Course Name: Introduction to Microwave and Optical Metamaterials
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Week-11
Lecture-51

Lec 51: Realizing Electromagnetic Cloaking using Metamaterials

Hello everyone, welcome to Lecture 51 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on realizing electromagnetic cloaking using metamaterials.

Lecture Outline

- Introduction
- Cloaking Theory based on Metamaterials
- Examples of Metamaterials-based Cloaking
  - Metamaterials Mirror-based Cloaking
  - Split Ring Resonator (SRR)-based Cloaking
  - Near Pi-Shaped Structure Cloaking
    - ✓ Rectangular Cloak
    - ✓ An “Eye-Shaped” Cloak
    - ✓ A “Triangular-shaped” Cloak

Here is the lecture outline. We will have a brief introduction to the topic, and then we will go into the Cloaking theory based on metamaterials or metasurfaces, in this case. We will also take up some examples of metamaterial-based cloaking. We will discuss metamaterial mirror-based cloaking and split ring resonator-based cloaking.

and then we will take up near pie shaped structure cloaking. Where we'll be discussing rectangular cloaks, an eye-shaped cloak, and a triangular cloak.

Introduction

- Metamaterials: Their unique properties enable a wide array of applications in engineering.
- A key application is in **invisibility cloaking**, making objects invisible to the human eye.
  - This is achieved by metamaterials and manipulating (bending) light in unnatural ways.
- Precisely engineered structures allow light to bend around objects, making them "disappear."
- **Metamaterial cloaking** involves bending electromagnetic waves around objects to make them invisible.
- This is achieved by manipulating the refractive index of the metamaterial.

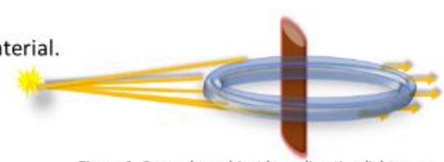


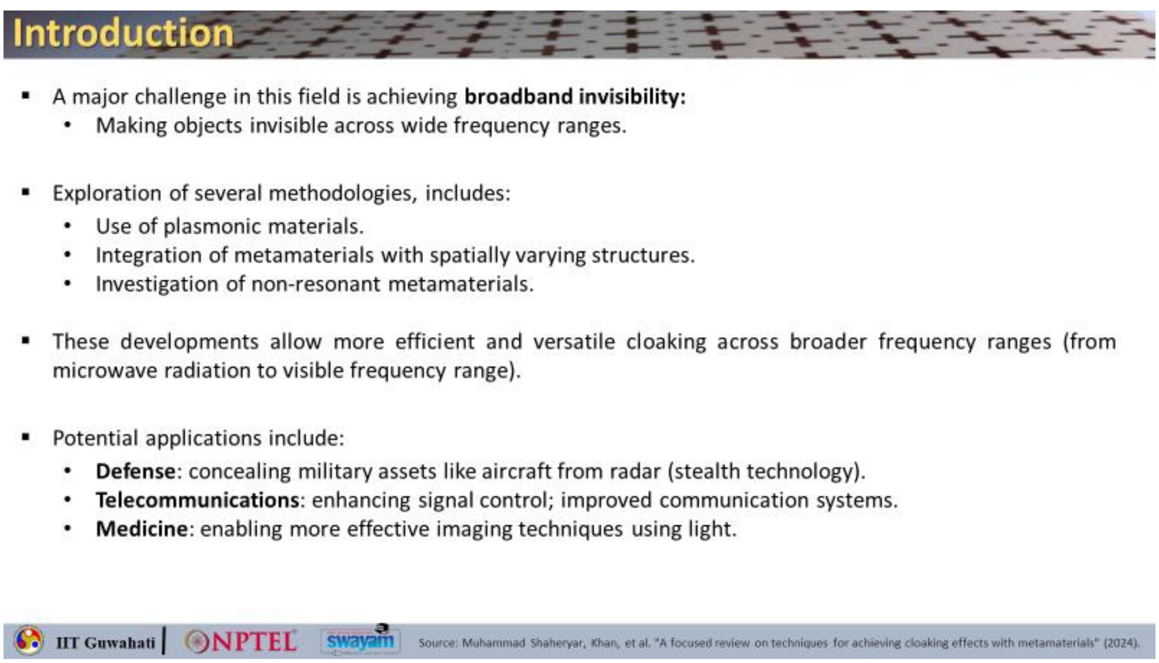
Figure 1: Conceal an object by redirecting light rays within the metamaterial

Source: Muhammad Shaheryar, Khan, et al. "A focused review on techniques for achieving cloaking effects with metamaterials" (2024).

So, from the beginning of this course, we have been discussing this particular feature of metamaterials. That these are artificial materials with some properties that are not found in nature.

So that allows you to make some unique properties that enables wide range of applications in engineering, one key application of which is always invisibility cloaking. That means you can make an object invisible to the human eye. And this can be achieved by metamaterials through manipulating or bending light in unnatural ways. So, if you can precisely engineer the structures that allow light to bend around any particular object, you can make those objects disappear. So that is where the field of metamaterial clocking shows promise.

