Fiber Optics
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Lecture - 40
Summary and Recent Advances

Now, we have reached the end of this course and in this final lecture I would like to present an overview, bring out some important points and would like to give you an idea about the recent advances in optical fiber communication system.

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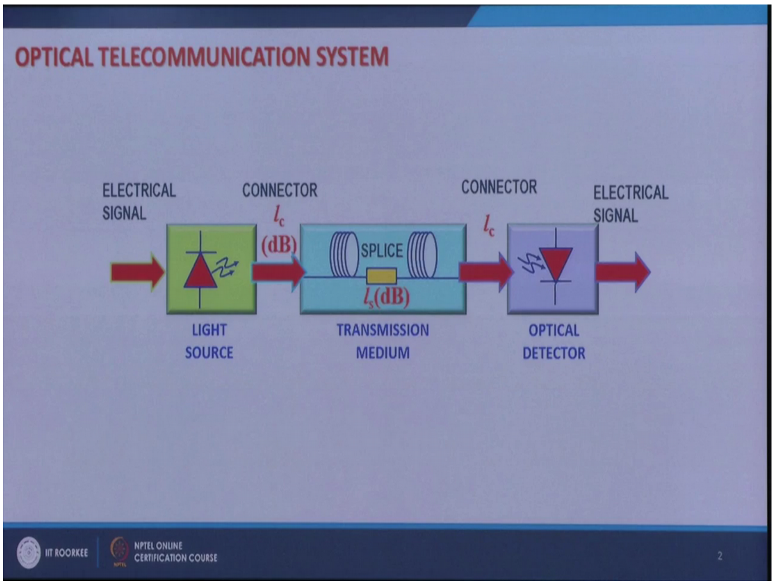

So, this is the complete system that we had, in this system at the transmitter end we have the light source for optical communication then in between we have transmission medium which comprises optical fibers, fiber based components specialty fibers and at the receiver end we have optical detector.

So, I will give you an overview of all these one by one.

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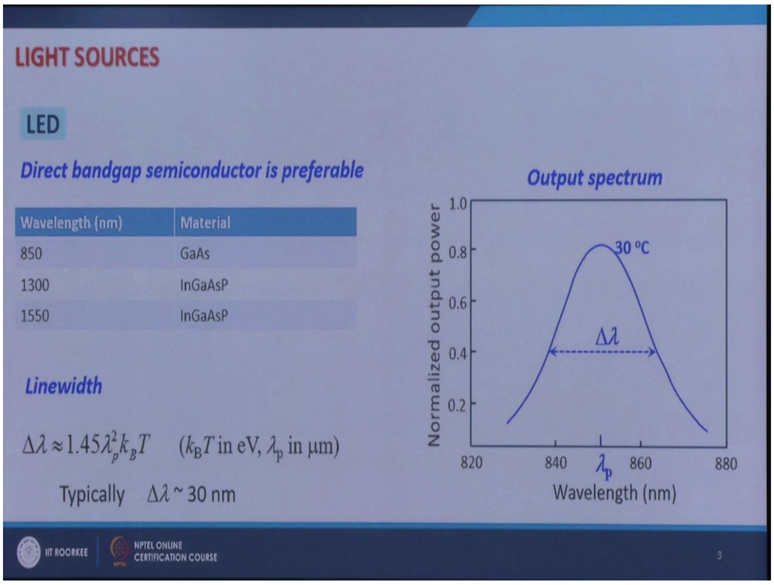

If we look at light sources, in light sources we have LED which can be made by semiconductor materials of direct band gap. There are certain materials and they are wavelengths at which we can make the light source at 850 nanometer wavelength the suitable material is gallium arsenide, while at 1300 and 1550 nanometer wavelength we use indium gallium arsenide phosphide. The output spectrum of an LED looks like this which is characterized by a peak wavelength lambda p and aligned with delta lambda, it is given by 1.45 times lambda p square times kB times T, where KBT is in electron volts and lambda p is in micrometer, typically for an LED delta lambda is 30 nanometers.

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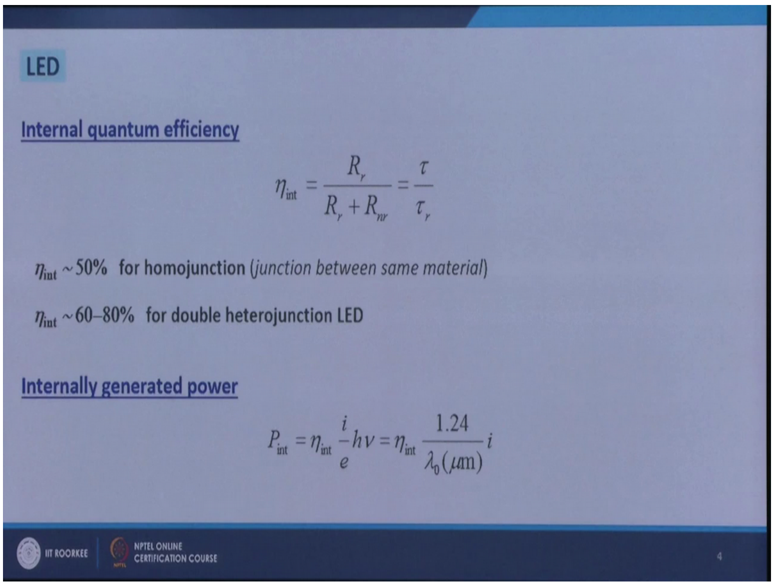

Some important parameters of LED are the internal quantum efficiency, internally generated power, extra quantum efficiency, responsivity and so on.

The internal quantum efficiency is given by Rr plus Rr plus Rnr where these R and r nr are respectively the radiative and non radiative recombination rates. It is equal to tau over tau r, your tau is the total lifetime and tau r is the radiative lifetime. Typically internal quantum efficiency of a homo junction LED is 50 percent, while of a double hetero-junction LED it is between 60 and 80 percent. The power which is generated inside the device is given by eta internal times I over e times h nu, which can be represented as e to internal times 1.24 over lambda naught where lambda naught is represented in micrometer times i.

