Introduction to LASER
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Lecture - 34
Fiber Lasers

Welcome to this MOOC on Lasers. As I had said earlier that fiber lasers form one of the important class of lasers with large number of applications, and they are becoming more and more important. Therefore, this lecture I will exclusively discuss fiber lasers, optical fiber lasers.

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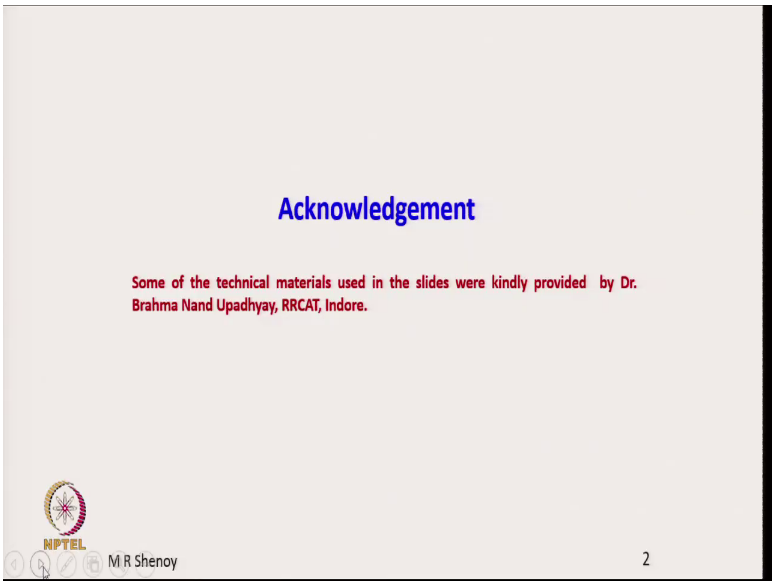

So, before I proceed I would like to acknowledge that some of the technical materials used in the slides were kindly provided by Dr. Brahma Nand Upadhyay who is currently a senior scientist at RRCAT, Indore. Dr. Upadhyay was our Ph.D., student and his Ph.D., was on fiber optic lasers, optical fiber lasers.

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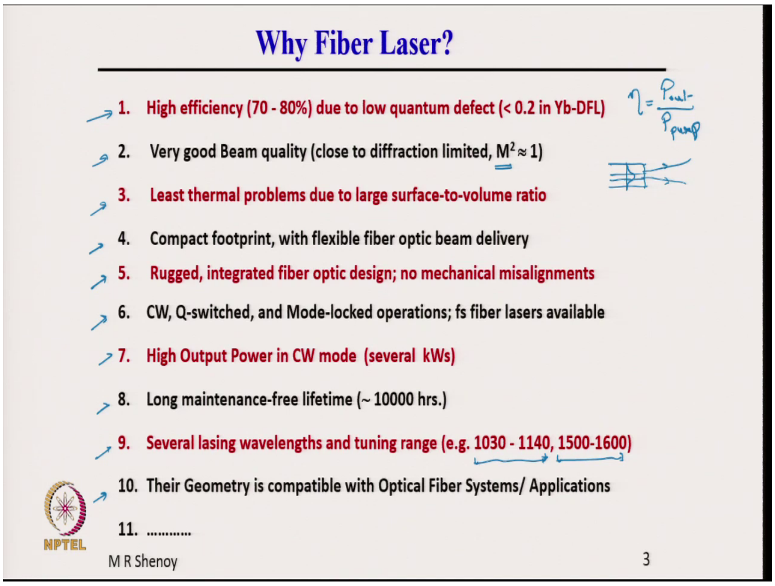

So, the first question is why fiber lasers? There are n number of reasons I have listed some of them here. So, very high efficiency, so efficiency here refers to the output power by the pump power. So, output power P out at the laser wavelength, so P out at the laser wavelength divided by P pump.

So, this is defined as the efficiency. Very good beam quality that is close to diffraction limited spot, M square is a parameter characterizing the beam, M square equal to 1 is the best, and usually M square is greater than 1. So, larger the value of M square it means the beam is poorer in quality. So, very good beam quality. This is primarily because the output comes from the fiber end here. So, it comes from the fiber end.

And the fiber has a circular cross section. So, I am showing the mode of the fiber here. And it has a perfectly circular cross section; therefore, the beam comes out as a nice Gaussian like mode. This has least thermal problems due to large surface to volume ratio.

As we would see that the gain medium is an optical fiber typically of the order of 10 meters, and therefore, the heat is dissipated all over the gain medium and the surface area available for heat dissipation is very large. And therefore, this is one of the laser systems high power laser systems with the least thermal problems.

It has a compact footprint because although the fiber used is about 10 meter in length, but we can spool it wind it into a small spool of 6 to 10 centimeter in diameter. And therefore, it forms a compact setup with flexible fiber optic beam delivery. The beam is delivered from the fiber end. And as we know that the fiber is a flexible medium, and therefore, the beam delivery is through a flexible fiber, and that is very advantageous in applications.

It is rugged and integrated fiber optic design which means fiber components are used to make all fiber lasers, and therefore, this does not have the problems of mechanical misalignments. As we will see later the configurations, there are very little provision for mechanical misalignments because they are all fiber components which are joined by permanent fusion splices.

All possible modes of operation namely continuous wave, Q-switched, and mode-locked operations are possible with fiber lasers. There are femtosecond fiber lasers now commercially available. High output power in the CW mode several killo watts, tens of kilowatts now and long maintenance free lifetime typically 10,000 hours, and several lasing wavelengths are possible with tuning range.

For example, this is the range shown for ytterbium-doped fiber laser, and this is the range shown for erbium-doped fiber laser as we will discuss in detail. And their geometry is compatible with optical fiber systems and applications. Because all optical fiber applications if they require a optical laser, then it is easier to have a fiber laser because the delivery and fiber can be spliced to the sensing system. There are many many advantages of fiber lasers.

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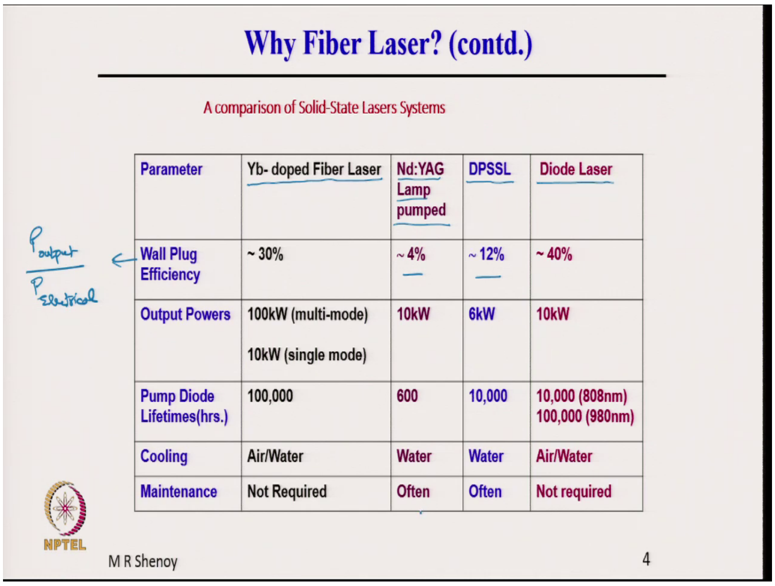

Again a very quick comparison of solid state laser systems here. So, what we have compared is Yb doped fiber laser and Nd YAG lamp pumped fiber laser. A diode pumped solid state laser we had already discussed that the diode pumped solid state lasers are more efficient.

As you can see the lamp pumped has efficiency of 3 to 4 percent while diode pumped solid state lasers can have much better efficiencies. This is the diode laser itself which we will discuss in the next lecture. Typical efficiencies are of the order of 40 percent. So, the wall plug efficiency can be as high as 30 percent. This is wall plug efficiency. This means P output of the laser, P output at the laser wavelength divided by P electrical.

So, this efficiency is typically about 30 percent. The efficiency which I had defined earlier which is P out by P pump is typically 70 to 80 percent, but this is the wall plug efficiency. Nevertheless, the wall plug efficiency is very high compared to the usual bulk lasers like Nd YAG lasers.

