**Course Name- Nanophotonics, Plasmonics and Metamaterials**

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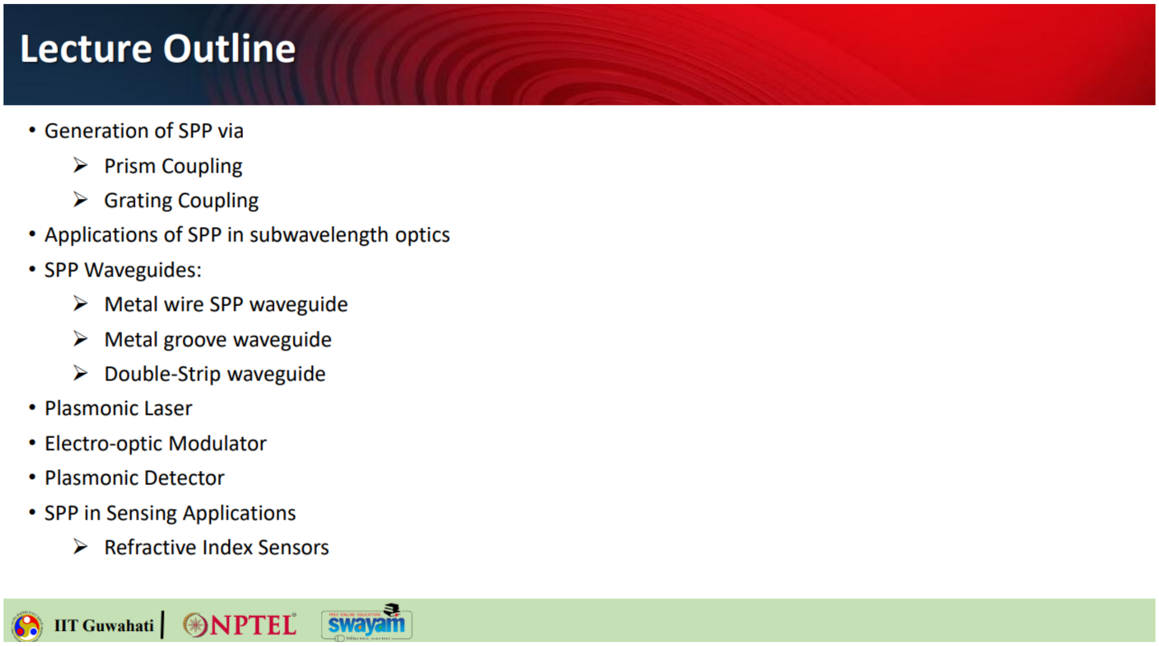
**Institute Name- Indian Institute of Technology Guwahati**

**Week-06**

**Lecture -18**

Hello students, welcome to lecture 14 of the online course on Nanophotonics, Plasmonics and Metamaterials. Today we will look into the applications of SPPs, that is surface plasmon polaritons. So here is the lecture outline. So, we will continue where we left in the last lecture. So, we will start with generation of SPPs. There are two methods, prism coupling and grating coupling.



## Lecture Outline

- Generation of SPP via
    - Prism Coupling
    - Grating Coupling
- Applications of SPP in subwavelength optics
- SPP Waveguides:
    - Metal wire SPP waveguide
    - Metal groove waveguide
    - Double-Strip waveguide
- Plasmonic Laser
- Electro-optic Modulator
- Plasmonic Detector
- SPP in Sensing Applications
    - Refractive Index Sensors

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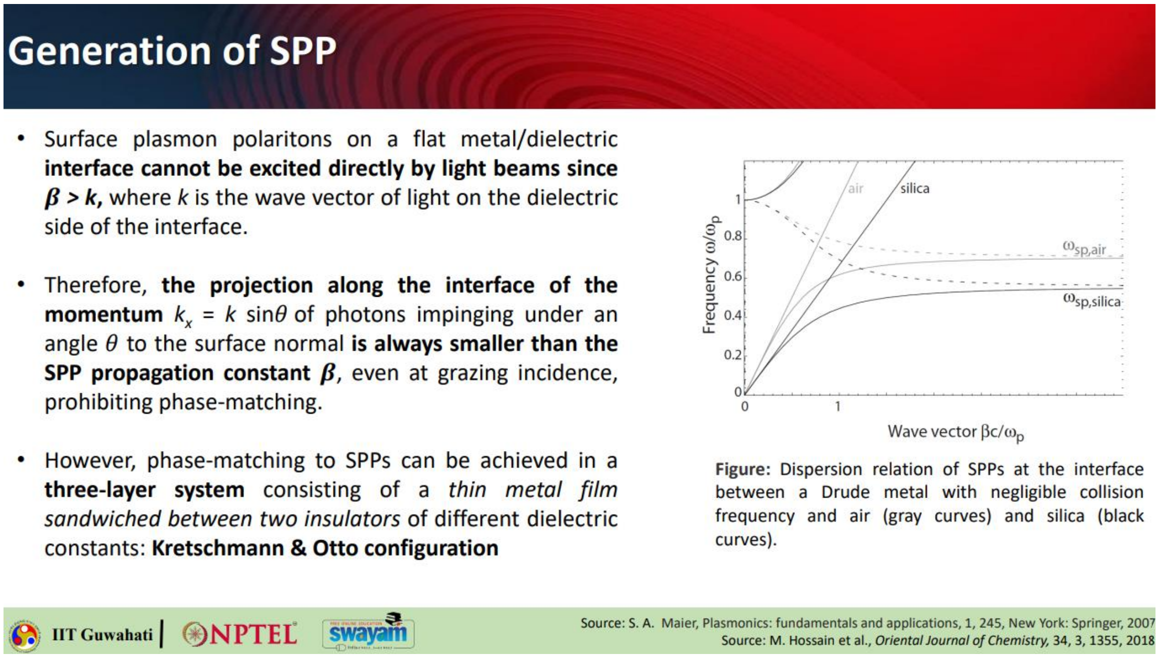
Then we will look for some applications of SPPs in sub wavelength optics. We will look into SPP waveguides like metal wire, SPP waveguide, metal groove waveguide and double strip waveguide. These are the different applications. We will also look into plasmonic laser, electro-optic modulator, plasmonic detector and application of SPP in sensing applications such as refractive index sensors.

So let us look into the generation of SPP. So, surface plasmon polaritons on a flat metal dielectric interface cannot be excited. So, if you remember from the last lecture that we have seen this particular dispersion relation right. And what was the reason that we described that this is the light line for air ok and this is the light line for silica. And here is the look at the solid curves not the dashed ones.

So if you look into this grey colour solid curve that is basically the dispersion relation of surface plasmon in metal air interface ok. And the black one shows the surface plasmon's dispersion relation in metal silica interface. So, this black line and this black line so this is for silica light line and this is the surface plasmon dispersion. So, when I say light line we basically talk about photons and here we are converting things from photons to plasmon's right. So there has to be a case where there is a momentum match.



## Generation of SPP

- Surface plasmon polaritons on a flat metal/dielectric **interface cannot be excited directly by light beams since $\beta > k$,** where $k$ is the wave vector of light on the dielectric side of the interface.
- Therefore, **the projection along the interface of the momentum** $k_x = k \sin\theta$ of photons impinging under an angle $\theta$ to the surface normal **is always smaller than the SPP propagation constant $\beta$**, even at grazing incidence, prohibiting phase-matching.
- However, phase-matching to SPPs can be achieved in a **three-layer system** consisting of a *thin metal film sandwiched between two insulators* of different dielectric constants: **Kretschmann & Otto configuration**

**Figure:** Dispersion relation of SPPs at the interface between a Drude metal with negligible collision frequency and air (gray curves) and silica (black curves).

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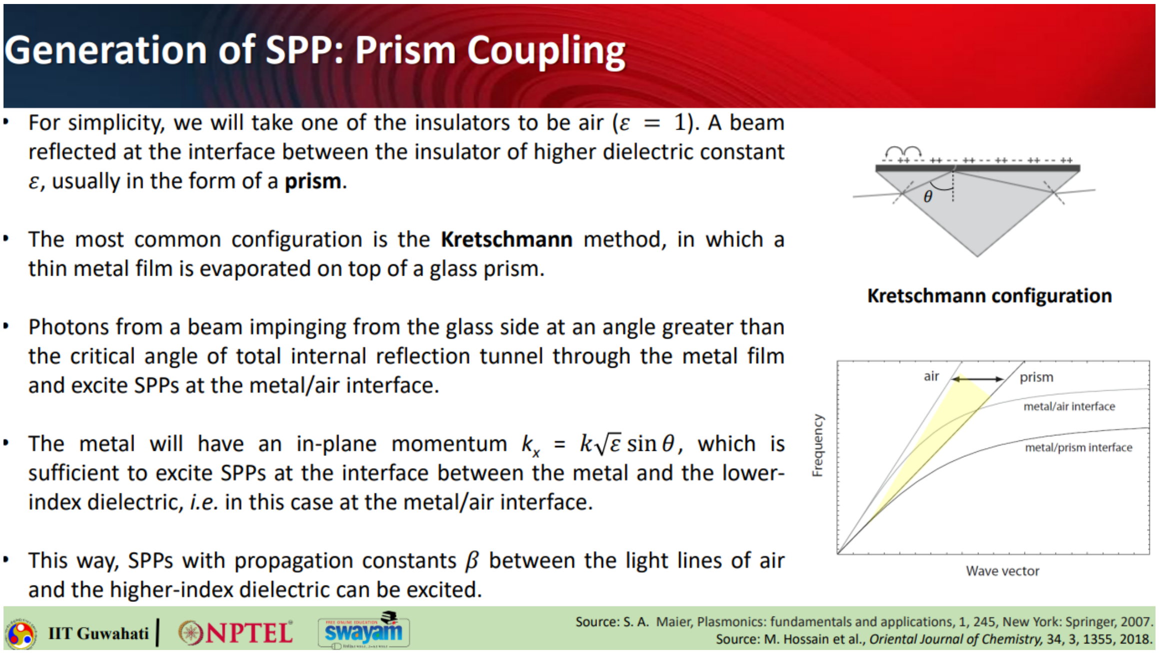
Source: S. A. Maier, Plasmonics: fundamentals and applications, 1, 245, New York: Springer, 2007
Source: M. Hossain et al., *Oriental Journal of Chemistry*, 34, 3, 1355, 2018

Now we have seen that in most of the cases beta that is the propagation constant of surface plasmon polaritons they are larger than the k that is the wave vector of light in dielectric medium. It can be air or silica in both case for air you see this is the photons and this is the dispersion relation of plasmon. So, it means the momentum at a particular frequency you can see the momentum of the plasmon is higher than that of photons ok. So, because of this momentum mismatch you are not able to transfer energy from photons to plasmon's. So, if you try to use some kind of you know light impinging on an interface like metal dielectric interface in that case the amount of momentum that you will be able to transfer is basically kx, x was the direction of propagation if you remember from the previous lecture then kx sin theta would be the component of the case the actual wave vector.

