Nature and Properties of Materials

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Lecture 34

Optical Fiber

Today we are going to talk about one of the beautiful applications of the optical properties of the materials, which is in the form of optical fibers. Optical fibers has become our everyday experience today and hence let us put our focus on the optical fiber.

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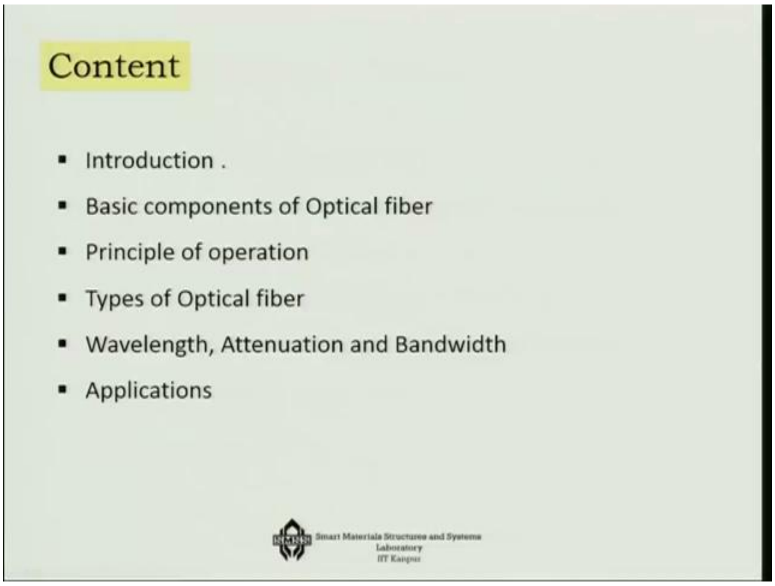

So this is the path we will go, we will first give an introduction, we will talk about what are the basic components of optical fiber, we will talk about the principle of operation, the types of optical fiber, then its wavelength, attenuation and bandwidth and finally some applications of the optical fiber.

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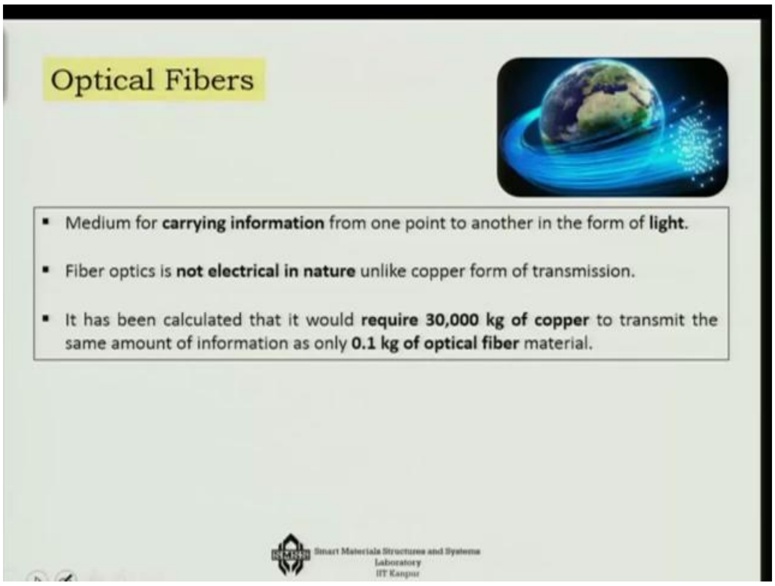

In today's world, the biggest revolution that has taken place is that if you compare to the earlier part of the 20th century, where the information used to be carried in the form of electrical signals. In comparison to that today most of the places, the information are carried in the form of light, which is a very big very-very big advantage because if you think of the speed of light, it is similar orders of magnitude higher than the speed of the electron and through the conductive wires and consider the losses, everything this is a very-very efficient way of transferring the information.

It has been calculated that it would require about 30,000 KG of copper if you want to say send the same amount of information through optical fiber it will be only 0.1 kg okay. So, imagine that 0.1 kg of optical fiber is equivalent to 30,000 KG of copper. And I told you earlier also that in terms of the availability of the resources copper is very-very limited, and hence how much green our world has become because of the optical fibers that one tenth 100 kind of or one tenth kg of optical fiber can actually substitute 30,000 KG of copper okay, so that is the one of the biggest contribution of the optical fibers.

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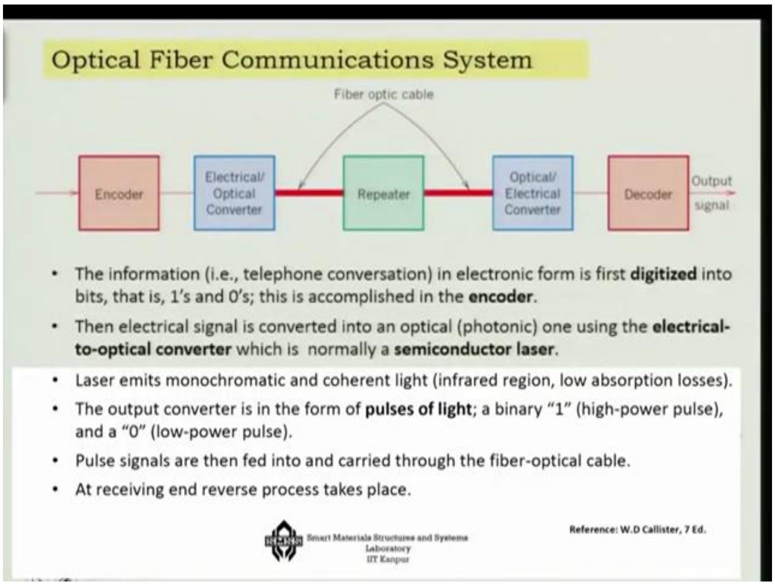

