Lec 1: Introduction to Microwave and Optical Metamaterials-I

Hello students, welcome to lecture 1 of the online course on Interaction with Microwave and Optical Matter Materials.

- Overview of Electromagnetic Spectrum

- Need of Metamaterials

- Building blocks of metamaterials: 'Meta-atoms'

- Timeline & Classification of Metamaterials

- Development of Microwave Metamaterials
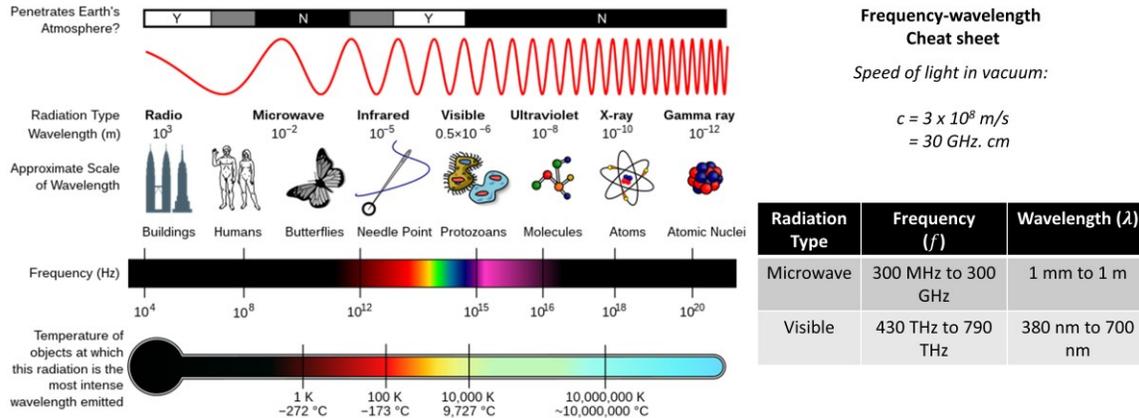
- Applications of Microwave Metamaterials

So, here is the lecture outline. We will discuss the brief overview of the electromagnetic spectrum. Then we discuss what the need for metamaterials is in this current era. What are the building blocks of these metamaterials, which are also known as meta-atoms? We will go into the history of metamaterials and discuss the timelines and classification of metamaterials. And in this particular video, we will discuss the development and application of microwave metamaterials.

Overview of Electromagnetic (EM) Spectrum

Penetrates Earth's Atmosphere?

	Y	N	Y	N

Radiation Type
Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray

Wavelength (m)
| 10^3 | 10^{-2} | 10^{-5} | 0.5×10^{-6} | 10^{-8} | 10^{-10} | 10^{-12} |

Approximate Scale of Wavelength
Buildings	Humans	Butterflies	Needle Point	Protozoans	Molecules	Atoms	Atomic Nuclei

Frequency (Hz)
10^4 10^8 10^{12} 10^{15} 10^{16} 10^{18} 10^{20}

Temperature of objects at which this radiation is the most intense wavelength emitted

1 K −272 °C   100 K −173 °C   10,000 K 9,727 °C   10,000,000 K ~10,000,000 °C

Frequency-wavelength Cheat sheet

Speed of light in vacuum:

$c = 3 \times 10^8$ m/s
$= 30$ GHz. cm

Radiation Type	Frequency (f)	Wavelength (λ)
Microwave	300 MHz to 300 GHz	1 mm to 1 m
Visible	430 THz to 790 THz	380 nm to 700 nm

So, before we begin the course, let us have a quick look at the entire electromagnetic spectrum. So, as you can see, the EM radiation, or electromagnetic radiation, occurs over an extremely wide range of wavelengths, starting from radio waves, which are measured in several hundreds of meters, down to gamma rays, which are basically 10 to the power of minus 12 meters. So, here you can visualize the wavelength; here is the approximate scale of the wavelength. So, radio waves are on the order of the building, okay.

Microwaves are in this particular range, okay. This is how the visible wavelengths are, and when you go down to gamma rays, they are basically the size of atomic nuclei. So, here is the corresponding frequency spectrum for these wavelengths. Okay, that is also really wide, as you can see. 10 to the power of 4 hertz to 10 to the power of 20 hertz, okay.

And this particular scale shows you the temperature of the objects. At which this particular radiation is the most intense wavelength that is emitted. What does it mean? So, if you take an object that is 100 Kelvin or minus 137 degrees Celsius, that will produce blackbody radiation with the dominant wavelength in this particular range. Okay. So, what is important here is to quickly remember the frequency and wavelength conversion.

So, for that, you can use this frequency-wavelength cheat sheet, okay. So, it tells you the speed of light in a vacuum is given by c, which is 3 times 10 to the power of 8 meters per second, or you can also write it as 30 gigahertz centimeters. That means if you have a 30 gigahertz frequency, you will have a 1 centimeter wavelength; if you have a 3 gigahertz frequency, you will have a 10 centimeter wavelength, okay. So, you can use this cheat sheet to convert wavelength and frequency, okay. Now, in this particular course, we will be focusing mainly on microwave and visible radiation.

