Semiconductor Optoelectronics
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Lecture - 45
Photogenic Integrated Circuits

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

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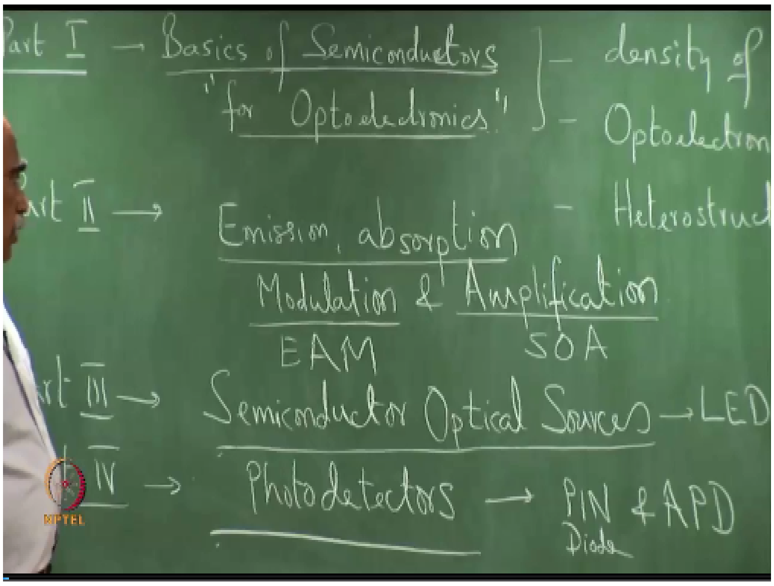

So we start with in part 1 let me just recapitulate. We discussed about the basics or basic physics of semiconductor optoelectronic devices that is basics of semiconductors for optoelectronics. Semiconductor physics as we mentioned is very broad topic and we have covered only the essential part of it for optoelectronics semiconductor optoelectronics. In particular, we have discussed here density of states.

Because as we have seen through the course density of states play an important role in the device characteristics and device performance. We then discussed about the semiconductor optoelectronic materials. So materials for optoelectronics semiconductor materials for optoelectronics and also we discussed about the heterostructures and need for heterostructures.

In the second part in part 2 of the course we discussed about emission, absorption, modulation and amplification. In particular, we have discussed 2 devices here the electro absorption modulator EAM and the semiconductor optical amplifier SOA. So 2 devices we have discussed in this part electro absorption modulator and semiconductor optical amplifiers. Then we came to part 3 which was semiconductor optical sources.

Here we have discussed about light emitting diodes LEDs and a variety of laser diodes. And finally in part 4 semiconductor photo detectors. So here we have discussed about of course the PIN and APD in particular PIN diodes and other detectors. So if I may list the modulator the amplifier the source and photo detectors.

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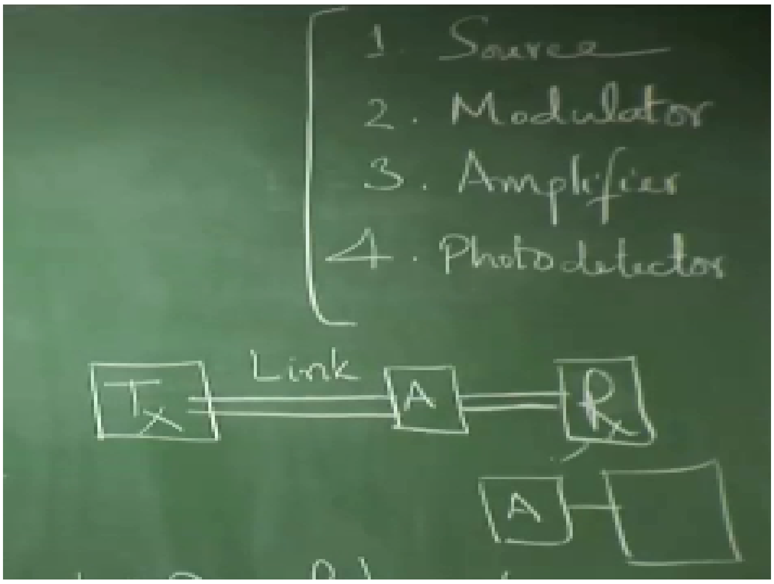

So we have the modulator, the source, modulator, amplifier and of course the photo detector. These are actually the basic ingredients of a communication system. So a communication system as we started in the first class has a transmitter here a link which is of course a passive link. There could be amplifiers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

So the transmitter apart the electronic circuitry comprises of an optical source in optical communication and optical source and a modulator and there could be power amplifiers which boost the power at the transmitter itself and there could be inline amplifiers and similarly at the receiver we may have a preamplifier. The receiver would have a preamplifier an amplifier here.

