Photonic Integrated Circuit
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Lecture No. 01
Photonic Integrated Circuit Course Introduction

Hello, welcome to this course on photonic integrated circuits. Today we are going to get a brief introduction about photonic integrated circuits. What are these photonic integrated circuits? Why do they create a lot of enthusiasm among the recent technologies? Let us dive in and look at what they are actually.

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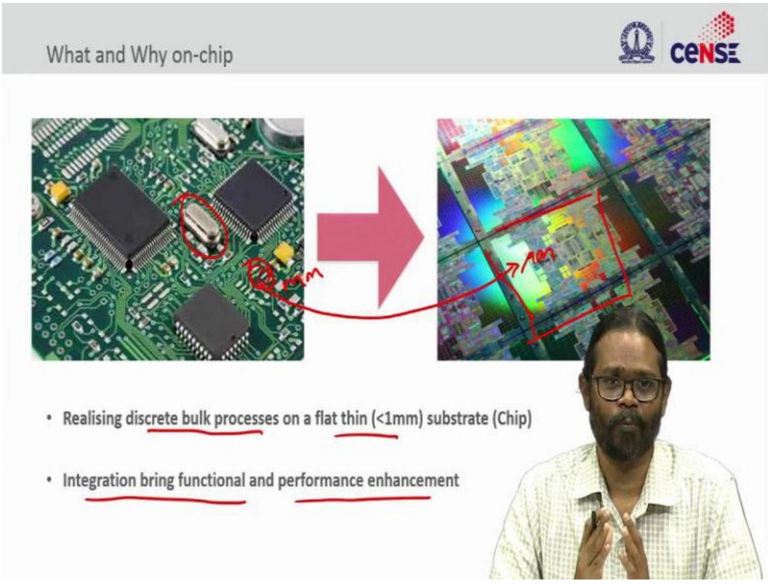

So, integrated circuits or integration on-chip has been a philosophy for microelectronics over the past couple of decades. So, the whole idea of integration coming from realizing bulk functionalities. So, you have various components that you see on the left side, there is an oscillator you have passive elements resistors and capacitors all in a circuit board. This is a printed circuit board.

But, then if I, if you want to miniaturize this and if you want to increase the functionality, the best way forward is make it on a single flat substrate. So, that is what we call a chip and there are reasonably thin substrates and all the components that we saw here they are all miniaturized they are now very, very small. So, from your going from millimetre scale here to micrometre scale here in some of the cases nanometres.

So, this miniaturization brings in lot of advantage so the integration of all these components is going to bring functional enhancement and also performance enhancement. So, that is what we strive for. For any system currently we have we would like to increase the functionality. See, if you look at mobile phones so mobile phones from generation to generation we are looking at various new features adding in, previous generations are slower than the current generation we have more memory and much faster. So, how do we achieve this?

This is all through integration and now we have more functionalities so we started with you know one camera so now we have 3-4, so the cameras are increasing but then your size is all remains the same and it is getting faster. So, in on the one hand you are increasing the functionality, now you can measure the pressure levels, now there are very smart bio sensors integrated onto your mobile phones as well.

So, the functionalities are increasing the performance is also increasing. So, how do we achieve this? This is all through what we call integration so instead of having one processor board that is addressing let us say one camera or one sensor and now we have 10 sensors all addressed by a single processor board. So, now this integration as I mentioned is going to be the key going forward with advanced technology so that is all about you know how and why we need to do this.

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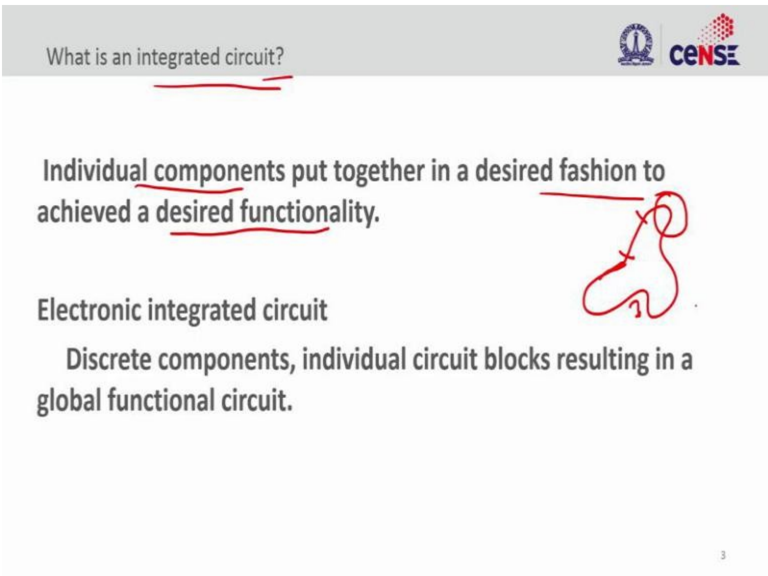

