**Integrated Photonics Devices and Circuits**
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**Lecture - 1**
**Course Background and Learning Outcome**

Hello everyone, we are now set to learn integrated photonic devices and circuits. So, in this first lecture, I will try to give you some background of the course. And then some structure of the lectures and learning outcome I will be discussing, let us move on.

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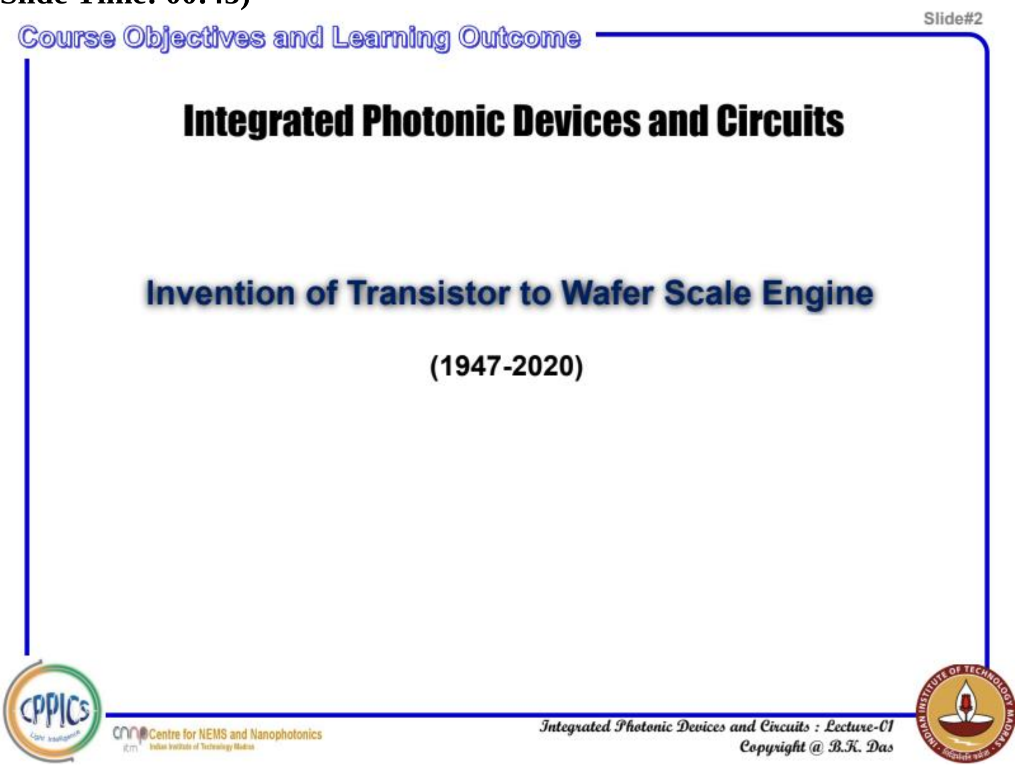


The first thing what we will learn that is actually the background. As I mentioned that we will be learning a bit about the background story of the subject integrated photonic devices and circuits and towards that direction, we need to learn first how the invention of transistor happened and what is the today's evolution of integrated circuit into Wafer Scale Engine? Sometimes it is called WSE, wafer scale engine and that is the outcome of the invention of transistor in 1947.

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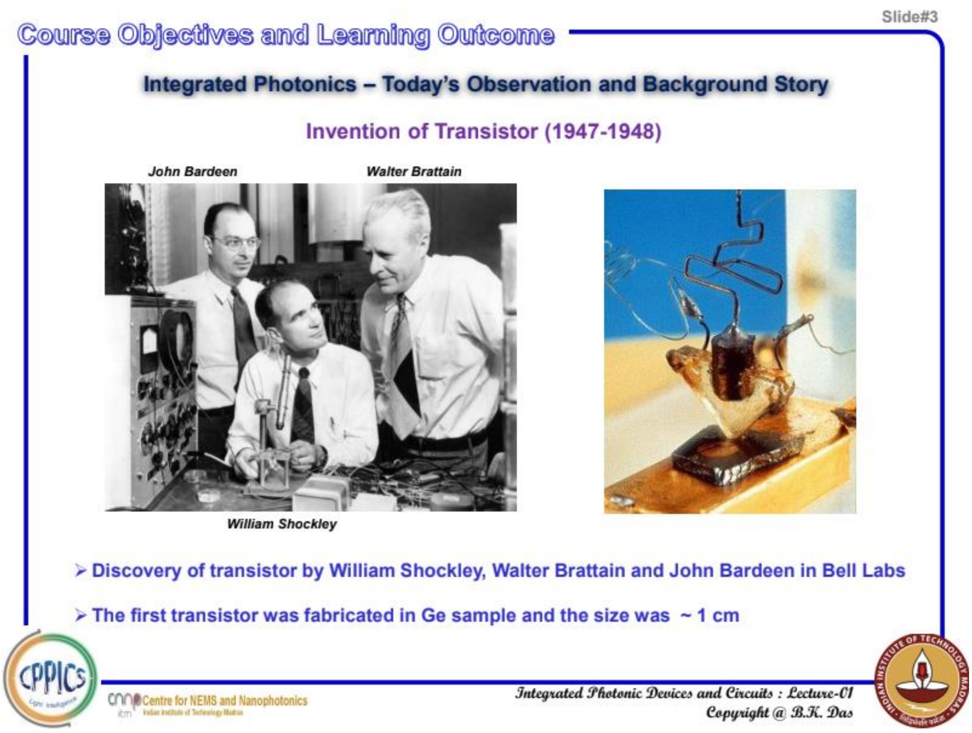


The transistor was first time demonstrated by 3 stalwarts, John Bardeen, Walter Brattain and then William Shockley. So, above is the photograph of the first transistor, what they had demonstrated in 1947 and the size of this transistor was about 1 centimeter by 1 centimeter and it was in germanium sample. Germanium is a semiconductor with a band gap of about 0.7 ev.

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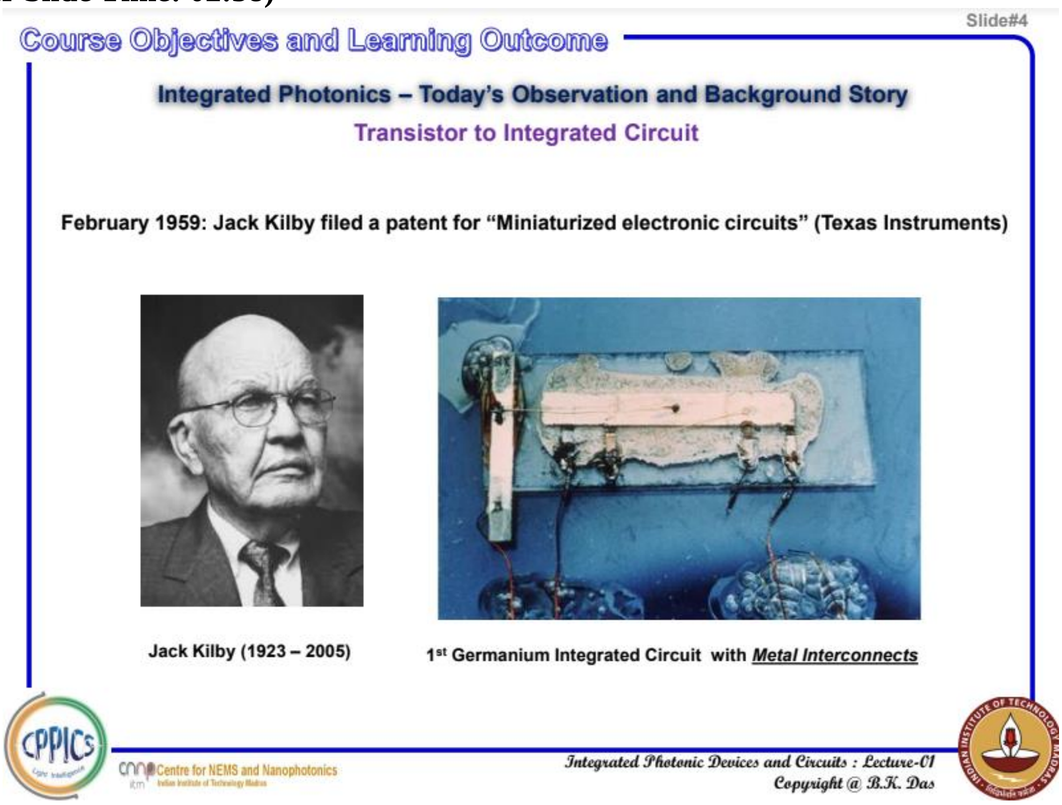

After the invention of transistor, it is about 12 years later or so, Jack Kilby while he was working in Texas Instruments he first time demonstrated miniaturised electronic circuit. So, from transistor to circuit that was the first experimental demonstration before that there was also proposal but, this was the first. This is the photograph you can see what first integrated circuit is. 3 transistors were integrated in this. If you see how dirty it is and it was just placed in a frame.

So, aluminium plate is the block where transistors were fabricated and then you have all the connecting wires everything outside it was shown. So, that is what they say that first germanium integrated circuit with metal interconnects. So, inside the semiconductor germanium sample there are transistors as well as metal interconnect transistors means this is an active device.

It is basically you can control you can actually tune the resistance, trans resistance. Resistance can be controlled by controlling the electron flow from one transistor to another transistor, you can have some certain kinds of functions, which we will see in later it is actually the success.

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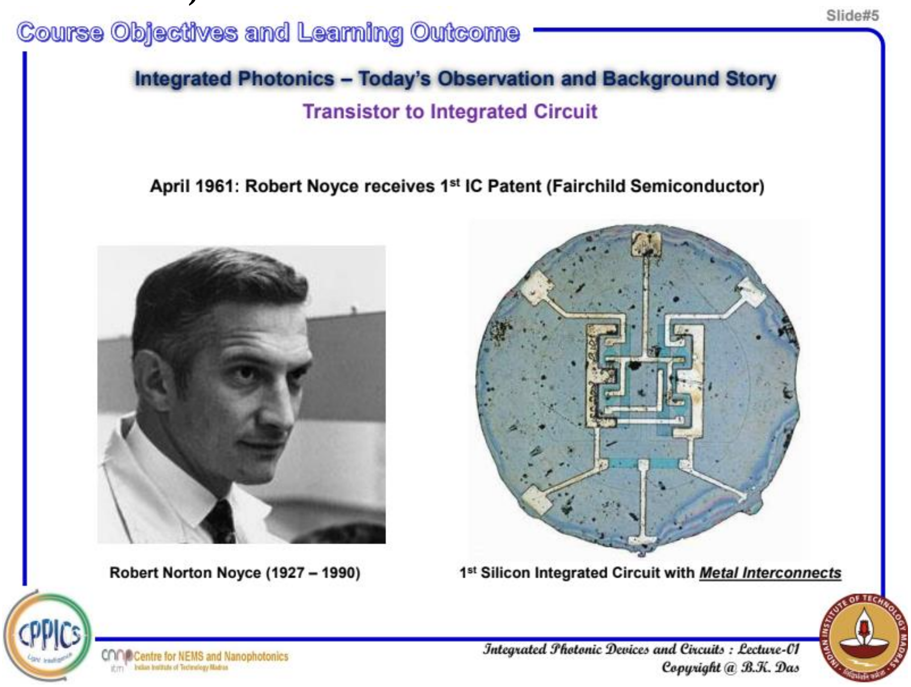


Because germanium was not so easy material and relatively easier material is silicon and band gap in silicon is also more than the germanium so that it can operate at higher temperatures reliably. So the integrated circuit was demonstrated in silicon within 2, 3 years later by Robert Noyce. It is kind of silicon wafer.

And 4 transistors were integrated and interconnected in silicon that has been done by Robert Noyce and his team while working in Fairchild semiconductor. So, the transistor to integrated circuit was demonstrated and it was shown that you can integrate more and more number of transistors which was feasible and that happened in 1961.

