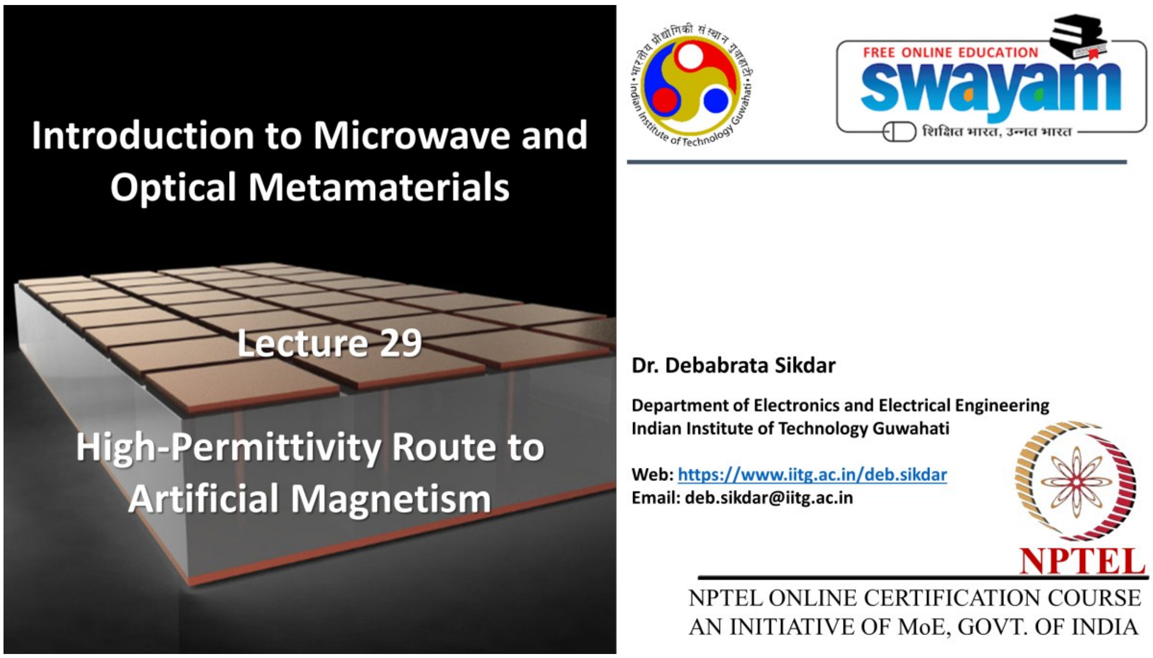
Course Name: Introduction to Microwave and Optical Metamaterials
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-6
Lecture-29

Lec 29: High-Permittivity Route to Artificial Magnetism



Lecture Outline

- High-Permittivity Route to Artificial Magnetism
- Applications of Magnetic Metamaterials
- Example of Magnetic Metamaterials

Hello everyone, welcome to Lecture 29 of the online course on Introduction to Microwave and Optical

High-Permittivity Route to Artificial Magnetism

- Alternative to Plasmonic Resonances:
  - Artificial magnetism can be achieved using Mie resonances in subwavelength dielectric resonators
- Mechanism:
  - High-permittivity dielectric particles support strong resonances
  - Resulting contra-directional displacement currents induce a strong magnetic field
- Advantages:
  - Large dielectric constant implies a small wavelength inside the high-permittivity region allows resonator size to be much smaller than the free-space wavelength
  - Enables the use of effective constitutive parameters to describe the medium's interaction with external waves

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

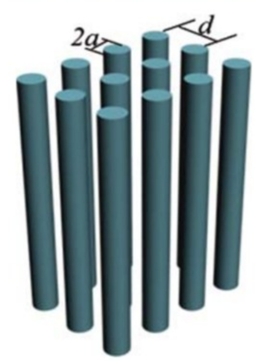
High-Permittivity Route to Artificial Magnetism

- High-Permittivity Materials:
  - Limited but effective options exist for microwave and mid- to far-infrared applications
  - Microwave frequencies: Ferroelectric ceramics like $Ba_xSr_{1-x}TiO_3$ (BST) with dielectric constants in the hundreds at GHz frequencies, usable at room temperature without external voltage
  - Infrared frequencies: Polaritonic materials such as $LiTaO_3$, $TlBr$, $TlCl$, and SiC are utilized

- Design Considerations for Metamaterials:
  - Lattice symmetry is non-essential due to localized Mie resonances
  - The geometry (size and shape) of each individual rods or spheres determines the spectral characteristics of Mie resonances
  - Packing density of resonators affects the effective parameters of the metamaterial

