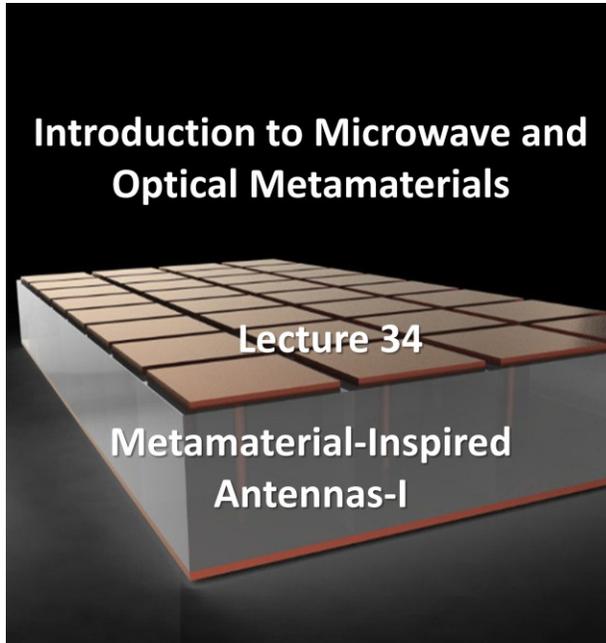


Course Name: Introduction to Microwave and Optical Metamaterials
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-7
Lecture-34

Lec 34: Metamaterial-Inspired Antennas-I



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Lecture Outline

- 2D Model of Microwave Antenna with Two Layer Metamaterial
- Antenna Miniaturization with Metamaterials



Hello everyone, welcome to Lecture 34 of the online course on Introduction to Microwave and Optical

2D Model of Microwave Antenna with Two Layer Metamaterial

- In the previous lecture, we discussed **one-layer** wire composite substrate with a magnetic superstrate
- A natural extension is to try **two layers** of non-magnetic metallic wires symmetrically embedded within the host dielectric substrate

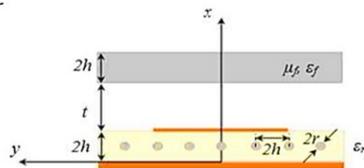


Fig. Metamaterial patch antenna with magnetic superstrate

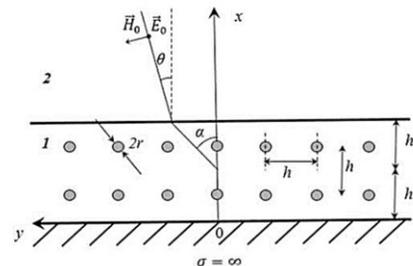


Fig. 2D geometry of rectangular patch antenna with two-layer wire composite substrate.



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

Metamaterials. In today's lecture, we will be looking into metamaterial-inspired antennas. So, this topic will take two lectures. So, that is why this is the first part. So, in this, we will first cover a 2D model of a microwave antenna with two-layer metamaterials. So, this is an extension of the one layer wire composite structure that we have seen in the previous lectures and then we will take up some topic of antenna miniaturization with metamaterials.

So, let us focus on this 2D model of a microwave antenna that has two layers of metamaterial. So, in the previous lecture, we discussed the one-layer wire composite structure mainly as a substrate for a patch antenna. And finally, we have also seen that putting a magnetic superstrate helped you know improving the antenna

2D Model of Microwave Antenna with Two Layer Metamaterial

Design	Substrate	Frequency (GHz)	Efficiency (%)	D_{max} (dB)	VPMGF (%)	
Standard (without superstrate)	Dielectric	7.307	40.72	4.6	–	From this, following conclusions can be drawn: 1. The miniaturized design outperforms the corresponding standard design 2. Incorporating ferrite superstrates significantly enhances the performance of patch antennas 3. Using composite metal-dielectric substrates enables patch antennas to operate in multi-band and multi-directional modes 4. Composite substrates with multi-layer wire grids cause a blue-shift (i.e., shift to higher frequencies) in the main resonant frequency, compared to those with one-layer wire grids
Standard (without superstrate)	One-layer wire grid	7.385	43.98	5.01	–	
Miniaturized (without superstrate)	One-layer wire grid	7.418	50.93	6.06	13.4	
Standard with superstrate	One-layer wire grid	7.322	46.1	5.92	–	
Miniaturized (with superstrate)	One-layer wire grid	7.404	54.34	6.59	13.4	
Standard (without superstrate)	Two-layer wire grid	7.518	44.82	5.26	–	

Table: Main Characteristics of Antennas

characteristics. Now, a normal extension to this work would be to try two layers of non-magnetic metallic wires which are symmetrically embedded within the host dielectric substrate and then again evaluate the antenna characteristics using the same parameters or metrics that we done for this one layer case.