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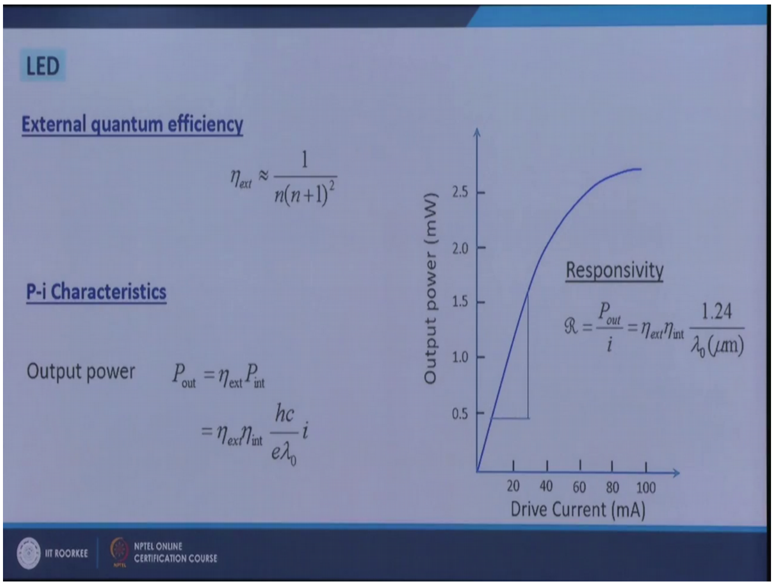

So, this is the internally generated power, but not all the internally generated power comes out of the device primarily because of the index contrast between the semiconductor material and outside air, outside medium which is air. The external quantum efficiency is approximated by 1 over n times n plus 1 square and the output power therefore, can be given by P out is equal to eta external times P internal and if I substitute for p internal from previous slide.

So, it would be eta external eta an internal times hc over e lambda naught times I, if we plot this output power is a function of drive current I, then it follows this kind of behaviour and this behaviour is characterized by responsivity which is nothing, but the slope of the curve in a linear region and it is given by eta external eta internal times 1.24 over lambda naught in micrometer.

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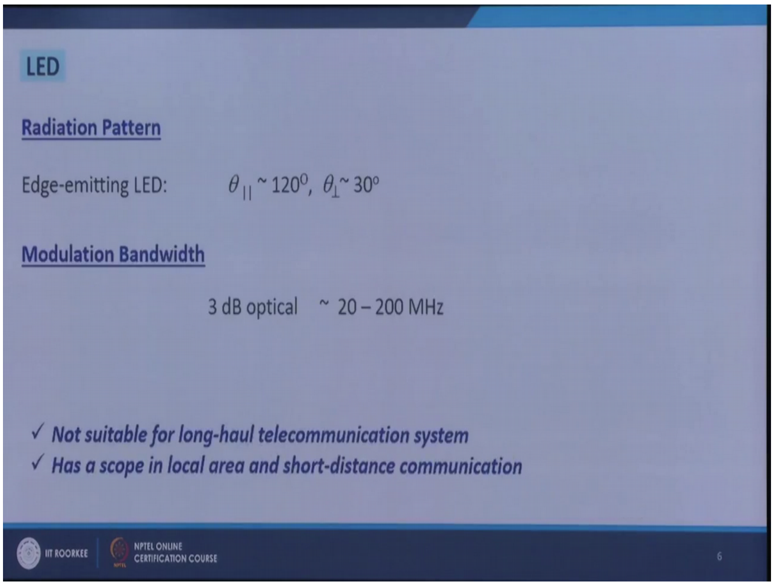

If you look at the directivity of an LED then it is not a very much directional source it is output is not directional, in one direction it spreads out over an angle of 120 degree from one side to another side, on the other side it spreads to about 30 degree. Optical 3 d bandwidth of an LED if you modulate it is typically 20 to 200 megahertz. So, this kind of light source is not suitable for long haul telecommunication system but it has a scope in local area and short distance communication.

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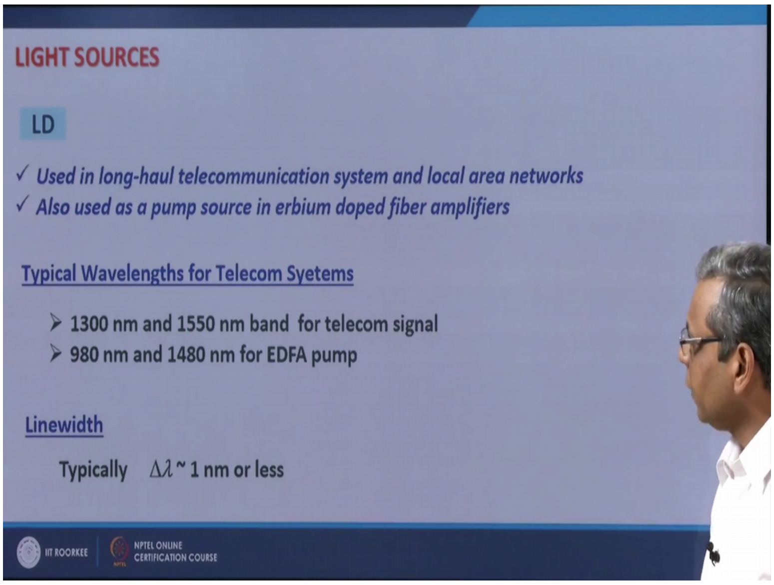

Another source for telecom system is laser diode LD; it is used in long haul telecommunication system and in local area networks. It can also be used as pump source in erbium doped fiber amplifiers. Typical wavelengths for telecom systems are 1300 nanometer and 1550 nanometer band for telecom signal, 980 and 1480 nanometer for EDFA pump, typical line width of a laser diode is one nanometer or less.

