Course Name- Nanophotonics, Plasmonics and Metamaterials

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Department Name- Electronics and Electrical Engineering

Institute Name- Indian Institute of Technology Guwahati

Week-01

Lecture -01

Hello students. I am Dr. Debabrata Sikdar from the Department of Electronics and Electrical Engineering, IIT Guwahati. Welcome to lecture one of my course on Nanophotonics, Plasmonics and Metamaterials. This course will provide a detailed introduction to these three pillars of the future photonic technologies by covering their fundamentals and recent advancements.

With the growing dominance of 5G technologies, Internet of Things, and emerging applications of artificial intelligence and machine learning in every aspect of human life, this course on nanophotonics has become more relevant and important than ever before. It is the solution to meet the demands of extremely high computational speed requirement and the ultrafast data transfer rate of the future besides keeping the power consumption minimal. Nanophotonics allows one to achieve terahertz speed at nanometer scale, bringing together the best of the electronics and photonics world. This course will first cover the fundamentals of nanophotonics, principles of photonic crystals, plasmonics or metal optics, excitation of surface plus bonds and their applications.

Later on, the course will also focus on metamaterials and metal surfaces, covering their fundamentals and various applications such as tunable devices, absorbers, superlens, hyperlens, transformation optics, cloaking, etc. The course will also introduce new alternative materials for nanophotonics to meet today's demand and summarize different techniques for fabrication and characterization of nanoscale devices. The course is designed for undergraduate and postgraduate students with basic knowledge of physics and electromagnetics. The course will actually bring the emerging fields of nanophotonics, plasmonics and metamaterials to your doorstep via the SWAM platform for the first time. We hope that UG and PG students with background in electronics, instrumentation, physics, chemistry, material science and engineering, chemical engineering and any researcher and industry people working in the broad areas of photonics will get benefited from this course.

This course will surely motivate you to explore and study further in this exciting field of research which has got truly endless opportunities. Here is the detailed course plan. We will cover 8 modules over the span of 36 lectures. As you can see, module 1 is introduction and it will be covered in the first week with 3 lectures covering the introduction of nanophotonics and plasmonics, introduction to metamaterials and metasurfaces and their overview and current status. The second module will be on fundamentals of nanophotonics which will be covered over week 2 and 3.

Module	Module Name	Week	Lecture No	Title of the lecture	Assignments
1	Introduction	1	1-3	▪ Introduction to Nanophotonics & Plasmonics ▪ Introduction to Metamaterials and Metasurfaces ▪ Overview & current status	-
2	Fundamentals of nanophotonics	2	4–6	▪ Electromagnetic theory of light ▪ Electromagnetic properties of material ▪ Electromagnetic waves in dielectric media	-
		3	7–9	▪ Polarization of light ▪ Reflection and refraction: Fresnel equations ▪ Absorption, dispersion, & scattering of light	Online
3	Electromagnetic waves in periodic structures	4	10–12	▪ Matrix theory of dielectric layered media ▪ 1D Photonic crystals ▪ Dispersion relation and photonic band structure	-
		5	13–15	▪ Real and reciprocal lattices; ▪ 2D and 3D Photonic crystals ▪ Emerging Applications of Photonic Crystals	Online
4	Metal Optics	6	16–18	▪ Optical properties of metals ▪ Surface Plasmon Polaritons (SPP): Fundamentals ▪ Applications of SPPs	-
		7	19–21	▪ Localized surface plasmon resonance (LSPR) ▪ Plasmonic nanoparticles: Antenna & Waveguides ▪ Applications of LSPR	Online

In week 2, we will discuss about the electromagnetic theory of light, electromagnetic properties of material and electromagnetic waves in dielectric media. So that will take care of the light-matter interaction. In week 3, we will first study the polarization properties of light, reflection and refraction in details when light hits at an interface using the Fresnel's equation and we will understand the absorption, dispersion and scattering properties of light. Module 3 will cover the electromagnetic waves in periodic structures. That will be covered in week 4 and 5.

So, lecture 10 to 12 will cover the matrix theory of dielectric layered media, 1D photonic crystals, dispersion relation and photonic band gap structures. In week 5, we will cover the real and reciprocal lattices, 2D and 3D photonic crystals and discuss emerging applications of photonic crystals. Module 4 will cover metal optics. That is, it will introduce plasmonics in details with its fundamentals. So, in week 6, we will cover optical properties of metal, then surface plasmon, polaritons, SPP, their fundamentals and application of SPPs.

In week 7, we will cover the localized surface plasmon resonance, plasmonic nanoparticles, based antennas and waveguides and different applications of localized surface plasmon resonance. Next, we will move on to module 4. That will be covered in week 8 and 9. And this module 5 will cover matter materials, their fundamentals and applications. Week 8 will cover the fundamentals of matter materials, effective medium theories and introduce single and double negative matter materials.

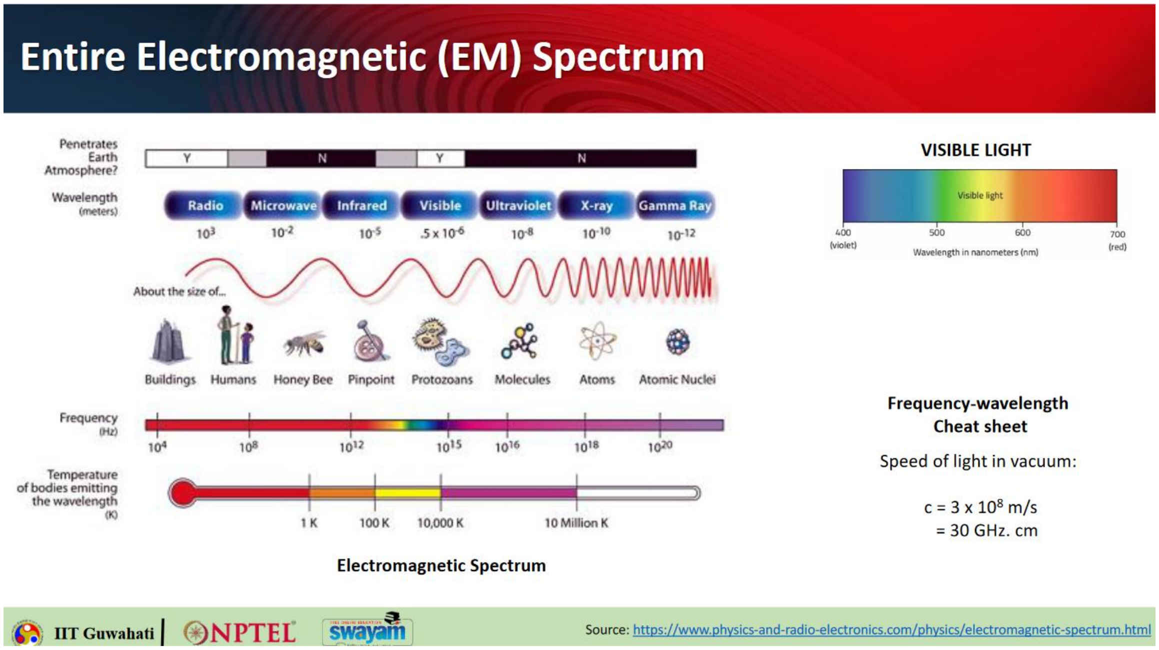
Week 9 will discuss perfect absorbers and superlens, hyperbolic matter materials and hyperlens, tunable photonic matter material based devices. Moving on to module 6, we will cover matter surfaces in week 10. And the lectures will cover matter surfaces and frequency selective surfaces, guided mode resonances, applications of matter surface and guided mode resonance based devices. Module 7 will be on transformation optics. That will be covered in week 11.

That will discuss transformation optics and invisibility clocks, carpet cloaking and transformation optics matter materials and introduction to different alternative matter materials. Or rather, different alternative materials for this kind of applications. Module 8 will discuss realization of nanophotonic devices. And that is the final module that will be covered in week 12 over lectures from 34 to 36. That will discuss the nanofabrication, different physical methods and chemical methods involved.

Module	Module Name	Week	Lecture No	Title of the lecture	Assignments
5	Metamaterials: Fundamentals & Applications	8	22–24	▪ Fundamentals of metamaterials ▪ Effective medium theories ▪ Single and Double-Negative Metamaterials	-
		9	25–27	▪ Perfect absorbers & Super lens ▪ Hyperbolic metamaterials and Hyper lens ▪ Tunable photonic metamaterial based devices	Online
6	Metasurfaces	10	28–30	▪ Metasurfaces & Frequency selective surfaces ▪ Guided mode resonances (GMR) ▪ Applications of metasurfaces & GMR devices	Online
7	Transformation optics	11	31–33	▪ Transformation Optics (TO) & Invisibility Cloaks ▪ Carpet cloaking & TO metamaterials ▪ Introduction to alternative materials	Online
8	Realization of Nanophotonic Devices	12	34–36	▪ Nanofabrication: Physical methods ▪ Nanofabrication: Chemical methods ▪ Lithography & Pattern transfer ▪ Nanophotonic characterization methods	-

And we will also discuss lithography and pattern transfer to obtain those nanoscale devices that we will be discussing in this course. Moreover, we will also discuss about the nanophotonic characterization methods. Now, before we begin the course, let us first have a look at the entire electromagnetic spectrum as you can see on the screen. So electromagnetic radiation ranges from radio to gamma rays. So in this figure, it shows the wavelength in meter.

