Course Name- Nanophotonics, Plasmonics and Metamaterials

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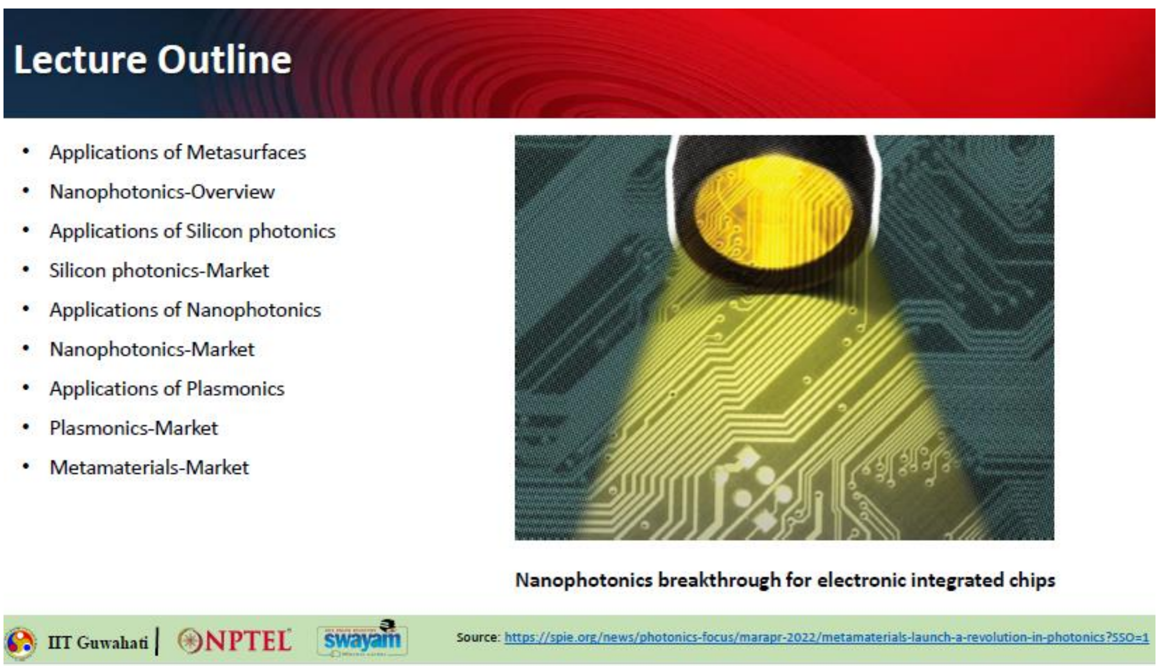
Week-01

Lecture -03

Hello students. Welcome to the third lecture of my online course on Nanophotonics, Plasmonics and Metamaterials. The title of this lecture is Overview and Current Status. So, in this lecture we'll be covering first the applications of metasurfaces which we could not cover in Lecture 2. And then I'll provide you a brief overview of Nanophotonics.

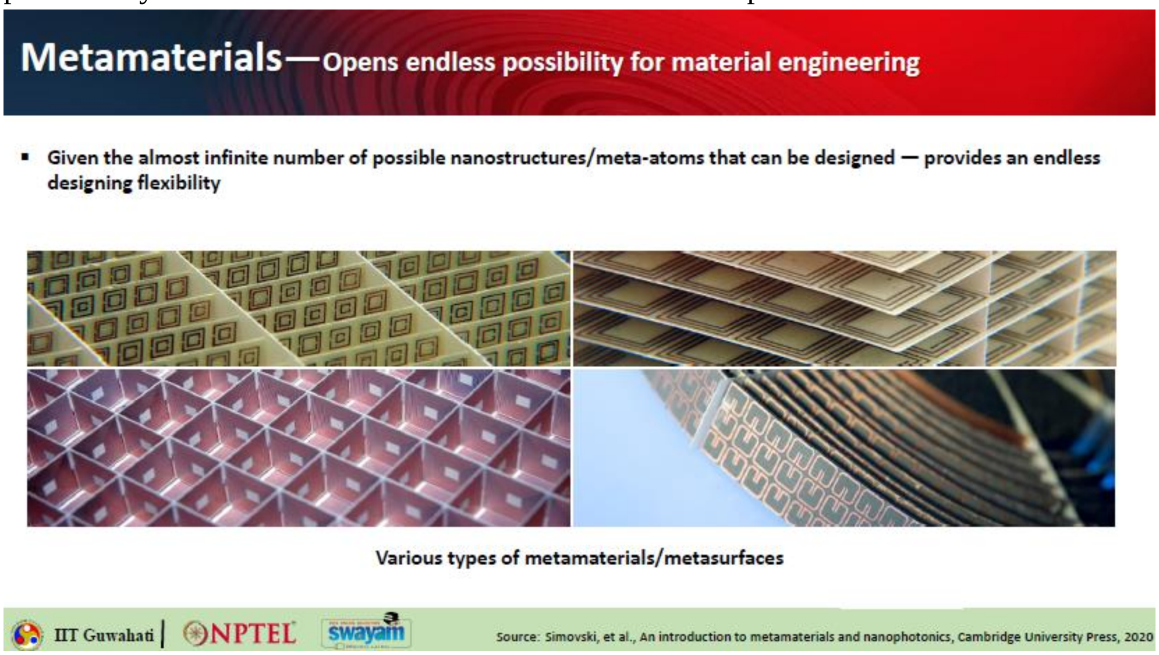
Applications of Silicon Photonics, we'll introduce these new terms here. We'll talk about the market, Silicon Photonics market. Applications of Nanophotonics, the market trend in Nanophotonics. Applications of Plasmonics, again the market trend of Plasmonics.



And also we'll talk about the Metamaterials market. Why I'm focusing a lot on the market scenario? Because we should be aware of the fact that what are the current trends in the technology. And going ahead in next 10-15 years where the technology focus is going to be. So that is why this particular lecture is particularly very important. Because that will give you a broad overview of this new field.

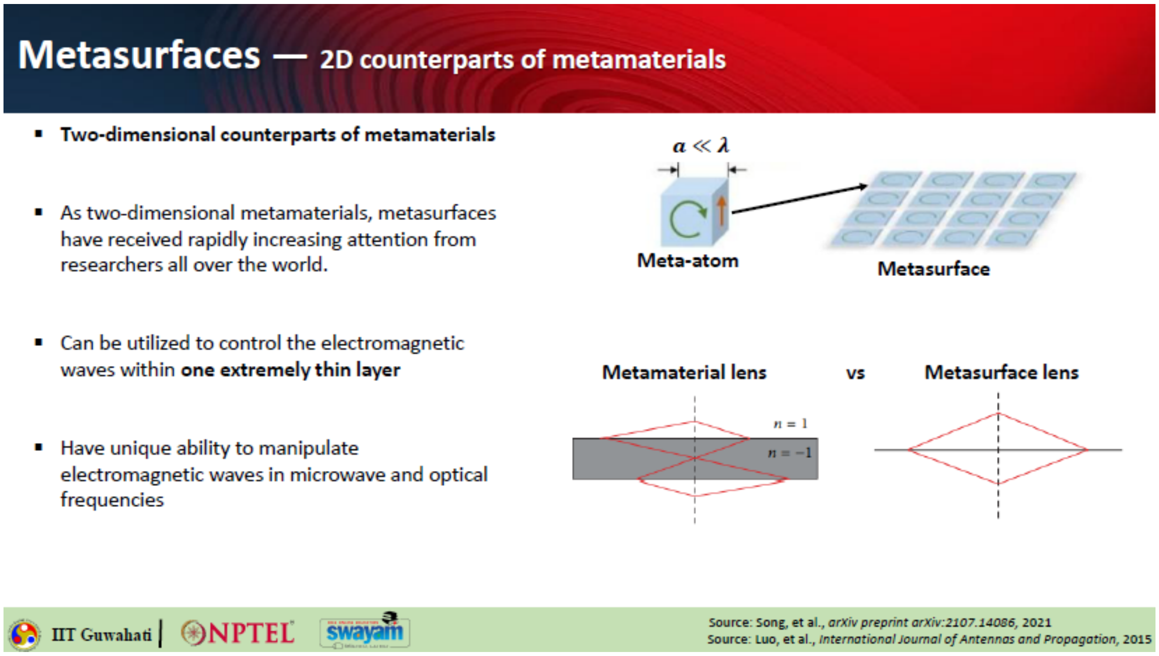
In terms of research, in terms of job situation and so on. So this particular schematic gives you an idea of Nanophotonics breakthrough for electronic integrated chips. So we'll come to those in due course of time. So first of all, a quick recap on Metamaterials that we have seen in yesterday's lecture. So Metamaterials opens endless opportunity for material engineering.

As we discussed that in Metamaterials, the property of the material depends not on the constituent atoms. But it depends on the physical structure of the meta-atoms. So that brings you almost infinite possibilities of designing nanostructures or meta-atoms. Which are the unit cells. And they actually define what should be the permeability and permittivity of this particular material.



So truly this brings in endless opportunity. And we have also seen that the development strategies for metamaterials and the functional materials. They mainly focus on the structures which give rise to these exotic properties. And they are not restricted only to optical field. We have seen mechanical, thermal, acoustic metamaterials.

So metamaterials indeed is the new wonder in material engineering field. And if you talk about their 2D counterparts, that's meta-surfaces. So simply speaking, meta-surfaces are 2D metamaterials. And if this is a 3D meta-atom, which is the building block of a metamaterial. You can think of a 2D kind of design as a meta-atom for the meta-surface.

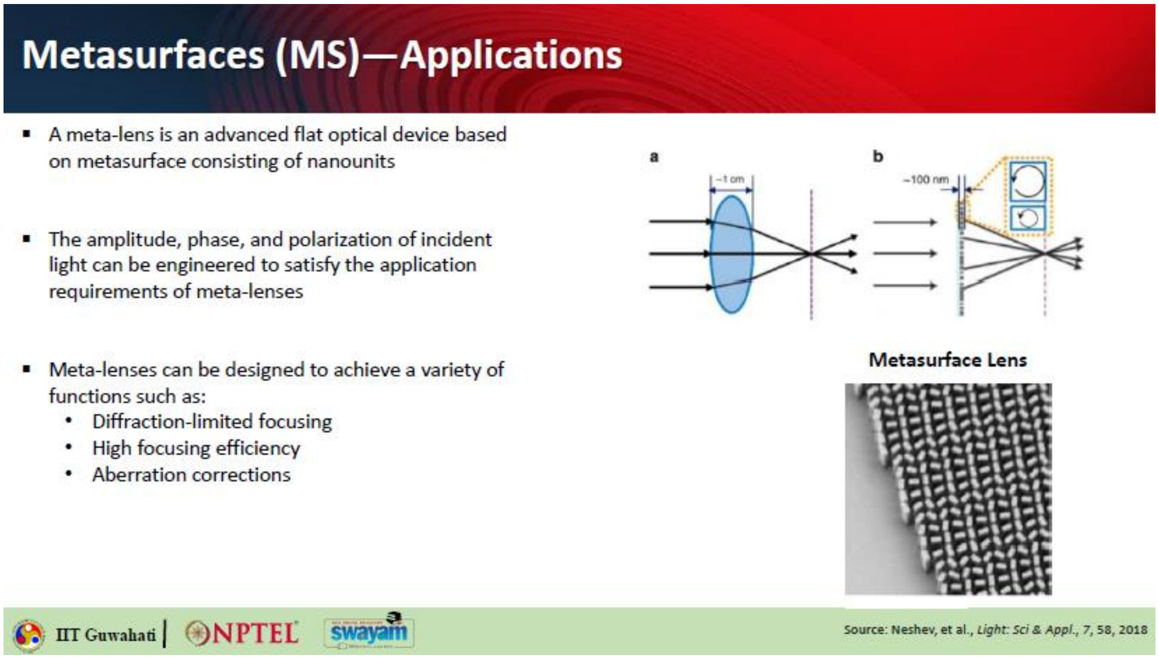


So, if you restrict one of these in the z direction, it becomes extremely thin. And that is what is a meta-surface. Then what about the dimension of these unit cells or meta-atom? They are again much, much sub-wavelength. So the wavelength is much, much larger than the feature size. So that is how meta-surfaces will be designed.

Now, why people wanted to go from metamaterials to meta-surfaces? Because there are certain features meta-surfaces can bring on the table. Something like the thin layer, ease of fabrication, then low cost, degree of freedom in integration in a particular constraint space. So all these new features that meta-surfaces are able to bring make them actually popular candidates. And they have unique ability to manipulate the electromagnetic waves over this surface in microwave and optical frequencies. So if you make a comparison between a lens made of metamaterial and a meta-surface, you can typically look into the difference meta-surface lens will bring on table.