High-Permittivity Route to Artificial Magnetism

- Example Structure:
  - A square lattice of high-permittivity dielectric cylinders
  - Cylinders are arranged in a 2D periodic pattern (diameter: $2a$, lattice constant: d)
  - The magnetic field of incident light is polarized along the cylinder axis



- Theoretical Analysis:
  - Mie scattering theory is used to calculate scattering property
  - Effective permeability: $\mu_{\text{eff}} = \langle \boldsymbol{B} \rangle / \mu_0 \langle \boldsymbol{H} \rangle$

    where $\langle \boldsymbol{B} \rangle$: average magnetic flux density over unit cell and $\langle \boldsymbol{H} \rangle$: average magnetic field along the unit-cell boundary

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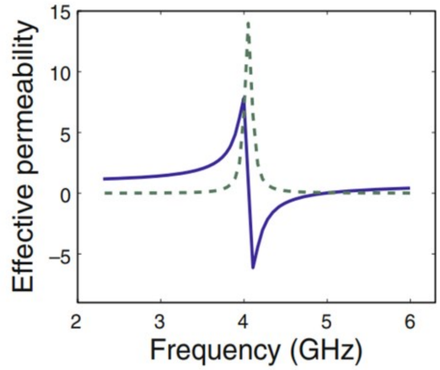
Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

High-Permittivity Route to Artificial Magnetism

- Results:
  - Using a cylinder permittivity of $200 + 5i$, the μ_{eff} for a system with a lattice constant of 5 mm and cylinder diameter 2 mm is plotted in figure
  - Strong Lorentz-shaped resonance in μ_{eff} is observed near 4 GHz
  - Confirms effective magnetic response in dielectric-based metamaterials



- Material Highlight:
  - Silicon carbide (SiC) stands out among ferroelectric and phonon-polaritonic materials

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

Metamaterials. Today's lecture will be on the high permittivity route to artificial magnetism. So, here is the lecture outline, we will look into the high permittivity route to artificial magnetism and then we will look into some applications of magnetic metamaterials and some examples of magnetic metamaterials. So, in the previous lecture, we achieved metamagnetic responses by using plasmonic resonances to introduce asymmetric current modes in sub-wavelength metal structures, right? So, as an alternative to this we can also obtain artificial magnetism using Mie resonances in sub-wave length dielectric resonators and that is what we will be looking into today's lecture, right. So, sub wavelength particles with high positive dielectric permittivity support strong resonances with large displacement currents, which may give rise to strong magnetic field induced by contradirectional displacement currents. Moreover, the large dielectric constant implies a small wavelength inside the high permittivity region.

Therefore, the physical size of the resonators can be much smaller than the free-space wavelength. So, you can get a miniaturized device, okay. So, this situation justifies the treatment of a system as a macroscopically homogeneous medium and thus the use of effective constitutive parameters to describe the mediums interaction with the external wave, right. So, although the choices for this kind of material are relatively limited.

Because you need high permittivity for both micro frequencies and far mid to far infrared frequencies, right? So, what you will see that at micro frequencies ferroelectric ceramics like barium, strontium, titanate are attractive candidates for this kind of purpose. So, such materials can exhibit very high dielectric constant okay in the hundreds okay at gigahertz frequency and typically they are usable at room temperature without any external voltage okay. For far and mid infrared frequencies, polyatomic materials like lithium tantalite okay or thallium bromide or thallium chloride and silicon carbide are also utilized. Now, when placing the sub wavelength resonator together to form a metamaterial, it is essential to follow certain design considerations okay, because the me resonances are basically localized okay. So, lattice symmetry is becoming non-essential in this case due to the localized modes of resonance.

Second important thing is that the geometry that is the shape and the size of each individual rods or spheres that basically determines the spectral characteristics of the me resonances. So intuitively the packing density of the resonators does have a impact on the effective parameters of the metamaterial because the macroscopic electromagnetic properties describe the volume appraised response of the material. Now following the discussion we use the square lattice as you can see here of high permittivity cylinders as an example that shows strong magnetic resonance in their electromagnetic response, okay. So here, the schematic shows the cylinder that is forming a 2D periodic pattern. Mind that the diameter is considered to be 2a here and the lattice constant is considered d, okay.