So, I will not repeat those calculations again, but I will just show you that if you consider different designs like the standard antenna with a dielectric substrate and no superstrate. In that case if you compare the 3 or 4 performance metrics like the resonance frequency

Antenna Miniaturization with Metamaterials

- What is ESA? - Electrically Small Antennas (ESAs) are small, low-profile antennas ideal for mobile, wearable, airborne, and IoT devices.
- What counts as “small”? $k\alpha < 1$ (or $k\alpha < 0.5$ without a ground)
 - α = radius of the smallest sphere enclosing the antenna
 - k = wave vector at operating frequency ($k = 2\pi/\lambda$)
- Core challenge: Although ESAs fulfill the need of compact transceivers, miniaturization often reduces radiation efficiency (η) and bandwidth.
- Traditional miniaturization (limitations): Lumped elements, shorting pins, or high- ϵ_r ceramics can degrade radiation characteristics.
- Metamaterial approach: Introduced to overcome these limits and enhance radiation properties while keeping size small.



IIT Guwahati



Source: Milius, C. et al., “Metamaterial-inspired antennas: A review of the state of the art and future design challenges,” *IEEE Access*, vol. 9, pp. 89846–89865, Jun. 2021

efficiency the maximum directivity ok and the percentage gain ok you can actually see that your standard antenna the resonance frequency is around 7.3, efficiency is 40.72 and D max is around 4.6 dB.

If you replace the dielectric substrate with a one layer wire grid it is not exactly replacing you can say if you put a one layer wire grid structure into the dielectric substrate that basically increases the frequency little bit, but on the other hand also increases the efficiency and the directivity right. So, that is a good improvement. Now, if you go for a miniaturized antenna with the same one layer wire grid, but without any super straight you see the frequency gets further increased efficiency also increases as you can see here along with the directivity. So, that is a that is a positive move. Right.

And then if you try to introduce super straight on this standard or like this one here, if you have one layer gate structure, but the standard antenna. And then you introduce the super straight; you will see you can actually compare these two. So, the frequency slightly reduces the gain or efficiency slightly increases same for the directivity right. And if you try the same thing on the miniaturized antenna with super straight, you can see the frequency is around 7.

4. The efficiency further improves. So, that is a good thing; you can compare this to this, and then finally, you can get the maximum directivity, which is 6.59 dB, right? So, those are all the cases that we have done for one-layer grid. Now, I am not showing the results, but you can show the parameters that we obtained for a two-layer wire grid structure. You can see that the frequency is around 7.

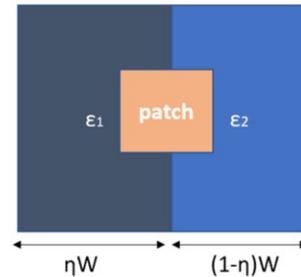
518, okay. So, the frequency slightly increases; this is for the standard antenna without any superstrate. So, you can actually compare this one okay along with this one; that is why they are painted the same color, okay. So, what you see that you know from 1 layer to 2 layer there is not

too much increase in the efficiency nor in the directivity. So, what you can conclude is that adding multiple layers of this kind of wire array.

The composite substrate does not really provide much significant improvement in the antenna

Antenna Miniaturization with Metamaterials

- An interesting theoretical investigation regarding miniaturization of patch antennas using metamaterial was presented by Alu *et al.*
- They used metamaterials to approach the fundamental limits of electrically small antennas (size vs. performance).
- Earlier studies largely minimized patch size for a certain resonant mode but ignored radiation quality.
- In other words, they explored the characteristics and the placement of metamaterial loadings not only for shrinking the antenna's dimensions but also for achieving good radiation properties.
- They considered the rectangular patch (shown in the figure), which is filled with two different materials, and evaluated the resonant frequencies by applying a standard cavity model.



characteristics, right? So, if you carefully look into this table, these are the conclusions that can be drawn. So, you can see that the miniaturized Antenna basically outperforms the standard design and when you put a superstrate that is going to significantly enhance the performance of the patch antennas. So, including a superstrate is a good thing. And again, using composite metal dielectric substrates basically enables patch antennas to operate in multiband and multidirectional modes. And what you have seen that when you have composite substrates with multiple layer wire grids like this you will experience a blue shift that means the resonance frequency will shift towards higher frequencies okay compared to that from the one layer grid.