So, as you can see, the frequency range for microwaves is from 300 megahertz to 300 gigahertz, which means the wavelength will be from 1 millimeter to 1 meter. Ok, and in the visible spectrum, we are going from 430 terahertz to 780 terahertz. Ok, and the wavelength range is from 380 nanometers to 700 nanometers. So, these are just to tell you that we are basically focusing on microwaves and visible light in this particular course. There is a particular reason for you to know focusing on these two, okay.

Need of Metamaterials

- Modern material engineering leads to the synthesis of many *novel chemical compounds* by **combining atoms of natural materials to obtain some desired electromagnetic property.**

- Engineering devices made up of these novel compounds can **exhibit combined or modified electromagnetic response** of its **constituent materials.**

- However, the **major bottleneck** is the **limited set of natural materials** appearing in the periodic table **exhibiting a fixed set of electromagnetic properties.**
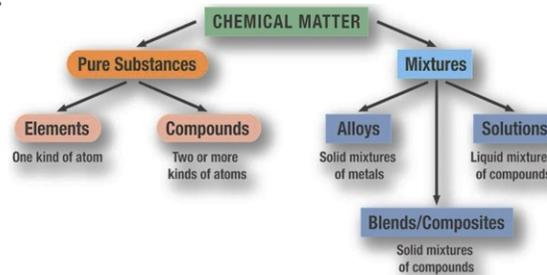
So, all the experimental initial demonstrations for metamaterials were done in this particular domain. Microwave domain because it is easy to fabricate those metamaterials, as we will discuss and see in this particular course, is okay to prove any concept that is also going to work in any other range, typically in the visible range as well. Now, the question is what the need for metamaterials is, or you can say, why metamaterials when so many materials are already available. So, modern material engineering basically leads to the synthesis of many noble chemical compounds. So, a lot of work has been done in chemistry and chemical engineering by combining atoms of, you know, materials to obtain, you know, some desired electromagnetic property.

So, this is the kind of, you know, chemical matter we have learned about till now. So, there are pure substances which can be elements or compounds; elements basically have only one kind of atom, while compounds have two or more different kinds of atoms. And then you also have mixtures such as alloys, where solid mixtures of metals occur, solutions, where liquid mixtures of compounds occur, or you can also have blends and composites, which are basically solid mixtures of compounds. So, with all these things in place, there is still a requirement for a particular

frequency range. They are not able to provide you with a custom required electromagnetic property, like permittivity or permeability.

We will go into the definition if you are not sure about this in the upcoming slides, but then they basically tell you how electric and magnetic fields behave with a particular material. So, engineering devices made up of novel compounds can exhibit combined or modified electromagnetic responses of their constituent materials. However, the limitation or bottleneck in this particular case is that there is a limited set of natural materials that appear in the periodic table. So, it basically exhibits a fixed set of electromagnetic properties, and you cannot tune everything. Though you can mix things up and go closer to a different kind of property, you cannot create something completely new or unusual.
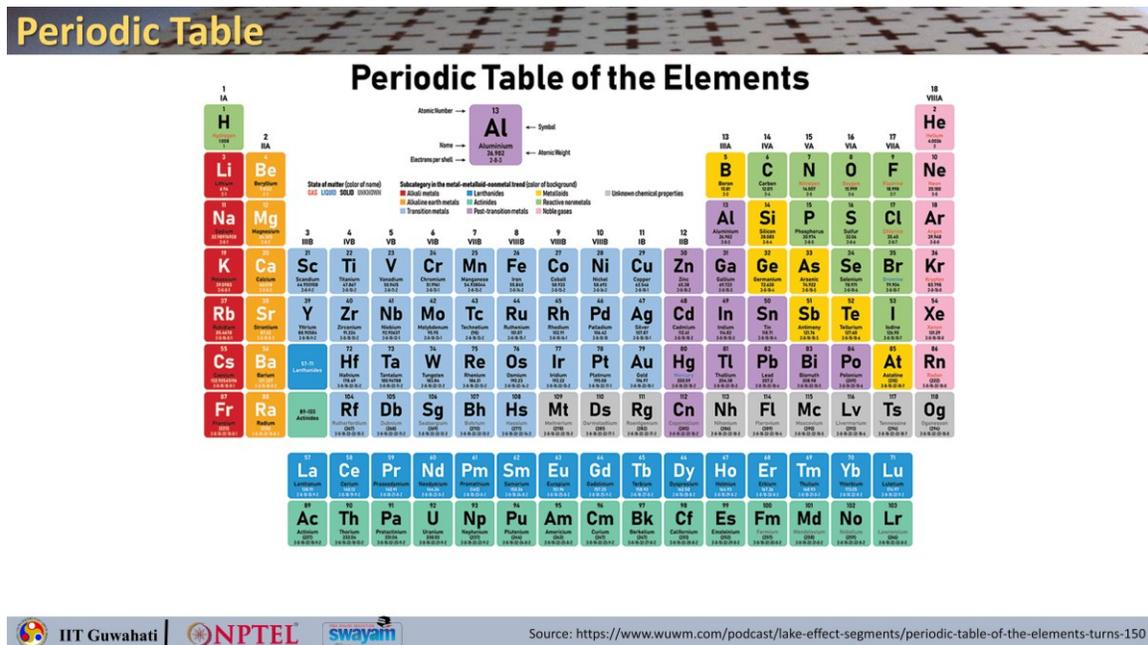
Right. So, for your convenience, I am just showing you the periodic table, which has 118 elements. Prior to the development of metamaterials, researchers were stuck with these basic elements and their mixtures and combinations to realize any new properties.

