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Photonic Integrated Circuit

Professor. Shankar Kumar Selvaraja

Centre for Nano Science and Engineering

Indian Institute of Science, Bengaluru

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Photonic Integrated Circuits evolution

Hello all, let us look at what is the technology evolution of this photonic integrated circuit. So, there should be origin or there should be a rational behind evolution of this technology. There is a need behind every technology. So, science evolves on its own based on curiosity. Technology evolves based on the requirement, so let us look at what are all the key events that has enabled growth of this photonic integrated circuit as a technology let us look at that.

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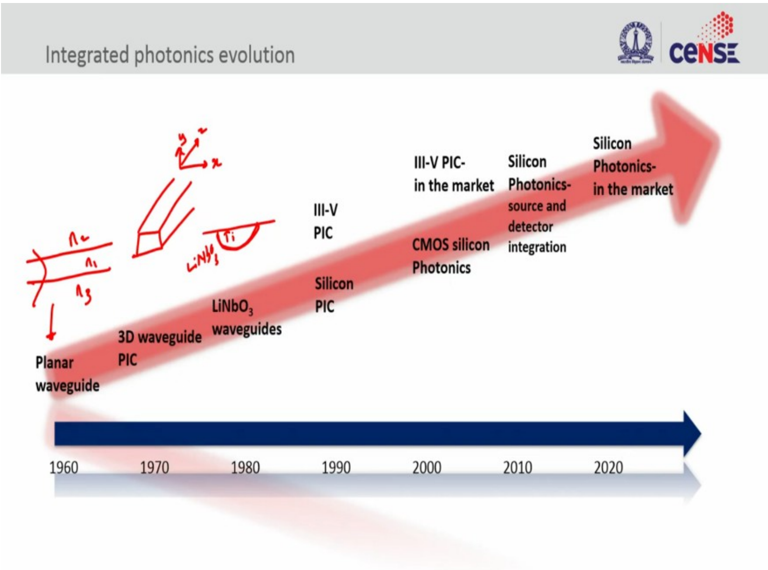

So, this whole journey started in early 60s, so where planar waveguide technology was introduced or proposed. So, the proposal came even earlier but, then the actual demonstration of light that could propagate through a planar waveguide was first demonstrated around the 1960s. So, then in about a decade or so a 3 dimensional waveguide structure was demonstrated; so, when we say planar we talk about just a guiding layer surrounded by either symmetric or asymmetric refractive indices. So, this is what we call planar, so light could propagate through this layer.

So, when you talk about 3 dimensional, then we are talking about confinement into dimensions and propagation in the third dimension. So, you are talking about confinement in x and y and light was propagating through along the the z direction. So, this was proposed and demonstrated between 70 and mid 70s. So that is when things got really interesting and during that time, what is the use of such guiding was in question; so, why are we trying to guide light? So, one of the primary purpose of confining light is to increase a light matter interaction, and also enable electro-optic and nonlinear effects.

And lithium niobate is a well known material platform at that point of time and around the 90s, 80s 1980s, the waveguides based on lithium niobate was already realized. So, the whole idea of these kind of waveguides was it is a slightly different kind of geometry. It was a 3 dimensional guiding system, but it was a buried channel waveguide let us say. So, you had lithium niobate but then here you had titanium diffused waveguide. So, these are all diffused waveguide technology which will see little later. But, for the discussion the lithium niobate based waveguide started to appear in in 80s already.

So, this this has caused a lot of disruptive technology in terms of handling light; so we are only able to use bulk optical components such as lenses and prisms and mirrors. And now we were able to handle light on chip and not just guiding light on chip; we were able to change the property of of the propagating light, like the phase of light could be changed. And the polarization of light could be handled and so on. So, this has really caused lot of interest and disruption in the way people used optical components.

And then about late 80s and early 90s is when compound semiconductor based photonic circuits and silicon based photonic circuit, concepts were introduced and also demonstrations started to come up. So, III-V meaning group 3 and group 5 elements; so gallium arsenide, indium phosphide, indium gallium arsenide and all those compound semiconductors start to merge in in photonic circuit configuration. And silicon which is a well known microelectronic material also was proposed as a guiding medium; so that is very important.