Once again, if you see the amount of improvement that you are making, it is too little to justify this extra effort. So, we will not proceed in this direction further to increase the number of layer grids of wear to improve the antenna performance. So, now let us look into other aspects, such as antenna miniaturization with the help of metamaterials. So, in this topic, you first understand what ESA is, okay? These are electrically small antennas. These are basically small, low-profile antennas that are ideal for mobile, wearable, airborne, or IoT devices.

Now, what counts as small? So, you have to understand that the $k a$ should be less than 1. And if you are having no ground, without a ground you should have $k a$ less than 0.5. Now, what is a ? a is basically the radius of the smallest sphere enclosing the antenna, and k is basically the wave vector at that operating frequency. So, you can obtain k from this relation: 2π by λ .

Now, what is the core challenge here is that you know although ESS the electrically small antennas can fulfill the need of compact transceivers. Okay,

Antenna Miniaturization with Metamaterials

- It consists of a metallic patch with dimensions ($L \times W$) placed over a ground plane (distance h).
- The underneath substrate is inhomogeneous, filled with two isotropic and homogeneous materials with permittivity and permeability $\epsilon_1(\omega)$, $\mu_1(\omega)$ and $\epsilon_2(\omega)$, $\mu_2(\omega)$.
- The quantity η represents the filling ratio of volume underneath the patch.
- It was shown that arbitrary low resonant frequencies can be obtained independently from the patch dimensions when the permittivities of the two materials have **opposite** signs.
- Extension to circular patches: Properly engineered underlayer materials can support efficient radiating modes similar to regular patches at smaller sizes.
- Takeaway:** Metamaterial loading (using opposite-sign permittivity pairs) provides a path to substantially smaller patches without sacrificing radiation performance.

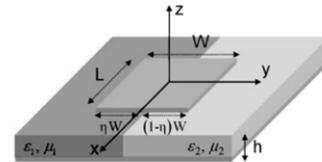


Fig. A rectangular patch antenna loaded with inhomogeneous substrate

Antenna Miniaturization with Metamaterials

- Another interesting approach for antenna miniaturization arises from the metamaterial transmission line (TL) approach.
- The dispersion curve of this TL (see Figure) illustrates- there is a frequency window where the propagation constant is negative, purely Left-handed (LH) and another one where the propagation is purely Right-handed (RH).
- A CRLH (Composite Right/Left-Handed) structure combines right-handed (RH) and left-handed (LH) propagation characteristics in a single medium.
- A bandgap separates these two regions
- The bandgap can be eliminated and that case is referred as the balanced case, since it provides a smooth transition between the LH and RH regions.
- The propagation constant (β) is zero at the transition frequency (ω_0) and thus, the guided wavelength ($\lambda_g = 2\pi/\beta$) becomes infinite.

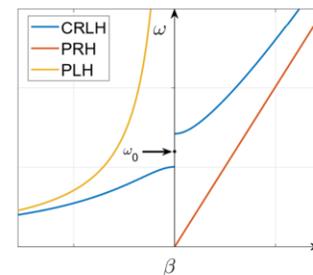


Fig. Dispersion diagrams of a CRLH TL, a purely Left-handed (PLH) TL and a purely Right-handed (PRH) TL

miniaturization often reduces the radiation efficiency and the bandwidth. So, normally when you do miniaturization the limitations such as you know come it comes from the lumped elements, shorting pins or high permittivity ceramics all these things can degrade the radiation characteristics. So, if you use a metamaterial approach, they basically allow you to overcome these limits and enhance the radiation properties while still maintaining a very small size. And

that is why people study antenna miniaturization using metamaterials.

Now this particular reference paper as you can see here it is in IEEE axis, it is a review of the state of the art and the future design challenges of metamaterial inspired antennas. So, from there we will discuss a couple of interesting designs today. So, the first one is an interesting theoretical investigation regarding miniaturization of patch antennas using metamaterials which was presented by Alou et al their group. So, they basically used metamaterials to approach the fundamental limits of electrically small antennas. So, that allows you to, you know, see the performance versus size issue.

So, earlier studies largely minimize the patch size for a certain resonant mode. But they ignored the radiation quality. So, in other words you can say that they basically explored the characteristics and the placement of metamaterial loadings Okay, not only for shrinking the antennas dimensions, but also for achieving good radiation properties. So, this is what Alu et al. or their group has done.

that their objective here is not only to you know shrink the antenna dimensions, but to also ensure that the radiation pattern or the radiation properties remain good which was not done in the earlier studies ok. So, they basically considered a rectangular patch which is shown here and they filled the bottom plane with two different materials and evaluated the resonance frequencies. By applying a standard cavity model. So, here you can see that one part has a refractive index of ϵ_1 , and the other one has ϵ_2 , okay. So, this is the total width.

