Course Name: Introduction to Microwave and Optical Metamaterials
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Institute Name: Indian Institute of Technology, Guwahati
Week-11
Lecture-54

Lec 54: Electrically Tunable Metamaterials

Hello students, welcome to lecture 54 of the online course on the introduction to microwave and optical metamaterials. Today's lecture will be on electrically tunable metamaterials.

Lecture Outline

- Electrically Tunable Metamaterials
  - Introduction
  - Graphene-based metamaterials
    - ✓ Electrically Tunable Graphene-Based Polarizer
  - Varactor diode-based metamaterials
  - Liquid crystal-based metamaterials

So, here is the outline of the lecture. We will give you a brief introduction to electrically tunable metamaterials. And then we will discuss graphene-based metamaterials. We will go into the details of a graphene-based polarizer that is electrically tunable.

Then we will discuss about varactor diode-based metamaterials and liquid crystal- based metamaterials. In the previous lecture, we saw magnetically tunable metamaterials. Here we will be using an electric field for tuning the metamaterial properties.

So, the topic is electrically tunable metamaterials.

Electrically Tunable Metamaterials

Introduction

- Electrically Tunable Metamaterials: A class of metamaterials with electromagnetic properties that can be actively and dynamically adjusted.
- Tuning is achieved by applying an **external electric signal or voltage**.
- This tunability allows for real-time control over how electromagnetic waves interact with the material.
  - Allows dynamic reconfiguration of device behavior during operation.
- The **core principle** is to integrate active, electrically sensitive materials into the metamaterial's structure.
- Applying a variable voltage alters the electrical properties of these active components.
- This alteration leads to changes in:
  - The resonant behavior
  - Effective permittivity and permeability

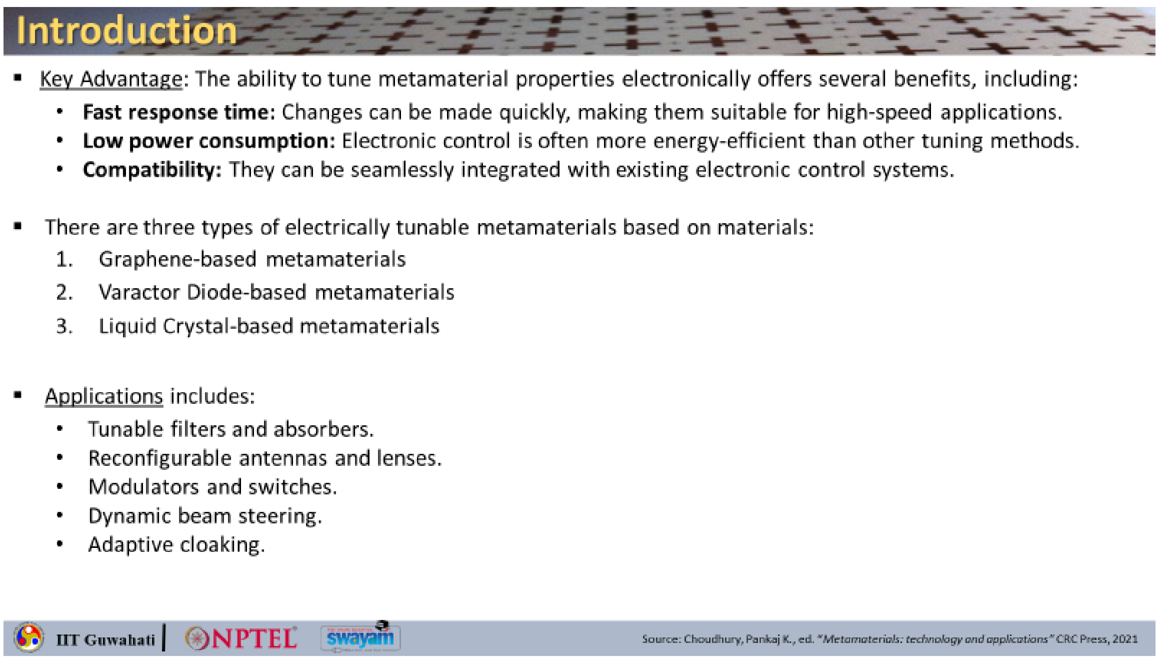
  } Tunable electromagnetic properties
- Therefore; Real-time tuning of the metamaterial's electromagnetic response.

Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

So, these are basically a class of metamaterials whose electromagnetic properties can be actively manipulated. or dynamically adjusted by changing an external electric signal or voltage bias. Now this tunability will allow for real-time control over how the electromagnetic wave interacts with the material. So, what is the benefit? It allows the dynamic reconfiguration of the device's behavior during its operation. So, the core principle here is to integrate actively electrically sensitive materials into the metamaterial structure.

So that when you change the electric field during its operation, it can behave differently. So, in this kind of metamaterials, applying a voltage bias or a variable voltage bias is used. Basically, alter the electromagnetic properties of the active components. So, this kind of alteration can lead to either the change in the resonant behavior via you know the change in effective permittivity or permeability. So, this is what we mean by tunable electromagnetic properties.

Real-time tuning of the metamaterials' electromagnetic response is possible. by this kind of external electrical signal or bias voltage that is being applied. Now, what is the key advantage of why we need to do all this?

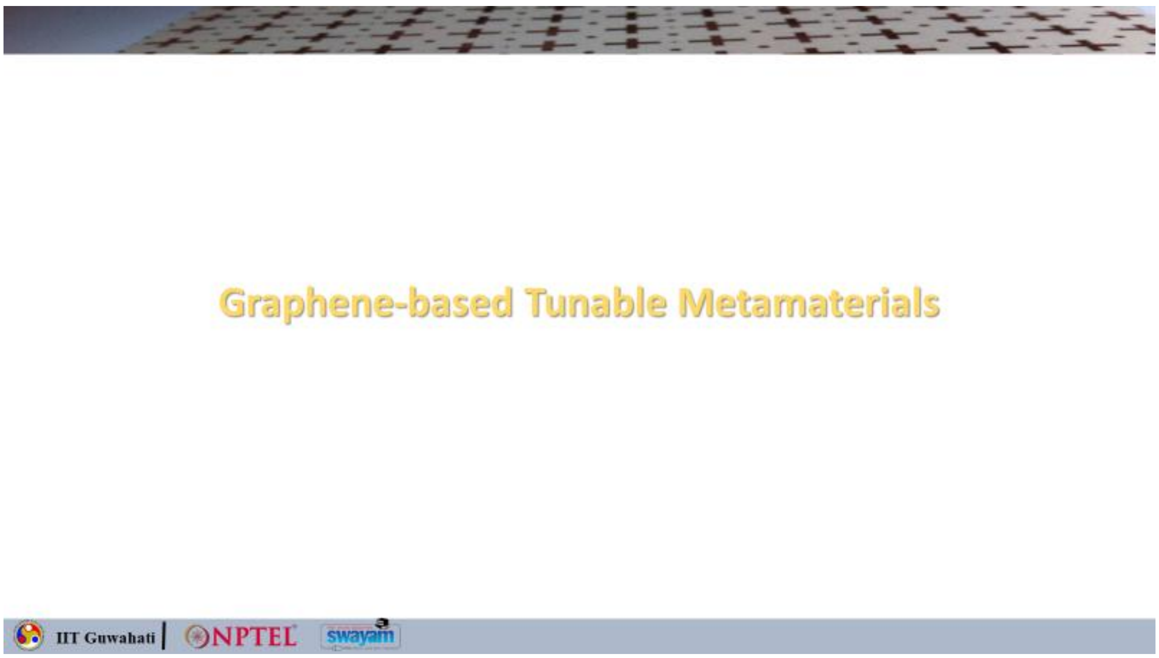


It is the ability to tune metamaterial properties electronically basically offers several benefits, including the fast response time, which means the changes can be made quickly. Making them suitable for high-speed applications, another important aspect is low power consumption.