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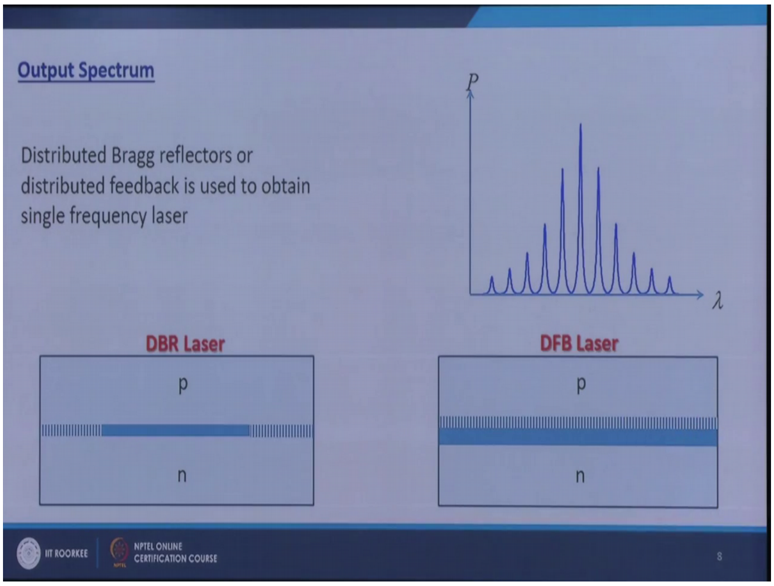

If you look at the output spectrum then typical output spectrum of a laser diode looks like this which has several longitudinal modes, but you can select a particular longitudinal mode and make the laser less at that particular mode if you use distributed that reflector or distributed feedback.

So, with the help of this you can obtain single frequency laser with line width as small as 0.1 nanometers.

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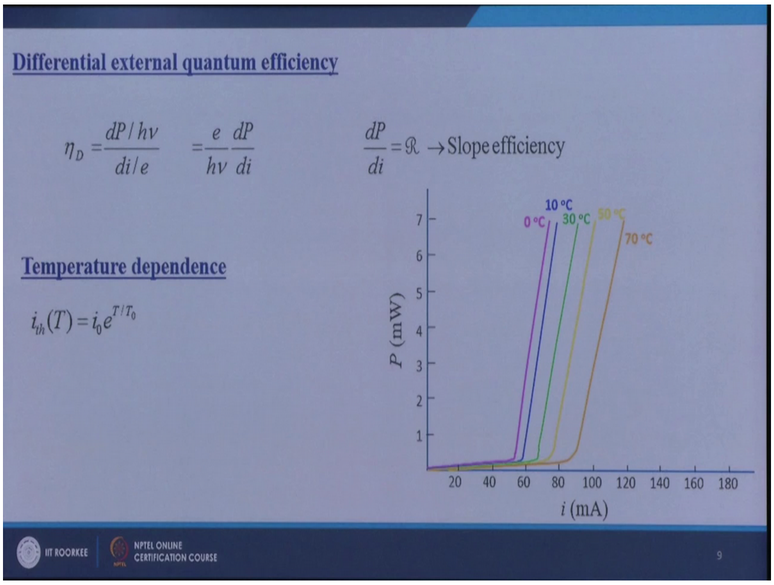

A laser diode is characterized by differential external quantum efficiency which is given by d P over h nu divided by di over e, which is e over h nu times dP over di where dP over di is the slope of the pi curve of a diode laser in the region i greater than i th. Where actually the laser action occurs, where the lasing occurs this dP over di is the slope of this this region slope of the curve in this region and it is defined as slope efficiency. If you change the temperature of a diode laser then its p I characteristics change notably the i th the value of i th increases with temperature and if you fit a relation between ith and the temperature T, it follows a relation i th is equal to i 0 e to the power t over tau naught.

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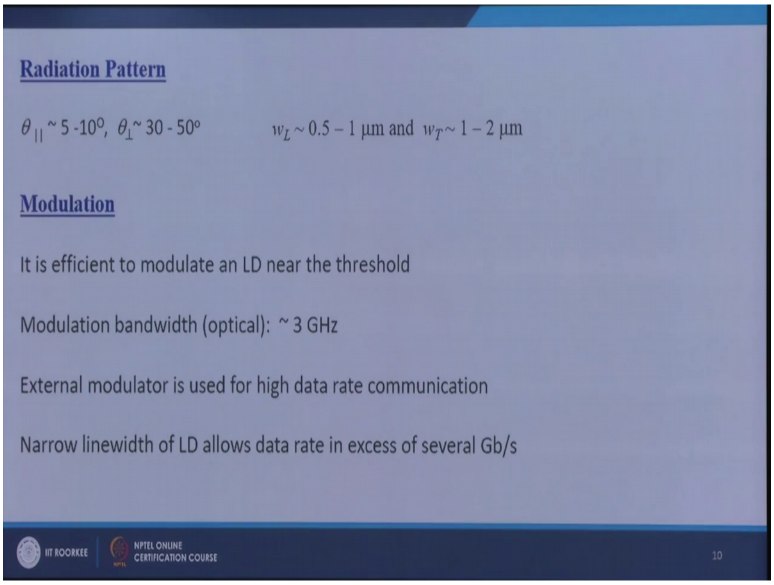

Directivity of a laser diode is of course, better than that of an LED, in one direction it spreads over an angular width of 5 to 10 degrees while in the other direction the angular width is 30 to 50 degrees. The spot size the spot that comes out of a diode laser is not perfectly circular it is quite elliptical and the width in one direction is 0.5 to 1 micrometer and in the other direction it is 1 to 2 micrometer. So, you can modulate laser diode directly by injection current modulation or you can modulate the light coming out of diode laser using an external modulator. If you choose to modulate the diode laser directly then you should modulate it near the threshold because it is efficient to switch on and switch off a diode laser when you operate it near threshold by applying a suitable bias, the modulation bandwidth optical modulation bandwidth of a diode laser is typically 3 gigahertz.