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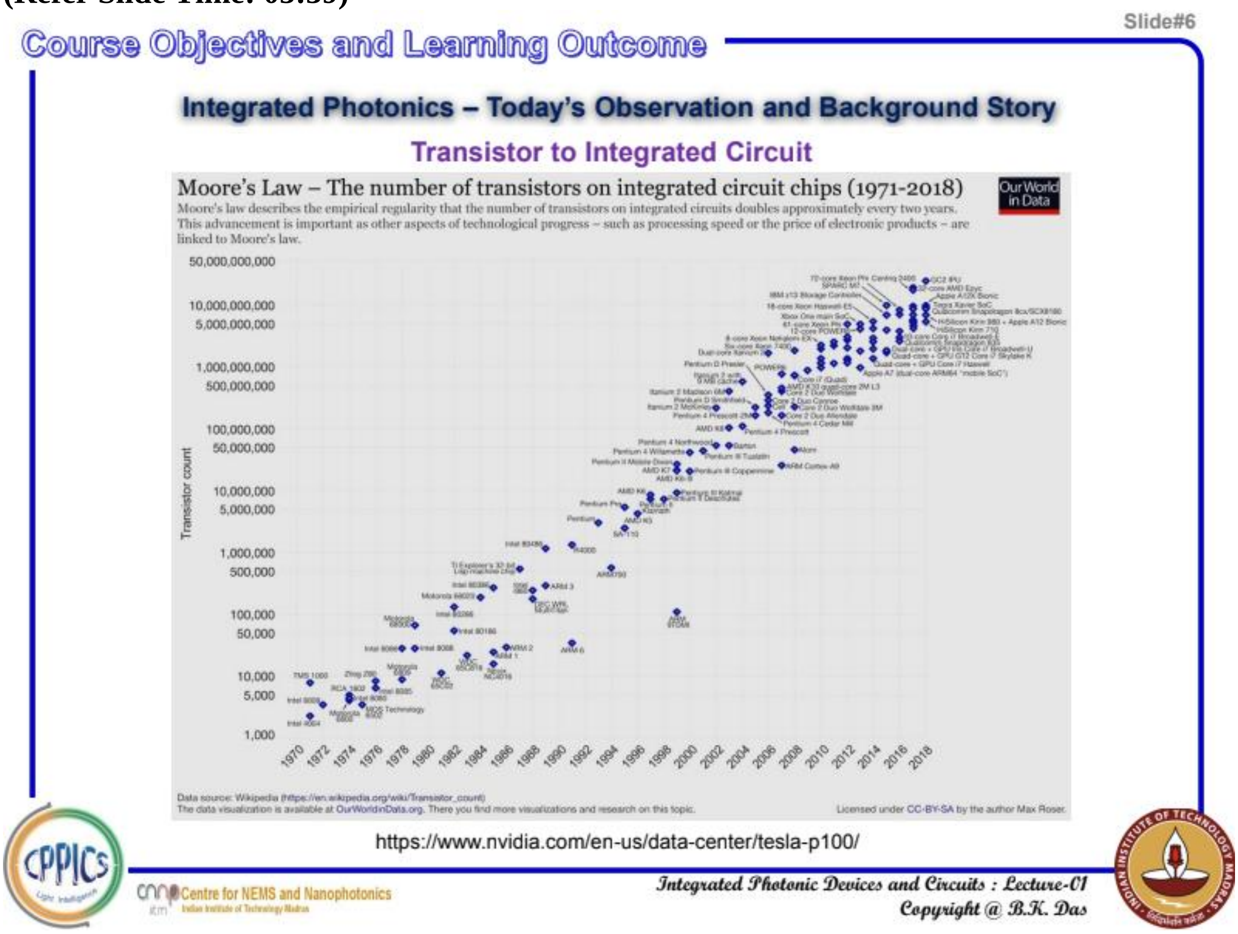


Now, we are in 2021 and here it is shown how the integrated circuit real evolution happened. This x axis is starting from 1970 and up to 2018.

So, every 2 years it is shown and y axis is actually showing the transistor count. So, 1000, 5000, 10000 and then1 lakh, 1 million and then is actually 1 billion and now is actually 50 billion transistors. This transistor integrated circuit later on it was used for microprocessor and CPU, GPU all the computer, motherboard etcetera demonstrated by various companies. These are actually different model number with various companies.

So, as the time passes from 1970 to 2018, we see that certain GPU's, CPU's are shown here, which is about 1 billion to more than 1 billion transistors could be integrated. And it has been shown that also in integrated electronics chips more than 10 billion transistor also particularly Tesla GPU, Nvidia GPU fabricated in TSMC, they are more than 15 billion transistors and it is not the end.

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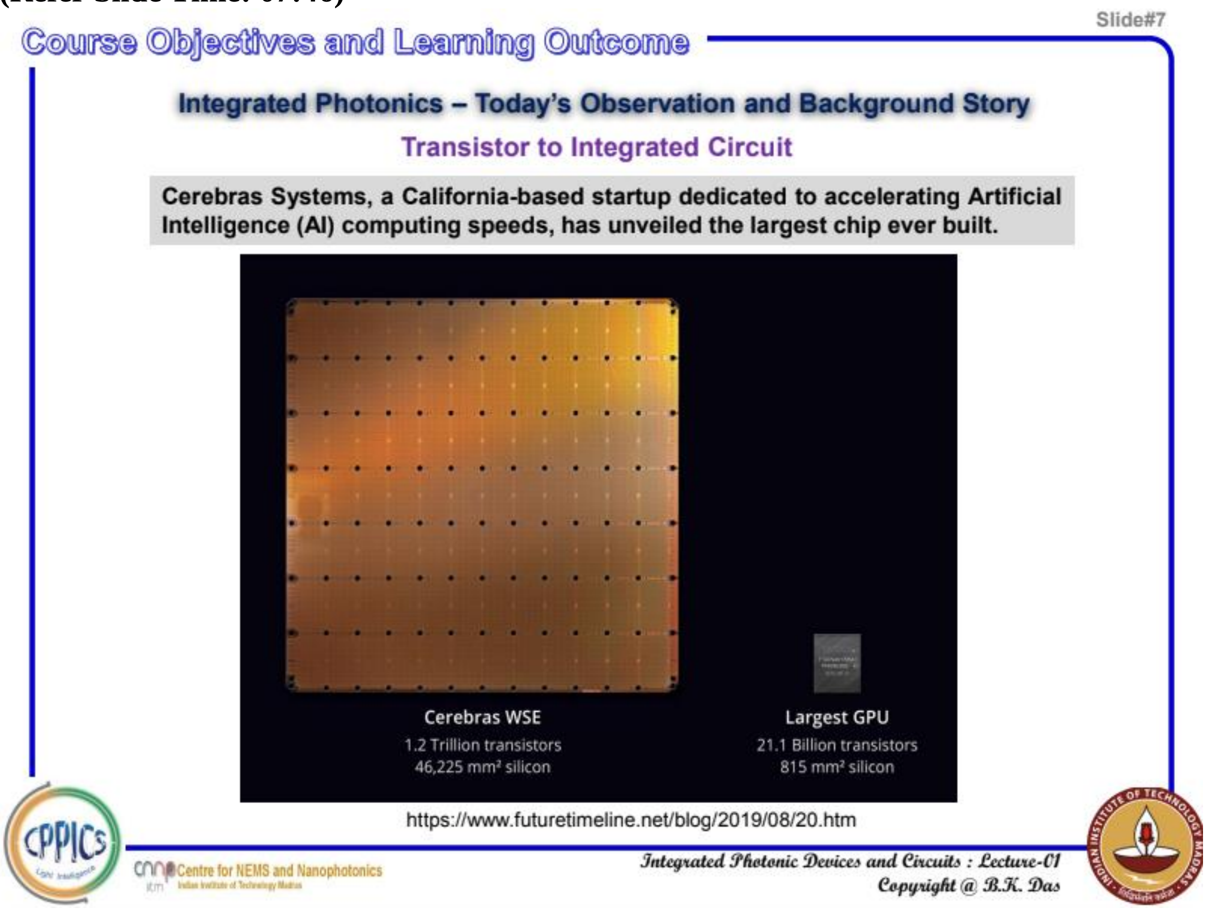


And very recently, actually Cerebras systems, a California based startup dedicated to accelerate artificial intelligence computing speeds. It has unveiled the largest chip ever built, so, called wafer scale electronics engine. So, this is the number about 1.2 trillion $(1.2 \times 10^{12})$ and that has been integrated in 46,225 millimeter square.

So, it is in the millimeter square that means full wafer in full wafer they have integrated 1.2 trillion transistors. And that has been used for targeted for artificial intelligence and machine learning before that largest GPU in a chip that was 21.1 billion transistors in 815 millimeter square that means about 8.1 centimeter square and so on in that circuit that is actually graphical processor unit normally people use for computer operations display and gaming all those type of things.

So, far so, good that transistor to integrated circuits, this is just announced in 2019 by the way, just 2 years back. Full silicon wafer now is available and they are being used in semiconductor foundry with a size of 300 millimeter diameter, so 30 centimeter diameter, you can imagine 30 centimeter diameter it is more than your lunch plate.

So, that type of wafer and full wafer you can integrate with trillions of transistors to get certain applications, so called wafer scale electronics engine that has been demonstrated and it is all about to be excelling.

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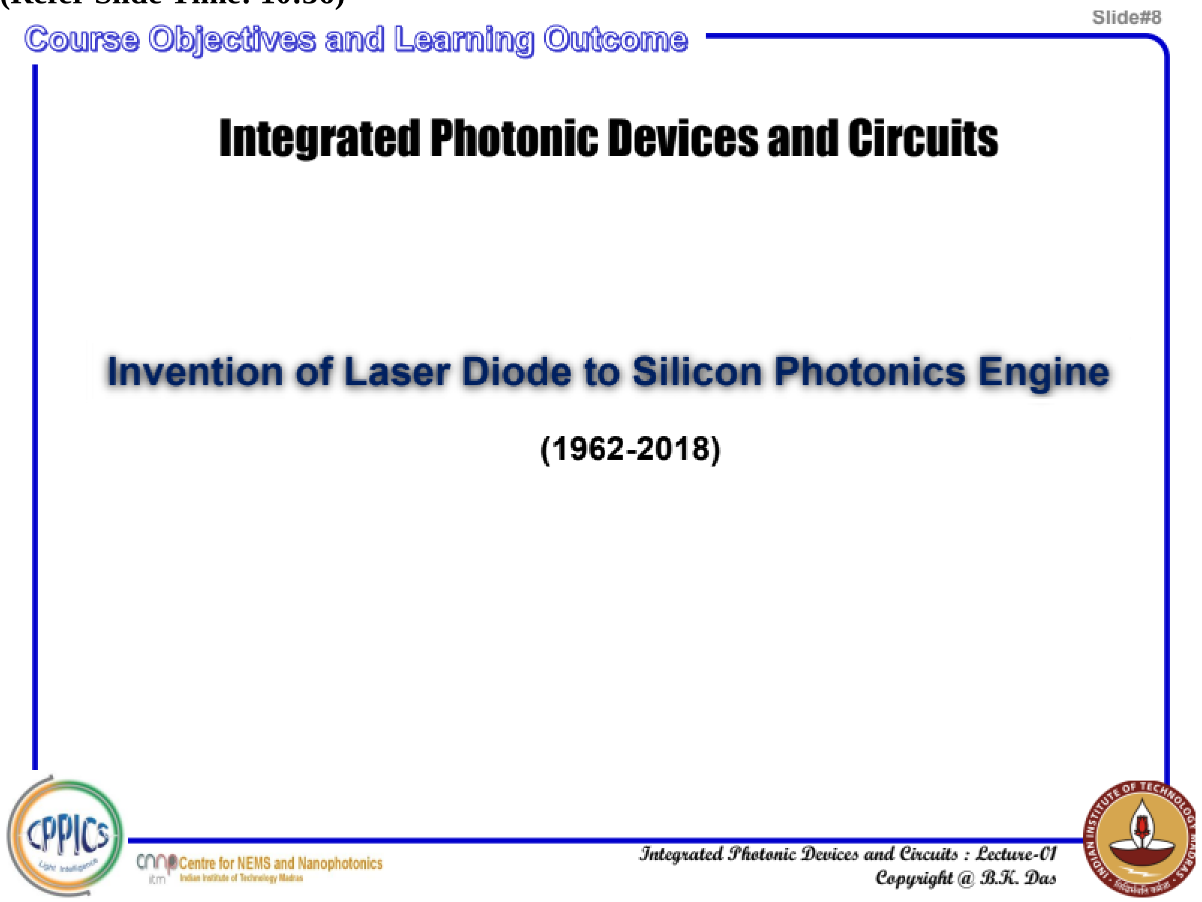


So, in one hand we see that there is a tremendous success of electronics industry starting from transistor to wafer scale engine. Now, parallel to that evolution another important area has been evolved, I just want to explain that in terms of just invention of laser diode, not laser by the way laser was demonstrated earlier. So, invention of laser diode that means solid state laser.

When it was demonstrated that opens up new area also and continuous research in academic domain and lately industrial recognition. Because of that, there was one interesting devices, interesting integrated circuit. It is another type of integrated circuit. Instead of electronics integrated circuit it is actually photonics integrated circuits and they are called silicon photonics engine.

So, we are talking about wafer scale electronics engine and parallely, we have silicon photonics engine the ultimately. How it is evolved that is the story I want to discuss before I enter into the course of so called integrated photonic devices and circuits because this electronics IC and silicon photonics engine you cannot think they are actually completely different area, they are actually an independent area. They are actually complementing each other. This two areas are basically merging that means photonics and electronics are merging and because of that merge actually the photonics industry is booming nowadays. So, I will try to give you some overview starting from laser diode how silicon photonics engine today has been evolved.

