Course Name: Introduction to Microwave and Optical Metamaterials
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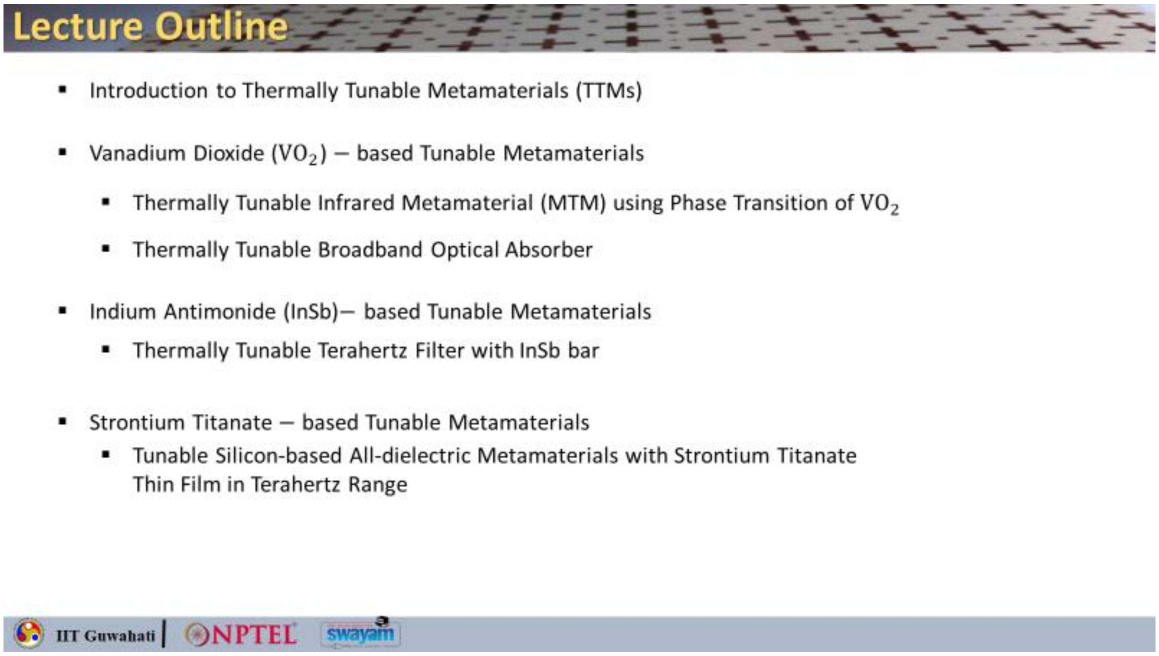
Institute Name: Indian Institute of Technology, Guwahati
Week-11
Lecture-55

Lec 55: Thermally Tunable Metamaterials

Hello everyone, welcome to Lecture 55 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture is about thermally tunable metamaterials.



So, here is the lecture outline. We will first have a brief introduction to thermally tunable metamaterials. Then we will consider three examples. First, we will consider vanadium dioxide (VO2)-based tunable metamaterials, where we will be considering.

Thermally tunable infrared metamaterials using the phase transition of VO2. And then we will look into a thermally tunable, broadband optical absorber. Next, we will look into indium antimonide (InSb)-based tunable metamaterials. We will see how thermally tunable terahertz filters can be obtained using InSb bars.

Then, in the end, we will look into strontium titanate-based tunable metamaterials. There we will see how tunable silicon-based all-dielectric metamaterials work. It can be made with strontium titanate thin films to operate in the terahertz range.

Thermally Tunable Metamaterials (TTMs)

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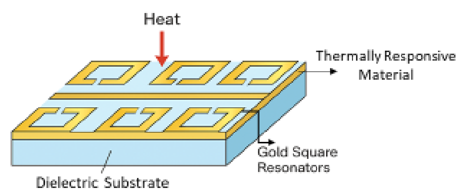
So, let us first consider the introduction to thermally tunable metamaterials.

Introduction

- TTMs: Offer active control over electromagnetic response by modulating material properties through temperature variation.
  - Enable dynamic control of resonance, absorption, and wave propagation.
- Working Principle:
  - EM response is tuned by temperature-induced changes in:
    - ✓ Dielectric constant
    - ✓ Electrical conductivity
    - ✓ Phase state of incorporated materials
  - Leads to tunable resonant behavior.



Thermally Tunable Metamaterial

- Tuning Mechanisms:
  - Passive heating: ambient or Joule-heating
  - Active thermal control: micro-heaters, laser pulses heating.

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

So, thermally tunable metamaterials basically offer active control over electromagnetic response.

By modulating material properties through temperature variation, that is why the name is thermally tunable metamaterials. So, this kind of material basically enables dynamic control of resonance absorption and wave propagation. So, what is the working principle?

Here, the dielectric response is basically tuned by temperature-induced changes in either the dielectric constant. or electrical conductivity or the phase state of the incorporated materials. So, this will basically lead to tunable resonant behavior in the metamaterials.

So, as you can understand, here you can see a schematic of a thermally tunable metamaterial. which is basically based on a dielectric substrate on top of which there are some gold-based resonators, Square resonators, and then you also have some thermally responsive materials placed in between. So, these materials will have some change in their properties, like dielectric constant and electrical conductivity. The phase state that will effectively change the resonance behavior of this entire metamaterial under heat and that is how this will give you tunable behavior or response. So, what is the tuning mechanism? It can be passive heating like ambient or joule heating, okay.

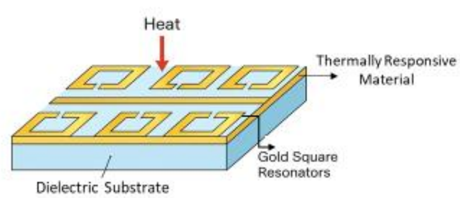
So, joule heating basically occurs when a current I flows through a conductor that has a resistance of R Causing the material to heat up due to collisions between the charge carriers, such as electrons. So, when voltage is applied across a resistor, electrons gain kinetic energy and as they move through the lattice of atoms in the conductor, they will basically collide and lose energy in the form of thermal vibration or heat.

And that will basically increase the temperature of the material. So, this is one mechanism that is passive heating; there is another one that is called active thermal control. That can be done using either microheaters or laser pulses for heating.

Introduction

- Effects of Thermal Tuning:
  - Shift in resonant frequency
  - Modulation of absorption, reflection, or transmission
  - Switching between different functional states (e.g., transparent ↔ absorbing)

- Common Thermally Responsive Materials:
  1. Phase-change materials (PCMs):
     E.g., Vanadium Dioxide (VO_2) –>
     Undergoes insulator-to-metal transition near 68°C.
  2. Semiconductors:
     E.g., Silicon (Si), Indium Antimonide (InSb) –>
     Temperature-dependent carrier density.
  3. Thermally Sensitive Oxides:
     E.g., Strontium Titanate ($SrTiO_3$) –>
     Exhibits large, temperature-dependent dielectric permittivity.



