Semiconductor Optoelectronics
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Lecture - 46
Photonic Integrated Circuits

Welcome to this last lecture of this course, semiconductor optoelectronics and I call this last lecture as epilog. So, let me first recall what we had studied in this course. Then we will discuss the topic that is, integrating various devices semiconductor optoelectronic devices into a photonic integrated circuit.

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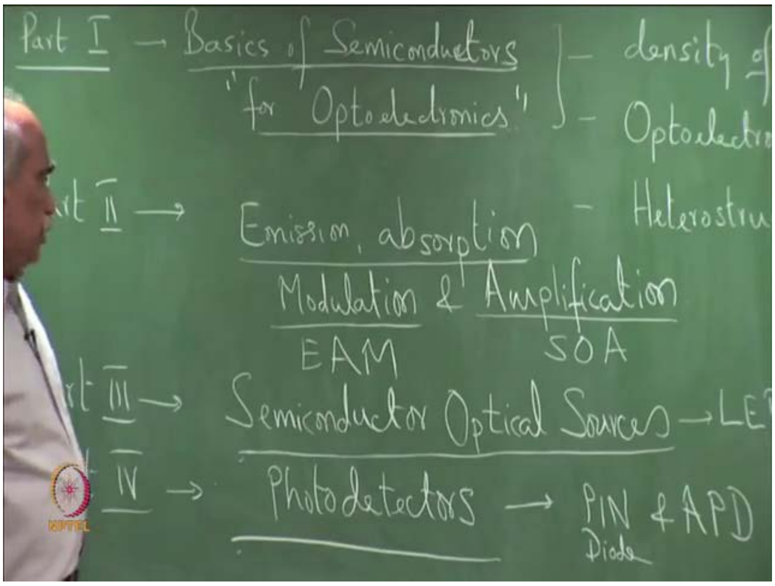

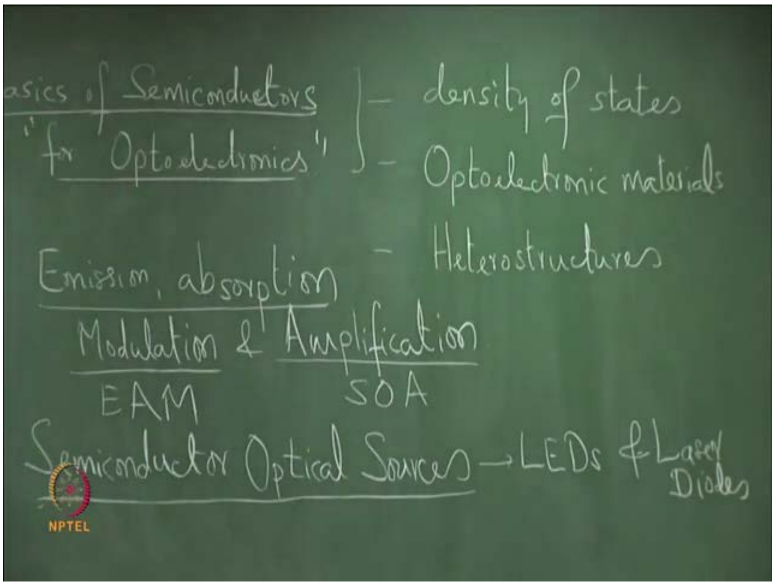

So, we started with in part one. So, in part one. Let me just recapitulate. We discussed about the basic, basics or basic physics of semiconductor optoelectronic devices. That is basics for basics of semiconductors basics of semiconductors semiconductors for optoelectronics. Semiconductor physics as we mentioned is a very broad topic. We have covered only the essential part of it for optoelectronics, semiconductor optoelectronics. In particular, we have discussed here density of states. Density of states because as we have seen through the course density of states play an important role plays an important role in the device characteristics and device performance. We then discuss about semiconductor optoelectronic materials.

So, materials for optoelectronics. Optoelectronic materials, semiconductor materials for optoelectronic and also we discussed about the heterostructures heterostructures and need for heterostructures. In the second part, in part two of the course, in part two we discussed about emission, absorption, emission absorption absorption modulation modulation and amplification amplification.

In particular we have discussed two devices here. The Electro absorption modulator EAM, electro absorption modulator and the Semiconductor optical amplifiers SOA. So, two devices we have discussed in this part, electro absorption modulator and Semiconductor optical amplifiers. Then, we came to part three part three, which was semi-conductor optical sources semiconductor optical sources semiconductor optical sources.

Here, we have discussed about the light emitting diodes LED’s and a variety of laser diodes laser diodes. Finally, in part four, in part four part four semiconductor photo detectors photo detectors. So, here we have discussed about of course, the PIN and APD in particular PIN and APD, pin diode and other detectors.