So, electronic control is often found to be more energy-efficient compared to other tuning methods. And finally, the compatibility. So, this can be seamlessly integrated with the existing electronic control system. So, that way, these electrically tunable metamaterials are more compatible. So, there are three types of electrically tunable metamaterials based on the types of metamaterials being used.

The first one is graphene-based metamaterials, the second one is varactor diode-based metamaterials the third one is liquid crystal-based metamaterials. Though this is not an exclusive list, there can be other different types of metamaterials. which is electrically tunable and that is an ongoing research area. So, the applications include making tunable filters and absorbers, and designing reconfigurable antennas and lenses. That operate at different frequencies, then modulators, switches, and also dynamic beam steering.

It can also be used for adaptive cloaking. So, if you think of individuality cloaking, that basically makes an object completely invisible. to an electromagnetic wave, such as radar or light. When you think of adaptive cloaking that basically dynamically hides or masks objects under changing environments or conditions.



So, now let us look into the first one, which is graphene-based tunable metamaterials.

Graphene-based Tunable Metamaterials

- Electrical conductivity of graphene can be tuned via change in its Fermi level.
- The Fermi level is adjusted using an applied voltage.
- This makes graphene ideal for electrically tunable metamaterials.
- Particularly works in the terahertz and infrared frequency ranges.
- Graphene based electrically tunable devices:
  - **Electrically Tunable Graphene-Based Polarizer**

Source: Z. H. Zhu *et al.*, "Electrically tunable polarizer based on anisotropic absorption of graphene ribbons," *Appl. Phys. A*, vol. 114, pp. 1017–1021, 2014.

So, in this case, you are basically using graphene as part of your structure and the electrical conductivity of graphene can be tuned via a change in its Fermi level that we all know. So, this Fermi level, if you put the graphene in a particular capacitor kind of a configuration, you can basically change this Fermi level by changing the applied voltage bias. So, we'll show you how this arrangement looks. So, this basically makes graphene ideal for electrically tunable metamaterials.

Now, typically, this kind of metamaterial works in the terahertz and infrared frequency ranges. So, you can make graphene-based electrically tunable devices such as electrically tunable graphene-based polarizers.

Electrically Tunable Graphene-Based Polarizer

- A polarizer with electrically controllable polarization direction is designed using graphene.
- Operates in the far-infrared range and can be extendable to terahertz (THz) radiation.
- Structure of Electrically Tunable Polarizer : (Shown in fig. 1)
  - Composed of two orthogonal periodic arrays of graphene ribbons with different widths.
  - These graphene ribbons have different widths, denoted as $\mathbf{W_1}$ and $\mathbf{W_2}$.
  - Arrays are placed on a dielectric film over a thick metal substrate.
- Geometric Parameters:
  - Period of the graphene ribbons: P
  - Thickness of the dielectric material: t_d
  - Thickness of the metallic material: t_m

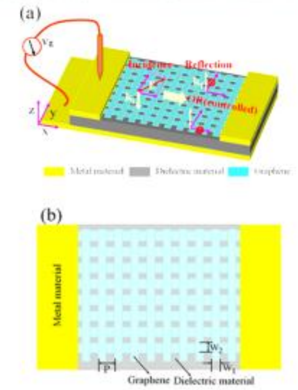


Figure 1.: Schematic representation of a polarizer with an electrically controllable polarizing direction: (a) Perspective view and (b) Top view

IIT Guwahati | NPTEL swayam Source: Zhu, Z. H., et al. "Electrically controlling the polarizing direction of a graphene polarizer." Journal of Applied Physics 116.10 (2014)

So, here is an example of an electrically tunable graphene-based polarizer. So, this is how it looks in the perspective view, and this is the top view; we will go into this in detail. So, this polarizer has an electrically controllable polarization direction that can be changed by applying a voltage bias across the graphene.

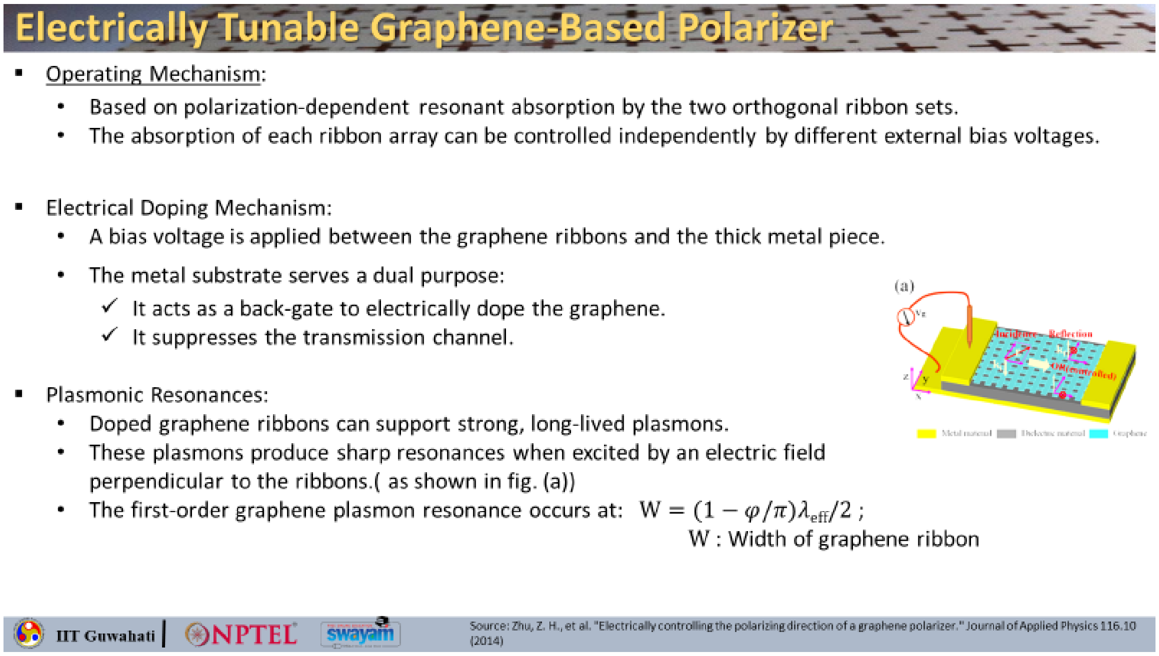
So, what is the operating range?

It typically operates in the far infrared, but you can also extend this to the terahertz radiation regime. So, here is the structure of this electrically tunable polarizer that we have been discussing. So, you can see it is basically composed of two orthogonal periodic arrays of graphene ribbons. So, there are X ribbons and Y ribbons, and they are of different widths. So, the width of the X ribbons are W_2, Y ribbons are W_1 and this is the periodicity that is P.