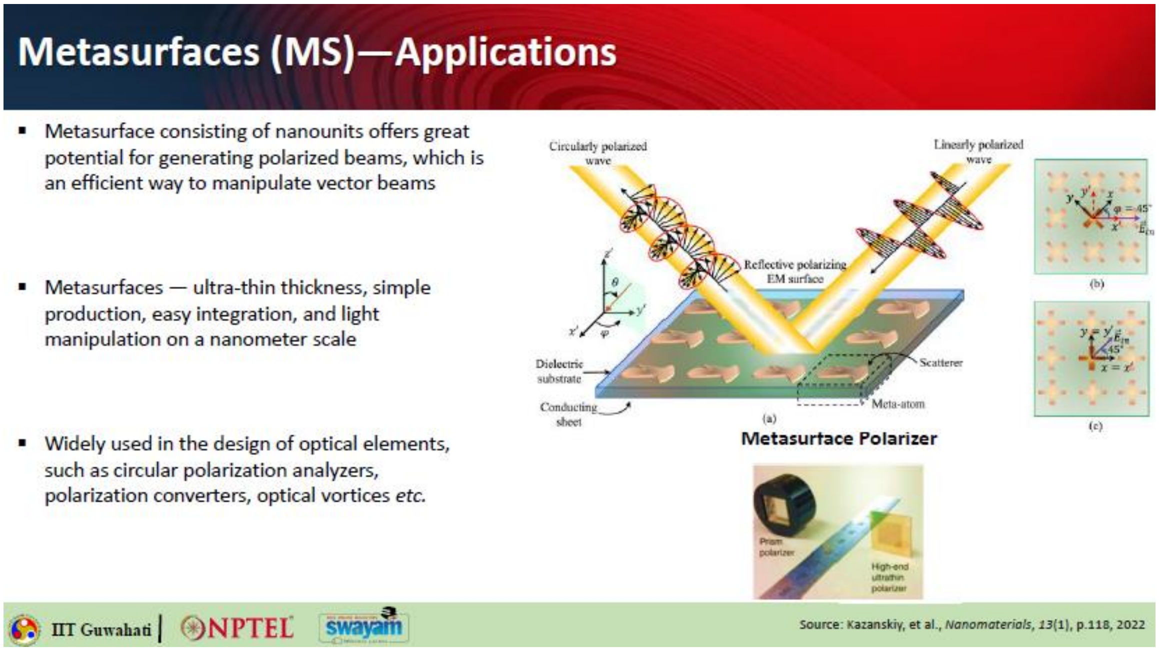
It can actually make the lens very, very thin layer. So that is where in a compact device, where the world is looking towards miniaturization of all components, meta-surfaces looks more promising. Now, let us discuss some promising applications of meta-surfaces. To continue, we will be talking about the meta-lens. So meta-lens is basically an advanced flat optical device which is based on meta-surfaces.

And here you can see a comparison. So this is a conventional lens made of glass or any other dielectric material and this is the typical thickness is in the order of centimeters. Whereas when you make a lens doing the same functionality of focusing the incoming beams to a point, you can see a meta-surface lens can be very, very thin of the order of 100 nanometer. So how does meta-surface work? The amplitude, phase and polarization of incident light can be engineered by this meta-atom's interaction to satisfy the application requirement. And that is how meta-surfaces can be useful.



So meta-lens can be designed to achieve a variety of functions something like diffraction limited focusing. So you can actually focus in a very, very tiny spot. Then you can actually go for high focusing efficiency. Also you can go for aberration corrections. Now if this term is new, I'd quickly tell you that in optics, aberration is a property of optical systems such as lenses that causes light to spread out over some region of space.

Rather than getting focused to a particular point. So aberration causes the images formed by the lens to be blurred or distorted. And this is kind of a distortion happening depending on the type of aberration. So meta-surface based lens can actually get rid of this effect and get you better focusing. So here is a typical design of a meta-surface lens.



As you can see this operates at 600 nanometer and it constitutes of titanium dioxide nanofilm on a glass substrate. So this is how the elements are patterned. And this is the cross-sectional view, the side view and this is the front view of the meta-surface or the top view you can see. Other application would be like a meta-surface polarizer. You can see why we need polarizer to induce polarization or change the polarization of the light.

So you can see a prism polarizer which is typically available in any optical bench. And this will be a high-end ultra-thin polarizer which is based on a meta-surface. So you can see the amount of compactness meta-surface brings on table. So meta-surface constituting nano-units can offer great potential of generating polarized beams. Which is an efficient way to manipulate vector beams.

So here in this figure you can see this is particularly the unit cell that is repeating over this meta-surface. So in this unit cell is called meta-atom. And in this unit cell you have a metallic scatterer on a dielectric substrate. The bottom is the back plane which is a conducting sheet. So this is how this meta-surface is constructed.

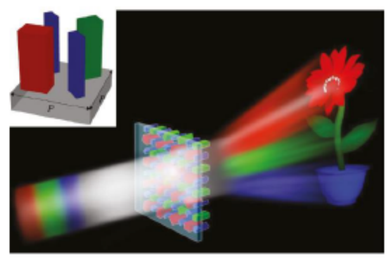
Now if you see there is an incoming light beam which is linearly polarized. And upon reflection from this particular surface it gets circular polarized. So you can actually change the polarization of the light upon reflection using meta-surface. Meta-surface can also be designed in transmissive mode where you can change the polarization of linearly polarized waves. Okay from say TE to TM and so on.

So this is just one example. So all these tiny scatterers they are doing the wonders. Okay they actually help you to rotate the plane of polarization. So meta-surfaces they are ultra-thin, they are easy to fabricate, easy to integrate. And they allow you to manipulate light on nanometer scale. So they are widely used in design of optical components such as circular polarizer or circular polarization analyzer, polarization converters, optical vortices and so on.

So you can actually think of all bulk optical components being replaced by these flat optical components which are typically meta-surfaces. Other applications would be meta-surface holography. Now holography is nothing but a way of making 3D images or 3D pictures using light. So meta-surface holography can be performed by mapping the configuration precisely to the position and the local scattering properties of nano-scale optical resonators which are patterned on the interface. So, when you compare meta-surface holograms with conventional holograms, meta-surface ones have got a lot of advantages.

Metasurfaces (MS)—Applications

- Metasurface holography can be performed by mapping the configuration precisely to the position and the local scattering properties of nanoscale optical resonators patterned at the interface
- Compared with conventional holograms, metasurface holograms have three major advantages:
  - Unprecedented spatial resolution, low noise and high precision of the reconstructed images
  - Significantly reduced subwavelength pixel size contributes to an improved holographic image compared to traditional holograms due to the elimination of undesired diffraction orders
  - Can provide large space-bandwidth products due to their ability to achieve large area fabrication



Metasurface Holography

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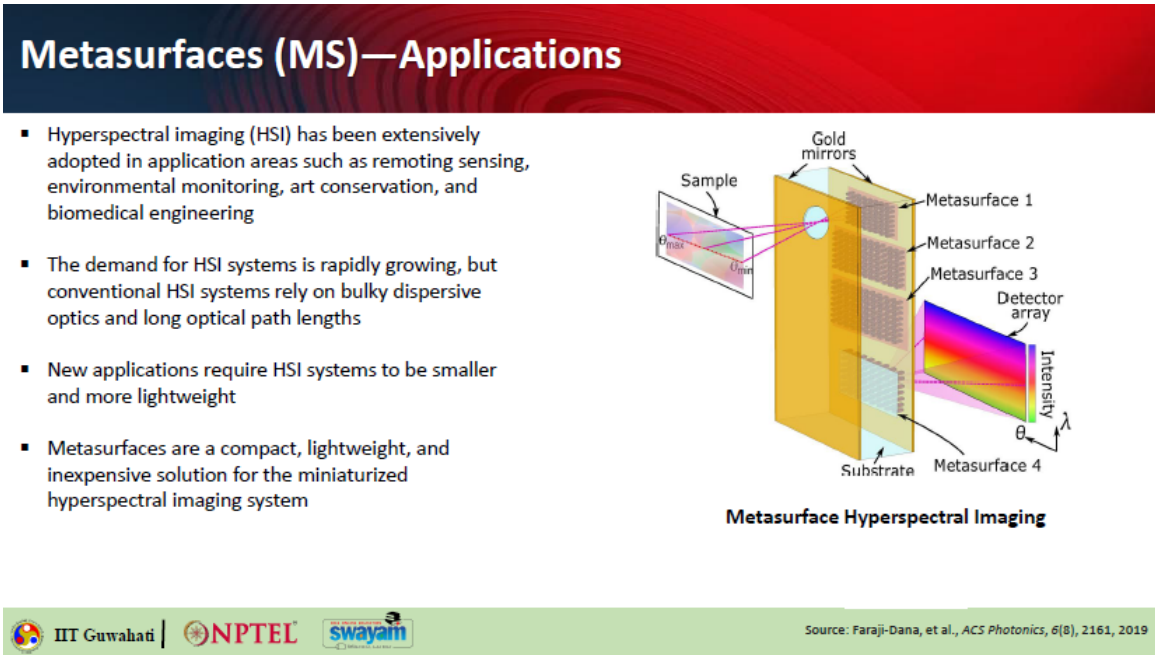
Source: Huang et al., *Nanophotonics*, 7(6), p.1169, 2018

Something like you can get unprecedented spatial resolution, low noise and high precision of the reconstructed image. Significantly reduced sub-wavelength pixel size contributes to improved hologram image compared to the traditional holograms due to the elimination of undesired diffraction orders. And they also provide large space bandwidth products due to their ability to achieve high or large area fabrication. So here you can see the schematic illustration of a multicolor dielectric meta-surface.

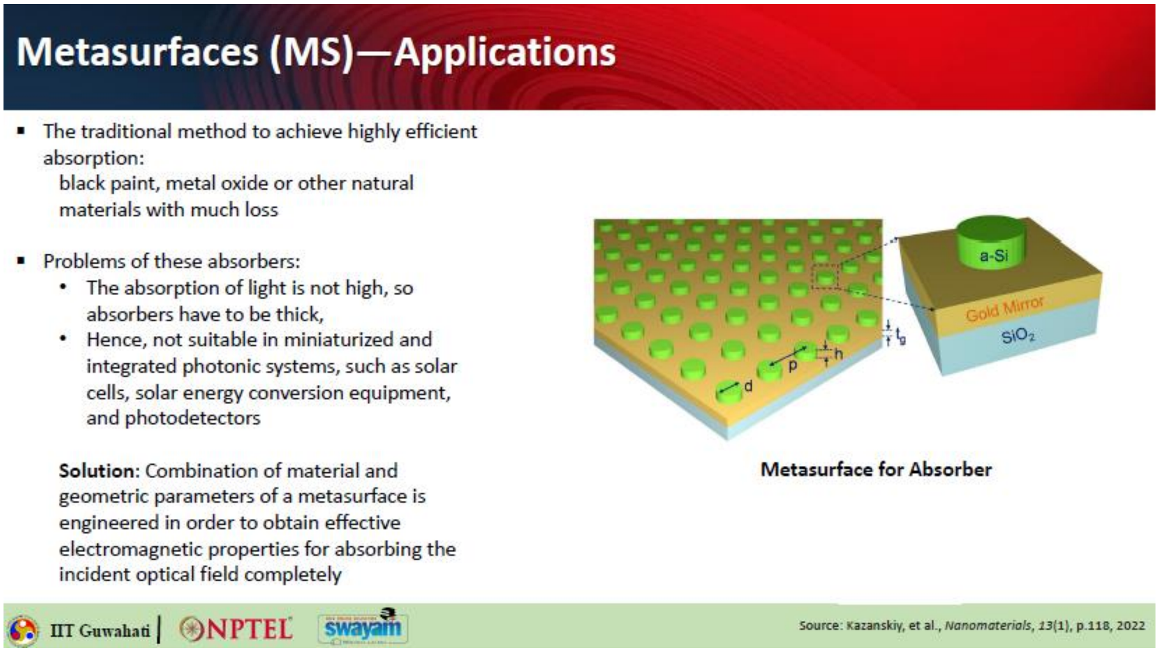
You see this one. And they are nothing but, this is one particular meta-atom which has got multiplexed or multiplexing of silicon nano-blocks of different shapes and orientation. So when light falls on this, you can see this hologram independently projects distinct colors like the red flower, the green peduncle and the blue pot. So all this information can be in the meta-atom and that can create this particular hologram. Other images, sorry, other applications can be in meta-surface hyperspectral imaging. Now what is hyperspectral imaging? It is basically a technique that analyzes a wide spectrum of light instead of just assigning the primary colors like red, green and blue to each pixel.



So when light strikes each pixel, it is broken into many different spectral bands in order to provide more information on what is getting imaged. So hyperspectral imaging has become extremely adopted or it is very very popular in application areas like remote sensing, environmental monitoring, art conservation and biomedical engineering. The demand for hyperspectral imaging is rapidly growing. But conventional hyperspectral imaging systems, they are bulky and they are based on dispersive optics and they require long optical path lengths.

So overall the device is bulky. So you want the new applications or the new application demands this hyperspectral imaging system to be really compact and lightweight and this is where meta-surfaces will come into the picture. Meta-surfaces are compact, lightweight and inexpensive solution for miniaturized hyperspectral imaging system. The schematic shown here is basically a scheme of a folded meta-surface hyperspectral imager. This device as you can see has got three reflective meta-surfaces and one transmissive meta-surface to perform optical function. So light enters through the input aperture here and it interacts with the reflective meta-surfaces while it is confined inside the substrate by these two gold mirrors.

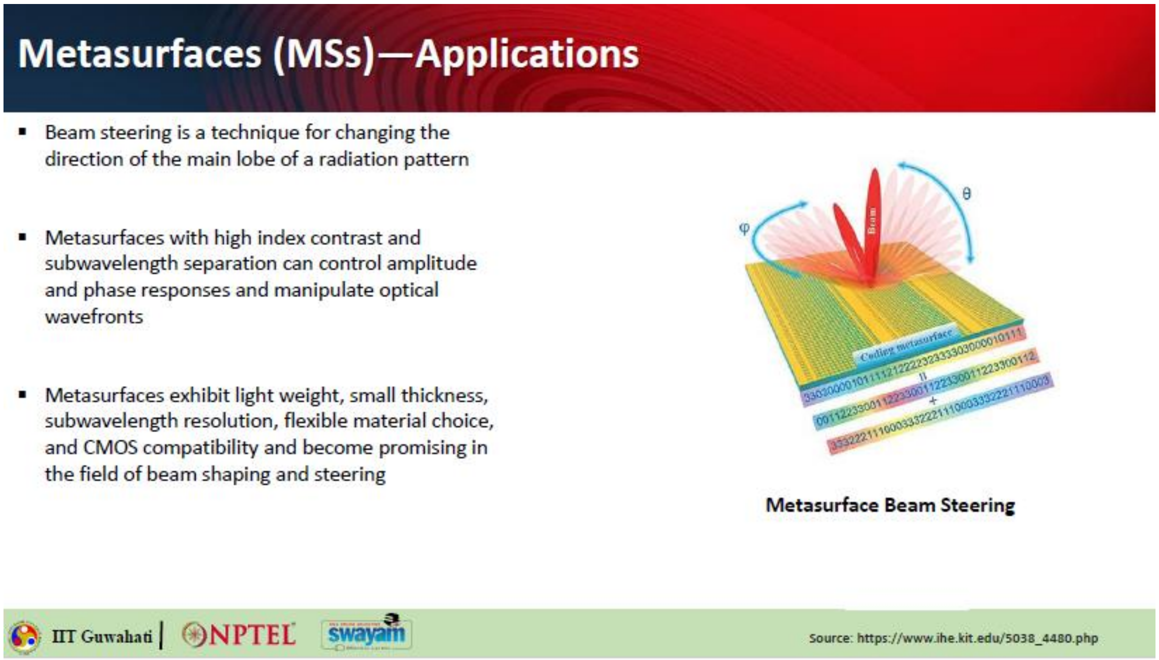
And then finally when it exits by this transmissive meta-surface you will see that different wavelengths are dispersed in vertical position. So this is how the wavelengths will be dispersed and also various input angles are focused at different horizontal positions. So that is how you are able to get hyperspectral imaging time using meta-surfaces. The other application would be absorber. As the name suggests, absorber will absorb electromagnetic radiation.



