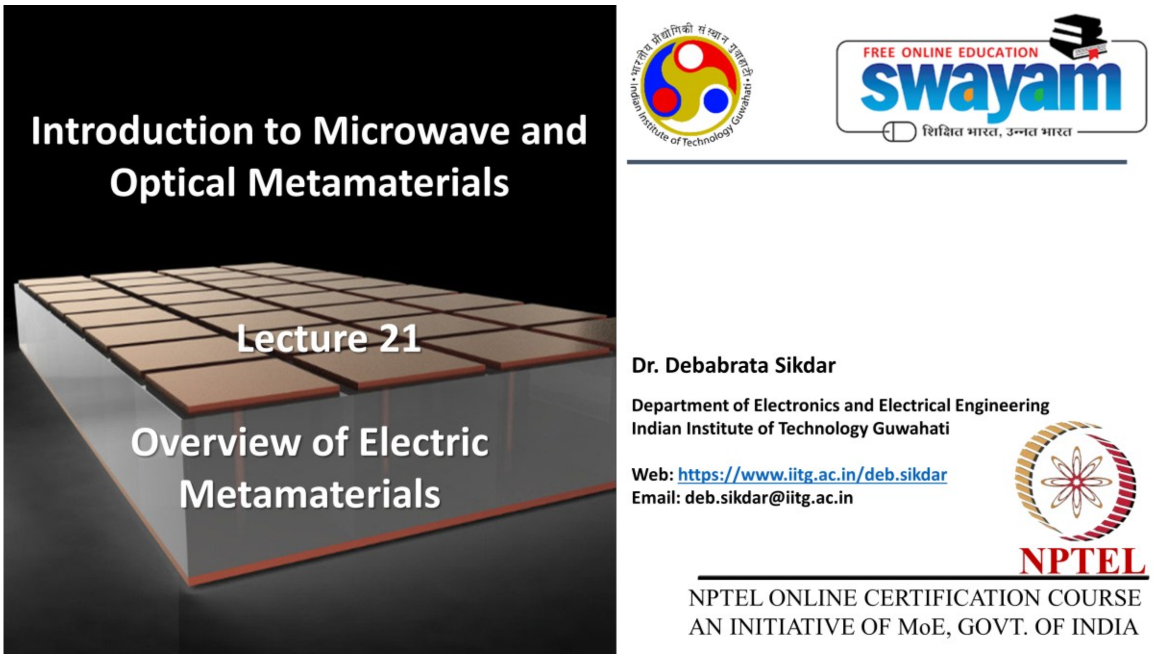
Course Name: Introduction to Microwave and Optical Metamaterials
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-5
Lecture-21

Lec 21: Overview of Electric Metamaterials



Lecture Outline

- Brief Overview of Electric Metamaterials (Artificial Dielectrics)
- EM Properties of Stratified Metal-Dielectric Composites
- Wiener Bounds

Hello students, welcome to Lecture 21 of the online course on Introduction to Microwave and Optical

Brief Overview of Electric Metamaterials (Artificial Dielectrics)

- Electric metamaterials – engineered to exhibit specific electric properties.
- The central concept is electric permittivity (ε)—a key parameter for describing a material's electric response.
- The main purpose of studying electric metamaterials is to create artificial metal-dielectric structures that possess a permittivity of a desired value.
- An example is the Roman glass artifact, composed of gold nanoparticles in a ruby host.
- The color properties of such artifacts can be understood using mixing rules for metal-dielectric materials.

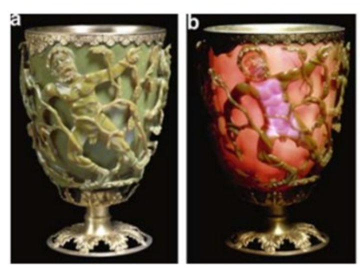


Fig. The Lycurgus Cup viewed (a) in reflected light and (b) in transmitted light.

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

Brief Overview of Electric Metamaterials (Artificial Dielectrics)

- From the 1940s to 1970s, electric metamaterials were studied mainly for radar technology.
- They were not yet known as "electric metamaterials" but referred to as “artificial dielectrics”.
- These materials consisted of periodic metal-dielectric units with subwavelength metal particles in a uniform background host.
- The term “artificial dielectrics” was prominent, used especially in microwave technology, to describe the man-made materials.
- They mimicked macroscopic analogue of natural dielectrics, except their atomic/molecular structure was artificially structured (engineered), a principle central to modern metamaterials.