So, III-V semiconductors we have been making LEDs and diodes even before that. But, then use of those material for guiding light and also doing electro-optic processes on with this material started to emerge. At the same time silicon was seen as an alternative to compound semiconductors. So, while III-V compound semiconductors were direct band gap material, where we could generate light; and also we could detect light very efficiently. Silicon was on other hand was an indirect band gap material, coming from a completely different strategy altogether; because, silicon was heavily used in the microelectronics industry.

And at that point of time when things were scaling up in terms of speed and so on, there was a need to improve the speed of how you to transport data and so on. So, silicon was already a material that was available and technology was also mature. So, the proposal was made why do not we use silicon, though it was indirect band gap, we are interested in light transport let us start from there. But, if you want to do electro-optic processes, one could do that as well; because silicon is a semiconductor.

So, you could apply electric field, you could apply current into the device and you should be able to manipulate the material property. Because light interacts with the material, we should be able to change the propagation properties of light. So, these were really a remarkable two proposals that came in and that is when the race to create components and circuits to serve the representative market. So, just 10 years from the first demonstration, III-V semiconductors already made it to the market. The reason for that was being a direct band gap material, light generation and light detection was relatively easy; so you could integrate it.

And the next thing to do is communicating light from one point of the chip to the other point of chip. So, that technology that understanding is already well established; so it was rather easy or straightforward for III-V based technology to evolve. And the other important thing is the propagation loss; the loss of photons within the within the chip. In both the cases it was reasonably high; however in III-V semiconductors loss was not a big problem.

The reason for that is the direct band gap advantage, since it was direct band gap, you could have amplifiers on chip. So, you could have light generators, light detectors, amplifiers, electro-optic modulators; so all these discrete components that are essential to create a complete functionality was already available. However, for silicon it was not the case; though the wave guiding technology was there; the there was no light source. You can make and the detector technology was also not there and the other thing is the technology that was used for microelectronic fabrication and photonic fabrication was not actually quite easy to transplant all those technologies.

It was initially thought that it would be relatively easy to take all the CMOS technology, and then use it for silicon CMOS technology, but that was not the case. There are very critical technological challenges that that that really stretch the timeline. The initial idea was told the technology is there, let us use it. But, photonics works in a different way, just to give you an example the losses initially was very high. Though silicon is transparent in let us say the telecommunication range 1300 and 1550 range, the propagation loss was high and during early days people were unable to understand why it was. Then it was figured out that it is not just the material, we have a structure it is a three dimensional structure.

So, light interacts because of high confinement, light interacts heavily with the side walls and all the interfaces. So, you have a wave guide that has 4 interfaces; so top and bottom and then the two sides. So, based on the polarization that you use, you had very high electric fields along the surface. So, because of that you had lot of scattering and the other thing is silicon and an air or oxide; refractive index contrast is very high compared to III-V platforms. So, because of this high refractive index contrast, the scattering was also high.

So, we know the scattering evolves with fourth power of of the refractive index contrast or delta n. So, because of this, the scattering loss was very high; we were unable to realize anything functional using this very high loss. So, that was a critical bottleneck and the second bottleneck was the technology itself the contamination for example. So, we all know light likes to be in a homogeneous medium and high refractive index, but at the same time you do not want any absorbing elements around the the waveguide. So, if there is any contamination in the oxide or during on the surface those contaminants would absorb; examples are some metal contaminations, carbon contamination, so they absorb light.

So, because of these factors, the technology was still trying to evolve to to meet photonic circuit technology moving away from the regular CMOS. So, there was a stretch in the in the timeline compared to what was achieved in a III-V base technology. So, once that that the whole thing was sorted, then we had this CMOS silicon photonics; so that means you are doing all all silicon photonics using CMOS processes. So, that was the main development in the in the last 10 years between 90 and 2000.

And from there on things started looking up for silicon photonics. Because III-V is already there in the market, they were selling products; and for silicon based integrated circuit that is when things started looking up. So, people started to integrate various materials, so whether we can integrate germanium as a light detector because germanium was available and as a part of CMOS development, silicon-germanium and germanium was used to make strained strain engineering in CMOS. So, we use those materials to to take leverage out of those developments and made detectors out of it.