So kx is that component x component that can be calculated as k sin theta right. Now at any angle what can be the maximum value of sin theta that can be 1 right. At any case you will see that these are basically smaller than the SPP propagation constant beta even at the grazing incidence. So that is the case so in every possible scenario if you simply take a metal dielectric interface and shine light on it even at very tilted angle of incidence you will not be able to excite surface plasmon's. It means phase matching has to be somehow achieved and for that you have to use a 3 layer system that means you have to insert a metal film sandwiched between 2 insulators of different dielectric constant.

So that is the only possible way to excite surface plasmon's as we will be seeing here. Not only that is one of the most popular one we will see another method also possible. So, in this particular case there are 2 configurations possible one is called Kretschmann and another is Otto configuration. So, this method is also known as prism coupling. So, for simplicity we will take one of the insulators to be air.



## Generation of SPP: Prism Coupling

- For simplicity, we will take one of the insulators to be air ($\varepsilon = 1$). A beam reflected at the interface between the insulator of higher dielectric constant $\varepsilon$, usually in the form of a **prism**.
- The most common configuration is the **Kretschmann** method, in which a thin metal film is evaporated on top of a glass prism.
- Photons from a beam impinging from the glass side at an angle greater than the critical angle of total internal reflection tunnel through the metal film and excite SPPs at the metal/air interface.
- The metal will have an in-plane momentum $k_x = k\sqrt{\varepsilon}\sin\theta$, which is sufficient to excite SPPs at the interface between the metal and the lower-index dielectric, *i.e.* in this case at the metal/air interface.
- This way, SPPs with propagation constants $\beta$ between the light lines of air and the higher-index dielectric can be excited.

**Kretschmann configuration**

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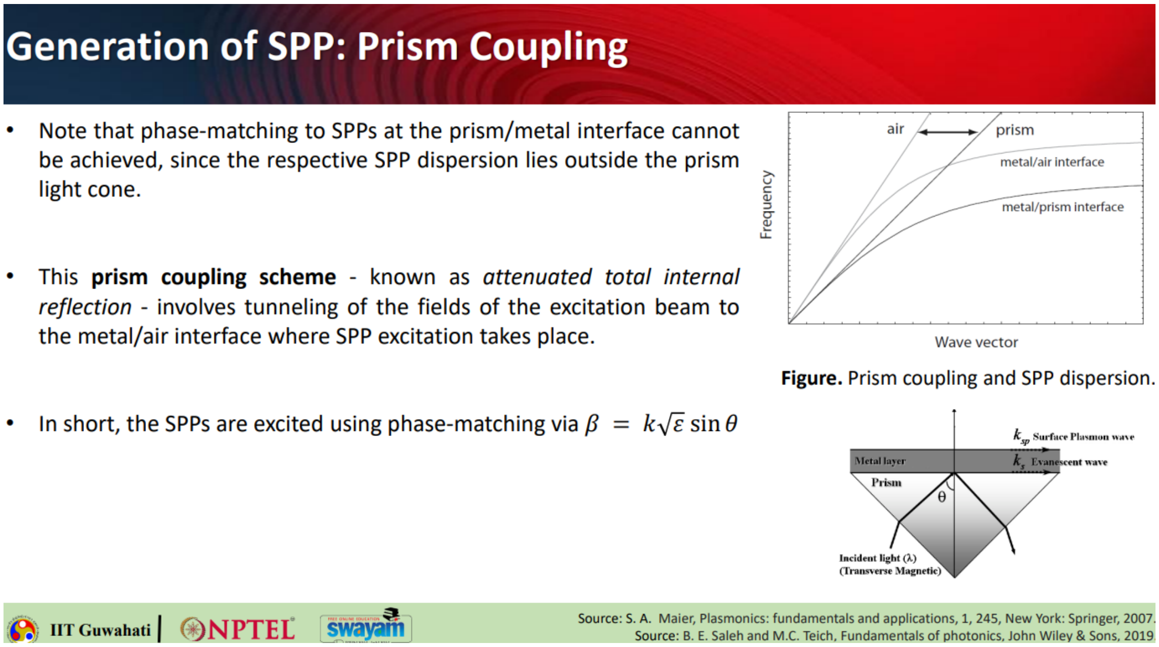
Source: S. A. Maier, Plasmonics: fundamentals and applications, 1, 245, New York: Springer, 2007.
Source: M. Hossain et al., *Oriental Journal of Chemistry,* 34, 3, 1355, 2018.

So, a beam will be reflected at an interface between the insulator of higher dielectric constant which is in the form of a prism. So, this dark slab here is basically metal on the top it is air and below the metal you have a glass prism. So, it is a higher dielectric constant. That is why it is called prism coupling because you are using this prism to excite surface plasmon's. Now this particular configuration is called Kretschmann configuration and this is the most common configuration and in this case you actually have a thin metal film evaporated on top of a glass prism.



## Generation of SPP: Prism Coupling

- Note that phase-matching to SPPs at the prism/metal interface cannot be achieved, since the respective SPP dispersion lies outside the prism light cone.
- This **prism coupling scheme** - known as *attenuated total internal reflection* - involves tunneling of the fields of the excitation beam to the metal/air interface where SPP excitation takes place.
- In short, the SPPs are excited using phase-matching via $\beta = k\sqrt{\varepsilon}\sin\theta$

**Figure.** Prism coupling and SPP dispersion.

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Source: S. A. Maier, Plasmonics: fundamentals and applications, 1, 245, New York: Springer, 2007.
Source: B. E. Saleh and M.C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.

So there is nothing between the glass prism and the metallic film ok. The film is actually deposited on top of the glass prism. Now if you look into the photons these are photons that are entering into the glass prism ok. So, when the angle of incidence is greater than the critical angle of this interface you will see that there is total internal reflection ok. And if you remember total internal reflection ok, there is some kind of evanescent wave also generated.

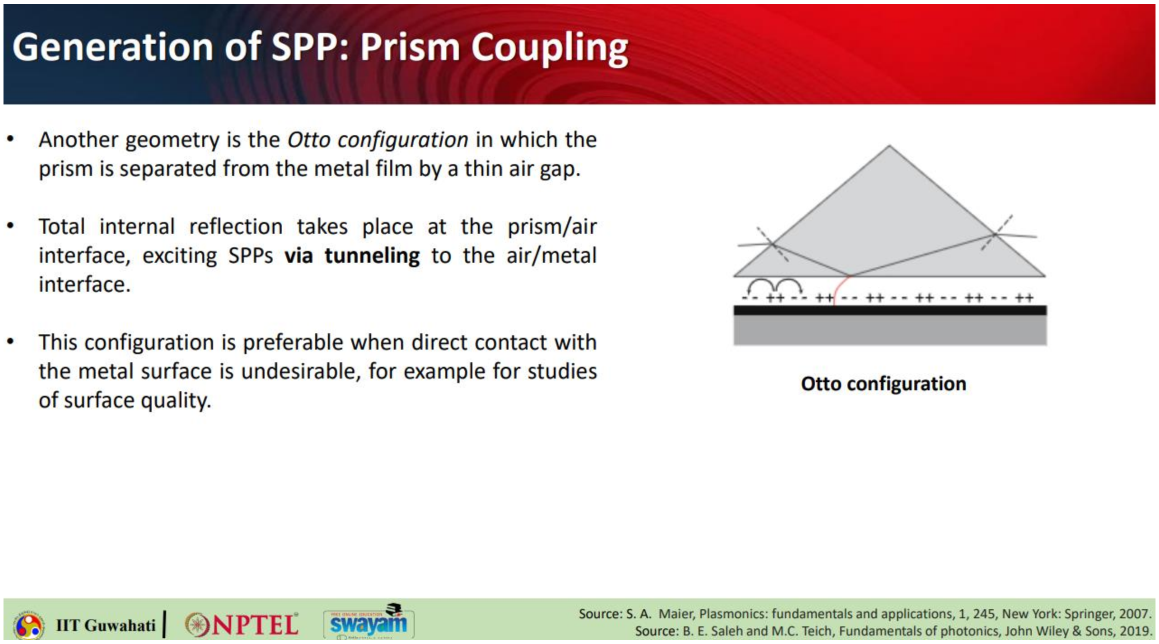
Now when there is total internal reflection happening ok, some part can actually tunnel through this thin metallic film and it can excite surface plasmon polar atoms on the metal-air interface ok. So, it will be able to do that on the top side ok, that is on the air side. Now the metal will have an in-plane momentum which is given as kx. You can write it as k square root of epsilon sin theta ok. And this will be sufficient to excite SPPs only at the interface between the metal and the lower dielectric constant that is air in this particular case.

You can see from this dispersion relation, so you can actually think of dispersion relation as the main look up thing in plasmonic case. So, this is the light line in air and this is in prism ok. So, prism is made of glass, so glass the refractive index it can be 1.55 roughly. So, what is happening? So, you see that if you take this particular if you are using this particular line for the incoming wave ok or incoming photons then you will see that there is a possibility that you can actually have plasmons which are having lower energy or you can say lower momentum ok not energy we will say in terms of momentum here.

Lower momentum or k vector as corresponding to this work for a given frequency ok.

So, if by changing the angle of incidence you will be able to match the kx component with the beta of the surface plasmon and this is how you will be able to match them. So which one is possible? Metal-air interface is possible. What about metal-prism interface? Because there is another metal dielectric interface now this one. There in no way you are able to match the momentum of the photon to this one.

So exciting plasmons on metal-prism interface is not possible ok as simple as that fine. Now as I mentioned so this way only SPPs with propagation constant beta that falls within the light lines of this air and prism this one can only be excited fine. So also note that the phase matching to SPPs this one cannot be achieved. So, you will be not in a position to excite surface plasmons on metal-prism interface fine. So, this particular prism coupling scheme is also known as attenuated total internal reflection and it involves tunneling of fields ok of the excitation beam to the metal-air interface where SPP excitation is taking place.



## Generation of SPP: Prism Coupling

- Another geometry is the *Otto configuration* in which the prism is separated from the metal film by a thin air gap.
- Total internal reflection takes place at the prism/air interface, exciting SPPs **via tunneling** to the air/metal interface.
- This configuration is preferable when direct contact with the metal surface is undesirable, for example for studies of surface quality.

