**Course Name- Nanophotonics, Plasmonics and Metamaterials**

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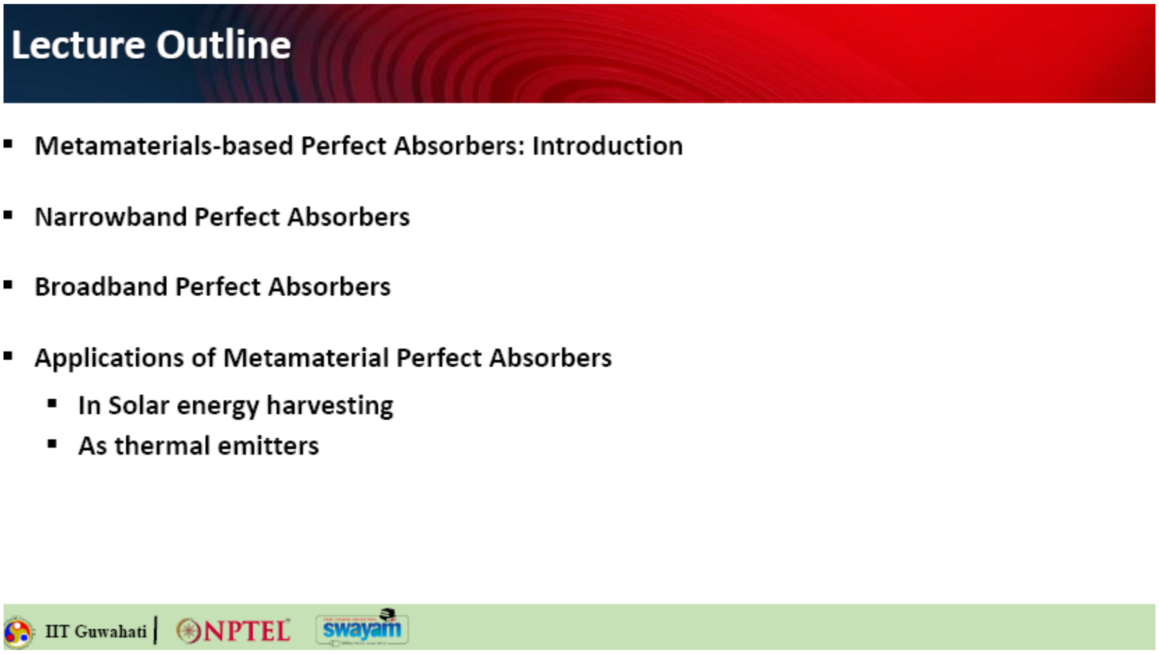
**Week-09**

**Lecture -25**

Hello students, welcome to lecture 25 of the online course on Nanophotronics, Plasmonics and Metamaterials. Today's lecture will be on metamaterial perfect absorbers. So here is the lecture outline, we will first look into what are these metamaterial perfect absorbers and then look into the classifications like narrow band perfect absorbers and broadband perfect absorbers. We will also take an example of ultra-broad band perfect absorber and then we will see the applications of these metamaterial perfect absorbers or MPA in short and their application in solar energy harvesting and as thermal emitters. So when we talk about metamaterials, the first thing that comes to our mind is that these are basically artificially engineered structures. So where the unit cell is designed in such a way that can give rise to some extraordinary properties which are not found in natural materials and the first thing that comes to our mind will be the negative index material, right? Negative refractive index but that is not all.



## Lecture Outline

- Metamaterials-based Perfect Absorbers: Introduction
- Narrowband Perfect Absorbers
- Broadband Perfect Absorbers
- Applications of Metamaterial Perfect Absorbers
  - In Solar energy harvesting
  - As thermal emitters

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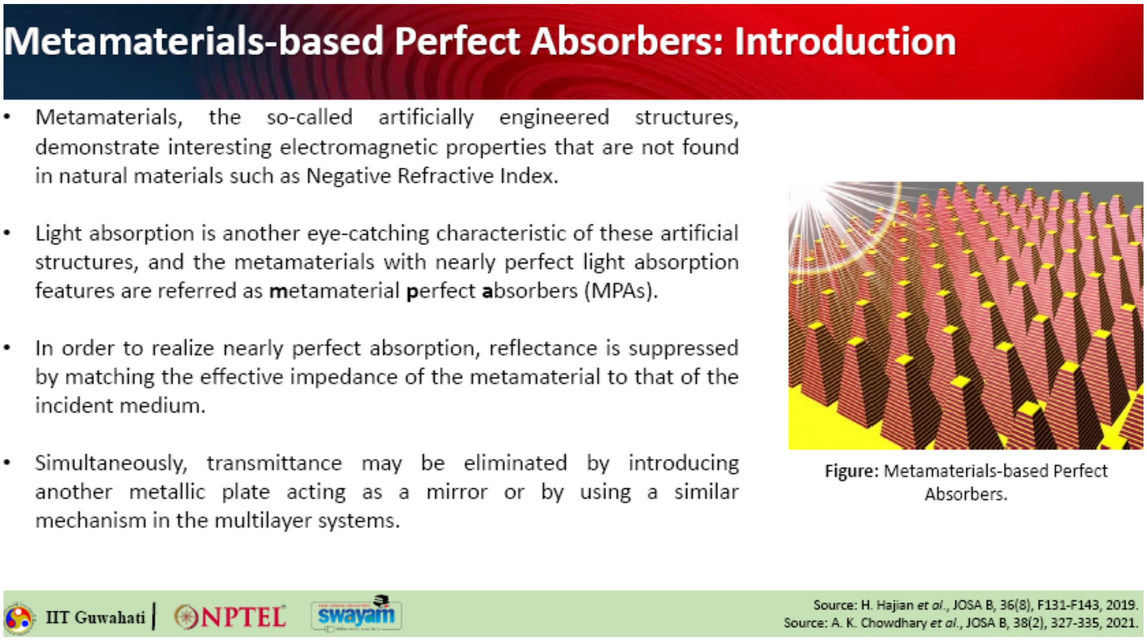
When you think about other applications of metamaterials, one most important application is towards light absorbing. Now light absorbing by any artificial structure has always been a matter of research because you want to maximize the absorption. Like why you need that? Like if you think of a solar cell where you are harvesting solar energy, so you want to absorb the entire solar radiation that is falling on the solar cell. You do not want anything to be reflected.

What goes back is actually a waste. So you are not efficient if you are not able to capture all of the solar radiation coming towards you. Similarly, a photodetector or any other such devices which are supposed to harvest light, you want them to first act as a perfect absorber so that you can absorb that, okay? And then you can convert that absorbed energy into some other form. So light absorption is another eye-catching characteristic of these artificial structures which are metamaterials and the metamaterials with near perfect light absorption are known as this metamaterial perfect absorbers MPA, okay? Now in order to realize perfect absorption, reflectance is suppressed. And how do you do that? You do that by matching the effective impedance of the material of the metamaterial to that of the incident medium.



## Metamaterials-based Perfect Absorbers: Introduction

- Metamaterials, the so-called artificially engineered structures, demonstrate interesting electromagnetic properties that are not found in natural materials such as Negative Refractive Index.
- Light absorption is another eye-catching characteristic of these artificial structures, and the metamaterials with nearly perfect light absorption features are referred as **m**etamaterial **p**erfect **a**bsorbers (MPAs).
- In order to realize nearly perfect absorption, reflectance is suppressed by matching the effective impedance of the metamaterial to that of the incident medium.
- Simultaneously, transmittance may be eliminated by introducing another metallic plate acting as a mirror or by using a similar mechanism in the multilayer systems.

**Figure:** Metamaterials-based Perfect Absorbers.

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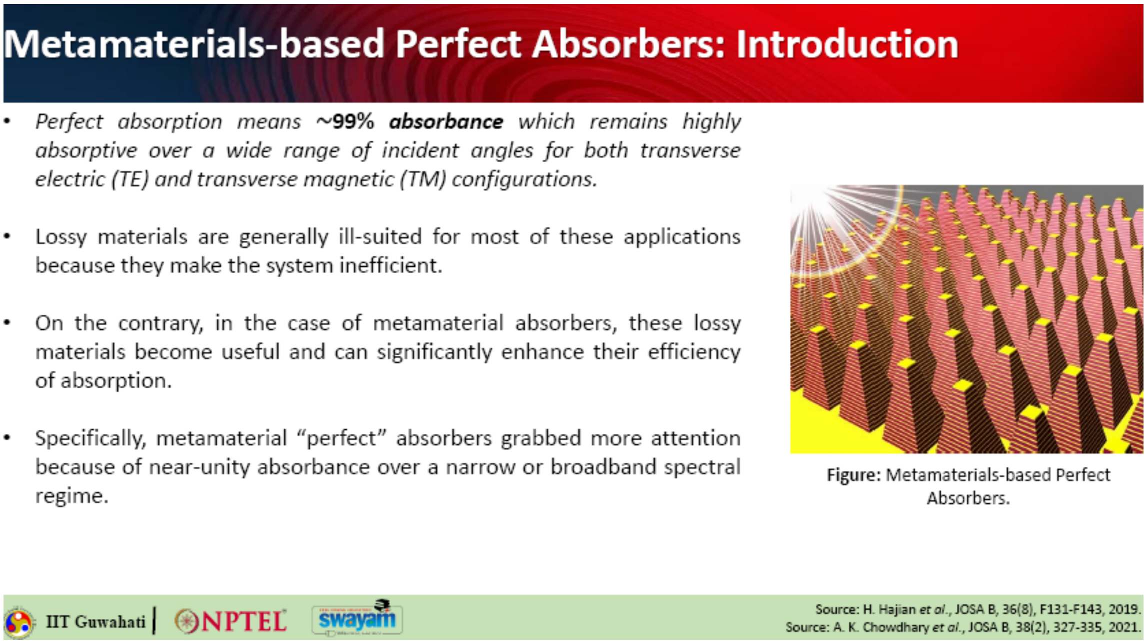
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: A. K. Chowdhary *et al.*, JOSA B, 38(2), 327-335, 2021.

So whenever there is no impedance mismatch, there is no reflection. And when light falls on an interface, there are three phenomena that takes place. One is reflection, one is absorption, the other one is transmission, okay? So you have to somehow in absorbers, you want the entire light to be absorbed. So you are trying to cancel the reflection by using some metamaterial absorber and also you are trying to get rid of the transmittance. And that you can do by introducing another metallic plate which acts as a mirror or by using similar mechanism that we have seen in the multilayer system.



## Metamaterials-based Perfect Absorbers: Introduction

- *Perfect absorption means* ***~99% absorbance*** *which remains highly absorptive over a wide range of incident angles for both transverse electric (TE) and transverse magnetic (TM) configurations.*
- Lossy materials are generally ill-suited for most of these applications because they make the system inefficient.
- On the contrary, in the case of metamaterial absorbers, these lossy materials become useful and can significantly enhance their efficiency of absorption.
- Specifically, metamaterial "perfect" absorbers grabbed more attention because of near-unity absorbance over a narrow or broadband spectral regime.