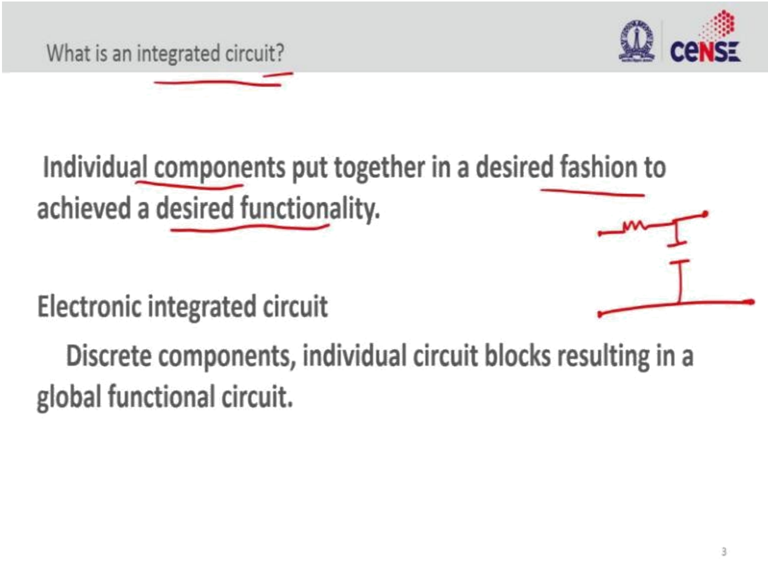

And the next thing is understanding what this integrated circuit is, for some it might be trivial for people who have done electronic integrated circuits it is very easy to understand what this integrated circuit is. But then, the integrated circuit in conventional sense is nothing but you know to put together a in a desired fashion so individual components are put together in a desired fashion to achieve a desired functionality.

It is a very important philosophy here. So, you are going to have multiple components so this components you know for all practical reason we can consider like resistors, capacitors that we understand. This could be also other components. I am not very specific about electronics maybe I have something to do with race cars. So, you also see this individual components in those racing circuits and that is the reason why we call the racing circuit instead of saying it as a track or a road.

So, it is called a circuit the reason for that is if you if you take a raising circuit you have various aspects to this racing circuit so you have a very tight bend where one need to slow down and there is a straight section where you demonstrate straight line speed and how you maneuverer here so this is all various components and you want to put it in a desired fashion in order to make this as a closed circuit.

And, then another interesting thing is to look at how we can put you know resistors and you know capacitors together so how do we do that and you have to put it together in certain fashion so that the functionality is something desirable. So, you cannot randomly connect things and call it as a circuit.

So, it has to be connected in certain desired fashion to achieve desired functionality all and electronic circuits to be specific here so that we you know have familiarity. So, discrete components so this discrete components are you know resistors, capacitors and inductors let us say.

Or individual circuit blocks it circuit blocks could be you know amplifier for example so amplifier is a circuit block resulting in a desired or you know global functionality. So, you want to realize a global functionality you want to put this discrete components or individual circuit blocks together in order to make a circuit and if they all going to control the flow of electrons so the all of this why are we doing this, we are going to control electron flow.

So, we want to control electron flow using this circuit and this is what we call electronic integrated circuit or there is a large scale integrated circuit, very large scale integrated circuit, ultra large scale integrated circuit. So, all these comes under the class of controlling electrons through a circuits, arranging various components in a certain fashion.

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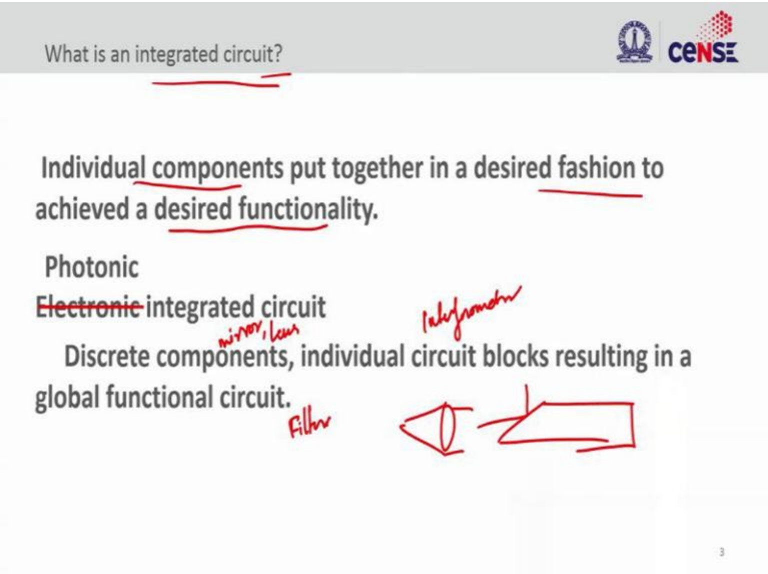

But, then what is a photonic integrated circuit? Can I use the same philosophy absolutely so what you have here in a photonic integrated circuit is you have discrete photonic components or optical components and you also have individual circuit blocks in this case the circuit is controlling a the photons to some extent. And this is all resulting in some global functionality. So, this global functionality could be you know for example a filter so you want to filter light and here the discrete component could be a mirror elements and we also use lens these are all discrete components.

