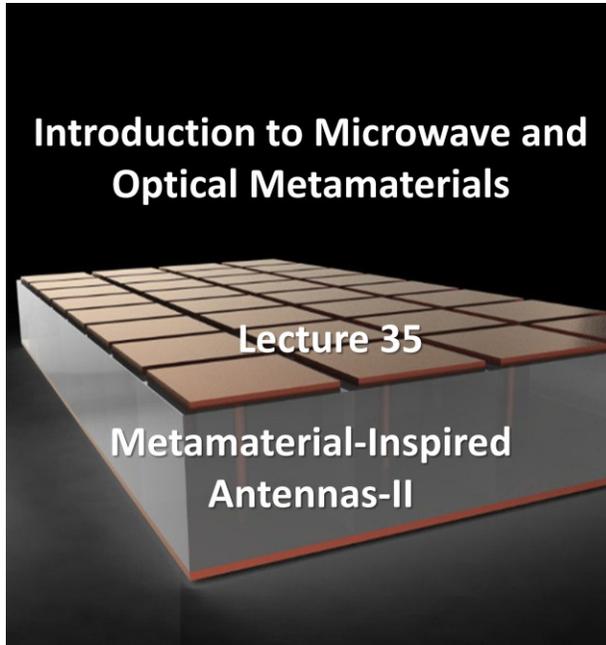**Course Name: Introduction to Microwave and Optical Metamaterials**
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-7
Lecture-35

Lec 35: Metamaterial-Inspired Antennas-II

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NPTEL ONLINE CERTIFICATION COURSE
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- Gain Enhancement using Metamaterials

- Isolation using Metamaterials

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Hello, students. Welcome to lecture 35 of the online course "Introduction to Microwave and Optical

Gain Enhancement using Metamaterials

High-Gain Antennas: Why and Implications

- Importance: Critical for fixed point-to-point links and radar systems

- Benefits of high gain:
  - Extends communication range for the same transmit power
  - More resistant to interference

- How high gain is achieved:
  - Directivity ∝ aperture size → larger electrical size ⇒ higher gain
  - Common practices are to use electrically large antennas or arrays with many radiating elements

- Size constraint: The directivity–size relation, limits small antennas for applications that require high gain

Gain Enhancement using Metamaterials

- Challenge: Ultra-compact, high-gain antenna platforms are difficult to implement

- Proposed solution: Use metamaterial radomes, superstrates, and lenses as low-cost gain enhancers
  - Form factor advantage: Increase gain without significantly increasing the antenna's volume/footprint
  - Placement: Structure is positioned above the radiating element
  - Operating principle: Modifies its far-field radiation pattern by interacting with the electromagnetic fields in the vicinity of the radiator

- Main metamaterial-based techniques that are capable of accomplishing gain enhancement:
  - Placement of ZIM (zero-index materials) or NZRI (near-zero refractive index) materials as superstrate
  - Deployment of AMC (artificial magnetic conductor) surfaces in the vicinity of the radiators
  - Placement on GRIN (Gradient Refractive Index) meta- material lenses in front of the antenna

ZIM or NZRI materials as superstrate

- NZRI materials have a refractive index n that approaches zero

- Given a metamaterial slab with $n = 0$ and according to the Snell's law, the transmitted wave will be focused perpendicularly to the medium interface regardless of the incidence angle

- In particular, Enoch *et al.* demonstrated that the radiation beam of an antenna embedded in a metamaterial will be refracted in a direction very close to the normal when the refractive index of the metamaterial medium is close to zero (seen from the figure).

- This interesting feature of transforming spherical waves into planar can be translated into a gain enhancement when such a medium is used as superstrate or enclosures an antenna.
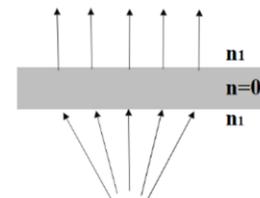

n_1

$n=0$

n_1

Fig. Transmission through a NZRI slab

Metamaterials." In today's lecture, we will be continuing our discussion on metamaterial-inspired antennas. So, we will be covering these two topics mainly we will discuss about gain enhancement using metamaterials and how we can obtain isolation using metamaterials. So let us first look into the gain enhancement of antennas using metamaterials. So as we will know that gain is one of the most important antenna characteristics, especially in fixed point to point communication and radar systems.

What are the benefits of high gain? So antennas with high gain are able to increase the communication range for a given transmitted power. And they are more resistant to interference. So, the question is how high gain is achieved? So, the first thing is that directivity of an antenna is proportional to its aperture size and thus it becomes obvious that deployment of electrically large antenna will give you higher gains, right. So, typically it is common practice to use electrically large antennas or arrays with many radiating elements to achieve higher gain.