Output powers again one can get of the order of 100 kilowatts in multi mode oscillations and of the order of 10 kilowatt in single mode operation. Whereas, typical powers with Nd YAG and DPSSL are given here, and diode lasers the laser stacks can typically go to 10 kilowatt output power.

Pump diode life times, again the lifetimes of the diode lasers are very large as we can see here, whereas the lamp has short lifetime. And therefore, diode pumping is now the most preferred pumping in lasers. Further, cooling because as we mentioned that it has very efficient cooling because of the large surface to volume ratio, and therefore, air or water cooling is sufficient.

Whereas most of the high power lasers require chilled water cooling such as Nd YAG and DPSSL. And maintenance, very little maintenance except for the diode supply and diode which may break down after 100,000 hours there is hardly any maintenance required for a fiber laser, whereas the normal bulk lasers require periodic maintenance ok.

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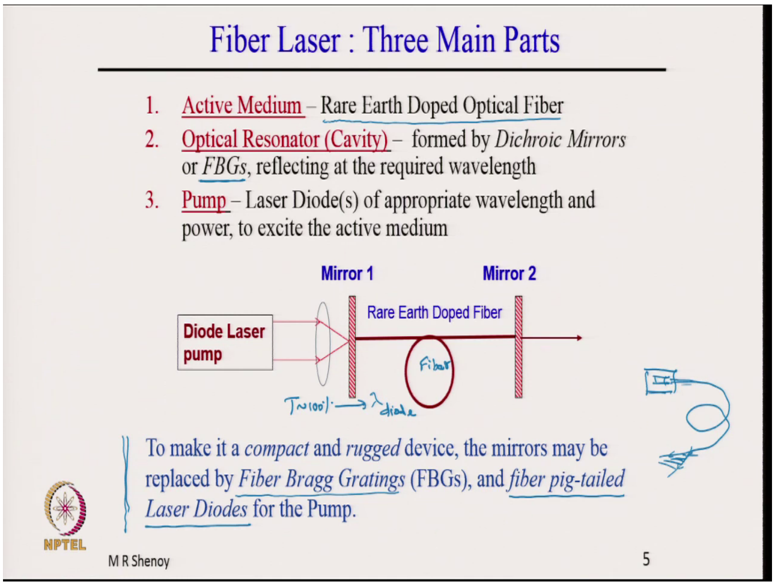

Let us come back to the fiber laser. The three main parts are the active medium, optical resonator and pump of any laser system. In the case of fiber laser, the rare earth doped optical fiber forms the active medium. The optical resonator is formed by Dichroic mirrors or Fiber Bragg Gratings.

We will discuss about this Fiber Bragg Gratings, reflecting at the required wavelength. And pump are usually laser diodes of appropriate wavelength and power to excite the active medium. So, it is shown here. A schematic the diode laser pump and the two Dichroic mirrors.

These are the Dichroic mirrors. Dichroic means this permits the diode wavelength, so lambda of the diode. So, transmitting at lambda of the diode, but reflecting at the laser wavelength, because only when it is reflecting at the laser wavelength, it would form a cavity. So, what is shown is the fiber rare earth doped fiber in the form of a loop is shown here. And this is the output coupler. So, mirror 1 and mirror 2.

So, this is transmitting highly transmitting. So, t of the order of 100 percent at the diode wavelength because that is the pump which has to enter into the fiber to excite the rare earth doped medium or rare earth ions, rare earth atoms in the medium.

To make the laser compact and rugged the mirrors may be replaced by Fiber Bragg Gratings because what is shown here are two bulk mirrors, and the fiber here in between. Whereas, if we make Fiber Bragg Gratings which are also in the form of optical fibers they are optical fiber components, the Fiber Bragg Gratings can be spliced can be joined to the rare earth doped fiber. We will discuss more about this later.

And instead of having diode lasers and a lens here for focusing the pump beam, one could use fiber-pigtailed laser diodes that is laser diodes which already have a fiber-pigtailed that is you have a laser diode here and what comes out is not a beam, but a fiber.

And the fiber is bringing the output. So, there is a fiber which is already pigtailed attached to the fiber laser diode chip itself here. So, inside there is a chip, and the fiber is attached and light comes out of the fiber, so in the form of a beam. So, they are called fiber-pigtailed laser diodes.

So, that makes it compact. The source has a fiber end, the Fiber Bragg Gratings is also fiber, and the rare earth doped fiber is also a fiber. In other words, it is an all fiber device and that makes very rugged all right.

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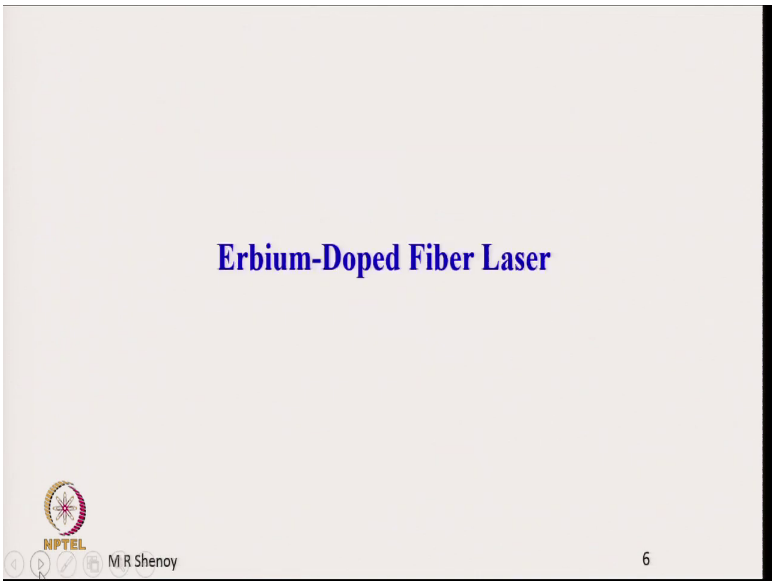

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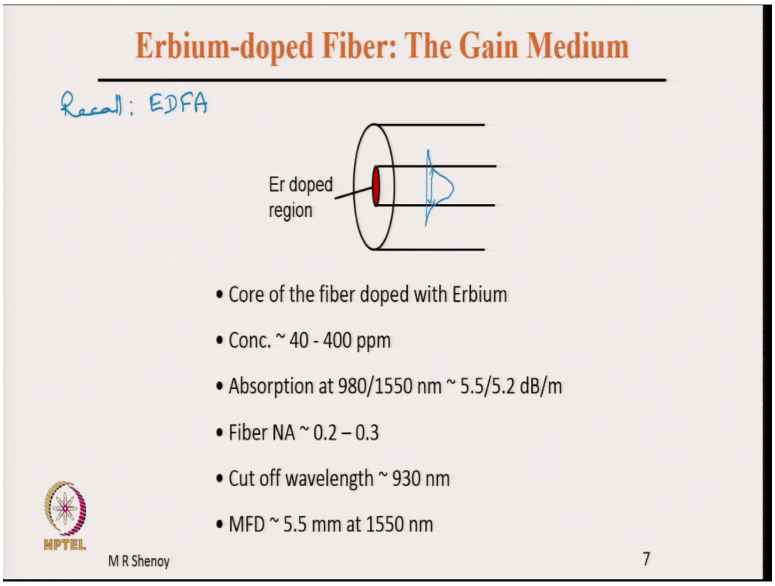

So, let us start with erbium-doped fiber laser, because we have already discussed about the erbium-doped fiber. And in the erbium-doped region, we have the core is doped with erbium. So, the core of the optical fiber is doped with the erbium ions.

The typical concentrations are 40 to 400 ppm parts per million and absorption at 980 and 1550 are given here. We had discussed this recall EDFA, the erbium-doped fiber amplifier as one of the laser amplifiers we had discussed EDFA.

And it is the same EDFA which has a erbium-doped fiber. The fiber numerical aperture, cut off wavelength, mode field diameter that is diameter of the mode. So, it is a single mode fiber which has a near Gaussian field distribution like this.

And mode field diameter refers to the 1 by E diameter of this or 1 by E square of the intensity is the mode field diameter. It is slightly different from the diameter of the core itself all right.