So radio waves typically have hundreds of meters as their wavelength. And it goes down to even 10 to the power of minus 12 meters for gamma rays. So this is how the wavelength is getting reduced when it moves from radio to gamma rays. And this particular demonstration shows you what is the comparable size of the wavelength. So, you can see radio waves are more or less of the size of the buildings.



Microwave, you all must be familiar with. Microwave radiation are typically having 10 to the power of minus 2. So that's like centimeter scale. And the size is typically of the honeybee. And as you go towards visible, ultraviolet, x-ray and gamma ray, the wavelength is getting reduced.

And the comparable sizes are also getting reduced. The corresponding frequency can also be seen here. So if you consider one particular case, something like microwave, which is a very commonly used device these days. So you can see in microwave the frequency range is in close to 10 to the power of 9 hertz, that is, gigahertz range. So that way you can actually look into the scale and find out what is the corresponding frequency for each of these waves that are included in the electromagnetic spectrum.

So keep this particular image in your mind because that will give you a clarity about what frequency range, what wavelength range we are talking about. Now the top part of the figure also tells that which rays are able to penetrate the atmosphere. Y means, it is able to penetrate. No means, it is not able to penetrate. When it is not able to penetrate earth's atmosphere, it means it is getting absorbed in the atmosphere.

And the bottom most one shows the temperature of the black bodies that are able to radiate. So what temperature of the black body will be able to radiate or will give up a radiation in this particular frequency range. So that you can see here. Like if you have an object which is like 1 Kelvin, you can get a microwave radiation. When you move to say 100 Kelvin or in the range of say 10,000 Kelvin, the object can emit visible radiation.

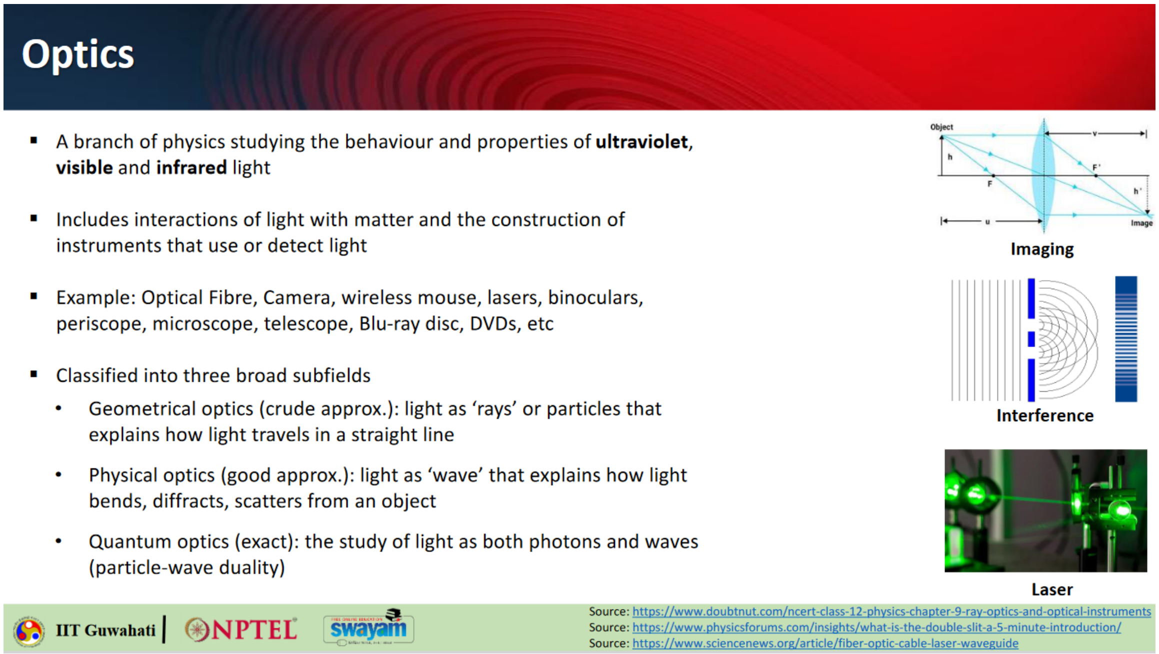
Now why we are focusing on visible to some extent? Because there is the only small fraction in this entire electromagnetic spectrum that is visible to human eyes. And it typically starts from violet to red. So 400 nanometer (or 380 nanometer to be precise) to 700 or 780 nanometer in some literature. So that is the range 380 to 780 nanometer is visible to human eye. And when we talk about this wavelength and frequency, I believe all of you remember this cheat sheet of converting frequency to wavelength.

So if you are able to express the speed of light in vacuum, C, that is 3 times 10 to the power of 8 meter per second as 30 GHz.centimeter. That allows you a quick conversion. So if you have 30 GHz frequency, the wavelength is 1 centimeter and so on. If you have 1 GHz frequency, the wavelength will be 30 centimeter.

So that way you can quickly convert between frequency and wavelength. Now to understand nanophotonics, which is the topic of this course, let us first begin with a very broad topic that all of us have studied in our school days. And that is optics. So what is optics? It is a branch of physics studying the behavior and properties of light. Now when I say light, I do not only mean visible light, I also mean ultraviolet, visible and infrared light.

So that is the range optics typically covers. And it includes the interaction of light with matter and construction of instruments that can actually, that uses this kind of light for manipulation or detection. Some examples like optical fiber, camera, wireless mouse, which I am using right now, lasers, binoculars, periscope, microscope, telescope, then Blu-ray devices, DVDs, etc. These are all based on optics. Now you can classify optics broadly into three sub-fields.

The first one is geometrical optics and it is a very crude approximation. So in this approximation light is considered as rays or particles. That explains how light travels in a straight line. So straight from our school book you can see using a lens you are able to image a particular object. And this can be very well explained using the ray approximation, that is the geometrical optics.



Now there are certain phenomena where this kind of approximation of geometrical optics is not enough. So we need to actually go to another sub-field which is called physical optics where light is considered as a wave. To explain certain phenomena something like bending of light, diffraction, scattering from an object, and the phenomena of interference that you might have seen or studied, done experiment as well in your school days. You are able to actually explain these interference fringes by considering light as a wave. The third one is the most exact approximation where light is considered as both particles, photons, and waves.

So that is also known as particle-wave duality. So the phenomena of laser is well explained in this particular. Now let us have a quick look into various sub-fields of this UV visible and IR spectrum. So if you closely look into this particular list shown here. Ultraviolet has got many sub-bands, Extreme UV, Vacuum UV, Deep UV, Mid UV, and Near UV.

And then these are the energy associated, shown in eV This is the wavelength range (in nm) and this is the frequency range (in THz). Similarly for visible you can start with violet to red. And you can see the violet is from 380 to 435. Red wavelengths are from 625 to 780. When I say infrared, there are three sub-ranges.

Near infrared, Mid infrared, and Far infrared. So there also in near infrared you can have IR A, IR B, and you can see these are the wavelength range. So I will not go into details of reading out each of these details. You can refer to this particular chart here. And you can understand different sub-ranges in this UV visible IR spectrum.

UV-VIS-IR Spectrum

Range	Subrange	Abbreviation	eV	nm	THz
Ultraviolet (UV)	Extreme UV	EUV	1240 - 12.4	1 - 100	3e5 - 3e3
	Vacuum UV	VUV, UV-C	12.4 - 6.53	100 - 190	3000 - 1580
	Deep UV	DUV, UV-C	6.53 - 4.43	190 - 280	1580 - 1070
	Mid UV	UV-B	4.43 - 3.94	280 - 315	1070 - 952
	Near UV	UV-A	3.94 - 3.26	315 - 380	952 - 789
Visible (Vis)	Violet		3.26 - 2.85	380 - 435	789 - 689
	Blue		2.85 - 2.48	435 - 500	689 - 600
	Cyan		2.48 - 2.38	500 - 520	600 - 577
	Green		2.38 - 2.19	520 - 565	577 - 531
	Yellow		2.19 - 2.10	565 - 590	531 - 508
	Orange		2.10 - 1.98	590 - 625	508 - 480
	Red		1.98 - 1.59	625 - 780	480 - 384
Infrared (IR)	Near Infrared	NIR, IR-A	1.58 - 0.886	780 - 1400	384 - 214
		NIR, IR-B	0.886 - 0.413	1400 - 3000	214 - 100
	Mid Infrared	MIR, IR-C	413 - 24.8 meV	3 - 50 μm	100 - 6.0
	Far Infrared	FIR, IR-C	24.8 - 1.24 meV	50 μm - 1 mm	6.0 - 0.3

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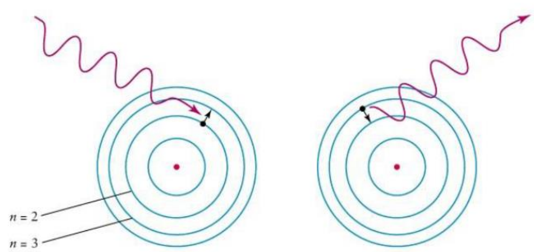
Now let us introduce a new term called Photonics. Where Photonics is basically a sub-category of optics that focuses on the size and technology of photons. So photonics is often used interchangeably with optics. But they do have distinct meanings.