**Figure:** Metamaterials-based Perfect Absorbers.

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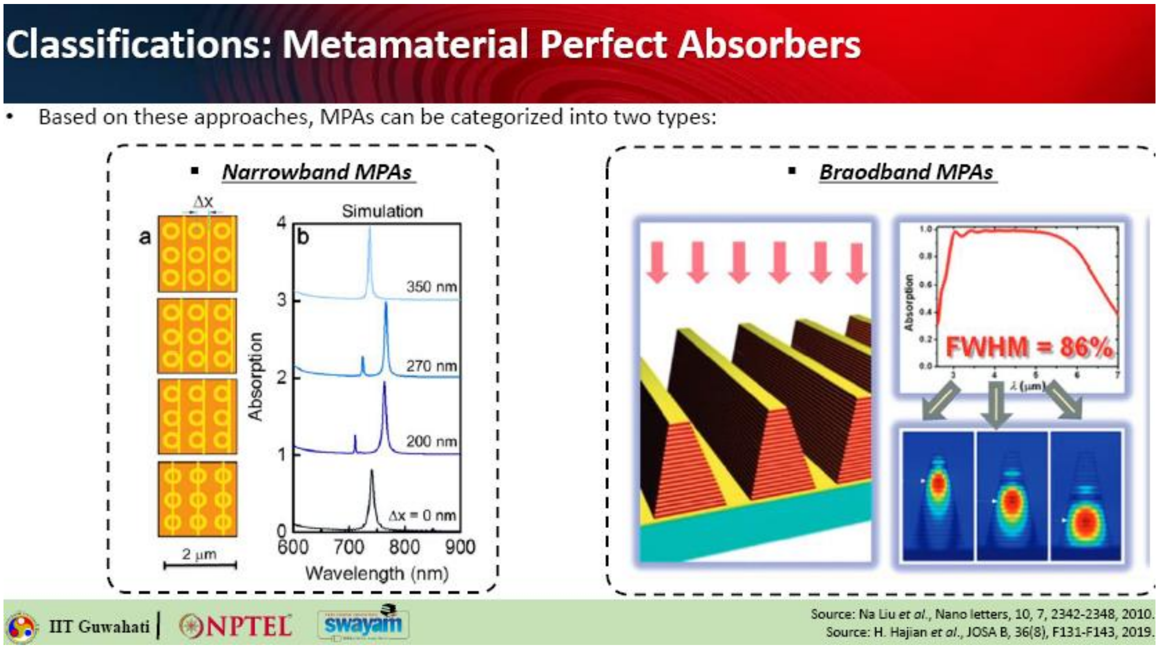
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: A. K. Chowdhary *et al.*, JOSA B, 38(2), 327-335, 2021.

So metamaterial perfect absorbers, they do not have any transmission, they also do not have any reflection. So whatever falls on them should get absorbed. Now what do you mean by perfect absorption? So we typically call a perfect absorber when it is close to 99% absorption, okay? And it remains highly absorptive over a wide range of incident angle, okay? For both TE and TM polarizations, okay? So if you recall our discussion, previous discussions, at larger angle, at gazing angle, you usually have larger reflection. But in that case, your light will not be that strongly absorbed. So at larger angle, there is a possibility of absorption to get reduced than 99%.

But still it should be like at least more than 95% or so, okay? So what do you basically take to make this kind of absorbers? Now when I tell you that this material is lossy, the first thing that comes to your mind is that okay, this is a lossy material, so it is not very good for waveguiding because there is high loss. Also it is not a very good material for creating a resonator cavity because it will have low Q because it is lossy material, so the full width of maximum will be large. But then lossy materials are useful, very very useful in case of metamaterial absorbers because these materials can then significantly enhance the efficiency of absorption, okay? So recently metamaterial perfect absorbers have grabbed a lot of attention because of their near unity absorption capability over narrow band or broadband, okay? So that takes us to the classification of this metamaterial perfect absorbers. So as you can see the based on the wavelength range they cater to, you can categorize them into two buckets, narrow band metamaterial perfect absorbers and then you also have broadband metamaterial perfect absorbers. So, if you carefully look at the narrow band structure, here you see figure A, you can see that these are basically overlapping rings and column and there is a gap between this column and the center of the ring that is called delta x.



# Classifications: Metamaterial Perfect Absorbers

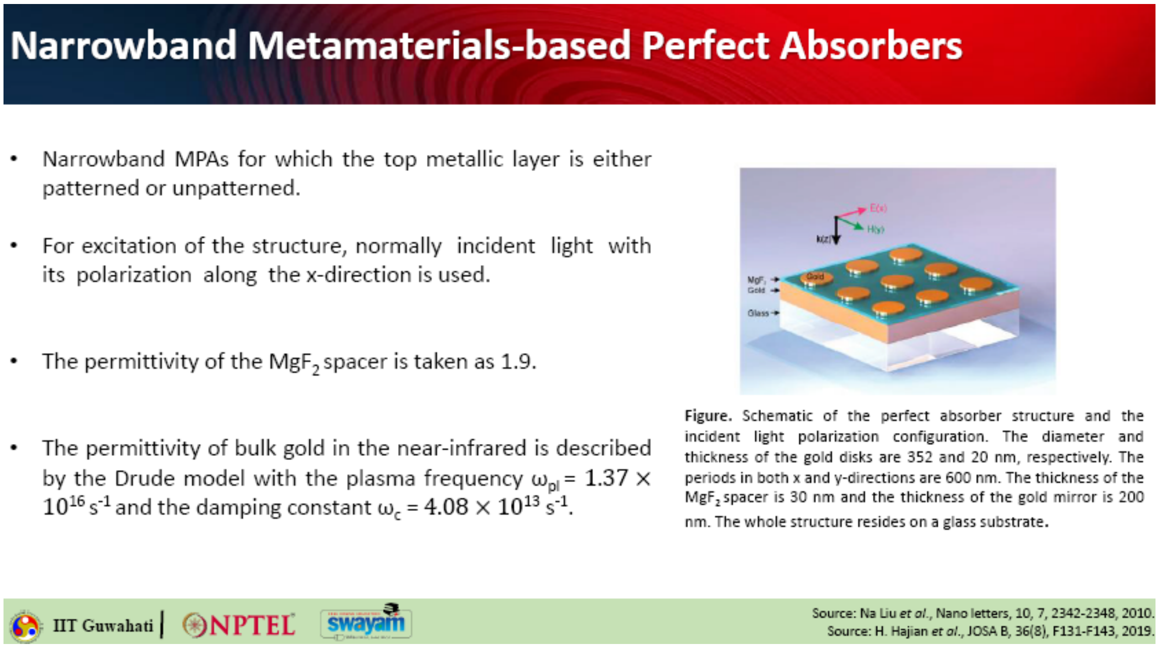
- Based on these approaches, MPAs can be categorized into two types:

▪ ***Narrowband MPAs***

▪ ***Braodband MPAs***

Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

So when delta x equals 0 you get almost like 90 percent of absorption, right? In this particular case. When you change delta x to 200 nanometer or so you get almost 95-99 percent of reflection, okay? Sorry, absorption. When you further increase it to 270 or 350 what is happening? The resonance is even getting sharper, so you are getting a high Q absorption peak and you are closing towards that perfect absorption mark which is very very close to unity absorption, right? So this is typically what I am not going to describe immediately the physics behind this, okay? These are kind of symmetry breaking high Q modes, okay? And I will just look into the features here because this is the narrow band. We will see in this lecture only how to develop a structure that can give you a narrow band metamaterial perfect absorber and we will also look into this particular structures which are able to give you broadband metamaterial perfect absorber. So here you can see that it is basically a broadband absorber.



## Narrowband Metamaterials-based Perfect Absorbers

- Narrowband MPAs for which the top metallic layer is either patterned or unpatterned.
- For excitation of the structure, normally incident light with its polarization along the x-direction is used.
- The permittivity of the $MgF_2$ spacer is taken as 1.9.
- The permittivity of bulk gold in the near-infrared is described by the Drude model with the plasma frequency $\omega_{pl} = 1.37 \times 10^{16}\ s^{-1}$ and the damping constant $\omega_c = 4.08 \times 10^{13}\ s^{-1}$.

**Figure.** Schematic of the perfect absorber structure and the incident light polarization configuration. The diameter and thickness of the gold disks are 352 and 20 nm, respectively. The periods in both x and y-directions are 600 nm. The thickness of the $MgF_2$ spacer is 30 nm and the thickness of the gold mirror is 200 nm. The whole structure resides on a glass substrate.

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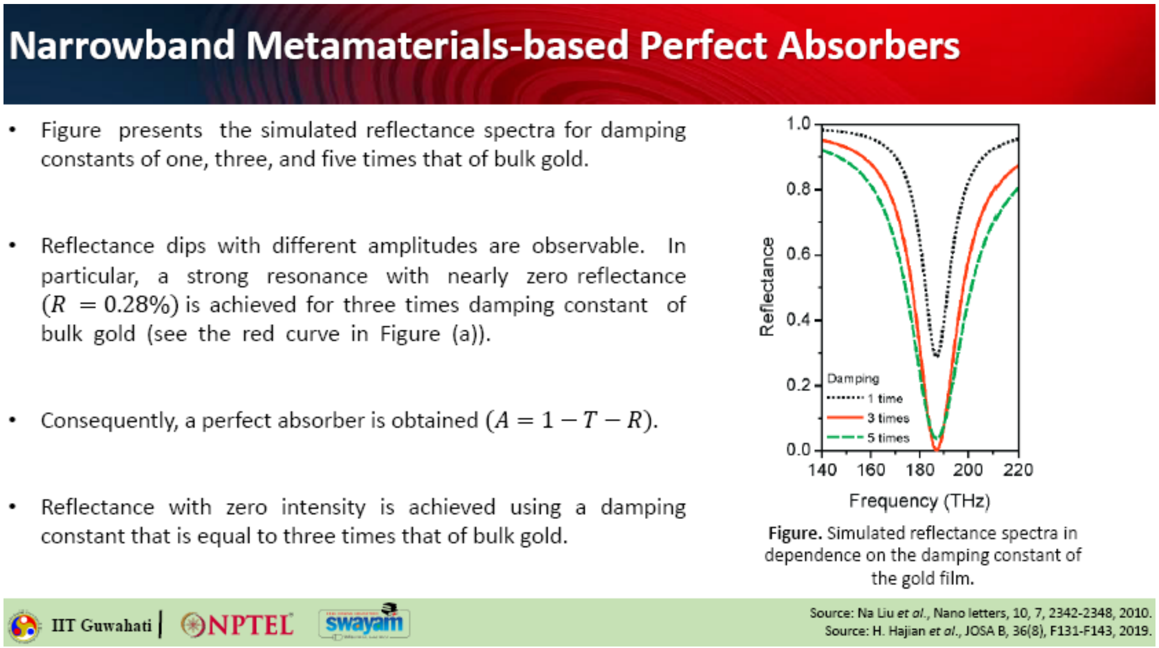
Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

So you can see it ranges from 3 to say 5.5 micron where the absorption is maintained over say 95 or 99 percent like that. Now what are these three arrows showing here is that a different different regime, different portion of the structure is playing the role of absorbing the light that is falling onto the structure. So here is the structure this is basically a this is the tapered shape, okay? You can also call it tapered tooth kind of a structure. So a different different wavelength, different different part of the structure is resonating and that is able to absorb the electromagnetic radiation.

Here you see a short wavelength the top portion of the structure is absorbing most of the incident electric field, magnetic field, okay? And at longer wavelength the bottom most part of the structure which is the widest portion of the structure is responsible for the absorption. Now let us look into some of these techniques of how do you design narrow band metamaterial based perfect absorbers, okay? So here is the schematic. So you need metal, lossy metal to design absorbers. So here is a schematic of a 2D array of gold discs, okay? So the diameter is 352 nanometer and the thickness is 20 nanometer and the periodicity along both X and Y directions are 600 nanometer. Then there is a spacer layer below this gold discs that is MgF2 that is magnesium fluoride and it has got a thickness of 30 nanometer and then you have a gold mirror which is 200 nanometer thick.

So this is basically that portion which is completely cancelling out any chance of transmission through this structure. So 200 nanometer gold film behaves like a bulk gold film and it is giving you zero transmittance and it will be able to act like a good mirror, okay? And this entire structure is placed on top of a glass substrate. Now you can make narrow band MPAs, okay? Metamaterial perfect absorbers for which the top metallic layer is either patterned or unpatterned. So here we are taking a patterned metallic layer, okay? Now in this case what we are using? You are using a normally incident light with X polarization. However, X and Y polarization hardly make any difference here because the structure is symmetric along X and Y, right? And you have taken the permittivity of magnesium fluoride is 1.



