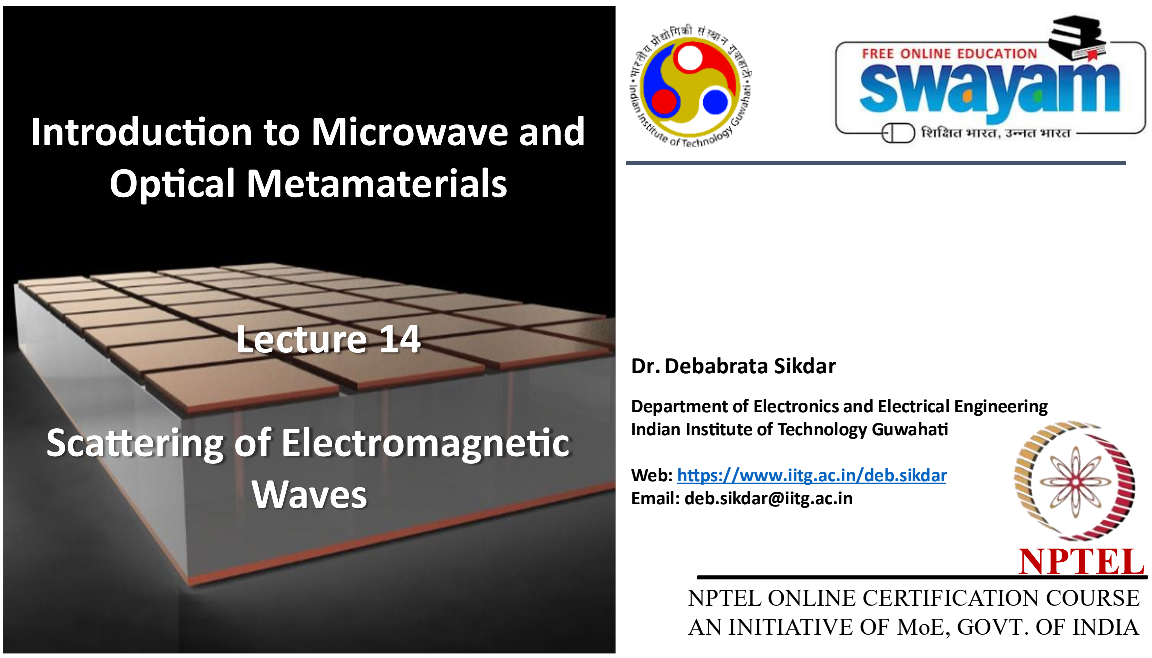
Course Name: Introduction to Microwave and Optical Metamaterials
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-3
Lecture-14

Lec 14: Scattering of Electromagnetic Waves



Hello everyone, welcome to Lecture 14 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on the scattering of electromagnetic waves. So, here is the outline of the lecture. We will briefly look into the scattering of electromagnetic waves. We will discuss Born approximation. Then we will move on to Rayleigh scattering, Mie scattering and Raman scattering and discuss in which cases this kind of scattering phenomena will take place.

Now on the right, you see the picture of Lord Rayleigh, who has made a significant contribution to this field of scattering. He was an English physicist and a Nobel laureate who made many contributions to the field of wave physics. Of sound and optics. He has basically formulated the theory of scattering of light by small particles and then the dependence of scattering on this 1 by λ to the power 4 ok.

Lecture Outline

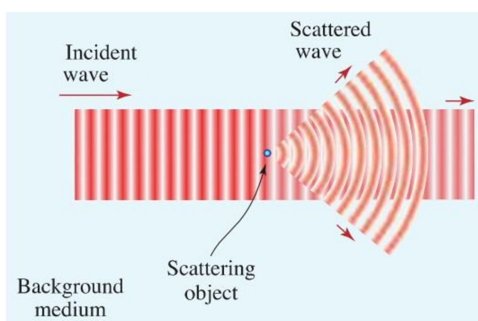
- Scattering of Electromagnetic Waves
- Born Approximation
- Rayleigh scattering
- Mie scattering
- Raman scattering

Lord Rayleigh (John William Strutt) was an English physicist (1842–1919) and a Nobel Laureate (1904) who made a number of contributions to wave physics of sound and optics. He formulated the theory of scattering of light by small particles and the dependence of scattering on $1/\lambda^4$ circa 1871. Then, in a paper in 1899 he provided a clear explanation on why the sky is blue.

