Fiber Optics

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Lecture - 04
Salient features of optical fiber – II

In the last lecture we had understood the propagation characteristics or light guidance in an optical fiber using ray theory. We had seen that using ray theory we can explain the light guidance in terms of successive total internal reflections. We have also seen that only a particular guidance cone is possible, which has a maximum light acceptance angle. So, only those rays which fall in this light guidance cone are guided, but in ray theory there are certain limitations, these limitations are number one when we go down to the fiber co dimensions which are comparable to the wavelength of light, then ray theory does not work it is not valid. So, if we talk about telecom fiber which has co dimensions of about 10 micron diameter. So, our ray theory would not work.

Second thing is there are certain intricacies of light guidance, which ray theory cannot explain in these intricacies, one is that when we launch light into an optical fiber, then light basically propagates or the light guidance in an optical fiber can be understood in the form of certain modes of propagation. These modes of propagation correspond to certain discrete angles, at which the light should be launched into the fiber, and these modes are discreet ray theory cannot explain these discrete modes.

Another thing is that when light propagates in an optical fiber, in certain amount of light also extends to the cladding. So, how light penetrates into the cladding region, ray theory is not able to give insight into that also. See in order to understand more accurately the light guidance in an optical fiber, we should resort to a more accurate theory and that is wave theory. So, in this lecture we will extend our understanding of light guidance in an optical fiber to wave theory.

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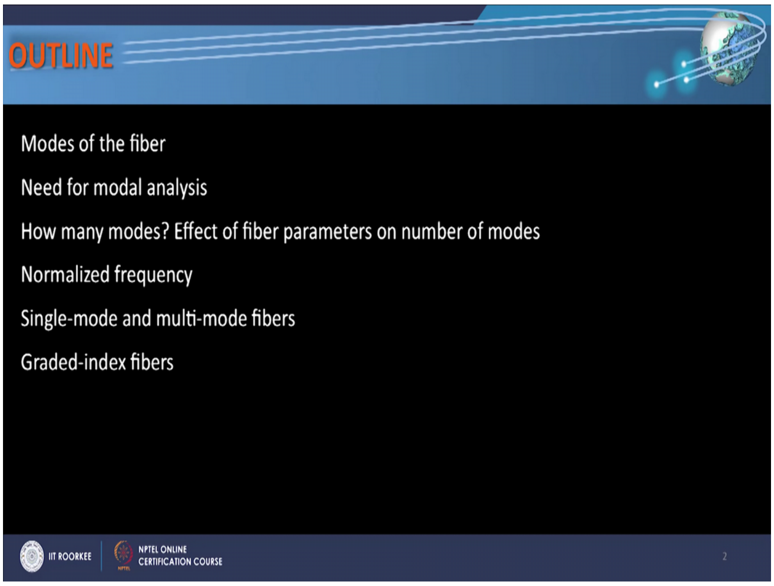

So, the outline of this lecture is in this way let first we will understand what is the meaning of modes of an optical fiber, and why after all we need to understand modes of an optical fiber what is the necessity for modal analysis of an optical fiber. When a natural question arises how many modes of fiber supports, and is they are some bearing on the number of modes on fiber parameters, and also it what would be the effect of fiber parameters on the number of modes possible in an optical fiber. We will also see that we can integrate all the parameters of the fiber and the wavelength of light into a single parameter, which is known as normalized frequency. Then we will try to understand what are single modes and what are multimode fibers and then graded index fibers.

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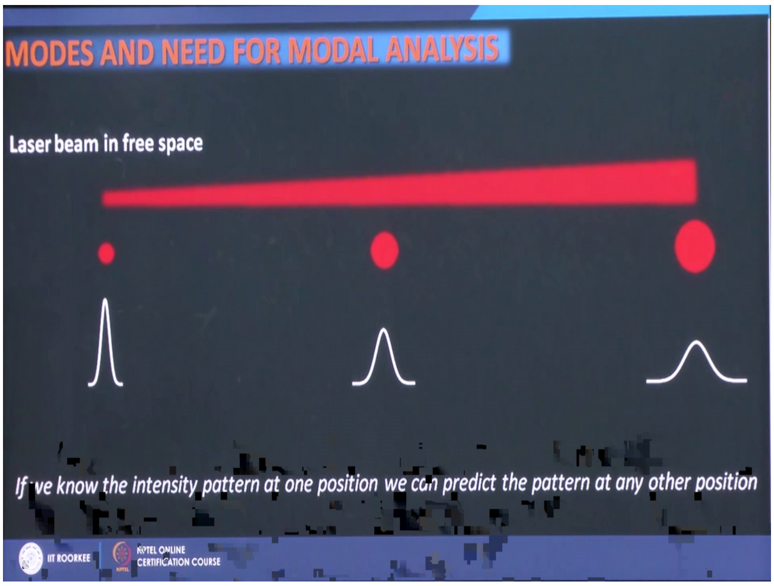

Let us first understand modes for that let me first take a laser beam a typical beam from a laser pointer for example, or typical beam from a single mode helium neon laser. If I look at this beam here when it just exits from the laser this spot looks like this, if I capture this beam just at the exit of this laser as soon as it comes out then this spot looks like this. And if I see how the intensity of this spot varies along a diameter it looks like this.

Now I like it propagate over a large distance and then after few meters I intercept this beam, then I see that the spot size has become a big bigger now and this is how the intensity profile would look like. If I go even further the spot size becomes even larger and the beam looks like this, and if I know the intensity pattern here I would be able to tell what would be the intensity pattern here or there, I know how this beam of light propagates in a medium.

