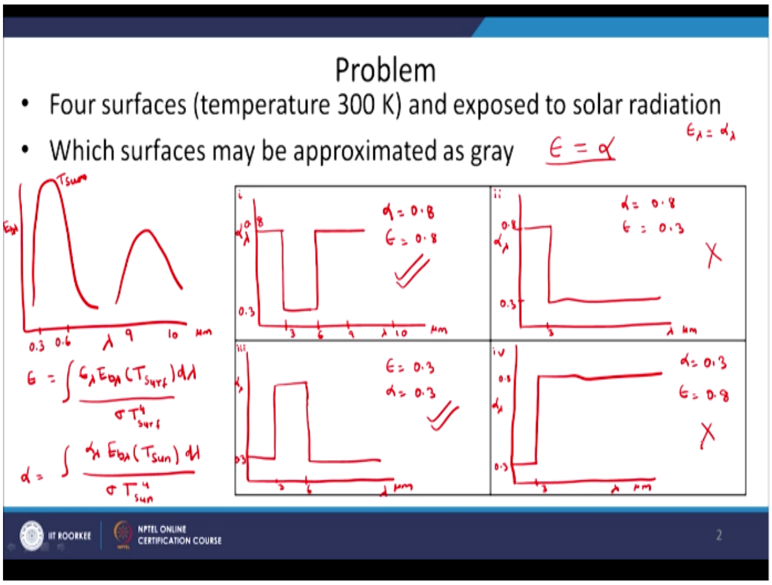
**Radiative Heat Transfer**
**Prof. Ankit Bansal**
**Department of Mechanical and Industrial Engineering**
**Indian Institute of Technology – Roorkee**

**Lecture - 05**
**Radiative Properties of Materials**

Hello friends. In the previous lecture, we learnt about the radiative characteristics of plane surfaces. In this lecture, we will do a couple of problems and I will introduce you to the radiative properties of materials.

**(Refer Slide Time: 00:40)**




In the first problem that we will discuss in this lecture, we have four surfaces, all the surfaces are at 300 Kelvin and they are exposed to solar radiation. We have to check which of these surfaces may be approximated as gray surface. So gray surface, what we mean by gray surface is that emissivity of the surface should be equal to the absorptivity or emittance of the surface should be equal to absorptance of the surface.

If this condition is satisfied, we can call this surface as gray. So the surface that we have in this problem, the first surface the distribution of absorptance spectral absorptance is given alpha lambda with respect to wavelength lambda, we have range 3 micrometer, 6 micrometer and so on and this looks like this. This value is 0.8 and this value is 0.3, so the first surface basically has absorptance of 0.8 in the spectral range less than 3 micrometer.

And it has absorptance of 0.3 in 3 to 6 micrometer spectral range. The second surface let us call this surface 1 and this is surface 2. Now this surface the absorptance of this surface is given, so again it has absorptance of 0.8 from 0 to 3 micrometer range and then the range is 0.3 from 3 micrometer onwards. The third surface the spectral absorptance is given, the value is 0.3 in the spectral range 0 to 3 micrometer.

Then, it is 0.8 in the spectral range 3 to 6 micrometer and then again it basically is given 0.3 beyond 6 micrometer and the fourth surface, this is third and this is fourth. This is the fourth surface, it has 0.3 absorptance okay and then this is 0.8 and then we have continuous 0.8 beyond 3 micrometer okay. Now if you look at the emittance and the blackbody emissive power in this spectral range, so we will see that the blackbody emissive power of sun will be in this range.

This is lambda and this is Eb lambda okay. So this is for sun, so this spectral emissive power peaks in the range of 0.3 to 0.6 micrometer and if you plot the emissive power blackbody emissive power of the surface which is maintained at 300 Kelvin, it will look like this which will peak in the range of 9 to 10 micrometer okay. Now we will try to calculate the spectral emittance and absorbance of the surface.

