Course Name: Introduction to Microwave and Optical Metamaterials
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Week-9
Lecture-45

Lec 45: Applications of Active Hyperbolic Metamaterials

Hello students, welcome to lecture 45 of the online course on the introduction to microwave and optical metamaterials. Today's lecture will be on the applications of active hyperbolic metamaterials.

Lecture Outline

- Applications of Active Hyperbolic Metamaterials
  - Supercollimation of THz light
  - THz modulators

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So, here is the lecture outline; we will discuss two more applications of active hyperbolic metamaterials. One is super collimation of terahertz light, and the other will be terahertz modulators.

Supercollimation of THz light

- Supercollimation at THz frequencies enables sub-wavelength focusing, crucial for:
  - High-resolution THz imaging.
  - Applications includes:
    - ✓ Security screening
    - ✓ Bio-detection
    - ✓ Weather navigation
- Topological Insulators based HMMs offer tunable dispersion:
  - Achieved by doping their surface states.
- Example:
  - Bismuth selenide (Bi_2Se_3) supports highly directional hyperbolic phonon polaritons.
    - ✓ Enables supercollimation of light in the THz regime.

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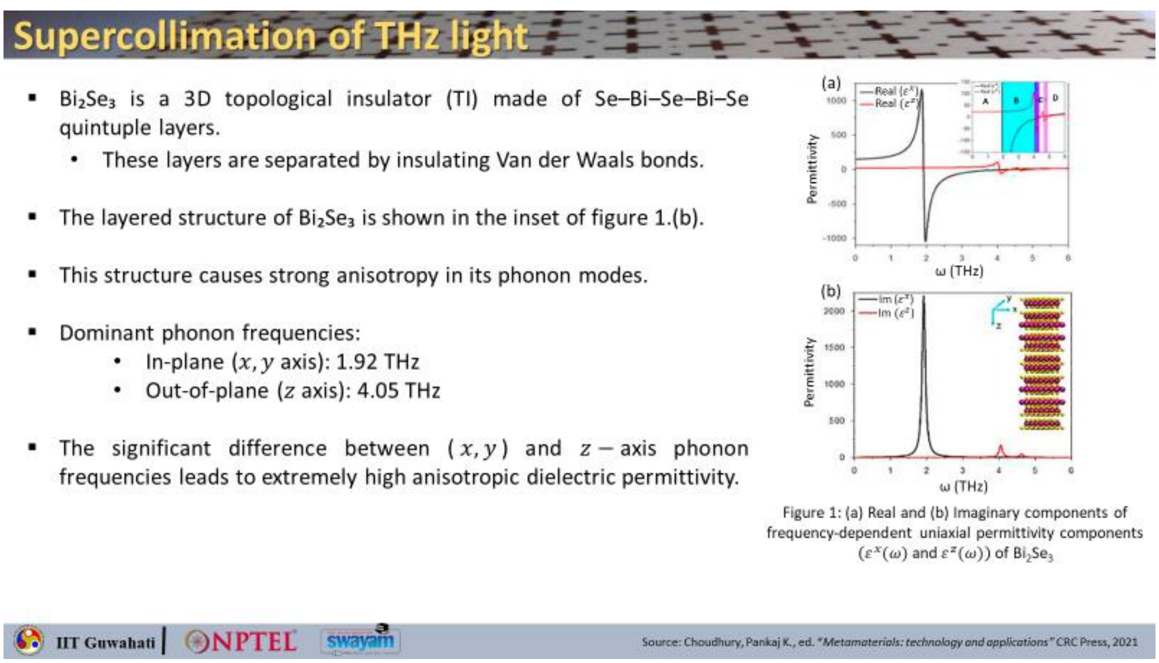
Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

So, let us begin with supercollimation of terahertz light in this lecture. So, in the previous lecture, we mentioned three applications of active hyperbolic metamaterials.

Among them, the first one we have already discussed in the previous lecture. So, now we will move on to discuss the second application of the active metamaterials, hyperbolic metamaterials, which is basically super collimation. Now super collimation at terahertz frequencies is particularly interesting, and it is an interesting feature. Because it enables super wavelength focusing, which is crucial for high-resolution terahertz imaging, and Other applications of this high-resolution terahertz imaging include security screening, bio-detection, weather navigation, etc.

Now, when I talk about super collimation, which is also known as self-collimation, it is basically an optical phenomenon. where a beam of light propagates through specially designed materials like photonic crystals or, in this case, Hyperbolic metamaterial without spreading out due to diffraction. That means it effectively maintains its width over a significant distance. So, this occurs because of the material's unique dispersive properties that basically counteract the natural tendency of light to diffract. So, topological insulator-based hyperbolic metamaterials offer tunable dispersion, which can be achieved by doping their surface states.

