Course Name: Introduction to Microwave and Optical Metamaterials
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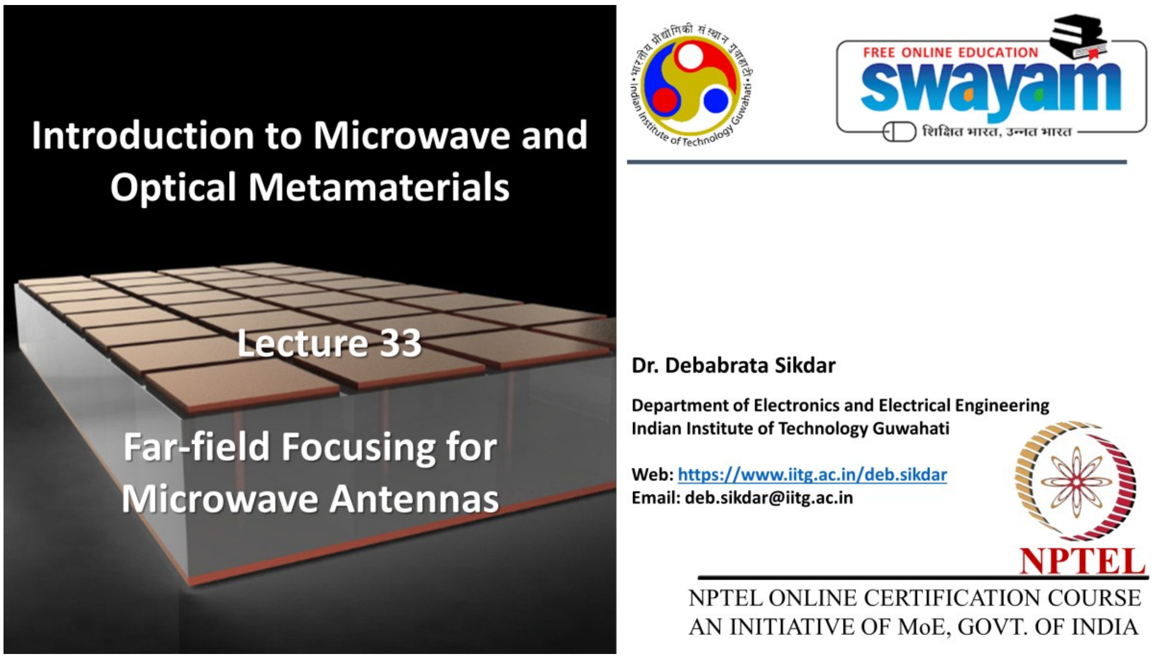
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-7
Lecture-33

Lec 33: Far-field Focusing for Microwave Antennas



Lecture Outline

- Fabry-Perot Approach for Patch Antenna with Superstrate
- Performance Analysis of Metamaterial-Based Microwave Antenna with Ferrite Superstrate

Hello everyone, welcome to Lecture 33 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on far-field focusing for microwave antennas. So, here is the lecture outline. We will first discuss about the Fabry-Pera approach for patch antenna with super straight and then we will conduct

Fabry-Perot Approach for Patch Antenna with Superstrate

- Superstrates in Patch Antennas:
  - Use of superstrates to enhance patch antenna performance is well-established
  - Attracts the attention of researchers for compact antenna design and near-field phase control
- Applications:
  - Beneficial in directive RF front-end antennas for point-to-point and satellite communications
- Additional Role:
  - Superstrates may offer environmental protection to antennas
- Gap in Research:
  - Prior studies mostly focus on non-magnetic superstrates

 Source: Choudhury, P.K , Metamaterials: Technology and Applications, CRC Press, 2021

performance analysis of

Fabry-Perot Approach for Patch Antenna with Superstrate

- Current Focus:
  - This study investigates ferrite superstrates
  - Superstrate design and positioning will be analyzed using Fabry-Perot cavity theory
- Setup:
  - The miniaturized patch antenna is placed on a composite substrate
  - A superstrate with identical geometry to substrate, covers the antenna

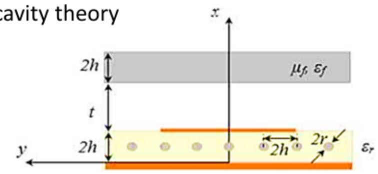


Fig. Metamaterial patch antenna with magnetic superstrate

- Material Properties:
  - Superstrate is characterized by relative permittivity (ε_f) and relative permeability (μ_f)
- Positioning:
  - The distance between the antenna patch and the superstrate is given by t

Fabry-Perot Approach for Patch Antenna with Superstrate

- Modeling Approach:
  - The antenna patch surface is treated as the lower surface of a Fabry-Perot cavity
  - The superstrate's lower surface serves as the upper surface of the cavity
  - The cavity's upper half has a finite thickness, while the lower half-space is modeled with a refractive index $n_{\text{eff}} = (\varepsilon_{\text{eff}})^{1/2}$