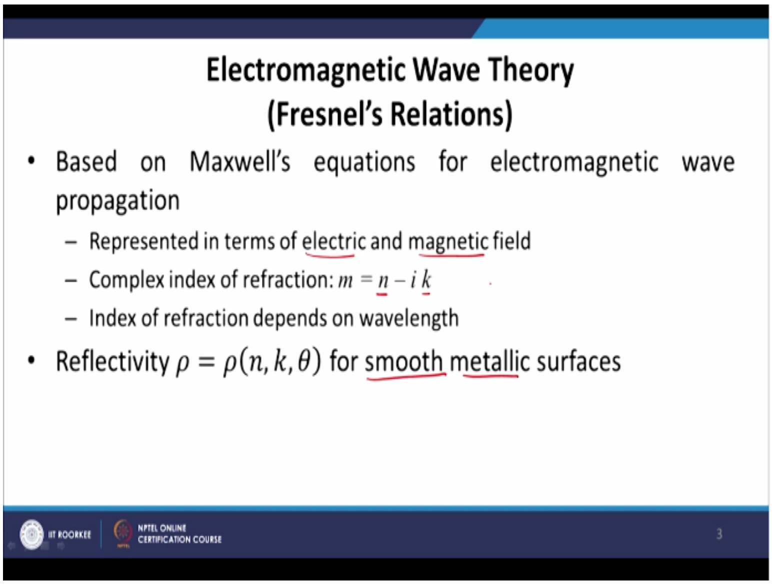
So we define emittance epsilon as equal to integral epsilon lambda Eb lambda at surface temperature d lambda and then over sigma T to the power 4 where T is the surface temperature while absorptance we define as alpha lambda Eb lambda at the surface temperature of the sun d lambda/sigma T to the power 4 where T is the sun temperature okay. Now if you look at if you substitute the value of alpha lambda so from Kirchhoff's law we have epsilon lambda is=alpha lambda okay.

So we will put this value of epsilon lambda and alpha lambda in these expressions and what we find is that for this surface okay, the surface number 1 the epsilon lambda and alpha lambda is 0.8 where the solar spectrum lies okay. So we will get alpha value is=0.8 and the value of epsilon in the 9 to 10 micron range also has the same value. So we get epsilon is=0.8 okay. For the second surface we get alpha is=0.8 and epsilon is=0.3.

For the third surface we get epsilon is=0.3 and alpha is=0.3 and for the fourth surface we get alpha is=0.3 and epsilon is=0.8. So from our definition of gray surface epsilon is=alpha that means total emittance should be equal to total absorptance, our surface 1 is gray and our surface 3 is gray okay while surface 2 is not gray because alpha is not equal to epsilon and surface 4 is gray because alpha is not equal to epsilon okay.

So this basically gives this example gives you an idea how can we characterize different surfaces as gray or non-gray so surface number 2 and 4 are non-gray, surface 1 and 3 are gray.

**(Refer Slide Time: 08:05)**

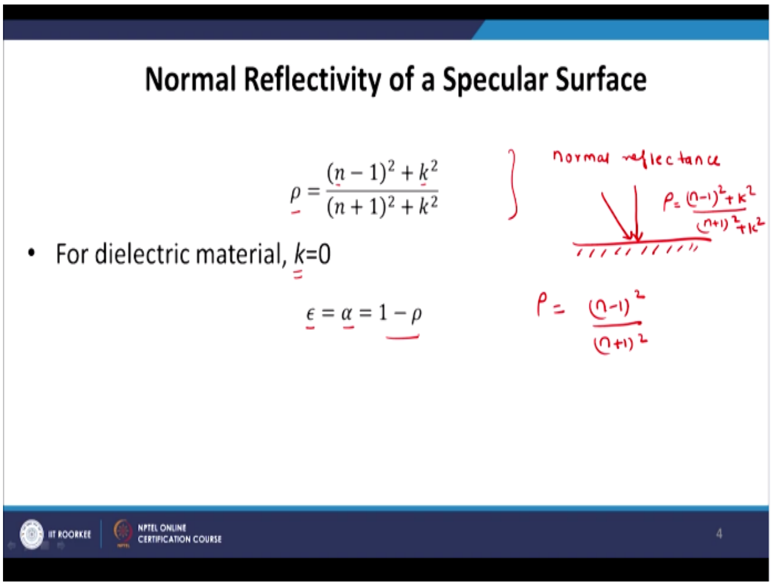



Now how do we calculate the properties of the surface? We in the previous lecture tried to find spectral, directional, hemispherical and total emittance, absorptance and reflectance. Now theoretically how can we calculate these properties? So in this lecture, I will just briefly introduce you to the electromagnetic wave theory and the Fresnel's relation.