So, you cannot have very high data rate if you directly modulate it using injection current. So, you will have to use external modulator for high data rate communication. But the diode laser has very small line width it can go upto 0.1 nanometer and this allows data rates in excess of several Gbps because the dispersion becomes very small when you have very small line width.

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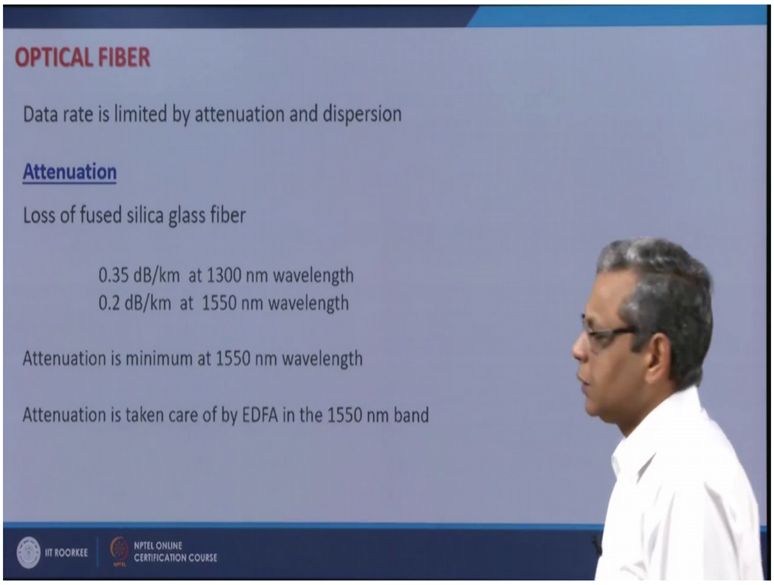

The next segment of the system is transmission medium where major component is optical fiber itself transmission fiber.

Data rate of a system is limited by the attenuation and dispersion of the fiber which you are using in the system. If I look at attenuation then the loss of fused silica glass fiber which is used in telecom system is about 0.3 dB per kilometer at 1300 nanometer wavelength and about 0.2 db per kilometer at 1550 nanometer wavelength and at attenuation is minimum at 1550 nanometer wavelength, but you can take care of this if you employ EDFA which is erbium doped fiber amplifier which amplifies signal in fifteen fifty nanometer band.

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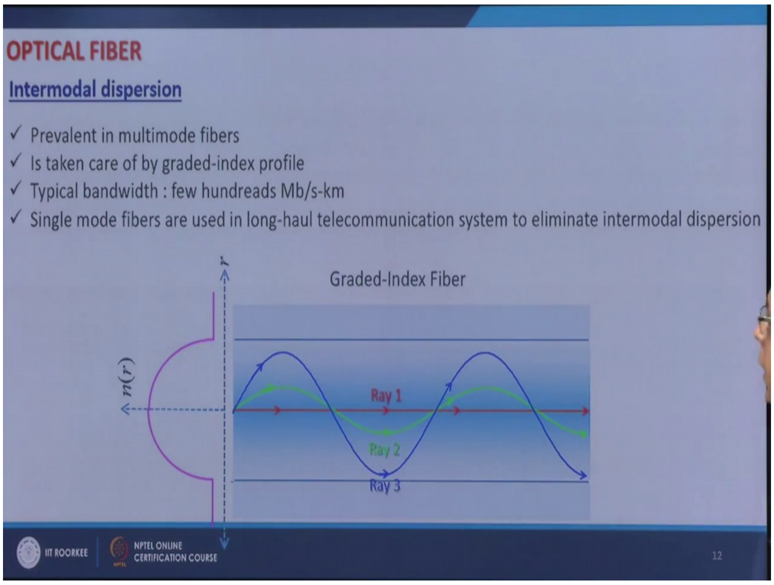

If you look at the dispersion then you have several kinds of dispersions in multimode fiber you have intermodal dispersion which is prevalent. If you want to minimize this intermodal dispersion then you will have to use graded index fiber and with graded index fibers you can have typical bandwidth of few hundreds of mbps times kilometer, but if you want to get rid of the intermodal dispersion completely then you will have to use single mode fiber.

Here I show how a graded index fiber can take care of intermodal dispersion as you know the, the mechanism behind intermodal dispersion is that because you have several modes in a fiber which correspond to different ray paths and each ray path in step index fiber will give rise to intermodal dispersion because the light launched in different rays will take different times to reach the output end. But in a graded index fiber since you are modifying the refractive index across the transverse direction of the fiber then the velocity of light in this region and in this region and in this region would be different.

So, the increase in velocity here takes care of increase in path length. So, that is how at the output all the rays will reach at approximately the same time and that is how intermodal dispersion is taken care of.

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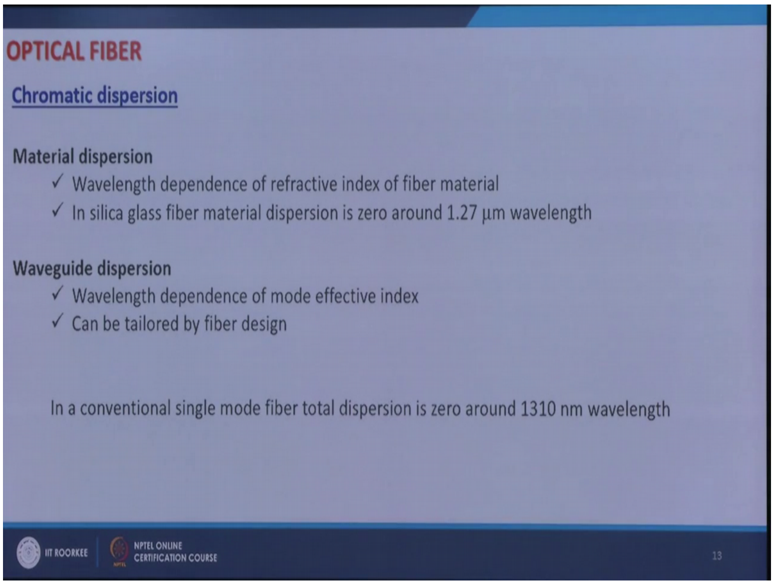

Another dispersion is chromatic dispersion which has 2 components material dispersion and waveguide dispersion. Material dispersion is nothing, but the wavelength dependence of refractive index of the fiber material, in silica glass fiber material dispersion is 0 around 1.27 micrometer wavelength waveguide dispersion has its roots in wavelength dependence of more defective index and so it can be tailored by changing the design of the fiber. In a conventional single mode fiber total dispersion is 0 around 1310 nanometer wavelength, if you include both the material and waveguide dispersion.

