Course Name: Introduction to Microwave and Optical Metamaterials
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Week-11
Lecture-53

Lec 53: Tunable metamaterials and Magnetically tunable metamaterials

Hello everyone, welcome to Lecture 53 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be about tunable metamaterials.

Lecture Outline

- Need for Tunable Metamaterials: Limitation of Conventional Metamaterials
- Introduction to Tunable Metamaterials
- Magnetically Tunable Dielectric Metamaterials
    - Ferrite/Wire Composite Structure
    - Structure of Ferrite Metamaterial Filter
    - Ferrite/Dielectric Composite Structure

Here is the lecture outline. So, we will first discuss the need for tunability in metamaterials. We will highlight the limitations of conventional metamaterials, and then we will briefly introduce the concept of tunable metamaterials. Take up some examples of magnetically tunable dielectric metamaterials in the form of ferrite wire composite structures.

Or you know of ferrite metamaterial filters and some ferrite dielectric composite structures.

Tunable Metamaterials

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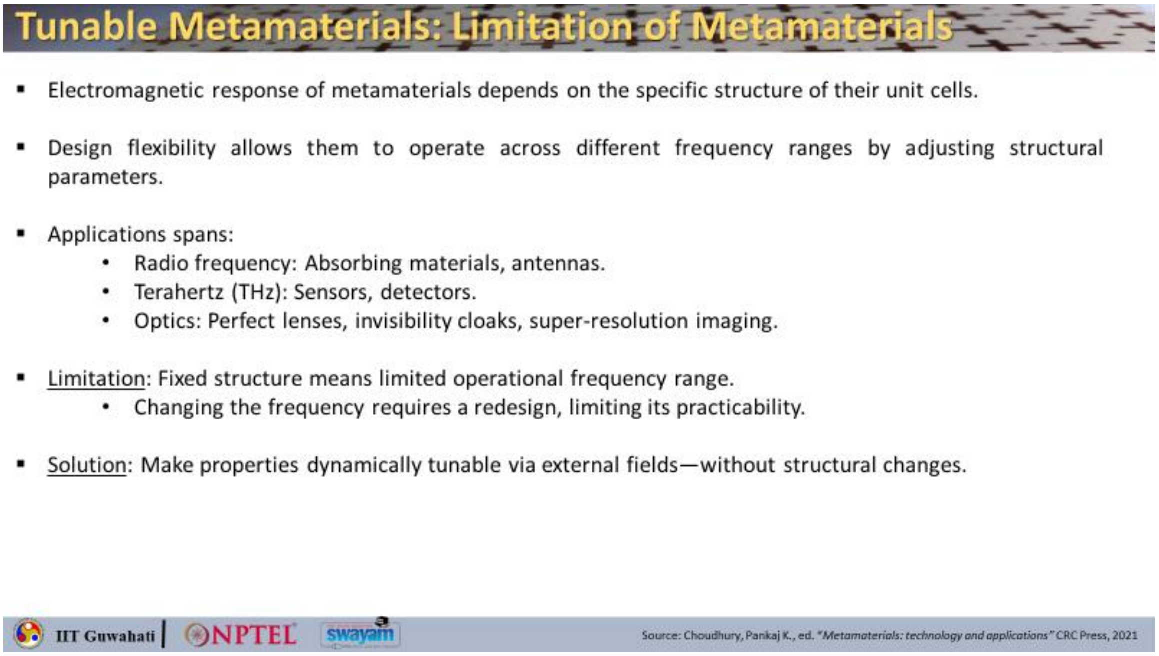
So, let us first see why tunability is required in metamaterials.



So, we have understood that the electromagnetic response of a metamaterial basically depends on the specific structure of its unit cells. And you can design different unit cells for metamaterials that operate at different frequencies.

So we have seen applications in the radio frequency domain; you can create metamaterials for absorption. So, they can work as meta-absorbers or antennas. In the terahertz domain, you can create sensors and detectors. In optics, we have seen you can make perfect lenses, invisibility cloaks, and also achieve super-resolution imaging. So, what is the problem? The problem here is that once fabricated, these fixed structures will operate within their specified frequency range; you cannot tune them right.

So, if you want the structure to operate at a different frequency range slightly even slightly different frequency range You need to redesign the structure and go through the, you know, process all over again. So, you know changing the frequency will require a redesign, and that is where the cost will also come into the picture, right? So, you have to do the process again. So, what is the solution? So, you can think of making these metamaterials dynamically tunable now via some external fields. that will act as stimuli without causing any physical or structural change to the metamaterials. So, that brings us to the concept of tunable metamaterials, and we will first look into tunable dielectric metamaterials, okay.

Introduction to Tunable Metamaterials

- Tunable Dielectric Metamaterials:
  - Sensitive to external stimuli: Magnetic field, electric field, temperature, and strain.
  - Enable real-time control of electromagnetic characteristics.
  - Key applications: Wireless communication systems, radar, smart antennas, microwave devices.

- Categorization of tunable metamaterials (based on tuning methods):

  1. **Magnetically Tunable Metamaterials**:
     - Adjust permeability and permittivity using external magnetic fields.
     - Advantages: Wider tuning range and faster response speed.
  2. **Electrically Tunable Metamaterials**: Modify unit cell properties via bias voltage.
  3. **Thermally Tunable Metamaterials**: Leverage temperature-dependent dielectric constant changes.
  4. **Strain/Stress Tunable (Flexible) Metamaterials**:
     - Electromagnetic properties altered by mechanical deformation.
     - Ideal for wearable and flexible electronic systems.

Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

These are basically sensitive to external stimuli such as magnetic fields, electric fields, temperature, and strain. And tunability in the visible and near-infrared range is also critical for advanced optical applications. So, as you understand, they enable real-time control of the electromagnetic characteristics. Their key applications involve wireless communication systems, radar, smart antennas, and microwave devices for this kind of metamaterials. In the case of optics, you will understand that there are different tunable optical devices.

that can be made from these metamaterials which are dynamically tunable. Now, let us categorize these tunable metamaterials. The category will be decided based on its tuning methods, okay.