So, you can take an example, and the most popular one that is known is bismuth selenide, Bi2Se3. That supports highly directional hyperbolic phonon polaritons. So, we will cover these terms in the next few slides. So, this basically enables a super collimation of light in the terahertz regime. So, this particular material is very interesting, and that is what we will be studying here today.



So, bismuth selenide is basically a compound of bismuth and selenium, which is a 3D topological insulator. That is made of selenium bismuth, selenium bismuth, and selenium, kind of, you know, quintuple layers. So, the quintuple basically means that it consists of 5 parts or 5 things, right? So, these layers are basically separated by insulating van der Waals bonds. So, in this particular figure, you can see the layered structure of this bismuth selenite. Now, this structure provides strong anisotropy in its phonon modes.

So, the phonon anisotropy that you will see in bismuth selenide arises from its crystal structure. It affects both acoustic and optical phonons. So optical phonons are particularly interesting in this context. They are basically a type of phonon that is nothing but quantized vibrational modes of the crystal lattice. So, they are characterized by the out-of-phase motion of atoms within the unit cell, meaning the neighboring atoms will vibrate in opposite directions.

So, this is basically the difference between optical phonons and acoustic phonons, where all the atoms move in phase. So, optical phonons become particularly interesting because their vibrational energy can be comparable to the infrared radiation allowing them to interact with light and that is why they got this name optical phonon. So, the dominant phonon frequency you can observe from this graph plots the permittivity values. You will see something is happening along the x or the y axis that is something happening here which is 1.92 terahertz and something also happening here.

For the E z that is the out-of-plane component, that is somewhere around 4.05 terahertz. Now you can also quickly see that we will go into the details of the figure later on, but just by looking at it. If you can understand that plotting the real part of the permittivities is the imaginary part of the frequency dependence, okay, it is being plotted. So, it is also showing that you know the x and y components are equal, while the z component is different.

So it is basically a uniaxial material, and these are all plotted for selenite, and what you can see is that there is a significant difference. that you observe here between the xy component and the z component of the phonon frequencies That leads to extremely high anisotropic dielectric permittivities.

Supercollimation of THz light

- Resulting optical behavior:
  - Real parts of uniaxial permittivity components ($\varepsilon^x(\omega)$ and $\varepsilon^z(\omega)$) become indefinite within a certain THz frequency range.
  - Bi_2Se_3 exhibits hyperbolic dispersion in the THz range for TM-polarized light.
- The dispersion relation is given by:

$$\frac{(k^x)^2+(k^y)^2}{\varepsilon^z(\omega)} + \frac{(k^z)^2}{\varepsilon^x(\omega)} = \frac{\omega^2}{c^2}$$

- To determine uniaxial Permittivity of Bi_2Se_3:

  A Lorentz–Drude oscillator model is used for anisotropic phonon polariton materials (Bi_2Se_3).

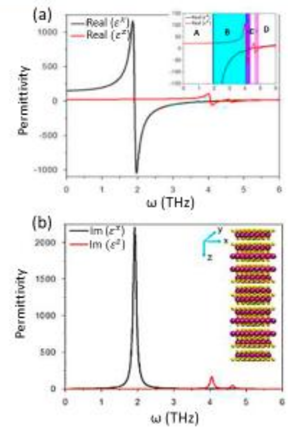


Figure 1: (a) Real and (b) Imaginary components of frequency-dependent uniaxial permittivity components ($\varepsilon^x(\omega)$ and $\varepsilon^z(\omega)$) of Bi_2Se_3