And the incident magnetic field is considered to be polarized along the axis of the cylinders. Now, the scattering properties of a cylindrical particle can be solved analytically by using the Mie scattering theory. with the calculated field distribution okay the effective permeability that is μ effective can be also obtained along the directional direction of this cylinder axis by evaluating this particular equation which shows μ effective = average magnetic flux density / unit cell / μ naught which is the vacuum permeability * Average magnetic field along the unit cell boundary is okay. So, here the average value of B is basically taken / a unit cell area that is D cross D and the average magnetic field H is basically taken along a line at the unit cell boundary that is parallel to the cylinders. So, assuming that the

High-Permittivity Route to Artificial Magnetism

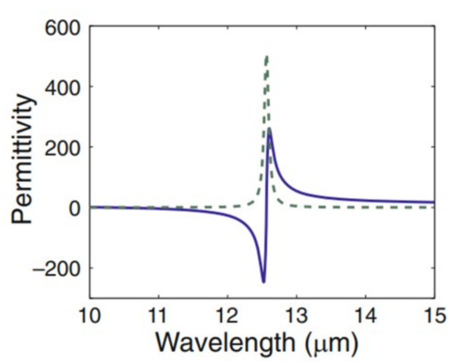
- Most suitable for optical metamaterials due to its mid-infrared phonon resonance.

- Key Properties of SiC:
  - Polaritonic material with a phonon resonance band centered at 12.5 μm (800 cm^{-1})
  - Exhibits a sharp Lorentzian behavior in its electric permittivity in the mid-infrared range

- Dielectric Function Model: The permittivity of SiC is described by:

$$\varepsilon_{\mathrm{SiC}} = \varepsilon_{\infty}\left[\omega^2 - \omega_{\mathrm{L}}^2 + i\gamma\omega\right]/\left[\omega^2 - \omega_{\mathrm{T}}^2 + i\gamma\omega\right]$$

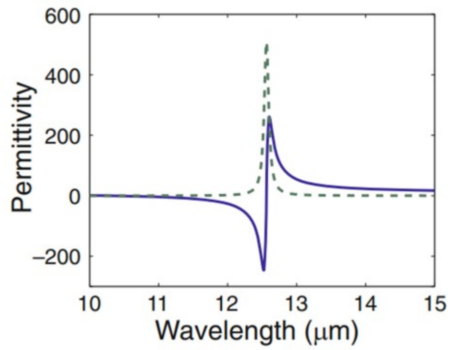
where $\varepsilon_{\infty} = 6.5, \omega_{\mathrm{L}} = 972\mathrm{cm}^{-1}, \omega_{\mathrm{T}} = 796\mathrm{cm}^{-1}$ and $\gamma = 5\mathrm{cm}^{-1}$



Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

High-Permittivity Route to Artificial Magnetism

- The dielectric function of SiC around its polaritonic resonance frequency is plotted in the figure.
- High-frequency side:
    - Dielectric function becomes strongly negative
    - SiC behaves like metals, enabling applications such as mid-infrared superlenses
- Low-frequency side:
    - Dielectric permittivity becomes strongly positive
    - Suitable for dielectric-based magnetic metamaterials via high-permittivity Mie resonators



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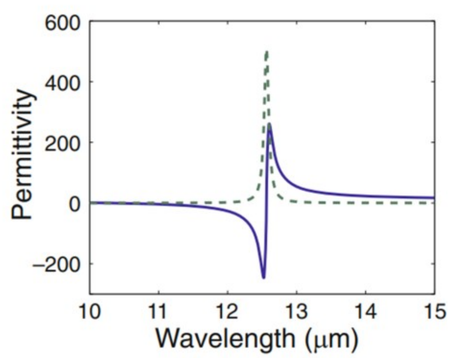
Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

High-Permittivity Route to Artificial Magnetism

- Application Focus:
    - Enables design of mid-infrared wavelength range metamaterials with magnetic properties
- Limitation of Dielectric-Based Magnetism:
    - Not extendable to visible or near-infrared regimes
    - At higher frequencies (above dielectric relaxation frequency), permittivity becomes relatively small
- Current Applicability:
    - Artificial magnetism with dielectric materials like SiC remains valuable



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permittivity of the cylinder material is around 200 + 5i.

So, you can see it is a very high dielectric constant. So, the effective permeability μ effective of the system where you are considering the lattice constant d to be 5 millimeter and the cylinder diameter that is 2a = 2 nanometer, okay. So, this particular figure shows how the effective permeability is changing as a function of frequency, right? So, what you can see here is that resonance behavior is basically seen in the permeability, right? So the solid line shows the real part, and the dashed line shows the imaginary part. So this is exactly where the real part is changing sign and the imaginary part goes to a maximum value. So this is where the resonance is.