So, η is basically the fraction that is covered by material ϵ_1 and then $1 - \eta$ will be the fraction * w will be the fraction that is covered by this basically the width $1 - \eta$ is the fraction ok. So, this is a 3D perspective view that gives you a better understanding of how things are done. So, this is a rectangular patch antenna that is loaded with an inhomogeneous substrate. So, here you consider a metallic patch that is having a dimension length L and width W that is placed / a ground plane okay that you see here at the bottom and the height is this or it is given as distance h . Now, the underneath substrate that you see here is basically inhomogeneous because it is filled with two different isotropic and homogeneous material which has got permittivity and permeability $\epsilon_1 \mu_1$ and the other one has got ϵ_2 and μ_2 .

So, this could also be, you know, dispersive. So, they are all functions of ω . Now, η is basically the filling fraction of the volume under the patch. So, ηw is basically this width, and $1 - \eta w$ is basically this width, right? So, it is shown that you know arbitrary low resonance frequencies can be obtained independently from the patch dimension when the permittivities of the two materials will have opposite sign right. So, that is main finding / here is that if you choose this two material permittivities to have opposite sign the effective permittivity will be very less and that will allow you very low resonant frequencies right.

You can also extend this to circular patches. So, if you properly engineer the underlayer materials, which can support efficient radiating modes similar to regular patches at a smaller size. So, you can also opt for circular patches. So, what do you take away from this particular exercise

that you know the metamaterial loading that can be done using two opposite sign permittivity pairs basically provides a path to substantially you know smaller patches without sacrificing the radiation pattern or radiation performance. So that basically tells us how you can minimize the antenna size while maintaining the radiation pattern.

Now, another interesting approach to antenna

Antenna Miniaturization with Metamaterials

- This transition occurs at the frequency:

$$\omega_0 = \sqrt[4]{\frac{1}{C_R L_R C_L L_L}}$$

- It is important to note that the propagation behavior of a CRLH TL is not purely LH in the LH regime or purely RH in the RH regime.
- This is also illustrated in the figure, where there is a clear discrepancy between the curves of a PLH and a CRLH operating at the LH regime and the same applies for the RH regime.

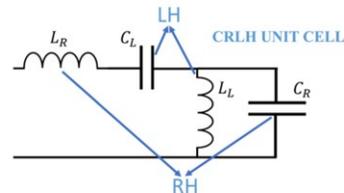
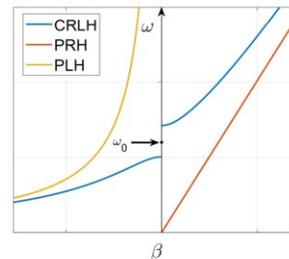


Fig. Unit cell of a CRLH TL consisting of series inductor and shunt capacitor (RH) and series capacitor and shunt inductor (LH).



Antenna Miniaturization with Metamaterials

- An example of a practical implementation based on distributed elements is depicted in figure, where a microstrip line is periodically loaded with interdigital capacitors (series capacitance C_L) and grounded stubs (shunt inductance L_L).
- So, a balanced CRLH TL, with no bandgap between LH and RH regions, has infinite guided wavelength ($\lambda_g = \infty$) at ω_0 since $\beta(\omega_0) = 0$.
- This can be translated into an arbitrary antenna size since the resonance frequency is independent of the physical volume and depends only on the LC values of the unit cell.
- Consequently, a significant size reduction can be achieved.
- This type of antennas are referred as zeroth-order resonators (ZOR), where the name originates from conventional TL mode numbering.

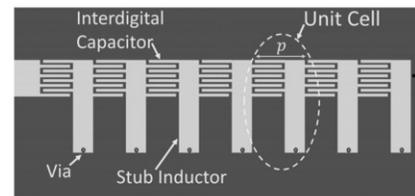


Fig. Practical implementation of CRLH TL with unit cells consisting of interdigital capacitors and stub grounded inductors

miniaturization arises from the

Antenna Miniaturization with Metamaterials

- This method was used by Sanada *et al.*, where 61% size reduction (in comparison to a conventional resonator) was accomplished by utilizing the cascaded unit cells of the figure (bottom left).
- Similarly, an antenna with a length of $\lambda/6$ was proposed by them as shown in the figure (bottom right).
- Here, meander-line inductors were introduced for the realization of the shunt inductance.