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

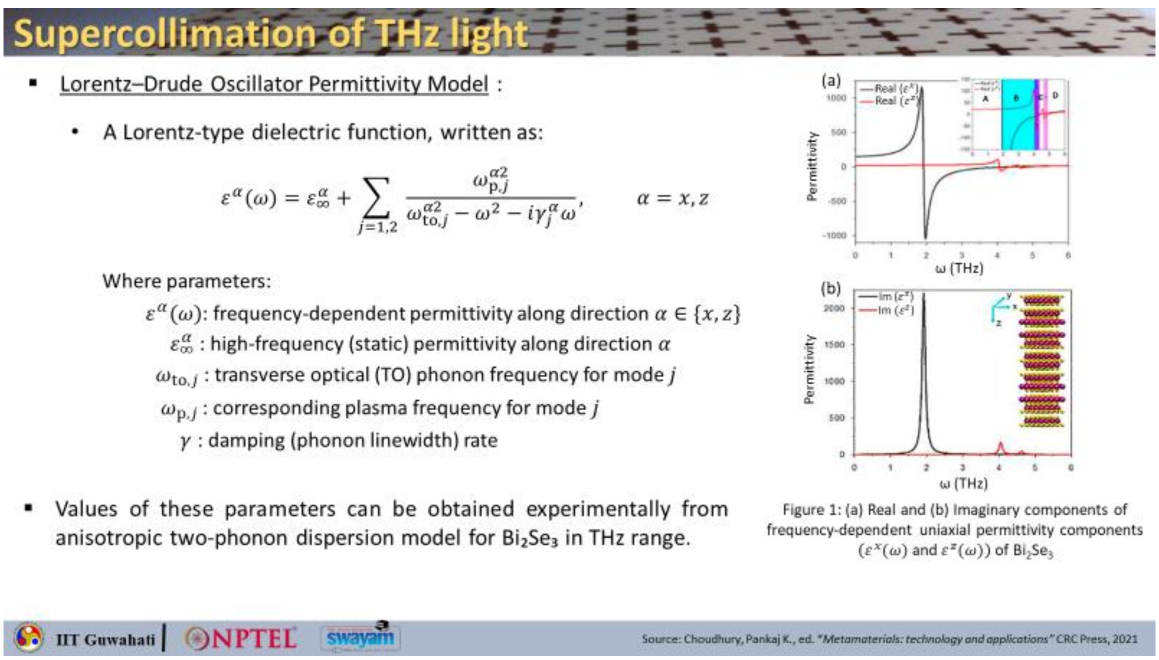
As a result, you will see the real part of the uniaxial permittivity components. These are the real parts, okay? So, epsilon x omega and epsilon z omega, which is this one. They essentially become indefinite within a certain terahertz frequency range.

And bismuth selenide basically exhibits hyperbolic dispersion in the terahertz range for TM polarized light. So, we will discuss the different kinds of regimes where it can operate as a hyperbolic metamaterial, okay? So, in this case, the dispersion relation of this material can be given as $\frac{(k^x)^2+(k^y)^2}{\varepsilon^z(\omega)} + \frac{(k^z)^2}{\varepsilon^x(\omega)} = \frac{\omega^2}{c^2}$. Now, to determine the uniaxial permittivity of this material, you can use a Lorentz-Drude oscillator model for estimating these anisotropic phonon-polariton materials, okay.

So, in bismuth selenide, you will see that phonon polaritons are basically a type of quasiparticle. That is formed by the interaction of light with lattice vibrations. So, that polariton is now coming from the optical interaction with a phonon. So, that is why it is a phonon polariton, right? So, these polaritons can exhibit unique properties due to the materials and isotropy. So, you can use this Lorentz-Drude oscillator model to understand and predict the behavior of phonon polaritons in different directions.

So, as the name suggests, this particular model combines the Drude model for free carriers and the Lorentz model for bound electrons. So, it incorporates both the dynamic response of the electrons in the material to the electromagnetic field and also the effects of damping, right? So, for anisotropic materials such as bismuth selenide, this model is applied separately for different directions. Accounting for the materials' directionally dependent optical properties. So, here is the model. So, you can use this particular dielectric function to write down the permittivity of this material in different directions.

So, alpha here stands for x, y, or z. We are just mentioning x and z because x and y are basically the same in this particular case. You can see that the direction x and y are basically the planar ones, and the z is basically the perpendicular one, Right.