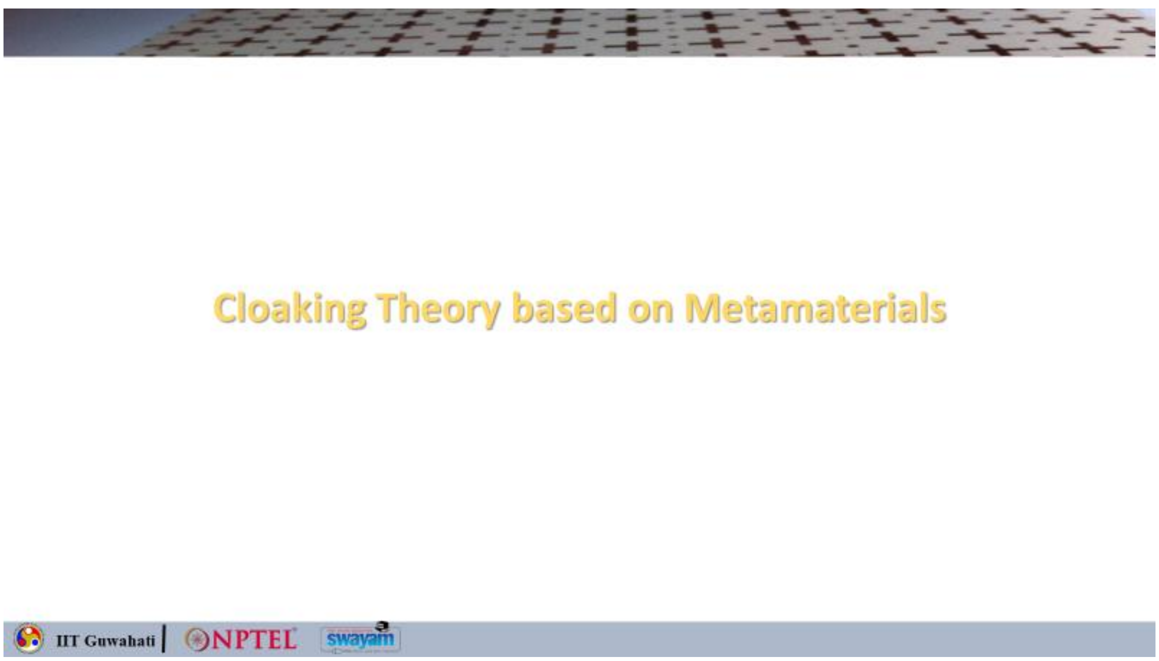
Because you can use, you know, metamaterial cloaks that can, as you can see here. Can you know how to band the electromagnetic waves around, So, this is the object that is being hidden from the electromagnetic waves because of this structure. That is basically made of metamaterials that can bend the electromagnetic rays around this object and then after. They exit from here in such a way as if there is nothing present in this particular ring. So, these kinds of things can be achieved by manipulating the refractive index of the metamaterials, right.



Now, what we understood from our previous lectures is that you know, A major challenge in this field is basically addressing broadband invisibility.

So, it is difficult to make objects invisible over a wide frequency range and for all the viewing angles, right. So, people have explored different methodologies, such as, you know, the use of plasmonic materials, integration of metamaterials with some spatially varying structures. Also investigated non-resonant metamaterials that are broadband in nature. So, this kind of development has basically allowed for more efficient and versatile clocking across a broader frequency range. Typically, from microwave radiation to the visible frequency range. Now, what are the potential applications of this kind of broadband invisibility. The first thing that comes to your mind should be defense, where you know you can conceal military assets such as aircraft from radars, so that is basically the stealth technology people are talking about; then you can have telecommunications. Where you can use this kind of technology to enhance signal control and also improve communication systems. They can also be used in medicine by enabling more effective imaging techniques using light or any other. electromagnetic waves that can actually help you in better diagnosis and targeted treatment.

Now, with this introduction, let us look into the cloaking theory based on metamaterials.



In the previous lectures, if you have seen, we discussed everything in terms of transformation optics. But here we are mainly focusing on metamaterials or their 2D counterparts, metasurfaces, right.

Theory

- Metamaterials are extensively used in ultrathin carpet cloaks due to their precise control over wave phase and amplitude.
- These metamaterials consist of many unit cells, allowing local phase compensation via varying unit cell sizes.
- Development of a transmissive metamaterial-based cloak is as shown in figure 2(a).
- It features a three-layer frame structure made of metasurfaces (2D metamaterials):
  - I, II, and III represent three transparent metasurfaces with their respective phase gradients as shown in figure 2(b).
- A y −polarized plane wave incident normally can bypass the obstacle using the cloak.
- The wave emerges undisturbed as a plane wave, demonstrating effective cloaking.

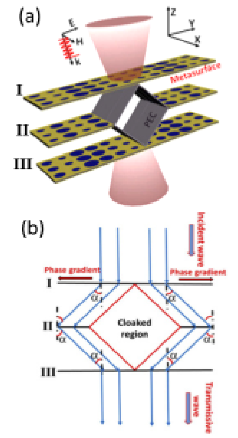


Figure 2:(a) 3D scheme of transmissive invisibility cloak. (b) Schematic diagram of transmissive metamaterial cloak

Source: Jing, Xufeng, et al. "Design of two invisibility cloaks using transmissive and reflective metamaterial-based multilayer frame microstructures." *Optics Express* 28.24 (2020): 35528-35539.

So, metamaterials are extensively used in ultrathin carpet cloaks. Which you discussed earlier due to the precise control over phase and amplitude, right. So, metamaterials are basically periodic structures made up of unit cells. And that allows local phase compensation if you vary the unit cell size. Some sort of development in the transmissive metamaterial-based cloak can be seen here.

So, in this figure, you can see that there are basically three layers of frame structure. which are based on very thin, you know, metamaterials, or you can call them 2D metasurfaces. So, layers 1, 2, and 3 are basically the three transparent metasurfaces with their respective phase gradients. So, you can see that the unit cell sizes are not the same throughout; they are basically changing. And this is the direction of the electric field, the magnetic field, and the wave factor.

So, what we are considering here is that the electric field is along the y vector. So, you can say it is basically a y-polarized plane wave that is normally incident, right. Now, what is the purpose here? You are basically making a cloaked region, okay? So, this is a boundary made of PEC, okay. So, inside this whatever you keep okay that will not be seen by this incoming light. So, at the end of this, you know you will see that the wave.

basically emerges undisturbed as a plane wave that demonstrates the effective cloaking property. So here in the schematic, you can also see how things work. So, this is the incident beam, and this is the first layer, and you have a phase gradient this way. Then you have the second layer, this one, and this is the cloaked region. So, these are basically the angles: okay, alpha, and then this is the refraction angle, basically from this.

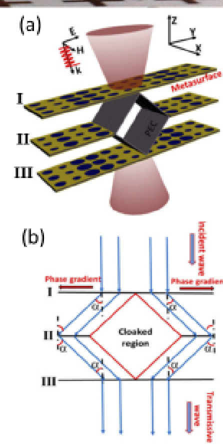
The transmitted angle from this metasurface, and then you have another metasurface over here, which basically bends it down. This way, and then again, it transmits as if nothing has happened in between. You just have the parallel rays coming out right, so all those things are possible because.

