

for the first few minutes i am going to talk about the importance of light how is that it has affected our daily lives and then i will talk about the evolution of the different models of light i will try to answer the question as to what light is the photograph on the left is that of a setting sun and the photograph on the right is a light beam getting guided through an optical fiber and that is my name and i used to be at iit delhi and that is my email address the study of light has fascinated mankind ever since he could see here we see a sadhu worshipping the light from the sun in fact in 2015 2015 was proclaimed as the international year of light on 20th december 2013 the united nations general assembly proclaimed 2015 as the international year of light and light based technologies and it was abbreviated as iyl 2015 and throughout the world there were numerous events that were organized and including many events in india in proclaiming this the united nations has recognized that light plays a vital role in our daily lives that light plays an extremely important role in our daily lives it has revolutionized medical diagnosis and treatment from eye surgery to the removal of a tumor it has revolutionized international communications via fiber optics and it has created extremely important devices for the industry and also defense why has this study of light becomes

so very important in the past people have been wanting to know what light really is but the study of light has during the last 50 years assumed tremendous importance because of which all major universities in the world have a separate program in the general area of optics and photonics why has this happened and that the answer is that theodore mayman who was an american scientist he fabricated the first laser in may 1960 on the left is a photograph of theodore mimon and on the right is the laser that he fabricated and as you can see the light coming out from this laser is very directional and it has only very small spread of wavelength it is said to be almost monochromatic what is the main difference between the light that comes out of a bulb and the light that comes out of the laser the photograph on the left is the light from an ordinary light bulb which spreads out in all directions on the other hand the photograph on the right which shows a laser beam launched from a telescope is very directional in this particular case it crossed the sky and created an artificial star at a height of 90 kilometers in the high earth's mesosphere one can see that the spreading of the light beam is extremely small this is one of the very important characteristics of a laser light and because it is directional it can be focused by an ordinary lens into a very small area in this diagram we have shown a very directional light beam to fall on an ordinary lens and it gets focused to a tiny region whose diameter is about $2\lambda f/a$

so where λ is the wavelength of the light f is the focal length of the lens and $2a$ represents the diameter of the incident beam thus if a collimated plane wave of diameter $2a$ of the type that is incident from a laser if that beam is incident on a lens of focal length f then the wave emerging from the lens will get focused to a spot of radius about $\lambda f/a$ which would be of the order of one micron one micron is one micrometer that is one millionth of a meter and just for comparison i thought i will tell you that the diameter of the human hair is about 100 microns now what do you mean by the wavelength of light you see light as i will discuss later is an electromagnetic wave and starting from gamma rays which are emitted in an atom bomb to x-rays which are used to diagnose human body to ultraviolet rays to infrared microwaves which you use in your microwave ovens and the radio waves which you receive on your radio and tv sets they are all electromagnetic waves they the only difference is the frequency of the gamma rays is extremely large and the frequency of the radio waves is comparatively much less than that of gamma rays they all travel with an identical velocity in vacuum and this velocity is exactly $299\,792\,000$.

458 kilometers per second all wavelengths all frequencies travel with an identical velocity in free space we will usually assume that this value is approximately three hundred thousand kilometers per second which is equal to 300 million meters per second that is the velocity of light in free space and as we all know because of this finite velocity it takes about eight and a half minutes for light to reach from the surface of the sun to the earth the visible region of the electromagnetic spectrum which occupies a very small region of the entire spectrum starts from the blue region which has the smallest wavelength of about 0.

4 micron and the green region has a wavelength of about 0.

5 micron the yellow region has a wavelength of about 0.

6 micron and the red region has a wavelength of about 0.

7 micron

so that is the wavelength associated with the the the visible part of the electromagnetic spectrum the corresponding frequency would be obtained by dividing the speed of light by the wavelength

so one will get from the green region about 600 terahertz one terahertz is about 10^{12} hertz

so this frequency will be 6 into 10^{14} hertz this frequency will be 5 into 10^{14} hertz

so therefore if we assume the yellow region of the spectrum

so the wavelength is about say 0.