Now, how does communication takes place in a optical fiber-based system? In order to carry, first of all we have to keep in our mind that optical fiber has to carry the signal in the form of light and if you think that you need a 1 0 type of encoding system, then it has to be in the form of pulses of light. Now, so that what it means is that you first need to actually convert the electronic form in a digitized form, so that is what is the role of the 1st part which is the encoder. So what it will do, this information in electronic form will be digitized in the bits of 1's and 0's, so any information can thus be digitized in the encoder.

Then you have to have, corresponding to these 1's and 0's of electrical signal, you have to generate the pulses of light and that is done by a electrical to optical converter, which is normally a semiconductor laser, so this is the electrical to optical converter. Now once you have converted it, your signal is now in the form of a laser which will emit monochromatic and coherent light that means that light will be of a single frequency in most of the cases although there are some applications today of multiple frequencies and it will be coherent that means there will not be phase difference between the individual light signals.

So hence it will take the information in a very cohesive manner for a very long distance. In between you may need repeaters whose job is just to relay the same information than other days good old days there used to be relays for electrical systems in which the same electrical data is to be actually boosted up and then sent through another cable, so that the loss can be compensated. The same thing is done here with the help of repeater and then from repeater at the other end, it is coming to an optical to electrical converter.

And now the signal is in electrical form, so now you need a decoder for that and then from the decoder you get the output signal, so at the receiving end this reverse process happens and finally you get the output signal, so that is how the optical fiber communication system works. Now, what exactly is the composition of the optical fiber?

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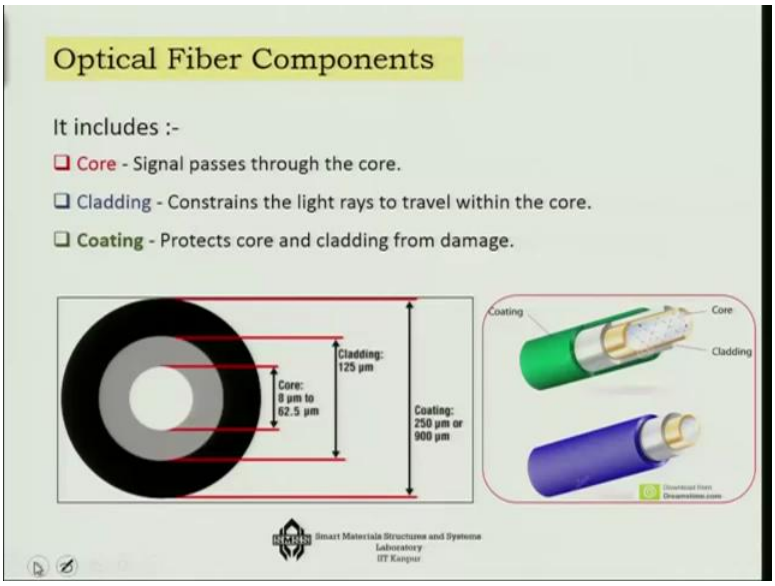

If you look at the optical fiber take a cross-section, you will see that at the very core, there is something which is about 0.8 micrometer to 62.5 diameter of the core that is there, which actually process the signal so that is the core part. Then on top of the core there is the cladding which is about 125 micrometer and on top of the cladding there is a coating which is 250 micrometer to 900 micrometer, so it is a 3 layered structure core, cladding and coating.

Core posses the signal, cladding constrains the light, it has a role in terms of creating total internal reflection, I will explain that in minute, but cladding constrains the light rays and coating protects both core and cladding from damage because that fiber-optic is made of various types of glassy materials and some of them are brittle in nature. So during handling there may be fracture. If there is fracture then all the optical property will be loss, there will be loss of signal, so hence coating has a very-very important role.

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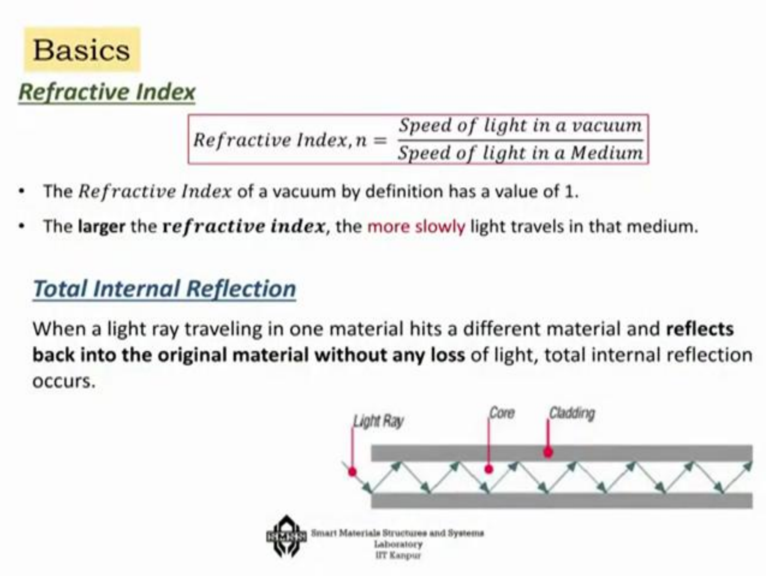