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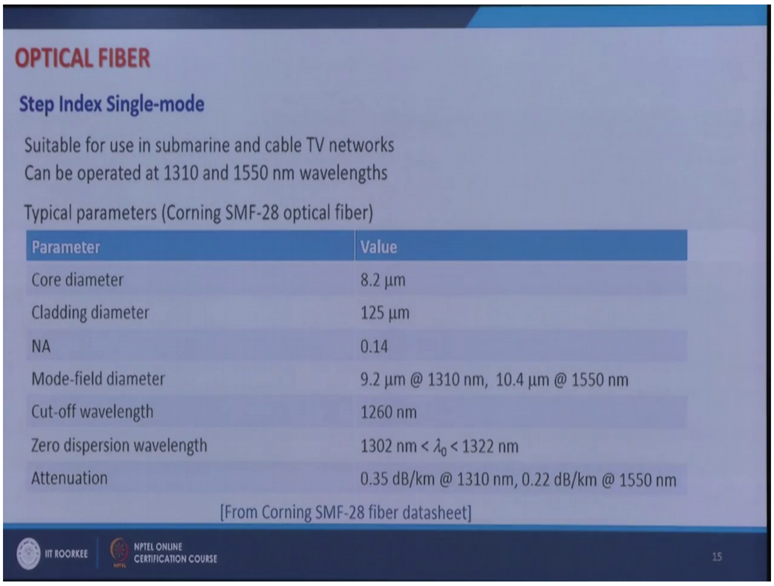

Now, if I look at typical fibers which are used in telecom system then you have graded index multimode fiber and step index single mode fiber. A graded index multimode fiber is suitable for local area network and campus wide network, what type of sources optical sources you would use while using this fiber well you can use 850 nanometer vertical cavity surface emitting LED or 1300 nanometer fabry perot cavity laser diode.

Here I have listed typical parameters of a cordoning 62.5 by 125 micron multimode fiber which I have taken from the cordoning fiber datasheet itself. So, where the core diameter is 62.5 micrometers, cladding diameter is 125, micrometer numerical aperture is 0.275 it attenuation is 3 dB per kilometer at 850 nanometer wavelength and 0.7 dB per kilometer at 1300 nanometer wavelength you see a bit higher figures for the attenuation because numerical aperture is quite high.

So, there is more germanium inside the fiber which causes more attenuation, 0 dispersion wavelength of this fiber varies from 1332 nanometer to 1354 nanometer. If you look at typical step index single mode fiber for telecom system then this fiber is suitable for long haul telecom system in submarine and cable TV network it can be operated at 1310 and 1550 nanometer wavelengths. Typical parameters of a corning smf 28 optical fiber are core diameter 8.2 micrometer, cladding diameter 125 micrometer, numerical aperture 0.14, mode field diameter 9.2 micrometer at 1310 nanometer wavelength 10.4 micrometer at 1550 nanometer wavelength, it has a cutoff wavelength of about 1216 nanometer 0 dispersion wavelength is between 1302 to 1322 nanometer.

That innovation of this fiber is 0.35 dB per kilometer at 1310 nanometer wavelength and 0.22 db per kilometer at 1550 nanometer wavelength.

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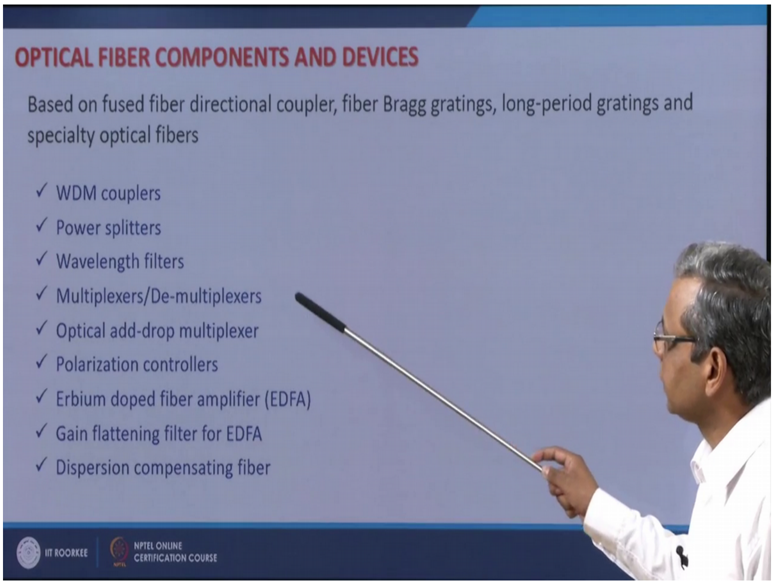

Then you have various optical fiber based components and these components are based on fused fiber directional, fiber Bragg gratings long period gratings and specialty optical fibers. I just listed these components here they are WDM couplers, power splitters, wavelength filters, multiplexers de multiplexers, optical add drop multiplexer, polarization controllers, Erbium doped fiber amplifier EDFA, Gain flattening filter for EDFA and dispersion compensating fiber. So, these are some typical fiber based components that are used in optical telecommunication system.