5 microns the focal length of the lens is about 10 centimeter and the diameter of the beam is let us suppose 2 centimeters then simple calculation will show that λf by a is about 5 microns

so that is the

so it gets focused to a distance of about 10 microns and because of that a even a low power laser beam can produce very high intensities at the focal plane of the lens here we see a laser beam getting focused by an ordinary lens and the and the electric fields at the focal point can be about a billion volts per meter and the electric field is

so large that that it can produce a spark in air similarly if you have a focused laser beam the laser beam is coming from here and it is getting focused by an ordinary lens and the power of the beam the intensity of the beam at the focal plane is

so large it can drill through concrete this particular photograph is from from an institute in india which is known as the raja ramana center for advanced technology in indore and therefore one can appreciate the power of the laser beam and in fact because a laser beam is almost parallel the lens of the eye will focus them down to a very small spot which can cause retinal burns and because it can it produces an extremely high intensity here it can also be used for treatment of retinal detachment

so this is one of the very important application of the laser

so if the intensity of a laser beam entering the eye is about 1 milliwatt per centimeter square then the intensity at the retina will be about 100 watts per square centimeter thus because the laser beam is extremely directional it can be focused to a very narrow spot and

so therefore whereas it is very safe to look at a thousand watt bulb which is emitting light in all possible direction but it is very unsafe to look at even a two milli watt laser beam

so one has to be very careful in handling a laser beam it can burn your skin it can burn the retina of the eye and because it can produce such high intensities it can also be used to to weld the retina to the eye itself

so it has tremendous applications in in eye surgery and in other areas i just

told you about the eye surgery but there are many other areas in which the laser beam is extensively used here is a very beautiful experiment in which there is a red light beam corresponding to the frequency ω incident on a suitably oriented crystal and the light that emerges from the crystal has double the frequency

so that the red light incident at a particular angle generates the blue light this area is usually referred to as the domain of nonlinear optics and has become extremely important area of research because of the advent of laser here is a laser beam coming out of a laser pointer you must have seen laser pointers in your school and colleges

so so the the green laser that comes out in many of the laser pointers there is a red laser inside which falls on a suitably oriented crystal and it generates twice the frequency here is a light beam which gets guided through an optical fiber and there is a human hand holding the end of the fiber laser pulses propagating through millions of kilometers of optical fibers now connect us through the oceans all major cities in india are also connected through optical fiber today you can telephone your relative in united states almost free of cost and this revolution is possible because of the fiber optics and also because of the availability of very high speed lasers that is lasers which can be modulated with extreme rapidity and

so therefore the internet revolution that has a that has occurred the telephone the telephones becoming almost free through dialing any part of the world that has become possible because of advances in the general area of optics and photonics and this has happened because of the advent of laser in fact the 2014 nobel prize in physics has been awarded to these three gentlemen for the invention of efficient blue light emitting diodes leds which has enabled bright and energy saving white light sources and these leds are going to revolutionize the illumination technology throughout the world particularly the developing world because we can use the solar energy to illuminate such bulbs and even in india there is a major effort to to have led bulbs installed operated through solar energy in remote areas in villages where there is no electricity

so this is a revolution that has occurred

so the future i have tried to tell you a few experiments which show you the great tremendous importance and applications of light and we feel that in generations to come it will be full of light implying that light will find applications in in most areas of working and

so therefore study of light is of extreme importance and as i mentioned earlier most universities abroad have a separate department of optics and photonics and intense research work in different areas of optics are going on throughout the world

so in the remaining part of this lecture i will try to tell you the various models describing what is light before that i thought i should also tell you why 2015 was chosen as the international year of light and that is because one thousand years back alhassan wrote the first book on optics and it was alhassan was from mesopotamia which is now in iraq and he wrote a seven volume treatise on optics which was used by all scientists in europe to to do research in the general area of optics to celebrate this and on the photograph on the right shows the cover page of a translated edition of alhassan's optics and to celebrate 1000 years of the first book on optics the year 2015 was declared as the international year of light nobel prize winner abdul salam said that alhajan was one of the greatest physicists of all times we have also been wanting to know what light is the light that comes from the sun what it contains sir isaac newton wrote the book on optics in 1687 which got published in the year 1687 and in that book he wrote and i am quoting newton that are not the rays of light