Now, how this cladding is able to contain the signal inside the core? To know that, we have to know a little bit of the basics of refractive index. In the last lecture also I told you that the refractive index n is defined as the ratio of speed of light in a vacuum and speed of light in a medium. So the refractive index of a vacuum by definition has a value of unity in the sense that it is the speed of light. Now, when we are going to a medium then the refractive index is actually larger and the more the refractive index is, more slowly light travels in that medium.

So essentially larger refractive index is actually denser medium and denser medium means you are, the light is getting more resistant and hence it is getting less amount of so to say in terms of you compare that like in a road with a huge traffic jam, so you would not able to move very fast so exactly like that to get a path to move is difficult and hence, light travels more slowly if the refractive index is more.

When a light ray is travelling in one material that has a different material and then depending on the refractive index it is possible that it reflects back into the original material without any loss of light. So that means it goes here but because of certain refractive index condition, it does not go inside this but it actually gets reflected from the surface and then this continuously happens and this is what exactly what happens in the optical fibers. Now, why this happens?

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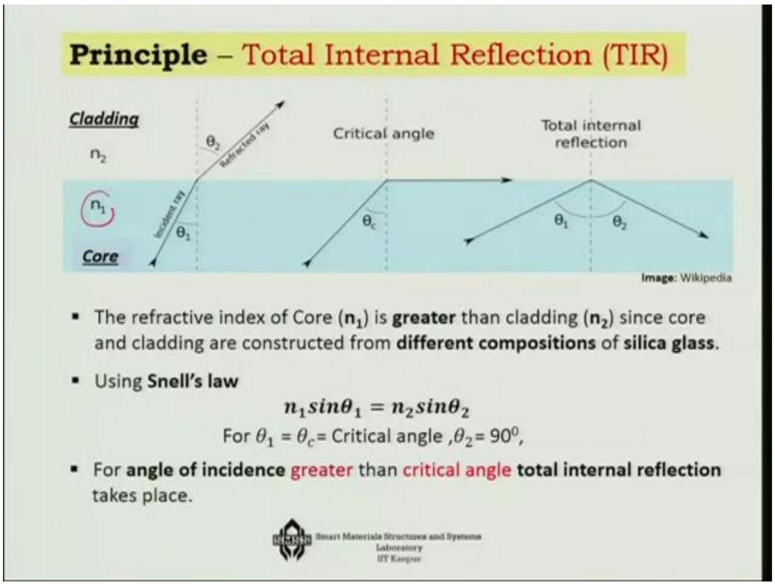

You consider that you have a core which has refractive index n 1 and you have a cladding which has refractive index n 2. So n 1 is generally greater than n 2, this is very important okay, so the medium is chosen in such a manner that refractive index of the core is greater than the refractive index of the cladding. So if the refractive index in the core is actually greater, what do you expect? You expect that because the other medium is rarer hence the main free path will be more and hence light will be deviated more from the normal, so it is deviated more, so this is interesting.

So that means if n 1 is greater than n 2, then theta 2 will be actually greater than theta 1, that immediately brings us to the question that what if I change the theta 1 in such a manner that theta 2 becomes 90 degree that is possible very much in fact, that is what is known as the theta critical. If I further increase the theta 1 greater than the theta critical suppose this is what is my theta critical and I have further increased it, then the light will not simply go into that cladding medium but it will get reflected inside, which is what is the total internal reflection that takes place.

So both the core and the cladding for the optical fiber system, they are made of silica glass but of different composition such that in one it is denser and the outer side it is actually more rarer the medium it is. Now, using the Snell's law you can also find out that what has to be this n 1. Suppose, I know n 2 and what is my theta 2 is say 90 degree is this case of critical angle, here this angle is known to you that it is 90 degree, so theta 2 is known to me and then I can find out theta 1 or I can find out n 1 either of them that suppose n 1 is known to me, then theta 1 will be simply sine inverse n 2 over n 1.

So that means you will know at which angle the ray is to be inserted into the optical medium that is a very important point, we will later see that there is a cone angle beyond which it actually does not work, so it has to so that the total internal reflection takes place. So angle of incident has to be greater than the critical angle for total internal reflection to take place that is the condition that brings us to the acceptance cone.