This particular equation, I believe, all of you have seen from your school days, right? It was done in 1871. And then, in a paper in 1899, he provided a clear explanation of why the sky looks blue. So, with that, let us move on and see the scattering of electromagnetic waves in a little more detail. So, what do you mean by scattering? So, when an electromagnetic wave propagates through an homogeneous medium and it encounters an object which has got a different optical property. The wave is supposed to get scattered or redirected into various directions, right? So, when can it happen? So, you can consider the light beam traveling through a medium that contains lot of small particles or inhomogeneities which are nothing but say local variations in the refractive index.

Scattering of Electromagnetic Waves

- When an electromagnetic wave propagating through a homogeneous medium encounters an object with different optical properties, it gets scattered into various directions.
- If a light beam travels through a medium containing small particles or inhomogeneities (e.g., local variations in refractive index), part of its energy is radiated away from its original path.



Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics (John Wiley & Sons, 2019).

Then the part of the waves or light beams energy will get radiated away from the original path. So you can see something like this: there is a background medium. This is the incident wave which is propagating and suddenly it encounters an object in its path and from there it basically scattered away. So some part gets scattered away; the remaining will continue to flow in the same direction, right? Now if you go into a little bit more details, you can understand that the scattering is occurring from a homogeneous medium which contains localized inhomogeneities, irregularities or you can say material defects such as grains or suspended particles. Now, both the medium and the scatterer or you can say the scattering object can be assumed to be you know dielectric with linear and isotropic optical properties.

Scattering — Born Approximation

- When an optical wave traveling in a given direction in a homogeneous medium encounters an object with different optical properties, the wave is scattered into other directions.
- This effect may be analyzed by solving Maxwell's equations and applying the appropriate boundary conditions.
- However, analytical solutions of this problem exist only in few ideal cases.
- A commonly used approximate approach for solving such problems, known as the **Born approximation**.
- It is applicable for *weak scattering*, *i.e.*, when the scattering object may be regarded as a small perturbation to the relative permittivity (or other optical properties) of the medium.
- To introduce the Born approximation, it is convenient to first address the scattering of a scalar wave and then to subsequently consider an electromagnetic wave.

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In that case scattering becomes a process by which some of the power in the propagating electromagnetic wave is going to be redirected as secondary electromagnetic waves as you can see here in various directions which are basically away from the original direction of propagation. So, I am going back and forth between optical waves and EM waves, but they basically follow the same kind of relevance here. So, when we talk about optical wave traveling in a given direction in homogeneous medium and it encounters an object with different optical property, again the wave is going to get scattered in other directions. Now, this effect may be analyzed by solving Maxwell's equations, and then you have to apply boundary conditions, right? However, there is a way to analytically understand these problems as well which could exist only in few ideal cases and commonly used approximate method in this field is known as the Born approximation. So, this approximation is applicable to weak scattering.

That is when the scattering object may be regarded as a small perturbation to the relative permittivity or you can say other optical properties of the medium. Now, to introduce the Born approximation, it is convenient to first address the scattering of scalar waves and then to consequently you know consider an electromagnetic wave. So, let us start with the scalar wave concept. So, if you consider the scalar complex amplitude U r. that obeys the Helmholtz equation, which looks like this: $[\nabla^2 + k^2(\mathbf{r})]U = 0$

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Scattering — Born Approximation

- The scalar complex amplitude $U(r)$ obeys the Helmholtz equation:

$$[\nabla^2 + k^2(\mathbf{r})]U = 0$$

- Inside the scattering object, the wavenumber is $k(\mathbf{r}) = k_s(\mathbf{r})$ and in the host medium, which is taken to be uniform, the wavenumber is $k(\mathbf{r}) \; = \; k$.

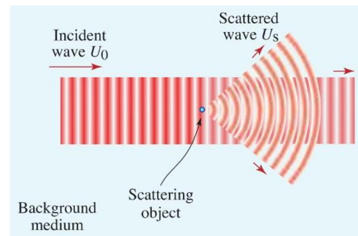
- By writing $k^2(\mathbf{r}) = k^2 + [k^2(\mathbf{r}) - k^2]$, the Helmholtz equation for the scattered complex amplitude $U_s(\mathbf{r})$:

$$(\nabla^2 + k^2)U_s = -S$$

With a source:

$$S(r) = [k_s^2(\mathbf{r}) - k^2]U_s(\mathbf{r})$$

that is localized within the volume V of the scatterer, and is zero outside of it.



Now, inside the scattering object the wave number kr can be written as ksr ok and in the host medium which is taken to be uniform the wave number kr can be taken as r ok. So, it is uniform so it does not have any you know position dependency you can simply k. So, k r will be simply k. Now, by writing k square r = k square + k square r - k square, the Helmholtz equation for the scattered complex amplitude u s r here s stands for scattered that can be written as$(\nabla^2 + k^2)U_s = -S$.

