Optical Wireless Communications for Beyond 5G Networks and IoT

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Lecture - 02
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Hello everyone. So, today we are going to discuss Basics of Lighting System which will be useful in this course. So, under lighting system we will discuss about Radiometry, Photometry and Colorimetry.

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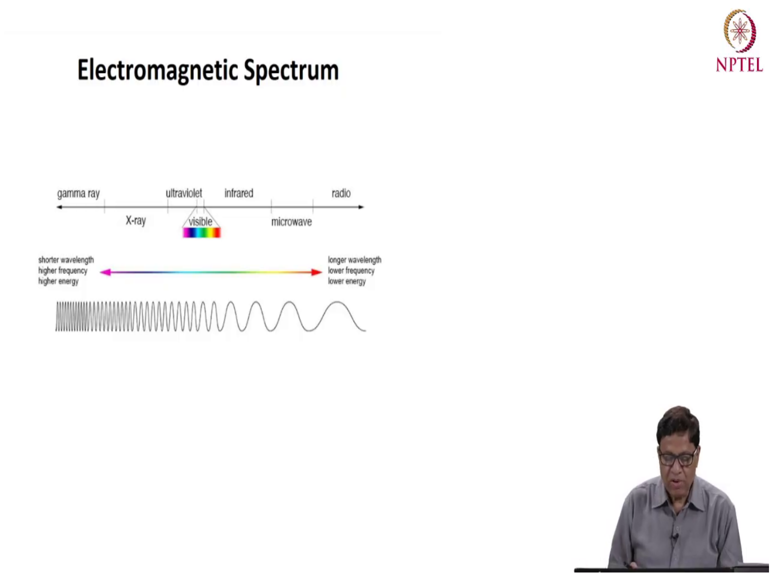

So, before going to further discussion, let us understand the electromagnetic spectrum. So, as you see here, the electromagnetic spectrum starts from gamma ray, shorter wavelength and thereof high frequency, and higher energy.

And then you have X-ray, and then you have ultraviolet ray here, ultraviolet spectrum, and then you have the visible part of the spectrum here, and then you have the infrared IR, and then microwave and radio. So, as we move it is a longer wavelength lower frequency and lower energy.

So, this particular course basically we are going to discuss communication in either in visible region or IR region or ultraviolet. So, we limit our self to this part of the spectrum.

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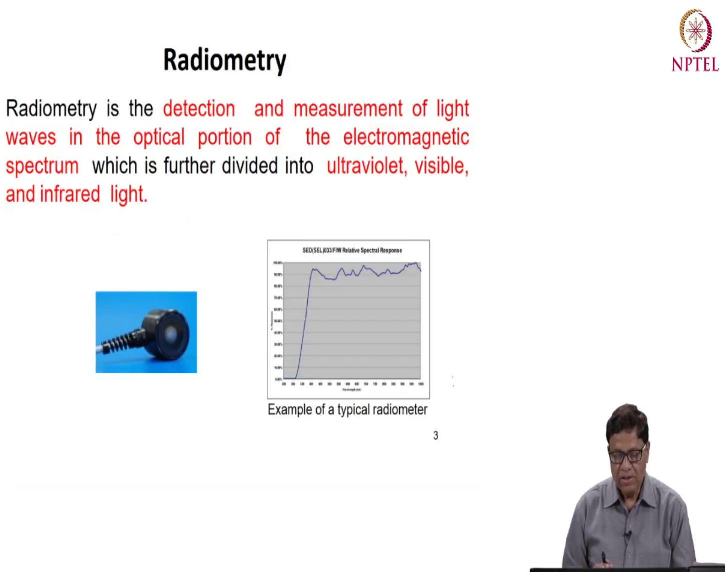

So, let us now first understand radiometry. A radiometry is the detection and measurement of light waves in optical portion of the electromagnetic spectrum which is further divided into ultraviolet, visible light and infrared.

So, this is a typical radiometer and if you see the output of a radiometer, it looks something like this. You have the wavelength on this side, and you have the percentage of light for that particular wavelength in that part of the in that part of the signal. So, this is the basic definition of radiometry.

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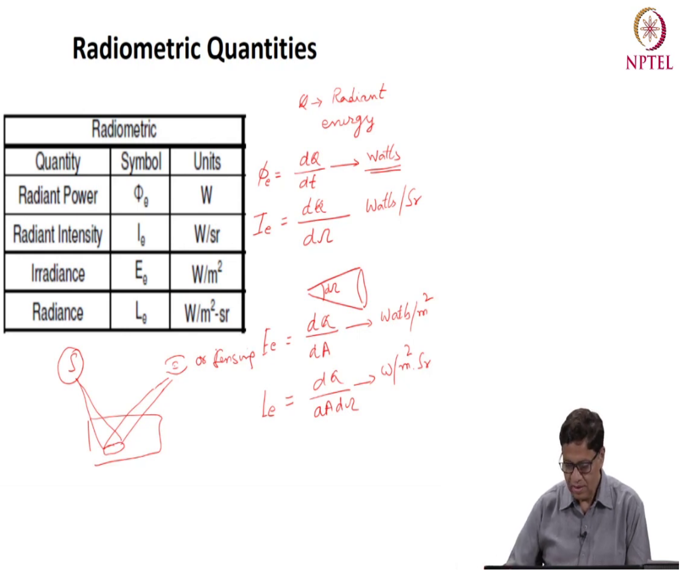

Under radiometry you have different quantities. So, first one is radiant power. So, assume Q is your radiant energy, then the radiant power is defined as dQ by dt, that is the radiant power and it is denoted as phi E and the units are in watts. So, this is radiant power.