Now, all is not good here because you cannot now keep on increasing the electrical size of the antenna because you basically have size constraint when you go for any practical application. So, that way the relation between antenna directivity and size basically prohibits the usage of small antennas for several applications where high gain is basically required. So it becomes obvious that you want an ultra-compact yet high-gain antenna platform, but these are difficult to implement. So, what is the proposed solution? So you can use metamaterial radomes,

ZIM or NZRI materials as superstrate

- More specifically, a superstrate consisting of metallic square-rings whose two corners are connected with metallic diagonal strips was proposed by Panda *et al.*

- The metallic square-rings exhibit zero permittivity at 2.6GHz and this NZRI superstrate was placed at a height of $\lambda/12$ above two microstrip patch antennas operating at the same frequency.

- The structure was fabricated and the gain of the patches was increased by 3.4dB, while the low-profile of the array was maintained.

- A layer of similar unit cells with small gaps on the rings was designed by Augustin *et al.* and according to full wave simulations, increased the gain of a planar antenna by 6.2dB
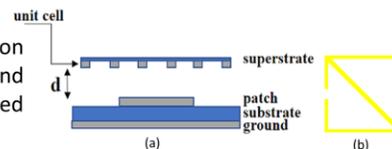
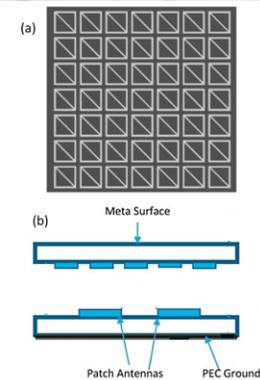**Fig.** (a) Superstrate placed above a patch antenna and (b) unit cell

Fig. (a) The NZRI metasurface and (b) Side view of antenna

superstrates, or lenses as low-cost gain enhancers. That can allow you to improve the antenna gain.

So they will have the form-factor advantage. So you can basically increase the gain without significantly increasing the antenna's size or footprint. You need to place the structure above the radiating elements, so the placement becomes crucial. And the operating principle remains that it basically modifies the fur field radiation pattern by interacting with the electromagnetic fields in the vicinity of the radiator. So, the main metamaterial-based techniques that are capable of accomplishing this kind of gain enhancement are basically these.

First is the placement of ZIM, which is zero index material, or NZRI, which is near zero refractive index material, as super straight. Then the second method will be the deployment of

AMC, which are artificial magnetic conductor surfaces, in the vicinity of the radiators. And third will be the placement of green graded refractive index

ZIM or NZRI materials as superstrate

- In parallel, Meng *et al.* proposed a combination of MSRRs (Modified Split-Ring Resonators) and small patches as a metamaterial cell that possesses zero permeability and permittivity simultaneously.

- The advantage of a superstrate synthesized by these cells is that it can be easier tuned to match to the characteristic impedance of free space.

- An H-plane horn antenna and a patch antenna were integrated with this zero-index superstrate and a 4.43dB and 6.6dB gain enhancement was observed respectively.

- By taking advantage of the same principle, a metamaterial lens of S-shaped cells with metal strips was designed and fabricated by Suthar *et al.*

- The placement of a single lens over a WLAN patch antenna resulted in a 2.05dB increase in gain, while additional 0.6dB enhancement was reported with a double lens.
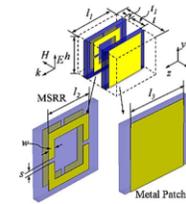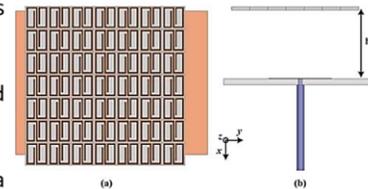
Fig. Structure of ZIM unit cell

Fig. The schematic diagram of proposed antenna: (a) Top view and (b) Side view

metamaterial lenses in front of the camera. So, we will basically look into each of these categories in a little detail to understand how they work. So, first let us consider zero-index material or near-zero refractive index material as super straight.

So, near-zero refractive index material has a refractive index that is close to zero; that is obvious from the name itself, right? Now, given a metamaterial slab which has got a refractive index close to 0, according to Snell's law you understand that the transmitted wave in this case will be focused perpendicularly to the medium interface regardless of the incident angle right. So, something like this. So, you have any incident angle, but if you have a material that has got a_0 refractive index the transmitted wave will come out in normal to this particular angle. So, particularly Anok and his group demonstrated that the radiation beam of an antenna which is embedded in a metamaterial will be refracted in a direction that is very close to normal. When the refractive index of the metamaterial medium is very close to 0, that is what has been shown here.