Scattering — Born Approximation

- The solution to $(\nabla^2 + k^2)U_s = -S$

$$U_s(\mathbf{r}) = \int_V S(\mathbf{r}') \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}' \quad \text{at positions } \mathbf{r} \text{ outside the volume } V$$

- However, the integral in cannot be readily evaluated to determine $U_s(\mathbf{r})$ since, in accordance with $S(\mathbf{r}) = [k_s^2(\mathbf{r}) - k^2]U_s(\mathbf{r})$, the source $S(\mathbf{r}')$ itself depends on the wave $U_s(\mathbf{r})$, which is unknown.

- If the scattering is weak, however, it is safe to assume that the incident wave $U_0(\mathbf{r})$ is essentially unaffected by the process of scattering within the volume V.

- The complex amplitude $U_s(\mathbf{r})$ in the expression for the scattering source $S(\mathbf{r}) = [k_s^2(\mathbf{r}) - k^2]U_s(\mathbf{r})$ may be approximated by the incident complex amplitude $U_0(r)$, whereupon:

$$S(r) \approx [k_s^2(\mathbf{r}) - k^2]U_0(\mathbf{r})$$

So, what is this $-S$? This is with having a source now and $S(r) = [k_s^2(\mathbf{r}) - k^2]U_s(\mathbf{r})$. So, that is basically the localized function which is localized within the volume of the scatterer and it is 0 outside of it. So, all these fields are basically inside this particular volume of the scatterer, which is a very tiny volume. Now, the solution to this particular equation $(\nabla^2 + k^2)U_s = -S$ will take this particular form which is usr = integration / the volume of the scatterer $\int_V S(\mathbf{r}') \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}'$. So, here the position you are calculating is outside the volume v; v is the volume of the scatterer.

However, the integral in this particular integral cannot be readily evaluated to determine this particular value since in accordance you have got S r you know what S r looks like it from the previous slide and you have seen that S r itself depends on U S r right which is unknown. So, in the case of weak scattering you can safely assume that incident wave which is U0r is essentially getting unaffected by the process of scattering within this volume of v. And with that approximation you can write the complex amplitude Usr in the expression of this can be approximated as U0r. So, you are basically removing this dependency, right? So this is only possible under the assumption that the scattering is very weak. So you can replace the scattered field with the you know incident complex amplitude U0r, okay.

Scattering — Born Approximation

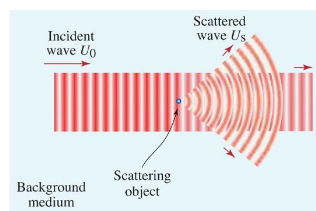
$$S(\mathbf{r}) \approx [k_s^2(\mathbf{r}) - k^2] U_0(\mathbf{r})$$

- This expression may then be used in: $U_s(\mathbf{r}) = \int_V S(r') \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}'$

  to determine the scattered complex amplitude $U_s(\mathbf{r})$.

- Implicit in the assumption of weak scattering is the condition that a wave scattered from one point in the scattering volume V is not subsequently scattered from another point, *i.e.*, multiple scattering is a negligible second-order effect.

- It is evident that the scattered wave $U_s(\mathbf{r})$ is then approximately a superposition of spherical waves generated by a continuum of point sources within the scatterer, as shown.



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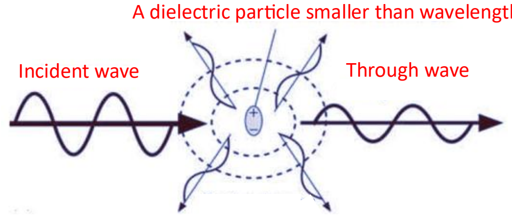
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics (John Wiley & Sons, 2019).

So this is the approximation that you are going to use. And once you put it back, now you have got this term which is dependent on U0r and then you can evaluate this particular volume integral and determine the scattered complex amplitude Usr, okay. So, here it is implicit in this assumption of weak scattering is a condition that a wave scattered from a point in the scattering volume v. is not subsequently scattered from another point. So, what is happening is that the multiple scattering is basically negligible, and because that is a second-order effect, right? So, the second order scattering is that the scattered wave is again getting scattered by another thing that is kind of removed here that assumption is made and it is evident that the scattered wave Usr will then be approximately be a superposition of the spherical waves which are getting generated by the continuum of point sources within the scatterer ok.