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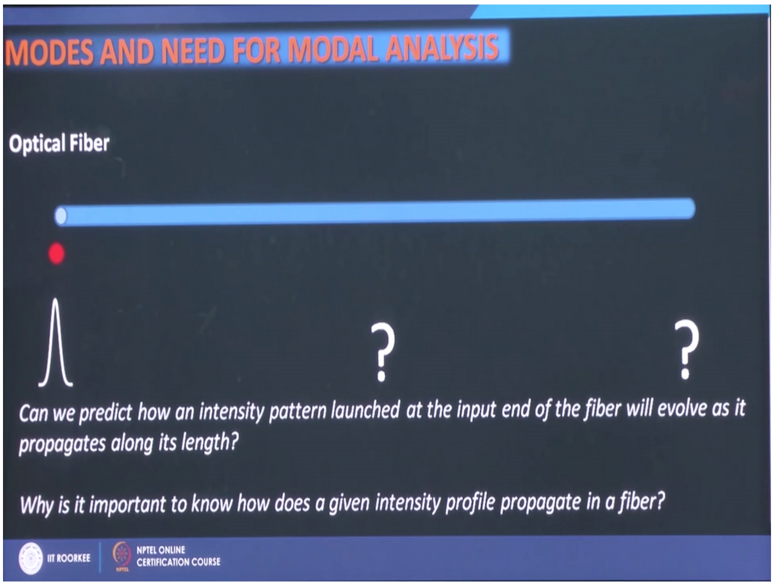

But if I have in the same way an optical fiber and I launch that laser beam which is not optimized perhaps for this fiber, I just take any laser beam or any intensity pattern and I launch it into this input end of the fiber. Then can you predict how would this intensity pattern change as it will go along the fiber or would it change at all or not, how would this propagate, how would this intensity pattern evolve as it goes along the length of the fiber, and another question is why after all it is important to know how does this intensity profile propagate in this fiber. Why it is necessary to know the evolution of intensity pattern in the fiber.

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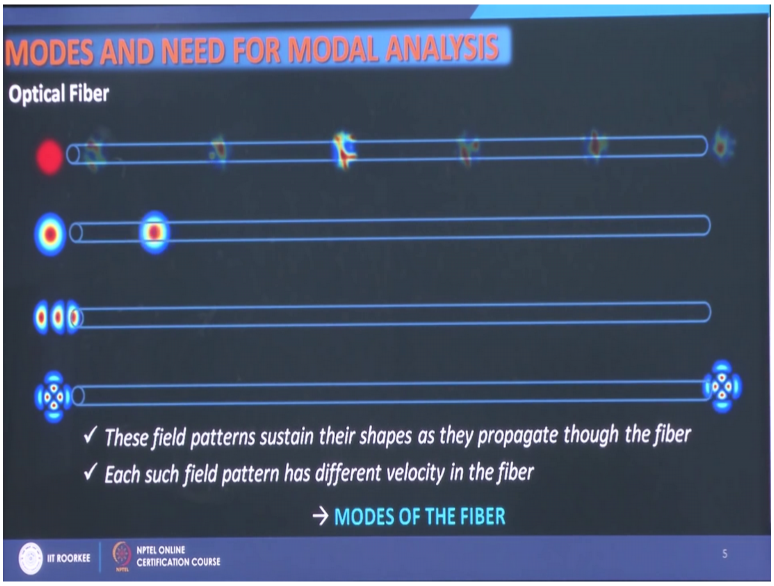

So, let me see how does it happen, these are some stimulated patterns. See if I launch some arbitrary intensity pattern in the fiber and I capture that at different lengths of the fiber, then I see that these intensity patterns at different lengths do not have any correlation with another. However, if I launch this particular intensity pattern in the fiber then what happens did it goes as it is, it does not change its shape similarly another one like this and yet another one. So, what I see that here are certain intensity patterns and corresponding amplitude patterns, which are sustained when they propagate through the fiber, their shapes do not change. And I also find out that each of such field patterns has certain definite velocity, and the velocities of different patterns are different. And I call these I call these field patterns which are sustained throughout the length of propagation of fiber as modes of the fiber.

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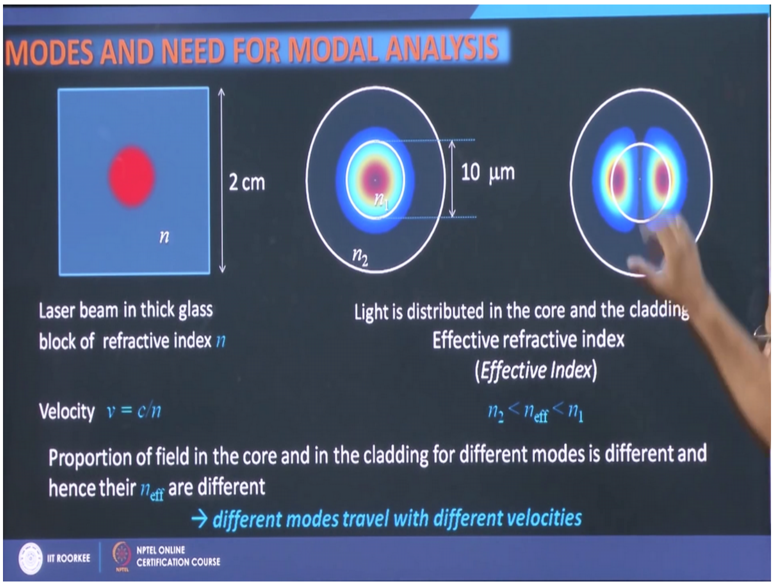

Now, let me take a laser beam and send it through a thick block of glass, which is let us say 2 centimeter by 2 centimeter block of glass and this laser beam has dimensions maybe 5 millimeter across and the refractive index of this class is n. Then I know the velocity of light in this block of glass of refractive index n can be given by c by n. We are c is the velocity of light in free space. My question is if I have a certain field pattern which is propagating in the fiber, what velocity would it have. So, let u see that.

This is a transport stop section of a fiber we are the core is 10 micron across and then you have a cladding, and this is one intensity pattern which I launch into this fiber, and which is the mode. So, it sustains its shape as it propagates, what do I see here that certain part of the intensity extends into cladding. So, this some proportion of power in the core and some proportion of power in the cladding, unlike in this case where the whole spot is in the refractive index region n, but here it is distributed in the regions of refractive indices n 1 and n 2.

So, what would be the velocity what would be the effective refractive index it would see intuitively I can say that the refractive index that this field pattern will experience would neither be n 1 nor it would be n 2, but it would be somewhere between n 2 and n 1 and this effective refractive index felt by or experienced by this particular shape is also known in short as effective index. So, from now onwards I will just call it effective index and I represent it by n effective. So, this n effective lies now between n 2 and n 1 and I know that there are different such patterns, and for different patterns or different modes the proportion of field in the core and in the cladding is different, and that is why they would experience different effective refractive index of this composite medium or they should have different effective indices. So, different modes would now travel with different velocities, they will have different effective indices, they will have different propagation constants.