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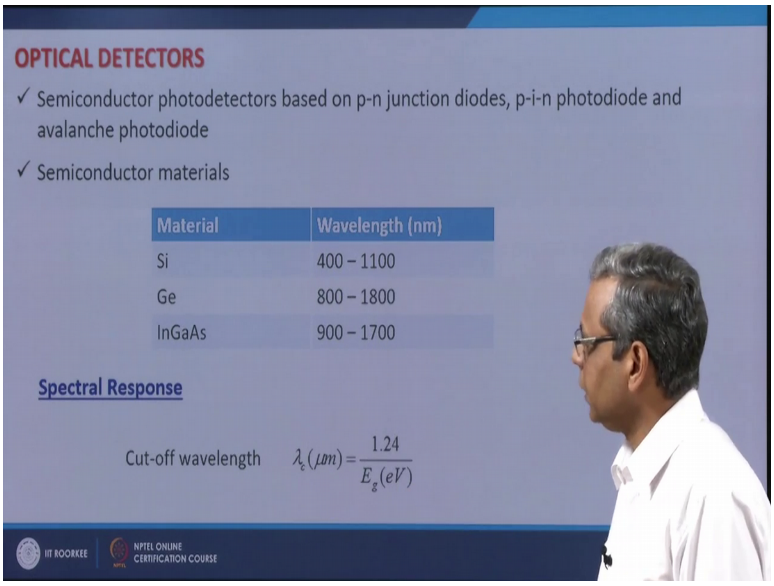

Now, I come to the receiver end at the receiver end we have semiconductor material based photo detectors and these detectors are based on pn junction diodes pin photo diodes or avalanche photo diodes apd. The materials which are typically used are silicon in the wavelength range 400 to 1100 nanometer, germanium from 800 to 1800 nanometer wavelength and indium gallium arsenide from 900 to 1700 nanometer wavelength and this is the widely used material for making detectors in optical communication system. If you look at the spectral response then a material responds only to certain wavelength regions depending upon the band gap of the material and the cutoff wavelength is given by lambda c in micrometer is equal to 1.24 divided by Eg in eV.

So, for all the wavelengths is smaller than lambda c the light would be absorbed while for the wavelengths lambda greater than lambda c the energy is not sufficient to overcome the band gap and therefore, they would not be absorbed.

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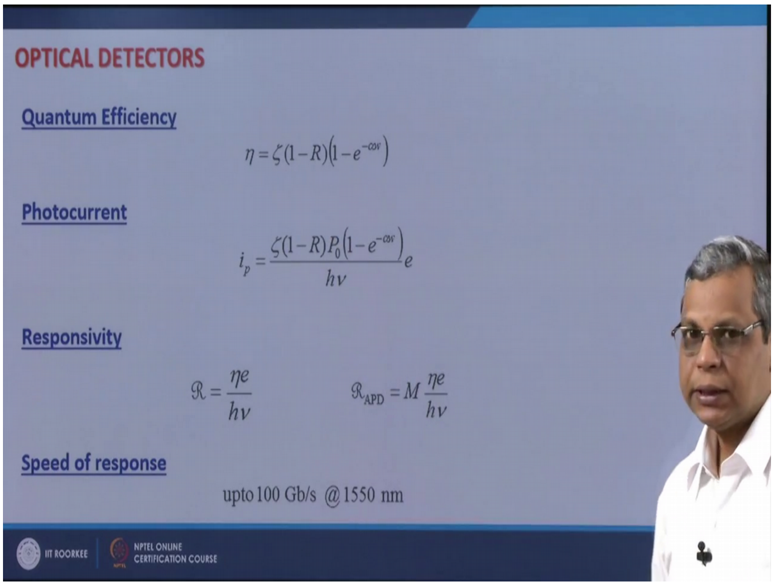

Optical detectors are characterized by various parameters like quantum efficiency which is given by eta is equal to zeta times 1 minus R times 1 minus e to the power minus alpha w where zeta represents the fraction of electron hole pairs that contribute to photocurrent, R is the final reflection coefficient alpha is the absorption coefficient and w is the junction width or depletion region width.

Photo current which is generated is given by ip is equal to zeta times 1 minus r times P 0 times 1 minus e to the power minus alpha w divided by h nu times e where P 0 is the incident power. So, this much incident power will generate this much current. The responsivity of the detector is defined by eta e over h nu and in case of avalanche if photo diode because there is internal gain mechanism. So, it gets multiplied by a multiplication factor m because of the gain.

Speed of response you can have now photo detectors which can go as fast as 10 Gbps at 1550 nanometer wavelength.

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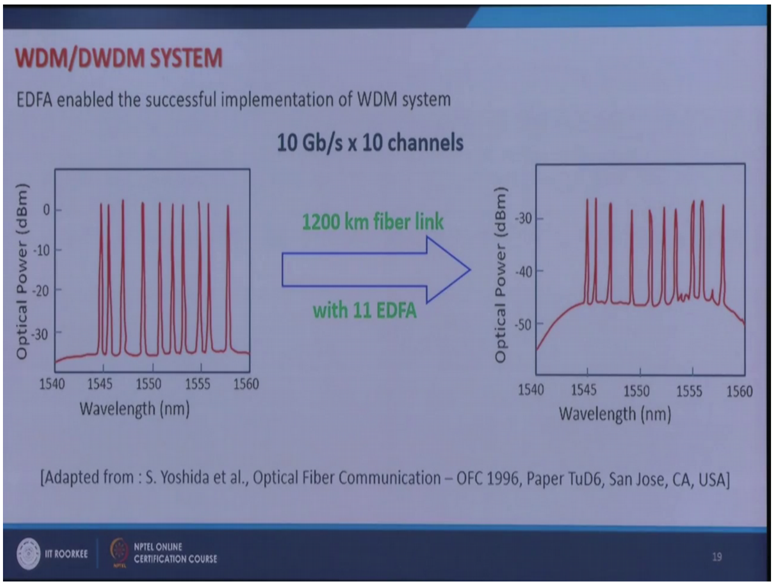

Then we have if I come to the system then we can sense several wavelengths in the fiber and each wavelength can carry data independently. So, we can have a wavelength division multiplexed system and erbium doped fiber amplifier EDFA has enabled the successful implementation of this WDM system and increase the data rate of a given fiber many folds, this is a typical WDM system which gives you a data rate of about 10 Gbps through a single fiber link of 1200 kilometer.