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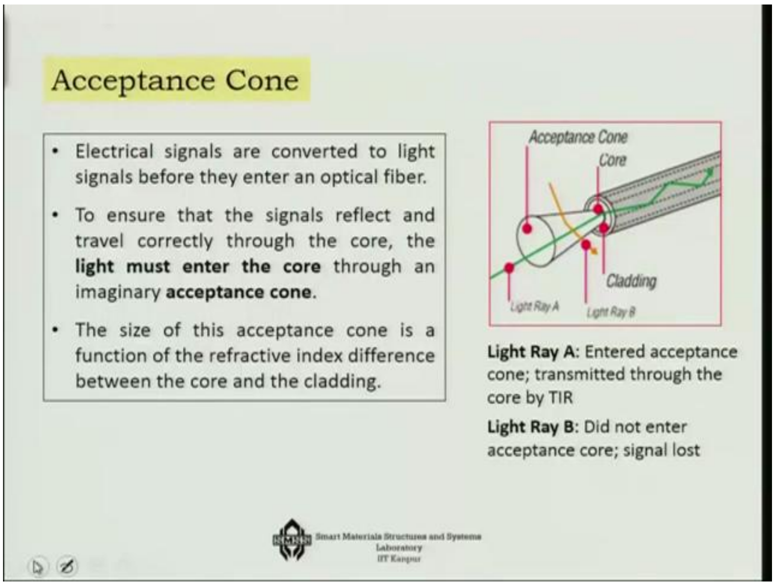

Because the electrical signals are converted to light signals just before they enter the optical fiber, now to ensure that the signals reflect and travel correctly through the core, the light must enter the core through an acceptance cone okay, because if the angle is more than the light will not be able to go inside the system and it will be lost, so it is the function of the refractive index difference between the core and the cladding.

This is something that is very important for example, you can see here the light ray A entered acceptance cone transmitted through the core by total internal reflection that is what is this light. But light ray B cannot enter the acceptance cone and hence that particular signal is actually lost, so which is the outside of the system any such light ray that we have drawn, so that is the acceptance cone.

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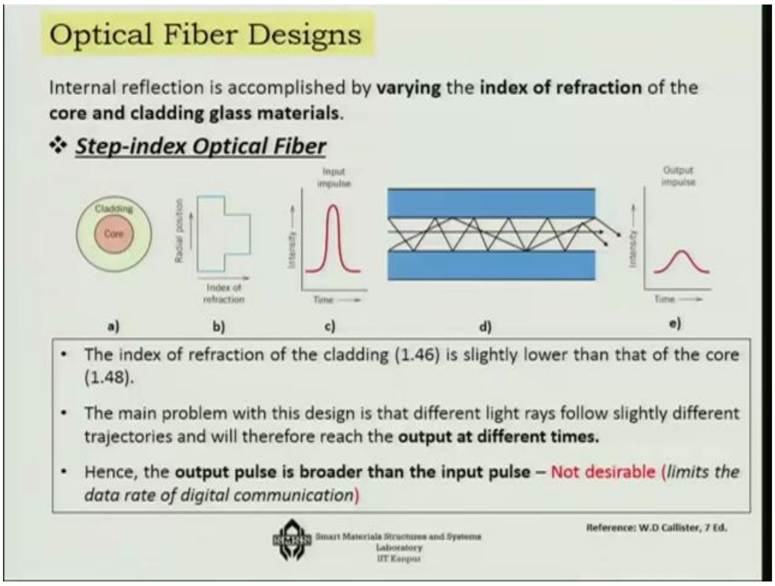

Now, we are going to discuss about the optical fiber designs. There are various designs possible; one of the simplest designs is the step index optical fiber as you can see it here, step index optical fiber design. And what it means is that between the core to cladding, there is just a step jump like this. Now the problem with the step index is that in this case refraction of the cladding is of course slightly lower than that of the core that is fine and otherwise you know, so it is 1.46 and another core is 1.48 otherwise, the total internal reflection will not take place.

But the problem here is that with this design, different light rays follow slightly different trajectories and will therefore reach the output at different times. You consider some light which is going straight okay and some light which is going through the total internal reflection, naturally, this will be slightly later than the earlier one, so this slight delay will create actually from the if this is what is my input impulse, it would look like this. That means the the output pulse will be broader than the input pulse, which is not desirable because if this happens, it actually limits the data rate of digital communication.

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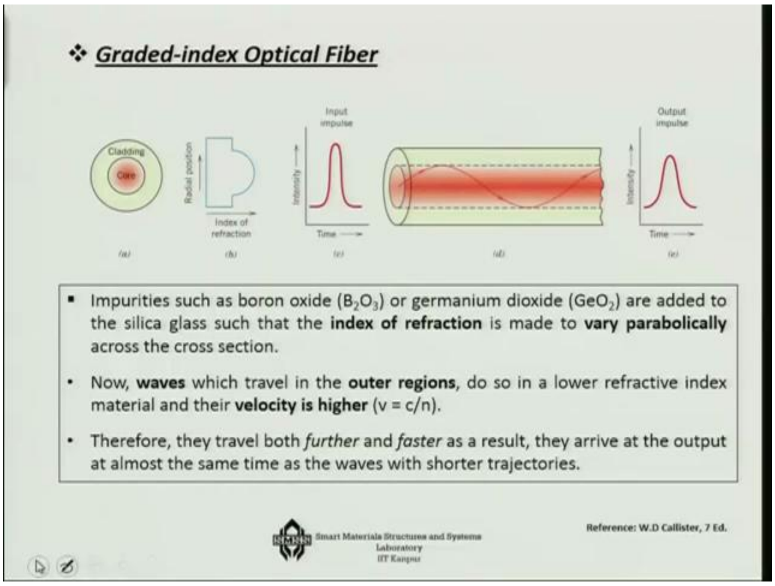

So hence today, slightly more kind of a complex design of optical fiber has come half in which this variation is not stake, but rather in this kind of a form of parabolic variation and this is done with the help of impurities such as boron oxide or germanium dioxide, which are added to the silica glass such that the index of refraction is made to vary parabolically across the cross-section.