Now, as you see here, these ribbons are basically placed on a dielectric film over a thick metal substrate. So, there is a thick metal substrate, and then you have this kind of metallic electrode on the top layer. So, when you apply voltage, this entire thing acts like, you know, an electrode; the bottom one is another electrode, okay? and then in between you have this capacitive effect right. So, these are the geometric parameters that are important: one is the periodicity of the graphene ribbons, which is P. The thickness of the dielectric material t_d also plays an important role.

The thickness of the metallic layer t_m is the bottom metal layer that you are able to see.

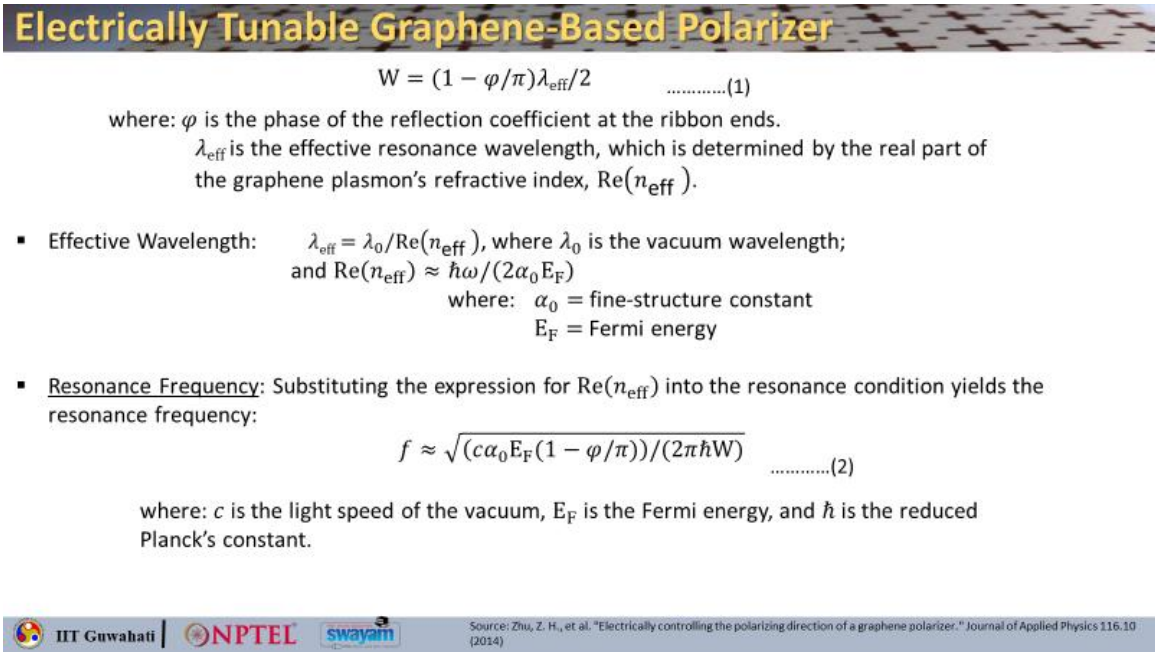
So, what is the operating mechanism in this case?



So, based on the polarization-dependent resonant absorption, you will have two different types because there are two orthogonal ribbon sets. So, it basically the polarizer operates based on polarization dependent resonant absorption. So, the absorption of each ribbon array varies because they have different widths. So, they have different absorption frequencies, and that can be controlled independently by applying different voltage biases.

So, how are you doing the electrical doping here? So, you can basically apply a voltage bias between these graphene ribbons and the thick metal piece at the bottom. So, here the metal substrate that you see at the bottom is a thick metallic plate that serves two purposes. First of all, it acts as a back gate to electrically dope graphene. Secondly, it also suppresses all the transmission that is going through the channel. So, whatever the incident light is shown like this is falling on the top, if it is not absorbed, it is basically reflected because nothing is getting transmitted.

So, now we also know that graphene in this particular frequency range supports plasmons. So, doped graphene ribbons can also support strong log lift plasmons, and these plasmons will produce sharp resonances. When they are excited by an electric field that is perpendicular to the ribbons, okay. So, you can see here that this is basically the k vector and this is the electric field vector, right? So, you can estimate the first-order graphene plus bond resonance to occur at $W = (1 - \varphi/\pi)\lambda eff/2$. So, this is basically the resonance condition; here, W is basically the width of the ribbon, right and then there are the other two terms φ and λeff .



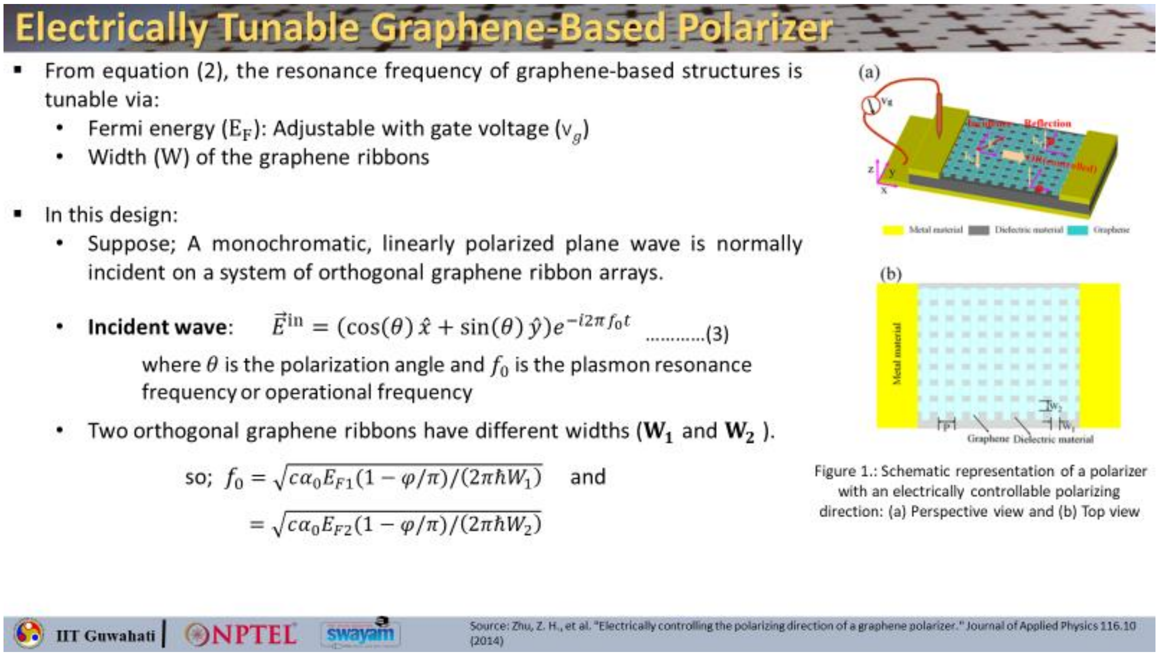
So, φ is basically the phase of the reflection coefficient at the ribbon ends, okay? And then you have λeff , which is basically the effective resonance wavelength. which is determined from the real part of the permittivity of graphene plasmons for the refractive index that is given by: $\lambda\mathrm{eff} = \lambda_0/\mathrm{Re}(n_{eff})$, okay. So, you get a new term here, effective wavelength, that is basically being calculated as λ_0 divided by lambda effective is nothing but $\lambda_0/\mathrm{Re}(n_{eff})$, right.

