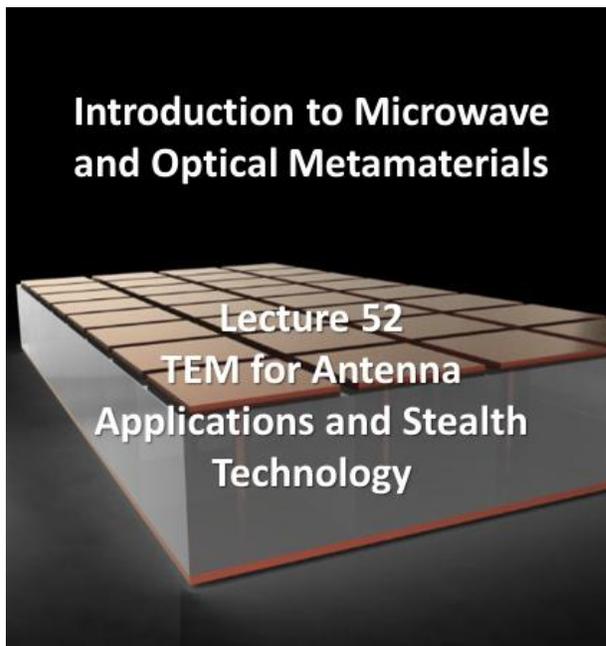


Course Name: Introduction to Microwave and Optical Metamaterials
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Week-11
Lecture-52

Lec 52: Transformation Electromagnetics for Antenna Applications and Stealth Technology



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Welcome to Lecture 52 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on Transformation Electromagnetics for antenna applications and stealth technology.

Lecture Outline

- TEM for Antenna Applications
 - Introduction
 - Theoretical Background
 - ✓ Discrete Coordinate Transformation
 - Design of Antennas Based on the Discrete Coordinate Transformation
 - ✓ Flat Parabolic Reflectors
 - ✓ Flat Lens Antenna

- Metamaterials for Stealth Technology
 - Introduction to Stealth and Metamaterials (MTMs)
 - MTM Structure for Stealth Technology



Here is the lecture outline. We will discuss electromagnetic transformation for antenna applications by first introducing the topic, and its theoretical background focusing on the discrete coordinate transformation. And then we will take up the design of antennas based on the discrete coordinate transformation.

We will discuss flat parabolic reflectors and flat lens antennas. Then we will move on to the topic of metamaterials for stealth technology, where we will introduce stealth and metamaterials. And we will see how metamaterial structures can be used for stealth applications.

So, let us first focus on transformation electromagnetics for antennas.



Transformation Electromagnetics for Antenna Applications



Introduction

- Currently electromagnetic cloak designs primarily rely on:
 - Metamaterials
 - Transformation optics/electromagnetics (TO/TEM)
- Free space cloaks are challenging to implement due to their requirement for materials with extreme properties.
- TEM serves as a valuable design tool for antenna engineers to develop novel antennas.
- One of the applications of TEM is for beam steering devices (such as antennas):
 - To focus and steer radiation
 - To control the direction of electromagnetic beams.
- Example antennas design include:
 1. Flat parabolic reflectors
 2. Flat lens antenna} These designs often require anisotropic and exotic materials.



Source: Hao, Yang, "Transformation electromagnetics in antenna engineering: Theory and implementation," 2011. XXXth URSI General Assembly and Scientific Symposium, IEEE, 2011.

So, currently, the electromagnetic cloak designs primarily rely on metamaterials and transformation optics or transformation electromagnetics. Free space cloaks are basically challenging; as we have discussed earlier, they are challenging to implement. because

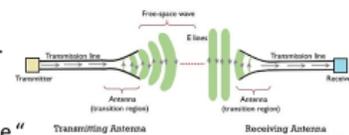
they impose requirements on metamaterials that have some extreme properties of permittivity and permeability. So, that theoretically they are possible but challenging to fabricate those kinds of devices, right. So, transformation electromagnetics will serve as a valuable design tool for antenna engineers here.

That can also help in developing some novel antennas. So other than cloaking, this transformation optics or transformation electromagnetic theory can also be used for beam steering devices such as antennas. So, you can focus or steer the radiation in a particular direction. You can also control the direction of the electromagnetic beams. So, some example antenna designs will include flat parabolic antennas and flat-lens antennas.

So, typically, these designs require isotropic and exotic materials.

Introduction

- TEM leverages the symmetry of EM fields, rooted in the form-invariance of Maxwell's equations under coordinate transformations.
- Transformation Electromagnetics (TEM):
 - Provides precise control over EM wave paths using engineered materials.
 - Mimics coordinate transformations to guide wave trajectories.
- This approach provides innovative ways to manipulate "electromagnetic space."
- Traditional Antenna Design: A well-established field.
 - Engineers typically rely on years of experience to develop new configurations.
 - Goal: Meet desired performance specifications better than legacy designs.
- Introduction of New Antenna Design Concepts via TEM:
 - **Method**: Maxwell's Equations are transformed from one coordinate system to another.
 - **Purpose**: To design the material parameters of the medium in which an antenna is embedded.
 - **Aim**: Achieve desirable antenna performance that is difficult with conventional approaches/media.