And then of course the processing circuit which may comprise of filters and photo detectors the demultiplexer 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 as standalone devices, but is it possible to integrate these.

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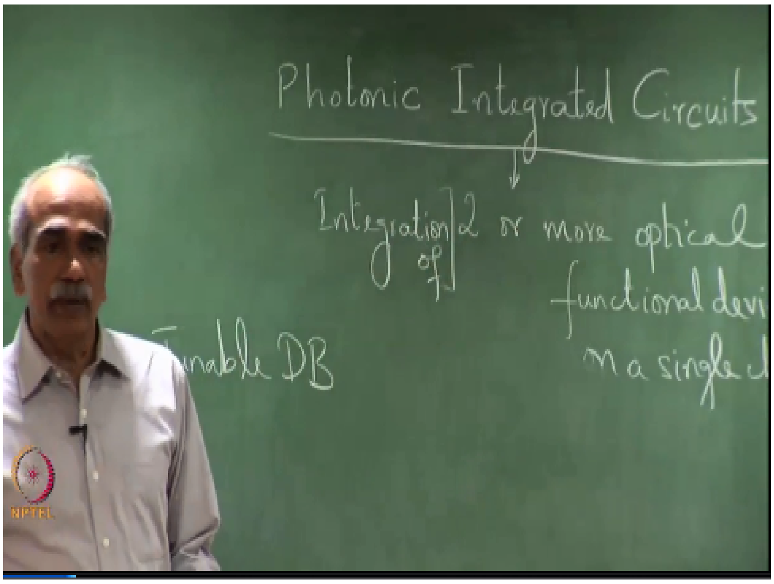

And that brings up to what are called PICs or photonic integrated circuits or simply called PICs. As the name indicates it refers to integration it refers to circuits or devices where 2 or more optical functional devices it refers to integration of 2 or more optical functional devices on a single chip. PICs are picking up now. They are becoming important. So let me briefly discuss some aspects of these photonic integrated circuits and as I have written it refers to devices which have 2 or more several functional devices on a single chip.

A simple example would be so let me pick up a simple example of a tunable DBR laser because the functional elements, functional devices could be passive devices or active devices. There could be passive devices or active devices.

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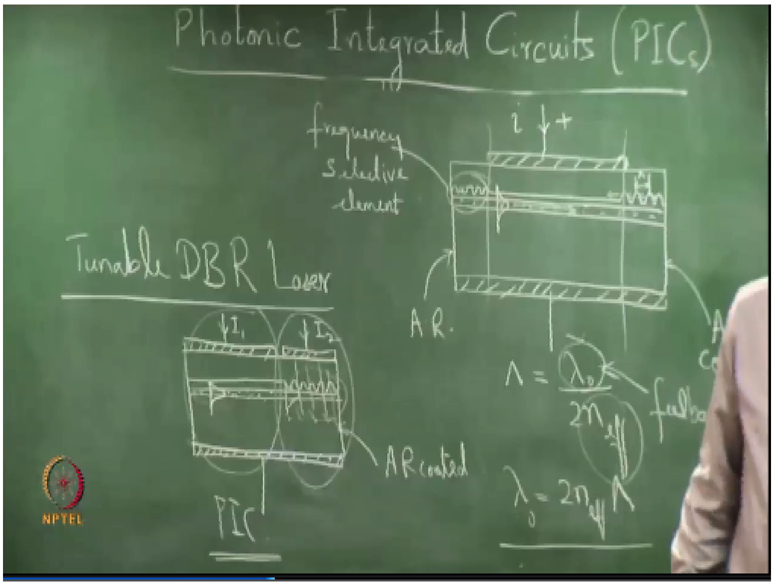

So let me pick up this tunable DBR we have already discussed DBR laser distributed Bragg reflector laser recall that the DBR laser has a double heterostructures. The lasing active region here and this may have 1 or 2 frequency selective elements what we had discussed earlier was with the 2 frequency selective gratings at the 2 ends. So this is what we had discussed and this is a longitudinal cross-section of the device.