Photonics: a subcategory of optics that focuses on the science and technology of photons

- Photonics is often used interchangeably with optics, but they have distinct meanings
- Optics is a broad branch of physics: studies the general behavior and properties of light, as well as vision and perception
- Photonics involves in generation, detection, and manipulation of light in form of photons
- Photonics is concerned with **absorption** & **emission** of light - besides its **transmission**, **modulation**, **signal processing**, **switching**, and **amplification**



a Absorption   b Emission

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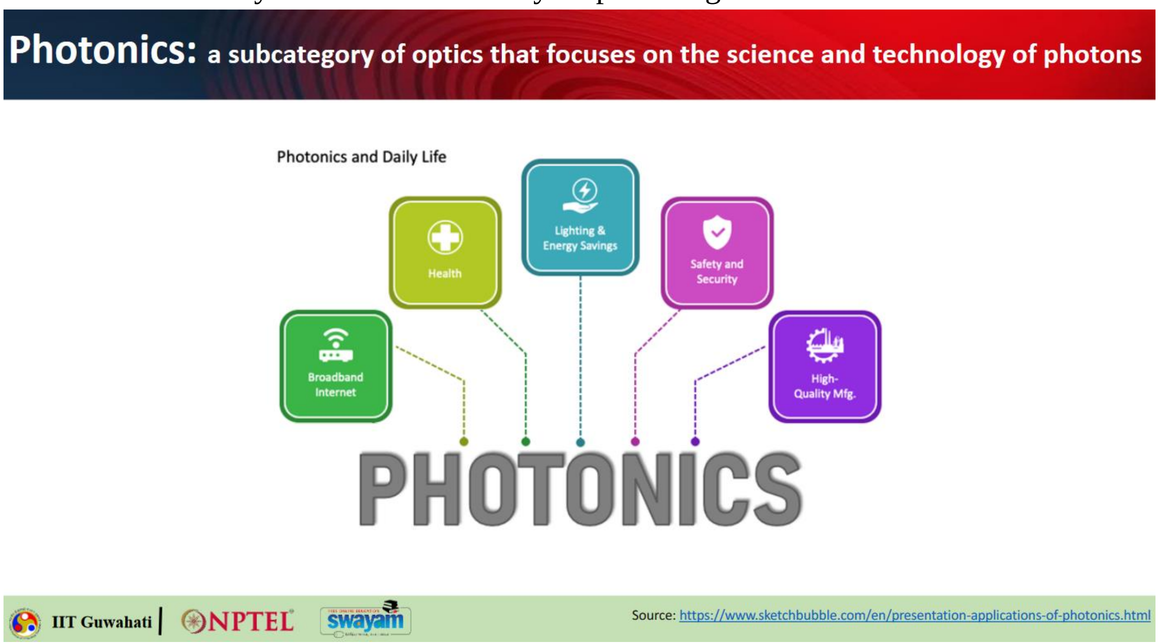
Source: https://www.sketchbubble.com/en/presentation-applications-of-photonics.html

They are not the same exactly. Optics: whenever we discuss optics, it is basically a broad branch of physics that studies the general behavior and properties of light. As well as vision and perception. Whereas photonics involves in generation, detection, and manipulation of light in the form of photons. So photonics is concerned with absorption and emission of light. Besides its transmission, modulation, signal processing, switching, and amplification.

So the picture here depicts absorption of a photon. Where the photon energy delivered to the electron moves it to a higher energy level or outer orbit. So this phenomena is called absorption. The opposite also takes place that when the electron jumps from a higher energy level to a lower energy level. A photon is emitted which has got energy equivalent to the difference between the two energy levels.

So this phenomena is called emission. Now photonics have got a lot of applications. So the typical application areas of photonics are in the field of broadband internet and information technology. So thanks to photonics I am able to reach to your doorstep today with this lecture. Because photonics or the optical fibers are the backbone of the entire internet. They are not only providing fast internet connection.



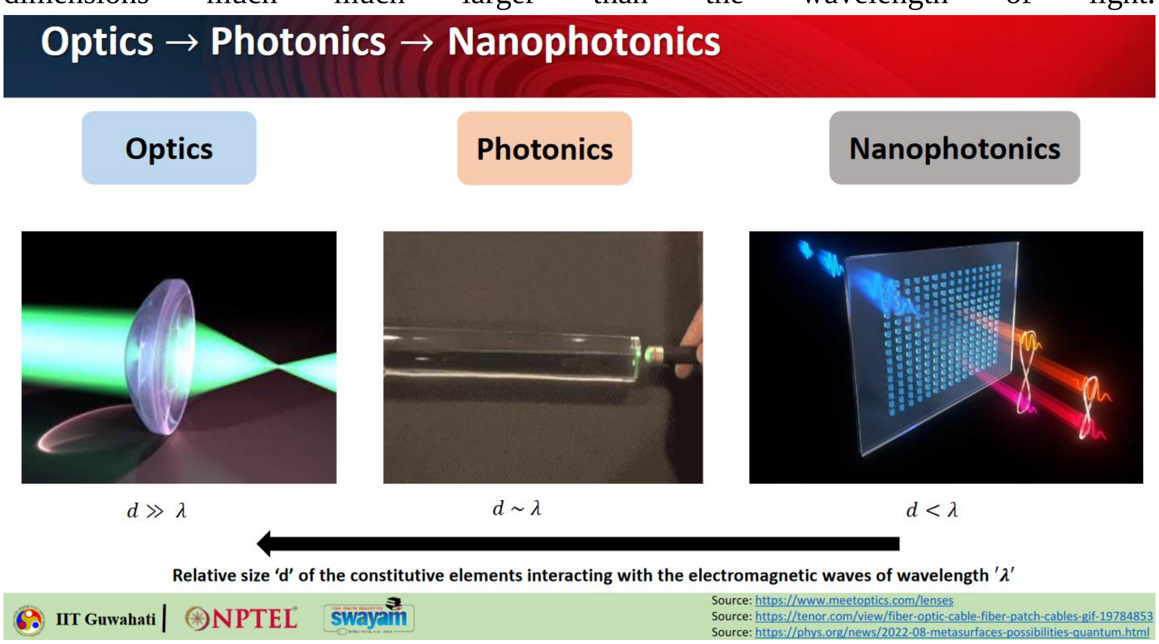
Photonics also enabling free space optical communications, optical computation for quantum photonics, and all these things. So there are going to be a lot of applications of photonics in the future. Healthcare and biophotonics. So photonics and optics are used in various non-invasive medical diagnostics. If you remember from the COVID time, SPO2 measurement, that was an application of photonics.

Laser based surgery that is happening day in and out. Targeted cancer therapy, ophthalmology, everything can be done using photonics. Lighting and energy saving. There is another big sector where photonics have tremendously contributed. Almost entire lighting industry and the display industry is shifting towards semiconductor photonics because they are more energy efficient.

So you see LED lighting almost everywhere these days. Moreover solar power with photovoltaic cell, they are also becoming one of the most popular renewable energy sources because of their competitive pricing against other renewable energy sources. Coming to safety and security aspects, photonics are also very much useful in providing safety and security by means of optical metrology. Means very fast run time measurement of distance and time using lasers. So that will be very important in autonomous vehicles. Moreover you can also think of security arrangements, something like fiber Bragg grating sensor based border fencing, high speed cameras, infrared motion detectors.

There are also defense based technologies, something like satellite surveillance system, navigation, imaging, night vision, anti-missile systems, high power directed weapon systems which are like laser guns. And all these things are becoming more and more popular in the modern world. Then the other application will be in the high quality manufacturing. So you can actually do high quality manufacturing and precise manufacturing using laser. Material processing, something like cutting, welding, soldering, marking, all these things, surface modification, all these things can be done using laser.

So as you can see photonics more or less has got application in almost every aspect of human life. And that is why it is a very very important subject to know right now. We have understood two things, optics and photonics. Now if you compare optics and photonics, what is the main difference? The main difference comes from the relative size d of the conservative elements which are interacting with the electromagnetic waves of wavelength say lambda. So, in optics we are actually dealing with constant elements, something like lenses, mirrors, prisms, beam splitter, all these things which are having dimensions much much larger than the wavelength of light.



Whereas in photonics we actually bring the dimensions comparable. That means the size of the material, of the matter that is interacting with light also has got a comparable dimension. So here you see a particular example of total internal reflection that is taking place in a glass rod. Now this particular phenomena is the basics of light propagation through optical fibers. When I consider optical fibers, that is a typical photonics application.

Why so? What is the dimension of the optical fiber? If you look into a single-mode fiber, it has got a diameter of 7 to 10 micrometer. And what is the wavelength of light? As we understand it is like 400 nanometers.

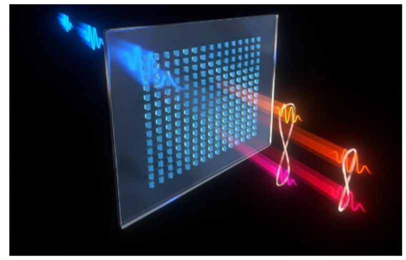
So it's like 0.4 micrometer to 0.8 micrometer. So they are almost comparable. So that is where photonics becomes relevant. So when I say photonics, this is the main factor that the size of the constituent materials or elements will be comparable to the wavelength of light. And that allows you generation, processing, guiding and sensing of light. So what are the typical applications? Lasers, amplifiers, photodiodes, light sensors, optical fibers.

So all these are basically the optical tools that fall under the bucket of photonics. So naturally there will be a curiosity to know that what happens when the size of the constitutive elements become much smaller than the wavelength of light. So that is where nanophotonics comes into picture. So nanophotonics is basically the field where the elements which are interacting with light has got dimensions sub-wavelength.