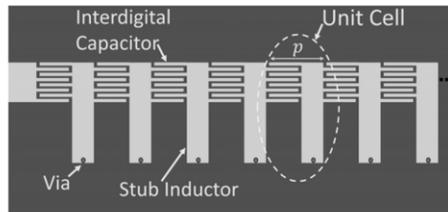


Fig. Practical implementation of CRLH TL with unit cells consisting of interdigital capacitors and stub grounded inductors

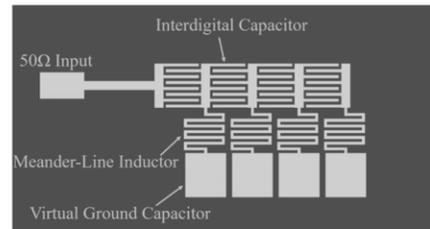


Fig. The planar miniaturized ZOR antenna. Light grey depicts metallization

metamaterial transmission line approach. So here you can see the dispersion curve for this transmission line. which illustrates that there is a frequency window where the propagation constant that is β is basically negative okay. So, that is true for purely left-handed ones like this, okay, and on the other one. Where the propagation is purely right-handed.

So, here you can actually see the dispersion curves of a composite right left handed structure that basically combines right handed which is RH and left handed that is LH propagation characteristics in the same medium. Right. So what you see here is that a band gap basically separates the two region and this band gap can be eliminated and that case can be referred to as the balanced case since it will basically provide a more smooth transition. Or you can say it provides a smooth transition between the left hand and the right hand regions okay. So, here the propagation constant is basically 0 at the transmission or transition frequency of ω naught.

And therefore, the guided wavelength, which is obtained as $\lambda_g = 2\pi / \beta$, because β is 0. So, this guided wavelength becomes infinite, okay. So, this basically this transition occurs at a frequency ω naught which is given as the fourth power of $1 / C_r L_r C_l L_l$. So, these are nothing but coming from this unit cell diagram of this composite right left handed transmission line model okay. That basically consists of series inductors and shunt capacitors, and you also have shunt capacitors and shunt inductors, okay, like this.

And this two basically represent LR and CR this is for the right-handed one and this is for CL and LL they are for the left-handed ones right. So, it is important here to note that the propagation behavior of a ah this kind of composite right left hand transmission line is not purely LH even in the left hand regime and it is not purely RH in the right hand regime right. So, this can be also illustrated in this particular figure where you can see there is a clear discrepancy between the curves of a PLH ok that you see here. And you see the curve of this composite that is in the blue region. So, they are not overlapping, and the same thing happens here as well.

So, you can understand that these are not purely left-hand or right-hand kinds of propagation, right? You can take the example of a practical implementation that is based on distributed elements. which is shown here in this figure where you have a microstrip line ok this ones ok that is periodically loaded with inter digital capacitors which basically have series capacitance C_I okay and then you have this grounded stubs okay. So, they basically give you shunt inductance, which can be considered as L_L , right? So, this is a practical implementation of this composite right- and left-handed transmission line structure. So, this is the unit cell that is shown here; the periodicity is P . And this basically consists of inter-digital capacitors and stub-grounded inductors, right? So, what you see here is that balanced CRLH transmission line will have no band gap between L_h and R_h regions ok and that will have infinite guided wavelength because β is 0.

So, you can have $\lambda_g = \text{infinity}$ at that ω_{naught} frequency, right? Because your β at ω_{naught} is basically 0. So, this can be translated into an arbitrary antenna size since the resonance frequency is basically independent of the physical volume and it only depends on the LC values of this unit cell. So, what happens because of that you know a significant size reduction can be achieved. And this type of antennas are basically referred to as zeroth order resonator or ZOR where this name is basically originating from the conventional transmission line mode numbering right. So, this method was basically used by Sanada and his team.

So, that is again from this paper where they achieved 61 percent size reduction as compared to conventional resonators and that was accomplished by utilizing this kind of cascaded unit cells ok. So, this is the unit cell that is periodically repeated. Similarly, here you can see an antenna with a length of λ by 6 that was proposed by them. So, same similar concept was used inter digital capacitors, then you have some minder line and then finally, you have some virtual ground capacitors and this is where you put the 50 ohm input. So, this is a planar,

Antenna Miniaturization with Metamaterials

- As far as practical designs of metaresonator small antennas, several miniaturized monopole variations were presented by Ntaikos *et al.* (Figure)
- They simulated a single SRR unit cell, tuned its geometric parameters to achieve resonance in desired band and then placed it in the proximity of monopoles with lengths of $\lambda/10 - \lambda/14$.
- Due to the magnetic coupling between the SRR and the monopoles, the frequency of the composite antennas was shifted towards the SRR's resonance (2.4GHz), while the initial monopole resonance (5.8GHz) was also maintained.

