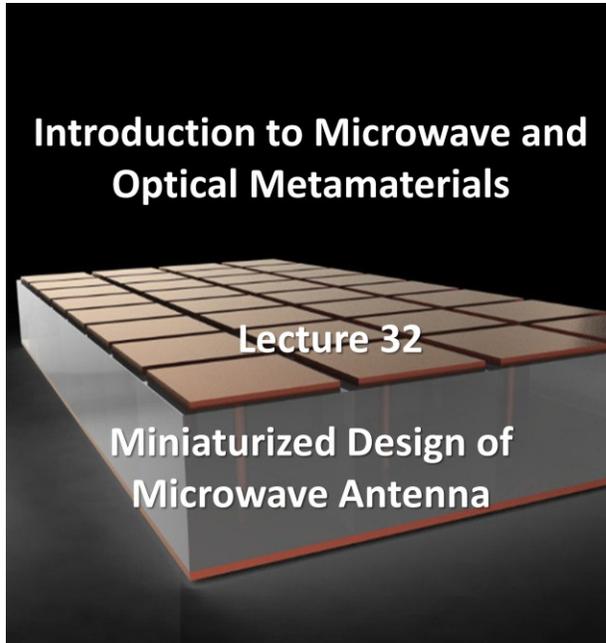


**Course Name: Introduction to Microwave and Optical Metamaterials**  
**Professor Name: Dr. Debabrata Sikdar**  
**Department Name: Electronics and Electrical Department**  
**Institute Name: Indian Institute of Technology, Guwahati**  
**Week-7**  
**Lecture-32**

Lec 32: Miniaturized Design of Microwave Antenna



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## Lecture Outline

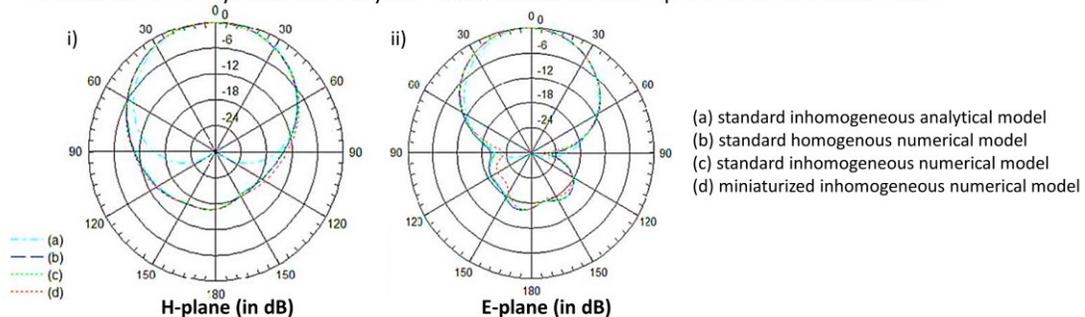
- Different Design Models of Microwave Antenna
- Miniaturized Design of Microwave Antenna



Hello, students. Welcome to lecture 32 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on the

## Different Design Models of Microwave Antenna

- Far-Field Patterns:
  - Evaluated in H- and E-planes at respective resonant frequencies
  - No major differences between analytical and numerical patterns, except back lobes
  - Back lobes are nearly absent in analytical model due to the assumption of infinite z-axis extent



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

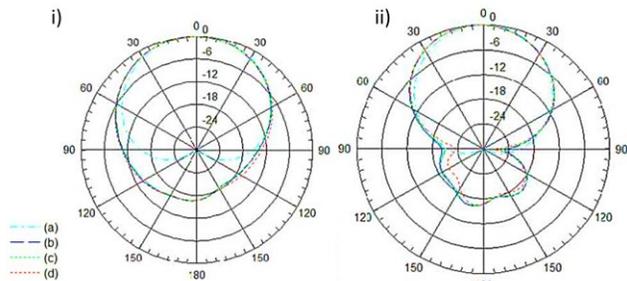
miniaturized design of microwave antennas. So, here is the lecture outline we will discuss different design models of microwave antennas and then we will go into a miniaturized design of the antennas. So, in the earlier lecture, we saw the results of FDTD simulations of the  $S_{11}$  spectrum, which is the reflection spectrum. So, today we will start with the far-field patterns.