Now, this interesting feature of transforming spherical waves into planar waves can be translated into a gain enhancement when such a medium is basically used as a super straight or it can be used as an enclosure for an antenna. So, some examples are here. So, you can think of a super straight which is consisting of this kind of metallic square rings whose two corners are basically connected with a metallic diagonal strip. So, this design was proposed by Panda and his team. So, as I mentioned all these different designs are described in this review article that you see in the reference you can go to this review article to read about more there you will get the reference of all these papers individual papers and you can go into the details of individual design and see how they have made it.

So, I will just give you a brief overview of what they have done. So, this is basically the near-zero refractive index

- Furthermore, three layers of ELC (Electric Field Coupled) resonators were utilized as a radome of a patch antenna by Li *et al.* and the realized gain was 80% of the radiation of a perfect radiating surface with the same area.

- Hence, the proposed structure accomplished a remarkable 7.8dB gain improvement in comparison to the conventional patch antenna.

- Khoutar *et al.* focused on design and analysis of rectangular microstrip patch antenna for operating in the microwave band at a frequency of 5.8 GHz, using metamaterial technology which is a layer of 9 × 9 matrix of a Circular split ring resonators (SRR).

- This circular SRR-based superstrate enhanced the beam focusing of a microstrip antenna by 4dB while the bandwidth was also improved due to the presence of this metasurface.
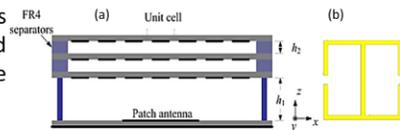
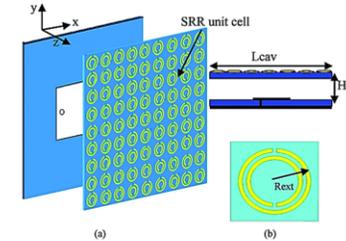**Fig.** (a) Patch antenna along with the metamaterial superstrate, (b) unit cell

Fig. (a) Top and front view of the antenna and (b) SRR unit cell

metasurface, and this is how the side view of the antenna looks. So, you see this is the patch antenna ok, you have this PEC ground and on top of that you use this metasurface as a substrate. So, what is the specialty of this? The metallic square rings basically exhibit zero permittivity at 2.6 gigahertz and this near zero refractive index substrate while it is placed at a distance say λ by 12 above these two microstrip patch antennas which are also operating in the same frequency.

Then you will get some gain enhancement. So, this structure was fabricated and the gain of the patches basically increased by 3.4 dB while you know the low profile of the antenna array was maintained. So, a similar kind of unit cell design was tried again by another group, Augustine and his team. And they have done the simulations where they actually changed the design little bit in this particular super straight instead of having this kind of solid rings they basically took this kind of small gaps in the rings.

this is the patch substrate in the ground ok, they simulated this and they found 6.2 dB gain

- Artificial magnetic conductor (AMC) surfaces have a great potential for gain enhancement and a standard configuration can be seen from the figure.

- A dual-band AMC was designed by Prakash *et al.* that consisted of square patches with annular slots

- The structure was placed at a distance of $\lambda/8$ behind a wideband patch monopole and resulted in a gain enhancement of almost 10dB while it also performed better than typical perfect electric conductor (PEC) reflectors of the same size.
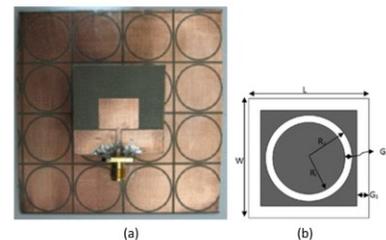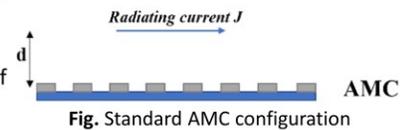

Fig. Standard AMC configuration

Fig. (a) Top view of fabricated antenna and (b) unit cell of AMC

enhancement because of this super straight ok, which is a near zero refractive index material. In parallel, other groups also developed designs similar to those of Meng and his group. They proposed a combination of MSRR that is Modified Splitting Resonators and small patches as metamaterial cell that you can see in this figure. So, these are basically the split-ring or modified split-ring resonators, and then you have this metallic patch on the right.

So, there the advantage of a super straight synthesized by this kind of cell they have seen and it has found that it is easy to tune and match to the characteristic impedance of the free space. So, they have done the experiment by placing an H-plane horn antenna and a patch antenna like this, okay. This is the patch antenna; the side view shows where they have put the superstrate. And they have seen that you know when you integrate this 0 index superstrate for this horn antenna and the patch antenna, you can get almost around 4.

43 dB and 6.6 dB gain enhancement respectively. Now, the same concept was again modified, and a similar pattern of experiment was conducted by Soutar and his group. So, here they have made a metamaterial lens which is basically nothing but an array of S-shaped, you can see here S-shaped metallic strips which were designed and fabricated. So, the placement of the single lens is / a WLAN patch antenna. So, this was a WLAN patch antenna, they have placed at a height h ok, you can see in more details in this paper about all these parameters and the design specifications.