The device is like this we are looking at the longitudinal cross-section the simplest longitudinal cross-section and here is the metal electrodes and the electrode here there may be many more layers here. I am just showing the essential layers so the gain region so here is the optical mode which propagates along the double heterostructure here and these are the electrodes.

Say + - a current i is flowing through this the 2 ends are AR coated anti-reflection coated AR coated to avoid any reflection from these ends because we need these frequencies selective gratings. So these are the frequency selective gratings this is the DBR not the tunable DBR. I am discussing the DBR that we had already discussed frequency selective element. The period is the periodic structure so the period here lambda the period is such that if we choose lambda= lambda 0/2 n effective where n effective is the effective index of the optical mode.

Here is the optical mode which is propagating back and forth. If the period is such that it is= lambda 0/ 2n effective, then lambda 0 the wave length here this is the optical wavelength this is the grading period. Lambda 0 would resonantly get reflected at these periodic structures the periodic grating leading to feedback 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 wavelength.

Thereby leading to realization of a single frequency laser or a laser oscillating at 1 frequency. One frequency we refer to 1 longitudinal mode of course there is a finite frequency spectrum associated with it. So this is the DBR that we had studied. There is a passive frequency selecting element here and this is the gain medium and laser oscillation takes place because of these frequencies 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 frequency selective elements we can have only 1 of the frequencies selective element in a tunable 2 segment tunable DBR we have this region it is the active region right up to the end and then the cladding region in the cladding region we have the periodic grating over 1 end of this and we have this end anti reflection coated AR coated.

This has 2 separate electrodes now. So the laser is treated as a 2 segment device here. There are 2 electrodes that is current I1 and current I2. 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 2 currents passing through the same device. There are 2 electrodes the current I1 primarily determines the gain here.

This is the active region the active region and the mode propagates here. The mode propagates through this structure. The active region the current I controls the gain of the active region and hence the power output whereas the current I2 here is primarily to control the selected frequency because a current injection leads to a variation in the reflective index and as we have already seen.

In this case the current was not flowing through the periodic grating elements here in the ends. Current was flowing only through the active region that is gain is provided only here in this. So there is no current flowing here and therefore the frequency selection is done by these gratings even if you vary the current here the frequencies 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 the choice of frequency which oscillates will depend on the n effective which depends on the refractive index of the mode, refractive index of the region here. Therefore, n effective can be affected so we have lambda oscillation= twice n effective * lambda here. The lambda oscillation can be varied by varying the n effective.

Lambda the grating period is fixed by changing this n effective it is possible to vary the frequency of oscillation. So we have 2 different currents here 1 current determining the power and the gain in the medium. The second current determines the injection of carriers into this so that the variation of effective refractive index in this region is determined by the second current.

And therefore n effective is controlled by the second current and therefore the output frequency is controlled by the second current I2. Please see that this has 2 segments 2 functional elements 1 is the gain region and the second region is the frequency selective element is a active both are active regions the frequency selective elements is here and so this is for example a simplest PICs.

A 2 segment a 2 element PIC photonic integrated circuit. We can have a many more complicated and complex PICs. For example, if we take a WDM transmitter or a receiver the current day WDM systems using a PICs if we were to realize the WDM transmitter or the WDM receiver using a PIC. The general layout would be like this.

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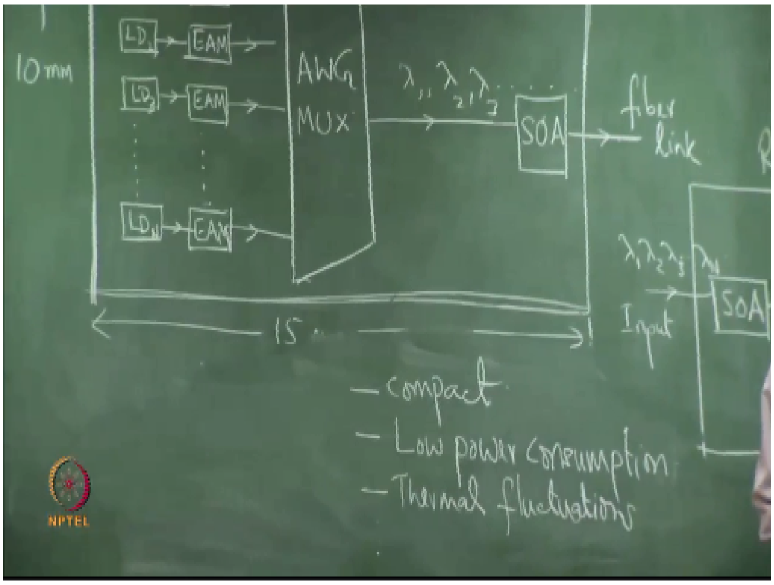

Let me show the layout. So we have lasers let say a 10-channel WDM system or a 40-channel WDM system could be 10 GBPS more recently there has been work reported where 100 GBPS 10 channels of 100 GBPS systems were integrated on a single PIC to realize transmitters so these are the LD 1 one standing for Lambda1. So this is wave length 1 LD 2 LD 3 and so on.