And individual circuit blocks, what could be a circuit block when it comes to a filter? It could be an interferometer. So, interferometer is wavelength selective so that is a small circuit so having all of this together we call it as a photonic integrated circuit. So, this mirrors and lens this is all in bulk sense so you have very large mirrors lenses that you have and you might also have mirrors, reflecting mirrors and you have lens systems so these are all bulky in nature.

So, what we would like to do is we want to miniaturize we want to make a circuit out of it similar to what we saw earlier discrete resistor now sits on a chip so now how do we convert this lens or mirror how do we bring that onto a chip we have to reduce the size of those devices what is the physics behind those reduction are there any limits to it and that is what we would like to understand in this course.

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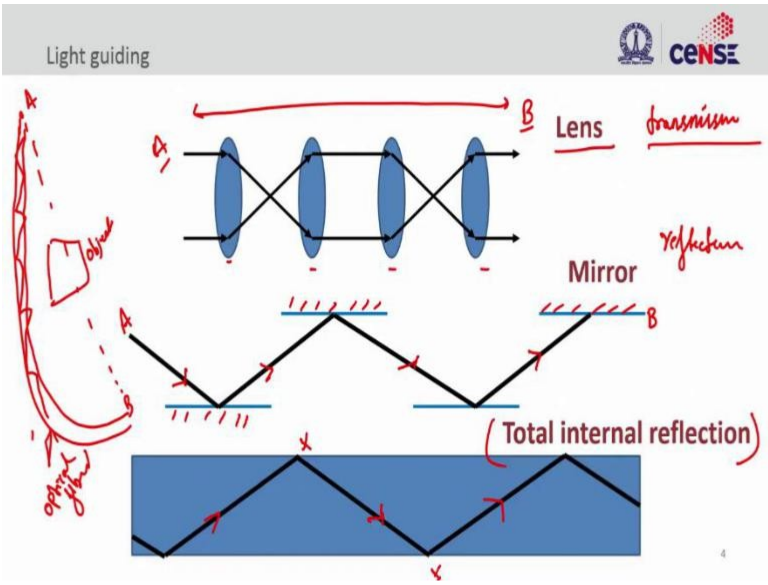

So, in order to understand how to convert this lenses and mirrors into circuit let us look at how do we guide light so we have to make sure you take a photon or light from point A to point Be, so we want to understand how we can do that. So, we can easily do it by using lenses series of lenses and that is the example that you have here. The cartoon there shows you how one can take a lens and then arrange it in series so that you can you know take light from point A to point B.

And this is all in a straight line. So, if I want to bend this light I can also do that we will look at it shortly and instead of lens so lens is a transmission or trans missive so you are doing this light propagation from or guiding from point A to point B by transmitting is through the lens here. You can also do it by reflection mechanism. So, through reflection so you have you can put mirrors so I have mirrors light always travels in straight line we know that so I can put mirrors and then make the light reflect these position and I can take the light from point A to point B.

So, these are all very simple way of looking at light transport from one point to the other point so this might look like pretty trivial but I can also realize light going from point A to some other point B here. So, there is an obstacle here let us say so there is an obstacle so I cannot do line of sight so normally what we do is you can you know do line of sight and light can reach point A to point B. But now I cannot do this because, there is an obstacle so there is an object sitting in between alright. So, how do we do that?

So, we have to go this way and put a mirror and then take it to point B. So, this is this is how we can realize this light transportation. So, now we need one additional element so there is a mirror required here. Again .you can see here it has to have a complete straight path here without any obstacle but then if I say I have to do this light transmission not in free space but underground how do we do that? It is nearly impossible to think about you know having all these mirrors underground and that is where we use you know optical fibres.

So, you can use optical fibre in order to transport light without you know worrying about what is there in the atmosphere so this is so this is optical fibre. So, the optical fibre will help you to transport light from point A to B without having any difficulty. And the light transport there also happens through reflection so light inside is getting reflected so let us look at how it can go so it is getting reflected inside and it follows a principle called total internal reflection. So, this is the principle that we use similar to mirrors.

So, the light is getting reflected within optical fibre and confined in inside without escaping outside without escaping to the environment and this is taken care by a phenomena called total internal reflection that mimics mirror like behavior alright and this is how you can transport light in a denser medium so you take optical fibre which is denser and you can also take silica slab like our mirror we have so you can take a mirror and then make light propagate through this mirror so these are all the ways to guide light alright.