So, here we will see that transformation electromagnetics will leverage the symmetry of electromagnetic fields, which is basically rooted in the form invariance of Maxwell's equations that undergo coordinate transformation. So, transformation electromagnetics will basically provide precise control over the paths of electromagnetic waves. using these engineered materials and it will mimic the coordinate transformation to guide you know wave trajectories.

So, this approach provides innovative ways to manipulate electromagnetic space. So, in traditional antenna design, which is a well-established field, this is typically how it works. You have a transmitter and then a transmission line. This antenna portion is

essentially the transition region where it radiates waves out to free space. Okay, it propagates as plane waves, as you can see, and then again on the receiver antennas, transition wave.

This is coupled to the transmission line and received at this particular receiver circuit, right? So, engineers basically typically rely on years of experience to develop new configurations right. And the ultimate goal is to meet the desired performance specifications better than the legacy designs. Now you can introduce a new kind of antenna design concept by using transformation electromagnetics. How you can actually take the help of Maxwell's equations, which are invariant when you transform from one coordinate system to another. This will basically help you design the material parameters of the medium in which an antenna is going to be embedded.

So, the final aim here is to achieve desirable antenna performance, which is otherwise difficult with conventional approaches or mediums.

So, for that, let us have some theoretical background, okay.



Theoretical Background

Theoretical Background

- TEM evolved from early cloaking concepts:
 - Used materials that could bend or reroute light to electromagnetically conceal objects.
 - Evolved from a concept of "magic cloaks."

- Methodology:
 - Original EM field setup is mapped to a Cartesian mesh (Fig. 1).
 - A 'bump' on a flat surface becomes flattened in the new coordinate system.
 - Material properties are modified via transformation equations to preserve wave behavior.

- Key Result:
 - Light travels undistorted in the transformed system.
 - Achieved by overlaying an inhomogeneous material blanket that bends light around imperfections (Fig. 2).

- Discrete coordinate transformation is a practical form of transformation electromagnetics.
 - Enables coordinate system transformations in a discretized format.

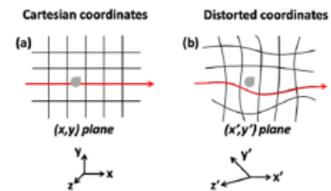


Fig. 1: Transformation Electromagnetics via coordinate transformation

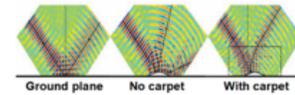


Fig. 2: The Carpet Cloak

So, we understood that transformation electromagnetics evolved from early, you know, cloaking concepts. which are basically used for materials that could bend or read out light to electromagnetically conceal objects. So, they basically evolved from the concept of magic cloaks. So, what do you see as the methodology in this case?

So, the original electromagnetic field setup can be mapped into a Cartesian mesh, which is shown like this.

Now, if you have a bump on a flat surface, it should become flattened in the new coordinate system. So, the material behavior should be modified via this transformation equation that will help you preserve. The earlier wave behaves as if the bump does not even exist. So, the key result will be to see that light is basically traveling undistorted in this transformed system. So, you can overlay an inhomogeneous material blanket that can bend light around imperfections.

So here it is like you have an imperfection. So, you just bend the light around this imperfection and exit in the same way it was entering this system. The same thing you can see here in the case of carpet cloak, where you have a flat ground plane. Then you have a bump. So, because of this bump, the reflected wave would have scattered in different directions.

But now, when you put a carpet cloak that conceals the bump in such a way that overall it gives you the effect of a flat ground plane. So that the reflected light goes as if there is nothing hidden. Okay, these concepts we have basically seen, but we will show you how a similar concept can also be used. Here to make antennas with some specific

functionalities, right? So, discrete coordinate transformation is a practical form of transformational electromagnetics. which enables coordinate system transformations in a discretized format, right.

Theoretical Background: Discrete Coordinate Transformation

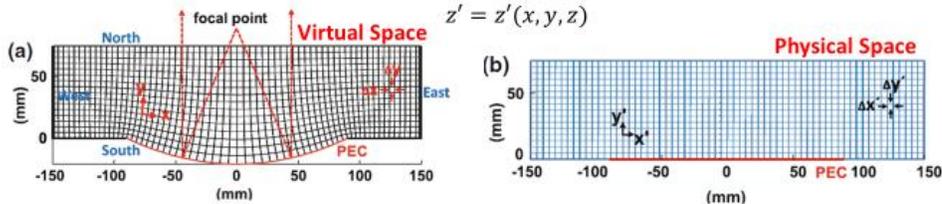
- Discrete Coordinate Transformation Implementation:
 - Both the virtual and physical spaces are discretized into small cells.
 - This is achieved using quasi-orthogonal local coordinate systems.
 - Illustrative Example: Transformation of a parabolic reflector in virtual space (Fig. a) into a flat one in physical space (Fig. b).