So these the DFB lasers so DFB single frequency stable DFB lasers LD n if there are n wavelength. So lambda1, lambda2 etcetera lambda n channels. The output of laser diodes here it passes through a modulator which is electro absorption modulator EAM the second device modulator EAM so this LD laser diode. Here we have EAM electro absorption modulator.

This is an SOA amplifier and this is a photo detector may be PIN. So EAM electro absorption modulator EAM 1, 2 and so on. So let me write it EAM. The output of there could be more elements, there could be amplifiers right here or the output of this goes to AWG MUX. So this is AWG MUX. AWG stands for Arrayed Wave Guide Grating. Let me briefly discuss about this.

AWG Arrayed Wave Guide Grating. 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 lambda1, lambda2. The output this is MUX multiplexor. So we have n lambda here so here is the output which has all the wave length coming here lambda2, lambda3 and so on.

There could also be an SOA here so just there could be 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 typical dimension could be 10 mm/ 10mm. So just I am giving some typical idea what is the dimension that we are talking so 10 mm/ 10 mm or 15 mm.

It is the kind of dimensions that we are talking of for a PIC. So these are PIC transmitter it is a WDM transmitter this could be a DWDM transmitter and a multiplexor. So we have laser diode the first device there EAM electro absorption modulators and of course multiplexors I have not discussed this multiplexor because this is not a semiconductor active device it is a passive device.

This multiplexor 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 wavelength lambda1 and lambda2 lambda3 lambda n enters the PIC here the input. First it is usually there is a preamplifier SOA an SOA preamplifier and then followed by the AWG DEMUX.

There could be more components and then it goes to the different channels, the different wave length going to different photo detectors. So the input containing all the wave lengths are amplified by an appropriately chosen SOA there may gain flattening filters associated with this. So that there is a flat band, flat gain band which is followed by DEMUX AWG DEMUX and the different wavelengths are then sent to high speed photo these are high speed photo detector lambda1, lambda2.

The output of the photo detector of course will be electrical here. This goes to further electronic circuitry so electrical output for further processing, electrical output for further 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 discussed the basic building blocks in this course except the AWG MUX which is a passive wave guide device.

And currently there are 100s of such components integrated on a single chip. So initially there were only 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 100s of components are integrated to realize a single photonic integrated circuit. We all know the importance of integrating components ICs the importance of electronic ICs we know where of course 10 of millions.

100s of millions of components are integrated on a single chip. Comparatively the numbers are very small. The number of components integrated on a chip is much smaller compared to the millions or nearly billions component on a single chip. Nevertheless, the advantage of integrating components 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 because the entire chip is maintained at unlike discrete 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 scenario. So let me before I wind up let me just briefly discuss this AWG. It is a very interesting device, very interesting optical device 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 Demultiplexer. AWG Demultiplexer.

So in the remaining 10 minutes 15 minutes let me briefly discuss the idea of AWG MUX, DEMUX.

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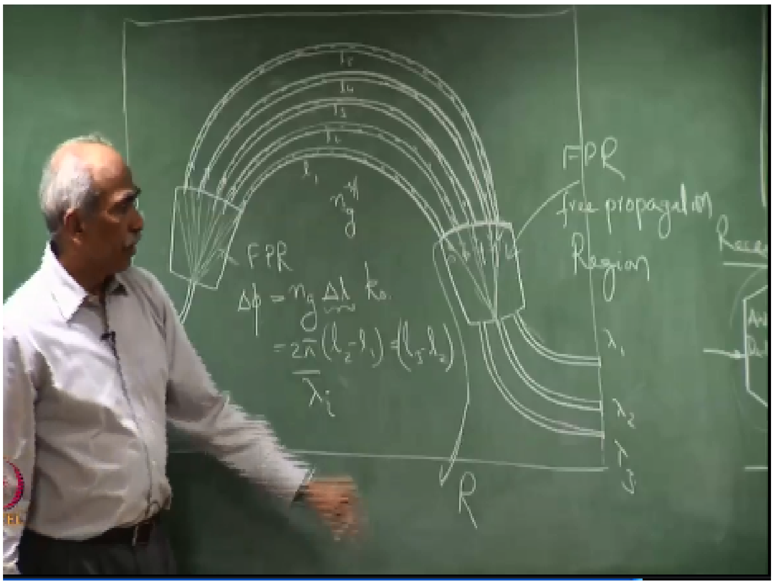