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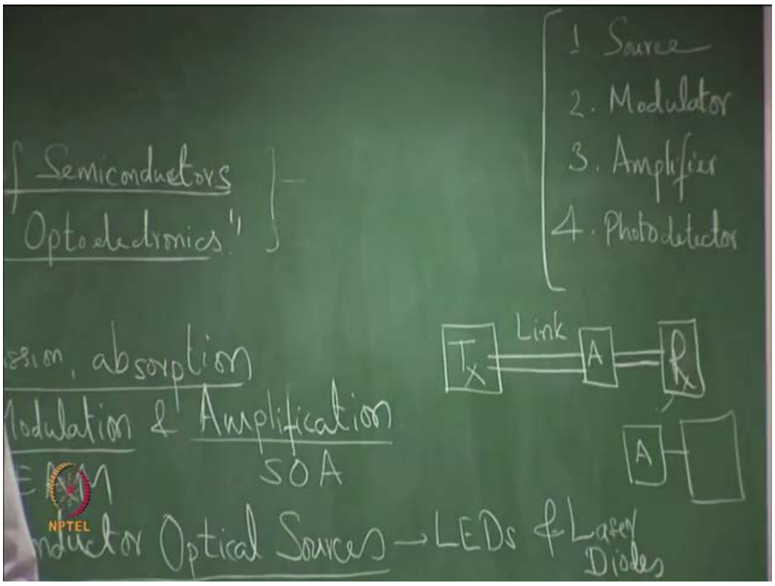

So, if I may list the modulator, the amplifier, the source and photo detectors. So, we have the modulator, the source, source modulator, modulator, the amplifier, the amplifier and of course, the photo detector photo detector. These are actually the basic ingredients of a communication system. So, a communication system as we started in the first class has a transmitter here. A transmitter, a link which is of course, a passive link, there could be amplifiers here, amplifiers. Then finally, the detector, the detector or the receiver the receiver, transmitter, link, amplifiers in between there may be amplifiers and receiver.

So, the transmitter apart from the electronic circuitry, comprises of a source an optical source in optical communication an, optical source and a modulator. There could be a power amplifier, which boost the power at the transmitter itself. There could be inline amplifiers and similarly, at the receiver we may have a pre amplifier. The receiver would have a pre-amplifier, an amplifier here. Then of course, the processing circuits, which may comprises of filters, photo detectors and de-multiplexers and so on. So, these are the important basic building blocks of a communication system. Just as in the case of electronics, where several components could be combined or could be integrated on a single chip. The question, is it possible to integrate these devices? We have studied the devices independently, a standalone devices. But is it possible to integrate these and that brings us to what are called PICS or Photonic integrated circuits?

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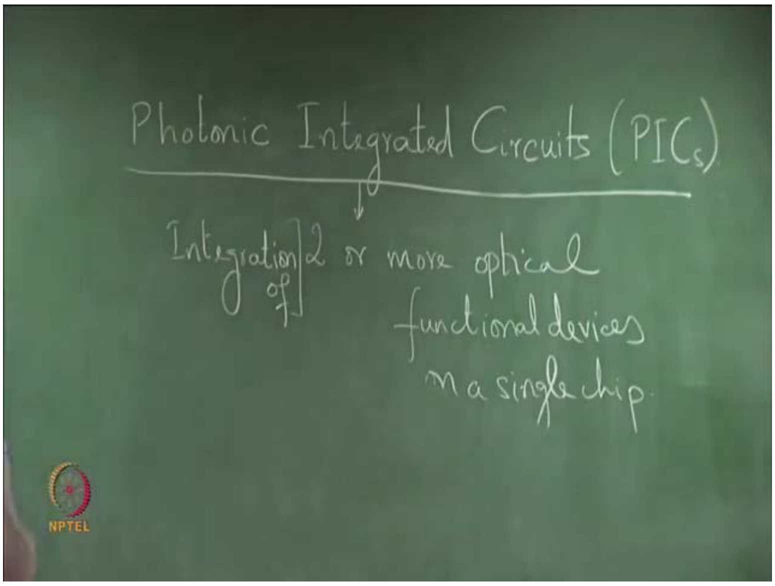

Photonic integrated circuits integrated circuits or simply called PICS, PICS photonic integrated circuits. As the name indicates, it is refer to integration. This refers to circuits or devices where two or more two or more optical functional devices, optical functional devices functional devices. It is refers to integration of integration of integration of integration of two or more optical functional devices on a single chip for a substrate on a single chip. PICS PICS are picking up, now they are becoming important. So, let me briefly discuss some aspects of these Photonic integrated circuits. As I have written it refers to devices, which have two or more several functional devices on a single chip.