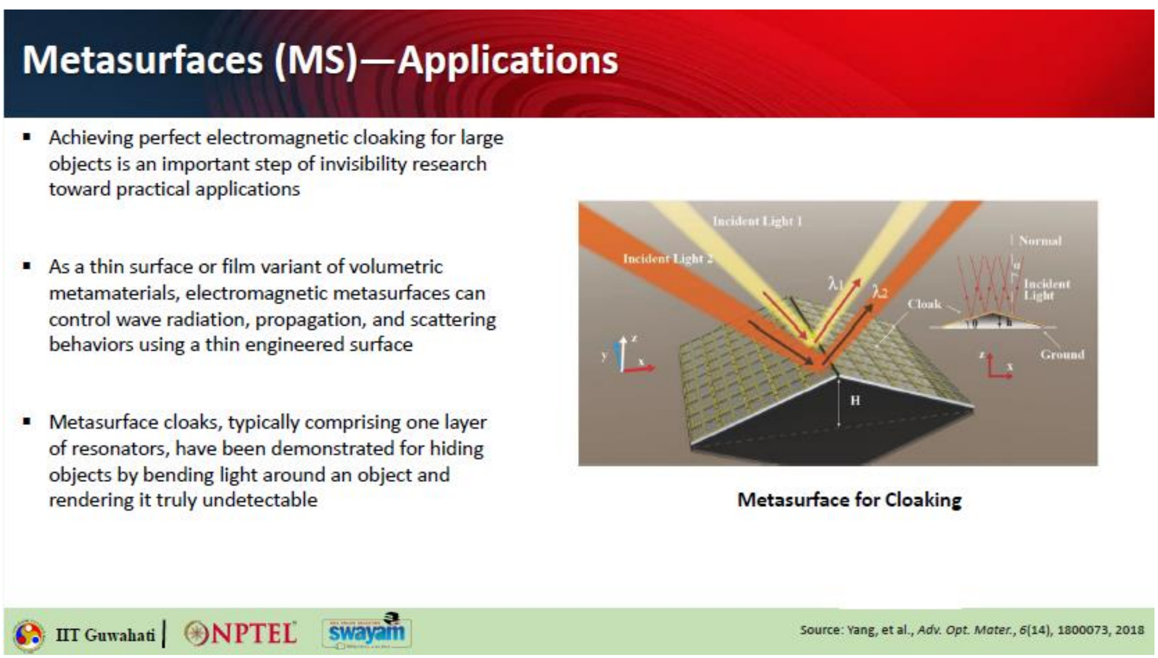
So the traditional methods to achieve efficient absorption would be by using black paint metal oxide or other natural materials with high loss. But the problem is that for this particular materials, the absorption of light is not typically very high. So the absorbers become very bulky. And as soon as they become bulky, they are not suitable to be miniaturized and integrated into integrated photonic systems such as solar cell, solar energy conversion equipment or photo detectors. So, what is the solution? Solution would be to look for meta-surfaces which is basically combination of material and the geometric parameters or the unit cells.

That will help you provide absorption over a particular band. So this is a typical image of a meta-surface absorber where you have silica as a substrate, you have a gold mirror, a thin gold mirror. On top of that you have a silicon nanopillar. So this particular one is able to give 100% absorption over a particular band.

Other applications would be like beam steering. So in beam steering you actually change the direction of the main lobe of the radiation pattern in a desired position. So that is very very important in different communication applications. So meta-surfaces with high index contrast and sub-wavelength separation can control the amplitude and phase responses and they allow you to manipulate the phase front. And that is how you can actually get beam steering done. So meta-surfaces exhibit ultra lightweight, small thickness, sub-wavelength resolution, flexible material choice and CMOS compatibility to become a promising candidate for devices such as beam shaper or beam steerer So these are the applications.

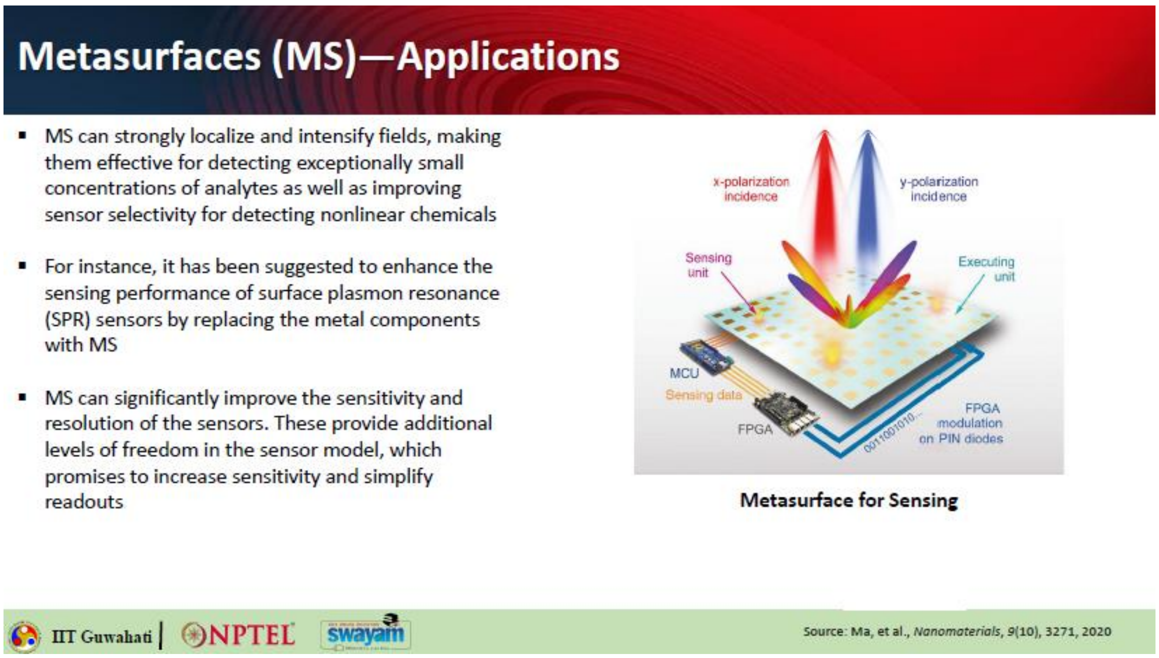


The other interesting application of meta-surfaces would be in the field of cloaking. Cloaking means hiding something. So you can actually look at the schematic here. It shows that the incident light is getting reflected by the meta-surface in such a way as if it is getting reflected from the flat surface. So, there is no change in the direction of the reflection.



So in that case, whatever is hidden below this particular meta-surface will not be seen because the reflection pattern is exactly like from the flat surface. So this is how the cloaking using meta-surface will work. So achieving perfect electromagnetic cloaking for large objects is very very important for invisibility research towards practical applications. So who are people interested in this kind of application? Obviously the defense people would be interested. So you can think of thin meta-surfaces instead of large volumetric meta-materials to do this job for you which can control the wave radiation, propagation and scattering using these thin engineered surfaces.

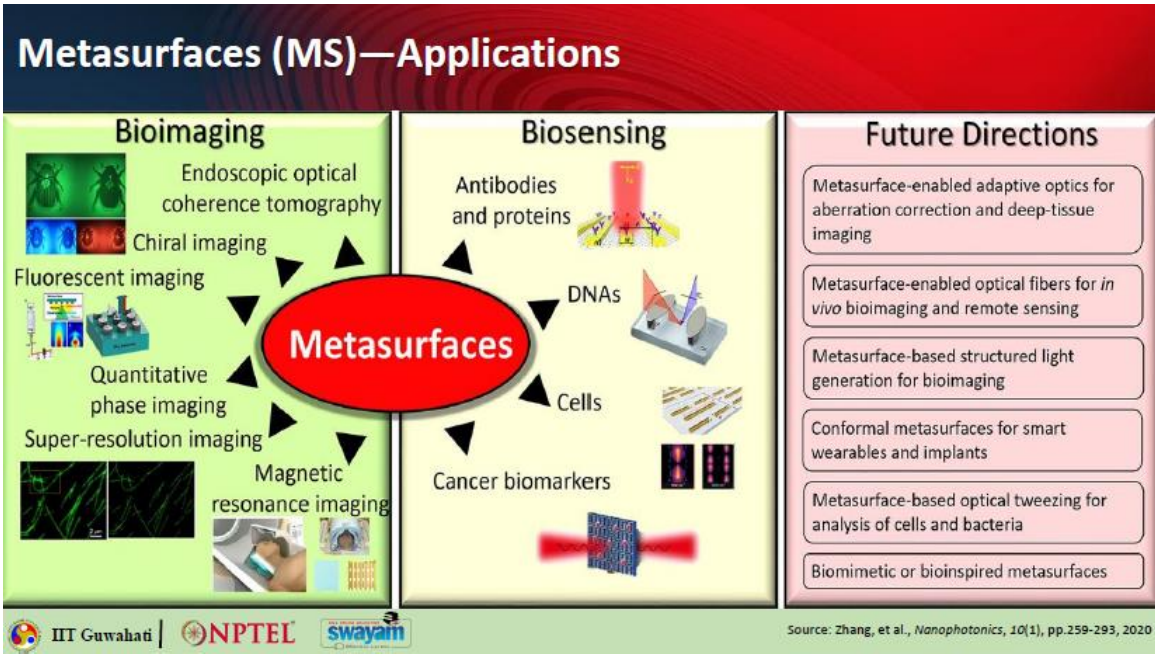
So meta-surface cloaks typically comprising one layer of resonators as you can see here. They have been demonstrated for hiding objects by bending light around the object. That was the one we discussed in the previous lecture. Or you can actually make sure that the reflection happens in such a way as that it is exactly same as if it is a flat surface. So, whatever is below this meta-surface will go undetectable.



Something like this. You can hide anything here so that the reflection spectrum or the reflection profile looks like as if the light is coming from a flat surface. The other application would be in the field of sensing. So we have seen plasmonic structures doing sensing but meta-surface can also strongly localize and intensify fields making them effective for detecting very small concentration of analytes as well as improving the sensor selectivity for detecting non-linear chemicals. So here each meta-atom or building block is a resonating element so they can actually work as a sensor. And it has been suggested to enhance the sensing performance of surface plasmon resonance based sensors by replacing the metallic parts there with meta-surfaces.

So meta-surfaces has got a promising future towards sensing as well. And these meta-surfaces can significantly improve the sensitivity and resolution of the sensors. This provides additional levels of freedom for sensor modeling which can also bring in more sensitivity and simplify the readout circuitry. All in all, here we can see that the recent advances in meta-surfaces in other application areas like bioimaging and biosensing.

Bioimaging areas include endoscopic OCT or optical coherence tomography, chiral imaging, fluorescent imaging, quantitative phase imaging, super-resolution imaging and also in the field of MRI, magnetic resonance imaging where meta-materials can be used to locally boost up the magnetic field so that the signals from the MRI can be boosted locally.



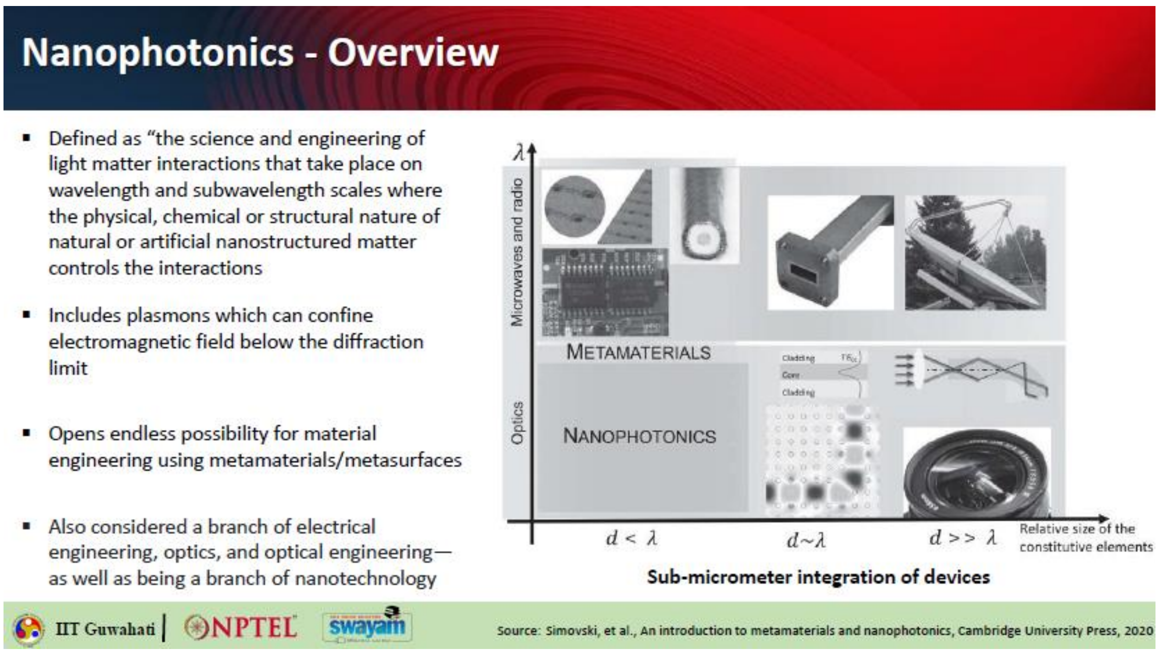
Meta-surfaces can also be used for biosensing to detect antibodies and proteins, DNAs, different cells, cancer biomarkers and so on. So what are the future directions of meta-surface research? To look into meta-surface enabled adaptive optics for abrasion correction and deep tissue imaging. So these are the areas where people are working on. Meta-surface enabled optical fibers for in vivo bioimaging and remote sensing. Meta-surface based structured light generation for bioimaging.