Rayleigh scattering

- **Rayleigh scattering** involves *small scatterers*.
- It is engendered by variations in a medium that are introduced, for example, by the presence of particles whose sizes are much smaller than a wavelength or by random inhomogeneities at a scale much finer than a wavelength.
- The process has been named in honor of *Lord Rayleigh*, who in 1871 published a research paper describing this phenomenon.
- Rayleigh scattering involves the polarization of a small dielectric particle or a region that is much smaller than the light wavelength.



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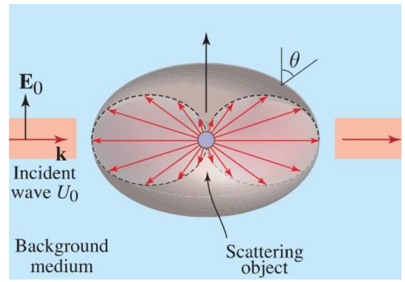
So, at each point or you can consider. So, here you can see the diagram; it clearly shows the incident wave, which has a scalar complex wave. The amplitude of u_0, and this is the amplitude of the scattered wave u s in this particular direction. So, if you consider that each point at position r prime creates a you know spherical wave which has got a amplitude of s r prime ok given that you know this is the kind of approximation for this spherical wave amplitude and in this type of scattering okay we are also considering this to be elastic scattering where the momentum is conserved and the frequency of the scattered light will remain same as that of the incident light. So that is Born approximation with that we move on to the next type of scattering which is Rayleigh scattering and Rayleigh scattering involves small scatterers.

So, it is basically coming from the variations in a medium which are introduced for example, in the presence of particles whose size are much smaller than a wavelength. or you can think of it coming from random inhomogeneities which are at a scale much finer than the wavelength of the electromagnetic wave or light. So, as you can see, this particular process is named in honor of Lord Rayleigh. Who in 1871 published a paper describing this particular phenomenon right? So, Rayleigh scattering basically involves the polarization of a small dielectric particle or a region that is much smaller than the wavelength of light. So, here you can see that this particular figure shows you.

This is the direction of incident wave propagation. So, there is a small scatterer that is much smaller than the wavelength of the light. So, that is basically a dielectric particle which is smaller than the wavelength of light and because of this you will have some scattered wave you can see and there are some through waves ok. So, the field the incoming light field forces dipole oscillations in the particle and that is done by polarizing the particle which leads to emission of EM waves in many direction. So, that a portion of the light energy is basically redirected or you can say directed away from the incident beam.

Rayleigh scattering

- The field forces dipole oscillations in the particle (by polarizing it) which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.
- The net effect is that the incident wave becomes partially reradiated in different directions and hence loses intensity in its original direction of propagation.
- Assumed a small particle so that at any time the field has no spatial variation through the particle, whose polarization then oscillates with the electric field oscillation.
- A transverse electromagnetic plane wave with electric field E_0 scattered from a point object (blue circle at center) creates a scattered electric-dipole wave E_s with a toroidal directional pattern
- Typically, the particle size is *smaller than one-tenth of the light wavelength.*



And the net effect is that the incident wave becomes partially re-radiated in different direction and hence there will be a loss of intensity in its original direction of propagation. So, the through wave will have less intensity as compared to the incoming wave. Now, assume a small particle so that at any time the field has no spatial variation through the particle. The polarization of the particle oscillates with the polarization of the electric field that is incident upon it. So, you can understand from this particular figure this is the background medium, this is the incident wave which has got a scalar amplitude of u_0, this is the direction of electric field polarization and this is how the dielectric polarization will also work.

Rayleigh scattering

- If the contrast between the optical properties of the scattering and surrounding media is low, *i.e.*, if the scattering is weak, then the Born approximation is applicable.
- If we consider a single scattering object, much smaller than the wavelength of light and located at $\mathbf{r} = 0$, the source distribution may be approximated as:

$$S(\mathbf{r}) \approx [k_s^2 - k^2]U_0 V \delta(\mathbf{r})$$

- $\delta(\mathbf{r})$ is the delta function and k_s is the wavenumber within the small scatterer. Substituting this in the integral:

$$U_s(r) = \int_V S(r') \frac{e^{-jk|r-r'|}}{4\pi|r-r'|} dr'$$

yields:

$$\boxed{U_s \approx (k_s^2 - k^2) V U_0 \frac{e^{-jkr}}{4\pi r}}$$

And then there will be the this is the scattering object that is scattering in different directions. These are the directions of the scattered waves, and this will be the through wave, right? So, transverse electromagnetic plane wave with electric field E_0 that is getting scattered from a point object as you can see this is the point object right. It is basically shown as a blue circle at the center. It creates scattered electric dipole waves, which are Es. With a toroidal, you know, directional pattern.