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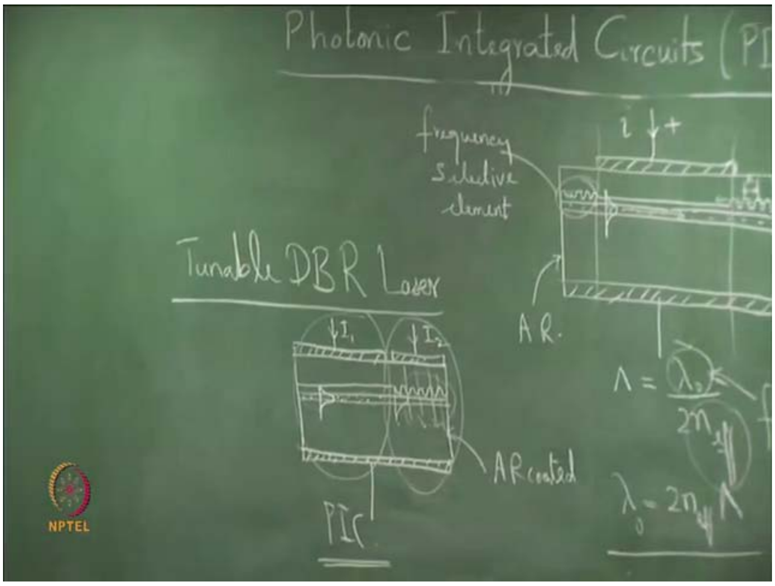

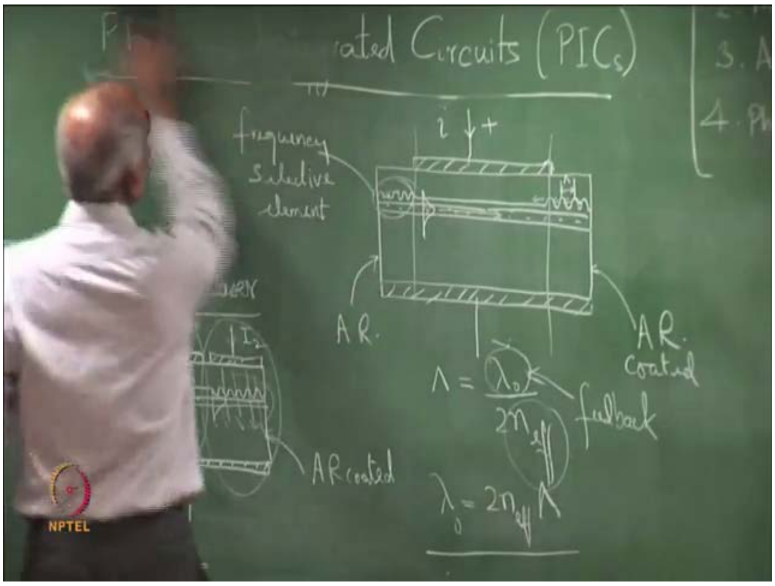

A simple example would be. So, let me pick a simple example of a tunable DBR lasers because the functional elements. The functional devices could be passive devices or active devices. There could be passive devices or active devices. So, let me pick up a this tunable DBR. We have already discuss DBR laser distributed brag reflected laser. Recall that the DBR the DBR laser has has a double hetero structure. The lasing active region here and this may have one or two frequency selective elements. What we have discussed earlier was with two frequency selective greetings at the two ends.

So, this is what we had discussed and this is a longitudinal cross section longitudinal cross section of the device. The device is like this. We are looking at the longitudinal cross section, the simplest longitudinal cross section. Here is the metal electrode and the electrode here, there are may be many more layers here. Just showing the essential layers, so the gain region. So, here is the optical mode which propagates which propagates, along the double hetero structures here. These are the electrodes say plus minus a current i flowing through this. The two ends are AR coated Anti reflection coated.

AR coated AR coated to avoid any reflection from these ends because we need these frequency selective gratings. So, these are the frequency selective ratings. Frequency this is the DBR not the tunable DBR. Discussing the DBR that we have already discussed. Frequency selective element element, the period is the periodic structure. So, the period here, lambda. The period is such that if we choose lambda is equal to lambda 0 divided by 2 n effective, where n effective is the effective index of the optical mode. Here is the optical mode, the optical mode, which is propagating back and forth. If the period is such that it is equal to lambda 0 by 2 n effective. Then, lambda 0 the wave length here, this is the optical wave length, this is the grating period.

Lambda 0 would reticently get reflected at these periodic structure. The periodic grating leading to feed back at this wave length only. So, feedback comes at this wave length, which means feedback. That is so essential for laser oscillation, comes only at this wave length. They are by they are by leading to realization of a single frequency laser or if laser oscillating at one frequency. One frequency we referred to one longitudinal mode. Of course, there is a finite frequency spectrum associated with it. So, this is the DBR that we had studied. So, there is a there is a passive frequencies selective element here and this is the gain medium the gain medium. Laser oscillation takes place because of these frequency selective.