Theory

- To control the refraction, the generalized Snell's law of refraction is used:

$$\sin(\theta_t) - \sin(\theta_i) = \frac{\lambda_0}{2\pi}\frac{d\varphi}{dx} \quad \text{..........(1)}$$

  Where θ_i : Incident angle; θ_t : Refraction angle; λ_0 : Working wavelength and $\frac{d\varphi}{dx}$: Phase gradient.
- From Eq. (1), the refraction angle θ_t can be fully controlled by adjusting the transmitted phase gradient.
- This concept enables the design of a transmissive invisibility cloak using metasurfaces.
- Design principle demonstrated in Fig. 2(b) with a multilayer metasurfaces frame consisting of three layers: Metamaterials I, II, and III.
- A y −polarized plane wave is normally incident on Metasurface I.
- The left and right sides of the structure have opposing phase gradients.



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Now you are able to control the refraction using metasurfaces. So, you are not only dependent on Snell's law; you are basically using a generalized Snell's law of refraction.

So, it can be written as: $\sin(\theta_t) - \sin(\theta_i) = \frac{\lambda_0}{2\pi}\frac{d\varphi}{dx}$. So, θ_i is basically the incident angle, and θ_t is the refraction angle. So, here you can see that it is normal incidence. So, θ_i is basically 0, θ_t is basically alpha, and λ_0 is the working wavelength. And you can see there is an important term here that is $\frac{d\varphi}{dx}$, which is basically the phase gradient.

So, x is this particular axis. So, from this equation, you can understand that the refraction angle theta t can be fully controlled. By adjusting the transmitted phase gradient. Now, you have that extra control, which is what you know about the metasurfaces. The 2D metamaterials are bringing something new into the picture, right. So, this concept basically enables the design of a transmissive invisibility cloak using metasurfaces.

So, the design principle, as I have already mentioned, is that you can see here that It bends like this again, goes back in the opposite direction, and finally escapes as a parallel beam, okay. So, to begin with, you are considering why polarized light is to be normally incident on this metasurface 1. On the left and right sides of the structure, you can see that you should have opposite-phase gradients. So that this beam bends this way and this beam basically bends in the opposite way, meaning in this particular direction, right.

Theory

- For the left side of Metasurface I, the angle of refraction is related to the phase gradient, which can be expressed as:

$$\sin(-\alpha)-\sin(\theta_0)=-\frac{\lambda_0}{2\pi}\frac{d\varphi_1}{dx} \quad \text{..........(2)}$$

- While, for the right side of metasurface I, this relationship can be expressed as:

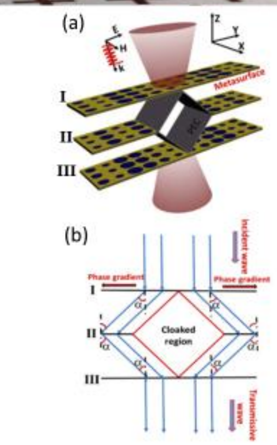
$$\sin(\alpha)-\sin(\theta_0)=\frac{\lambda_0}{2\pi}\frac{d\varphi_1}{dx} \quad \text{..........(3)}$$

- Similarly, the left and right sides of the metasurfacess II and III can be denoted as:

$$\sin(\alpha)-\sin(-\alpha)=-\frac{\lambda_0}{2\pi}\frac{d\varphi_2}{dx} \text{ ....(4)}; \quad \sin(-\alpha)-\sin(\alpha)=\frac{\lambda_0}{2\pi}\frac{d\varphi_2}{dx} \text{ ....(5)}$$

$$\sin(\theta_0)-\sin(\alpha)=-\frac{\lambda_0}{2\pi}\frac{d\varphi_3}{dx} \text{ ....(6)}; \quad \sin(\theta_0)-\sin(-\alpha)=\frac{\lambda_0}{2\pi}\frac{d\varphi_3}{dx} \text{ ....(7)}$$

where α is the value of each corresponding angle.



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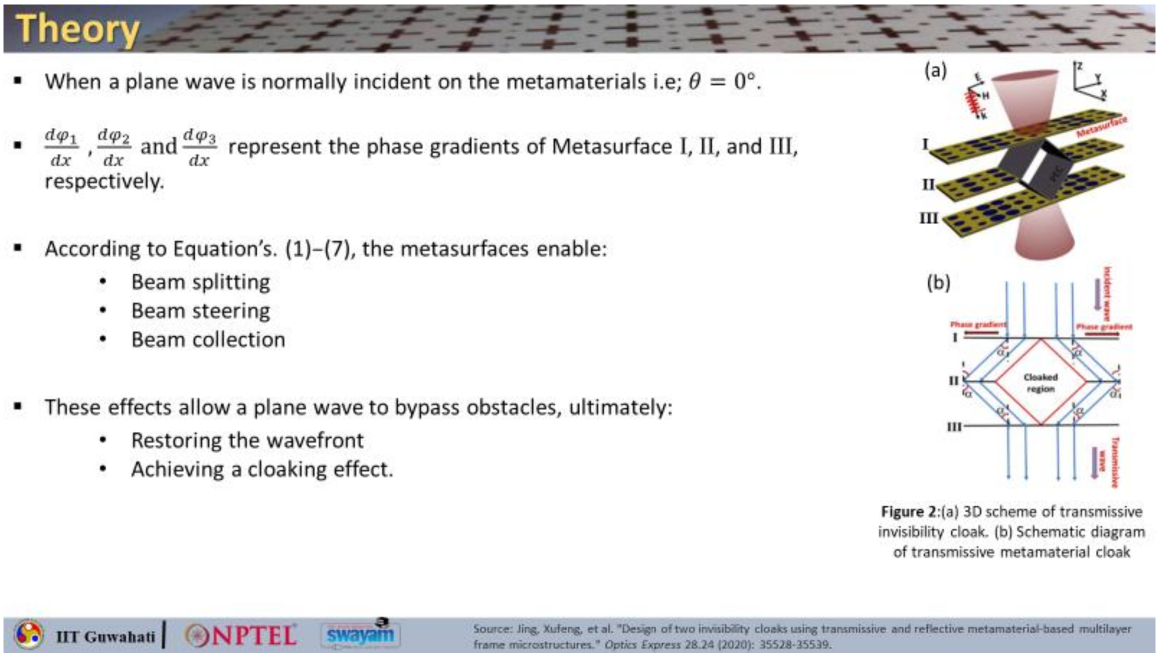
So, on the left side of the metasurface, you are basically bending it like this, right? So, the angle of refraction is basically related to the phase gradient, and you can get it like: $\sin(-\alpha)-\sin(\theta_0)$. So, you can consider this angle as $-\sin(\theta_0)$, which is basically θ_0; the incident angle equals $-\frac{\lambda_0}{2\pi}\frac{d\varphi_1}{dx}$, and on the right side, you have $\sin(\alpha)-\sin(\theta_0)$, it will be equal to $\frac{\lambda_0}{2\pi}\frac{d\varphi_1}{dx}$, or you can also say $\frac{d\varphi_2}{dx}$, okay. So, it all depends on you, doesn't it?