Conformal meta-surfaces for smart wearables and implants. Meta-surface based optical tweezy for analysis of cells and bacteria. And bio-mimic or bio-inspired meta-surfaces. So there are a plethora of applications of meta-materials and meta-surfaces as you can see. So all this actually brings in infinite possibilities of engineering the interaction of electromagnetic waves with matter.

Now the matter is completely in your control. So waves, you bring it in with the matter, the new design, you can actually make the wave do what you want to do. Okay? So going ahead let us quickly have an overview of nanophotonics. So look into this particular figure where we discussed about the relative dimension of the devices when compared to the wavelength. And this is the wavelength axis.

So smaller wavelength typically is the optics area. And larger wavelength will be the microwave and radio waves. And we have seen that when the size is much, much larger than the wavelength, that is where the bulk optics come into picture. When they are comparable, that is like the photonics field. And when the device size is smaller than the wavelength, we have nanophotonics.

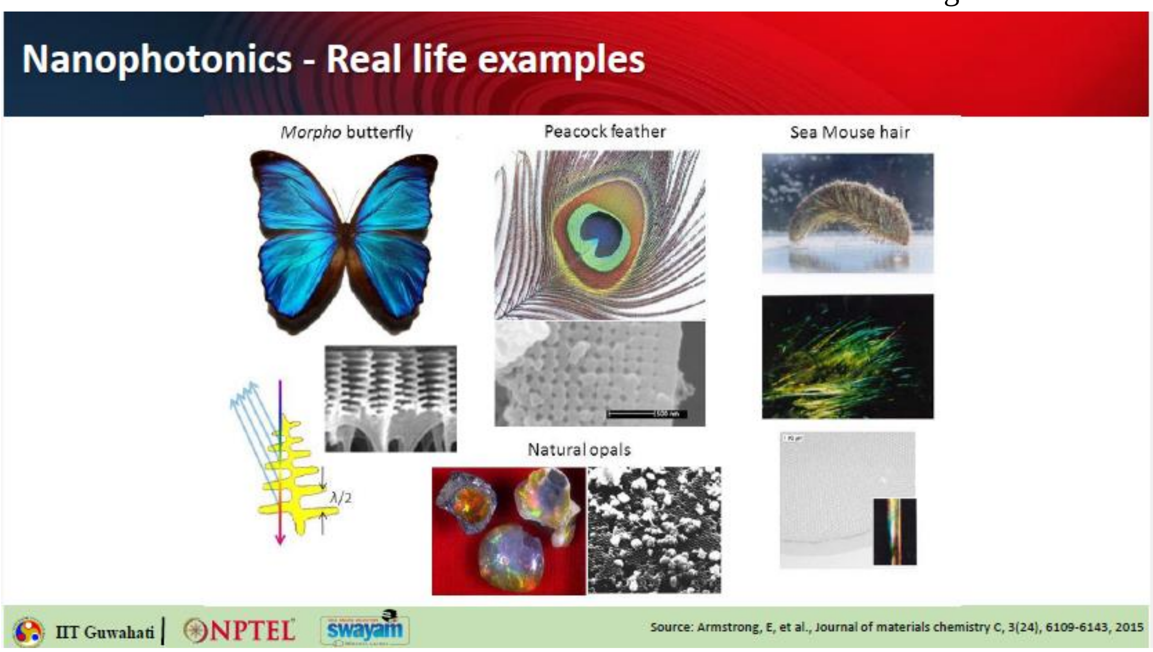
So that is what happens in the optical area. The same thing also applicable for microwaves and radio. You see the large antennas, you see the waveguides which are comparable to the wave dimension. And then you also have metamaterials in microwave and radio domain where the device dimension is much smaller than the wavelength. So all in all this gives you a complete overview of the field of nanophotonics and metamaterials. So if anyone asks you what is nanophotonics? Now you should be able to tell that nanophotonics is basically the science and engineering of light-matter interaction.



That takes place on the wavelength and sub-wavelength scale. Where the physical, chemical and structural nature of the natural or artificial nanostructured matter that controls the interaction. So nanophotonics also includes plasmons that could confine electromagnetic radiation well below the diffraction limit. And this particular field overall opens infinite possibility of material engineering using metamaterials and metasophices. So that actually the metamaterials and metasophices have actually added a feather to the cap of nanophotonics. Where you have infinite freedom to design the device with the functionality you want.

So once again I am repeating myself that this is particularly a branch where multidisciplinary nature is completely seen. So people from electrical engineering, optics, optical engineering, chemistry, physics, chemical engineering, material science and engineering can come in. And it is also a branch of nanotechnology because finally you have to make those devices using nanotechnology. So these are some real world examples of nanophotonics because we are not the pioneers. The nature, the almighty has already used nanophotonics to make our world look so beautiful.

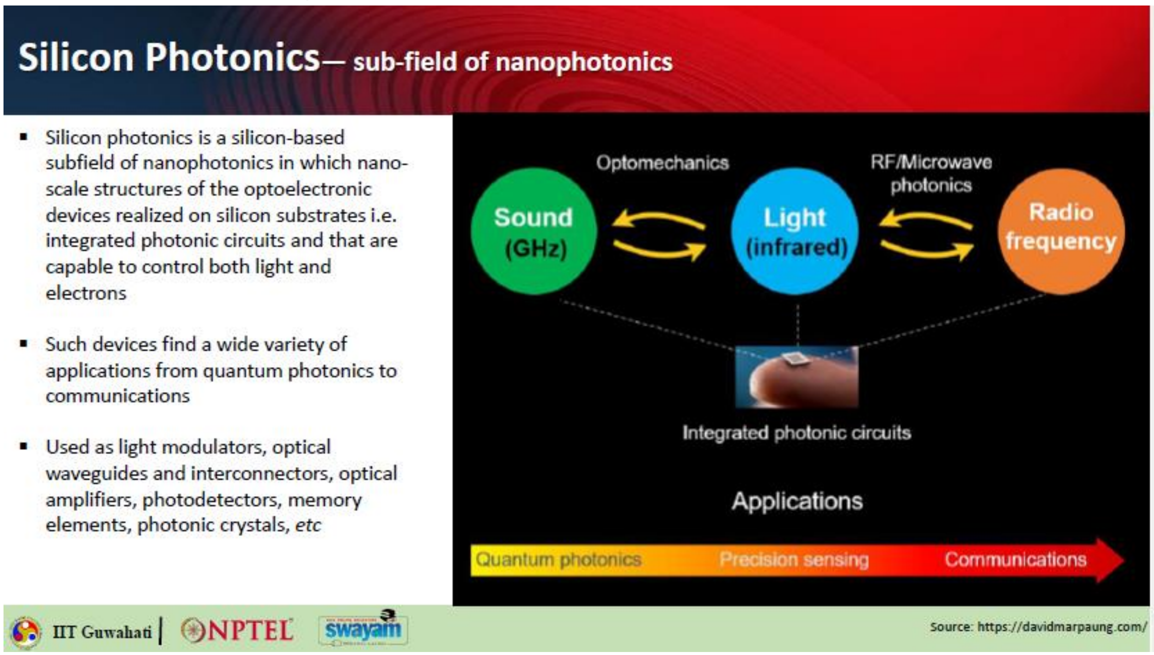
So if you look into the wings of a butterfly and the colors that you see, that are not basically from the pigment. But from the structures, the nanostructures that are embedded into the wings of the butterfly, they can actually reflect a particular light. So that this bright color is seen. Similarly if you look into the feather of a peacock, this beautiful color or the pattern that you see is not basically from the pigmentation but from the structure that is embedded there. Similarly, the natural opals, they also have this internal structure that does all these bright colors.



If you look into the sea mouse, their hair also actually have photonic crystal kind of arrangement of hexagonal cylinders that give these different colors when you look at them from different angles. So these are natural examples of nanophotonics. So we see a lot of beautiful stuff thanks to the nanophotonics embedded in them. Now when we try to make something, we need to have the industry support. And that is where when you think of nanophotonics, we have to also think of what kind of industry or foundry can support this kind of nanophotonic devices.

The first obvious answer comes to our mind is that can we look at the silicon industry which has grown significantly over the last couple of decades. So that brings us to a topic which is known as silicon photonics. So this is again a subfield of nanophotonics. But here you want to do all the nanophotonic functionalities on silicon platforms so that you can use the semiconductor foundries to make your devices.

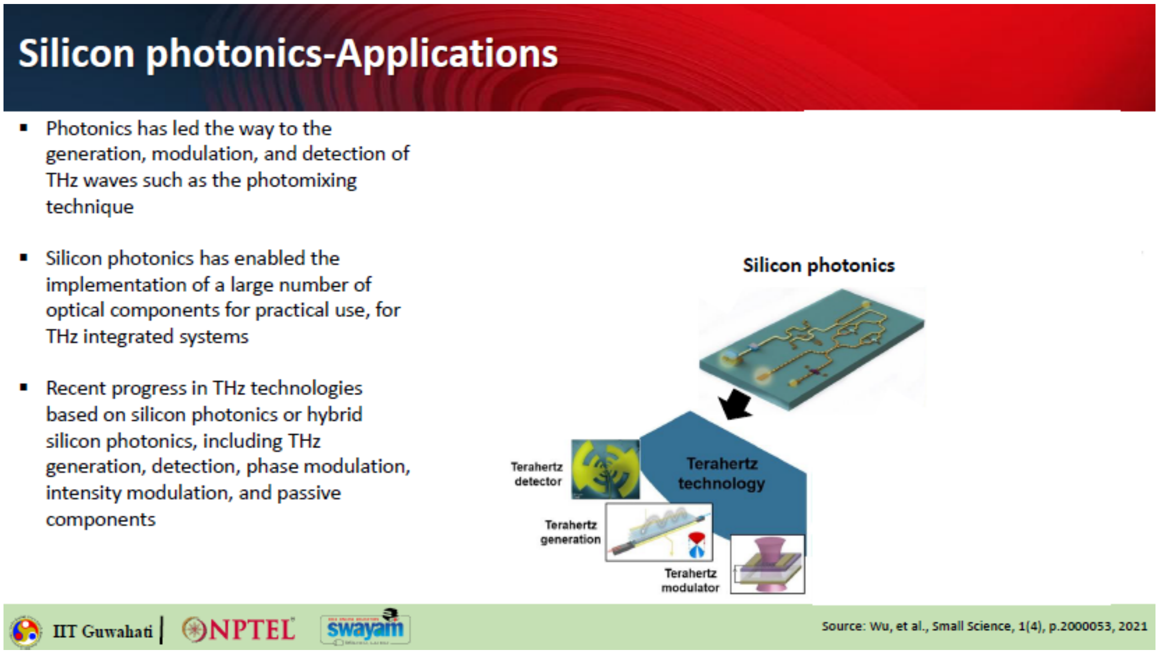
So here the material choice is kind of limited. We are not talking about any other material other than silicon or CMOS foundry compatible materials. So here our material choice is kind of limited. So silicon photonics is basically a silicon-based subfield of nanophotonics in which the nanoscale structures of the optielectronic devices are realized on silicon substrates. That is you are basically making integrated photonic circuits which are capable of controlling both light and electrons. Such devices will find a variety of applications starting from quantum photonics to communication.



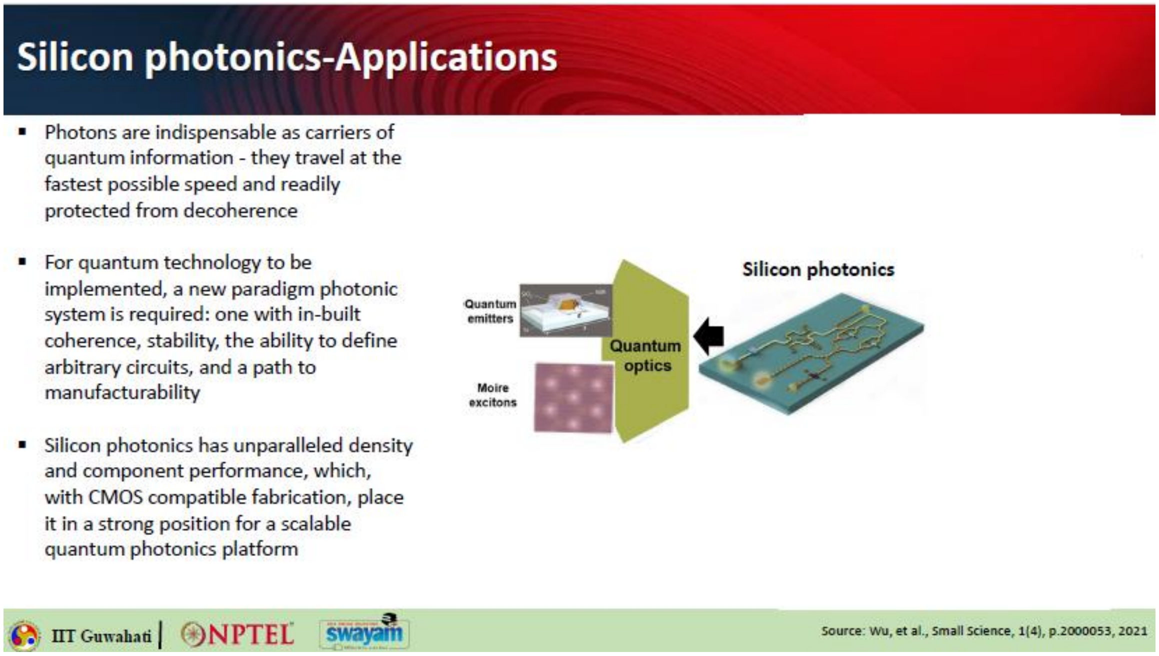
And what are the different applications? As you can see you can use them as light modulators, optical waveguides and interconnects, optical amplifiers, photodetectors, memory elements, photonic crystals, etc. So if you see integrated photonic circuits, there you actually have integration between light, radio frequency and also sound. In a way that you know how light and radio frequency they are interacting. There is a field called microwave photonics which we have discussed briefly in the previous lecture.