The single frequency oscillation is ensured by the periodic structure. In a tunable DBR structure, if I, there is no need of having both the frequencies elective elements. We can have only one of the frequency selective element. In a tunable two segment tunable DBR, we have this region. There is a active region right up to the end. Then the cladding region, in the cladding region we have the periodic grating over the over one end of this. We have this end anti reflection coated AR coated AR coated.

This has two separate electrodes. Now, so, the laser is treated as a two segment device here. There are two electrodes. So, there is current I 1 and current I 2. So, the current I here again longitudinal cross section of the device. This is what we had already discussed and here we have a device, where we have two currents passing through the same device. There are two electrodes. The current I 1 primarily determines the gain here. This is the active region the active region and the more propagates here the more propagates through this structure.

The active region the current I controls the gain of the active region and helps the power output. Whereas, the current I 2 here I 2 is primarily to control the selected frequency because a current injection leads to current injection leads to a variation in the refractive index. As we have already seen in this case, the current was not flowing through the periodic grating element here in the ends. Current was flowing only through the active region. That is the gain is provided only here in this. So, there are no current flowing here. Therefore, the frequency selection is done by these gratings, even if you vary the current here. The frequency is do not change because frequency selection takes place in these region by these gratings.

However, in this case because current also flows through this here, the frequency, choice of frequency which oscillates will depend on the end effective, which depends on the refractive index of the mode. Refractive index of the region is here. Therefore, n effective can be effected. So, we have lambda oscillation is equal to twice the n effective into lambda here. The lambda oscillation can be varied by varying the n effective. lambda the grating period is fixed grating period is fixed by changing this n effective. It is possible to vary the frequencies of oscillations. So, we have two different currents here. One current to determining the power and the gain in the medium, the second current determinings the injections of carriers into this.

So, that the variation of effective refractive index in this region is determined by the second current. Therefore, n effective is controlled by the second current. Therefore, the output frequency is controlled by the second current I 2. Please see, that this has two segments. Two functional elements, one is the gain region and the second region is a frequency selective element, is a active both are active regions. The frequency selective element is here. So, this is for example a simplest PIC. A two segment a two element PIC photonic integrated circuits.

We can have many more complicated and complex PICs. For example, if we take a WDM transmitter or a receiver. The current day WDM systems using a PIC, if you were to realize a WDM transmitter or a WDM receiver using a PIC. The general layout would be like this.

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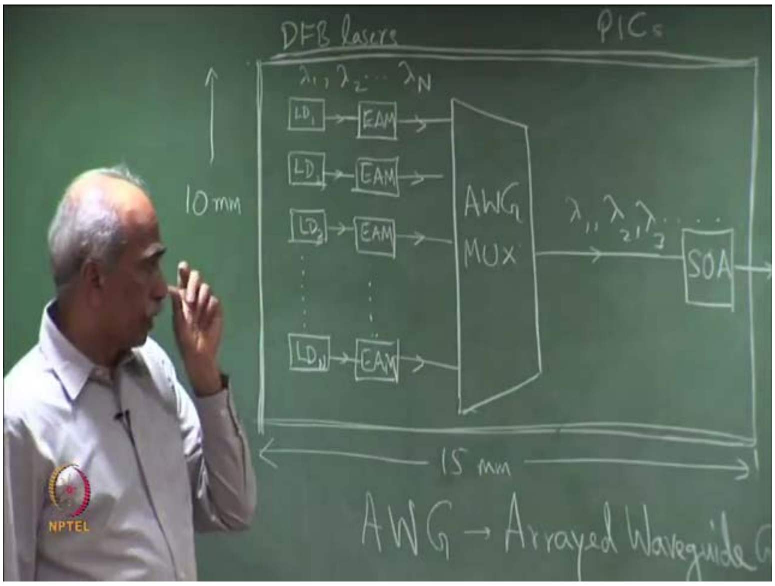