So, the far-field patterns are evaluated in the H and E planes for all the antenna models that we discussed earlier. These are the four models. They are basically shown at their own resonant frequencies, right? So, this figure 1 tells you about the H-plane characteristics, and this is the far-field pattern in the E-plane. So, here different types of lines basically tell you the 4 models.

So, A is basically telling about the standard

## Different Design Models of Microwave Antenna

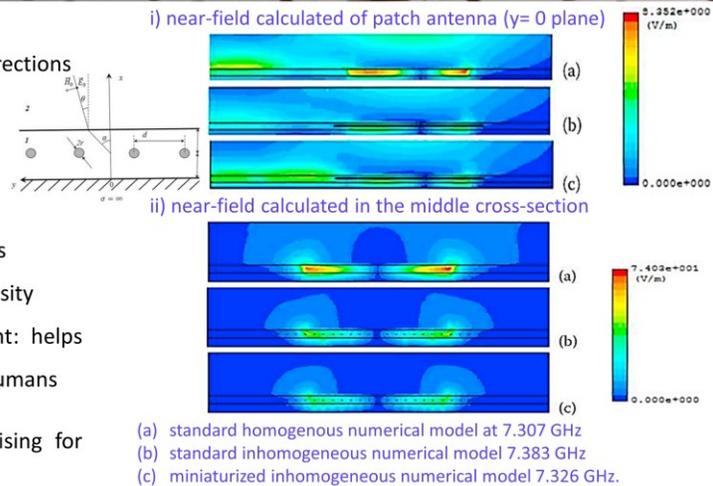
- Maximum Power Gain:
  - Standard Homogeneous Numerical Model:
    - ✓ Gain: 4.6 dB at  $\theta = -2^\circ$
    - ✓ Efficiency: 40.72%
  - Standard Inhomogeneous Analytical Model
    - ✓ Gain: 4.84 dB at  $\theta = 0^\circ$
    - ✓ Efficiency: 42.76%
  - Standard Inhomogeneous Numerical Mode
    - ✓ Gain: 5.01 dB at  $\theta = -2^\circ$
    - ✓ Efficiency: 43.98%



- Conclusion:
  - Results support the study's main idea – using composite substrates improves antenna performance

## Different Design Models of Microwave Antenna

- FDTD Near-Field Simulations:
  - Conducted in two perpendicular directions
  - Figures display corresponding field distributions
- Key Observation:
  - Composite/metamaterial substrates significantly reduce near-field intensity
  - Important for gadget development: helps reduce EM radiation exposure to humans
- Implication: Such antennas are promising for new transponder designs



inhomogeneous analytical model, B is standard homogeneous numerical model, C that is basically this dotted lines tells you standard inhomogeneous numerical model and finally, you have D which is a miniaturized inhomogeneous numerical model. So, remember that they are all calculated at their respective resonant frequencies. So, as you can see from the figure that no significant differences are observed between the analytical and numerical field patterns except for the back lobes okay. So, the back lobes are in fact mostly absent in the far field patterns of the analytical model and this is due to the consideration of the antenna model as infinite in the direction of z axis. The analytical modeling using the equations and the numerical modeling using the FDTD commercial software have shown two important things.

First, you should know that the maximum power gain of the standard homogeneous numerical model is around 4.6 dB, and it was found at - 2. Degrees that is  $\theta = - 2$  degrees. Also, it is found that the appropriate efficiency value comes out to be around 40.72 percent in the case of the standard homogenized numerical model.

Now, in the case of standard inhomogeneous numerical model, the gain, so that is case B. The gain was reported to be around 4.84 dB and it was found at  $\theta = 0$  degree. The efficiency value came out to be 42.76% in this particular case.

In the standard inhomogeneous numerical mode, The gain was reported to be maximum okay and there you got around 5.01 dB at an angle of  $\theta = - 2$  degrees with an efficiency of 43.98%. So, these results are basically in good agreement with the main idea of the study which basically focuses on improving the antennas performance using composite or metamaterial structures. So, in this study, FDTD simulations for the near field around the antenna are performed in two mutually perpendicular directions.