So, this gave a $_0$.6 dB enhancement. when they used double lens ok. So, this is another structure where you have you know FR4 separator and then you have three layers of ELC that is electric field coupled resonators ok. So, these resonators were utilized as a radome.

For the patch antenna. So, this is where the patch antenna is located, and this is the unit cell of the design or the resonator. So, this was done by Lee and his group and they realized that the gain was 80 percent of the radiation of a perfect radiating surface with the same area. So, the three

layers of resonators were separated by FR-4. Okay. So, this proposed structure accomplished a remarkable 7.

8 dB gain enhancement as compared to the conventional patch antennas right. Now there is another design that was proposed by Cawthor and his group. So, they designed and analyzed a rectangular microstrip patch antenna that is operating. So, that is the patch antenna, okay. So, it was operating in the microwave band and they choose the frequency of 5.

8 gigahertz and then they used a metamaterial ah of layer it is basically a complementary split ring resonator as you can see circular ones. So, this is a circular complementary split ring resonator, and the metamaterial layer is based on a$_9$ by 9 matrix of such arrays. So, this is basically the front view; this is the side view of this. So, you can see how it is placed similarly at a height h. So, this basically allows the beam focusing of the microstrip antenna to be enhanced by around 4 dB while the bandwidth was improved due to the presence of this metasurface.

So, what it tells that all these different kind of designs people have tried to come up with this non-zero refractive index matter materials. So, they allow you to improve the gain of the antenna without basically increasing the footprint. Next, we will look into the

Deployment of AMC Surfaces near Radiators

- Assimonis *et al.*, optimized an electromagnetic band-gap structure (EBG) in order to maximize the frequency window in which wave propagation is prohibited (i.e. imaginary wave number), while such a structure also exhibited a reflection phase response.

- Hence, a dipole antenna was improved in terms of reflection coefficient and gain when placed at a distance of 1.5mm from the top of the EBG surface.

- The proposed design are easy to fabricate, which are based solely on metallic surfaces on layer interfaces.

- The gain increased by a maximum of 5.7dB within the operating bandwidth, while contrary to a PEC placed at a same distance from the antenna.
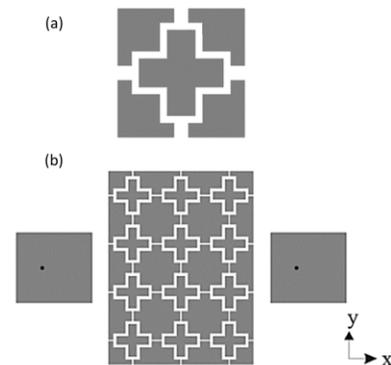

Fig. (a) Unit cell of EBG structure, (b) Two coupled patch antennas separated by a 3×4 periodic cross-EBG structure

deployment of artificial magnetic conductor surfaces near the radiators that can also be used for gain enhancement. So, artificial magnetic conductor surfaces basically have great potential for gain enhancement. And a standard configuration of this can be seen here.

So, you have these elements, okay. So, this is basically your AMC, and you have the radiating current going this way. So, people have made it. So, this is the design shown by Prakash and his group. So, here a dual-band AMC was designed that consisted of a square patch with annular slots like this, okay.

So, this structure was placed at a distance λ by 8 behind a wide band patch monopole and this resulted in a gain enhancement of almost 10 dB. Okay, while it also performed better than typical PEC reflectors of the same size. So, artificial magnetic conductors are very good in you know enhancing the k. So, there is another design proposed by Simonis and his group. They basically optimized an

Placement on GRIN lenses in front of the antenna

- GRIN (Gradient Refractive Index) lenses are known for their ability to focus electromagnetic radiation and transform spherical waves into planar ones.

- This is accomplished by a gradual variation of the refractive index $n(x, y, z)$, where x, y, z are the Cartesian coordinates, that is capable of manipulating and shaping the radiation beam.

- A GRIN lens can be synthesized by different layers (meta-layers), where each one of them consists of metamaterial cells that exhibit different index of refraction according to their geometry.

- With the placement of these layers as in figure, the total distribution approximates the one required for beam collimation.