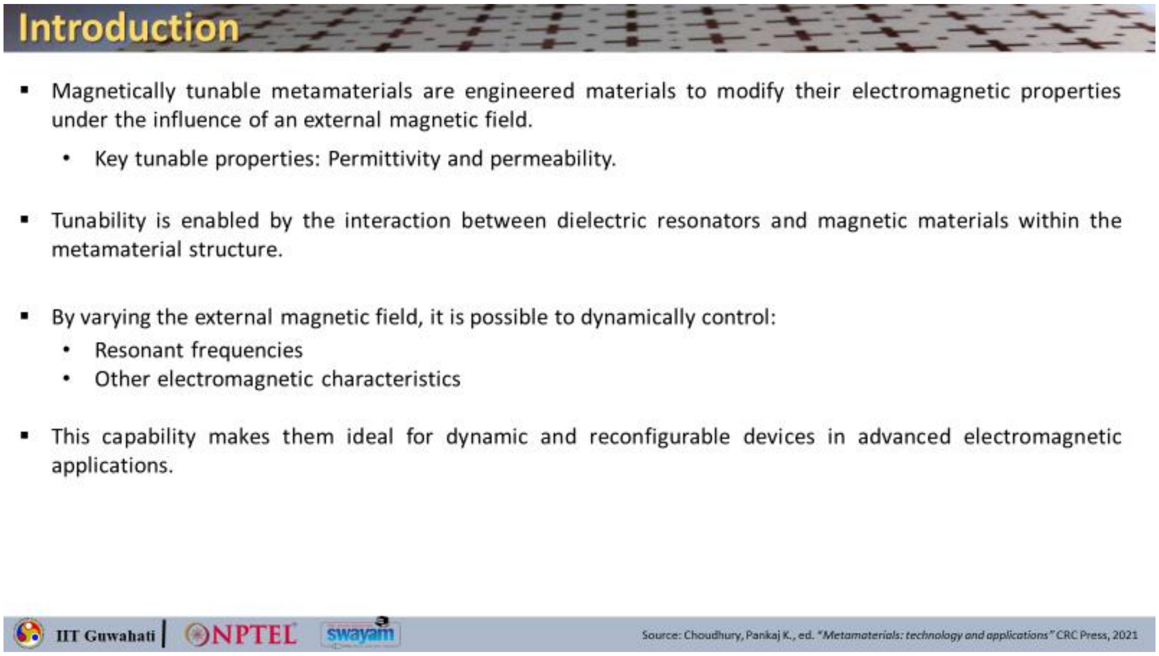
So, let us first consider magnetically tunable metamaterials that can adjust permeability and permittivity by using external magnetic fields. The advantages here will be that you can achieve a wide tuning range and faster response speed.

Then you can also think of electrically tunable metamaterials. So, here the properties of the unit cells can be changed by changing the bias voltage, okay. And then you will have thermally tunable metamaterials. So, here you are basically using the external stimulus of temperature, right. So, you basically have the scope to leverage the temperature-dependent dielectric constant changes, right. So, you can stack VO_2 over TiO_2 in this kind of multilayers. Using the metal-insulator phase transition in VO_2, which is a very common phenomenon.

The dispersion can be tuned from elliptic to hyperbolic dispersion, which you have already discussed in this course. So that can help you to gain that tunability. Next, you can also use strain stress. For tuning the metamaterials. So, here the electromagnetic properties will be altered by mechanical deformation, right. So, these are ideal for wearable and flexible electronic systems.

So, among these, let us focus on magnetically tunable metamaterials because of their wider tuning range and faster response speed.

So, this is what we will be looking at right now: magnetically tunable dielectric metamaterials.



So, magnetically tunable metamaterials, again, you can understand that these are metamaterials or engineered structures. which allows modification of the electromagnetic properties under the influence of an external magnetic field. So, the key tunable properties, obviously, are the, you know, permittivity and permeability, right. So, the tunability is basically enabled by the interaction between dielectric resonators.

And the magnetic materials within the metamaterial structure. So, when you vary the external magnetic field. It is possible to dynamically control the resonance frequencies as well as. Other electromagnetic characteristics, like local field distribution, in this kind of structure. So, this capability basically makes them ideal for dynamic and reconfigurable devices in advanced electromagnetic applications.

Introduction

- Ferrite is a gyromagnetic medium that exhibits ferromagnetic resonance under an external magnetic field.
- This resonance enables realization of negative magnetic permeability within specific frequency ranges.
- Tunable frequency ranges:
    - The resonance frequency band showing negative permeability; can be precisely tuned by adjusting strength of the external magnetic field.
- Applications of ferrite materials include design of tunable electromagnetic devices such as:
    - Negative refraction metamaterials
    - Metamaterial-based antennas
    - Metamaterial-based band-pass filters
    - Metamaterial-based band-stop filters

Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

Ferrite is a gyromagnetic medium, that exhibits ferromagnetic resonance under an external magnetic field. So, this particular resonance enables realization of negative magnetic permeability within a given frequency range. So, tunable frequency ranges where you can have this negative permeability can be adjusted by tuning the applied external magnetic field. So, when you bring ferrite materials into your metamaterial design, that is basically it,
enabling you to develop tunable electromagnetic devices such as negative refraction metamaterials, Metamaterial-based antennas, metamaterial-based bandpass filters, and bandstop filters. So, now let us look into a particular application of this kind of structure.

Ferrite/Wire Composite Structure

- A ferrite-based metamaterial using yttrium iron garnet (YIG) ferrite rods and copper (Cu) wires designed to achieve magnetically tunable negative refraction.
- The metamaterial structure consists of: (see Fig. 1(a))
  - YIG rods; Cu wires and
  - An external magnetic field applied along the long axis of ferrite.
- Transmission measurements (Fig. 1(b)) show:
  - As the magnetic field increases from 1,600 Oe to 2,300 Oe:
    - ✓ Center frequency shifts from 8.2 GHz to 10.7 GHz.
    - ✓ Tuning response speed reaches 3.5 GHz/kOe.
- This structure enables dynamic, continuous, and reversible magnetic tunability across a broad frequency range.
  - Indicates that the operating frequency can be easily adjusted by changing the external magnetic field.