- Coordinate Transformation Definition:
 - The transformation between the virtual space (local coordinates: x, y, z) and the physical space (local coordinates: x', y', z') is defined as:

$$x' = x'(x, y, z)$$

$$y' = y'(x, y, z)$$

$$z' = z'(x, y, z)$$



So, let us look into this discrete coordinate transformation and how it is implemented. So, here you can see the virtual space and the physical space. So, you have a parabolic reflector, okay. So, let us implement this discrete coordinate transformation. So, here you can see that both the virtual space and the physical space are discretized into small cells.

So, what you have here is a parabolic reflector, as you can see. This is a PEC, and this is the virtual space that has now been mapped into a physical space that is uniform and flat. So, in both cases, it is basically that you have used quasi-orthogonal local coordinate systems. So, this is a transformation of a parabolic reflector in virtual space. So, you can see this is the parabolic reflector that can be transformed into a flat one in physical space.

So, these are the new coordinate systems x prime and y prime, right? So, what will the definition of this coordinate transformation be? So, the transformation between the virtual space, which has local coordinates of $x, y,$ and $z,$ and the physical space, which has the local coordinates of $x', y',$ and $z',$ can be defined like this: that x' is basically a function of $(x, y, z);$ y' will also be a function of $(x, y, z),$ and z' is a function of (x, y, z) again.

So, you have to find out what the transformation is. We have already seen that the transformation can be mapped to the physical property of the material.

So, you have to find out the new permittivity tensor that will actually absorb this coordinate transformation.

Theoretical Background: Discrete Coordinate Transformation

- Material Tensor Calculations:

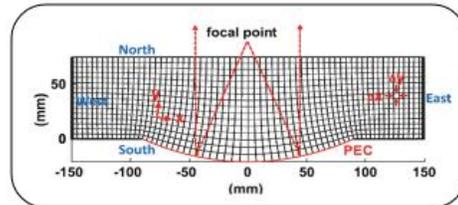
- Permittivity tensor in physical space: $\epsilon' = \frac{J\epsilon J^T}{\det(J)}$
- Permeability tensor in physical space: $\mu' = \frac{J\mu J^T}{\det(J)}$

where:

J is the Jacobian matrix;
 ϵ and μ are the original permittivity and permeability tensors;
 J^T is the transpose of the Jacobian matrix and $\det(J)$ is the determinant of the Jacobian matrix.

- Jacobian Matrix (J): Defined as the matrix of partial between two coordinate systems:

$$J = \begin{bmatrix} \partial x' / \partial x & \partial x' / \partial y & \partial x' / \partial z \\ \partial y' / \partial x & \partial y' / \partial y & \partial y' / \partial z \\ \partial z' / \partial x & \partial z' / \partial y & \partial z' / \partial z \end{bmatrix}$$



- Initial Material Properties in Virtual Space:

- Since parabolic reflector (curved PEC in Fig.) is in free space, the original tensors are: $\epsilon = \epsilon_0 I$ and $\mu = \mu_0 I$; where I is the identity matrix.

So, you can obtain ϵ' , which is the new permittivity tensor that is given as: $\epsilon' = \frac{J\epsilon J^T}{\det(J)}$, okay. The permeability tensor will also have the same form; μ' will be $\frac{J\mu J^T}{\det(J)}$. So, these are the new permittivity and permeability tensors in physical space.

Now, what is J ? You already remember from the previous lectures that we have seen that J is nothing but the Jacobian matrix.

Epsilon and mu here are the original permittivity and permeability tensors. So, J^T is nothing but the transpose of the Jacobian matrix, and this is nothing but the determinant of the Jacobian matrix. So, once you know the coordinate transformation that is the relationship between the new axis and the old axis, you can calculate J . which is basically obtained as a matrix of the partial derivatives of the two coordinate systems. So, $\partial x' / \partial x$, $\partial x' / \partial y$, $\partial x' / \partial z$; (x, y, z) are the old system, $(x', y', \text{and } z')$ are the new system, right.

So, this is how you can calculate; I am not reading out all the parameters; you already know this. So, what you can see is that the initial material properties in the virtual space can be obtained for this kind of parabolic reflector. So, the original tensors were considered to be so because it is a simple parabolic reflector, which is nothing but a

curved PEC kept in free space. So, the original tensors can be taken as $\epsilon = \epsilon_0 I$ and $\mu = \mu_0 I$, where I is basically the identity matrix.

Theoretical Background: Discrete Coordinate Transformation

- Thus; ϵ' and μ' are position-dependent tensors — they vary with space.
- These new ϵ', μ' make EM waves behave as if the space was curved.
- **Scenario:**
 - Assumes a 3D volume of space in a Cartesian coordinate system (x, y, z) .
 - A second volume described by a distorted coordinate system (x', y', z') .
 - 2D cut-planes of these spaces are illustrated in Fig. 1.
- The incident electronic waves travel from point to point in both the two coordinates, but their routes are different.
- In the distorted coordinate, the wave will not reach the grey object (fig.1(b)).
- Result: Space Transformation => Material Design
- These “engineered materials” guide EM waves along curved paths.