So this is how the optielectronics part is working. And then you also have sound or mechanics in GHz range. So this is where sound or acoustics is interacting with optical field and this field is called optomechanics. So these are different applications broadly. Now let us also look into the other application areas of silicon photonics because right now silicon photonics is the immediate future. Whereas the other fields like metasurfaces are still in its infancy and they will require some time to grow.

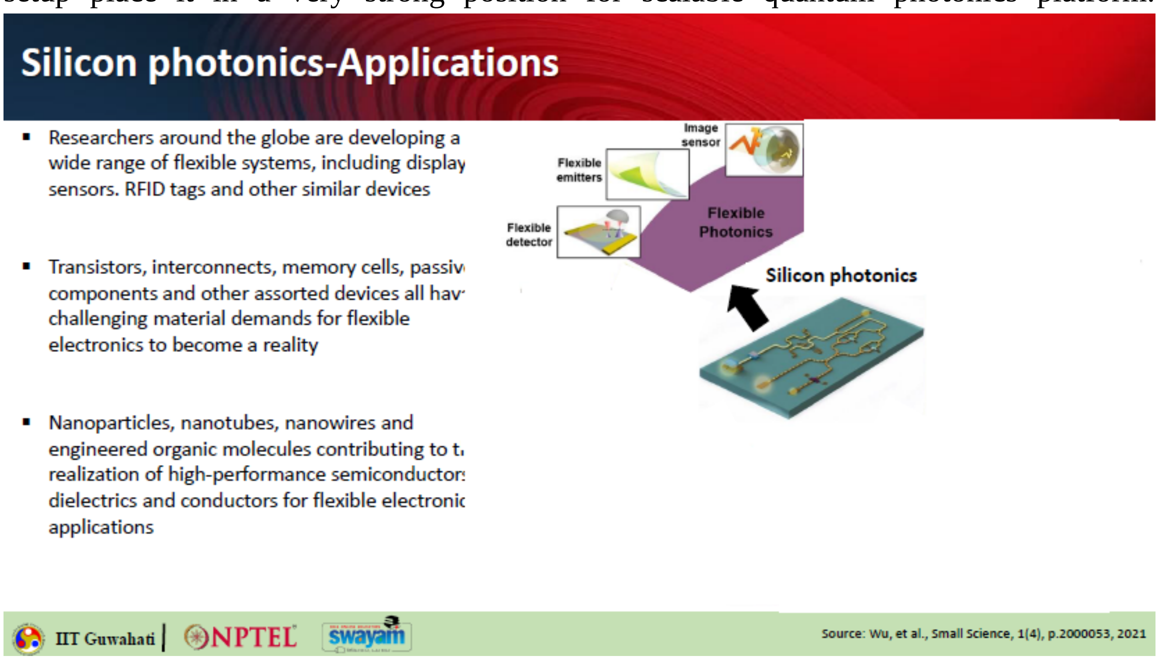
But if you think silicon photonics because of the fabrication support silicon photonics can get from the semiconductor industry, this is an immediate field of research. And application. So photonics has led the way to the generation, modulation and detection of terahertz waves. Now terahertz is the frequency gap between the infrared and microwaves. So, photonics can help you generate, modulate and detect terahertz waves such as photomixing technique.



So you can use them for terahertz detection, generation and modulation as shown here. Silicon photonics has enabled the implementation of large number of optical components for practical usage such as for terahertz integrated systems. And the recent progress in terahertz technologies based on silicon photonics or hybrid silicon photonics includes this kind of generation, detection, phase modulation, intensity modulation and developing other passive components. So the terahertz technology is getting support from silicon photonics. The other area will be the quantum optics area where it is possible to have quantum emitters and moire excitons.

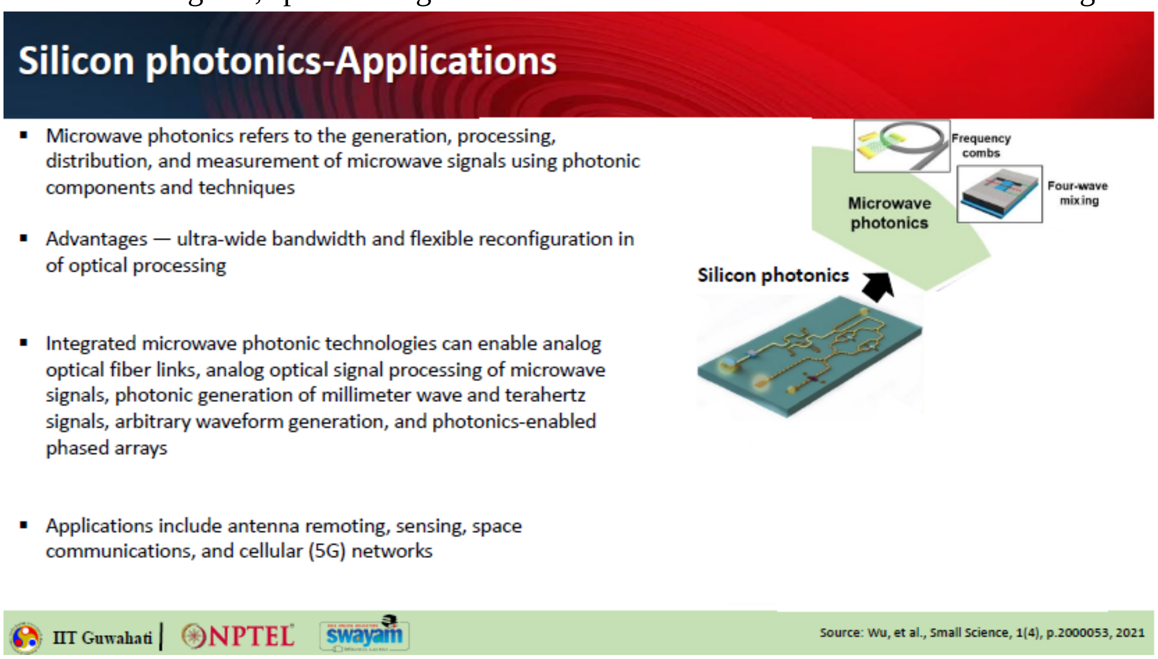


So photons are indispensable as carriers of quantum information. They travel at the fastest possible speed and readily protected from decoherence. For quantum technology to be implemented, a new paradigm photonic system is required. One is built with coherence, stability and the ability to define arbitrary circuits and a path towards manufacturability. Silicon photonics has unparalleled density and component performance that we have already seen. Which with the CMOS compatible fabrication setup place it in a very strong position for scalable quantum photonics platform.



The next application would be in flexible photonics. So researchers around the globe are developing wide range of flexible systems including flexible display, sensors, RFID tags and similar devices. You can think of image sensors, emitters, detectors, all are flexible based on flexible substrate. Transistors, interconnects, memory cells, passive components and other assorted devices will have challenging material demands for flexible electronics to become a reality. Nanoparticles, nanotubes, nanowires and engineered organic molecules are contributing towards it. Towards the realization of this high performance semiconductor dielectrics and conductors for flexible electronics application.

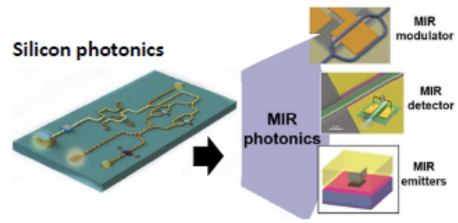
You can also think of microwave photonics that refers to generation, processing, distribution and measurement of microwave signals using photonic components and techniques. Some examples are shown here like frequency combs and four wave mixing. So what are the application or advantages here? They offer ultra wide bandwidth and flexible reconfiguration of optical processing. So integrated microwave photonics technologies can enable analog optical fiber links, analog optical signal processing of microwave signals, photonic generation of millimeter wave and terahertz signals.



Arbitrary waveform generation and photonics enabled phase arrays. So all these applications, all these new devices are possible. So the applications will include antenna, remote sensing, space communication and cellular 5G networks. You can also see silicon photonics being part of mid infrared photonics. So, there is a persuasive need to open up the mid infrared area of the spectrum, EM spectrum for spectroscopic sensing in the fields of, fields as diverse as bio and medical photonics.

Silicon photonics-Applications

- There is a persuasive need to open up the Mid-Infrared (MIR) part of the spectrum for spectroscopic sensing in fields as diverse as bio- and medical photonics, manufacturing control, environmental monitoring and security
- The MIR covers important atmospheric windows and strong fundamental absorptions of molecular species
- Since the mid-infrared (MIR) region has a significant role in various fields, rapid progress has been made on photonics and optoelectronics applications using 2D materials
- The progress in the photonics devices that exploit the unique properties of 2D materials for a range of MIR applications, focusing on ultrafast light generation, MIR light modulation, and photodetection



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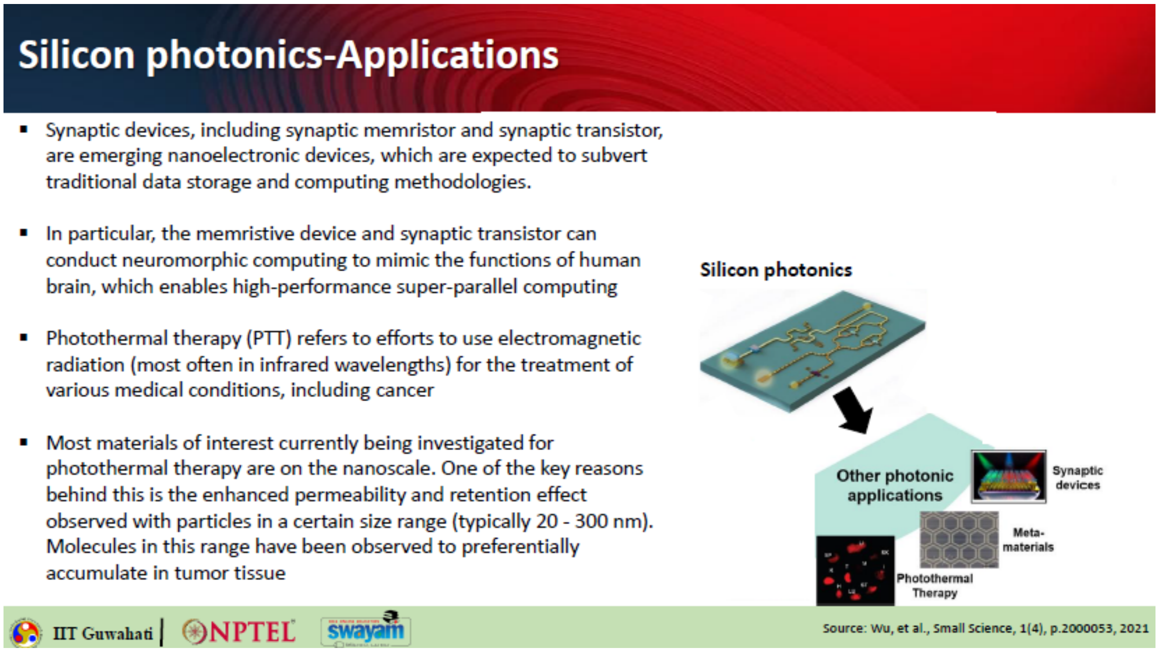
Source: Wu, et al., Small Science, 1(4), p.2000053, 2021

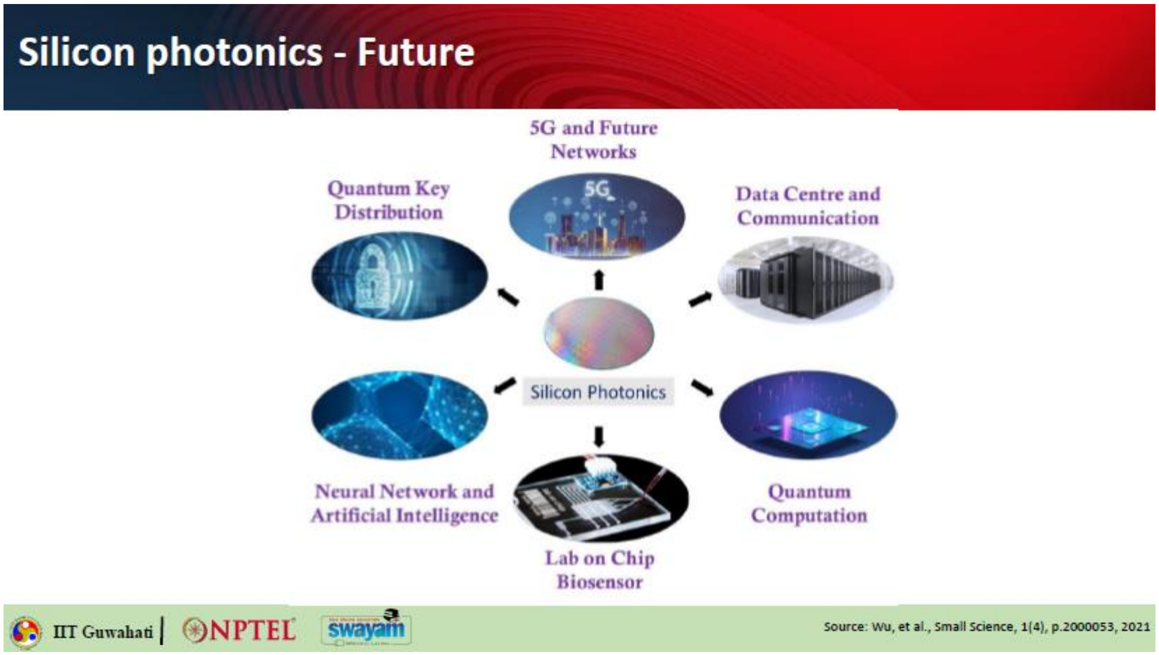
Manufacturing control, environmental monitoring and security. So for that what you require? You require modulators, detectors and emitters. So that is where also silicon photonics is going to help. So mid infrared typically covers important atmospheric window and strong fundamental absorptions of molecular species. So since MIR region has a significant role in various fields, rapid progress has been made on photonics and optoelectronics applications using 2D materials in this area. The progress in the photonic devices that exploit the unique properties of 2D materials for the range of mid infrared applications are mainly in ultrafast light generation, mid infrared light modulation and photodetection.