**Otto configuration**

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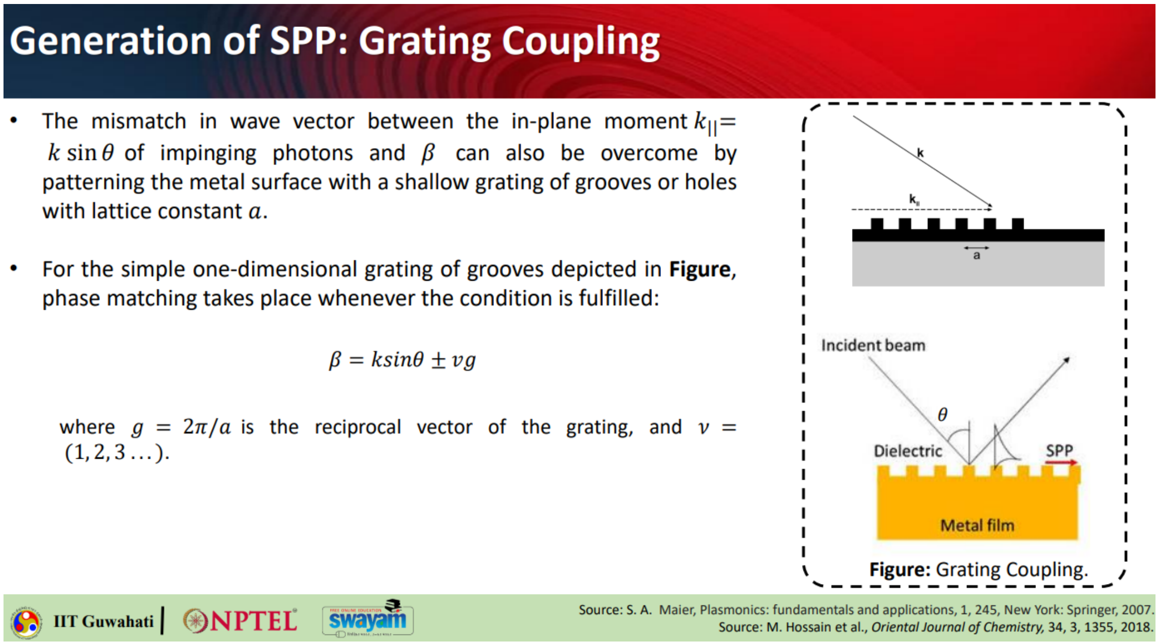
Source: S. A. Maier, Plasmonics: fundamentals and applications, 1, 245, New York: Springer, 2007.
Source: B. E. Saleh and M.C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.

So if you look into this particular diagram so here is a prism you have a thin metallic layer and then you have air on the other side. So, this is the incident beam typically as we have seen that only TM excitation is allowed so you can think of a TM beam to be incident that is total internal reflection. Some energy will be there but along the metal-prism interface it will be evanescent wave. So that will die off very quickly ok that will not be able to propagate. But then some part can actually tunnel through and then excite surface plasmon on the metal-air interface and that can propagate along the surface of the metal for certain distance ok.

So in short the SPPs are excited they can be excited using phase matching condition where the condition will be beta equals k square root of epsilon sin theta. So, this is the condition with which you are able to generate SPP. Now there is another configuration in prism coupling which is called Otto configuration ok. Now in this case there is a gap between the prism and the metal film. So, there is basically a thin air gap ok.

Now in such case what happens again total internal reflection takes place and then the SPP excitation on the metal-air interface takes place via tunneling to the air metal interface. So, from here to here the excitation has to tunnel and then you can excite the surface plasmon on the metal-air interface. Now in which case this will be useful this kind of configuration is useful when no direct contact with the metal surface is allowed Something like say you want to study the surface quality of a particular metal in that case you will not be able to touch the metal surface. So, in this case auto configuration will be useful because the prism is placed at a particular gap from the surface fine. So, with that we can think of another method of SPP generation besides prism coupling.

So that is grating coupling. Now the problem remains same here because that there is a phase mismatch between the incoming photons and the surface plasmos which are supposed to generate. So how do you match the momentum of the phase ok. So here you can see that the in-plane moment which is k parallel is nothing but k sin theta right. If you take this as your theta so this component is nothing but k sin theta right and beta is the propagation constant of the surface plasmon.



## Generation of SPP: Grating Coupling

- The mismatch in wave vector between the in-plane moment $k_{||} = k\sin\theta$ of impinging photons and $\beta$ can also be overcome by patterning the metal surface with a shallow grating of grooves or holes with lattice constant $a$.
- For the simple one-dimensional grating of grooves depicted in **Figure**, phase matching takes place whenever the condition is fulfilled:

$$\beta = k sin\theta \pm \nu g$$

where $g = 2\pi/a$ is the reciprocal vector of the grating, and $\nu = (1, 2, 3 \ldots)$.

**Figure:** Grating Coupling.

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Source: S. A. Maier, Plasmonics: fundamentals and applications, 1, 245, New York: Springer, 2007.
Source: M. Hossain et al., *Oriental Journal of Chemistry,* 34, 3, 1355, 2018.

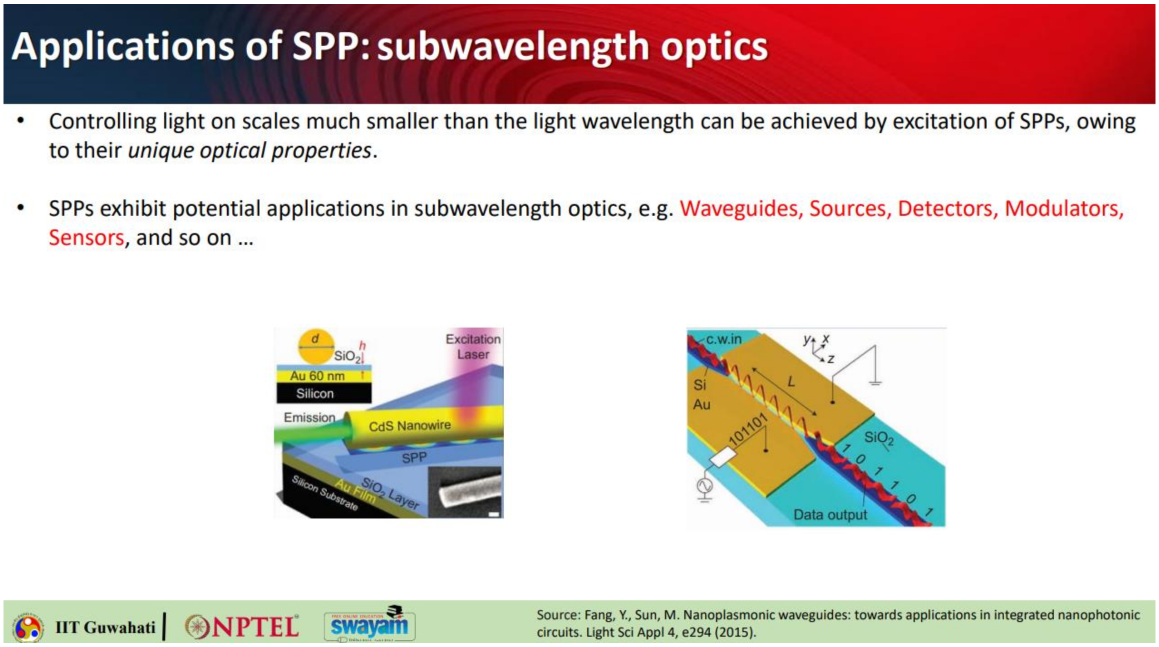
So what you can do you can actually generate a grating of groups or small holes with lattice spacing of A. So, if you do that what happens you can actually get because of this one dimensional grating of groups phase matching can take place by this particular condition being satisfied. That beta will be k sin theta plus minus nu g. What is nu that is integer 1, 2, 3 and g is basically the reciprocal vector of this particular grating which is 2 pi by A. So, with those possible cases ok so you will be able to generate or you will be able to transfer energy between photons and plasmas ok.

If you try to think intuitively what will happen because of this grating when light falls on it ok it will be it will allow you to excite all different modes not only the fundamental mode, first order mode, second order mode, third order mode and all higher order modes. So, there is a possibility that with one of these modes the beta the propagation constant of plasmons will have a phase match and that is how you will be able to excite. And here also it is shown with a notation as you can see more field is towards the dielectric side and there is less field penetration into the metal side. So, this is an example of grating coupling for generation of SPPs. Now let us look into some applications of SPP.

First sub wavelength optics ok. Now controlling light on scales much smaller than the light wavelength can be achieved by excitation of SPPs. Now that is the reason why people have moved to plasmonics that it allows us to break the fundamental diffraction limit of light and allow you to get much smaller wavelength at a particular given frequency. So, if you go back and see the dispersion relation the everything lies here in the dispersion relation we will go to this one the first one I have shown. So here you see that the dispersion relation in air or any other dielectric photonics it is linear. So, omega equals c k or you can say omega equals c by n k where n is the refractive index of the dielectric medium.

But in case of SPPs you have seen that omega is basically a non-linear function like this. So that allows you to actually have for one particular frequency you can see you can have very large wave factor that is also possible. So, say you choose this particular frequency for optics this will be the wave factor or the k value. But for the plasmon this is the wave vector value. So you can see that the wave factor is very very large and k and lambda they are inversely proportional.

So when you have you are able to get a large wave factor it means you are able to get very small lambda and that allows you to confine and guide light in a wavelength scale which is much much smaller than the photons wavelength ok or you can say you can actually go to x-ray scale while you are still in the optical frequency. So that is the beauty of plasmonics ok. I am going back to the slide where we left yeah. So SPPs they have potential application in sub wavelength optics. Obviously you can use them for wave guiding they can be used as source detector modulator sensor and so on.



## Applications of SPP: subwavelength optics

- Controlling light on scales much smaller than the light wavelength can be achieved by excitation of SPPs, owing to their *unique optical properties*.
- SPPs exhibit potential applications in subwavelength optics, e.g. Waveguides, Sources, Detectors, Modulators, Sensors, and so on …

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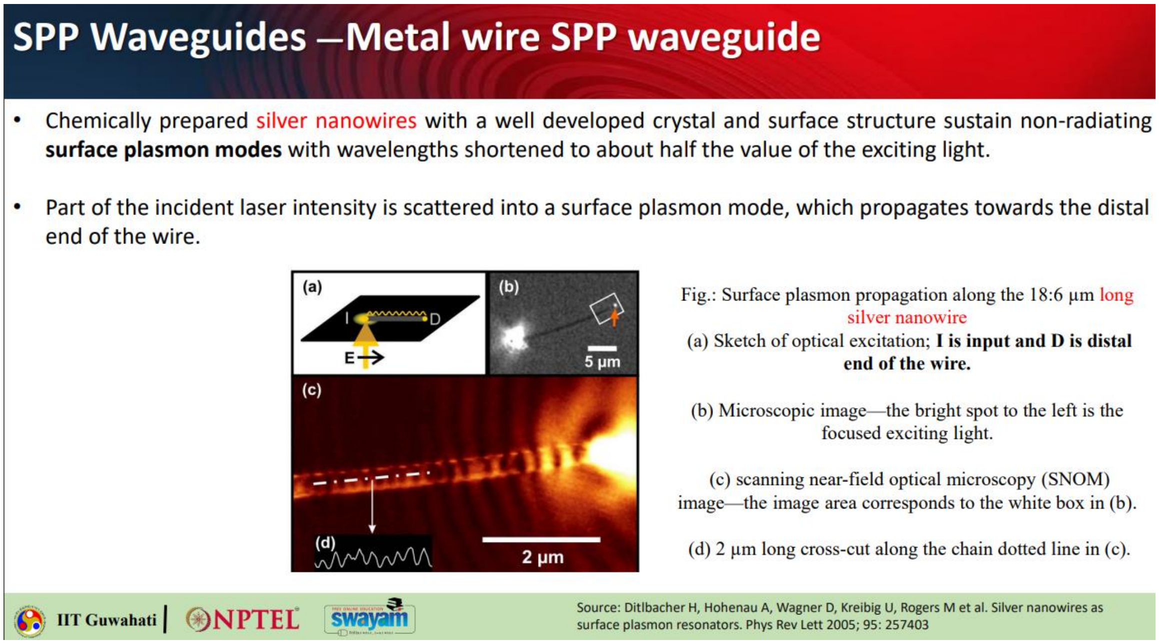
Source: Fang, Y., Sun, M. Nanoplasmonic waveguides: towards applications in integrated nanophotonic circuits. Light Sci Appl 4, e294 (2015).

