Fiber Optics
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Lecture – 31
Optical Fiber Components and Devices-IV

In the previous lecture we worked out the phase matching condition for fiber Bragg grating at what wavelength there would be peak reflection. We had seen the reflection spectrum, we had also seen what is the line width of the spectrum and we also understood how the coupling occurs between the forward and backward propagating modes, what is the coupling coefficient, how fiber parameters affect the coupling coefficients.

In this lecture we will continue with the fiber Bragg grating let us work out some examples and we will also look into how to fabricate these gratings and what are the applications.

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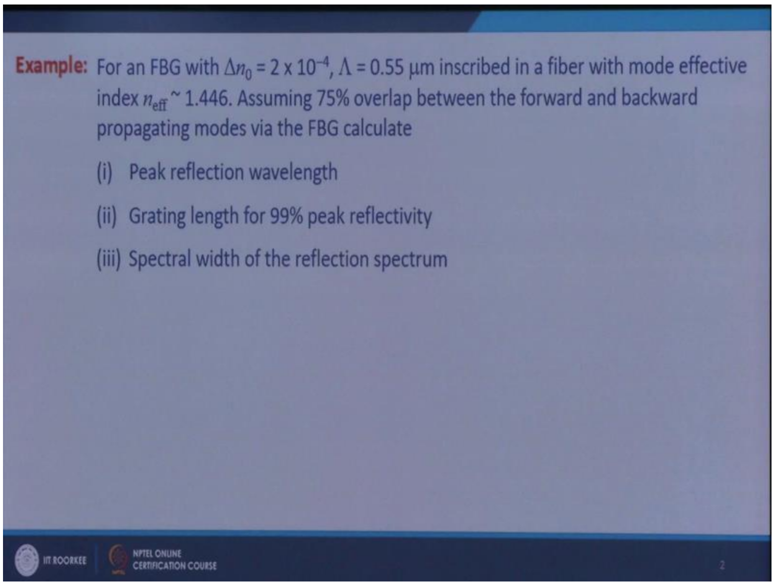

So, let us continue with the examples, if I have a fiber Bragg grating with $\Delta n_0 = 2\times10^{-4}$ and grating pitch or grating period is 0.55 micrometer and this grating is inscribed in a fiber with mode effective index 1.446. If I assume that the overlap between the forward and backward propagating modes via FBG is 0.75 or 75%; then what is the peak reflection wavelength, what is the grating length for 99% peak reflectivity, and what is the spectral width of reflection spectrum.

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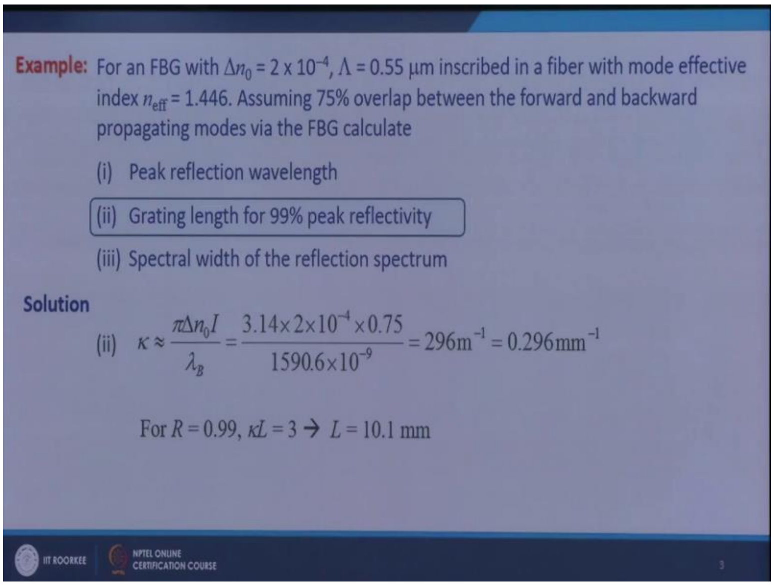

So, peak reflection wavelength is given by the phase matching condition which is $\lambda_B = 2 n_{eff} \Lambda$. So, if I plug in these numbers here then it comes out to be 1590.6 nm. What is the grating length for 99% peak reflectivity? Well I know that $\kappa = \frac{\pi \Delta n_0 I}{\lambda_B}$. So, κ comes out to be about 0.3 mm^{-1} and then I can find out the length for peak reflectivity 99%. I know that for $\kappa = 3$, $R = 0.99$ and since I have already calculated the value of κ. So, L will be immediately given by this relationship. So, it comes out to be about one centimeter or 10 mm.

What is the spectral width of reflection spectrum? So, I know that spectral width is given by this expression I have everything here, If you go back if then this $\lambda_B = 1590.6$ nm and n_{eff} is already given.

