Course Name: Introduction to Microwave and Optical Metamaterials
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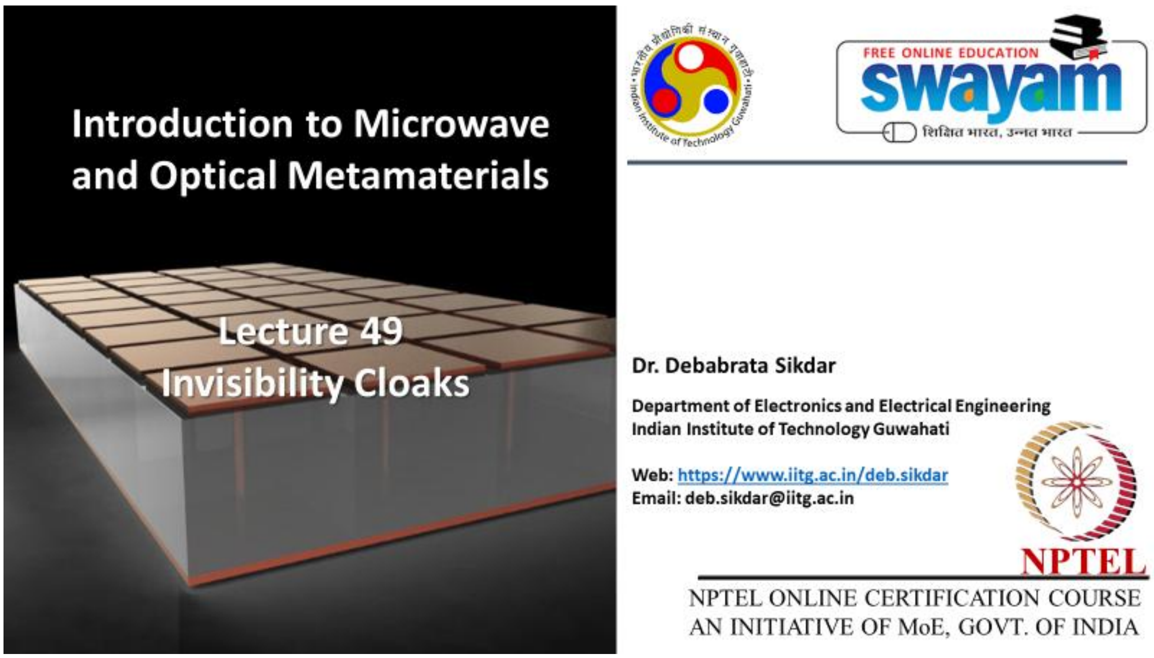
Institute Name: Indian Institute of Technology, Guwahati
Week-10
Lecture-49

Lec 49: Invisibility Cloaks



Hello everyone, welcome to Lecture 49 of the online course on Introduction to Microwave and Optical Metamaterials. This lecture is on invisible clocks.

Lecture Outline

- Invisibility Cloaks
- Cloaking Mechanism
- How to design Invisibility Cloaks

So, here is the lecture outline: we will briefly introduce you to invisibility cloaks, which are an extension of the final topic of the previous lecture. We will discuss about the cloaking mechanism and we will go into the depth of how to design invisibility cloaks ok.

Invisibility Cloaks

So, what are invisibility cloaks? So, normally you will see that when light interacts with an object, it is either absorbed or reflected; that makes the object visible. So, at its core, invisibility technology basically relies on manipulating light waves, which are responsible for our visual perception.

Invisibility Cloaks

- Normally, when light interacts with an object, it is either absorbed or reflected, making the object visible.
- At its core, invisibility technology relies on manipulating light waves, which are responsible for our visual perception.
- Researchers have developed innovative approaches that bend and redirect light, effectively concealing objects from view.
- However, achieving a full-blown invisibility cloak across the entire visual spectrum is a huge challenge.
- Previously, scientists have made fighter jets invisible to radar and made thermal invisibility jackets that hide soldiers from enemy thermal cameras.
- But to conceal something from the naked eye as if it never was there requires some serious engineering.

Figure: An illustration of real life invisible cloaks.

IIT Guwahati | NPTEL swayam Source: https://www.zmescience.com/feature-post/technology-articles/inventions-1/real-life-invisibility-cloaks/

I'm talking about light waves mainly because the word "invisibility" comes from the optical domain itself, right. So, researchers have developed innovative approaches that blend and redirect light that effectively consoles objects from view So here is an illustration of a real-life invisible cloak so you can see the person standing in front of a tree. With a cloak in hand, it is basically invisible. Okay, and the background is kind of seen, so that renders that person invisible, and the person is now like kind of see-through, right? So this is an illustration of what the challenge is; you'll see that achieving a full-blown invisibility cloak is difficult. That works across the entire visual spectrum, say 380 to 780 nanometers, is a huge challenge.