So if it happens parabolically, then waves which travel in the outer region do so in a lower refractive index material and their velocity is higher and those which are in the inner, their velocity is small so as a result you are getting the same nature of the input and output pulse, so that broadening of the pulse does not takes place, so that is the better part of the graded index optical fiber. Now, there are 2 different types optical fibers you will see.

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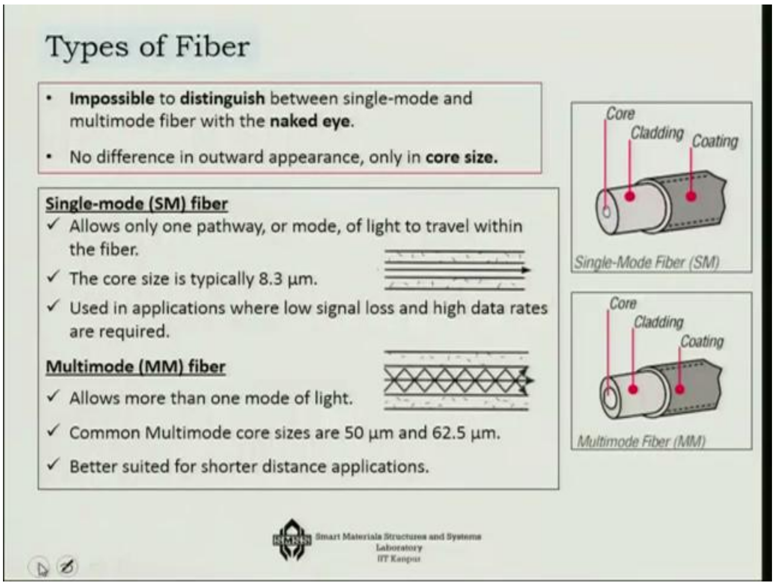

There are 2 different types optical fibers and which you may not be able to actually distinguish with the naked eye, but it is actually if you can see it with the help of a magnifying glass, you will see the difference. In one case it is a single mode SM fiber, this allows only one pathway or mode of light to travel within the fiber, the core size here is typically about 8.3. So this is applied for cases where you need a very low signal loss and a high data rate required let us say for encrypted cable signal for science security, bank Security signals, etcetera.

However, there is more common multimode fiber and here it has more than 1 mode of light and then the core size is more, it is like 50 to 62.5 micrometer, so earlier case it was 8.3 micrometer and this is better suited for short distance applications and it carries more information with a less data rate this is something and it is cheaper also, so this is something that goes as a multimode fiber. So single mode fiber and multimode fiber, these are the 2 different types.

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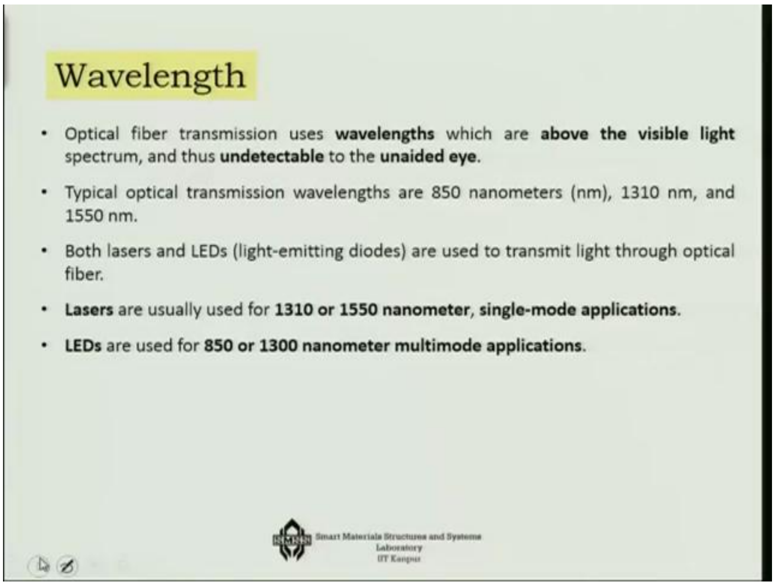

Next is the wavelength. Optical fiber transmission uses wavelength which are above the visible light spectrum and thus undetectable to the unaided eye. And I told you that typical optical transmission wavelengths are 850 nanometer and 1310 nanometer and 1550 nanometer. Both the lasers and LEDs light emitting diodes are used to transmit light through the optical fiber. And lasers are usually used for 1310 and 1550 nanometer in single mode applications whereas; LEDs are used for 850 or 1300 nanometer in multimode applications. So LEDs when you use, it is slightly cheaper but lasers are more expensive and they are used for single mode applications for the highest quality of the data rate.