So here is the AWG so let me start with the Arrayed Wave Guide. There is an array of wave guide. So I am drawing like this here. So an Array of Wave Guides I am showing only a few of them. In practice, the number of wave guides. So these are wave guides. So what we see is top view of a chip. So in all the diagrams that I have drawn here what we have seen is the top view. So it is looking from the top.

So the chip is here and what we are seeing is the top view of a chip. And Array of Wave Guides. Okay let me show all of them without leaving any gap. So I think we will have 5 wave guides. The number could be much larger, but I have chosen 5 here just to distinguish. So these are optical wave guides so 5 channels which enters here. The channels which are opening into this free propagation region these are FPR free propagation region.

So I am showing this DEMUX free propagation region. So this is another FPR. So here is the input that is this input the input which is entering the DEMUX is here. So here is the wave guide an optical wave guides made on the semiconductor chip. So here is light entering this all the wavelengths lambda1, lambda2 and lambda3. Let me take 3 wave lengths just 3 wavelengths to illustrate 3 different wavelengths which are demultiplexed so 3 wavelengths.

I will not go into the design mathematics, but concepts only I will just be able to discuss the concepts. So the 3 wave lengths lambda1, lambda2, lambda3. So let say this there may be several components on a single chip, but I am showing that this is an AWG chip. So lambda1 the input is multiplexed wavelength stream and output is lambda1, lambda2, lambda3 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 multiplex channels. So this is the free propagation region. So there is diffraction taking place. So light diffracts into all the channels here. They are actually quite close so light enters so there are many therefore almost all the light is collected, but I have shown only (()) (34:30) it looks as if there is a large gap, but a major part of the light which is propagating through here is collected by these wave guides or they excite the modes of the wave guides which then propagate along this R.

As you can see that if this is L1, Ll2, L3, L4 L5 usually they are all of the same dimension so that the model effective index n effective of the guide or ng n effective of the wave guides are identical. So if L1, L2, L3 L5 are different are length of the various waveguides here. Then when they reach here there is a propagation delay between the adjacent there is a phase delay between the 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 * ng. is the path difference multiplied by of course, k0 will give you del phi the phase difference. So this delta L here corresponds to l2-l1 or = generally this can be taken such that they are equally separated or l3 or l2 and so on. So the light which is reaching here has a constant phase difference between the light which is emerging from here.

We see that these are all single frequency lasers and therefore the coherent lengths are very large and therefore even if we have a phase difference here a part delay they are all well within the coherence length. So all of them with respect to this if I say the phase here is phi 0 or 0 then this is 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 pi 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 could depend on so this is del phi is going to k0 so this is= 2 pi/lambda. So lambda is different for the different wave length and therefore if lambda1 enters from here. Let us say that the phase difference corresponding to lambda2 is 0.

Phi=0 then the phase difference will have a certain – phi here corresponding to lambda1 and corresponding to lambda3 this could be +phi. So the phase differences are different here for the 3 different wavelength. If the phase difference is 0 then all these waves when they propagate because they are situated on R of certain chosen radius there is a radius R here so that all of them focus to this waveguide.