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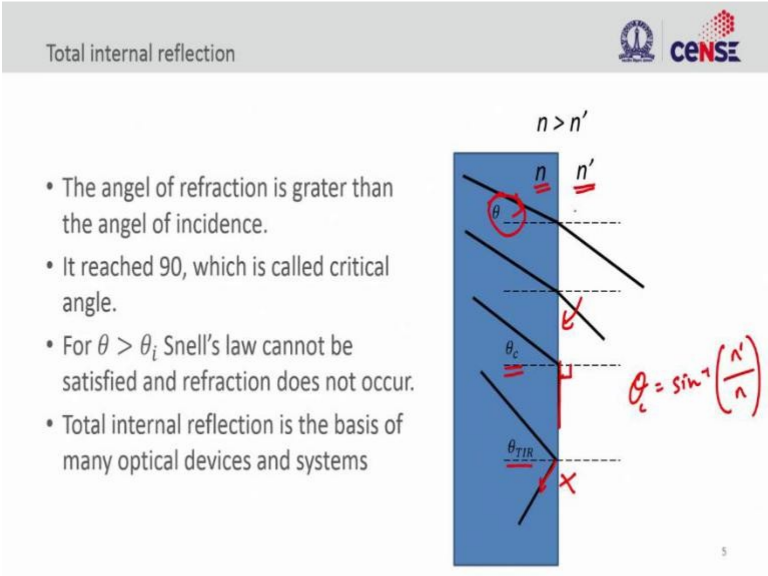

So, let us look at this total internal reflection we discussed about you know how to you know keep the light inside the denser medium. So, we all understand light reflection and refraction alright. So, this is something that you might have learned in the introduction to photonics course. So, when you have light inside this medium so it can refract and it will also reflect. There are two processes that happens at the interface so when the refractive index of the medium where the light is sitting is higher compared to the environment alright.

So, this this phenomena will happen but our idea is to keep the light inside we do not want this refraction. So, how do we achieve that? This can be done by changing the angle. So, so you we have this angle here so that is the incident angle so when you change the angle the angle of refraction also changes, so it comes closer and closer at a particular angle what we call the critical angle the light reaches you know nearly 90 degrees. So, it makes 90 degrees with the normal here.

So, that means the light is propagating at the interface between the higher refractive index and the lower refractive index medium and this is this is a really an interesting point beyond this angle all the light is reflected inside and that is what we call angle of total internal reflection and based on this principle we can confine light inside the medium. So, there is no light escaping and the way that we can understand this by you know from our Snell's law so we study this $\theta = \sin^{-1}\frac{n'}{n}$.

So, this is how you can find what is the critical total internal reflection angle the moment you know the refractive index of the material inside and what the material is outside, you should be able to find what is the critical angle beyond which I can keep the light inside. And this is how all the guiding wave principle works. So, when you take optical fibre, this is the principle. So, single mode optical fibres, multimode optical fibre so there is a concept of light confinement inside and this confinement is through this total internal reflection. Not only for fibres later on we will just see that even in photonic circuits that we do it on plane flat surfaces you can still use this total internal reflection principles. Let us move on.

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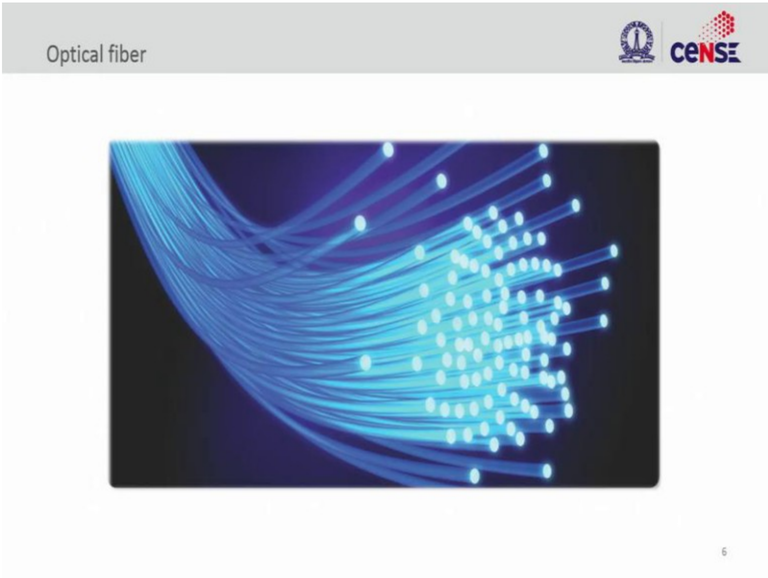