- *What if* we could design materials whose properties are independent of their chemical composition?

- *What if* a material's electromagnetic behavior was determined not by its constituent atoms or molecules, but by their physical arrangement?

- Here is the *Metamaterial*

  - μετά (meta) = "beyond" or "after"
  - Materia = "matter" or "material"

- *Metamaterial made of*

  Meta-atoms — Artificial atoms or engineered 'unit cells'

- *The term "metamaterial" is introduced by Walser in 1999.*

Natural materials   **Metamaterial**

Atoms   **Meta-atoms**
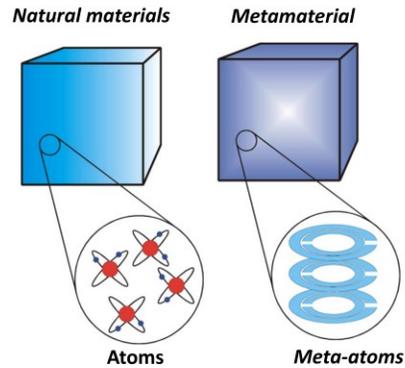
But when you go for metamaterials, that is where you know you could design materials with properties that are completely independent of their chemical composition. And that opens a whole new area where you know that it opens up a whole new area. Where you know you can engineer the design and change the electromagnetic behavior of that particular material, okay? So, what is basically defining that? So, you are basically looking for a material's electromagnetic behavior, which should be decided not by its constituent atoms or molecules, but by the physical arrangement, and that is where metamaterials come in.

Way better in the sense of flexibility they provide as compared to natural materials. So, natural materials are composed of atoms, similarly to metamaterials, which are artificial materials; they are basically composed of unit cells, which can be called meta-atoms. So, what is Meta? Meta means beyond; it is a Greek word, okay, beyond or after. Materia means it is material, right? So, you are basically telling me that where the natural materials stop, you can start using metamaterials to obtain those exotic or extraordinary electromagnetic properties. So, what we learn from here is that metamaterials are basically composed of meta-atoms; they are artificial atoms or engineered unit cells.

So, this particular term, metamaterial, was introduced by Walsh in 1999.

- **Nature uses atoms to build materials**.

- The interaction of these materials with the electromagnetic waves is governed by *the frequency (f) dependent material properties such as permittivity, $\varepsilon(f)$, and permeability, $\mu(f)$.*

- All the naturally occurring materials have positive permittivity, $\varepsilon(f)$, and permeability, $\mu(f)$, which govern the electromagnetic responses of these materials.

- However, for various modern technological advancements in communication, imaging, and sensing, engineers need precise control over the behavior of electromagnetic waves interacting with these materials to achieve specific functionalities.

- Metallic, semiconductor, and insulating structures can be designed as '*meta-atoms*' or '*building blocks*' to construct metamaterials.

- *Provide tailored/artificial material properties such as negative permittivity $\varepsilon(f)$ and/or permeability $\mu(f)$ over a specific electromagnetic band.*

Nature uses atoms to build materials.

So, the interaction of these materials with the electromagnetic wave is governed by the frequency-dependent material properties, such as dielectric permittivity and magnetic permeability. The interaction of these materials with the electromagnetic waves is governed by the frequency-dependent material properties such as permittivity epsilon $\varepsilon(f)$ and permeability mu $\mu(f)$.

So, all the naturally occurring materials have positive permeability and positive or negative permittivity, like metals that have negative permittivity, right? These are the properties that govern the electromagnetic responses of these materials. However, due to various modern technological advances in communication, imaging, and sensing, engineers basically demand precise control over the behavior of electromagnetic waves when they interact with materials to achieve specific functionality. So, is that matter okay or in that particular direction? When you are using metallic, semiconductor, or insulating structures to design metatoms or the unit cell for the metamaterials, you can basically obtain that kind of control over the material's properties. so that you can guide or make the electromagnetic wave behave in the way you want. So, metamaterials can provide tailored or artificial responses because you can create negative permittivity and permeability over a specific electromagnetic band.