So all the light which is coming from here are in phase and therefore when they diffract they focus at 1 particular wave length, 1 particular special point and there this wavelength this wave guide is located at that special points which means that particular wave length will come through this wave guide. 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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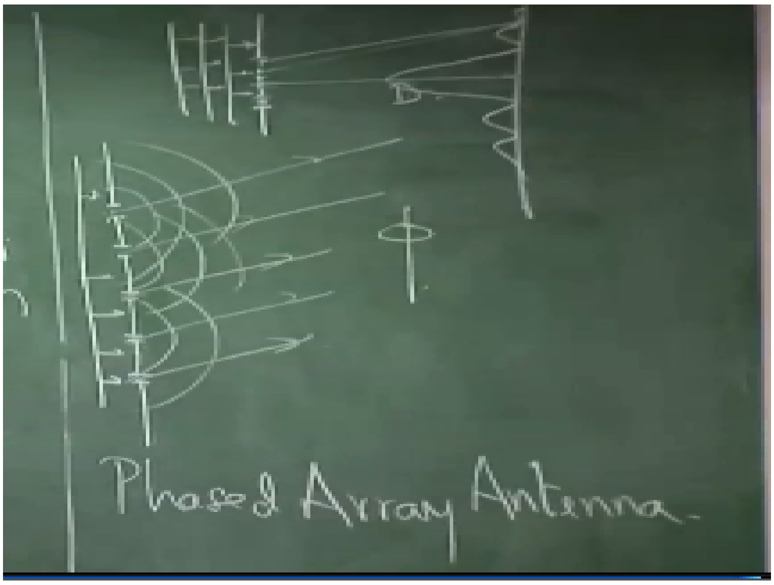

From a single slit, we may recall or phased array antenna so those of you are familiar with the phased array antenna. So we have point sources or sources here which are the sources are emitting if I consider these as optical sources they are point sources if I consider this as point sources then each one of them is emitting like this. If the input here is a plane wave 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 in deriving the diffraction patterns of a single slit a plane wave which is incident here. So the slit is considered as comprising of multiple points and then we determine the interference patterns due to these multiple source points on the screen which is placed at a distance d or capital D. And then considering the path difference between them we obtain the diffraction pattern the standard diffraction pattern which is the (()) (40:48) pattern.

So we get maximum and minimum here. So we get this pattern so that the peak remains exactly in the center peak exactly okay let me show the slit here. So these are the various points. Peak remains exactly 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 that 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 phi will lead 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 even phi=0 let say here is the antenna this is the principle of phase array antenna.

So when phi= 0 if here is the antenna then the output predominantly comes in the forward direction and if you give an appropriate curvature then it is possible to find to focus the beam at a particular distance and a particular special 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 sources here it is possible that the output, comes at this angle or whatever angle.

And if you sweep this phase phi then you can sweep the direction in which the EAM wave is focused. This is the basic principle of phased array antenna. It is the same thing here that if all of them are in phase which means integral multiple of 2 pi they will come straight here and focus at the radius of curvature of this curve here. Now if there is a phase difference phi 2 phi, 3 phi and so on.

Then they will focus at a different point. They will come and focus at a different point so all the light here now comes and focuses at a different point. Similarly, if instead of phi if we have –phi then it all of them will focus at the third point here. These wave guide the position of these wave guides are located such that it is at the focus of the output from these wave guides.

Now phi or –phi is determined by the wave length. So one can choose delta L that is the structure here design delta L is chosen such that delta L and the positions of the output wave guides are chosen such that at wave length lambda1 all of them focus here so that lambda1 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 lambda2 all of them focus at the radius of curvature of this at the center here, center of this radius of curvature.

So all of them focus here and at the third wave length lambda3 all of them focus here. So that is determined by delta L because ng determined by the dimensions of the wave guide the refractive index and the width of the wave guide the mode effective index and k0 contains the wavelength therefore delta phi is different for different wavelength. It is constant from 1 array to anther array it is an array of wave guides.

From one wave guide to another wave guide adjacent wave guides the difference is the same phase difference is the same, but that phase difference is different for different wavelength and therefore the output will focus at different special positions accordingly the location of the output wave guides are positioned. So what we have is a multiplexed input I have illustrated considering only 3 different wave length.

The number of wave guides here in the array has nothing to do with the number of wave length, but it is depending on the requirement of resolution and depending on how much loss can be tolerated there could be different number of wave guides in this array. So the input here enters the free propagation region diffract so all the channels are carrying all the wavelengths all the wave guides are carrying all the wave length.

Here different wave length has different phase shifts and therefore accumulated phase is different and therefore they focus at different points. The output wave guides are then located at the appropriate positions. So we have a demultiplexer functioning like this. As I said the whole dimension could be phi mm/phi mm or less. So it is a very small device and details of the designs we are 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 and more and more PICs would appear in the new communication systems to exploit the advantages of integration both in terms of the design and fabrication there are several challenges in particular reducing the loss, reducing the cross talk 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 right at the beginning in the first course that this is an introductory level course and I have dealt with it in an introductory self-explanatory level and here it is all good things have to come to an end. So I close the course here.