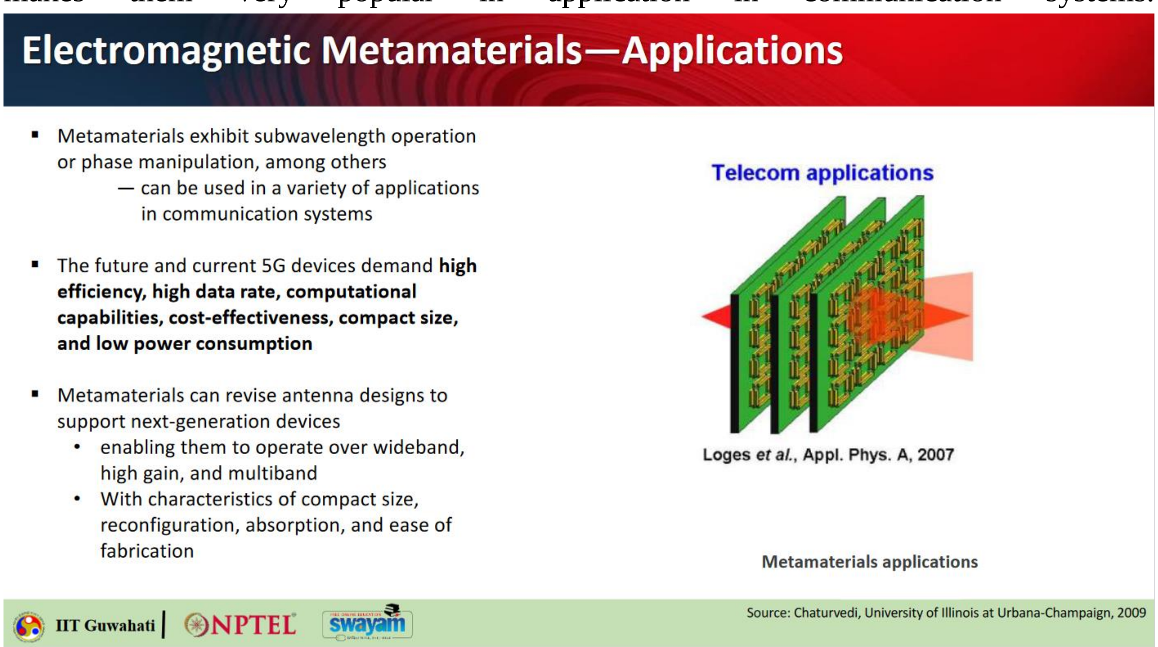
Metamaterials—Applications



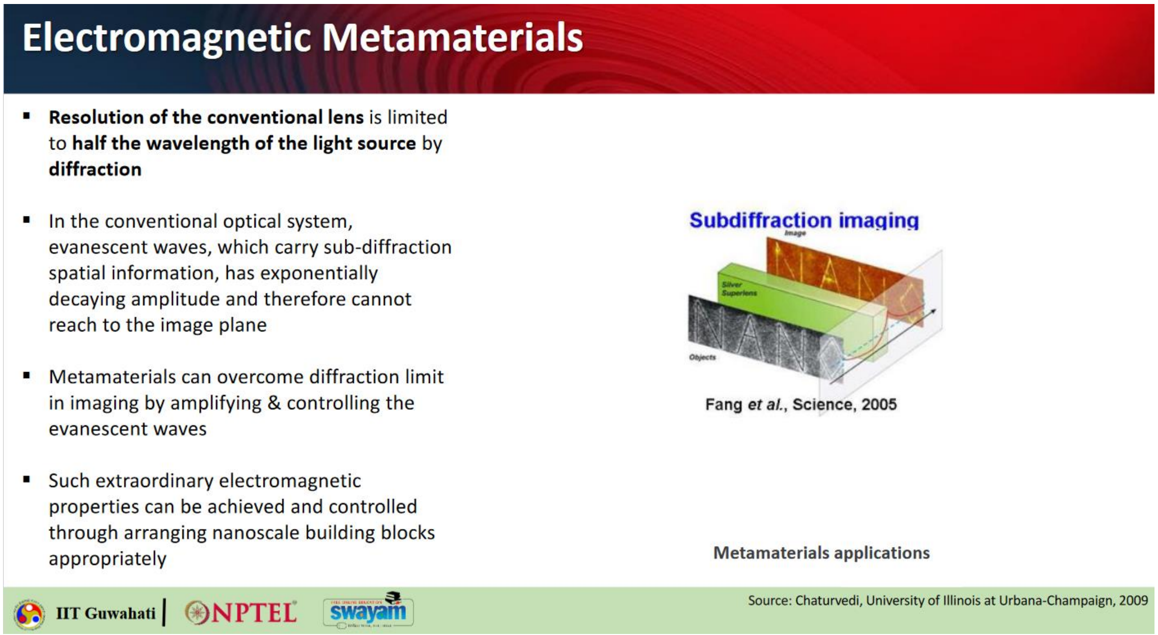
Source: Fan, J., et al., *Materials Today*, *50*, pp.303-328, 2021