- Metamaterials show electromagnetic properties **not depending on their raw material composition** but from assembly of **sub-wavelength sized** individual elements *i.e. meta-atoms*

- **Meta-atoms:** — resonantly couple to both the electric or magnetic components of the incident electromagnetic fields.

- **Meta-atoms**

  - made-up of conventional materials such as metals and dielectric

  - are of the sub-wavelength size-scale ($a \ll \lambda$)

  - much smaller than conventional optical elements, such as lenses and prisms

- Metamaterial *cannot be obtained from any continuous and homogenous medium*, which is why the metamaterials are always of a composite nature.

- Usually, metamaterials are constructed from discrete resonant micro- and nanometer-scale objects which mimic the electromagnetic reaction of atoms and molecules of natural substances to make them interact with light and other forms of energy in specific controllable ways.
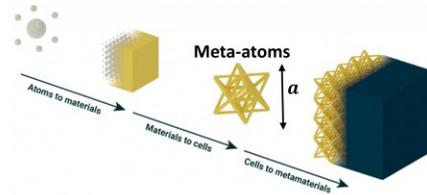
So at the end of the day, a question may come to your mind: are these metatoms also made of some material? And how about the properties of those materials dictating the overall properties of the metamaterials? Now, this is something interesting because in metamaterials, they show electromagnetic properties that do not depend on their raw material composition. But from the assembly of individual atoms or individual elements called meta-atoms of sub-wavelength size. So, you can see that you have these atoms. With that, you are forming a material that you are using to design your unit cell, which is a meta-atom, and the periodic arrangement of this meta-atom determines the overall properties of the material that you are making, okay? So, your metamaterial properties are essentially independent of the constituent materials' properties.

Right. So, meta items can be resonantly coupled to both the electric and magnetic components of the incident electromagnetic waves. So, that is how meta items work. They are basically made of conventional materials, just like metals and dielectrics. And one important feature is that these matter atoms are sub-wavelength size. That means the size of the unit cell or the matter atoms is much smaller than the wavelength of the electromagnetic wave they are interacting with. So, they are much more conventional than optical elements such as lenses and prisms. So, metamaterials cannot be obtained from any continuous and homogeneous medium, and this is why metamaterials always have a composite nature. So, metamaterials are usually constructed from discrete resonant micro and nanoscale objects depending on the frequency range you are targeting. If you are going for optical metamaterials, there will be nanoscale objects. If you are working with microwave metamaterials, your unit cells may be in millimeter sizes.

Scale okay. The whole idea is that you have to have the meta atoms sub-wavelength in size, okay. And this will mimic the electromagnetic reactions of atoms and molecules of natural substances to make them interact with light and other forms of energy in specific, controllable ways.

Metamaterials – Timeline
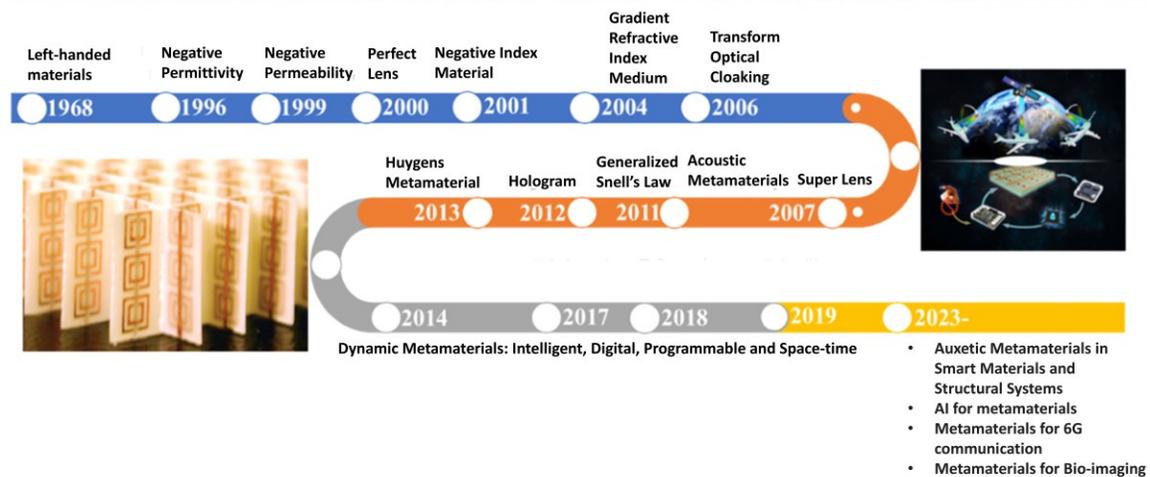
So, here is a brief outline. Here is a brief timeline of these metamaterials. So, you can see on the left that it all started with Soviet physicist Viktor Vasilago, who theoretically proposed left-handed materials (LHMs) with simultaneous negative permittivity and permeability, predicting unique wave features such as negative refraction.