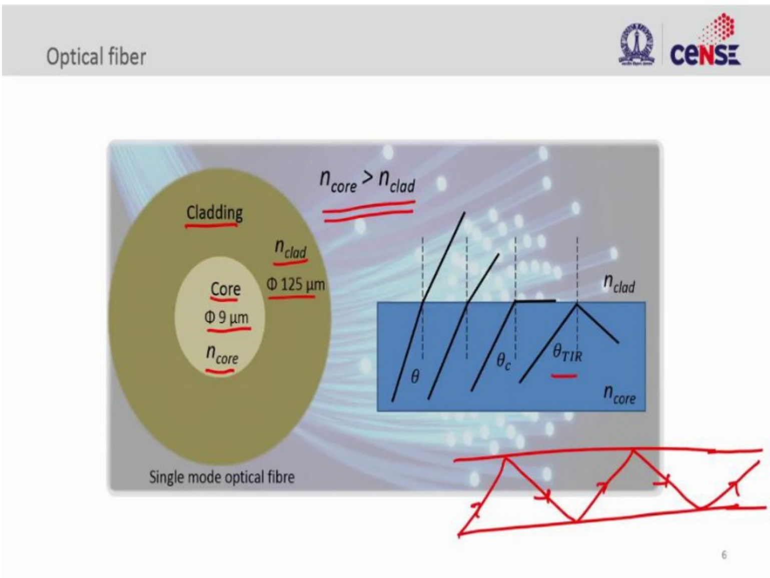

To look at optical fibre so optical fibres we all know it is a glass material and it consists of two material system one is core and the other one is cladding. So, the core is the one that is at the centre and for a single mode fibre the refractive the diameter is about 9 micrometre and the refractive index we call it as n_{core}. And then outside cover is called cladding and the refractive index of that cladding material is n_{clad}. and the diameter is roughly about 125 microns. So, this is almost you know thickness of your hair slightly larger.

So, the important condition here for the light to be kept inside the core is n_{core}. that is the refractive index of the core should be greater than the refractive index of the cladding. And only then we will have this total internal reflection so this image if you remember we already saw at a certain input angle now all the light is confined and I can at a particular incident angle this light is going to stay there forever so it will keep on bouncing back and forth without any loss so this is the reason why you can make optical fibres of kilometre long yet without you know any appreciable loss.

We are talking about you know 0.02, 0.01 dB per kilometre very very small loss so all the energy is confined inside this is very essential the reason for this is you are going to communicate to somebody who is sitting or servers that are sitting tens or hundreds of kilometres apart. So, you are watching this video right now and this video is streamed from a server you know it could be 100 kilometre, it could be 1000 kilometre from where you are sitting.

But this information is now traveling through this optical fibre and this optical fibre should not lose this signal and that is the reason why the loss of this signal should be very low and this total internal reflection is one of the reasons why you are able to transport photons with very low loss. So, that is that is all about how we propagate light through optical fibres and through this total internal reflection.

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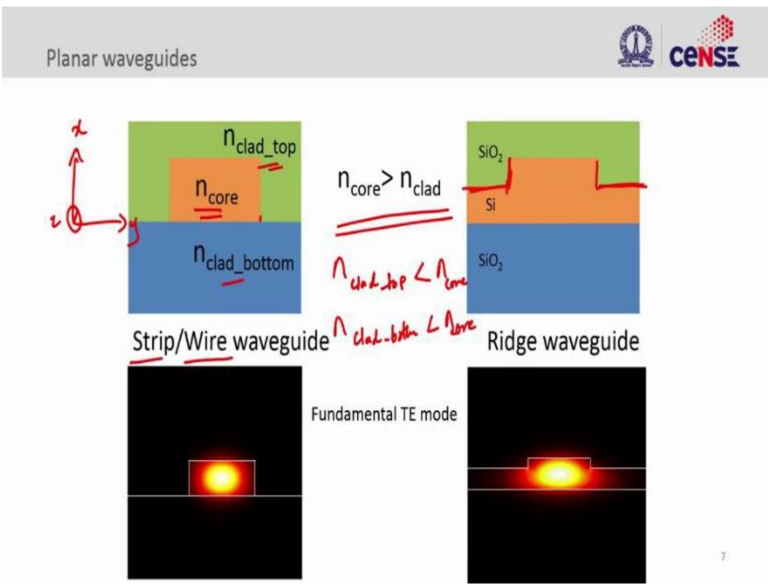

Let us look at how things are in a planar waveguide so optical fibres are nice we understand it very well but our interest is to make photonic circuits on a chip or in a flat surface. So, there you cannot make circular geometries so, there we are looking at rectangular type waveguides or structures. So, the condition still remains your refractive index of core should be greater than refractive index of cladding, so this is the condition that that should be satisfied.

So, now we have a core material here and it is surrounded by a cladding material so we can say top cladding and bottom cladding. So, for general purpose I have mentioned that you know top cladding and bottom cladding two different colours but it can be same material as well so it can be same material so the material can be same or different but the n clad top should have lower refractive index than n core, same thing is true for n clad bottom should be less than n core.