And then, how about source? So, source it is a long shot; because silicon is indirect. However, efforts are made to make germanium emit light; so by doping germanium and by pulling one of the indirect band gap up, and then trying to do some band engineering there. People were able to demonstrate light generation from a photonic IC with germanium doped with tin; so, that was a monolithic integration.

So, on the other hand, there were effort to integrate III-V semiconductors on top of silicon. So, this happened between 2000 and in 2010. During that time, people started integrating III-V semiconductors direct band gap semiconductors on top of silicon. So, this has really enabled a fully integrated photonic IC. So, that means you have silicon photonic which is indirect band gap material based photonics. However, you have III-V sitting on on the chip through heterogeneous integration; and we had germanium monolithically integrated. So, things started looking really integrated all the functionalities.

So, from there on things went into commercial root and now you can buy silicon photonic based products or silicon photonic integrated circuit based products in the market now. So, this is a brief evolution of the key game changers that happened from the first proposal or first demonstration of light guiding in a planar wave guide till now. So, I have I just took only the two main players in the field; but there are other platforms that evolved along with this photonic circuit. So, the initial the plane wave circuits a plane planar light wave circuits were first developed based on low index contrast platform like silica.

So, still you get silica based PLCs or photonic light wave circuits in the market that came very early on in the eighties already. And we also had other platforms like Titania, alumina based photonic circuits; and also doping the titania or alumina based material with active ingredients like erbium, in order to make active components like light emitters on chip. So, those developments were happening in parallel, so what I mentioned today was primarily catering towards data com and telecom and compute kind of application. But, you of other platforms such as Titania, alumina polymer based circuits are parallel development that happen over this duration. And recently things are also evolving in in other ways.

We have silicon and we also have silicon based material like silicon oxy nitride, silicon nitride are evolving silicon carbide as another material. So, these are all alloys of silicon let say; so they are they are used explode as a material to expand the potential of photonic integrated circuit. So, all we need to do is to find a suitable transparent material that can be deposited onto a flat surface; and we should be able to pattern it. So, it has gone to that to an extent where we are exploring beyond what is what is rightly available now. So, this is this is briefly the integrated photonics evolution particularly catering towards Datacom and Telecom kind of application.

So, PLC as I mentioned oxide based circuits started very early on and perhaps at around 80s; the circuits were already there. It was much more matured and between 80s and nineties it was available commercially as well. So, let us look at how this technology evolved based on demand. As I mentioned the technology evolve based on demand; it is we do not just develop technology and wait for an application. There is always a push and based on that push the technology evolves.

So, there are two big requirements that has pushed the photonic circuit technology. The first and foremost is the communication, so data communication and telecommunication; and the second part is compute application. So, if in loose sense, the compute is also a part of communication problem solving a communication problem; but at a very smaller scale which we will see shortly.

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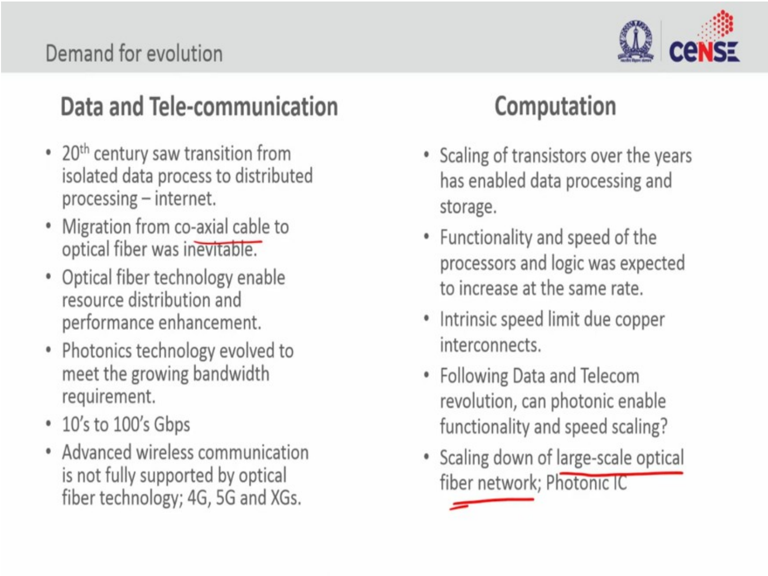