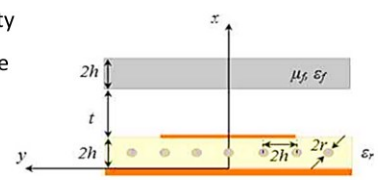


Fig. Metamaterial patch antenna with magnetic superstrate

$$\left.\begin{aligned}
L &= \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 0.824\cdot d\frac{(\varepsilon_{reff}+0.3)(W/d+0.264)}{(\varepsilon_{reff}-0.258)(W/d+0.8)},\\
\varepsilon_{reff} &= \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{d}{W}\right]^{-1/2},\\
W &= \frac{c}{2f_r}\sqrt{\frac{2}{1+\varepsilon_r}},\\
L_a &= L + 6\cdot d, \quad W_a = W + 6\frac{\log 16}{\pi}d,
\end{aligned}\right\}$$

metamaterial based microwave antenna with ferrite

Fabry-Perot Approach for Patch Antenna with Superstrate

- Modeling Approach:
  - The antenna patch surface is treated as the lower surface of a Fabry-Perot cavity
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  - The cavity's upper half has a finite thickness, while the lower half-space is modeled with a refractive index $n_{\text{eff}} = (\varepsilon_{\text{eff}})^{1/2}$

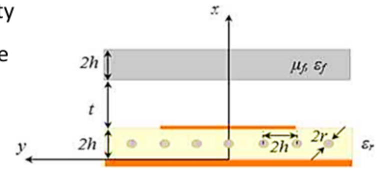

Fig. Metamaterial patch antenna with magnetic superstrate

- Let us assume that:
  - $R = |R|e^{i\delta_R}$ as the full reflection coefficient of the superstrate
  - $T = |T|e^{i\delta_T}$ as the full transmission coefficient of the superstrate
  - $\rho_l = |\rho_l|e^{i\delta_l}$ as the Fresnel reflection coefficient of the cavity's lower surface

  where δ_R is the phase shift due to reflection at the superstrate, δ_T is the phase shift upon transmission and δ_l is the phase shift due to reflection at the lower surface of the cavity

superstrate. So, let us go into the first subtopic, which is the Fabry-Perot approach for patch antennas that have it right. So, the idea of using super straight is to basically improve the performance of the patch antenna, and this idea is not new.

But it still attracts the attention of researchers working on designing compact antenna systems and near-field phase control. The near field phase transforming structures are developed for directive radio frequency or RF front end antennas for

Fabry-Perot Approach for Patch Antenna with Superstrate

- The component of electric intensity vector $\boldsymbol{E}$ in the far-zone consists of the vector sum of partial rays of the electric field component, as a result of the reflections from the cavity surfaces (shown in figure).

- Theoretical Basis:
  - A formal expression for the electric intensity vector component

$$E(\theta) = E_0 \cdot D(\theta) \cdot T \cdot \sum_{n=0}^{\infty} \left(|R| \cdot |\rho_l| \cdot e^{-i\Phi}\right)^n \quad (1)$$

  where $\Phi = 2\frac{2\pi}{\lambda_r} t \cdot \cos\theta - \delta_R - \delta_l$, $D(\theta)$ is the electric field pattern, and λ_r is the resonant wavelength of the patch antenna

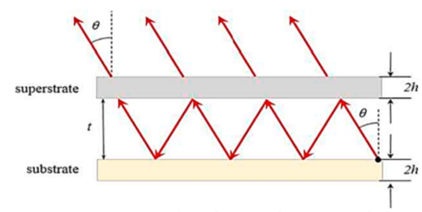

Fig. Ray distribution between the superstrate and free space

- The sum in the right side of Eq. (1) is the infinite geometric progression. That is why it can finally be rewritten in the form

$$E(\theta) = \frac{E_0 \cdot D(\theta) \cdot T}{1 - |R||\rho_l|e^{-i\Phi}} \quad (2)$$

Fabry-Perot Approach for Patch Antenna with Superstrate

- Full reflection and transmission coefficients can be written as:

$$R = \rho_l + \frac{t_l \tilde{t}_u \tilde{\rho}_u \exp\left\{-i\frac{2\pi}{\lambda_r} l \cdot \cos\theta\right\}}{1 - \tilde{\rho}_u^2 \exp\left\{-i\frac{4\pi}{\lambda_r} l \cdot \cos\theta\right\}}$$

$$T = t_l \tilde{t}_u + \frac{t_l \tilde{t}_u \tilde{\rho}_u^2 \exp\left\{-i\frac{4\pi}{\lambda_r} l \cdot \cos\theta\right\}}{1 - \tilde{\rho}_u^2 \exp\left\{-i\frac{4\pi}{\lambda_r} l \cdot \cos\theta\right\}} \quad (3)$$

where $\tilde{\rho}_u$ is the Fresnel reflection coefficient at the upper surface, t_l is transmission coefficient at the lower (upper) surface and $\tilde{t}_u$ is transmission coefficient at the upper surface.