What is λ_0, which is basically the vacuum wavelength; real part of the n effective can be estimated as $\mathrm{Re}(n_{eff}) \approx \hbar\omega/(2\alpha_0 E_F)$. So, α_0 is basically the fine structure constant, okay, and E_F is basically the Fermi energy, right.

So, once you know this, you can also obtain the resonance frequency. So, you can do that by substituting the expression for the real part of the effective n into the resonance condition that we have seen here.

And that can give you the resonance frequency f, which is estimated as: $f \approx \sqrt{(c\alpha_0 E_F(1 - \varphi/\pi))/(2\pi\hbar W)}$. So, ħ is nothing but the reduced Planck's constant, and all other terms have already been discussed; W is basically the width of the ribbons. So, this equation basically shows a direct relationship between tunable Fermi energy and the energy resulting in resonance frequency. So, that is something very interesting, okay.

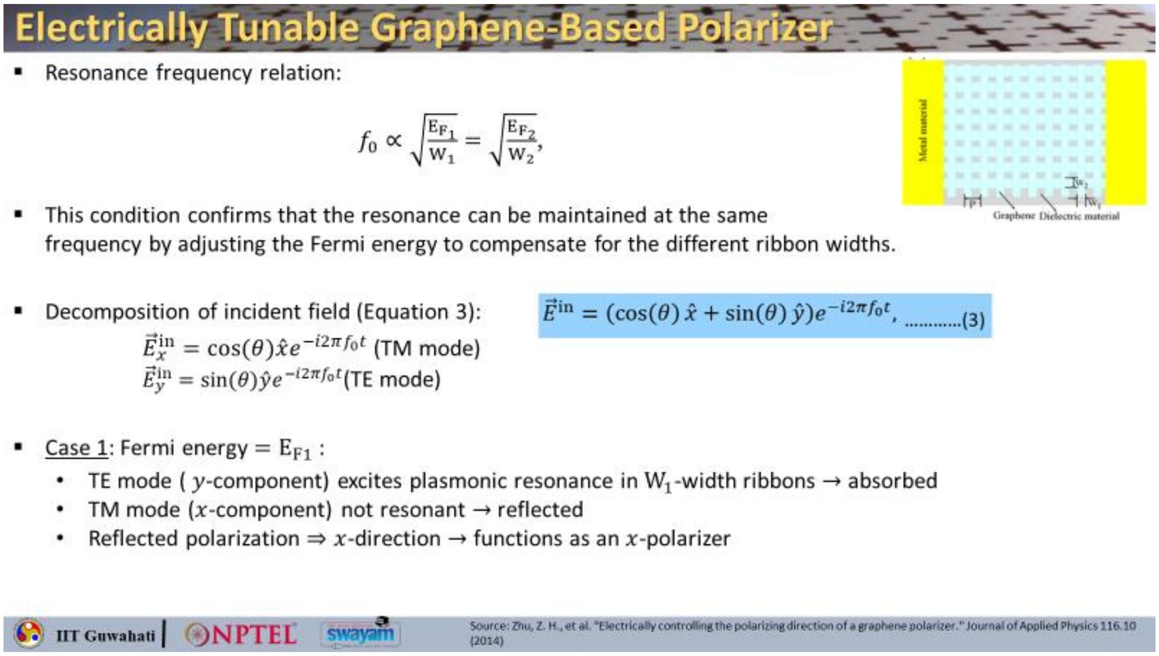
Now, this equation also tells us that the resonance frequency of the graphene-based structures is tunable.



So, if you just change the Fermi energy by adjusting the gate voltage as shown here, you can change the resonance frequency. Also, you can change the width of the graphene ribbons, which will also change the resonance frequency. So, in this design, suppose a monochromatic, linearly polarized plane wave is normally incident on this particular system of two orthogonal graphene ribbon arrays, okay.

So, you can write the incident wave in terms of this incident electric field, which is nothing but $\vec{E}^{\text{in}} = (\cos(\theta)\,\hat{x} + \sin(\theta)\,\hat{y})e^{-i2\pi f_0 t}$. So, f_0 is nothing but the plasmon resonance frequency, or you can say the operational frequency and θ is basically the polarization angle, okay. Now, because you have two different ribbons here, or ribbon widths W_1 and W_2.

So, you can correlate that f_0 will be equal to E_{F1}, and W_1 for the first ribbon and for the other ribbon. It will be the Fermi energy E_{F2}, and the width will be W_2, with all parameters remaining the same.



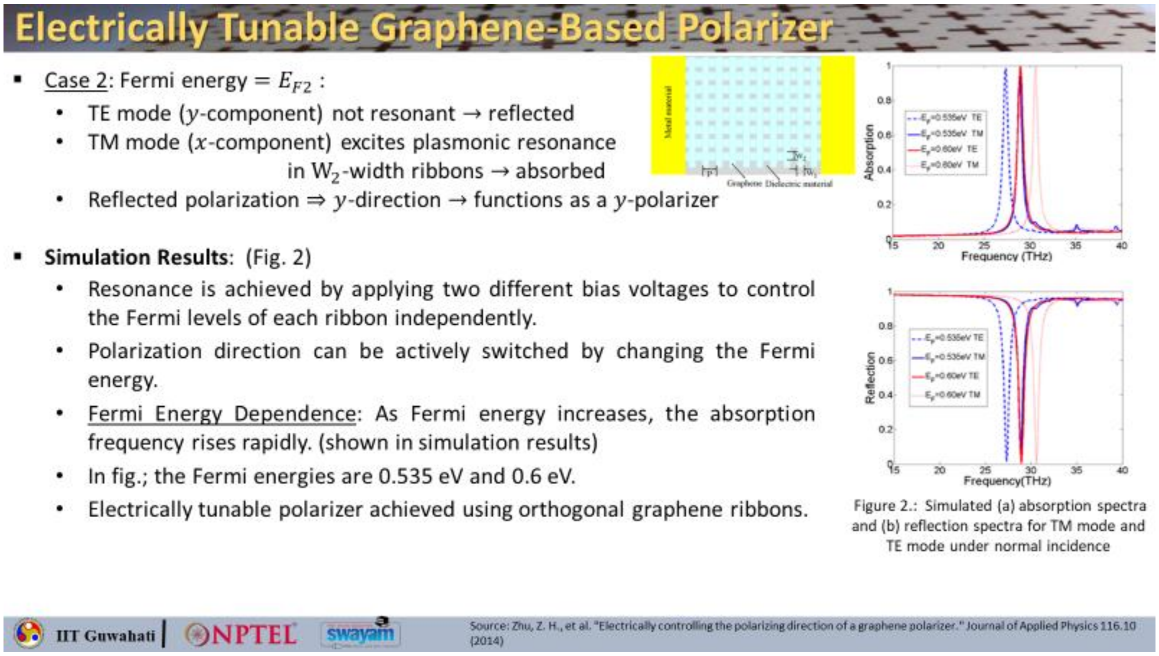
So, what does it tell you that you can say that your resonance frequency is basically proportional to square root of Fermi energy by width ratio. So, you can write $\sqrt{\frac{E_{F_1}}{W_1}} = \sqrt{\frac{E_{F_2}}{W_2}}$. So, this tells you that the resonance frequency basically depends on both the fermi energy and the ribbon width.