So, because we are considering metasurface 1, we can consider this phase gradient as $\frac{d\varphi_1}{dx}$. Similarly, the left and right sides of metasurfaces 2 and 3 will also be denoted in this way. So, here the incident angle is also α, and the transmitted angle is also α. So, you have or $-\alpha$ rather.

So, you have this term and you have this term on the right that is: $\sin(\alpha)-\sin(-\alpha)=-\frac{\lambda_0}{2\pi}\frac{d\varphi_2}{dx}$ And then on this side, you have $\sin(-\alpha)-\sin(\alpha)=\frac{\lambda_0}{2\pi}\frac{d\varphi_2}{dx}$.

In this case, this is the incident angle, and θ_0 will be your transmitter angle. So, you can write $\sin(\theta_0) - \sin(\alpha) = -\frac{\lambda_0}{2\pi}\frac{d\varphi_3}{dx}$ and on this side you can write $\sin(\theta_0) - \sin(-\alpha) = \frac{\lambda_0}{2\pi}\frac{d\varphi_3}{dx}$, Right. So, here, as you can see, alpha is basically the value of each corresponding angle.

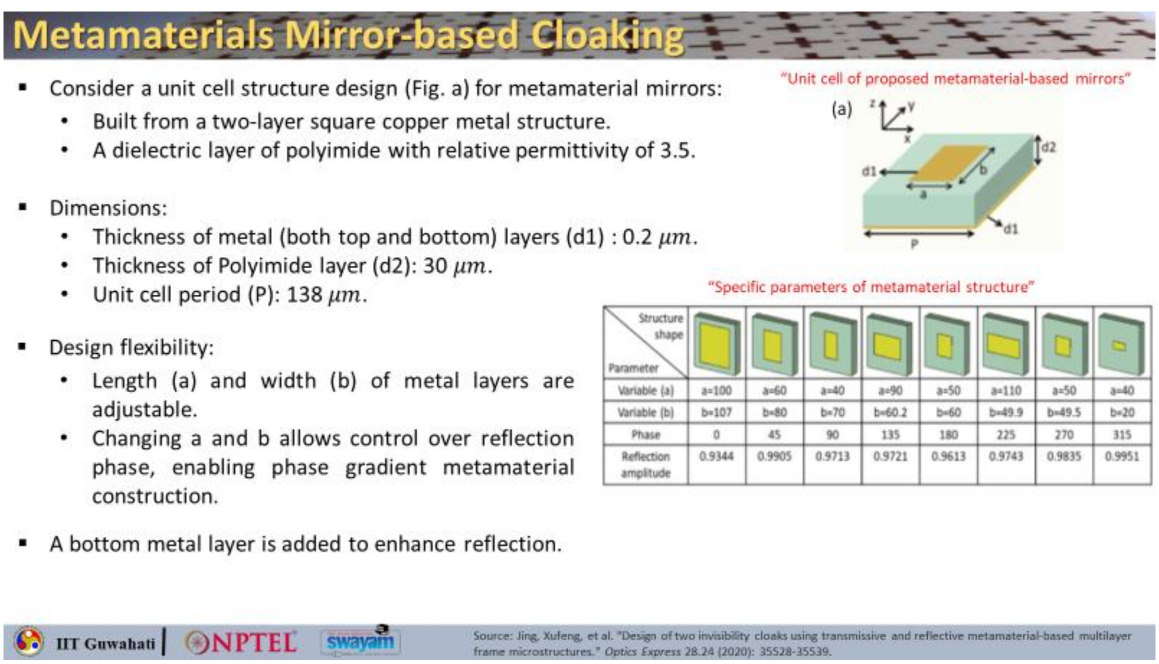


Now, if you consider the case of normally incident light as shown here, you can simply take theta equal to 0 degrees, i.e.; $\theta = 0°$, right and these three terms $\frac{d\varphi_1}{dx}$, $\frac{d\varphi_2}{dx}$ and $\frac{d\varphi_3}{dx}$ represents the phase gradients of matter on surfaces 1, 2, and 3 are correct. So, using this, you can always perform beam splitting, beam steering, and beam collection, Right.

All this, you know, because you have control of the phase, means you can basically bend the transmitted beam. in whichever direction you want and you can actually do that for all these different applications, Right. So, these effects basically allow a plane wave to bypass obstacle and that finally allows you to restore the wavefront is effectively giving you a cloaking effect because you are bypassing one particular region in the path.