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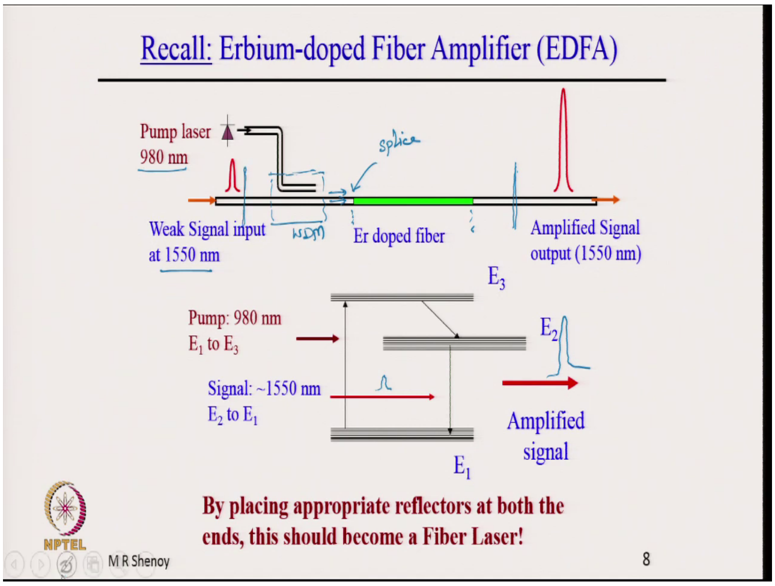

So, recall this erbium-doped fiber amplifier, same diagram we had discussed when we discussed the erbium-doped fiber amplifier earlier. So, it has a 980 nanometer pump laser to excite the erbium ions in the doped fiber. So, this region here is the doped fiber. And these are the joints optical fiber splice, they are called splice.

Splice is a joint it is usually done by arc fusion and the two fibers are joined permanently. And a weak signal which enters through the optical fiber here and this portion was a WDM coupler. If we recall, we have discussed this again in detail.

So, this region is the wavelength division multiplexed coupler which combines the signal wavelength here. Signal wavelength is around 1550 nanometer, and the pump wavelength is around 980 nanometer. They are combined by this WDM coupler. Both the wavelengths then enter the doped fiber region.

The pump excites the erbium ions and the signal gets amplified by stimulated emission. The pump creates population inversion in the medium, and the signal draws energy from the population inversion and gets amplified.

So, the energy level diagram is shown here. So, it is a quasi three level system here. So, the pump raises, so this is the pump. So, pump transition from the E 1 level to E 3, we have discussed all the details of the nomenclature of these levels earlier. And from there it rapidly comes down to a level E 2.

And the E 2 to E 3 transition is the stimulated emission, amplification by stimulated emission takes place for this transition. And the weak signal which is coming as a small pulse or as a signal will get amplified as illustrated by stimulated emission.

Now, the amplifier is already there, namely the active medium and the pump forms the amplifier. If we place two mirrors at the two ends, so one end is here, so if I place a mirror here, for example, let me just show here, so if we have two mirrors here, will it form a laser? The answer is yes. It forms a laser.

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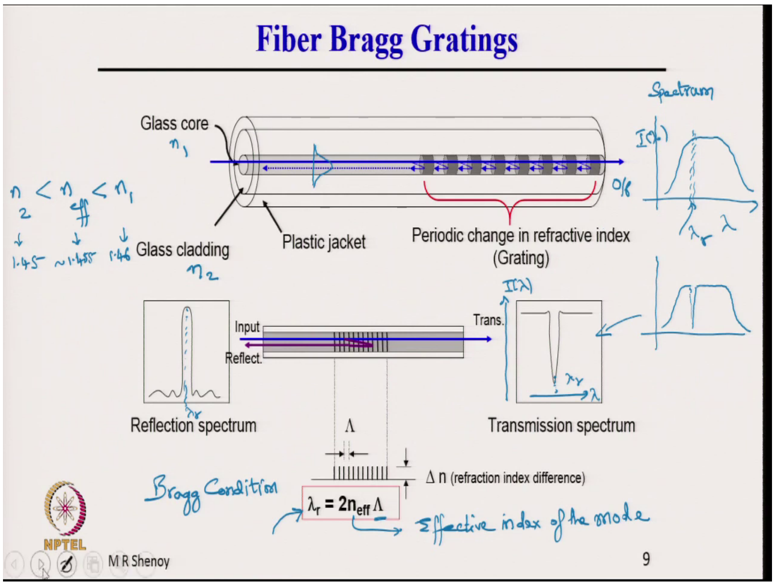

Now, as I mentioned earlier that the mirrors here instead of using bulk mirrors which then have alignment problems, it is much better to use what are called Fiber Bragg Gratings. So, for those of you are not familiar, Fiber Bragg Gratings have high reflectivitys at the design wavelength. So, the period is chosen in such a way that at the design wavelength there is very high reflectivity.

So, what is schematically shown here is a Fiber Bragg Grating. It is a fiber with the core, cladding, and plastic as usual. But, in the core, there is a periodic refractive index perturbation which has been engraved or which has been written by using a grating writing technique. By using UV lasers, it is possible to write periodic grating in the core of the fiber.

But what is important for us is the periodic structure has resonance reflection for one particular wavelength which satisfies the Bragg condition. Lambda r is equal to 2 n effective into lambda. n effective is the effective index of the mode. So, this is effective index of the mode. So, effective index because it is a fiber it is not free space.

Therefore, the refractive index is replaced by effective index of the mode of the mode which is propagating in the fiber. It is a single mode fiber. And the mode propagates like this. It is a near Gaussian field distribution.

The mode is characterized by an effective index. And this effective index is very close to the refractive index. As we know the fiber has a core of refractive index n 1 and cladding of refractive index n 2, the effective index n effective lies between n 2 and n 2, n effective less than n 1.

So, typically if I take n 2 to be 1.45 just as an example, and n 1 as 1.46, these are typical numbers. And then n effective may be approximately it is in between so of the order of 1.455. So it is very close to the refractive index, but to be precise n effective has to be used not the core refractive index. So, this is called the Bragg condition.

So, this is the Bragg condition. A wavelength which satisfies the Bragg condition will be resonantly reflected back. As you can see what is shown is a blue input here, the blue input is a broadband spectrum. Broadband spectrum means; if you see the spectrum, spectrum is I of lambda intensity of lambda versus lambda. So, this is called the spectrum; spectrum of the source.

So, the source which is coupled to the fiber out of this one wavelength which satisfies the Bragg reflection condition will be reflected back here, which means out of these let us say if one wavelength here satisfies the Bragg reflection. So, lambda r here, then and the output we will have if we see the output here, so this is the output we will have the same spectrum, but a dip there because that wavelength has gone back. So, that wavelength has gone out, and then rest of them remain the same. So, that is what is shown here.

So, in the transmission, we will have a dip. So, the dip is because so this is lambda axis, and this is the intensity I of lambda, so I of lambda or transmittivity if we say transmitivity almost

1. So, there is a dip at the lambda r wavelength. So, this is at lambda r resonance, because lambda r has been reflected.

So, if you see the reflected spectrum, then we have a small band of wavelengths around lambda r gets reflected. In other words, the fiber Bragg grating acts as a high reflectivity mirror for a particular wavelengths all right. So, the mirrors are replaced by Bragg gratings of appropriate period.

The reflection is required at the lasing wavelength. So, the period has to be chosen, the grating has to be fabricated with a period. So, lambda is the period. So, periodic refractive index change in the medium.