Previously, the same concept has also been tried and tested in microwave and RF frequencies. So, scientists have made fighter jets invisible to radar and have also created thermal invisibility jackets. which are typically in the infrared range that can hide soldiers from enemies' thermal cameras. But to conceal something from the naked eye is really, really difficult because it requires some serious engineering. So true transparency would require light to pass through an object undisturbed, as if the object were not at all there.

Invisibility Cloaks

- True transparency would require light to pass through an object undisturbed, as if it were not there.
- To achieve this, a cloaking device would need to redirect light from all directions around the object, so that it appears invisible from any angle.
- Metamaterials, engineered materials with unique properties not found in nature, play a pivotal role in creating invisibility cloaks.
- By designing these materials with carefully arranged nanostructures, scientists can control the behavior of light waves.
- This field, known as transformation optics, allows for the manipulation of light around an object, making it appear invisible.

Figure: An illustration of real life invisible cloaks.

IIT Guwahati | NPTEL swayam Source: https://www.zmescience.com/feature-post/technology-articles/inventions-1/real-life-invisibility-cloaks/

So, to achieve this kind of a feat, a clocking device would basically need to redirect light from all directions. Around the object, it should be, you know, invisible from every angle, so that makes it even more complicated. That you want it to work for the entire visible range for all the angles, okay? So that is where you need metamaterials. which are basically engineered materials with unique properties that play a vital role in creating this kind of invisibility cloak. So, we have seen so far that by designing metamaterials with carefully arranged nanostructures, Scientists have gained control over the behavior of light waves. So, this field is also known as transformation optics, or you know, this is a special branch of transformation electromagnetics.

It allows for the manipulation of light around an object, making that object invisible.

Invisibility Cloaks

- Several cloaking mechanisms have been proposed and developed to achieve invisibility.
- One approach involves bending light around an object, creating a “cloak” that renders it optically transparent.
- Another method utilizes the redirection of light, making an object appear as if it were not there.
- These techniques require precise control over the speed, direction, and intensity of light waves to achieve the desired effect.

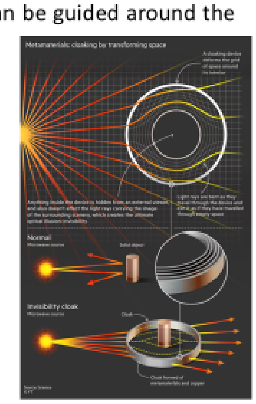
Figure: An illustration of real life invisible cloaks.

So, several clocking mechanisms has been proposed and developed till now to achieve you know the final goal of invisibility. One approach basically involves bending light around the object. So, it becomes optically transparent. The other method basically utilizes redirection of light to make an object appear as if it is not there.

So, these techniques they require precise control over the speed direction and intensity of light waves to achieve this kind of effect.

Cloaking Mechanism

- Metamaterial cloaking is a technique that uses artificially engineered materials (metamaterials) to manipulate electromagnetic waves (like light or microwaves) around an object, making it appear invisible.
- By carefully controlling how these waves interact with the metamaterial, the waves can be guided around the object, rendering it undetectable by an observer.
- How it works:
  - Metamaterial cloaks are designed with a specific arrangement of subwavelength structures to control the refractive index of the material.
  - By carefully tuning this refractive index, light can be guided around the object, making it appear invisible.
- Applications: Cloaking technology has potential applications in various fields, including:
  1. **Defense:** Concealing military equipment from radar detection.
  2. **Medical imaging:** Improving the ability to see inside the human body.
  3. **Telecommunications:** Potentially creating more efficient optical devices.



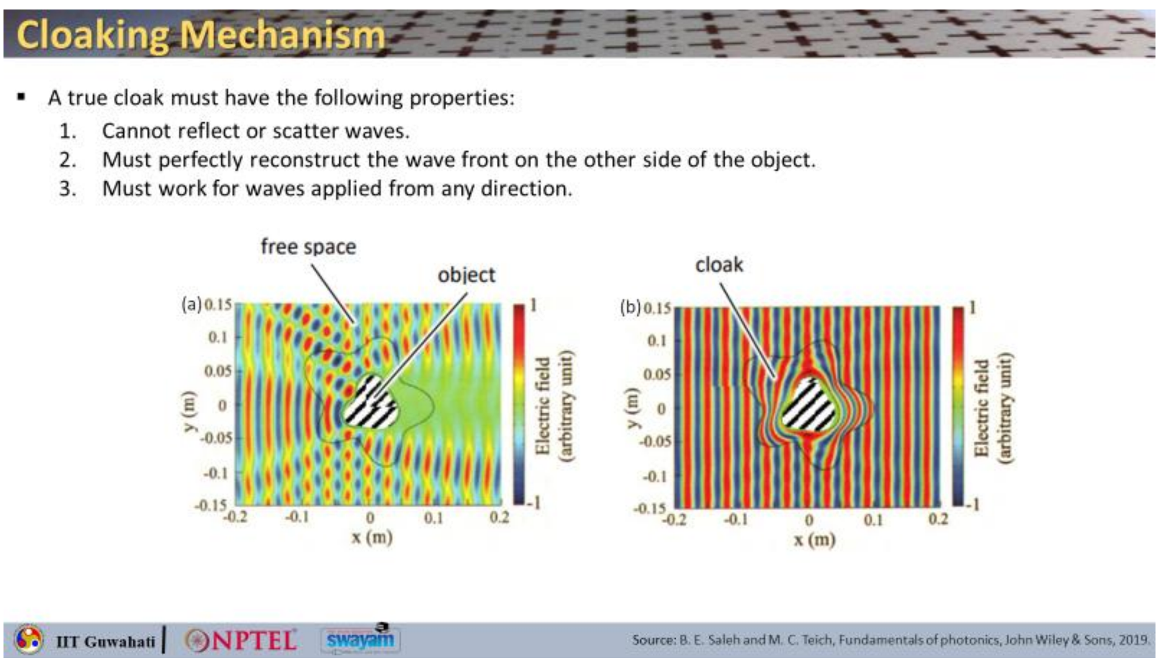
“Cloaking Mechanism”