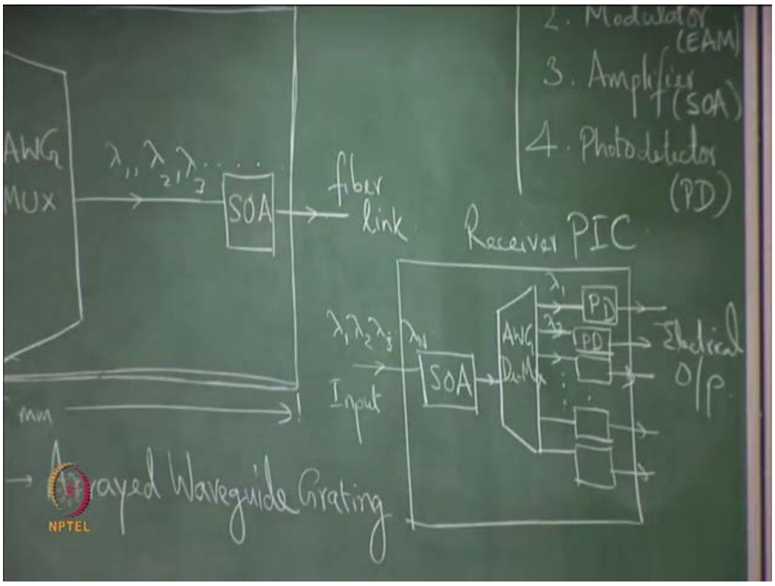

Let me show the layout. So, we have lasers. Let say a 10 channel WDM system or a 40 channel WDM system could be 10 GBPS. More recently there has been work reported were a 100 GBPS, 10 channels of 100 GBPS systems where integrated on a single PIC to realize transmitters. These are the L D, L D 1, 1 standing for lambda 1. So, this is wavelength 1, L D 2, L D 3 and so on. So, these are DFB lasers. So, DFB lasers, single frequency stabled DFB lasers. L D N. If there are N wavelengths, so lambda 1, lambda 2 etc. lambda N. N channels. The output of laser diodes here passes through a modulator, which is an electro absorption modulator EAM. EAM The second device modulator EAM.

So, this is L D. Laser diode. Here we have EAM electro absorption modulator. This is an SOA amplifier and this is a photo detector photo detector. May be pin or a. So, EAM electro absorption modulator EAM 1 2 and so on. So, let me write it EAM. The output of these there could be more elements. There could be amplifier right here or the output of these goes to a mux. A AWG mux. So, this AWG mux AWG mux. AWG stands for Arrayed wave guide gratings. Let me briefly discussed about this. AWG, Arrayed waveguide gratings. These are now almost one of the fundamental blocks building blocks in WDM and DWDM PIC transmitters. Transmitters based on photonic integrated circuits. So, AWG here.

So, this is lambda 1 lambda 2. The output, this is a MUX multiplexer. So, we have N lambdas here to here is the output, which has all the wavelengths coming here lambda 2 lambda 3 and so. There could also an SOA here. So, just so, there could be an SOA before it goes over to the transmission line to the fiber link. So, this whole thing could be integrated. For example, on a single semiconductor chip the whole thing. So, there are reports of realizing such PICs. So, PIC this is a PIC. Typical dimension could be 10 mm by 10 mm. So just I am giving some typical idea, what is the dimension that we are talking so 10mm by 10 mm or 15 mm 15 mm as a kind of dimensions that we are talking up for a PIC. This is a PIC transmitter, is a WDM transmitter. This could be a DWDM transmitter and a multiplexer.

So, we have laser diode. The first device there. EAM electro absorption modulators and of course, multiplexers have not discussed this multiplexers because this is not a semiconductor active device. It is a passive device, this multiplexer is a passive device. Let me briefly discuss this and then as you see the SOA is here. The receiver could be. So, let me draw the receiver as well, very briefly. So, here is the receiver the input with all the wavelengths lambda 1 lambda 2 lambda 3 lambda N, enters the PIC here, the input. First it is usually as a there is a pre-amplifier SOA, an SOA pre-amplifier. Then followed by the D-MUX, so D-MUX, AWG D-MUX there could be more components AWG D-MUX AWG D-MUX. Then it goes to the different channels, different wavelengths going to different photo detectors.

So, photo detectors. So, the input containing all the wavelengths are amplified by an appropriately chosen SOA. There may be gain flattening filters associated with this. So, that there is a flat band, flat gain band, which is followed by a D-MUX AWG D-MUX.

The different wavelengths are then send to high speed photo, these are high speed photo detectors lambda 1 lambda 2. The output of the photo detector of course, will be electrical here. This is this course to further electronic circuitry. So, electrical output for further processing electrical output for processing. So, this is a receiver PIC or PIC receiver. As we can see almost all the components of a current modern transmitter and receiver.

We have discuss the basic building blocks. This course except the AWG MUX, which is a passive waveguide device. Currently there are hundreds of such components integrated on a single chip. So, initially there are knowingly lasers and modulators or modulators and then at the output photo detectors, amplifiers and photo detectors where amplifier and photo detector were integrated. But now hundreds of components are integrated to realize a single photonic integrated circuits. We all know the importance of integrating component ICs. The importance of electronic ICs we know there of course, tens of millions hundreds of millions of components are integrated on a single chip. Comparatively the numbers are very small. The numbers of components integrated on a chip is much smaller compared to the millions or nearly billion component on a single chip. Nevertheless the advantage of integrating components.