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

Brief Overview of Electric Metamaterials (Artificial Dielectrics)

- Winston Kock, a Bell Labs engineer in the 1940s, is considered a pioneer of artificial dielectrics.
- Kock proposed several lens structures consisting of parallel metal plates or metallic sphere arrays embedded in a dielectric matrix.
- Key contributions:
  - Used equivalent material parameters to describe electromagnetic responses.
  - Explored periodic metal-dielectric structures with effective refractive indices both larger and smaller than unity.
  - Introduced terms “phase delay” and “phase advance” to describe wave behavior.
  - Drew a clear analogy between artificial and natural crystalline dielectrics.

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

Metamaterials. Today's lecture will be an overview of electric metamaterials. Here is the lecture outline. We will have a brief overview of the electric metamaterials, also called artificial dielectrics. We will look into the electromagnetic properties of stratified metal

Brief Overview of Electric Metamaterials (Artificial Dielectrics)

- The "rodded medium" is one of the most important artificial dielectric, made of a periodically arranged lattice of metallic rods in vacuum or dielectric material.
- The rodded medium is also known as the wire grid or wire mesh.
- This structure can mimic plasma behavior like that of a Drude metal.
- The plasma frequency of the composite material can be tuned by varying the geometrical parameters of the wire array.
- A similar concept was reinvented by Sir John Pendry in the late 20th century.

IIT Guwahati | NPTEL swayam

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

dielectric composites and discuss about Weiner bounds in details. So, here is an overview of electric metamaterials.

So, as you understand, these are engineered materials that are made to exhibit specific electric properties. So, when you talk about electric metamaterials, the central concept is that you are going to custom-design the electric permittivity. Right, so that's a key parameter that describes the material's electric response or makes response to an electric field. The main purpose of studying electric metamaterial is that you can create artificial metal dielectric structures which can provide a custom made permittivity value / A particular frequency range, so if you look back in history, you will see that this particular cup, which is also known as the Lycurgus Cup.

It is a Roman glass artifact that is composed of gold nanoparticles in a ruby host. So now this cup has something special. So, you will see that when you shine light from the outside, the cup appears green. That means you are seeing the reflected light that appears green. However, if you put the light source inside the cup, And you see the transmitted light, the cup appears red.

So there is something interesting happening in this particular cup. And these color properties are basically coming from the mixing rules of metal-dielectric materials. People have seen that there are gold nanoparticles in this glass, which has a ruby host. So, what is happening? There are metal dielectric properties that are giving some peculiar electromagnetic responses. Now, if you look at the history of this electric

Brief Overview of Electric Metamaterials (Artificial Dielectrics)

- Artificial dielectrics working at optical frequencies were initially impractical due to the limitations in nanofabrication.
- Despite this, early researchers adopted optical terminology when studying microwave-frequency artificial dielectrics.
- The refractive index was commonly used to describe wave behavior in such media at microwave frequencies.
- Researchers could engineer the magnitude, value, and dispersion in the effective refractive index of artificial dielectrics in a controlled manner.
- Many microwave studies used the phrase “optical properties” when the radio wave behavior is characterized using the refractive index even though they didn’t operate at optical frequencies.

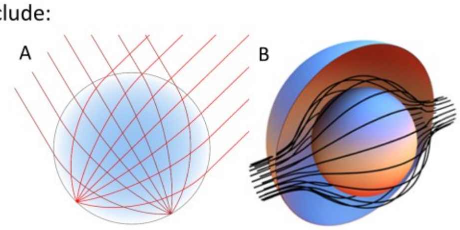
IIT Guwahati | NPTEL swayam Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

metamaterials, they were mainly studied for radar technology and / the years the 1940 to 1970s, right.