So these applications are supported. So other photonic applications you can think of in the synaptic devices. Synaptic devices like where this is the same technique like how nerve cells communicate with each other. So you can actually think of synaptic memristor, synaptic transistor. These are the emerging nanoelectronic devices which are expected to subvert the traditional data storage and computing methodology. So, with the need of more and more storage people are looking for this kind of technologies, nanoelectronic technologies.



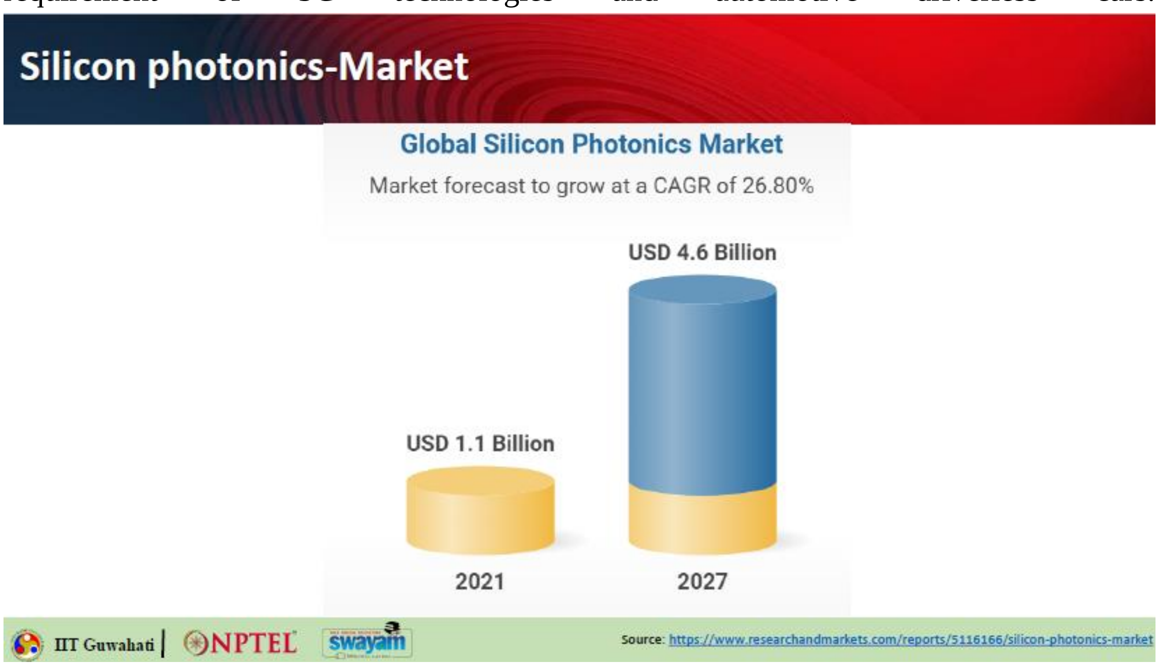
So in particular the memristor device and synaptic transistor can conduct neuromorphic computing. So just like the way our brain computes things, so these devices are also trying to conduct neuromorphic. So it's like kind of mimicking the brain to enable high performance super parallel computing. I understand all these new terms you are encountering during these lectures. But then we don't worry, we will not go into all details of all the terms. The overall idea here is to give an overview of this field and what are the new developments happening in and around nanophotonics.

And this is why I am showing all these things to you that actually give you a better overview and idea that this field is growing exponentially in almost every direction. You can also think of photothermal therapy which refers to the effort of using electromagnetic radiation for the treatment of various medical conditions including cancer. So these are the applications that you can think of. Silicon Photonics can be useful in 5G and future networks, data center and communication, quantum computation, lab on chip biosensor, neural network and artificial intelligence and also in quantum technologies.

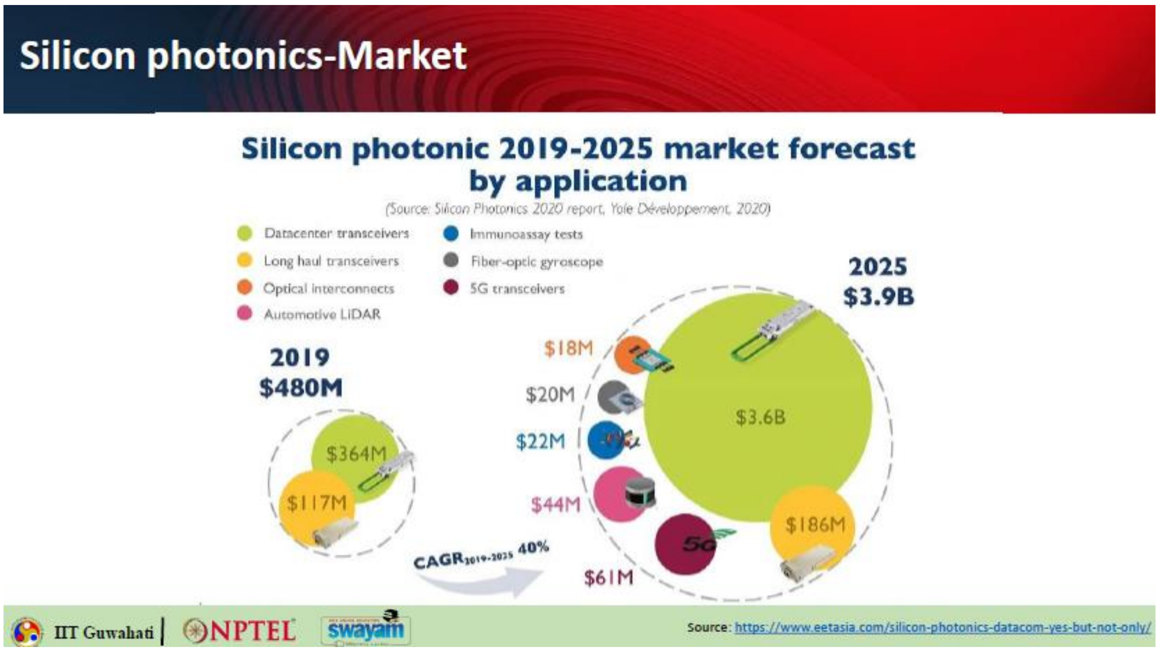


Now this particular slide shows you the growth of Silicon Photonics market which was 1.1 billion USD in 2021 and it is expected to grow up to 4.6 billion USD by 2027.

So you can see a compound annual growth rate or a mean growth rate of around 26.8%. So that's huge. So that's a good time to dive into this particular technology market. So here we can also show you the component wise. In 2019 the main market was focused on data center transceivers and long-haul transceivers. But now you can see with the requirement of 5G technologies and automotive driverless cars.

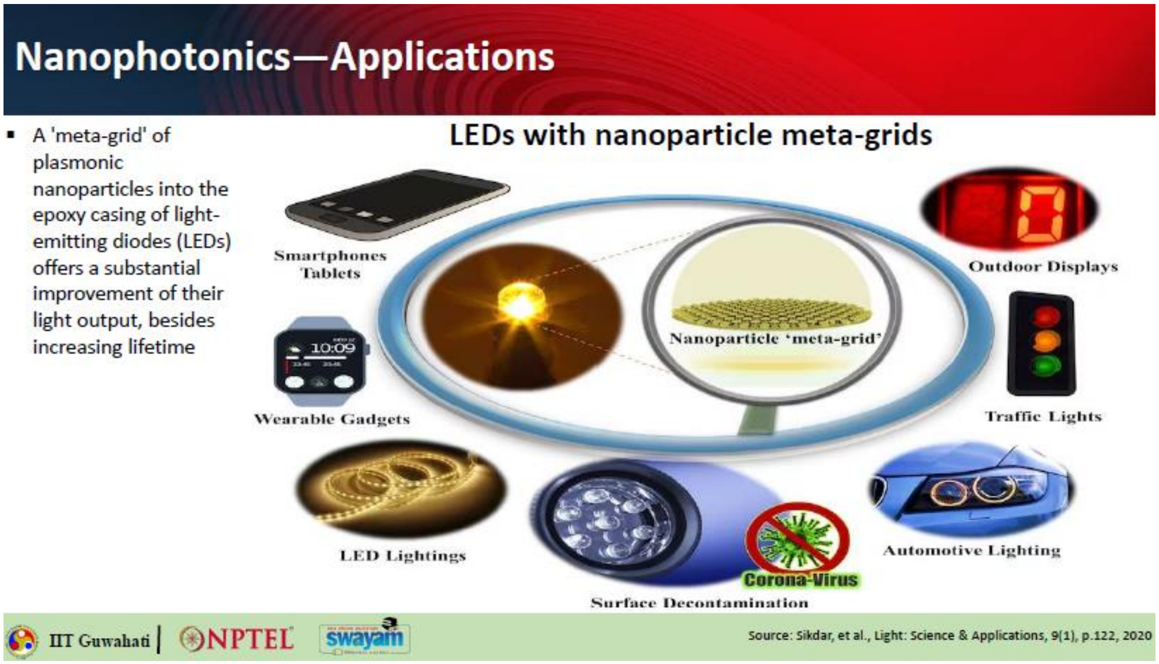


So new technologies are getting into consideration. So by 2025 you can see optical interconnects, LIDAR technology, then sensing, immunoassay tests, fiber optic gyroscope and 5G transceivers. They are also going to grow equally. After we understand the Silicon Photonics market and this is one of the obvious solutions in the current era people will look for. There are also possibilities of exploring other materials not only silicon. Because if we are able to show that there is enough potential in those materials there will be drive to set up those foundries and facilitate fabrication of those nanoscale devices in large scale.

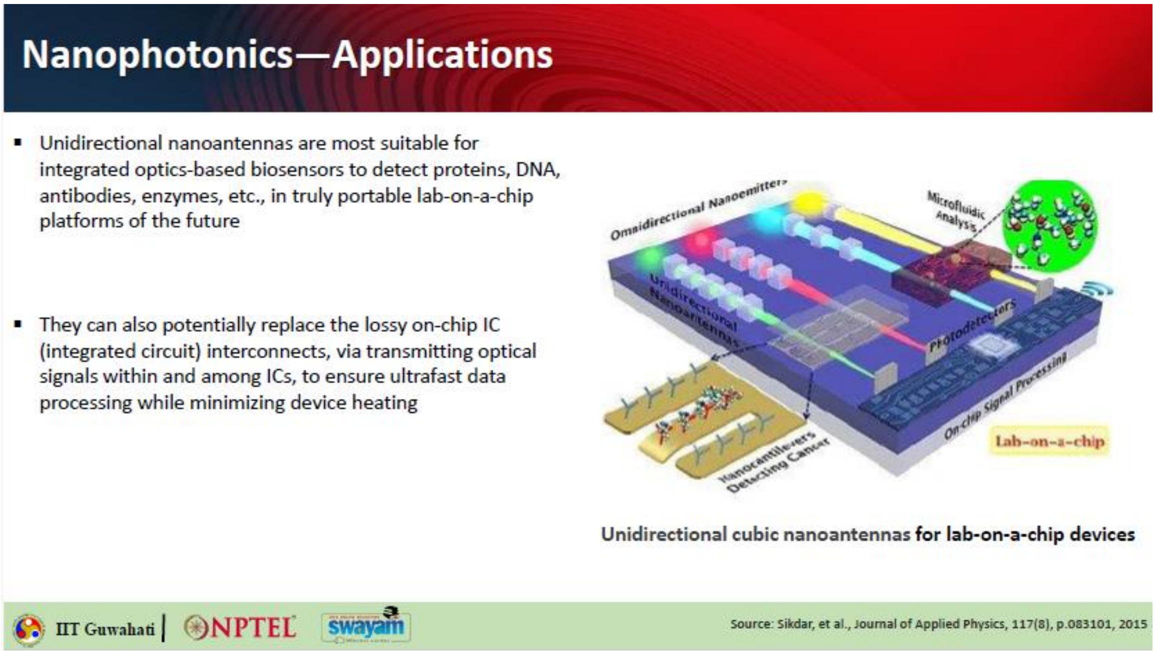


One such example I will be showing here today is use of nanoparticle metagrid. Metagrid is nothing but a two-dimensional array of nanoparticles. For enhancing the light extraction from LEDs. LEDs all of you know that these are one of the most widely used device in lighting and automotive industry these days. You can think of you know outdoor displays, traffic lights, automotive lighting, even surface decontamination using UV LEDs during COVID time.