The radiant intensity is defined as, radiant intensity it is defined as I e dQ over solid angle. So, basically it tells you how much light is falling onto the surface defined by this solid angle. So, that is called as a radiant intensity. And the units are watts per steradian.

And the third quantity is irradiance which is E e. This is the amount of light, amount of radiant energy falling onto a surface of unit area. And this is defined as dQ over dA and the units are watts per meter square.

The third quantity is the radiance which is denoted by L e. This is defined suppose you have a source here, this is a source, and this is your surface and some light is falling on to some area here for example, here. And this is your detector could be eye for example, or it could be a photodiode or photodiode or some sense I am sensing material. So, this light which is falling on to this eye or any sensing material is called as radiance.

So, the it is how it is defined? It is defined as dQ over dA d omega and the units are watts per meter square steradian. So, these are the 4 quantities which are useful. And these quantities come under radiometry.

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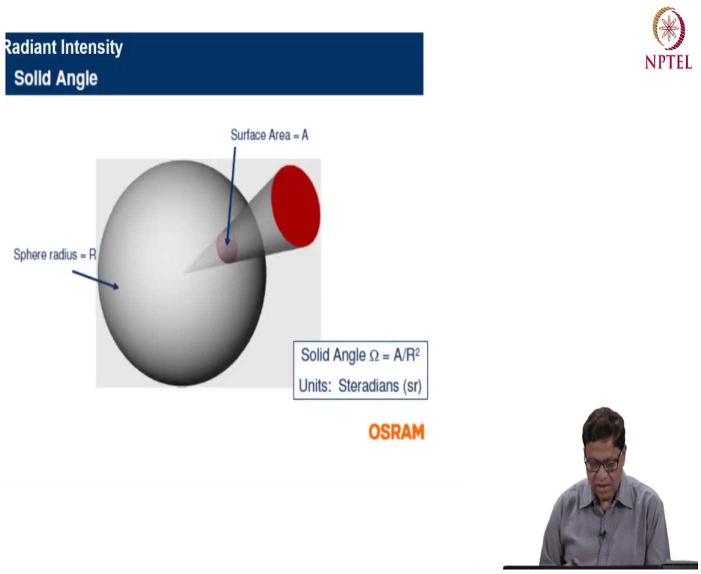

So, this is the definition of solid angle. Suppose there is a point source point source and then this is the d area on the surface of the sphere, and then for a point source the solid angle is defined by A by R square, where A is the area and R square is the radius of the sphere.

So, this will be using in you know when we are analyzing optical wireless communication system. Sometimes it is easy to assume point source. So, that mathematically you are able to solve you know and you are able to get good insight of the problem.

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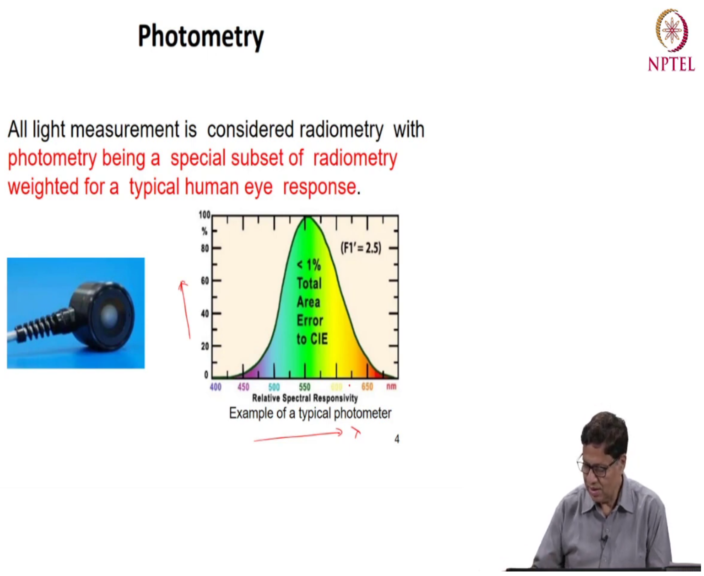

So, the second part is photometry. Photometry is actually subset of radiometry. All light measurements under radiometry is a special subset weighted for a typical human eye response. So, as we see in this diagram here, you have the wavelength here and this is the percentage of light which is you know sensitive to human eye and human eye responses to this particular set of wavelength. So, we can say this is as weighted or scaled version of radiometry with respect to human eye response.