And they were not yet known as electric

Brief Overview of Electric Metamaterials (Artificial Dielectrics)

- Various artificial dielectrics, both periodic and disordered, serve as the foundation for more complicated metamaterial structures and devices such as negative-index materials and optical hyperlenses.
- Any metamaterial must have an electric response distinct from its constituent materials.
- Thus, all metamaterials are inherently electric metamaterials, whether or not electric properties are the focus of primary study or not.
- Artificial dielectrics are crucial when the desired device requires a gradient in the material property.
- Examples of structures with a varying permittivity requirement include:
  - (A) Luneburg lens (conventional device).
  - (B) Optical cloak (modern innovation device).



IIT Guwahati | NPTEL swayam Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

metamaterials; rather, they were referred to as artificial dielectrics. These materials typically consist of periodic metal-dielectric units, with subwavelength metal particles in a uniform background medium or host. So, the name artificial dielectrics was prominent and was used particularly in microwave technology. That was done to describe and differentiate that these are man-made materials. So, what did they use to do? They mimicked the macroscopic analog of natural dielectrics except their atomic or molecular structure which in this case will be artificially structured in that form of meta atoms that we have briefly discussed earlier and that is the principle you know central to this modern metamaterials.

So, Winster Koch, he was a Bell Labs engineer, he basically is considered to be the pioneer of this artificial dielectrics and he worked on this in 1940s. So, he aimed to develop low-loss, lightweight, cost-effective radio wave lenses. So, Koch basically proposed several lens structures consisting of, say, parallel plates, parallel metallic plates, or metallic sphere arrays that are embedded in a dielectric matrix. So, his key contributions are okay, or you can say he pioneered a couple of interesting fields in this research on metamaterials. He used equivalent material properties to describe the electromagnetic response of such composites.

He explored periodic metallic dielectric structures with effective refractive indices, both larger and smaller than unity. He also introduced the terms phase delay and phase advance to describe wave behavior. And he was able to draw a clear analogy between artificial and natural crystalline dielectrics. So, among different media, the rodded medium is one of the most important artificial dielectrics. So, the name itself tells you it is nothing but a periodically arranged lattice of metallic rods in a vacuum or dielectric medium.

So, this rodded medium is also known as a wear grid or wear mesh. So, early researchers who contributed to the development of this topic include Brown, Rotman, and Golden. So, the structure was able to mimic the plasma behavior of a Drude model metal and the plasma frequency. The properties of the composite material can be tuned by varying the geometrical parameters of the wire array. And this is where this artificial dielectric or the artificial metal kinds of concept came in because in natural materials the plasma frequency is a fixed quantity you cannot tune it, but here based on the geometrical parameters of the structure you can tune that very fundamental property ok and that is where you know the metamaterial concept came in.

So, a similar concept was reinvented by Sir John Pendry of Imperial College London in the 20th century. However, they adopted the optical terminologies something like you know the refractive index was commonly used to describe the wave behavior. In such media, even at radio or microwave frequencies. So, researchers could engineer the magnitude value and the dispersion in the effective refractive index of these artificial dielectrics in a controlled manner. And this is where the engineering aspect comes into the picture; you can actually tune the value of the dispersion based on the physical

EM Properties of Stratified Metal-Dielectric Composites

- Here we examine a periodically layered composite made of two isotropic materials.
- Materials are arranged in parallel manner.
- Bulk permittivity of the two constituents are denoted as ε_1 and ε_2.
- Volume filling fraction of material 1 is f_1, while material 2 has $f_2 = 1 - f_1$.
- The two key configurations analyzed are:
  - External electric field parallel to the interfaces.
  - External electric field perpendicular to the interfaces.

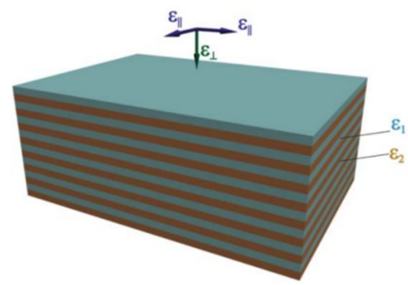


Fig. Schematic of a layered metal-dielectric structure

EM Properties of Stratified Metal-Dielectric Composites

- The aim is to determine effective permittivity ($\varepsilon_{\parallel}$ or $\varepsilon_{\perp}$) for two principal polarizations.
- Regardless of the incident wave electric field polarization, the basic constitutive relation holds for each constituent layer as well as for the whole composite: $D_i = \varepsilon_i E_i$

