Advanced Microwave Guided Structures and Analysis
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Lecture No. 10
Instantaneous Form of Maxwell's Equations (Contd.)

So, welcome to this next session of the lecture on Instantaneous form of Maxwell's equations; let us continue to the slides.

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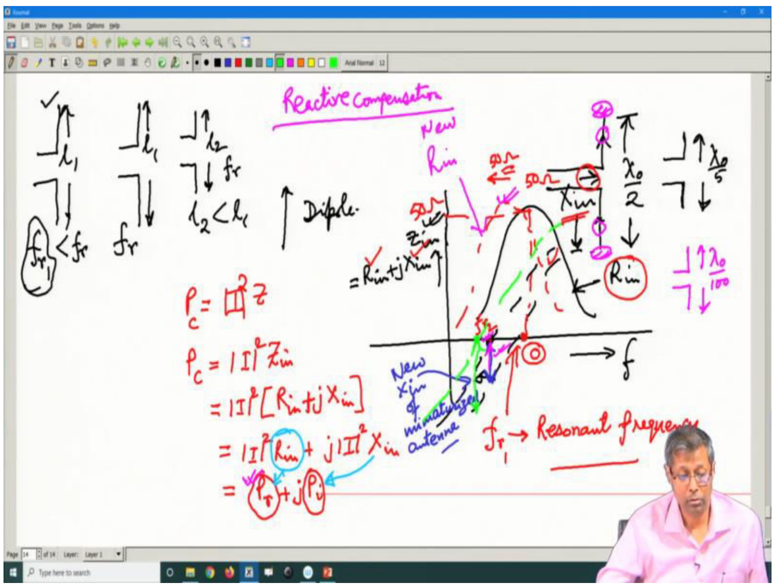

So, actually let us start from here, from where we were from where we left. So, we were seeing that the resonant frequency has to shift to the left in order for the antenna to be miniaturized, or the dipole to be miniaturized. So, this will happen if you see that this extra reactance; this is the extra reactance, which has to be compensated; because the reactance curve has to move here. So, this is my new reactance curve; new Xin curve of the miniaturized antenna. This is the new Xin of the miniaturized antenna.

So, in this curve, my this amount of capacitance, which is indicated in blue must be compensated. If I can compensate this, then I can bring the reactance curve here. And then I will have there will be issue of behind this resistance curve as well; which is also going to shift here. So, we will have established a new resonance, which where we will have the maximum power radiated here, by the new Rin curve.

So, the maximum power will be radiated here corresponding to this resonance. So, at this point the Rin is peaking the new Rin is peaking; it has it is achieving its highest value. Its physical significance is that the Pr is getting maximized, Pr is getting maximized. And at the same time the imaginary part is crossing the 0-axis, which is achieving the; which is what resonance means; so, that the reactance curve is crossing the 0-axis. So, this can be achieved by compensating this amount of reactive load.

So, we achieved we call this exactly by the term; we call it reactive compensation, we call this reactive compensation. So, we can achieve reactive compensation by adding an inductive load; so that this capacitance is miniature. So, this capacitance is nullified; we can do that by various kinds of loading schemes. Like for example top loading scheme, we a top loaded element; or loading by means of loops, a loop here a loop there.

So, why we I perform different kinds of mechanisms in order to my fundamental goal is to reduce this or to nullify, or to compensate this capacitance by an equivalent inductance. By that token my resonance frequency is going to shift to the left; the antenna is going to resonate at a lower resonance frequency; and thereby miniaturization is going to be achieved. Hope this is clear to you.

Now, let me ask you a second question, and that is let us say I want to miniaturize this antenna by not lambda 0 by 5. Let us try to make it lambda 0 by 100. The dipole size is lambda 0 by 100; it is a very very tiny dipole. And yet I want to make it resonate. I yet want to extract power out of it, and want to make it radiate. So, by extending this concept, you will appreciate that as I try to shift my resonance frequency further; and further to the left side. I will encounter larger and larger values of the capacitance in which I have to compensate.

Because the more I shift to the left hand side, the more I shift to the left hand side. I have a larger amount of capacitance in this case; this amount of capacitance which has to be nullified. So, the more I want to miniaturize, the larger this value of capacitance. A point will come where you will not be able to get a suitable inductive load; because the necessary inductance in order to compensate the capacitance will be very very high. How will you get that inductive load such a large inductance? So, one method by which this was solved was using novel materials. And what is this?