- These coefficients are defined as:

$$\rho_l = \frac{\varepsilon_{\text{reff}} \cdot \cos\theta - \sqrt{\varepsilon_{\text{reff}} - \sin^2\theta}}{\varepsilon_{\text{reff}} \cdot \cos\alpha + \sqrt{\varepsilon_{\text{reff}} - \sin^2\alpha}}, t_l = \frac{2 \cdot \sqrt{\varepsilon_{\text{reff}}} \cdot \cos\theta}{\varepsilon_{\text{reff}} \cdot \cos\alpha + \sqrt{\varepsilon_{\text{reff}} - \sin^2\theta}}$$

$$\tilde{\rho}_u = \frac{\sqrt{\varepsilon_{\text{reff}} - \sin^2\theta} - \cos\theta}{\sqrt{\varepsilon_{\text{reff}} - \sin^2\theta} + \cos\alpha}, \tilde{t}_u = \frac{\sqrt{\varepsilon_{\text{reff}}}\sqrt{\varepsilon_{\text{reff}} - \sin^2\theta}}{\sqrt{\varepsilon_{\text{reff}} - \sin^2\theta} + \cos\theta} \quad (4)$$

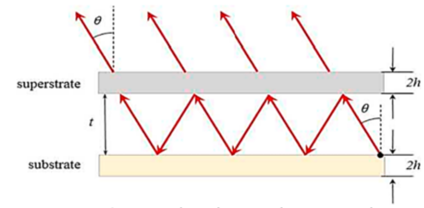

Fig. Ray distribution between the superstrate and free space

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Fabry-Perot Approach for Patch Antenna with Superstrate

- Taking into account Eq. (2), the power pattern $P_E(\theta)$ can be written in the form

$$P_E(\theta) = \frac{|T|^2}{1 - 2|R||\rho_l| \cdot \cos\Phi + |R|^2|\rho_l|^2} |D(\theta)|^2 \quad (5)$$

- As seen from Eq. (5), the power pattern achieves its maximum value in the forward reflection direction ($\theta = 0°$) when $\cos\Phi = 1$.
- The last conclusions lead to the formula for evaluating the optimal value of t as a function of parameters of the patch antenna and superstrate: $t = \frac{\lambda_r}{4\pi}(\delta_R + \delta_l)$ (6)
- This provides the maximum possible value of the power pattern $P_E(\theta)$.

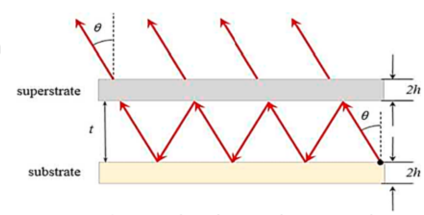

Fig. Ray distribution between the superstrate and free space

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applications such as point to point communication and satellite communication. So, a hard material superstrate can also play the role of giving protection to the antenna from environmental hazards, right? So, there is a gap in the research; a lot of prior studies mostly focused on non-magnetic superstrates. So, in this study, we will consider ferrite superstrates.

So, the superstate positioning is going to be defined in terms of the Febripero cavity theory and that is why we consider this as a Fabry-Perot approach for patch antennas with superstrates right.

So, let us consider the miniaturized patch antenna on a composite substrate, the design we have already seen earlier in this part. So, this is basically a 1D array of metallic wires, and this is the patch antenna. So, you are basically seeing the side view of it, okay. So, what we assume here is that a super straight with identical geometry to the substrate is basically placed on top of the antenna.

So, it basically covers the antenna, right? It is also assumed that the super straight is situated at a distance t. okay from the antenna patch and it has got a material parameter of relative permeability given as ε f and relative permeability of μ f. And the overall thickness of this substrate as you can see is same as the thickness of the substrate that is 2H. Ok. And this is how you can consider the x, y, and z axes to be along the axis of the wires, okay.

So, now the modeling is average, right? So, in order to model this, we are going to consider the antenna patch surface as the lower surface of the Fabry-Perot cavity. So, there is a cavity formed between the superstrate and the antennae. So, you can see the patch antenna surface will act as the lower surface of the cavity and the superstrates lower surface this one will basically act as the upper surface of the cavity. And you can model the upper half of the cavity to have some finite thickness and the lower half space can be modeled to have a you know effective refractive index of n effective which is basically given a square root of ε effective and that you have seen earlier ok. So, this is, you know, ε effective, okay, will be given by this formula where you have all these parameters of the patch going in.

So, you can just look back 1 or 2 lectures before and you see that this can be used right for designing of the patch antenna we have already used this. Now, let us assume that you have r that is basically given as modulus of r e to the power i δ r that is the full reflection coefficient of the super straight. Capital T which is also given as modulus of t e to the power i δ t that basically tells you the full transmission coefficient of the super straight. And then you have this reflection coefficients like rho L that is nothing but you know modulus of rho L e to the power i δ L. So, this is basically the Fresnel reflection coefficient of the cavities lower surfaces that is this one right.

And all these different phase terms that you have seen. So, δ capital R is basically the phase shift. due to reflection at the super straight, δ T is the phase shift upon transmission ok and δ L is basically the phase shift due to reflection from the lower surface of the cavity. So, the component of the electric intensity vector E is. in the first zone that will consist of the vector sum of the partial rays of the electric field component as a result of the reflections from the cavity surfaces as you can see in the figure right.

So, from there, there is some partial transmission and some reflection that is getting reflected from here again. Hitting the surface, some parts are getting transmitted, some are getting trapped in the cavity, doing multiple reflections and finally coming out right. So, this is your substrate, this is the superstrate, the thickness of the cavity is T, the thickness of each of the substrate and this is the substrate and the superstrate both have 2 H thickness. So, the theoretical explanation of the modeling tells that from this you can obtain a formal expression of the electric intensity vector component which is given as E θ, θ is this particular angle. So, it can be written as E naught d θ * T and the summation / n = 0 to infinity, and then you have these terms.