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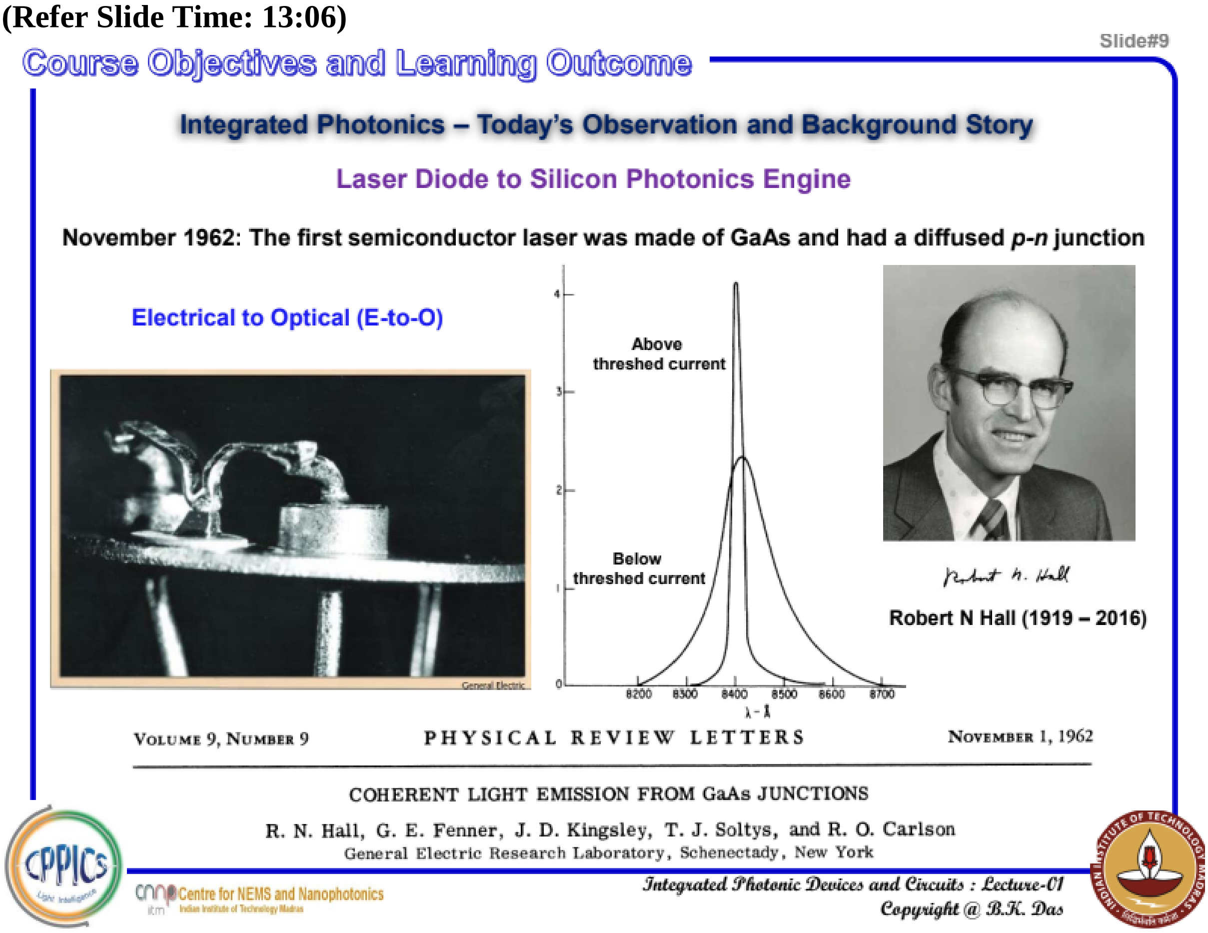
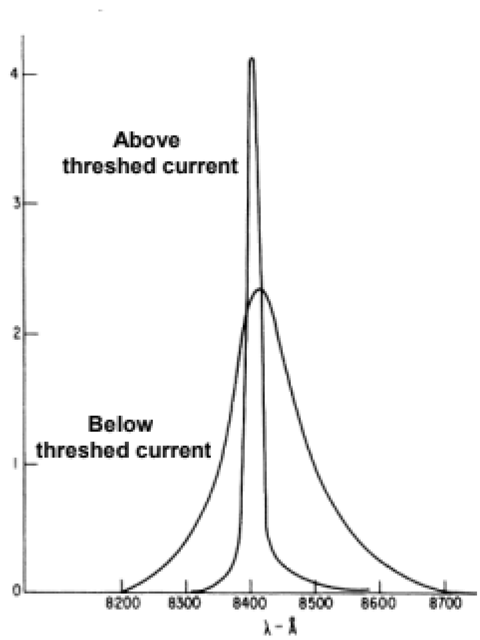



Laser diode was actually reported in 1962 in the literature physical review letters by Robert Hall. His team presented the first semiconductor laser made out of gallium arsenide. Gallium arsenide is also a compound semiconductor that is not like silicon and germanium. It is an elementary semiconductor. It is a compound semiconductor alloy. Gallium arsenide together make some kind of compound and that is also semiconductor, direct band gap semiconductor. It is something different property than indirect band gap semiconductor like silicon and germanium and because of that direct band gap semiconductor, it is actually possible to demonstrate laser. Laser means nothing but it is a laser diode. It means actually it is a p-n junction, p type doping, n type doping. When you give a forward bias electron and hole will be combined in the depletion region. And that electron will lose energy and then you can have light electromagnetic wave. So, that is what it is said that laser diode is nothing but it is a device which converts electrical energy into optical energy. So, I say E(Electrical) to O(Optical) and above is the first photograph of the semiconductor laser diode made out of gallium arsenide.




You are just slowly, slowly increasing the forward bias or current. So, initially below threshold current in the diode, you see a light electromagnetic wave will be emitting with a spectrum looking like that x axis if you see this is lambda starting from 8200 angstrom that means 820 nanometer to 870 nanometer.

So, you see around peak is around 840 nanometer, more than 840 nanometer. This is a broad spectrum you are getting, but as you keep on increasing the forward current in the diode and you cross a certain threshold then emission intensity power electromagnetic wave, it is actually enlarged many times, it was almost doubled it is shown just above threshold current and at the same time you see narrowing down the spectrum.

So, earlier it was broad, below threshold and now, above threshold you see now, if you increase further current, it will be narrowing down further and your power will be intensified around a certain wavelength around 840 nanometer 850 nanometer you can get so.  That was actually a landmark success.

Normally the semiconductor diode, semiconductor transistor, it actually helped the electronics industry. And another type of device came out where electrical to optical energy conversion possible. And this optical energy, whatever it is generating it is completely very nice, narrow almost monochromatic.

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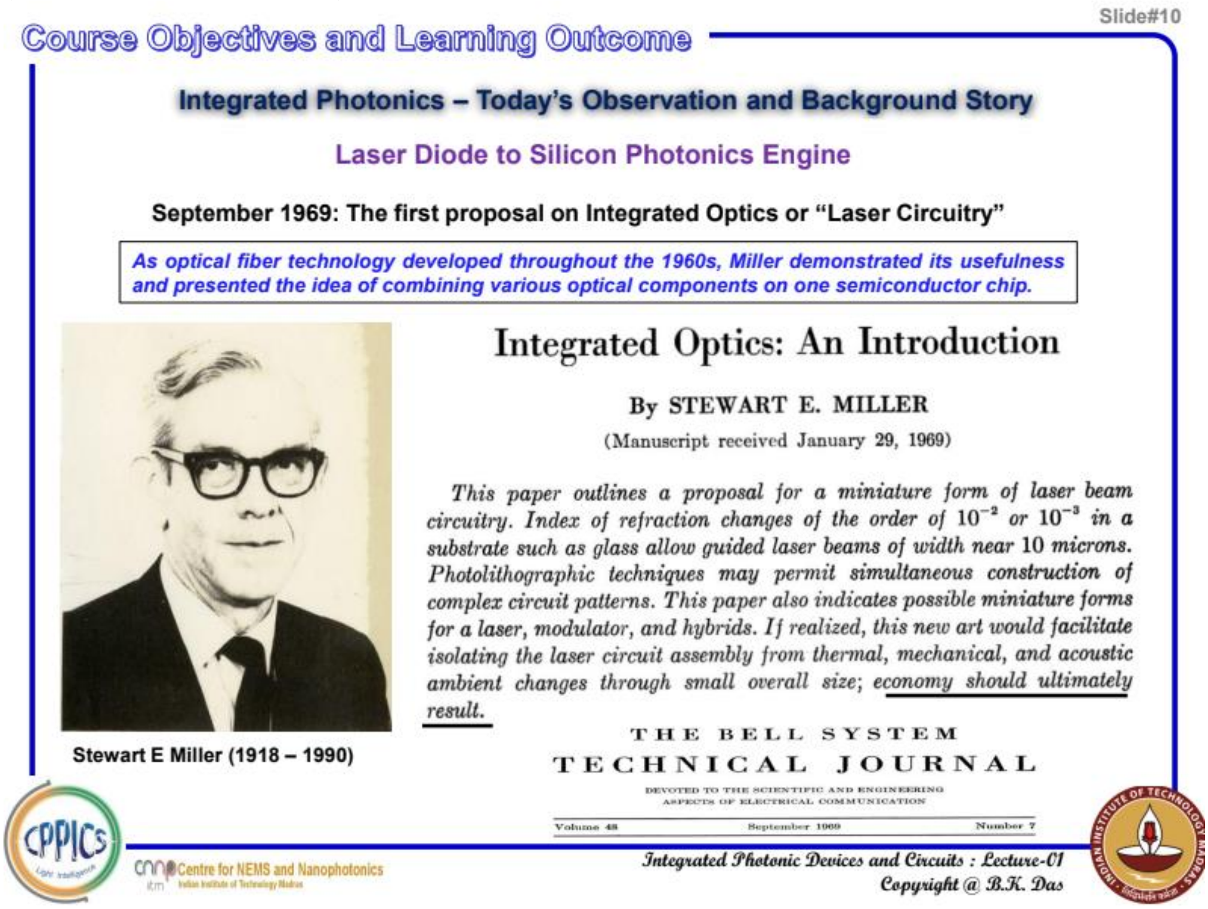


And that opens up another area that area is called integrated optics. So, that was demonstrated in around 1960s and in 1969 Stuart E Miller, he reported he wrote a proposal article, the article in which he proposed the subject called integrated optics. And it was published in Bell system technical journal that time he was working for the Miller was working for the Bell labs. So, as here just comment here, this is the first proposal of integrated optics how the proposal came.

So in 1960s, fibre optic technology developed throughout 1960. Miller demonstrated its usefulness and presented the idea of combining various optical components on one semiconductor chip that is Stuart Miller's contribution, but in this paper what he mentioned very interesting, you see, as he writes, this paper outlines a proposal for a miniature form of laser beam circuitry.

Please note the phase laser beam circuitry that circuit term basically, borrowed from integrated electronic circuitry. In integrated electronic circuitry, you have electron beam circuitry, in which you have to have a circuit where you can control the electron flow, but here he is proposing can have a laser beam circuitry.

And that is possible by changing refractive index, index of refraction. He says in the order of 10 to the power minus 2 ($10^{-2}$), 10 to the power minus 3 ($10^{-3}$), within a cross section of 10 microns cross sections. If you just vary the refractive index by little amount 0.01 to 0.001, compared to your surrounding region, then you can actually confine light or laser beam within that cross section and as long as you maintain that cross section light will be guided. So, you can take light to your desired destination depending on this circuitry, but how that circuitry that guide laser beam circuit how that can be fabricated? He says that is possible. How that is possible? He says this paper also indicates possible miniature forms for a laser, modulator, hybrids and that can be done by means of photolithographic technique. Photolithographic technique was invented for the demonstration of integrated electronic circuit. Same technique you can use to demonstrate laser beam circuitry and not only just laser beam guide you can also think of a platform where actually you can integrate laser itself.

Modulator is a very interesting component device, we will be learning in this course of course, where actually you can convert electrical data information into optical information. That is modulator and hybrid type of circuit you can design and the most important comment was in the abstract he says, if that is happen, this type of circuitry is realised then economy should ultimately result. So, ultimately you know, it should be cost effective, it should be economical. So, if integrated optics is possible, then you can have that type of thing.

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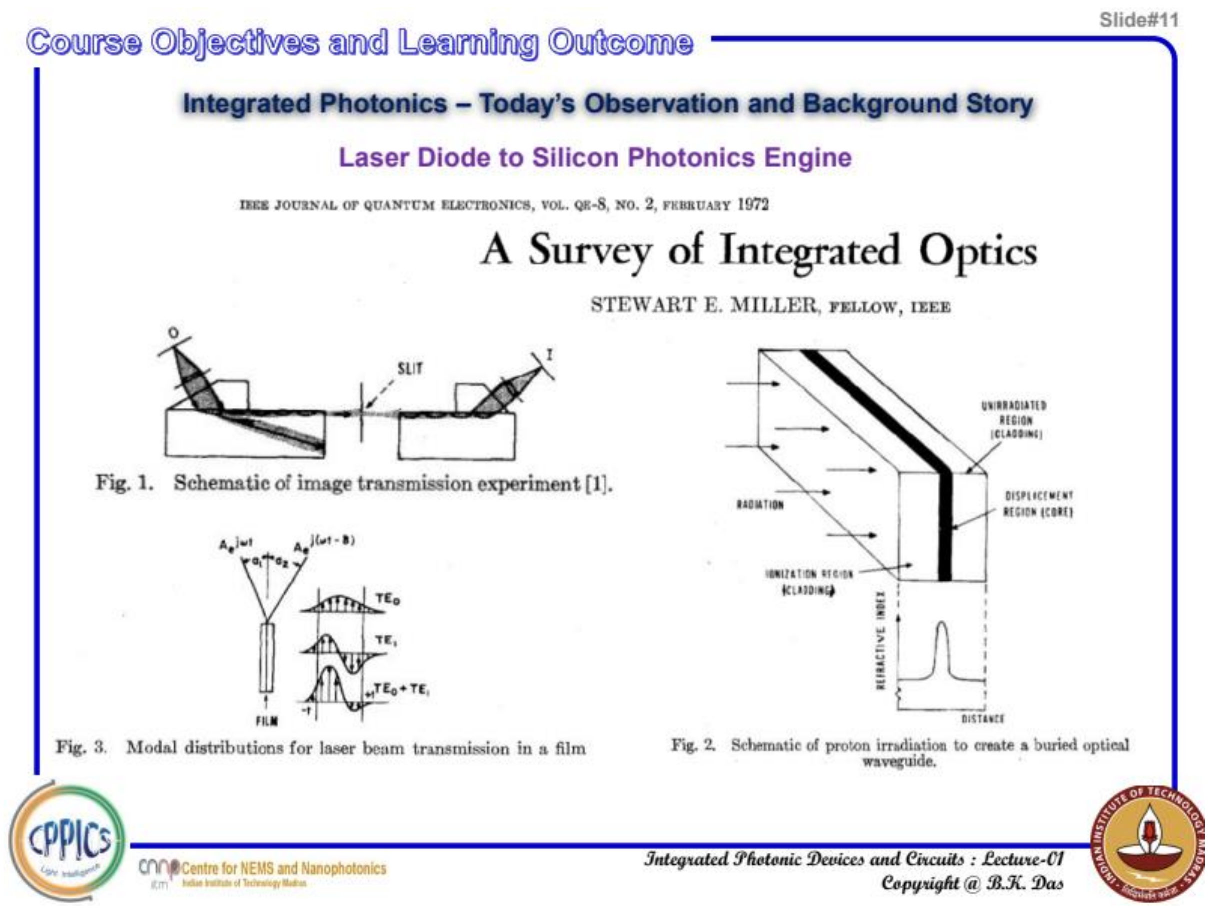


Now, once it is proposed from bell labs, many people started working and within 3 years, Stuart Miller wrote another review paper where the title was survey of integrated optics and that was published in journal of quantum electronics. This was a bit of elaborated paper where he demonstrated and discussed what so, far happened towards integrated optics.