We will also see each of these application here just some schematics we will see them in details in the next slides. So first one is a metal wire SPP waveguide ok. So chemically prepared silver nanowires with a well-developed crystal and surface structure can sustain non radiating surface plasmon modes with wavelengths shortened to about half the value of the exciting light ok. So that way you are able to guide light in a scale which is much smaller than the wavelength.

So that is actually sub wavelength. Now part of the incident laser is basically scattered into surface plasmon mode which propagates towards the distal end of the wire. So, you can actually see in this figure that I is the input D is the distal end. So, you are first shining a laser excitation to the input end and then you allow light to get converted into plasmon and propagate to the distal end. So, it is something like this you are having the excitation here and it travels through these particular nanowire and towards the end it again gets back to light and which is also visible ok. So, these are this actually shows the scanning near field optical microscope image and shows how exactly the plasmon is propagating in this nanowire.



## SPP Waveguides –Metal wire SPP waveguide

- Chemically prepared silver nanowires with a well developed crystal and surface structure sustain non-radiating **surface plasmon modes** with wavelengths shortened to about half the value of the exciting light.
- Part of the incident laser intensity is scattered into a surface plasmon mode, which propagates towards the distal end of the wire.

Fig.: Surface plasmon propagation along the 18:6 µm long silver nanowire
(a) Sketch of optical excitation; **I is input and D is distal end of the wire.**

(b) Microscopic image—the bright spot to the left is the focused exciting light.

(c) scanning near-field optical microscopy (SNOM) image—the image area corresponds to the white box in (b).

(d) 2 µm long cross-cut along the chain dotted line in (c).

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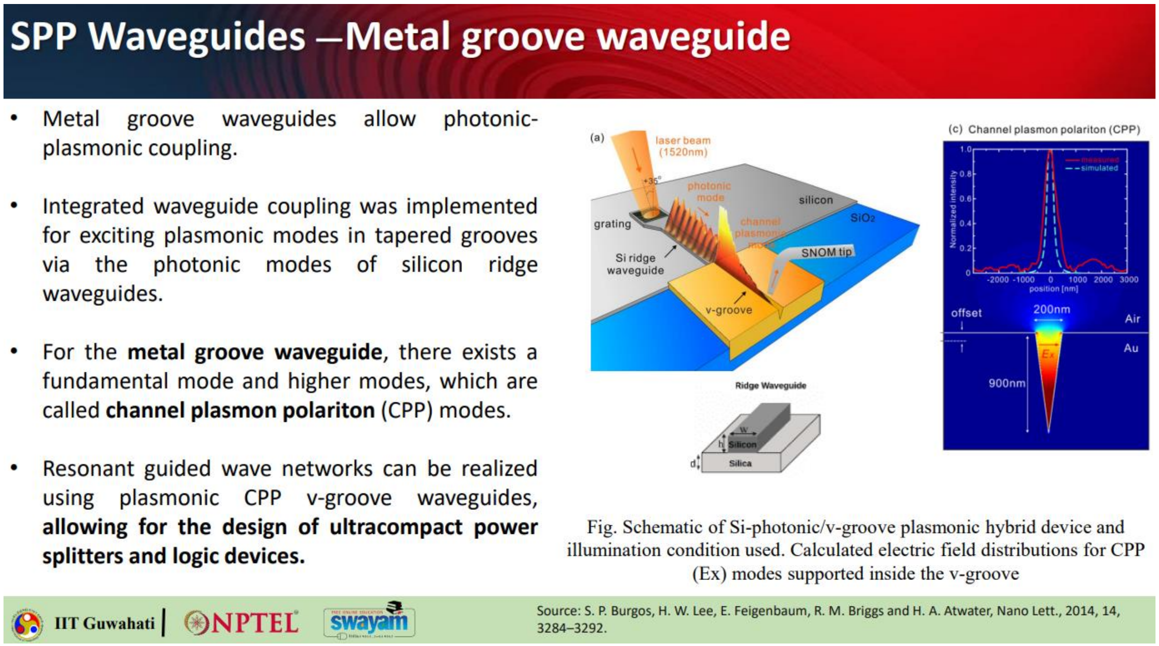
Source: Ditlbacher H, Hohenau A, Wagner D, Kreibig U, Rogers M et al. Silver nanowires as surface plasmon resonators. Phys Rev Lett 2005; 95: 257403

So there are other types of waveguides also possible. So, some important ones are like metal groove waveguides. So, what is that this groove waveguides they actually allow photonic and plasmonic coupling. So integrated waveguide coupling was implemented for excitation of plasmonic modes in tapered grooves.

So tapered grooves are like this V shaped ok. So, they actually allow plasmonic mode excitation via the photonic modes of silicon ridge waveguide. So, silicon ridge waveguide you understand that they are actually much larger in dimension but then you can actually make metallic groove waveguides and convert photonic modes to plasmonic modes and then allow them to propagate or carry that information in a sub wavelength regime. So, for the metal groove waveguide there exists a fundamental mode and higher order mode which are also called channel plasmon polaritons or CPP. Some example you can see here that there is a grating on top of that laser light. So, this is the optical signal that you are taking.

You have a grating coupler that converts your light into surface plasmon right. And once it is getting coupled you can actually yeah so you can actually get plasmons over here but then you actually put a silicon waveguide from this one to the V groove. So, this is how the V groove will look like ok. So, there will be very strong confinement of electric field towards the narrow end of the groove and this allows you to have photonic and plasmonic coupling right. So first you have this laser light falling on the grating then you have the silicon ridge waveguide that sorry silicon ridge waveguide that that actually carries the photonic modes ok.



## SPP Waveguides –Metal groove waveguide

- Metal groove waveguides allow photonic-plasmonic coupling.
- Integrated waveguide coupling was implemented for exciting plasmonic modes in tapered grooves via the photonic modes of silicon ridge waveguides.
- For the **metal groove waveguide**, there exists a fundamental mode and higher modes, which are called **channel plasmon polariton** (CPP) modes.
- Resonant guided wave networks can be realized using plasmonic CPP v-groove waveguides, **allowing for the design of ultracompact power splitters and logic devices.**

Fig. Schematic of Si-photonic/v-groove plasmonic hybrid device and illumination condition used. Calculated electric field distributions for CPP (Ex) modes supported inside the v-groove

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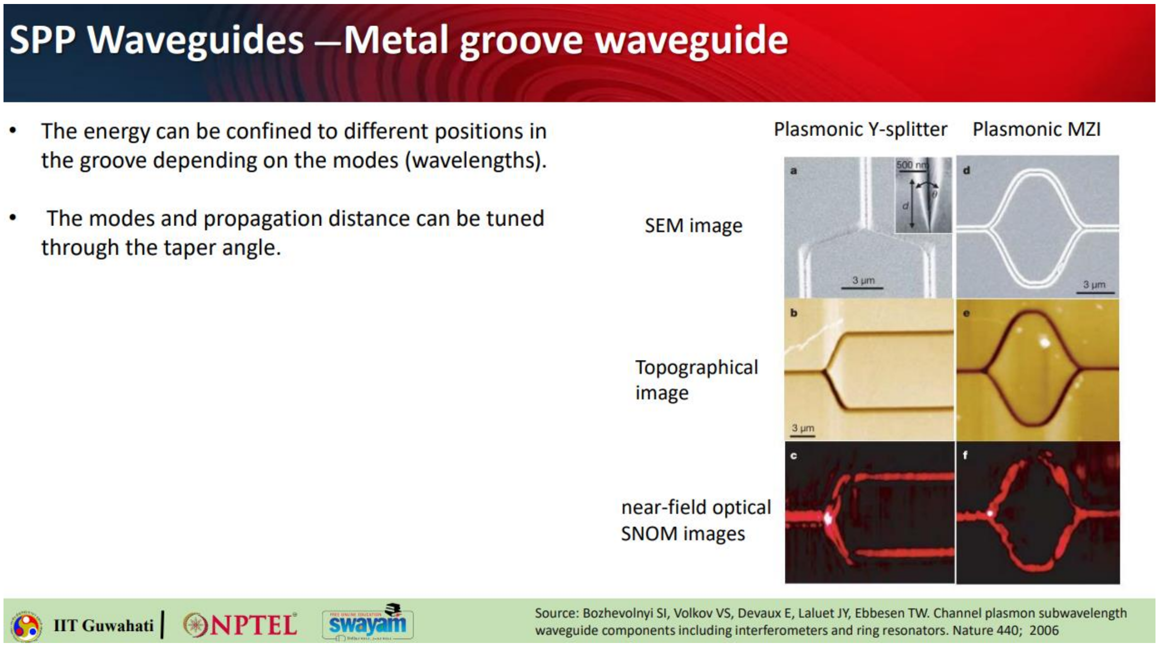
Source: S. P. Burgos, H. W. Lee, E. Feigenbaum, R. M. Briggs and H. A. Atwater, Nano Lett., 2014, 14, 3284–3292.

So to couple to this photonic mode also you need grating ok. So, this is not converting directly to plasmons but then from here you are actually exciting channel plasmon modes. So, this is the coupling that happens between the photonic and plasmonic modes. So, the resonant guided wave network can be realized using plasmonic CPP V groove waveguides. They also allow design of ultra-compact power splitters and logic devices.

Because you can actually do this kind of splitting and manipulation in a much smaller scale as compared to the photonic integrated circuits ok. So here is an example of plasmonic Y splitter. So, this is the SEM image of the Y splitter you can see these are basically the grooves. So, the depth is D the angle of the groove is theta. This is the topographical image that is from the top how it looks like.

So this is the Y splitter and this is the near field optical SNOM image that shows you how the splitting is taking place. The similar thing is also shown for plasmonic mags under interferometer you might have heard of mags under interferometer as modulators in optics. So, you can actually have plasmonic mags under interferometer as well using this kind of groove structure ok. So, the energy can be confined to different positions in the groove depending on the modes and wavelengths. So, depending on the modes and the wavelength you may actually confine energy at different different position of the groove.