- A tremendous advantage of GRIN lenses in comparison to the previous methods is their wide bandwidth and low loss since the metamaterial cells are far from their narrowband resonance and can offer great performance.
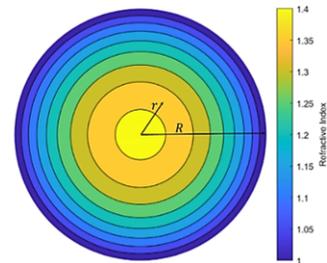
Fig. Gradient refractive index distribution of the cross section of a spherical Luneburg lens

electromagnetic band gap structure in order to maximize the

Placement on GRIN lenses in front of the antenna

- Singha *et al.* reported a lens composed of thin wires, where seven layers were placed in front of a wideband monopole (distance of $\lambda/2$ at the center frequency)

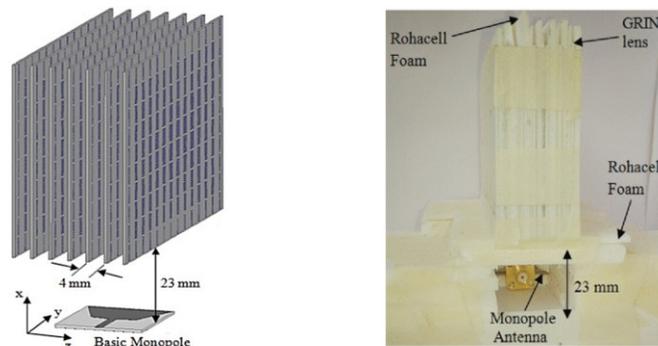- Due to GRIN lens, the peak gain of the basic monopole antenna is increased by 5.3 dB at 8.8 GHz

Fig. (a) Arrangement of the GRIN with basic monopole, (b) fabricated antenna with 7 GRIN lens

frequency window in which wave propagation is basically prohibited.

That means the waves have an imaginary wave number. While such a structure exhibited a reflection phase response. So, a dipole antenna was basically proposed in terms of reflection coefficient So, a dipole antenna was improved in terms of the reflection coefficient and the gain when it was placed at a distance of 1.5 mm from the top of the EBG surface. So, here you can see this is the unit cell of the EBG electronic bandgap structure, the electromagnetic bandgap structure, okay.

Here you have the two coupled patch antennas, which are separated by this overall structure. This is basically a a_3-by-4 periodic cross EBG structure. So, what is the advantage here the proposed structures are easy to fabricate which are solely based on metallic surfaces on layer interfaces as you can see. And because of this structure you can obtain a gain enhancement of 5.7 dB while the operating bandwidth while contrary to PEC placed you know within the operating bandwidth this is in contrary with the PEC when placed at the same distance from the antenna.

So, when you compare a PEC placed on the antenna and then you have this electromagnetic band gap structure placed at the same height from the antenna you see a_5.7 dB gain enhancement in the later case. Next, we will discuss the placement of green lenses in front of the antenna. So, green is basically a gradient refractive index lens. They are known for their ability to focus electromagnetic radiation, and they can be useful for transforming spherical waves into planar ones.

So, this can be accomplished by a gradual variation in the refractive index. So, you can have the refractive index as a function of all three: x, y, and z. So, x, y, z are basically the Cartesian coordinates, and this allows you to manipulate and shape radiation beams. So, a green lens can be synthesized by different layers, which are basically metamaterial layers or metal layers. Where each one of them will consist of a metamaterial cell that basically exhibits a different index of refraction, which comes from their different geometries.

So, you can think of this kind of a distribution of the refractive index along the cross section of a spherical Lundberg lengths that you can achieve you by placing different type of metamaterials ok along these different positions ok. So, what are the advantages of this kind of green lens in comparison to the previous method? The first one is that they have wide bandwidth and low loss since the metamaterial cells are far from their narrowband resonance and that basically can offer great performance. So, Shingha and his group they basically reported a lens which is composed of thin wires where 7 layers were basically placed in front of a wide band monopole at a distance of λ by 2 at the center frequency. So, the gap between the antennas are 4 mm like the thin layers which are basically you know these are the lenses which are composed of thin wires that you can see right all are going through. So, this is basically the fabricated structure; you can see they have put foam in between the green lenses, okay.

So, you can see that the thin wires all have different sizes, okay. So, this is an antenna; the same thing was done in the experiment, okay. So, because of this green lens, the peak gain of this basic

monopole antenna was increased by 5.3 dB at 8.

8 gigahertz, which was the center frequency. Right. So, another

Placement on GRIN lenses in front of the antenna

- Another interesting feature of GRIN lenses is the fact that they can enhance the radiation towards a desired direction regardless of the input wave's incident angle.

- This characteristic emerges in symmetric lenses and is attractive for beam steering applications, where the gain has to be high as the steering angle varies and not only towards the boresight direction.

- This is illustrated in the figure, where the spherical waves of the feed antenna are transformed to planar waves at the output of the GRIN lens independently of the feed's orientation.