And finally you can also think of subsurface imaging and earthquake resistant infrastructure. They can be constructed on meter to kilometer scale that can also manipulate seismic waves. So more or less metamaterials can actually work on any kind of waves. So there has to be relationship between the metamaterials constituent blocks that is meta atoms and they should be comparable to the wave they are dealing with. So metamaterials application as you can see it is not only electromagnetic metamaterials where the main applications would be electromagnetic cloaking, electromagnetic absorber or terahertz electromagnetic metamaterials.

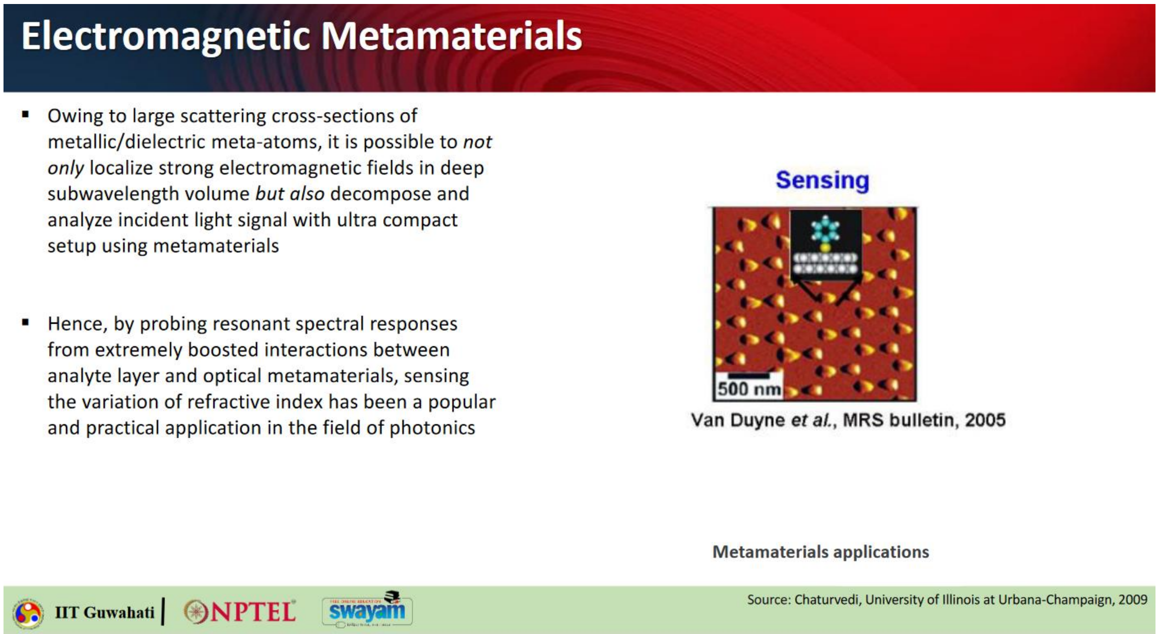
We can also have metamaterials in acoustic, thermal, and mechanical fields. In acoustic metamaterials you can think of acoustic cloak means you can actually make a region where sound waves will not enter. You can actually make absorber and you can also make sound waves focus at a particular place that is a acoustic focus. Similarly you can have in thermal field you can have thermal cloak, thermal emission and heat flux control. In mechanical, you can have minimum shear modulus, then you can have negative Poisson ratio materials and different energy applications. So, if you talk about electromagnetic metamaterials the main applications are in the telecom areas where metamaterials they exhibit sub wavelength operation or phase manipulation and that makes them very popular in application in communication systems.