So, this tells you about the multiple reflections that are going on. modulus of r dot modulus of rho l * you have e to the power - i φ ok and whole to the power n right. So, this φ is basically giving you 2 into 2 π/λ r into t cos θ - δ r - δ l. So, this is the phase factor ok. for the cavity ok and then you have d θ that is basically the electric field pattern and λ r is nothing but the resonant wavelength of the patch antenna.

Now, this summation that you see is basically giving you an infinite geometric progression, right? So, you can actually simplify this using this formula which is e θ. So, you can after simplification you can write it as e naught d θ into t and this whole part can be written as 1 / 1 - a. So, this is this one 1 - modulus r modulus rho L e to the power - i φ ok. So, the full reflection and the transmission coefficients can then be written as r = rho L So, these are basically the reflection and transmission or transmittance. So, this is rho L that depends on T L, T U, rho U.

So, these are basically the coefficients of transmission at the lower and the upper boundary of the cavity, rho basically are the reflection coefficients. So, this way you can see that these are all Fresnel coefficients; basically, there are four Fresnel coefficients, as you can see. So, with that, you can find out what the reflectance and transmittance are, right? So, as I mentioned, so rho u will basically tell you the Fresnel reflection coefficient at the upper surface, tL is the transmission coefficient okay at the lower surface. So, T_L is the transmission coefficient at the lower surface, and T_U is the transmission coefficient at the upper surface. And this is how these coefficients are defined.

So, they are basically defined based on the refractive index or you can say the permittivity and the angle right, say angles that are involved. So, this tells you about the 4 Fresnel coefficients; you can plug them in there and get the reflection and the transmission. Now, taking into account equation 2, which we have just seen here in the previous slide, this equation of the electric intensity vector component is okay. You can write the power pattern that is P e θ ok that can be written in this particular form where you have modulus T square / 1 - 2 modulus r modulus rho L * cos φ + modulus r square rho L square and then you have d θ whole square. So, as you can see from this particular equation the power pattern will achieve its maximum value in the forward reflection direction that is for θ = 0 degree when this cos term is basically 1 right.

So, this basically gives an conclusion that for you can from this you can also obtain what is the optimal value of this thickness of the cavity for the patch parameter patch antenna parameters and the super straight. So, you can obtain this as t = λ r / 4 π * δ r + δ l, okay. So, this should be the ideal thickness of your cavity, and this will provide the maximum value of the power pattern P(θ). Now, with that, we will move on to analyze the

Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

- From the power pattern $P_E(\theta)$, the radiation density of the antenna with superstrate can be defined by:

$$P_E(\theta) = \frac{|T|^2}{1-2|R||\rho_l|\cdot\cos\Phi+|R|^2|\rho_l|^2}|D(\theta)|^2$$

$$U(\theta,\varphi) = \frac{k_0^2}{8\pi^2 Z_0}\frac{(1+\cos\theta)^2}{4}\frac{|T|^2}{1-2|R||\rho_l|\cdot\cos\Phi+|R|^2|\rho_l|^2}|f(\theta,\varphi)|^2 \quad (7)$$

where θ and φ are the angles of the spherical coordinate system, and $f(\theta,\varphi)$ is the radiation pattern without superstrate.

$$f(\theta,\varphi) = \int_S E_2(2h, y)\cdot e^{ik_{2y}y+ik_{2z}z}dydz= = 4|A|\cdot S\cdot \sin c\left(\frac{L}{\lambda_2}(\cos\varphi-1)\sin\theta\right)\cdot \sin c\left(\frac{L}{\lambda_2}\sin\theta\sin\varphi\right)\cdot \sin c\left(\frac{W}{\lambda_2}\sin\theta\cos\varphi\right)$$

- Then, the radiation pattern of the antenna with superstrate is given by:

$$f_{\sup}(\theta,\varphi) = 4S\frac{A\cdot T}{1-|R||\rho_l|}\operatorname{sinc}\left(\frac{L}{\lambda_r}(\cos\varphi-1)\sin\theta\right)\cdot\operatorname{sinc}\left(\frac{L}{\lambda_r}\sin\theta\sin\varphi\right)\cdot\operatorname{sinc}\left(\frac{W}{\lambda_r}\sin\theta\cos\varphi\right) \quad (8)$$

- Thus the expression for the efficiency of antenna under consideration can be written in the form

$$\eta = \frac{|T|\cdot\mathrm{Re}(A)}{1-|R||\rho_l|}\left(1+\frac{j_0 S}{\mathrm{Re}(A)}\sqrt{\frac{\omega\mu_0}{2\sigma_i}}\right)^{-1} \quad (9)$$

Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

- The expression for the directive gain is given by:

$$D(\theta,\varphi) = \frac{(2k_0S|A|)^2}{\pi Z_0}\frac{(1+\cos\theta)^2}{\mathrm{Re}(A)}\frac{|T|^2}{1-2|R||\rho_l|+|R|^2|\rho_l|^2}\times$$
$$\times\operatorname{sinc}^2\left(\frac{L}{\lambda_r}(\cos\varphi-1)\sin\theta\right)\cdot\operatorname{sinc}^2\left(\frac{L}{\lambda_r}\sin\theta\sin\varphi\right)\cdot\operatorname{sinc}^2\left(\frac{W}{\lambda_r}\sin\theta\cos\varphi\right) \quad (10)$$