very small bodies emitted from shining substances that is he assumed that tiny particles are emitted from a body which is emitting light and he thought that he said that because light was found to travel almost in straight lines however if we sit on the staircase of a shadow we can still read a book there is still some light which enters the shadow that is not due to the phenomenon of diffraction that is due to the phenomenon of scattering scattering of light by air molecules the nitrogen and oxygen that is present in the air scatters the light beam into the shadow what is scattering you see for example i have tried to show you the orbit of a comet a comet comes in gets attracted by the force of the sun by the attractive force of the sun and its trajectory gets deflected

so this deflection of the trajectory is known as scattering which is we can say that the comet undergoes scattering because interacting with the field created by the sun

so similarly the light also this undergoes what is known as rayleigh scattering which is inversely proportional to the fourth power of the wavelength smaller the wavelength as we had seen earlier the blue color the blue region of the spectrum has a smaller wavelength the smaller the wavelength greater will be the rayleigh scattering

so higher the wavelength smaller will be the rayleigh scattering and as we had told you earlier that the blue region of the spectrum has a very small wavelength and the red region has a large wavelength and

so therefore the light from the sun scatters predominantly the blue component and that is why the sky appears blue

so once again the sky is blue because the blue component of light gets predominantly relay scattered by the atmosphere and the setting sun is red because the blue component of light gets predominantly really really scattered by the atmosphere

so the white light that we the light that we receive on our looking at the sun the blue component is out

so therefore the sun appears predominantly red in color if we are on the surface of the moon as you all know moon does not have any atmosphere or just very very little atmosphere

so the shadows are perfectly dark you will not be able to read a book in in your own shadow if you stand in the sun and let us suppose the sun is on your back and you can easily read a book in your own shadow because as i told you the light enters the shadow region because of scattering by the air molecules but those air molecules are not present on the surface of the moon and

so therefore the shadows are completely dark and very sharp and you will not be able to read a book in your own shadow if you are standing on the surface of the moon

so here you see on the photograph that the sky is completely dark this is on the surface of the moon this is earth and the sun is falling in this direction and this the shadows are very sharp and the shadows are very dark which shows that light almost travels in a straight line i thought i should mention that much before newton early in the 17th century pierre gascendy and in 1637 rene descartes had put forward the corpuscular model of light

so it seems newton was aware of this but in in his book on optics he did not mention the works of these two gentlemen and since his book became very popular the corpuscular model of light is usually attributed to newton although two three scientists before him had put forward the corpuscular model of light

so therefore we do this experiment this diagram has been adapted from the famous feynman lectures that there is a gun which is emitting tiny bullets and the and this is an arrangement of two holes

so the bullets are emitted from the gun in all possible directions and they hit

the the hole and and arrive on this screen and there is a detector on the screen
so let us suppose only hole number one is open and hole number two is closed
then the arrival rate of the bullets is something like somewhat like what is
given by p_1 the arrival rate at the on at the the at the screen if hole
number 1 is closed and hole number 2 is open then the maximum gets shifted and
you have an intensity distribution or a rival rate distribution which is given
by p_2

so you have a detector which collects the bullets in a particular interval of
time let us suppose one hour and then you repeat the measurement scanning the
entire screen however if both holes are open then the bullets
either go through hole number one or through whole number two and

so therefore you obtain an intensity distribution which is given by $p_1 + p_2$
which is just the addition of the numbers p_1 and plus p_2 because these are
tiny bullets which either pass through hole number 1 or whole number 2 and we
say that there is no interference now around the time of newton christian hugh
huygens the dutch astronomer put forward the famous wave theory of light around
sixteen fifty