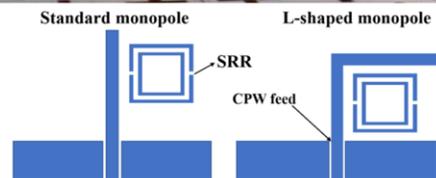


Fig. Miniaturized SRR-based monopole antennas

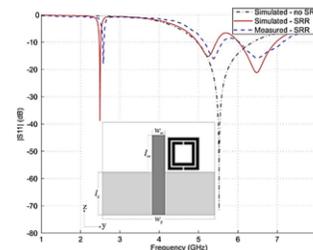


Fig. Simulated and measured results for the microstrip straight monopole

miniaturized ZOR antenna.

So, these are basically the metal parts that are shown in the light grey color, the same here as well. So, these meander line inductors were basically introduced for the realization of the shunt inductance, right? So, that was replaced by these meandering lines. Now, as far as practical designs of meta-resonator-based small antennas go. are concerned ah several miniaturized monopole variations were basically presented by ah Tycos and his group ok. And these are some miniaturized spectrum resonator-based monopole antennas.

So, this is a standard monopole; this is the SRR that is shown here. So, this is basically a

Antenna Miniaturization with Metamaterials

- The negative permeability of the single resonator cell cannot be regarded as the main cause of the miniaturization, since more unit cells are required to form an effective medium that has a macroscopical impact.
- Therefore, the miniaturization is attributed to the subwavelength resonant nature of the SRR
- Moreover, the efficiency and bandwidth of the antennas were acceptable and varied between 0.24 – 0.48 and 30MHz–127MHz (at 2.4GHz) respectively.
- Dong *et al.* proposed two complementary split-ring resonators (CSRRs) and reactive impedance surface (RIS) as illustrated in the figure.
- They noted that while the CSRR is a high-Q subwavelength resonator, it radiates poorly due to fields radiated by its slots cancel each other out in the far field thus leads to poor efficiency.

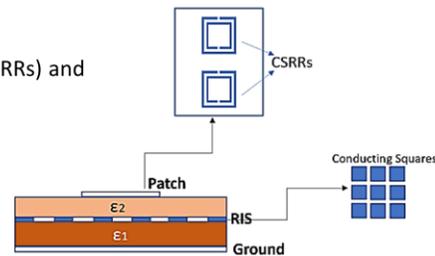


Fig. Small patch antenna with two CSRRs on patch and a RIS underneath

complementary structure, okay. And then you also have an L-shaped monopole, and this will get a CPW feed, right? So, they basically simulated this kind of single SRR unit cell and then tuned its geometric parameters to achieve resonance in the desired band and then placed it in the proximity of monopoles with lengths λ by 10 to λ by 14 ok. So, that is the length. Now, due to magnetic coupling between the SRR and the monopoles what will happen the frequency of the composite antennas basically get shifted towards the SRRs resonance that is around 2.

4 gigahertz while the initial monopole resonance which is around 5.8 gigahertz remains maintained ok. So, this is basically a graph that shows the S_{11} parameter as a function of frequency, this has got simulation as well as measured data. So, the simulation is basically the solid line, okay.

So, here you can see you have this 2.4 gigahertz and also 5.8 gigahertz somewhere here, okay. Now, there are two simulations done there is another simulated curve that is with this one the dash dot dash dot that you see here. So, that is what happens when there is no SRR.

So only the monopole is present. So, that is around 5.5 here.

Okay, and this is more or less close to 2.4, 2.5. But when you see the measured one, that is basically the dashed curve. So, that is basically matching the one with your simulated SRR, right? So, that is basically this solid curve, right? So, you can basically predict the performance of this antenna very well with the help of simulations. Now, what is the cause of this

Antenna Miniaturization with Metamaterials

- Therefore, they considered the coupling between the CSRRs (resonant cells with poor radiation) and the patch (non-resonant at the desired frequency but with good radiation) as the key for miniaturization.
- In addition, the RIS stores the magnetic energy and increases the inductance of the antenna, thus used to miniaturize the size of a patch type antenna.
- But resonance frequency also decreases as inductance value increases
- By adding RIS, the resonance frequency has been moved down to 2.4 GHz as compared to 2.75 GHz for without case.
- The patch size is around $0.099\lambda \times 0.153\lambda$, which is very compact (as seen from figure)
- The sizes of the RIS and ground are $0.22\lambda \times 0.22\lambda$ and $0.272\lambda \times 0.272\lambda$, respectively.