It employs 11 EDFA in between.

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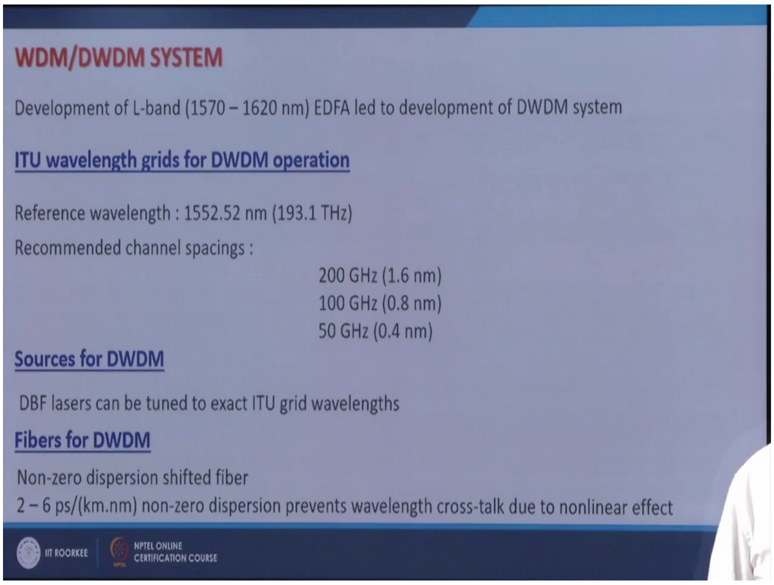

You can further increase the data rate if you have more and more wavelengths, if you squeeze more and more wavelengths in a fiber and with the development of l band EDFA which extended this wavelength range itself into this region also 1570 to 60 1620 nanometer wavelength range, then it LED to development of DWDM system dense wavelength division multiplexed system.

Then ITU wavelength grids for a DWDM operation are given by reference wavelength 1552.52 nanometer which is about 193.1 terahertz and recommended channel spacings are 200 gigahertz which is approximately 1.6 nanometer 100 gigahertz corresponding to 0.8 nanometer and fifty gigahertz corresponding to 0.4 nanometers, these conversion are based on reference wavelength or 1550 nanometer.

So, you have you have ITU recommended wavelength grid to to keep the standards and now there are sources for DWDM system where you have DFB lasers which can be tuned to exit ITU grid wavelengths. Now, what are the fibers for DWDM? Should we worry about fibers for that can be used for DWDM, yes we should because when you are squeezing a large number of wavelengths in a single fiber and each wavelength carries signal. So, basically you are pumping lot of power into the fiber, it increases the power density and gives rise to non-linear effects. So, we should have a fiber which can avoid non-linear effects and to avoid non-linear effect we should have 2 things, one is that I should have large mod area another is that I should not allow the phase matching condition to be fulfilled for various non-linear effects.

So, in order to avoid this fulfillment of phase matching conditions if I have certain non 0 dispersion, you remember that ideally I should have 0 dispersion, but if I have 0 dispersion then all the wavelengths which I am pumping in will start across stop because of non-linear effects because, phase matching condition would be satisfied then because dispersion is 0. So, I should keep certain minimum dispersion which is non0 and at the same time I should have large effective area. So, there are certain fibers which have been developed which are non 0 dispersion shifted fiber. So, so you have non 0 dispersion shifted fiber. So, dispersion minimum dispersion wavelength is shifted now to 1550 nanometer band from 1310 nanometer band and minimum dispersion is not 0 it is about 2 to 6 picoseconds per kilometer nanometer to prevent non-linear effects.

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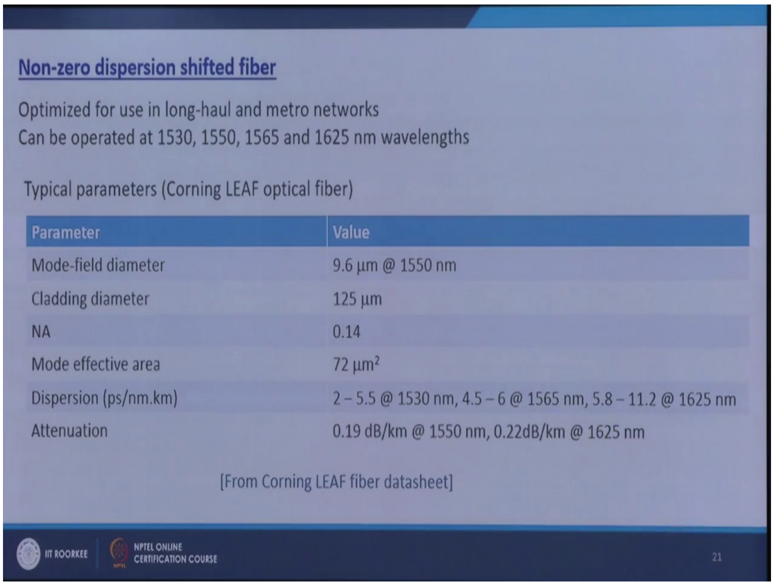

So, this is a typical non 0 dispersion shifted fiber which is optimized for use in long haul and metro networks, it can be operated at 1530, 1550, 1565 and 1625 nanometer wavelengths and here I have listed typical parameters of corning large effective area fiber it is non0 dispersion shifted fiber which has mode field diameter 9.6 micrometer at 1550 nanometer wavelength, cladding diameter 125 micrometer, numerical aperture 0.14 effective area of the mode 72 micrometer square and it has got dispersion about 2 to 5.5 at 1550 1530 nanometer wavelength. 4.5 to 6 at 1565 nanometer wavelength, 5.8 to 11.2

at 1625 nanometer wavelength. If I look at attenuation it is 0.19 db per kilometer loss at 1550 nanometer wavelength and 0.2 to db per kilometer loss at 1625 nanometer wavelength, it is popularly known as corning leaf fiber.