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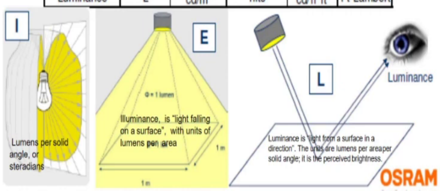
Photometric Units and Symbols

Photometric Units					
Quantity	Symbol	Metric Units	Name	English Units	Name
Luminous Flux	Φ	lumens (lm)	lumens		
Luminous Intensity	I	lm/sr	candela (cd) or candlepower		
Illuminance	E	lm/m^2	lux (lx)	lm/ft^2	Ft-candle
Luminance	L	cd/m^2	nits	$cd/\pi*ft^2$	Ft-Lambert



So, similar to radiometry, we have different quantities in photometry. First one is luminous flux, the symbol is phi and the units are lumen, it is denoted as lm. And the second quantity is luminous intensity, the symbol is I, and it is lumen per steradian or also this is known as candela.

So, first let us see the luminous intensity here. So, the lumen the lumens per unit solid angle in this case is called as luminous intensity and the units are as I mentioned is either lumen per steradian or candela, denoted as cd.

The third quantity is illuminance which is represented by E. This is the light falling onto a surface and the units are lumen per meter square. And this is also called as lux. So, this is also lumens per meter square is also called as lux.

The fourth quantity is luminance which is represented is L. The units are candela per meter square which means the light falling from a source in some solid angle d omega and from the reflected surface, from the surface it is reflected and it is collected by the eye. And that part of the eye, the that part of the light is called as luminance. And as you change the position of the eye this luminance might change.

So, this is the basic parameters which are used in photometry luminous flux, luminous intensity, illuminance and luminance.

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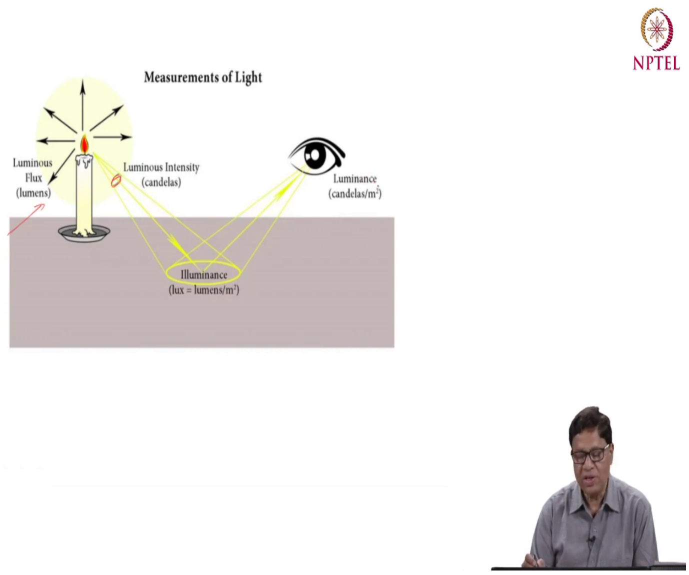

So, in order to clear understand this more. So, this is a source of light where you have luminous flux which are called as lumens. And then the light falling in a particular solid angle is called as luminous intensity or candela.

And then it falls onto a surface. So, the area which is reflected, the light which is reflected from the surface is called as illuminance. The units are lumens per meter square and then it is collected by the eye. So, which is called as the luminance. And the units are candela per meter square.

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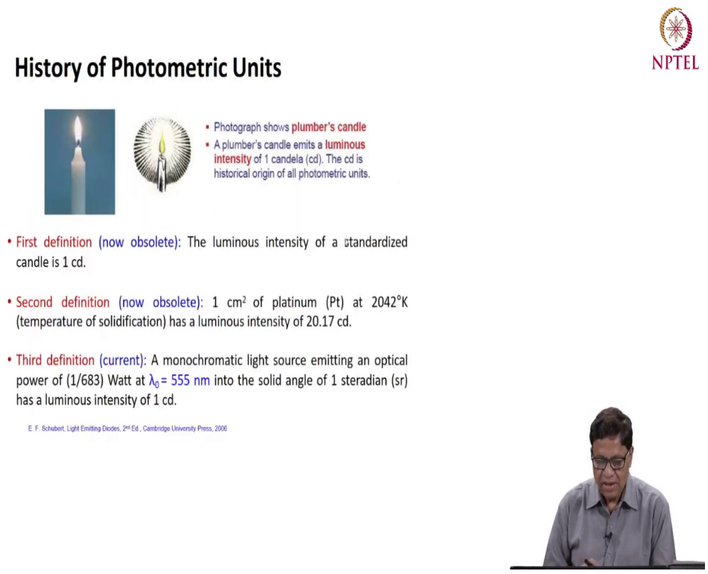

So, let us just briefly understand about the history of photometric units. So, the first definition of 1 candela is you know the luminous intensity of a standard candle, I mean which is a very vague definition. So, it is now obsolete.

The second definition is 1 centimeter of platinum at 2042 degree which is the temperature of solidification has a luminous intensity of 20 candela. So, this is another standard. Again, this is an obsolete very difficult to measure this.

The third definition which is the current definition and which is an accurate definition is you use a monochromatic source of light source which has a power of 1s by 68, 1 by 683 watt at lambda is equal to 555 nanometer into a solid angle of 1 steradian, then the luminous intensity will be called as 1 candela.

So, I will repeat the correct definition of candela that you use a monochromatic source which has a power of 1 by 683 watts and the lambda 0, the wavelength is 555 nanometer and it falls and you are measuring in a solid angle of 1 steradian, then it will give you a luminous intensity of 1 candela.