So, now let us look into the cloaking mechanism. So, I briefly discussed in the last lecture that you basically use metamaterials to achieve this feed. where you can manipulate electromagnetic waves, be it light or microwave, to bend around an object So that you know, if you look back towards the source, you will not see that object; okay, you will just see that. As if the light is coming from a source without any disturbance, right. So, this is the art, or.

The magic of metamaterials is that the waves can be guided around. the object using this, right. So, how it basically works is that metamaterial cloaks are designed with a specific arrangement of sub-wavelength structures. That can control the refractive index of the material. So, you are basically getting a kind of, you know, graded index material where the light can slowly bend around, okay? and then you can when the light rays exit and if you trace back it comes from the same source without getting any disturbance right.

So, that basically makes the object invisible. So, why this particular technology is very interesting is that it has several applications, particularly in the field of defense. It can allow you to conceal military equipment from radar detection. You can also do medical imaging that improves the ability to see inside the human body. That this can also be used for telecommunication purposes, okay.

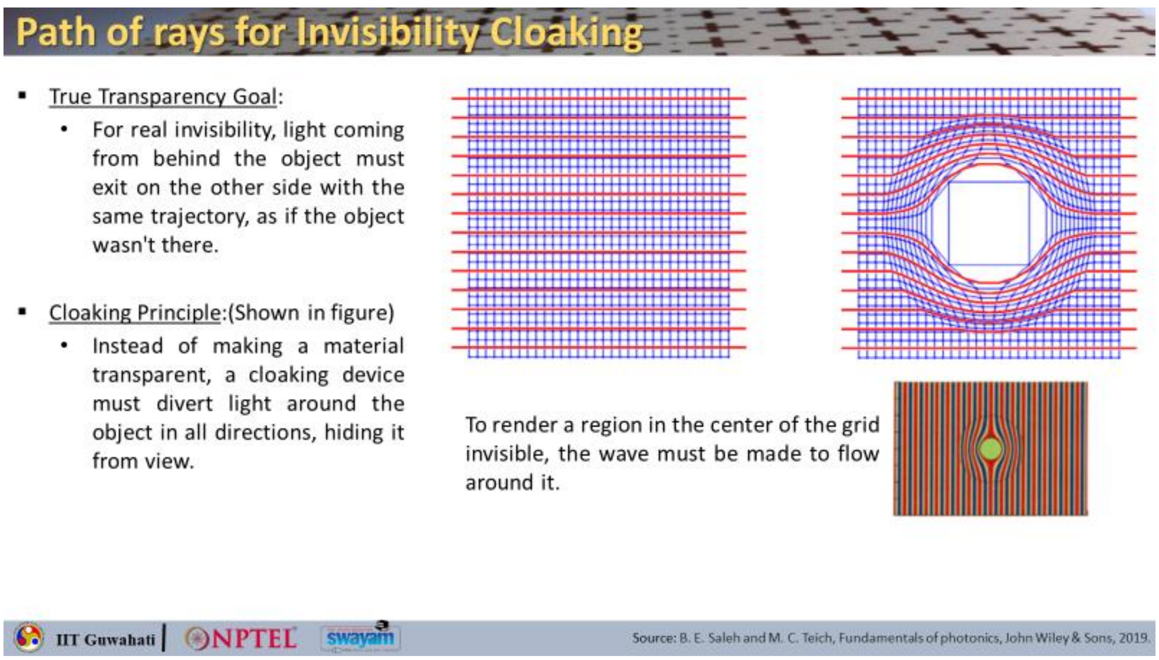
But once again, it is mainly attractive for stealth applications for defense purposes, right.



So, a true cloak must have the following properties, as you can see here. So, ideally, it should not reflect or scatter waves, and it should perfectly reconstruct the wave front on the other side of the object. So, if there is an object and you put a cloak around it, the wave front before and after the object should look exactly the same. So, that is how it should be able to reconstruct it. So, this is without a cloak; you see just an object in free space.