Case 1: When the electric field is parallel to the interfaces:

$$E_1 = E_2 = E_e$$

- The effective electric flux density (D_e) is the volume-weighted average of the flux densities from both layers:

$$D_e = f_1 D_1 + f_2 D_2$$

- The effective permittivity for parallel polarization is given as:

$$\varepsilon_{\parallel} = f_1 \varepsilon_1 + f_2 \varepsilon_2$$

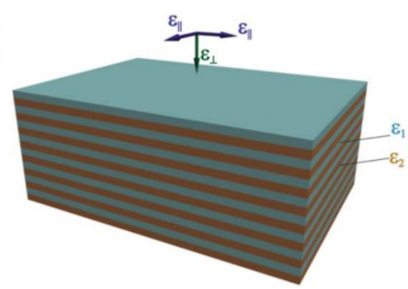


Fig. Schematic of a layered metal-dielectric structure

EM Properties of Stratified Metal-Dielectric Composites

Case 2: When the electric field is perpendicular to the interfaces:

$$D_1 = D_2 = D_e$$

- The effective electric field (E_e) is a volume-weighted average:

$$E_e = f_1 E_1 + f_2 E_2$$

- Combining the relations gives the effective permittivity:

$$\varepsilon_\perp = \frac{\varepsilon_1 \varepsilon_2}{f_2 \varepsilon_1 + f_1 \varepsilon_2}$$

- The effective permittivity of a layered composite can also be derived using Bruggeman's effective medium theory as:

$$f_1 \frac{\varepsilon_1 - \varepsilon_{BG}}{\varepsilon_1 + \kappa \varepsilon_{BG}} + f_2 \frac{\varepsilon_2 - \varepsilon_{BG}}{\varepsilon_2 + \kappa \varepsilon_{BG}} = 0.$$

- $\kappa = 0$: field is perpendicular to the layers → recovers $\varepsilon_\perp$
- $\kappa \to \infty$: field is parallel to the layers → recovers $\varepsilon_\parallel$

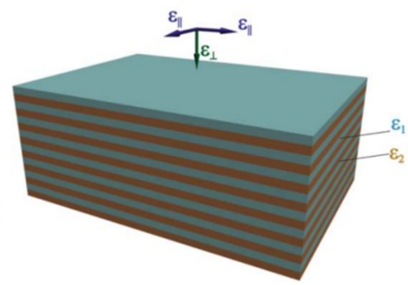


Fig. Schematic of a layered metal-dielectric structure

IIT Guwahati | NPTEL swayam

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

EM Properties of Stratified Metal-Dielectric Composites

- These two extreme cases correspond exactly to the two principal orientations of the layered system as shown in figure.
- The formula of effective permittivity can be generalized for periodically layered systems consisting of more than two materials as:

$$\varepsilon_\parallel = \sum_i f_i \varepsilon_i$$

$$\varepsilon_\perp^{-1} = \sum_i f_i \varepsilon_i^{-1}$$

- For a multi-material layered composite, the sum of all volume fractions ($\sum f_i$) must equal 1.

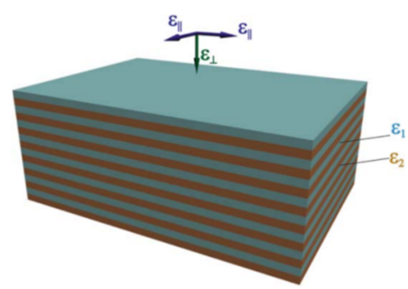


Fig. Schematic of a layered metal-dielectric structure

IIT Guwahati | NPTEL swayam

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

properties of the design.

So, many microwave studies basically use this phase optical properties when the radio wave behavior is characterized using refractive index even though they do not particularly operate at the optical frequencies. So, various artificial dielectrics it can be both periodic or disordered they basically served as foundation for more complicated

EM Properties of Stratified Metal-Dielectric Composites

- When the electric field is parallel to the layers:
  - The effective permittivity is the weighted arithmetic mean of all constituent permittivities.
- When the electric field is perpendicular to the layers:
  - The effective permittivity is the weighted harmonic mean of the permittivities.
- For an arbitrary two-phase composite, the permittivity values ($\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$) act as upper and lower bounds for the effective permittivity.
- These bounds correspond to extreme field screening cases:
  - Full screening ($\kappa = 0$) and no screening ($\kappa \rightarrow \infty$).