so the best way to understand the propagation of wave is to make a a pointed
needle vibrate on the surface of water and the circular ripples appear to
emanate from the center there is a propagation of a disturbance the water
molecules do not travel they just transfer the energy from one molecule to the
other and the disturbance get spreads out horizontally in the outward direction
each molecule then by they are actually not strictly transverse waves but for
the sake of simplicity we assume that they are transverse waves that is the
water molecules move in an up and down fashion

so so it let us suppose it is moving up and down and it with a certain
frequency that is 10 times in a second or 20 times in a second it moves up and
down and then the disturbance gets propagated in the outward direction the
distance between two points which are vibrating in the same phase is known as
the wavelength

so what is a wave another simple demonstration of the wave is through a string
let us suppose i am holding one end of the string and you are holding another
end of the string and i make it oscillate in the x direction then i create what
is known as an x polarized wave and associated with an x polarized wave the
displacement is given by x or as a function of z and time is equal to $a \cos(kz - \omega t)$
if you ask a mathematician what is a wave he will say that this
equation represents a wave

so let me tell you what i imply by that that the displacement of the string is
given by x of z of t a represents the amplitude and the cosine $kz - \omega t$
this equation describes a wave

so let us suppose at time t equal to 0 the displacement will be x of z at time
 t equal to 0 will be equal to $a \cos(kz)$ i write k is equal to $2\pi/\lambda$
and this becomes $a \cos(2\pi z/\lambda)$

so i plot this i plot this displacement as a function of z

so i will get a cosine curve i get a cosine curve this corresponds to the
displacement at t equal to 0 the horizontal axis is the z axis and the
displacement is x this is the actual displacement of each point on the string
and this distance

so at z is equal to zero this is one and at z is equal to λ this
becomes $a \cos(2\pi)$ which is again one

so this distance between two crests or two troughs that is equal to the
wavelength now i write the same equation again x of z t is equal to $a \cos(kz - \omega t)$
i can use equally well the assign function or i can use if add a phase term here
it does not make any difference

so at z is equal to 0 the displacement will be as a function of time will be given by a \cos of ωt i write ω as equal to $2\pi\nu$

so then this becomes a $\cos 2\pi\nu t$ and if i plot this as a function of time now as a function of time then i will get a curve like this this is how the displacement of a point will vary with time and it will come back after a time equal to t equal to $1/\nu$ then this becomes $\cos 2\pi$

so this is known as the time period this is known as the time period

so so this equation this equation represents a wave propagating in the z direction

so as i mentioned just now that at x at this is the equation representing the displacement of each point on the string and i can take the k outside then this becomes $z - vt$ where v is equal to ω/k please see i have taken k outside

so this becomes $z - \omega/k$ into t i replace ω by k by v

so i get an expression like this

so that at t equal to 0 as i had mentioned a few minutes back the displacement will be this term will be zero

so it is $\cos kz$ and at a slightly later time it will be a $\cos kz - v\Delta t$

so the solid curve here the horizontal the vertical line is the displacement of the string and the horizontal line is the z axis and the solid line represents the displacement at t equal to 0 and the dashed line represents at a slightly later time

so the whole disturbance has moved through a distance the the whole disturbance has moved through a distance $v\Delta t$ in a time Δt

so that v which is defined to be equal to ω/k represents the velocity of propagation of the wave i repeat this that this is the displacement this is the displacement at t equal to 0 at a slightly later time at t equal to Δt the displacement is given by $z - v\Delta t$

so the if i plot the displacement at t equal to Δt the whole curve gets shifted by a distance $v\Delta t$ and

so therefore in time Δt it has shifted through the displacement has shifted through a distance $v\Delta t$ and

so therefore v which is defined to be equal to ω/k represents the velocity of the wave similarly this distance λ as i had mentioned a few minutes earlier is equal to $2\pi/k$ the parameter k is known as the wave number

so here is an animation which i have got through the internet and i will give you the reference just now and you see i am trying to generate a transverse wave on the string on a string and this end of the string is made to move up and down in an oscillatory motion and the wave is propagating in the z direction which in this case is in this direction notice let me the frequency is one hertz that is it goes one up up and down one cycle per second