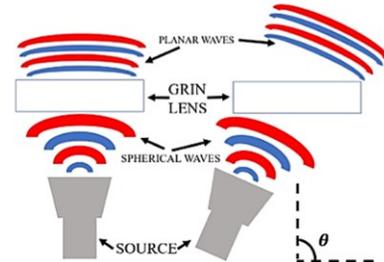- Although the lens is depicted as a square for simplicity, it usually has a symmetric shape

Fig. Illustration of transformation of a spherical wave into a quasi-planar one (through a GRIN lens) for different incident angles θ

interesting feature will be the placement of green lens right. So, it is important to note that this green lenses can enhance the radiation towards a desired direction regardless of the incident waves incident angle or you can say input waves incident angle. So, this basic characteristic emerges in symmetric lenses. And therefore, it is attractive for beam steering application where the gain has to be high as the steering angle varies and not only towards the board side direction.

 So, this can be seen in this figure where the spherical waves of the feed antenna okay are transformed to planar waves at the output of the green lens okay and that is independent of their feeds orientation right. So, this is coming straight and this is coming at an oblique incidence, but you are getting plane waves on the other side of the green lens. So, although the lens here is shown as just a square or a rectangle for simplicity, it typically has a symmetric shape. So, what are the important takeaways here is that you know When you use NZRI that is near zero refractive index

Gain Enhancement using Metamaterials

- Takeaways:
  - NZRI superstrates: best suitable for antennas that already have a directive radiation pattern
  - AMC surfaces: good for turning omni-directional radiators into directional ones
  - GRIN lenses:
    - superior performance in terms of bandwidth
    - compatible with beam steerable antennas
    - can keep gain nearly constant over steering with symmetric lenses
    - Exhibit lower loss—but they are more complex to design in comparison to NZRI and AMC surfaces as multi-layer gradients are required

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Source: Milias, 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

metamaterial as super straight, they are best suitable for antennas that already have a directive radiation pattern. You can think of using AMC surfaces, or artificial magnetic conductor surfaces, which are good for turning omnidirectional radiators into directional ones.

And then you can think of green lenses where they show superior performance in terms of bandwidth. They are compatible with beam steering or beam-steerable antennas, and they can keep the gain nearly constant / steering using symmetric lenses. Moreover, they exhibit lower loss, but they are more complex to design in comparison to the above to materials that is NZRI and AMC surfaces as multilayer gradients will be required. So, this is the summary or takeaway from the gain enhancement of antennas using metamaterials. Now, let us look into another aspect, which is isolation: how you can achieve isolation using metamaterials.

Now, isolation is of great

Isolation using Metamaterials

- Isolation is of great importance for innumerous applications, in which the antenna elements are placed in close proximity either due to the system's design (e.g. typical λ/2 inter-element spacing in antenna array configurations) or for minimizing the structure's volume.

- As a result, crosstalk arises because of the electromagnetic coupling between the antennas

- In particular, for planar antennas that are printed on the same board, surface waves are regarded as the main source of crosstalk

- Surface waves are TE or TM modes that propagate along the antenna's substrate and get diffracted on the air-dielectric interface.

- The cut-off frequencies of the modes is given by: $f_c = \frac{nc}{4h\sqrt{\epsilon_r - 1}}$

  where $n = 1, 3, \ldots$ for TE, $n = 0, 2, \ldots$ for TM, h and ϵ_r are the substrate's height and relative permittivity respectively

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Source: Milias, 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

importance for various

Isolation using Metamaterials

- It is clear that the TM_0 is always excited and it is not possible to prohibit its propagation with proper substrate design

- Furthermore, applications like Repeaters, Beamforming, MIMO, Radars, etc. requires decoupling of antennas and suppression of surface waves for optimum performance

- Emphasis is mainly placed on isolation enhancement in planar antenna topologies, since they are low-profile and suitable for most of the applications but also suffer from high coupling due to the excitation of surface waves and space waves.
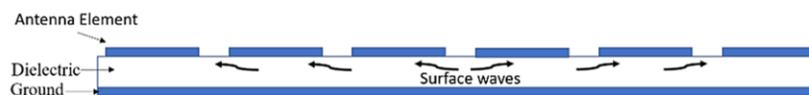

Fig. Illustration of coupling due to surface waves in multi-antenna platforms

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Source: Milias, 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

applications. in which antenna elements are basically placed in close proximity due to either the system design that is you know typical λ by 2 inter element spacing needed in an antenna array combination or for minimizing the overall structure volume. So, as a result cross stroke may rise ok due to the basic electromagnetic coupling between the antennas and in particular For planar antennas that are basically printed on the same board surface waves are regarded as the main source of crosstalk. Now, this surface waves are basically T or T m modes that can propagate along the antenna substrate and get diffracted on the air dielectric interface. you can see the cutoff

frequency of this fc will be or nc I think this is a subscript / 4 h square root of ε r - 1.