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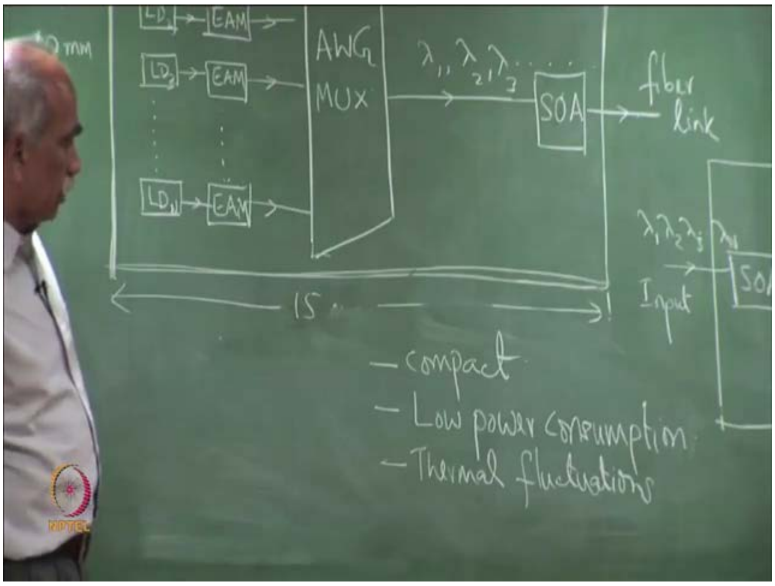

For example, the Advantages of integrating components is very well known. The first one is of course, compact it makes a compact device. Most important very low power consumption, low power consumption. Much less sensitive to thermal fluctuations thermal fluctuations, because the entire chip is maintained at unlike discreet components. The entire chip is maintained at a particular temperature and many more advantages reliability and so on.

So, the same advantages are true for these as well and PICs are picking up in a big way in the current optical communication scenarios. So, let me before I wind up let me just briefly discuss this AWG is very interesting device very interesting optical device, which can, which is, which can be analyzed by classical theory of diffraction. The design comes from the classical theory of diffraction of light. So, let me consider a De multiplexer AWG De multiplexer. So, in the remaining 10, 15 minutes let briefly discuss the idea of a AWG MUX, De MUX. So, here is the AWG.

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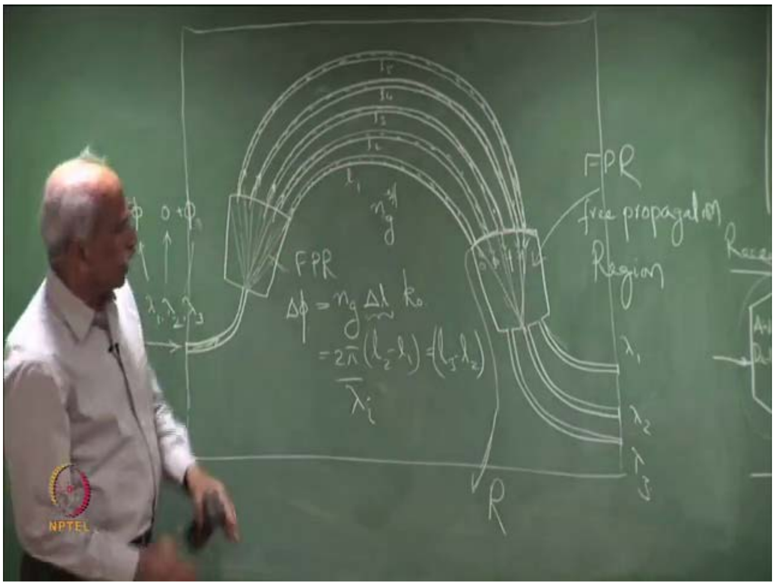

So, let me start with arrayed wave guides. There is a there is an arrayed of waveguides. Some drawing practice here. It is an array of waveguides. I am showing only a few of them in practice the number of waveguides. So, these are the waveguides. So, what we see is top view of a chip. So, in all the diagrams that I have drawn here, what we have seen is the top view. So, it is a looking from the top. So, this the chip is here and what we are seeing is the top view of a chip. An array of waveguides, okay? Let me show all of them without leaving any gap. I think you will have 5 wave guides.

The number could be much larger, but I have chosen 5 here, just to distinguish. So, these are optical waveguides. So, channels light channels here. So, which enters here, the channels, which are opening into this free propagation region. These are FPR free propagation region FPR free propagation region. So, I am showing this De Mux. Free propagation region. This is another FPR. FPR So, here is the input, that is this input. The input which is entering the De MUX is here. So, here is the waveguide. An optical waveguide made on the semiconductor chip. So, here is light entering, this all the wavelengths lambda 1 lambda 2 lambda 3. Let me pick three wavelengths, three wavelengths, just three wavelength to illustrate three different wavelengths, which are De multiplexed, three wavelengths.