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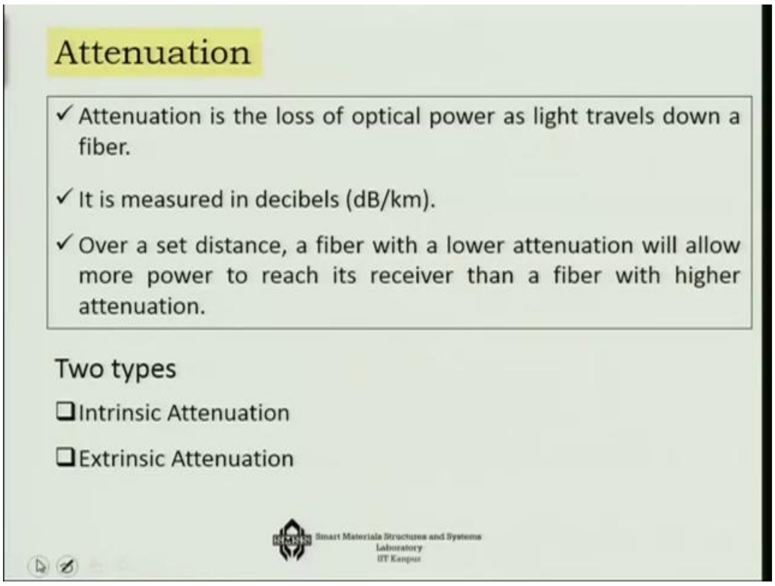

Even then, the attenuation would take place which is the loss of optical power as the light travels down a fiber. There can be many reasons for this for example, the cladding there are defects in the cladding, so the light may pass through that, so this loss is measured in decibels dB per kilometer. Over a set distance, fiber with a lower attenuation will allow more power to reach its receiver than a fiber with higher attenuation. Now there are 2 types of attenuation, one is called intrinsic attenuation another is called extrinsic attenuation.

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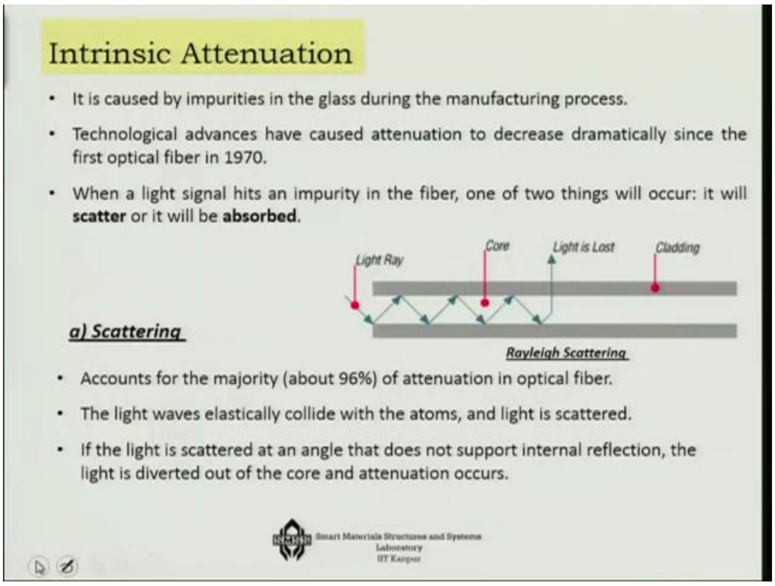

Intrinsic attenuation is caused by the impurities in the glass during the manufacturing process itself. The technological advances have caused this manufacturing defects to come down, so this attenuation to decrease dramatically in the first optical fiber in 1970, today we get a much better one, so much less intrinsic attenuation. When a light signal actually hits an impurity in the fiber one of 2 things will occur, it will either scatter or it will be absorbed. So if it scatters, this accounts for the majority about 96% of attenuation in the optical fiber.

Then the light wave elastically collides with the atom and light is scattered. And if the light is scattered at an angle that does not support internal reflection, then the light gets diverted out of the core and hence the attenuation would occur. So scattering me disturb that critical angle constraints so that is and that can happen through the impurities.

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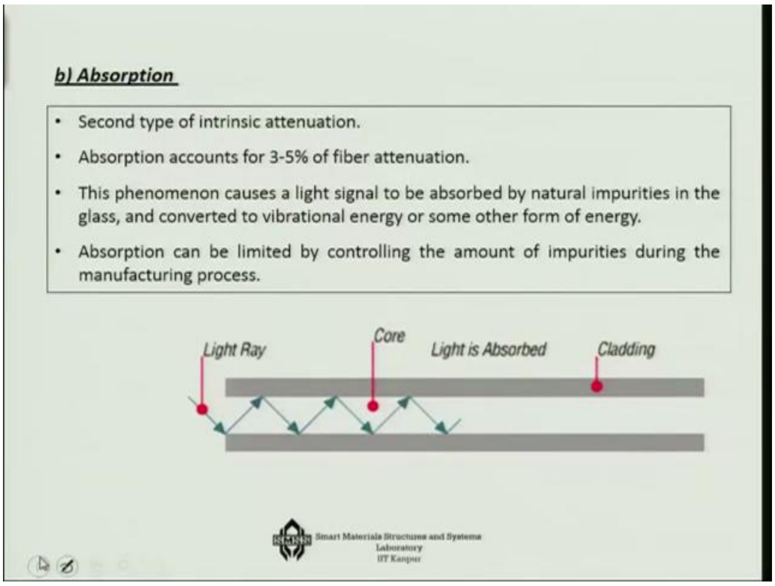

The other intrinsic attenuation problem is due to absorption. The absorption accounts for about 3 to 5% of the fiber attenuation. In this case, light signal is absorbed by natural impurities in the glass and converted to something like vibration energy or similar other form of energy. Absorption can be limited by controlling the amount of impurities during the manufacturing process. So in one case, it does not support the total internal reflection due to scattering, in the other case it simply transformed the energy from light energy to some other energy, so these are the intrinsic attenuation.