Thermally Tunable Metamaterial

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

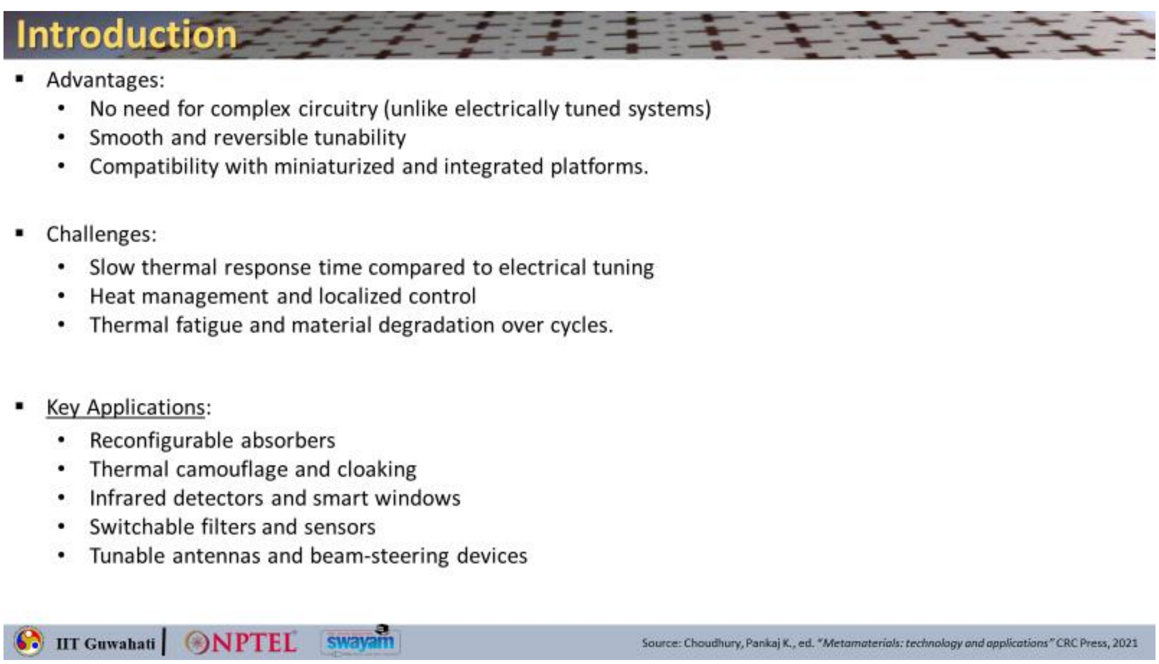
So, what is the effect of thermal tuning?

It basically introduces a shift in the resonance frequency of the metamaterial. So, that allows modulation of the absorption, reflection, and transmission characteristics of electromagnetic waves.

falling on this particular metamaterial structure. So, you can also switch the metamaterial between different functional states. So, it can be transparent to the incident electromagnetic wave or it can be an absorber. So, you can actually switch between the two states. So, what are the common thermally responsive materials that are showing promising applications in this field of tunable metamaterials? The first thing that will come to your mind is a phase change material called vanadium dioxide.

So this basically undergoes an insulated to metal transition near 68-degree temperature, 68 degree centigrade. There are other materials, such as semiconductors like silicon or indium antimonide. So, they basically have temperature-dependent carrier density. So that also affects the dielectric properties or the conductivity. And then you have thermally sensitive oxides like strontium titanate.

So, basically, they exhibit large temperature-dependent dielectric permittivity, right? So, this is a phase change; it has a temperature-dependent carrier density and This has, you know, temperature-dependent dielectric permittivity. So, we will now take each of this material in one example and see. How we can make thermally tunable metamaterials from this kind of material.

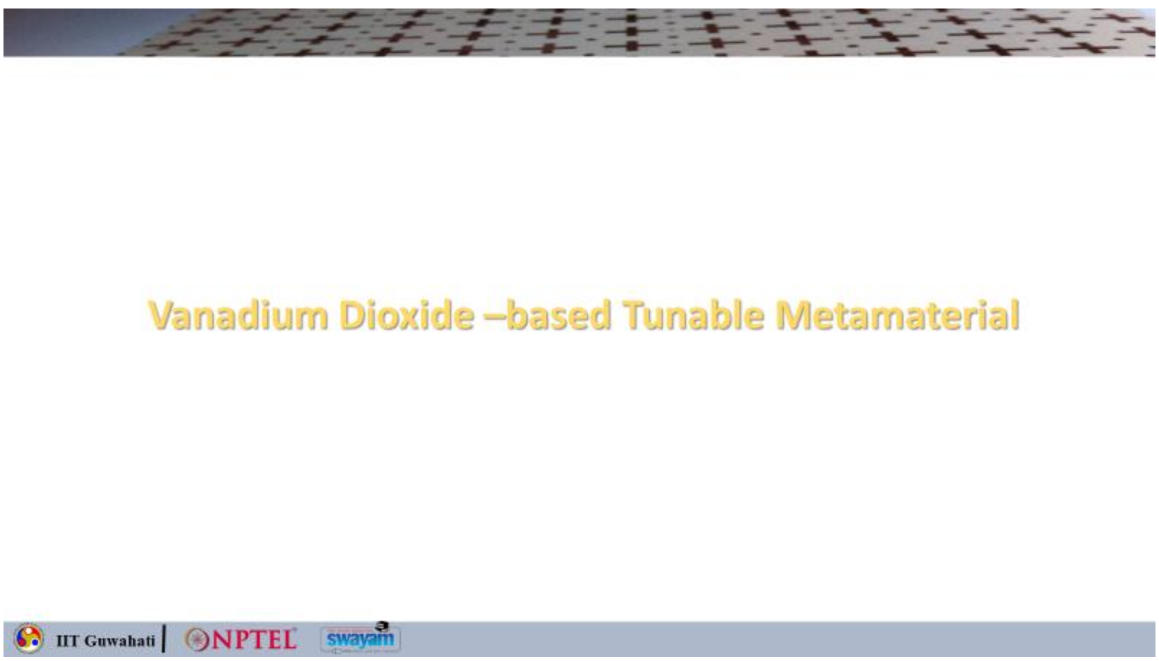


So, the first thing you have to understand is why we are doing this: the advantages that you get from thermally tunable metamaterials are that You do not need complex circuitry like an electrically tuned system. It actually allows for smooth and reversible tuning.

Moreover, it is also compatible with miniaturized and integrated platforms. However, all is not good; there are some challenges associated with this thermal tuning procedure. The first thing is that the response time is slow compared to electrical tuning, and then as you apply heat. So, there are issues with heat management and localized control. There could be thermal fatigue and material degradation over multiple cycles.

Despite all this, they are popularly used in different applications such as reconfigurable absorbers and thermal camouflage. Cloaking, infrared detectors, smart windows, switchable filters, and sensors. Also, tunable antennas and beam-steering devices. So, with that, let us first go into the first type of thermally tunable metamaterial, which is a phase change material-based design.

So, we will consider a vanadium dioxide-based tunable metamaterial.



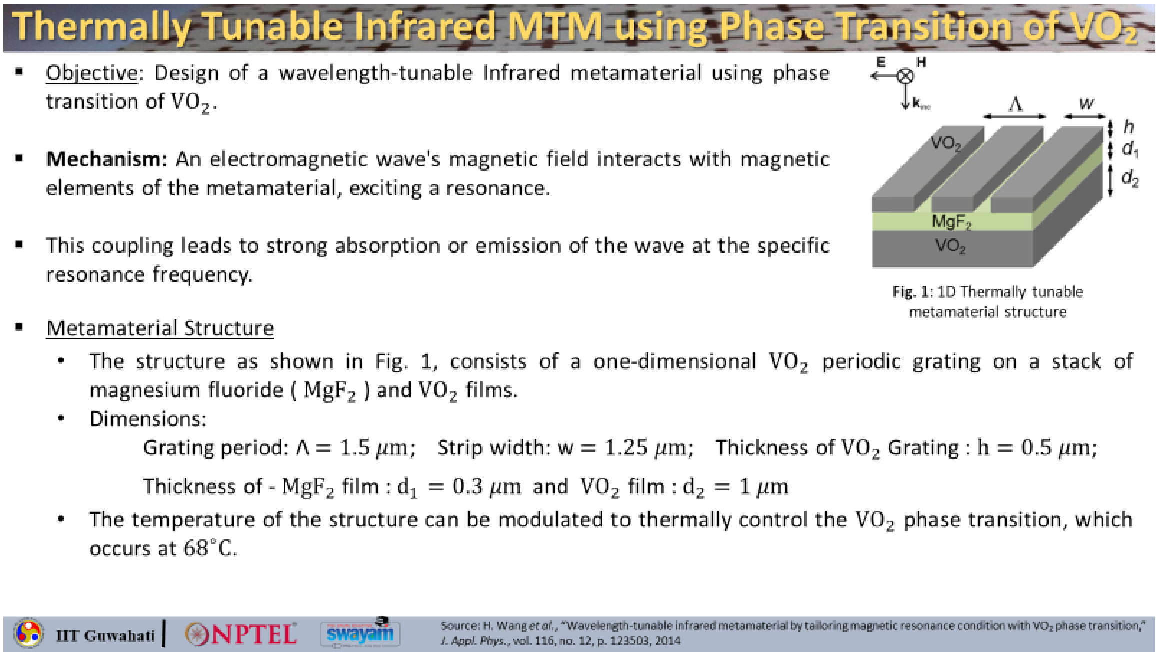
Vanadium Dioxide –based Tunable Metamaterial