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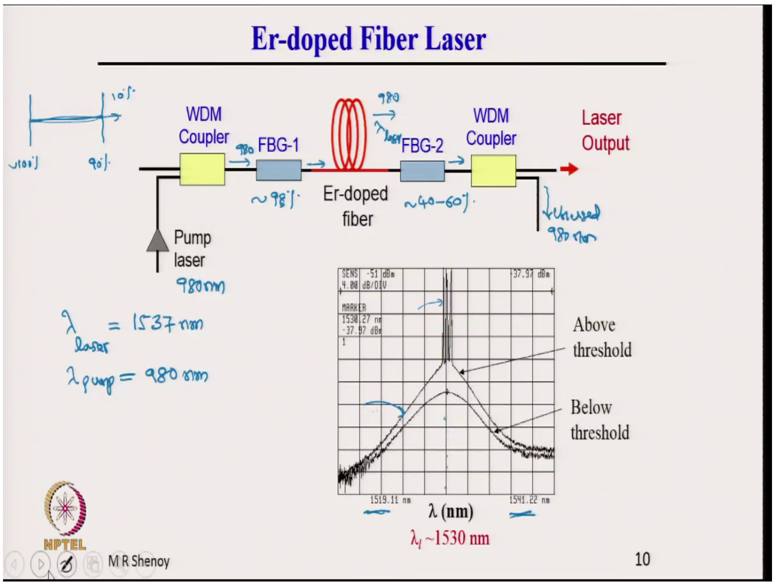

Now, here is the erbium-doped fiber laser schematic. So, what I had discussed was a WDM coupler to couple the pump. So, this pump laser is at 980 nanometer. And this is the WDM coupler. There is no input, there is a laser. In an amplifier, we gave a weak signal input here but now there is no input. But the pump is coupled here into the fiber Bragg grating. The fiber Bragg grating is highly reflecting at the laser wavelength.

For example, if the laser wavelength lambda laser is 1537. So, let me write 15, we have a laser here. So, this is equal to 1537 nanometer. Then fiber Bragg grating is highly reflecting at this wavelength, but it is transmitting. So, lambda pump is 980 nanometer. So, this the grating is not reflecting at 980, therefore, 980 simply passes through.

So, 980 nanometer passes through into the erbium-doped fiber, and excites the erbium ions and creates population inversion. The laser wavelength at 1537 in this case gets reflected back and forth by two Fiber Bragg Gratings.

One, this reflectivity is approximately 95 to 98 percent. And the reflectivity here could be anywhere from 40 to 60 percent, because we need output from here, normally, it depends depending on the power this could also be 10 percent.

But one of the gratings is of high reflectivity, because we do not want the laser to pass come backs. If we want the FBG 1 here to be highly reflecting at the wavelength just like in the case of bulk lasers when I showed you, usually I write this as nearly 100 percent reflecting, and the other end is nearly 90 percent reflecting which means 10 percent output comes out. So, the laser is building up here and 10 percent output comes out.

Similarly, here it is 98 percent or 99 percent reflecting is one of the gratings. The other grating could be as low as 10 percent. 10 percent to normally 40 to 60 percent so that we get the laser output here. It passes through the WDM. So, if there are any unused pump remaining, please see 980 is entering.

So, when it comes out here, there will be some 980 and some lambda laser. So, both will come out here. And unused 980 would come here, 980 nanometer that is the unused pump or residual pump, unused 980 nanometer which can be dumped. So, there is a pump which is pumping from here. And the WDM coupler takes out the unused or residual pump, and what you get here is the laser output.

So, what is shown here in the diagram is below threshold, we see that this is the spontaneous emission spectrum around so this wavelength here in this case is about 1538, this wavelength central wavelength. And we can see here this is from 1515 to 1541. So, that is the span over which the spontaneous emission spectrum below threshold. Above threshold suddenly we see the longitudinal modes of the laser.

The laser is lazing at several wavelengths. So, we clearly see suddenly the laser power shooting up at the lasing wavelengths which are the longitudinal modes. Note that this is a log scale. And therefore, the power the spontaneous emission power which we have here is much smaller compared to the power which is here.

We have already seen when we discussed about variation of laser power around threshold, as soon as you cross the threshold the power shoots up all right. So, that is about an erbium-doped fiber laser.

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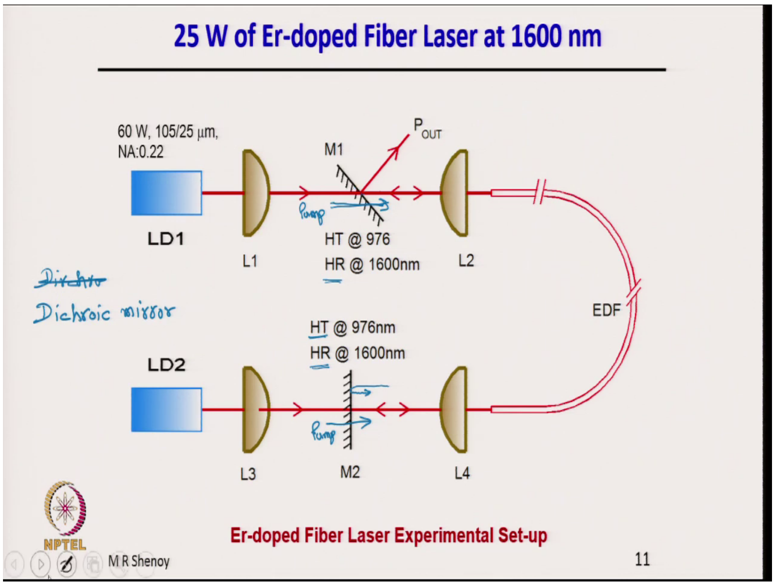

What is shown here is using bulk components a 25 watt erbium-doped fiber laser lasing at around 1600 nanometer. So, in this case let me go back and show this. There are two WDM couplers. We have shown one pump laser here. So, this is P 1.

One pump laser coupling from the forward direction, this is called the forward means along with the signal. Pump is flowing along with the signal. But we could also couple a pump using another WDM coupler from the reverse direction because after all the role of the pump is to excite the erbium-doped fiber.

The role of the pump is to excite the fiber. It does not matter whether we pump from this end, forward end or backward end like from the other end from the opposite end also it can be used that is why two WDM couplers are shown here.

So, when high power is required from the laser, sometimes there are double end pumping is used. And what is shown in the next diagram is two pump laser diodes, pumping the fiber from two ends. So, this is the bulk version of the fiber laser where you have a Dichroic mirror.

The pump is at 976 nanometer. It is highly transmitting which means all of the pump passes through the mirror, but we need a cavity. And therefore, at the laser wavelength 1600 nanometer, it reflects back, because it is highly reflecting this is high reflecting high transmission, high transmission, high reflection. So, the pump is transmitted. And another lens couples it into the fiber and this is the EDF typically 8 to 10 meters, and the pump excites the fiber.

Similarly, there is a pump from the other end which is also exciting the fiber here. There is a mirror which is placed at an angle to take the output. The mirror is reflecting as before at 1600 nanometer, and therefore, a part of the 1600 nanometer comes out here, but it is highly transmitting for the pump wavelength.

So, the pump again transmits 100 percent almost 100 percent through this. So, this is pump, the blue one I am showing is pump. So, the pump is 100 percent transmitting through the mirror, it is a Dichroic mirror.

They are called Dichroic mirror which means for two different wavelengths, the reflectivity is different Dichroic, sorry Dichroic mirror. So, the mirrors used are Dichroic mirrors which means at one wavelength it is highly transmitting, and it is highly reflecting at another wavelength.

So, the cavity is here. So, this is the cavity, the laser cavity with the mirrors m 1 and M 2. M 1 is also an output coupler. A part of the light is reflected out of the cavity at mirror M 1. So, this is a experimental setup which uses double ended pumping.

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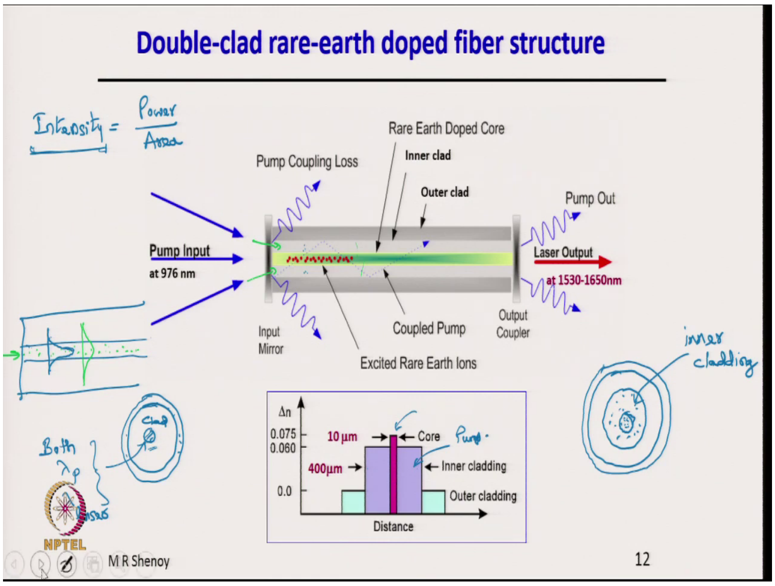

When we use high power lasers, normally double-clad rare-earth doped fibers are used. What is a double clad rare doped fiber? So, we if we see here, so there is a core, and there is a cladding, and then we have the plastic normally. So, so this is the plastic in a normal fiber.