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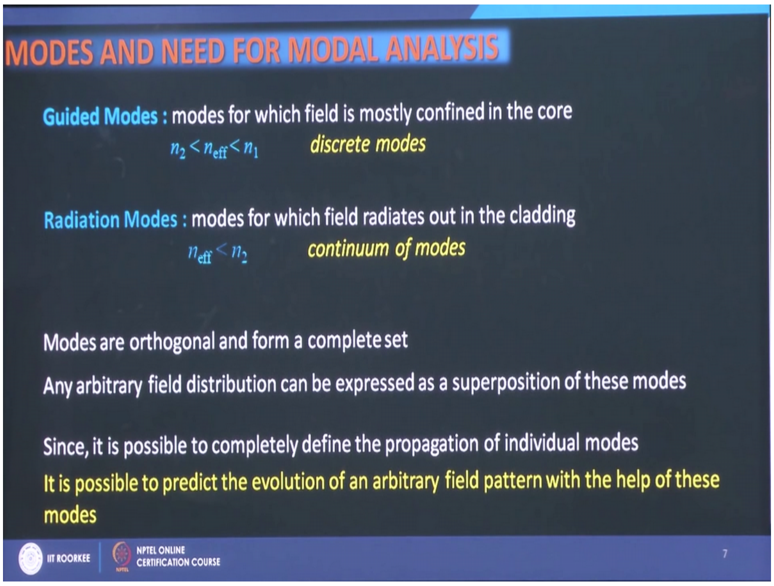

So, in a fiber these kind of intensity patterns I have seen that they extent to cladding, but energy does not propagate out up to infinity into cladding. The energies still guided in the core, it certain part of the energy is only extended to the cladding and these modes are called guided modes of the fiber, and for these modes n effective lies between n 2 and n 1, and there are only certain discrete patterns certain discrete field patterns. So, these are discrete modes.

Apart from these there are certain modes which carry energy in the cladding up to infinity. So, energy radiates out these modes are called radiation modes and for these modes the effective index or n effective is less than n 2 and they form a continuum. So, they are continue of modes radiation modes, they are not discrete; and what I also see is that these modes are orthogonal and they form a complete set what does it mean that if I have any arbitrary field pattern then that arbitrary field pattern can be expressed as the superposition of all these modes, and since it is possible to completely define the propagation of these modes, I know the propagation characteristics of these modes how do they propagate in a fiber, what are the field patterns, what are their respective effective indices and correspondingly velocities, then it is possible to predict the evolution of any arbitrary field pattern when it propagates in an optical fiber. So, that is why understanding of modes is very important.

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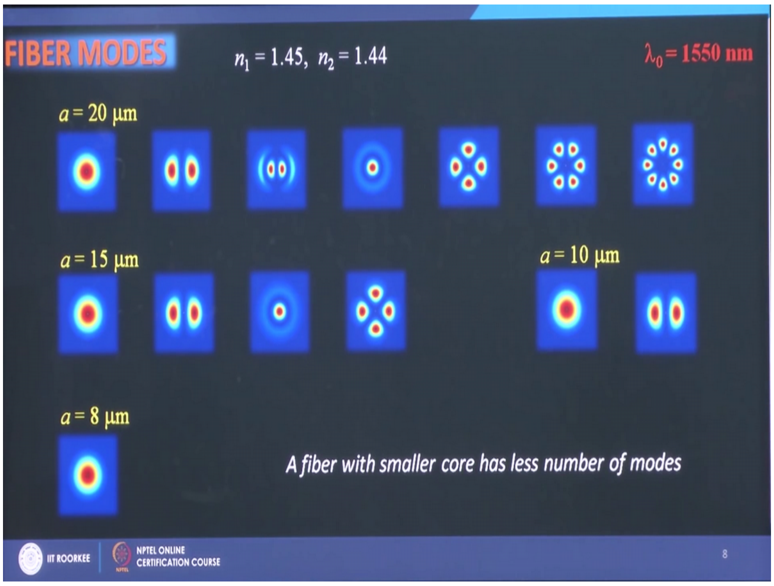

Let us now see if I have a fiber with core refractive index 1.45, cladding refractive index 1.44 and I make a fiber of core radius 20 micrometer and find out the modes of the fiber at 1550 nanometer wavelength. If I launch a light of wavelength 1550 nanometer into this fiber then what are the possible guided modes of this fiber. We will learn how to calculate these modes how to find out these nodes as we go along in this course, but let me just give you that for this fiber at this wavelength, these are the possible intensity patterns and some of their orientations. So, these have different orientations also, when I change now the core radius I bring down the core radius from 20 to 15, I see that in such a fiber these 2 patterns are missing they are not supported.

If I further bring down the core radius, then only these 2 patterns are supported. Even further bringing down the radius gives me only one pattern which is possible. So, what do I see that if for a given core and cladding refractive index and giving wavelength, if I change the radius of the core if I decrease the radius of the core, then the number of modes become smaller and smaller. So, a fiber with smaller core has less number of modes.

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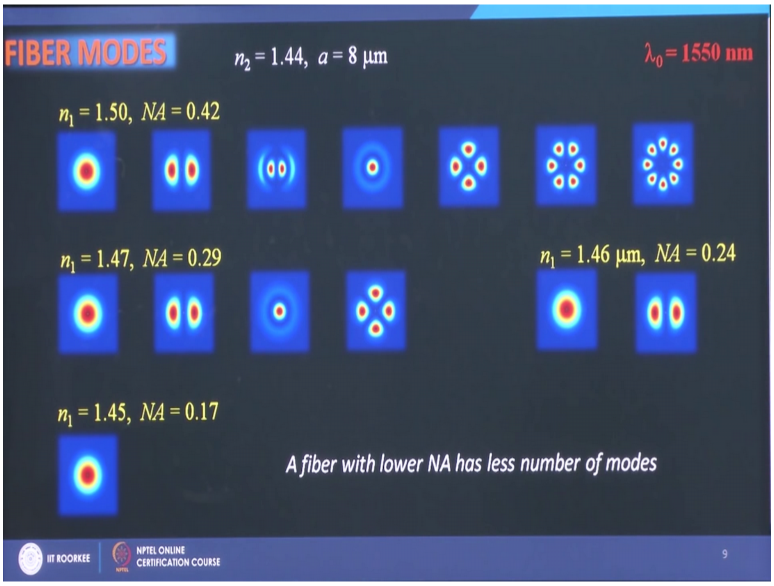

Now, what I do? I fix the cladding refractive index 21.44 and the core radius 28 micrometer, again I launch light of wavelength 1550, but now I change the refractive index of the core and hence the numerical aperture of the fiber. So, for this combination of n 1 and n 2 the numerical aperture of the fiber is 0.42 and I see 8 such sorry 7 patterns propagating in this fiber. If I change n 1 from 1.5 to 1.7, and correspondingly I change numerical aperture from 0.42 to 0.29 I decrease the number of modes, and for 0.2 numerical aperture there are only 2 and then if I bring down the numerical aperture to 0.17 there is only one mode. So, I see that a fiber with lower numerical aperture has less number of modes.