## SPP Waveguides –Metal groove waveguide

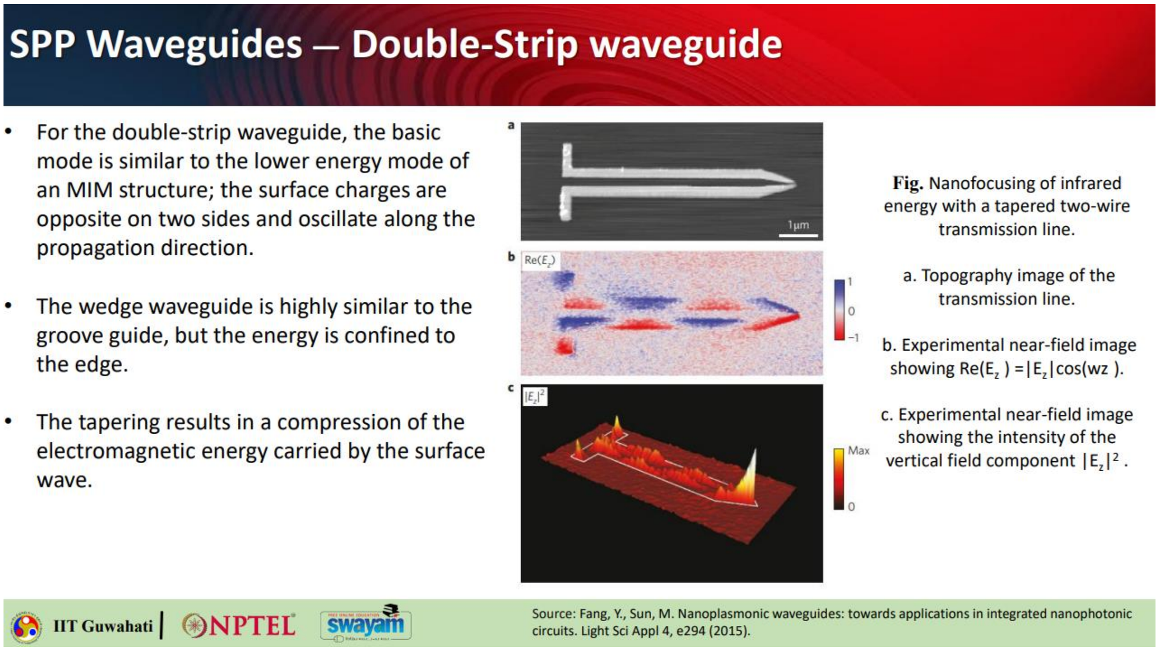
- The energy can be confined to different positions in the groove depending on the modes (wavelengths).
- The modes and propagation distance can be tuned through the taper angle.

Source: Bozhevolnyi SI, Volkov VS, Devaux E, Laluet JY, Ebbesen TW. Channel plasmon subwavelength waveguide components including interferometers and ring resonators. Nature 440; 2006

So that is why the groove structure is also very interesting. The modes and propagation distance can be tuned through the taper angle. So that actually allows you this taper angle is the theta. So that will also decide what will be the mode that is being supported or propagating and what is the propagation distance ok. So now let us look into another one which is called double strip waveguide.

So for the double strip waveguide the basic mode is similar to the low energy mode of an MIM structure that is metal insulator metal kind of structure. And the surface charges are opposite on two sides. So, this is how the structure looks like it is a double strip waveguide there is an edge or tapering towards the end. And if you see the surface charges they are basically opposite when they are oscillating along the propagation direction. So, this wedge waveguide is highly similar to the groove structure and you see the energy is confined in the edge.

Here also you can see this is the near field image of the intensity pattern ok and you see towards this particular groove you have the highest energy concentration. So, the tapering results in the compression of the electromagnetic energy that is being carried by the surface wave. So, this way you are able to localize energy at a particular point or you can take out energy from particular points. So that way you are able to guide manipulate the optical field or optical energy in sub wavelength dimension.



## SPP Waveguides – Double-Strip waveguide

- For the double-strip waveguide, the basic mode is similar to the lower energy mode of an MIM structure; the surface charges are opposite on two sides and oscillate along the propagation direction.
- The wedge waveguide is highly similar to the groove guide, but the energy is confined to the edge.
- The tapering results in a compression of the electromagnetic energy carried by the surface wave.

**Fig.** Nanofocusing of infrared energy with a tapered two-wire transmission line.

a. Topography image of the transmission line.

b. Experimental near-field image showing Re($E_z$) = $|E_z|$cos(wz ).

c. Experimental near-field image showing the intensity of the vertical field component $|E_z|^2$ .

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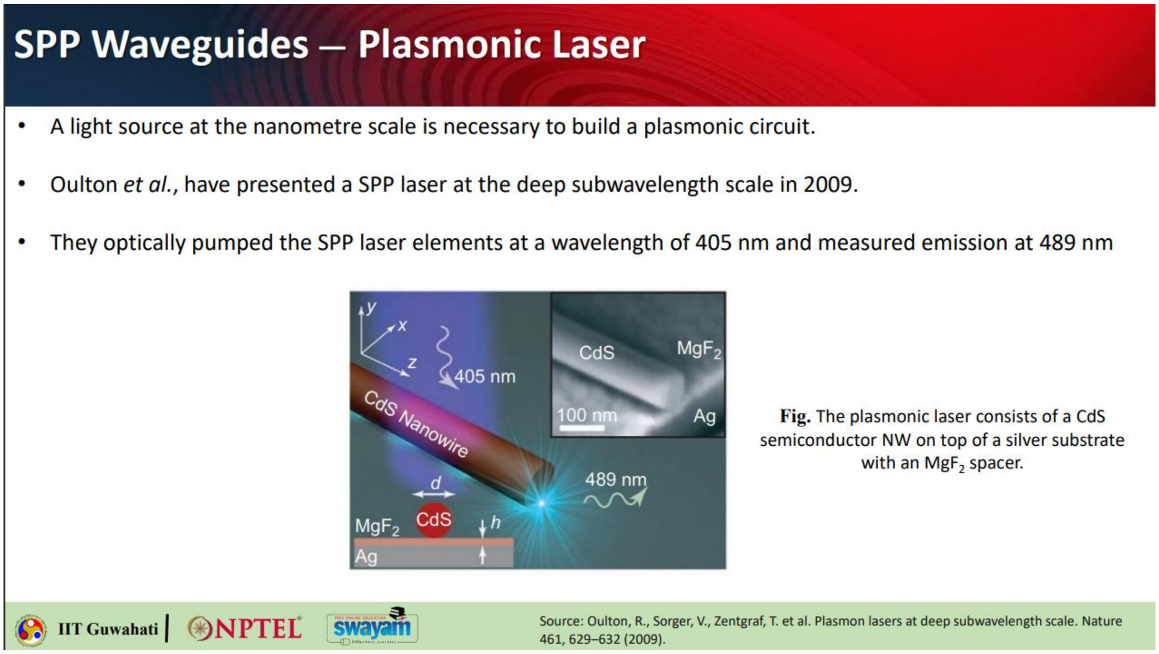
Source: Fang, Y., Sun, M. Nanoplasmonic waveguides: towards applications in integrated nanophotonic circuits. Light Sci Appl 4, e294 (2015).

Another application is of plasmonic laser. So, a light source at the nanometer scale is very important to build a plasmonic circuit. So, if you have all the components of your circuit in nanometer scale you also want your lights light source to be in that nanometer scale right. So out and all they have presented a SPP laser at the deep sub wavelength scale in 2009 and they optically pumped the SPP laser elements at a wavelength of 405 nanometer and they found emission at 489 nanometer. So typically, this was the structure of the plasmonic laser. So, it consists of a cadmium sulfide semiconductor nanowire on top of a silver substrate with a magnesium fluoride spacer.



## SPP Waveguides – Plasmonic Laser

- A light source at the nanometre scale is necessary to build a plasmonic circuit.
- Oulton *et al.*, have presented a SPP laser at the deep subwavelength scale in 2009.
- They optically pumped the SPP laser elements at a wavelength of 405 nm and measured emission at 489 nm

**Fig.** The plasmonic laser consists of a CdS semiconductor NW on top of a silver substrate with an MgF$_2$ spacer.

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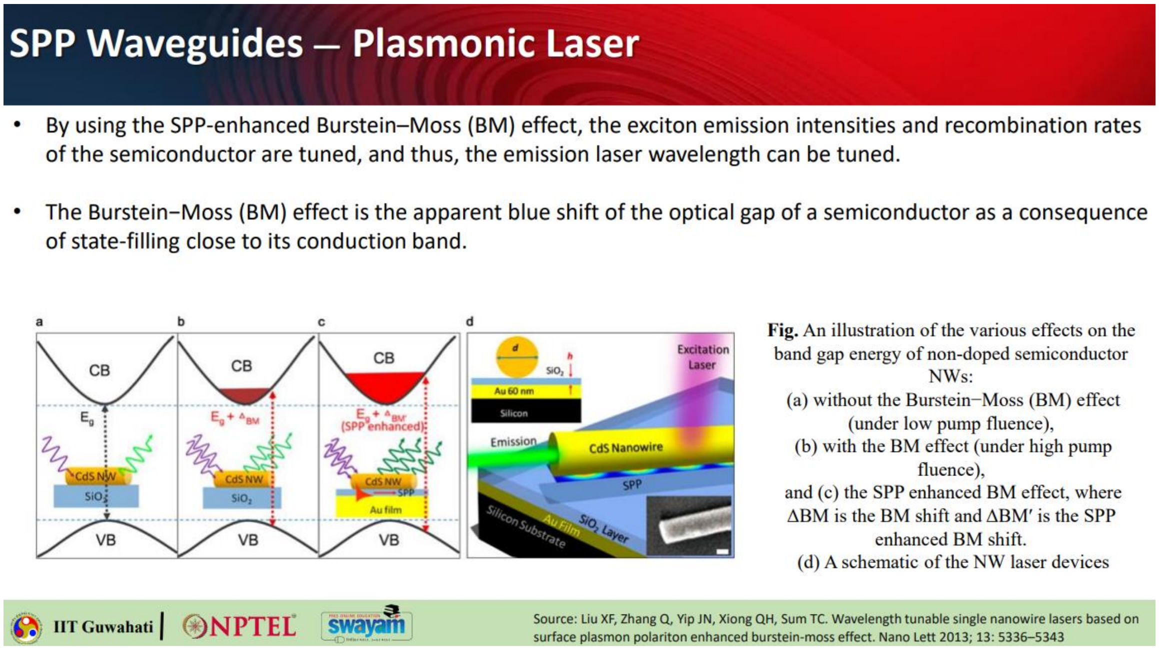
Source: Oulton, R., Sorger, V., Zentgraf, T. et al. Plasmon lasers at deep subwavelength scale. Nature 461, 629–632 (2009).