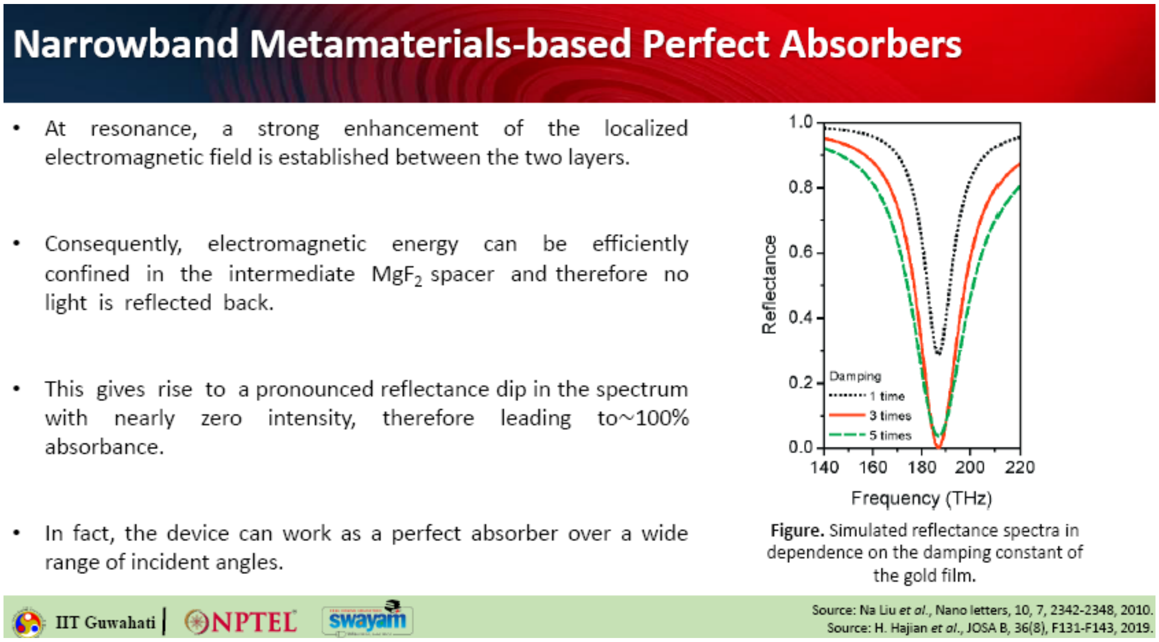
## Narrowband Metamaterials-based Perfect Absorbers

- Figure presents the simulated reflectance spectra for damping constants of one, three, and five times that of bulk gold.
- Reflectance dips with different amplitudes are observable. In particular, a strong resonance with nearly zero reflectance ($R = 0.28\%$) is achieved for three times damping constant of bulk gold (see the red curve in Figure (a)).
- Consequently, a perfect absorber is obtained ($A = 1 - T - R$).
- Reflectance with zero intensity is achieved using a damping constant that is equal to three times that of bulk gold.

**Figure.** Simulated reflectance spectra in dependence on the damping constant of the gold film.

Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

9 and these are the parameters that describe the bulk gold permittivity near the near infrared wavelength range. You can use Drude model with a plasma frequency of 1.37 into 10 to the power 16 hertz, okay? And damping constant is this one, okay? So with that you can figure out that one, so these are basically simulated reflection spectrum which is plotted when the damping constant is considered to be 1 times, 3 times and 5 times of the bulk gold. So here you see when you are basically, there is significant difference in the reflection spectrum or reflection dip, okay? And you can see that when it is 3 times when the damping constant is basically 3 times of that of the bulk gold you are able to get negligible reflection, okay? So it is 0.28 percent, okay? And this is a scale up to 1 so you can understand, so this is basically 0.0028. So it is almost 0 reflection, right? And as I told you in this perfect absorber A is basically calculated from what is reflected and then what is transmitted these two are taken out from 1. So because of this bulk gold there is 0 transmission so if there is no reflection the entire thing is getting absorbed, okay? So here it shows the reflection with 0 intensity is achieved using a damping constant that is equal to 3 times of that of the bulk gold. So that actually tells us that what should be the ideal thickness of those discs, okay? So if you are able to use very thin discs so you can actually get this high damping constant that can give you this perfect absorption. So that is where the design of this metamaterial comes into picture. At resonance a strong enhancement of the localized electromagnetic field takes place between the two layers the two metallic layers.



## Narrowband Metamaterials-based Perfect Absorbers

- At resonance, a strong enhancement of the localized electromagnetic field is established between the two layers.
- Consequently, electromagnetic energy can be efficiently confined in the intermediate $MgF_2$ spacer and therefore no light is reflected back.
- This gives rise to a pronounced reflectance dip in the spectrum with nearly zero intensity, therefore leading to~100% absorbance.
- In fact, the device can work as a perfect absorber over a wide range of incident angles.

**Figure.** Simulated reflectance spectra in dependence on the damping constant of the gold film.

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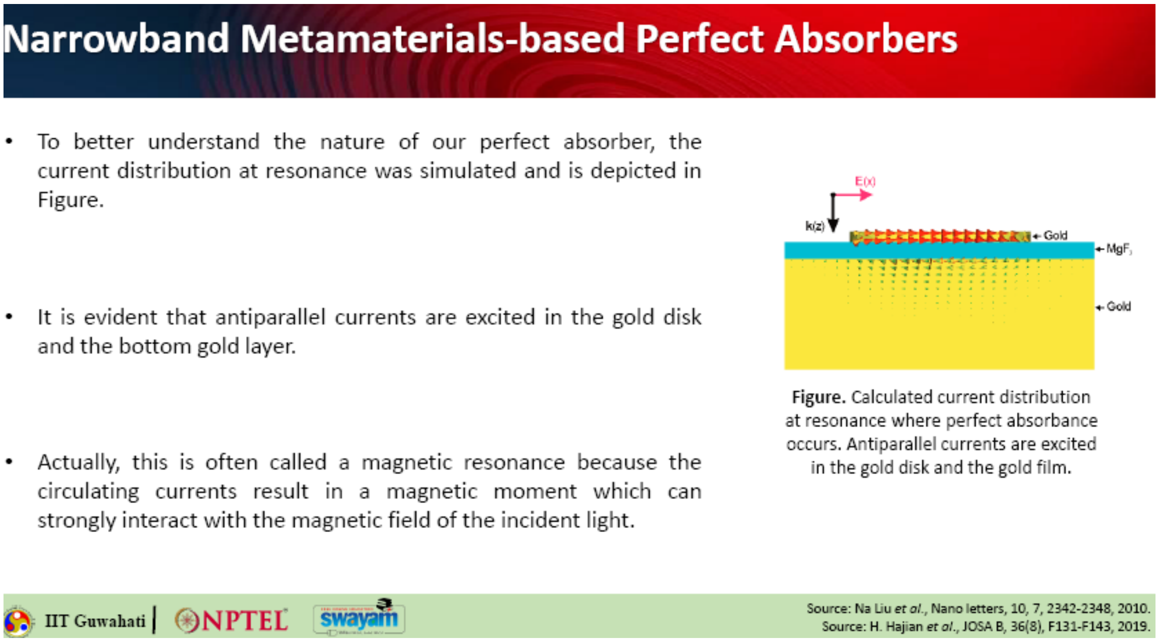
Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

So there is a gold disc and then there is a gold film and in between there is a thin spacer layer which is a dielectric. So this electromagnetic energy can be efficiently confined in this intermediate spacer layer and that ensures that no light is reflected back. So you are basically trapping the energy. So this gives rise to profound reflectance dip in the spectrum with nearly 0 intensity and that in turn give rise to nearly 100 percent absorption. So, in fact this kind of devices work as perfect absorber over a wide range of incident angles.



## Narrowband Metamaterials-based Perfect Absorbers

- To better understand the nature of our perfect absorber, the current distribution at resonance was simulated and is depicted in Figure.
- It is evident that antiparallel currents are excited in the gold disk and the bottom gold layer.
- Actually, this is often called a magnetic resonance because the circulating currents result in a magnetic moment which can strongly interact with the magnetic field of the incident light.

**Figure.** Calculated current distribution at resonance where perfect absorbance occurs. Antiparallel currents are excited in the gold disk and the gold film.

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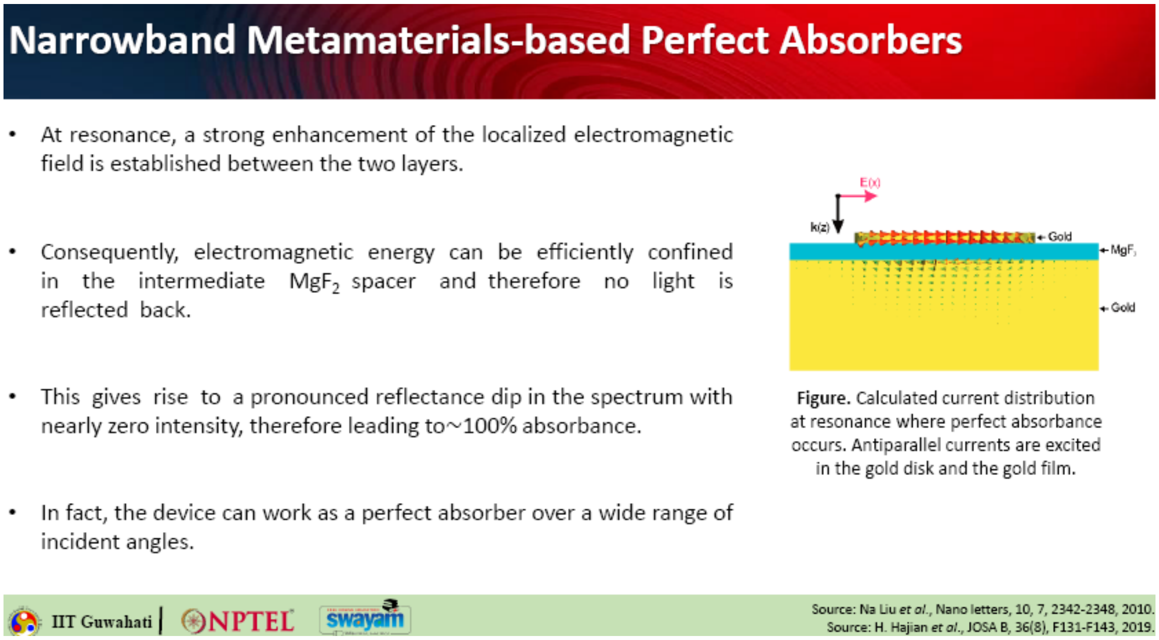
Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

Now to better understand the nature what is happening in this particular perfect absorber we should look into the current distribution at resonance which was simulated and this is the figure that shows that, okay? So here you can see that there are basically anti-parallel current distribution in the gold disc and the bottom gold layer. So here it goes like this and here it is like this. So you can think of a circulating current like this and this is basically can be thought of as a magnetic resonance which comes from the circulating current and this current basically results in a magnetic moment which strongly interacts with the magnetic field of the incident light. Now at resonance what will happen? A strong enhancement of the localized electromagnetic field is established between these two layers, okay And that is the reason why you will be having a trap of energy in this magnesium fluoride spacer layer and no light is going back. Now simulation study has also been conducted to see the angular dispersion of the absorption peak because right now the peak is very very attractive it is giving you almost 100 percent absorption but you have done only for a normal incidence that is theta equals 0.