IIT Guwahati | NPTEL swayam

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

metamaterial structures and devices such as negative refractive index materials or optical hyperlenses. Ok. So, we have understood that any metamaterial gets its electric response from the structure, which is basically very different from its constituent material properties. So, it does not really depend on the chemical composition; it rather depends on the physical structure of the meta-atoms.

Thus all metamaterials you will see that you know they are inherently electric metamaterials whether or not the electric properties are the main focus of this primary study or not ok. So, artificial dielectrics are crucial when the desired device requires a gradient in the material properties. So, some examples of this kind of structure which has got varying permittivity requirement will include this Lundberg lens which is conventional design. So, you can see the blue shading, which is∝the refractive index values; this is the cross section of a standard lumber length, okay. And the other one shows the optical cloak where you can have an object hidden inside this cloak, and this cloak allows the light waves to bend around the object.

So, that you know, they can, after passing the object boundary, again converge in the same way they were before the object, okay. So, it looks like nothing is here, okay. So, this cloak material will also have this kind of, you know, spatially varying permittivity, right? So, you can design these things based on this artificial dielectric. So, now let us look into the electromagnetic properties of stratified metallic electric composites. So, that will take us forward to understanding how exactly this artificial dielectrics can be designed.

So, in this example we examine a periodically layered composite of two isotropic materials So, you can see the materials are basically arranged in parallel manner there are two different material one has got permittivity of$\varepsilon 1$ another has got$\varepsilon 2$ ok. So, these are basically the bulk permittivities of the two constituent materials. and we can consider the volume fraction of material 1 to be F_1 and then the volume fraction of the second material will be F_2 which is nothing but 1 - F_1. So, F_2 and F_1 are related, right? What can you do here? The first important thing you need to keep in mind is what the thickness of each layer is. The layer thickness is considered to be much smaller than the wavelength of the incident light and that is when only the system can be considered as a metamaterial or it will behave like metamaterial right.

So, in this kind of system, there are two principal situations that can be considered. The first one is that the external electric field is parallel to the interface, which is when the electric field is parallel to this interface. The second one will be the one when the electric field is perpendicular to the interface, right? So, you are basically marking those with two different permittivities,εparallel andεperpendicular, for the two polarizations, right? So, you can see this is marked withε So, there are two cases when you can have parallel one along this axis also along these axis, but this one is the perpendicular one. So, that is calledεperpendicular. Now, regardless of the incident wave's electric field polarization.

The basic constitutive relation holds for each constituent material as well as for the whole composite. So, you can write di equalsεi ei. So, ei is basically the electric field, and d is basically the displacement field, right? So, now let us look into case 1. So, case 1 is when the incident field is considered parallel to the interface of this layered system. So, what do you do? When you apply the boundary condition, it states that the electric field must be continuous across the boundary between the layers, and these are dictated by Maxwell's equations.

So, you can write at the interfaces that $E_1 = E_2$, and that can be taken as E, which is basically the overall effective medium. So, E here stands for the overall effective medium, right? So, the effective electric flux density \(D_e \) can also be calculated as a volume-weighted average of the two flux densities \(D_1 \) and \(D_2 \). So, D e is nothing but the effective electric flux density that you can write as $F_1 D_1 + F_2 D_2$, right? So, that helps you to find out the effective permittivity also for the parallel polarization and that can be simply calculated as εparallel = f 1ε1 + f 2ε2 ok. So, how is it coming? So, you are basically combining the equations, and that allows you to obtain the effective

Wiener Bounds

- The bounds are sometimes known as the Wiener bounds, named after Otto Wiener (1912).
- The Wiener bounds are useful for assessing the range of possible permittivities in a system.
- They can be visualized in the complex permittivity plane, with:
  - Real part on the horizontal axis.
  - Imaginary part on the vertical axis.
- Each constituent's permittivity (ε_1 or ε_2) is plotted as an isolated point on the complex plane:
  - Represented as $\varepsilon = \varepsilon' + i\varepsilon''$ (real + imaginary parts).

permittivity, which isεparallel. So, that is basically the effective permittivity along the interface, and that is the case when the electric field is directed along the layers.