- As one can observe from Eq. (10), the maxima of directive gain is achievable at $\theta = 0°$. Then, the maxima of gain is given by:

$$G_{\max} = \eta D_{\max} = \frac{8k_0^2}{\pi Z_0}\frac{|T|^3\mathrm{Re}(A)|_{\theta=0}}{(1-|R||\rho_l|)^3}\frac{S^2|A|^2}{\mathrm{Re}(A)|_{\theta=0}+j_0S\sqrt{\frac{\omega\mu_0}{2\sigma_i}}} \quad (11)$$

- Taking into account Eqs. (6) and (7), we derive the expression for the normalized gain in the form:

$$g(\theta,\varphi) = \frac{(1+\cos\theta)^2}{4}\frac{|f\sup(\theta,\varphi)|^2}{|f\sup(\theta,\varphi)|^2_{\max}} = \frac{(1+\cos\theta)^2}{4}\frac{|T|^2\cdot(\mathrm{Re}(A))^2}{(1-|R||\rho_l|)^2}\left[\frac{(1-|R||\rho_l|)^2}{|T|^2\cdot(\mathrm{Re}(A))^2}\right]\Bigg|_{\theta=0^0}$$
$$\times\operatorname{sinc}^2\left(\frac{L}{\lambda_r}(\cos\varphi-1)\sin\theta\right)\cdot\operatorname{sinc}^2\left(\frac{W}{\lambda_r}\sin\theta\cos\varphi\right)\cdot\operatorname{sinc}^2\left(\frac{W}{\lambda_r}\sin\theta\right) \quad (12)$$

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Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

The expressions for the normalized gain along the two principle planes are given as follows:

- For the H-plane, we set $\varphi = 0°$ in Eq. (12):

$$g_H(\theta) = \lim_{\varphi \to 0^0} g(\varphi, \theta) = \frac{(1+\cos\theta)^2}{4} \frac{|T|^2 \cdot (\text{Re}(A))^2}{(1-|R||\rho_l|)^2} \left[\frac{(1-|R||\rho_l|)^2}{|T|^2 \cdot (\text{Re}(A))^2} \right] \Bigg|_{\theta=0^0} \cdot \text{sinc}^2\left(\frac{W}{\lambda_r}\sin\theta\right) \quad (13)$$

- For the E-plane, we set $\varphi = 90°$ in Eq. (12):

$$g_E(\theta) = \lim_{\varphi \to 90^0} g(\varphi, \theta) = \frac{(1+\cos\theta)^2}{4} \frac{|T|^2 \cdot (\text{Re}(A))^2}{(1-|R||\rho_l|)^2} \left[\frac{(1-|R||\rho_l|)^2}{|T|^2 \cdot (\text{Re}(A))^2} \right] \Bigg|_{\theta=0^0} \cdot \sin c^2\left(\frac{L}{\lambda_r}\sin\theta\right) \quad (14)$$

performance of the metamaterial-based microwave antenna, which has a ferrite superstrate. So, from the power pattern you can obtain the radiation density of the antenna with substrate it can be written as U θ comma φ.

So, this is the power pattern, okay. So, it depends on k_0 square / 8 π square z naught and then you have 1 + cos θ whole square by 4 * this parameter right ok. And then you also have this radiation pattern, which is the modulus of f θ φ squared. So, what are these angles, θ and φ? These are basically the angles of the spherical coordinate system. Okay, and you will see that f(θ, φ) tells you about the radiation pattern without the super straight.

So, I have reproduced this here from one of our previous lectures, which tells you about the function f(θ, φ). Now, in the presence of the super straight, the radiation pattern of the antenna will be modified like this, okay. You will have F super straight θ φ, which will be given as 4s; s is nothing but W cross L, that is the area of the patch antenna. ok and then you have A t / 1 - R modulus of R modulus of rho L. A is basically the normalized coupling coefficient between the incident electric field and the complex conjugate of the kind distribution we have seen earlier and t is basically the Transmittance that you have seen is okay.

And then you have sinc L/λ r cos φ - 1 * sin θ then you have another sinc function L/λ r sin θ sin φ * sinc W/λ r sin θ cos φ. So, with this, you can obtain the expression for the efficiency of the antenna that is under consideration. You can write it as η = the modulus of t real of a - 1 - modulus / 1 - the modulus of rho r rho l. * 1 by this factor which is 1 + j naught s / real of a square root of ω μ naught / 2 σ i. So, all these

Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

- Let us analyze the performance of the antennas on composite substrates with ferrite superstrate.
- In order to do that, we initially define the constitutive parameters of the antenna.
- Superstrate Material:
  - Chosen material: $MgO.Fe_2O_3$
- We are going to use the following values of the superstrate: $\varepsilon_f = 9.66 - 0.174i$ and $\mu_f = 1.2 - 0.974i$
- Superstrate Properties:
  - Dimensions: Identical to the antenna substrate
  - Distance from patch (t): Calculated using Eq. (6) → $t = 0.0004\,m$

$$t = \frac{\lambda_r}{4\pi}(\delta_R + \delta_l)$$

Source: Choudhury, P.K , Metamaterials: Technology and Applications, CRC Press, 2021

parameters we have discussed earlier.

So, you can just look back at the previous lecture and understand those. So, from that you can obtain the expression of the directive gain which is given as d θ φ ok as 2 k_0 s * modulus of a whole square / π z naught * 1 + cos θ whole square / real of a ok. Then you have another fraction which is modulus t square / 1 - 2 r modulus of r modulus of royal + modulus r square modulus royal square and then you have this sinc terms which are basically getting square. So, as you can see from this particular expression that the maximum of the directive gain can be achieved for θ = 0 degree and the maxima of the gain can be given as g max which will be η d max and the value stand out to be this which is 8 k_0 square by π z naught. Then you have the modulus of t cubed, real of a computed at θ = 0.