Ok. However, because of the absence of natural left-hand materials, no experiment could be conducted at the time to verify this kind of prediction. And then there was a long wait until 1996, when Sir John Penry from Imperial College London proposed a wire structure to realize negative permittivity. So, there you can control the dimensions and the periodicity of the wires to control the plasma frequency. So, you can make artificial metal. So that way, you can achieve negative permittivity over a particular wavelength range.

In 1999, Professor Pendry again proposed split ring resonators that could realize negative permittivity. With that, when you have both negative permittivity and negative permittivity artificially created or designed. In 2000 and 2001, David Smith was the first to realize a medium with an effective negative index of refraction. So, that is when the perfect lens was proposed by Professor Pendry and David Smith; they made this device, which is shown here, the first negative index material or metamaterial. So, in this flowchart, you can see that from 2004, 2005, and 2006, a lot of evolution happened in this area of metamaterials, where people have looked for gradient refractive index media, transformation optics, and optical cloaking.

And then new areas came up, or application areas emerged, like superlenses. Acoustic metamaterials generalized Snell's law, creating hologram Higgins metamaterials, and then, right now, from 2014 to 2017, people have worked towards dynamic metamaterials, the intelligent digital programmable, you know, space-time variable, you know, metamaterials. Over the years 2017, 2018, and 2019, people are also focusing on auxetic metamaterials, smart materials, and structural systems. So, these are kind of mechanical metamaterials. People have involved AI in designing the unit cells to give you, you know, unique properties.

People are designing metamaterials for 6G communication, bioimaging, and other applications. There are a lot of things happening in this area of metamaterials and metasurfaces, which are basically the 2D version of these metamaterials.
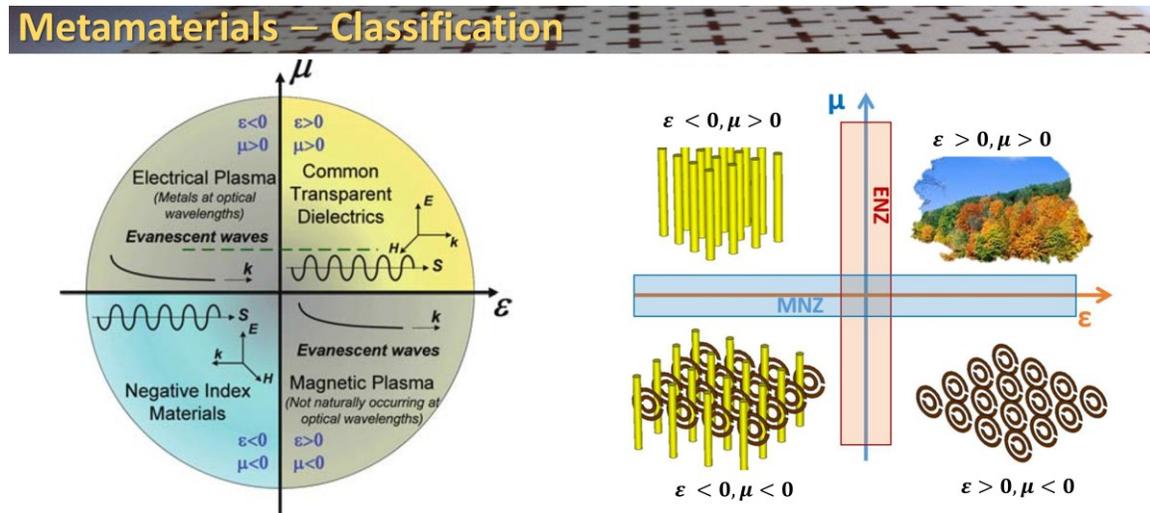
Now, the important part in metamaterials is also to classify the materials. So, this classification is done by these two important properties of material, which are the permittivity epsilon and permeability mu. So, these are the properties of every material.

So, this basically measures the opposition offered against the formation of an electric field in the case of epsilon ok. So, it indicates the number of charges required to generate one unit of electric flux in a given medium. Similarly, if you think of permeability mu, that is basically the measure of the ability of the material to allow the formation of magnetic lines of force, or you can say, a magnetic field within. So, it basically speaks of the ability of a material to be magnetized by any applied magnetic field. So, on the basis of permittivity and permeability, that is, epsilon and mu, the materials can be classified into four groups.

So, you can see the top right first quadrant. Here, the materials have both permittivity and permeability as positive. So, it is also called double positive materials, and most commonly occurring media, like common transparent dielectrics, fall into this category. So, you can see that if this is E and H, they follow the right-hand rule. So, you can find that both the wave propagation vector and the pointing vector are in the same direction.

Perfectly fine. So, this is where the common dielectrics lie. Then you go to the second quadrant, or the top-left quadrant. So, here the material has, you know, negative permittivity but positive

permeability. So, it is also called epsilon-negative material in a certain frequency range. So, here waves cannot propagate as you can see there are evanescent waves, okay.