So, in in twentieth around twentieth century they were dawn of twentieth century there; we saw a huge shift in terms of data processing and how we handled data processing, both in terms of communication and also computing. So, we all went from an isolated process station to a distributed processing and thanks to internet for that. So, we were all connected and this whole connect was taken care by copper coaxial cables. So, this copper coaxial cable did its job for a while; but then it was inevitable that we have to move to a much faster mode of transport, and that was optical fiber.

So, we migrated from coaxial cables to optical fibers and this optical fiber technology has enabled all these resource distribution, and also performance enhancement. So, when we talk about resource distribution, you do not need to have everything in one place. So, today we you are watching this video and this video is stored some somewhere in the country; so you do not know which server is actually streaming this. And this could be located in multiple places and it is true for any streaming application that you are using.

Similarly, you have a live streaming that is happening and those live streaming are happening without any delay. So, you do not see any time delay at all noticeable time delay and thanks to this light speed technology; that is brought to you by optical fiber, and this has enabled at the growth of of bandwidth. So, so as you move along most of the population was brought under this access umbrella. So, when people join in to access this technology, then there is a requirement to improve the bandwidth; and the technology also evolved with that. So, now in any infrastructure you can get tens of hundreds of gigabits per second bandwidth; so this is this is becoming a norm.

And these days you can have fiber to the home based on your internet service provider; you can have a few Gbps to 10's of Gbps coming to your home. So, that is the access level that is created because of advancement and widespread implementation of this infrastructure called optical fiber based technology. And now we are moving even beyond this wired technology; so now all these 4G, 5G and I do not know what are all other G's we are going to have are catering towards wireless communication, but then the access is going to be multi gigabits per user; we are talking about per user not aggregate. So, if that is the case, then how are we going to handle all this bandwidth and optical fiber comes in to help?

So, right now the advanced wireless communication networks that we have are all supported by optical fiber technology. So, so we have done away with heavy cables that were limiting bandwidth; so now everything is optical. So, the fiber is a transport only but then when you want to split the signal or you want to combine the signal, most of the times these things are handled at the aggregate level through photonic ICs at a higher level.

And the next thing is about computation; so computation is an interesting evolution. So, communication evolution with optics happen much faster and it is already much more matured state. But, on the computation side, things were related to how microelectronics scaling happened. So, we started by scaling the transistor, so defined by ITRS roadmap we started reducing the size of the transistors. Why we did that? Because we want to increase the functionality.

So, more the number of transistors, you can provide more number of functionalities. And that is the reason why when you buy cell phones, so from one generation to the other generation; the size does not change. But, then you see new features are getting added; so more number of processors and speed is getting added by improving the number of transistors that we have. So, there is a there is a problem in the scaling. So, when you increase the number of transistors, it is not just the numbers; but all these transistors should simultaneously work.

So, you should give data to them and they should work; and how you transport data between the transistors or the functional is through copper interconnects. So, the copper lines are connecting different functional blocks, and we this problem is well known that we already encountered with the coaxial cable with the communication. So, we are facing the same problem, so though the coaxial cables there are advanced versions. But, even then we are talking about gigahertz here; so can we handle those speeds and there are some fundamental limitation.

And following the data and telecom revolution, there is a lesson to be learned. So, why do not we implement a similar kind of bandwidth scaling by using optical fiber? So, let us move away from copper interconnects and use optical interconnects. Use light to transport data within a processor, so that is that is when things started looking really interesting for photonic

ICs. Because the whole idea here is we should scale down the very large scale optical fiber network, and put it on a photonic IC, so that is basically what computation demands were asking for.