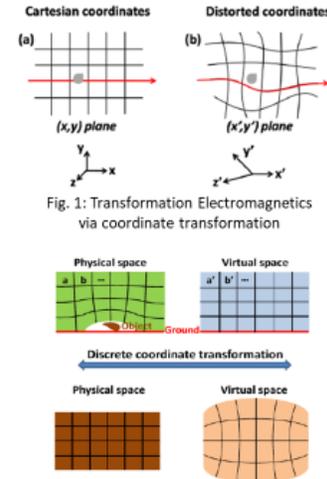


Fig. 1: Transformation Electromagnetics via coordinate transformation

Now in the transformed system, ϵ' and μ' will both be position-dependent tensors. That means they vary with space and these new values of permittivity and permeability will make the electromagnetic wave behaves as if the space is basically curved like this.

So, you can assume some scenarios, like the 3D volume of space in the Cartesian coordinate system.

And then you can think of another second volume that is given by this distorted coordinate system. Right, from where you can take 2D cut planes, and they will basically look like this particular figure, right. So, here the incident electromagnetic wave basically travels from point to point in both coordinates. So, the end-to-end propagation remains the same; it's just that within the system, their routes are different. So, in the distorted coordinate, the wave is not going to reach that grey object, and that is how it is basically skipping it, right.

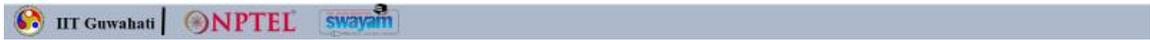
So, what is happening is that the space transformation is basically going into the material design, right. Here also are the practical examples that you already have a physical space with the object.

So, that distorts you can move it to the virtual space with like uniform Great, so this can

be now back and forth either way. This can be the physical space. This can be a virtual space, and so on, right? So, all these things can be done. By you know coordinate transformation, and you have to find these engineered materials. that basically help you guide the electromagnetic waves in this distorted coordinate system following some curved paths.



Design of Antennas Based on the Discrete Coordinate Transformation



So, let us look into the design of antennas based on discrete coordinate transformation.

Flat Parabolic Reflectors

- **Parabolic Reflector Antenna:**
 - One of the most commonly used antennas across radio to optical frequencies.
 - **Function:** Transforms a spherical wave from its focal point into a plane wave.
 - **Result:** Generates highly directive beams.
 - **Disadvantages:** Can be very large at low frequencies and challenging to construct due to its parabolic shape.

- **Design Parameters and Geometry (Fig. 3):**
 - Based on the parabolic equation: $R(\theta) = \frac{2F}{1 + \cos \theta}$

where,

R: Radial distance from focus to reflector surface at angle θ ;

F: Focal length;

θ : Angle from the central axis and Aperture: Physical width across the reflector opening

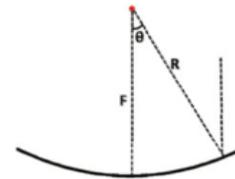


Fig. 3: Geometry of the parabolic reflector

So, the first example we will be taking here is the design of flat parabolic reflectors. So parabolic reflector antennas are among the most commonly used antennas across radio and optical frequencies. Their main function is to transform a spherical wave from its focal point into a plane wave. So, the result is that you know it can generate highly directive beams, and one disadvantage is that the antenna size can be really large at low frequencies, and it could be challenging to construct due to its parabolic shape.

So, one may think of an all-dielectric flat reflector if it can be designed to replicate the performance of these parabolic reflector antennas. But everything is done in a very compact volume. So, you can think of using this discrete coordinate functionality or discrete coordinate transformation functionality. that can flatten your structure while preserving the feature of the antenna right. So, this is how the parabolic reflector typically looks.

So, based on the parabolic equation, you can write $R(\theta) = 2F / (1 + \cos\theta)$. where R is basically the radial distance from the focus to the reflector surface at an angle θ . F is basically the focal length, θ is the angle from the central axis, and the aperture is basically the physical width across the reflector opening.

Flat Parabolic Reflectors

- This type of antenna designed to operate over a wide frequency range (C & X bands).

- Suppose;

- E.g.: If designed for C-band (4–8 GHz) and X-band (8–12 GHz);
 - ✓ Focal length (F): 108.6 mm
 - ✓ Angle (θ): -45° to $+45^\circ$; means the design is optimized to collect or radiate energy over a 90° field of view, typical in reflector antennas.
 - ✓ And Aperture: 180 mm, which is the horizontal opening between two edges of the parabola at $\pm 45^\circ$

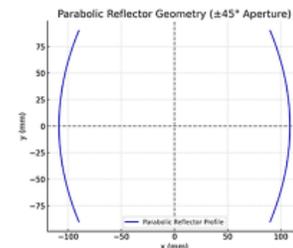
- With these values:

$$R = \frac{2 \times 108.6}{1 + \cos(45^\circ)} \approx 127.3 \text{ mm}$$

- C-band (4 – 8GHz) and X-band (8 – 12GHz) correspond to wavelengths:

75 mm(4GHz) to 25 mm(12GHz)

- So, the aperture (180 mm) spans: 2.4λ to 7.2λ across the full band i.e.; the reflector is electrically large and can provide good gain and directivity in both bands.