So, I have seen that the number of modes depend upon the core radius, and the index contrast or numerical aperture. Index contrast between core and cladding refractive indices or numerical aperture the question is this wavelength also affect the number of modes that can propagate in an optical fiber for that let me perform a very simple experiment.

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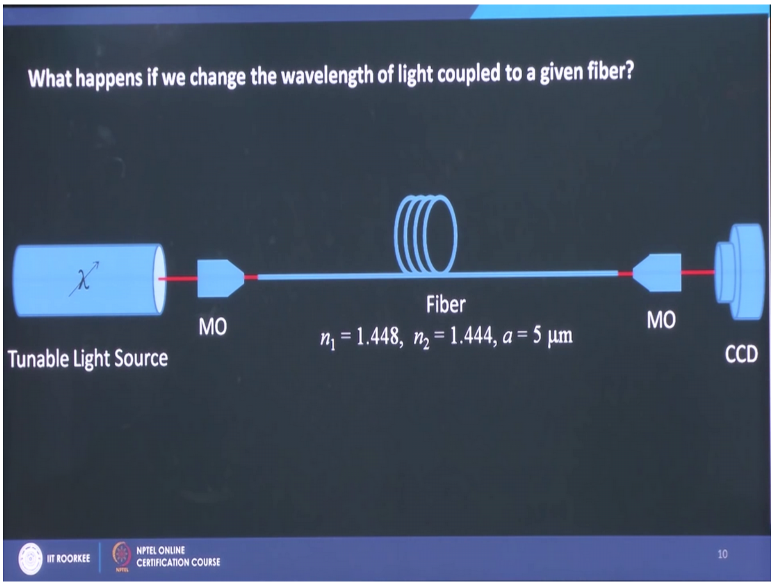

So, what I do? I take a fiber which is given which is fixed. So, n 1 n 2 and a they are fixed, now I launch light into this fiber monochromatic light from tunable light source tunable laser whose wavelength I can change, and I capture the output from the fiber using a microscope objective and image it onto a CCD. So, that I can see the pattern what I wish to do is when I change the wavelength I would like to see how the output pattern changes.

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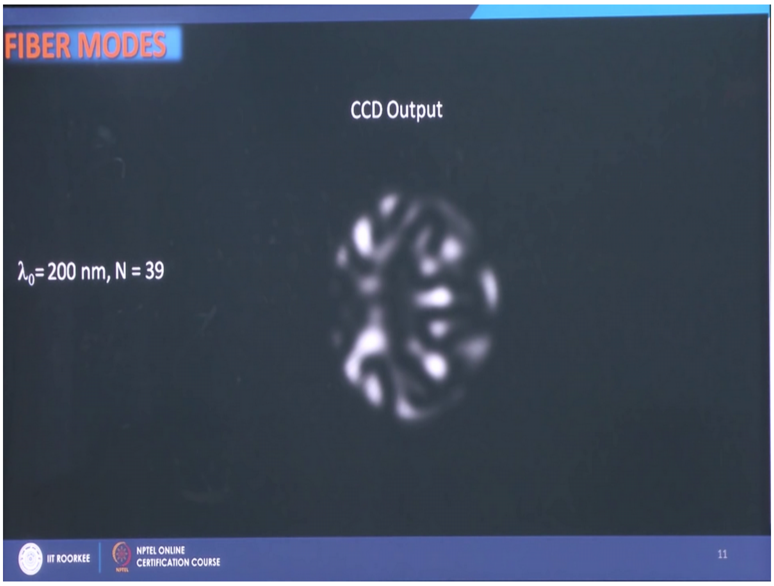

Let me perform this let me see the CCD output, when I launch wavelength 200 nanometer light of wavelength 200 nanometer, then this is the kind of pattern I see. I see a speckle pattern this is nothing, but the interference between all the possible modes of the fiber and my calculations tell me that this fiber supports 39 modes, at this wavelength at 200 nanometer wavelength. So, this is the interference of 39 intensity patterns of field patterns.

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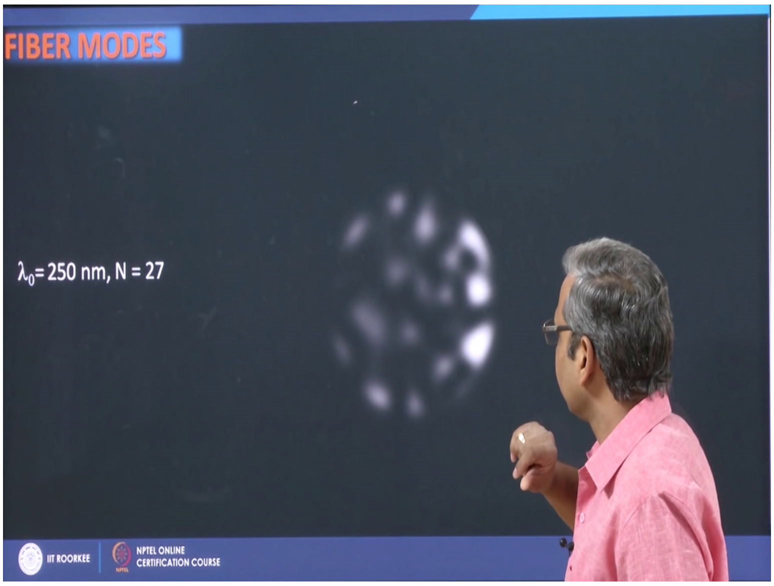

When I change the wavelength from 200 to 250 this changes the grain size of speckle here increases slightly number of modes they are decreased.

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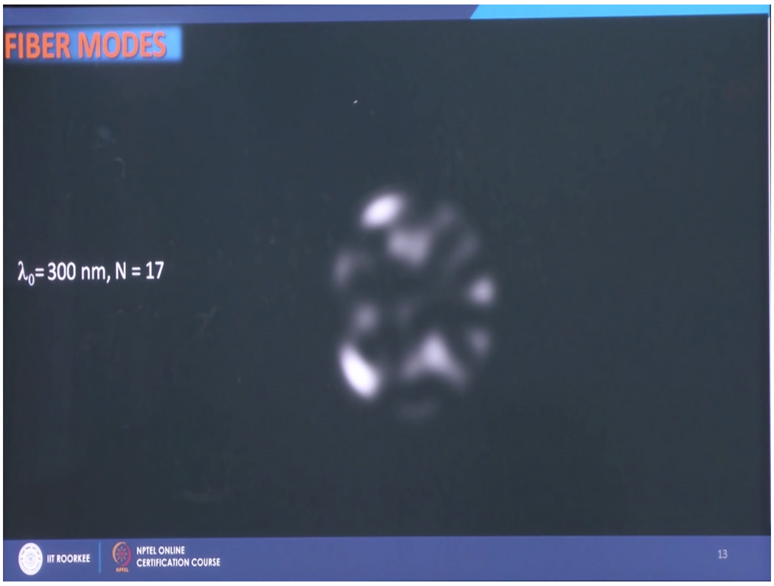

I further change it to 300 nanometer the number of modes are now 17, I increase it to 350 nanometer number of modes are 13, 400 nanometer number of modes are 10.