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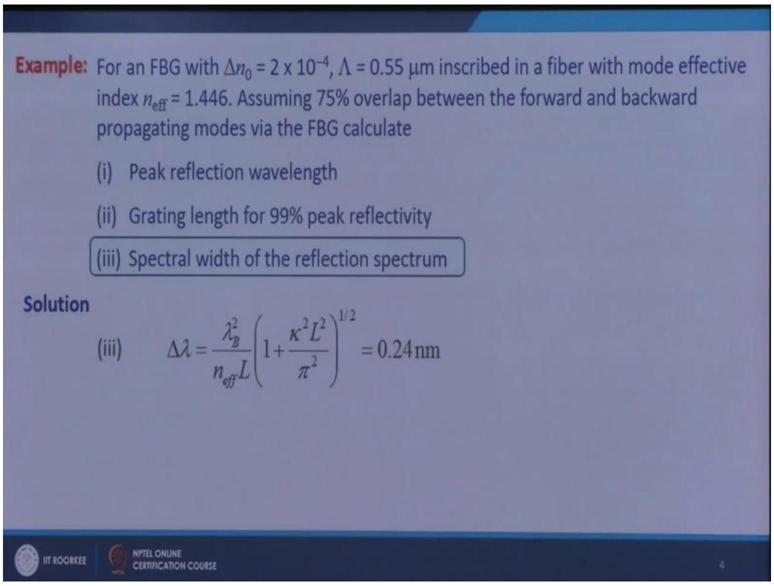

L we have already calculated kappa we have already calculated. So, if I plug in all these numbers then this width of the spectrum reflection spectrum comes out to be 0.24 nm.

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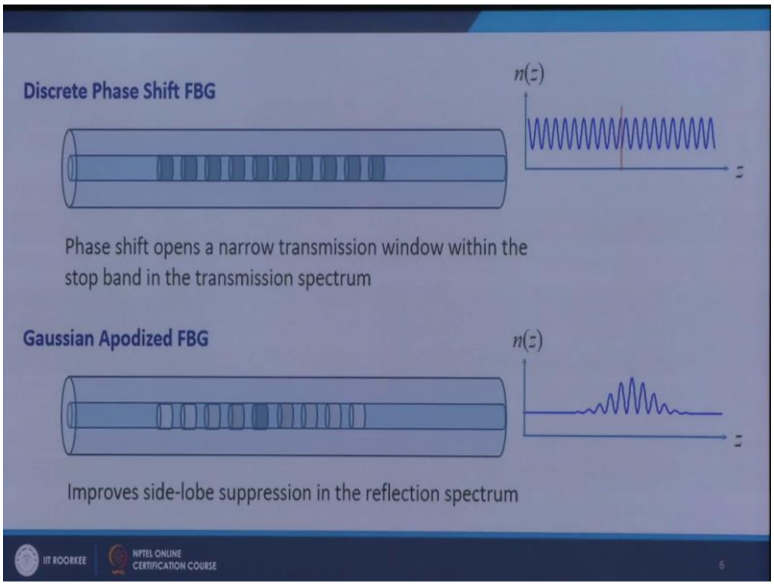

Then we I can have various types of fiber Bragg grating structures, the Bragg grating we have considered till now is uniform grating. I can also have tilted fiber Bragg grating where the grating is titled and this tilt angle affects the peak wavelength and the spectral width of the reflection spectrum. I can also have discrete phase shift grating. The grating which I have considered till now has sinusoidal refractive index variation along its entire length, but I can also introduce a phase shift here there is this abrupt change in phase that this kind of phase shift opens a narrow transmission window with in the stop band of transmission spectrum.

I know that if you have a uniform grating then in the transmission spectrum certain wavelength band is stopped around the peak wavelength, but if I introduce this kind of phase shift then in that stop band I can open a narrow transmission window. I can also have Gaussian apodized fiber Bragg gratings where the refractive index modulation is not uniform it changes and it follows a Gaussian pattern with the help of this I can suppress the side lobes in the reflection spectrum. If you recall the reflection spectrum if you look back at the reflection spectrum of the grating I have the peak reflectivity and then I have side lobes there.

So, in order to suppress these side lobes I can apodize the grating. I can also have chirped fiber Bragg grating where the grating period varies with length this kind of chirping can introduce specialized dispersion characteristics in the grating.

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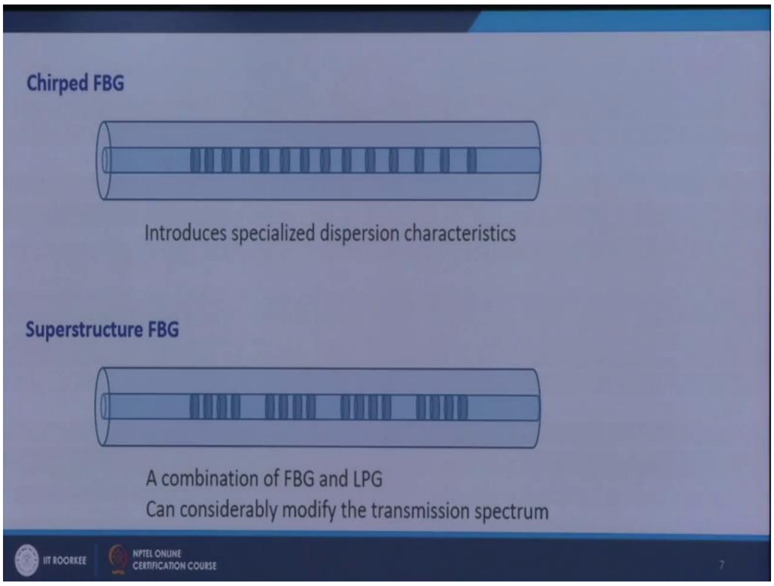

I can also have super structure of BG where I have this kind of refractive index variation then after certain distance this and this and this and this also follows a periodic variation. This is nothing, but a combination of fiber Bragg grating and long period grating and it can considerably modify the transmission spectrum of the grating.