So the future and current 5G devices they demand high efficiency, high data rate, computational capabilities, cost effectiveness, compact size and low power consumption and all these things are possible with metamaterials. So metamaterials can revise the antenna design, the conventional style of designing antennas to support the new generation devices that will give them wide band, high gain and multiband operation. Also they will bring in compact size, configuration or reconfigurability, then absorption and the ease of fabrication. Next important application could be in the field of sub diffraction imaging. As you can see in conventional lens the resolution is mostly limited by the diffraction limit of light as we understood and it happens because in conventional optical system the evanescent waves which carry sub diffraction spatial information they actually have a decaying amplitude.



So, they decay. But then if you actually have a metamaterial that can amplify your evanescent field and control them that can actually help you image this particular information over a distance. So there was a paper in 2005 they have shown this sub-diffraction imaging is possible using metamaterials. And all these things you can actually achieve by choosing the building block properly. Next application would be in the field of sensing. As you can understand that if you are able to focus electromagnetic waves in very, very small volume you should also actually probe the trace amount of molecules which are present on that particular surface.



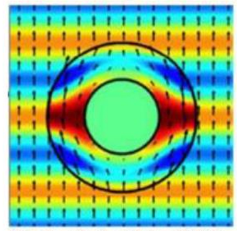
And when you think of metamaterials which are made of resonating elements and this resonance also depends on the surrounding materials so they can also be used for sensing the change in refractive index of a material. So that can be used for sensing kind of applications. Another important application will be in cloaking. As you can see here the waves are coming from this direction there is an object but then the waves actually bend around.

So this is a metamaterial cloak that is able to save this object from detection. So what happens when light actually falls on an object typically the light is either absorbed So if it is absorbed and nothing is getting detected here that means somehow you know that there is an object present okay. In that case the object is not transparent. So it is getting detected. Now if the light is getting reflected from the object then also you do not get anything here that means the object is now getting illuminated and you are able to see the object directly.

Electromagnetic Metamaterials

- Under normal circumstances, when you bombard any material with light of any wavelength, the typical behavior is either absorption or reflection
- If the light is absorbed, then any background light and signals will be obscured, alerting you to its presence
- In other words, the object won't be transparent

Invisibility cloaks



Chen *et al.*, PRL, 2007

Metamaterials applications

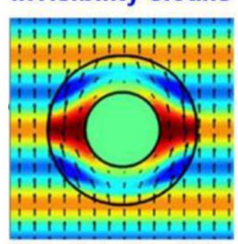
Source: Chaturvedi, University of Illinois at Urbana-Champaign, 2009

So again the object is not transparent. So the object is not transparent to the waves. So how do you actually make it transparent or invisible or get it away from the detection? The way is to bend the electromagnetic waves around it. So that is possible by covering this object with this metamaterial. So this is the metamaterial that is allowing the light rays to bend around it and after it exits from the metamaterial they actually become in the same pattern they were before they entered this particular metamaterial area. So that way the observer over here will think that there is nothing that is disturbing this electromagnetic wave and that way this object is undetectable. So, you can actually think of a lot of applications, different kind of application based on this metamaterials okay.