In this figure 1, it is shown the guiding of light practically. Earlier it was proposed. Now, practically refractive index is changed in the surface layer of a glass substrate. Whenever you will shine light from the object, you can focus that light through a prism coupler, then light can actually tunnel into the substrate and part of the light actually propagates or the guided mode in the surface layer and something is actually it is being refracted to the substrate.

So, when it is guided, it will have a particular shape very nice beam without diffraction it can come and you can take it out. So, you can have a slit and you can clean up then you can again launch into another waveguide planar waveguide and again if you wish to use another prism you can take it out.

So, that is how the first thing happened. Remember that transistor was how dirty looking, integrated circuit how dirty it was looking, but now also you see waveguide also it is demonstrated. It is something looking very bulky and at that first time whatever demonstrated can be looking bad, but inherent information get sufficient stimulus to the academic community.

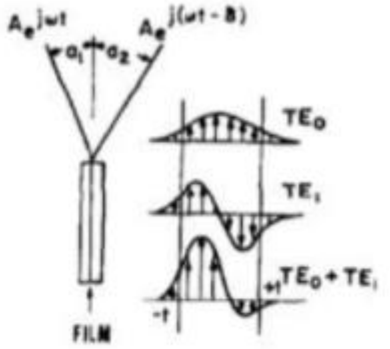


Fig. 3. Modal distributions for laser beam transmission in a film

And they went on to demonstrate that in this guide, they are a different type of field, their pattern of field intensity electromagnetic wave can be there like TE0, TE1 they are actually kind of mode guided mode that actually characteristics profile. Here different types of modes are shown how it will be looking and they will be guided orthogonally without interfering each other. They can carry energy in the waveguide.

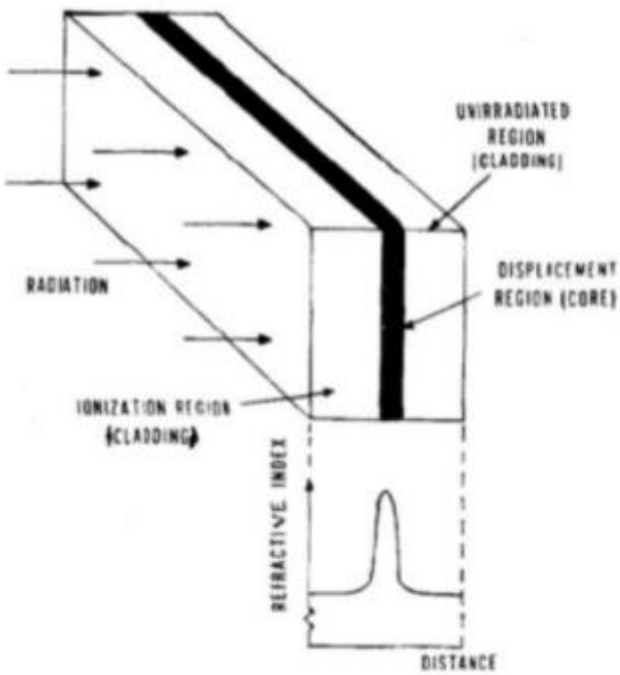


Fig. 2. Schematic of proton irradiation to create a buried optical waveguide.

And here actually it is shown how they have been fabricated this planar waveguide structure by just ion implantation, ion bombardment. Energetic ion the bombarded from the site and depending on the energy it can penetrate up to a certain length and in that certain area there it will be just stabilised and be incorporated and doped and in that doped energy refractive index will be changed.

And that diffractive index change will be around in the order of 10 to the power minus 2, 10 to the power minus 3 according to the proposal. And you will see the profile field strength that is light whenever we are launching inside the field distribution intensity profile, how it will be looking like it is shown here. That is amazing that it was proposed that if waveguide can be fabricated, integrated optic circuit can be demonstrated.

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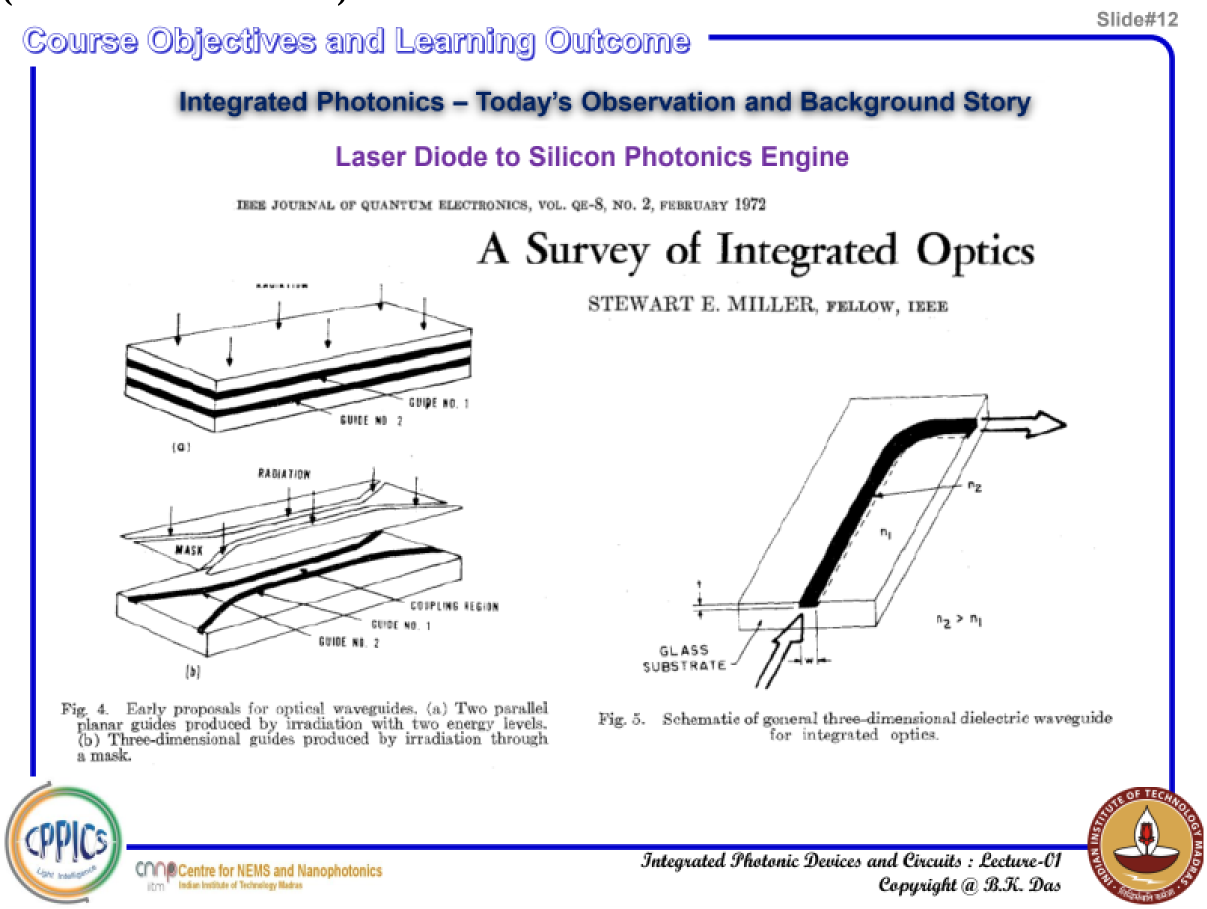
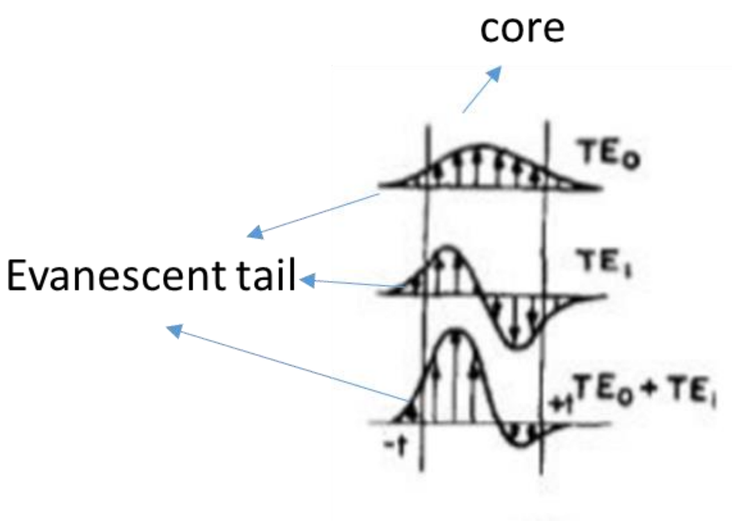


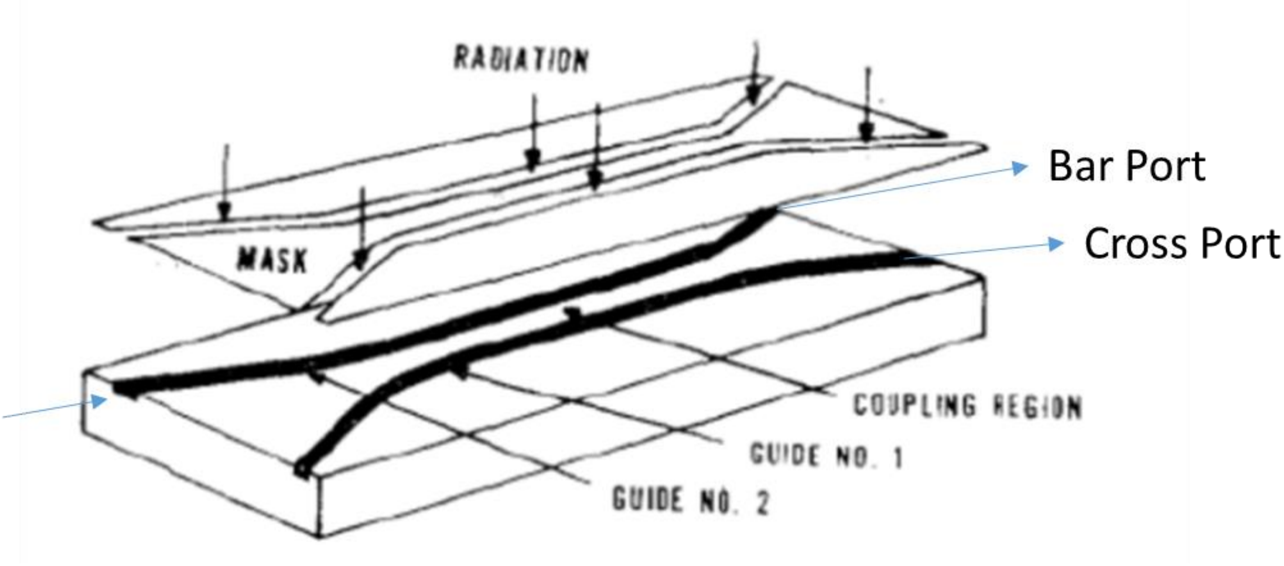

And then in the same paper also it is shown you can have 2 waveguide here for example 2 planar waveguides, 2 planar guide in the upper 2 different energy if you are just bombarding then you can have a higher refractive index change in 2 different layers. That means, in vertically, you can have 2 different planar waveguide where refractive index is more and you can actually confine light in the upper layer as well as a lower layer also.

And if you can design properly, it has been shown that if 2 wave guides are there for example, this is a certain kind of waveguide structure this black in the surface layer, the planar waveguide structures. So, interesting part is that those two waveguides at the beginning are far apart and then when they are coming closer and closer, the guided modes which extends outside the core region interact with each other. Where refractive indexes are higher, we will be calling that as a core and outside this is evanescent tail that is called evanescent filed.