This is the core, and this is clad, this is core, and this is the plastic. In a double clad fiber, we have the core here, then we have a cladding, and then we have one more outer cladding, and then we have the plastic. So, there are two claddings. The laser wavelength is guided in this core, the pump wave or the pump beam is guided by this inner cladding.

So, inner cladding is to guide the pump. The pump is coupled into the inner cladding. Why do we have an inner cladding? Because the inner cladding can have a large area or large volume if we put in the same core both as in the normal laser both lambda p pump and lambda s or lambda laser are in the same core here, both are in the core.

And therefore, if I show a transverse picture here of the fiber core, then the pump has a field distribution which is like this. And let me show the signal with the different color. And the signal has a field distribution which is because it is at a longer wavelength it is more spread, but the two field distributions overlap.

The important point is all the signal and the pump both are launched here into the core. But in the case of a double clad fiber as shown here, the pump is launched into the outer cladding here because outer cladding is bigger. And therefore, the power density the intensity of the pump need not be very high because it is a large area. Please see, what is the purpose of doing this?

Let me so intensity equal to power per unit area. So, intensity equal to power per area, here area of cross section. If we launch a high power pump here into a small core, then the intensity would become very high. And therefore, high intensity leads to non-linear optical effect.

Whereas, if I make the core area very large here, then the intensity would not be high enough to create non-linear optical effects. What are these non-linear optical effects? We will discuss a little later. But in very high power lasers, one uses double clad fibers.

The inner core guides the laser beam because the inner core is doped, whereas, the inner cladding which is outside here is to carry the pump to excite the rare earth ions. And then the outer cladding is of course to guide the pump.

And therefore, as you can see here, this gives a very good picture that the typical dimensions of the core is 10 micrometer. The cladding here is about 400 micrometer, inner cladding to accept large amount of pump power. And also to note that the numerical aperture of the inner cladding here is very large compared to the numerical aperture of the core.

So, this guides the laser beam this one, and this guides the pump. So, that is what is meant by a double-clad rare-earth doped fiber structure all right.

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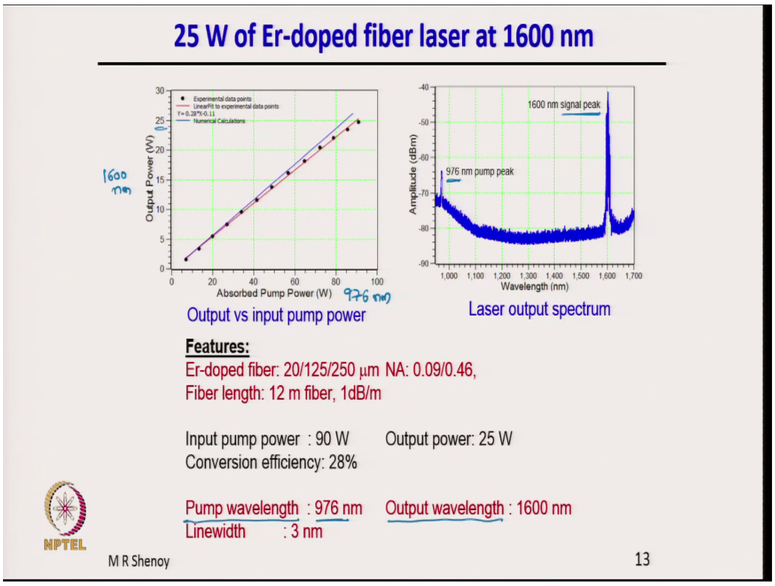

So, let us quickly see the output of the device which I had showed here. So, this is the configuration as I already mentioned that this was provided by Dr. Upadhyay. And what you see is the absorbed pump power and the output power of the laser. So, absorbed pump power, pump wavelength is here 976nanometer.

And the output wavelength is 1600 nanometer. It is a erbium-doped fiber laser. So, you can see the spectrum this is the optical spectrum analyzer which shows wavelength versus the intensity, the amplitude at the pump wavelength here the peak, and the signal peak which is shown here at 1600 nanometer.

So, what is shown here is the output power at 1600 nanometer. And on the x-axis this is the pump power at 976 nanometer. So, we see that almost a straight line as pump power increases, the output power increases. You see that 25 watt of CW output power in this graph.

Nowadays, there are 100s of watts of output CW power is routinely achieved. But this is just a graph to show that the linear variation of the output power with the absorbed pump power all right.

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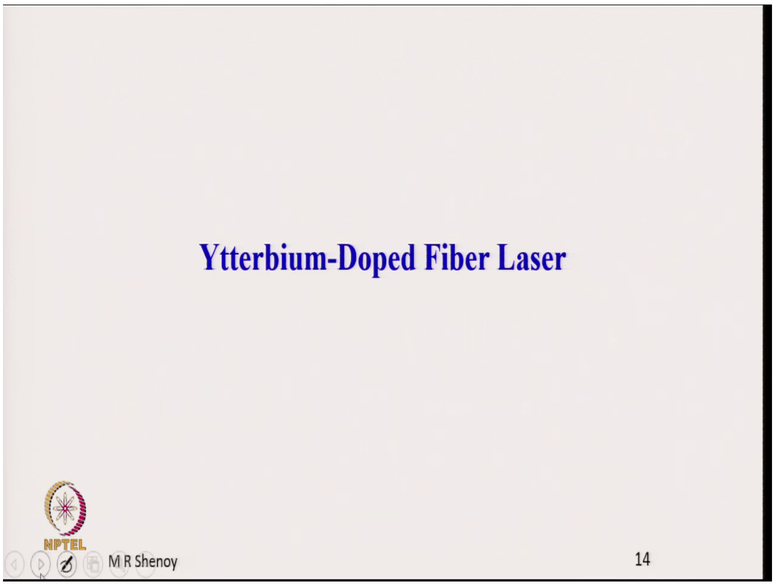

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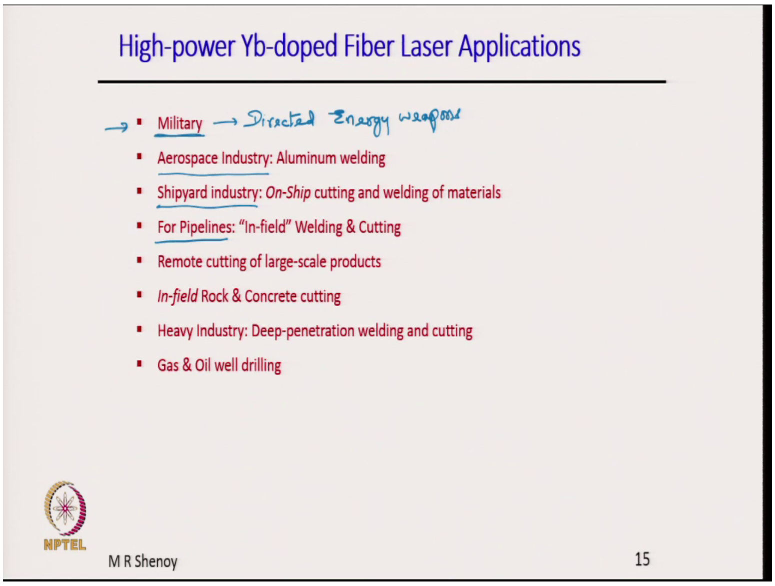

Let me now discuss very briefly the ytterbium-doped fiber laser. So, two important lasers, erbium-doped fiber lasers and ytterbium-doped fiber laser. There are many other lasers as well. Why ytterbium-doped fiber lasers?

These have very important applications in military, various applications in military to directed energy weapons. So, for example, directed energy weapons, because you need high powers. Aerospace industry for example for welding aluminum is a very difficult task which can be done by using fiber lasers.