And this condition also confirms that the resonance can be maintained at the same frequency. By adjusting the Fermi energy to compensate for different ribbon widths. Because in this case, we are taking W_1 and W_2. So, E_{F1} and E_{F2} need to be like, correspondingly adjusted So that you still get the same resonance frequency from the two different nano ribbons, okay. From the incident electric field, you can decompose it and find the fields that will correspond to the TM mode and TE mode.

So, you can consider Ex incident to be equal to $\vec{E}_x^{\text{in}} = \cos(\theta)\hat{x}e^{-i2\pi f_0 t}$, which will correspond to the TM mode. And then on the other side, you can write Ey. So, these are basically the electric fields along x and y. that corresponds to TM and TE mode respectively. So, Ey in will gives as: $\vec{E}_y^{\text{in}} = \sin(\theta)\hat{y}e^{-i2\pi f_0 t}$.

So, that is basically the TE mode, ok. Now, let us consider in the first case that the Fermi energy is E_{F1}. So, in that case, you know that you will see the TE mode, which is basically the Y component. That will exhibit the plus bond resonance in W_1 with ribbon. So, in that case, the energy will get absorbed, and the TM mode, which is basically The X component will not show the resonance; in that case, the energy of the incident beam will be reflected. So, the reflected polarization is basically coming from the x-direction.

So, the structure basically functions as an x polarizer.



Now, if you consider that you have set the Fermi energy to E_{F2}. So, what is happening?

The reverse will happen: your TE component, which is basically the y component, will now be non-resonant. So, it will be reflected, whereas the TM component, which is the x component, will excite a plus 1 resonance. So, it will get absorbed in the W_2-width ribbons, fine.
So, what you are seeing is that the reflected polarization is basically the y polarization and that means this structure is now performing as a Y polarizer when the Fermi energy is set to F_2. The simulation results also confirm this. So, here you see the absorption spectrum; here you see the corresponding reflection spectrum. So, you can see that the absorption is basically achieved. So, these are two different bias voltages for the corresponding polarization modes that are shown.

So, it is clearly seen that the polarization direction can be actively switched by changing the Fermi energy levels. And as you see here, as the Fermi energy is increasing, the absorption frequency also rises rapidly. So, you can see that the energy is also moving to higher energy levels. So, what are the two Fermi energies considered here? One is 0.535 electron volts; the other is 0.6 electron volts.
So, what we achieved here is basically an electrically tunable polarizer using orthogonal graphene ribbons.

So, one thing you can cross-check is that whenever there is a strong absorption, it also gives you a reflection dip. Because what is getting absorbed is not being reflected, and transmission is zero because of that thick metallic plate as a substrate. So, this you can correlate is the Fermi level and the polarization of the beam, right. So, this is how you can make an electrically tunable graphene-based polarizer.

Now, let us move on to the next application, which is varactor diode-based metamaterials.

Varactor Diode-based Metamaterials

Electrically Tunable Metamaterial using Varactor Diodes

- A tunable microwave metamaterial absorber is designed using split square loops (SSLs) with varactor diodes as shown in figure 3.
- In this design, varactor diodes are embedded in split square loops (SSLs) of a metamaterial absorber.
- Varactor diode:
  - A semiconductor device based on the principle of variable capacitance between PN junctions.
  - This diodes provide variable capacitance controlled by applied voltage.
  - When loaded onto SSLs, they alter resonance characteristics.
- Structure: Compact, planar with a simple feeding network.
  - Designed as a metal-dielectric-metal structure with a copper ground for zero transmission.

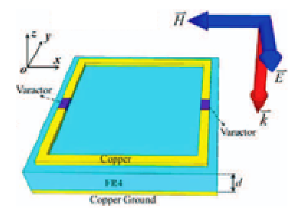


Figure 3.: Unit cell of SSL of metamaterial absorber with two varactors under TE wave illumination

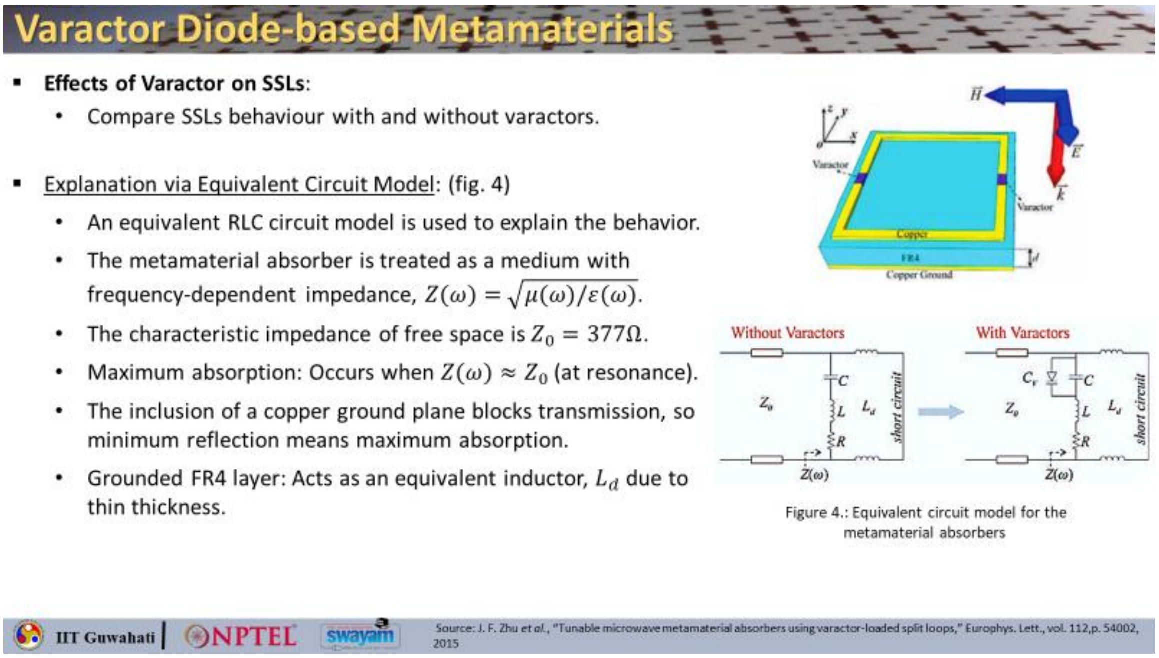
Source: J. F. Zhu *et al.*, "Tunable microwave metamaterial absorbers using varactor-loaded split loops," Europhys. Lett., vol. 112, p. 54002, 2015

So, here we are discussing electrically tunable metamaterials that are based on varactor diodes. So, we will take an example here, which is a tunable microwave metamaterial absorber. That is designed using split square loops, as you can see here; these metallic loops have two splits, okay. So, you are basically placing varactor diodes in those gaps, right. So, in this design, varicative diodes are basically embedded in these split square loops or SSLs, okay, of the metamaterial absorber.

You can see the structure clearly. This is a copper loop; below this, there is an FR-4 substrate of thickness d, and then you have a copper ground plane on the other side. So, this is the direction of the incident wave, and then this is the direction of the electric field and magnetic field. So, you are considering the two varactors under TE wave illumination, right? Now, what is a varactor diode?