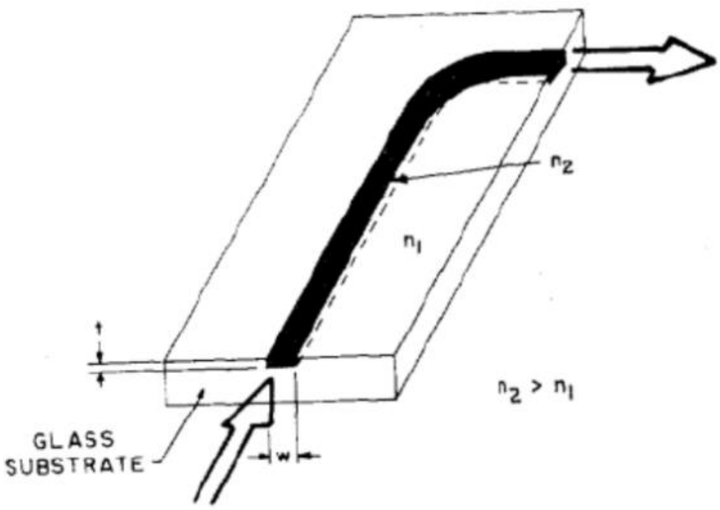

So, in this case if these 2 waveguide if you are guided mode if you are bringing them together.

So, what happens the evanescent field of the one waveguide is interact with the neighbouring waveguide and in this way light can tunnel. So, that you can have one input and if you launch a light, it can tunnel to the secondary guide and you can get output at both waveguide ends depending on the designs. And if you can just make certain kinds of active actuation then it is possible that light can be switched back and forth from one waveguide to another waveguide. Corresponding to inpit port, bar port and cross port is shown in the below figure.




So, in this way actually you can make switch power splitters so on and also if you see you need a certain area where actually the waveguide after a certain interaction length in the beginning and at the end you need to take it apart so that you can stop interacting the waveguides should be decoupled.

So, for that purpose, you need to bend the waveguide structure. So, that is also demonstrated. You can bend light because this kind of refractive index change, the cross section about 10 micron you are considering, higher refractive index where light will be confined because of total internal reflection principles etcetera. And as long as if you bend the structure cross section and then light can also guide.



However, here if you see $n_1$ is the substrate refractive index and here core region $n_2$ where $n_2$ greater than $n_1$. So, we can say that $n_2$ - $n_1$ in the order of 10 to the power minus2 to 10 to the power minus 3 that is proposed that is theoretically one can also analyse if the area cross section area is about say 10 micrometres diameter. .

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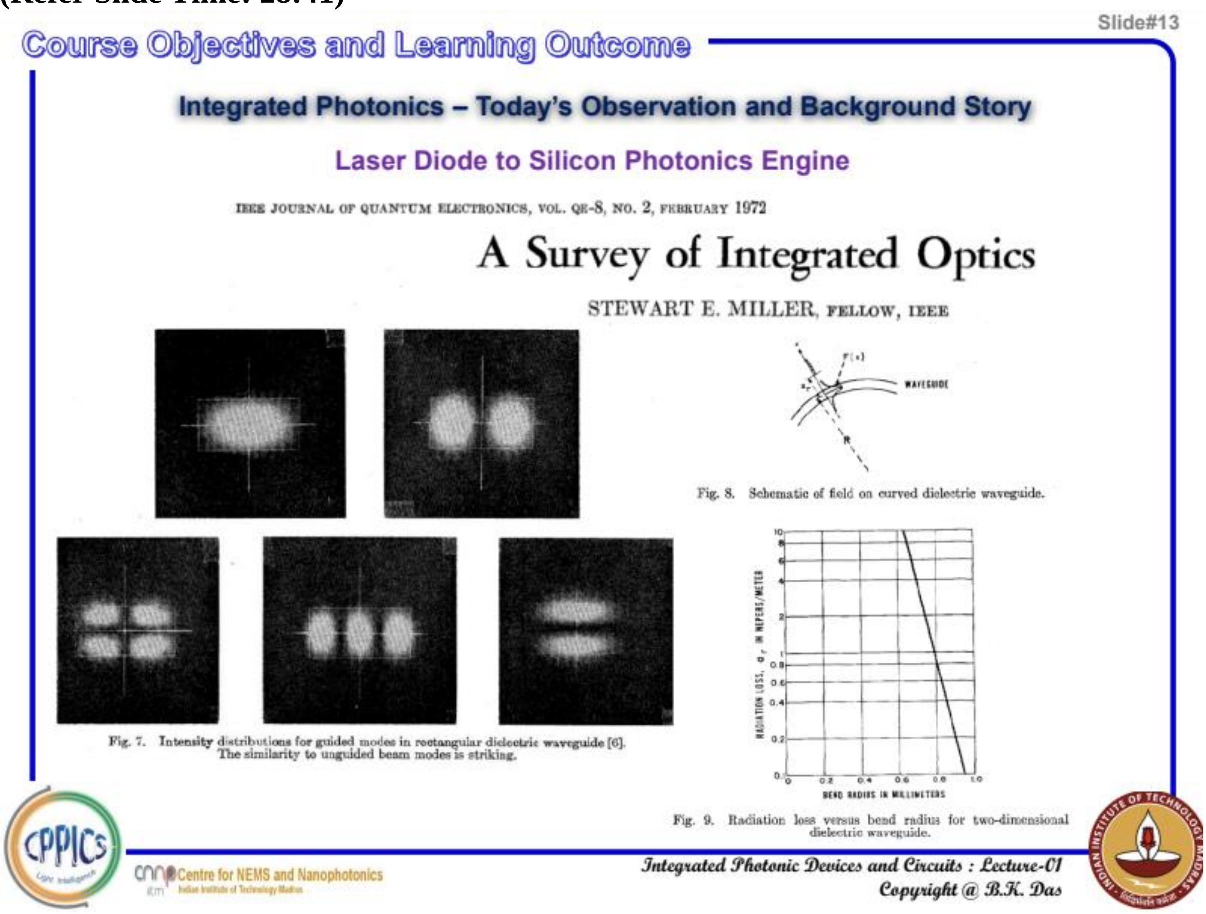
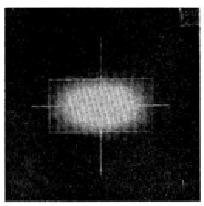
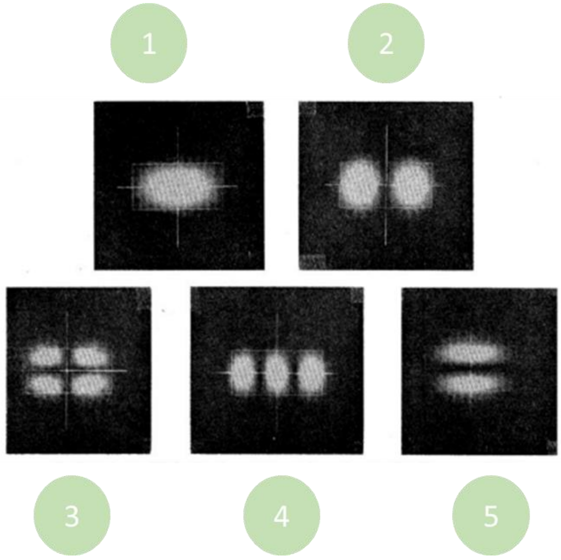



So, now, this is the demonstration in the same paper. It is showing the demonstration of guided mode when it is actually imaged in the polished output. For example, here in this case if you have all the light you are coupling and coming out and you put a camera to image then you will see interestingly that different type of pattern by controlling the input angle or little bit translation here and there people could show that different type of modes whatever earlier schematically shown the field distribution of the guided light.



It is you see it is like a simple first one is it like a simple laser spot beam, this would be called as first order mode. This first mode, mode number 1. This is the tightest confinement will happen here tightest confinement beam.

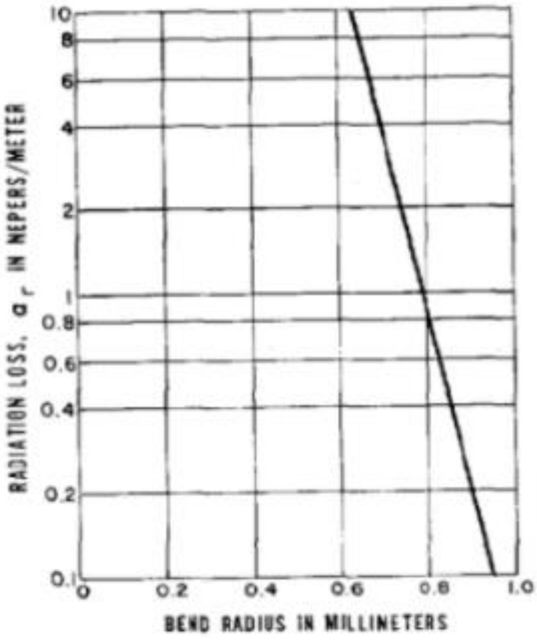



So that will be actually next tighter mode that we will be calling a mode number 2, and then we can call mode number 3 or number 4, how they are distribution, light intensity distribution, as a different mode, that will be there. And we will learn later that these different types of modes, all these modes, as you go higher and higher, you will see that confinement will be slowly, slowly reducing.

And as you go for higher and higher, higher more than that will not be no more confined and also each of this distribution will propagate with a distinct phase velocity. So, phase velocity of mode 1 will be the lowest. Phase velocity of mode 2 will be the next lowest and so on slowly phase velocity will be increasing. And suddenly it will be like a homogeneous medium.

So light guide circuitry, everything is coming up and if you are bending a structure, normally in the bend region light can leak also bit. It can be lost.

So, that is another problem of the waveguide circuitry, because you cannot just bend the waveguide according your wish. Because once you bend, the property of the mode guidance is disturbed and there is a possibility that it will be leaked. So, here they also demonstrated that at bend radius, how the loss is actually increasing as you increase the bend radius.




So, straight waveguide loss is lower and as you bend then loss will be increased and for tighter and tighter bent, loss will be increased more.

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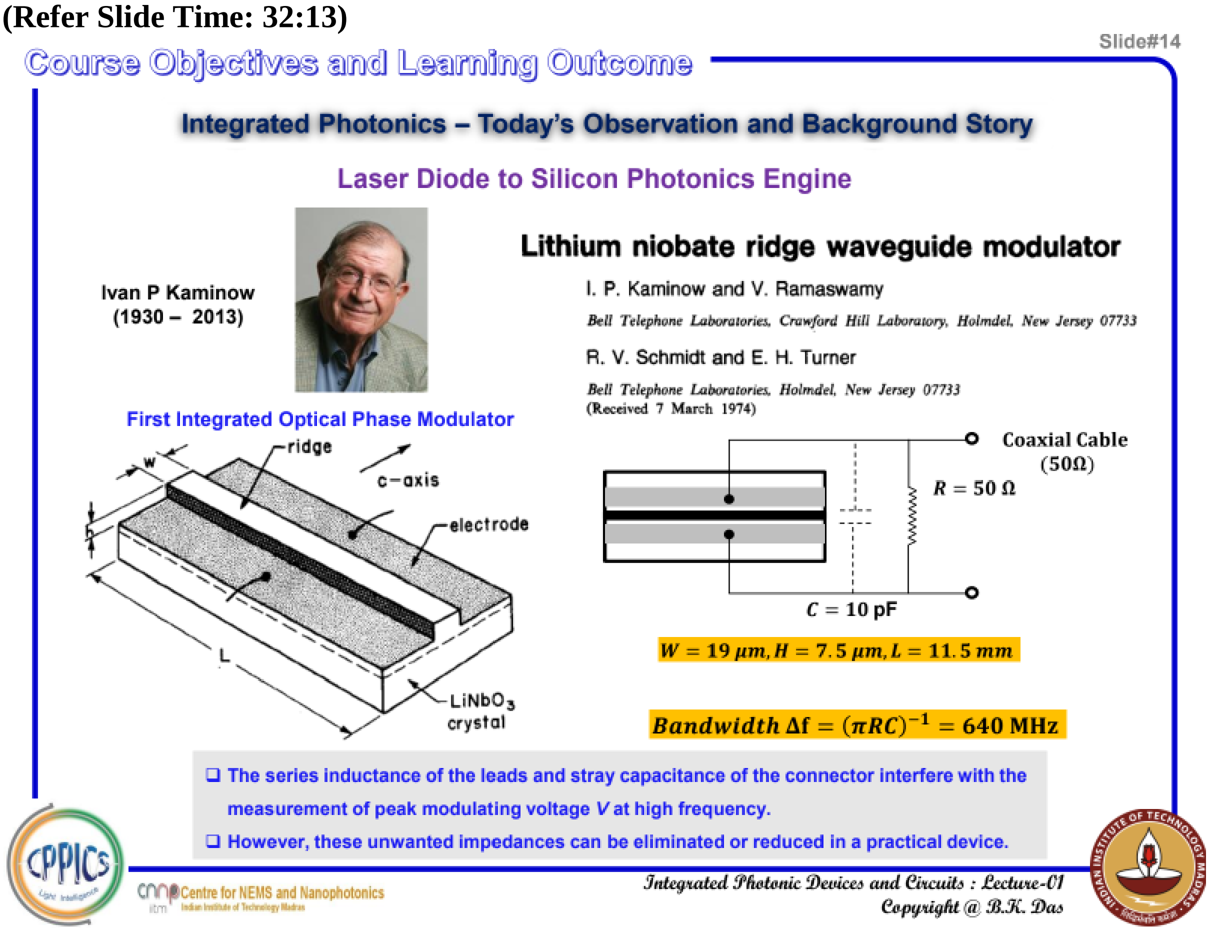
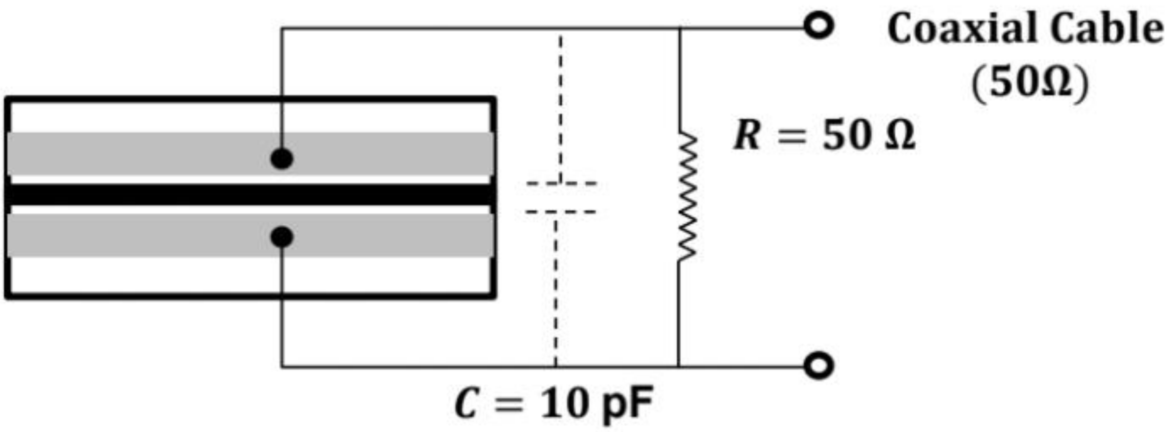


Ivan Kaminow(1930-2013) fabricated the waveguide with rib structure cross section in lithium niobate. This is another material not glass that is actually synthetic material. Lithium niobate is a ferroelectric electric material and lithium niobate crystal.