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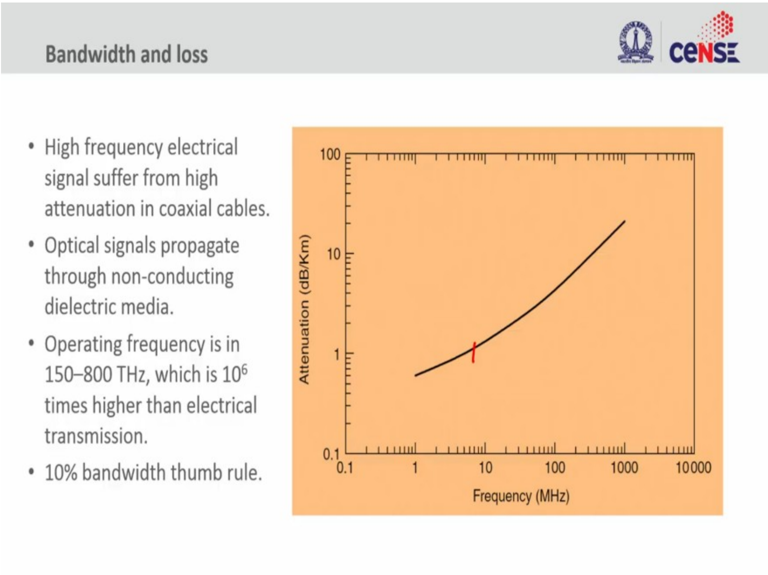

So, as I mentioned the bandwidth and loss is really a killer when it comes to communication. So, high frequency electrical signals really they suffer from for attenuation in the cables and in atmosphere as well, when you increase the frequency. So, you are talking about 10, 30, 40 dB when you cross the 1 gigahertz mark. So, even for 10 megahertz, your loss is rather high. So, if you go beyond that, it is 2, 3 dB per kilometer, this is this is very high loss you are talking about communication within a city within a country and between continents.

So, the advantage of using optical signal based transport is doing all this in a dielectric. So, you are not relying on the electrical signal that is going through, so you are now talking about optical signals in dielectric. So, the losses can be much lower and the operating frequency is very high. So, you are talking about 150 to 800 Terahertz depending on the wavelength range, which is 6 orders higher than the electrical transmission; that we we were once we were using. And the that was on the loss front, we were able to justify going to higher frequencies and using a non conducting dielectric material would solve the problem.

The next question is how about the loss, how about the bandwidth. So, bandwidth, a thumb rule for any communication engineer is the bandwidth is roughly about 10 percentage of the carrier. So, if you are using 100 Megahertz as the carrier, then you will have 10 Megahertz as your bandwidth; so that you can use. When now we are talking about Terahertz, so if you are using 100 Terahertz; then 10 Terahertz of bandwidth is available which is huge, which is unheard of during the copper days.

So, from the bandwidth perspective optical signal transmission was very-very favorable and scalable as well; because at that point of time we did not have that much traffic actually to fill up the bandwidth that we had. So, that was the complete rationalization of why going from an electrical based system to an optical based system is very advantageous.

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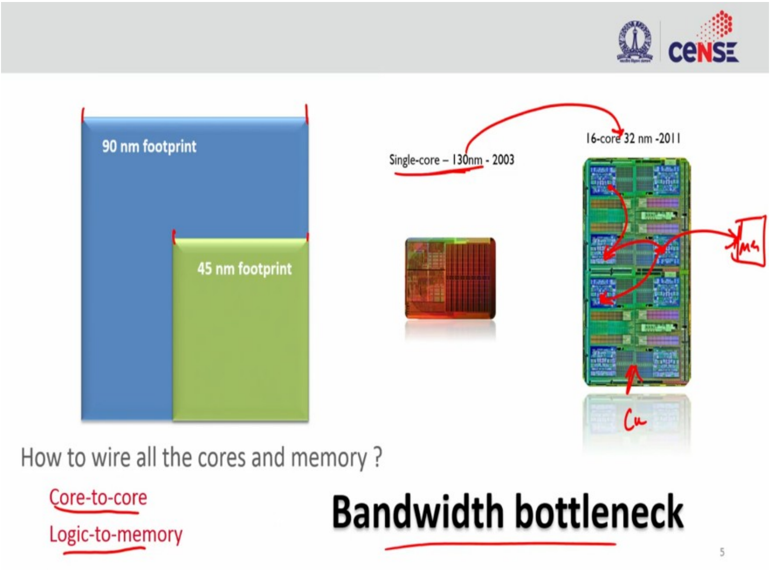