- VO_2 is a metal oxide known for its temperature-sensitive phase transition properties.
- Phase transition temperature: 341 K (≈ 68°C).
- Phase transition from dielectric to metal occurs— allows easy tuning with heat.
- Tuning Mechanism: Magnetic resonance is excited through the phase transition of VO_2.
- Magnetic resonance in metamaterials: Occurs when an external electromagnetic wave interacts with magnetic resonance excited within the metamaterial's structure.
- The large tunability is due to different magnetic resonance excitation conditions in the two phases of VO_2 :
  - In the Metallic phase of VO_2: Magnetic Resonance assisted by **plasmons**.
  - In the Dielectric phase of VO_2: Magnetic Resonance driven by **optical phonons**.

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

So here, VO2, or vanadium dioxide, is a metal oxide that is popularly known for its temperature-sensitive phase transition properties and the temperature you need to keep in mind is 68 degrees centigrade, which is around 341 Kelvin, right? So, what happens is that a phase transition takes place from dielectric to metal. So, vanadium dioxide changes from a dielectric state to a metallic state at this temperature. So, this allows for easy tuning with heat, okay. So, the tuning mechanism remains such that the magnetic resonance is excited through the phase transition of vanadium dioxide.

and this magnetic resonance in metamaterials basically occurs when an external electromagnetic field interacts with the magnetic resonance that is excited within the metamaterial structure. So, large tunability can be observed due to different magnetic resonance excitation conditions in the two phases of VO_2. So, in the metallic phase of VO_2, you can understand that the magnetic resonance is basically assisted by the plasmons. Whereas in the case of the dielectric phase of VO_2, the magnetic resonance is basically driven by the optical phonons.

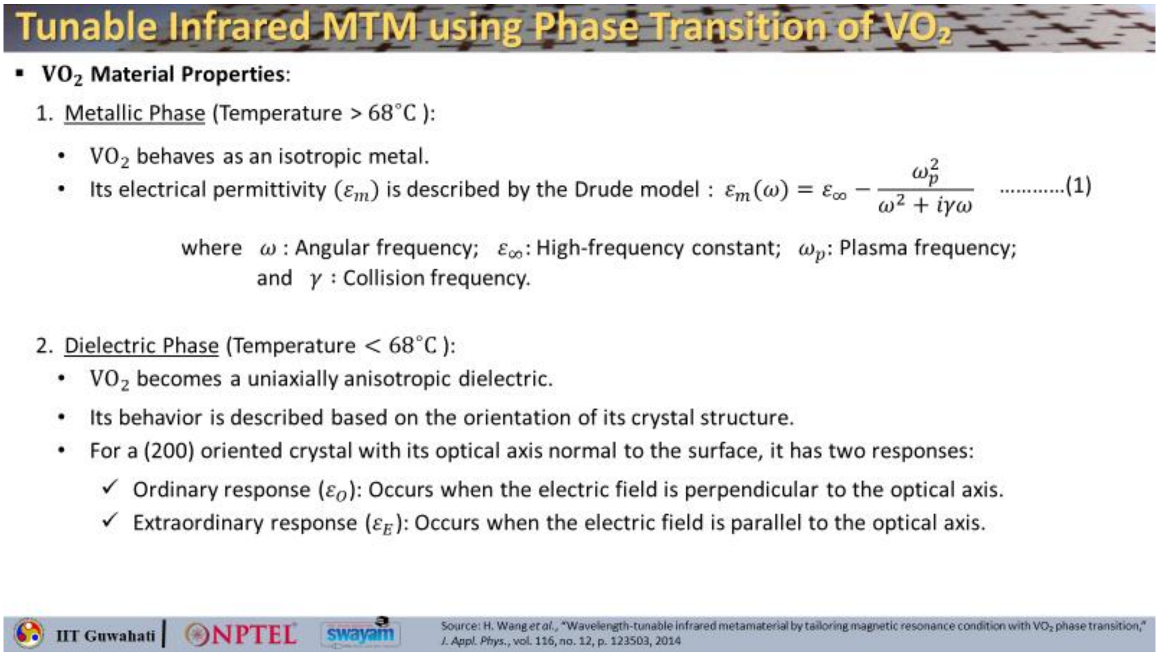


So, here we will see a thermally tunable infrared metamaterial that is based on the phase transition of VO_2.

So, this is a design for a wavelength-tunable infrared metamaterial. So, the mechanism that is shown here says that an electromagnetic wave's magnetic field interacts. With the magnetic element of the metamaterial that excites the resonance. So, in this particular structure, you can see you have VO_2, then you have a dielectric magnesium fluoride, and Then again, you have 1D strips of VO_2, which have a width of W and a periodicity of capital lambda. So, this is the height; then you have d_1 thickness and d_2 thickness of the two layers.

This is the direction of the incident electromagnetic field. So, the electric field is along the width of the strips, and the magnetic field is along the length of the strip, okay. Now, because of this kind of magnetic coupling, it basically leads to strong absorption. or emission of the wave at a particular resonance frequency. So, we have already seen the metamaterial structure; this is nothing but a one-dimensional VO_2 periodic grating.

That is lying on a stack of magnesium fluoride and VO_2 films. So, here are the parameters that are considered in this particular example: lambda and capital lambda. The periodicity is considered to be 1.5 microns; the strip width w is 1.25 microns. The thickness of the VO_2 grating, which is H, equals 0.5 microns, and the thickness of this magnesium fluoride film is 0.3 microns. The VO_2 film is 1 micron, and this structure is okay because it is based on VO_2. So, the temperature of the structure can be modulated to control thermally, the VO_2 phase transition which basically occurs at 68-degree centigrade right.



Now, if you look into the material properties of VO_2 for temperatures above 68 degrees centigrade, it is basically in the metallic phase. So, VO_2 behaves like an isotropic metal. So, you can describe its electrical permittivity using the popular Drude model. So, you can write $\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$, right.

So, ω is basically the angular frequency, and ε_∞ is the high-frequency constant. ω_p is the plasma frequency, and γ is the collision frequency, right? The dielectric phase will basically occur for temperatures below 68 degrees centigrade. There, VO_2 basically becomes a uniaxially anisotropic dielectric. So, its behavior is described based on the orientation of its crystal structure because it is a uniaxial material.

So, for a kind of oriented crystal with its optical axis normal to the surface, it basically shows two responses. Ordinary response epsilon o will occur when the electric field is essentially perpendicular to the optical axis. An extraordinary response that is epsilon E will occur when the electric field is parallel to the optical axis.

So, both of these components can be described by a classical oscillator model.

Tunable Infrared MTM using Phase Transition of VO_2

- Both of these components can be described by a classical oscillator model as:

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_{j=1}^{N} \frac{S_j \omega_j^2}{\omega_j^2 - i\gamma_j \omega - \omega^2} \quad \text{...........(2)}$$

Where- ω_j : Phonon vibration frequency; γ_j : Scattering rate; S_j represents the oscillation strength; and j : Phonon mode index.