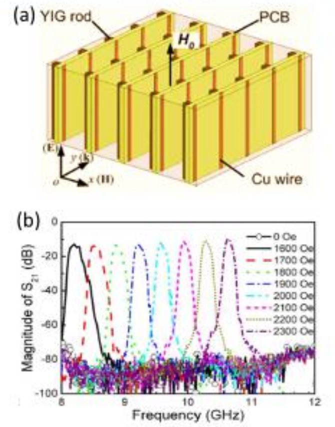


Figure 1: (a) Schematic of tunable left-handed material; (b) Transmission spectra for metamaterial under a series of applied magnetic fields

Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

So, here you can see a ferrite-based metamaterial using yttrium iron garnet ferrite rods with copper wires in this particular structure. So, this is designed to achieve magnetically tunable negative refraction. So, you can carefully see this particular structure, it consists of YIG rods and copper wires on either side of the PCB substrate.

And then you have an external magnetic field that is H naught, okay, that is applied along the long axis of the ferrite. So, this is how the wave will propagate through this metamaterial. So, this is the wave direction, and you will have this as the x-axis and this as the z-axis. So, the wave is propagating along the y-axis that is marked with the wave vector k. The magnetic field of the incoming wave will be along the X-axis, and the electric field will be along the Z-axis.

This is the schematic. So, you can see this is a periodic structure made of, you know, YIG rod. On the backside, you have copper wires on two sides of the PCB, okay. So, this is the metamaterial, and when you obtain the transmission spectrum for this metamaterial over a frequency range of 8 to 12 gigahertz. So, this is the magnitude of S21 that tells you about the transmission coefficient of transmittance, okay. So, you hear that the same thing is obtained for different applied magnetic field strengths. So, the solid black one is for 1600 OE.

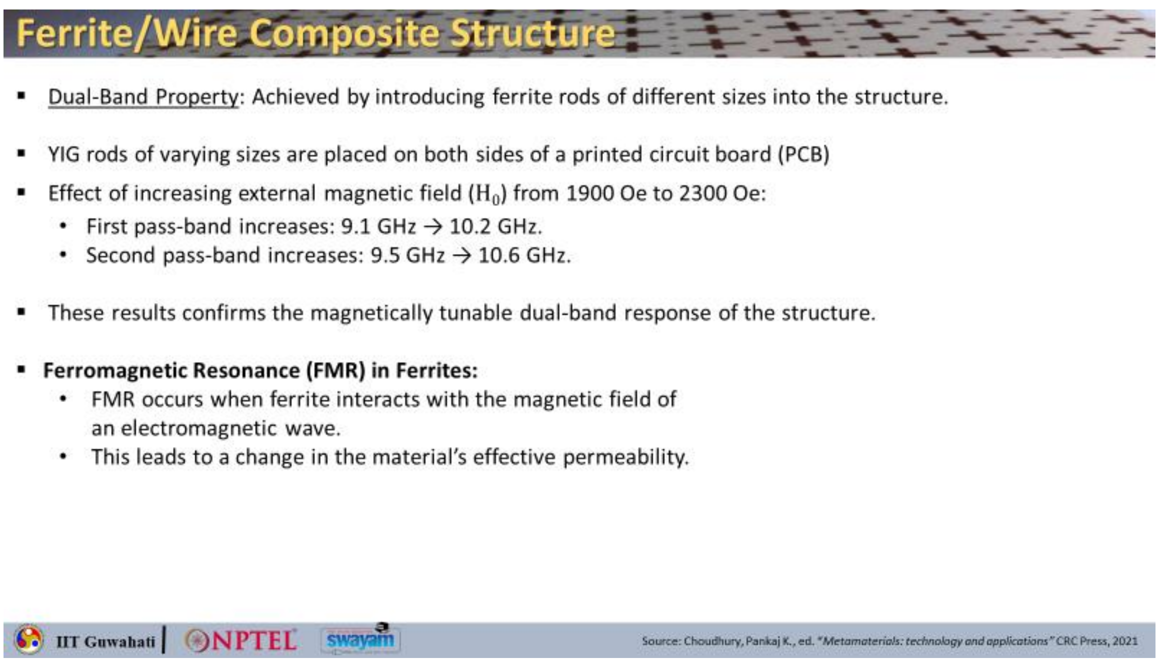
So, OE is basically Oersted, which is another unit of magnetic field strength. So, if you want to correlate with Tesla, 1 Oe is basically equal to 12.566 millitesla, okay. So, that way you can correlate between oersteds and Teslas. So, here you can see the magnetic field has increased from 1600 oersted to 2300 oersted.

And that has allowed the center frequency to shift from 8.2 to around 10.7 gigahertz. And the tuning response speed basically reaches 3.5 gigahertz per kilo oersted, okay.

So that is how you can tune the bandpass property of this particular structure, right? Now this structure enables dynamic continuous and reversible magnetic tunability Across a broad frequency range that you can see here. Now, the term reversible basically refers to the ability of the structure to return to its original electromagnetic state. When the external magnetic field is removed or reduced, right.

So, the reversible behavior here basically means that the magnetically tuned electromagnetic property. such as negative refraction or the transmission window that you see here, they can be both increased and restored depending on the applied magnetic field. So that basically enables dynamic and repeatable control over the performance of the metamaterials.

So, you can say that this metamaterial structure exhibits broadband magnetic tunability. So, the best thing is that the operating frequency can be easily adjusted by changing the external magnetic field without altering anything in the structure.