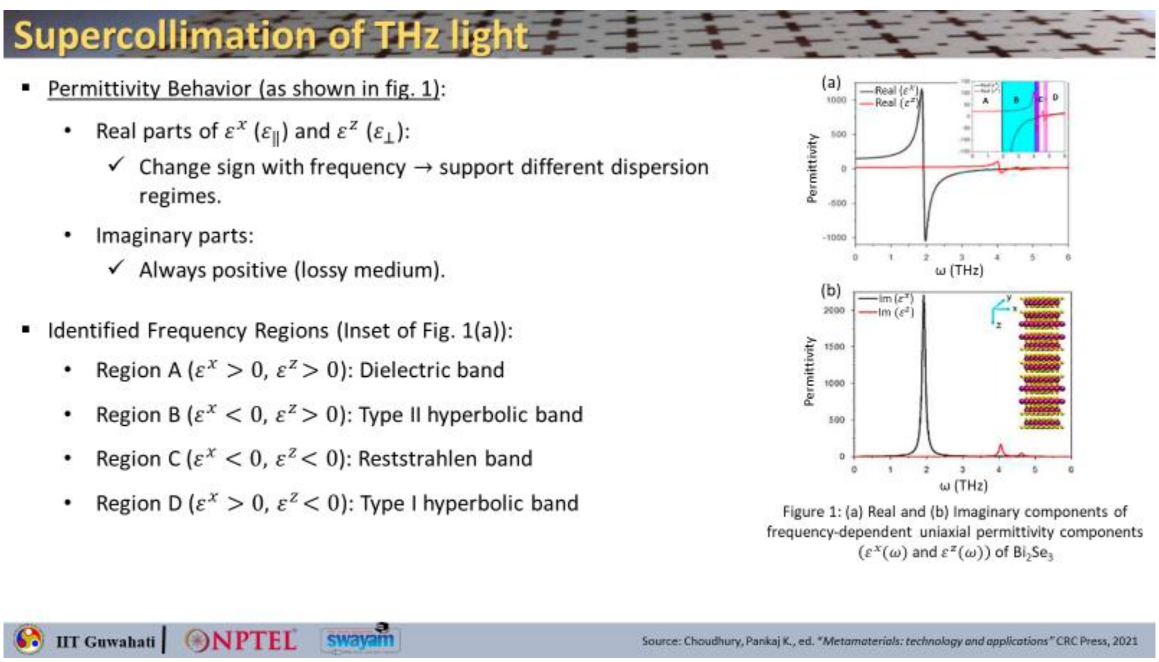
So, epsilon alpha omega { $\varepsilon^{\alpha}(\omega)\} = \varepsilon_{\infty}^{\alpha} + \sum_{j=1,2} \frac{\omega_{p,j}^{\alpha 2}}{\omega_{to,j}^{\alpha 2} - \omega^2 - i\gamma_j^{\alpha}\omega}$; j = 1, 2; these are the two modes, okay. So, what are these parameters? So, this basically tells you the frequency-dependent permittivity along the x or z direction. Epsilon infinity alpha tells you about the high-frequency static permittivity along direction alpha, okay. Omega to j is basically the transverse optical phonon. So, "to" is standing for transverse optical; this is the phonon frequency of mode j.

Okay, alpha tells you about. The direction and wherever you see p, that is basically the plasma frequency associated with that mode. So, omega p j alpha square tells you about the plasma frequency, and gamma is basically the damping or the phonon linewidth, okay. So, that is basically the collision rate, right? So, this is how you actually get the Lorentz-Drude oscillator model for modeling the permittivity of this material. Now, the values of these parameters that you see can be obtained experimentally from anisotropy.

The phonon dispersion model for bismuth selenide in the terahertz region. Now, when you talk about the two-phonon dispersion model for bismuth selenide in the terahertz region, it basically focuses on the understanding of how pairs of phonons interact and contribute to the material properties in the terahertz frequency range is important. So, the model is critical for analyzing phonon dynamics, which are essential for understanding the thermal and optical properties of bismuth selenide. Particularly in applications such as thermoelectrics and various potential optical devices. So, in short, you can say that you know the phonon dispersion describes how the frequency of phonons Which are nothing but quantized vibrations of the crystal lattice that vary with their, you know, wave vector or momentum.

So, that is typically the, you know, definition of the dispersion, right, and the two-phonon process that involves simultaneous creation or annihilation of two phonons, which can be crucial for energy transfer and relaxation within the material.

So, now let us carefully look at the plot. So, this is basically the plot of the permittivity that we have just seen in the equation right now, okay?



So, here you can carefully see that the real part epsilon x is nothing but epsilon parallel, as I mentioned. x and y are equal, and they are basically along the plane of the material.

So, they are considered parallel, and epsilon z is basically the perpendicular one. Okay.

So, you see that change sign with frequency, which means it supports different dispersion regimes. and imaginary part this is the imaginary part and these are very large values. So, you can see the imaginary part is always positive; that means it basically behaves like a lossy medium.

Now let us identify the different frequency regimes in this permittivity plot. So, you have to compare and see this one when you have both epsilon x and epsilon z. It is basically the parallel and the perpendicular; both are positive. That means it behaves like a dielectric. So that you can mark a region as A, okay, that is the dielectric band.

Then you have region B, where you know the parallel part becomes negative. So, this is the zero line. So, this is where the parallel part becomes negative, while the perpendicular one remains positive. So, that is where it behaves like a type 2 hyperbolic band, okay? So, you can mark that region as B, okay. So, this is basically the dispersion curve, omega k, and then you can write down the region, okay? Then you have epsilon x is negative, epsilon z is also negative; both are negative, so that is called the reststrahlen band.