So there is a thin layer on top of the silver one and this is the structure. So, they used 405 nanometer as pump and they were able to excite emission coming out at 489 nanometer. We will not go into too much of details of how this lasing action happens here but this is very similar to the photonic lasers ok the pump thing pumping and all the concepts are also very similar ok. So here is an explanation of how it works. So, when you look for plasmonic laser there is another effect that helps you to tune the laser wavelength that is called surface plasmon polar return SPP enhanced Bernstein-Moss effect BM effect.



## SPP Waveguides – Plasmonic Laser

- By using the SPP-enhanced Burstein–Moss (BM) effect, the exciton emission intensities and recombination rates of the semiconductor are tuned, and thus, the emission laser wavelength can be tuned.
- The Burstein–Moss (BM) effect is the apparent blue shift of the optical gap of a semiconductor as a consequence of state-filling close to its conduction band.

**Fig.** An illustration of the various effects on the band gap energy of non-doped semiconductor NWs:
(a) without the Burstein–Moss (BM) effect (under low pump fluence),
(b) with the BM effect (under high pump fluence),
and (c) the SPP enhanced BM effect, where ΔBM is the BM shift and ΔBM′ is the SPP enhanced BM shift.
(d) A schematic of the NW laser devices

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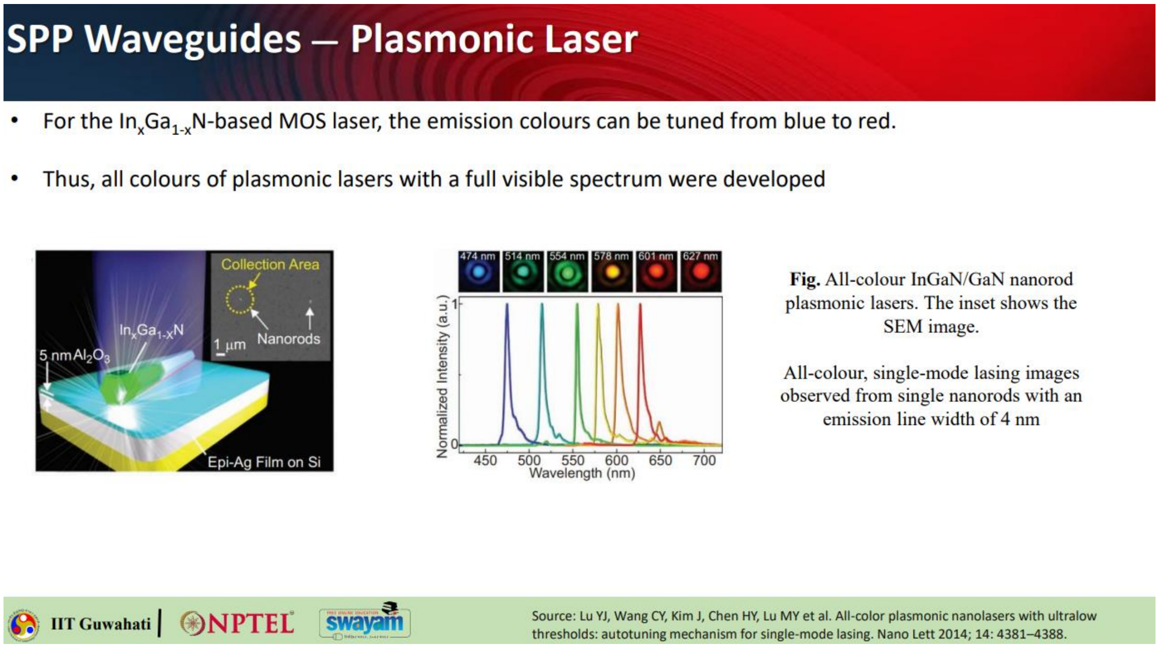
Source: Liu XF, Zhang Q, Yip JN, Xiong QH, Sum TC. Wavelength tunable single nanowire lasers based on surface plasmon polariton enhanced burstein-moss effect. Nano Lett 2013; 13: 5336–5343

Now what is this effect? So, Bernstein-Moss effect is basically a phenomena in which the apparent band gap that you see in a semiconductor is basically increased as the absorption edge is pushed higher ok. Because some states which are lower ok they are basically being populated. So, if you want to jump from your valence band to conduction band these states are already filled up so you cannot actually go there so you have to go to higher energy level in the conduction band and this can this effect itself is called this shift that you see delta BM is basically the BM effect and that takes place when you use high pump fluence ok. So, this is under normal or low pump fluence ok there is no BM effect Burstein-Moss effect. In this case ok you are actually using high pump fluence and you are able to see this particular effect ok but when you actually excite you set up this particular geometry.

So here it is only cadmium sulphide nanowire on top of silica. So, there is no possibility of exciting surface plasmons but when you bring silver film and then there is a thin layer dielectric layer ok you are able to excite surface plasmons and those surface plasmons will actually enhance this particular effect and it is called SPP enhanced BM effect. So that allows you to see more change in the absorption level so obviously the emission laser wavelength will also be different or changed. So, the excitation emission intensities and recombination rates of the semiconductor can be tuned and thus the emission laser wavelength can also be tuned. And this particular effect is the apparent blue shift of the optical gap of a semiconductor and it comes from the state filling close to the conduction band. So this is the region that you know the states close to the conduction band valley are already filled up and that is why you have to move to the upper energy levels and that gives you that particular tuning.



## SPP Waveguides – Plasmonic Laser

- For the $In_xGa_{1-x}N$-based MOS laser, the emission colours can be tuned from blue to red.
- Thus, all colours of plasmonic lasers with a full visible spectrum were developed

**Fig.** All-colour InGaN/GaN nanorod plasmonic lasers. The inset shows the SEM image.

All-colour, single-mode lasing images observed from single nanorods with an emission line width of 4 nm

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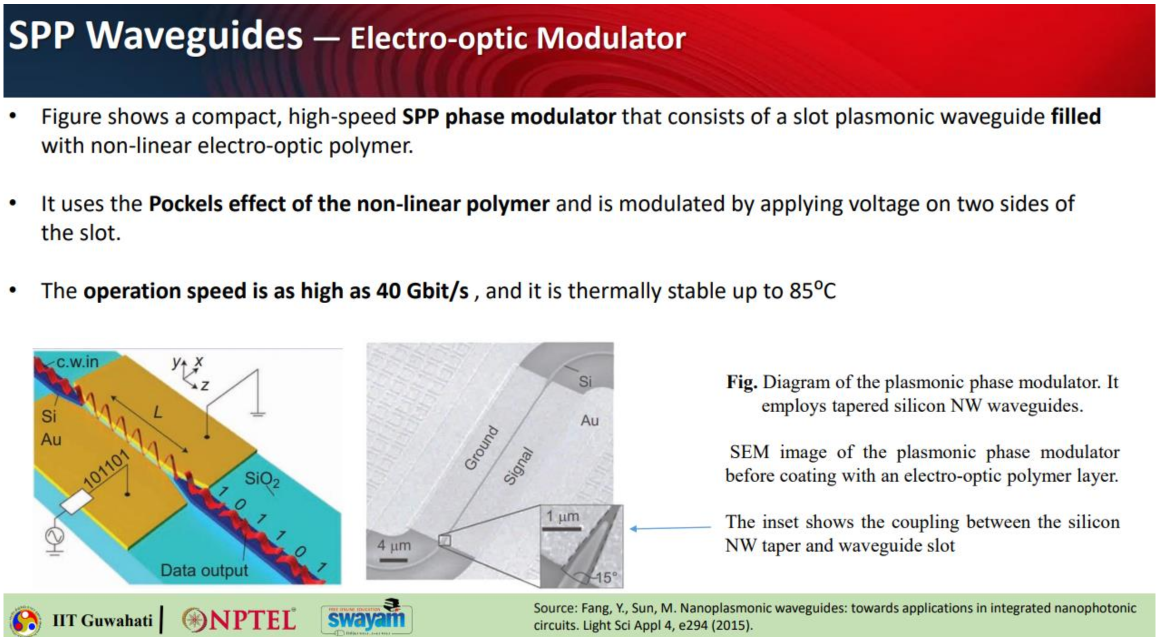
Source: Lu YJ, Wang CY, Kim J, Chen HY, Lu MY et al. All-color plasmonic nanolasers with ultralow thresholds: autotuning mechanism for single-mode lasing. Nano Lett 2014; 14: 4381–4388.

Now here is another plasmonic laser it is basically indium gallium nitrate based plasmonic laser in a MOS metal oxide semiconductor configuration as you can see here this white shiny piece is basically silver film on silicon silicon so this yellow one is silicon and then you have a 5 nanometer spacer which is aluminum oxide alumina Al2O3 on top of that you have the semiconductor nanowire or nanorod. So, what is happening it is basically metal oxide semiconductor kind of arrangement and you are able to see that this indium gallium nitrate or gallium nitrate nanorod plasmonic lasers are able to give all different colors ok. So, all color single mode lasing images as you can see here starting from 474 that is kind of blue and then 627 that is red. So, all this can be observed from single nanorod with emission with line width of around 4 nanometers so that is very good. So, what you have to change you have to actually change the size of the nanorod and that will allow you to get different different colors out of it.

You can also make electro optic modulator based on this SPP waveguides so this was the structure that we have briefly seen before. So here it shows a high speed SPP phase modulator so you can see continuous wave coming in then you have gold plates here there is a kind of slot in between ok and that is the plasmonic waveguide which is filled with some kind of non-linear electro optic polymer. Now when you apply you know voltage in the sense of 101101 this kind of voltage you will be able to do some shift ok in the material property of that polymer ok and that will allow you to introduce some kind of phase modulation. So, 101101 this is how the output is actually getting phase modulated. Now what happens here it will actually use the Pockels effect of this non-linear electro optic polymer.