So, this condition should be satisfied so your core refractive index should be greater than the surrounding mediums. So, one should keep that in mind. So, they can be different the top and bottom can be different but then they should be lower than the core refractive index. And while understanding this let us look at two different type of wave guides we can have planar wave gates that you can have, so this is all cross section this is a a cross section of the of a waveguide let us say this is X and this is Y and this is the propagation direction. So, this is Z so this is the propagation direction.

So, when you have a rectangular structure like what you see on the left side we call this as a strip or wire waveguide so wire waveguide its simple similar to you know electrical wires. So, the wire lines that you have in your PCB board looks similar so they are rectangular in nature and they can guide light. On the right side what you see is this is partial removal of of material here so you see a slight step here so the material is not completely defined as a wire but you have a shoulder on the sides and this structure can also propagate light so confine and propagate light and this this structure is called a ridge wave guide.

So, you know once you have this two different structures, we need to understand whether light will propagate through this you there is no need for you to believe that you know when I say this structures will confine and allow light to propagate so you should question that so why do you say that so how can we believe that light would propagate through this structure and that is where our good friend you know Maxwell comes in. We have studied about Maxwell equations in our basic courses like introduction to photonics and in that course probably you must have understood that you know in order to define an electromagnetic wave we need to understand the 4 golden equations and then a wave equation that represents light.

So, we take advantage of those definition and then solve the structure to see whether light will exist in this particular structure and if you do that this is what you get. So, what you see the two images at the bottom are nothing but the intensity of light when you do Maxwell solution to when you find the Maxwell solution to this structure that that that was represented with the two cartoons at the top. So, light is nicely sitting at the center if I do a cross section of it, it will look something like this a nice Gaussian profile? And similarly, here as well you see light sitting in.

So, from you know the Maxwell solvers or you can do it analytically or you can do it numerically you can find whether light will be guided in this so we will look at how and so on later part of the course but indeed you can find take any structure and find whether light will be guided in this and based on the solution you can say whether I can use this structure for guiding light.

You can you can come up with any kind of geometry so we said we went from a circular geometry to the fibre to a rectangular geometry here and you can think of some triangular geometry let us say or a trapezoidal geometry you can be as creative as you want but then there is a boundary condition to that creativity it can be geometrically looking nice for you that I can put light into this particular structure but then you have to ask Maxwell for that.

So, the Maxwell will tell you whether that particular structure you came up with will guide light or not so those are all the things that we will look at in the introduction or refresher that we are going to have on the electromagnetics. So, why are we really interested in this photonic circuit? So, we said we can confine light and we can do live propagation through this structure what is the use of this so the use of it comes from various applications that are that are really impactful and disruptive.

So, just to give you a few you know motivation why this photonic integrated circuits are really good in this particular slide I just compiled what I what could be interesting. So, photonic integrated circuits is a disruptive technology and it leverages matured CMOS infrastructure so fabrication of this structures are very important the circuit fabrication are very important similar to microelectronics where all these chips are made in huge microelectronics foundries we want to make sure this photonic circuits should be able to be fabbed in such large establishments or infrastructures. So, using those infrastructure can we fabricate our circuits? And the answer is, yes. So, we can do that.

The next thing is material. So, invariably you know almost more than 90 percentage of you know circuits are made out of silicon. So, you say 90 percentage what happens to the other 10 percentage? There are other RF applications where people use 3-5 component semiconductors, it could be 10 it could be less than 10 depends on the application domain that you are looking for but then when you look at the processors that we use in everyday life it is 100 percentage it is all silicon. But then there are application in high frequency and so on where people use compound semiconductors.

Similarly, in photonics we have silicon we can use silicon and silicon alloys as well silicon nitride, silicon carbide, silicon oxy nitride and silicon based compounds for example germanium could be used there as well. So, all CMOS compatible or microelectronics compatible materials could be used and also compound semiconductors so when you say compound semiconductors gallium, arsenide, indium, phosphide basically 3-5 group elements.

So, if you make alloy out of it, we can make use of those technologies as well because of this richness in material technology, it is highly you know scalable the mature technologies are available and you can do monolithic or hybrid integration of devices and material technology so it gives you a lot of versatility in this platform. And above all photonics you know is EMI and EMC free. So, that means you can use it in very you know harsh environment where you have radiation where you have a lot of interference and also it is high speed, so light travels at the speed of light there is no contest there so you can communicate information very fast.

And also the interesting thing is unlike electronics you can do parallel processing you can you can do a lot of information sharing in parallel because of wavelength that you have. So, just to summarize you can have versatile platform high speed you can do a lot of signal processing at high speed and then you can do sensing as well using light you can probe information. So, those are all real application of photonic integrated circuits.