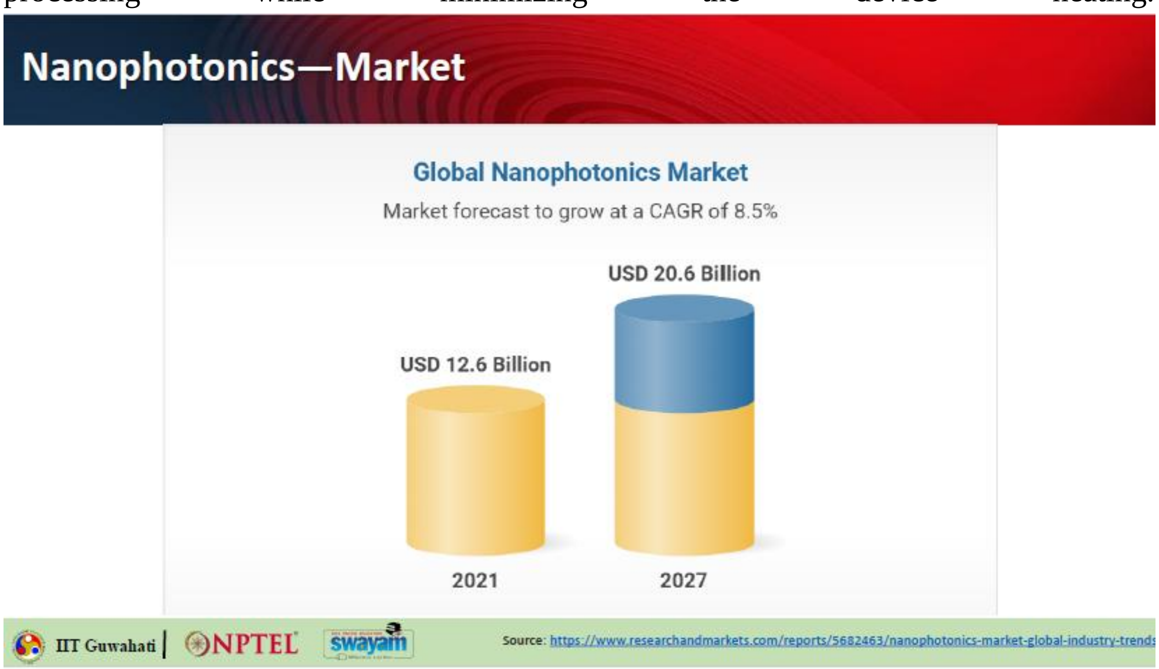
Wearable gadgets, smart phones, displays, everywhere OLEDs or LED light emitting diodes are used. So you can actually use nanoparticle metagrid to extract more light that is being generated in the semiconductor chip of an LED. And you can actually take out that light for final usage. Right now, a lot of light is basically lost and that cannot be extracted.



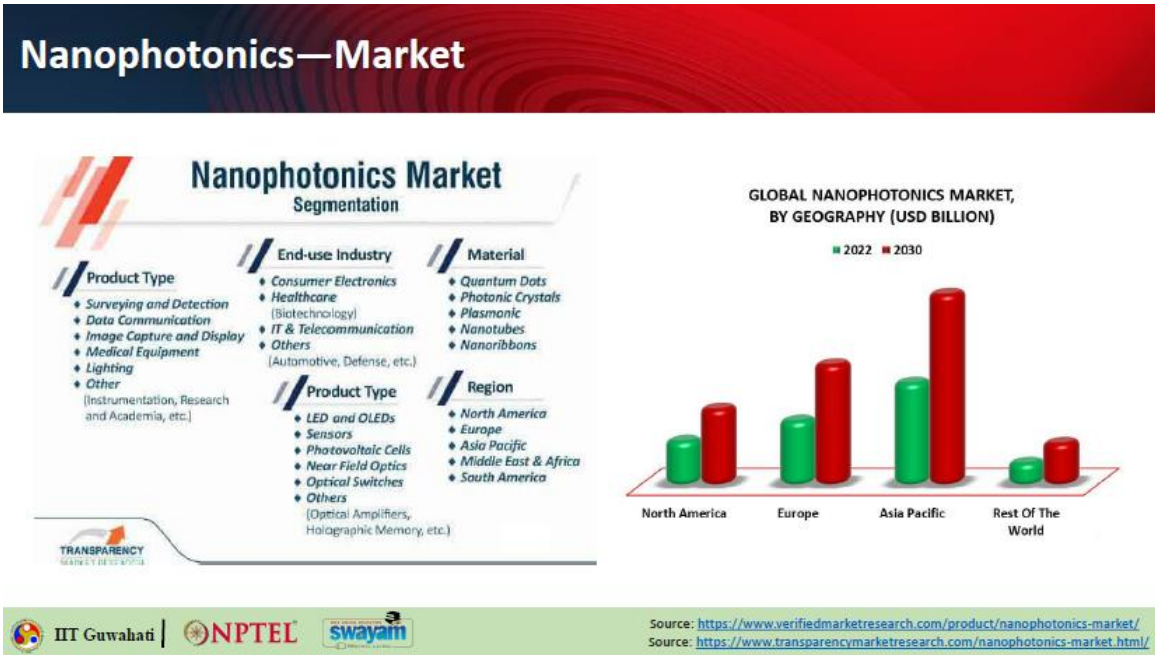
So nanoparticle metagrid can actually help you do that. So this lighting industry, display industry is huge. So if nanoparticle metagrid can make a substantial contribution towards bringing down the energy requirement of lighting industry. Also this can help LEDs to get longer lifetime and contribute towards climate change in a positive way like reducing the energy requirement. This can be a motivating factor for people to explore this kind of technologies. Other applications could be in sensing in future level chip devices by using dielectric nano antennas as you can see here. Since dielectric nano antennas are able to focus light and by making a different array or chains of these nano antennas you can basically focus light in different regions that can be used for sensing applications.



So, these nano antennas can also potentially replace the lossy on-chip interconnects via transmitting optical signals to different ICs. So instead of sending signals over metallic patch you can actually send optical signals by using these nano antennas for intra-chip communication or inter-chip communication. So that will also ensure ultrafast data processing while minimizing the device heating.

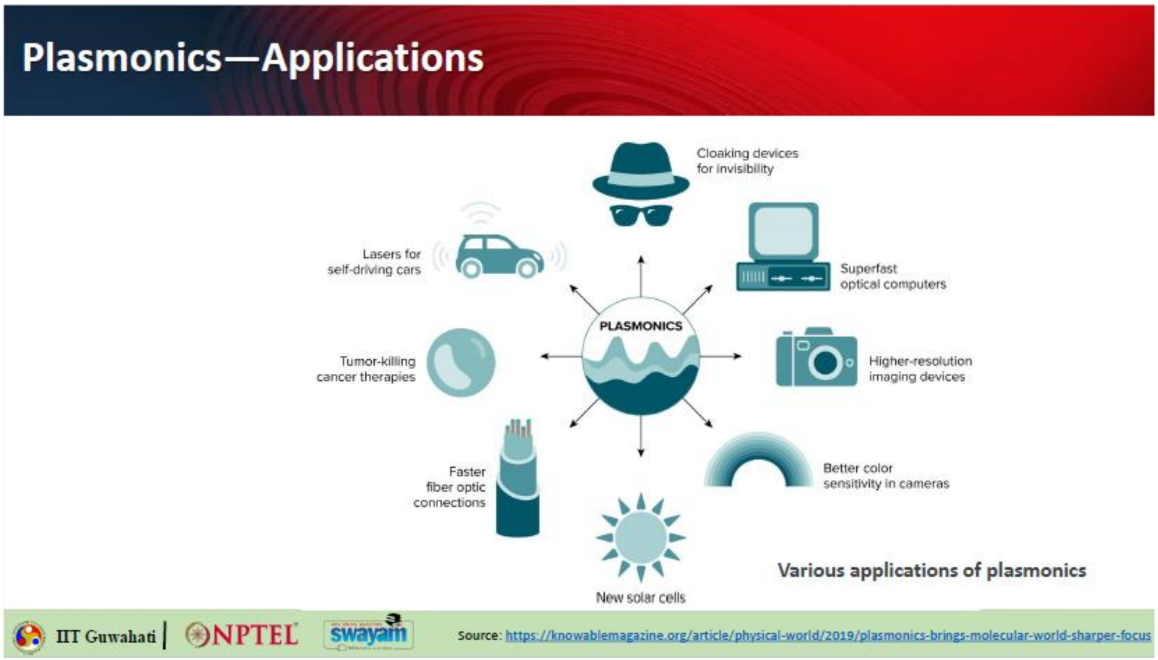


So you can also see the global nanophotonics market on its own. So right now 2021 you can see USD 12.6 billion is the market size which will grow up to 20.6 billion in 2027. So it has got a growth rate of 8.5%. So, it is not growing at the same rate of silicon photonics but yes, nanophotonics market is also growing that allows you to explore the new materials.

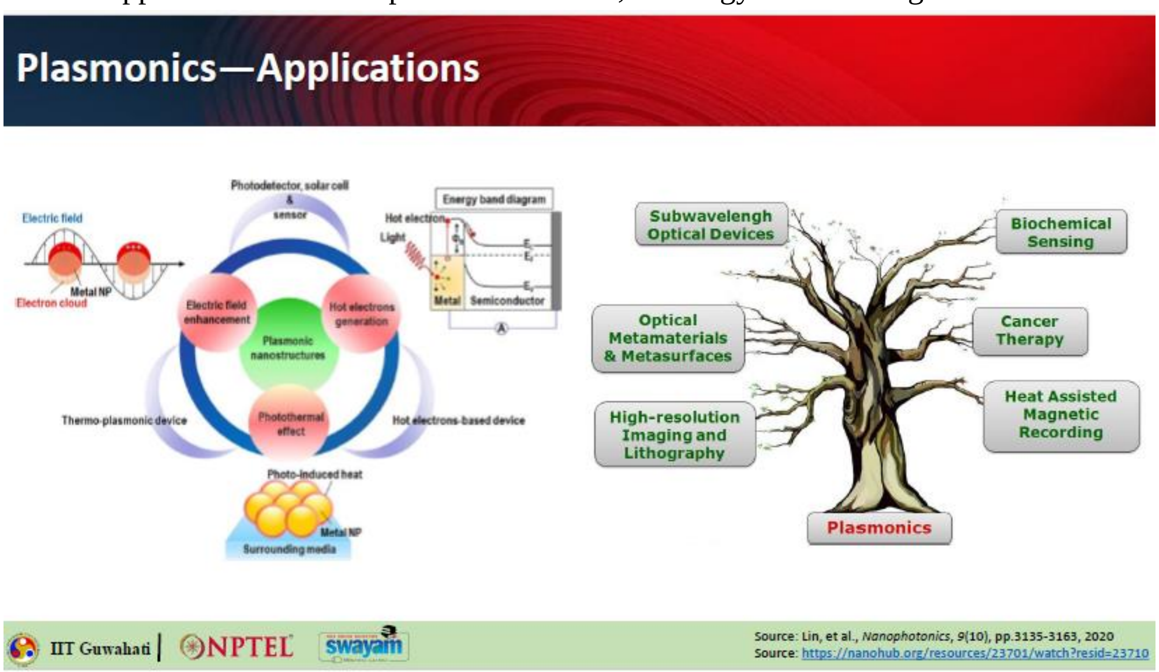


And if you see the different segments in the nanophotonics market, LED and OLED is one particular area. Other one is like sensor, photovoltaic cells, near field optics, optical switches, optical amplifier, holographic memory. These are the different products they are focusing on. So the end use industry would be the consumer electronics, healthcare, biotechnology, IT and communication, automotive, driverless cars, defense technologies and so on. So what are the different materials people are exploring? Quantum dots, photonic crystals, plasmonics, nanotubes, nanorebons.

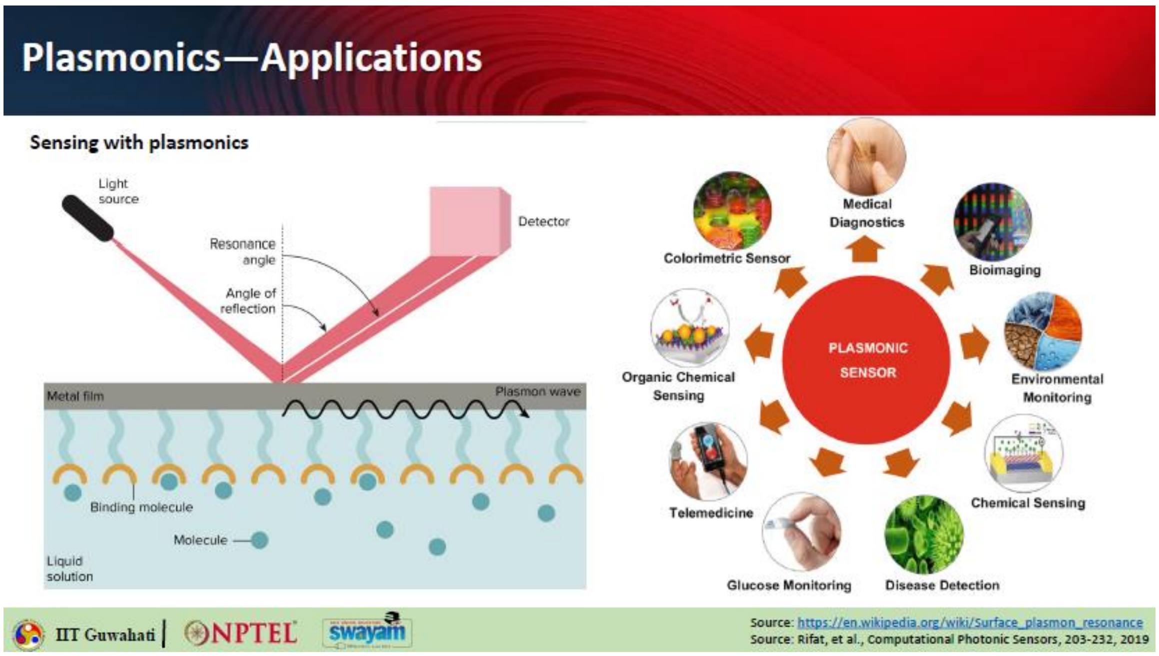
These are the materials getting explored. And right now as you can see that there is a huge competition between North America and Asia Pacific to be a leader in this particular nanophotonics market. So that is a very very positive sign for us. A part of nanophotonics is plasmonics as we all know and the different applications for plasmonics are shown here. One could be in cloaking devices for invisibility. You can look for ultrafast optical computers, high resolution imaging devices, better color sensitivity in cameras, new type of solar cell with higher efficiency, faster fiber optic communication.