So basically for smooth surfaces, smooth and metallic surfaces, one can solve Maxwell's equation of electromagnetic radiation which basically includes electric waves and magnetic waves and based on the solution of these waves, we can find out the amount of radiation reflected from the surface. Now it depends on the magnitude of electric and magnetic field, that means it will depend on the wavelength, it depends on the complex index of refraction.

You all know that index of refractive index but not everybody knows that it is a complex quantity. We have a real part and which we normally call index of refraction and there is an imaginary part also with magnitude k. So complex index of reaction is basically used to calculate the properties of the surface and both n and k they depend on wavelength okay.

**(Refer Slide Time: 09:40)**



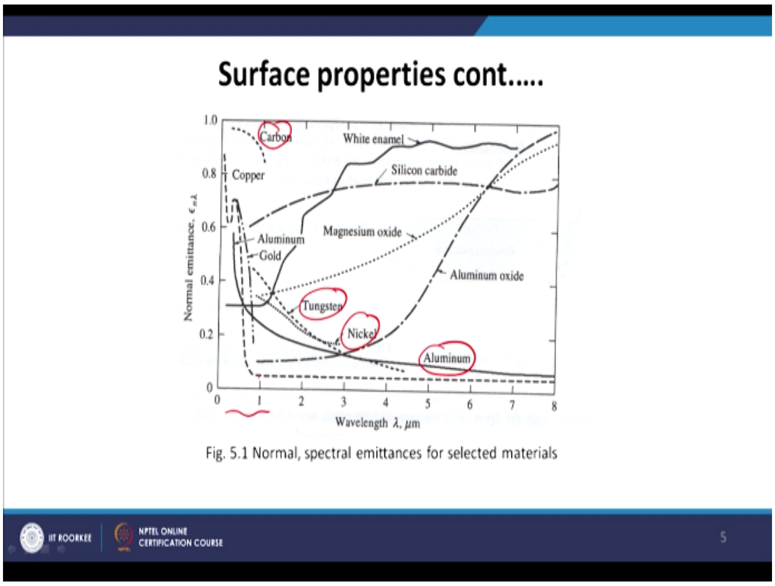

So the electromagnetic wave theory, Maxwell's electromagnetic wave theory gives us an expression of reflectance rho in terms of complex index of refraction. The two parameters are n the real part of complex index of refraction and k the imaginary part of index of refraction. So the expression for reflectance rho is=n-1 whole square+k square/n+1 whole square+k square. Now this gives you normal reflectance.

That means if there is a surface and it is smooth and it is a metallic surface, smooth metallic surface, the normal radiation that means falling perpendicular to the surface, the amount of radiation reflected from the surface will be given by this relation and n-1 square+k square/n+1 square+k square. So this is for the normal direction. Similar expressions exist for radiation falling at an angle okay.

From different angles different relations exist but the relations are little complicated. So I will just introduce you to the normal reflectance. That is the radiation falling perpendicular to the surface okay. Now this is for metallic surface, for dielectric material the imaginary part of index of refraction is 0, k is=0 and the expression for reflectance for a dielectric material will simply be equal to n-1 square/n+1 square, the k is=0.

Once we know the reflectance of a smooth metallic surface or a dielectric surface, we can calculate its emittance, absorptance as equal to 1-rho okay.