In shipyard industry, large number of industrial applications on ship cutting, welding of materials; for pipelines in the field welding and cutting; remote cutting of large scale products because there is a fiber delivery system so which can be controlled remotely.

And in field rock and concrete cutting all these are applications of high power Yb-doped fiber lasers. Heavy industries, deep-penetration welding that is welding inside deep-penetration welding and cutting, and then gas and oil well drilling. Various large number of applications for high power Yb-doped fiber lasers.

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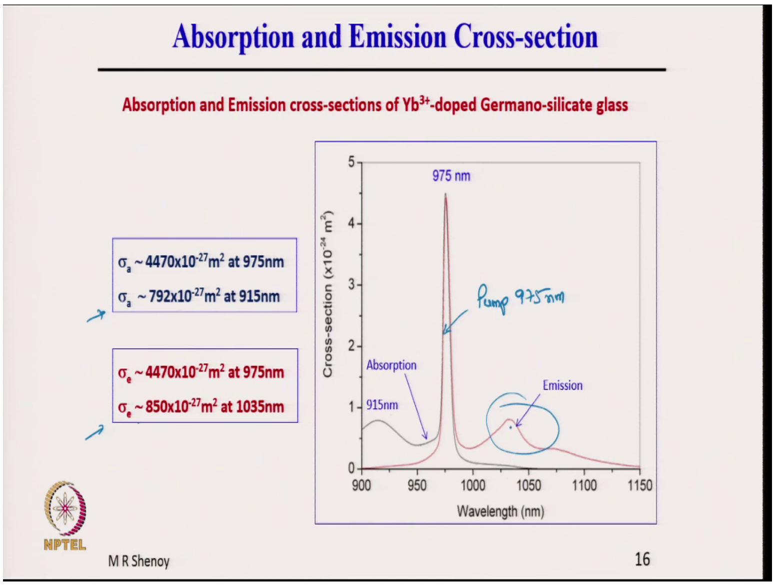

So, what is shown here is the absorption and emission cross section of a Yb-doped fiber. So, we can see that this curve is for absorption, it is the absorption spectrum, and the other one is the emission spectrum. What we see is the emission and absorption has a peak at 975, and the emission spectrum also has a peak around 1050 or 1030 nanometer.

So, there is a range of wavelengths, there is an emission peak which covers a range of wavelength. Therefore, this gives an indication that if we have a pump which is at 975 which absorbs so if we use a pump at 975 nanometer, then we can have an emission spectrum over a range of wavelengths here.

So, this is the importance of seeing the absorption and emission spectrum of the given dope end ion. So, there are some numbers which are given here typically sigma e and sigma a at various wavelengths. We have used sigma e and sigma a that is the emission cross section and absorption cross section earlier.

The typical numbers are given here. So, we see that the emission has a cross section about this much around 1035. So, this peak is around 1035 nanometer.

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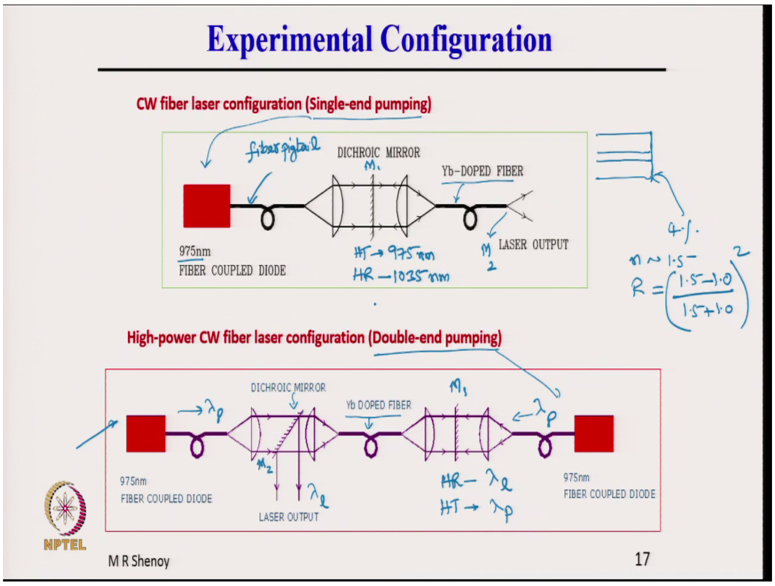

And therefore, the experimental configuration is shown here a fiber pigtailed. So, this is the fiber pigtail. Pigtail means the laser diode at 975 nanometer. The power output is delivered by a fiber, so fiber pigtail. This is the doped fiber. So, this one is the doped fiber.

So, the output from the fiber is collimated, and then coupled to the fiber. There is a Dichroic mirror here as before. So, this Dichroic mirror is highly transmitting at 975 nanometer, so that the diode energy is passed through it. So, it is as good as it is not there, but it is highly reflecting at the laser wavelength. So, let us say in this case it is at 1035 nanometer.

Of course, it can be chosen such that different wavelengths can lase inside the laser. This is mirror M 1. Where is the mirror M 2? In this case, the cleaved fiber end itself forms a mirror M 2, the fiber end. So, let me show it enlarge.

So, this is the cleaved fiber end. So, this itself would provide a reflection of 4 percent, because the refractive index is around 1.5 n is nearly 1.5. Therefore, the reflectivity r is equal to 1.5 minus 1.0 that is air refractive index divided by 1.5 plus 1.0 whole square, so that is 0.2 square, it is 0.04 and the reflectivity is 4 percent.

In a Yb-doped fiber, since the gain is very large and the length of the gain medium is large, even if you do not have a mirror at the other end the 4 percent reflection from one end itself is sufficient to form the cavity.

So, one end we have a mirror high reflecting mirror, and other end there is no mirror at all, even then there is lasing taking place in such fiber lasers. What is shown here is double ended pumping. So, this is single end pumping which means there is only one pump laser here.

And this is double end pumping which means there are two lasers which are pumping. I already showed in the case of a erbium-doped fiber laser, and that is the same thing which is shown here in Yb-dope the fiber laser.

So, there is the first pump whose output is collimated and fed to the Yb-doped fiber which is this one, and there is a mirror here. This mirror is a Dichroic mirror. So, highly reflecting at the laser wavelength lambda l, let me write lambda l, and highly transmitting at the pump wavelength so lambda p.

So, the pump wavelength which is coming from here, so this is lambda p lambda p here. It is transmitted into the doped fiber to create population inversion excite the doped fiber. There is a mirror which is here there is a Dichroic mirror here.

So, this is highly reflecting at the laser wavelength, but here a part of the laser output is taken by keeping a mirror at an angle. So, this is the laser wavelength lambda l which is taken out, but the pump is absorbed in the Yb-doped fiber here.

So, the laser cavity comprises of mirror M 1 here now. So, let me call this as M 1 because usually we take the output from M 2 and M 2 here output is taken from here. This is a configuration which is implemented to generate high power laser.

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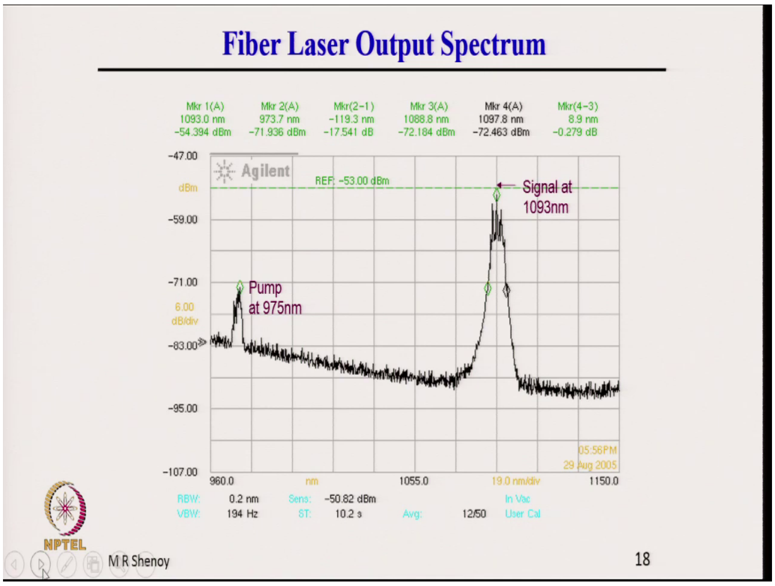

And we can see the output spectrum again. The pump at 975 nanometer a peak. And the signal in this case is coming at 1093 because the spectrum is over a range of wavelengths and depending on the reflectivity of the mirrors at the wavelength depending on the reflectivity of these Dichroic mirrors we can get different wavelengths.