And there are metals that behave like this in the optical frequency range. The bottom right of this one is the fourth quadrant. So, here a material has positive permittivity but negative permeability. So, it is also called negative mu metamaterial or material. So, in certain frequency regimes, some zyromagnetic materials can exhibit these characteristics, but typically not at naturally occurring optical wavelengths.

So, here also waves cannot propagate; it can only support evanescent waves, okay. Now, the most important quadrant in this metamaterial field is this third quadrant, or this bottom left quadrant, where a material gets simultaneously negative permittivity and negative permeability. So, it is also called double negative material, and this kind of metamaterials or materials can only be fabricated artificially. Here you can see that the E and H will have the wave vector in the other direction, meaning it is following the left-hand rule, whereas the pointing vector goes in the right direction. So, here we can also quickly see the engineered materials that can give you this kind of properties.

So, this tells you about the natural materials happening over here. Then, in the second quadrant, you can see that an array of metallic rods can behave like metal, giving negative permittivity over a particular frequency band. You can have an array of split-ring resonators that can give you negative permeability over a specific band. And when you club them together and make, you know, an array of rods along with an array of split ring resonators, you can get simultaneous negative permittivity and permeability.

- With an almost **limitless** array of possible meta-atoms, metamaterials offer **unparalleled design flexibility**.

- Metamaterials, with its electromagnetic properties dictated by their physical structure, can be designed for applications across the **microwave domain to the optical range**.

- Complementary split-ring resonator (copper patterns in FR4 substrate) based **Microwave metamaterials** resonating at f = 13.5 GHz *i.e.* λ = 2.22 cm.

Λ = 10 mm
a = 4.1 mm
$a \ll \lambda$

Here, $a \cong \lambda/5$

- Complementary split-ring resonator resonator (copper patterns in quartz substrate) based **Optical metamaterials** resonating at f = 1 THz *i.e.* λ = 300 µm.

Λ = 42.85 µm
a = 36 µm
$a \ll \lambda$
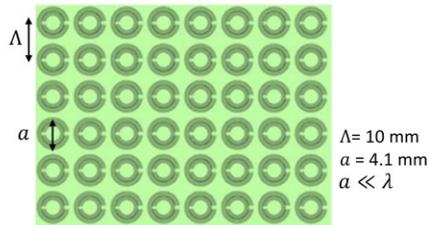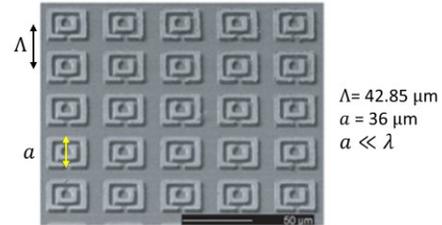
Here, $a \cong \lambda/7$

So, with almost you know limitless possibilities of designing this meta atoms you can understand that metamaterials offer unparalleled design flexibility. Metamaterials with their electromagnetic properties are basically dictated by the physical structure that can be designed for applications across microwave and optical frequencies. So, here is a complementary splittering resonator structure. These are basically copper patterns on an FR4 substrate. Based microwave metamaterials resonating at 13.5 gigahertz. So, the wavelength is around 22.2 centimeters. So, here you can see the period and the size of the elements. So, they are all sub-wavelength, okay. Similarly, in the optical regime, you can see that the scale is much smaller. So, this you can fabricate easily; this you have to go for nanofabrication.

So, this scale is around, you know, 50 microns. So, here also it is a complementary spectrum resonator structure; these are again copper patterns on a quartz substrate. So, these are working in the optical regime or optical frequency band. So, f is around 300 microns; lambda is typically 300 microns. You can see the periodicity and thus the element size.

- The concept of LHMs received little attention _for almost 30 years_ until the realization of _**negative permittivity**_ using _artificially composed metallic wires_ in 1996 by J. B. Pendry in microwave frequency range.

- The structure represents an array of thin metal wires.

- An electric field applied parallel to the axes of the wires generates a current in them, which produces equivalent electric dipole moments.

- When averaged, these dipole moments reveal the structure's permittivity with a plasmon-type frequency dependence:

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 + i\omega\zeta}$$

Electron Plasma Frequency
$$\omega_{pe} = \sqrt{\frac{2\pi c^2}{p^2 ln\left(\frac{p}{a}\right)}}$$

Damping Parameter
$$\zeta = \frac{2\omega_{pe}^2 \varepsilon_0}{\pi\sigma}\left(\frac{p}{a}\right)^2$$
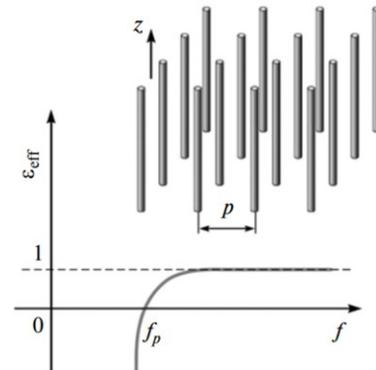
Inter-wire spacing: p Radius of wire: a c: velocity of light   σ: conductivity of the wire

Note: Interwire spacing p is much smaller than λ_g ($p \ll \lambda_g$), where λ_g is the length of the wave propagating in the structure.