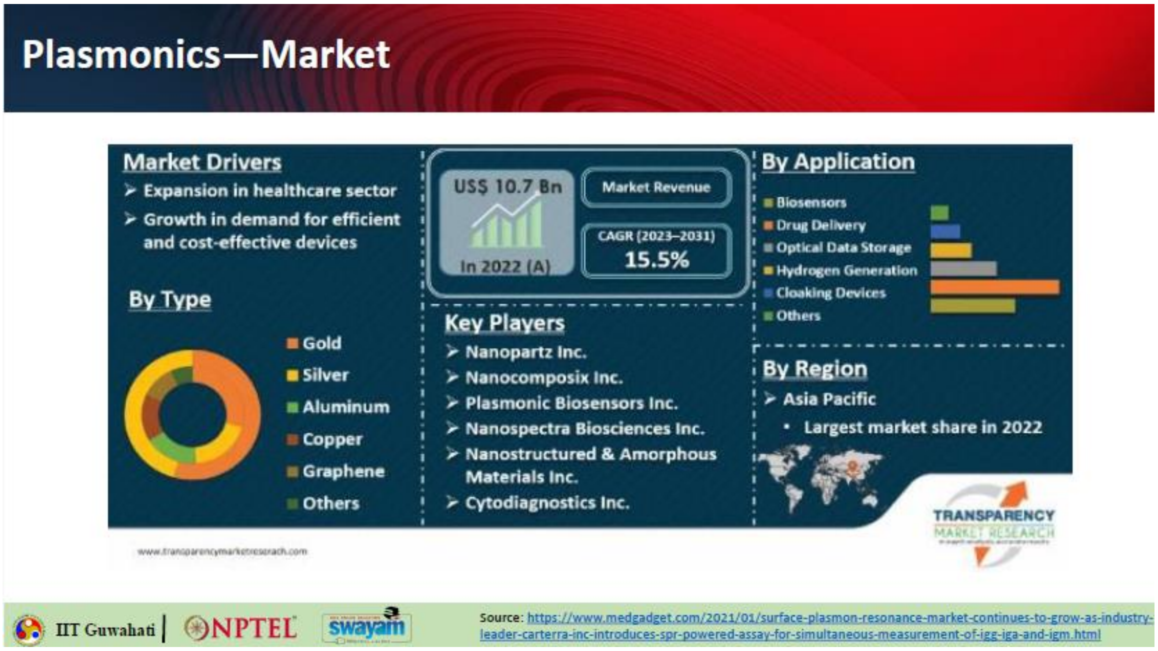
You can think of tumor cell killing cancer therapies and lasers for self-driving cars. So if you look at plasmonics, plasmonics basically deal with surface plasmonics and that actually brings in three main effects. Something like electric field enhancement, hot electron generation and photothermal effect. So this near field enhancement actually helps better photo detection, increase the efficiency of solar cell and sensors. There are many hot electron based devices that are possible and also thermo plasmonic devices from the photothermal effect that is associated with the absorption of photons by these plasmonic nanoparticles. You can use photothermal effect for maskless lithography and other applications like photo detection, energy harvesting and so on.



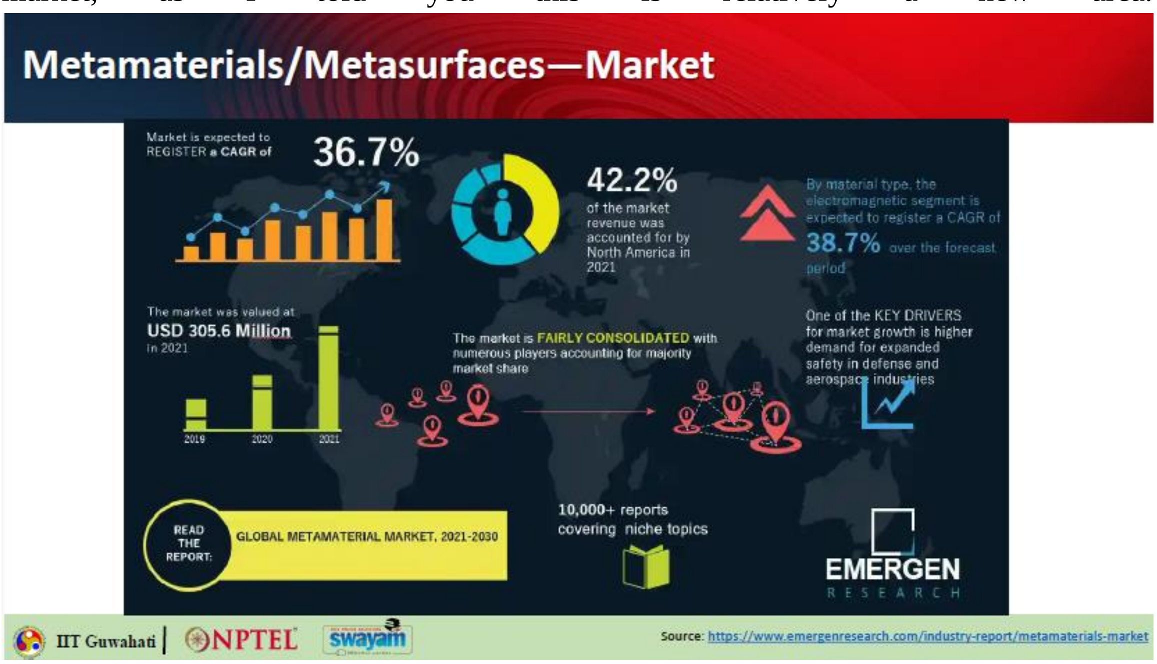
So if you look into all different branches of plasmonics, you can divide them in biochemical sensing, cancer therapy, heat assisted magnetic recording, high resolution imaging and lithography, optical metamaterials and metasurfaces, sub-wavelength optical devices etc. Sensing is also done with plasmonics, not only localized surface plasmonics, you can also use propagating surface plasmonics or SPP based sensors. So you can think of different kind of applications like glucose monitoring, disease detection, cholera metric sensor, medical diagnosis, all these things are possible. Because they are very sensitive to any biomolecules getting attached to the metal dielectric interface through which the plasmon is propagating. So, if there is any change in the refractive index, there will be change in the angle of reflection of light and that will get detected.



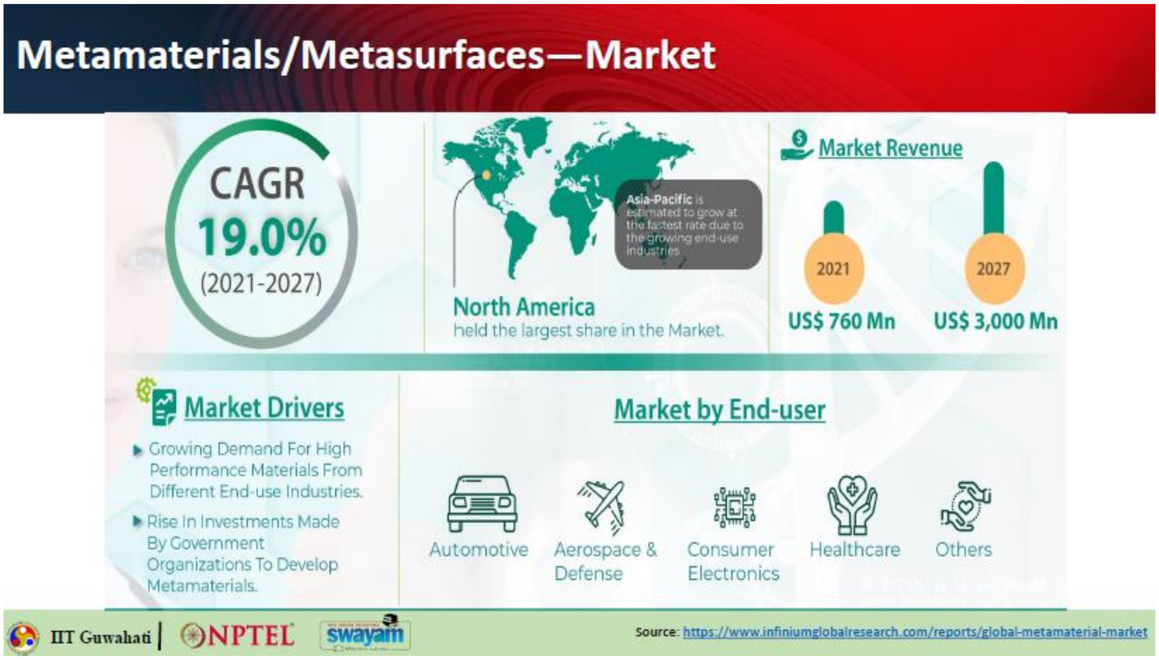
So this allows you to do a very trace amount of molecule detection using plasmonics. So if you look into the plasmonics market, the main drivers is basically the expansion in the healthcare sector and also there is a growth and demand in the cost effective and efficient devices. The materials involved for plasmonics are typically gold, silver, aluminum, copper, graphene etc.



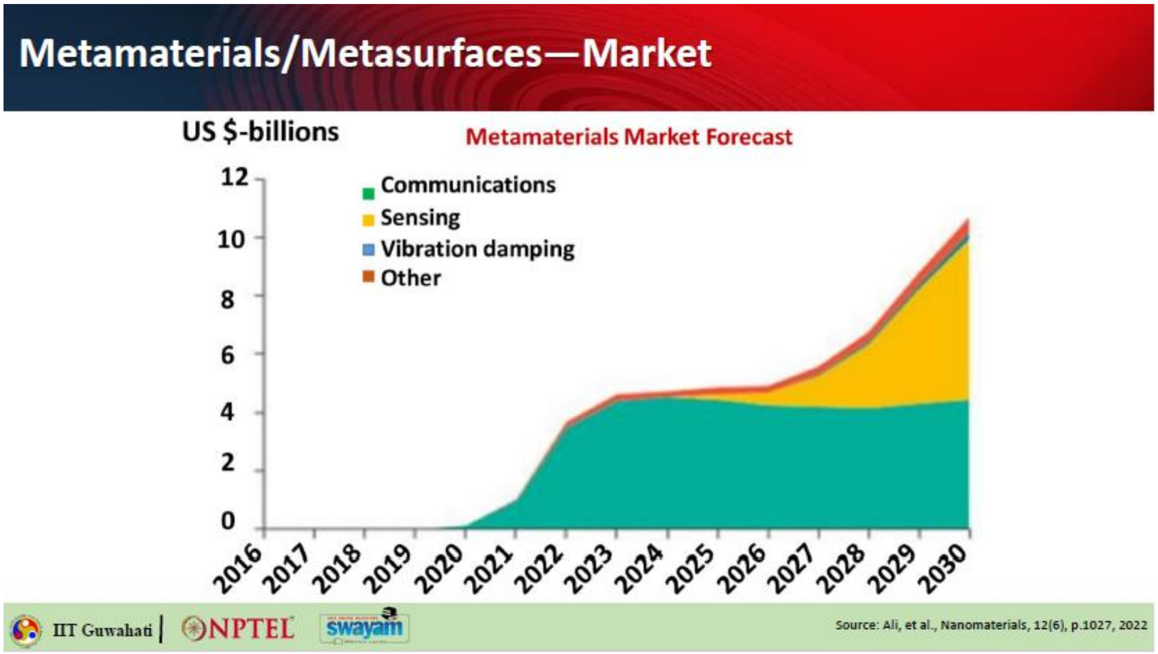
New materials are also being explored. In 2022 the market of all these things was around 10.7 billion and there is a 15.5% growth rate towards 2031. So that's a big growth rate. But as you see here, the biomedical application is one of the major focus areas of plasmonics. On the other hand, if you look into the metamaterials and metasurface market, as I told you this is relatively a new area.



So the market share right now in 2021 is 305 million USD. So that's comparatively low. But it has got a very high growth rate of 36.7%. And right now as you can see, almost 42% of the market is in North America. But then with the interest in communication applications in defense and aerospace, there is a huge drive towards metamaterials and metasurfaces. So, you can expect by 2027 a 19% growth rate in overall market of metamaterials and metasurfaces.



Asia Pacific is also expected to grow at a faster rate because of the growing end user industries. So the main market drivers for metamaterials and metasurface market is basically the growing demand for high performance materials for different end use industries. So by end use industries, I want to name automotive, aerospace and defense, consumer electronics, healthcare and others. And also the good thing is that there is a rise in investment made by government organizations to develop metamaterials. People have understood that there will be no limitation in or restriction in material properties if you are able to master the art of designing metamaterials. So, this particular graph actually shows you that by 2030, you can actually see that metamaterials for communication can actually go up to 10.



7-billion-dollar market by 2030. So by 2025, all the communication users are the leading ones, but slowly the sensing market will also catch up and that will kind of overpower or overdo the communication markets. So this is more or less the complete market scenario of this new upcoming field of nanophotonics, plasmonics, metamaterials and metasurface. I hope this motivates you to understand each of this topic to a great extent. And we will try to go into more technical details of each topic starting from the next lecture that will give you the fundamentals of all these new areas that we are discussing till now. Thank you. Any queries you can write to me at this particular email address. .