You see the waves are getting distorted, giving you... The signature that the wave is present here; this is the scattered wave that you see here, this one and this one, but here. You see, it is completely the same; it is able to reconstruct the wavefront.

So, the wave is not disturbed at all by this. So, most work for the waves applies from any, and the other requirement is that you know. This should also work for waves that are coming from any direction. So, there is a frequency band over which this should work; also, it should work for any angle, okay. So, now let us look into the path of rays and how they need to be banned to achieve this invisibility cloaking.



So, our true transparency goal is to achieve real invisibility of light coming from behind. The object must exit on the other side with the same trajectory. As if the object is not there, this is the way the parallel rays are before entering the object, and this is how they should exit the object. So, whatever you do in between is the art of cloaking. So, here you can see that if there is an object placed in this square hole, this is the cloak that is bending the light beams around.

So, after exiting, they are exactly the same as the incident light beams, which means you are able to hide the object that you are putting here. Okay. So, what are you doing instead of making a material that makes your object invisible or transparent? You are basically making a cloaking device that is basically diverting the light rays around your object in all directions. Thus, it is able to hide it from view. So, here also you can see that you have an object cylindrical object with a cloak and then the wave front is completely reconstructed.

So, there is no disturbance created by this object, and this is what we want.

Now, how to design these invisibility cloaks, and this is the reason why we have studied transformation optics. or coordinate transformation because it will be utilized in this particular example now.

Invisibility Cloaks

- An invisibility cloak is a device that guides light around an object such that the object appears transparent, and therefore invisible.
- For example, the trajectories shown below avoid a sphere of radius a, emerging as if they had followed straight lines and passed right through it.
- Following the design steps for transformation optics, we begin with the straight-line trajectories shown in Fig. (b) in a Cartesian-coordinate system (x_1, x_2, x_3).

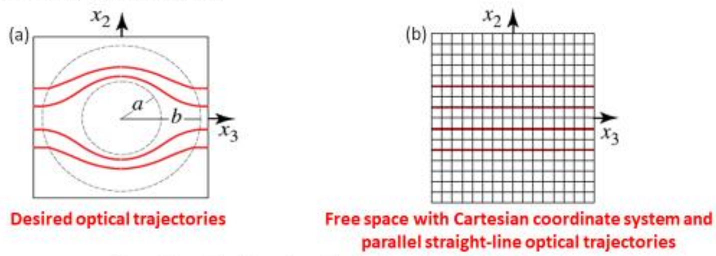


Figure: Geometrical transformation implementing cloaking of a sphere.

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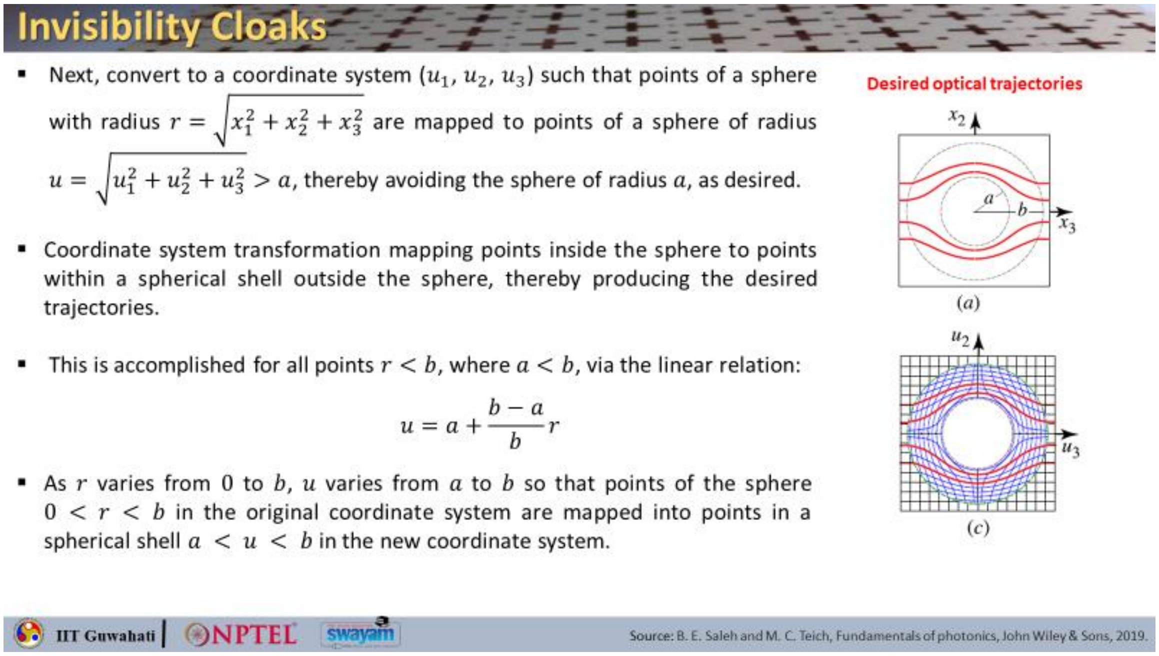
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.