Now, you move to the second situation where the circumstances are quite different because here the electric field is basically polarized perpendicular to the interface. So, we are looking here, right? So, in this case, the electric flux D_i must be continuous across the boundary between two adjacent layers due to the absence of surface charges. So, you can simply write $D_1 = D_2 = De$. So, in this case, the effective electric field will be calculated as a volume-weighted average. So, you can writeεsorry E e that is the effective electric field will be F_1, $E_1 + F_2\ E_2$.

So, from that, if you combine the two equations, what do you get? You can get they are related this two will be related byεperpendicular and then you can calculateεperpendicular asε1ε2 / F 2ε1 + F 1ε2 ok. Now, the effective permittivity of this composite layer can also be derived by Bregman's effective medium theory, which we have already discussed in one of our previous lectures. You can calculate it as F 1ε1 -εbg /ε_1 + kappaεbg I will tell you what kappa is +ε_2 sorry + f_2 timesε2 -εbg /ε_2 + kappaεbg = 0. Now, here you see this new term; this was not discussed earlier. This kappa, ok, is basically a parameter that represents the screening of the external field by a medium.

So, the screening factor can reach its maximum value of ∞ when all the boundaries of the composite are parallel to the electric field and also this kappa can reach a value of 0 if the field is normal to the boundaries ok. So, you can simply write it like this: when kappa = 0, that means the field is perpendicular to the layers. So, the effective permittivity recovers ε perpendicular. And when kappa = infinity, that is, the field is parallel to the layers, that means it will recoverεparallel, okay. Now these are the two extreme cases that correspond exactly to the two principal orientations of the layered system, as you can see in this figure.

Now you can extend this kind of effective medium approach for this periodically layered system where more than two materials can be involved. So, say you have more materials you can find out the parallel permittivity as summation / i F iεi. So, F_i will be the volume fraction of materialεi or material i you can say and the perpendicular permittivity will be written as 1 byεperpendicular will be summation / i fi byεi ok. So, that way you can calculate and you have to just remember that for a multi material layered composite the sum of all the volume fractions should add up to 1. That means if you do summation / fi that should equal to Now, when the electric field is parallel to the layers, we have seen that the effective permittivity is basically the weighted arithmetic mean of all the constituent permittivities.

And on the other hand, if you consider the electric field to be perpendicular to the layers, the effective permittivity is basically the weighted harmonic mean of the permittivities, right? So, these are the main differences ok for an arbitrary two phase composite this permittivity values that you have seenεparallel andεperpendicular act as a upper and the lower bound for the effective permittivities. So, these are the two you know limiting cases as you can think of. So, these bounds basically correspond to the extreme field screening case. So, you can see that when there is full screening, kappa is 0; when there is no screening at all.

So, kappa becomes infinite. So, that one gives you correspondingly, you know, for kappa = 0, we have seen you getεperpendicular, and kappa = ∞ will give you.εis parallel. Now, with that, you can discuss and understand that these are basically the bounds. And these bounds are also known as Wehner bounds, which are named after Otto Wehner; in 1912, he discussed this. The Wiener bounds are useful for assessing the range of possible permittivities in a system.

So, you got to understand that what range you can you know within which range you can vary the permittivity based on a particular given system. So, they can be basically visualized in a complex permittivity plane where you plot the real part of the permittivity on the horizontal axis and you put the imaginary part on the vertical axis and each constituents permittivity likeε1 orε2 can be plotted as an isolated point on that complex plane. and you can represent each of these as its real part and the imaginary parts because you can always write any permittivity the complex permittivity asεprime + iεdouble prime. So, this is the real part; this is the imaginary part.

So, let us see how it looks. So, if you consider the case of two dielectric materials, okay. So, you are basically having titanium, which is - 4, okay. So, it is like here, this is the real axis, okay, real permittivity; this is the imaginary permittivity. So, these are basically the Wehner bounds for the permittivity of a titanium-silicon composite at a_{600}-nanometer wavelength. So, how do you plot it? Let us consider the permittivity of titanium to be - 4 + 12i.

So, that turns out to be this point. So, this - 4 and this 12 are on the imaginary axis, and then silicon has got 15 + 0.2i. So, that is slightly above the real axis. So, now as you can see that when the filling fraction f of material ε_1 that vary.