So, that is on the communication front, I I briefly mentioned about compute application. So, if you take a footprint of a 90 nanometer CMOS node; this is the real footprint that you that you see here. So, when you reduce the size to 45 nanometer technology, then it reduces the size of the transistor reduces the footprint requirement now reduces. So, the chips can be made very-very small for that particular functionality. So, I have a lot of free space now. So, what can I do? I can add more number of functionalities or processors there.

So, that is the reason why we went from a single core processor by using 130 nanometer node technology to a 16 core processor with 32 nanometer technology. This was already 10 years ago; so now you can have the whole wafer with processors if you want. There are thousand cores you can make easily, but what is the problem? We can keep on making these processors. But, then those processors should be able to talk to each other; so one processor should then send data to another processor for making some calculation, and further on given to another functional block to do another step and so on.

So, there is a successive transport of data that should happen within the processor. So, in order to do that, you need fast communication within the chip; it is not just communication within the chip, you also want to communicate with the memory. There is a part where you will have to talk to the memory within the chip; but also you need to talk to the memory that is sitting outside. So, how do you make this transport of data between memory and your logic or the core or within the core reasonably fast; because all these things use copper.

So, as we know copper is bandwidth limited; we already saw from our coaxial cable days. So, going beyond a few 10s of Gigahertz is going to be very hard; your loss is going to be very high. So, this is the term that we use to define this bottleneck, it is a bandwidth bottleneck; so, you need to have enough bandwidth. We do not have to sweat a lot.

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Because the solution is already known, so we have this huge optical fiber infrastructure that is already available. So, what we need to do is to scale this down and put it onto a chip, which is centimeter scale. So, we have to scale down thousands of kilometer long network into centimeter scale; so this is where real interesting scaling comes in, and it is not just reducing the size. When you reduce the size, we know there is a physics involved in this; so it is not that straightforward. And that is the reason why photonic integrated circuits are interesting.

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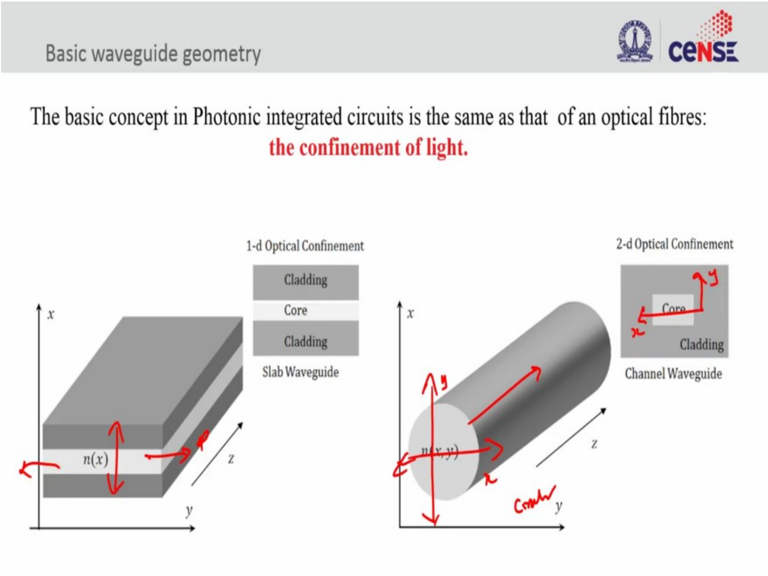

So, how do we do this? So the way to do this is by making light confined into a very small space that we could manipulate. So, the basic concept of a photonic integrated circuit is is same as that of an optical fiber; so there is no difference. The whole idea is confinement of light; so how do you confine light? So, the two traditional ways of confining is there is 1-d confinement and there is 2-d confinement. So, in 1-d confinement so this is infinitely thin slab; but then it is confined vertically; so, the light cannot escape vertically and this is one dimensional confinement.