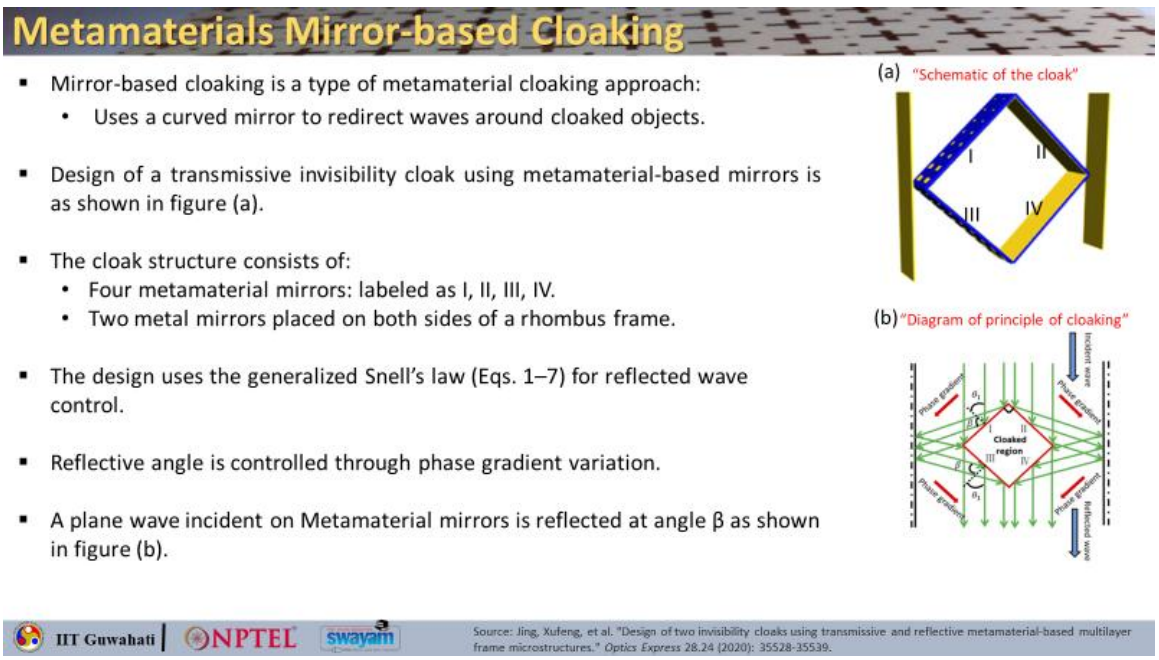
So, with this concept, let us now go into some practical examples of metamaterial-based cloaking.

So, let us first consider metamaterial-based mirror cloaking.



Parameter \ Structure shape								
Variable (a)	a=100	a=60	a=40	a=90	a=50	a=110	a=50	a=40
Variable (b)	b=107	b=80	b=70	b=60.2	b=60	b=49.9	b=49.5	b=20
Phase	0	45	90	135	180	225	270	315
Reflection amplitude	0.9344	0.9905	0.9713	0.9721	0.9613	0.9743	0.9835	0.9951

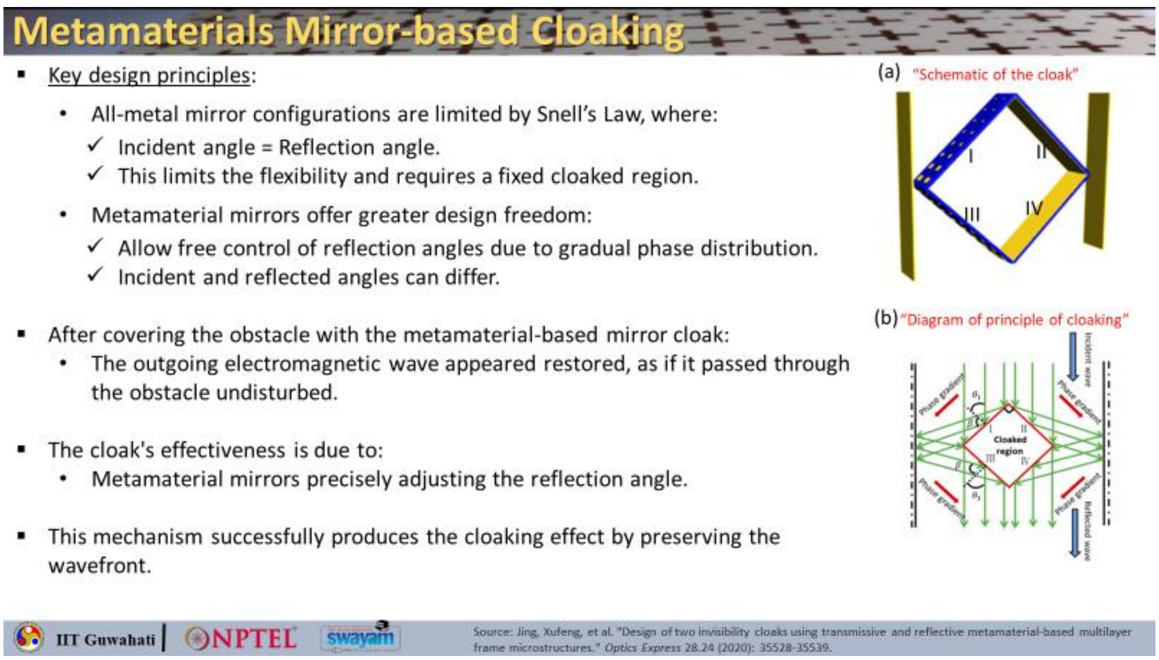
So, let us consider this particular unit cell. For the metamaterial mirrors. So, it is basically built with a two-layer square copper metal structure. So, one on the top, one at the bottom, and then there is a dielectric layer. Polyimide in between has a relative permittivity of 3.5. Now, what are the dimensions used here? The thickness of the metal in the top and bottom layers is taken as 0.2 microns. The thickness of the polyamide layer is 30 microns, and P, which is the periodicity of the unit cell, is 138 microns. Now, as you can see that you know this very a and b are basically the length and the width of the metal layer is adjustable. So, this particular table shows different structure sizes where you are basically changing a and b, okay? And you can see that when a equal 100 and b equals 107, the phase is 0, and your reflection amplitude is 0.9344, right? So, as you keep changing this dimension, you can gradually increase the phase while keeping the amplitude of the reflection almost the same. Now, what is the purpose of this bottom metal plate, since it is more or less always the same? The purpose is to enhance reflection. So, based on that, now let us make a mirror-based cloaking. So, what you are doing here is that you are showing the schematic of the cloak first. So, you have these four mirrors: 1, 2, 3, and 4.