I will not go into the design mathematics, but concepts concepts only. I will just, be able to discuss the concepts. So, the three wavelengths lambda 1 lambda 2 lambda 3. So, let say this is the there may be several components on a single chip, but I am showing that this is an AWG chip. So, lambda 1 the input is the multiplexed wavelength stream and output is lambda 1 lambda 2 lambda 3, which could then be coupled to optical fibers if required or it could be coupled to the photo detectors. Light, which is entering here the multiplexed channels. So, this is a free propagation region. So, there is a there is a diffraction taking place.

So, light diffracts in into all the channels. Here, all they are actually quite close. So, light enters, so there are many. Therefore, almost all the light is collected but I have shown only four. So, it looks as it there is a large gap. But a major part of the light which is propagating through here is collected by these waveguides or they excite the modes of the waveguide, which then propagate along this arc. As you can see that if this is l 1 length l 2, l 3, l 4, l 5. Usually they are all of the same dimension. So, that the model effective index n effective of the guide or n g n effective of the guides the guides wave guides are identical.

So, if l 1, l 2, l 3, l 5 are different are lengths of the various waveguides here, then when they reach here, there is propagation delay, between the adjacent there is a phase delay between the output which is coming from here, output which is coming from here and so on. The phase delay or the path delay the path difference is delta l. If delta l into n g is the path difference multiplied by of course, k naught will give you delta phi. So, this delta l here corresponds to l 2 minus l 1 or equal to… Generally, they are the this can be taken such that, they are equally separated or l 3 minus l 2 and so on.

So, the light which is reaching here has a constant phase difference a constant phase difference between the light which is emerging from here. We, see that these are all the single frequency lasers. Therefore, the coherence lengths are very large and therefore, even if we have a phase difference here a path delay. They are all well within a coherence length. So, all of them with respect to this, if I say the phase phase here is phi naught or 0 . Then this phi, this is 2 phi, this is 3 phi and this is 4 phi and so on. So, they come at different phase differences. It is possible that this phi could be integral multiple of 2 phi in which case all of them are in phase. Or they could be in different phases. So, depending on the phase difference phi the output the output could depending on…

So, this is (( )) phi is equal to k naught. These equal to 2 phi by lambda. So, lambda is different for the different wavelengths. Therefore, if lambda 1 enters from here, let us say that the phase difference corresponding to lambda 2 is 0. Phi is equal to 0, then the phase difference will have a certain minus 5 here corresponding to lambda 1 and corresponding to lambda 3, this could be plus 5. The phase differences are different here for the 3 different wavelengths. If the phase difference is 0, then all these waves when they propagate because they are situated on a arc of certain chosen radius there is a radius R here. Radius R here

So, that all of them focus to this wavelength. So, all of them all the lights which is coming from here are in phase. Therefore, when they diffract they focus at one particular wavelength one particular spatial point and there this wavelength this waveguide is located at that special point, which means that particular wavelength will come through this waveguide. It is easy to understand this, if we recall the basic theory of diffraction from multiple point sources in the theory of diffraction.

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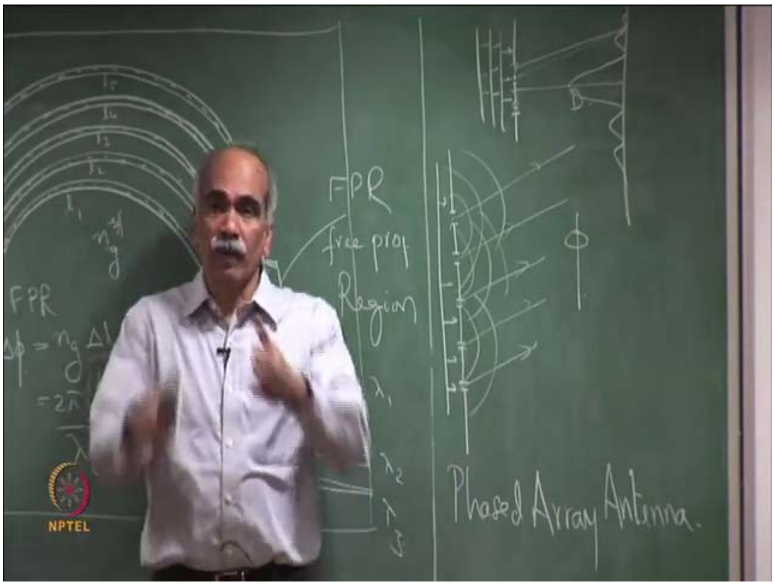

From a single slit, we may recall or phased array antennas. So, those of you are familiar with phased array antennas. So, we have point sources or sources here, which are the sources are emitting in if I considered this as optical sources. They are point sources. If I considered this as point sources, then each one of them is emitting this. If the input here is a plane way, which means all the point sources, so this is the input. What I am describing is diffraction by a single slit. So, we are all familiar that the in deriving the diffraction pattern of a single slit. A plane way which is incidence here.