In both sides of rib structures, he put electrodes and after putting electrode and he showed that, if you just apply electric field, then refractive index of this waveguide cross section can be controlled. And by controlling that, depending on the signal you are giving the phase or refractive index of the waveguide can be changed. And when refractive index can be changed that guided mode will see different phase velocity. So, in this way one can actually demonstrate phase modulator that is very, very important component for your integrated optical circuits. So, you need a laser, you need a modulator, you need waveguide. And he has shown that if you just consider this type of circuitry, you can model like this thing.

So, your coaxial cable is 50 ohm cable. If you are just giving your electrical or microwave signal whatever depending on that you can have also impedance matched load 50 ohms. So, that maximum power can be transferred. So microwave power can be transferred to the electrode structure and depending on that signal, you can control the refractive index and then you can have your light propagation, you can actually modulate.




And you can analyse electrical circuits with this resistance this capacitance is basically coming out of because of these 2 electrodes. The capacitance typically they measure about 10 pico farad. So, if you analyse that thing that this type of circuitry the bandwidth of this modulator structure is shown up to 640 Mz. Later on with more advanced waveguide structure, with advanced electrode structure, with advanced circuit etc, people could demonstrate modulator up to 40 -100 GHz and so on. Here it is mentioned that the series inductance have the leads and stray capacitance of the connector interfere with the measurement of the peak modulating voltage V at high frequency. It limits the bandwidth.

So, that is in 1974 about 47 years ago. However, these unwanted impedance can be eliminated or reduced in a practical device that was proposed and in fact, it has been done also later on.

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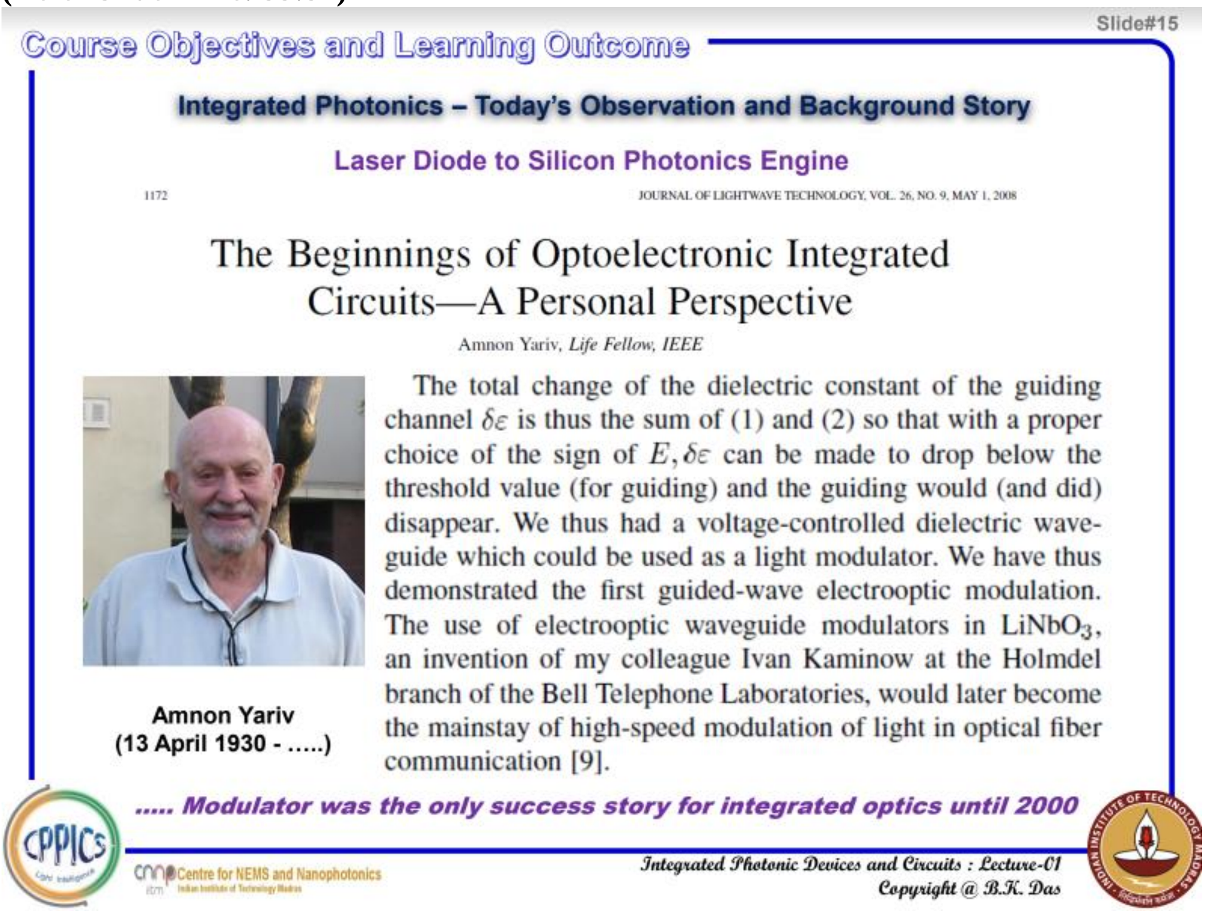


Amnon Yariv  actually says that the modulator demonstrated by Ivan Kaminow earlier in lithium niobate that saw the success. However, this first the modulator that means the device where actually you can transfer data from electrical domain to optical domain that was first time demonstrated by Amnon Yariv. But that was in semiconducting material. However, lithium noibate is found to be more robust and more good property efficient properties. That is why it saw the success. Unfortunately, his credit actually taken away by the guy Ivan Kaminow, but he was the man who demonstrated first the modulator in semiconductor. Amnon Yariv, his work in photonics guided wave optics, everything is phenomenal. He had written a very nice book “Photonics: Optical Electronics in Modern Communications”. Some portion of this course will be covering from that book also. He mentioned that modulator was the only success story for integrated optics until 2000. That reason being you see from 1947, the transistor to integrated electronic circuits evolution is phenomenal. But laser also demonstrated laser diode was in 1960. But until 2004, integrated optics proposal to optical circuits proposal to the different types of device demonstration etcetera, until 2000 only the modulator that sees the commercial success. Reason because there was no good material like silicon for it like what happened in the electronics industry, but for photonics optics, you did not have some good material to demonstrate laser, waveguide, modulator, detector etc. People were trying different material platform, but not so successful.

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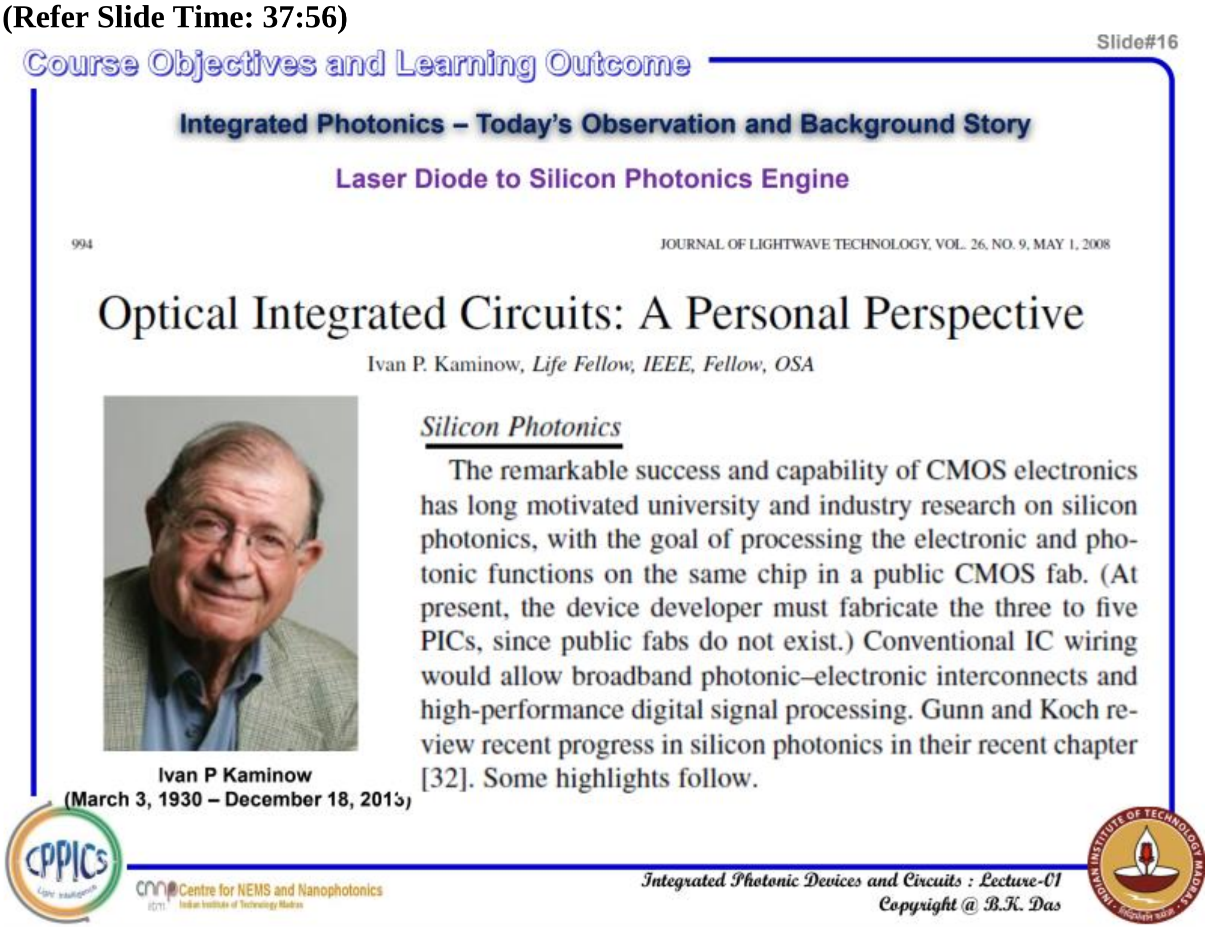


So, now in the same issue, journal of light technology, where Yariv commented that modulator was the only success story until 2000, IP Kaminow who was actually the key person to demonstrate lithium niobate modulator which has been used in fibre optic communication, he says that, well, silicon photonics actually is the taking over. So his writing in 2008, but once upon a time, he himself was thinking that lithium niobate modulator could be fabricated high speed modulator could be fabricated in lithium niobate.

So lithium niobate could be the silicon of optics world. However, it was not happened. So, he himself confessed that, the new material platform silicon and silicon photonics technology is coming up and that is actually going to rule for photonics integrated photonics instead of so called integrated optics what was proposed originally. So, silicon photonics actually is huge subject towards realising integrated photonic device circuits. That is the conclusion in 2008. That means, this conclusion came in the meantime silicon photonics technology already evolved.

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It is actually 2019 story. Photonics Company, Ranovus has announced the Odin platform, scaling its 100 Gbps per lambda silicon photonics engine from 800 Gbps to 3.2 terabit per second in a single chip transmitter silicon photonics transmitters and it was named as a silicon photonics engine that is actually the future. That is the market today.