Electromagnetic Metamaterials

- If the light is reflected, any signal you send out will be bounced back to you, illuminating the object and allowing you to observe it directly
- Again, the object won't be transparent
- The only way to achieve actual transparency would be if the light coming from behind the object could somehow still arrive, with the same trajectory, in front of the object, as though the light were transmitted directly through the object

Invisibility cloaks

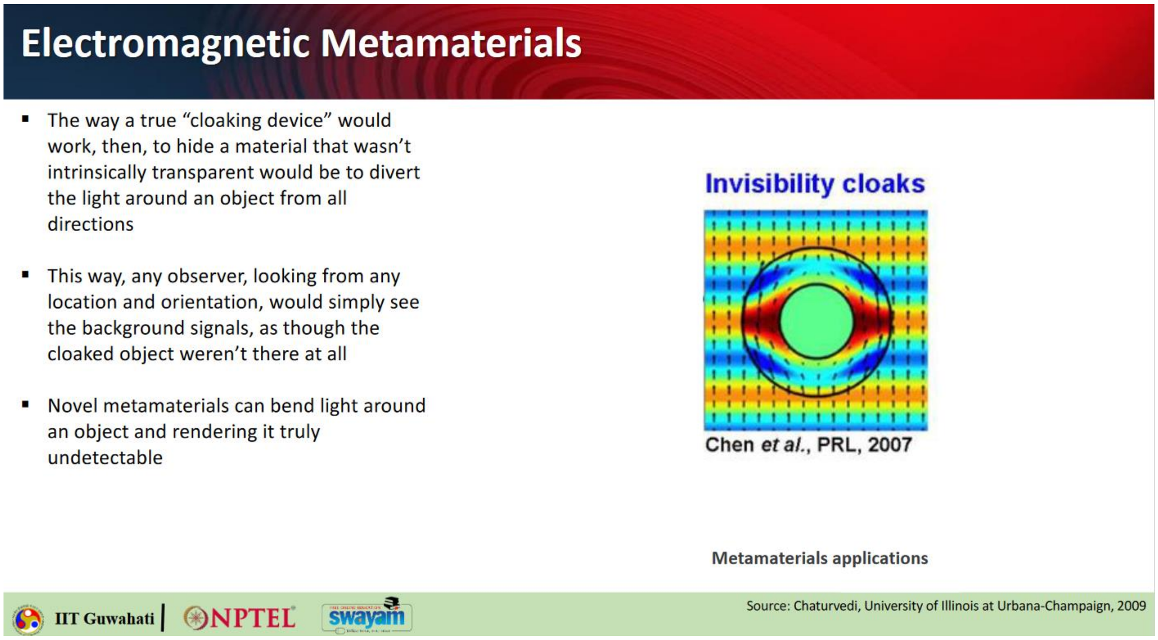


Chen *et al.*, PRL, 2007

Metamaterials applications

Source: Chaturvedi, University of Illinois at Urbana-Champaign, 2009

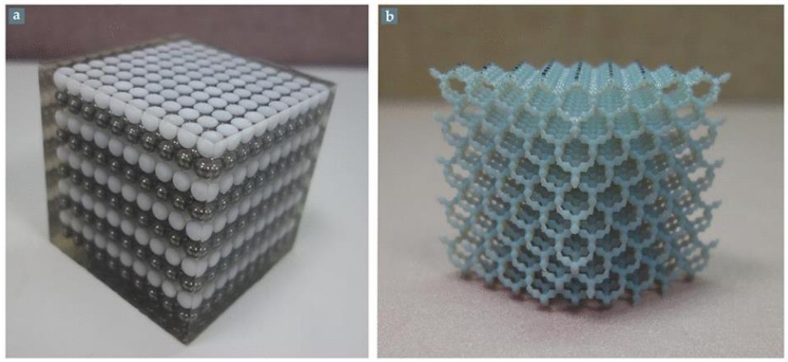
So a true cloaking device will actually hide this object from detection for light that is coming from any direction. So that makes it more challenging basically. So you are just not working in one direction you have to design it in such a way that whichever is the direction of the incident electromagnetic wave the wave should actually go around and then exit. So that is how you can actually develop a cloak. So novel metamaterials we will see in the subsequent lectures how to develop this kind of metamaterials, what are the properties, how do you do mathematically and how do you actually come up with such a design.