## SPP Waveguides — Electro-optic Modulator

- Figure shows a compact, high-speed **SPP phase modulator** that consists of a slot plasmonic waveguide **filled** with non-linear electro-optic polymer.
- It uses the **Pockels effect of the non-linear polymer** and is modulated by applying voltage on two sides of the slot.
- The **operation speed is as high as 40 Gbit/s** , and it is thermally stable up to 85°C

**Fig.** Diagram of the plasmonic phase modulator. It employs tapered silicon NW waveguides.

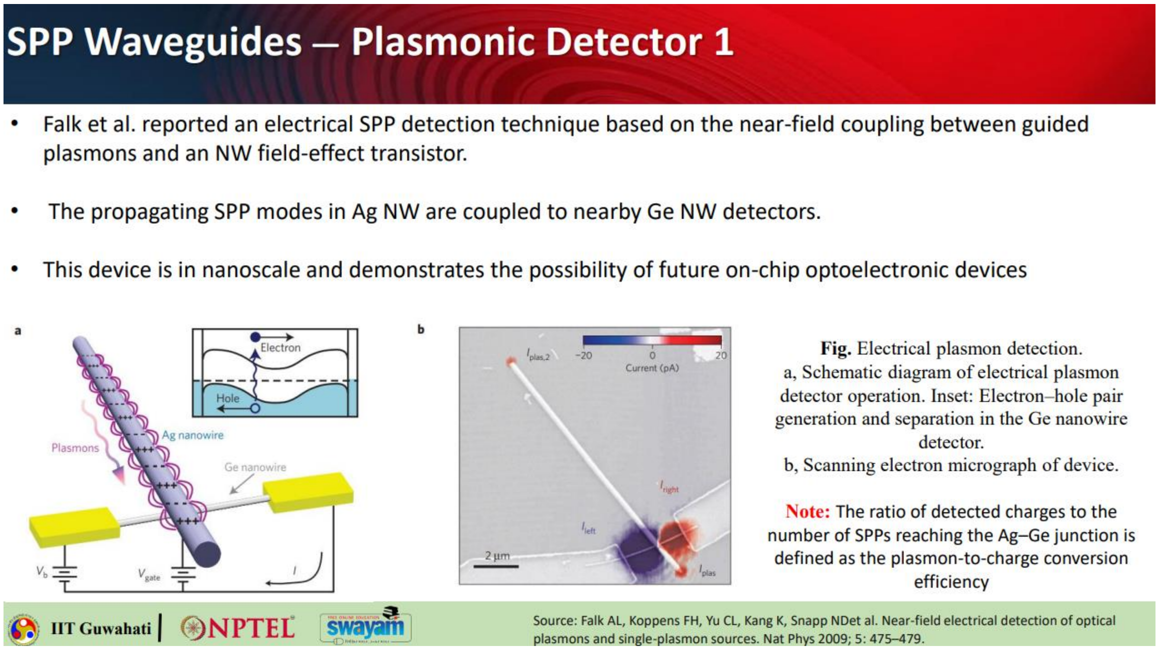
SEM image of the plasmonic phase modulator before coating with an electro-optic polymer layer.

The inset shows the coupling between the silicon NW taper and waveguide slot

Source: Fang, Y., Sun, M. Nanoplasmonic waveguides: towards applications in integrated nanophotonic circuits. Light Sci Appl 4, e294 (2015).

Now when I say Pockels effect it is basically the Pockels electro optic effect and it is also known as the linear electro optic effect it means the Pockels effect is a directionally dependent linear variation in the refractive index of a optical medium in the response of an applied electric field right. So, when you apply this electric field across this material which is an electro optic polymer there will be certain changes in the refractive index property and that will allow you to get this kind of modulation done. So here also this V group kind of thing it is not complete V it is like this ok slot is there in between. So, this is the fabricated structure seen from the scanning electron microscopy image SEM image. So, if you look into this part and you see the zoomed in so this is how it looks like ok.

So there is a taper ok and in this region that electro optic polymer is located. So, you are able to obtain a high operation speed like 40 Gbps and this particular modulator is thermally stable up to 85 degree centigrade. So that is quite high so you can understand that this particular device or modulator is very very stable. You can also think of plasmonic detectors so Foll-Cannell in this particular paper in 2009 they have reported an electrical SPP detection technique based on near field coupling between the guided plus bonds and a nanowire field effect transistor. So first you have a silver nanowire so that is bringing your plus bonds and then here you have this nanowire so it is a germanium nanowire field effect transistor.



## SPP Waveguides – Plasmonic Detector 1

- Falk et al. reported an electrical SPP detection technique based on the near-field coupling between guided plasmons and an NW field-effect transistor.
- The propagating SPP modes in Ag NW are coupled to nearby Ge NW detectors.
- This device is in nanoscale and demonstrates the possibility of future on-chip optoelectronic devices

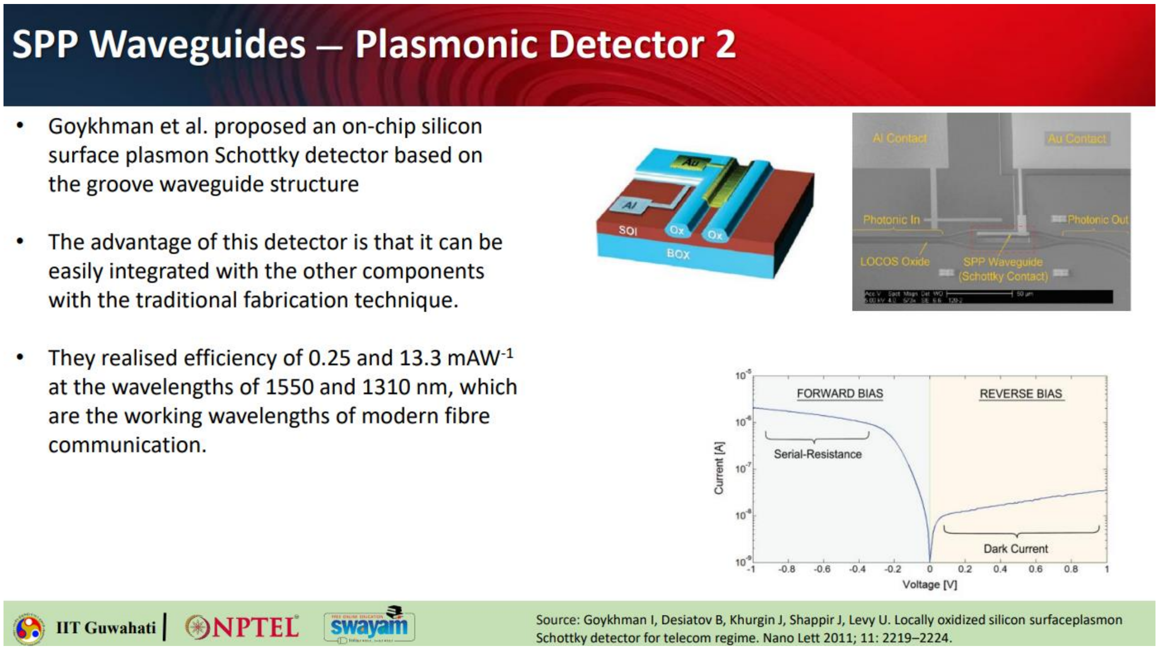
**Fig.** Electrical plasmon detection.
a, Schematic diagram of electrical plasmon detector operation. Inset: Electron–hole pair generation and separation in the Ge nanowire detector.
b, Scanning electron micrograph of device.

**Note:** The ratio of detected charges to the number of SPPs reaching the Ag–Ge junction is defined as the plasmon-to-charge conversion efficiency

Source: Falk AL, Koppens FH, Yu CL, Kang K, Snapp NDet al. Near-field electrical detection of optical plasmons and single-plasmon sources. Nat Phys 2009; 5: 475–479.

So these are the bias voltage gate voltage and everything connected ok. So, whenever there is propagating SPP modes they in this silver nanowire they get coupled to this germanium nanowire detector and they excite you know electron hole pair and this electron holes they propagate and there is a current in the circuit which is measured ok. So, this device is in nanoscale and it demonstrates the possibility of future on-chip optoelectronic devices. So, you can see here this is the setup or schematic in which this plasmon detection will work and this is the SEM photograph of the device ok and always remember that the ratio of the detected charges to the number of SPPs reaching this particular silver germanium junction is defined as plus bond to charge conversion efficiency. So higher this efficiency better will be this detector right plasmonic detector. There are other types of detector as well so that was proposed by Goykhman et al in this particular paper in 2011.

They proposed an on-chip silicon surface plus bond Schottky detector so Schottky means it is a metal semiconductor junction is there. So you can see this kind of groove waveguide structure there is gold metal there is aluminium connectors so here is aluminium contact this is the SEM image you can see the gold contact here. You have a SPP waveguide so this is how photonic in and photonic output ok. So, this is basically silicon on insulator and this is buried oxide this is the oxide layers so this is how the structure looks like for this particular detection. Now the advantage of the detector is that it can be easily integrated with other components with traditional fabrication technique because they are using all the conventional materials and they actually achieved an efficiency of 0.



## SPP Waveguides – Plasmonic Detector 2

- Goykhman et al. proposed an on-chip silicon surface plasmon Schottky detector based on the groove waveguide structure
- The advantage of this detector is that it can be easily integrated with the other components with the traditional fabrication technique.
- They realised efficiency of 0.25 and 13.3 $mAW^{-1}$ at the wavelengths of 1550 and 1310 nm, which are the working wavelengths of modern fibre communication.

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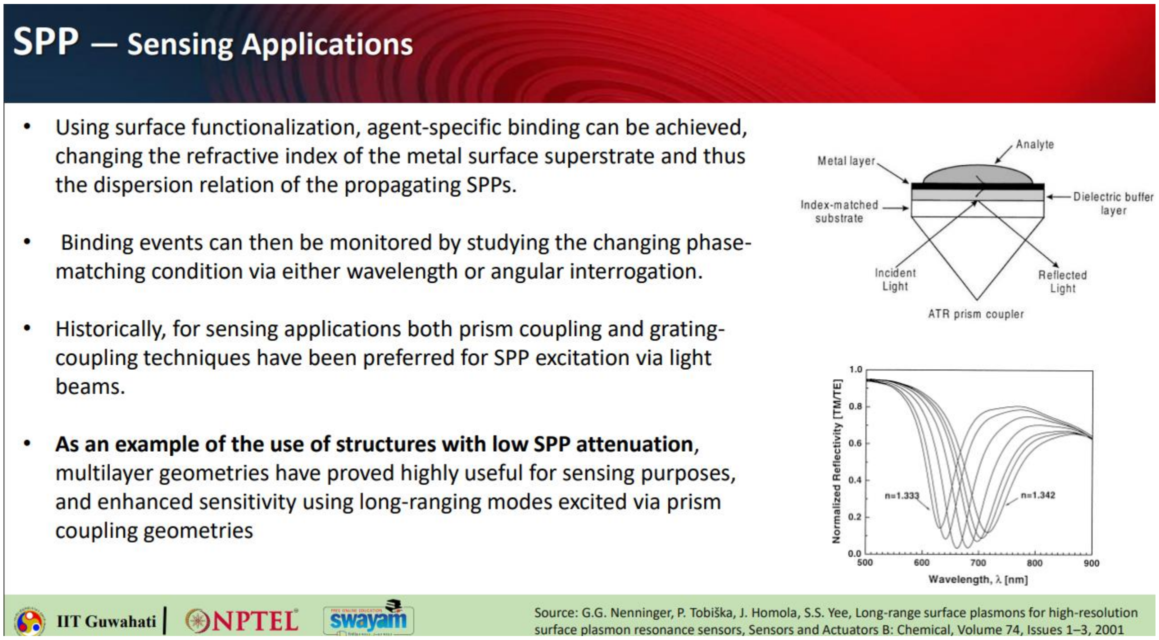
Source: Goykhman I, Desiatov B, Khurgin J, Shappir J, Levy U. Locally oxidized silicon surfaceplasmon Schottky detector for telecom regime. Nano Lett 2011; 11: 2219–2224.