That is much smaller than the wavelength of light. So nanophotonics typically covers light-matter interaction at nanoscale. So nanophotonics allow you to design devices which can slow down, enhance, produce or manipulate light by understanding how light behaves as it propagates or travels through sub-wavelength dimensions. And in short, nanophotonics will actually tell you about the photon interactions with nanostructures such as nanomatallic particles or nanoparticles you can say, nanocrystals, semiconductor nanodots, photonic crystals and biomaterials such as tissues, DNA's, etc. So this is where nanophotonics comes into the picture. In short, nanophotonics is the study of the behavior of light on the nanometer scale.

Nanophotonics

- Nanophotonics is the study of the behavior of light on the nanometer scale, and of the interaction of nanometer-scale objects with light.
- It covers the study of the interaction of matter and light at the nanometer scale.
- It is possible to design nanometer scale devices to slow down, enhance, produce, or manipulate light at will by understanding how light behaves as it travels through, or when it interacts with, materials at the nanometer scale.
- In short, *Nanophotonics* focuses on the interaction of photons with nano-structures, such as metal nanoparticles, nano crystals, semiconductor nano dots, photonic crystals, biomaterials such as tissues and DNA etc



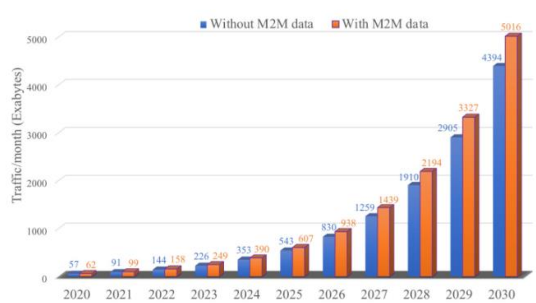
$d < \lambda$

Source: https://phys.org/news/2022-08-metasurfaces-possibilities-quantum.html

Or you can say it is the interaction of a nanometer scale object with light. So again it covers the interaction, light-matter interaction at nanoscale. Why it is important you know? Because it allows you to manipulate light at nanoscale. And that capability, that spatial power comes to you when you actually make light to interact with some elements which are having much smaller than the wavelength of light. Now, why should we study nanophotonics? We understood what is nanophotonics starting from what is optics, what is photonics and then we understood what is nanophotonics.

Why Nanophotonics?

- In era of information and technology, world's economy is digitalized using Internet
- Computers, smart phones, tablets, smart watch and so on became inseparable parts of our daily life
- This growing demand for data sharing, makes the Internet a huge storehouse of data
- Global internet users reached more than 5 billion (~ 60% of worldwide population)
- Global data-traffic to reach almost more than 475 exabytes per month of traffic by 2023 end
- But that's not all!
  A Tsunami of data traffic is approaching…



Gigabyte	1,024 megabytes
Terrabyte	1,024 gigabytes
Petabyte	1,024 terrabytes
Exabyte	1,024 petabytes
Zettabyte	1,024 exabytes
Yottabyte	1,024 zettabytes

Global data-traffic forecast

Source: CISCO

Now, we need to know why we should study nanophotonics. Now, in this era of information and technology you can see that the world economy is more or less getting digitized using internet. Like e-entertainment, then e-commerce, everything is booming.

So you need a backbone infrastructure that can support that thing and the development that is happening. If you take computers, smartphones, tablets, smart watches, these items have become an inseparable part of our life.

You cannot actually imagine a day without this. And everybody is now having multiple devices. So that actually puts a lot of load on the internet. And with this growing demand of data sharing, internet also becomes a huge storehouse of data. So whenever you are googling something or you are making a search, you want the data to come to you very fast.

But where from? You have to store it somewhere. So you also need a lot of storage, a lot of computation power to search in this huge storage what you have looked for. So all these things are putting a huge load in terms of energy requirement, speed requirement, computing speed and the power requirement. So everything is becoming more and more complex. And you can see the rise of global internet users. So with world population being 8 billion, right now we have more than 5 billion internet users.

That's like more than 60% of the world population. And do you think it's going to be less? No. It's going to be even more and more in the future. Even kids are now getting into using all these tablets and smartphones. So the global data traffic is going to reach 475 exabytes per month.

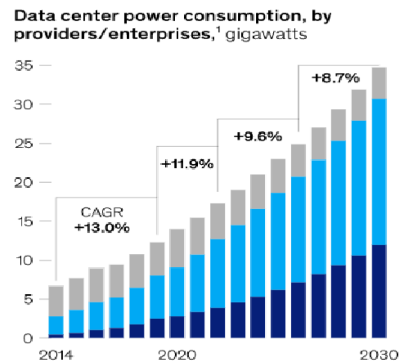
And that's the traffic estimated by the end of 2023. And do you think that's all? No, that's not all. That is just the tip of the iceberg. If you see, the tsunami of data traffic is actually approaching.

Look at this particular graph. So here you can see 2023, here we are. So M2M is like machine to machine. When a machine is talking to another machine, like a chatbot or something like that. And without M2M, that is like human to human and all these things. So, there are two categories the data has been split. So, you can see the total traffic per month is 475 exabytes by 2023. And that will go up to this level in 2030. So that's a huge jump. And if you are wondering what is exabyte, so let's start with GB.

I think all of us are well aware of GB now. So 1 GB is 1024 MB. Then you take 1024 GB, you get a terabyte. You take 1024 terabytes, you get a petabyte. 1024 petabytes will give you one exabyte. So, this is the scale of data we are talking about. Now, with such a huge thing coming, we need to be prepared. And one of the key challenges for 21st century has been to supply efficient accessibility over internet to billions of people. So you want more and more people to be connected. And that is the desire. So that will require huge bandwidth and error-free connections.

Why Nanophotonics?

- One of the key challenges for the 21st Century — to supply efficient accessibility over internet to billions of people
- Requires huge bandwidth and error-free connections
- Internet or "cloud" is millions of data centers linked with cables under the sea globally
- One of the most visited site "Google.com" emits nearly 500 kg CO_2 into the air in every second
- Data Centers are likely to face challenges in limiting their energy consumption (to increase at 10% yearly)



Data center power consumption forecast

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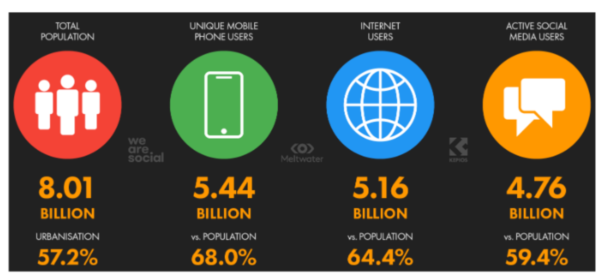
And if you think only of internet as a cloud, that's not correct. Internet also means millions of data centers are actually linked to each other. They are talking to each other through the transoceanic cables, the optical fiber cables which are laid through the ocean floor to connect different continents. And this is carrying so much of data you can't imagine. So all this is happening at a cost. So, when you actually say, you know, you are doing a Google search and you are getting your search results, that particular Google search actually emits almost 500 kg of CO2 every second.

Motivation

- With the growing internet penetration rate around the world there is demand for:
  - High speed connectivity
  - Scaling up store-and-process of data traffic
- By scaling up data centers buildings, overall carbon footprints also increase linearly
- The Need of the hour is to develop ***miniaturized & energy efficient systems*** for modern communication technologies

Jan 2023



Overview of connected devices and services by January 2023

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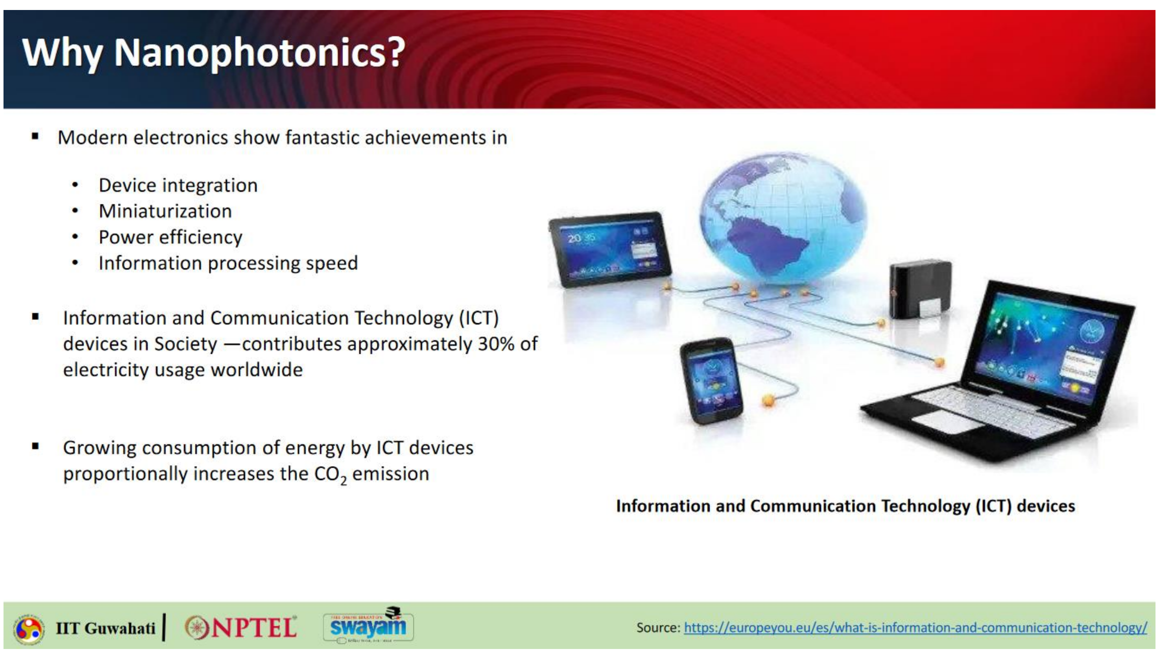
Now you can understand how much power is being utilized, how much energy is being consumed. And that is how it will also affect the global warming issue. So what do you want? You actually want power efficient systems. And this is the problem that data centers are likely to face challenges in limiting their energy consumption, which is likely to go up at a rate of 10% per year. So this is a forecast of how the energy consumption in data centers will increase from 2014 to 2030.