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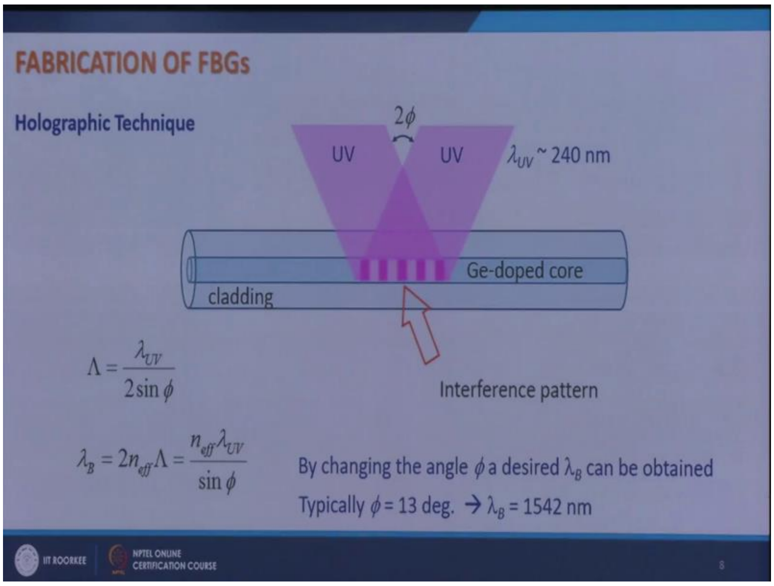

How do I fabricate grating I have several techniques to fabricate grating here I will discuss 3 primary techniques. The first one is hallow graphic technique what do you do here well you take 2 UV beams and you make them interfere and focus this interference pattern in the core of the fiber. Core of the fiber is germanium doped and here we utilize the fact that germanium is photo sensitive, it absorbs UV light and its refractive index changes and this change is permanent.

So, if I have this interference pattern of UV beams in Ge-doped core then this interference pattern will get translated into the refractive index variation and that is how I will have a grating inscribed in the fiber core. The periodicity of this grating can be tuned by the angle between the 2 beams because this angle between the 2 beams will give you the spacing between the fringes and it can be given by $\Lambda = \frac{\lambda_{UV}}{2\sin\phi}$. So, if I change this ϕ I can the periodicity and if I change the periodicity then I can change the Bragg wavelength because Bragg wavelength is given by $\lambda_B = 2n_{eff}\Lambda$. So, by changing the angle ϕ a desired λ_B can be obtained.

Typically for $\lambda_B = 1542\ \text{nm}$ $\phi = 13^0$.

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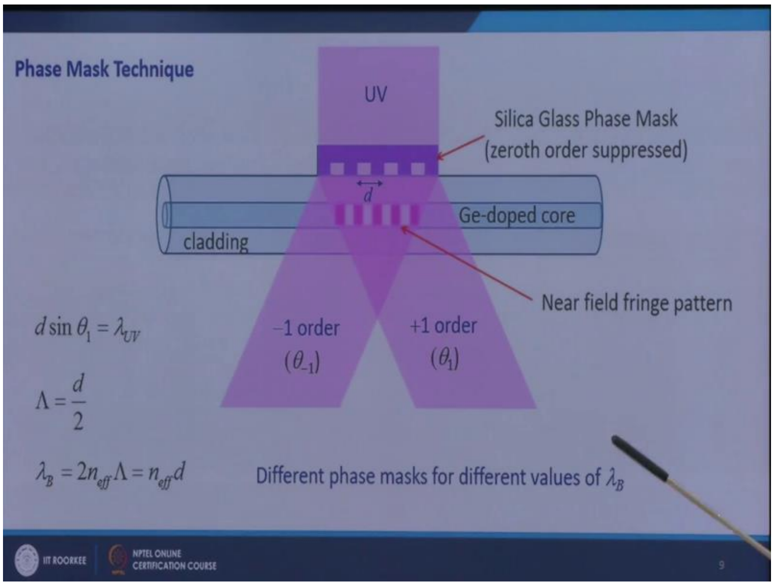

Another technique is phase mask technique what do I do here I have a phase mask which is made of silica glass and it is designed in such a way that when light falls on this phase mask then of course, it diffracts light and the design is such that the 0th order is suppressed. So, what do I have? I have plus 1 order beam coming here in minus +1 order beam coming here and these beam these 2 beams interfere in the Ge-doped core and create near field fringe pattern.

So, this fringe pattern via the photosensitivity creates the refractive index modulation in the germanium doped core and the periodicity of the grating or the grating period is given by *d/2* if *d* is the periodicity of this phase mask. So, by just changing this periodicity in the phase mask I can change the grating period and hence I can change the Bragg wavelength. I can see from here that if I want to design my grating for different values of λ_B then I will have to change my phase mask, but what are the advantages of this phase mask technique.