**(Refer Slide Time: 11:44)**



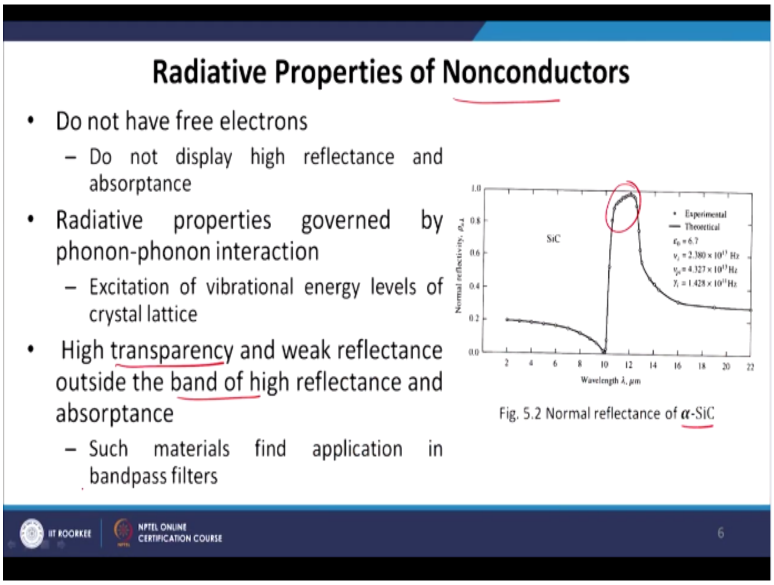

So the reflectance calculated from the theory and experiments have very good agreement. On this slide, you see the normal emittance which is basically 1-the normal reflectance for some materials including metals and nonmetals. So what we see is basically the wavelength dependence of this emittance and what we observe is that for most part of the spectrum the metals aluminium for example nickel, tungsten, they have very low value, very small value of emittance okay.

While for carbon which is very much of interest to us, the emittance is more or less constant at around 0.9 okay in the wavelength region which is basically mostly useful for heat transfer applications. So we can assume carbon to be mostly like gray, the emittance is more or less constant over the wavelength regions of interest. In furnaces for example in boiler furnaces the walls of the furnaces are basically coated with the suit material that is carbon material.

And we can assume these surfaces to be black or at most gray because the emittance of this carbon is weakly dependent on wavelength okay. Similarly, with silicon carbide which has very weak dependence on wavelength but metals also show weak dependence but there is a strong emittance in short wavelength region for aluminium for example, for tungsten example.

So at short wavelength region, they have a strong large value of emittance. At larger wavelength, the remittance is small but more or less constant with wavelength.

**(Refer Slide Time: 13:41)**




Now radiative properties of nonconductors, so metals have free electrons and they display very high reflectance, very small value of emittance as we have seen in the previous slide, very small value of emittance, they have very high reflectance. So metallic surfaces are highly reflective okay because they have free electrons and they also have strong absorptance so whatever is not reflected from the metallic surface will be absorbed strongly within the metal, so they are very poor transmitter of radiative energy.

On the other hand, nonconductors for example the alpha silicon carbide do not free electrons and they do not display high reflectance and absorptance. So very less amount of energy is reflected from nonconductors and whatever energy passes through the medium is basically transmitted and is not absorbed. So they have low value of reflectance as well as low value of absorptance.

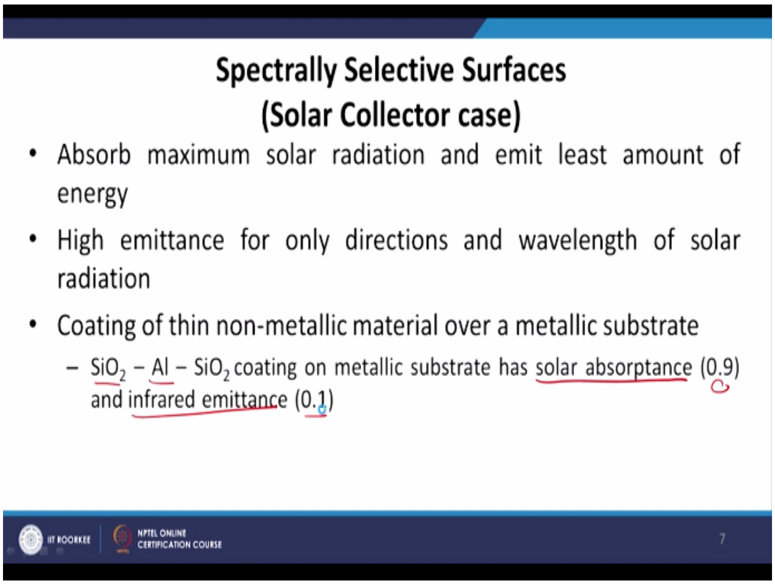
The phenomena basically governed by phonon-phonon interaction. So in nonconductors when radiation energy is absorbed, the energy basically excites the vibrational levels of crystal lattice and due to this vibrational excitation, the radiation energy is absorbed. Now the phenomena of this vibrational excitation does not happen at all wavelengths. It happens only at selected wavelengths.

For example, on this figure what you basically see is a strong reflectivity and strong absorption also in the wavelength region between 10 to 12 microns okay. So this material will strongly reflect as well as strongly absorbed only within the small region. This is called band okay, so they have what we called absorption bands or reflection bands okay.