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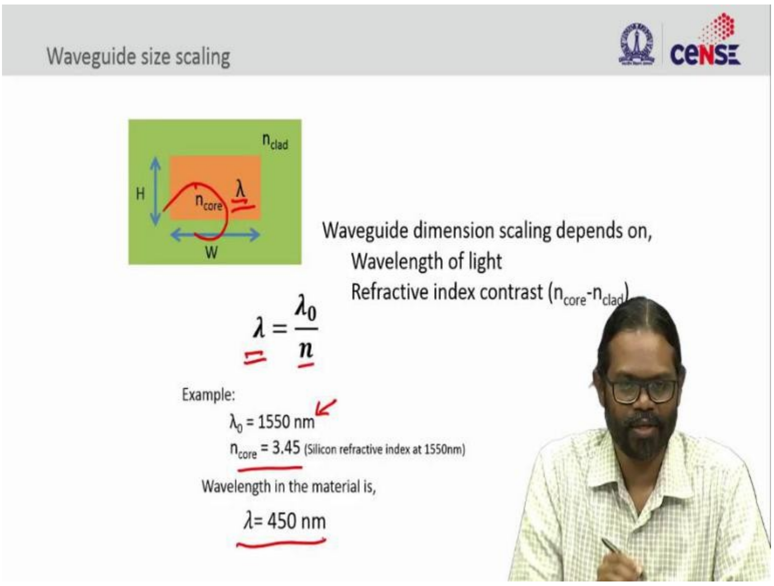

And the next important thing is, how small can I make this circuit? So, this is a very important question to answer. I am making a circuit so how small a circuit could be we are primarily limited by the diffraction particularly a guided wave system so we all know you know the wavelength of light inside the medium depends on the refractive index of the medium. So, the wavelength of light inside the medium is profiled by the refractive index so that is lambda naught which is the free space wavelength divided by the refractive index of the medium.

So, just to give you an example, a 1550 nanometre light source or wavelength of light inside silicon, silicon is 3.45 that is the refractive index of silicon the wavelength inside the material is 450 nanometres so now you can see we had 1.5 micrometre of wavelength in free space so now when you put this light into silicon it becomes 450 nanometre so we can squeeze the light by just choosing a high refractive index material.

Then for some of you might be thinking oh if I put 1550 nanometre light into silicon, then my wavelength goes from 1550 to 450, can I do wavelength conversion? That is the question that probably pop pops up but you cannot do that the reason for that is the wavelength or the color is frequency dependent not wavelength is a representation in space. So, frequency is what you should do to understand colours alright. So, size depends on the wavelength of light and the medium that you are propagating and this is what gives you the confinement. How small can you do?

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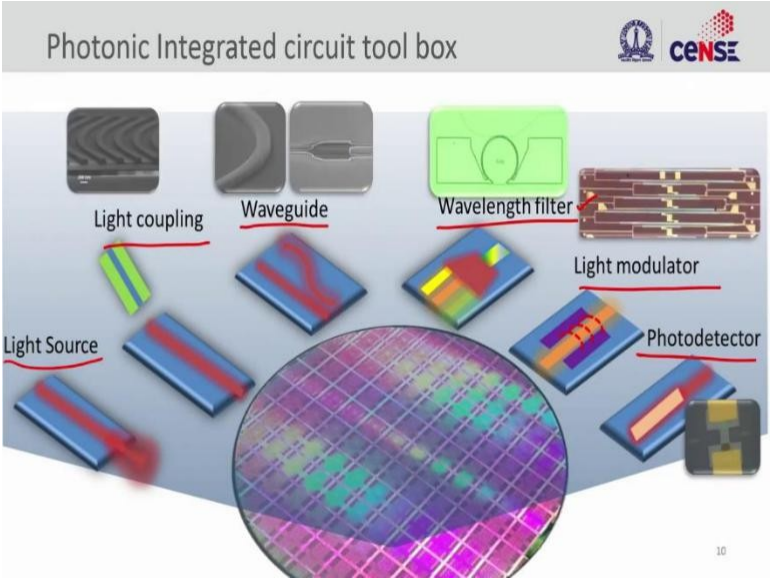

And you want to think what are all the type of devices that you can make in this photonic circuit. So, what you need? You need a light source to generate this photon and then once you generate the photons you want to couple let us say or to the outside world or even within so you need a good light chip coupling. So, once you have the coupling done, then you want to have a waveguide structure so that that can guide the light wherever you want. So, you go from point A to point B inside the circuit how do you do that so that is using waveguides so that is another component there.

And then, wavelength selective filters this is a an excellent you know property or really amazing property of light compared to electrons, it has wavelengths and these wavelengths they do not talk to each other they will not share energy in a linear sense in non-linear photonics that is what you try to do, but in linear low power world these photons will not share energy so they will you know hold on to the information they have. So, you can send in multiple wavelengths in parallel and how do you discriminate these wavelengths and you need a wavelength filter for that.