Now this type of antenna can be designed to operate over a wide band of frequencies in the C and X bands. Suppose it is designed for C band, it will work between 4 and 8 gigahertz, and if it is for X band, it will work between 8 and 12 gigahertz.

In such cases, typically the focal length is around 108.6 millimeters, and the angle theta is considered to be from minus 45 degrees to 45 degrees. That means the design is

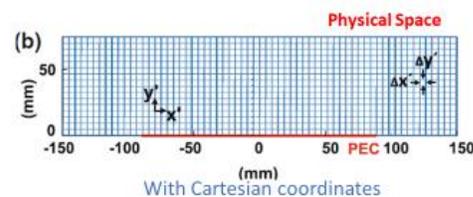
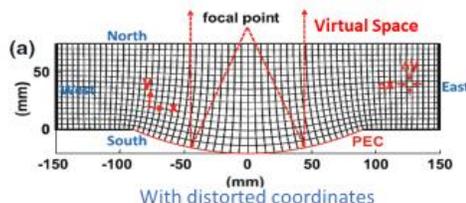
basically optimized to collect and radiate energy over a 90-degree field of view, which is typical in reflector antennas. And the aperture is also 180 mm, which is the horizontal opening between the two edges of the parabola at plus or minus 45 degrees. So, here is how the parabolic reflected geometry looks with a plus or minus 45-degree aperture.

So, with these values, you can obtain what should be R, which is $\frac{2 \times F}{1 + \cos(\theta)}$, that comes out to be 127 millimeters. So, when you talk about C band, which is again 4 to 8 gigahertz, and expand, which is from 8 to 12 gigahertz.

So, they basically correspond to wavelengths of typically 75 millimeters, which is for 4 gigahertz, and on the upper hand, it will be like 25 millimeters for the case of 12 gigahertz is typically around 25 mm, so this is basically the lower bound for the wavelength. Because this is the higher bound of the frequency, typically from 25 mm to 75 mm, that is the lambda we are talking about. So, you can see the aperture is basically spanning somewhere between 2.4 lambda and 7.2 lambda across the full band that means the reflector is actually large, but it can provide good gain and directivity in both bands.

Flat Parabolic Reflectors

- Therefore; with 180 mm aperture and 108.6 mm focal length, it offers:
 - High gain
 - Moderate beamwidth
 - Good directivity; but it is **electrically large**.
- Objective: Create a flat alternative to the parabolic reflector using discrete coordinate transformation.
- **Alternative Parabolic Reflector using Discrete Coordinate Transformation**:
 - ✓ Uses discrete coordinate transformation to flatten the structure (fig.(b)) while preserving functionality.
 - ✓ Possesses a compact, flat all-dielectric reflector to replicate parabolic performance.



So, what do you see with a 180 mm aperture and a 108.6 mm focal length?

The antenna is able to provide high gain, moderate bandwidth, and good directivity. But it is electrically large because it needs several lambdas to operate, right? So, physically it is big, okay, in that sense. So, here the objective is to create a flat alternative to this parabolic reflector using discrete coordinate transformation.

So, one alternative to the parabolic reflector would be to, you know, flatten out the

structure. You can see here the use of discrete coordinate transformation while preserving the functionality. So, here you can see the actual antenna, right? So, it is the parabolic antenna or parabolic reflector that is located in free space, as you can see illustrated by a curved PEC. And this is the physical space with the Cartesian coordinates. So, here the parabolic reflector is basically transformed into a flat PEC.

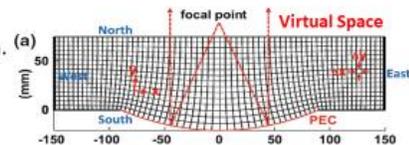
So, that is the difference between the two cases in the physical space we are going to design now. So, what are we gaining out of it? We are able to make a flat all-dielectric reflector that can replicate, you know, the parabolic performance. So, the shape constraint can be reduced.

So, here are the implementation details.

Flat Parabolic Reflectors

Implementation Details:

- A parabolic reflector designed for ~10 GHz with aperture: 180 mm.
- Transformation region (Fig. (a)): Applied over 300 mm × 75 mm area.
- Quasi-orthogonal grids generated using PointWise software:
 - ✓ Applied in both virtual and physical spaces (Fig. (a & b)).
 - ✓ Leads to the creation of an all-dielectric flat reflector.



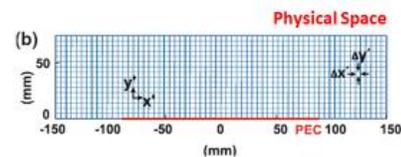
Permittivity distribution of the Flat reflector:

- Calculated using eq.'s.:

$$n'^2 \approx \epsilon'_z / \epsilon_0 = \frac{1}{\det(J)} \quad \& \quad n'^2 \approx \frac{1}{\frac{\partial x'}{\partial x} \frac{\partial y'}{\partial y}} \approx \frac{\Delta x \Delta y}{\Delta x' \Delta y'}$$

where:

n' : Effective relative refractive index; and
 $\Delta x, \Delta y, \Delta x', \Delta y'$: Dimensions of cells in the two spaces



So, a parabolic reflector designed for around 10 gigahertz can have an aperture of around 180 mm.