And you can see more or less it is kind of increasing steadily at a rate of 10% every year. So with the growing demand of internet penetration over the world, there is also demand for high-speed connectivity, scaling up store and process of data traffic. And this is a forecast, not forecast, this is a result or report showing that by January 2023 we already have almost 60% urbanization. People connecting to cities, and then you have 68% population using mobile phones, almost 64% people using internet, and more or less about 60% people are also active social media users. So these are all actually trends showing you how much load is going to come on the internet. So, scaling up the data centers to handle this much amount of incoming data traffic is one solution.

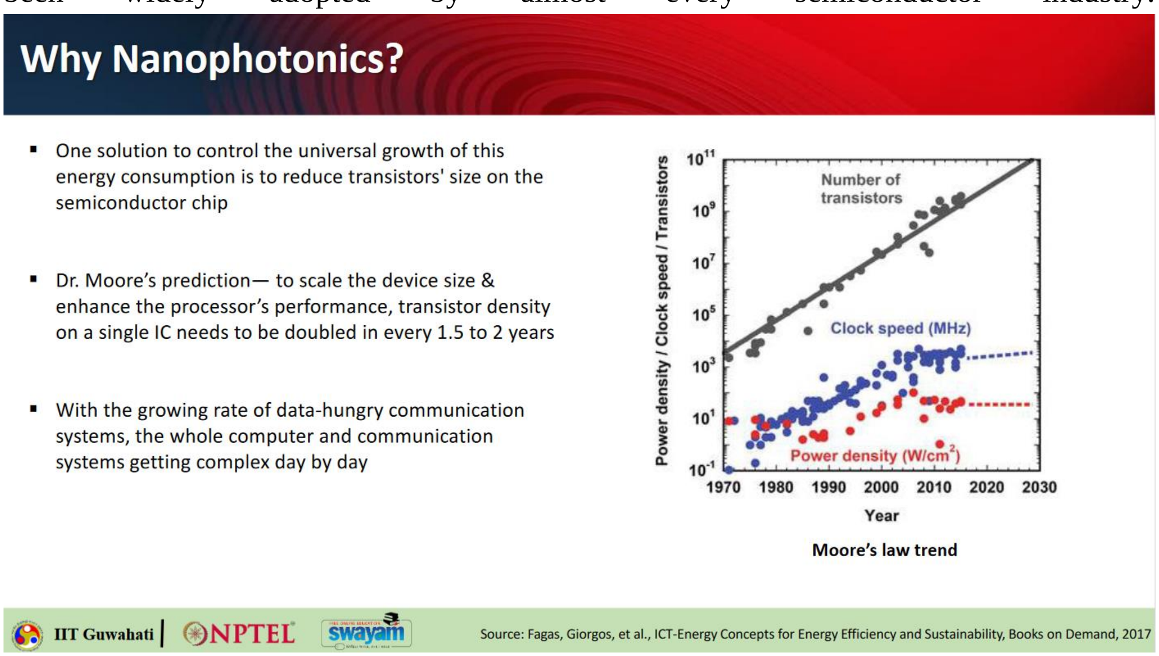
But that will also take the overall carbon footprint very, very high, because almost linearly the carbon footprint will also increase. So, the need of the hour is to develop miniaturized and energy efficient systems for modern communication technologies. We'll first look into that is modern electronics capable of handling this? So modern electronics have done fantastically well so far. It has achieved a lot in terms of device integration, miniaturization, power efficiency, and information processing speed.



No complaints, they have done tremendously well. Information and communication technology devices in the society, they contribute approximately 30% of the electricity usage worldwide. So, they are now becoming a major factor who is consuming energy and power. So, these are all different devices which are connected to internet and they are also consuming power because they are continuously computing, processing information. So, the growing consumption of energy by these ICT devices will also proportionally increase the CO_2 emission.

So all these things are not going to make our life simple. With too much of data, computation, carbon dioxide emission is also increasing, hence more global warming. So that is going to get back to us very badly. So how do you handle this? So, one solution to control the universal growth of this energy consumption is to reduce the transistor's size on the semiconductor chip. Why so? Because smaller transistors will require less power for their functioning.

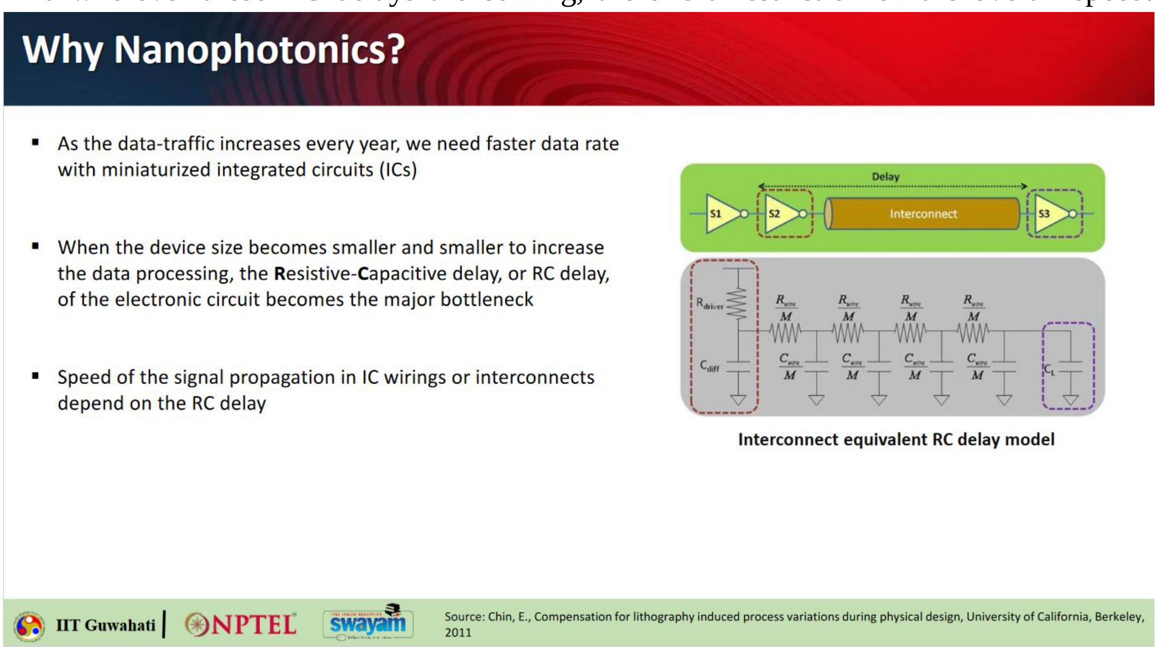
And this will reduce the overall power consumption of the chip. And less power means the chip will also get less heated up and that will also allow us to increase the clock speed further. So, it is actually helping us to a great extent. Now, since the announcement of integrated electronics, the semiconductor industry had adopted an approximation predicted by Dr. Moore or Gordon Moore. In 1965, Dr. Moore predicted that in order to scale up the device, scale the device size and enhance the microprocessor's performance, the transistor density in a particular chip or a single IC needs to be doubled every 1.5 years to 2 years. That means within 18 to 24 months, the number of transistors in the chip will roughly double. And over the last 50 years, this assumption has been the roadmap for all the electronics industry. And although Moore's law is not a natural law, but the growing rate of data-hungry communication system, more or less, this law has been widely adopted by almost every semiconductor industry.



But however, with billions of transistors in the chip, so this is how, till now, things are going fine. So, it's doubling, you know, clock speed and the power density as you can see here, all these are going the way Moore has predicted. But with the requirement increasing day by day, there is a point where Moore's law will no longer be able to sustain itself. So that is where you have to think of some alternative. So as the data traffic increases every year, we need faster data rate with miniaturized IC.

So this is our requirement. But then what is stopping us in getting higher and higher speed? That will be, you know, the RC delay. With the device sizes becoming smaller and smaller, that actually increases your data processing in a small volume. But the RC delay or resistive capacitive delay in the electronic circuit, they become a major bottleneck. Now why do you see this RC delay? Any transistor you can model as an equivalent RC network.

Every node in an electronic circuit can be thought of a capacitive nature. So, to charge or discharge that node, there is a finite time, charging and discharging time. And that restricts the speed beyond which you cannot go. Also, when you think of IC wiring or interconnect, there also you can model the interconnect using equivalent RC delay model. And wherever these RC delays are coming, there is a restriction on the overall speed.