A next is a light modulator so, how do you change the properties of light? So, if I want to change the intensity of light and this intensity of the light change should be correspondent with an electrical signal. So, I want to transmit an electrical signal through an optical fibre, how do I do that? So, I have to change the intensity of light that that should you know correlate with change in the electrical signal and that is what you do with light modulators.

And then the next thing is how do you detect light so I want to convert the photons into electrons so how do you convert that and that is what photo detectors are all. So, now you have this toolbox and all of this I want to be present on a chip. So, this is the whole philosophy of having photonic integrated circuits. So, all these components, all these elements, all these functionalities should be available on chip so that is the main idea of this course. We will understand each and every component and then see how we can put it together to realize really fascinating applications all. So, these are all some of the images of these devices.

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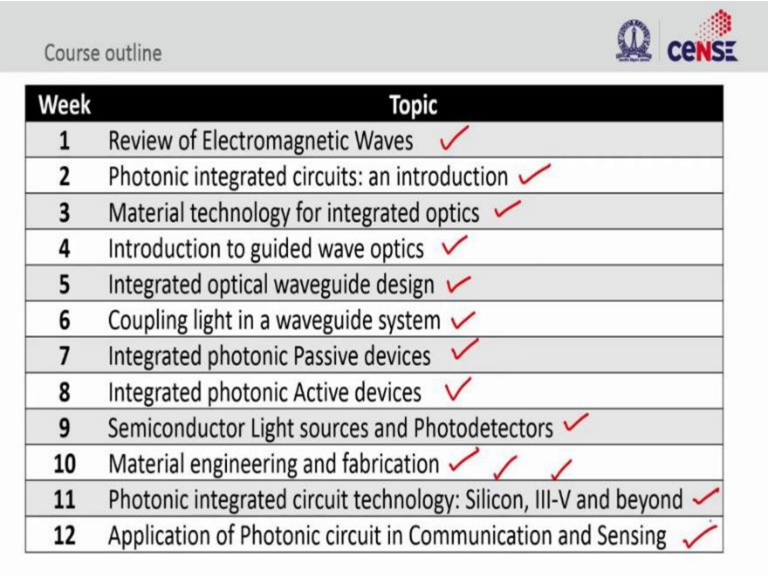

So, let me wrap up with going through the course outline what we are trying to do in this particular course in the next 12 weeks. So, we will start with a brief review of electromagnetic waves so that everyone is up to speed, so some of you might have done this electromagnetics long time ago and we will make it very specific to this course we are not going to look at you know whole electrodynamics. So, we will look at what is appropriate for this course.

And then, in the next week we will look at a brief introduction about the circuit so what is all this photonic integrated circuit is all about each component what they do and how you can exploit that. And the next thing is material technology so what kind of material one can use and how do you grow this material, how do how you can use and exploit this material particularly for integrated optics.

And then, next we will look into the guided wave optics how do you guide light in the circuits. So, we will look at guiding mechanisms and then we will move into design of this waveguide, so how do we design a waveguide within which you can confine and propagate light and how do you couple light between two different devices on chip? And also how do you couple light between optical fibre from the external world into your chip?

And we will look at some of the passive components like filters, splitters and all those passive components and then active components meaning here light generators. So, you how do we generate light inside the circuit and also how do we detect light inside the circuit? So, those are all active functionalities where we are not controlling light we are actually changing the property of light and modulators as well, how do you change light property like intensity and phase? So, we will look at that in active devices.

And then we will also look at semiconductor light source and detector separately so we are going to look at how we can generate light in a semiconductor, how we can detect light using semiconductor and also how can you put this in a chip configuration. And finally, we will look at fabrication and engineering of this material for specific application. You might be using different wavelengths. So, the material should be transparent in those wavelengths at the same time we should be able to make the kind of devices that we want so what are the fabrication challenges we have in doing so.

And in week 11 we will look at some of very specific material platforms we will look at silicon photonics we look at 3-5 photonic circuits and also we will look at some of the new emerging areas of the circuits that are coming up that one can exploit for various application. And finally we will we will look at some of the case studies of how to use the circuits for communication and also sensing purposes so that will be at week 12.

So, with this course you should be able to have a comprehensive understanding of what this photonic circuit is and how you can design various devices, discrete devices and how are how can one put this together in order to realize a certain functionality and also look at some case studies of what material that one can use to realize for example communication application you are going to transmit data how can I use photonic circuits to transmit data and also receive data.

And the other application is sensing, how I can use this photonic circuit to sense the environment? So, this could be you know gas sensing it could be fluid liquid sensing for example. So, we will take a case study on that so it will wrap up a complete understanding of this field which is really emerging and lot of interesting things are lined up in this particular technology and also in this course. I hope all of you will enjoy you know understanding this. Thank you very much.