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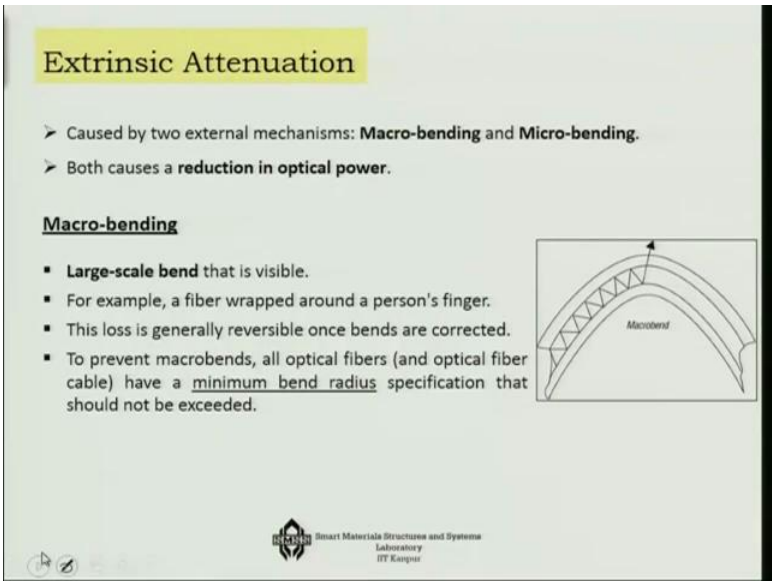

Now what happens in the extrinsic attenuation? There are 2 external mechanisms of extrinsic attenuation; one is called macro-bending and another is called micro-bending, both of them cause a reduction in optical power. In case of macro bending, large-scale these are like large-scale bend that is visible type. So for example, fiber is wrapped around a particular area, the loss is generally reversible once the bends are corrected.

To prevent such macro bends, all optical fibers have minimum bend radius specification because if you bend it more than that, then what happens is the light through a ray can actually escape, so this macro bending can be prevented by maintaining the minimum bend radius for the reduction of the extrinsic attenuation.

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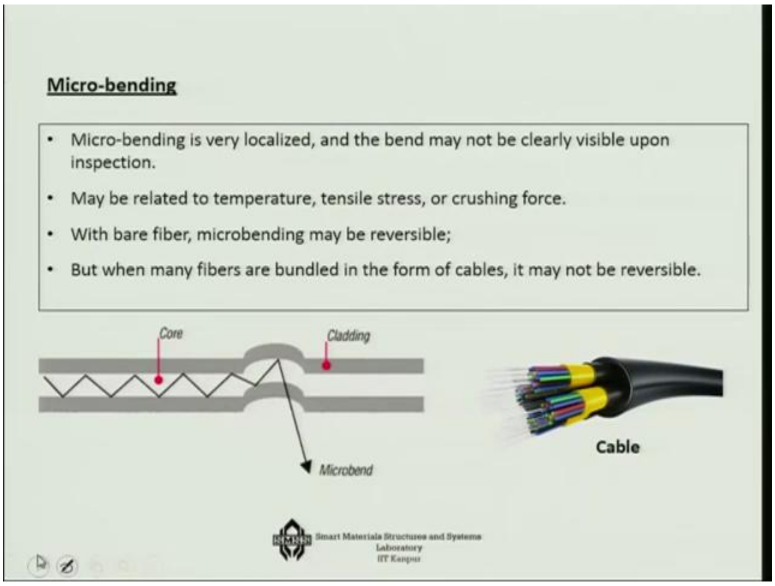

Micro-bending on the other hand is very-very localised like suddenly there is a bending in the cladding here and this may not be clearly visible upon inspection. It may be related to temperature, tensile stress or crushing force, etcetera. And with bare fiber, micro-bending may be reversible but when many fibers are bundled in the form of cables like this, then micro-bending are not reversible, you cannot make it straight, so you have to allow that much of loss of signal in the micro-bending part of it.

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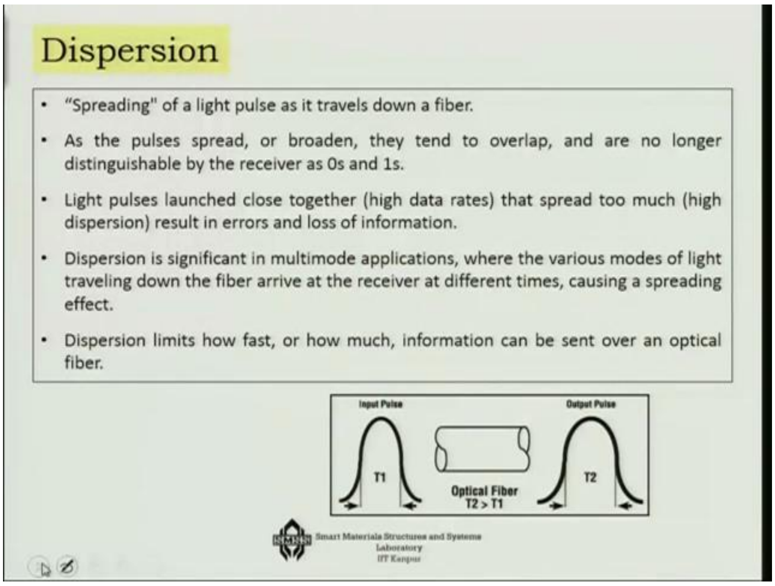