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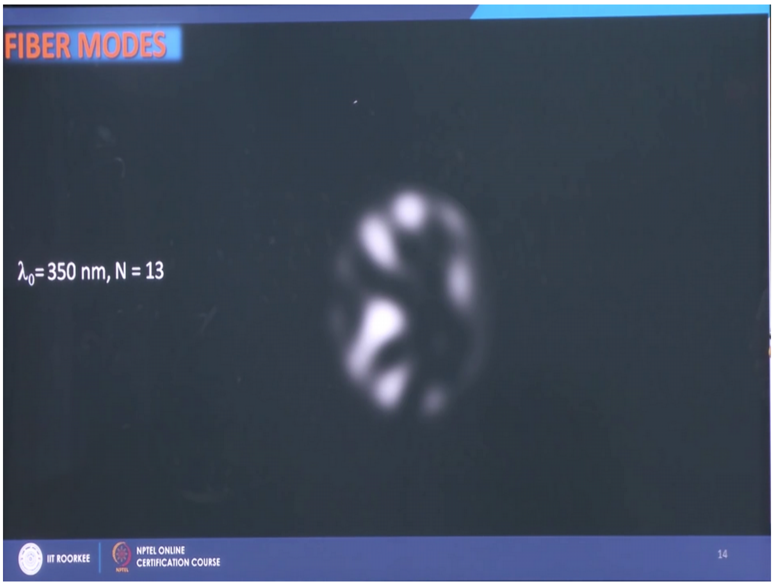

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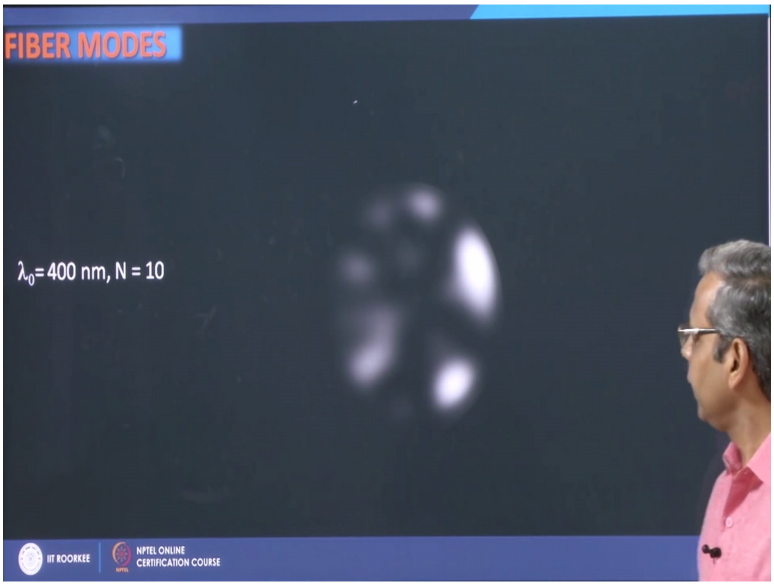

And now you can see the grain size in the speckle pattern; 500 nanometer 7 modes 600 nanometers.

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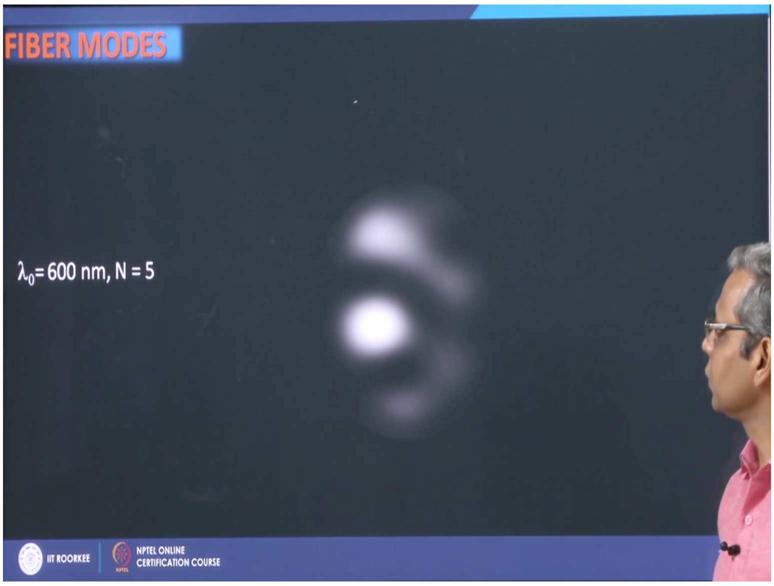

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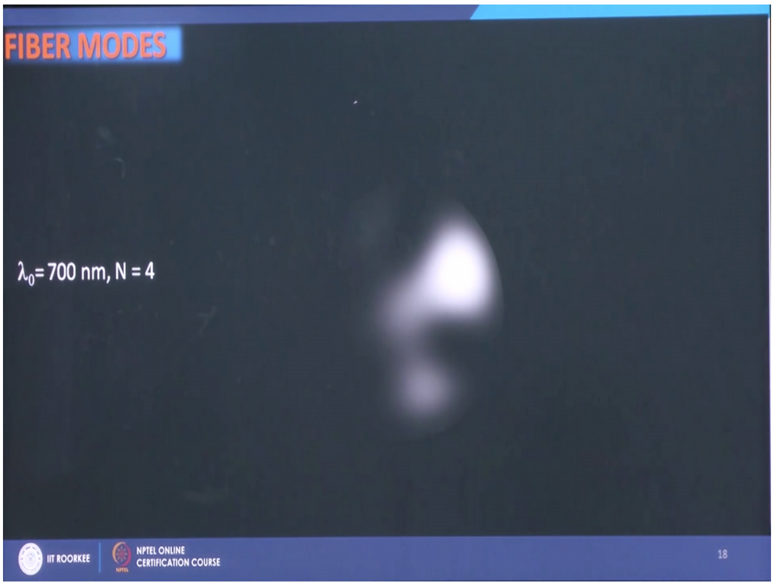