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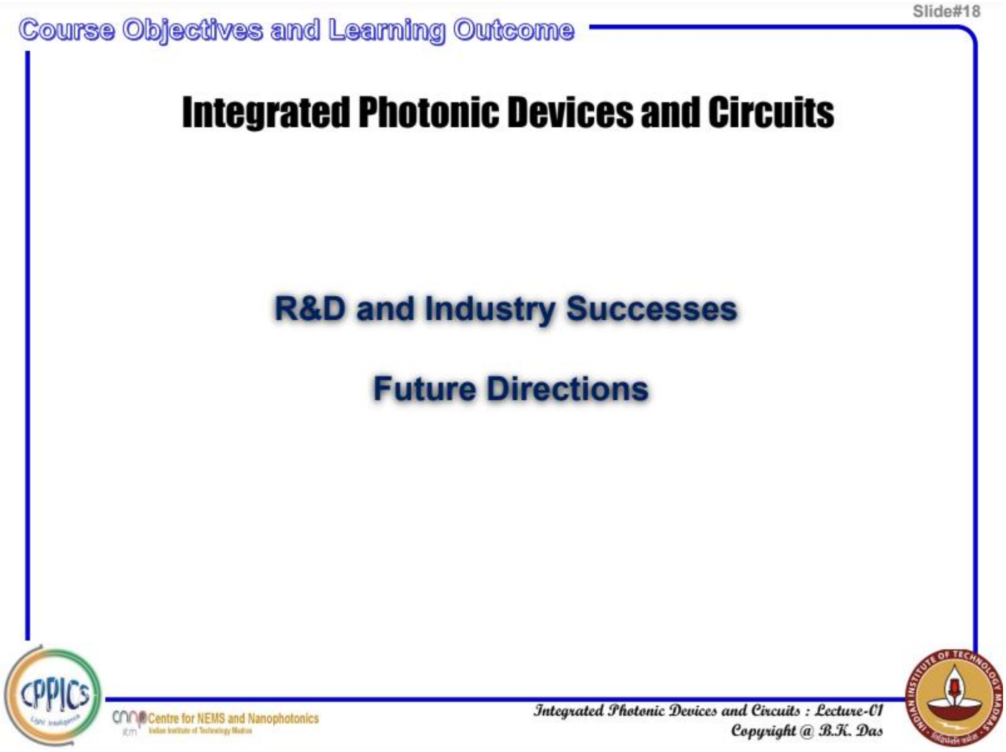


So, next with this I just want to give you very quickly how the R and D and industry success and future direction is happening.

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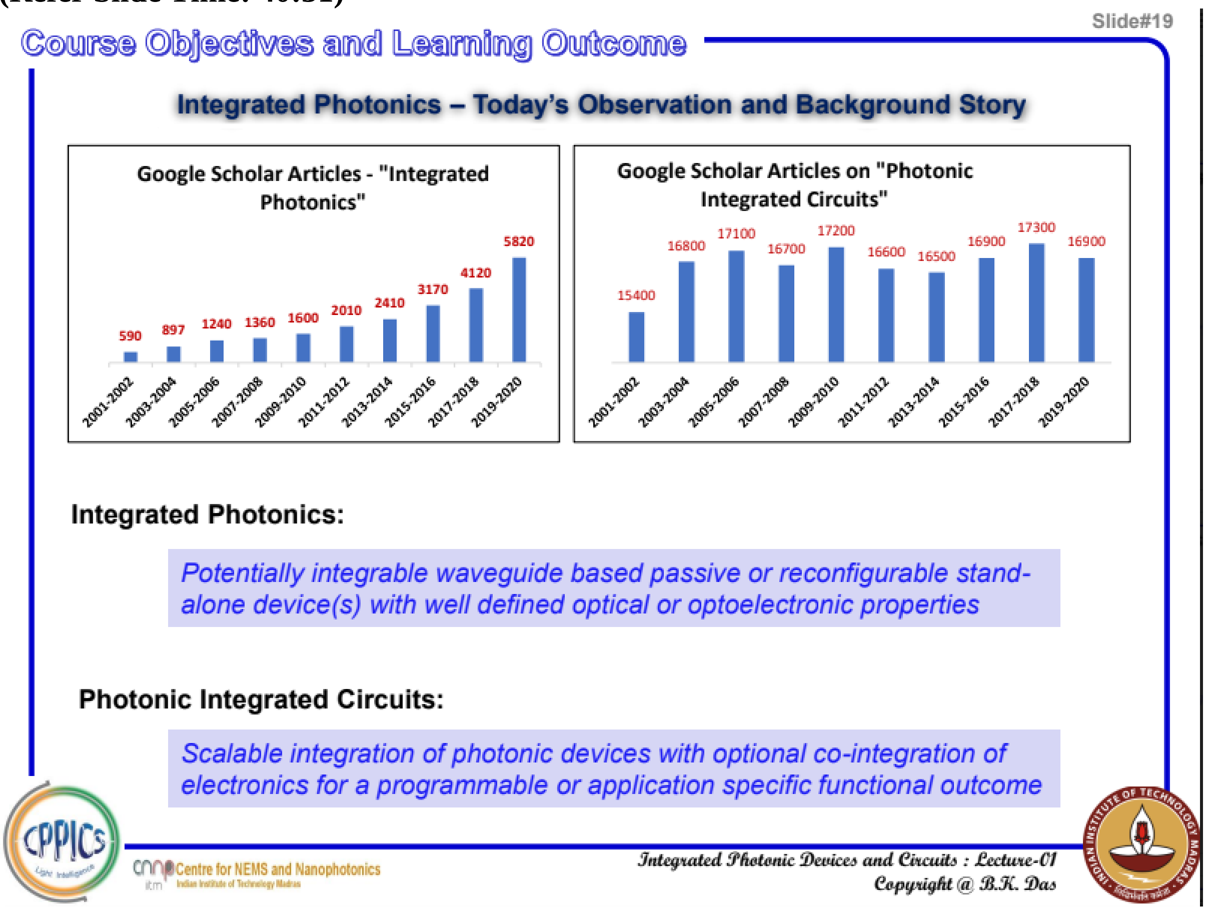

If you search today integrated photonics in Google Scholar, then you will see plenty of articles coming out and you have option to filter year wise how many articles are there. So, in 2001, 2002 integrated photonics article it was 590 and it is slowly exponentially growing and 2019, 2020 it is 5820. So, that is the interest growing among the academic society, academic community and when you are searching for photonic integrated circuits, it was 15400 in 2001.

The future the prospect of the photonic integrated circuit was known for a long time, but because of the shortage of good material platform and good technology, advanced technology needed. That is why not many circuitry were being demonstrated because not many people can access those types of advanced sophisticated technology. This is why it has not been improved a lot also. But certain industry everything continuously trying and to see year wise that more or less published article almost flat around 16,000, 17,000 or so on.

So, now, this is photonic integrated circuit what is the difference between integrated photonics and photonic integrated circuit? Here I try to distinct them. So, for integrated photonics basically, people are meaning component or devices that is potentially integrable with waveguide based passive or reconfigurable standalone devices just one device one function. And that can be on different platforms. It can be silicon, it can be lithium niobate, it can be glass, it can be indium phosphide, it can be polymer, different type of platform, but functional standalone devices, those type of research article that means integrated photonics and when you say photonic integrated circuit that means more than few components will be integrated depending on the technology available and suitability of the platform.

So it is kind of functional circuitry or we can say that application specific photonic integrated circuits are those type of things which are being heavily researched in how the academia and industry.

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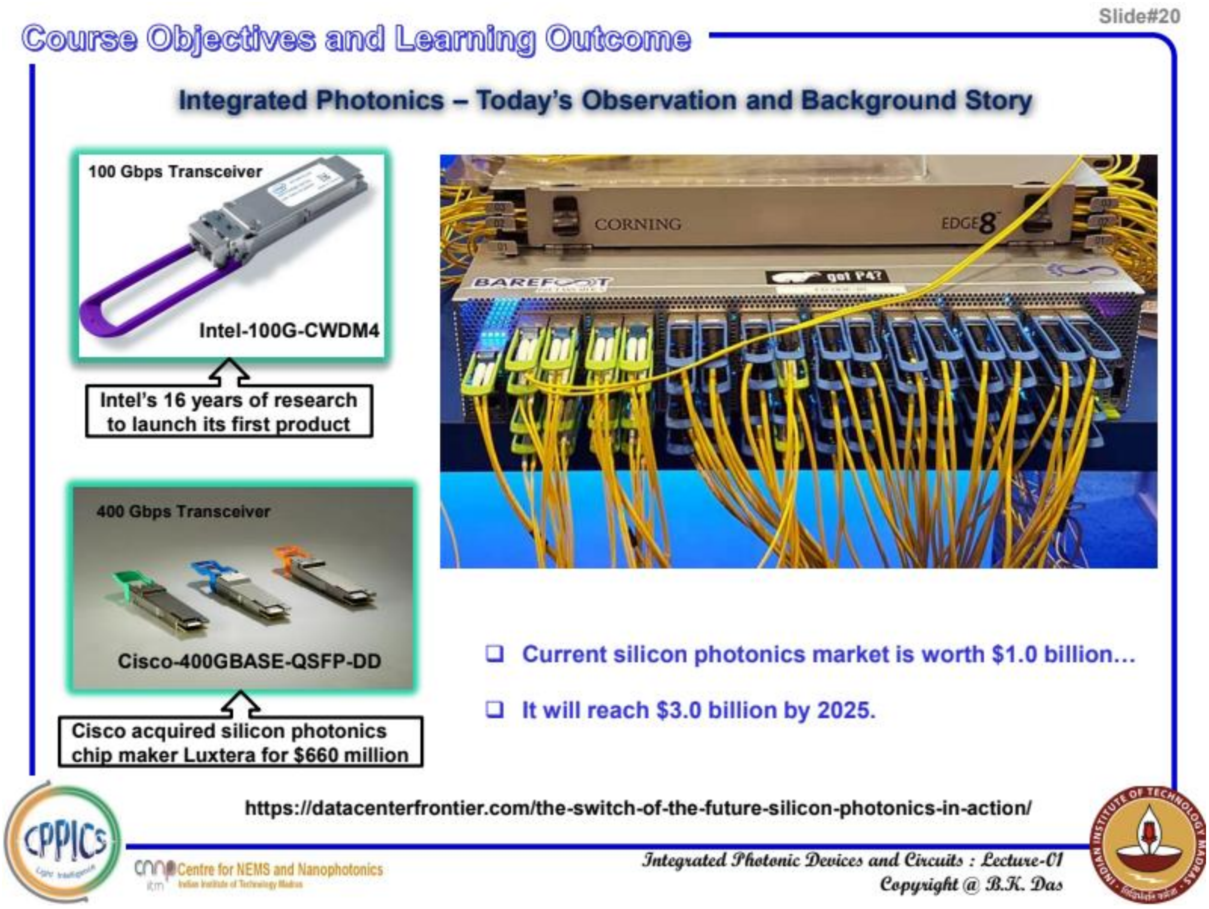


And this is the industrial success photonics of silicon photonics engine. Intel, Cisco all they they have been already selling products like 100 Gbps transceiver, 400 Gbps transceivers. Actually people are using those transceiver for communicating just to replace copper wire in data centres. this is what it is shown in the above figure. That kind of switch and transceiver together can be useful for various data centres where actually power bandwidth limitation of copper cables could be get rid of by using optical fibres. Here 65 switches are shown. 65 transceivers are plugged into a switching network and because of that basically every year actually 3 million transceivers Intel alone is actually exporting, selling. So, today if you search silicon photonics market, it is about 1 billion and in future it can be 3 billion market by 2025.

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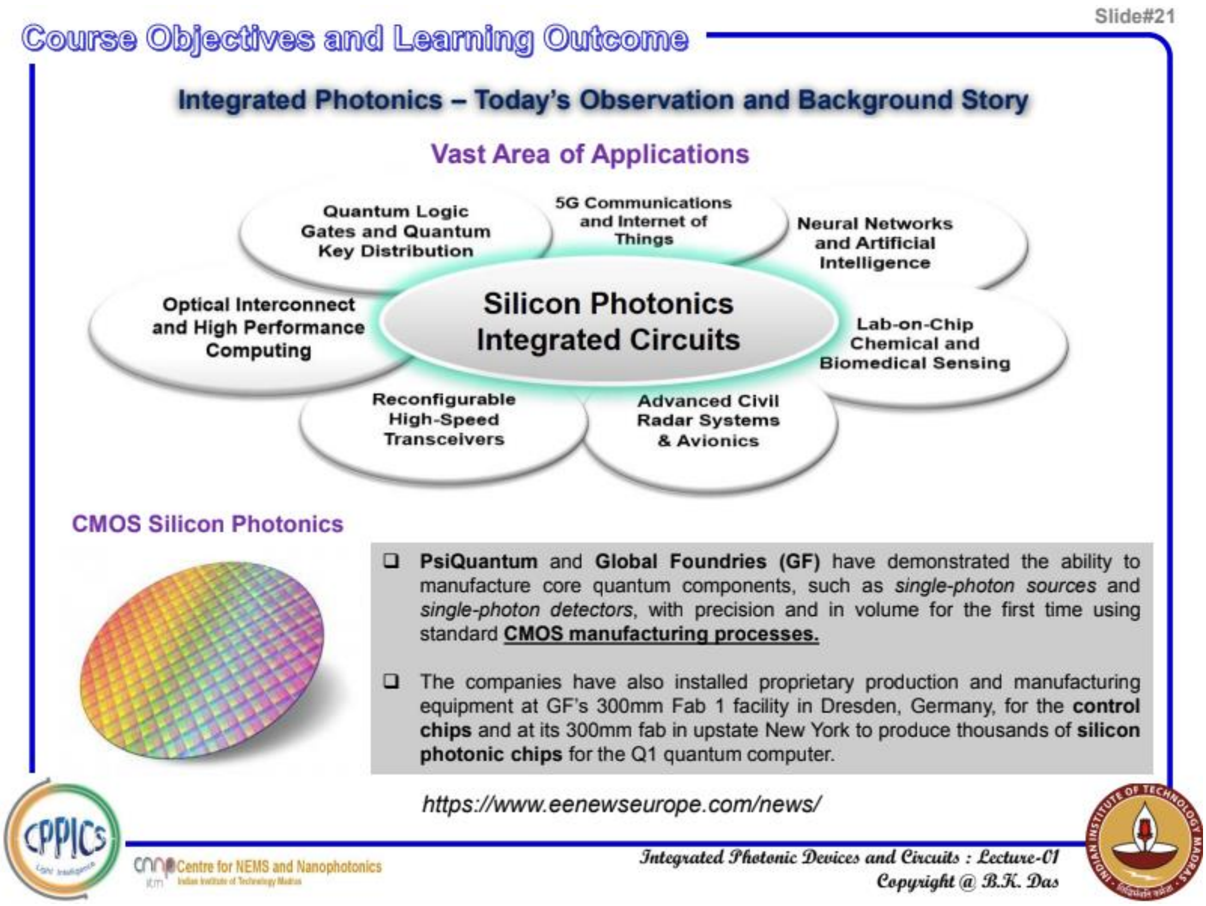


And here it is shown that other than to this transceiver, silicon photonics engine has many other application areas. It has application in some microwave photonics; not only for civil radar systems and avionics microwave photonics but also for 5G, 6G communications and IoT (Internet of Things).