So, what you observe here that is strong Lorentz shape resonance can be seen at around 4 gigahertz ok and this confirms the magnetic response in this kind of dielectric based

Applications of Magnetic Metamaterials

- Magnetic metamaterials are engineered materials with unique magnetic properties stemming from their structure, not composition.
- Enable manipulation of magnetic fields in unconventional ways.
- Applications:
  - Energy and Electronics:
    - ✓ Used in energy harvesting, electromagnetic shielding, and high-frequency devices
  - Medical:
    - ✓ Aid in MRI enhancement and diagnostics in biomedical applications
  - Industrial:
    - ✓ Enable sensing, actuation, and may support advanced manufacturing such as 3D printing

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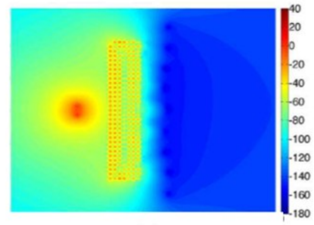
metamaterials. Now, among all the ferroelectric and phonon polyatomic materials that can be used for this kind of high permittivity schemes, it has been found that silicon carbide by far stands out to be the most attractive choice in this optical metamaterial research. Now, the reason behind this is that the phonon resonance band falling in the mid infrared range of the optical spectrum So, silicon carbide is basically a polyatomic material with its phonon resonance band centered around 12.5 micrometer that is typically 800 centimeter inverse that basically exhibits or introduces a sharp Lorentzian behavior in its electric permittivity in the mid infrared range. Now, that is the dielectric function.

The properties of this silicon carbide in the mid-infrared can be described using this particular dielectric function. You can write ε silicon carbide as equal to ε infinity * ω square - ω L square + i γ ω / ω square - ω t square + i γ ω. So, this ε infinity is 6.5 ω L is given as 972 centimeter inverse, ω t is 796 centimeter inverse and γ is given as a γ is a collision frequency given as 5 centimeter inverse. Now we can also see from the figure that you know the dielectric response of silicon carbide around its polyatomic resonance in the mid infrared range is calculated with the analytical model that we have seen just now.

Now, on the high frequency side that is this side, you will see that the dielectric function is strongly negative, it is very strongly negative, it is almost going up to - 200 right. So, that makes the optical response similar to that of metals. Okay. So, you can use these in

Applications of Magnetic Metamaterials

Electromagnetic Shielding and Absorption



- Magnetic metamaterials are effective at absorbing electromagnetic radiation.
- Ideal for electromagnetic shielding, particularly in sensitive environments.
- Applications:
  - Used in electronic devices to minimize electromagnetic interference (EMI)
  - Beneficial in electronic devices and medical equipment, where EMI can disrupt accurate functioning
- Importance:
  - Crucial for ensuring reliable performance and signal integrity in electronics
  - Supports the safe and stable operation of high-precision medical technologies

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Applications of Magnetic Metamaterials

Energy Harvesting and Storage

- Magnetic metamaterials enhance energy harvesting efficiency
- Improve wireless power transfer by amplifying magnetic fields between transmitter and receiver
- Impact:
  - Demonstrated significant efficiency increment in wireless power transfer
  - Considered a promising solution for next-generation charging technologies
- Benefits:
  - Enable more efficient charging of devices
  - Support cable-free energy transfer, making systems more convenient and flexible

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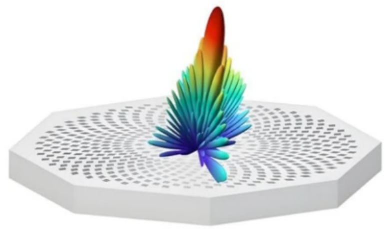
applications like mid-infrared superlenses and so on. Now, on the low frequency side, which is on the longer wavelength side, you will see that the dielectric response is strongly positive.

So, it is like going up to + 200. So, that is pretty strong okay and You can see that silicon carbide can be a very attractive candidate for producing dielectric based magnetic metamaterials using such high permittivity mid resonators in the mid infrared wavelength range. So, such a response allows you to have you know both metallic kind of behavior in this range and you know dielectric kind of behavior on the other side of the resonance. Now, let us focus on the applications. So, you can see that this enables the design of mid-infrared wavelength range

Applications of Magnetic Metamaterials

High-Frequency Devices and Antennas

- Magnetic metamaterials enable better performance in high-frequency devices and antennas.
- Electromagnetic Wave Manipulation:
  - Ability to manipulate electromagnetic waves, allows for the design of antennas that are smaller and more efficient than traditional designs



- Use of Metamaterial in Antenna Design Benefits:
  - Miniaturization: Allowing for smaller antennas without sacrificing performance
  - Beam Steering: Enabling the direction of the electromagnetic beam without physical movement of the antenna

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metamaterials that can show magnetic properties, okay.