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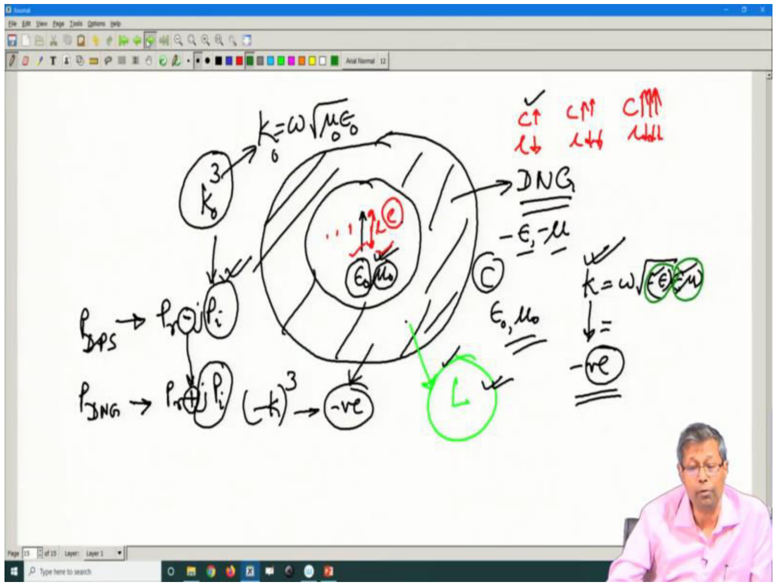

If I have a dipole which is radiating in a medium; let us say free space $\varepsilon_o \ \ \mu_o$. And I surrounded by another shell, it is called what we call a spherical shell; it is called double negative material. So, its epsilon and mu are minus epsilon and minus mu. Now, we will not go to the details of how such medium is fabricated; because that is going to take us into the domain of Meta material. But, my entire objective is to tell you how the media parameters are important in electromagnetics. What kind of role they play and suppose this is $\varepsilon_o \ \ \mu_o$.

Now, it so happens it so happens that the reactive part of the power radiated in a double positive medium, which is free space. This is double positive medium because both epsilon and mu are of positive sign; so this is a double positive medium. So, the reactive power, so power real plus j power imaginary. So, this part of the power is capacitive; it is capacitive for a small dipole. And it is dependent on an odd power of K; it is dependent on K cube, where K is given by omega root mu epsilon. It is dependent on k_o^3, where k0 is equal to omega 0 mu epsilon 0. It is dependent on the odd power of K.

Similarly, therefore the power radiated in a double negative medium, where epsilon and mu are both negative. Then, K will be equal to omega root of minus epsilon minus mu. So, it will be the sign will be, the sign of this K will be negative. We will not go to this argument as to why these two signs will not annihilate each other, and give me a positive sign. Again there is a lengthy argument in the meta material that such a thing cannot be done; and it leads to non-casual behavior and instead we must use both the negative signs.

And pull out the negative sign out of the square root to give me a net negative sign; which means that the sign of K will be negative. And if the sign of K is negative, then this k_o^3 becomes negative. Because minus K to the, it will become $-k_o^3$, which is a negative quantity inside the double negative medium. So, if the power radiator changes sign; the reactive part of the power radiator changes sign. That means the sign of the reactance seen by this dipole has changed; as we saw in the last slide. We saw in the last slide that the sign, if this sign of this Xin changes, then the imaginary part of Pc will change.

If the imaginary part of Pc changing means the sign of Xin has changed. So, therefore what I did achieve was that the Xin for this capacitance; the for this dipole radiating in this medium, which is free space is capacitive. That means as you miniaturize this antenna, this dipole as you make it smaller and smaller and smaller. It is seeing a progressively higher and the higher and even a higher capacitance. As you make this dipole antenna as you make this length smaller and smaller and smaller. The dipole is seeing free space as a progressively higher and higher capacitance.

In order to counteract this phenomenon, I cannot bring in a huge inductance to match beyond a particular level. So, what I have to do or what I would do is to achieve have of establish a medium or surround it with a medium. We call that a double negative medium that will give me an inductive load. So, this medium gives me an effective L; it gives me an effective L.

There is a small error here; this sign here should be, this sign should be negative. We are starting with I mean conceptually we are, it will be just the opposite sign. So, we are starting with a negative sign, because I told you that initially the dipole is looking at a capacitive load. So, capacitive load means that this radiated power is capacitive in nature and it is an odd function of K; so then and that is also reflected by this slide.