And in case of 2 dimensional, you can either take a simple optical fiber; where both in x and y direction it is confined, you cannot escape in both x and y direction, it is confined; while it propagates in is z direction. Similarly, you can have a channel waveguide type, this is a circular waveguide type and this is a channel waveguide; which is rectangular waveguide where you have a 2 dimensional confinement here again. So, by using this confinement we should be able to put light into action on a single chip.

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Optical system evolution

	1st Generation	2nd Generation	3rd Generation
Technology	Conventional	Micro-optics	Integrated Photonics
Components	Mirrors, prisms, and lenses.	LED, Laser diodes, lenses, and optical fibers	Single-mode channel waveguides, laser diodes, LEDs
Alignment	Necessary	Necessary	Unnecessary
Propagation	Free-space beam	Free-space beam	Waveguide
Device size	m^2	cm^2	mm^2

So, let us look at some of the evolution that happened on this optical system. So, the first generation what we call the conventional optical system; we used mirrors, prisms, lenses and so on. Just give you a flavor of what all the components that we used, and how do you align or put all these components into use by aligning them. So, you have to align all these components in an optical table, and then use their functionality to realize a global functionality. So, how the light propagates from one to the other? Component is through free space beam. So, you had a free space this could be inside vacuum or in air; we were able to transport light through free space.

And this is all in a very large size, so you take a optical table; this is all in meter scale circuits, even if you want to turn a light beam. So, a right angle turning requires a lens system here and then a mirror here and lens here; which will easily take a meter by meter let say. So, if you are going to do that for any experiments. So, then the second generation people try to make use of the semiconductor technology, and wave guiding schemes. So, the semiconductor technology gave us light emitting diode; so now we had very small diodes instead of gas lasers; I could say here gas lasers. So, we were using gas latest as very high light emitting sources.

In the second generation we were using micro-optics, so we reduced the size of all these diodes; and we were doing light emitting diodes were doing laser diodes and the lenses were really thin now. So, instead of just lenses you could also say thin lenses; so we were able to confine or reduce the size of this lens by using different type of material. And then optical fiber was used to confine light and propagate as well.

However, we still needed alignment between these discrete components, so if you want to couple light from a laser diode to an optical fiber, you still needed a lens right in between these two. At the same time you have to align these 3 components. So, you had laser diode, you had lens and then you had optical fiber. So, if you if you want to put light from a laser diode into your fiber, you have to align it. So, that means the alignment becomes necessary and the light was in free space, when it is not guided in the optical fiber. So, however at the circuits are now at least the configuration or the system is now centimeter scale. Because we have thin lenses and the laser diodes are now semiconductor diodes; they are reasonably small in size.

And then came the third generation of technology that is or integrated photonics technology. So, in integrated photonics, we try to squeeze the light even into small volume. So, it it resulted in single mode channel waveguides compared to multimode technology that was earlier used and we had laser diodes and LEDs which were now integrated into a single platform. So, the alignment was not necessary here at all because you can have light sources, you can have detectors, you can have waveguides and you can have all the functionalities electro-optic, acousto-optic.

Any kind of functionalities you want is now integrated on chip; so, that was a big improvement. So, we did not see any need for external alignment; so everything is already aligned during fabrication process itself. So, now the propagation is through waveguide; so light is not coming out at all. So, it is generated on chip, detected on chip and manipulated on chip, so there is no need for light to come out as a free space beam. So, now the light is now guided using waveguides.

And because of this high refractive index and the material that we are using to realize these circuits, now the circuit size is only few millimeter or the max centimeters right. So, it depends on what kind of platform that you use; so you can really squeeze the light into I know square millimeter now, which was initially happening in the footprint of centimeter scales with micro optic.