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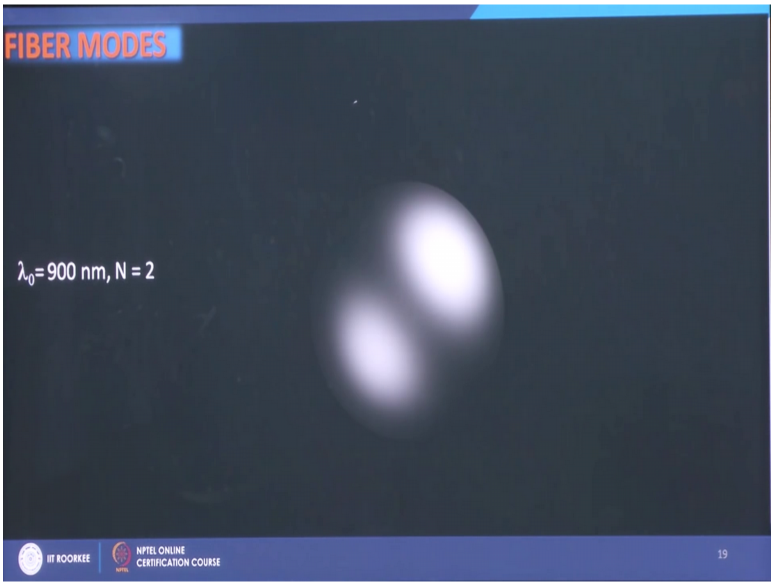

5 modes 70 nanometers 4 modes 900 nanometers only 2 modes.

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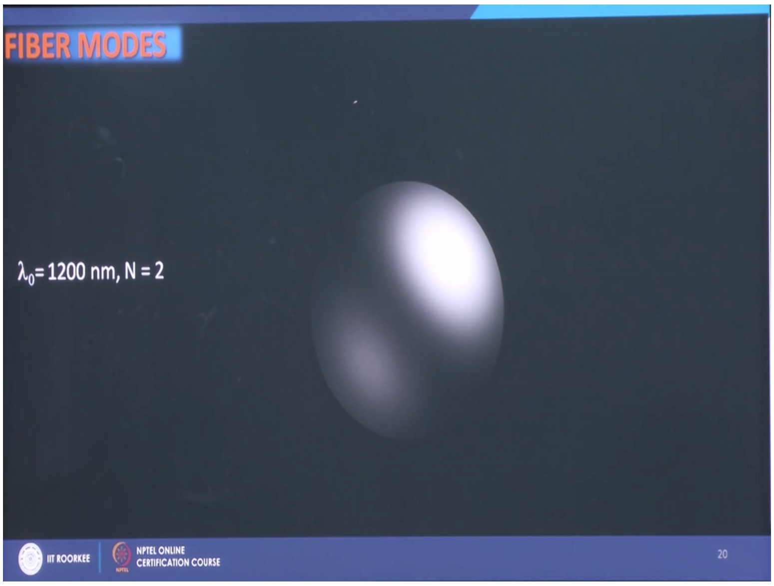

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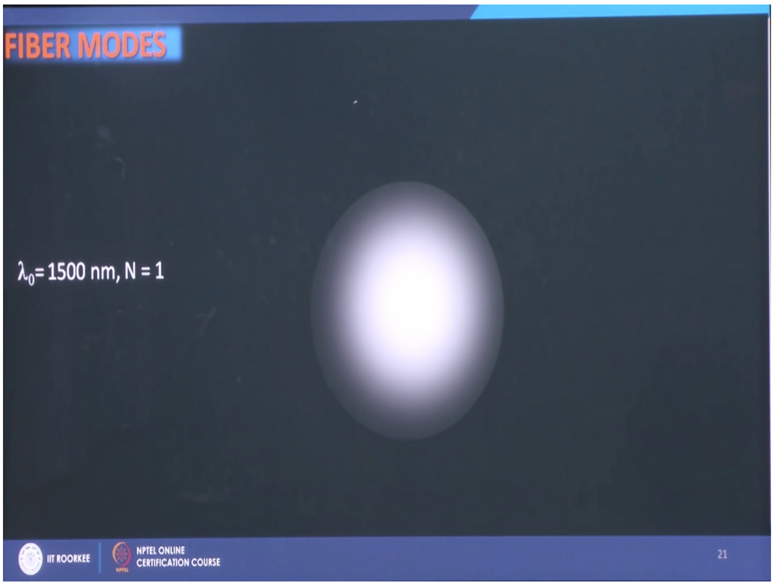

And you just see the pattern here 1200 nanometers again 2 modes and when I have 1500 nanometer I see a very clean pattern here, which is the fundamental mode which means that there are no speckles here which means that there is only one mode.

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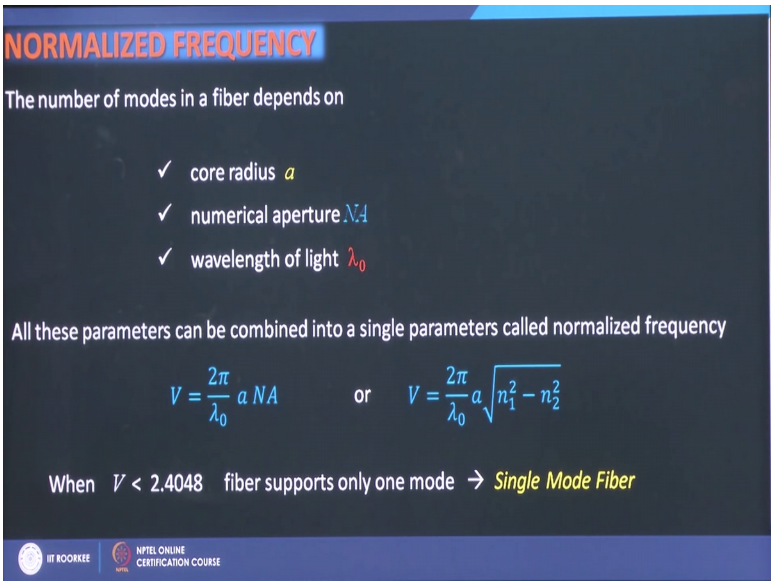

So, when I increase the wavelength, I see the number of modes decrease. How can I integrate all these observations? What I can see is that what I see is that the number of modes depends upon core radius, numerical aperture and wavelength. And I can integrate all these parameters into a single parameter which is known as normalized frequency because that it goes as 1 over lambda, which is defined as V is equal to 2 pi over lambda naught times a times numerical aperture, and since numerical aperture is defined as a square root of n 1 square minus n 2 square. So, V is defined as 2 pi over lambda naught times a times square root of n 1 square minus n 2 square.