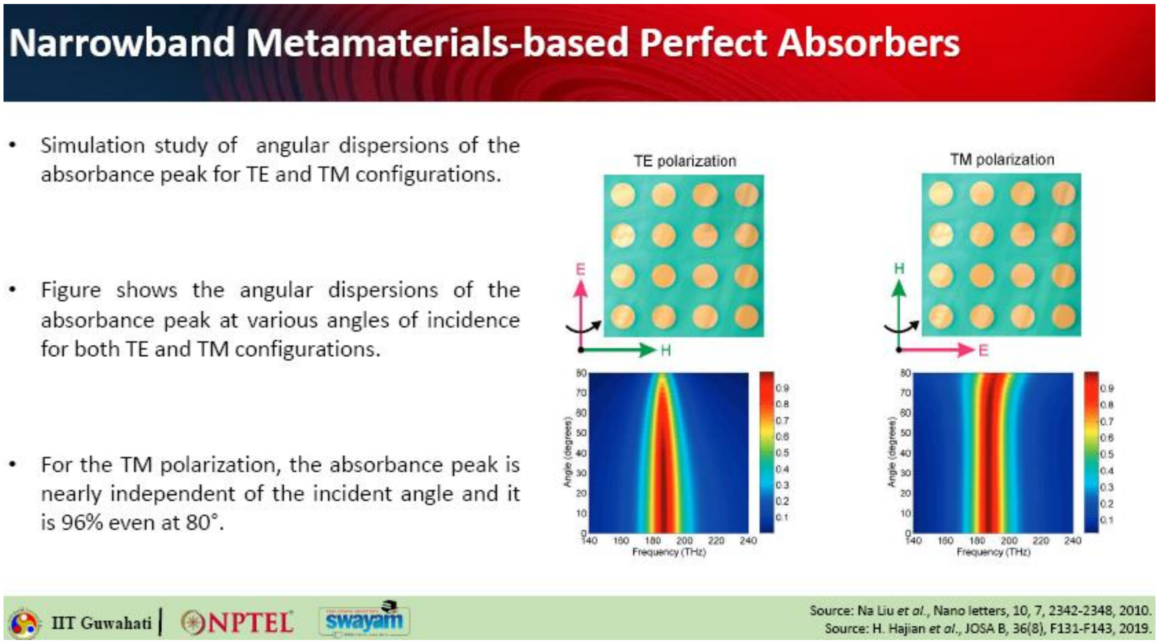
## Narrowband Metamaterials-based Perfect Absorbers

- At resonance, a strong enhancement of the localized electromagnetic field is established between the two layers.
- Consequently, electromagnetic energy can be efficiently confined in the intermediate $MgF_2$ spacer and therefore no light is reflected back.
- This gives rise to a pronounced reflectance dip in the spectrum with nearly zero intensity, therefore leading to~100% absorbance.
- In fact, the device can work as a perfect absorber over a wide range of incident angles.

**Figure.** Calculated current distribution at resonance where perfect absorbance occurs. Antiparallel currents are excited in the gold disk and the gold film.

Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

Now when you do the different angle for both the polarization these are the plots that shows you with frequency and angle how the absorption peak is changing. So this is for TE polarization and this one is for TM polarization. So if you look at the TM polarization first the one on the right the absorption peak is seen to be nearly independent of the incident angle. So here on the y-axis you are varying the incident angle so it varies from 0 to 80 degrees and here you see that more or less it is independent of the incident angle then that is amazing and even at 80 degree you are able to at the same wavelength you are able to heat almost 80 percent of absorption sorry 96 percent of absorption and that is that is tremendous, okay? That is really working well and this is because of the fact that the direction of the magnetic field of the incident light remains unchanged with various incident angles and it can effectively drive the circulating currents at all angles of incidence and that is why for TM polarization you hardly see any difference. However when you look into this particular figure on the left the contour plot here the magnetic field cannot drive the circulating currents efficiently at very large angles so any anywhere above 50 degree or so you see the absorption has dropped significantly, okay? So, at 80 degree you actually land up having like 50 percent of absorption so that is a lot of drop from the perfect absorber to that.

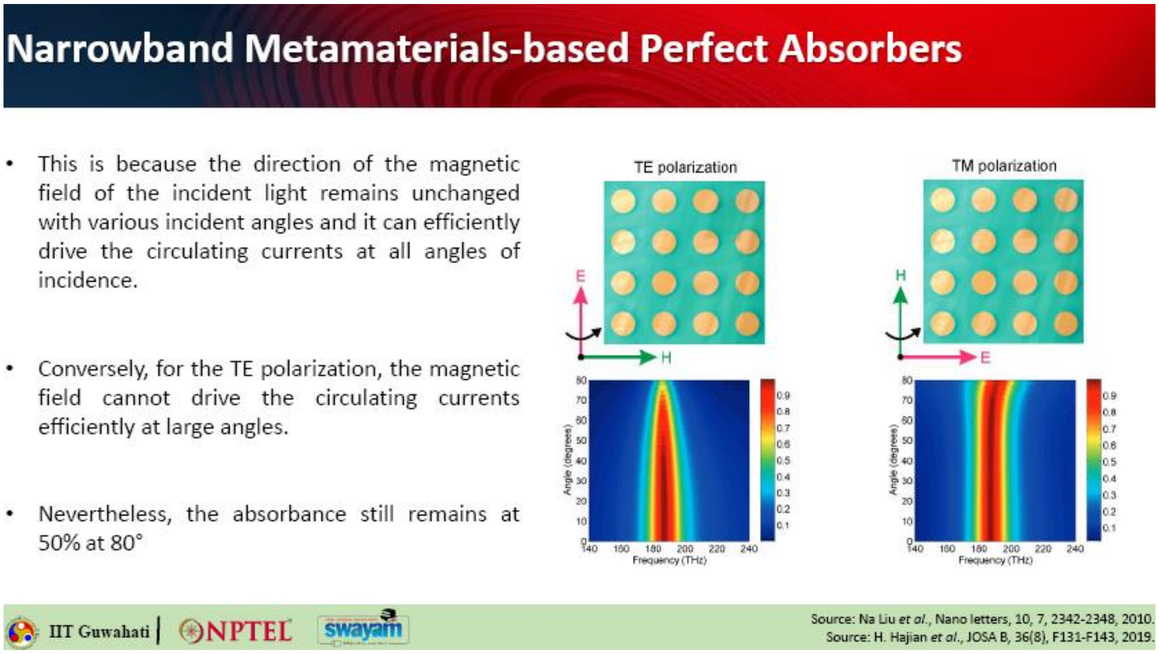


## Narrowband Metamaterials-based Perfect Absorbers

- Simulation study of angular dispersions of the absorbance peak for TE and TM configurations.
- Figure shows the angular dispersions of the absorbance peak at various angles of incidence for both TE and TM configurations.
- For the TM polarization, the absorbance peak is nearly independent of the incident angle and it is 96% even at 80°.

Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

So this is one study that tells you how to design metamaterial perfect absorber and always remember that when you change the size of the disk and the periodicity that would help you tune the position of this absorption peak, okay? Right now it is shown at a particular wavelength and it is or it is in frequency scale so it is close to say 188 terahertz or so and if you change the periodicity or the size of the disk you should be able to tune that, okay? So that is how you can design application specific narrowband perfect absorbers.



## Narrowband Metamaterials-based Perfect Absorbers

- This is because the direction of the magnetic field of the incident light remains unchanged with various incident angles and it can efficiently drive the circulating currents at all angles of incidence.
- Conversely, for the TE polarization, the magnetic field cannot drive the circulating currents efficiently at large angles.
- Nevertheless, the absorbance still remains at 50% at 80°

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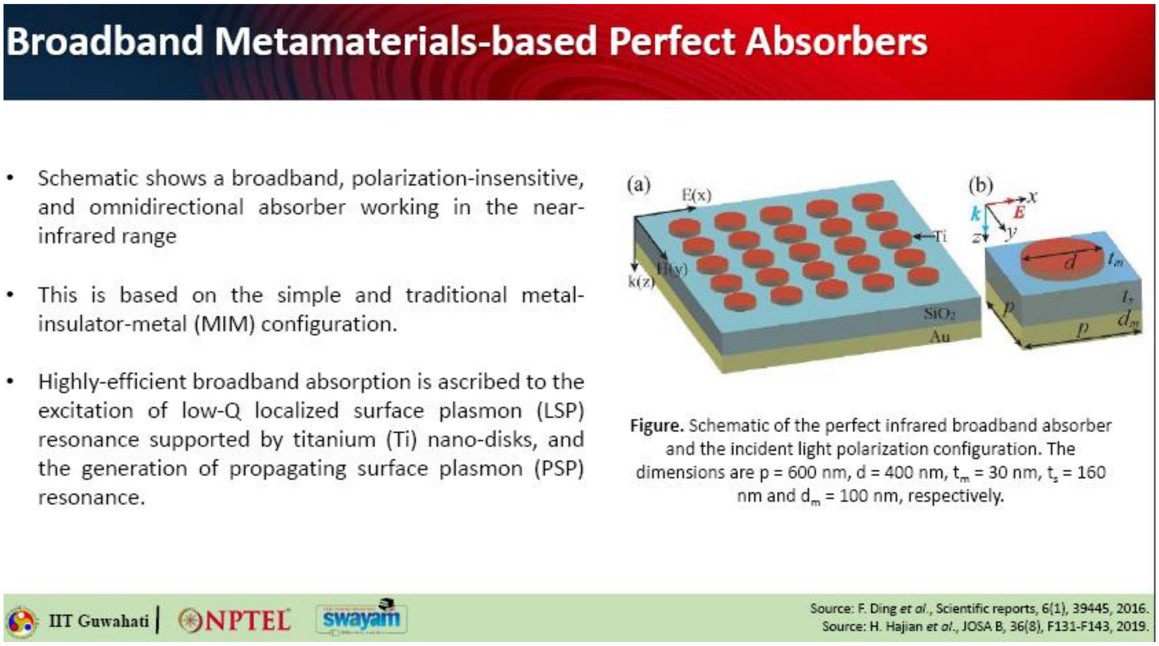
Source: Na Liu *et al.*, Nano letters, 10, 7, 2342-2348, 2010.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

Now moving on to the broadband perfect absorbers let us see how you do that. Now the name itself tells you that you are designing something broadband so you should have kind of a possibility where you can cater to multiple peaks that can overlap spectrally and that can give rise to this broadband nature, right? So broadband definitely you are catering to a much wider wavelength range right now. So here is a schematic of that broadband absorber but surprisingly it is more or less similar kind of a structure but then here the material property is different you are basically using a titanium disk, okay? On top of a gold film with a silica layer on the top acting as a spatial layer, right? So this particular schematic shows a broadband polarization insensitive and omnidirectional absorber working in near infrared range. So that is the range here it has been targeted to and it is based on a simple traditional metal dielectric metal or metal insulator metal configuration.



## Broadband Metamaterials-based Perfect Absorbers

- Schematic shows a broadband, polarization-insensitive, and omnidirectional absorber working in the near-infrared range
- This is based on the simple and traditional metal-insulator-metal (MIM) configuration.
- Highly-efficient broadband absorption is ascribed to the excitation of low-Q localized surface plasmon (LSP) resonance supported by titanium (Ti) nano-disks, and the generation of propagating surface plasmon (PSP) resonance.

**Figure.** Schematic of the perfect infrared broadband absorber and the incident light polarization configuration. The dimensions are p = 600 nm, d = 400 nm, $t_m$ = 30 nm, $t_s$ = 160 nm and $d_m$ = 100 nm, respectively.