So, you can just say this is basically F_1. So, if there is a two material system it is very easy that if you know f_1 f_2 is simply 1 - f_1. So, you can just talk about one material's filling fraction. So, what you see here is that the lower screening bound basically traces a straight line between these two permittivities,ε_1 andε_2. The higher boundary, so that is basically the lower one, is always the parallel oneεparallel. Now, the higher screening bound, which is theεperpendicular, forms a circular arc.

Okay. So, the circular arc through, you know,ε_1 andε_2, then comes with the origin, right? So, how do you understand or interpret this graph? So, you can say this is titanium, right? So, when the filling fraction changes from 0 to 1, that means you are basically moving from, say, this lower bound to the upper bound, right? So, as for the metal component, which is titanium, the filling fraction is changing from 0 to 1. You can see that the parallel

Wiener Bounds

- As filling fraction f (of material ε_1) vary:
  - The low-screening bound traces a straight line between ε_1 and ε_2.
  - The high-screening bound forms a circular arc through ε_1, ε_2, and the origin.
- As metal (Titanium) filling fraction changes from 0 to 1:
  - Parallel polarization ($\varepsilon_{\parallel}$): permittivity moves linearly from ε_2 to ε_1 (solid line).
  - Perpendicular polarization ($\varepsilon_{\perp}$): permittivity follows a dashed circular arc.

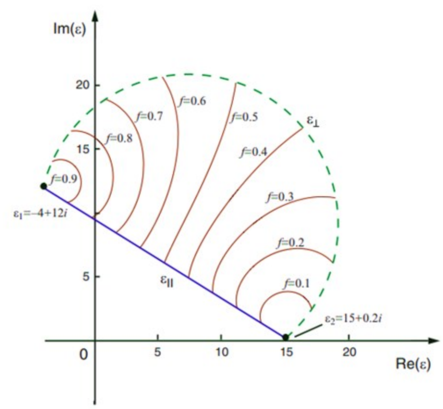


Fig. The Wiener bounds for the permittivity of a titanium–silicon composite at λ = 600 nm.

IIT Guwahati | NPTEL swayam Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

polarization

Wiener Bounds

- For a fixed metal fraction, shape-dependent effective medium theory describes a thin curve in the plot.
- Layered metal-dielectric composites enable permittivity values that are unattainable in bulk materials.
- Special cases:
  - $\varepsilon_{\parallel} \rightarrow 0$ when $f_1/f_2 = -\varepsilon_2/\varepsilon_1$
  - $\varepsilon_{\perp} \rightarrow \infty$ when $f_1/f_2 = -\varepsilon_1/\varepsilon_2$

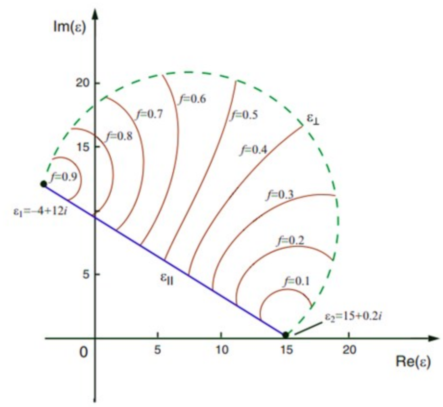


Fig. The Wiener bounds for the permittivity of a titanium–silicon composite at λ = 600 nm.

Wiener Bounds

- If the imaginary parts of ε_1 and ε_2 are small:
  - Their corresponding points on the complex plane lie near the horizontal axis.
  - As a result, the circular arc for $\varepsilon_{\perp}$ can extend to extremely large values.
- Extreme permittivity values ($\varepsilon \approx 0$ or $\varepsilon \rightarrow \infty$) are suitable for photonic nanocircuits at optical frequencies.

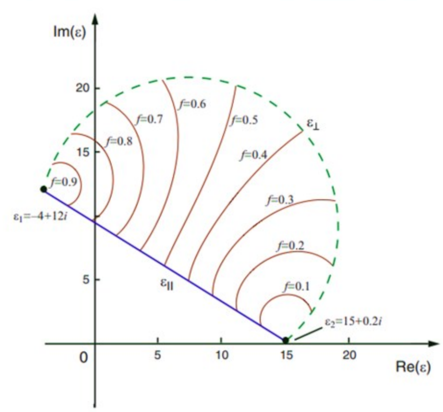


Fig. The Wiener bounds for the permittivity of a titanium–silicon composite at λ = 600 nm.