So, the corresponding fields are basically plotted in figures 1 and 2. So, here you can see in figure 1 you are plotting the near field calculated at the cross section in basically  $y = 0$  plane of the patch antenna. Again, A stands for the standard homogeneous numerical model that has a resonance at 7.307 gigahertz, okay. Then B is for the standard inhomogeneous numerical model.

having a gain at 7.383 gigahertz. And the last one is for the miniaturized inhomogeneous numerical model having a gated gain at 7.326 gigahertz, right? So, this is for the near field calculated for the patch antenna at the  $y = 0$  plane. And figure 2 it basically shows you the near field calculated in the middle cross section along the x axis of the patch antenna again for the three cases, okay.

So, these are all V/m. These are basically electric field values that are plotted. Now, as you can observe in these figures, the implementation of the composite or metamaterial substrates basically result in considerable decrease in the intensity of the near field around the antennas as you can see here clearly. Right. So, this result is specifically important with a viewpoint of creating gadgets because of the possibility of a considerable decrease in the negative impact of the EM radiation you know on humans and other living objects ok.

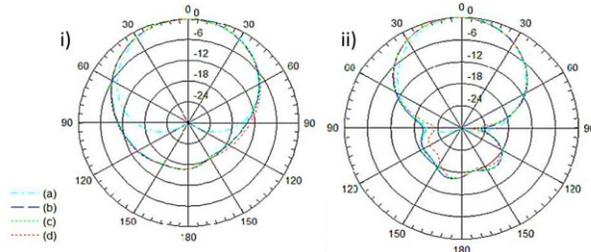
Moreover, as was also shown by Rabin's group, such antennas can be basically used for creating novel transponders. Thus, taking into account the above

## Miniaturized Design of Microwave Antenna

- Miniaturized Antenna Design:
  - Based on values of  $d$ ,  $\epsilon_r$ ,  $\mu_r$ , and  $f_r$ .
  - Achieved through numerous FDTD simulations

- Design Parameters (FDTD Simulation):
  - Length  $L = 0.0117$  m
  - Width  $W = 0.0156$  m
  - Resonant frequency  $f_r = 7.418$  GHz

- Performance Highlights:
  - Most impedance-matched design in the study
  - Far-field patterns are similar to other designs except for back lobes



performance analysis of all this kind of considered antenna models, we can say that the proposed analytical model of the rectangular patch antenna can be used for designing patch antennas of new generation. So, let us find a

## Miniaturized Design of Microwave Antenna

- Miniaturized patch antenna:
  - Exhibits lower near-field intensity compared to the standard model
- Volume Profile Miniaturization Gain Factor (VPMGF):

$$\text{VPMGF} = \left( 1 - \frac{W_{\min} \cdot L_{\min}}{W \cdot L} \right) \cdot 100\%$$

- VPMGF indicates the reduction in antenna size due to miniaturization.
- Higher values possible with increased real part of effective relative permeability in substrate.

miniaturized design of a microwave antenna for the given values of  $d$ ,  $\epsilon_r$ ,  $\mu_r$  and resonance frequency  $f_r$ . So, taking into account numerous FDD simulations, we are able to obtain the appropriate antenna design with length of 0.0117 meter and width of 0.

156 meter, resonating at 7.418 gigahertz. So throughout the study, we will basically call the approximate antenna design of, we will call the approximate or appropriate antenna design. the miniaturized inhomogeneous numerical model or design, right. And this was evaluated at 7.

418 gigahertz, as you can see. Now it is important to mention that the miniaturized design theoretically gives the most impedance-matched antenna. Compared to all previously considered antenna designs in the study. And now, moreover, no significant differences are observed between the far-field radiation patterns of the miniaturized antenna design. And the other antennas presented in our, you know, resonant frequencies except for the back lobes, as you can see in the figure.

So, the intensity of the near field around the miniaturized patch antenna is less than that of the standard patch antenna on the dielectric substrate, right? So, in order to evaluate the advantage of the miniaturized design in the volume profile with regard to the analytical design. Let us use this volume profile miniaturization gain factor, it is also called VPMGF okay and you can obtain this as  $1 - W_{min} * L_{min} / W_{into} L_{into} 100\%$ . So, here  $L_{min}$  and  $W_{min}$  are basically the length and width of the patch in the miniaturized design. So, this gain factor basically indicates the reduction in antenna size due to miniaturization. So, in fact you know VPMGF can reach larger values for large real part of the effective relative permittivity of the composite and or we say metamaterial substrates.