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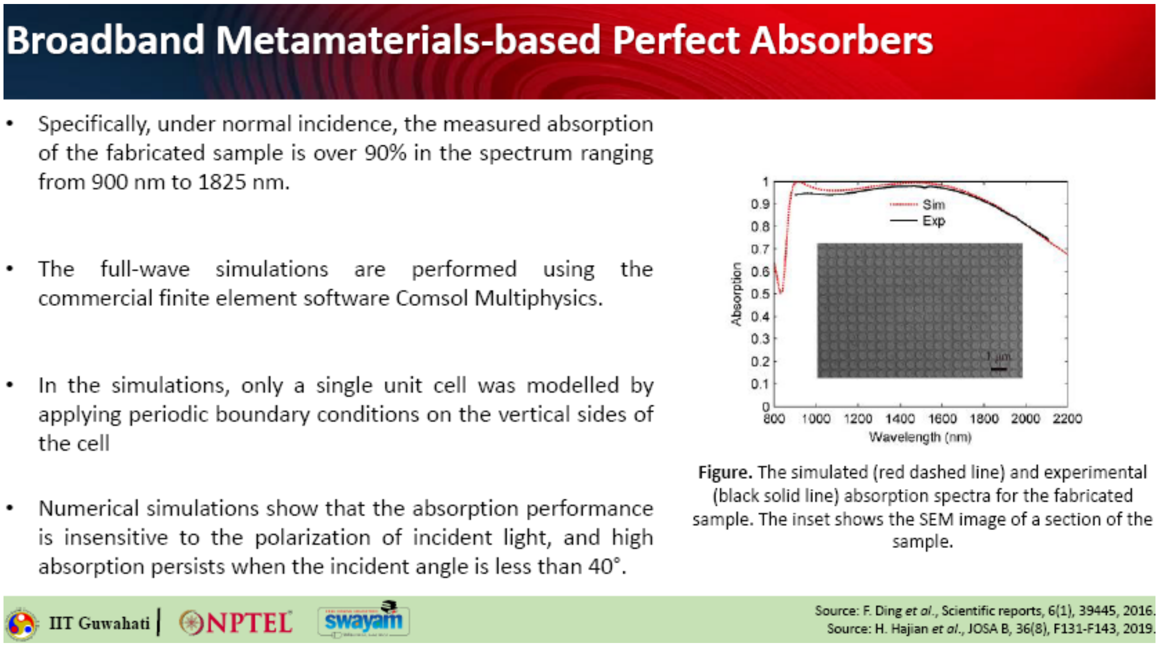
Source: F. Ding *et al.*, Scientific reports, 6(1), 39445, 2016.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

So here what happens the highly efficient absorption is mainly coming from the excitation of low Q localized surface plus bond resonance which are supported by the titanium nanodisks and you are also generating the propagating surface plus bond resonance in the interface between gold and gold film and silica. So let us look into the spectral characteristics here. So this is the black line shows experimental result and the dotted line over there shows the simulation result and then they are matching very very closely and you can say this like a perfect match between simulation and experiment. So here you can see that under normal incidence so here we are only considering theta equals 0, okay? The measured absorption of this fabricated sample is over 90% in the spectrum ranging from 900 to 1825. So this is the range till which it is more than 90%, okay? So this is the experimental one and when you do console multi physics numerical simulation for the same structure you also see very very similar result and in the simulation you are basically considering a single unit cell which has got periodic boundary conditions on both sides to repeat it in both X and Y direction and that can give you this particular structure, okay? So numerical simulation also shows that it is very very close and because the structure is symmetric along X and Y so it will be independent of the polarization of the incident light and you can get very high absorption when the incident angle is less than 40 degree.



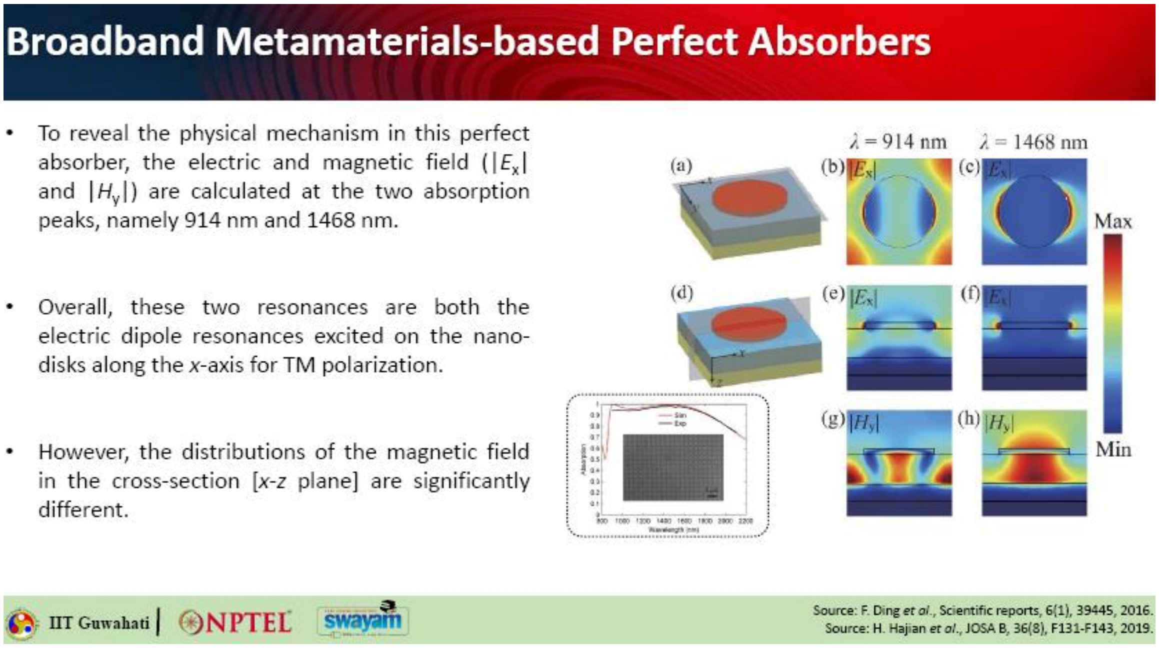
## Broadband Metamaterials-based Perfect Absorbers

- Specifically, under normal incidence, the measured absorption of the fabricated sample is over 90% in the spectrum ranging from 900 nm to 1825 nm.
- The full-wave simulations are performed using the commercial finite element software Comsol Multiphysics.
- In the simulations, only a single unit cell was modelled by applying periodic boundary conditions on the vertical sides of the cell
- Numerical simulations show that the absorption performance is insensitive to the polarization of incident light, and high absorption persists when the incident angle is less than 40°.

**Figure.** The simulated (red dashed line) and experimental (black solid line) absorption spectra for the fabricated sample. The inset shows the SEM image of a section of the sample.

Source: F. Ding *et al.*, Scientific reports, 6(1), 39445, 2016.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

So beyond that there will be drop in the absorption. So here are some simulation results that shows you how it works, okay? So to reveal the physics physical mechanism in the perfect absorber you can actually plot the electric and the magnetic fields, okay? At the two absorption peaks so if you carefully see that there is basically one peak and then there is another peak here, okay? So there are basically two peaks which are spectrally overlapping one is a narrow peak and another one is a pretty broad peak. So there is a peak at 914 and another one at 1468 nanometer, okay? And if you look into the electric field distribution these two resonances both look like electric dipolar resonances, okay? On the nanodiscs when you are considering the TM polarization.

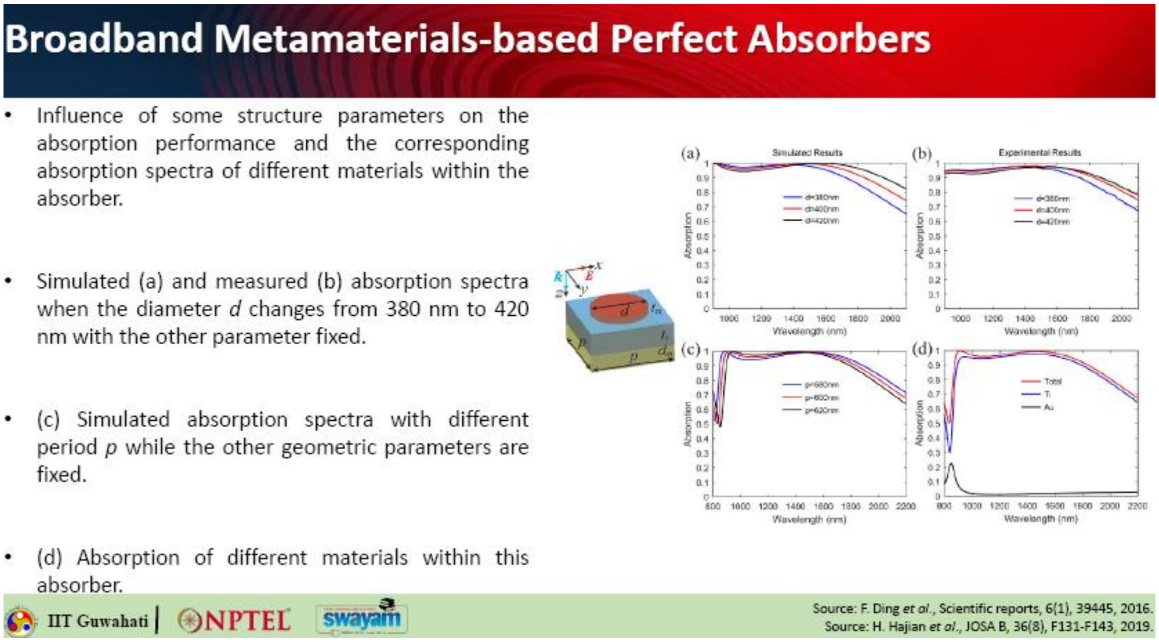


## Broadband Metamaterials-based Perfect Absorbers

- To reveal the physical mechanism in this perfect absorber, the electric and magnetic field ($|E_x|$ and $|H_y|$) are calculated at the two absorption peaks, namely 914 nm and 1468 nm.
- Overall, these two resonances are both the electric dipole resonances excited on the nano-disks along the *x*-axis for TM polarization.
- However, the distributions of the magnetic field in the cross-section [*x*-*z* plane] are significantly different.

Source: F. Ding *et al.*, Scientific reports, 6(1), 39445, 2016.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

However, the magnetic field distribution that you see here is pretty different in these two cases. And if you also analyze that what is the origin of this peak then you can say that the short wavelength resonance that you are seeing at 914 nanometer is basically considered to be the propagating surface plus bond PSP, okay? Resonance that comes between the continuous gold film and the silica spacer where the magnetic field is not only strongly confined in the gap region between the nanodiscs but also strongly enhanced between the nanodiscs.



### Broadband Metamaterials-based Perfect Absorbers

- Influence of some structure parameters on the absorption performance and the corresponding absorption spectra of different materials within the absorber.
- Simulated (a) and measured (b) absorption spectra when the diameter *d* changes from 380 nm to 420 nm with the other parameter fixed.
- (c) Simulated absorption spectra with different period *p* while the other geometric parameters are fixed.
- (d) Absorption of different materials within this absorber.

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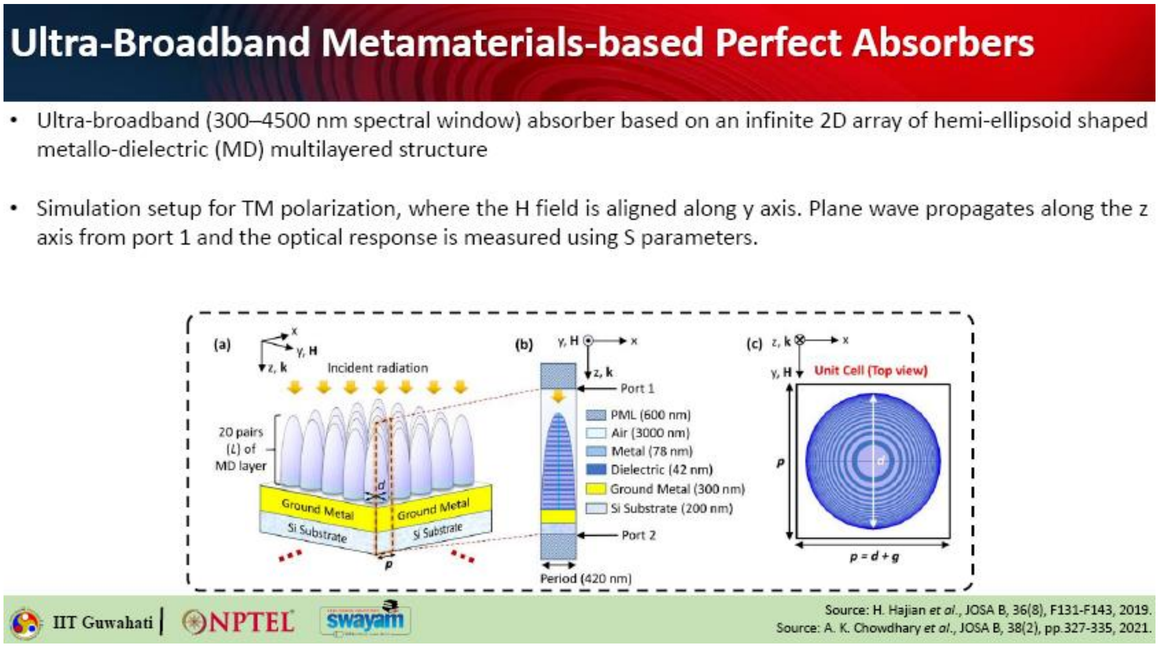
Source: F. Ding *et al.*, Scientific reports, 6(1), 39445, 2016.
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.