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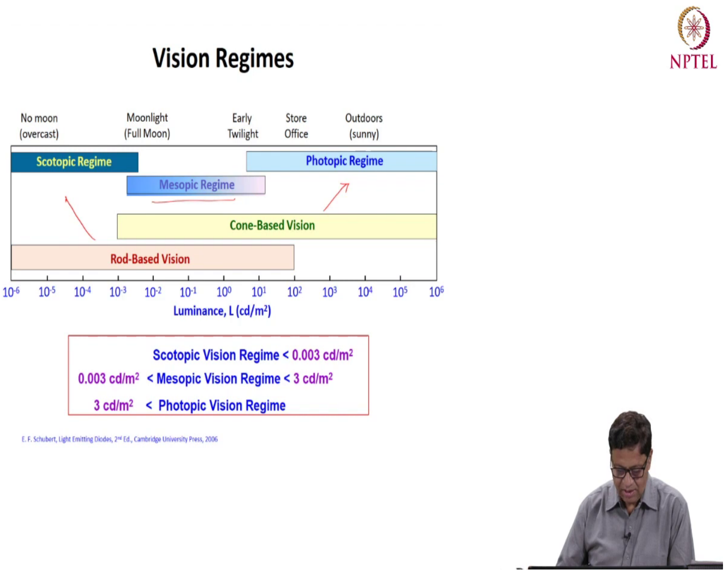

So, there are different regimes. This I am referring to the basically the visible part of the spectrum. So, it is divided into two parts, the regimes, the photopic regime where you have good amount of light or it is a well-lit situation. For example, outdoor sunny or in a store where lot of lighting is there or you know early twilight. So, these are all examples of photopic regime.

And then you have the another regime which is called as scotopic regime where there is you know very less light, it is poorly lit. For example, there is no moon or it is a overcast. So, that is called as scotopic regime. And the light which is in between is called mesopic regime. So, basically there are three regimes depending upon whether the situation is well-lit or poorly lit or somewhere in the middle.

Now, as you know the eye has two types of photoreceptors, one is cone, other is rod. So, cone is sensitive to photopic regime where the light intensity is high or you say very lit, very lit environment. And the rod are sensitive to scotopic region where the light is very less.

And these are some values of scotopic region, less than 0.003 candela per meter square and mesopic lies between 3 and 0.003 candela per meter square, whereas, the photopic vision region is greater than 3 candela per meter square.

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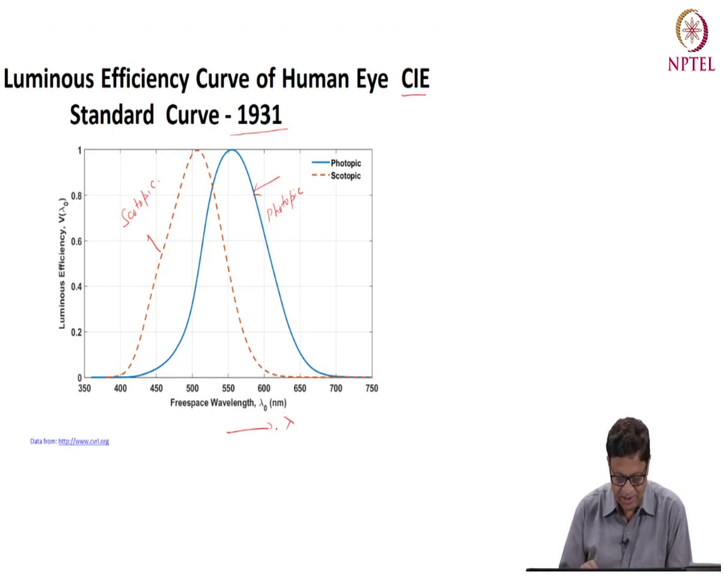

And if you see the eye sensitive eye sensitivity of the human being and this is as per the CIE 1931, this is the standard. So, it has different luminous efficiency for photopic and scotopic.

So, this the blue line here is actually photopic and this red line which you see here is scotopic and on this side you have wavelength. So, you have different sensitivity experienced by the eye for photopic and scotopic region.

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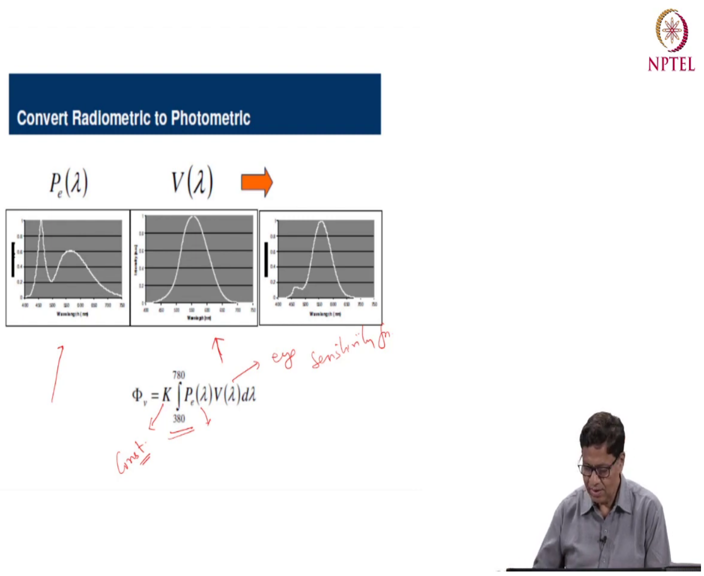

How do you convert a radiometric quantity to photometric quantity? So, this is the powers power spectral distribution of the source which is P e lambda and this is V lambda which is eye sensitivity function and then when you multiply and integrate from 380 to 780 which is the visible range.