25 and 13.3 micro ampere per watt at the wavelength of 1550 and 1310 this is the telecom wavelengths ok and they were able to get this to particular efficiency ok. So, this is how you can also detect surface plasmons. Surface plus bonds are also very very important for sensing applications so this is one particular prism coupling arrangement that you have already seen before. So using the surface functionalization agent binding or agent specific binding can be achieved and that will change the refractive index of the metal surface super straight and that actually changes the dispersion relation of the propagating surface plasmon.



## SPP – Sensing Applications

- Using surface functionalization, agent-specific binding can be achieved, changing the refractive index of the metal surface superstrate and thus the dispersion relation of the propagating SPPs.
- Binding events can then be monitored by studying the changing phase-matching condition via either wavelength or angular interrogation.
- Historically, for sensing applications both prism coupling and grating-coupling techniques have been preferred for SPP excitation via light beams.
- **As an example of the use of structures with low SPP attenuation**, multilayer geometries have proved highly useful for sensing purposes, and enhanced sensitivity using long-ranging modes excited via prism coupling geometries

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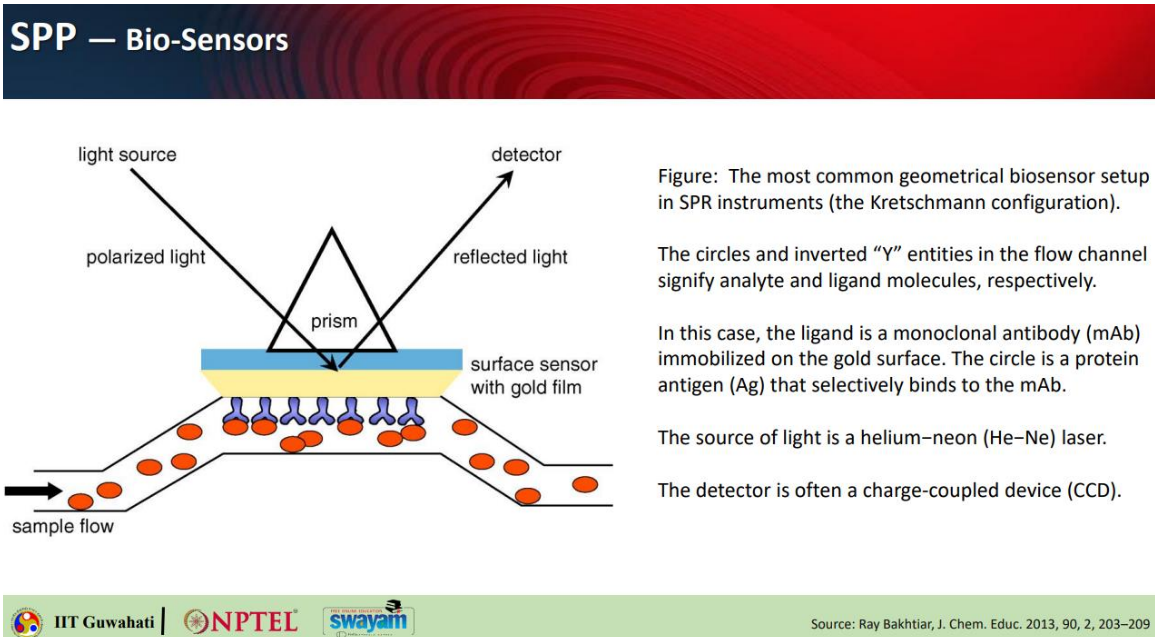
Source: G.G. Nenninger, P. Tobiška, J. Homola, S.S. Yee, Long-range surface plasmons for high-resolution surface plasmon resonance sensors, Sensors and Actuators B: Chemical, Volume 74, Issues 1–3, 2001

So this is basically the funda behind surface plasmon based sensing. So here you can see you have got the prism then you have index mesh substrate ok then you have this dielectric buffer layer in between. So, this is the metal layer where surface plasmon will be excited and on top you have got a super straight ok. So that is basically some kind of functionalization to do some agent specific binding. Now the binding event can then be monitored by studying the changing phase matching conditions which is achievable by either changing the wavelength or the incident angle right. So, these are called wavelength or angular interrogation so you change the wavelength of the incident photon or you change this particular angle ok you will be able to excite different different surface plasmon.



## SPP — Bio-Sensors

Figure: The most common geometrical biosensor setup in SPR instruments (the Kretschmann configuration).

The circles and inverted "Y" entities in the flow channel signify analyte and ligand molecules, respectively.

In this case, the ligand is a monoclonal antibody (mAb) immobilized on the gold surface. The circle is a protein antigen (Ag) that selectively binds to the mAb.

The source of light is a helium–neon (He–Ne) laser.

The detector is often a charge-coupled device (CCD).

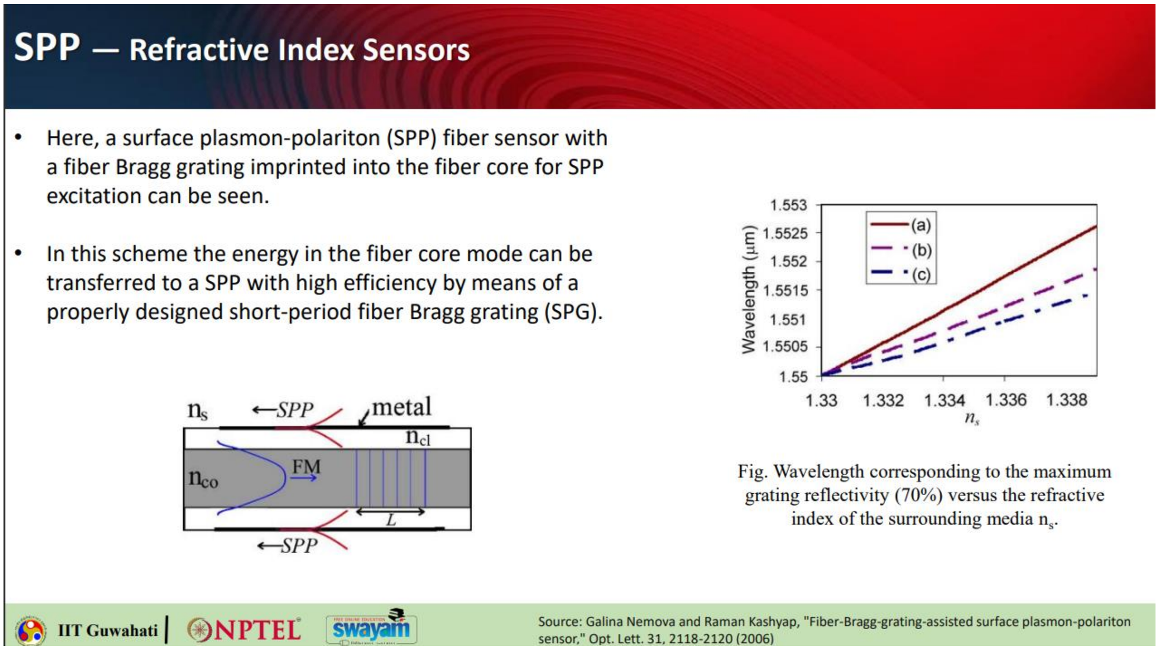
Source: Ray Bakhtiar, J. Chem. Educ. 2013, 90, 2, 203–209

So historically for sensing application both prism coupling and grating coupling techniques have been preferred for SPP excitation via light beams. So, this is an example of such kind of arrangement. So, what you will do you can actually send light from here and here you will have a detector. So, depending on the analyte and if they are able to do some agent specific binding there will be a change in the refractive index here and that changes the dispersion relation of the plus bonds.

So plasmon will then get excited at different different wavelengths. So that is what is also seen here that when n is 1.333 you get the deep here. Deep in the reflected spectrum means the energy is basically getting transferred to some other form ok. It is not coming back to you it means it is getting transferred.

So where it gets transferred it actually gets converted into plasmons. So, this is the case but while the refractive index of this analyte or this medium changes to 1.342 ok the wavelength shifts to this particular value. So, you can see you can actually detect them very easily so that is a popular application of SPP. So here also it is it is been used or it is shown in a much better configured manner. So, you look at the circles here they are basically the analyte and the Y entities that you see these are basically the ligands.

So this is again the same kind of arrangement just shown in a top down manner. So, you can have a microfluidic channel like this ok and you can let this analyte move and whenever they get binded here this is basically the gold film which has got this surface sensor. So as there will be more binding there will be change in the refractive index in this region that will change the wavelength of that plasmon excitation and that can be detected. So usually you use helium neon laser as light source and CCD or charge coupled display device ok or charge coupled device CCD as that detector. There can be other type of refractive index sensor as well using SPPs. So here is the surface plasmon polariton fiber sensor with a fiber break grating imprinted on the fiber core for SPP excitation.



## SPP — Refractive Index Sensors

- Here, a surface plasmon-polariton (SPP) fiber sensor with a fiber Bragg grating imprinted into the fiber core for SPP excitation can be seen.
- In this scheme the energy in the fiber core mode can be transferred to a SPP with high efficiency by means of a properly designed short-period fiber Bragg grating (SPG).

Fig. Wavelength corresponding to the maximum grating reflectivity (70%) versus the refractive index of the surrounding media $n_s$.

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Source: Galina Nemova and Raman Kashyap, "Fiber-Bragg-grating-assisted surface plasmon-polariton sensor," Opt. Lett. 31, 2118-2120 (2006)

So this is a typical fiber as you can see this is the core this is the cladding and this is the substrate that is the surrounding media ns. So, there is a short grating in this particular it is called short period fiber break grating as you see of length L. So, what we will do it will particularly reflect a specific wavelength. So that wavelength when it comes back ok it can leak out to this particular cladding and there is if there are metal deposited on top of this cladding there is a metal dielectric interface and that light can excite surface plasmons which will be propagating along this metal dielectric interface. How does it help? So, depending on the refractive index of the surrounding medium ok the wavelength of this excitation will change and that can be measured here as you see.

So when ns is changing ok you are able to see the difference in wavelength. So, you can actually make refractive index based sensor because whenever there is a change in refractive index the wavelength of light that is getting coupled to the surface plasmon is also changing. So that way you will be able to measure the change in the refractive index and people are able to do really really high sensitivity like sensing of refractive index using SPP sensors. Even change in refractive index of the order of 10 to the power minus 7 was also possible using this kind of sensing. So, you can understand how sensitive this particular mechanism of SPP excitation is to the surrounding medium ok. So, with that we will stop here today and in the next lecture we will take you to another aspect of surface plasmons that is the localized surface plasmons ok.

So if you have got any queries on SPPs on their applications you can drop an email to me at this particular email address make sure you mention MOOC on the subject line. Thank you.