It is basically a semiconductor diode based on the principle of variable capacitance between p-n junctions, right. So, in this diode, you can have variable capacitance that is controlled by the applied voltage. So, when you load them into these split square loops, they can basically alter the resonance characteristics. So, this structure basically shows a compact planar and a simple feeding network.

So, it is designed as a metal dielectric kind of structure, and it has a copper ground plane that ensures zero transmission.

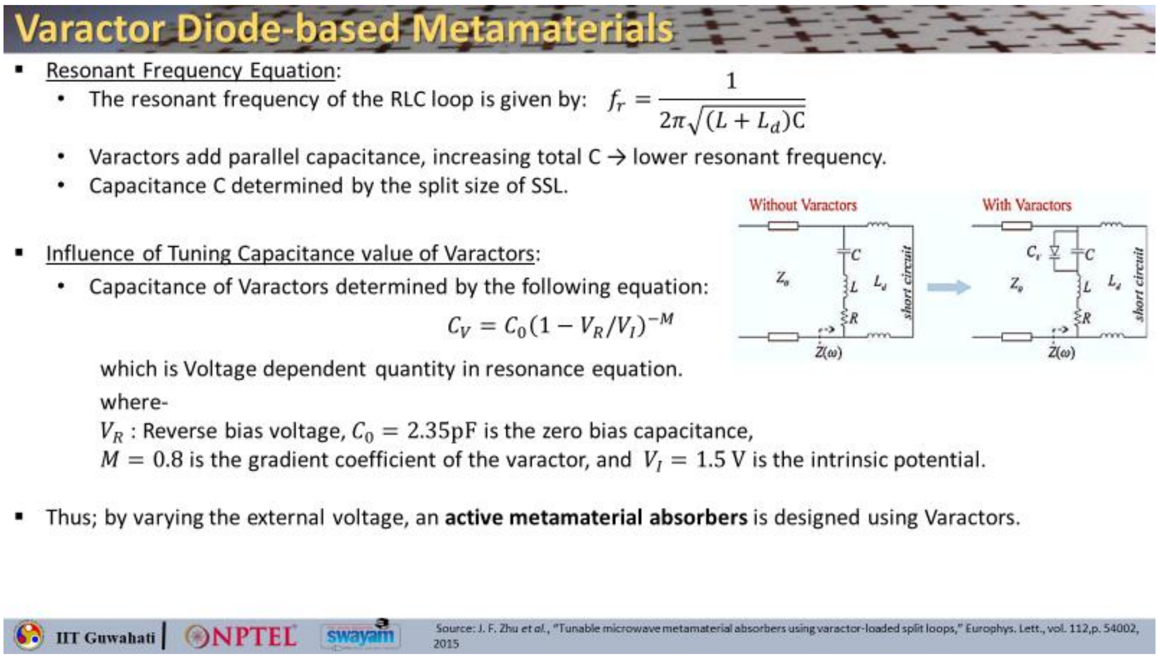


So, now let us look into what the effect of these varactors is on the split square loops. So, for that, you have to compare the SLL's behavior with and without varicators, right.

So, let us use an equivalent circuit model for this metamaterial absorber, and that will help you compare the two cases. So, this is the RLC equivalent circuit model that can be used for the case without any varactor. So, this metamaterial absorber can be treated as a medium which has got a frequency dependent impedance $Z(\omega)$ that you can see here.

So that can be obtained from $\sqrt{\mu(\omega)/\varepsilon(\omega)}$ and then, this is the free space impedance, or you can say the impedance of free space; the value is around 377 ohms, as all of you know. Now, so what will happen is that this is an absorber. So, the maximum absorption can happen when this $Z(\omega)$ is equal to Z_0 .
So, that should happen at the resonance, right. So, because you have also incorporated a copper ground plane, it can block transmission.

So, whenever there is impedance matching, that means maximum absorption will take place, and that will also ensure minimum reflection, right and you also have a grounded FR-4 layer which acts as an equivalent inductor, okay, and you can model it as Ld due to its thin thickness. So, this is how the loop is modeled. So, you have the inductance, you have the resistance, and also the gaps are modeled as capacitors, right.



So, in this case, normally the resonance frequency of this RLC loop can be obtained using this formula. So, you can write $f_r = \frac{1}{2\pi\sqrt{(L+L_d)C}}$, right.

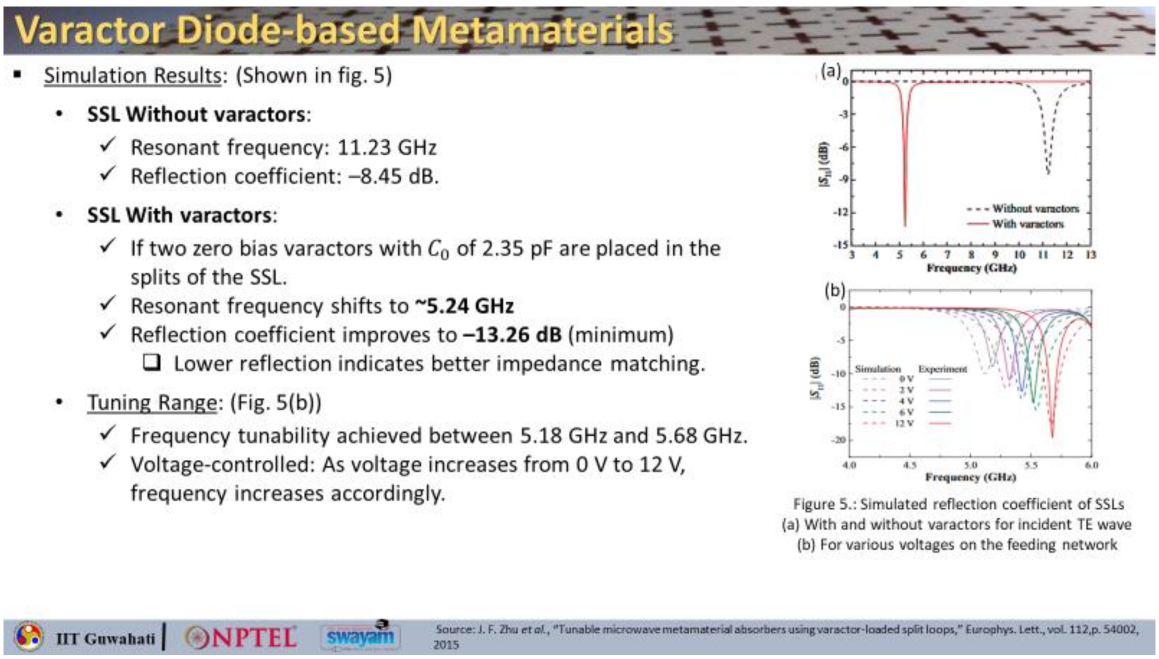
Now, when you connect a varactor into those gaps, the capacitance from the varactor will appear in parallel with the capacitance here. So, what is happening? The overall capacitance is basically increasing.

So, if the denominator increases, your resonance frequency will decrease. So, it basically lowers the resonant frequency. Right, and the capacitance C is basically determined by the size of the split of the loops, right.