Similarly you can also think of metamaterials in other fields like acoustic metamaterials. They allow control, direct and manipulate sound waves or phonons you can say in gases, liquids or solids. So these are two real world example of acoustic metamaterials. So this is a periodic 3D crystal kind of thing, this is called a sonic crystal. So here one particular range of sound frequencies cannot propagate in a certain direction.

Acoustic Metamaterials

- Control, direct, and manipulate sound waves or phonons in gases, liquids, and solids
- Used as acoustic stealth cloaks, acoustic perfect transmission, underwater sound absorption, *etc*.



Real-world acoustic metamaterials look like this

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Source: Haberman, et al., *Phys. Today*, *69*(6), pp.42-48, 2016

So, this is very much analogous to photonic crystal if you already know about it. What else we will discuss photonic crystal and then you will see that these are basically based on photonic crystal kind of concept. And this is called pentamode metamaterial which supports stress in only one of the six possible modes. And it has inspired many acoustic metamaterial design. So these are different examples. So, they can be used as acoustic stealth cloak, acoustic perfect transmission, underwater sound absorption and so on.

Thermal Metamaterials

- Thermal metamaterials have unique capabilities of controlling heat transfer
- Heat transfer and thermodynamics are now also of central importance to modern technologies including power generation and conversion, night vision, microelectronics, aerospace, etc.
- Thermal metamaterials could help dissipate heat in a deterministic manner and avoid local hot spots in advanced nanoscale devices
- Few examples:
  - Thermal shields/camouflages protect an area from transient diffusive heat flow
  - Thermal concentrators can focus thermal flux on a small area
  - Thermal inverters (also called thermal rotators) change the direction of the thermal gradient in an area