So, fc is the cutoff frequency n is 1 3 dot dot dot for Te and n will be 0 to the even numbers for Tm, h is basically the substrate's height and ε r is the relative. Permittivity of the substrate. So, how do you obtain isolation using

Isolation using Metamaterials

- More specifically, a compact MIMO platform consisting of two printed monopoles operating at 2.4GHz was examined by Ketzaki *et al.*

- The distance between the two antennas was λ/8 and thus the coupling between them (S_{21} and S_{12} coefficients) has a high value of -5dB

- The authors proposed an easy to fabricate and efficient solution

- They first examined the electric field of the structure, in order to find the path through which the power flows from one antenna to the other.

- After this, they placed a capacitive-loaded split rectangular loop (CLSRL), exactly at the point where the power flow is maximum. In this manner, more than 30dB coupling reduction was accomplished

- Furthermore, two meander-like structures were placed between two closely spaced patch antennas (figure)

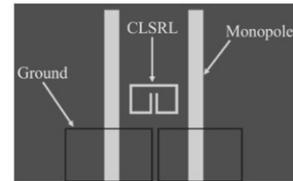- The resonators provided an isolation improvement of 16dB at 4.5GHz

Fig. Decoupling of two closely spaced monopole antennas with a single metamaterial CLSRL unit cell
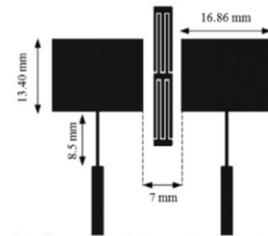

Fig. Proposed slotted meander-line resonator decoupling unit

Isolation using Metamaterials

- Mu-negative isolation technique for densely packed monopoles (left figure) was proposed by Thummaluru *et al.*

- The authors considered this metamaterial-structure as a filter, that decouples the antennas over the whole operational bandwidth.

- In a similar manner, SRR inclusion pairs were inserted between monopoles (right figure) by Bait-Suwailam *et al.* and resulted in 25dB coupling reduction, while the impedance matching of the antennas was not affected.
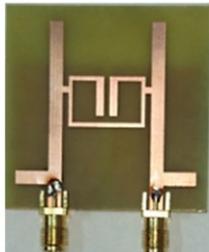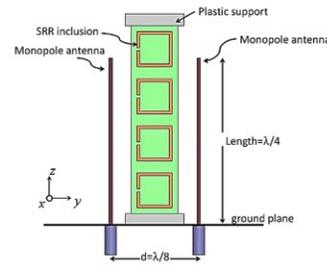

Fig. Fabricated two-port MIMO antenna

Fig. Lateral view of the two-monopole antennas with SRR inclusions

Isolation using Metamaterials

- Liu *et al.* presented a systematic approach for a dual-band metasurface design that significantly decreases the coupling between two adjacent elements in two frequency bands (2.6 GHz, 3.5 GHz).

- The metasurface layer consists of double layer cut wires of different lengths and is placed above the antennas as a superstrate.

- Moreover, dual-band (2.34-2.47GHz, 3.35-3.65GHz) isolation improvement was presented from Panda *et al.*

- After they designed an electrically small CSRR-based antenna, they placed two of those in proximity (e.g. edge-to-edge spacing of 10 mm).

- For the decoupling, they utilized a 2 × 3 array of modified CSRRs that exhibit a bandgap in the corresponding frequencies and thus resulted in coupling reduction in both bands.
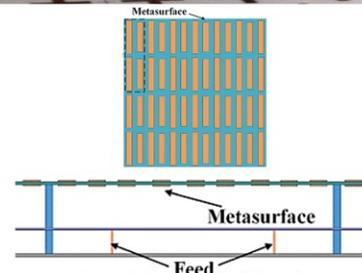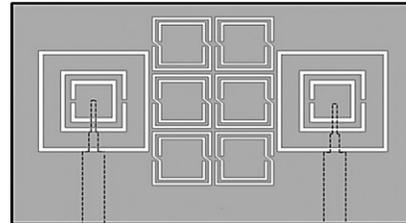
Fig. Front view of the two dual-band antennas

Fig. MIMO antenna system with 2 × 3 CSRR slots

metamaterials? So, you can see here that this is basically a coupling due to surface waves in a multi-antenna platform. So, this is different antenna elements that you see here this is the dielectric and this is the ground plane and this is how surface waves are propagating. So, it is clear that when you have T m_0 that is getting always excited and it is not possible to prohibit its propagation with proper substrate design.

Furthermore, in applications such as repeaters, beamforming, MIMO, radars, etc. That will require the decoupling of antennas and the suppression of surface waves for optimum performance. So, the emphasis, therefore, is placed on the isolation enhancement in planar antenna technologies. Since they are low profile and they are basically suitable for most of the applications, but they have the limitations and because they suffer from high coupling due to excitation of the surface waves and space waves. So, more specifically if you consider a compact MIMO platform consisting of two printed monopoles okay like this okay which are operating at 2.