- For metallic phase, by considering in eq. (1):

$$\varepsilon_\infty = 9\,; \quad \omega_p = 8000\ \text{cm}^{-1}; \quad \text{and} \quad \gamma = 10000\ \text{cm}^{-1}$$

  - The simulation result of real parts of permittivity at different wavelength is as shown in fig. 2.

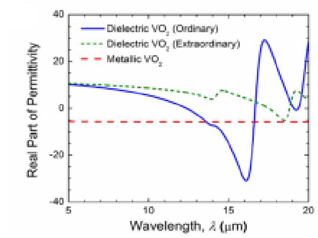


Fig. 2: Real parts of permittivity of VO_2 at different phases

- Therefore, simulation results show that:
  - Metallic VO_2 phase → Negative real permittivity, enabling plasmonic resonances (similar to noble metals).
  - Dielectric VO_2 phase → Multiple phonon modes in both ordinary (ε_O) and extraordinary (ε_E) components.
    - ✓ Negative permittivity ranges in dielectric phase for ε_O : $12.4 - 16.7\ \mu\text{m}$ and for ε_E : $17.5 - 18.8\ \mu\text{m}$.

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Source: H. Wang *et al.*, "Wavelength-tunable infrared metamaterial by tailoring magnetic resonance condition with VO_2 phase transition," *J. Appl. Phys.*, vol. 116, no. 12, p. 123503, 2014

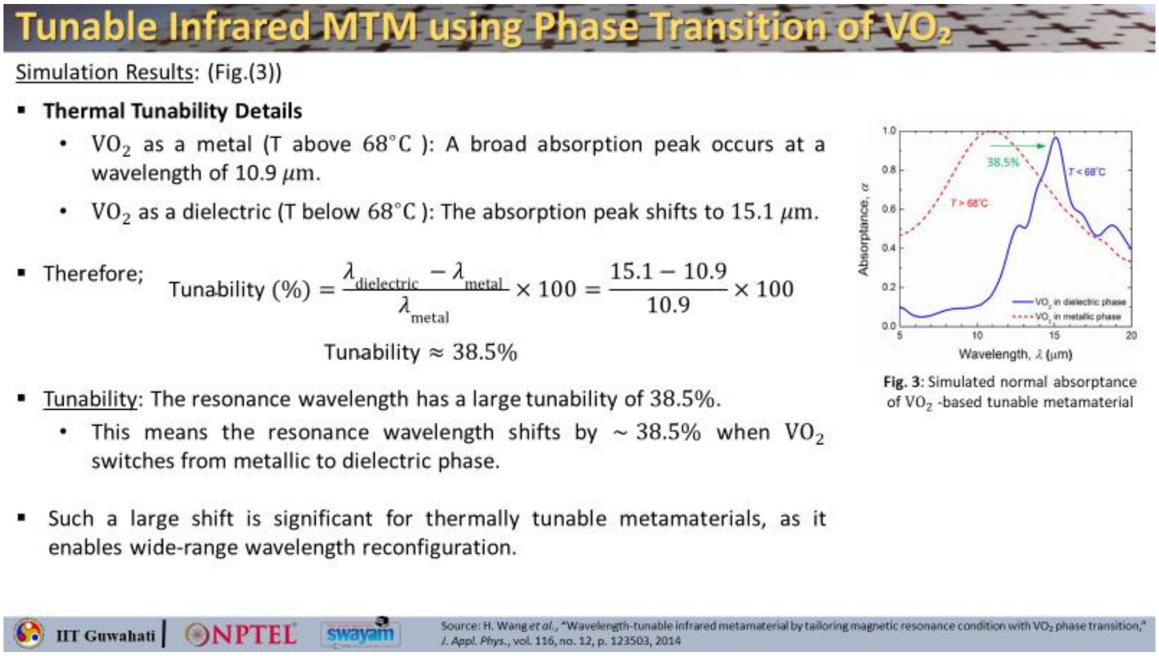
So, you can use this particular model. So, $\varepsilon(\omega) = \varepsilon_\infty + \sum_{j=1}^{N} \frac{S_j \omega_j^2}{\omega_j^2 - i\gamma_j \omega - \omega^2}$. So, these are the number of oscillators that you are adding, okay. So, ω_j is nothing but the phonon vibration frequency, γ_j is the scattering rate, and S_j represents the collision frequency. The strength, sorry, collision strength, not frequency, and j is basically the phonon mode index.

So, for the metallic phase that is given by the Drude permittivity, there we have considered epsilon that is given in Equation 1, which we have seen previously. So, the infinity or the high frequency permittivity ε_∞ is given as 9, ω_p is considered 8000 centimeters inverse, and γ is basically 10000 centimeters inverse. Now, with this kind of data, you can input the values of this permittivity. We are basically plotting the real part of the permittivity as a function of λ here.

So, the blue curve shows the ordinary permittivity of the dielectric VO_2. This red dotted curve basically shows the extraordinary permittivity. And this is how the metallic VO_2 permittivity looks over this particular range. So, what you see here is that, for the metallic phase, you basically have a negative real permittivity. Enabling plasmonic resonances, which are similar to noble metals.

And for the dielectric phase, multiple phonon modes can be seen in both ordinary and extraordinary components. Here, you can also get some negative permittivity. that you can see in both ordinary as well as in extraordinary refractive index so or permittivity.

So, for epsilon o between 12.4 and 16.7 microns, you have negative values; for epsilon E, you have negative values between 17.5 and 18.8 microns, right.



So, here we see the details of thermal tunability. So, when VO_2 acts as a metal that is at a temperature above 68 degrees, you can see that there is a broad. So, the metallic phase is this dotted one; as you can see, a broad absorption peak is appearing at 10.9 microns okay, and for VO_2 working as a dielectric, that is for temperatures below 68 degrees centigrade. This absorption peak is basically shifting to 15.1 micrometers.

So, you can see there is a wide tunability, and if you find out the percentage tunability as: $\text{Tunability}\ (\%) = \frac{\lambda_{\text{dielectric}} - \lambda_{\text{metal}}}{\lambda_{\text{metal}}} \times 100$, which comes out to be 38.5 percent and that is a very large tunability of the resonance wavelength, okay.

So, this basically implies that the resonance wavelength can shift by up to 38.5 percent when VO_2 switches from the metallic to the dielectric phase. So, such a large shift is basically significant for thermally tunable metamaterials at as this is basically enabling wide range wavelength reconfigurability.

So, now let us look into another design, which is again based on VO_2.

Thermally Tunable Broadband Optical Absorber

- This design uses patterned plasmonic metasurface with thermo-chromic VO_2 spacers as shown in figure 4.
- The structure is composed of:
  - A group of multi-width $Cr - VO_2$ sub-cells is placed on the surface of a uniform Cr substrate.
  - The surrounding material is air.
- Geometric Parameters:

  Period (p): 1900 nm; Widths of sub-cells (w_1, w_2, w_3, w_4): (200 nm, 300 nm, 400 nm, 500 nm); Gaps(g_1, g_2, g_3) : (80 nm, 120 nm, 140 nm) and Thicknesses (t_1, t_2, t_3): (300 nm, 260 nm, 30 nm).
- Tuning mechanism: The absorber's properties are dynamically tuned using the insulating–metallic phase transition of VO_2 , which is triggered by temperature changes.

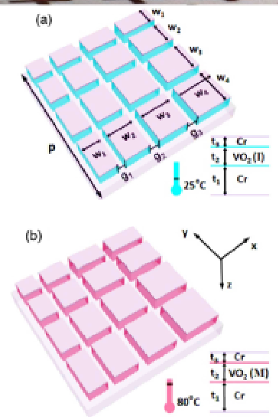


Fig. 4: Schematic diagrams of tunable metamaterial ultra-broadband absorber with VO_2 spacer in the (a) Insulating phase and (b) Metallic phase.