So, there are sub-wavelengths, okay. So, here is what I want to show: the same concept can be applied in both the microwave and optical regimes. So, this is how metamaterials can be designed for specific applications. So, here is a quick overview of the development of microwave metamaterials. So, here the concept of left-hand materials was received almost 30 years before the realization of the first negative permittivity using artificially composed metallic wire arrays by Sartre and Pendry, and that was done in the microwave frequency regime. So, as you can see, there is a structure that represents an array of thin metallic wires.

So, p is basically the periodicity, and when you have an electric field applied along the axis of the wires, they generate a current in them, which produces equivalent electric dipole moments. So, when you average them, the dipole moments reveal the structure's permittivity. With a plasmon-type frequency dependence, you can see that the relative permittivity of this structure takes this particular form. Where omega p is basically the electroplasma frequency, which depends on the physical parameters p and a — where p is the wire spacing and a is the radius of the wire. So, what you can see here is that the metallic property, or the metal you are using, does not appear here, and that is how the structure basically defines the property.

What is c? c is the speed of light, okay. So, sigma (σ) plays a bit of a role in the damping because that is where the material parameter will get in, okay. So, how wide the resonance will be or how the damping parameter will take care of the conductivity. So, this is where the material of these wires will get into, but typically you can see that you can design a new material with the custom-made plasma frequency, okay. So, what you have to remember here is that the interparticle spacing is much smaller than the wavelength of the light or wave that is propagating through this structure. And when people have achieved getting artificial structures that give you negative permittivity, next, people have to explore what structures can give you negative permeability.

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 + i\omega\zeta}$$
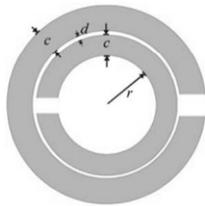
Electron Plasma Frequency
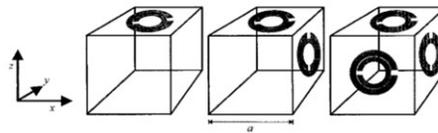$$\omega_{pe} = \sqrt{\frac{2\pi c^2}{p^2 ln\left(\frac{p}{a}\right)}}$$

Damping Parameter
$$\zeta = \frac{2\omega_{pe}^2\varepsilon_0}{\pi\sigma}\left(\frac{p}{a}\right)^2$$

Development of Microwave Metamaterials

- Complementary split-ring resonators show _**negative permeability**_ in the GHz range, developed by J.B. Pendry is shown below:

Designed complementary split ring

Building 3-D symmetry: each successive restacking of the structure adds a ring to another side of the unit cell.

Sequence of split rings shown in their stacking sequence to form columns of rings
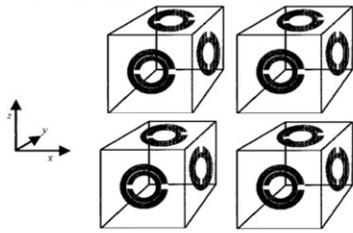
$a = 1.0 \times 10^{-2}$ m
$c = 1.0 \times 10^{-3}$ m
$d = 1.0 \times 10^{-4}$ m
$\ell = 2.0 \times 10^{-3}$ m
$r = 2.0 \times 10^{-3}$ m.

And that is also done by Professor John Pendry; he demonstrated that the complementary split ring resonator structure can give you negative permeability in the gigahertz range. So, this is the design of the complementary split ring. So, this is a C. And then you have the opposite kind of C over there. These are the structural parameters, all typically in the millimeter range.

So, if you want to make a 3D symmetric design, you have to stack this kind of structure on each side of the unit cell. So, finally, you can use this one and repeat it periodically. OK. So, this is how the stacking has to be done.

So, one splitting resonator is here; the other one will be below. Similarly, in all three directions, it has to go and replicate itself. So, that is how you can make a 3D cubic symmetry structure, you know. So, here I just copy-pasted the unit cell to show you what you have on the top surface. So, there is nothing on the bottom surface; this top surface will go and align with that here. Also, on the right surface, you have the left surface, which is blank.
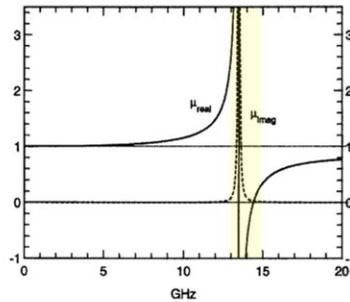
Structure with cubic symmetry

- The resonant frequency (ω_0) can be calculated using dimensional parameters as:

$$\omega_0 = \frac{3lc_0^2}{\pi \ln \frac{2c}{d} r^3} = 2\pi \times 13.5 \text{ GHz}$$

$a = 1.0 \times 10^{-2}$ m
$c = 1.0 \times 10^{-3}$ m
$d = 1.0 \times 10^{-4}$ m
$\ell = 2.0 \times 10^{-3}$ m
$r = 2.0 \times 10^{-3}$ m.