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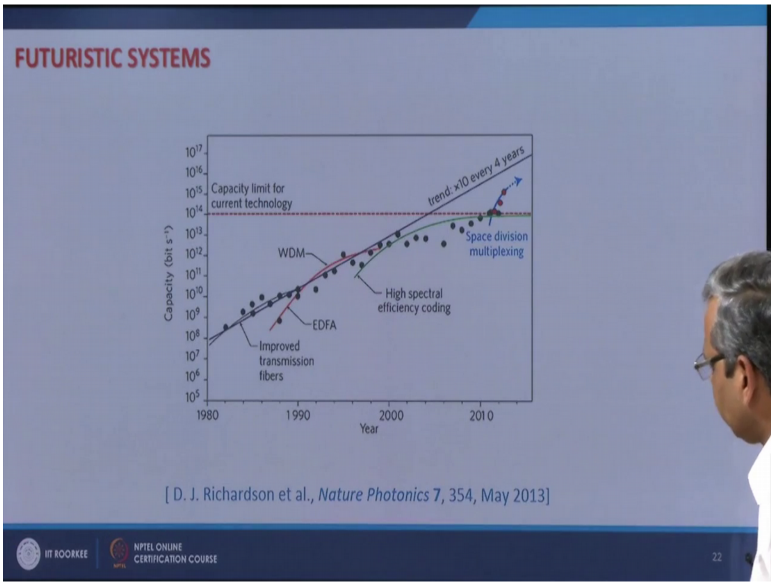

Now, what we are looking at now where we are heading, to understand it I am here presenting a view graph from a paper which is published in nature photonics in 2013 by Dave Richardson at all where this view graph shows how the capacity of optical fiber telecommunication system has evolved over time. If you look at it this blue line shows that the capacity of an optical fiber communication system becomes 10 times every 4 years and this is started this strength started with the improvement in the transmission of optical fiber in initial years of development of fiber optic communication system.

Then later on this trend could be maintained by the development of EDFA and WDM system then after 2000 year 2000 people tried to maintain it by high spectral efficiency coding, but now we have approached to this limit which is about 100 tbps, which is the capacity limit of current technology we have where we have utilized everything high spectral coding DWDM everything. So, now, if I want to keep up with this trend then we will have to do something new, otherwise we would not be able to meet the demand of bandwidth. So, a new kind of system and new fibers are coming up and this system is a space division multiplexing.

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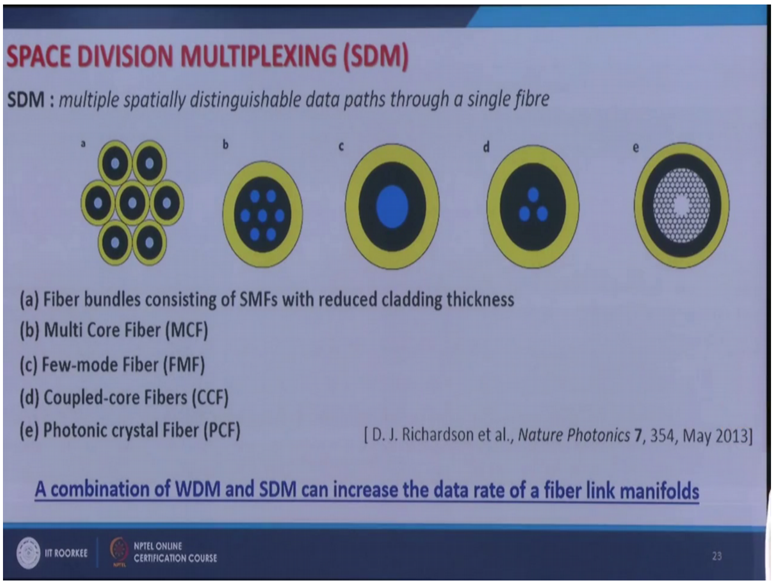

This is again from the same paper in nature photonics.

We have this they have proposed this, they have summarized the, they have summarized the developments in SDM system. So, where people are now looking at multiple is spatially distinguishable data paths through single fiber. So, apart from now wavelength division, now people are looking at space division multiplexing and these can be achieved through various routes. One is you can have fiber bundles consisting of several single mode fibers with reduced cladding thickness, but there is problem of compactification in this kind of approach, then people are using multi core fiber where you have multiple codes sharing the same cladding.

So, here you will have to take care of the cross talks between different codes then there is few more fiber, there are different modes of the sys of the fiber itself can work as independent data channels so, but there you will have to take care that there is no exchange of information between the 2 modes and this is taken care of by mimo, multi input multi output technology then you can have coupled core. So, where you have for example, 3 cores and they made the super they make the super modes of the system and each super mode can carry data independently and then people are also looking at photonic crystal fiber where you have a fiber you have a fiber in which holes, air holes run throughout the length of the fiber. So, there is a periodic arrangement of holes in the silica material.

So, this this gives you a band gap, you know in solid you have periodically arranged atoms and it gives you an electronic band gap, here you have periodically arranged holes and it gives you a photonic band gap. So, this is known as photonic bandgap fiber. So, in this kind of fiber if you have photonic band gap here and you create a defect here that is you remove periodicity periodic arrangement from here. So, this excess defect site if you launch light into this defect because the light sees band gap everywhere then light is confined in this region. So, this is photonic crystal fiber you can make hollow core fiber art of it where there is no material. So, there is dispersion very less loss.

So, people are looking at all these possibilities and it is envisaged that a combination of WDM and SDM can increase the data rate many fold. So, at this node I finish the course and thank you very much for being a part of this course and if you have any further queries I can always be reached at this email.

Thank you very much.