So, how many modes would be supported by a fiber will depend upon what is the value of V. And we find that when V is less than a certain number 2.4048, we will find out from where this number has come later on, but when V is less than 2.4048 then fiber supports only one mode, and such a fiber is called single mode fiber and where it is larger than 2.4048 then the number of modes are more ok.

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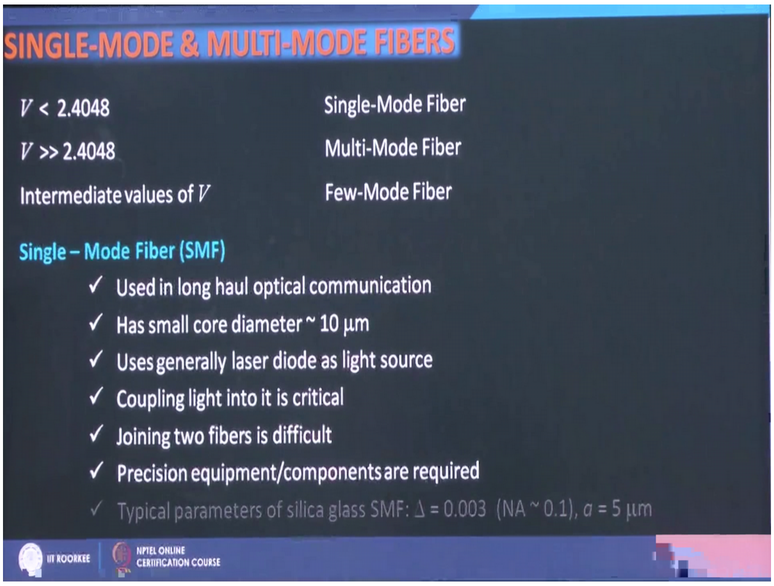

So, for V less than 2.4048 it is single mode fiber, and if V is much much larger than 2.4048 then we call it multimode fiber, for intermediate values of V we can call it few mode fiber.

Let us look at single mode fiber typical single mode fiber; it is used in long haul optical telecommunication. The fiber which is laid on sea bed is single mode fiber, it is a small core diameter typically 10 micrometer, and you can couple light into this fiber or the light source which we use with this fiber is usually laser diode. Since its dimensions are very small. So, coupling light into this fiber is critical and since you are using it a transmission fiber to carry data over long distances, then you will have to joint 2 fibers at some point and since the dimensions of this fiber are very small. So, joining of 2 fibers is difficult. You require precision equipments while handling and working this fiber, and the components which are used in the system which employs this fiber are also should be very compact and precise.

Typical parameters for a silica glass single mode fiber are relative index difference between the core and cladding is 0.003 or 0.3 percent which corresponds to numerical aperture of 0.1 and core diameter of sorry core radius of about 5 micrometer.

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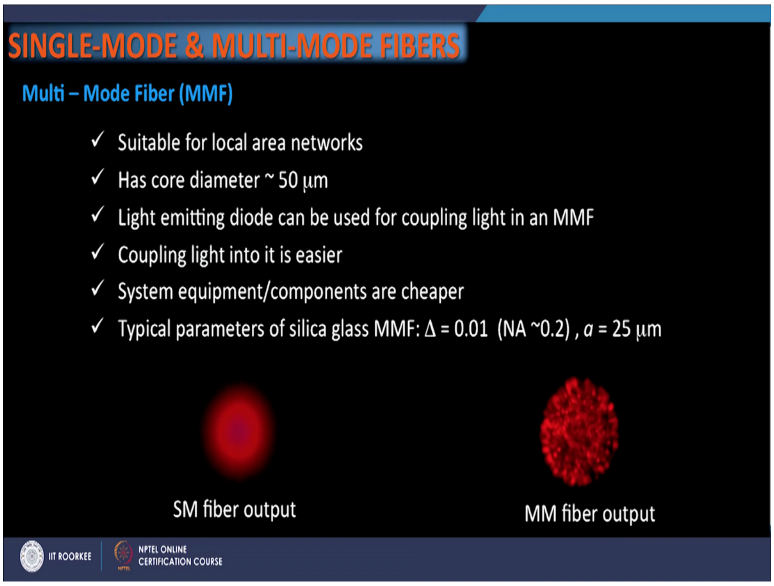

If I look at multimode fiber this multimode fiber, is suitable for local area networks. We will see why single mode fiber is used for long distance communication, while multimode fiber is suitable for local area network and not for long haul telecommunication. This fiber has a core diameter which is much larger 50 micron and we can use light emitting diode also to couple light into the a multimode fiber since it has got large dimensions. So, coupling of light is easier and system equipments and components are also cheaper.

Typical parameters of a silica glass multimode fiber are delta is about 1 percent which corresponds to 0.2 numerical aperture, and core radius is about 25 micron. Well it is single mode fiber or multimode fiber usually the cladding diameter is 125 micron, what changes is only core diameter and on top of that you have acrylic coating. So, overall diameter is most of the time 250 micron. So, if you look at a single mode fiber or multimode fiber you would not be able to tell which fiber it is it single mode fiber or it is multimode fiber you can only find out whether it is single mode or multimode where you launch light into this and observe the output. This is the output from a single mode fiber and this is the output from a multimode fiber, the patterns the explanation of these patterns is obvious because it is single mode. So, that has got only one intensity pattern and this is the fundamental mode and it is multi mode. So, there are large number of modes. So, this is the interference of all the modes, this is a speckle pattern.