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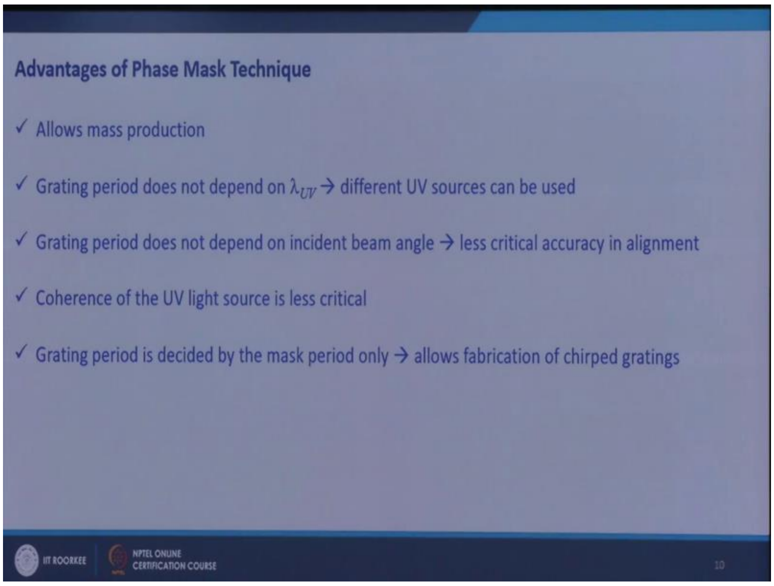

First thing is that it allows mass production, so you just create some phase mask for a given la λ_B and then you can make thousands of gratings out of that phase mask very quickly you just put the phase masks irradiated with UV beam and your grating is there.

Another advantage is that grating period does not depend upon λ_{UV} it is it does not depend on the wavelength of UV. So, different UV sources can be used. Also the grating pitch grating pitch is just $d/2$ it does not depend upon the incident beam angle. So, alignment is less critical here. And since I am not very particular about that interference pattern, so coherence of that UV light source is also less critical since the grating period is decided by the period of mask only. So, I can fabricate the chirped grating very easily only thing is I will have to introduce that kind of chirp in the mask then I can translate that into the grating also.

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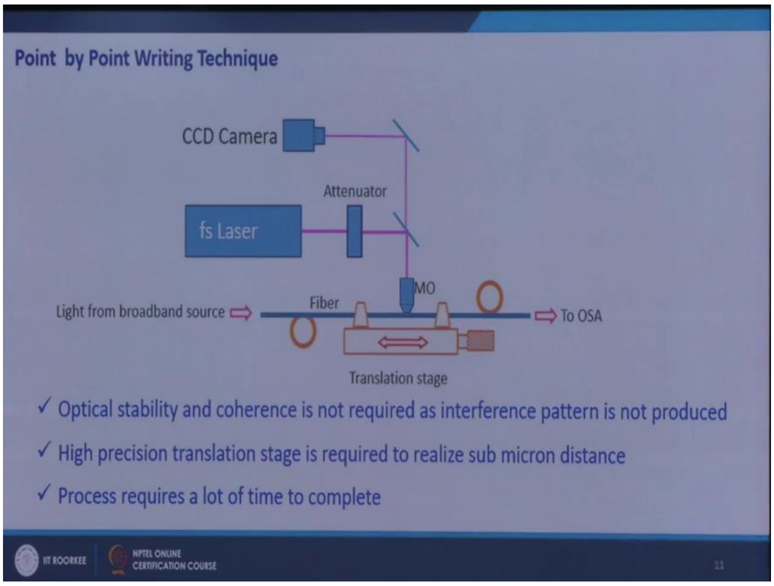

Another technique is point by point writing, what do I do here? I have a fiber which I put on a precision translation stage, I take a femtosecond laser, so short laser pulses and then I focus these laser pulses using a microscope objective of very high numerical aperture on to the core of the fiber. So, when I focus it here. So, at one point there is a laser beam at that point the germanium absorbs this laser UV light and the refractive index changes. Now, I shift this translate this fiber and then again irradiate this beam then another point is written then I again shift it then another point written. So, that is how I can write the grating point by point.

So, in such kind of setup I do not require very high optical stability and coherence because I do not produce interference pattern. Also that, but it has some limitations some disadvantages the disadvantages are I need to have high precision translation stage remember that I want to create a grating which has a periodicity of 0.5 micron. So, I would require very precise translation stage to create that kind of grating and since it is point by point writing. So, this process is very tedious and takes lot of time to complete.