So, the last miniaturized design. has shown that the miniaturization of rectangular patch antenna on enhanced non-resonant composite metamaterial which has got real part of the related permeability positive also the permeability is also greater than equal to 1 that is possible in principle right. Moreover, its quantitative estimation can be evaluated using this formula. So, that tells us the effect of this volume miniaturization. Now, however, you will see that the equation says nothing about how to calculate these values of  $l_{min}$  and  $w_{min}$  directly.

So, in other words, the appropriate miniaturization concept for rectangular patch antennas is required. And the concept will be able to bring breakthroughs in the domain of compact antennas with extra capabilities of reconfigurable and wearable antenna systems with regard to band tuning operation, beam steering operation, and so on. So we found that the volume profile of the rectangular patch antenna on substrate created on the basis of enhanced non resonant composite or metamaterial is being decreased by increasing the value of the real part of the complex effective permittivity of the substrate. Now in this way it is logical to answer the question like to what extent can we increase the value of the real part of the complex relative complex effective relative permittivity of the substrate in order to minimize the antennas volume profile right. So, in order to answer that question, we have to solve the miniaturization problem of the volume profile of a rectangular patch antenna with variable parameters, okay.

So, the resonant frequency  $F_r$  that is  $\omega$  by  $2\pi$  of the antenna ok that also gives you its wavelength  $\lambda_r$  that is given as  $C$  by  $F_r$ . Okay, the thickness of the antenna substrate  $D$  and the effective relative permittivity  $\epsilon_r$  of the antenna substrate are considered. So, the goal is to

identify the optimal parameters that will minimize the antenna's volume profile. So, the antenna part of the volume created by the patch =  $S V = S * D$ . So,  $S$  is basically the surface area of the antenna and  $D$  is basically the substrate thickness ok.

Now, the above mentioned miniaturization problem for the antenna volume profile is reduced to the non-linear mathematical programming problem with the objective function enough represented by the maximum gain of the patch antenna which is  $g_{max}$  given as a function of surface area  $S$  and the resonant wavelength  $\lambda_r$  or frequency  $f_r$  which can be related as  $f_r = c/\lambda_r$  right. So, it is basically, you know, you have reformulated the miniaturization problem as a non-linear mathematical programming problem, okay. And here the constraints are like you know substrate thickness  $d$  and relative permittivity  $\epsilon_r$  which are take can be taken as the given parameters of the fixed parameters. Thus, the mentioned miniaturization problem can be defined as follows. So, you want to find the maximum a gain okay for  $s$  and  $\lambda_r$  for given  $s$  and  $\lambda_r$  okay.

Subject to you know  $\lambda_r$  within this limit that is  $\lambda_r$  by square root of  $\epsilon_r \mu_m$  should be greater than  $4D$  but less than equal to  $10D$ . So,  $D$  is basically the thickness of the substrate. So, here the last two inequalities basically define the condition for the composite metamaterial to be non-resonant. So, it means that the resonance phenomena related to the wave diffraction on the lattice of wires are not taken into account, while the resonance inside the wires are basically taken into account ok. So, after analysis, we finally obtain the values for  $W_{min}$  and  $L_{min}$ .

So,  $W_{min}$  can be written as  $C / 2 F R m$ . \* the square root of  $2 / 1 + \epsilon_r$  and  $L_{min}$  can be written as  $S_{min} / W_{min}$ . So, once you know  $W_{min}$ , you can find what  $S_{min}$  is. Now, what is  $S_{min}$  here  $S_{min}$  is basically the minimum required surface area of the patch and  $f_{rm}$  is basically the resonant frequency of the miniaturized antenna okay that is basically determined from solving a transcendental equation right. So, from the previous lecture we got to know the maximum gain equation was the  $g_{max}$  given as  $\eta d_{max}$  which =  $8 k_0$  square by  $\pi z_0$ .