Now here you can see that this depends on the size of the loops and This is C_V, which is the capacitance of the varactors that can be determined using this equation. You can consider $C_V = C_0(1 - V_R/V_I)^{-M}$. So, this is basically a voltage-dependent quantity, okay in this resonance equation.

So, here V_R stands for the reverse bias voltage, and C_0 is basically 2.35 picofarads, which is considered the zero-bias capacitance. You have this M, which is basically considered to be 0.8, the gradient coefficient of the varactor. And then you have V_I, which is basically the intrinsic potential, and it is taken as 1.5 volts. So, you can see that when you vary the external voltage, an active metamaterial absorber can be designed using a varactor. Because this value will change, it will change the resonance frequency of the whole structure.

So, here are some simulation results. So, the first one shows the S_{11}, which is basically the transmission characteristics. Sorry, this is S_{11}; basically, it is showing the reflection coefficient, okay.



So, this basically shows the reflection coefficient of the square split square loops, both without and with varactors.

So, without a varactor, you can see the resonance frequency is around 11.23 gigahertz, and the reflection coefficient is minus 8.45 dB. But when you introduce varactors into those splits, you will see that if to zero bias varactors Those which have a capacitance of 2.35 picofarads are placed in these loops. You can see that the resonance frequency basically shifts to 5.24 gigahertz. And you also see that the reflection coefficient improves to minus 13.26 dB that is the new minimum and lower reflection basically ensures better impedance matching.

So, it is a very good thing. And this one basically shows that the frequency tunability that you can achieve between 5.18 gigahertz and 5.68 gigahertz, okay, when you are applying different voltages to the feeding network, right. So, as you can increase the voltage from 0 volts up to 12 volts, these are the simulation, and the solid one shows the experimental values, okay.

You can see the shift in the resonant frequency. So, I hope the role of the varactor is very clear: adding a varactor is equivalent to connecting a capacitor in parallel with the inherent capacitance of those splits. So, this basically increases the overall capacitance in the circuit, and that way your resonance frequency will also decrease. So, that is how you can tune it.

Now, the last topic that we will be discussing today is liquid crystal-based metamaterials.

Liquid Crystal-based Metamaterials

- **Liquid Crystal (LC) Properties:**
  - LC is an "interstate" substance between crystalline and liquid states.
  - It is extremely sensitive to external fields.
    - ✓ Powered on: LC molecular arrangement become orderly, leading to special physical properties.
    - ✓ Powered off: LC molecules become disordered.
- It has been widely used for:
  - Tuning the band gaps of photonic crystals at optical frequencies.

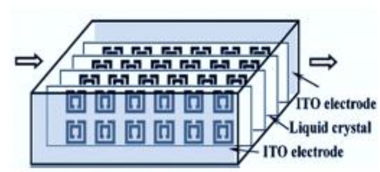


Figure 6.: Schematic of the electrically tunable negative permeability metamaterial consisting of SRRs and infiltrated LC

- Nematic Liquid Crystal (NLC) in Metamaterials:
  - Electrical tunability achieved by using nematic liquid crystal (NLC) in metamaterials.
  - It can be used to **dynamically control the permittivity of metamaterials**.
  - This control allows for tuning of reversed electromagnetic behaviors of the metamaterial (e.g., negative permittivity or permeability).
- **Design:** A split-ring resonator (SRR) array is immersed in NLC as shown in figure 6.

IIT Guwahati | NPTEL swayam Source: Q. Zhao, L. Kang *et al.*, "Electrically tunable negative permeability metamaterials based on nematic liquid crystals," Appl. Phys. Lett., vol. 90, p. 011112, 2007

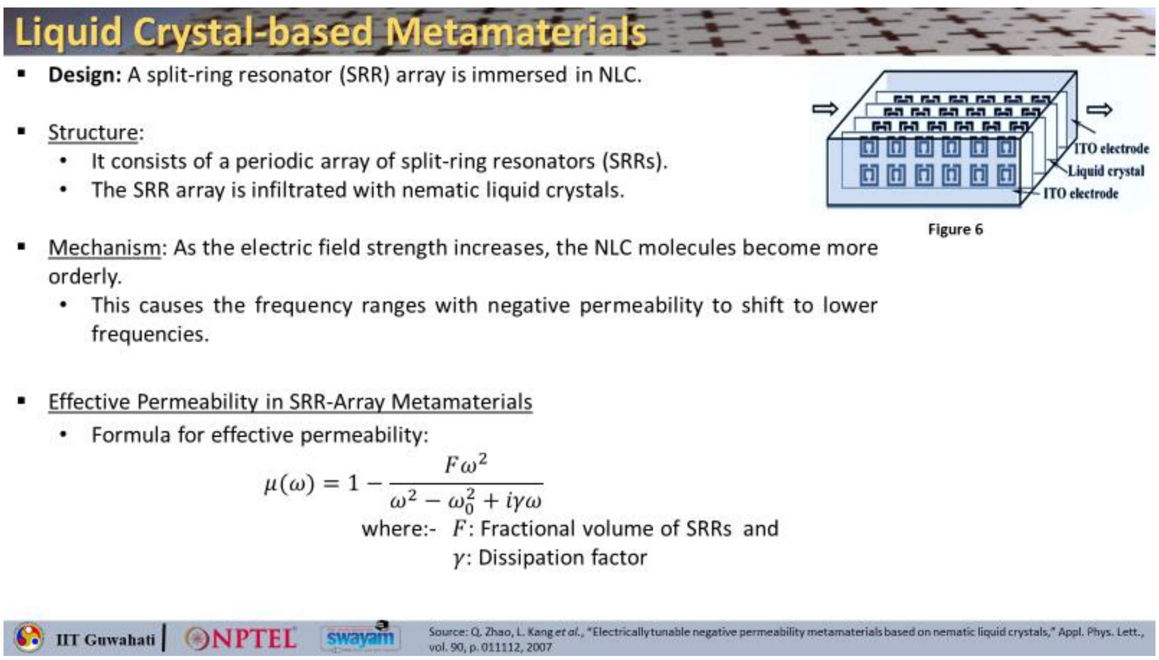
Now, the properties of liquid crystals are very interesting. Liquid crystals are basically intermediate substances between crystalline and liquid states, and they are extremely sensitive to external fields. So, in the power-on state, you will see that when the field is present, the liquid crystal molecular arrangement becomes orderly. leading to some special physical properties. And when in a powered-off state, okay, these liquid crystal molecules become disordered. Now it has been widely used to tune the bandgap of photonic crystals at optical frequencies.

Here we will be focusing on metamaterials in the microwave range, and there, nematic liquid crystals play a very important role. So, these nematic liquid crystals are basically a state of matter characterized by the molecules that exhibit long-range orientational order.

It means that they tend to align along a common direction, but they lack positional ordering. This means that they are not arranged in a regular lattice. However, there is a long-range order, right? So, they are a type of liquid crystal, which is basically a phase of matter, as I discussed.

That has properties between the conventional liquid and solid crystals. Now, you can achieve this electrical tunability in the metamaterials by using a nematic liquid crystal in the structure itself. So, it can be used to dynamically control the permittivity of the metamaterials. And this control allows for tuning of reversed electromagnetic behaviors of the metamaterial such as, you know, negative permittivity or permeability.

So, here is a design of a split ring resonator array being immersed in a neumatic liquid crystal, okay.