However, this technology cannot be extended into visible and near infrared optical region because you can see that at higher frequencies which are above the dielectric relaxation frequency the permittivity value becomes very small right. So, the in other words you can say that the permittivity of such ferroelectro ferroelectric or polyatomic materials become relatively very small for frequencies above this resonance or you can say dielectric relaxation right. So, in this case you can think that artificial magnetism with dielectric materials such as silicon carbide can be still very useful ok, but they are suitable only in this mid infrared range. Now magnetic materials, metamaterials are nothing but we have already seen these are the engineered or artificial structures that can show you unique properties stemming from their structure not from their composition right. So, these properties enable manipulation of magnetic waves in unconventional ways.

So, these properties are basically as you know they are coming from the structure okay not from the composition, they can have lot of unique

Applications of Magnetic Metamaterials

Industial Uses

- Sensing and Actuation:
  - Enhances sensor sensitivity and actuator responsiveness in industrial control systems
- Advanced Manufacturing:
  - Enables creation of geometries and structures with tailored magnetic properties
  - The integration of magnetic metamaterials with 3D printing technology could enable the production of complex devices with unique magnetic properties
  - Impacts multiple industries including aerospace and healthcare
  - Example Applications:
    - ✓ Customized MRI coils: Designed for individual patients to improve diagnostic accuracy
    - ✓ Advanced sensors: With higher sensitivity and selectivity for various industrial uses

applications across various fields okay. In the field of energy and electronics, you can use them for energy harvesting, electromagnetic shielding, and high-frequency devices. In the field of medical they can be used for biomedical applications such as you know aid in MRI enhancement and diagnostics okay. For industrial applications, they can enable sensing, actuation, and may also support advanced manufacturing such as 3D printing. So, let us look into a few of these in a little more detail, okay? So, in electromagnetic shielding and absorption, you will see that magnetic metamaterials are working very effectively.

And we have already seen this kind of design earlier in our course, okay. So, you can see that magnetic metamaterials were ideal for electromagnetic shielding, particularly in sensitive environments, right? And this was done using an inhomogeneous metamaterial that could provide you, you know, blockage of the magnetic field up to - 180 dB; that is all that is remarkable. Right. Other applications include, you know, like they can be used in electronic devices to minimize electromagnetic interference. They can be beneficial in electronic devices and medical equipment where EMI disrupts accurate functioning.

So, such metamaterials are crucial for ensuring reliable performance and signal integrity in electronics. They also support the safe and stable operation of high-precision medical technologies. In the field of energy harvesting and storage, metamaterials can be designed to enhance the efficiency of energy harvesting. For example, they can be used to improve wireless power transfer by amplifying magnetic fields between the receiver and transmitter or the transmitter and receiver, and vice versa, right? So, their impact can be demonstrated in the form of significant efficiency improvement during the wireless power transfer process and hence they can be considered as promising solution for next generation. Wireless charging technologies.

So, what are the associated benefits? As you can see that such materials or metamaterials enable more efficient charging of devices and they support wireless or cable free energy transfer making the systems more convenient and flexible. Another important application of such metamaterials or magnetic metamaterials comes in the field of high-frequency devices and antennas. So they can also be used to create high-frequency devices and antennas with improved performance. When I say improved performance, you will see that the designs can be made smaller and the antennas can be more efficient as compared to the traditional designs. So, electromagnetic wave manipulation is an important feature of this kind of metamaterials.

So, the metamaterials can manipulate the electromagnetic field and bring down the overall footprint of your antenna design and make them more efficient as compared to the traditional ones. Now, the use of

Applications of Magnetic Metamaterials

Biomedical Applications

- MRI Enhancement:
  - Magnetic metamaterials improve magnetic field homogeneity and strength in MRI machines
  - Results in better image resolution and shorter scan times
- Other Biomedical Uses:
  - Diagnostics: Enhanced sensing for more accurate diagnostics
  - Therapeutics: Enables targeted drug delivery using magnetically guided nanoparticles