Other than these bands, they are virtually non-reflective, very low value of reflectance and they are good transmitters also. So most of the energy that is not reflected from the material surface will be transmitted okay. So nonconductors are highly transparent with weak reflectance and they have a band of high reflectance and absorptance. So nonconductors they absorb and reflect only within a band okay.

And the application of such materials for the non-conducting material is basically in bandpass filters. Whenever we want to devise a filter for radiation, a bandpass filter these types of materials are used because of this characteristic of reflectance and transmittance.

**(Refer Slide Time: 16:37)**



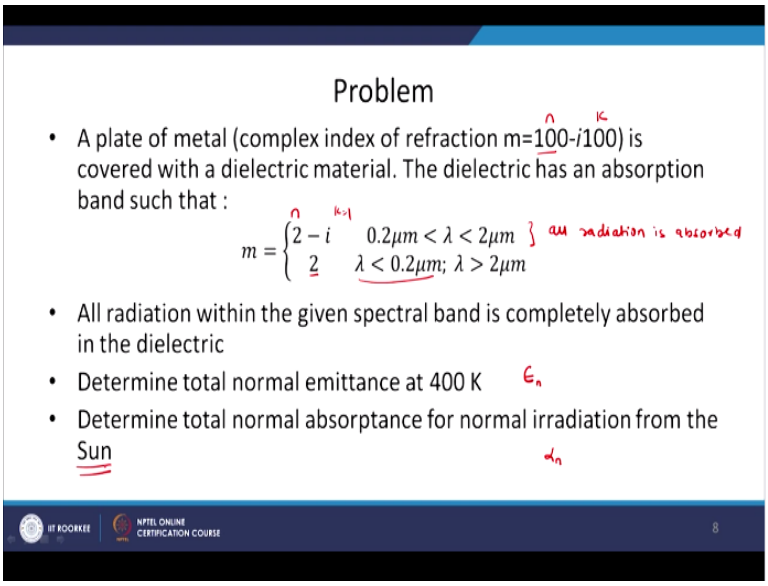

There is another class of materials which has find much application in solar collector case and their spectral selective surface. Now what we desire in solar collectors is a type of surface that absorbs most of the solar radiation coming from all whatever direction by the direct or diffuse at the interest of wavelengths, some part of visible and infrared.

But simultaneously we also desire that the solar surface, the collector surface should not emit much of radiation but what we have learnt so far from Kirchhoff's law, any surface that absorbs maximum radiation or absorbs radiation also is a good emitter. A good absorber is also a good emitter. So there is a conflict here, we want a surface which absorbs radiation good amount of radiation.

But we also want a surface which does not emit much of radiation. So in this case what is basically done is we combine the properties of more than one material. We put some kind of coating, for example silicon oxide coating over an aluminium substrate gives you good amount of absorptance for solar energy which is around 0.9 but simultaneously also gives poor infrared emittance which is at 0.1.

So by combining the properties of this non-conducting and dielectric materials with metallic substrate, we can achieve good absorptance of solar radiation simultaneously with poor emittance of infrared radiation which is basically the case of the solar collector. So we have to combine the properties, we have to combine the number of materials into a sandwich structure.