So, this is how it shows the directional pattern of the scattered waves. And the typical size of this particle is that it is one tenth of the incident light wavelength. In contrast to the optical properties of the scattering and the surrounding media, if it is low, then the scattering is weak. And in that case, you can say that the Born approximation is applicable. So, if we consider a simple scattering object which is much smaller than the wavelength of the incident light and assume that it is located at r = 0, then the source distribution may be approximated as this $S(\mathbf{r}) \approx [k_s^2 - k^2]U_0 V\delta(\mathbf{r})$.

So, δ r is the δ function, and ks is basically the wave number within the small scatterer. And when you substitute this in this integral which you have seen earlier that $U_s \approx (k_s^2 - k^2)VU_0\frac{e^{-jkr}}{4\pi r}$. So, this will basically give you the value of us which is approximately equal to k square - k square v u_0 e to the power - j kr by 4 π r. So, that is for the case where you are located at r = 0 right. So, this basically represents a single spherical wave that is concentrated about r = 0, which is at the location of the scatterer with an amplitude that is basically proportional to the incident wave's amplitude, u_0, right.

Rayleigh scattering

- The intensity of the scattered wave is therefore:

$$I_s = |U_s|^2 \approx (k_s^2 - k^2)^2 \frac{V^2}{(4\pi r)^2} I_0 \qquad \text{where } I_0 = |U_0|^2$$

- Since the scalar scattered wave is isotropic, the total scattered power $P_s = 4\pi r^2 I_s$ becomes:

$$P_s \approx \frac{1}{4\pi}(k_s^2 - k^2)^2 V^2 I_0$$

- Reveals that *the scattered power is proportional to the square of the scatterer volume V.*

- Since k_s and k are both proportional to ω, it is clear that the scattered power is proportional to ω^4 or, in terms of wavelength, to $1/\lambda^4$ known as the ***Rayleigh inverse fourth-power law***.

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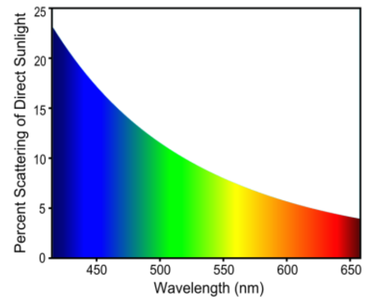
This is what you can interpret from this equation. Now, once you know the amplitude you can always estimate the intensity of the scattered wave which is calculated as I s that is nothing, but modulus u s square. So, you simply square it up you get k square - k square whole square divided * v square / 4 π r whole square * I_0 and I_0 is nothing, but modulus U_0 square. Now, since the scattered scalar wave is considered isotropic, So, the total scattered power P s = 4 π r square I s and that will become So, you can write from here that P s will be nothing but $\frac{1}{4\pi}(k_s^2 - k^2)^2 V^2 I_0$

Rayleigh scattering

- **Rayleigh inverse fourth-power law** indicates that incident waves of short wavelength undergo greater scattering than those of long wavelength.
- As an example, the Rayleigh scattering of blue light at a wavelength of $\lambda_0 = 400$ nm exceeds that of red light at a wavelength of $\lambda_0 = 800$ nm by the factor $2^4 = 16$.
- Rayleigh scattering from the density fluctuations of air, which are finer than the wavelengths of light in the visible spectral band, is responsible for the blue color of the sky.
- The short-wavelength (blue) light is preferentially scattered over a large range of angles, whereas the light arriving directly from the sun is reduced in blue and therefore appears to have a yellowish tint.



- In silica-glass optical fibers, Rayleigh scattering is responsible for the greater attenuation of visible than infrared light.

So, this is how you can find the total scattered power. Right, considering the scattered wave is isotropic, right. So, what you can see from here is that the scattered power is basically proportional to the square of the scatterers volume because it is proportional to v square. Also, since you can see here that ks and k are both proportional to ω. So, clearly, there is a whole square term, okay.

So, you can see that there are squares, and then there is a square again. So, you can see that the scattered power is basically proportional to ω to the power 4 or you can say in terms of wavelength it will be 1 / λ to the power 4 and that is popularly known as the Rayleigh inverse fourth power law. So, what does this law indicate? So, Rayleigh inverse fourth power law indicates that incident waves of short wavelength will undergo greater scattering than those of the long wavelength ok. So, as an example the Rayleigh scattering of blue light at a wavelength of λ_0 = 400 nanometer will exceed that of the red light which has got a wavelength of around 800 nanometer and the amount of scattering will be by a factor of 2 to the power 4 which is 16 ok. That means the blue light will get scattered 16 times more than red light.