4 gigahertz you can see this coupling happening. So, that was examined by Kedzaki and his team. So, they considered the distance between the two antennas to be λ by 8 and and thus the coupling between them that is S_{21} and S_{12} coefficients has a very high value of - 5 dB. So, what they have done this authors basically proposed an easy way to fabricate an effective solution. So, they first basically examine the electric field of the structure and in order to find the path through which the power flows from one antenna to another. So, after observing the electric field pattern and the way the electric field gets coupled to the other one, they placed a capacitively loaded split rectangular loop that is called CLSRL.

They put it exactly at the point where the power flow is maximum. So, when they do this that power is basically getting coupled here. So, you are basically allowing the two monopoles to decouple, okay? So, in this manner, they could achieve a $_{30}$ dB coupling reduction. So, further

enhancement in the design happened where people put two meander like structures placed between two you know closely spaced patch antennas and that also gave decoupling between the two antennas, whereas they are busy very close physically located ok. So, in this case this resonator could provide an isolation improvement of 16 dB at 4.

5 gigahertz. My negative isolation technique can also be used for densely packed monopoles, as you can see here. That was proposed by Thumullaru and his group. So, this group considered this

Isolation using Metamaterials

- Metamaterial isolators (SNG/DNG) give smart, low-profile decoupling with minimal impact on antenna size/behavior

- Main limitation: attributed to the narrowband metamaterial response → challenging to decouple wideband antennas

- In parallel, most of the works regarding isolation have focused on antennas for communication systems, where the specifications are less strict (i.e. usually −20dB for MIMO arrays)

- Radars are more demanding and require as high transmitter-receiver isolation as possible

- Hence, metamaterial solutions that provide extreme levels of isolation (e.g below −100dB) are necessary for improving radar performance and maintaining a low profile by avoiding the placement of large metal sheets between the transmitter and the receiver

metamaterial structure to be a filter that basically decouples the antenna / the whole operational bandwidth. In a similar manner, split ring resonator inclusion pairs were inserted between monopole antennas as you can see here that was proposed by Bate and Swaylam. And they could obtain a a_{25} dB coupling reduction while the impedance matching of those antennas was not.

So, these are the two antennas which were monopole antennas separated by λ by 8 and there they put this SRR inclusion which is called a plastic support in between and they give this much of 25 dB coupling reduction. Liu and his group they presented a systematic approach for a dual band metasurface design that significantly could decrease the coupling between two adjacent element into frequency bands they consider 2.6 and 3.
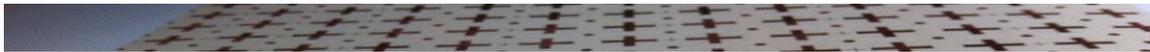
5 gigahertz ok. So, this is how you can see what the unit cell is. So, this metasurface basically consists of double layer cut wire which are of different length and they are basically placed above the antenna as a super straight. So, these are the feeds of the antenna, and this is the antenna. You know the metasurface. So, this is basically a dual-band antenna. So, you can see that the dual bands these are the bands and because of this structure this is another structure that is proposed by Panda and his group.

So, here these are the antennas and there in between they basically designed electrically small

CSRR based antennas ok and they placed them very closely. So, you can see 2 by 3 CSRR slots being placed between the 2 antennas and the edge to edge spacing between the antennas were only 10 mm ok. Because of this distance when they put this kind of a$_2$ by 3 array of this modified splittering resonators or complementary splittering resonators that could exhibit a band gap in the corresponding frequencies and they allowed reduction in the coupling in both the bands ok in both of these bands. Finally, you can also think of metamaterial isolators as single negative or double negative materials. They can provide smart low-profile decoupling with minimal impact on the antenna size and behavior.

However, the main limitation can be attributed to the nanoband metamaterial response, which will make it challenging to decouple wideband antennas. However, in parallel, most of the work regarding this isolation has focused on antennas for communication systems where the specification is less strict. So, typically around - 20 dB for MIMO arrays. Radars on the other hand are more depending and they require as high you know transmitter receiver isolation as possible. So, you can basically think of this kind of metamaterial solution to provide extreme levels of isolation, okay.

Even below - 100 dB where it is necessary to improve the radar performance while maintaining a low profile by avoiding placing you know large metal sheets between antenna and receiver. So, that is where metamaterials can play a big role. So, with that, we conclude this lecture. So, next we will discuss negative index metamaterials. If you have any query regarding this lecture, drop an email to this email address mentioning the course name and the lecture number on the subject line. Thank you.

Slides inserted by fallback (review if needed):

Thank You