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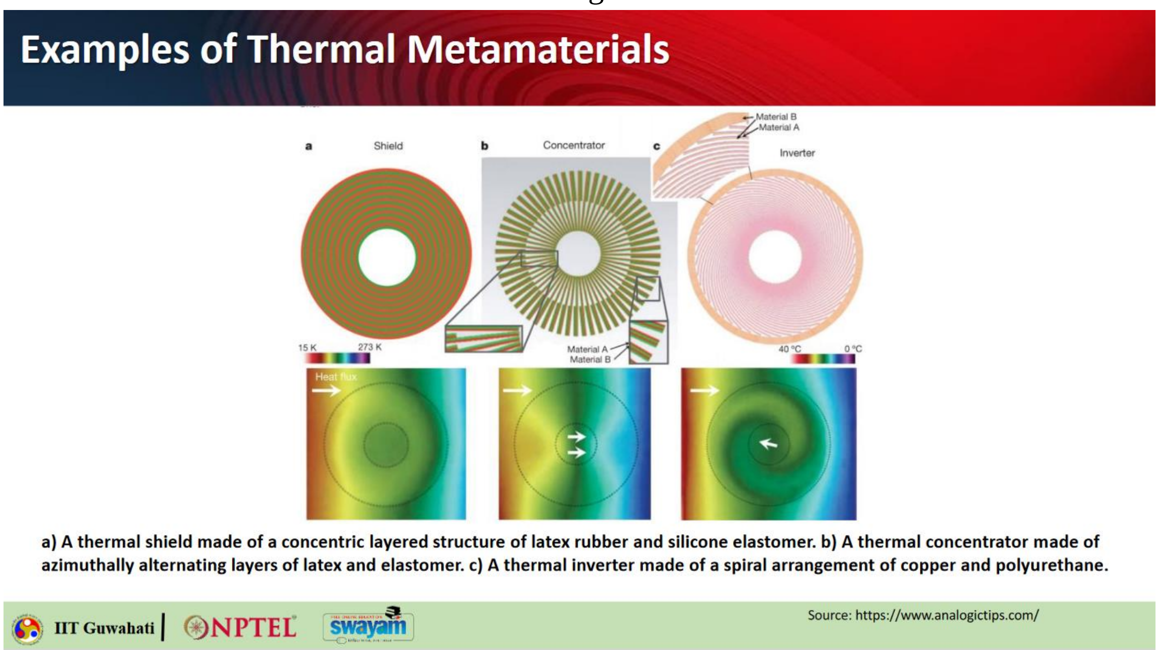
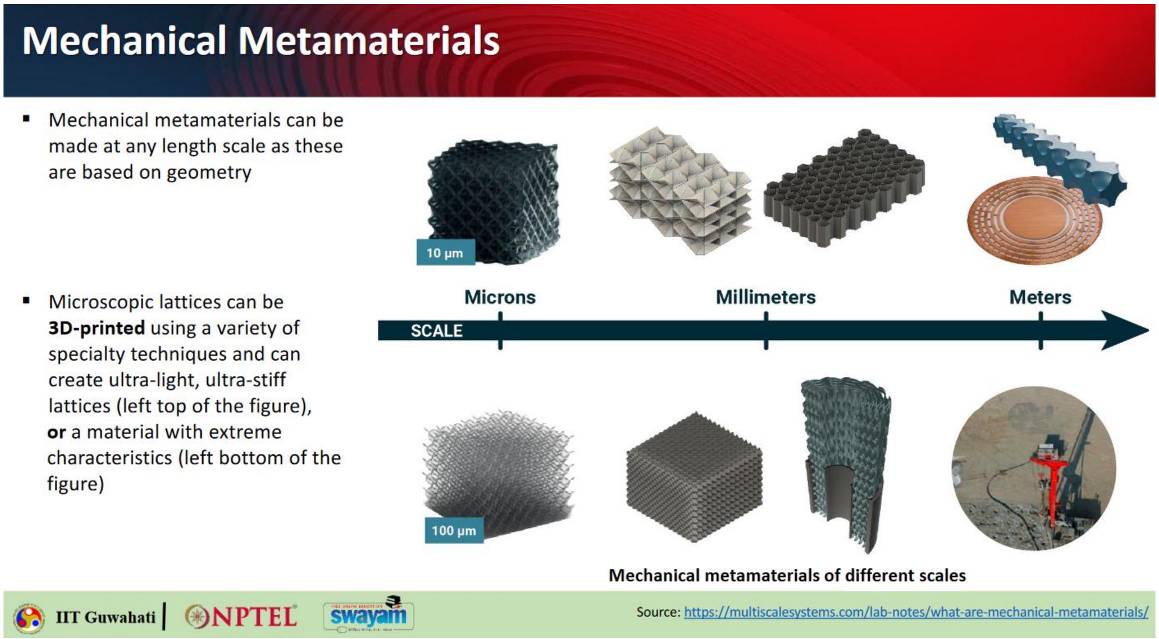
Similarly in the field of thermal there are metamaterials which have unique capability of controlling heat transfer. And heat transfer and thermodynamics are very important topic in today's world including power generation and conversion, night vision, microelectronics, aerospace and in other fields. So thermal metamaterials could help dissipate heat in a deterministic manner and it will allow you to guide heat in a particular path and avoid local hotspots in advanced nanoscale devices. So when you go to nanoscale as we discussed in the first lecture, heating is also a very important issue that we have to take care of.

So there are a few examples of thermal metamaterials. One is thermal shield or camouflage. So what does it do? It protects an area from transient diffusive heat flow. So that is what shield does. It saves one area from getting exposed to heat. There are thermal concentrators as the name suggests it can focus thermal flux on a very small area. There are thermal inverters or thermal rotators which can help you to change the direction of thermal gradient in an area.