And there is a constant here, there is a constant here, then you can get you know photometric units. So, this is eye sensitivity function. It could be for both for photopic or scotopic. And this is the power spectral distribution and this is constant. So, if you do this integration, you get the photometric quantity, corresponding photometric quantity.

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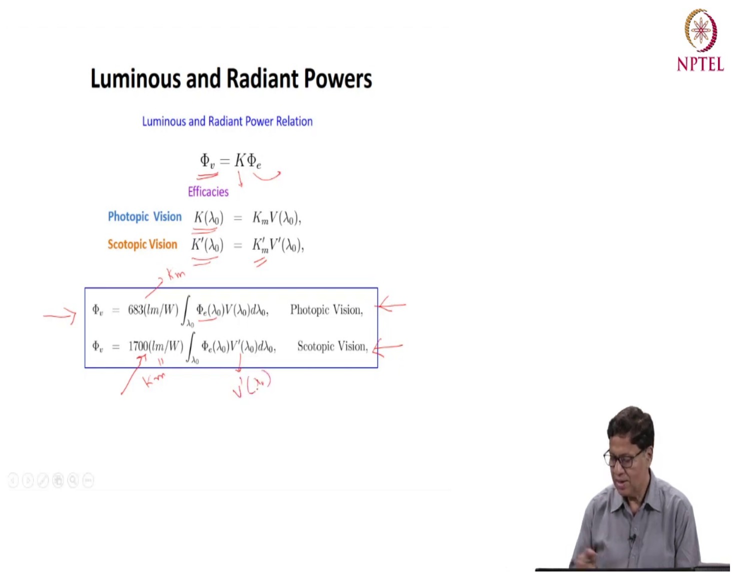

So, this is another way of explaining for both the regions luminous and radiant powers. So, the relationship is you have luminous power as phi phi V, V stands for visual, this is some constant and this is some radiometric radiant power which is phi e.

And then if you have the photopic vision, then this constant is actually K m into V lambda naught. Whereas, for scotopic is a different constant K m prime and V prime lambda. As we had discussed in the earlier graph V lambda 0 that is the eye sensitivity function is different for photopic and different for scotopic. So, V lambda and V dash lambda are for photopic and scotopic.

And then K m, K m dash they are the constant. And this is how you get the value of K lambda naught and K dash lambda, and then you for the photopic vision the equation becomes phi phi V which is the luminous power, 683 lumens per watt.

This is the constant which is you know K m here. And lambda 0 is over the visible range. And this is your phi e is your radiant power into eye sensitivity function. d lambda 0 gives you the value of luminous for the photopic.

Similarly, we can find out for the scotopic vision where the where the constant is different, the it is K m dash which is 1700 lumens per watt. And then this is also, eyes sensitive function is also different which is V dash lambda 0.

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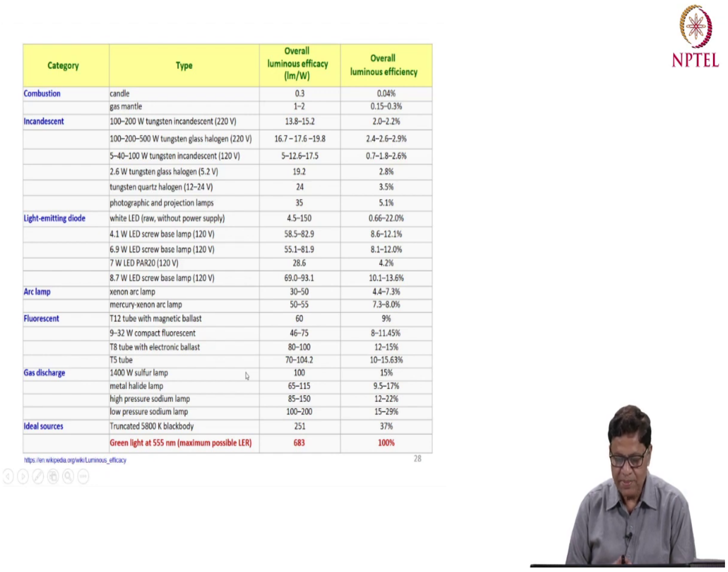