so the time period is one second

so let me show this in slow motion that each point is moving up and down as you can see from the green ah bead here it is moving up and down and this motion transfers the energy from one point to the other and the wave propagates in this direction

so this distance between two consecutive maxima is known as wavelength and the number of oscillation that it makes per second is known as the frequency

so i will show this that once again that each point on the string makes an up and down motion in a harmonic motion that is why the displacement let us suppose is in the x direction and the whole string always lies in the exact plane

so it is also known as a plane polarized wave and since the displacement the

vertical axis is the x axis and the horizontal axis is the z axis the displacement is always along the x direction

so it is also known as an x polarized wave

so let me go back to my slides

so this is an x polarized wave in which the displacement is a cross $kz - \omega t$ each point on the string moves up and down in an oscillatory fashion as i had shown you earlier

so then we calculated the displacement at time t equal to zero and t equal to Δt and define the wavelength and also the concept of the velocity of the wave in order to get this website i would advise all students to operate this himself you make a google search for wave on a string and you will get a website by this you click on that and you will get the animation that i had shown you that animation is very easy will make it much easier for you to understand the concept of wave motion on a string as i said earlier that this is the displacement of a particular point on the string let us suppose that x is equal to zero as a function of time the horizontal axis is the time and the vertical axis is the displacement

so so the the the each point as i had told you that each point on the string makes a movement in this fashion

so the displacement is something like a $\cos \omega t$ or you can write it as a $\cos \omega t - \phi$ and that is how the this is an oscillatory periodic motion you can also move the string in a circle

so if i move the end of the string on a circle then each point on the string moves on the circumference of a circle and you create what is known as a circularly polarized wave and in this case since this since each point is rotating in a clockwise direction as the wave is propagating outwards from me this is known as a right circularly polarized wave if i rotate it in the anticlockwise direction then you will create what is known as a left circularly polarized wave

so in a circularly polarized wave the displacement of the each point of the string is along the circumference of the circle and mathematically i can obtain this by superposing two waves x of $z - t$ and y of $z - t$ with the phase difference of π by two if i do that then you will have a $\cos kz - \omega t$ and y of the y component of the displacement is a $\sin kz - \omega t$ if i square and add i will get $x^2 + y^2$ is equal to a square now we consider two harmonic motions that are generated on the surface of water

so s_1 is a point source s_2 is another point source let us suppose we have two needles let us suppose we have two needles on the calm pool of water and each needle is vibrating up and down in phase

so each sends out a wave and these two waves interfere with each other now what is interference that let us suppose one molly one wave would have produced a displacement like this and the other wave produces a displacement just the opposite of that then the two waves will interfere destructively to produce zero amplitude on the other hand if one wave produces a displacement like this the other wave also produces a displacement in phase then the resultant will be the sum of the two because of what is known as the principle of superposition that if there is more than one wave then the resultant displacement is the vector sum of the displacements produced by each wave source and this leads to the phenomenon of interference and it is a characteristic of the wave

so if light is a wave then it must demonstrate it must show interference fringes this is an animation that shows the phenomenon of interference between two waves generated on the surface of water

so the phenomenon of interference is based on the superposition principle according to which the resultant displacement at a particular point produced by

a number of waves is the vector sum of the displacements produced by each one of the disturbance

so let us suppose i have two point sources and the the source s_1 if the source s_2 was not present the the displacement y is the vertical component here represents a displacement given by $\omega t - \phi_1$ where ϕ_1 is 2π by $\lambda s_1/p$ and displacement at p produced by the source s_2 is given by a $\cos \omega t - \phi_2$ where ϕ_2 is as i told you earlier is 2π by λ times the distance s_2/p

so so we are assuming that s_1/p and s_2/p the distance between s_1 and s_2 is so small that the amplitude produced by s_1 and s_2 at this point is the same we are assuming same value of a

so if both waves are present then the resultant displacement will be $y_1 + y_2$

so which i have to sum these two \cos terms and if i sum this i will get another harmonic wave another harmonic displacement with this