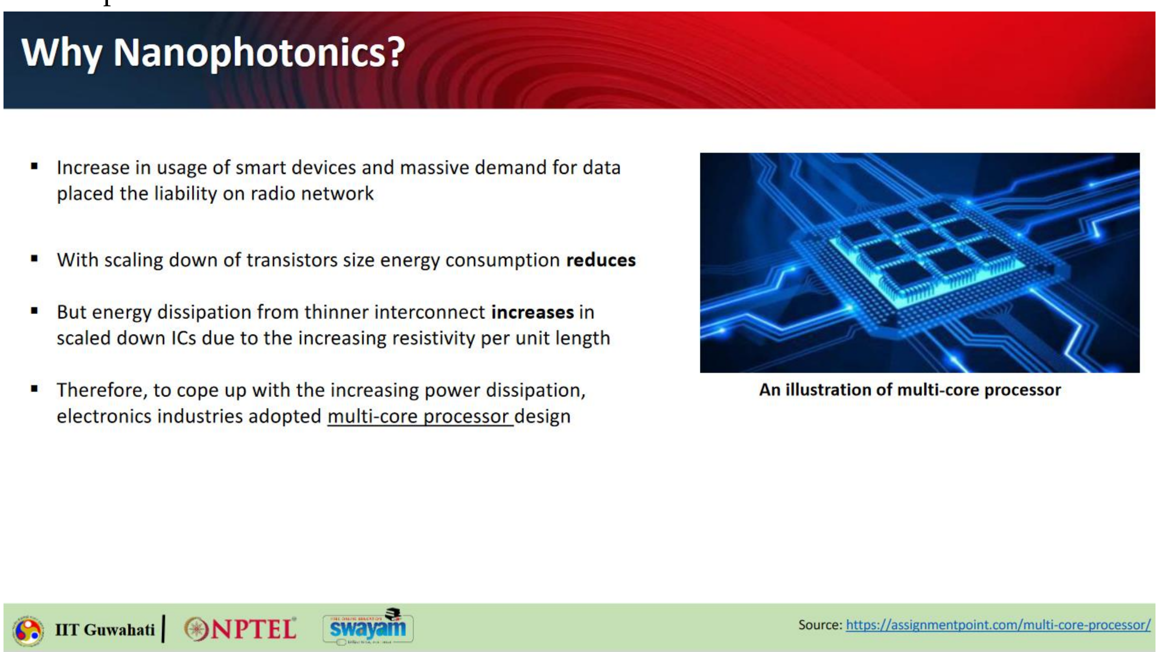


So you cannot actually get better. And why miniaturization actually impacting that? Because when you miniaturize your electric interconnects, they are getting thinner. And with that, the resistivity per length is actually increasing. So, miniaturization allows you to pack more devices, but then the speed is getting reduced because of these RC delays getting into the picture. So, we want to increase the usage in the smart devices and meet the demand of data that will be placing huge liability on the radio network.

So we understood that scaling down of transistors can reduce the energy consumption.

But that will also bring in few issues. Something like the energy dissipation from thinner interconnects will increase. Because the resistivity per unit length will increase for a shorter interconnect. Then semiconductor people, industry, actually moved on to explore what is called multi-core processor design. So instead of having only one core, you can actually split your cores and parallelize the processing so that can actually bring down the overall power consumption.

But is this going to help us in the long run with the amount of data traffic that we have seen coming our way? We have seen a tsunami of data traffic coming to our way. So, we have to somehow move on to optical technology where there is no RC delay. That is restricting the amount of data rate that we can achieve. So, we have to go to photonic technologies to handle this enormous amount of data traffic. And that will also, when you do everything in the optical field, that will also reduce the power and energy consumption at the data centers.

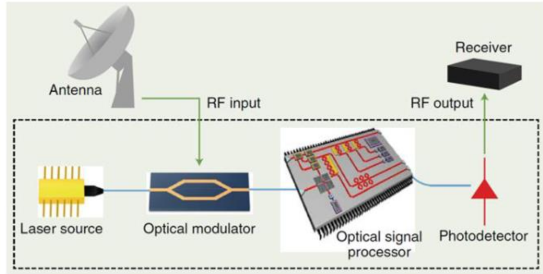


So integrated microwave photonics have done well. It can actually... So, this is a particular or typical diagram of a canonical microwave photonics system. Where you have a RF system or antenna that is bringing in the RF input. You have a laser source that is giving you the light.

You have an optical modulator. You do the signal processing in the optical domain. You detect it. That means you are finally converting it back to current. And then you give the RF output to the receiver. So that way you can incorporate photonics with microwave and can speed up the system.

Why Nanophotonics?

- Infrastructure of mobile networks needs to sustain with rapid growth of the data traffic
- To handle large volumes of data traffic, **photonic technology** plays a vital role in
  - providing unprecedented data rate (no RC delay)
  - reducing consumption of energy at data centers
- Integrated microwave photonics can
  - reduce device footprint by confining light in ultra-small volume to enhance light–matter interaction
  - offer a less complex signal processing architecture
  - provide higher data transfer speed with improved SNR and a lower power dissipation



A canonical microwave photonic system

Source: Marpaung, D., et al., "Integrated microwave photonics," Nature photonics, 13, 2, pp.80-90, 2019

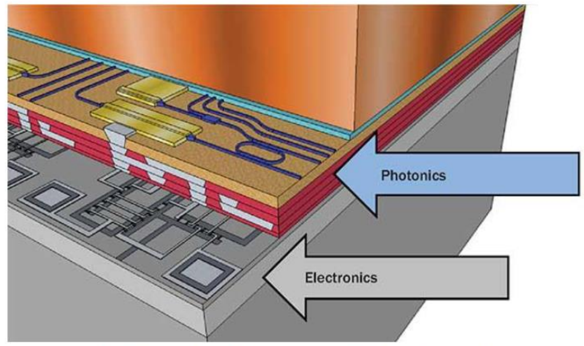
So integrated microwave photonics can reduce the device footprint. That is possible to some extent. By confining light in the ultra small volume and that will enhance the light matter interaction. So, they will definitely offer a less complex signal processing architecture. Here you will be doing the optical signal processing.

And you can also achieve a higher data transfer rate with improved SNR. And you can get a lower power dissipation. So, looks like integrated microwave photonics can solve all our major problems. Something like handling of the high speed data traffic. Lowering of the energy consumption per unit data. And also meeting the bandwidth requirements. And it is also possible to do some integration with the existing intra-chip and inter-chip electrical data communication systems.

Such as this one. So, this is a typical diagram which shows integration between electronics and photonics circuits on the same chip for better signal processing. So, what is the problem then? What is stopping microwave photonics? Or it is able to provide us all the solutions that we are looking for. One problem that you can think of in microwave photonics is that when you are in the field of photonics you cannot scale down your devices to nano scale. Is that clear? So, when you are in photonics you have a limit called diffraction limit of light.

Why Nanophotonics?

- Although, integrated microwave photonic systems have **potential** to solve major problems such as:
  - Handling of high-speed data traffic
  - Lowering energy consumption per unit data
  - Meeting bandwidth requirements
  - Integration with existing intra-chip and inter-chip electrical data communication systems
- integrated photonic systems has **limitation** in scaling down to nano-scale devices
- Due to 'diffraction limit of light':
  inability to squeeze light into dimensions very much smaller than the wavelength



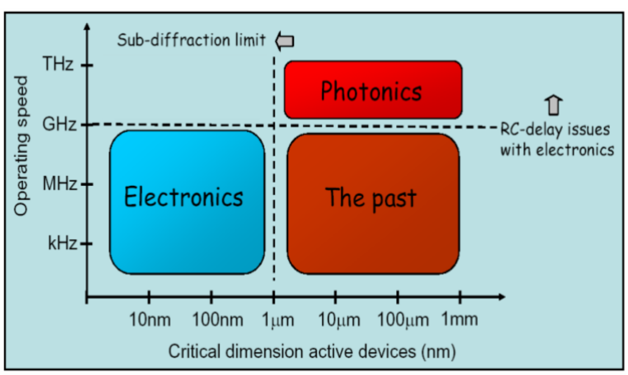
An illustration of electronics and photonics circuits

IIT Guwahati | NPTEL swayam Source: https://photonicsreport.com/blog/the-fascinating-relationship-between-photonics-and-electronics/

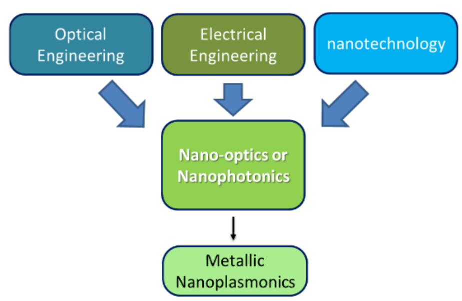
Diffraction limit of light tells you that light cannot be squeezed in a volume which is lesser than lambda by two. So, you cannot actually go sub wavelength with photons. Or you can say light cannot be squeezed into sub wavelength volumes. So, this is where the technology situation right now is. Electronics industry has done very well in terms of miniaturization.

So you can get your critical device dimension down to 10 nanometer or even below. But the maximum speed that you can get from electronics devices is restricted up to gigahertz. You cannot go beyond that because of the RC delays. Now if you look into photonics they have done very well in overcoming the RC delay issues.

Technological Evolution



Graph of the operating regimes of different technologies



IIT Guwahati | NPTEL swayam Source: http://large.stanford.edu/courses/2012/ph240/esfandyarpour-m1/

But there is a particular size restriction for the photonic circuits. And this limit is set by the diffraction limit of light. So, you want to have something here which can actually go and work in terahertz speed. But allow you also to give device dimensions which are in nanometer scale. And this is where Plasmonics will come into picture. So Plasmonics is a field that brings in the best of both electronics and photonics world.