So, in this case, the peak is at 1093 nanometer that is what we meant by a tunable range over a range of wavelength by choosing appropriate reflectivities of the Dichroic mirrors or the Fiber Bragg Gratings that we use to form the cavity ok.

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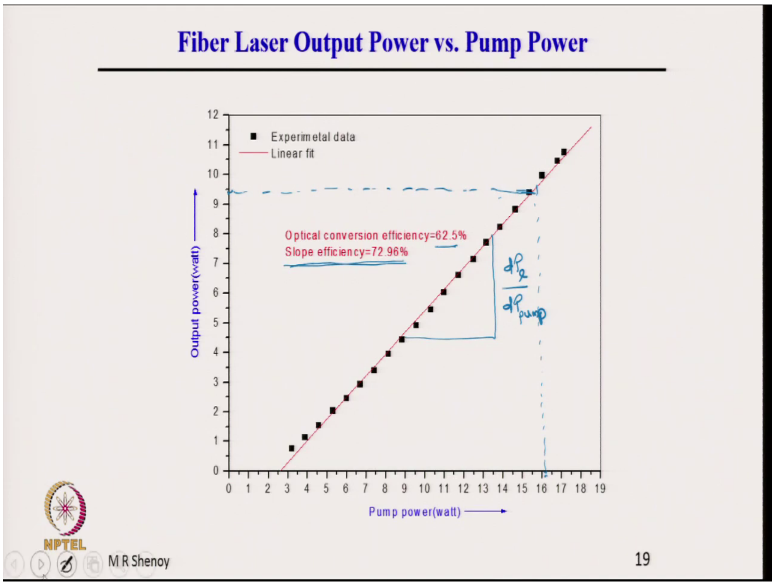

So, this is the output. What is shown here is pump power versus output power. This is similar to what I showed earlier for erbium-doped fiber laser. And this is for ytterbium-doped fiber laser. Note that the slope efficiency is 72.96 percent and the optical conversion efficiency is this much.

Slope efficiency is the slope of this line. So, this one is called the slope efficiency. This is d P laser divided by d P pump. This is the slope efficiency. And the actual efficiency is of course is here at any value that is the laser output power divided by pump power that is relatively less compared to the slope efficiency all right.

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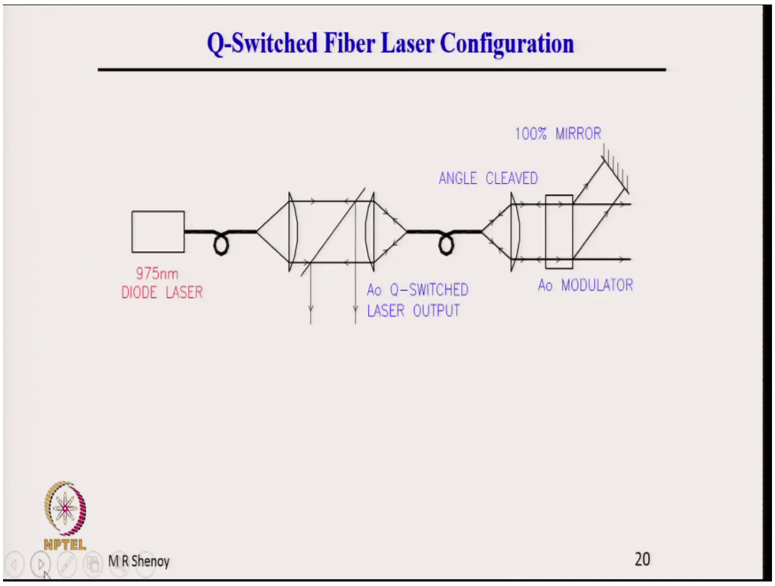

So, this is a configuration of Q-switched laser I discussed this when we discussed Q switching as a means to obtain pulsed output from a laser. So, there is the acousto optic modulator Ao modulator here which diffracts the beam out.

So, this acousto optic modulator has an RF. So, an RF is fed to this. So, there is a RF. And as we discussed already there is a piezoelectric transducer. And it creates a periodic phase grating in the medium which results in diffraction of the beam whenever the RF is present and this is a method of Q switching.

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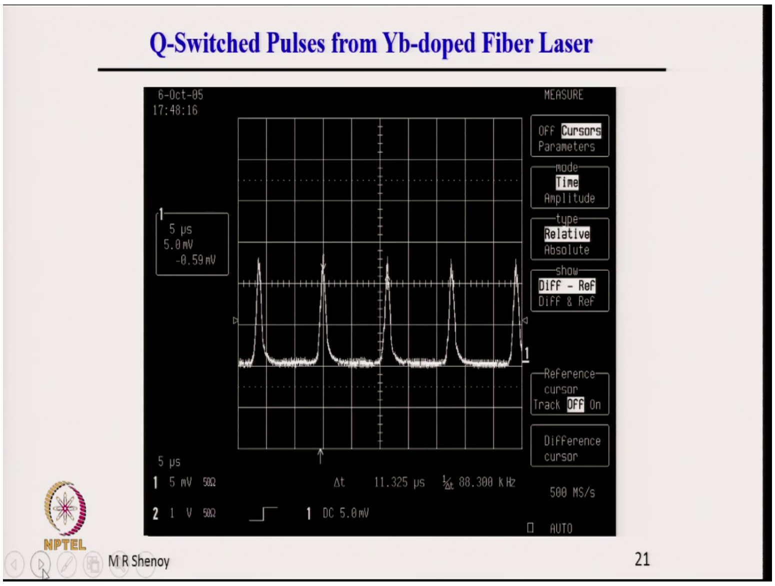

And what is shown here is the Q-switched output. The same graph I had shown earlier when I discussed Q-switched pulses. As you can see very nice high energy pulses periodic pulses coming out of the laser ok.

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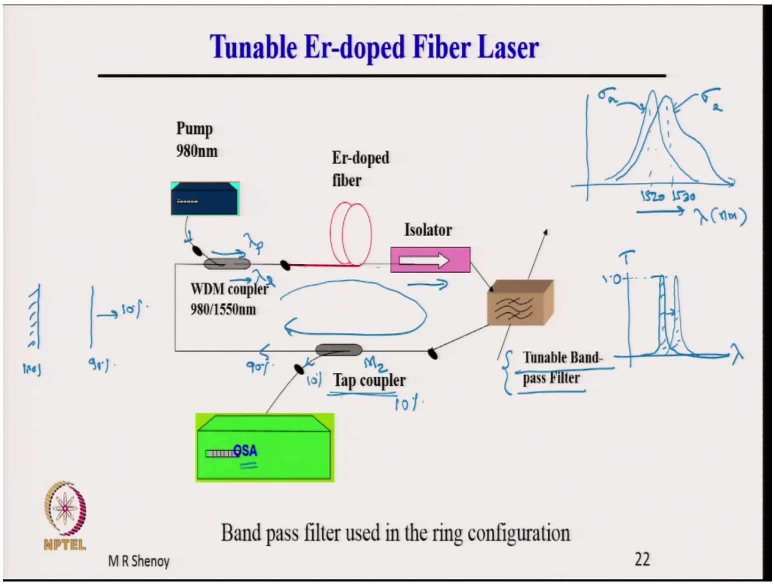

Last point is tunable erbium-doped fiber laser. So, as we discussed if you take a erbium-doped fiber, then it has an absorption cross section something like this. We had discussed this earlier when I discussed EDFA, I had given the graph.

And an emission cross section which varies something like this. So, there is a range of wavelengths. So, this is sigma e what I have plotted is sigma e and sigma a. And this is wavelength lambda. So, this peak this could be around 1530 or 1520, so 1520, and this may be around 1530 nanometers. So, lambda in nanometers.