So, this reststrahlen band basically refers to a specific wavelength range where a material does. Exhibits strong absorption and high reflectivity. So, in this particular region, you will see that the absorption is also very high because the permittivity is completely negative. So, it is a very highly reflective material, particularly in this infrared region. So, this occurs due to the interaction between electromagnetic radiation and optical phonons.

which are nothing but the lattice vibrations within the material's crystal structure. That is basically the residual ray’s band, a spectral region where you can see the materials become highly reflective. For the electromagnetic waves, that basically comes from the phonon-polariton resonance. So, especially in ionic crystals such as silicon carbide, aluminum nitrate, and gallium nitrate. And topological insulators like this bismuth selenide, you will see this kind of effect.

So, this basically lies between the transverse optical and the longitudinal optical phonon frequencies of the material, which are TO and LO. And the last band is where you will see that your epsilon x is the parallel one. becomes positive, and the epsilon z becomes negative. So, that is the type 1 hyperbolic material, and that region can be marked as region D.

Supercollimation of THz light

- Hyperbolic Bandwidths in Bi_2Se_3 :(inset of figure 1(a))
  - Type II hyperbolic band: Region B
    - ✓ Bandwidth = 2.14 THz (from 1.91 to 4.05 THz)
  - Reststrahlen band: Region C
    - ✓ Bandwidth = 0.35 THz (from 4.05 to 4.4 THz)
  - Type I hyperbolic band: Region D
    - ✓ Bandwidth = 0.3 THz (from 4.6 to 4.9 THz)
- Key Insight:
  - Bi_2Se_3 based HMMs supports both Type I and Type II hyperbolic dispersion in the THz range.

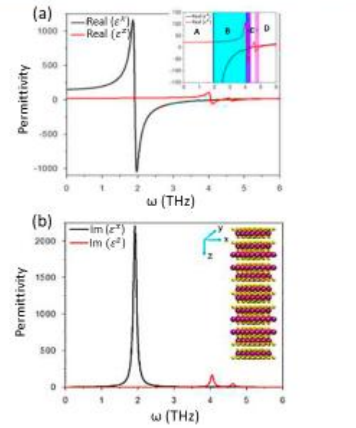


Figure 1: (a) Real and (b) Imaginary components of frequency-dependent uniaxial permittivity components ($\varepsilon^x(\omega)$ and $\varepsilon^z(\omega)$) of Bi_2Se_3

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

Now let us focus one by one. So, we have seen that region B is marked as this one. That is where you have type II hyperbolic bands because your parallel permittivity is negative and perpendicular permittivity is positive. So, it has a bandwidth of 2.

14 terahertz. So, it basically starts from 1.91 to 4.05 terahertz. So, it has a very wide bandwidth. This band is relatively new to the regions and narrows the Raststrahlen band that is.

Region C has a bandwidth of only 0.35 terahertz, where both are negative. So, that basically lies from 4.05 to 4.4 terahertz and the region D that represents type 1 hyperbolic metamaterial kind of behavior Where you have epsilon parallel positive and epsilon perpendicular negative, that also has a narrow bandwidth of 0.3 terahertz ranging from 4.6 to 4.9 terahertz right. So, what is the main key point in this particular discussion? You have seen that bismuth selenide-based hyperbolic metamaterials can support both type 1 and type 2 hyperbolic metamaterial dispersion in this terahertz regime.

Supercollimation of THz light

- Bi_2Se_3 supports highly directional, deeply sub-diffractional hyperbolic phonon-polariton modes.
  - Enables supercollimation and superlensing applications.
- In HMMs, wave propagation occurs only within the resonance cone (RC) defined by hyperbolic dispersion.
- Half of the RC angle: $\alpha_{RC} = \tan^{-1}\left(\sqrt{\frac{\varepsilon^x(\omega)}{\varepsilon^z(\omega)}}\right)$; where $\varepsilon^x(\omega)$: In-plane (lateral) permittivity and $\varepsilon^z(\omega)$: Out-of-plane (vertical) permittivity.
- Supercollimation condition:
  - Occurs when $\alpha_{RC} = 0°$, i.e.; when $\varepsilon^x(\omega) = 0$ or $\varepsilon^z(\omega) = \infty$.
- Figure 2 shows minimum RC angle (≈ 0°) at 4.05 THz — the transition point between the Type II band and Reststrahlen band.

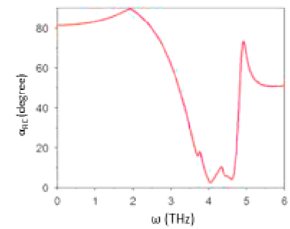

Figure 2: Half of the resonance cone angle as a function of THz frequencies for Bi_2Se_3

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

So, that tells you that you know bismuth selenide can support highly directional, deeply sub-diffraction hyperbolic phonon-polariton modes, okay. So, that will basically allow you to use super collimation and superlensing applications.