So, we saw that you know the invisibility clocks are going to guide lights around the object. So, if you want to hide this object, what do you have to do? You have to map this region into this shell region correctly.

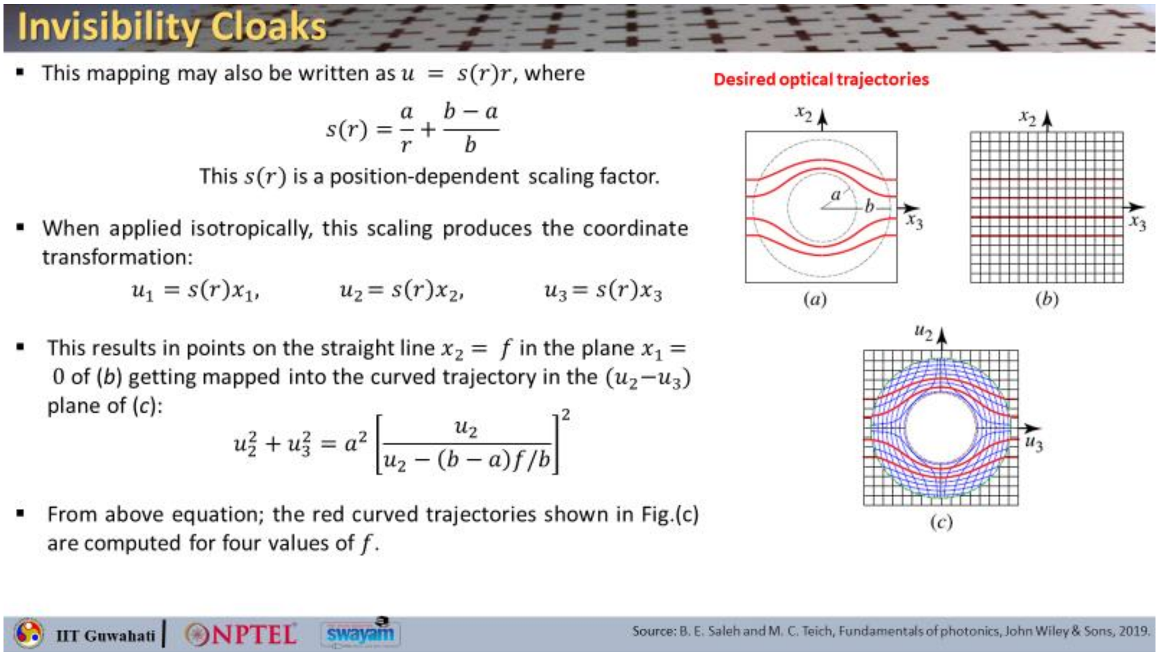
In that case okay you can you know put anything inside this core region that will not be disturbing the light rays, because the light rays are not going through the core region, they are rather bent around this shell region. and they exit exactly in the same fashion as the way they entered, right? So, the following design steps from coordinate transformation need to be followed. So, you begin with straight-line trajectories, as you can see here in a Cartesian coordinate system, which is called x_1, x_2, and x_3 as the axes.



Then, you convert to a coordinate system u_1, u_2, and u_3 such that the points of a sphere with radius r which is given as: $r = \sqrt{x_1^2 + x_2^2 + x_3^2}$, can be mapped onto a sphere of radius u Which is larger than this radius 'a' now. So, you are basically avoiding the sphere of radius a.