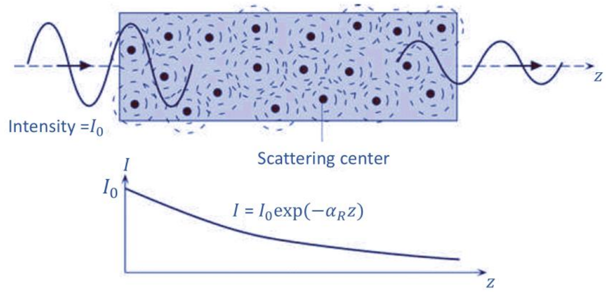
So, Rayleigh scattering from the density fluctuations of air which are basically much finer than the wavelength of light in the visible band is basically responsible for the blue color of the sky. The shorter wavelength that is blue is preferentially scattered / a large range of angles. Whereas the light arriving directly from the sun is reduced in blue and therefore appears to have a yellowish tint. So, if you look into the silica glass optical fibers their rayless scattering is responsible for the greater detonation of visible light than the infrared light right. So, this particular figure also tells you the percentage of direct sunlight scattering as a function of wavelength.

Rayleigh scattering

- The intensity of a light beam in a medium with small particles decreases as the beam propagates due to Rayleigh scattering.
- The intensity at a position z inside the medium from the radiation receiving face is given by:

$$I = I_0 \exp(-\alpha_R z)$$

where α_R is the **attenuation coefficient** due to Rayleigh scattering.



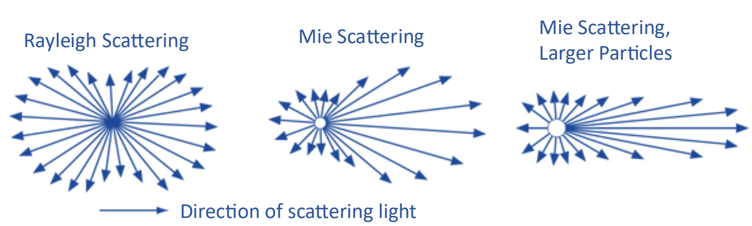
- Here:

$$\alpha_R \propto N.a^6.\frac{1}{\lambda^4}.\left(\frac{n^2 - n_0^2}{n^2 + n_0^2}\right)^2$$

So, you can see that red is getting less scattered and blue is getting having the largest scattering right. So, when you talk about the scattering of light by air molecules or dust particles ok or water droplets that are present in the atmosphere. And from this diagram, you can always understand that the blue light is scattered much more than the red light. So, when you look at the sky far away from the sun our eyes basically receive this scattered light which appears to be blue and that is why sky looks blue to us. And if you also wonder why the sky looks, you know, red.

Mie scattering

- Mie scattering refers to the scattering of light from scatterers that have dimensions comparable with, or greater than, the wavelength of light.
- For example, Mie scattering would occur for light scattering from long organic molecules in a solution, or scattering from various particulate pollutants (as in smog) in the atmosphere, including dust particles.
- The scattering depends on the ratio of the scattering particle diameter to the wavelength of light, and favors scattering in the forward direction.



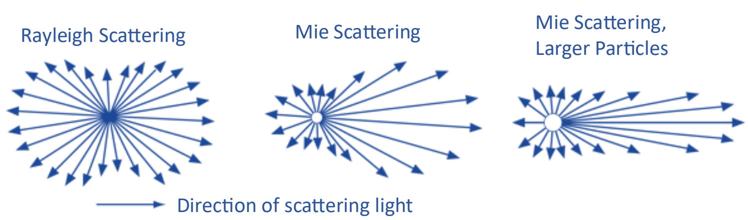
Of the sun at sunrise and sunset. So, what happens at sunrise and sunset? The rays come directly from the sun, and they have to traverse the longest distance through the atmosphere. So, the short wavelengths, such as blue and violet, are scattered even more during their longer path of travel through the air. And when you look towards the sun you can you only see the red colour because they are least scattered and they can reach to you right. So, the long wavelength of the sunrise or you can say the sunlight which get hardly scattered by the atmospheric scatterers and that gives the red colour to the sun at those particular time. So, when there is scattering, that means you know the energy or the intensity of the incoming light is lost.