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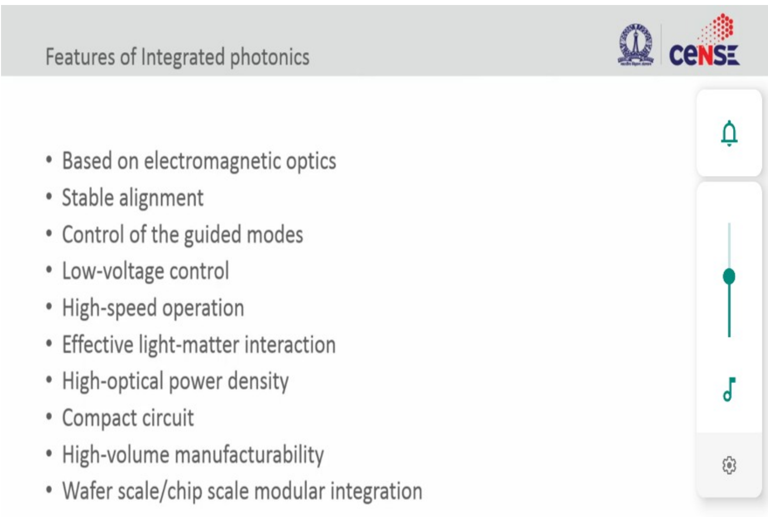

So, these are all some of the interesting features of integrated photonics; let us go ne by one and why they are very interesting. First of all we can use electromagnetic optics, in order to understand integrated optics. Unlike, micro-optics and conventional optics, where ray theory was still useful. When you go to integrated photonics, ray theory will not help you. The reason for that is the structures that we are going to use are much smaller than the wavelength itself. So, when you have structures smaller than wavelength, then ray optics fails.

So, you need wave optics and if you want to have extensive understanding and design basics, you need electromagnetic optics; which we understood very well; so that platform is available. And there is no alignment problem, so it is a stable alignment and everything is fabricated on chip; we do not have to worry about external alignment. Unless, you want to take the light out and put the light in; so that there is an alignment needed, when you are coupling light from a fiber or a diode from outside onto a chip.

So, you can control the modes inside, so you say guided boards, these are all the solutions to the waveguide structure that you have the Maxwell solution to the to the waveguide. And the energies are now transported using this guided mode and you can control the propagation of this mode. We will see in the components section in the next class, how we can do this. And you can use very low voltages to control light now.

So, let us take an electro-optic effect. You apply an electric field to control the propagation. So, now the light is confined in a small volume so that means you do not need very large voltages; so like kilovolts of voltages is what people used to use for similar kind of processes, now it needs millivolts to volts few volts only and you should be able to operate these devices at high speed. Again, thanks to this confinement and low voltage, you can swing your voltage really fast; because the time constants are now going to be very small, the material would react very quickly to the voltage that you have. At the same time the light will also react to these changes in material with high speed.

And the next thing is once you confine light, you can have very efficient light matter interaction which is interesting both for technology aspect and also understanding light and science aspect as well. So, now you are confining light in a sub wavelength regime and if you can do that, your optical power density increases. So, that is next point so optical power density increases if one could increase optical power density, you can do interesting linear and nonlinear optics optical experiments on these kinds of things. And this is not only confined to experiments, you can do nonlinear processes that would result in new wavelengths for example. And you can do interesting optical signal processing using this high optical confinement.

Next thing is compact circuits, so we already saw because of this integration and high refractive index; you can make complex circuits and compact circuits. And by choosing the right material platform, you can make this integrated circuit manufacturing high volume. For example, we talked about III-V semiconductors where we can use wafer scale technology. Similarly silicon, we can use CMOS microelectronics fabrication technology in order to do large scale high volume manufacturing. We can do polymer photonics where we can just use printing process; so, wafer scale/chip scale manufacturing can be easily realized.

And the other interesting thing is you can integrate different chips together functionally different. For example, I can take a sensor chip that can be integrated with a photonic chip. I can take an electronic chip and then integrate it with a photonic chip; so, then it becomes modular. So, you the modular approach brings you a lot of richness in functionality realization. So, these are all the features that one can get by going through photonic integrated circuit; route compared to discrete micro or conventional optics route.

It is first still for some of the application people prefer to use conventional optics; for example high power application and even imaging application, people use conventional optics, but things are moving now closer to integration; where you could realize all the functionalities that you want onto a single chip with lot of advantages that we just discussed. I think with this you must have gotten a clear understanding of the technology evolution and what actually pushed the evolution of photonic integrated circuits, and its features as well. Thank you.