Source: Lei, Lei, et al. "Tunable and scalable broadband metamaterial absorber involving VO2-based phase transition" *Photonics Research* 7.7 (2019): 734-741.

But this time, we are making a thermally tunable broadband optical absorber. So, this design basically uses a patterned plasmonic metasurface with thermochromic VO2 spacers, as you can see here. So, the structure is basically, so I am just, this is the schematic of the structure. A shows the insulating phase, and this is the metallic phase of the structure.

So these are the temperatures for 25 degrees. This is for 80 degrees. The structure remains the same. It is basically chromium, then you have VO2 in the insulator phase here, and then again you have chromium, okay. This is the this is stack and then you have different width of this you know sub cells which are repeated.

The surrounding medium is air, okay. The same thing is here, just because the temperature has risen. So, VO2 is currently in the metallic phase. So, the values of the geometric parameters are given here; the period is around 1900 nanometers. There are different widths of the subcells w1, w2, w3, and w4. Similarly, here their gaps are also mentioned: g1, g2, g3, and the thicknesses of the different layers are given.

So, what is the tuning mechanism in this case? The absorber's properties are basically dynamically tuned using the insulating metallic phase transition of VO_2. Which is essentially triggered by temperature change, right.

Thermally Tunable Broadband Optical Absorber

Absorption Performance through Simulation: (Fig. (5))

- Room temperature ($25^\circ C, VO_2$ dielectric phase)
  - Absorber functions as a metal/dielectric/metal structure.
  - Ultra-broadband high absorption: $BW_{0.9} > 3000$ nm(1627 – 4696 nm).
  - Average absorbance (AA) > 93.5%.
  - Near-perfect absorption: 3173-3404 nm, peak 97.6% at 3297 nm .
- Elevated temperature ($80^\circ C, VO_2$ metallic phase)
  - Structure becomes all-metal metamaterial.
  - Narrower absorption: 1443 – 2066 nm ($BW_{0.9} = 623$ nm).
  - Average absorbance increases to 96%.
  - Peak absorption rises to 99.4% at 1706 nm .
- Performance: It achieves a simultaneous and active tuning of both absorption bandwidth and the peak resonant wavelength in the near- to mid-infrared (NMIR) region.

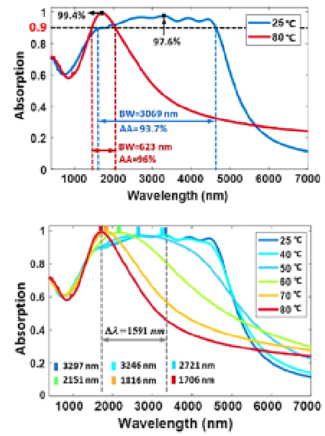


Fig. 5: Simulated Temperature-dependant absorbance spectra.

IIT Guwahati | NPTEL | swayam — Source: Lei, Lei, et al. "Tunable and scalable broadband metamaterial absorber involving VO2-based phase transition" *Photonics Research* 7.7 (2019): 734-741.

So, let us analyze what is happening if you consider room temperature, which is 25 degrees centigrade; VO_2 is in the dielectric phase, right. So, the absorber basically here functions like a metal-dielectric-metal kind of a structure, right. So, you can see the blue curve that is for 25 degrees centigrade. So, you can see that you are getting a very high or broadband very high ultra broadband absorption So you can see the bandwidth if you consider absorption to be greater than 0.9. You are getting a bandwidth of more than 3000 nanometers, starting from 1627 to 4696.

And the average absorption in this range is more than 90, sorry, 93.5 percent, and the peak one is around 97.6 percent. Right. So, you get almost near-perfect absorption in this range of 3173 to 3404 nanometers, okay, and you have the peak around here.

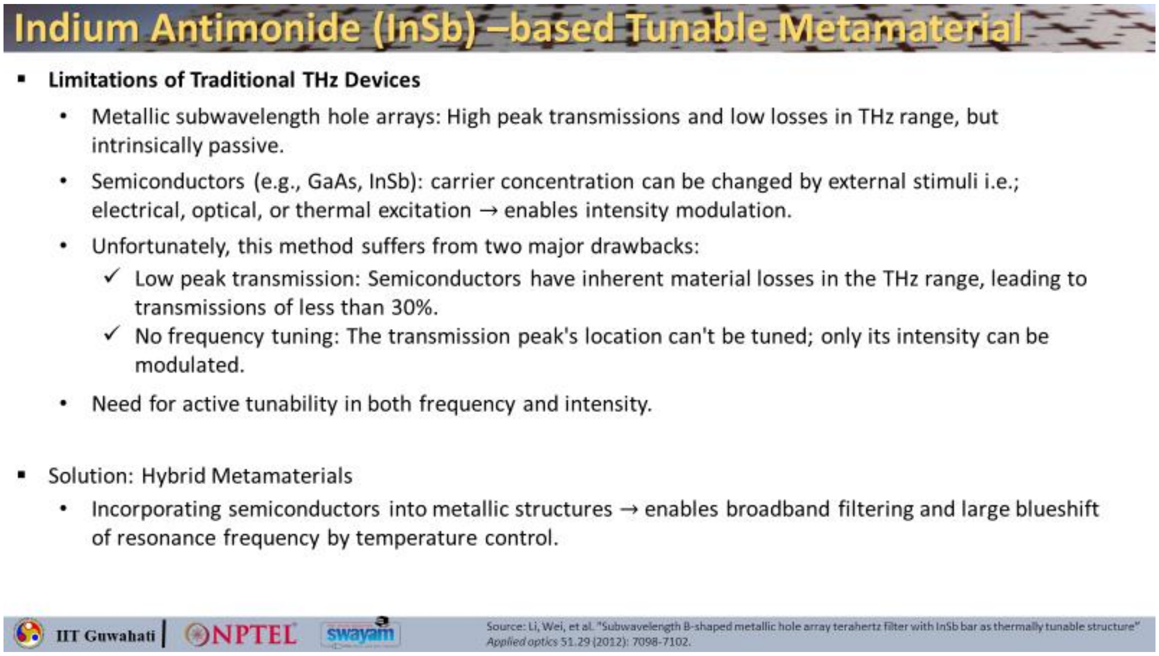
Now what happens when you increase the temperature to 80 degrees centigrade if you again measure the same thing? You will see that now it has converted into metallic fields. So, now the structure has essentially become all metal, kind of a metamaterial. So, what happens is that the absorption peak becomes very narrow; it is only from 1443 to 2066.

So, the bandwidth above 0.9 absorption is only 623 nanometers. So, the average absorption basically increases here, but the bandwidth has dramatically reduced. The peak absorption is also recorded to be 99.4 percent, which is at 1706 nanometers. So, what we see here is that these are the two cases, and here you can also find out about different temperatures. These values are plotted just to show you how the transition has happened from 25 degrees to 80 degrees, okay? So, this graph basically shows you how the transition takes place.

So, this basically allows you to achieve a simultaneous and active tuning of both absorption bandwidth and the peak resonant wavelength is in the near to mid-infrared region, okay. So, that has a lot of applications. So, that is why this kind of metamaterials is very useful.

Next, we look into the other type of metamaterial that is indium antimonide-based tunable metamaterials.

So, why do we study these metamaterials? Because if you look into the traditional terahertz devices.



There are limitations in the form of metallic sub-wavelength hole arrays. So, the metallic sub-wavelength hole arrays basically offer peak transmissions and low losses in the terahertz range. But intrinsically, they are passive, meaning their intrinsic nature cannot be changed by electrical, optical, or thermal methods. Meaning that the terahertz transmission cannot be actively controlled. On the other hand, if you consider semiconductors like helium arsenide and indium antimonide to be okay, they can have their carrier concentration changed by external stimuli, just like using electrical, optical, or thermal excitation.