So, the intensity of incoming beam or a light beam in a medium that has got small particles ok, the intensity of the light will basically decrease as the beam propagates through that medium and that is because of the relay scattering. So, you can see that if you have got a medium which is called a lot of scattering centers The intensity of the incoming light is considered to be I_0 and if you want to measure the intensity as a position of z inside the medium ok. This is the formula that describes that to $I = I_0$ exponential - α r z. So, α r represents the attenuation coefficient which is mainly because of the Rayleigh scattering and you will see that the intensity basically decreases exponentially with position. And if you try to look in more details α r this attenuation coefficient is basically proportional to n which is the concentration of scattering particles a square a sorry a to the power 6, a is basically the radius of those scattering particles times 1 by λ to the power 4.

So, λ is the wavelength of the incident light. And then you have n squared - n_0 squared / n squared + n_0 squared. So, here n is basically the refractive index of the scattering spheres and n_0 is basically the background. So, it also depends on the difference in refractive index mismatch between the two.

Mie scattering

- The dependence on the wavelength is weaker than Rayleigh scattering.
- The scatterers are assumed to have a refractive index significantly different from that of the surrounding medium.
- Mie scattering produces the almost white glare around the sun when a lot of particulate material is present in the air. *It also gives us the white light from mist and fog*.



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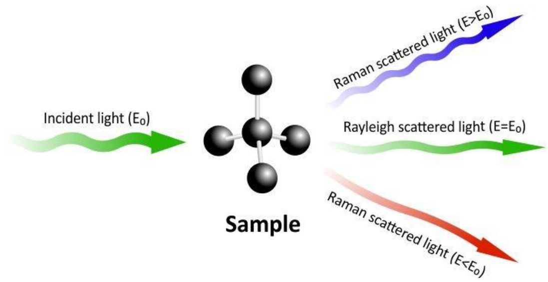
Medium. One is the medium; another is the scatterer, right? So, next we will see Mie scattering. This is also a type of scattering of light from scatterers, but there is a slight difference compared to Rayleigh. Here in Mie scattering, the dimension of the scatterers are comparable with or you can say greater than the wavelength of the incident light. So, for example, here miss scattering would occur for light scattering from long organic molecules in a solution ok or scattering from different particulate pollutants such as smog in the atmosphere also including the dust particles. So, the scattering basically depends on the ratio of the diameter of the scattering particles to the wavelength of light.

And it favors scattering in the forward direction. So, here you can see a comparison between the two or three types of scattering. So, Rayleigh scattering happens in all directions. Here, the particle or the scatterer is much smaller than the wavelength of light. In Mi scattering the particle or the scatterer is kind of comparable with the wavelength of light and then when the particle gets even larger, it prefers a forward direction, right.

Raman scattering

- When light encounters molecules in the air, the predominant mode of scattering is elastic scattering, (*e.g.* Rayleigh scattering).
- It is also possible for the incident photons to interact with the molecules in such a way that energy is either gained or lost so that the scattered photons are shifted in frequency.
- Such *inelastic scattering is called Raman scattering.*



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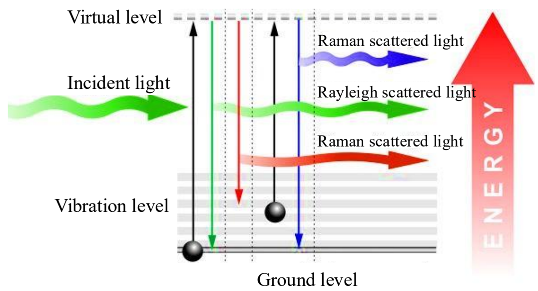
So, you will get some directionality in the scattering. Now, what you can understand from Mie scattering is that the dependence on wavelength is basically bit weaker than Rayleigh scattering. And the scatterers are assumed to have a refractive index which is significantly different from that of the surrounding medium. So, Mi scattering basically produces almost white glare around the sun and that is a the case when a lot of particulate material is present in the air. So, it also gives us white light from the mist and the fog.

The next type of scattering, which is also very important, is Raman scattering. So, when light encounters molecules in the air, the predominant mode of scattering is elastic scattering that we have seen that is the Rayleigh scattering. It is also possible that for the incident photons could interact with molecules in such a way that and energy is either gained or lost, so that the scattered photons will show some shift in frequency. So, this kind of inelastic scattering is called Raman scattering. So, here you have a sample; you have an incident light E_0.

Raman scattering

- The photons from the laser beam interact with the molecules and excites the electrons in them.
- The excited electrons are in a "virtual state" which is not stable, so they immediately fall down to the ground level.
- As electrons lose energy and fall down to the ground state, they emit photons.
- There are three different scenarios of how light can be re-emitted after energy had been absorbed by an electron:
  - Rayleigh scatter
  - Stokes Raman scatter
  - Anti-Stokes Raman scatter



Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics (John Wiley & Sons, 2019).