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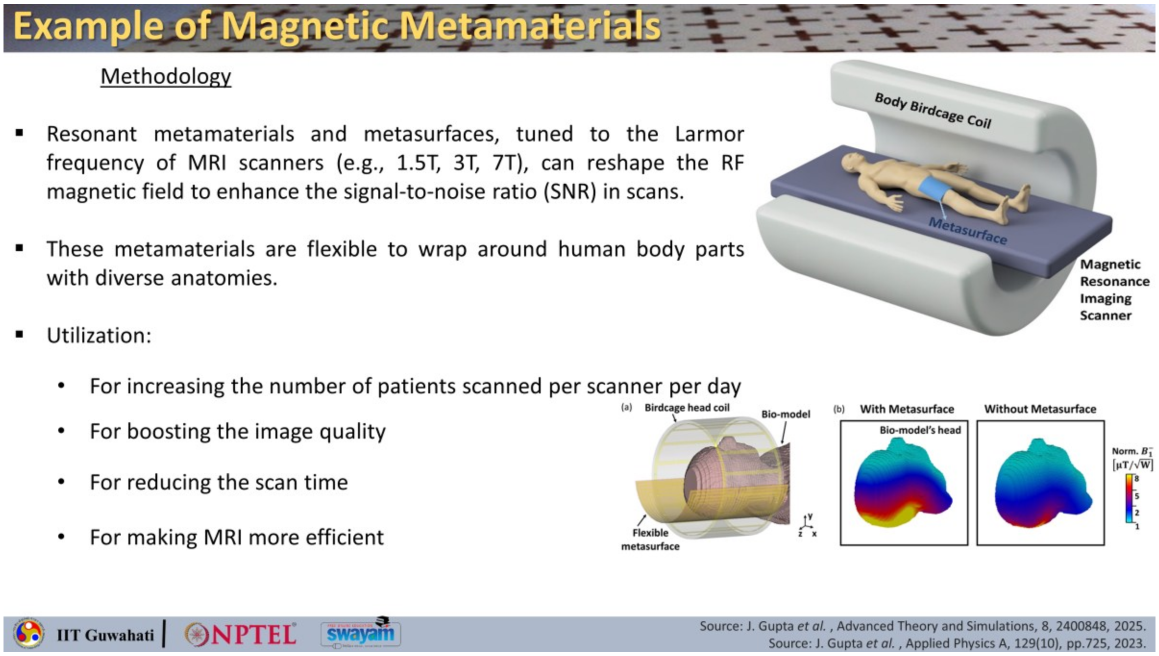


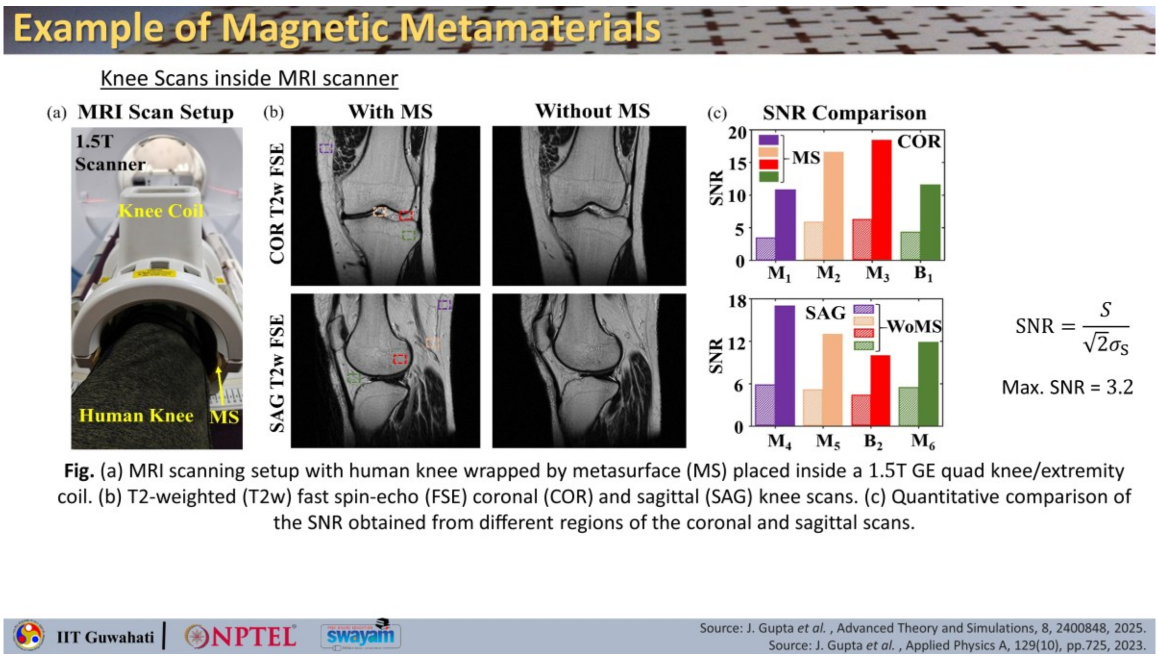
metamaterials in antenna design benefits, first of all, from miniaturization. So, you can make smaller antennas without sacrificing the performance and they also enable beam steering that means you will be able to change the direction of the electromagnetic beam without physically moving the antenna. Right. And another important application of these magnetic metamaterials lies in the field of industry.