$S$  and then you have modulus of  $A$  at  $\theta = 0$  degree whole square / real of  $A$  again evaluated at  $\theta = 0$  degree \* the  $\eta$  value which was  $1 / 1 + J$  naught  $S$  / real of  $A$  evaluated at  $\theta = 0$  degree \* square root of  $\omega \mu$  naught /  $2 \sigma i$  right. Now we know that you know this equation does not basically take into account the fringe phenomena that is happening on the edge of the

## Miniaturized Design of Microwave Antenna

- Miniaturization of Rectangular Patch Antennas:
  - Proven feasible using enhanced non-resonant composite/metamaterial substrates with:
    - ✓  $Re(\epsilon_r) > 1$
    - ✓  $Re(\mu_r) \geq 1$
- Quantitative Estimation:
  - Possible via equation  $VPMGF = \left(1 - \frac{W_{min} \cdot L_{min}}{W \cdot L}\right) \cdot 100\%$  for volume miniaturization.
  - But, the equation lacks a method to determine  $L_{min}$  and  $W_{min}$  directly
- Need for a Miniaturization Concept:
  - A systematic method is required to design and predict miniaturized dimensions
  - This concept could enable next-generation antennas with: reconfigurability, wearable antenna, band tuning, beam steering, etc

rectangular patch of the antenna and this omission may lead to some more complex near field distribution. So, as a result, the  $S_{11}$  spectrum of the antenna with composite

## Miniaturized Design of Microwave Antenna

- Volume Miniaturization Insight:
  - Decreasing antenna volume is achievable by increasing the real part of the substrate's effective relative permittivity
- Proposed Solution:
  - Frame this as a minimization problem involving:
    - ✓ Resonant frequency  $f_r = \omega/2\pi$
    - ✓ Wavelength  $\lambda_r = c/f_r$
    - ✓ Substrate thickness  $d$
    - ✓ Effective relative permittivity  $\epsilon_r$
- The goal is to identify the optimal parameters that minimize the antenna's volume profile.

substrates can contain additional peaks of interest for the antenna. except as a result the  $s_{11}$  spectrum of the antenna with composite substrates can contain additional peaks of interest except for the peak of the main wave so let us give an example the for this purpose you can consider the  $s_{11}$  spectrum of the miniaturized inhomogeneous numerical model in the frequency range of 5 to 20 gigahertz as you can observe here the other secondary peaks They also appear at 9.

556, then 11.29 gigahertz, 13.72 gigahertz, 14.45 gigahertz, and 15.

93 gigahertz. 16.84 and 18.57 gigahertz correspondingly. So, these are all secondary peaks, right? Now, these peaks are of interest with a viewpoint of the possibility of the miniaturized antenna to be reconfigurable one in frequency functionality right. So, the FDDT simulations for the farfield patterns okay and efficiency and power gain of the frequency peaks have shown that the peak located at this frequency of 16.84 gigahertz maybe of some interest and you can see that here okay. So, the blue one basically shows that 16.

84 gigahertz and the red dotted one shows 7.38 gigahertz and So, this is basically the far field pattern in H plane, this is the far field pattern in E plane. So, indeed you can see by comparing the far field patterns of this 16.84 gigahertz with the far field pattern of the first peak that is at 7.

38 gigahertz. Okay. And you can assume that the miniaturized patch antenna okay on this composite or metamaterial substrate can be multiband and multidirectional as you can also see here right yeah. So, this is especially evident from this 3D radiation pattern, which is shown here. So, here the figure shows you the 3D radiation far-field radiation pattern of the miniaturized antenna at the main peak frequency which is 7.383 gigahertz the figure on the left and you can also see it for the other frequency that is 16.

84 which we have considered. So, the key finding here is that the maximum power gain at the frequency of 16.84 gigahertz is also not bad it is 6.87 dB which is obtained at an angle of  $\theta = -10$  degree right and it has got an efficiency value of around 71.73 percent. So, this result is particularly interesting from the point of view of designing reconfigurable compact antenna systems in frequency functionality and polarization.

So, taking into account the case of standard numerical model with composite substrate, it is logical to conjecture that the intensity of near field distribution around the miniaturized antenna at frequency of this 16.84 gigahertz is quite low, isn't And figure 1 here basically shows you the near field calculated at the cross section of  $y = 0$ . Figure 2 provides information about the near field calculated in the middle cross section along the x-axis of the patch antenna. So there are two cases here: A and B. A is for the standard homogeneous numerical model calculated at 7.

5. 307 gigahertz, and B is basically a miniaturized version using the metamaterial, okay. So, that is obtained at 16.84 gigahertz, okay. So, both figures basically show you the FDDT simulations of the near-field distribution, okay? And this also tells you about the similar low intensity near field being observed in the standard inhomogeneous model as well. So, what are the implications? So, it basically says a lot about the above-mentioned idea of using additional resonant frequencies of the patch antenna on composite or metamaterial structures.