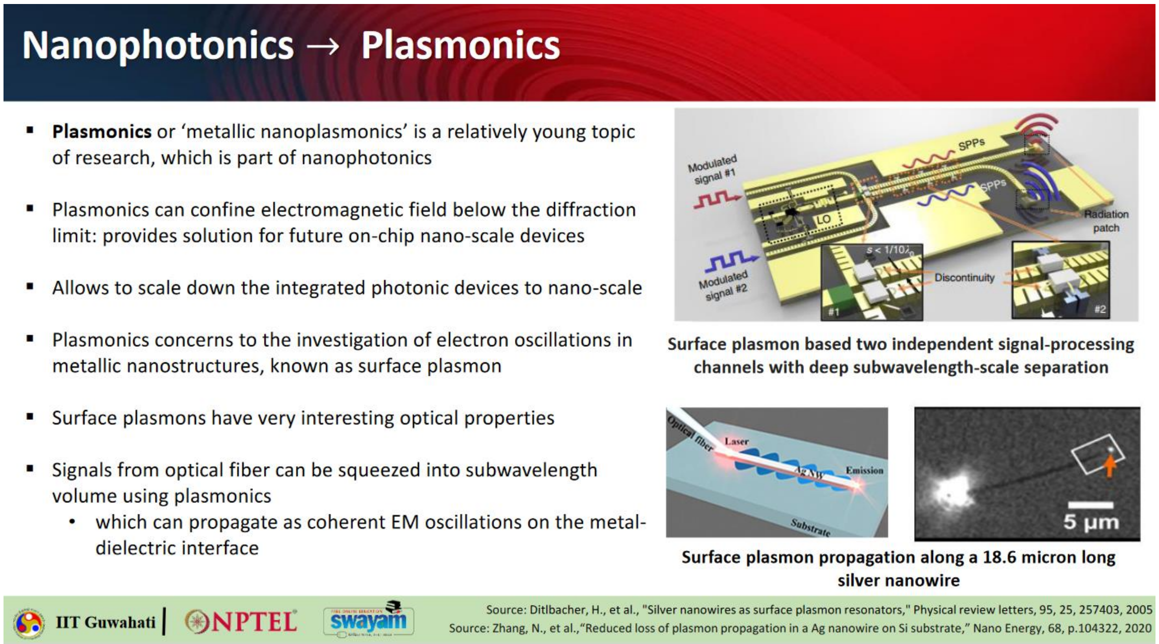
So Plasmonics will naturally interfere with similar size electronics devices. So, it is very easy to match with the electronics part. As well as they can also naturally interfere with the photonics one because they have similar operating speed. So, the situation is like this. Electronics can provide miniaturized devices with critical dimensions less than 10 nanometer. But the maximum speed you can achieve is restricted to gigahertz due to the RC delay issues with the electronics.

And if you look at photonics, photonics can help to reach terahertz operating speed. But the miniaturization is not possible below 1 micrometer. That is typically the critical device dimension for photonics. And this limit is set by the diffraction limit. So, what is the way out? So that is where Plasmonics coming to the picture.

So Plasmonics will enable an improved synergy between electronics and photonics. Because Plasmonics naturally interfere with similar size electronic devices. And Plasmonics can naturally interfere with also similarly operating speed photonic network. So Plasmonics is in a position to offer terahertz speed in nanometer scale. Bringing together the best of both electronics and photonics worlds.

And as you can see that this field will require inputs from optical engineering, electrical engineering and nanotechnology. So, it becomes a truly interdisciplinary field of study. And that is how Nanophotonics and a sub part of it is metallic Nanoplasmonics or simply Plasmonics. That can help deliver the best of the two worlds.

And this can actually help us meet the upcoming data traffic requirements. So, we understood how Nanophotonics and then what is Plasmonics. So, if you say Plasmonics you can also call it metallic Nanoplasmonics. They are more or less interchangeably used. This is a relatively young branch of research.



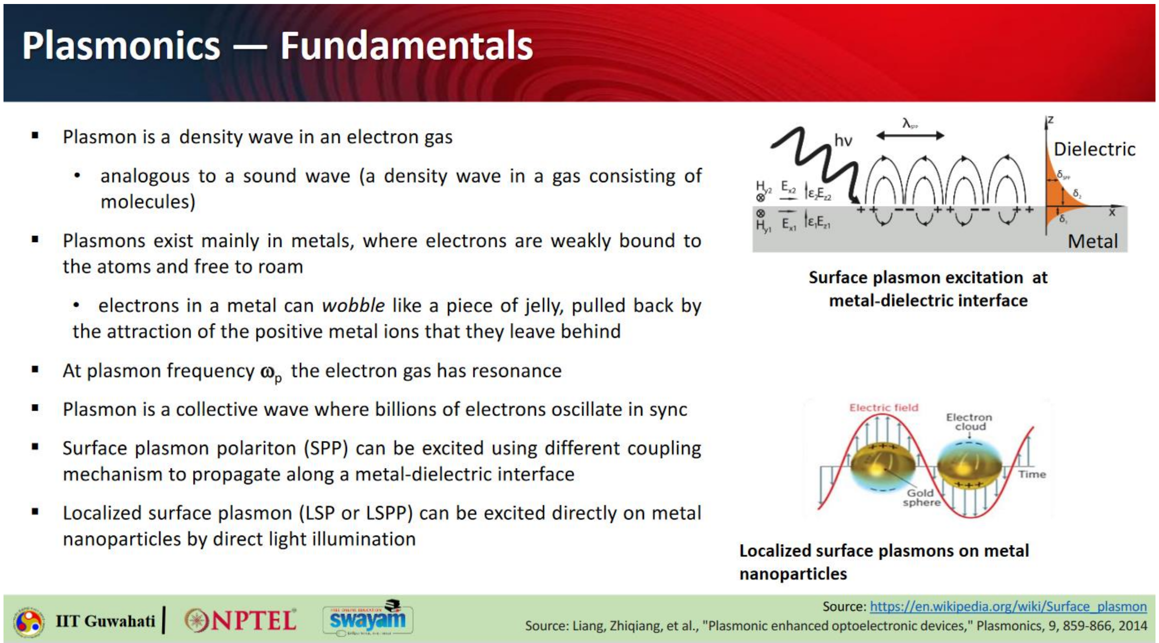
And as you understand this is a part of Nanophotonics. Plasmonics can confine electromagnetic field below the diffraction limit. So, this is where the good thing is. And it provides solution for future on-chip nanoscale devices. It allows to scale down the integrated photonic devices to nanoscale. So, the miniaturization is possible here.

Plasmonics concerns about the investigation of electron oscillations in metallic nanostructures which are known as surface plasmon. And what are these surface plasmon? We will come to that soon. These surface plasmon have very interesting optical properties. So, signals coming from an optical fiber can be squeezed into sub-wavelength volume using Plasmonics by taking help of surface plasmon.

As you can see in this figure surface plasmon can propagate as a coherent electromagnetic oscillation on the... So SPP means surface plasmon polaritons which are the propagating surface plasmon. So, they can propagate along metal dielectric interface. So, in this case you can think of gold as a metal.

So gold-air interface it can propagate. And you can also see here that the dimension is deep sub-wavelength. The separation S is less than 1 by 10 times lambda naught. So, you are basically talking about separation which are lambda naught by 10. So, this tiny or deep sub-wavelength scale separation is also supported by surface plasmon. You can also make surface plasmon to propagate a long distance.

Here an experimental result shows that if you take a silver nanowire and you launch light in one end of it. Say here this bright spot shows light excitation in one end of the silver nanowire. And then the light of the photons is converted into surface plasmon. So, what are surface plasmon? These are basically surface electrons. So, from photons you are actually transferring back your energy to some kind of electrons.



And those surface electrons propagate along the surface of this nanowire. That is at the interface of say if it is a silver nanowire and air is the surrounding media. So, the electron wave will propagate along silver-air interface. And at the end it can again come back as light. So, this kind of propagation and squeezing of energy in deep sub-wavelength scale is possible in plasmonics.

So I have taken the name of plasmon several times while talking about plasmonics. Let's try to understand what is plasmon? Plasmon is basically a density wave in an electron gas. So, if you try to imagine what is a density wave you can think of a sound wave. That is basically a density wave in a gas consisting of molecules. Where do plasmon exist? They exist mainly in metals where there are abundance of electrons and the electrons are weakly bound to the atoms and they can freely roam around.

So the electrons in a metal can actually ooble like a piece of jelly. That is like it can actually move like this. So, pulled back by the attraction of the positive metal ions. So, when the electrons move up they leave the positive metal ions. So that attraction actually pulls them back. So that is how the oobling of the electron cloud takes place.

And when all the electrons oscillate in the same frequency we call that as Plasmon Frequency Omega P. And that is the case where the electron gas has resonance. And when we say resonance it is like the billions of electrons oscillate in sync. And we can also define plasmons as a collective wave where these billions of electrons oscillating in sync. So, we have discussed two types of surface plasmons are there. One could be propagating surface plasmons or surface plasmon polaritons.

That can be excited with different coupling mechanism that we will study in details later on. But you can actually make surface plasmons to propagate along a metal dielectric interface.

As shown here. So, there is H-nu, there is light being used to excite. So, the exciting mechanism is not shown. I will discuss that. The direct excitation is not possible. But by taking help of some kind of grating or prism couplers you can actually excite surface plasmons. So, this is the metal and dielectric interface. And as you can see metal has got a large negative permittivity at this optical frequency.