So, there you can use this metamaterials for sensing and actuation where metamaterials could definitely improve the sensitivity and the response of this sensors and actuators that are typically used in industrial control systems. They are also very useful in advanced manufacturing, where you can create geometries and structures with tailored magnetic properties. And the interaction of these magnetic metamaterials with 3D printing technology could also enable the production of complex devices with unique magnetic properties. And they could impact multiple industries, such as aerospace and healthcare. So, some example applications involved you know you can design customized MRI coil which can be designed for individual patients to improve the diagnostic accuracy.

You can also think of making this for neonates, infants, or babies, okay? And you can also think of making advanced sensors using metamaterials where you can achieve higher sensitivity and selectivity depending on the differences. Industrial applications. Now, let us also focus on an interesting and emerging area of biomedical application, where this is one of the most promising applications of magnetic metamaterials. The first thing is the quality of MRI, which is magnetic resonance imaging. Magnetic resonance imaging on its own is one of the most complicated machines that humans have produced to image any part of human anatomy in detail.

So, it basically produces contrast between the soft tissues and your bones and allows you to see what each of your organs looks like. So, it is a high-resolution imaging technique that is based on magnetic resonance, okay. So, there you can apply magnetic metamaterials that can improve the magnetic field homogeneity and strength in MRI machines. Right. So, what happens you know using the enhancement of local magnetic field done by this kind of magnetic metamaterials, you can get better image resolution and for a given or the standard image resolution you can bring down the scan time.

Other biomedical uses include enhanced sensing for more accurate diagnostics. You can also look for

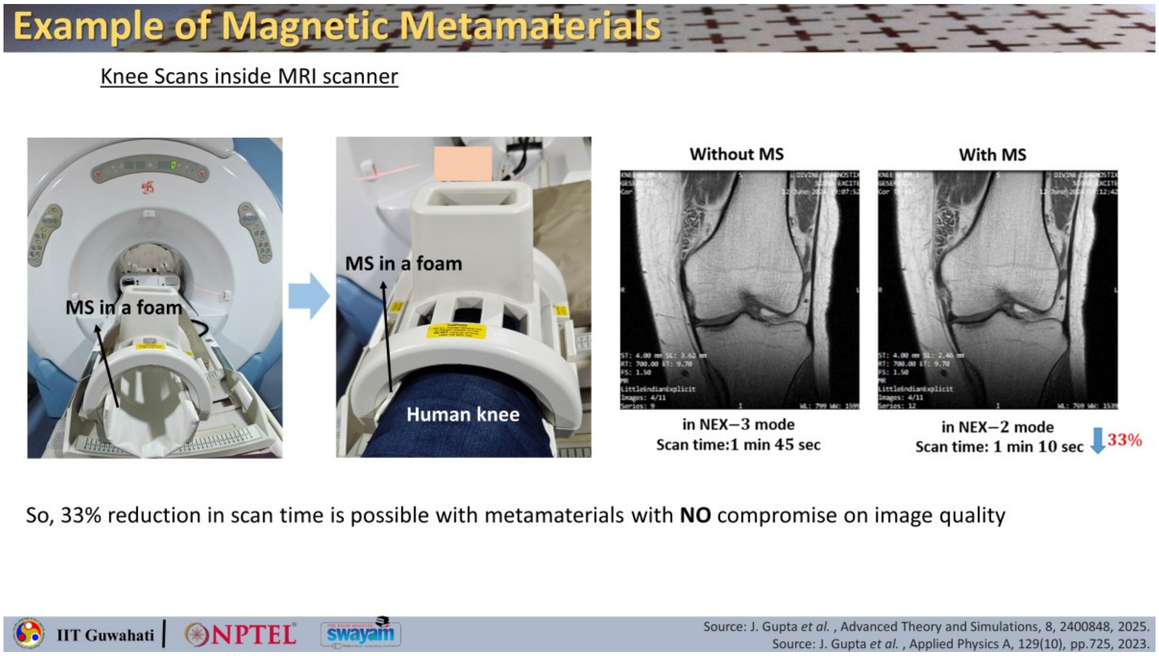


different therapeutics application which can think of you know targeted drug delivery using magnetically guided nanoparticles and so on. So, what is the methodology? Let us look into this in more detail. So, when you design magnetic metamaterials and metasurfaces that are resonant, and when I say resonant, they need to match the resonance frequency of the MRI scanner. So, MRI scanner based on their strength of the magnetic field whether it is a_1.