So, the transformation region in this particular figure is applied over 300 mm and 300 mm this way, from minus 150 to 150, and around 75 mm. So, this is the overall space. So, these quasi orthogonal grids that you see they are basically generated using point wise software. They are basically applied in both virtual and the physical space and that basically leads to the creation of an all dielectric flat reflector. So, what we are worried about now is that we need to find out the permittivity distribution for this flat reflector.

So, using the equations that you have seen earlier, you can calculate n'^2 , which will be

nothing but $n'^2 \simeq \epsilon'_z / \epsilon_0$, that is $\frac{1}{\det(J)}$, okay. So, J is the Jacobian matrix for this transformation, which we have discussed earlier, and n'^2 is okay is also nothing but, $\frac{\Delta x \Delta y}{\Delta x' \Delta y'}$, okay I think there is a typo, so it will be double prime, okay. So, this n' is basically the effective relative refractive index. These are nothing but $\frac{\Delta x \Delta y}{\Delta x' \Delta y'}$ are nothing but the dimensions of the cells in these two particular spaces: the virtual space and the physical space. From there, you can also obtain this, right, yeah, so this is n'^2 .

Flat Parabolic Reflectors

- **Permittivity map** (Fig.4): composed of 64×16 square blocks.
 - Permittivity distribution is illustrated in Fig. 4.
 - Simplifications applied to:
 - ✓ Eliminate sub-unity permittivity values.
 - ✓ Approximate the structure using a cluster of dielectrics.
 - ✓ Enhances realizability and ease of fabrication.
- **Comparative Analysis:** (Fig. 5)
 - Compared the flat reflector to a conventional parabolic reflector.
 - Electric field distributions shown in Fig. 5:
 - ✓ Plane wave incidence: Similar focal lengths observed (Fig. 5a & 5b).
- **Result:** Flat reflector can effectively transform spherical waves into plane waves, achieving highly directive radiation.

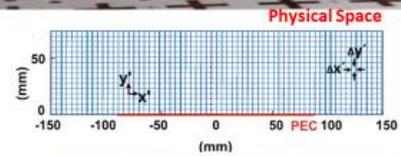


Fig. 4: Permittivity map consisting of 64×16 blocks

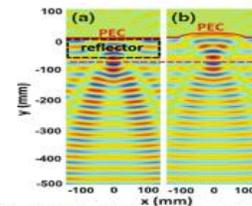


Fig. 5: Electric field distributions at 8 GHz for: (a) Flat reflector; (b) Conventional parabolic reflector

So, next we have to map the permittivity, which is shown here in figure 4. Okay, that is composed of 64 by 16 square blocks. So, you can see the permittivity distribution; the colour scale shows you the values of the permittivity that have been obtained, okay.

So, what do you see here? This particular kind of simplification has been applied. To eliminate sub-unity permittivity values, which are very difficult to achieve. So, all these values are practically easy to achieve. Okay, and you can approximate the structure using a cluster of dielectrics. So that makes it easy to fabricate, and it is also, you know, easily extendable, right? So, if you compare the performance of this with that of the conventional parabolic reflector shown in this particular figure.

So, this is the electric field distribution plot shown at 8 gigahertz for the flat reflector and the conventional parabolic reflector. So, you will see that you have maintained the plane wave incidence for a similar focal length. Okay, and the performance is very similar. So,

what you can see is that the flat reflector can effectively transform spherical waves into plane waves. Achieving highly directive radiation as it is supposed to work for the parabolic antennas, right? So, these are basically the electric field ones that are showing you the wave fronts, right.

Next, we look into the following design, which is a flat lens antenna.

Flat Lens Antenna

- Convex Lens: Common in antenna systems.
 - Converts:
 - ✓ Spherical waves (from a point source or from a feed) into plane waves on the opposite side.
 - or
 - ✓ Cylindrical waves (from a line source in 2D) into plane waves on the opposite side.
 - or
 - ✓ Incoming plane waves focus at a point]- Rx mode
- } Tx mode
- Objective: To design an all-dielectric flat lens for C-band and X-band using discrete coordinate transformation.

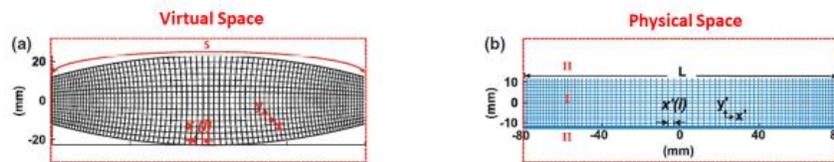


Fig. 6: (a) The virtual space with distorted coordinates. A convex lens made of dielectric with $\epsilon_r = 3$ is imbedded in the air. (b) The physical space with Cartesian coordinates.

So, typically you will see that convex lenses are very common in antenna systems. They can convert spherical waves coming from a point source or a feed into plane waves on the other side. Or you can see that cylindrical waves are coming from a line source in 2D. That can be converted into plane waves on the opposite side for the transmitter module. Or you can also use this kind of lens for incoming plane waves to be focused at a point that will be on the receiver side.