**(Refer Slide Time: 18:35)**

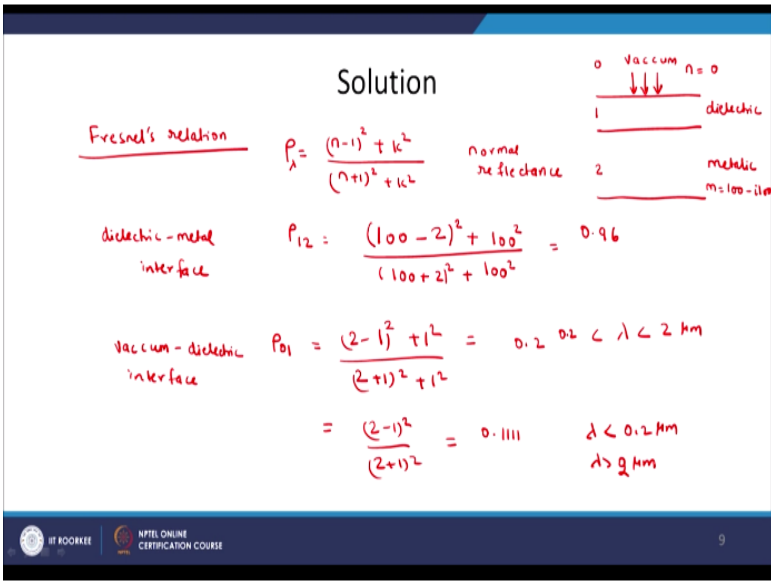



Now a similar problem, the one that we discussed here, I will discuss with the help of an example where we have a plate of metal, the metal has complex index of refraction which is basically the real part and is 100 and the imaginary part is also 100 okay. So we have this metal plate and it is covered with a dielectric material. The dielectric has an absorption bands such that the complex index of refraction is 2-i, k is=1.

For wavelength range 0.2 microns and 2 microns and it has a value of 2 that is k is=0 within the wavelength range lambda <0.2 microns and lambda >2 microns okay. So all radiation within the given spectral band is completely absorbed. It is also given that all radiation within the given spectral band is completely absorbed in the dielectric. That means in this range 0.2 micron to 2 micron all the radiation is absorbed.

And nothing basically reaches the metallic surface okay. So what we have to find in this problem, so we have to find determine the total normal emittance that is epsilon okay in the normal direction okay. We have to determine total normal absorptance that means we have to find alpha n okay and that is from the solar radiation okay. The absorptance depends not only on the surface but also the radiation coming in.

**(Refer Slide Time: 20:12)**




So let us solve this problem okay. So let us first draw the diagram. So we have vacuum at the top from which solar radiation is falling okay. The refractive index is 0. On top of the substrate, we have this dielectric material okay and then we have this metallic surface okay. So complex index of refraction m for this is 100-i 100 and this has a complex index of refraction that depends on wavelength okay.

So first of all what we will do is we will apply the Fresnel's relation to find out the reflectance okay. So we apply Fresnel's relation to find out the reflectance okay. So Fresnel relation is given by rho. Now we will call it rho lambda because the dielectric property depends on wavelength. While for the metallic substrate, it is independent of wavelength. So let us write in general rho lambda.

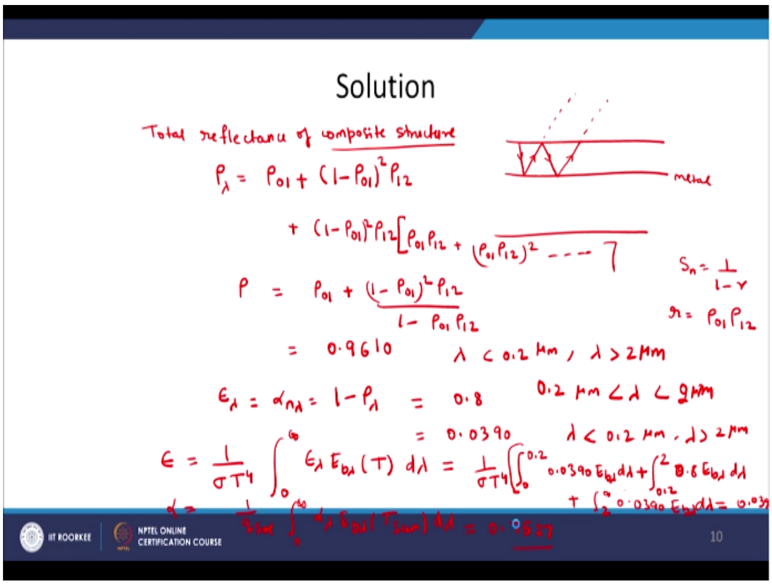
So rho lambda is=n-1 square+k square/n+1 square+k square. This is normal reflectance okay. Now I will call this medium as 0, this medium as 1 and this medium as 2. So rho 12 is basically the reflectance at this interface between 1 and 2 okay. So reflectance at the interface rho 12 will be given by 100 the real part of the metallic substrate-2 so just I would like to go back, 2 is the real part of the dielectric.

So 2 is the so this will be basically the real part of the interface, 1 will be when we have interface with a vacuum, so n is the medium 2 so let us just call it n2-n1 or n2+n1 okay. So 100-2 square okay+k, k value is=100 and then we have 100+2 square+100 square okay. So this is the reflectance at the interface 1 and 2 okay. Had it been vacuum and metallic substance instead of 100-2 I would have taken 100-1.