So, this is one particular case where you have electrodes on either side to apply the biasing voltage.

These are liquid crystals, okay, where the splitting resonator arrays are basically embedded or immersed. So, it is understood that the structure basically consists of a periodic array of splitting resonators. But these arrays are basically infiltrated with nematic liquid crystals whose properties will change depending on the applied voltage bias. So, now when you apply voltage bias, the electric field strength will increase, and this pneumatic liquid crystal molecules will become more orderly. So, this will cause the frequency ranges of the negative permittivity to shift to a lower frequency, okay. We will see that also.

So, how are they connected? So, the effective permeability in split-ring resonator array metamaterials follows this particular relation. where you have $\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\gamma\omega}$. We have seen this before. So, F is basically the fractional volume of the split-ring resonators, and γ is the dissipation factor.

Now, when you calculate the S_{21} from this kind of system, you can see there is a transmission dip through this metamaterial.

Liquid Crystal-based Metamaterials

- Performance: (Fig. 7(a))
  - The transmitted resonance dip can be continuously and reversibly adjusted using an applied electric field.
  - The maximum frequency shift of the resonance dip is approximately 210 MHz (0.21 GHz).
  - This shift occurs relative to a resonance frequency of around 11.08 GHz.

  Using eq.: $\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\gamma\omega}$

  Here; e.g.- $F = 0.05$ and $\gamma = 10^{10}/4\pi$; (for simulation)

- Simulation Result: (Fig. 7(b))
  - Without LC infiltration:
    - ✓ Negative permeability observed in $13.24 - 13.54$ GHz
  - With LC infiltration (no electric field):
    - ✓ Redshift in negative permeability range
    - ✓ New range: $11.08 - 11.36$ GHz

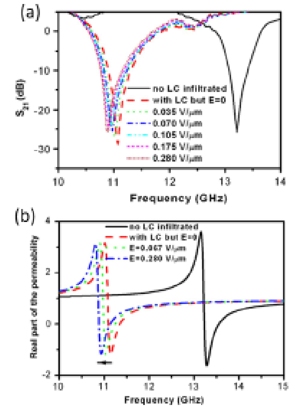


Figure 7.: (a) Transmission spectra for SRR-based metamaterial under different dc electric fields; (b) Calculated effective permeabilities of metamaterials under different electric fields.

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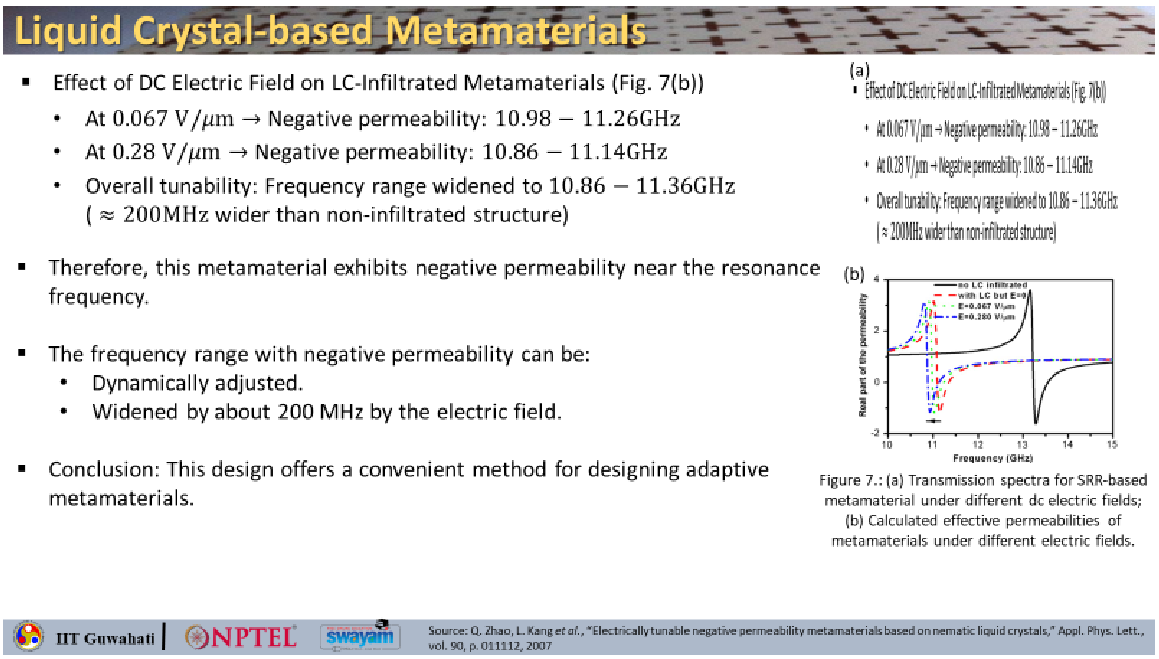
Source: Q. Zhao, L. Kang *et al.*, "Electrically tunable negative permeability metamaterials based on nematic liquid crystals," Appl. Phys. Lett., vol. 90, p. 011112, 2007

And the black solid line shows that there is no liquid crystal present, okay, and then as soon as you put the liquid crystals, the peak basically shifts to this red position, and this is when no electric field is applied. And later on, you keep applying the electric field biasing, and you will see the dip.

The transmission dip is basically shifting to a lower frequency. So, what is seen here is that the maximum frequency shift of the resonance dip is approximately 210 megahertz, which is 0.21 gigahertz. And this shift is occurring in relation to the resonance frequency, which is around 11.08 gigahertz. Now, from this formula you can use this formula and see here you are getting F equals 0.05 and γ is taken as 10 to the power of 10 divided by 4 pi for simulation, and that will give you, so that thing you can also see here. So, the black solid line shows that when there are no liquid crystals in the device, the red dashed line shows.

When liquid crystal is present, there is no biasing, and these are for two different biasings, right? So, what do you see clearly is that the negative permeability ok was observed when there is no liquid crystal That is observed around 13.24 to 13.54 gigahertz here, okay, in this region. But as soon as you put liquid crystal, with no electric field biasing, you see a very strong redshift.

The new range is somewhere between 11.08 and 11.36 gigahertz, and then you can apply the DC electric field slowly.



And then you can apply a DC electric field to this liquid crystal in infiltrated metamaterials. And you will see that now, when the electric field is 0.067 volts per micrometer, the negative permeability shifts towards lower frequency.

It is now between 10.98 and 11.26 gigahertz, and if you further increase the field to 0.28 volts per micrometer, it shifts further towards blue okay, no, it is not called blue; it is towards lower frequency. So, lower frequency is basically redshifted in terms of wavelength. So, you can say these are basically undergoing redshift.

So, what we observe here is that overall cleanability is between, you know, 10.86 and 11.36 gigahertz. It is almost a 200-megahertz tuning range, which is wider than the non-inflated structure. So, you can understand that this metamaterial exhibits negative permeability near its resonance frequencies. So, the frequency range with negative permeability here can be dynamically adjusted by changing the applied electric bias.

Which is the DC electric field, okay, and it can be widened by about 200 megahertz by the electric field.

So, you can conclude that the design essentially offers a convenient method of developing adaptive or tunable metamaterials.

So, with that, we conclude this lecture. So, we will continue our discussion on thermally tunable metamaterials in the next lecture. If you have 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.