Category	Type	Overall luminous efficacy (lm/W)	Overall luminous efficiency
Combustion	candle	0.3	0.04%
	gas mantle	1–2	0.15–0.3%
Incandescent	100–200 W tungsten incandescent (220 V)	13.8–15.2	2.0–2.2%
	100–200–500 W tungsten glass halogen (220 V)	16.7 – 17.6 – 19.8	2.4–2.6–2.9%
	5–40–100 W tungsten incandescent (120 V)	5–12.6–17.5	0.7–1.8–2.6%
	2.6 W tungsten glass halogen (5.2 V)	19.2	2.8%
	tungsten quartz halogen (12–24 V)	24	3.5%
	photographic and projection lamps	35	5.1%
Light-emitting diode	white LED (raw, without power supply)	4.5–150	0.66–22.0%
	4.1 W LED screw base lamp (120 V)	58.5–82.9	8.6–12.1%
	6.9 W LED screw base lamp (120 V)	55.1–81.9	8.1–12.0%
	7 W LED PAR20 (120 V)	28.6	4.2%
	8.7 W LED screw base lamp (120 V)	69.0–93.1	10.1–13.6%
Arc lamp	xenon arc lamp	30–50	4.4–7.3%
	mercury-xenon arc lamp	50–55	7.3–8.0%
Fluorescent	T12 tube with magnetic ballast	60	9%
	9–32 W compact fluorescent	46–75	8–11.45%
	T8 tube with electronic ballast	80–100	12–15%
	T5 tube	70–104.2	10–15.63%
Gas discharge	1400 W sulfur lamp	100	15%
	metal halide lamp	65–115	9.5–17%
	high pressure sodium lamp	85–150	12–22%
	low pressure sodium lamp	100–200	15–29%
Ideal sources	Truncated 5800 K blackbody	251	37%
	Green light at 555 nm (maximum possible LER)	683	100%

https://en.wikipedia.org/wiki/Luminous_efficacy

28

So, this particular slide basically tells about the luminous efficacy and luminous efficiency. So, there are various light sources combustion which includes candle, incandescent, light emitting diode, arc lamp and so on and so forth. So, basically let us consider on the light emitting diode because this is the one which we are going to use during our discussion in optical wireless communication system. So, these are the typical values of a light emitting diode.

So, suppose I take a white led here, then the luminous efficacy which is actually lumens per watt; that means, if I have 100 watt of source or 100 watt of source, it will give you say for example, 1000 lumens. Then, the luminous efficacy is 1000 by 100 which is ten lumens per watt. So, this is how the luminous efficacy is described.

And this ranges from 4.5 to 150. There are some sources which I have got much better luminous efficacy. So, we are looking for such sources which are good for illumination as well as they will be used for communication. That we will see in later in you know in forthcoming lectures.

And this is the luminous efficiency this is actually expressed in percentage. So, the amount of light which is produced by the source not everything comes out. For example, in led, inside the led lot of photons are generated, but ultimately you know some percentage of the photon comes out.

So, basically this define, this is defined as luminous efficiency that is in and the units are in percentage. So, for a typical led is of the order of 0.66 to 22 percent. And the loss is because of some absorption happening; and some for example, in light emitting diode not everything is converted into radiative recombination. There are some non-radiative recombinations, so there is some loss, there are some loss because of reflection and things like that.

So, basically, whatever you get actual output is much less than what it is produced in the fixture which actually which is defined by the term luminous efficiency.

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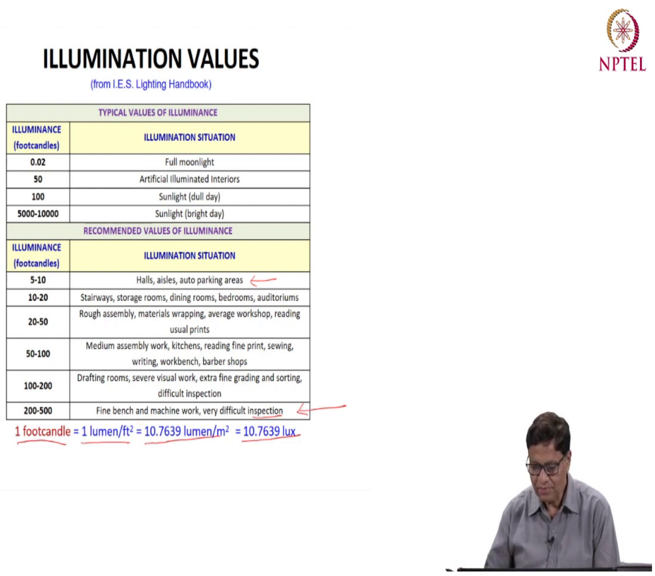

These are some of the illumination values which are which are as per IES standards. So, this is given in terms of foot candle. So, let us understand what is a foot candle. So, 1 foot candle is nothing, but 1 lumen per feet square and this can be converted into 10.7639 lumens per meter square which is actually equal to 10.7639 lux.

So, 1 foot candle is roughly equal to you know 11 lux. So, that is a very approximate way of relating foot candle and lux. So, for example, in a parking area for example, or halls or aisles you know typical you require 5 to 10 foot candles or in terms of lux it will be 50 to 100.

For example, if we go to the other extreme in a fine bench where you are working on a minute you know equipments or very very difficult inspection areas then the then the illuminance which is required is about 2000 to 5000 lux.

So, depending upon the situation whether it is some stairways or it is some drafting room or some reading fine print and things like that, so this illumination criteria changes. So, this is some of the typical values of illumination because as we will see that we are going to use the current led which are mounted inside the room or inside the office for communication.

But ideally those LEDs are mainly for illumination giving you know this much amount of lux. So, the same power I need to use for communication. So, that is why these things will be you know relevant when we discuss the communication part of it.