You see the radiated power, it is capacitive in nature as you miniaturize the as you try to make this dipole smaller, the reactance becomes more capacitive. So, as you when you enter the double negative medium; the sign of K changes and this becomes inductive or positive. But, the essential thing is that this there is a change in sign of this to the positive sign. So, while this achieves a capacitance this will achieve an inductance. And the capacitance of this medium, the capacitance of this medium, the capacitance of this medium; they will be compensated by the inductance of this.

Now, you see who is contributing to this inductance, this (con) the; it is contributed by these two essentially these two quantities epsilon and mu, minus epsilon minus mu. So, you see now the emphasis on materials in order to miniaturize an antenna. So, you see microwave research and material research go hand in hand together. This is the this is one of the areas in which we find; that this is one of the examples in which we find how the medium parameters are tailored to achieve miniaturization. The same thing can be demonstrated in a planar environment in order to elucidate the concept further.

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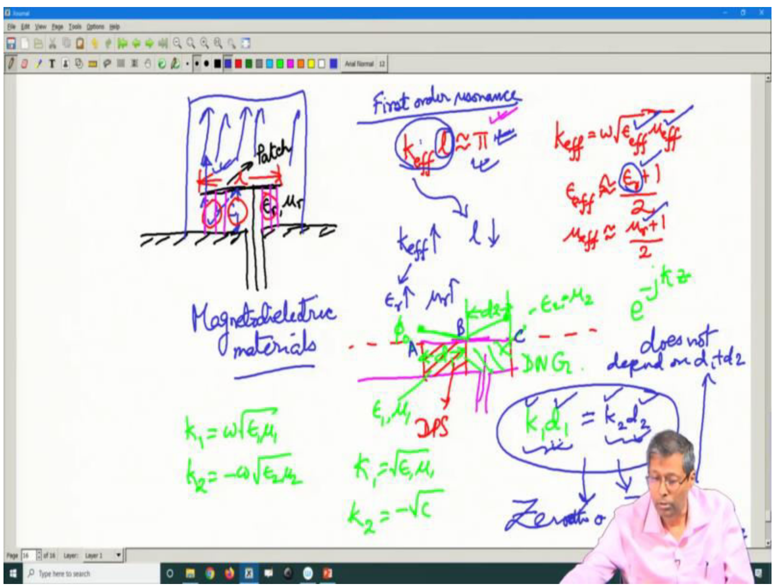

So, consider a patch antenna being fed by a probe. So, this is a substrate having permittivity epsilon r and permeability mu r, this is the ground plane; and this is a conducting patch, this is a conducting patch. So, you say now the length of this patch if it is l k effective times l will approximately be equal to Pi; where K effective is omega root epsilon effective mu effective. And to a rough average epsilon effective will be equal to epsilon r plus 1, approximately equal to by 2, and so is mu effective.

So, we see that as you enhance K effective, as this is enhanced as K effective is enhanced l is reduced by this relationship, to establish the first order resonance condition. So, this is the first order resonance. So, as you increase K effective l is reduced that means as you enhance epsilon r or mu r, l is reduced. That means as you increase the permittivity or permeability here, the l will be reduced. But, how far will you increase the permittivity; therefore if you want to miniaturize the antenna, your basic goal is to enhance epsilon or mu.

But, the question is if you want to miniaturize this antenna a lot by a large extent, just like the dipole antenna we measured. We investigated before what are going to do. You cannot enhance epsilon and mu to be a large value because large permittivity substrates are also very brittle; and they will also enhance the quality factor of the design. They will reduce pull down the efficiency, because as we increase epsilon r; the stored energy here is going to enhance. And this increase in stored energy is going to enhance the quality factor of the antenna.

So, as you try to miniaturize the antenna, the quality factor of the antenna is going to increase. So, one way in order to see this kind of a design is to additionally use; see this in additionally appreciate this relationship. Additional to that we have to see that how this antenna radiates. For this antenna you will see you will you have to first look at the microstrip patch in the phenomenon, that the microstrip patch is inherently a bad radiator.

Why is it a bad radiator? Because it is inherently a capacitance; there is a capacitance form between two metal plates. A capacitor does not radiate, it tends to store energy; so as you try to make the microstrip patch smaller and smaller in size. This capacitive effect will dominate and will pull down your radiation efficiency. How to counter or how to fight against this?

The way to fight against this is to see how the energy is being how the energy is radiated to free space. For that we model the microstrip line this part of the circuit as a transmission line; so that the waves are going from here to here and then going there. So, in addition to seeing that the resonance frequency is reduced, as the resonance frequency is reduced; we have to basically see that the radiator become the microstrip patch remains a good radiator. And therefore, we have to see a matching condition between this transmission line and that transmission line.