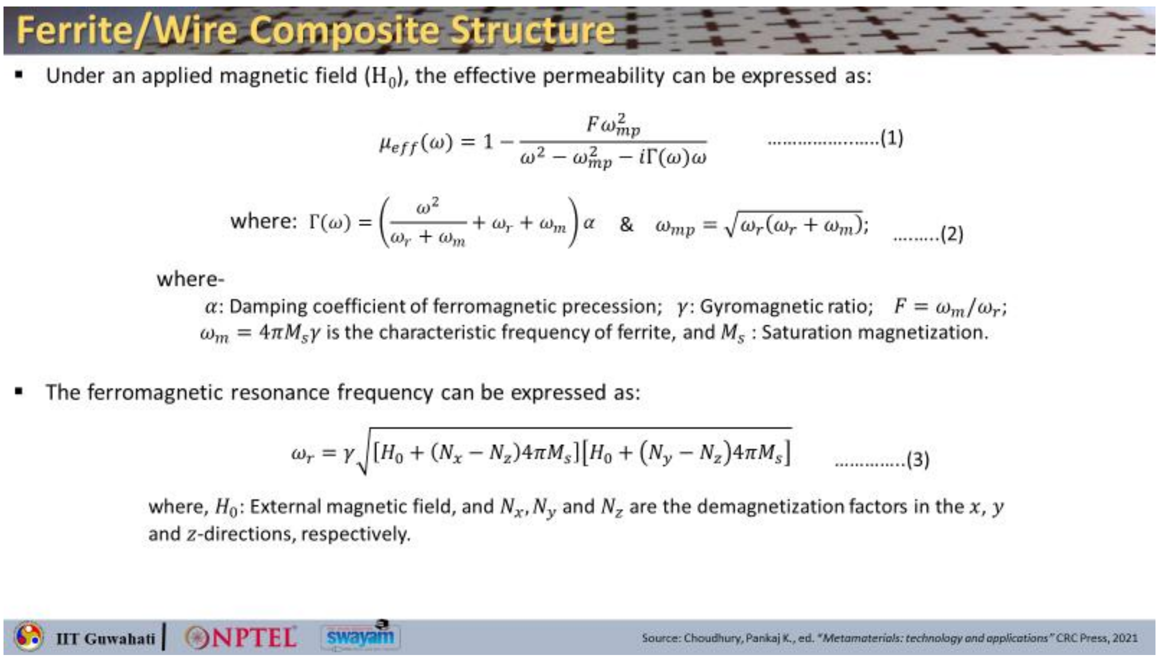


This can be further extended to achieve dual-band property. You can introduce another set of ferrite rod of different sizes into the structure.

So when you have YIG rods of varying sizes placed on both sides of the printed circuit board, they are not shown here. But if you repeat the same exercise that you change the external magnetic field H naught from 1900 oersted to 2300 oersted, you will see that you will get basically two passbands now. So, the first pulse band can be moved from 9.1 gigahertz to 10.2 gigahertz when you change the magnetic field from 1,900 to 2,300 oersted.

And the second pulse band can also be shifted from 9.5 to 10.6 gigahertz for this magnetic field change. So, this kind of result confirms that you know you have a magnetically tunable dual-band response from the structure. So, these are ferromagnetic resonances, also called FMR, that you see in ferrites.

So, this FMR, or ferromagnetic resonance, occurs when ferrite material interacts with the magnetic field of an electromagnetic wave. And this basically leads to a change in the material's effective permeability, which is causing the change. So, let us see how it happens.



So, under an applied magnetic field H naught, you can write down the effective permeability ($\mu_{eff}(\omega)$) in this particular form. So, you can write $\mu_{eff}(\omega)$ as a function of omega, which will be: $\mu_{eff}(\omega) = 1 - \frac{F\omega_{mp}^2}{\omega^2 - \omega_{mp}^2 - i\Gamma(\omega)\omega}$.

So, here $\Gamma(\omega)$ is basically given by: $\Gamma(\omega) = \left(\frac{\omega^2}{\omega_r + \omega_m} + \omega_r + \omega_m\right)\alpha$.

So, α is the damping coefficient of ferromagnetic precision and then you have this F, this constant F which is nothing but ω_m/ω_r.

So, ω_r is the resonance frequency, and ω_m is nothing but the characteristic frequency of the ferrite that is given as: $\omega_m = 4\pi M_s \gamma$.

This γ is the gyromagnetic ratio, and M_s is nothing but the saturation magnetization, right.

So, from this, you can find the ferromagnetic resonance frequency, which is ω_r , that can be expressed as: $\omega_r = \gamma\sqrt{[H_0 + (N_x - N_z)4\pi M_s]\left[H_0 + \left(N_y - N_z\right)4\pi M_s\right]}$.

So, these are basically the demagnetization factors along a particular direction, okay. So, H_0, as I mentioned, is the external magnetic field; N_x, N_y, and N_z are basically, the demagnetization factors in the x, y, and z directions are respectively.

So, based on these equations that you see here: 1, 2, and 3. So, you can understand that the magnetic permeability of ferrite is strongly dependent on resonance frequency, right.

Ferrite/Wire Composite Structure

- Magnetic Permeability Insight:
  - Based on Eqs. (1)–(3), magnetic permeability of ferrite is strongly depends on resonance frequency.
- Dual-Resonance Effect:
  - Two different sizes of ferrite rod result in:
    - ✓ Two negative permeability regions near their respective ferromagnetic resonance frequencies.
    - ✓ Formation of two left-handed pass-bands when combined with a metal wire array, providing negative permittivity.
- Therefore; ferrite/metal wire combine structure is a typical structure of the left-handed material configuration.
- This structure supports low-loss, magnetically tunable characteristics and simple to construct.

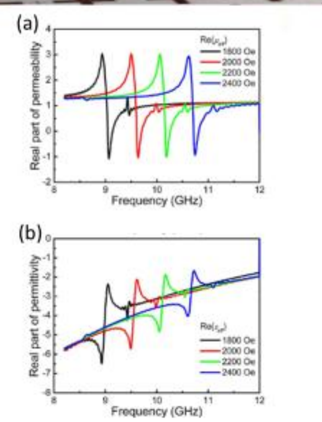


Figure 2: (a) Permeability and (b) Permittivity for the combination of the rods with copper wires at different passband frequencies