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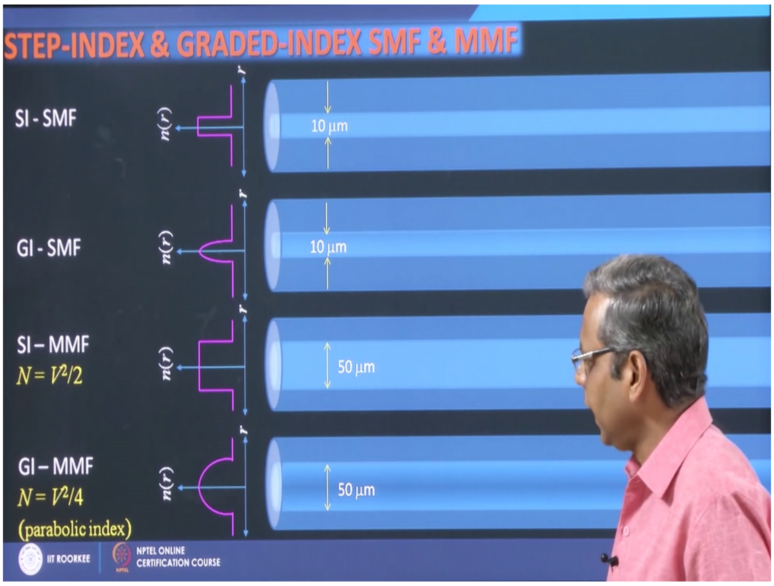

Now, you can also have a step index and graded index fibers, this is step index single mode fiber where the core diameter is about 10 micron and the refractive index in the core and in the cladding is uniform. In the same dimensions you can also have refractive index in the core which changes with radial position, then it is called graded index single mode fiber.

If you have core dimensions of the order of 50 micron core diameter typically 50 micron, and the refractive index in the core and in the cladding is uniform then it is a step index multimode fiber, and the number of modes supported by this fiber can be estimated by V square by 2, where V is the normalized frequency. In such a situation you can also have index variation refractive index variation in the core something like this. So, this is then called graded index multimode fiber, and if this variation is parabolic then the number of modes can be approximated by V square by 4 in such a fiber.

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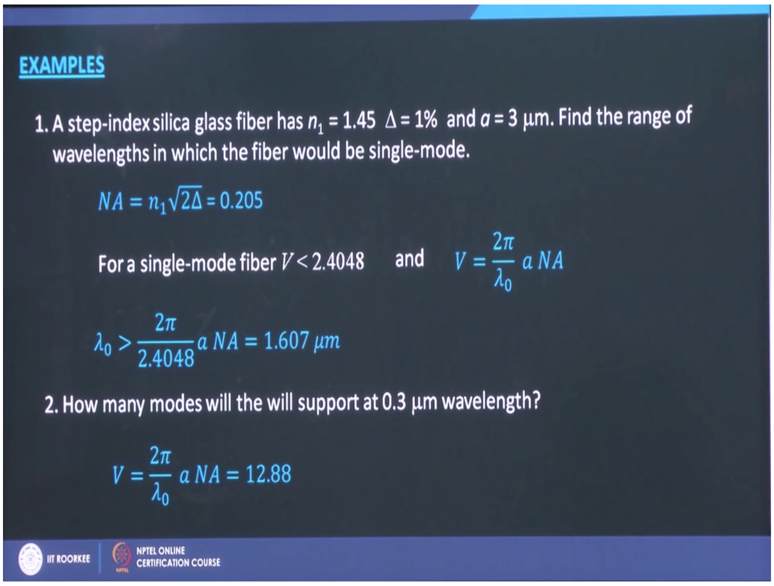

Let us take an example, I have step index silica glass fiber which has n 1 is equal to 1.45 delta is equal to 1 percent and core radius 3 micrometer. What would be the range of wavelengths in which the fiber would be single mode it if I want to find that out. Then I know that from these parameters I can immediately calculate the numerical aperture of the fiber, which comes out to be 0.2025, and I also know that for fiber to be single mode it V should be less than 2.4048, and since V is defined as 2 pi over lambda naught times a times NA, then lambda naught should be greater than this number. So, for all the wavelengths which are longer than 1.607 micrometer, this fiber would be single model and for the wavelength shorter than this the fiber will support more than one modes.

Now, can I find out how many modes will this fiber support, if I change the wavelength to 0.3 micrometer. So, it is easy I can immediately find the value of V at this value of lambda naught and it comes out to be 12.88, and since it is much larger than 2.4048 then the number of modes can be approximated by V square by 2 let me tell you that these number of modes n is equal to V square by 2 for a step index and n, n is equal to V square by 4 for graded index fiber spray parabolic index fiber, they are valid only when V is much much larger than 2.4048 typically more than 10 k.

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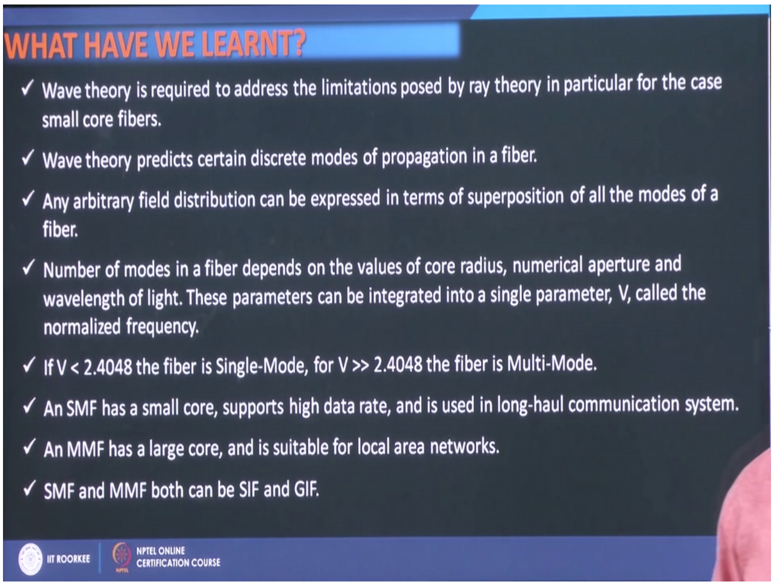

So, what we have learnt in this lecture?

We have seen that wave theory is required to address the limitations posed by ray theory in particular for the case of small core fibers. Where it completely breaks down ray theory completely breaks down, wave theory predict certain discreet modes of propagation in a fiber and any arbitrary field distribution can be expressed in terms of superposition of all the modes of a fiber. Number of modes in a fiber depends on the value of core radius refractive index difference between the core and the cladding, and the wavelength, but all these parameters can be integrated into a single parameter which is called V the normalized frequency. If V is less than 2.4048 the fiber is single mode and if it is much larger than 2.4048 it is a multimode fiber.

A single mode fiber has a small core it supports high data rate and it is used in long haul telecommunication system, while a multimode fiber has a large core and it is suitable only for local area networks. Apart from other applications other than telecom applications, and single mode fiber and multimode fiber both can be step index fibers or graded index fibers.

Thank you.