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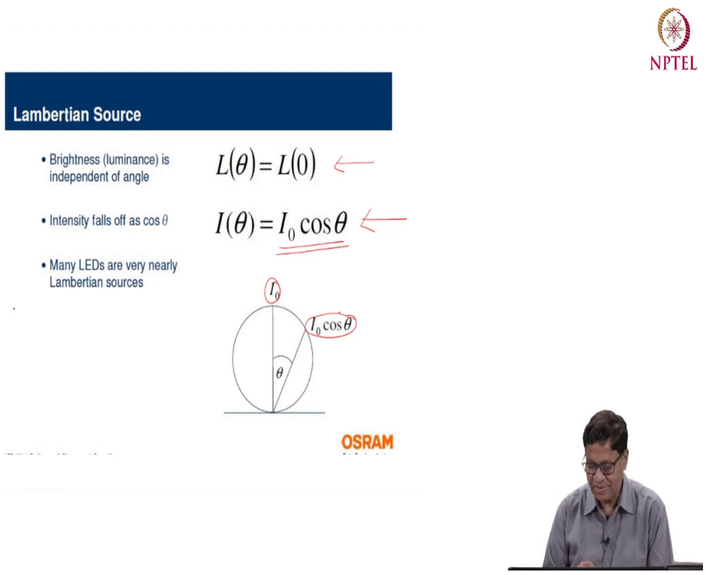

Another thing which we will frequently encounter is the Lambertian source. So, what is a Lambertian source? Lambertian source the brightness or the luminance is independent of angle that is L theta is equal to L naught. So, whatever the theta the value is constant.

Whereas, the intensity falls as cos of theta. So, this is a very approximate representation of a source. Not all source will meet this criteria, but to make it more you know mathematical friendly, we normally take source as Lambertian source. So, I theta is equal to I 0 cos theta, intensity is falling of as cos theta as it is clear in this diagram.

So, the intensity here is I 0 and as at an angle theta it is I 0 cos theta. So, most of the LEDs which are there, they nearly they are nearly Lambertian surfaces.

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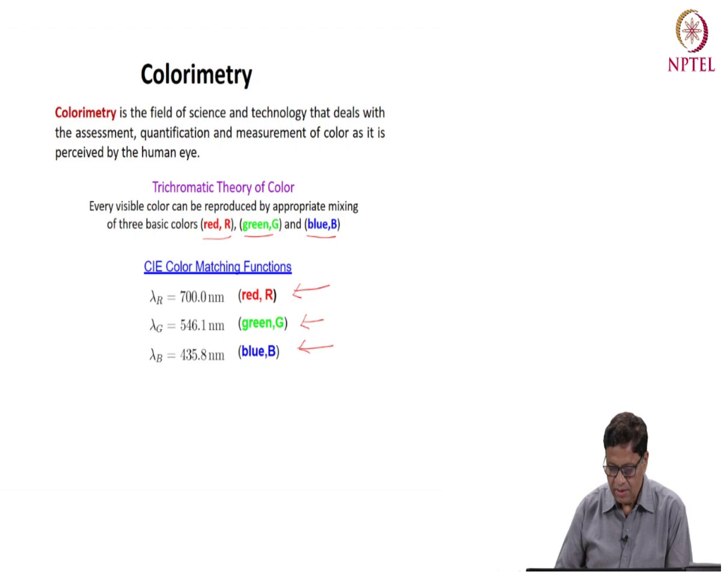

Now, let us now come to colorimetry. It is a field of science that deals with the assessment and the quantification and the measurement of color as it is pursued by the human eye. So, as you know the there are 3 basic colors, red, green and blue. So, you can produce any color using R, G and B. And the wavelength for red is 700 nanometer, for green it is 546 and for blue it is 435.

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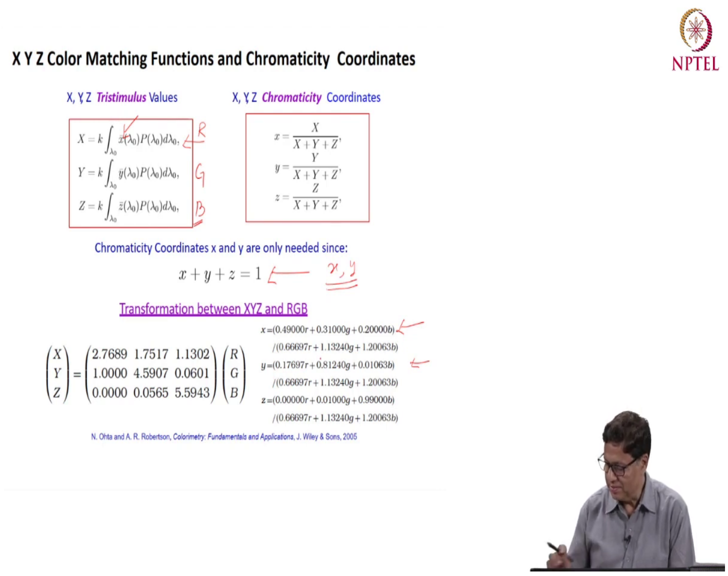

So, now I want to convert this any color into some sort of coordinates. We will see whether you know you require 2 coordinates or 3 coordinates. But right now suppose these are the tri-stimulus values X, capital X, capital Y, and capital Z is actually the power of the source scaled down by visual response of the eye which is X lambda 0 here.