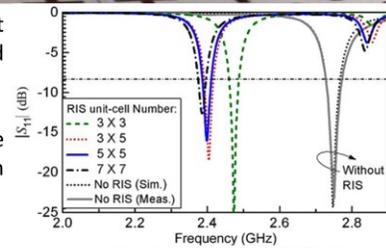
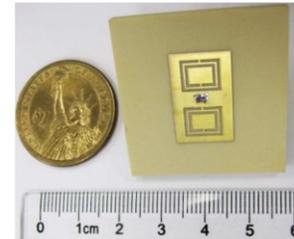


Fig. A comparison of $|S_{11}|$ for the proposed antenna



Antenna Miniaturization with Metamaterials

- Sharawi *et al.* designed a 2×2 MIMO antenna platform consisting of small CSRR-based patch antennas.
- This time the CSRR was etched on the ground plane and resulted in 76% size reduction and 29% efficiency.
- Highlighting miniaturization, Zhu *et al.* presented a dual-band metamaterial inspired small monopole antenna.
- The antenna was loaded with an interdigital capacitor and an inductive slot as shown in figure and has extremely small dimensions of $1/13.3\lambda_0 \times 1/21.4\lambda_0$ at 2.45GHz.
- While the unloaded monopole resonates at 5.8GHz, the metamaterial loading (T-shaped slot combined with the interdigital capacitor) forces the currents to wrap around it at 2.4GHz and results in an additional radiating mode at a lower frequency.

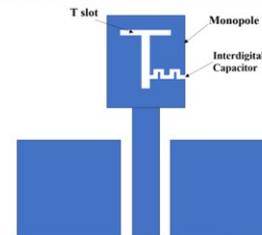
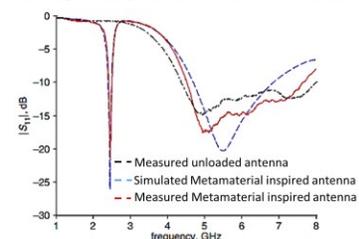


Fig. Small monopole antenna loaded with interdigital capacitor and inductive slot



miniaturization that you are achieving? First thing you can think of that the negative permeability of the single regenerative cell okay that is the SRRs, they cannot be regarded as the main cause of this miniaturization. Since more unit cells are basically required to form an effective medium that has gotten you know macroscopical impact, here only one SRR is there and that cannot be the main factor behind all this. So, therefore, the miniaturization is basically attributed to the subwavelength resonant nature of the SRRs.

Moreover, you can see that the efficiency and the bandwidth of the antennas are acceptable and vary between 0.24 and 0.48. And the bandwidth can be between 30 megahertz and 127 megahertz at this 2.

4 gigahertz center frequency. And based on that. Dong and his group proposed two complementary splitting resonators, which are these ones. So, there the structure also had complementary splitting resonators. So, they have used a reactive impedance surface that is RIS along with that, okay. So, they have a small patch antenna with two CSRRs on the patch. Okay, so this patch basically looks like this, and it has a reactive impedance surface that looks like this underneath.

So, they noted that while the complementary splitting resonator is a high quality factor subwavelength resonating structure, it radiates poorly due to the fields radiated by slots basically cancel out each other in the far field and therefore, it basically gives you poor efficiency. So, therefore, what they have done is consider the coupling between these complementary splitting resonators. that means the resonating cells with poor radiation with the patch which is non resonant at the desired frequency, but it has got a good radiation pattern right. So, this is basically the key to miniaturization here. In addition you will see the RIS basically stores the magnetic energy and hence it increases the impedance of the sorry the inductance of the antenna and thus it can be used to miniaturize the size of the patch type antenna.

But you know if you play with the inductance your resonance frequency will decrease because when the inductance increases resonance frequency decreases and that you can see here ok. So, by adding RIS the resonance frequency has been moved down to you know 2.4 as compared to 2.75 gigahertz which is for without that RIS case right.

So, this is basically the structure. So, this patch basically has a dimension of 0.099λ by 0.513λ . So, it is very compact as you can see ok and the size of the RIS and ground are basically 0.

22λ by 0.22λ this is square ok and then you have 0.272λ that is basically the ground. So, by 0.272λ , respectively. So, here you can also see the comparison of S_{11} . Versus frequency, you can see that the unit cell numbers of the RIS have basically changed here.

So, first this this curve is basically for 3 by 3, then you have 3 by 5, then you have 5 by 5, then you have 7 by 7 ok. And for reference you also have you know you have these two cases that is no RIS for simulation and the solid one is a measurement curve. So, these two basically tells you when the RIS is not there and when it is there the curves basically behave like this and you can

see that you know. With a larger number of elements, you are basically shifting towards lower frequency, right? Another design was proposed by Saravi and his team. They designed a 2×2 MIMO antenna that is a multiple input multiple output antenna platform consisting of small CSRR-based patch antennas.