so you will get where the amplitude a becomes $2a \cos \gamma$ γ is equal to $\phi_1 - \phi_2$ is equal to 2π by λ $(s_2/p - s_1/p)$ please see that if $s_2/p - s_1/p$ is equal to say $\lambda/2$ then this quantity γ becomes π and a becomes zero and if this quantity γ becomes a multiple of π then a square becomes four a square

so the intensity pattern which is square proportional to the square of the amplitude resultant amplitude has a $\cos^2 \gamma$ factor

so whenever γ is a multiple of $\pi/2$ or five $\pi/2$ or seven $\pi/2$ then this will be zero and when γ is equal to zero π etcetera then this becomes intensity

so this leads to a variation of intensity and this is a characteristic of any wave phenomenon

so here there is the actual interference pattern produced by two thin rods vibrating at two points on a ripple tank on a water tank and it produces the interference pattern the we although the wave theory of light was first put forward in the 17th century it was only in 1801 that thomas young carried out a beautiful interference experiment this is a double hole interference experiment he allowed the sunlight to pass through a filter and then on two pin holes and the pin holes the waves emanating from the pin holes interfered to produce dark and bright fringes

so he could say that light plus light produce darkness and this could be possible only if light was a wave phenomenon

so this is the original layout of the of thomas young's experiment you have two pin holes there and you have approximately straight line interference fringes that occur here the bright spot corresponds to the waves arriving in phase and the dark fringes correspond to the waves arriving out of phase thomas young's interference experiment is considered to be one of the 10 most beautiful experiments in in physics and if i measure the distance between two consecutive fringes

so if the waves appear in phase arrive in phase you have a bright fringe if the waves arrive out of phase then you have a dark fringe and that is how dark and bright pattern are obtained on the screen

so if i measure the distance between two consecutive fringes then that distance is known as the fringe width and it is usually represented by the symbol β and then elementary calculation shows that the wavelength of light is equal to the β times the distance between the two pin holes divided by the distance between the this screen and the screen

so if i am able to measure the fringe width the distance between two conjugative fringes and if i can measure the value of d and determine the value

of capital d i can determine the value of wavelength and thomas young found that the wavelength of the yellow region of light was about half of a micron and since the wavelength of light is

so small interference experiments are usually slightly difficult to perform so these are the computer generated interference pattern and they are straight line fringes if you look at them closely then they are actually hyperbole because the locus of the points for $s_2 - p$ minus $s_1 - p$ is a constant is a hyperbola but if you look at a small portion of the difference fringes then they are straight line fringes and the distance between two bright consecutive bright or consecutive dark fringe is known as the fringe width using which you can determine the wavelength of light i am now quoting dennis gabor that the wave nature of light was demonstrated convincingly for the first time in 1801 by thomas young by a wonderfully simple experiment he let a ray of sunlight into a dark room placed a dark screen in front of it pierced with two small pinholes and beyond this at some distance a wide screen he then saw two darkish lines at both sides of a bright line which gave him sufficient encouragement to repeat the experiment this time with spirit flame as light source with a little salt in it to produce the bright yellow sodium light if you have a flame and you put a little salt in it you get very bright sodium color light sodium light is yellow in color this time he saw a number of dark lines regularly spaced and read the second the next line the first clear proof that light added to light can produce darkness this phenomenon is called interference and is a consequence of the wave nature of light thomas yang had expected it because he believed in the wave theory of light denis gabor who discovered holography said all this in his noble lecture in december 1971

so then by the first in during the first 10 15 years of the 19th century there were large number of experiments which demonstrated that light was indeed a wave although diffraction experiments were little difficult to perform the question was how could it propagate through vacuum because a wave requires a medium for example as you all know sound waves if there is no air between you and me you will not be able to hear me because sound waves require a medium any wave people thought would require a medium and light propagates through empty space there is between the sun and the earth there is very little there is there is empty space and sunlight reaches the earth shows that that light can propagate through vacuum

so if light was indeed a wave how could it propagate through vacuum and the answer came in the middle of the 19th century around the middle of the 19th century by james clark maxwell which established the electromagnetic nature of light waves that we will discuss in the next lecture thank you