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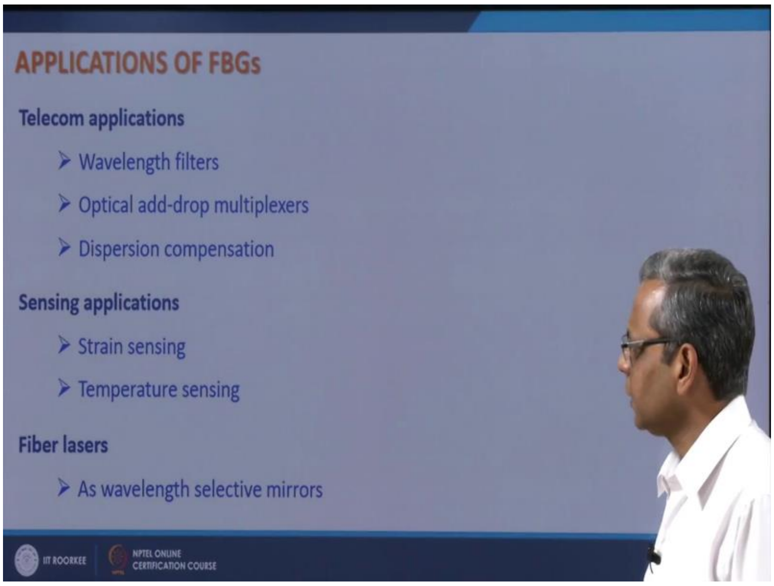

Let us now look into the applications of fiber Bragg gratings the applications I can divide into 3 parts primarily telecom applications, sensing applications and fiber lasers. In telecom applications the most obvious one is wavelength filter I can create filter for a given wavelength because that wavelength would be rejected in the transmission spectrum. I can use it in optical add drop multiplexers. So, if I have a fiber and several wavelengths are propagating in that fiber particularly in telecom applications and at one point if I want to drop one particular wavelength I can drop it, at another point if I want to add some wavelength I can add it. So, this kind of system is called optical add drop multiplexer. So, this can be realized with the help of fiber Bragg gratings and circulators.

I can also use these fiber Bragg gratings for dispersion compensation. So, out of these I will discuss here only this one optical add drop multiplexer dispersion compensation I will discuss when I do the lecture on dispersion management. Then I also have sensing applications for fiber Bragg gratings I can do sensing of strain and temperature and I can also use gratings as highly wavelength selective mirrors to make fiber lasers. So, if I have a fiber in which I create amplification of light I will discuss fiber amplifiers in the subsequent lectures. So, if have a fiber amplifier and if I put these Bragg gratings at the input and output end then I can make a laser out of it.

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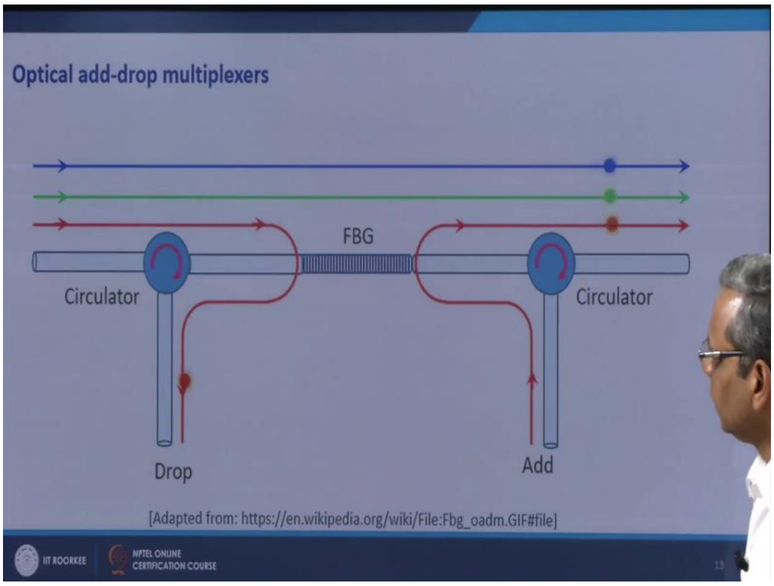

So, let us look at optical add drop multiplexer. So, if I have a fiber and it has a several wavelengths are propagating in this fiber and if I put an FBG in between this FBG has resonance wavelength which corresponds to this red then all the other wavelengths let us say this blue and green they will pass through if I incident these wavelengths from here. So, they will pass through file the red wavelength will get reflected. I use a special kind of device here which is known as circulator this circulator let pass the power which goes in this direction, but whatever power comes from this end it reflects into this *R*. This is known as circulator.

So, if the resonance wavelength of this grating is this then when I launch this light into this fiber then this circulator will let pass this light, but the grating will reflect this light and this reflected light will be rerouted into this arm with the help of circulator. So, this red wavelength will not be allowed to pass through it will be dropped. Similarly, if I want to add this wavelength then I launch this wavelength from this end this will go here in the fiber Bragg grating will reflect it and reflected wavelength will come from this side.

So, this is how an optical add drop multiplexer can be realized using the combination of fiber Bragg grating and circulators.

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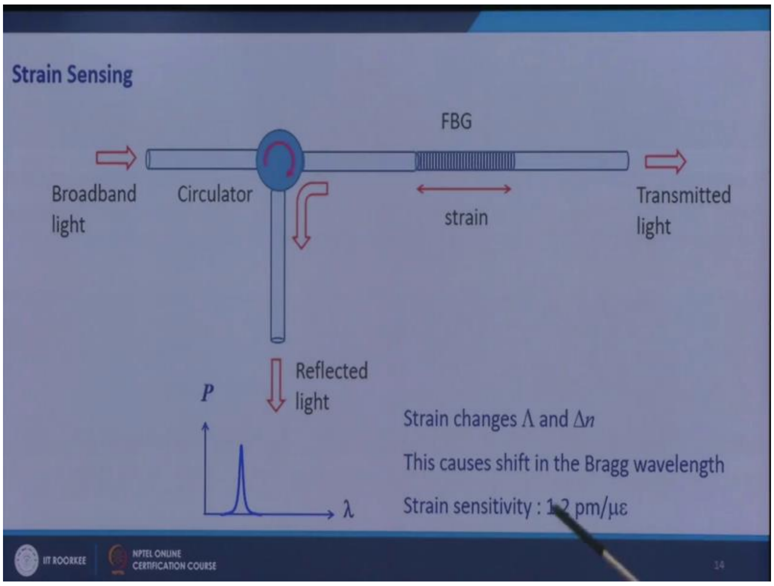