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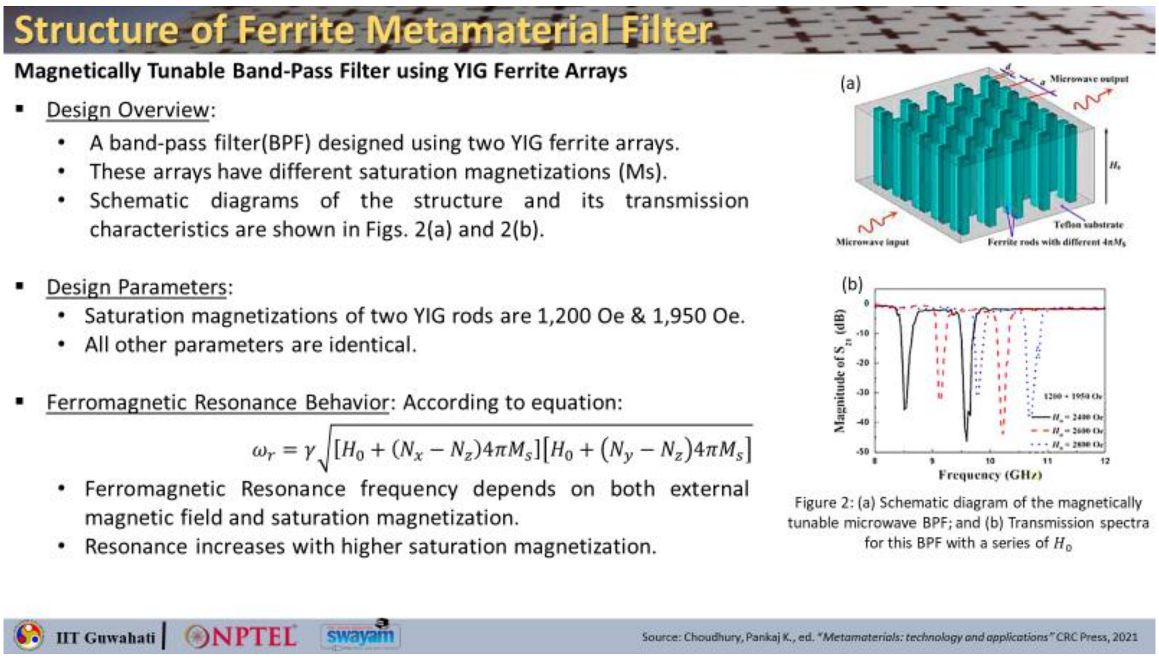
Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

So, here you can actually see the real part, so here you can actually see in this figure, so the permeability and the permittivity, so here are the real part of the permeability and the real part of the permittivity. Over this given frequency range, the data is plotted for different applied magnetic fields: 1800, 2000, 2200, and 2400 oersted. So, you can actually see that where you are getting negative permeability, and here you are getting negative permittivity in all the cases, Okay.

So, these are basically for the combination of the ferrite rods with copper wires, okay, at different passband frequencies, right. So, we have also discussed the dual resonance effect. So, when there are two different sizes of ferrite rods, you basically start getting two negative permeability regions. near their ferromagnetic resonance frequencies, and that allows the formation of two left-handed pass bands. when it is combined with metal wire array which is providing negative permittivity, right. So, you can see that this ferrite metal wire combined structure is typically a structure that gives you left hand material configuration, right. So, this structure basically supports low-loss magnetically tunable characteristics, and the best thing is that it is very simple to construct.

Now, let us look into the structure of a ferrite metamaterial filter, okay.



So, this is a magnetically tunable bandpass filter using YIG ferrite arrays, okay. So, the design overview tells us that you are going to design a bandpass filter using two YIG ferrite array.

So you can see this particular diagram. Okay, so you can see that two different colored rods are shown; these are basically two different ferrite rods. With different $4\pi M_s$ magnetization properties, and then you have a Teflon substrate in which the entire thing is embedded, okay. So, the gap between the rods is considered to be d, and a is the periodicity; this is where the microwave enters. This is where it exists; this is the overall height of the structure. And this is the direction of the external magnetic field that is being applied, okay.

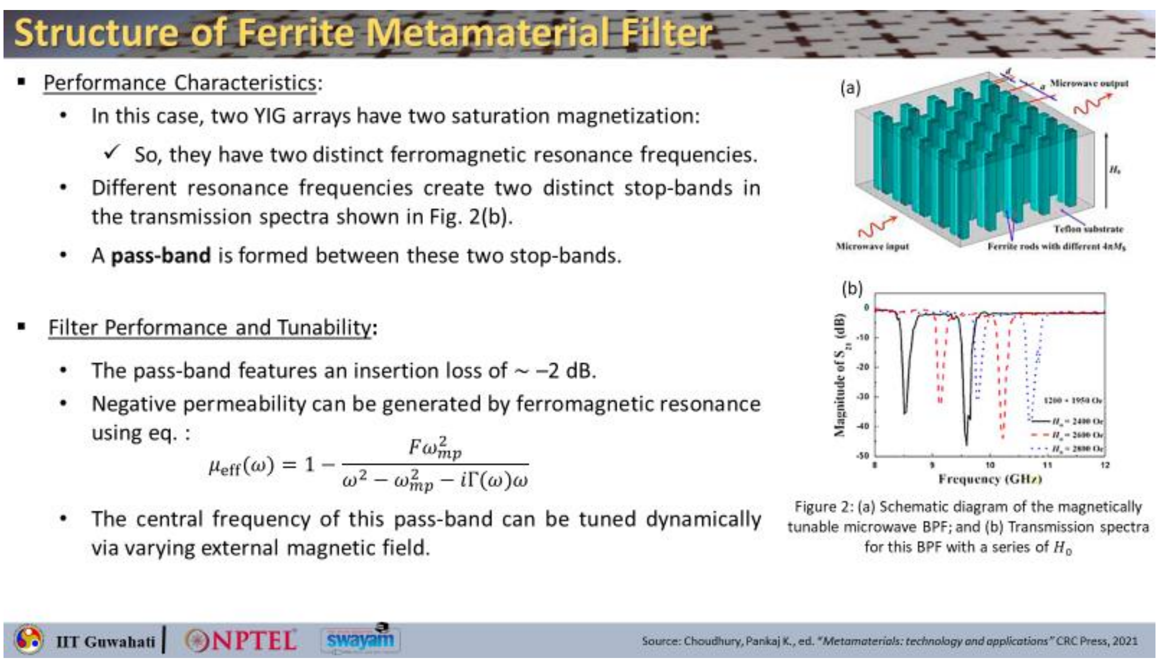
So, as you understand, these arrays will have different saturation magnetization M_s, okay. and their corresponding transmission characteristics are plotted here. So, what is important to note here is that you are getting basically two dips. In between, you are getting a flat band, and this is the bandpass filter characteristics. And this is possible because of the use of two different ferrite rods with different saturation magnetization.

Now, saturation magnetization is a fundamental magnetic property of ferromagnetic materials, such as YIG (Yttrium Iron Garnet). That basically tells you the maximum magnetization of a material that can be achieved when fully magnetized by an external magnetic field. So, here you can see the values of the saturation magnetization for the two YIG rods. One is 1200 Oe and the other is 1950 Oe, okay. All other parameters are essentially taken as identical.

So, you can obtain the ferromagnetic resonance behavior according to this equation:

$$\omega_r = \gamma\sqrt{[H_0 + (N_x - N_z)4\pi M_s][H_0 + (N_y - N_z)4\pi M_s]}$$, right.