So, the slit is considered as comprising of multiple points. Then we determined the interference pattern due to these multiple source points on the screen, which is placed at a distance D, at a distance D or capital D. Then considering the path difference between them we obtain the diffraction pattern. The standard diffraction pattern, which is the arrey patterns, so we get maximas and minimas here.

So, we get this pattern, so that the peak remains exactly in the center peak exactly. Let me show the slit here. So, these are the various points peaks remains exactly on the center, at the center and here is the diffraction pattern that we get. This is by assuming that all the point sources are in phase. But if we assume at these point sources are separated by a phase difference of phi a phase difference of phi, then depending on the phase difference phi, the peak will shift to that side or this side depending on the phase difference phi. A constant phase difference is phi will leave to different positions of the peak and by continuously. If we continuously change the phase difference here. It is constant, but if we change phi, the angle…

So even phi is equal to 0, let say here is the antenna. This this is the principle of Phased array antenna phased array antenna. So, when phi is equal to 0 if here is the antenna, then the output predominantly comes in the forward direction. If you give an appropriate curvature, then it is possible to find to focus the beam at a particular distance and at a particular spatial point. Appropriate curvature given to the antenna. If without mechanically changing the position or the orientation of the antenna, it is possible by simply changing the phase here relative phase between alternate alternate sources here. It is possible that the output come this angle or whatever angle. If you sweep this phase phi, then you can sweep the direction in which the e m wave is focused.

This is the basic principles of phased array antenna. It is the same thing here, that if all of them are in phase, which means integral multiples of 2 phi, they will come straight here and focused at the radius of curvature of this curve here. Now, if there is a phase difference in phi 2 phi and 3 phi and so on, then they will focus at a different point. They will come and focus at a different points. So, all the lights here now comes and focuses at a different point. Similarly, if instead of phi if we have minus phi then it all of them will focus at the third point here. These waveguides the position of these waveguides are located such that it is at the focus of these, the focus of the output from these waveguides.

Now, phi minus phi is determined by the wavelength. So, one can choose delta l that is the structure here designed. Delta l is chosen such that delta l and the positions of the output waveguides are chosen such that at wavelength lambda 1 all of them focused here. So, that lambda 1 comes out of this. Because there is a constant phase difference. Therefore, it does not come straight. It comes at an angle. At the center wavelength lambda 2, all of them focused at the radius of curvature of this. At the center here center of this radius of curvature. So, all of them focused here and at the third wavelength lambda 3 all of them focused here.

So, that is determined by delta l because n g determined by the dimentions of the waveguide, the refractive index and width of the waveguide. The more defective index and k naught contains the wavelengths. Therefore, delta 5 is different for different wavelengths. It is constant from one array to another. It is an array of waveguides from one waveguide to another waveguides adjacent waveguides the difference is the same. Phase difference is the same, but that phase is different for different wavelengths. Therefore, the output will focus at different spatial positions. Accordingly the location of the output waveguides are positioned. So, what we have is a multiplexed input I have illustrated considering only three different wavelengths.

The number of waveguides waveguides here in the array has nothing to do with a number of wavelengths, but it depends depending on the requirement of resolution. Depending on how much loss can be tolerated, there could be different numbers of waveguide in this arrays. So, the input here enters the free propagation region diffracts. So, all the channels are carrying all the wavelengths. All the wavelengths are carrying all the wavelengths. Here different wavelengths have difference phase shifts. Therefore, accumulated phase is different and therefore, they focus at different points. The output waveguides are then located at the appropriate positions. So, we have a De multiplexer functioning like this. As I said the whole dimension could be 5 mm by 5 mm or less.

So, it is a very small device and details of the design we have not going into, but this is a very important device in realizing transmitters and receivers in DWDM systems. So, we have discussed most of the components of a photonic integrated circuit. More and more PICs would appear in the new communication systems with the to exploit the advantages of integrations. Both in terms of the designs and fabrications, there are several challenges in particular reducing the loss and reducing the cross talks among the various channels in an AWG. These are being discussed. These are being looked into. So, there we come to the end of this course because of time limitation, we have to stick to whatever is possible to cover in this course.

As I said, write at the beginning in the first course, that this is an introductory level course. I have dealt with it in an introductory self-explanatory level. There it is, all the good things have to come to an end. So, I close the course here.