And the other case which is the long wavelength mode so at you can call this as lambda 2 this one is lambda 1. So you can say the long wavelength mode which is at lambda 2 1468 nanometer this is basically a localized surface plus bond resonance peak where the magnetic field is mainly concentrated within the gap between the topmost nano antennas and the gold underlay, okay? And since titanium is dispersive it is very dispersive and has a relatively large imaginary part okay if you look into the dispersion relation you will get to know that the intrinsic absorption coefficient of titanium is very large, okay? So you can actually understand that the quality factor of the resonance of this localized surface plus bond resonance peak here is rather low and that gives you this broadening of the absorption and that is how and this is the difference between that gold discs and titanium discs and why we actually opted for titanium discs here when we are planning to make a broadband absorber, okay? So once again we can attribute this broadband absorption to the combination effect of propagating surface plus bond and low Q localized surface plus bond resonance. Now you can see here some of the parametric sweep result it means like the influence of some parameters on the absorption performance and how the absorption spectra looks like for different materials. So this one is a simulated result where d is the disc diameter that has been changed from 380 to 400 to 420 nanometer. The same thing is also seen experimentally and you can see how it changes so they are sensitive to the dimensions as I mentioned so you can actually design the discs based on your requirement.



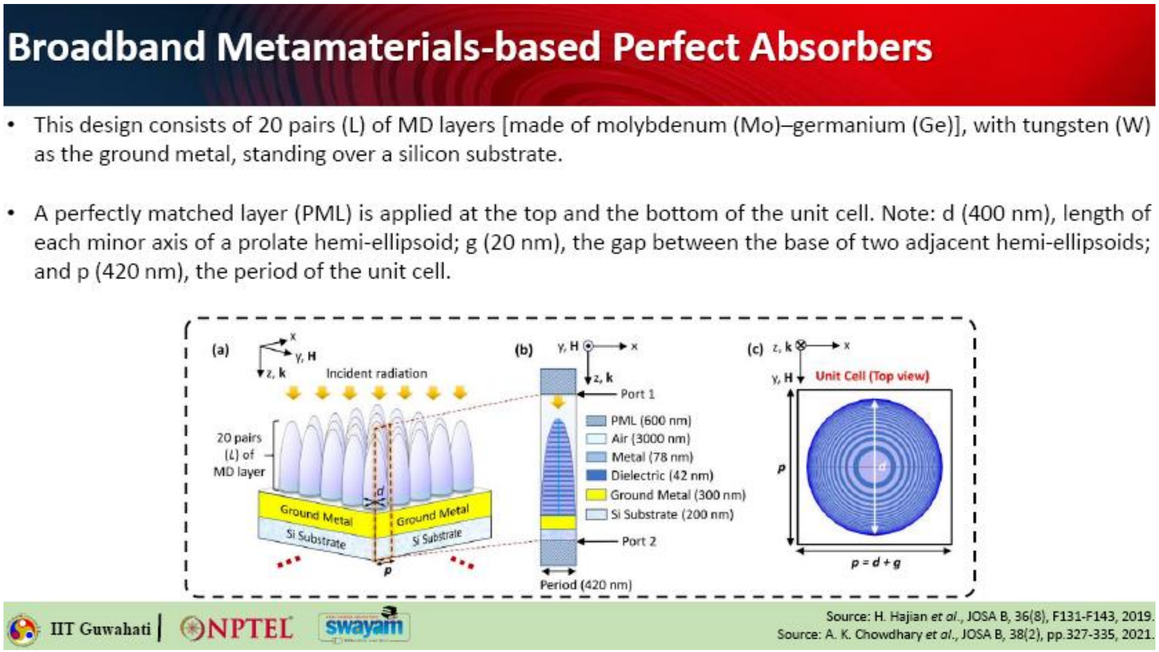
## Ultra-Broadband Metamaterials-based Perfect Absorbers

- Ultra-broadband (300–4500 nm spectral window) absorber based on an infinite 2D array of hemi-ellipsoid shaped metallo-dielectric (MD) multilayered structure
- Simulation setup for TM polarization, where the H field is aligned along y axis. Plane wave propagates along the z axis from port 1 and the optical response is measured using S parameters.

Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: A. K. Chowdhary *et al.*, JOSA B, 38(2), pp.327-335, 2021.

So again, the periodicity is changed here and the periodicity also tells you it actually gives you the range over which you want to have this broadband absorption. So here periodicity of 580, 600 and 620 nanometer has been studied and simulated results and experimental results they are very very close to each other, right? And here also you can see if you take the contribution to this absorption coming from gold and titanium you can clearly see that titanium is contributing to the most of the absorption. So that is the case here this absorber is mainly based on this titanium nano discs. Now we understood that how we can make narrow band we understood how we can make broadband absorbers now we have to understood we have to understand how we can make ultra broadband metamaterial based perfect absorbers. When I say ultra broadband I am thinking of a window something as large as 300 to say 4500 nanometer.

So it starts from typically you know UV visible near infrared and then short and mid IR something like that. So it is typically catering to a very very broadband and this is the kind of structures we call them as ultra broadband absorbers. So how do you make it? You can actually design them using 2D infinite array of hemi ellipsoid shaped metallo-dielectric multilayer structures. So here is the top view of the structure so these and this is the side view so you can see it is like a hemi ellipsoid so half of the ellipsoid and it is alternating metal dielectric metal dielectric structure. So, it is based on a silicon substrate but then you have a ground metal ok it is it can be gold it or silver it can it has to be 300 nanometer so it blocks light completely and it will reflect ok.



## Broadband Metamaterials-based Perfect Absorbers

- This design consists of 20 pairs (L) of MD layers [made of molybdenum (Mo)–germanium (Ge)], with tungsten (W) as the ground metal, standing over a silicon substrate.
- A perfectly matched layer (PML) is applied at the top and the bottom of the unit cell. Note: d (400 nm), length of each minor axis of a prolate hemi-ellipsoid; g (20 nm), the gap between the base of two adjacent hemi-ellipsoids; and p (420 nm), the period of the unit cell.

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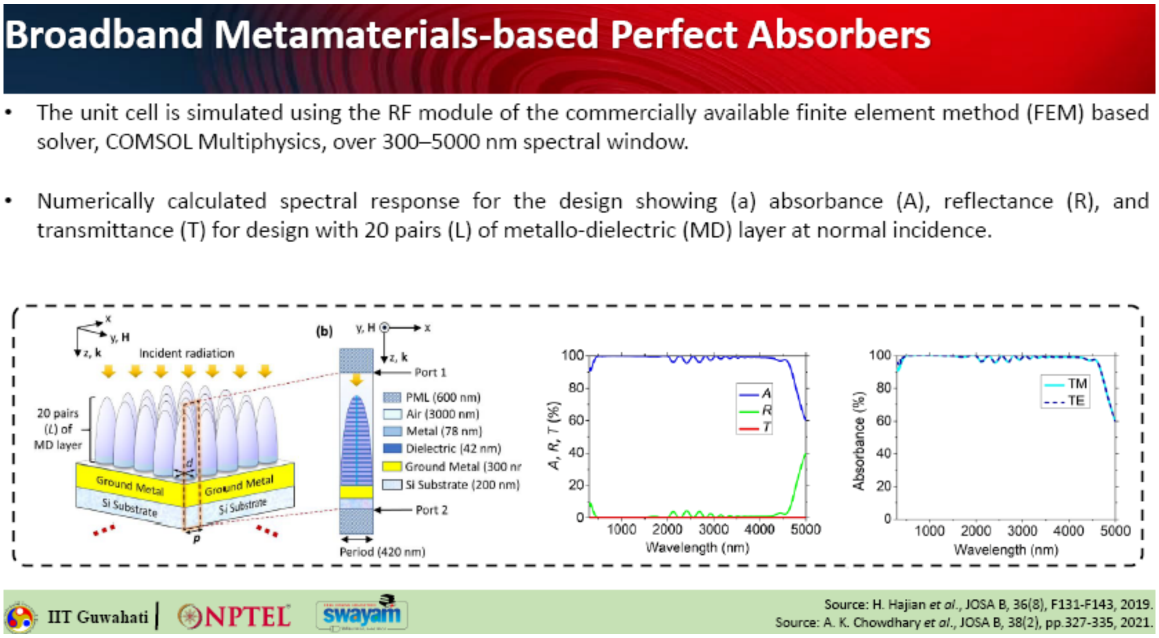
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: A. K. Chowdhary *et al.*, JOSA B, 38(2), pp.327-335, 2021.

And then you have dielectric metal dielectric metal you have these are the simulation setup basically with PML perfectly matched layers. So this allows you to do a simulation of this particular structure for TM polarization ok. Here the H field is considered to be along Y axis and the wave propagation is considered to be along Z axis ok and port 1 is the excitation port and port 2 is the other port. So, if you calculate $S_{11}$ you can get the reflection characteristics and if you calculate $S_{21}$ you can find out the transmission characteristics from the S parameter matrix ok. And here is the periodicity p that is basically the size d and the gap g between the hemi ellipsoids.

So how many layers we have considered 20 layers of metal dielectric alternate structures here molybdenum and germanium are considered and not gold we are using tungsten as a ground metal and this is standing over a silicon substrate ok. So a perfectly matched layer as I mentioned has been applied here on the top and bottom of the unit cell. So this is the side view of the unit cell this is the top view of the unit cell that you can see here. d is the diameter of this hemi ellipsoid the base diameter that is 400 nanometer and then gap is 20 nanometer ok. The periodicity is 420 nanometer and these are the parameters that we have used and other parameters are mentioned in this particular figure I will not read out each of them.