So, here you will see that the ferromagnetic resonance frequency depends on both the external magnetic field H naught, as well as the saturation magnetization of the material, is correct, right and the resonance frequency basically increases with higher saturation magnetization.



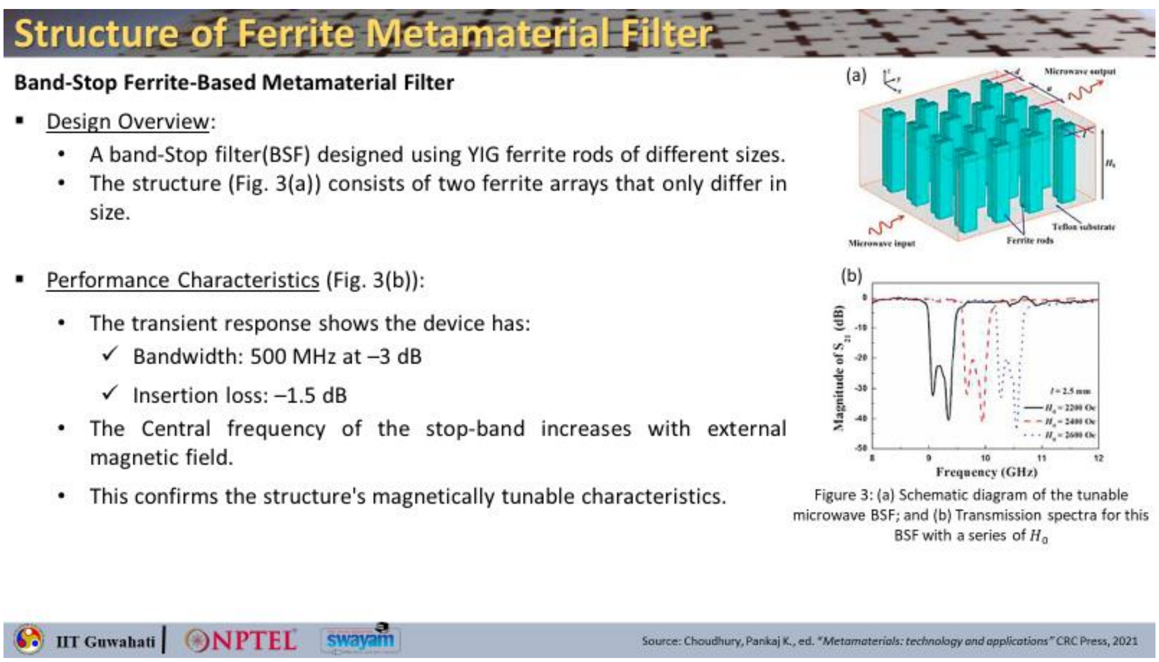
So here you can see that in this case, because you have two YIG arrays, which have two different saturation magnetizations, you basically have two different resonances, ferromagnetic resonance frequencies. And these two ferromagnetic resonance frequencies basically give you two distinct stopbands, as you can see here.

So, a pulse band is basically formed. So, we are just talking about the solid black line, which corresponds to the case of 2400 Oersted, okay. Fine. So, these two dips basically tell you about the two stop bands, and there is a pass band in between. And the best thing here is that you can see that the passband has an insertion loss of only minus 2 dB. So, it is a very good performance for the filter, and it is pretty flat as well.

So, the negative permeability here can be generated by ferromagnetic resonance. You can take this equation, which you have seen earlier; $\mu_{\text{eff}}(\omega)$ as a function of ω can be written as: $\mu_{\text{eff}}(\omega) = 1 - \frac{F\omega_{mp}^2}{\omega^2 - \omega_{mp}^2 - i\Gamma(\omega)\omega}$.

So, the central frequency of this passband, that is, this one, can be dynamically tuned by changing the magnetic field strength. So, if you change it to 2600, you will see you are getting two red dips, these red dashed lines.

So the passband is actually shifted here. If you further increase the external magnetic field to 2800. You are looking at the blue dotted line. So, the passband basically shifts over here, right.



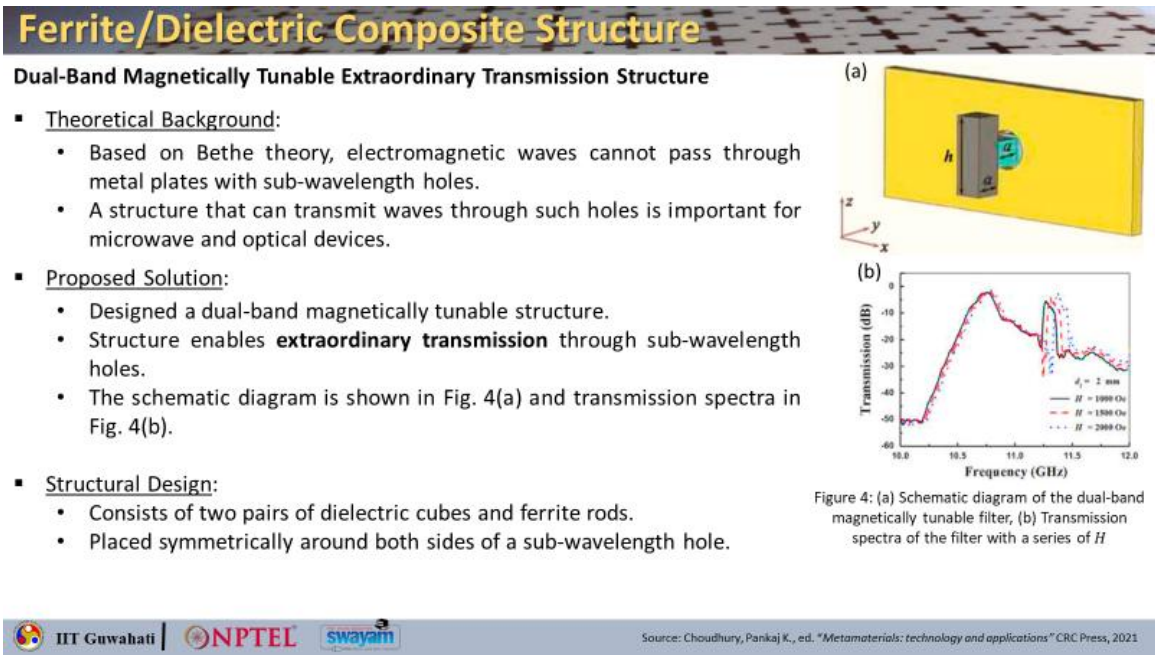
So, now let us look into the opposite kind of filter that is a band-stop filter based on these ferrite-based metamaterials, okay. So, you can also design a band-stop filter using YIG ferrite rods, but this time you can go with different sizes of rods, okay.