So, in hyperbolic metamaterials, we have already seen this concept, but here we will focus on. It is even more that the wave propagation occurs only within the resonance cone, which is called RC, and that is defined by the hyperbolic dispersion. Now, a resonance cone basically refers to a specific angular distribution of electromagnetic energy. That arises due to the unique anisotropic properties of these materials. Specifically, in hyperbolic metamaterials, the resonance cone basically describes how electromagnetic waves propagate.

Creating a cone-shaped energy distribution around the source. So, you can calculate half of this resonance cone angle alpha RC $(\alpha_{RC}) = \tan^{-1}\left(\sqrt{\frac{\varepsilon^x(\omega)}{\varepsilon^z(\omega)}}\right)$. So, $\varepsilon^x(\omega)$ is nothing but the epsilon parallel; it is the in-plane or, you can say, lateral permittivity. $\varepsilon^z(\omega)$ is nothing but out-of-plane or vertical permittivity. Now, what is the condition for supercollimation? You will see that super collimation, okay, means the parallel wavefront or the propagation.

The light beams will occur when alpha RC becomes 0. That means this term becomes 0 and that is possible when your epsilon x omega will become 0 or epsilon z omega will become infinity, okay. So, figure 2 basically shows a plot of this alpha RC as a function of terahertz frequencies for this bismuth selenide material.

Supercollimation of THz light

- Supercollimation effect in Bi_2Se_3 occurs specifically at 4.05 THz:
  - Because the resonance cone (RC) angle is nearly zero at this frequency.
- As the RC angle increases, the intensity spectrum broadens, reducing collimation. (as shown in figure 3.)
- The supercollimation frequency can be tuned by:
  - Adjusting the inversion point between the Type II band and Reststrahlen band.
  - Achievable via doping the surface states of Bi_2Se_3.

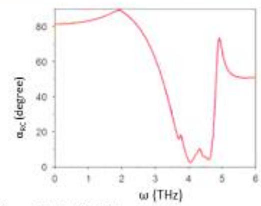

Figure 2: Half of the resonance cone angle as a function of THz frequencies for Bi_2Se_3

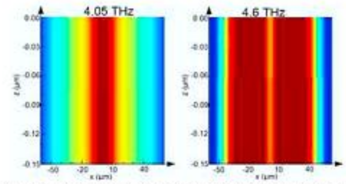

Figure 3: Line profile of normalized intensity recorded at the bottom of quintuple layered Bi_2Se_3

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

So, here you can see the minimum RC is happening somewhere close to this 4.05, which is almost close RC equals 0 degrees, not exactly, but very close. So, this is the transition point between the type II band and type II hyperbolic metamaterial band.

The domain C is your Reststrahlen band right. So, you can see that the supercollimation effect in this material, bismuth selenide, will take place specifically at this frequency. 4.05 terahertz and this is because that your resonance cone angle is almost nearly zero at this frequency. Now, what will happen if the resonance cone angle increases are that you will see the spectrum get broader, and you will reduce the collimation. So, here you can see the line profile of the normalized intensity that is recorded at the bottom of the quintuple-layered bismuth selenite.

So, here you can see exactly at that angle of 4, exactly at 4.05 terahertz where alpha rc is almost 0; you see, you know it is very narrow. But as soon as you move a little away from this at 4.6 terahertz, you can see that the intensity spectrum has basically broadened.

So, that will reduce collimation. So, the super collimation frequency can also be tuned by adjusting the inversion point between this type II band. and the Reststrahlen band and that can be achieved by doping the surface states of the bismuth selenide, right. So, that is the application that you have seen from the supercollimation aspect of these hyperbolic metamaterials.

THz modulators

- Essential components in THz communications, spectroscopy, and imaging.
- THz Modulators are created by integrating photonic structures with tunable conductive materials:
  - Materials include semiconductors, superconductors, perovskites, 2D materials (e.g., graphene, MoS_2), phase-change materials and liquid crystals.
- There are two kinds of THz modulators based on solid-state and non-solid-state with broad or narrow bandwidth responses.
- Narrow bandwidth THz modulators:
  - Often use resonant effects (e.g., Metamaterials, Plasmonics).
  - Require intensive lithography processes.
- Broad bandwidth modulation:
  - Essential for many applications.
  - Achievable using non-resonant, graphene-based solid-state devices.

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

Next, we will move on to terahertz modulators. Terahertz modulators are essential components in terahertz communications, spectroscopy, and imaging.