Plot of μ_{eff} for the cubic split ring structure calculated using the chosen parameters.

So, the right surface will be periodically extended; the top surface is periodically extended, and then the whole thing, the plane, can be thought of as extending in the y direction. So, that is how you can make a structure with cubic symmetry, and once you calculate the resonant frequency of this kind of structure, you can see that they all depend on the structural parameters like r, c, d, and l. So, all these parameters are shown here; l is basically this particular spacing. So, here you also understand that the frequency at which the negative permeability will be seen basically depends on the structure. So, that is how you are able to make artificial materials for giving you custom-made permittivity and permeability for a particular frequency range.

$$\omega_0 = \frac{3lc_0^2}{\pi \ln \frac{2c}{d} r^3} = 2\pi \times 13.5 \text{ GHz}$$

- By combining the two underlying artificial structures, _D. R. Smith_ and his research group realized **_negative permittivity and permeability_ simultaneously** and observed negative refraction in experiment for the first time in 2001.

Negative ε_{eff} of the metallic-rod metamaterial
+
Negative μ_{eff} of the metallic split-ring metamaterial
=
Double-negative metamaterial
_i.e._ **negative-index/left-handed material**
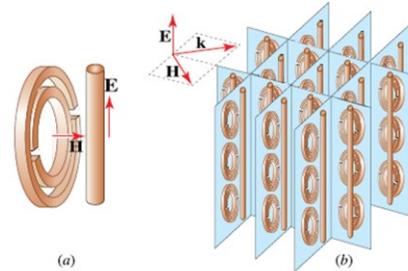
- Implementation is achieved by repeating the combined rod and complementary split-ring element in two directions.

- _This design was first experimentally demonstrated in the microwave region, and its dimensions were subsequently scaled down for operation at optical frequencies._

Figure: (_a_) Combined rod and complementary split-ring element. (_b_) Left-handed metamaterial comprising an array of the elements shown in (_a_), oriented along **two** orthogonal directions.

So, with that, when you have two things ready independently. And you can mix them together. So, effective negative permittivity and negative permeability from the split ring resonator, the first one coming from the metallic rod, were combined together. So, why don't you make a unit cell like this and repeat it periodically? So, this is the structure that can give you both permittivity and permeability negative simultaneously over a particular frequency range, and that is what was called the first demonstration of negative index material or left-handed metamaterials. So, the design was shown in the microwave region, but its dimensions can be scaled down for operation at optical frequencies.

So, this is the first photograph of the left-hand material sample. So, you can see that there are, you know, split ring resonators made on, you know, fiberglass circuit board material; on the back side, there are these metallic wires, and then they have been assembled into an interlocking lattice to make this kind of structure, and this was the actual calculation of the negative refractive index, okay. It shows that you are actually able to get a negative refractive index for this left-handed material over 10 gigahertz. So, there are some asymptotes because of the limitations of the measurements. Teflon was used as a reference, but you can see that at this particular frequency, you are able to get, you know, negative permeability and a negative index of refraction, right?

- This structure built at University of California San Diego (UCSD) by Smith and Schultz comprising split rings and wires designed to give negative refraction at around 10 GHz.
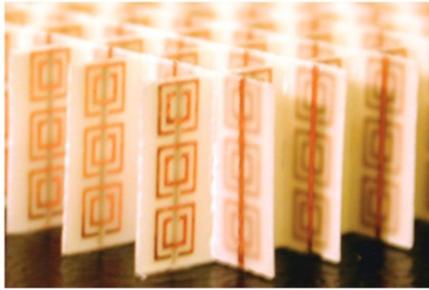
Fabricated structure on FR4
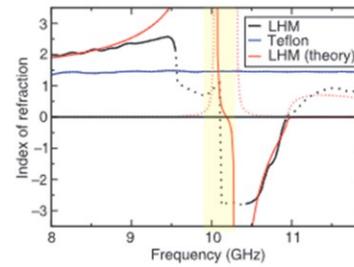
Index of refraction versus frequency

So, this structure was built at the University of California, San Diego, by Smith and Schultz. So, they actually brought two things together, and this was the first demonstration.

And this has opened a lot of applications and a lot of interest among researchers, allowing you to design your own material. You don't need to depend on natural materials or be limited by their particular wavelength range or dispersion diagram. You can create material with a desired refractive index and desired permittivity or permeability. So, you can actually control the way electromagnetic waves will interact with your designed materials.

So, with that, we will stop here, and if you have any queries. Regarding this particular lecture, you can always drop an email to this email address deb.sikdar@iitg.ac.in, but make sure you mention MOOC and the course title in the subject.