I can do strain sensing with the help of this fiber Bragg grating I use the fact that if I apply strain here this strain can change the periodicity of the grating and Δn and if periodicity is changed or effective index is changed Δn is changed then it can cause shift in Bragg wavelength because I know Bragg wavelength is $2n_{eff}\Lambda$.

So, there would be a shift in Bragg wavelength and if I measure the shift in the Bragg wavelength then that can give me an estimate of strain. So, this is how it works if I apply the strain the Bragg wavelength will shift. Typical strain sensitivity that can be obtained using these Bragg gratings is $1.2\, pm/\mu\varepsilon$. I can also do temperature sensing if I change the temperature then it changes Λ and Δn and this also causes shift in Bragg wavelength and by measuring the shift I can sense the temperature.

Typical temperature sensitivity that can be obtained is 10 pm/^{0}C. So, in both the cases if you look the experimental set up is similar it you launch light into the fiber Bragg grating inscribed in a fiber using a circulator. So, this is the broad band light you incident. So, broad band light goes there one particular wavelength is reflected back and is collected here this you can feed into optical spectrum analyzer or any wavelength meter. Then you find out the peak reflection wavelength and when the temperature changes or a strain changes then this will shift the Bragg wavelength.

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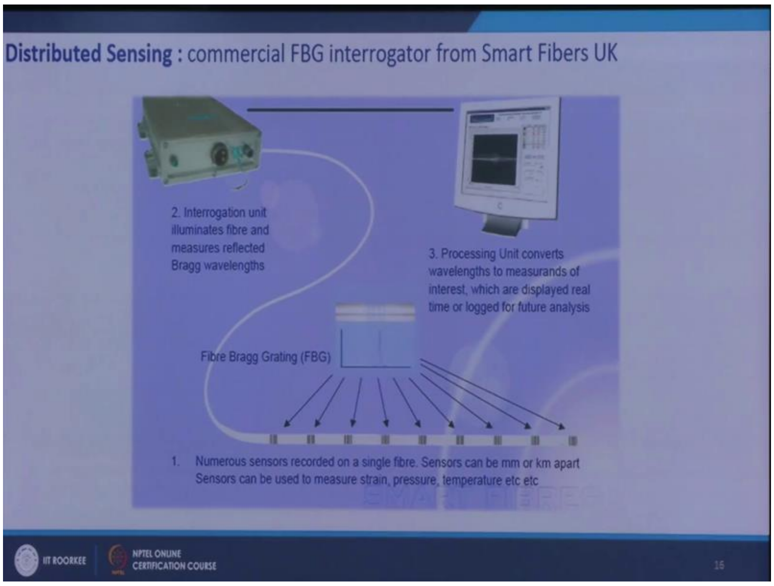

This is a typical distributed sensing system which is commercially available and this one is from a smart fibers where what you can do is it is the amazing thing that you can use a large number of gratings and do distributed sensing. These kind of structures can be used for example, in flyovers kilometers long flyovers. So, if there is let us say 1-kilometer-long flyover and if you want to if you want to sense the strain at different point let us say 100 m apart. So, you can put several gratings every 100 m you can put several gratings every 100 m you can put one grating and each of these gratings will have different Bragg wavelength.

So, when you launch light from the broad band source and then collect the reflected light coming from different gratings then the same device basically works as the interrogator you connect it to the computer and it will show you the Bragg wavelengths λ_{B1}, λ_{B2}, λ_{B3} and so on. And you know that these λ_{B1}, λ_{B2}, λ_{B3}; correspond to what points on the flyover then you can do continuous monitoring of these Bragg wavelengths and if I see that one particular wavelength is shifting let us say λ_{B3} is shifting then you know that something is happening at point 3. So, in this way you can have distributed sensing and these kind of sensors can be used to measure strain pressure temperature etc etc.

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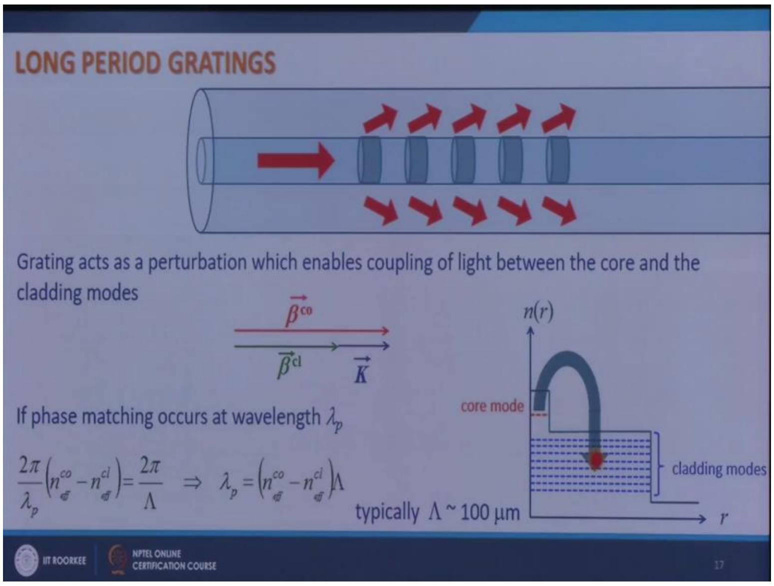