This is for a particular color say for this may be for say R. Similarly, this Y tristimulus value is for say G and this is for B. And this X Y, corresponding X, Y, Z chromaticity coordinates are given by X is equal to X divided by X plus Y plus Z and so on and so forth. And if you see here if you add these things they become 1.

So, basically I need to I need only two quantities. Once I know X and Y, the Z can be found out. So, basically I want to translate any type of color into X Y coordinates. So, that is what this color matching function and chromaticity coordinates does. So, this is a transformation between X, Y, Z, this tristimulus values, and red green and blue. So, they are you know related in this fashion and these are the X Y Z.

So, Z one of the quantity is not required because we know x plus y plus z is equal to 1. So, basically we require just two components X and Y, and X can be represented in terms of some constant into the R, the red component, the green component, the blue component, and similarly Y can be represented in terms of R, G and B.

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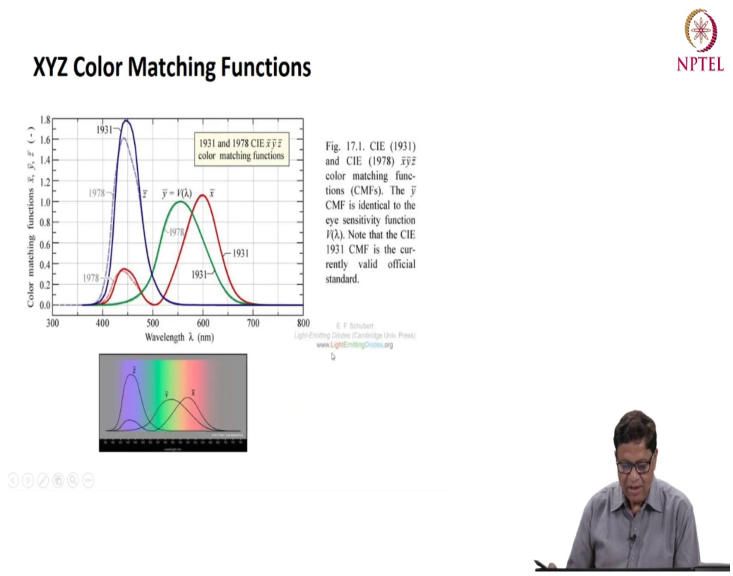

So, this is typical color matching function, XYZ color matching function. So, basically there are two standards 1931 and 1978. 1931 is adopted in most places and quite accurate, but here for comparison you know both the standards have been given, but more or less they overlap.

So, these are the X, Y and Z function which I call them as color matching function. They are represented here. And on Y axis you have the wavelength.

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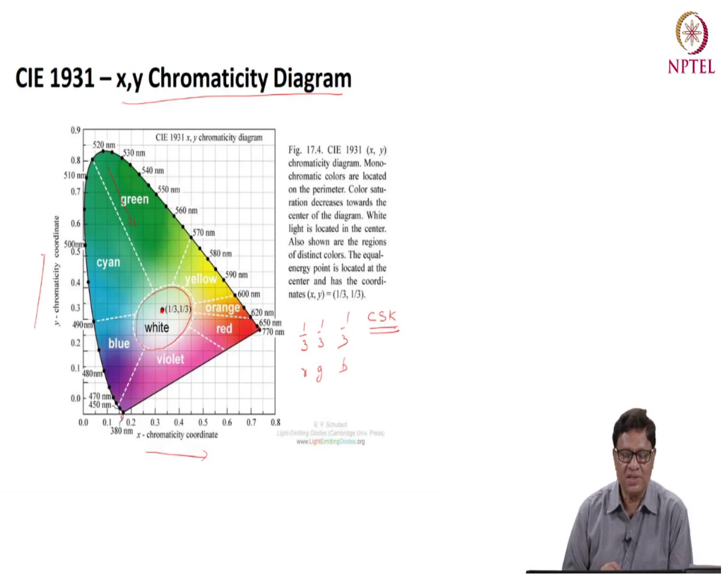

So, finally, what we get CIE x, y, z chromaticity diagram. So, here in this diagram you see these are the x coordinate and these are the y chromaticity coordinate. And on the edges you will see the monochromatic light here, monochromatic light here. As you move towards the center, this color saturation actually is decreasing, this color saturation is decreasing as you move to the center.

And in the center where you have all the components of x and y and z, you get actually white light. So, this is the white light region here. And there are different shades of white light. And this is the point of same energy that is you know this black point which has 1 by 2, 1 by 3, 1 by 3, for both R, G and B. And basically if you have equal energy point or equal contribution of R, G, B you will get white light of this which is defined by this point, particularly this point.

So, this kind of analysis will be used in communication where we will be using this diagram. For example, you know in RF we must have we might have heard of constellation diagram. So, different points or signals are represented by different constellation diagram.

Here also we will represent the different constellation point using some combination of R, G, B. And we will try to make a group of constellation diagram which will be used for you know modulating the input signal. So, that part is called as color shifting that we will discuss in detail at a later point. But this diagram will be useful when we discuss a color based modulation scheme.