/ 1 - rho r or you can say 1 - modulus of r modulus of rho l whole cube * a square then you have modulus of a square / again the real part of a calculated at θ = 0 degree + j naught s square root of ω μ naught / 2 σ i. So, when you take into accounts the equation 6 and 7 that you have seen, you can derive the expression for the normalized gain which is given by g θ φ and that basically takes this particular form. So, it is basically computed as (1 + cos θ) squared / 4. And the ratio of the radiation pattern F super straight θ φ whole square / that is the modulus square / the maximum value of that. So, that is basically given this particular equation if you expand it.

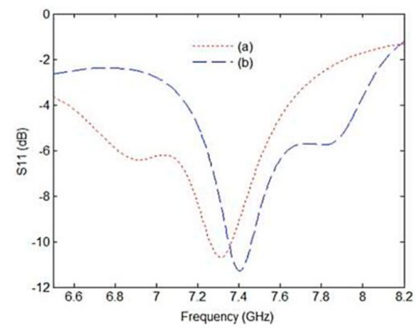
So, this is the expression for the normalized gain, okay. Now, once we have obtained that, you can always plot the gain in the two planes: the h-plane and the e-plane, okay? So, for the h plane, you can set φ equal to 0. So, you get the expression for g h θ ok that is nothing but you are putting a limit of φ = 0 degree to this generalized expression and this is what you obtain ok. For the e-plane, you have to put φ equal to 90 degrees. So, that means you can write Ge θ that will be same as limit of φ tending to 90 degree on this generalized expression and then you have this term.

So, you can compare the two patterns and you can see that this first term is identical you have a sinc square W/λ r sin θ term here, whereas here you have sin square L/λ r sin θ term right. So, that is the only difference remaining other term is basically same. So, with that, we can now analyze the

Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

- The results of FDTD simulations regarding the S_{11}-spectra of antenna designs with ferrite superstrate are shown in the figure.
- Impedance Matching:
  - Both designs are well impedance-matched
  - Miniaturized design shows superior impedance matching
- Resonant Frequency Shift:
  - Miniaturized design (in b): Resonates at 7.404 GHz → most blue-shifted
  - Standard design (in a): Resonates at 7.312 GHz → closest to theoretical value (7.3 GHz)

Simulated S_{11}-spectra



numerical model with ferrite superstrate
(a) standard
(b) miniaturized

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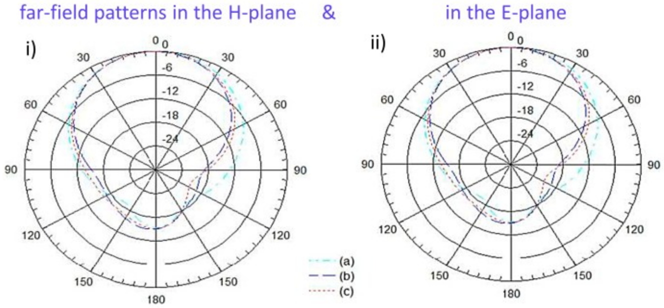
Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

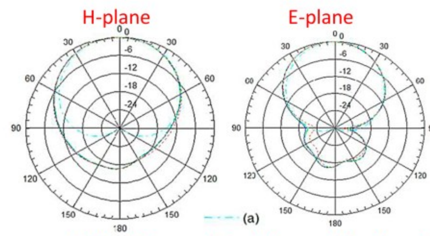
The results of FDTD simulations of far-field patterns for all the antenna designs with ferrite superstrates:

As compared to previous designs without superstrates

- H-Plane: No significant differences
- E-Plane: Less coincidences of the far-field patterns

far-field patterns in the H-plane & in the E-plane





Without Superstrate (a) – analytical model

With ferrite superstrate
(a) standard inhomogeneous analytical model
(b) standard inhomogeneous numerical model
(c) miniaturized inhomogeneous numerical model