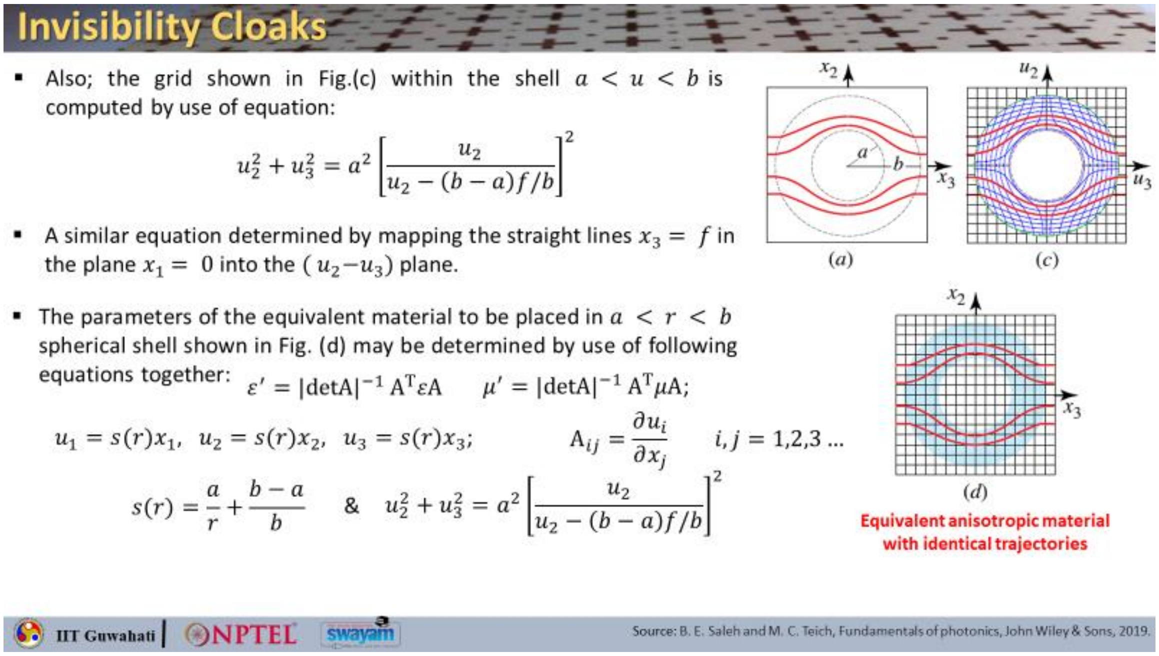
So, you just want to move out of this range. So, the coordinate transformation is basically mapping the points inside a sphere to the points within a spherical shell like this, okay and you can actually compute this kind of transformation through this linear relationship. So, you can say that $u = a + \frac{b-a}{b} r$. So, basically, whatever is within this region r < a is now mapped within this shell region, which has a radius of b minus a.

And this is the transformation of the relationship between the old coordinate system and the new coordinate system, right? So, as r varies from, you know, 0 to b, okay, u will basically vary from a to b, okay. So, in that case, that tells you that this region is not covered here, okay. So, what you can say is that this entire region, you know, ranging from 0 to b in the original coordinate system, is now mapped into this spherical shell where the u value ranges from a to b in the new coordinate system.



So, once you know the mapping, you can also write $u = s(r)r$. So, you can calculate what this $s(r)$ is . So, $s(r)$ is basically the position-dependent scaling factor. So, $s(r)$ can be written as $s(r) = \frac{a}{r} + \frac{b-a}{b}$. And then, when you apply the scaling factor isotropically, it will give you the correct coordinate transformation. So, you can write $u_1 = s(r)x_1$, $u_2 = s(r)x_2$, and then $u_3 = s(r)x_3$. This is because you are applying it isotropically.

So, this will result in points on the straight line that have x_2 equal to f in the x_1 equal to 0 plane. that is in this particular plane that is basically getting mapped into a curved trajectory that you see here in the $(u_2 - u_3)$ plane ok. So, the relationship is: $u_2^2 + u_3^2 = a^2\left[\frac{u_2}{u_2-(b-a)f/b}\right]^2$. So, from this equation, you can see the red curved trajectories shown in this particular figure. And that is calculated for 1, 2, 3, and 4 values; you can see here 4 values of f, right.



Also, the grid that is shown in this particular figure C within this particular shell is computed using the equation.

So, the grid is no longer rectangular. It can also be calculated as: $u_2^2 + u_3^2 = a^2 \left[\frac{u_2}{u_2-(b-a)f/b}\right]^2$. So, you can find a similar equation determined by the mapping of the straight line $x_3 = f$ in the same plane x_1 equals 0 into your u_2, u_3 plane.

So finally, the parameters of the equivalent material to be placed in this spherical shell of radius between A and B can be seen here. So you can obtain this from this equation. So epsilon prime shows this blue shaded region that represents a new material. which is called the permittivity of epsilon prime given by: $\varepsilon' = |\text{detA}|^{-1}\, \text{A}^{\text{T}} \varepsilon \text{A}$.

Similarly, you have it for mu prime $\mu' = |\text{detA}|^{-1}\, \text{A}^{\text{T}} \mu \text{A}$, OK. And this is the transformation that you are using, where $s(r)$ is given by this and the relationship between u_2 and u_3, and this particular axis or the grid system is given by this. A is the Jacobian matrix that you can calculate; we have been seeing this for a long time, Okay. you already know how to do that.

Invisibility Cloaks

- Thus; result is:

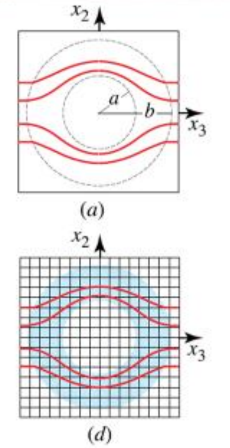
$$\varepsilon_0^{-1}\varepsilon' = \mu_0^{-1}\mu' = \frac{b}{b-a}\frac{1}{v^2}\begin{bmatrix} v^2-u_1^2 & -u_1u_2 & -u_1u_3 \\ -u_2u_1 & v^2-u_2^2 & -u_2u_3 \\ -u_3u_1 & -u_3u_2 & v^2-u_3^2 \end{bmatrix};$$

where, $v^2 = \dfrac{u^4}{2au-a^2}$

- Clearly, the dielectric and magnetic properties of the material in the spherical shell are both inhomogeneous and anisotropic.