So the field penetrates very less towards the metal and mostly it is in the dielectric interface. And this is how it will propagate. While propagating the field is also leaking out as you can see. And as the field will die down while propagation that will be the distance over which the plasmons can propagate. There is another type of plasmon also possible that is called localized surface plasmon.

And as the name suggests that these plasmons are basically localized on nanostructures. Something like metallic nanoparticles. And these plasmons can be directly excited using just by shining light on it. You do not require a special mechanism to excite those plasmons. And if you look into plasmonics the funny thing is the plasmonics, though it is a saviour of mankind in the future.

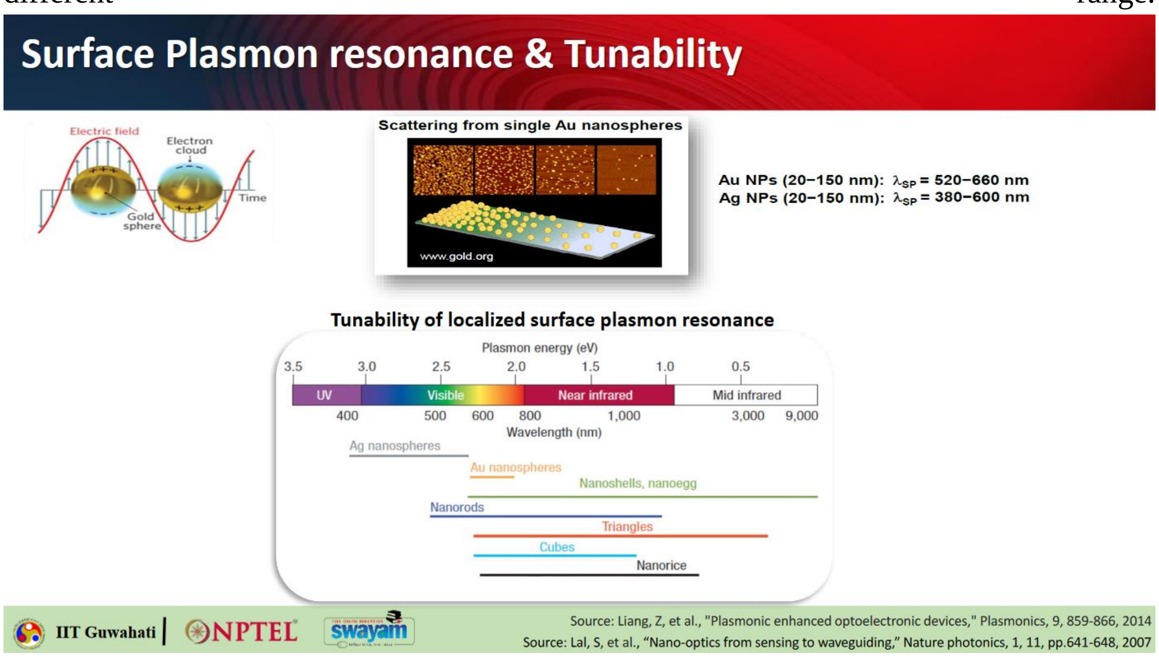
But the history or the genesis of plasmonics dates back to Roman. So, Romans were the nanotechnology pioneer. How this came into picture? So, you look into the figure here.

It shows the image of the same Lycurgus cup.

It is a cup. So that is kept in British Museum. So, when you put light from the front to see what is the colour of the cup you see it is green. But if you put the light source at the back, the cup appears red. That is something amazing. Usually if you take a yellow kind of thing, yellow glass or whatever, just think of it that when you look it from front or back more or less it will look same.

But here in this case there is a difference in the colours. When you are looking from the front and the back. When scientists actually look into the details of this glass they have figured out that there are tiny nanoparticles involved in this particular Lycurgus cup. So that is where the nanotechnology actually came in. And because of these nanoparticles only, in the scattering mode this glass is looking green.

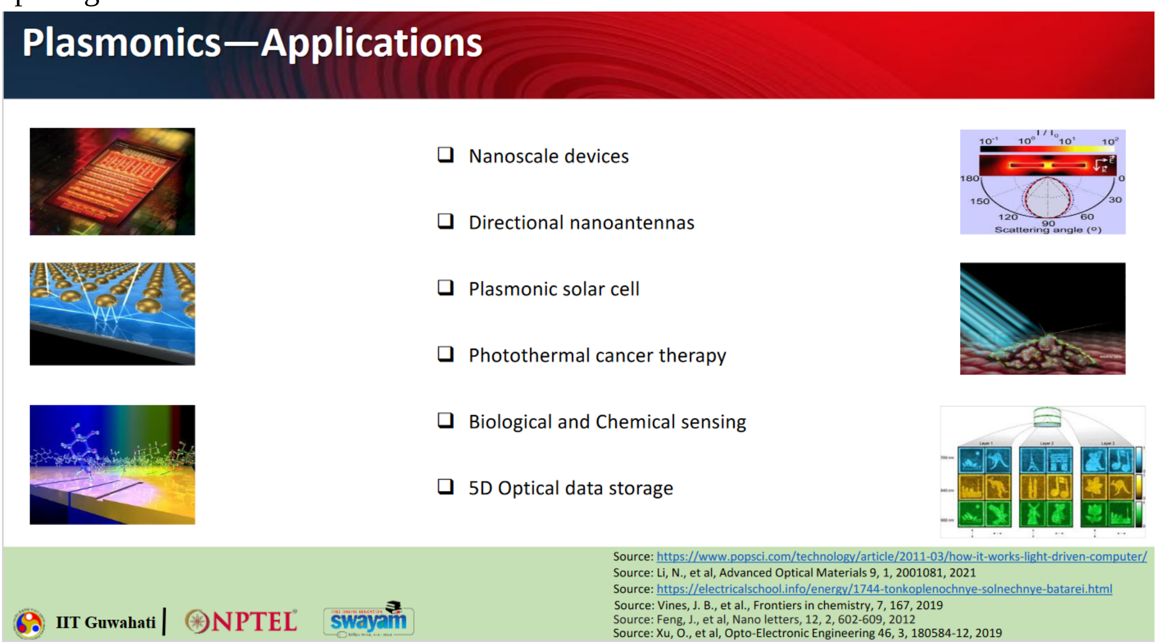
And because of the absorption of the nanoparticles, I will go into more details of it later on. This cup is looking red. So, surface plasmon, when they resonate with the frequency of the incoming light you can actually get surface plasmon resonance. And this resonance will significantly enhance the light scattering and absorption capability of these tiny nanoparticles. As you can see here, if you take gold nanoparticles over size 20 to 150 nm, the resonance wavelength can change from 520 to 660 nm. For silver, if you consider the same size you can actually tune the resonance of surface plasmon over a different range.



It is again similarly wide range but different range 380 to 600 nm. So, one need to keep in mind that this resonance is not only dependent on the material of the nanoparticles, their size, it is also dependent on their shape and also the surrounding media. That is around this particular nanoparticles. So, there is a graph of localized surface plasmon resonance tunability.

As you can see here, this is for silver nanosphere. This is the range over which you can choose silver nanosphere and change the size of it to go from UV to visible range. You can look for gold nanospheres that can give you more or less within visible range only. But if you choose nano shells or nano eggs, these are like ellipsoid kind of structure, you actually get a very wide tunability starting from visible to mid-infrared. Similarly, you can choose for nano rods which are like cylinders, nano cylinders, triangles, cubes, nanorides, all different shapes are possible.

So, you are able to change this surface plasmon resonance over a wide frequency range. But as you can see, everything within UV, visible and infrared. Why is this important? So, the ability to focus light and manipulate light at the nanometer scale has got a lot of potential. And this is what has been claimed by the pioneer of Plasmonics, Professor Harry Atwater at Caltech, US. So, he actually foreseen that this field is going to be very, very exciting and it is compelling because you can see a lot of applications of this particular field. In nanoscale devices, as you have seen, you can propagate surface plasmonics over nanoscale distances, you can confine energy with deep sub-wavelength spacing.



So, all those will allow you to get nanoscale devices. You can make directional nano antennas for your circuits using this kind of metallic nanoparticles or dielectric nanoparticles. You can think of plasmonic solar cells where nanoparticles with enhanced absorption at their resonance will allow you to absorb more light to be converted into electricity. So, they can be added to solar cells to increase their efficiencies. You can think of photothermal cancer therapy using nanoparticles where plasmonic nanoparticles can be injected into bloodstream with some targeted delivery so that these nanoparticles go and sit on a cancer tumor.

And you can shine light from the outside. Neon infrared light is able to penetrate the skin and can go inside. Nanoparticles having resonance at that particular wavelength will be able to absorb light very strongly and that with absorption the nanoparticles will get heated up and that increase in temperature will kill the cancer cells. So, you can see these nanoparticles can be your savior. They can be also used for biological and chemical sensing where the change in the refractive index of the surrounding media of the nanoparticles can be sensed as shift in the plasmon resonance peak wavelength.

So, you can actually sense very, very tiny amount of molecules present using this kind of sensors. This also can help you achieve very high density optical storage something like this one. 5D optical storage. So, here the images are imprinted in different layers at different wavelengths and polarization.

So, these are only some specific applications. You can think of a lot more applications using plasmonics. So, this is the future going ahead. So, that is all for today's lecture and we will try to cover the introduction to matter surfaces and materials in the next lecture.

So, thank you. In case you have any query you can send it to me at this email address deb.sikdar@iitg.ac.in. But do not forget to mention MOOC in the subject of your email. Thank you. .