Note: All evaluated at the resonant frequencies

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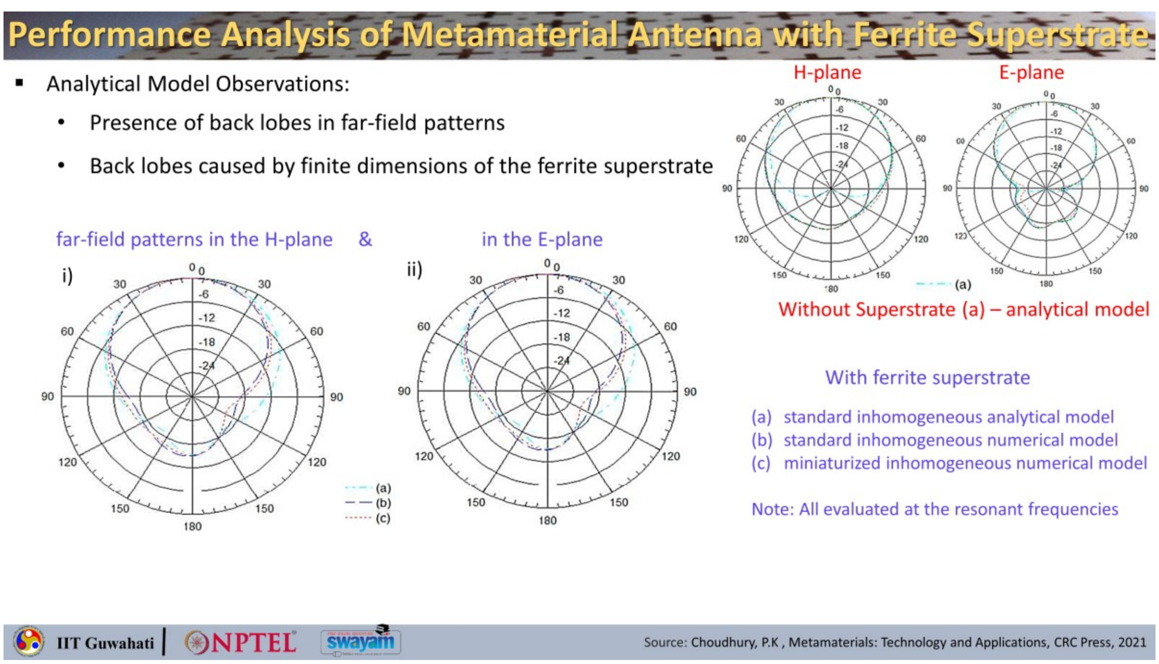
performance of this metamaterial antenna with ferrite super straight. So, in order to do that, let us initially define the constitutive parameters of the antenna. So, let us choose the super straight material; we can choose magnesium ferrite, okay? And then we are going to use these particular values of ε f and μ f, okay.

So, the value is 9.66 - 0.174 i μ f can be written as 1.2 - 0.974 i, right? So, what are the properties of the substrate? We have considered dimensions identical to the antenna substrate; that is the property of the superstrate. Okay, and then you can obtain the distance from the patch that you can calculate from the expression you have seen here.

So, that comes out to be 0.0004 meters. Furthermore, you can do the FDDT simulation, okay? So, that allows you to obtain the S_{11} spectrum of the antenna design with the ferrite super straight. So, as can be obtained as or you can see from the figure that this antenna designs are well impedance matched. So, there are two patterns as you can see these are basically this one the dot dotted one is for the standard numerical model and the DEST one is basically the miniaturized antenna model. So, you can see that the miniaturized one is showing a better impedance matching and it is also you know closer to the theoretical value of 7.

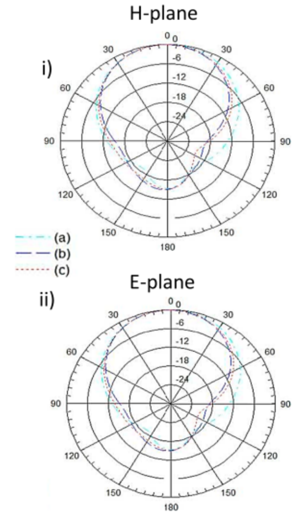
3 gigahertz right sorry this one. So, okay, you can see from the impedance matching that the miniaturized design, which is basically this DEST one, shows superior impedance matching. However, if you consider the standard numerical model okay that basically resonates at 7.312 gigahertz which is very basically very close to the theoretical value of 7.3 gigahertz. So, the previous ε f and μ f values were mentioned at that frequency; okay, I forgot to mention that.

But here you can see in the miniature edge design okay there is a bit of a blue shift ok because the frequency is increasing here of the resonance and it is around 7.404 gigahertz correct. So, now the results of FDDT simulation for the far field patterns for all the antenna designs with ferrite super straights are compared with those without the super straight. So, here is the one with super straight and this one shows you the same antennas



Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

- Performance Enhancements with Ferrite Superstrate:
  - Maximum Power Gain:
    - ✓ Standard inhomogeneous analytical model (a): 6.01 dB at $\theta = 0°$
    - ✓ Standard inhomogeneous numerical model (b): 5.92 dB at $\theta = -2°$
    - ✓ Miniaturized inhomogeneous numerical model (c): 6.59 dB at $\theta = 0°$
  - Efficiency Values:
    - ✓ Analytical model (a): 49.37%
    - ✓ Numerical model (b): 46.01%
    - ✓ Miniaturized numerical model (c): 54.34%
- Improvement Mechanisms:
  1. Fabry-Perot resonant cavity effect



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Source: Choudhury, P.K , Metamaterials: Technology and Applications, CRC Press, 2021

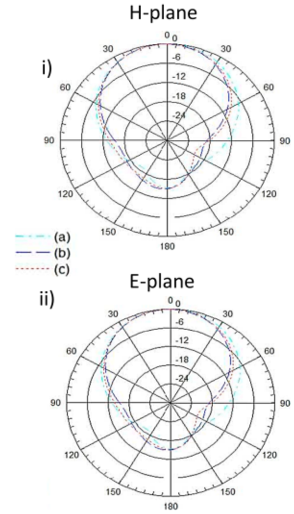
performance without the super straight and you can see this dash dot line this one okay it is bit light though. So, that is from the analytical model we will compare with this one, okay? So, as you can see that from this figures you can see that the H plane has no significant difference, but you know for the so overall they look similar, but E plane this is the E plane ok.