The modulators can be created by integrating photonic structures with tunable conductive materials. such as semiconductors, superconductors, perovskites, and 2D materials like graphene and MoS2, Different phase change materials, like VO2 and liquid crystals, right? So, there are two types of terahertz modulators based on solid state and non-solid-state technologies, with broad or narrow bandwidth responses. So, among them, you will see that the narrow bandwidth terahertz modulators typically rely on resonant effects. which are enabled by the metamaterials or plasmonics and they are often realized using this kind of modulators.

Solid-state or non-solid-state platforms. So, if you focus on narrow-band terahertz modulators, they will require intensive lithography processes. Because they are based on metamaterials and plasmonics, you have to make that kind of resonator structure. that will give you that narrow bandwidth feature. The other one can be the broad bandwidth modulation that is important for many applications. It can be achieved by, you know, non-resonant and graphene-based solid-state devices, okay.

Because it depends on non-resonant materials, that is why you get a broad bandwidth.

THz modulators

- Active control of THz modulators with high intensity and phase tunability is crucial for many applications.
- High-performance THz modulators should have:
  - High modulation depth
  - Broad operational bandwidth
  - High modulation speed
- Active control of polarization state of light across different spectral bands has wide applications in optics.
- For effective reflective-type active polarization switches, two conditions must be met:
  1. s-polarized reflected intensity must remain unity with or without external stimulus.
  2. p-polarized reflected intensity at resonance must have nearly 100% modulation depth (enables active switching).
- Achieving 100% modulation depth at THz frequencies is challenging.

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

So active control of terahertz modulators with high intensity and phase tunability is critical for many applications. And when we talk about high-performance terahertz modulators, they should have a high modulation depth. So, the difference between the high state response and the low state response should be very, very large. You should have a broad operational bandwidth and high modulation speed.

Active control of the polarization state of light across different spectral bands also has wide applications in optics, right? For effective reflection-type active polarization switches, the following two conditions must be met. So, one thing is that now the s-polarized reflected intensity must remain unity, with or without external stimulus. For the p-polarized reflected intensity at resonance, it must have nearly 100% modulation depth. That means it will enable active switching. So, you can see that achieving 100% modulation depth at terahertz frequencies can be challenging.

So, what is the proposed solution in this case?

THz modulators

- Proposed solution:
  - A THz modulator/active polarization switch based on a high- T_c (critical temperature) superconductor HMM.
  - In Hyperbolic Metamaterials (HMMs), high- T_c superconductors can be used as components to achieve low-loss, tunable THz response.
- YBCO (Yttrium Barium Copper Oxide, $YBa_2Cu_3O_{7-x}$) is an example of a high-Tc superconductor. ($T_c \approx 90$ K).
- Below T_c, YBCO exhibits metallic behaviour:
  - Characterized by negative permittivity, making it suitable as a metallic layer in metamaterials.
- Exciting the Brewster mode of a hyperbolic metamaterial (HMM) enables:
  - Over 98% intensity modulation.
  - 100% phase tunability.
- Temperature variation is used as the external stimulus to actively control these properties.

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You can think of a terahertz modulator or active modulation switch based on high critical temperature. Superconductor hyperbolic metamaterials, okay. So, when you say high critical temperature superconductor, they basically refer to superconducting materials. that become superconducting at relatively high temperatures, typically above 30 Kelvin, as compared to conventional superconductors. Now in hyperbolic metamaterials terms, these high critical temperature superconductors can be Used as components to achieve low loss and a tunable terahertz response.

So one example of this kind of high critical temperature superconductor that has a Tc This YBCO, yttrium barium copper oxide, is of around 90 Kelvin. This is the chemical composition of it. So how does it work? Below this critical temperature, YBCO exhibits metallic behavior that can be characterized by its negative permittivity. So, it is suitable as a metallic layer in the metamaterial. and in that case, so it can else also excite the Brewster mode ok for this hyperbolic metamaterial and that can enable over 98 percent intensity modulation and 100 percent of phase tunability.

THz modulators

- The YBCO –LAO HMM is a Type II HMM (as shown in figure 4).
- This structure exhibits hyperbolic dispersion in a specific frequency range where:
  $\mathrm{Re}(\varepsilon_{\perp}) > 0, \quad \mathrm{Re}(\varepsilon_{\parallel}) < 0$
- Type I HMMs: support Brewster mode because their real $\varepsilon_{\parallel}$ components are positive.
- Type II HMMs:
  - Do not support Brewster mode as their real $\varepsilon_{\parallel}$ components are negative. (figure 5)
- However, it enables THz intensity and phase modulation when:
  - Incidence angle is near the Brewster angle.