So, this matching condition between this or the the impedance of this part of the transmission line; and the impedance of this part of the transmission line. If they are matched that will yield another relationship in addition to this, which is going to enable design of a reduced size microstrip patch with an acceptable q factor. Easy thing to say in the blackboard, but a difficult thing to achieve in reality. So, here is there is also this brings us into like into picture; the effect of what we call magnetodielectric materials.

Magnetodielectric materials where we tailor our both epsilon and mu; both epsilon and mu in order to achieve miniaturization and in order also to make the antenna, an efficient radiator. So, this is an example again of a situation in which the epsilon and mu, effective epsilon and mu of a medium is tailored. It can be tailored or it can be modified by means of inclusions, or any other means. By loading in order to achieve the particular value that will enable miniaturization of the antenna; and establish or or gain a decent q factor.

So, these are examples of as I said this can be achieved by loading this material with loops; so, that the mu is emphasized. Or, loading these with wires; it can be wires so that it will enhance epsilon. So, periodic loading with wires or periodic loading with loops in the host substrate would enhance epsilon and mu and lead to the achievement of our reduced resonance frequency and a decent q factor.

But, it must be remembered that many important things are there, or many important conditions are there regarding this loading; because this loading has to be achieved. The inclusion size must be very small compared to the wavelength; because we do not want to achieve scattering, we want to achieve an effective medium characteristics. So, that the dimensions of the inclusions must be electrically small with respect to wavelength; only then it will be achieved.

You consider a third example. As we said that this is the establishment of the first resonance in a microstrip patch. We also dealt with the concept of our double negative material; so, if I imagine that the same microstrip patch now a probe coupled patch. It is partially filled with; so this is your substrate. So, it is partially filled with a double positive medium on the left, and a double negative medium on the right. So, from this point if the phase of the wave is phi 0; so in a double positive medium, there is a phase decay as the wave goes forward.

Because it is e^{-jkz}, and in the double negative medium there is a phase gain as the wave goes forward. Because the double negative medium, the physics is, the phase and the energy vector they are oppositely directed. So, there is a phase gain in the direction of propagation. So, in this phase decay and if the phase gain are exactly the same. So, if I say that this is this distance is d1, and it is better to draw here; this distance is d2 this distance is d2.

Therefore, the phase loss the phase, the reduction in phase from this point to this point is k1d1; where, if the permittivity is epsilon 1 and the permeability is mu 1. And the permeability here is minus epsilon 2 mu 2, minus epsilon 2 minus mu 2. So, k1 is given by root of epsilon 1 mu 1, and k2 will be given by minus root of; k1 is given by k1 is given by omega root of epsilon 1 mu 1; and k2 is given by minus omega root of epsilon 2 mu 2.

So, k1 d1 is the phase reduction in phase from point A to point from point A to point B. And k2d2 is the phase gain from point B to point C. If the phase loss k1d1 is the same as the phase gain k2d2, if this is the same, we have achieved a resonance called a zeroth order resonance; we have achieved a resonance called a zeroth order resonance. You see the first order resonance is controlled by the physical length l; the zeroth order resonance does not depend on d1 plus d2. It does not depend on d1 plus d2; it instead depends on the ratio between d1 and d2.

Then that means that we can achieve a resonance by choosing particular values of k1 and k2, which satisfies this relationship; and have a resonance establish a resonance in an arbitrarily small sized patch. Now, there are a lot of questions as to what this what is q factor will be and those things. But, this is our type of resonance in which there is ongoing research, which is called the zeroth order resonance. And this is again characterized by tailoring the media parameters.

So, in a nutshell we see that the establishment of the resonances have a very important dependence on the media parameters in many cases. And we can tailor the media parameters in order to surpass traditional limits in miniaturization. It is not a difficult thing to miniaturize an antenna; but it is difficult to miniaturize an antenna and maintain appreciably low quality factor that is the difficult thing. In order to miniaturize the (reso) reduce the resonant frequency and to maintain its efficiency.

There is a much more difficult that is a much more difficult thing than shear miniaturization; which by itself will carry little value, if the efficiency is not adequate. So, all these exemplify or all this demonstrate how the media parameters play a vital role, in order to solve this traditional problem of reduction in efficiency due to miniaturization; and gaining efficiency out of a miniaturized antenna. So, you now see how the media parameters are play a vital role in electromagnetics. Let us stop here for this session; we will continue.