Now, after fiber Bragg gratings let me discuss another kind of grating which is long period grating. If you remember that in fiber Bragg grating there is coupling from forward propagating mode to backward propagating mode and both the modes are core modes guided modes. Here in this case what is done you incident light in the forward propagating core mode and this grating couples light from core mode to cladding modes, if you actually look into the structure of fiber this is the refractive index profile I have a small core and then I have a large cladding after cladding there is air.

So, I have this which is the core mode, but since this cladding is also finite then it also has certain modes and since it is very large then there are large number of modes here which are very closely spaced. What I can do with the help of this periodic perturbation? I can couple light from a core mode to one or more cladding modes and this coupling would be efficient if the phase matching condition is satisfied. If I look at the propagation constant of the core mode it is this and the propagation constant of cladding mode is this. So, in order to complete the phase matching I need to have this $\vec{K}$ and this $\vec{K}$ is provided by this grating if grating pitch is Λ then this $\vec{K}=\frac{2\pi}{\Lambda}$.

So, if the phase matching condition is satisfied at wavelength λ_p then this give $\frac{2\pi}{\lambda_p}(n_{eff}^{co}-n_{eff}^{cl})$ it should be equal to $\frac{2\pi}{\Lambda}$. This is nothing, but $\beta_{core}-\beta_{clad}=K$ and this gives me

$\lambda_P = (n_{eff}^{co} - n_{eff}^{cl})\Lambda$. And since the difference between the propagation constants or the effective indices of the core and cladding modes is not very high then this Λ is much larger because this is a small and $\Lambda = \frac{\lambda}{\Delta n_{eff}}$ is lambda divided by this delta *n* effective. So, Λ is much larger typically it is 100s of microns.

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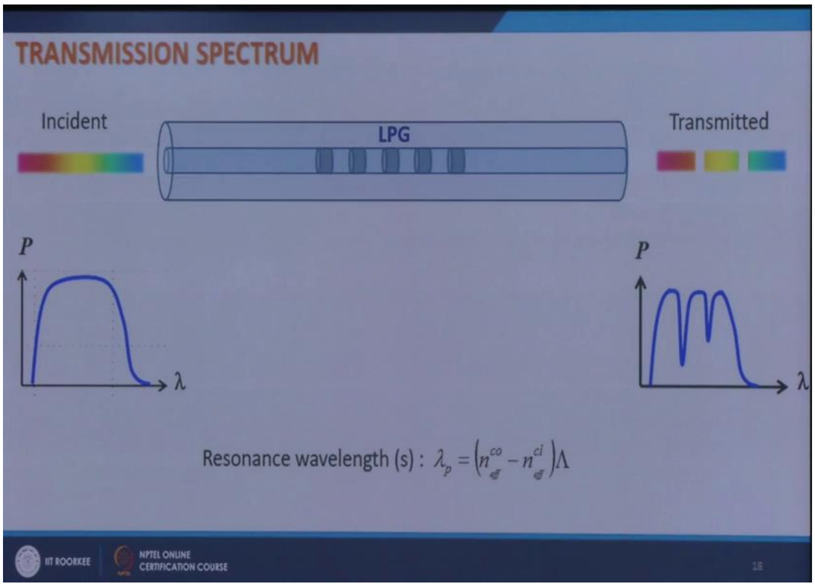

If I look at the transmission spectrum, so I incident light from broad band source into this then at certain wavelengths light will get coupled into cladding modes. You can see that for a given value of capital lambda, you can have coupling at one wavelength from the core mode to one cladding mode and at another wavelength from the core mode to another cladding mode. So, you can have various rejection bands here multiple rejection bands; phase matching condition can be satisfied for a given Λ for various combinations of λ_p, n_{eff}^{co} *and* n_{eff}^{cl} .

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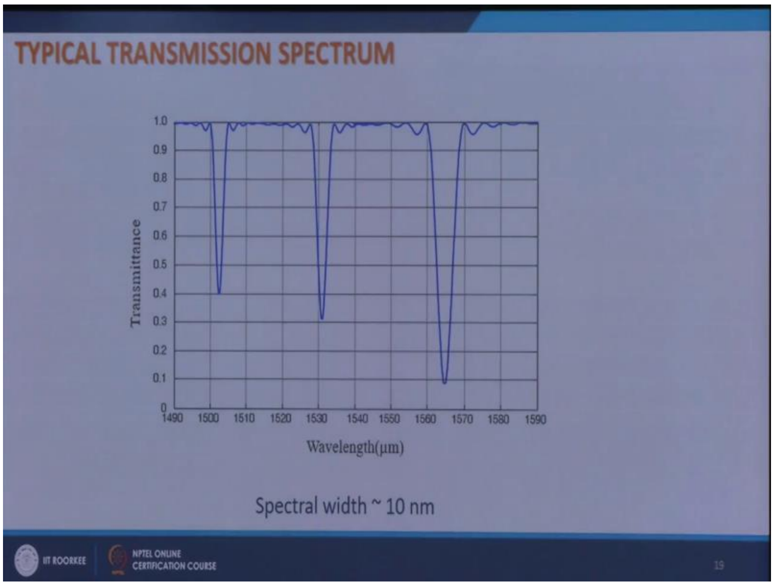