- For example, at points on the x_1 axis $(u, 0, 0)$, we have:

$$\varepsilon_0^{-1}\varepsilon' = \mu_0^{-1}\mu' = \frac{b}{b-a}\begin{bmatrix} 1-u^2/v^2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Equivalent anisotropic material with identical trajectories

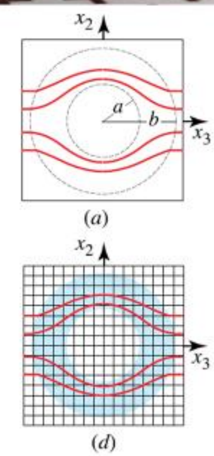
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.

So, once you compute this, this is what you get: you get the new value of the material parameters. Where, for simplicity, you can assume $v^2 = \frac{u^4}{2au-a^2}$. So, that is the matrix right now that will tell you the new permittivity and permeability tensors. So, clearly as you can see that you know it is not very easy to get this kind of a material because the dielectric and the magnetic properties of this material in the spherical shell, which is shown here in the highlighted region It is both inhomogeneous and anisotropic, right? So, if you take an example on the x_1 axis that is where you have u, 0, 0 you can have this values that you know $\varepsilon_0^{-1}\varepsilon' = \mu_0^{-1}\mu'$, that is $\frac{b}{b-a}\begin{bmatrix} 1-u^2/v^2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$; this is the value for that, okay. Now, at these points, the principal axes are aligned with the Cartesian coordinates x_1, x_2, and x_3, as you can see.

Invisibility Cloaks

$$\varepsilon_0^{-1}\varepsilon' = \mu_0^{-1}\mu' = \frac{b}{b-a}\begin{bmatrix} 1 - u^2/v^2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- At these points, the principal axes are aligned with the Cartesian coordinates (x_1, x_2, x_3).
- The principal value ε_1 varies from 0 to $\varepsilon_0(b-a)/b$ as u varies from a to b, while the principal values ε_2 and ε_3 are fixed at the value $\varepsilon_0 b/(b-a)$.
- Similar results apply for μ.

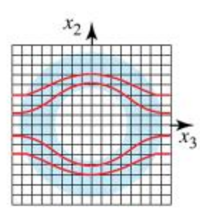


Equivalent anisotropic material with identical trajectories

Now, the principal value of epsilon 1 will vary from 0 to $\varepsilon_0(b-a)/b$, as your u will vary from a to b. Okay, and while the principal values, like epsilon 2 and epsilon 3, will remain fixed. Because they will be simply $\varepsilon_0 b/(b-a)$, okay? And the same thing will also apply for mu. So, you will be able to get, you know, the invisibility cloak, but you can see that the constraints from coordinate transformation. Transformation optics resulting in the new material properties of permittivity and permeability are really challenging.

Invisibility Cloaks

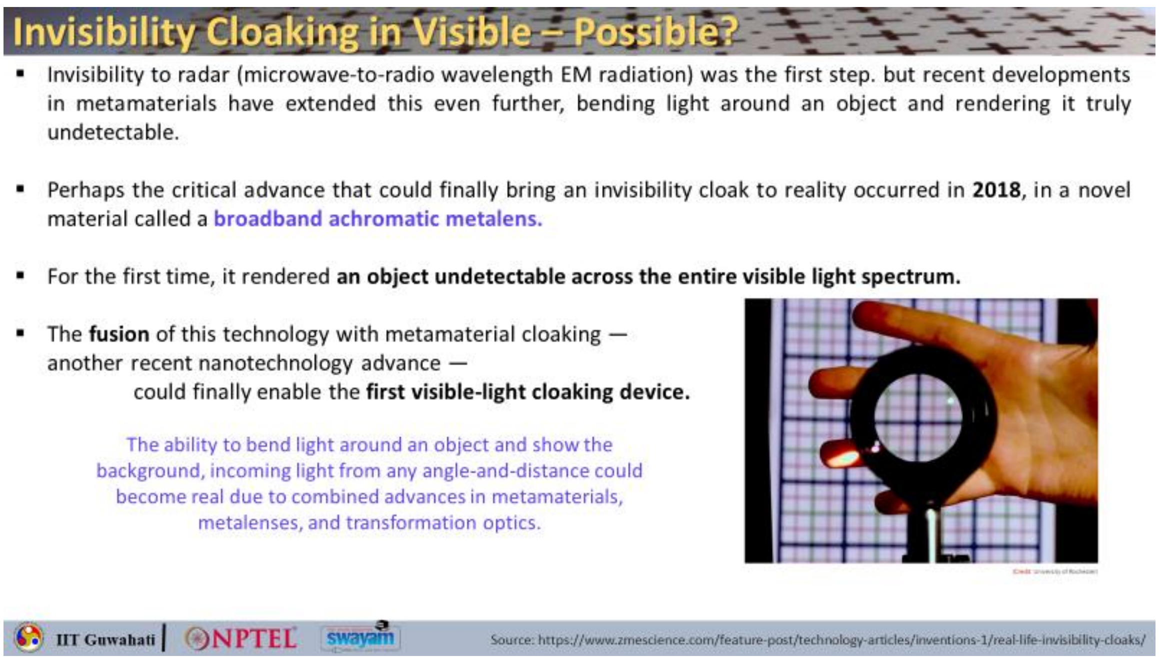
- At optical wavelengths, the implementation of invisibility cloaks via metamaterials requires the use of advanced nanofabrication technologies such as electron-beam or focused ion-beam lithography.
- The constituent dielectric and magnetic elements, which have various shapes and dimensions, must be intricately designed and precisely laid out.
- Since such elements are highly resonant, the electromagnetic properties of the metamaterial depend strongly on wavelength so that such devices typically operate only over narrow spectral bandwidths.