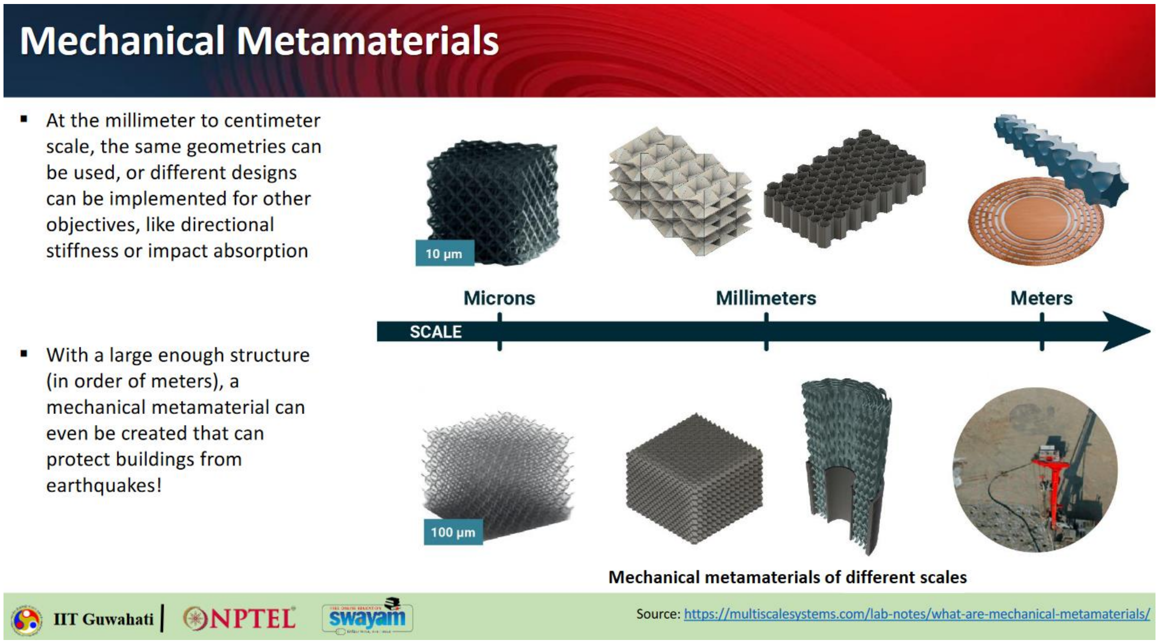


So here are the examples as you can see. This particular one shows a thermal shield. So anything put here will not have any effect on temperature change outside. So this is the shield. Here is the thermal concentrator which actually helps you to bring more thermal flux in the central region as shown here. And this is one metamaterial which is actually able to do the redistribution of the thermal gradient.

So this is thermal inverter. You see the thermal flux is this way but inside it is in the opposite direction. So this is a thermal inverter. Now if you go to mechanical domain, in mechanical domain also the metamaterials can be of any length scale based on the geometry. If you think of micron scale, so you can actually have 3D printed microscopic lattices with variety of special techniques which can give you ultra light or ultra stiff lattices like this or you can have materials with extreme characteristics like this one which is shown. You can also look for millimeter or centimeter scale metamaterials with applications like directional stiffness or impact absorption. You can think of even larger scale like meter scale or even beyond which can be used for protecting a structure from earthquake.



So this kind of metamaterial can actually help you block a structure from seismic waves. So, even the oil rigs in the ocean can actually have kind of metamaterial structure that can shield them from the tsunami waves. So that way you can actually think of any waves and you can think of metamaterial that can guide that wave in a particular direction. So you can think of shield, you can think of concentrator and all these different applications are possible. All you need to remember is that the size of the meta atom should be comparable to the wavelength of the wave that you are dealing with. So, with that we will try to conclude here because we are running short of time for this lecture to cover the applications of metasurfaces that we will cover in the next lecture.



But what I want to stress here is that metamaterials bring infinite possibilities of defining materials and that is where this has taken the material engineering in any field to the next level. So metamaterials field is also not only restricted to photonics engineering or nanophotonics but it has done wonders in all other fields as you can see here in thermal, acoustic, mechanical fields. You can design amazing shock absorbers based on impact absorbers using metamaterial concept and so on. So this field is very much researched in all different disciplines and it has got a very bright future.

But in this course we will mainly focus on optical metamaterials which have got applications in nanophotonics. So we will stop here and we will cover the applications of metasurfaces and the overall overview of this field in the next lecture. Thank you. Any queries you can write to me at this email address mentioning the MOOC course on the subject line. Thank you.