This is the typical transmission spectrum of a long period grating where the coupling is from core mode to various cladding modes. If you look at the spectral widths of these then this spectral widths here are much larger these are of the order of 10 nm. Remember that in fiber Bragg grating, the spectral width was very small 0.1-0.2 nm here it is 10s of nm.

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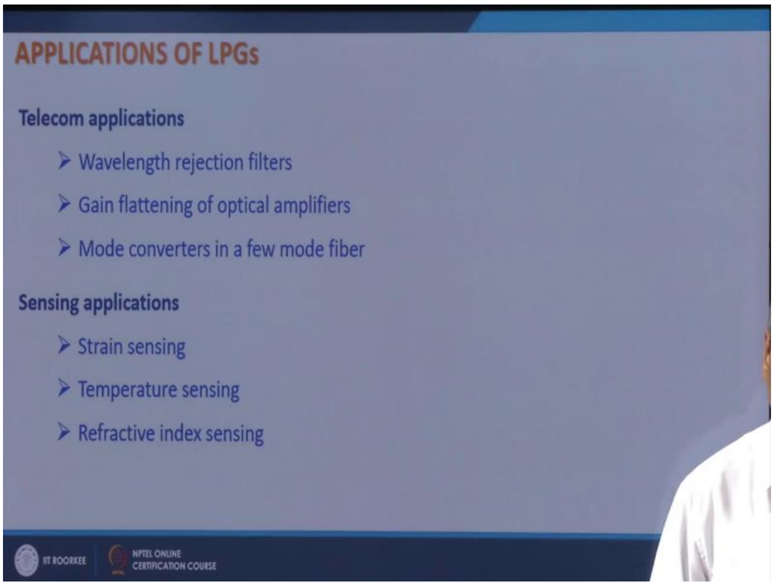

What are the applications? Applications are in telecom and in sensing systems, you can create wavelength rejection filters using long period gratings, you can flatten the gain of optical amplifiers because you can create rejection filters. So, you can flatten the gain I will describe this. You can also make mode convertors in a few mode fiber, if you have few mode fiber then you can convert LP_{01} mode into LP_{02} mode and so on if you inscribe a right long period grating. So, instead of coupling light from core mode to cladding modes if you couple light from one core mode to another core mode then it you can make mode convertor.

Then you can also have sensing applications just like you had with fiber Bragg gratings, you can have a strain sensing, temperature sensing and also refractive index sensing, if you expose the core of the fiber with the external medium or analyte of different refractive indices. So, here I will just discuss this gain flattening of optical amplifiers.

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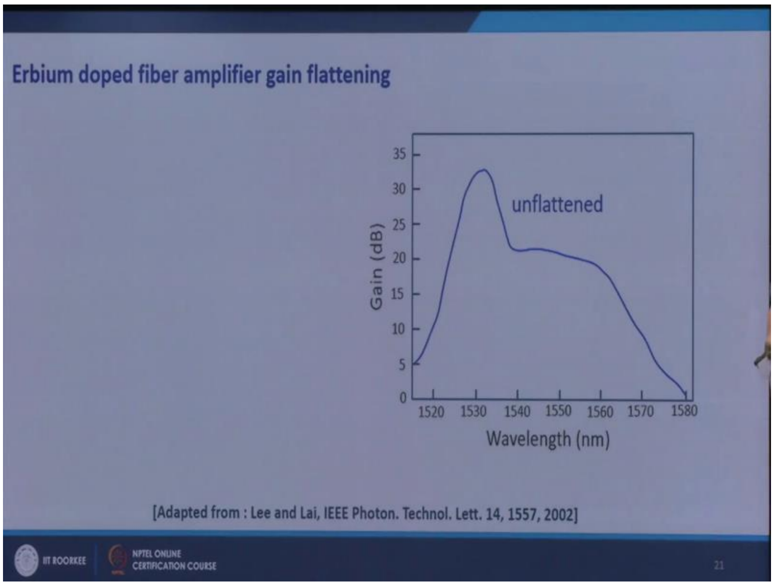

So, here you have a typical optical amplifier which is erbium dope fiber amplifier it has a gain spectrum given something like this.

What do I see here, that in this gain spectrum there is a big peak here and for telecommunication purposes I need to have a gain spectrum which is flat. So, if I want to remove this peak then I can use long period gratings. So, if I design my long period grating whose rejection band is like this then I put this grating in that amplifying fiber then this would be rejected according to this filter and I can obtain the flattened gain.

With this I finish discussion on fiber gratings. In the next lecture, I would look into few more devices which can be made using optical fibers.

Thank you.