IIT Guwahati | NPTEL swayam Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.

So, at optical wavelengths, the implementation of invisibility cloaks via metamaterials will require really advanced nanofabrication techniques. such as electron beam or focused ion beam lithography. The constituent dielectric and magnetic elements, which have various shapes, Dimensions must be integrally designed and precisely laid out. Now, since each element is highly resonant, the electromagnetic properties of the metamaterial also depend strongly on the wavelength. So, typically this kind of cloaking device will operate only over narrow spectral band.

So, it is very difficult for you to get it over the entire visible range. So, the question comes that in invisible cloaking, invisible is it really possible?



So, the invisibility to radar that is typically in the microwave to radio wavelength EM radiation was the first step has been achieved, but recent developments in metamaterials have actually extended this idea further. That has allowed us to bend light around the object and, you know, in a way, make it completely undetectable. So, recently in 2018, a novel material called a broadband achromatic metal lens was developed. And this is the first time it has rendered an object undetectable across the entire visible spectrum.

So this is a real-world experimental photo where the fingers of the person are not visible, right. So, the fusion of this technology with metamaterial clocking, which you know, and with the, you know, Recent advancements in nanotechnology can enable the first visible light clocking device for all angles. So, it is actually a very, very complicated task, but the research is still in progress to achieve this particular feat. So, as you can understand, the ability to bend light around an object and to show the background And that too, for you know, incoming light from all angles and all distances is really a complicated problem. It can only be solved when you bring in the advances in the field of metamaterials and metal lenses. Transformation optics, the nanofabrication technology brings everything together.

Invisibility cloaks are not just possible, but are becoming reality

- By bending light around an object, the science of transformation optics could enable the first working, 3D cloaking device.
- A new advance in metalenses, if successfully applied, could extend a cloak to the visible light portion of the spectrum, enabling the first true "invisibility cloak."

Source: https://bigthink.com/starts-with-a-bang/invisibility-cloak-183582/

In the other field, like in the field of electromagnetics, everything is much more advanced. even a company called hyper stealth they are also making real life invisibility cloaking, okay for the optical wavelengths, you can see that there are basically three hammers. This is the toy models and one covered with this invisibility cloak, which is showing you the background but not the hammer, right. So, by bending the light around an object, you can see that you can make a 3D cloaking device. So, a new advance in metal lenses, if successfully applied, could extend a cloak to the visible light portion of the spectrum. And that will be the first realization of a true invisibility cloak, okay.

So, here you can also see that this is the sheet covering this tank. So, from the front, you cannot see it, okay? So, this is also one application of this hyper stealth; they also call it quantum stealth. that makes you know invisible military becoming a reality.

Invisibility cloaks are not just possible, but are becoming reality

- Observer's Perspective:
  - When successfully cloaked, an observer from any angle or location would only see the background, not the object itself.
- Real-World Demonstration:
  - Quantum Stealth technology is claimed to make military objects like the **M1 Abrams Tank invisible** by manipulating light paths (as shown in images).
- Application Outlook:
  - The demonstration hints at potential military invisibility solutions becoming a practical reality.

Quantum Stealth; The Invisible Military Becomes A Reality

Website: https://www.hyperstealth.com/Quantum-Stealth/

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Source: https://bigthink.com/starts-with-a-bang/invisibility-cloak-183582/

So, what do you see here that successfully cloaks an observer from any angle or location could see only the background, not the object itself. So, this is the real-world demonstration of this quantum stealth technology they claim to have.

make a military object like a you know tank invisible by manipulating the light paths and This kind of demonstration hints that there is a huge, you know, potential military invisibility solution. Coming up, which will change the shape of modern warfare, okay.

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Send your queries at deb.sikdar@iitg.ac.in

So, with that, I will conclude this lecture on invisibility cloaks. In the next discussion, we will talk about carpet cloaking, okay, and where it is applicable. So, with that, I will thank you, and if you have any queries, you can drop an email to this email address mentioning the course title and the lecture number in the subject line. Thank you.