So, the objective here would be to design an all-dielectric flat lens for the C band and X band using discrete coordinate transformation. So, this particular figure shows the virtual space with distorted coordinates. So, this is typically a convex lens made of dielectric with permittivity epsilon r equal to 3 embedded in air. And this is the physical space with the Cartesian coordinate system.

Flat Lens Antenna

- The principle discussed previously (likely TEM/discrete coordinate transformation) is extended to compressed flat lens design.
- Lens Construction (Fig. 6):
 - The flat lens aperture uses 14 x 2 conventional dielectric blocks.
 - This is a key point, as it employs dielectric blocks instead of metamaterials that would have simultaneously dispersive permittivity and permeability.
- Permittivity distribution is calculated using same as in previous antenna example.
- **Permittivity map** (Fig. 7):
 - Permittivity distribution of the flat lens is illustrated in Fig. 7.

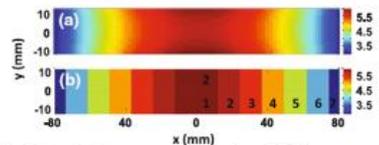
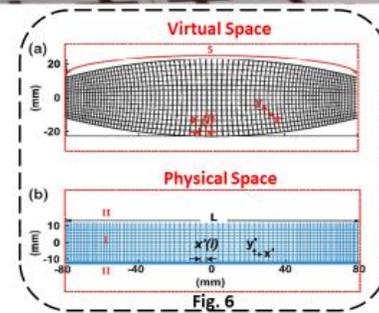


Fig. 7: Permittivity maps of the flat lens. (a) The map consisting of 80 x 15 blocks; (b) The map consisting of 14 x 2 blocks.

So, the principle discussed previously is like the transformation electromagnetics or discrete coordinate transformation is also extended to this compressed flat lens design. So, the flat lens with an aperture basically uses 14 by 2 conventional dielectric blocks. Here, different colors indicate the maps of these various blocks. So, this first one is basically made up of 80 by 15 blocks.

So, it is much smoother. And this is like only 14 by 2 slots. So, you can see the colors more discretely; each color stands for different permittivity values, okay. So, the point here is that even you can make a flat plane aperture. Using this kind of 14 by 2 conventional dielectric blocks is okay. And the key point here is that it employs dielectric blocks, okay, instead of metamaterials. that could have simultaneous dispersive permittivity's and permeabilities the way to calculate the permittivity distribution can basically be followed from what You have seen in the previous example, right. So, the permittivity distribution you can see over here gives this kind of physical space, and this one will work as a convex lens.

Flat Lens Antenna

- Comparative Analysis:

- Compared field distributions under plane wave excitation for:
 - ✓ 14×1-block low-resolution flat lens (Fig. 8a)
 - ✓ Conventional convex lens (Fig. 8b)

- Focal length measurement:

- Measured from center of lens to max field amplitude point.
- Focal Length Results:
 - ✓ Flat lens: 130 mm
 - ✓ Convex lens: 131 mm
- **Conclusion:** Both lenses focus energy at nearly the same position, despite different profiles.

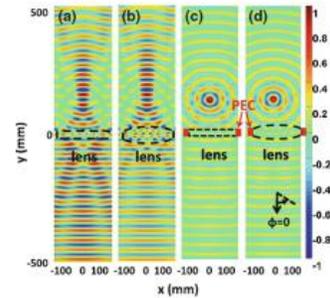


Fig. 8 : Electric field distributions at 8 GHz (a) & (b) for plane wave excitation and (c) & (d): when a line source is located at the focal point to feed. (a) & (c) Flat lens; (b) & (d) Conventional lens

- Electric field Results (Fig. 8c & d):

- E-field distributions show emerging plane waves on the output side.
- Confirms the flat lens performs comparably to the conventional lens.

Now you have to compare the performance of this flat lens antenna that you have just thought of designing. So, you can compare the field distribution under plane wave excitation for the two cases. So here we again show the electric field distribution at 8 gigahertz for these two cases, okay, for plane wave excitation. So, these are using, so here you have the conventional convex lens, and here you have a 14 by 1 block, low-resolution flat lens, right? Then, on the other side for C and D, here basically the line source is located at the focal point to feed, and this is again the flat lens.

And this is the conventional lens, and that is showing you how you are getting the same kind of waves out of these two lenses. So, you can also measure the focal length. You can measure it from the center of the lens to the maximum field amplitude point. Okay, so if you take the measurement, you will see that in a flat lens you are getting it at 130 mm.

And for the convex lens, you are getting it at 131 mm. That means both lenses are able to focus energy almost exactly at the same point despite having very different profiles. Okay, so these two cases are basically showing you the emerging plane waves on the output side, right? coming from the lens. So, what does it tell you that this confirms the flat lens? It basically performs almost comparably to the conventional lens, and these are much easier to fabricate.

Now, let us move on to the last topic, which is metamaterials for stealth technology.