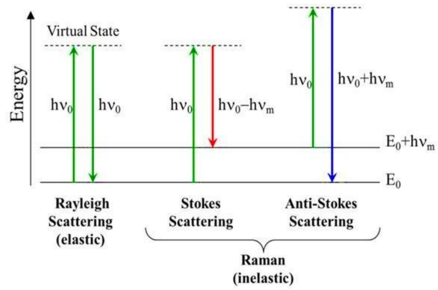
Now, you can have a blue shift if the energy E is greater than E_0. The energy of the scattered light is greater than that of the incident light energy. If the energy remains the same, then that is basically a Rayleigh kind of scattered light. But then, if the energy is again different, but this time it is less, you can say it is red-shifted Raman scattered light. So, both of these possibilities are there, but these are the cases where the momentum or the energy is not conserved.

You are basically seeing inelastic scattering, right? So, the photons from a laser beam will be allowed to interact with molecules and excite the electrons in them and you will see that the excited electrons will be in a virtual state which is not stable. So, they can immediately fall down to the ground level and in that process when the electrons lose energy, and fall down to ground state they will basically emit photons. So, there are three scenarios of how light can be reemitted after energy has been absorbed by an electron. We have already discussed one method that can be Rayleigh scattered light.

where the two levels are the same. You can also have Stokes Raman scattering and anti-Stokes Raman scattering. So either of these two is okay; I will go into details and show you which one is which. So this can be explained well using this particular diagram, which is basically showing the energy. So when an electron falls down to the original ground state, there is no change in energy. So, you see the amount of energy it took to go to the ground state and the energy it released are the same.

Raman scattering

- An electron falls down to the original ground state and there is no energy change, therefore light of the same wavelength is re-emitted. *This is called Rayleigh scattering*.
- After being excited, an electron falls to a vibrational level, instead of the ground level. This means the molecule absorbed a certain amount of energy, which results in light being emitted in a longer wavelength than the incident light. *This Raman scatter is called "Stokes".*



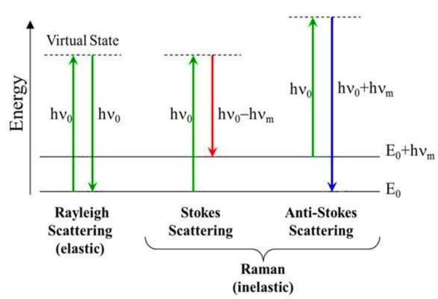
IIT Guwahati | NPTEL swayam Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics (John Wiley & Sons, 2019).

That means the light of the same wavelength is getting re-emitted and this is called Rayleigh scattering and this is basically a elastic type of scattering. Now, there could be a possibility that after being excited the electron is basically falling to a vibrational level instead of the ground level. So, this is the ground level E_0. So, instead of that, it is basically falling to this one, which has energy of $E_0 + h\upsilon$, okay.

So, this energy is not same as $h\upsilon_0$ which was required. So, rather, this energy is $h\upsilon_0 - h\upsilon_m$, okay. So, in that case, the energy of the photon is lesser. So, it will emit a longer wavelength compared to the incident light. So, this kind of Raman scattering is called Stokes Raman scattering. So, you are getting a redshift in the wavelength because of this, okay? And then there could be the other possibility also that if The electron is excited from a vibrational level.

Raman scattering

- If an electron is excited from a vibrational level, it reaches a virtual level with higher energy.
- When the electron falls down to the ground level, the emitted photon has more energy compared to the incident photon, which results in shorter wavelength. *This type of Raman scatter is called "Anti-Stokes".*



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So, say the electron is not at the ground level when it is getting excited, as in the previous case. So, let us assume it is basically started from here that is from a level E_0 + h nu m, it started from here and then it reached to this virtual level with high energy. Now, when the electron falls back, it basically comes down to the ground level. That means it will have energy of $h\upsilon_0$ + this particular gap, which is $h\upsilon_m$. So, what is happening the released photon or the emitted photon is now having more energy as compared to the incident photon that means it will result in a shorter wavelength.

So, this is also a type of inelastic scattering, but this one is called anti Stokes because it is completely opposite to the case of the previous one. So, this is called anti-Stokes Raman scattering; this is called Stokes Raman scattering. So, with that, we will conclude this lecture. If there is any query regarding this lecture, you can drop an email to this email address mentioning the course title and the lecture number on the subject line. Thank you.