That can modulate the intensity of the transmission peaks. Unfortunately, this also suffers from some sort of drawbacks. So, one reason could be that you have low peak transmission because semiconductors have inherent material losses in the terahertz regime. That leads to the transmission of less than 30%, and there is no frequency tuning. So, the peak transmission location cannot be tuned; only its intensity can be modulated. So, what you require you basically can see that there is a requirement of active tunability in both frequency and intensity, right.

So, that is where the solution comes to make hybrid metamaterials, where you incorporate semiconductors into metallic structures that basically enables broadband filtering and also ensures large blue shift of the resonance frequency by introducing temperature control. So, let us see how it is done.

Indium Antimonide (InSb) –based Tunable Metamaterial

- Since; Semiconductors have temperature-dependent permittivity, allowing more flexibility than metals.
- Design of B-shaped metallic hole array filter with thermally tunable InSb as shown in figure 6.
- **Materials and Tuning Mechanism**
  - The filter's metallic hole array is made of Copper (Cu), while the thermally tuning medium is Indium Antimonide (InSb).
  - InSb is chosen because its electromagnetic properties are highly sensitive to temperature changes.
- **Electromagnetic Properties of InSb**
  - For temperatures between 160 K and 350 K, the complex-valued relative permittivity of InSb is given by the simple Drude model.

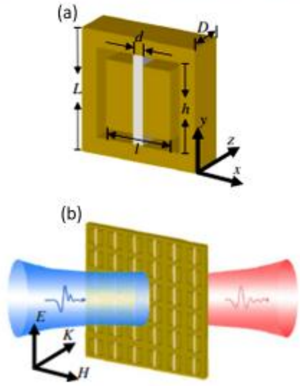


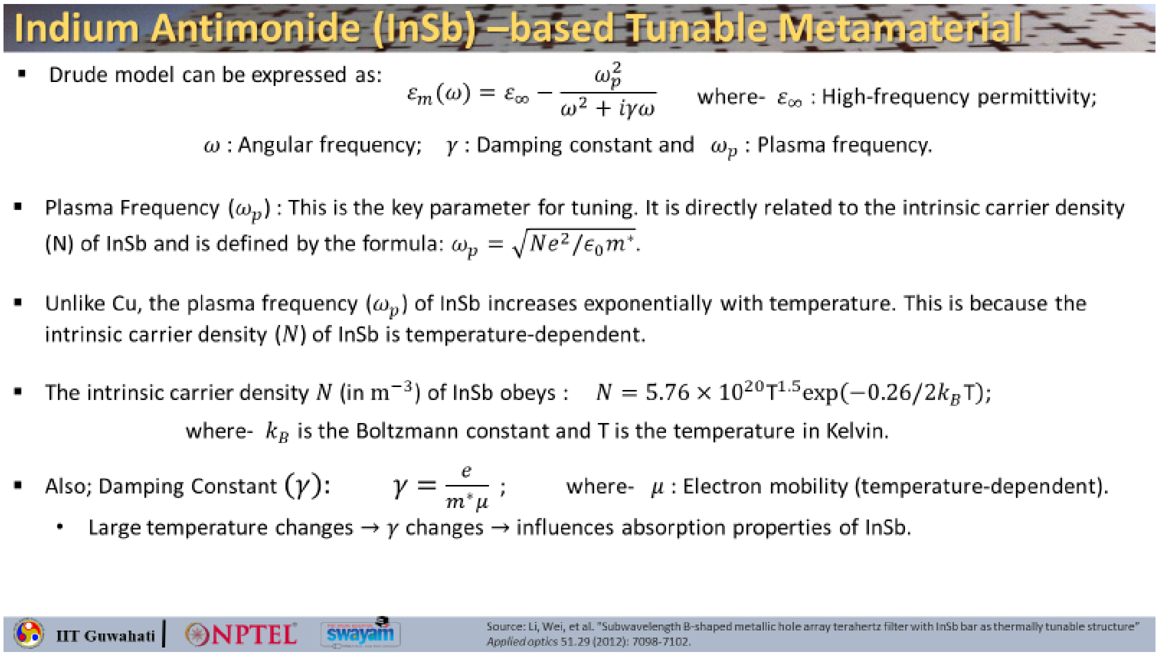
Fig. 6: (a) Geometric structure of a unit cell; and (b) Schematic view of the device

Source: Li, Wei, et al. "Subwavelength B-shaped metallic hole array terahertz filter with InSb bar as thermally tunable structure" *Applied optics* 51.29 (2012): 7098-7102.

So, since semiconductors have temperature-dependent permittivity. So, they are basically more flexible than metals.

So, here you can see the design of a B shape. Okay, this is a B-shaped object; you can see that it is a B-shaped metallic hole array. So, this is the unit cell design and this is the overall device structure okay which has got a thermally tunable indium antimonide, okay. So, you can see that the filters' metallic hole array is basically made of copper, and there are some thermally tuning mediums. placed in between, which is basically the indium antimonide. Now, why did we choose indium antimonide? It is because its electromagnetic properties are highly sensitive to temperature changes.

So, how has it changed? So, if you consider the temperature between 160 Kelvin and 350 Kelvin, the complex relative permittivity of indium antimonide is given by the simple Drude model.



So, you can consider this model, which is $\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2+i\gamma\omega}$. We have seen this a couple of times. So, what is important here is that the key parameter for tuning is this plasma frequency, because the plasma frequency is directly related to the intrinsic carrier density of indium antimonide by this formula, because ω_p is related to N by: $\omega_p = \sqrt{Ne^2/\epsilon_0 m^*}$.

So, unlike copper, the plasma frequency of indium antimonide increases exponentially with temperature. This is because N, in the case of indium antimonide, is basically temperature dependent. So, you can actually express the dependency.

So, n is basically the carrier density. So, it is expressed in per cubic meter. So, it basically obeys this formula that: $N = 5.76 \times 10^{20} \mathrm{T}^{1.5} \exp(-0.26/2k_B \mathrm{T})$.

k_B is the Boltzmann constant, and T is the temperature in Kelvin. So, you can see that there is a temperature dependence, and the damping constant γ is given as: $\gamma = \frac{e}{m^*\mu}$.

μ is basically the electron mobility, which is also temperature-dependent. So, for large temperature changes, you will see that gamma also changes. And that also influences the absorption properties of the indium antimonide, okay.

Thermally Tunable Terahertz Filter with InSb bar

- Structure: (shown in fig. (6))
  - A subwavelength B-shaped metallic hole array filter with an embedded thermally tunable indium antimonide (InSb) semiconductor bar.
- Geometric Parameters of unit cell:
  - $L = 120$ μm, $D = 20$ μm, $l = 68$ μm, $h = 88$ μm and $d = 10$ μm.
- In the device structure, the unit cell is arranged in a square lattice with a period of 120 μm. (fig. 6(b))
- Tuning Mechanism:
  - Temperature control of InSb changes electrical properties of the structure.
  - The resonance frequency of the filter is actively tuned by controlling the temperature of the InSb.