Metamaterials for Stealth Technology



Introduction to Stealth and Metamaterials (MTMs)

- Radar Cross Section (RCS) is the primary measure of how detectable an object is by radar.
- Stealth technology aims to reduce RCS through shape, coatings, and now metamaterials.
- Metamaterials => artificial materials engineered to manipulate EM waves in novel ways.
 - Properties : Negative permittivity (ϵ) or negative permeability (μ).
 - **Condition for metamaterial behavior**: unit cell size (p) \ll guided wavelength (λ_g).
- MTMs in Stealth Technology is also known as “Radar Absorbing Materials (RAM)” :
 - Used for ships, aircraft, tanks.
- Electromagnetic Stealth Using Metamaterials: Radar Cross Section (RCS) Reduction
 - Metamaterials can:
 - ✓ Absorb radar waves (metamaterial absorbers)
 - ✓ Deflect waves away from source (gradient-index metasurfaces)
 - ✓ Scatter cancellation (e.g., plasmonic cloaking)



Source: Meng, Zhen, et al. "Multifunctional integrated metamaterials for radar-infrared-visible compatible multispectral stealth" *Optics Express* 32.10 (2024): 17869-17878.

So, one important aspect of stealth technology is the radar cross-section. that is basically the primary measure of how detectable an object becomes to the radar. So stealth technology basically aims to reduce this RCS, which is radar cross section, through different approaches. such as shape mimicking or applying some coating and also you can have metamaterials So metamaterials, we have already seen that they have an amazing capability to manipulate electromagnetic waves in different new ways. because

of their negative permittivity and negative permeability as well the one thing to remember is that metamaterial behavior can be seen when the unit cell size is much, much smaller than the guided wavelength. So, when you talk about metamaterials in stealth technology, they are basically known as radar-absorbing materials or RAM, that is basically used for ships, aircraft, and tanks.

So electromagnetic stealth can be obtained using metamaterials, where you can achieve RCS reduction. So, you can apply metamaterials that absorb radar waves. So, you are basically making a metamaterial absorber over the frequency ranges in which radar operates. Or you can actually use some kind of material that can deflect the waves away from the source.

That is also possible. In that case, the radar will not receive your reflected beams. That can be achieved using gradient-index metasurfaces or you can also think of scattering cancellations as some sort of cloaking for core-shell types of cloaking. Where a destructive interference pattern can cancel out the scattering. So again, the radar receives very little signals.

So, here we will show one particular example of a composite left-right handed structure.

MTM Structure for Stealth Technology

- CRLH Metamaterials & Radar Absorbers
 - **CRLH:** Composite Right/Left-Handed structures – combine negative & positive parameters for broadband behaviour.
 - Built using split-ring resonators (SRR) and metal wires:
 - ✓ Wires create **negative ϵ**
 - ✓ SRRs generate **negative μ**
 - Used to absorb radar waves by tuning to resonance and impedance matched to air → **minimal reflection**
- Metamaterial absorber structure for Stealth application as depicted in figure 9.
- Simulated results are shown in figure 10.
 - Operating frequency range: 8–18 GHz.

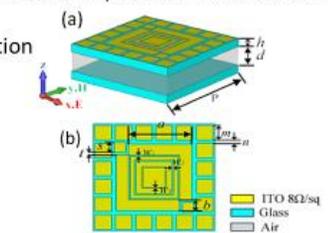


Fig. 9: The schematic diagrams of the proposed metamaterials: (a) 3-D view and (b) Top view

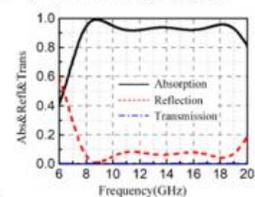


Fig. 10: Simulated absorption, reflection and transmission of the proposed metamaterials under normal incidence

That combines negative and positive parameters for broadband behavior, okay.

So, this can be built using splitting resonators and metal wires. So, a wire array can give you negative permittivity, and splitting resonators can give you negative permeability, which you have already seen. So, this can be used to absorb radar waves by tuning to the resonance and matching the impedance to the air.

Make sure that you get minimal reflection of the radio waves coming from the radar. So, a metamaterial absorber for stealth applications typically looks like this. Here it is designed for an operating frequency of 8 to 18 gigahertz. It is basically an ITO pattern on top of a glass substrate.

The glass substrate has a thickness of 0.3 mm, a dielectric constant of 4.6, and a loss tangent of 0.015. There is an air layer in between; the thickness is D , which is 1.8 mm.

So, you can see, the entire metamaterial structure is roughly 2.4 mm. Okay, this is the top view of the structure. So, when you repeat this periodically, this is what you will get. Okay, you can see that the absorption is very high over this entire band, right? So that means whatever, you know, the radar waves will be coming toward this absorber, okay, it will get absorbed, and very little will bend. So, that is a significant method of RCS reduction, and that is how you can use metamaterials for stealth technology.



So, with that, we conclude our lecture. We will discuss tunable metamaterials in our next lecture. If you have any queries regarding this topic, you can send an email to this email address mentioning the course name and the lecture number in the subject line. Thank you.