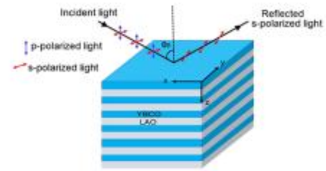

Figure 4: Schematic of YBCO-LAO type II HMM and Principle of the Brewster's angle effect in it

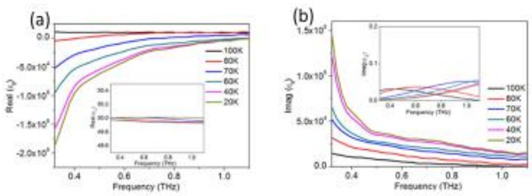

Figure 5: (a) Real parts of parallel and perpendicular permittivity components. (b) Imaginary parts of parallel and perpendicular permittivity components for YBCO-LAO HMM

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Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021
Sreekanth, et al. "A terahertz Brewster switch based on superconductor hyperbolic metamaterial" *Journal of Applied Physics* 128.17 (2020).

Now, when we talk about Brewster mode in hyperbolic metamaterials, these are a way to excite and utilize. The unique optical properties of these materials for sensing and other kinds of applications. The hyperbolic metamaterials with their anisotropic permittivity exhibit unusual wave propagation characteristics. The Brewster angle is where p-polarized light is not reflected.

So that plays a crucial role in their behavior. So, by exciting Brewster modes, enhanced sensitivity for refractive index sensing can be achieved. So, hyperbolic metamaterials can be designed to act as you know intensity and phase modulator for terahertz light by tuning the Brewster angle ok. So, that is where you can achieve this kind of 98 percent intensity modulation or 100 percent phase tunability. In doing so, temperature variation can be used as the external stimulus that can give you this active control of the properties, okay. So, the YBCO, which is yttrium barium copper oxide, and LAO, which is lanthanum aluminate, this hyperbolic metamaterial is basically a type II hyperbolic metamaterial, which is shown here.

So, this structure basically exhibits hyperbolic dispersion in a specific frequency range. So, you have the perpendicular one to be positive and the parallel one to be negative; that is why it is type II, okay. So, you can see that unpolarized light incident on this HMM splits into S and P polarization. The reflected lights are also SNP polarized; similarly, the reflected ones will also be right. So, when you talk about type 1 HMM hyperbolic metamaterials, they basically support the Brewster mode.

Because of their real parallel component of the permittivity being positive. Now, if you look for type 2 HMMs, they basically do not support the Brewster angle because their real part of the parallel permittivity is negative, right? As you can also see here, those are negatives. However, it can enable terahertz intensity and phase modulation when the incident angle is near the Brewster angle. So, in this case, for this kind of material where you have alternating layers of YBCO and LAO. So, YBCO will behave like a metal because the parallel one is negative and the perpendicular one is positive.

So, LAO is also behaving like a dielectric. So, this is the multi-layer anisotropic medium, and this structure is tunable using temperature. Across your critical temperature or using some magnetic field, which is useful for terahertz modulators, super lenses, or even quantum devices.

THz modulators

- Modulation principle:
  - Based on optical topological transition of YBCO–LAO HMM.
  - Transition from elliptical dispersion (in dielectric phase) to Type II hyperbolic dispersion (in superconducting phase).
- In the dielectric phase of YBCO, Brewster mode is supported:
  - Allows modulation of both intensity and phase of THz light.
  - Achieved by temperature tuning across the superconductor transition temperature.

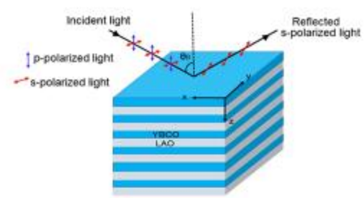

Figure 4: Schematic of YBCO-LAO type II HMM and Principle of the Brewster's angle effect in it

Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021
Sreekanth, et al. "A terahertz Brewster switch based on superconductor hyperbolic metamaterial" *Journal of Applied Physics* 128.17 (2020).

So, let us look into the modulation principles for this kind of device. So, as I mentioned, this is the YBCO and LAO type II HMM, and we will see the principle of the Brewster angle effect in it. So, the transition from elliptical dispersion in the dielectric phase to type II hyperbolic dispersion That which is in the superconducting state happens in this particular material.

So, the dielectric phase of this YBCO is where you know the Brewster mode is supported and that allows modulation of both intensity and phase of the terahertz light. So, this can be achieved, but temperature tuning is needed across the semiconductor transition temperature. So, playing with Tc is an important role, right? So, as I understand it, the dielectric phase of the YBCO is basically working for you here. So, you can modulate the phase and intensity of terahertz light using this concept.

So, with that, we will stop here and we will discuss active hyperbolic metamaterials in various spectral bands in the next lecture.

So, if you have any queries regarding this lecture, you can drop an email to this email address. Mention the course name and the lecture number in the subject line. Thank you.