So this value is=0.96 okay so highly reflective. The reflectance of the metallic substrate is 0.96 okay. So this is dielectric metal interface okay. Now we have rho 01 that means the interface between vacuum and dielectric, so vacuum dielectric interface okay. So rho 01 we have value equal to n=1 so 1 square 2-1 square+1 square 2+1 square+1 square okay and this value is going to be equal to 0.2 and this is for wavelength region 0.222 micrometer.

And the same value will be=2-1 square/2+1 square is=0.111 for wavelength region <0.2 micrometer and >2 micrometer okay. So this is going to be the reflectance at this interface. So now let us try to find out total reflectance of this complex material.

**(Refer Slide Time: 24:53)**




So total reflectance of composite structure so how do we find total reflectance of composite structure? So let us look at it. This is our composite structure. So some radiation basically I am going to draw it an angle just for the purpose of understanding. Instead of drawing normal direction I will just do it at an angle. So this is the amount of radiation that is not reflected but transmitted from the dielectric vacuum interface okay.

Some part of it will hit the metallic interface so this is metal. Now some part of it will be reflected here and some part will be transmitted and then some part will again reflected and again reflected and so on okay. So there will be multiple reflections between the interface okay. This is the transmitted radiation at the dielectric vacuum interface. This is the reflected part from the metal interface.

This is again reflection at metal sorry dielectric interface and this is again reflection. So we define rho lambda okay is=rho 01 okay so this will be=rho+1-rho 01 square rho 12+1-rho 01 square rho 12 and then there will be a series in this, rho 01 rho 12+rho 01 rho 12 square and so on. So there will be multiple reflections. So this is the reflectance of the composite structure okay.

This is the geometric series with sum of geometric series given by for infinite terms 1/1-r. So r is the value of the coefficient that we were multiplying with rho 01 rho 12 okay. So this series the reflectance will be=rho 01+1-rho 01 square rho 12 1-rho 01 rho 12. So all these values rho 01, rho 12 we have calculated already okay. So this value will be=0.9610 for lambda <0.2 micrometer and >2 micrometer okay.

So this is going to be the reflectance. Now let us see how the total emittance is found okay. So total emittance epsilon lambda is=alpha n lambda is=1-rho lambda and this value will be equal to 0.8 for wavelength region 0.2 micrometer and <2 micrometer okay and this value will be=0.03 1-0.961 0.3904 for lambda value <0.2 micrometer and lambda value >2 micrometer okay.

So this is the value of emittance we have found and same thing is with absorptance. So now we find the total value that is epsilon will be equal to 1/sigma T to the power 4 where T is 300 Kelvin integrated over 0 to infinity okay epsilon lambda okay Eb lambda at the temperature equal to 300 and d lambda okay and this value will be equal to we have to substitute 0.8 so we can just write 1/sigma T to the power 4 0 to 0.2 okay.

The value will be=0.0390 Eb lambda d lambda+0.2 to 2 Eb lambda, this value will be 0.8 Eb lambda d lambda and then beyond this 2 to infinity the value will be again 0.0390 Eb lambda d lambda and when we solve this, we get the total value is=0.039 okay. The value we get is 0.039 for the total emittance and similarly alpha is also calculated. I will just give you the result 1/q solar, the solar flux upon alpha lambda Eb lambda.

Now this will be at the sun temperature okay d lambda. Just like we solved for emittance we solve for absorptance 1/q solar that is sigma T to the power 4 okay upon 0 to infinity alpha lambda Eb lambda and evaluated at the sun temperature and integrated over all the wavelengths and this value will be coming to 0.7527 okay. So what we see in this example is that just by combining a dielectric sheet with a metal substrate what we have achieved?

We have achieved the total emittance which is very low, the value is 0.039 and we have achieved the high absorptance the value is 0.7527. Had we used only metal, we have got good amount of reflectance okay. The absorptance of the metal is very poor okay. Had we used only dielectric, the dielectric also gives you good absorptance 0.2 or 0.1 but it also gives you good emittance.

So it will no doubt absorb more but it will also emit more but by combining the two, the dielectric and the metal, we have achieved best of both the worlds, good amount of absorptance and low amount of emittance okay. Thank you.