And then also medical applications and also quantum information processing, various topics are being covered by so called CMOS silicon photonics technology. Some of the information here it is shown that psi quantum and global foundries have demonstrated the ability to manufacture core quantum components. Quantum computers you know, hearing much but mostly they are demonstrated using superconducting nanowire which operates at very, very low temperature.

But people are trying to demonstrate quantum photonic processor in silicon photonics platform. So that it can be at least part of the quantum computer can be operate at room temperature. That is how the target. These are the reasons why this subject is very hot and very attractive today and one must learn the basic things; how it evolved and what is the future and how the technology is progressing, how it can be improved and that is why the subject is very much relevant today.

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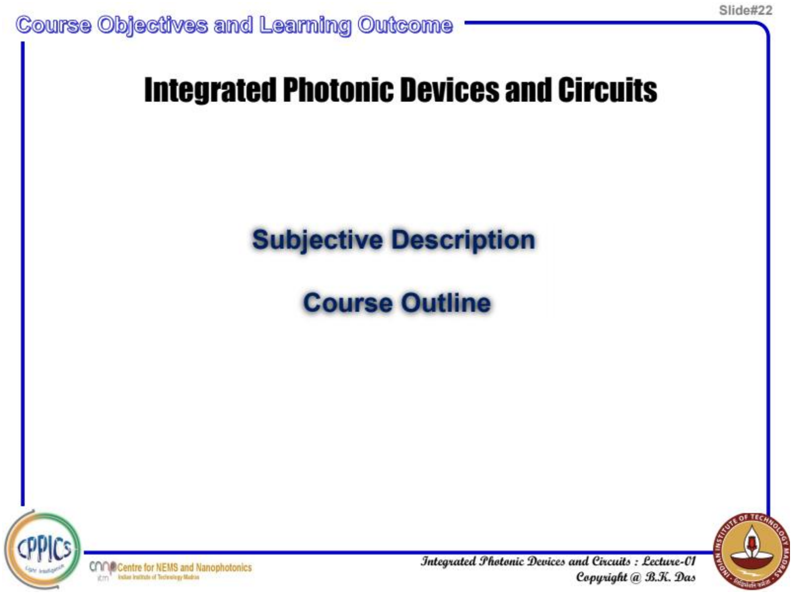
Here is the subjective description and course outline.

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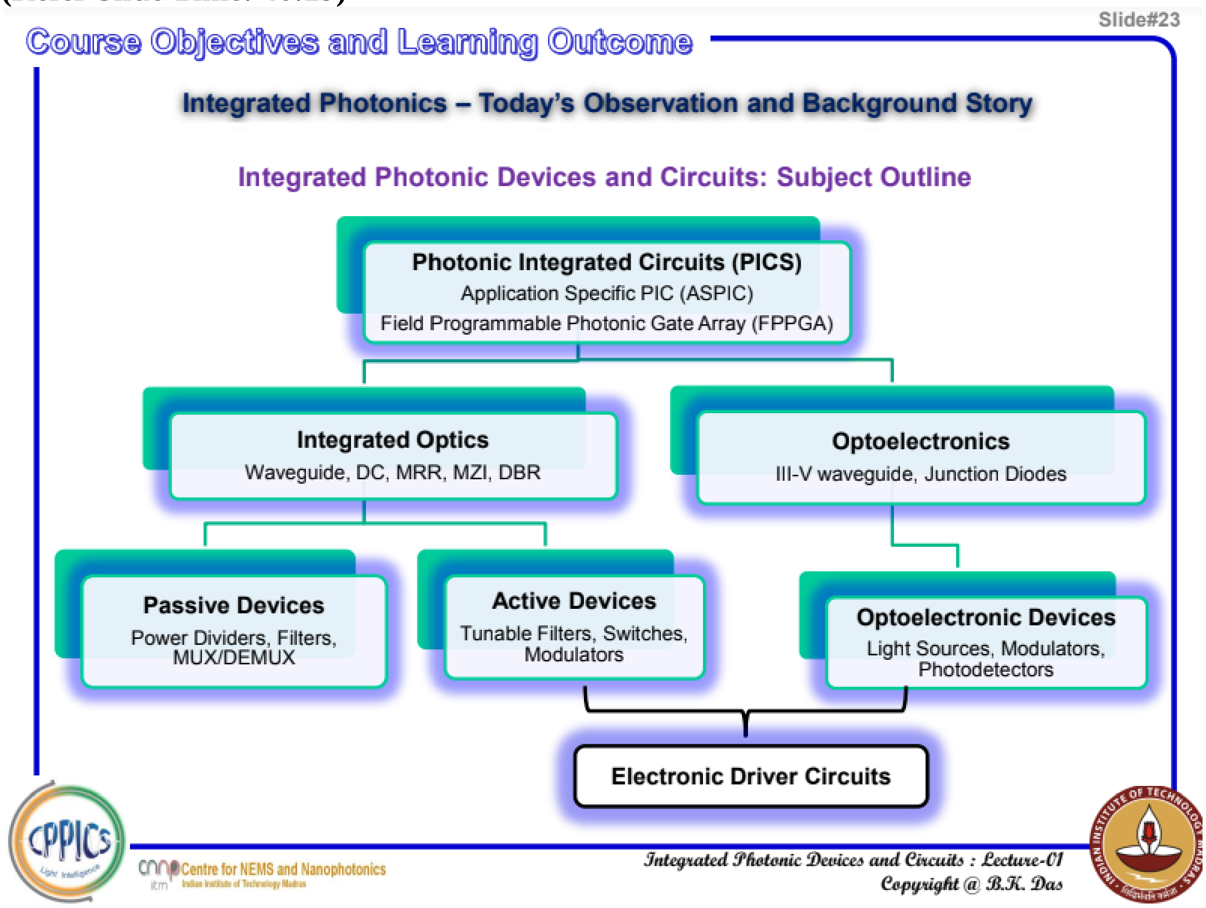

That is how we will be going through. So, if I want to learn the entire subject, starting from the working principle to technologies to integration capabilities, all those types of things photonic integrated circuit, so called application specific and programmable photonics, so called Field Programmable Photonic Gate Array FPPGA.

Similar to electronic FPGA, Field Programmable Gate Array, this thing has 2 distinct part one is integrated optics and other is optoelectronics. Integrated optics means some component structures, you can actually use for different type of passive functions as well as active functions like passive constantly power divider, filters, multiplexing  and demultiplexing wavelength and active devices like tunable filters, switches, modulators, all those types of things.

And optoelectronics is the mostly III-V semiconductor waveguide devices basically diodes where you can have laser sources and put detectors as well as modulators also. So, this is kind of optoelectronics where actually optics and electronics can exchange energy. Electron loses energy which can get some photon emission and photon is lost to create electron hole pair to generate current that is important for detector. So, those type of things where electrons and photons. Optoelectronic devices also are the part of photonic integrated circuit. And also, electronic driver circuits is important for these modulators and other active devices. You need electronic timer circuit to drive them or to convert electrical signal into electro optical signal or back

So, that is a very much part of photonic integrated circuits. But since those type of electronic driver circuits are well known, and you can learn many things from other subjects. It will not be covered here. But we will be trying to understand the functionalities, their capabilities, their technological limitations, etcetera in this course.

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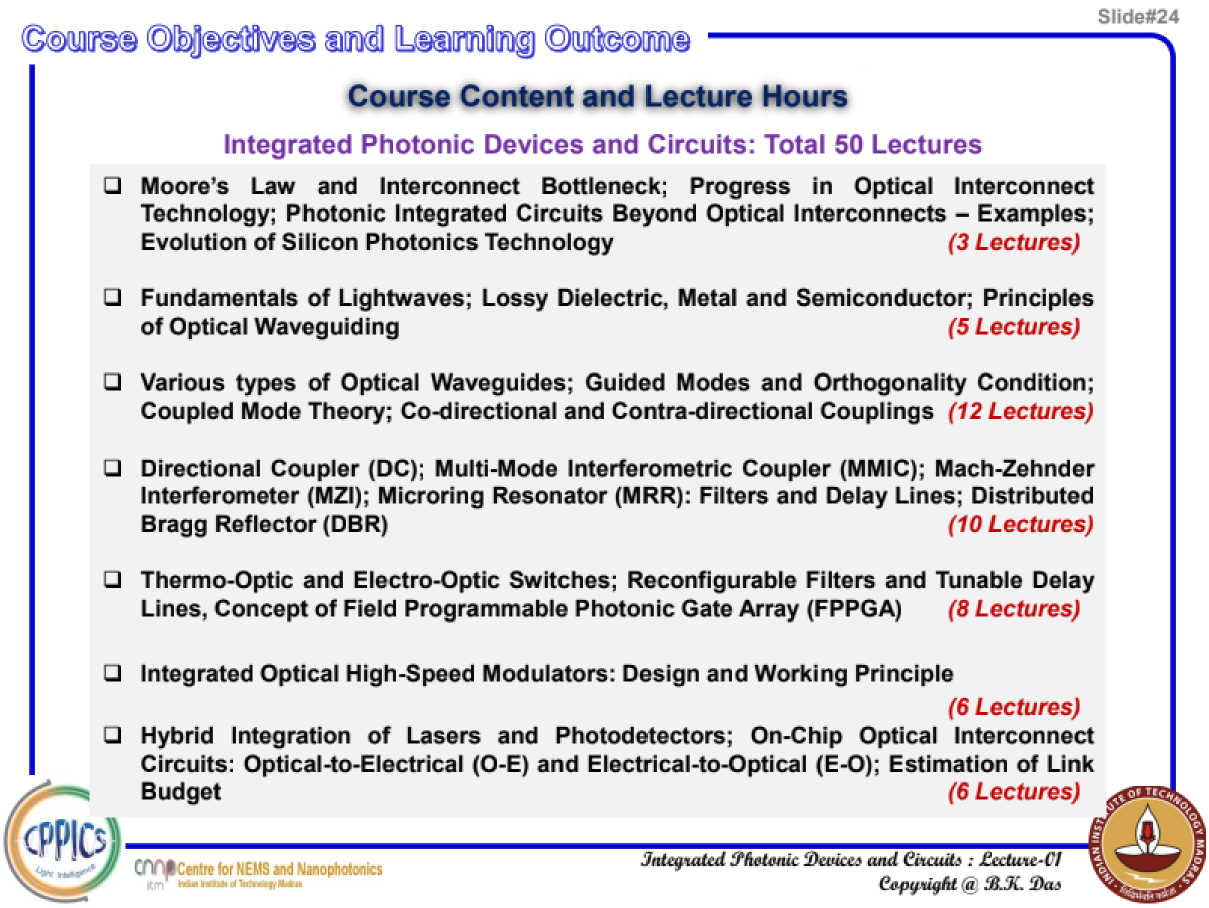
Basically, this is the whole syllabus I can mention it can be divided into 7 chapters.




In chapter 1 I will be discussing maybe 3 lectures starting from Moore's Law, some background theory etcetera, all those types of things.

And they in chapter 2, 5 lectures are required for fundamental of light waves, lossy dielectrics and metal semiconductor principle. These are the things required for integrated photonics circuitry. And then waveguide is the basic building block that I will be discussing how the waveguide theory developed and orthogonality conditions betwwen guided modes and their interactions like how they couple, exchange power from one waveguide to another waveguide.

And then different types of standalone functions component, how they are, they can be designed, their working principle etcetera, that is you have in chapter 4, for example, directional coupler multimode, interferometer magenta interferometer, this terminology for the moment you just keep in your mind, so that in course of time it will be coming and you have to learn that.

And then how those types of passive devices, you can make it reconfigurable or programmable or tunable. All those types of things that I will be discussing in chapter 5.

And in chapter 6 it will be dedicated to high speed modulators. Their design and working principle are the key of how first and efficiently you can transmit the data per bit, how minimum energy you can use to transmit.

And then finally, I will be discussing bit of optoelectronics because I said that silicon photonics is the major thing, but only limitation of silicon photonics is that you cannot integrate efficient laser source there because silicon is the indirect band gap semiconductor. So, sometimes hybrid integration is required for laser purpose, for photo detection purpose. Heterogeneous integration and some kind of budget link, everything I will be discussing in chapter 7. And all those types of things, how can be improved in future that will be discussed.

So, this is all about your course. I hope you all will be enjoying.