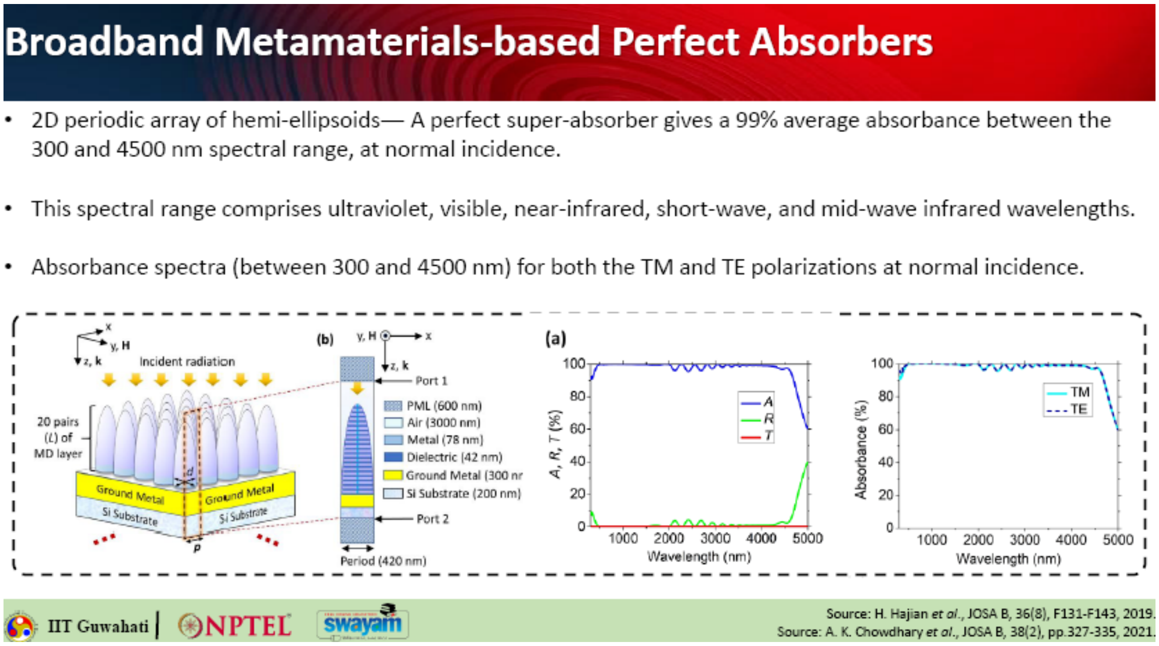


## Broadband Metamaterials-based Perfect Absorbers

- The unit cell is simulated using the RF module of the commercially available finite element method (FEM) based solver, COMSOL Multiphysics, over 300–5000 nm spectral window.
- Numerically calculated spectral response for the design showing (a) absorbance (A), reflectance (R), and transmittance (T) for design with 20 pairs (L) of metallo-dielectric (MD) layer at normal incidence.

Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: A. K. Chowdhary *et al.*, JOSA B, 38(2), pp.327-335, 2021.

And then we have then using the RF module of the console multi physics software the absorption spectrum has been calculated for 300 to 5000 nanometer spectral window ok. And this allows one to get absorption reflectance and transmittance for this structure at normal incidence. So this is that particular structure absorption reflectance and transmittance and as you can see here the transmittance the red one is completely flat. So there is zero transmittance across the structure and you can also see that the absorption reflectance sorry absorption is almost 100 percent of other than this few ringing effects that come from multiple resonance here ok. And more or less it is a very flat wide band absorption ok and what is not absorbed is kind of reflected.



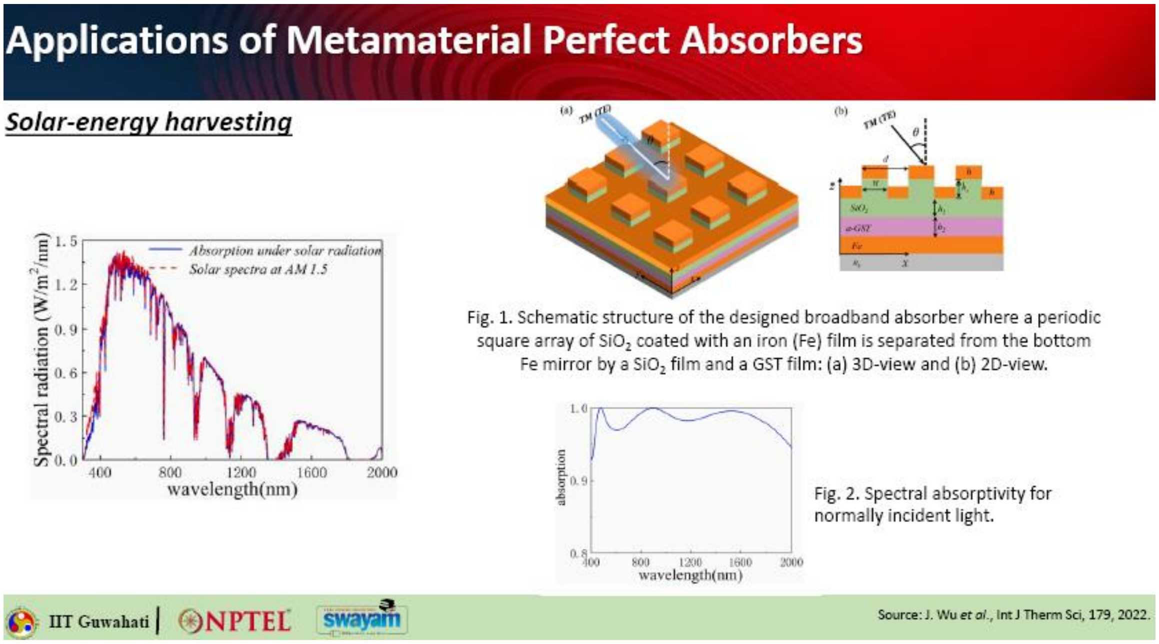
## Broadband Metamaterials-based Perfect Absorbers

- 2D periodic array of hemi-ellipsoids— A perfect super-absorber gives a 99% average absorbance between the 300 and 4500 nm spectral range, at normal incidence.
- This spectral range comprises ultraviolet, visible, near-infrared, short-wave, and mid-wave infrared wavelengths.
- Absorbance spectra (between 300 and 4500 nm) for both the TM and TE polarizations at normal incidence.

Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: A. K. Chowdhary *et al.*, JOSA B, 38(2), pp.327-335, 2021.

So the green curve shows you the reflection curve and this is the plot for the two polarization TE and TM polarization for normal incidence and they are perfectly matching because the structure is also symmetric right. So this particular structure as I mentioned it is a ultra broadband metamaterial based perfect absorber or this kind of absorbers are also called super absorbers because they give you almost 99 percent average absorption and that is a big thing 99 percent average absorption between 300 to 400 nanometer spectral range at normal incidence. And this particular spectral range it comprises as I mentioned earlier UV visible near infrared short wave and mid wave infrared wavelength. So that is pretty wide range ok. So this kind of metamaterial absorbers can be designed.

Now let us look into the applications of this metamaterial perfect absorbers. The first application that comes to our mind is solar energy harvesting and when we talk about solar energy harvesting the most important thing for us is to know that how the solar spectrum looks like ok. So you can see this is the solar spectrum or solar spectral radiation ok versus wavelength. So it actually follows this particular pattern ok. So, you can actually have a blackbody radiation that blackbody radiation picking around 5500 I believe ok that can match this 5500 Kelvin ok that can match this particular solar spectrum.



Applications of Metamaterial Perfect Absorbers

Solar-energy harvesting

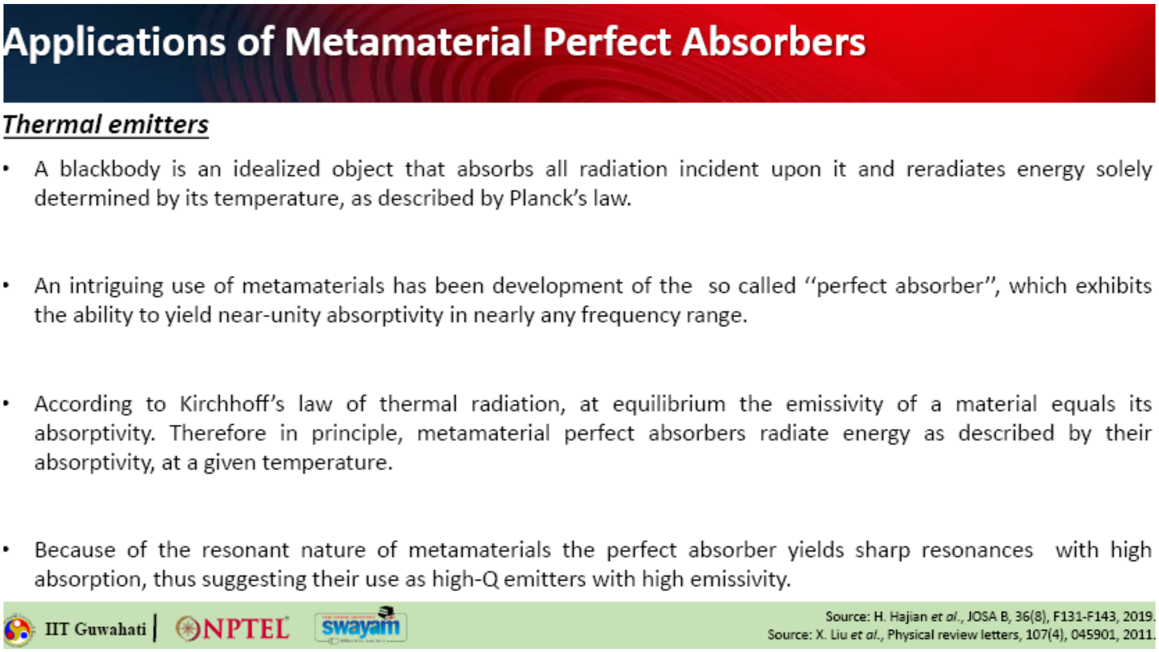
Fig. 1. Schematic structure of the designed broadband absorber where a periodic square array of $SiO_2$ coated with an iron (Fe) film is separated from the bottom Fe mirror by a $SiO_2$ film and a GST film: (a) 3D-view and (b) 2D-view.

Fig. 2. Spectral absorptivity for normally incident light.

Source: J. Wu *et al.*, Int J Therm Sci, 179, 2022.

But then what is important here is that it tells you the range over which you are supposed to absorb. Now if you do not absorb anything beyond say 1800 you are not losing much you are only having a very small portion of the solar spectrum which lies beyond 1800. So you can actually design your absorber until here ok. There are many atoms basically in the literature to design this kind of perfect absorber. One such design has been published in this paper that I am showing here.

So this is a broadband absorber where you have a periodic square array of silica which are coated with iron film ok and this is separated from a bottom iron mirror by another silica film and a GST film. So this is the 3D view and this is the 2D view of the structure. Again you can calculate what is the spectral absorptivity of this structure. You can see that this structure can absorb very strongly from 400 to 2000 that is the entire band that we are looking for ok. Now this is the absorption that is from this particular structure.



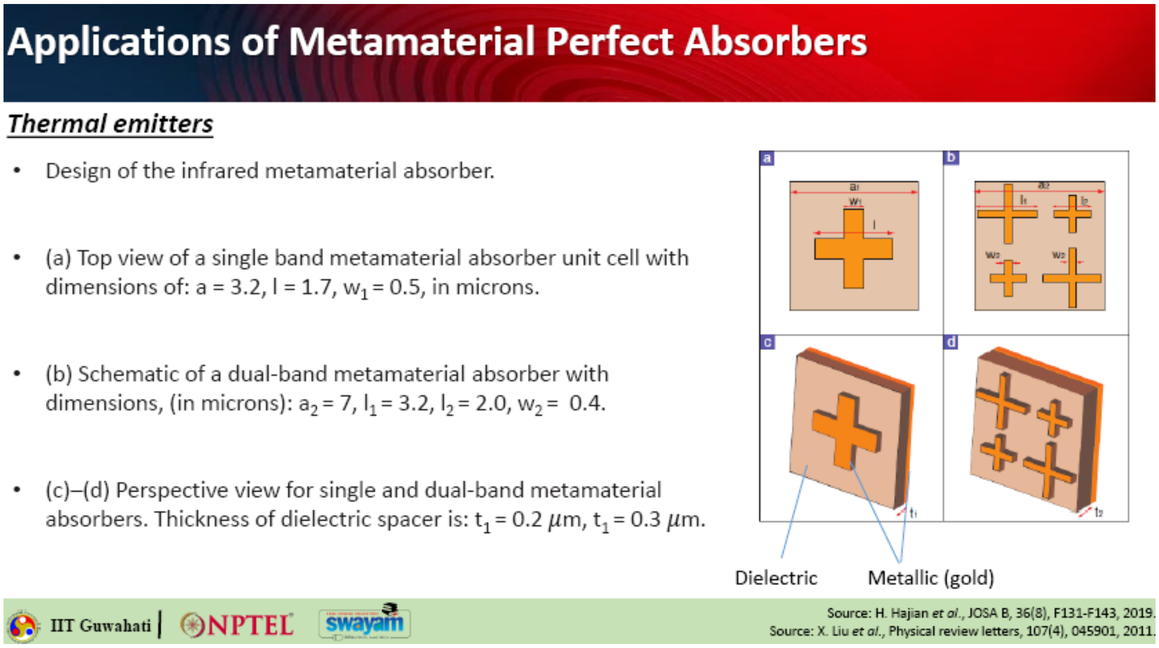
## Applications of Metamaterial Perfect Absorbers

***Thermal emitters***

- A blackbody is an idealized object that absorbs all radiation incident upon it and reradiates energy solely determined by its temperature, as described by Planck's law.
- An intriguing use of metamaterials has been development of the so called "perfect absorber", which exhibits the ability to yield near-unity absorptivity in nearly any frequency range.
- According to Kirchhoff's law of thermal radiation, at equilibrium the emissivity of a material equals its absorptivity. Therefore in principle, metamaterial perfect absorbers radiate energy as described by their absorptivity, at a given temperature.
- Because of the resonant nature of metamaterials the perfect absorber yields sharp resonances with high absorption, thus suggesting their use as high-Q emitters with high emissivity.

Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: X. Liu *et al.*, Physical review letters, 107(4), 045901, 2011.

Now if we tweak this structure a little bit or you redesign this structure your aim would be to have a flat absorption line over this entire window and the discussion we had previously those kind of structures can give you almost 100% of absorption over this band. Now the question is why then we need to design this one again if that previous structure is giving us all that we need. Now if you see the previous structure fabrication wise that structure is very very challenging. It is a hemispherical shape with alternating layers of metal dielectric and then you have to maintain that reducing dimension as well. So that is a very challenging structure on in comparison to that this is much easier structure and that can give you an average absorption of almost a 90% or so 90 to 95%.



## Applications of Metamaterial Perfect Absorbers

***Thermal emitters***

- Design of the infrared metamaterial absorber.
- (a) Top view of a single band metamaterial absorber unit cell with dimensions of: $a = 3.2$, $l = 1.7$, $w_1 = 0.5$, in microns.
- (b) Schematic of a dual-band metamaterial absorber with dimensions, (in microns): $a_2 = 7$, $l_1 = 3.2$, $l_2 = 2.0$, $w_2 = 0.4$.
- (c)–(d) Perspective view for single and dual-band metamaterial absorbers. Thickness of dielectric spacer is: $t_1 = 0.2\ \mu m$, $t_1 = 0.3\ \mu m$.

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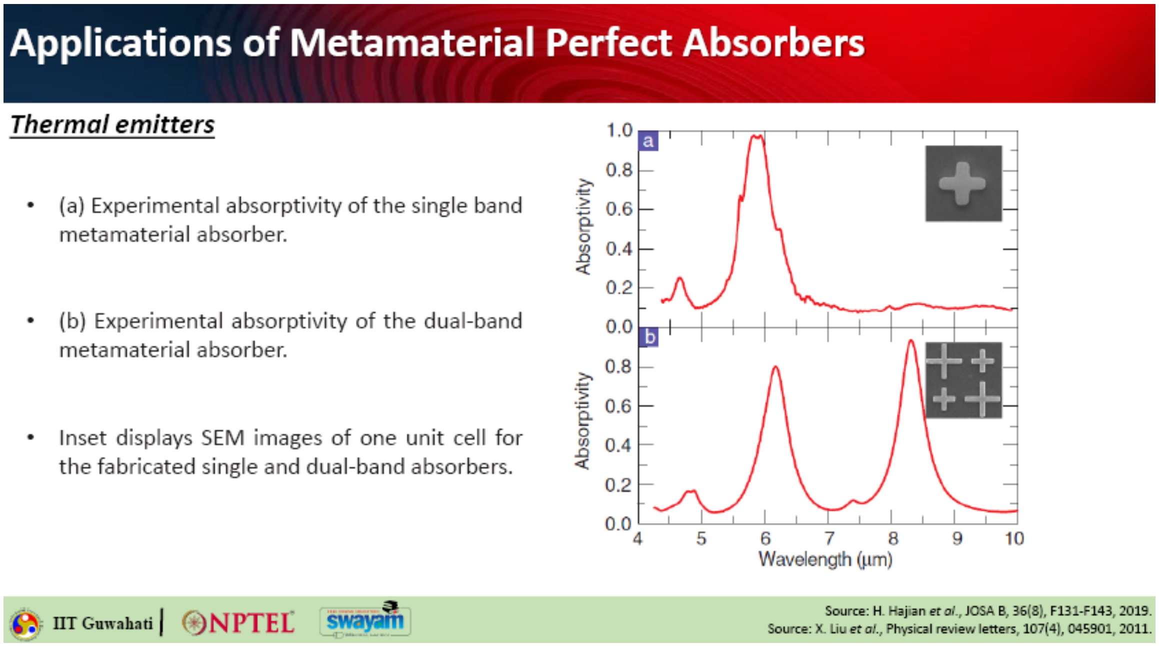
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: X. Liu *et al.*, Physical review letters, 107(4), 045901, 2011.

So, in some cases where you do not have the facility to fabricate those complicated structures you can still be happy with this kind of a structure. What are the other applications? So this one is basically an application of a broadband metamaterial perfect absorber. Now you can also have applications of narrow band metamaterial perfect absorbers as thermal emitters. Now what are these thermal emitters? Now if you think of a black body it is basically an idealized body that can absorb all radiation which falls on it and it re-radiates energy solely determined by its temperature as described by the Planck's law. Now when you develop metamaterials okay and you are targeting an application of perfect absorber which exhibits the ability to have near uniform or near unity absorption in a frequency range you are basically making it like a black body.

So this same material can also behave like a thermal emitter right just like black body radiates your metamaterial can also radiate. According to Kirchhoff's law of thermal radiation at equilibrium the emissivity of a material equals to its absorptivity. Therefore in principle the metamaterial perfect absorbers can radiate energy as described by their absorptivity at a given temperature. Now because of the resonant nature of the metamaterials the perfect absorber the narrowband perfect absorbers they yield very sharp resonances with high absorption that means they will basically act as very high q thermal emitters and they will also have very high emissivity. So that way you can actually make very high q high emissivity thermal emitters.



## Applications of Metamaterial Perfect Absorbers

***Thermal emitters***

- (a) Experimental absorptivity of the single band metamaterial absorber.
- (b) Experimental absorptivity of the dual-band metamaterial absorber.
- Inset displays SEM images of one unit cell for the fabricated single and dual-band absorbers.

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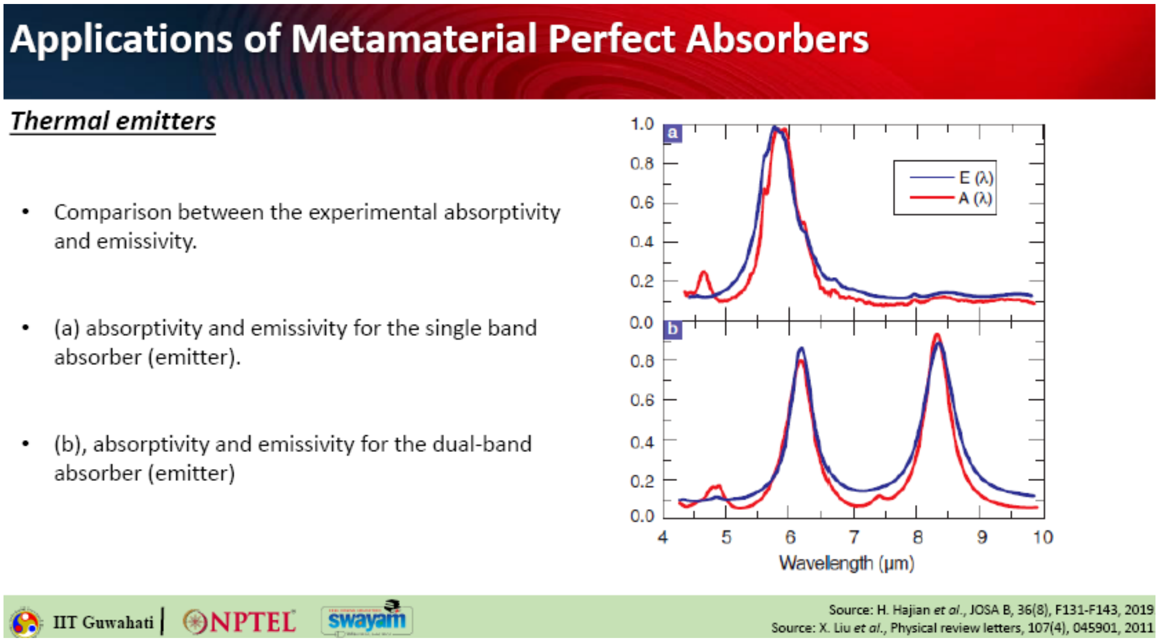
Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019.
Source: X. Liu *et al.*, Physical review letters, 107(4), 045901, 2011.

So here is one design of infrared metamaterial absorber that will also work as a thermal emitter we will see that. So here is a structure first you start with a plus type okay plus kind of a structure. So this is a metallic structure gold structure on a dielectric and on the back side also you have another gold layer okay. So this is the top view of the single band metamaterial absorber and these are the dimensions okay all are in microns here length, width, periodicity all are given okay and this is a dual band so this is basically a mixture of the small and the large there are two structures which resonate at two different frequency band and that is why it is called a dual band metamaterial absorber and the dimensions are given here all are in microns again. And these two shows the top view these two figure shows the perspective view and in the two cases the thickness of the dielectric spacer is 0.2 micron here for the single band metamaterial absorber and it is 0.3 micron in the case of dual band metamaterial absorber. Now when you do the experimental absorption study of this structure so here in the inset you can see the SEM images. So for the single band structure you get this peak which is pretty good and also these are all experimental pictures okay for the dual band you get these two bands which are absorbing very strongly right. So that way you can also compare the experimental absorptivity with the emissivity and you see that they do follow the law of Kirchhoff that we have discussed that the absorption pattern is same as their emission spectrum right.



## Applications of Metamaterial Perfect Absorbers

***Thermal emitters***

- Comparison between the experimental absorptivity and emissivity.
- (a) absorptivity and emissivity for the single band absorber (emitter).
- (b), absorptivity and emissivity for the dual-band absorber (emitter)

Source: H. Hajian *et al.*, JOSA B, 36(8), F131-F143, 2019
Source: X. Liu *et al.*, Physical review letters, 107(4), 045901, 2011

So that way you can actually see that you can develop a thermal emitter a high Q thermal emitter at a single band a dual band or multiple bands depending on the design of your metamaterial absorber okay. So this one shows the absorptivity and emissivity of a single band absorber or you can say emitter whereas this one shows a dual band absorber or emitter okay. So that way you can actually design the materials. So what is important here you to understand that the structures the emission spectrum spectrum is completely dependent on the structure that you are designing okay. If you choose a different shape, if you choose a different material, if you choose a different periodicity or a thickness the resonance peak can be changed.

If you want to play with the Q factor of the resonance you can choose if you want to lower high Q okay means you want a sharper resonance peak you should select materials which are less lossy and then if you want a resonance with a broader Q okay you should actually choose materials with high loss that we have seen. Now while choosing the material properties you got to be very careful about the dispersion. So you have to choose the material property that is suitable for the range the frequency range that you are considering. So usually there are websites like refractiveindex.info where you can download and see the dispersion curves of different materials and that helps you understand which material could be useful in designing what kind of emitters at what frequency band okay.

So with that I think we have covered the topics and that is all for this lecture we will consider the topics of smart sorry superlens and hyperlens in the next lecture and in case you have got any queries on this particular lecture you can drop an email to this email address with in the subject line. Thank you.