So the 3rd problem is the problem of dispersion. This is the spreading of a light pulse as it travels down a fiber. As the pulses spread or broaden, they tend to overlap and are no longer distinguishable by the receiver as 0s and 1s. Light pulses launched close together high data rates that spread too much result in errors and loss of information. Dispersion is actually significant in multimode applications, where the various modes of light travelling down the fiber arrive at the receiver at different times causing a spreading effect. Dispersion limits how fast or how much information the typical baud rate can be sent over an optical fiber.

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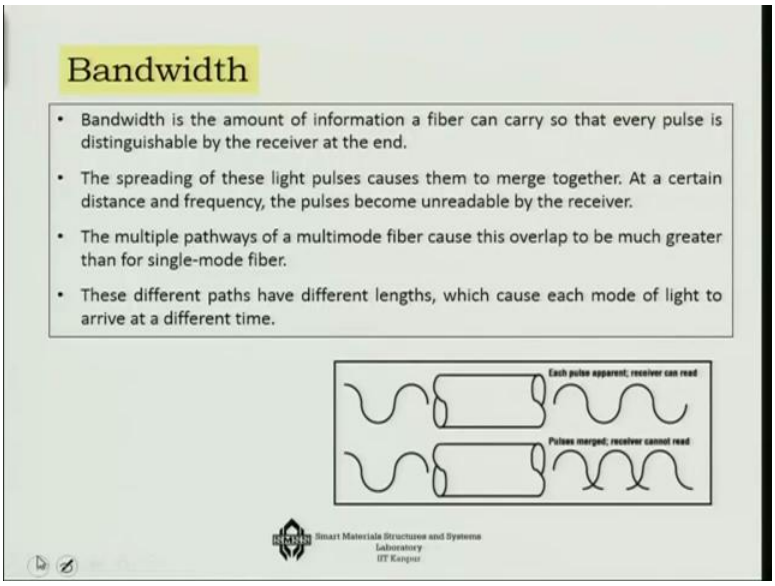

Then there is a question of bandwidth, this refers to the amount of information a fiber can carry so that every pulse is distinguishable by the receiver at the end. The spreading of this light pulse actually causes these things to pulses to merge together. At a certain distance and frequency, the pulses may become unreadable by the receiver in fact, that is why you will need the repeater. The multiple pathways again with a multimode fiber cause this overlap to be much greater than for a single mode fiber. These different parts have different length, which cause the mode of light to arrive at a different time, so you need a repeater to avoid this problem.

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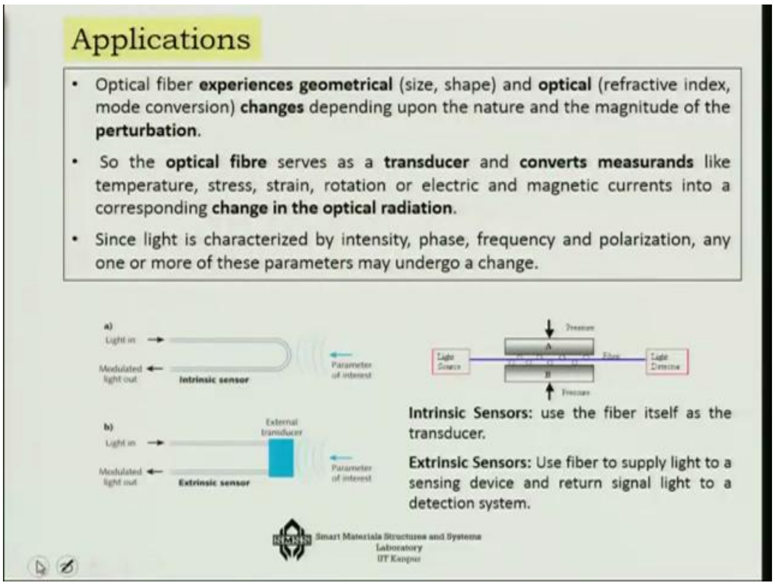

Next is in terms of the applications. Optical fiber experiences geometrical change and optical changes, so size and shape or refractive index or mode conversion depending upon the nature and the magnitude of the perturbation. So it can work like a sensor, like a transducer, which can convert the measurands like change in temperature, change in stress, strain, rotation, electric or magnetic current into a corresponding change in the optical radiation. So suppose I am sending a light in and I am getting our light out and there is a change in parameter of interest in between, so as a result this will become an intrinsic sensor.

The other thing is that, you take the light in and there is an external transducer which notes the change and you get it back again through the extrinsic sensor, so these are the 2 types that is the intrinsic sensor where the fiber itself is used as transducer and extrinsic sensor which use fiber to supply light to a sensing device and return signal light to a detection system, these are the 2 different types of applications of optical fiber. So this is where we are going to close on optical fiber and in the next lecture we will learn about the thermal properties thank you.