The appropriate FDD simulations have shown that the same quantitative or qualitative result occurs for the standard inhomogeneous model. So, this basically enables us to come up with a general conclusion about the multidirectional and multiband nature of the patch antennas on this kind of composite or metamaterial substrate right. So, what are the design advantages of this

miniaturized design of microwave antennas that allow for integration? Receiving and transmitting functionalities in a single-antenna system. They also eliminate the need for multiple antennas in communication systems and some potential

## Miniaturized Design of Microwave Antenna

- Antenna Volume Definition:
  - The antenna's covered volume is given by  $V = S \cdot d$  where  $S$  is the surface area and  $d$  is substrate thickness
- Optimization Objective:
  - Reformulate miniaturization as a non-linear mathematical programming problem
  - Goal: Maximize the antenna gain  $G_{\max}$  as a function of:
    - ✓ Surface area  $S$
    - ✓ Resonant wavelength  $\lambda_r$  or frequency  $f_r = c/\lambda_r$
- Constraints:
  - Substrate thickness  $d$  and relative permittivity  $\epsilon_r$  are fixed

## Miniaturized Design of Microwave Antenna

- Thus, the mentioned miniaturization problem is defined as follows:

$$\begin{aligned} & \max G_{\max}(S, \lambda_r) \\ \text{subject to } & 4d < \frac{\lambda_r}{\sqrt{\epsilon_m \mu_m}} \leq 10d \end{aligned}$$

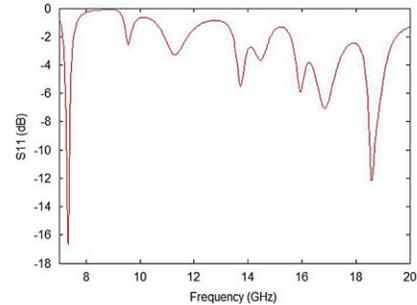
- Scope of Analysis:
  - Resonance phenomena from wave diffraction on the wire lattice are not considered
  - However, resonances inside the wires are included in the analysis
- After analysis, we finally obtain:  $W_{\min} = \frac{c}{2f_{rm}} \sqrt{\frac{2}{1+\epsilon_r}}$ ,  $L_{\min} = \frac{S_{\min}}{W_{\min}}$ 
  - where  $S_{\min}$  is the minimum required surface area of the patch and  $f_{rm}$  is the resonant frequency of the miniaturized antenna

## Miniaturized Design of Microwave Antenna

- We know that the maximum gain equation  $G_{\max} = \eta D_{\max} = \frac{8k_0^2 (S|A|_{\theta=0})^2}{\pi Z_0 \operatorname{Re}(A)|_{\theta=0}} \left( 1 + \frac{j_0 S}{\operatorname{Re}(A)|_{\theta=0}} \sqrt{\frac{\omega \mu_0}{2\sigma_t}} \right)^{-1}$  does not account for fringe effects on antenna patch edges.

### $S_{11}$ -Spectrum Implications:

- Antennas with composite substrates may show additional peaks beyond the main one
- Example:** The miniaturized inhomogeneous numerical model (frequency range: 5–20 GHz) shows several secondary peaks at 9.556 GHz, 11.29 GHz, 13.72 GHz, 14.45 GHz, 15.93 GHz, 16.84 GHz, 18.57 GHz

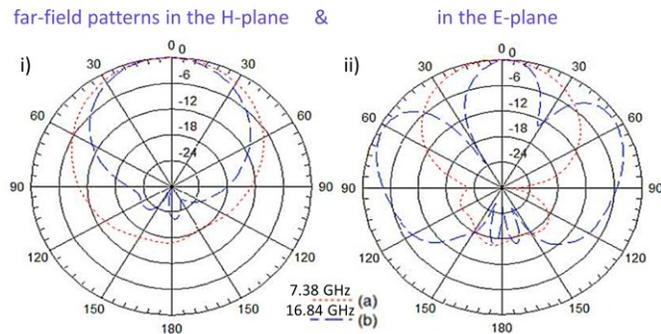


## Miniaturized Design of Microwave Antenna

- Design Insight:** These extra peaks suggest the potential for frequency reconfigurability in the miniaturized antenna
- FDTD simulations for the far-field patterns, efficiency and power gain of frequency peaks have shown that the peak located at the frequency 16.84 GHz may be of some interest.