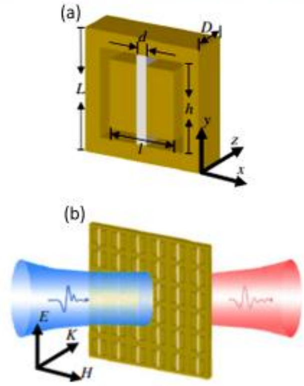


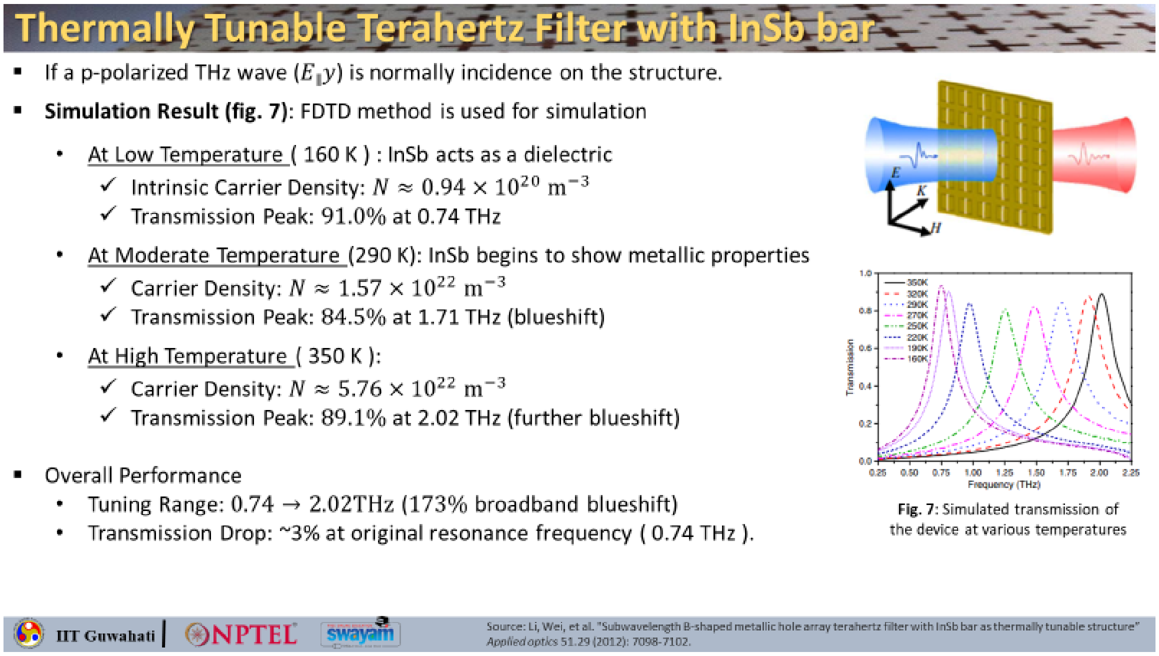
Fig. 6: (a) Geometric structure of a unit cell; and (b) Schematic view of the device

Source: Li, Wei, et al. "Subwavelength B-shaped metallic hole array terahertz filter with InSb bar as thermally tunable structure" *Applied optics* 51.29 (2012): 7098-7102.

So, if you carefully look into the structure, you can see that there is a sub-wavelength B-shaped metallic hole, ok that is placed hole array filter ok and that is embedded in this embedded in a thermally tunable indium antimonide bar.

So, you can consider L to be 120 microns; D is basically this one, the width or thickness, which is 20 microns. small l is this length okay that is 68 microns. h is 88 microns and small d is 10 microns, and then you will see that the periodicity is 120 microns in a square lattice. This is the unit cell that is repeated to make the devices. So, what is happening here? So, because of this embedded thermally tunable indium and thallium semiconductor bar, okay.

So, in this particular device, you can also get temperature control, okay via this indium antimonide because it changes the electrical properties of the structure. So, the resonance frequency of this filter can be actively tuned by controlling the temperature of indium antimonide.



So, if you consider a p-polarized terahertz wave that is normally incident on the structure. So, you can see from the FDTD simulation that at different temperatures, the black is 350 K and this side is 160 K.

And this is the transmission graph. So, you can see that from 350 to 160 k, you can tune the transmission okay, heavily between, say, 2 point. or around 2 terahertz to somewhere 0.7 terahertz, right. So, you can also see that at a low temperature of 160 Kelvin, indium antimonide basically acts as a dielectric.

Where you have a low carrier density of 0.94 into 20 per cubic meter, you are getting a transmission peak of 91% at 0.74 terahertz. Whereas, when you go to a moderate temperature like 390 Kelvin, which is basically this one, the dotted one. So, it starts showing metallic properties, and you can see that the carrier concentration is much higher at 1.

57 into 10 to the power of 22 per meter cubed. and there the transmission peak is around 84.5 percent at 1.71 terahertz. So, there is a huge blue shift. And if you go to a higher temperature, like 350 Kelvin, the carrier concentration further increases to 5.

76 times 10 to the power of 22 per cubic meter. And you have a transmission peak of 89.1% at 2 terahertz. Right. So, overall performance, you can see that you can tune from 0.74 to 2 terahertz; okay, that is like a 173 percent broadband blue shift. And the

transmission drop is only around 3 percent at the original resonance frequency, which is at 0.74 terahertz.

Strontium Titanate (STO)–based Tunable Metamaterial

Now, let us briefly look into the last material for today. So, that is a strontium titanate-based tunable metamaterial.

Strontium Titanate (STO)–based Tunable Metamaterial

Tunable Silicon-based All-dielectric Metamaterials (SAMs) with Strontium Titanate Thin Film in Terahertz Range

- Silicon-based all-dielectric metamaterials (SAMs)
  - Advantages: Low loss, simple structure.
  - Limitations: Narrow bandwidth and low tunability, restricting their practical applications.
- Solution:
  - A tunable SAM is designed in the terahertz (THz) range.
  - This is achieved by covering the SAM with a layer of an active medium: **Strontium Titanate** (STO). (Fig. 8(b))
- Tuning mechanism:
  - The THz response of the SAMs can be thermally tuned.
  - This is possible because STO has a temperature-dependent permittivity, meaning its electrical properties change with temperature.

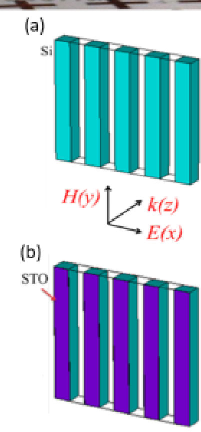


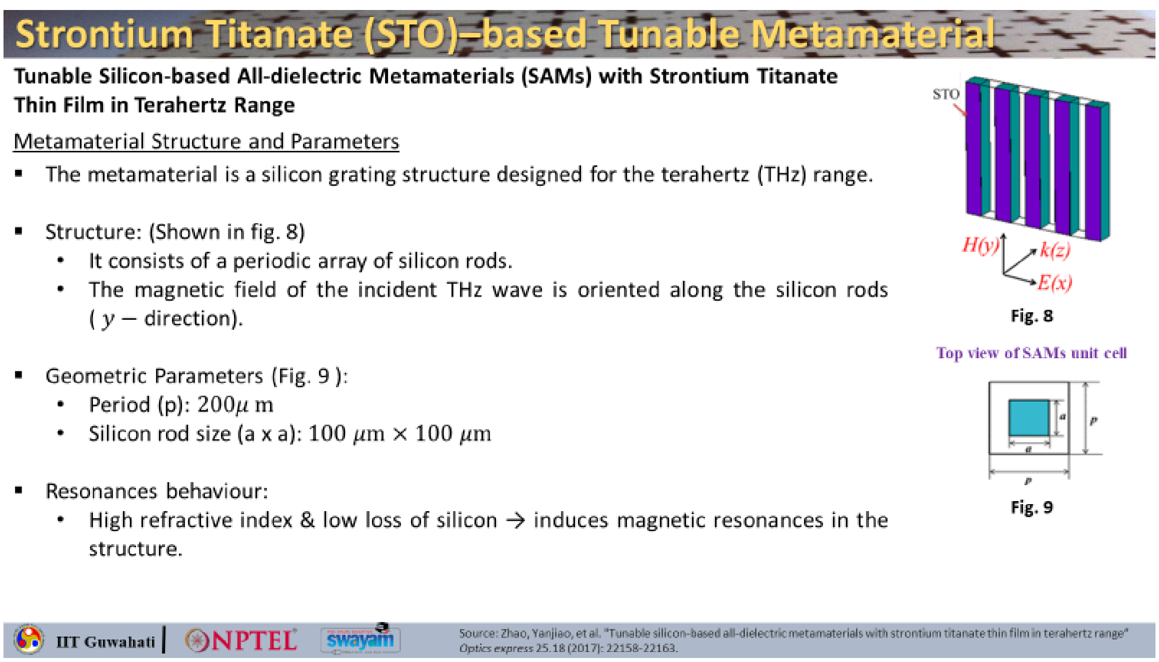
Fig. 8: (a) Schematic illustration of SAMs (b) Tunable silicon/STO all-dielectric metamaterial

Source: Zhao, Yanjiao, et al. "Tunable silicon-based all-dielectric metamaterials with strontium titanate thin film in terahertz range" *Optics express* 25.18 (2017): 22158-22163.