So, this mirror-based cloaking is also a type of metamaterial cloaking approach where you can see. You are basically using curved mirrors to redirect waves around a cloaked object that will be kept here, okay? So, the design of a transmissive invisibility cloak using a metamaterial mirror is shown in this figure. So, what is seen clearly is that there are four mirrors leveled at 1, 2, 3, and 4, and then There are two vertical mirrors also present on both sides of this rhombus frame. Okay, and this particular design basically uses the generalized Snell's law for the control of the reflected wave. we have seen earlier that that we have basically seen for the transmitted one.

Similarly, you can have the generalized Snell's law for reflection, and there you will see that as well. The reflective angle, or the reflection angle, can be controlled only by the phase gradient variation. So, this is how the schematic is showing that the principle of cloaking how it is working. So, you can consider a plane wave incident on this metamaterial mirror; then it is reflected at an angle B, which is further reflected again. So, there are phase gradients along this, this, this, and this.

Finally, your objective is whatever the incoming wave is after crossing that region. You should also get the same kind of parallel incoming waves or outgoing waves. So, that plane wave should not change direction. So, that will allow you to have this cloaked region. Okay.

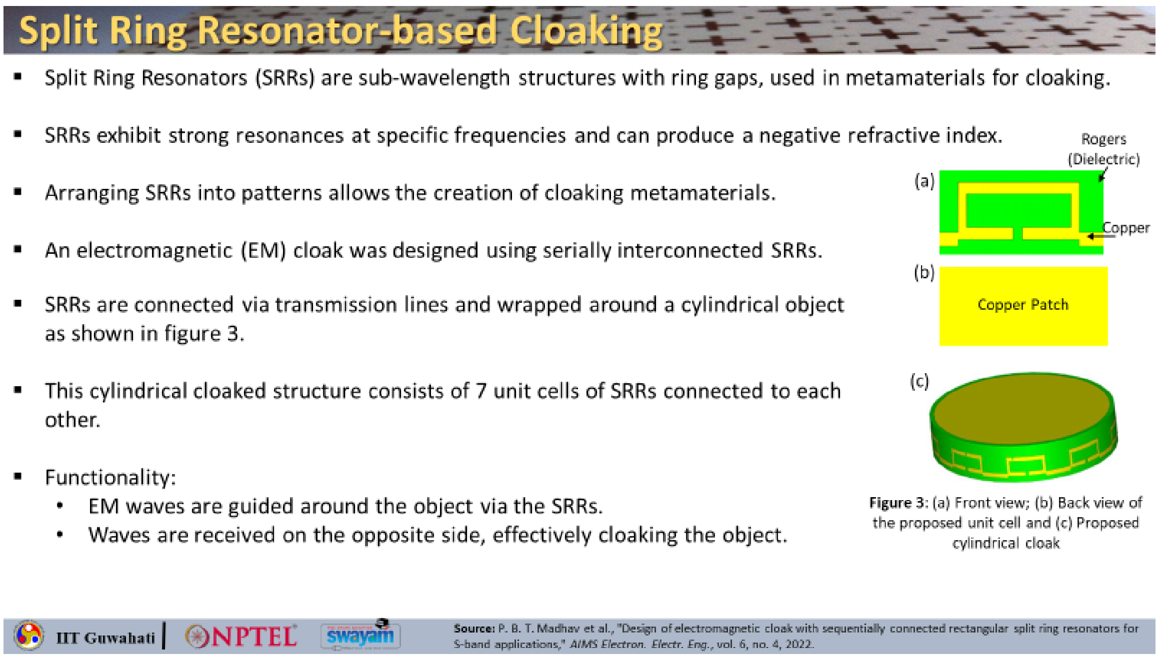


So, what are the key design principles? In this case, you have to remember that you are using all-metal mirror configurations.

Now, if you consider this. All metal mirrors will also work in this case, but typically, they are limited by Snell's law, right, where your incident angle will be equal to the reflection angle. So that will basically restrict your flexibility, and it will require a fixed, cloaked region. But if you make this with metasurfaces or metamaterials to work as mirrors, they will give you a much greater degree of freedom. Because it allows for control of the reflection angle from the gradual phase distribution. And in that case, the incident and reflected angles may vary.

So after covering the obstacle that you are going to cloak with this kind of metamaterial-based mirror cloak, you will see that the outgoing electromagnetic wave appears to be restored as if it were passing through the obstacle undisturbed. Right, so how is this cloak going to be effective? This is mainly because of the metamaterial mirrors. they are able to precisely adjust the reflection angle okay and bring the you know outgoing wave back here okay in the same path as the incoming wave so this mechanism successfully produces the cloaking effect by preserving the wave front, that is the most important thing.

Now, let us look at another example, which is based on a split ring resonator that is used for cloaking. So, split ring resonators are now well-known structures.



These are sub-wavelength structures with some ring gaps, as you can see. This is a copper one on Rogers dielectric. Okay, this can be used in metamaterials for cloaking. So, it has been observed that splitting resonators exhibit very strong resonances at specific frequencies. And they can also produce a negative refractive index.

Now, if you arrange split ring resonators into patterns that allow for the creation of cloaking metamaterials. So here are the front view and back view of the proposed unit cell. So, you see, at the back, you just have a copper patch; on the top, you have this split-ring resonator printed. That is on the Rogers dielectric. So, you can basically make an electromagnetic cloak using serially interconnected splitting resonators.

So, the splitting resonators shown here, this is the unit cell; they can be connected via a transmission line. and wrapped around a cylindrical object, as you can see in this particular figure. So, here specifically, there are seven-unit cells of splitting resonators that are connected to each other to cover the cylindrical cloaked structure. and how it works that electromagnetic waves are now guided around this object via the splitting resonators and the waves are received on the opposite side ok effectively you know cloaking the object.

Next, we move on to another type of structure that is a pie-shaped structure based on geometry.

that can be used for cloaking based on near zero refractive index metamaterial.