So, there is less coincidence of the furfield patterns in the two cases with and without super straight. So, here we are also plotting the three cases A, B, and C. What are those? They are basically A it stands for standard inhomogeneous analytical model, B is standard inhomogeneous numerical model and C is basically the miniaturized inhomogeneous numerical model. Right. So, another important observation is that the analytical model for the case A you can see that here you can see some side lobes in the presence of the ferrite

Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

2. Increased energy stored in the magnetic component of the EM field radiated by the antenna:
   - Due to the tendency of the magnetic moment of ferromagnetic superstrate to be aligned with the magnetic component of the EM field produced by the antenna and to reinforce it by virtue of its own magnetic fields

- Additional Benefit:
  - Ferrite superstrate can serve as one of the antenna housing panels.



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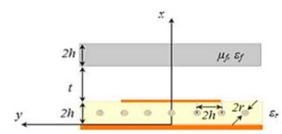
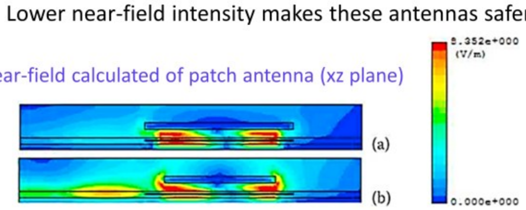
Performance Analysis of Metamaterial Antenna with Ferrite Superstrate

- Near-Field Distribution Insights:
  - Observations based on two perpendicular field directions
  - Fields are mainly concentrated beneath the ferrite superstrate
  - Lower intensity of near-fields compared to initial dielectric substrate antenna

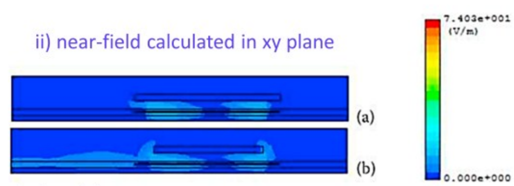


- Practical Implication:
  - Lower near-field intensity makes these antennas safer for use in gadgets

i) near-field calculated of patch antenna (xz plane)



ii) near-field calculated in xy plane



(a) standard inhomogeneous numerical model
(b) miniaturized inhomogeneous numerical model.

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superstrate which was not the case in the when there was no ferrite superstrate.

So, here you see there is absolutely no back lobe or backscattering, okay. So, you can see the back lobe is getting you know prominent when the ferrite super straight is there and this is mainly because of the finite dimensions of the ferrite super straight. So, right now we are going to show the presence of the ferrite super straight can be energetically advantages and you will see that you know the appropriate FDD simulations and analytical calculations have shown that the maximum power gain of the standard inhomogeneous analytical model which is again shown as A okay. That is giving the maximum gain power gain as 6.01 dB calculated at 0 degree for the case of standard inhomogeneous numerical model which is B this dashed line here.

You are getting 5.92 dB at $\theta = -2$ degrees and for the miniaturized inhomogeneous numerical model that is this dotted one for C you are getting the highest gain which is 6.59 dB at 0 degree θ right. Again, if you compare the efficiency model, you can also see that the analytical model is giving you an efficiency of 49.37. The numerical model is giving around 46 percent, whereas the miniaturized numerical model is giving an efficiency of around 54.

34 percent. So, why is there an improvement? You can see that the gain is improving and the efficiency is improving. It plays the improvement is taking place because of two mechanisms. The first one is the Fabry-Pérot resonant cavity effect that is working here. And the second important effect is that you know the increased energy stored in the magnetic component of the EM field that is radiated by the antenna. And this is coming because of the tendency of the magnetic component of the ferromagnetic superstrate to be aligned with the magnetic component of the EM field which is produced by the antenna and then to reinforce it by the virtue of its own magnetic fields.

So, that is why you get a higher gain as well as higher efficiency when you have the ferrite superstrate on top of your miniaturized antenna. So, what are the additional benefits as I already mentioned this you can use this ferrite superstrates they can also serve as one of the antennas housing panels. So, here are the near field patterns that are obtained from the FDDT simulation for both antenna designs. So, this is the antenna with that wire array which we have been considering, but this time considering the ferrite substrate. So, what you see is that these are the near field plots, okay.

So, in each case, we are considering the near field calculated at the xz plane. So, z is basically along the axis of the wires. So, the xz plane is basically the $y = 0$ plane, okay. So, you can see the length of the wire here and these are the two cases a and b. So, one is for the standard inhomogeneous numerical model, the other one is for the miniaturized inhomogeneous numerical model.

And the same goes for here. Here it is along this XY plane. So, you can consider at any point, say $z = 0$, at the middle of the patch. So, what do you see the observations are based on two perpendicular field directions? And the field, as you can see, is mainly concentrated beneath the ferrite substrate, okay. And you also notice that there is a lower intensity of the near field compared to the initial dielectric substrate antenna. So, if you compare it with the previous case, you will see that the near field intensity has basically gone down, okay.

So, what does it mean the practical implication is that when you have lower near field intensity that makes your antenna safer for use in gadgets where there can be many more other components in the same package ok. So that way, it will be very useful. So, with that, we conclude this lecture. So, we will start discussion about the model of rectangular patch antenna with two layer wire composite or you can say metamaterial substrate in the next lecture. So, if you have got any query regarding this lecture, you can drop an email to this particular email address mentioning the course name and the lecture number on the subject line. Thank you.

Slides inserted by fallback (review if needed):