So, here we consider a tunable silicon based all dielectric metamaterials or SAM ok with strontium titanate thin film in the terahertz range. So, what are the advantages of the silicon-based all-dielectric metamaterial? They are basically low loss, and they have a simple structure. However, they have some limitations in the form of a low narrow bandwidth.

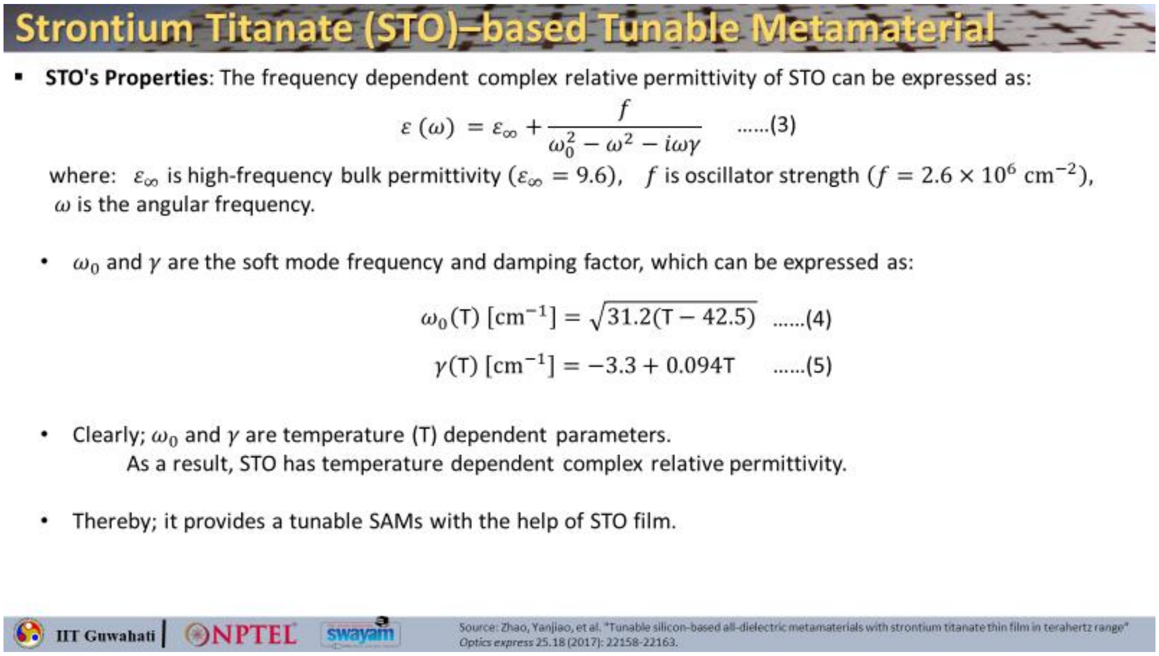
and low tunability that basically restricts its practical application. So, the solution is that you can make a tunable SAM in the terahertz range, and this can be achieved by covering a SAM. So, this is basically a silicon-based all-dielectric metamaterial, and here you can see that. You are basically covering that with STO as an active layer, and that is giving you a tunable metamaterial. So, the tuning mechanism here is that the terahertz response of this kind of all-dielectric metamaterials, Silicon all-dielectric metamaterials can be thermally tuned. And it is possible because STO is a material that has got a temperature dependent permittivity that means the electrical properties basically change with temperature, okay.

So what you have done here, you can closely see that.



The structure is basically a silicon 1D grating that is designed for the terahertz range. These are nothing but a periodic array of silicon rods, and this is the unit cell design. So, the magnetic field of the incident terahertz is basically considered along the lengths of the rods. And this is the cross section that shows you the periodicity is considered to be 200 microns and the size of the rod is 100 by 100 microns.

And the resonance behavior shows that this high refractive index and low loss of silicon can allow you know it can induce magnetic resonance in the structure.



And because you have STO, which is called a frequency-dependent, Complex relative permittivity can be expressed as follows: $\varepsilon(\omega) = \varepsilon_\infty + \frac{f}{\omega_0^2 - \omega^2 - i\omega\gamma}$,

Where ε_∞ is basically the high-frequency bulk permittivity, here considered as 9.6, f is the oscillator strength, and ω is the angular frequency. Here, ω_0 and γ are basically the soft mode frequency and the damping factor, which are expressed in terms of temperature.

So, you can see that these two are basically temperature-dependent parameters. And that is why STO has a temperature-dependent complex relative permittivity, okay and because of this, it is providing tunable tunability in the silicon all-dielectric metamaterial structure.

Strontium Titanate (STO)–based Tunable Metamaterial

Analysis of a silicon grating structure: Simulated transmission curve is shown in figure 10

- Without STO film (pure silicon grating)
  - Two resonance dips observed:
    - ✓ First dip: 0.678THz → linear enhanced magnetic field induced inside rod (first magnetic resonance mode).
    - ✓ Second dip: 0.903THz → two opposite linear magnetic fields inside rod (second magnetic resonance mode).
- With STO film (500 nm thick layer of STO Placed on surface of silicon grating)
  - Temperature-Dependent Permittivity: The relative permittivity of the STO film changes with temperature (can be calculate using eq.'s 3-5).
  - **Effect of STO film on Transmission**: (observed in fig. 10)
    - ✓ Both resonance dips red-shift (shift to lower frequencies) due to increased thickness from STO layer.
    - ✓ Temperature tuning changes STO permittivity → dynamic control of resonance frequencies.

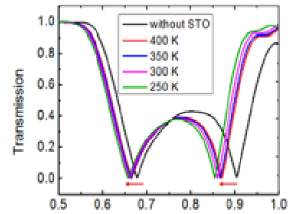


Fig. 10: Transmission spectrum of tunable SAM at different temperatures

Source: Zhao, Yanjiao, et al. "Tunable silicon-based all-dielectric metamaterials with strontium titanate thin film in terahertz range" *Optics express* 25.18 (2017): 22158-22163.

So, once you analyze this grating structure by calculating or simulating the transmission curve. So, here you can see that without STO, the black curve shows the transmission.

You basically have two resonance dips. The first one is around 0.678 terahertz, which is from the linear enhanced magnetic field. Induced inside the rod, which is basically the first magnetic resonance mode. And the second one is around 0.903 terahertz; this is coming from the two opposite linear magnetic fields inside the rod.

So, that is basically giving the second magnetic resonance mode. Now, when you apply the STO films that is basically you are putting a 500-nanometer thick layer of STO on the surface of the silicon grating. When you change the temperature, you will see that you are basically able to move these dips to lower frequencies. You can actually calculate the change in the relative permittivity of the STO with temperature. Using the equations that you have seen earlier. So, here you can see that both the resonant dips are basically experiencing a redshift, which means They are shifting to lower frequencies, and that is mainly because of the increased thickness of the STO layer.

And you can also do it for when you change the temperature; for the same thickness, you are again able to see that similar kind of shift. So, that means you can gain dynamic control of the resonance frequency using temperature as a tool. So, this is how we can make thermally tunable metamaterials.

So, with that, we conclude this lecture.

If you have any queries, you can always drop an email to this email address mentioning the course number and the lecture name on the subject line. Thank you.