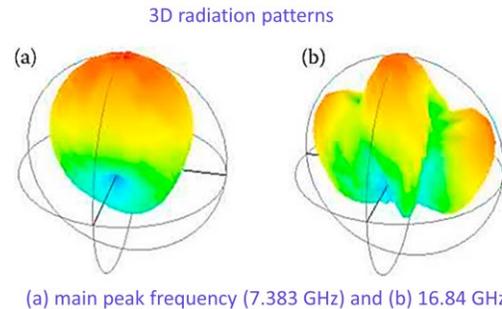
- Compared to the main peak, far-field patterns suggest that miniaturized patch antennas on composite/metamaterial substrates can be:

- Multi-band
- Multi-directional



## Miniaturized Design of Microwave Antenna

- This is especially evident from 3D radiation patterns depicted in the figure.
- Key Findings:
  - The maximum power gain at the frequency 16.84 GHz is equal to 6.97 dB, and it is found at  $\theta = -10^\circ$
  - The appropriate efficiency value is 71.73%.
- Potential Application:
  - Promising for reconfigurable compact antenna systems in terms of frequency functionality and polarization



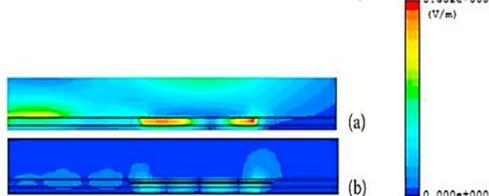
application of such a design could be like Avoid the use of multiple antennas for instance you can use the same antenna operating in the GSM 1800 megahertz band and also for WLAN 2.

4 gigahertz application bands ok. So, that allows you miniaturization of the overall antenna system. So, with that, we conclude our lecture. So, we will start discussing the far-field focusing of microwave antennas with composite and metamaterial substrates in the next lecture. If you have got any query regarding this lecture you can always drop an email to this email address mentioning the course title and the lecture number on the subject line.

## Miniaturized Design of Microwave Antenna

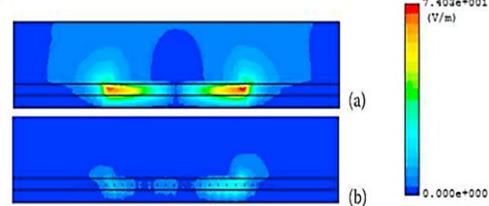
- Near-Field Analysis:
  - FDTD simulations confirm very low near-field intensity around the miniaturized antenna at 16.84 GHz
  - Similar low-intensity near-fields observed in the standard inhomogeneous model as well
- Implication:
  - Validates the multi-frequency usability of patch antennas on composite/metamaterial substrates
  - Supports the idea of multi-band and multi-directional behavior

i) near-field calculated in the cross-section  $y = 0$



(a) standard homogenous numerical model calculated at 7.307 GHz

ii) near-field calculated in the middle cross-section



(b) miniaturized numerical antenna model at 16.84 GHz

## Miniaturized Design of Microwave Antenna

- Design Advantage:
  - Enables integration of receiving and transmitting functions into a single antenna system
  - Eliminates the need for multiple antennas in communication systems
- Potential application for dual operation in:
  - GSM 1800 MHz
  - WLAN 2.4 GHz



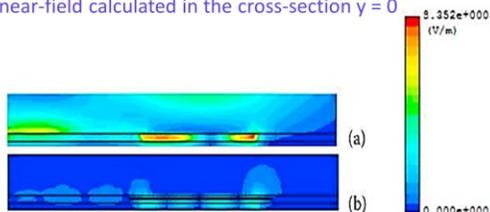
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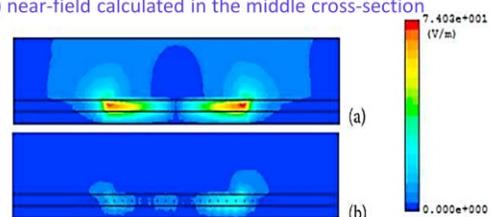
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*Thank You*