5 tesla scanner or a_3 or 7 tesla scanner there is a Larmor frequency associated right. Now, the Larmor frequency with a static field B naught is typically given as F naught that is the Larmor frequency that will be γ by 2 π * B naught. So, γ is the gyromagnetic ratio which has a value of 42.5 megahertz per Tesla. okay so you can see that you know for a_1.

5 tesla mri scanner the larmor frequency turns out to be somewhere around 64 megahertz so you are supposed to make a magnetic metamaterial or metasurface that can also resonate at that particular frequency and then it should allow you To distribute the electromagnetic field in such a way that the electric fields are essentially moved away from the human body parts that are undergoing the scan. So, this is how you can see this is the body birdcage coil it is it is basically fully covered coil it is just open from this side to show you how the human body goes inside the scanner. This is how you can think of the metasurface, which can also be made flexible to wrap

around the human body part that is undergoing a scan. Now when you do this kind of scanning using magnetic



metamaterials, so your part will be to make sure that the electric hotspots are away from the human body and you can have homogeneous magnetic field enhancement within the region that is undergoing scan. So, this is some of the metamaterial work reported in this particular paper, okay.

So, this is a kind of spirals for magnetics for copper spirals on FR4 substrate and there is a sandwich of some high permittivity material and on the other side you also have the same kind of material placed. So, you can actually use this to place below the human body when it is undergoing a spine scan or something like that, okay. So, you can use it for improving the signal to noise ratio of your MRI scan so that you can get more number of patients scanned in a MRI scanner per day. And they definitely boost the image quality and reduce the scan time.

You can also think of flexible one. They can actually wrap around any curved anatomy, like the head, leg, or your arm. So, they are also doing the same thing as the flat ones are doing just that they are able to fit any curved anatomy and that way you can make MRI more efficient. So, this is one of the most promising applications of magnetic metamaterials. Here you can see there is a birdcage head coil this is a human biomodel and below the head you are putting this flexible metamaterial and here is a comparison of the received magnetic field. When you have the metamaterial, you see that a much stronger magnetic field is localized in this part of the head.

Okay, as compared to without metamaterial, you see. So, in this case definitely you will get much stronger signal coming from the human head and your MRI image quality will be much higher and if you are if you want to you know maintain the same kind of image quality you can bring down the scan time. The similar kind of thing was also used for the knee coil. So, this is a dedicated knee coil, and that is a_1.

5 Tesla MRI scanner setup. So, what you can see that you know you can put the human knee below this particular metasurface and when you take the MRI scan for two different sequences coronal and sagittal view for T_2 sequence will full. So, this is the sequence that is being followed. So, it is basically a T_2-weighted first spin echo sequence that is done for coronal and sagittal scans of the knee of the same patient. This left column is for the case when the metamaterial is present; this is for when the metamaterial is not present. So, you can see a clear improvement in the image quality with the metamaterial.

And when you want to do a quantitative analysis for the SNR improvement, you can actually take samples from different marked regions; the same regions are also taken from here. So, in this four marked regions, you can see that you know the metasurface basically shows enhancement and you can calculate ah the overall SNR as S / square root of σ S. S is basically the mean signal intensity you can obtain from the image and σ S is basically the deviation or the standard deviation of the Background noise. So, that shows that you are getting a maximum signal to noise ratio enhancement of around 3.

2 which is which is pretty good. So, it means you are able to improve the image quality by about three *. So, this is how it will typically look. So, you can put the metasurface, which is basically a flexible magnetic metamaterial printed on flexible PCBs, okay. and that can be used for this kind of scans and this is what we have also shown that if you are not worry about the image quality improvement and you are just happy with the similar kind of image quality in the case of with and without metasurface, you can see a drastic reduction in you know scan time. So, you can see that you know "next" means the number of excitation.

So, this is the next 3 mode, which means the entire sequence was run 3 * and the signals were averaged, resulting in this image. Now with meta surface you can run the sequence only for 2 * and get the same quality of image and in that way you can achieve 33 percent reduction in scan time. So, you can get similar image quality without, you know, compromise by using metamaterials, and that can give you a_{33} percent reduction in scan time. And if you want to do it for the same number of * or the same sequence, you can get a_3 * boost in the signal quality. So these are some of the examples of real magnetic metamaterials that can be used for real world applications okay.

So, with that, we will conclude here. In the next lecture, we will look into the modeling of microwave devices using metamaterials. If you have got any query regarding this lecture you can drop an email to this email address mentioning the course title and the lecture number on the subject line.

Slides inserted by fallback (review if needed):