Near Pi-Shaped Structure Cloaking

- This structure made of two orthogonal copper arms forming a near π-shape.
- To achieve near-zero refractive index behavior:
  - Series branch must contain inductance or capacitance.
  - Shunt branch must contain the opposite reactance.
- Two unequal gaps at each arm end create a capacitive effect (denoted by "g" and "s").
- Also; each unequal metal arms generate inductance.
- The thickness of all the copper lines: 0.035 mm.
- The structure construsted on epoxy resin fiber (FR-4) substrate material:
  - Dielectric constant: 4.2
  - Dielectric loss-tangent of 0.002.

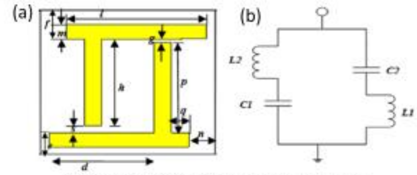


Figure 4: (a) The proposed unit cell structure; and (b) Equivalent circuit of the unit cell

Table 1. Unit cell parameters

Unit cell parameters	Value (mm)
d	6
e	1.5
f	2
g	0.33
h	6
l	8
m	1
n	1.5
p	6.27
q	1
s	0.5

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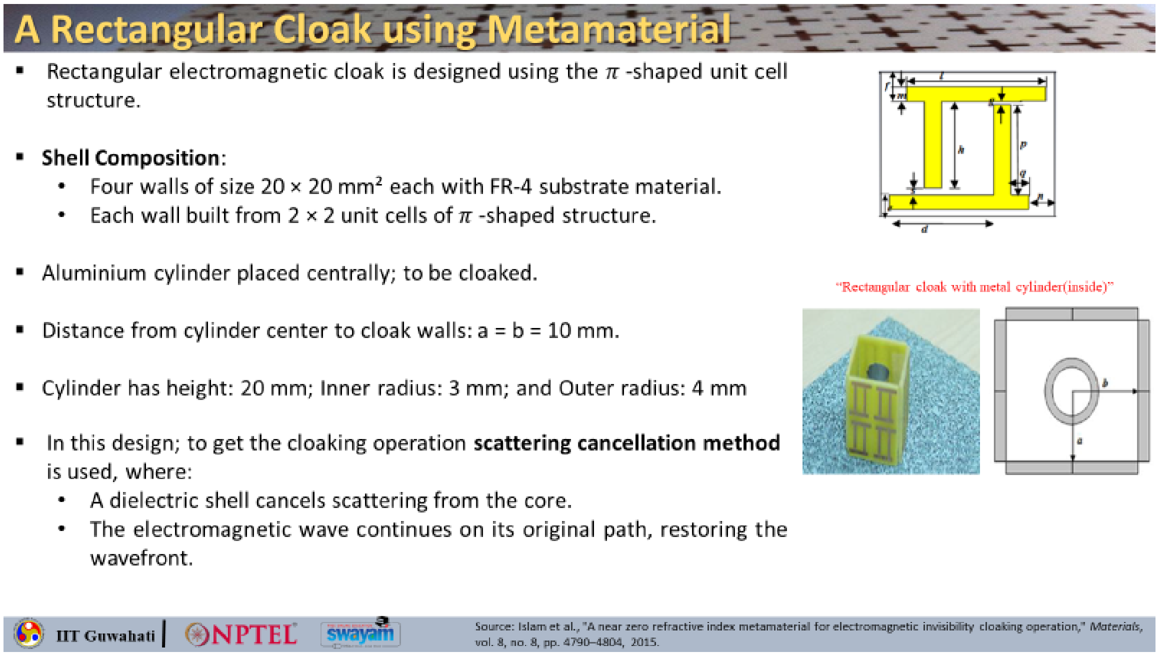
Source: Islam et al., "A near zero refractive index metamaterial for electromagnetic invisibility cloaking operation," *Materials*, vol. 8, no. 8, pp. 4790–4804, 2015.

So, this is the structure I was talking about. It is a near pie shaped structure which is basically made of two orthogonal copper arms that form a pie kind of a shape. The design parameters for this kind of structure are listed here. So, you have all these parameters: d, e, f, g, h, l, m, n.

Okay, p, q, and s, all these things are given in terms of, you know, millimeters. Right now, you see the series branch. For this unit cell structure, it must basically contain an inductance or capacitance, and the corresponding shunt branch must contain. The opposite order of the reactants is correct, and you can see that from the equivalent circuit. Unit cell, right? There are also two unequal gaps present at each arm, and this gives you a capacitive effect that is denoted by g and s.

So, these are the two gaps you can see; they are different, you know, the gaps are different, and conversely. You will see that each unequal metal arm is also responsible for generating inductance, right? and the overall structure has got now the all the copper lines to have the same thickness of 0.035 millimeter and this particular structure is constructed on an epoxy resin fiber FR-4 substrate material, which has a dielectric permittivity of 4.2. The dielectric loss tangent is 0.002.



so, this is a rectangular electromagnetic cloak. That is designed using this kind of pie-shaped unit cell; therefore, this is the cloak. So, anything you keep in the center of this cloak is hidden. Okay, this is the top view. As you can see, you can call it a core-shell kind of structure.

So, the four walls basically have dimensions of 20 by 20 millimeters each with an FR4 substrate material, as you can see from the figure. So, in each wall, you can also see that 2 by 2-unit cells are basically used, where each unit cell is basically having a pie-shaped structure. Now, what are we clocking in here? We are clocking an aluminum cylinder that is placed centrally, and we are maintaining it. The distance from the center of the cylinder to the clock walls on both sides is 10 mm. And in this particular case, they considered the height of the cylinder to be 20 mm.

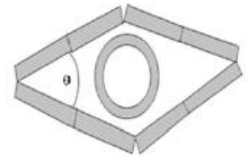
The inner radius is 3 mm, and the outer radius is 4 mm. So, it is not a solid cylinder; it is also a core-shell kind of cylinder, right? So, in this particular design, the cloaking operation is based on the scattering cancellation method. where the dielectric shell basically cancels out the scattering from the core and the electromagnetic waves. in this case continues to move along the original path that is restoring the wave front and giving you the cloaking effect.