And this time the CSRR was etched on the ground plane and that resulted in 76 percent size reduction with 29 percent efficiency will show you how it is ok. You can also find the details in this particular paper; it is not mentioned in the slide, though. But you can see another design here that highlights the miniaturization factor proposed by Zhu et al. and means Zhu and his group.

They presented a $\lambda/12$ -band

Antenna Miniaturization with Metamaterials

- One of the most efficient miniaturized antennas was designed by Li *et al.* as seen from the figure
- The radiating element is a rectangular patch which is fed by a standard microstrip line
- An electric-LC (ELC) structure was placed underneath the antenna and tri-band operation (2.5/3.5/5.8 GHz) was achieved (desired bands for WLAN and WiMAX applications.)
- Over 90% efficiency was achieved while the antenna's footprint was $\lambda/6 \times \lambda/10$.
- We can conclude that although metamaterial ESAs have a great potential, further investigations and designs that push the frontiers and accelerate the design process are still necessary.

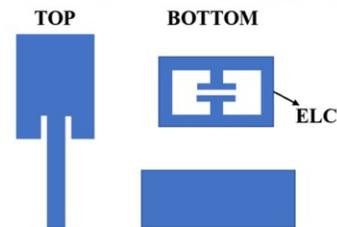
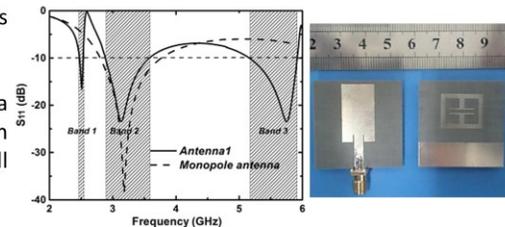


Fig. Small antenna loaded with ELC cell



metamaterial-inspired small monopole antenna. So, you can see this is the monopole and then it has got a slot T slot with some interdigital capacitor. So, this antenna was basically loaded with an inter digital capacitor and a inductive slot that you can see in the figure and it has got very small dimensions.

It is 1 by 13.3λ naught and 1 by 21.4λ naught at 2.45 gigahertz. So, you can understand that you know. This is a very small size; this is a small monopole antenna that is loaded with this capacitor and inductive slots. So, while the loaded monopole is unloaded, you can use that for comparison, okay.

So, this is the unloaded one; these dashed lines are okay. So, they do not have this dip here, as you can see, right? So, the unloaded monopole antenna basically only resonates around 5.8 gigahertz, okay. It is somewhere here; yeah, this one, it is around 5 gigahertz, okay. And when you put this metamaterial loading that means you can have this T shaped slot that is combined with this inter digital capacitor that basically forces the currents to basically wrap around it.

So, that happens around 2.4 gigahertz and that is why you start getting this dip and that is basically an additional radiating mode that you obtain at this lower frequency because of this kind of loading. Another design is shown here that was created by Lee and his group. So, this is one of the most efficient miniaturized antennas, okay. So, this is a small antenna that is loaded with an ELC cell, which is basically an electric LC structure.

So, the top looks like this, and this is the bottom. So, you have this electric LC structure that is placed underneath the antenna and is basically giving you tri-band operation. You have operations at 2.5 gigahertz, 3.5 gigahertz, and also at 5.8 gigahertz, which are band 1, band 2, and band 3, right? So, the solid line shows the antenna 1, and the dotted line shows you only the monopole antenna, right? So, that is used for comparison.

So, here is what is happening: the radiating element is basically a rectangular patch that is fed by this standard microstrip line. Now, because we have put this electric LC structure beneath the antenna, You are getting this tri-band operation, which is important for WLAN and WiMAX applications. So, this is the fabricated view of this antenna. This is the top view, and this is the bottom view of this antenna.

The gray one shows the metallic parts. Right, and this is the scale for comparison. So, you were able to obtain 90 percent efficiency for this antenna's footprint, which was typically λ by 6 by λ by 10. So, we can conclude that although this metamaterial ESS have a great potential you still require further investigations and more designs that can push the frontiers and accelerate the design process in this direction and these are still underway and it is necessary. So, with that we conclude this lecture and in the next lecture we will continue discussing more metamaterial inspired antennas and if you have got any queries regarding this lecture drop an email to this email address mentioning the course name and the Lecture number on the subject line. Thank you.



Thank You

Slides inserted by fallback (review if needed):



Thank You