IIT Guwahati | NPTEL swayam Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

permittivity moves linearly from ε_2 to ε_1. That is how the solid line is drawn. So, you will actually move along this line.

So, here you can consider f to be 0. Because you do not have any titanium at all. So, it is purely silicone material. So, you have this permittivity ε_2, but then when you keep on increasing the fraction it will move along this line and finally, here your f = 1 and you will have completely titanium material. However, if you look at the same thing for

Wiener Bounds

- A number of metamaterial devices have been proposed and demonstrated based on layered metal-dielectric composites.
- By selecting suitable permittivities and filling ratios, it is possible to create a highly anisotropic material with:
  - $\varepsilon_{\parallel} \approx 0$ (parallel direction) and $\varepsilon_{\perp} \rightarrow \infty$ (perpendicular direction) simultaneously.
- These highly anisotropic materials are used in superlenses and hyperlenses.
- With dedicated control of the spatially varying thickness combinations, the stratified metal-dielectric structure has also been used in the design of an optical cloaking device in a cylindrical geometry.

IIT Guwahati | NPTEL swayam

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

perpendicular polarization, you will basically go along this line, okay. So, along with different volume fractions, you are basically moving along this circular arc.

Now, what happens with a fixed metal fraction? You can see that the shape-dependent effective medium theory will describe a thin curve in this plot, okay, something like this here. So, anything in between, you know,εparallel andεperpendicular, okay? So, you are basically moving along these thin curves. So, this thin curve for a given filling fraction basically lies between the two Wehner bounds. So, that actually tells you that these are the two absolute limits beyond which you cannot go. So, layered metal-dielectric composites could enable permittivity values.

that you can see that are unattainable in the bulk material. So, for f = 1, you can go on this particular curve; for f = 2, you can go like this. So, this is your lower bound, this is your upper bound, and so on, okay. So what are the special cases you can consider you can see that when f_1/f_2 becomes you know equal to $-\varepsilon_2$ byε1 in that case the parallel productivity tends to 0. and if f_1/f_2 becomes $-\varepsilon_1$ byε2 in that case of permittivity the perpendicular one or the upper limit in the permit permittivity goes to infinity.

That means these are the two extremes okay that you can always think of and this is the allowed region of the permittivities that you can obtain from this particular system. Now if the imaginary part of bothε1 andε2 is very small. So, what will happen here is 12. So, it is very high. So, if it is also very small, you will see that their corresponding points on the complex plane will lie very close to the horizontal axis, right? As a result, you will see that this particular arc can extend to extremely large values, right? Because if this entire line is very close to the horizontal axis.

So, that way you can have extreme permittivity values, okay, something likeεvery close to 0,εnear 0, orεinfinity, which are also very suitable for photonic nanocircuits at optical frequencies. So, in such nanocircuits,εinfinity materials are needed as conducting wires for optical displacement currents, and if you look for ε near 0 medium, they can serve as insulators to isolate each functional element. So, what we understood is that these bounds basically tell us the possibilities of a number of metamaterial devices that can be proposed and that people have already demonstrated based on metal-dielectric composites. By selecting suitable permittivities and filling ratios for this kind of layered structure, it is possible to obtain highly anisotropic material, where you can achieve almost 0 parallel permittivity and almost infinite or very large permittivity in the perpendicular direction simultaneously. So, this kind of highly anisotropic material has found applications in superlenses and hyperlenses; we will go into details of this too.

So, these are some peculiar applications of metamaterials that are very interesting, and with dedicated control of these specially varying thickness combinations, you will see that the stratified metal-dielectric structure can also be used for designing optical cloaking devices in cylindrical geometry, which people have also demonstrated. So, with that, we will conclude here for this lecture. In the next lecture, we will describe the periodic array of metallic wires in more detail to tell you how exactly that allows you to tune the permittivity and the plasma frequency. So, if you have any queries regarding this lecture, drop an email to this email address mentioning the course number, the lecture number, and the course name in the subject line.

Slides inserted by fallback (review if needed):

Thank You