And what you see is emission is over a range of wavelengths. Therefore, it is possible to select if we have a tunable band pass filter in the cavity, then we can select which so the tunable band pass will pass a certain range of frequencies. So, it is a band pass filter. So, this is the transmission.

So, transmission is nearly one as a function of wavelength. So, a range of wavelength is transmitted. So, this is around the wavelength that would, so and this can be shifted. In a tunable band pass filter, we can tune this to a new position here, so that transmission of another wavelength is maximum, so that is a tunable band pass filter.

Now, in a ring resonator cavity, what we have is the WDM coupler, there is a 980 pump which is coupled into the cavity, there is an erbium-doped fiber here. This is an isolator; it is like an optical diode. It permits light to flow in one direction but does not allow light to come back.

So, this is a ring cavity. So, light is taking a path like this it is going like this. So, the pump enters the doped fiber, it excites the doped fiber. And lasing takes place at the laser wavelength in the ring cavity. The cavity is giving a feedback.

Now, this is like M 2 a tap coupler. A part of the light is taken out and fed to an optical spectrum analyzer where you see the spectrum. So, this is the configuration of a ring cavity. A tap coupler means the meaning of tap coupler is for example, a tap is 10 percent tap which means 10 percent of the energy is taken out rest of it continues like this.

So, 10 percent comes here and 90 percent goes in the cavity. So, it is a ring cavity. So, every time 10 percent is just like the mirror where you have the output mirror. So, if this is 90 percent reflecting, it means 10 percent comes out. But this tap coupler is an all fiber component it is not a bulk mirror, it is an all fiber component.

It is a WDM coupler. It is a tap coupler which is a fiber component. So, this is 100 percent and that is 90 percent. So, the 90 percent coupler is here. The rest of it goes back into this.

This pump is combined. So, the pump from here 980 nanometer enters. Therefore, we have here lambda p and lambda laser. Both entering this and building up again in the amplifier, and then feedback amplification feedback.

The point is if we use a tunable band pass filter, then feedback would come at the wavelength that we have chosen that is the filters pass band wavelength. And this way we can select different wavelengths to lase in the resonator.

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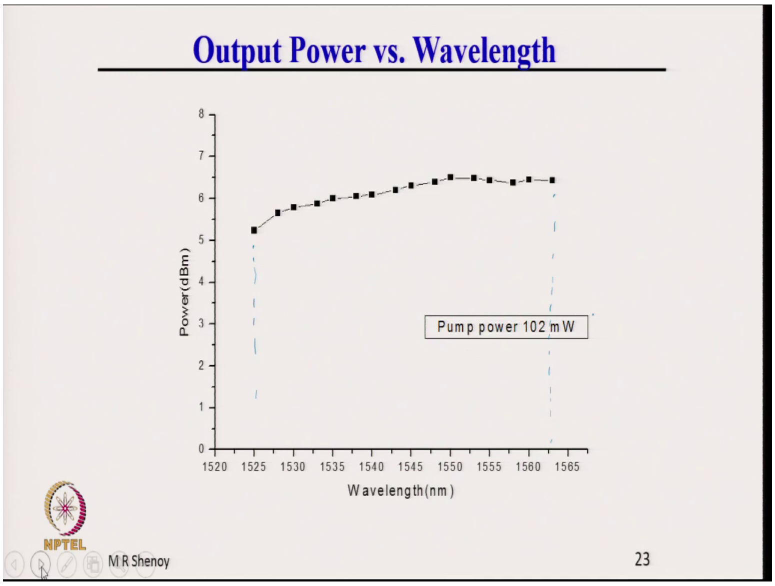

And what is the output? So, the output is shown here. This is one of our own results which are early experimental results where we had tuned the laser you can see from 1525 right up to 1565.

This is the change in wavelength for the same constant pump power, but what we had done is we had used a band pass filter in the cavity as shown here. And by changing the band pass wavelength we could make the laser to oscillate at different wavelengths. So, this is a tunable laser same erbium-doped fiber laser, but the output wavelength can be tuned over about 30 to 40 nanometers all right.

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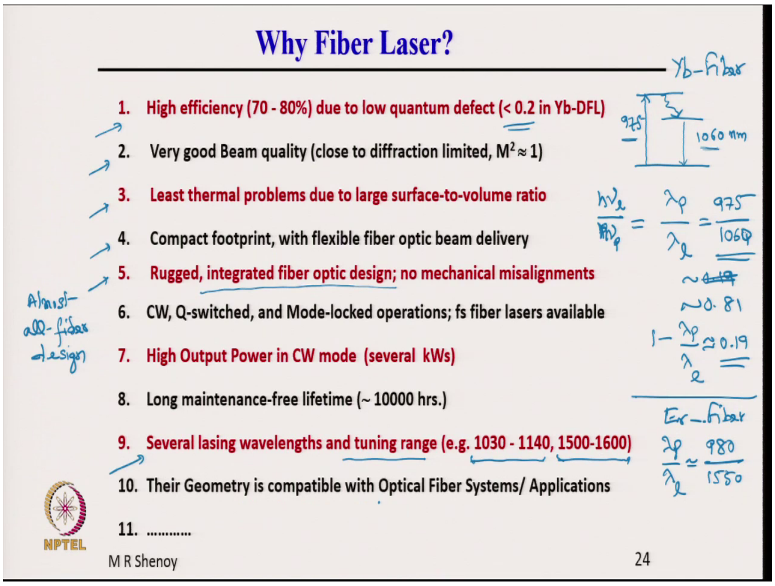

Now, I come back to the question, why fiber lasers? As before high efficiency we have discussed these numbers in detail with low quantum defect. What is this quantum defect? So, if you see a three level scheme like this, we had a 975 nanometer here pump in Yb-doped case and then it comes down rapidly here and this is the lasing wavelength.

Let us say this is 1064 or 1060 nanometer or 1030 nanometer whatever here. Then for every photon which is absorbed of the pump wavelength, there is a photon which is created at the lasing wavelength. And therefore, the maximum efficiency which is possible is simply lambda p divided by, so lambda p divided by lambda l.

How did we get this? So, h nu l is the generated photon energy, and h nu pump is so h nu p is the energy of the pump photon. And therefore, this is equal to lambda p divided by lambda l, nu l by nu p is c by lambda l divided by c by lambda p. And therefore, this is equal to lambda p by lambda l.

In this case, you see that it is 975 divided by 1064, 1060, nanometer. So, this is approximately I think 0.18 or 19, this is 1 minus. So, this is approximately 0.8, so approximately 0.81. And therefore, the quantum defect is one minus lambda p by lambda l which is about 0.19 or 0.2 that is what is written here.

So, quantum defect here indicates what is the maximum energy that you can get per photon. And ideally if 975 photon absorbed gives out a 975 at the laser wavelength, then there will be no quantum defect, but of course, we know that it is not possible.

If I show for example, if I take the, this is for Yb-doped fiber laser Yb fiber laser. For erbium-doped fiber laser, erbium fiber what is the quantum defect? So, here lambda p by lambda l, l standing for lambda laser is approximately this is 980 divided by 1550.

So, note that the fractional power which is coming out per photon is much smaller compared to the fractional power which comes out in the case of Yb-doped fiber all right. So, very good beam quality because it is a fiber output we have already discussed this, least thermal problems, it is a compact, it is integrated.

All the components I showed you that the mirror the coupler the beam splitter everything is in the form of fiber. And therefore, it can be an except for the pump laser which is a semiconductor laser all other components are almost all fiber component, almost all fiber, it is an all fiber.

Except for the pump laser, it is an almost all fiber design that is what is meant by integrated design no mechanical misalignments because all of them are fiber devices. So, all of them are spliced the fibers are spliced, and therefore, there is no mechanical misalignments.

All forms of lasers Q-switched, mode locked and tunable lasers also I showed towards the end tunable, so several lasing wavelengths and tuning range. So, this is for the Yb-doped, and this is for the erbium-doped fiber lasers. Long and maintenance free lifetime, high output powers we already discussed.

And the geometry itself is compatible with all optical fiber systems, and optical fiber applications including sensor applications. Because the output comes in the form of a fiber, and therefore, coupling it to any fiber system becomes straight forward, and there are many many advantages. It is a very important laser.

Thank you.