Next, we will look into another type. So instead of having a rectangular cloak, you can also make an eye-shaped cloak using the same materials.

An "Eye-Shaped" Cloak using Metamaterial

- Eye-shaped cloak is created using the same material as the rectangular cloak.

"Eye-shaped" cloak with metal cylinder (inside)



- Structure Details:
  - Utilized the same number and size of walls as in rectangular cloak design.
  - Four walls arranged to form an eye shape as shown in figure.
  - Connection: Pairs of walls joined at one end at an angle of θ = 45° (see Fig.).
- Results (as shown in fig.):
  - Effective cloaking occurs at microwave frequencies band i.e.; 5 GHz and 8.70 GHz.
  - Obtained scattering width: 0.12

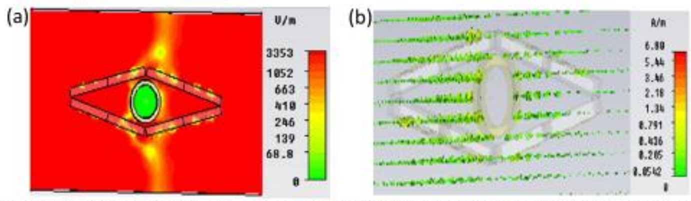


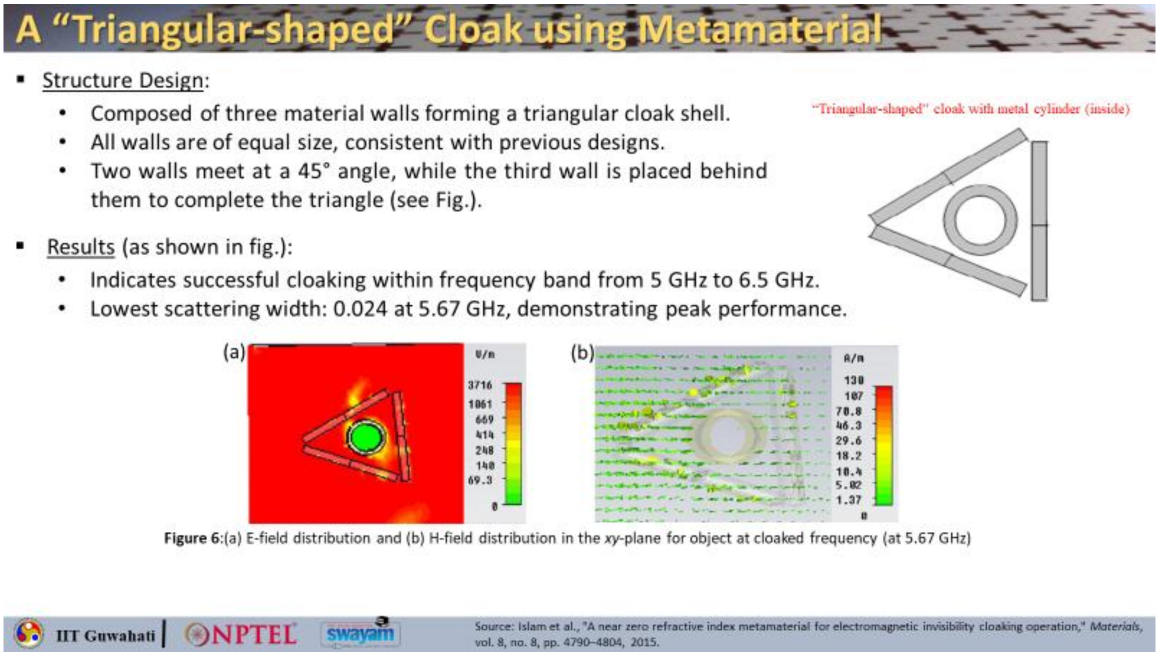
Figure 5:(a) E-field distribution and (b) H-field distribution in the *xy*-plane for object at cloaked frequency (at 5 GHz)

Source: Islam et al., "A near zero refractive index metamaterial for electromagnetic invisibility cloaking operation," *Materials*, vol. 8, no. 8, pp. 4790–4804, 2015.

So, this is the schematic, or you could say the top view, of the eye-shaped cloak with the metal cylinder in between. So, the structural details here remain very similar to what we have seen in the previous slide; it utilizes the same number. And the size of the side walls, as it was in the rectangular cloak region, is okay. So, as you can see, the four walls are basically arranged to Form an eye shape in the figures. The pair of walls is basically joined at one end, and typically the angle is around 45 degrees.

And this is the result of the electric field distribution and the magnetic field distribution along this XY plane for the object. Considering a clock frequency of 5 gigahertz in this case, you can see that the electric field outside is pretty homogeneous. So that is how you can say that the effective cloaking is taking place.

So the overall scattering width is only 0.12. So, it is giving you a very small scattering signature.



You can also make a triangular-shaped cloak using the same type of material. So, in this case, instead of four walls, there will be three walls forming a triangular cloaked shell. So, all the walls are considered to be of equal size, which is consistent with the previous designs we have discussed. Here you will see that the two walls meet physically at a 45-degree angle.

And then you place the third wall behind it to complete the triangle and here also you can you know study the electric field and the magnetic field distribution along the xy plane or in this particular plane, okay, you can see that you can achieve successful cloaking between 5 gigahertz and 6.5 gigahertz. So, this is the result that has been plotted for 5.67 gigahertz. So, you see the surrounding medium more or less everywhere the electric field remains constant.

There is no separate scattering signature revealed for this particular object. So that way, you are able to get a triangular-shaped cloak using metamaterials. And here, you can further reduce the scattering width.

So, it comes out to be 0.024 at 5.67 gigahertz. So, that demonstrates the clock's best performance.

So, with that, we come to the conclusion of this lecture. So, we will start discussing transformation electromagnetics for antenna applications. And some metamaterials for stealth technology in the next lectures. So, if you have any queries regarding this particular topic, you can always send an email to this email address mentioning the course name and the lecture number on the subject line. Thank you.