So, one is big, one is small as you can see here, and the remaining structure looks pretty much similar to the previous one, okay. So, you are here again just making two ferrite arrays, but this time they are different in size.

So, what do you see. You can obtain the transmission characteristics and transmission spectrum, and it shows a stop band. And you can see the stop band has a bandwidth of around 500 megahertz at minus 3 dB, and the insertion loss for this is typically minus 1.5 dB. So, the solid black line shows you the band stop filter at a 2200 Oersted applied magnetic field. If you change it to 2400 it moves to this red one so this becomes the new filter.

At 2600 the blue dotted one shows you the filter characteristics. So, you can actually shift from somewhere, say 9.2, the center frequency to somewhere around 10.5, okay. So, that way you can change the central frequency of the stopband and increase it with the increasing external magnetic field.

So, this basically confirms the structure's magnetically tunable characteristics.



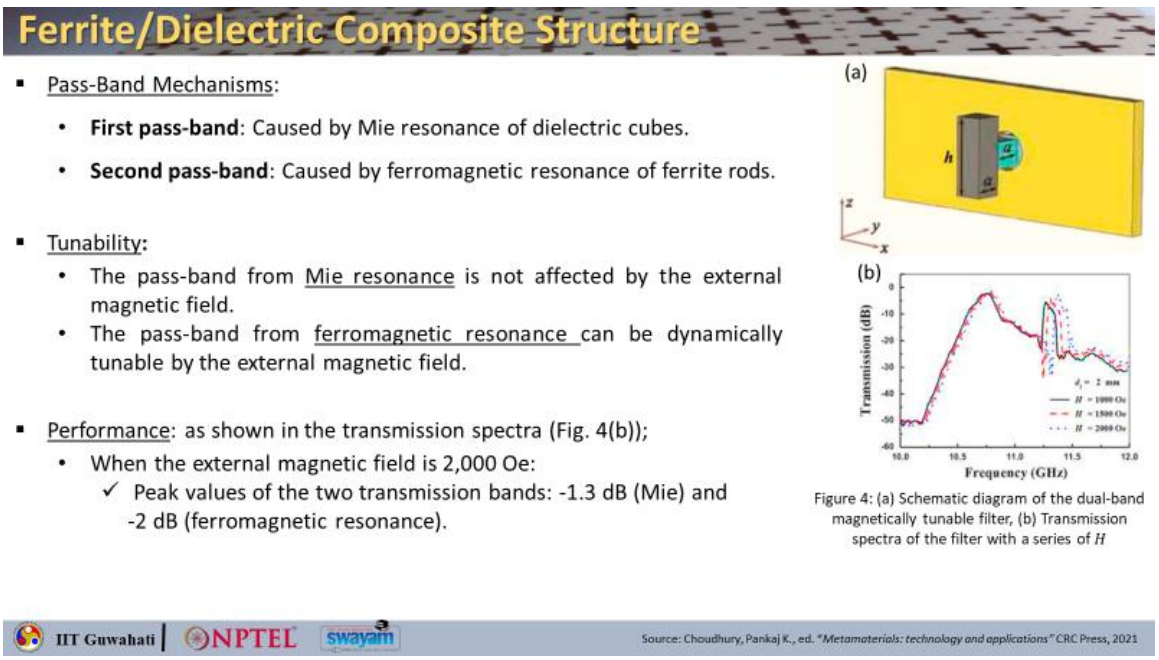
Now let us also look into some more ferrite-dielectric composite structures that allows dual band magnetically tunable extraordinary transmission. So, based on the Bethe theory, electromagnetic waves cannot pass through metal plates with sub-wavelength holes, okay.

Now a structure that can transmit waves through such holes will be very important for microwave and optical devices. So, a proper solution to this kind of phenomenon would be to design a dual-band magnetically tunable structure. So, this structure basically enables extraordinary transmission through this sub wavelength holes. So, here you can see that sub-wavelength hole, and you can see this is the schematic diagram of. the dual band magnetically tunable filter and this is the transmission characteristics okay.

There are two bands, basically, right. So, what is the structure here?

The structure basically consists of two pairs of dielectric cubes and ferrite rods, so one on the other side as well. They are basically placed symmetrically on both sides of the sub-wavelength hole. So, the same structure is on the other side as well, right? So, you will see that you have basically a dielectric cube that you see here, and then you have a ferrite rod.

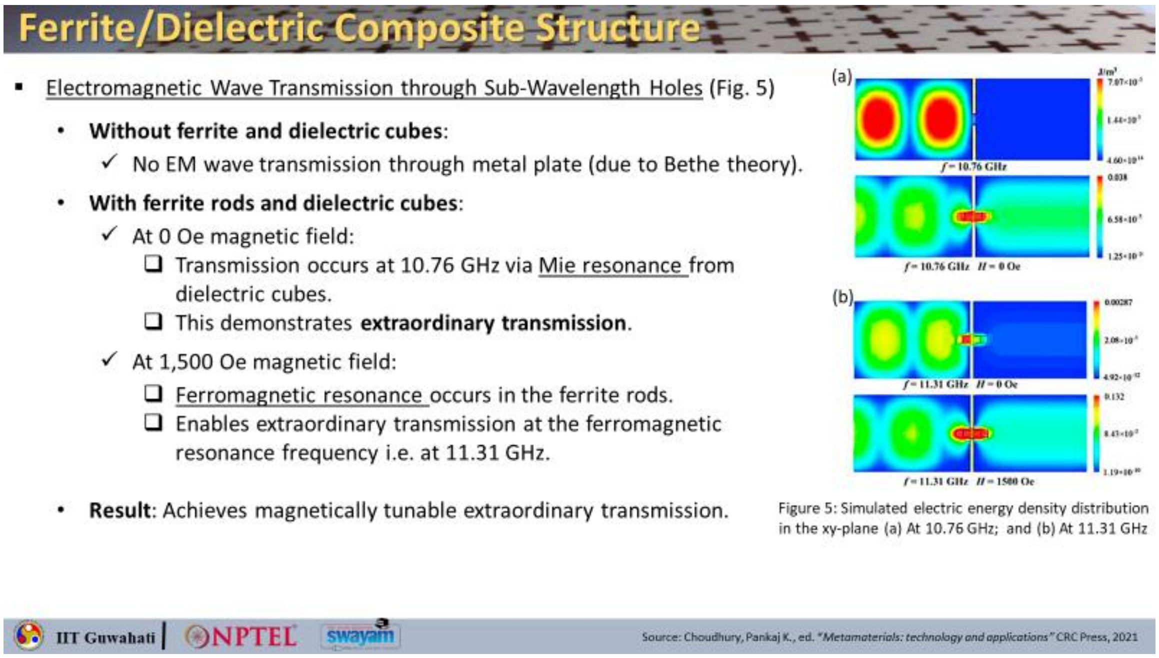
Now these two materials basically have different characteristics, and that is why you get the first passband.



That is coming from the Mie resonance of these dielectric cubes, okay. And then you have the second passband that is basically coming from the ferromagnetic resonance of the ferrite rods. Now, if you think of tunability, the passband that is originating from the resonance is not affected. by an external magnetic field because it is coming from the dielectric structure. But the passband that is coming from the ferromagnetic resonance is coming from a ferrite material.

So, it can be dynamically tuned by changing the external magnetic field. So, h is changed from 1000 to 1500 to 2000, and you can see this is how the second pulse band is changing, right? So, what few important observations here are that when the external magnetic field is 2000 Oersted, okay. So, the peak value of the two transmission bands will be somewhere close to minus 1.3 dB, which is for the Mie case. And this one is around minus 2 dB, which is coming from the ferromagnetic resonance.

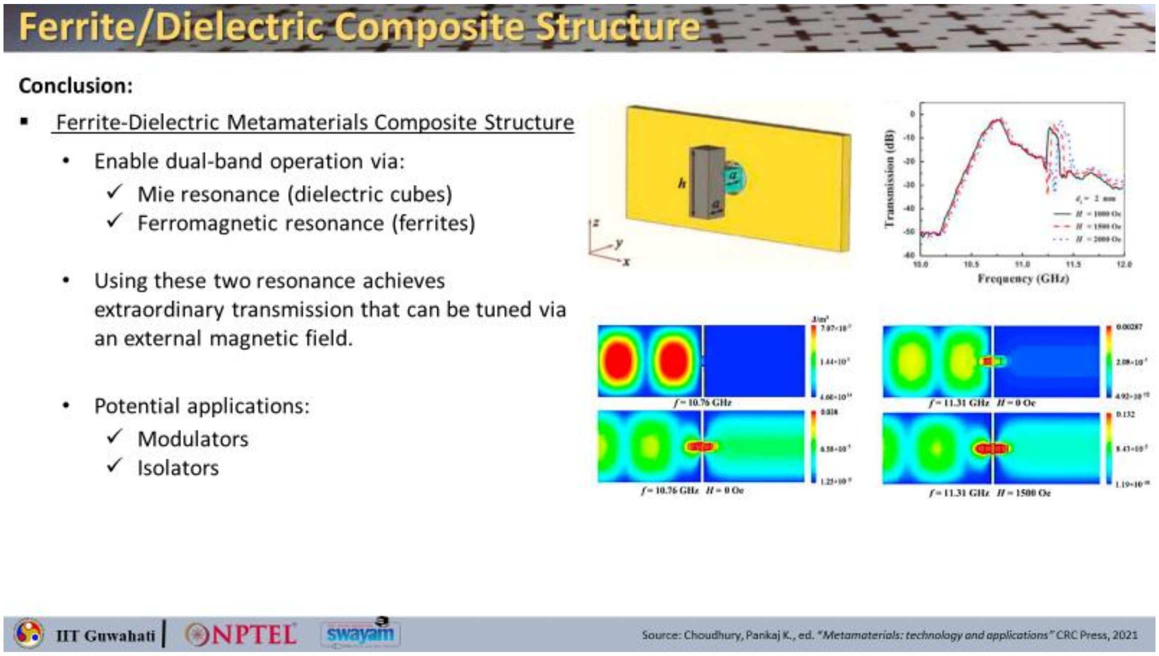
Now here are some simulated electric energy distribution profiles in the xy plane that are calculated at two different frequencies, okay.



So, this allows us to see the electromagnetic wave transmission through the sub-wavelength hole. So, this is that sub-wavelength hole, and this is the structure on which you have placed a dielectric cube and a ferrite rod on either side, okay. So, you can see that when you do not put anything, okay. So, no EM wave is basically transmitted through this metallic plate. So, this is the metal plate with the sub-wavelength hole that has no transmission at all, and this is due to the Bethe theory.

And when you put the ferrite rods and dielectric cubes, you will see that even at zero magnetic field, you will see the transmission is occurring at 10.76 gigahertz. That basically corresponds to the Mie resonance of the dielectric cubes. So, there is transmission here.

So, this is the phenomena of extraordinary transmission. And at 1500 oersted, you see that ferromagnetic resonance will take place. So, it will occur at 11.31 gigahertz frequency. So, you are basically getting again extraordinary transmission but this time at a different frequency Because of the applied magnetic field, this is happening at 11.31 gigahertz.



So, in a sense, you are basically able to tune the extraordinary transmission frequency by also changing the applied magnetic field.

So, what you observe from here is that this ferrite-dielectric metamaterial composite structure basically enables dual-band operation. It is coming from the Mie resonance supported by the dielectric cubes and the ferromagnetic resonance supported by the ferrite rods. Which is also seen here, this is the me resonance; these are from the ferromagnetic resonance of the ferrite rods.

By using these two resonances, you can achieve extraordinary transmission. That is basically getting tuned from 10.76 gigahertz to 11.31 gigahertz, right. So, you can actually use this concept for making modulators, isolators, etc.

So, with that, we conclude this lecture.

So we will discuss electrically tunable metamaterials in the next lecture. If you have any queries regarding this lecture, drop an email to this email address mentioning the course title and the lecture number on the subject line. Thank you.