Course Name- Nanophotonics, Plasmonics and Metamaterials

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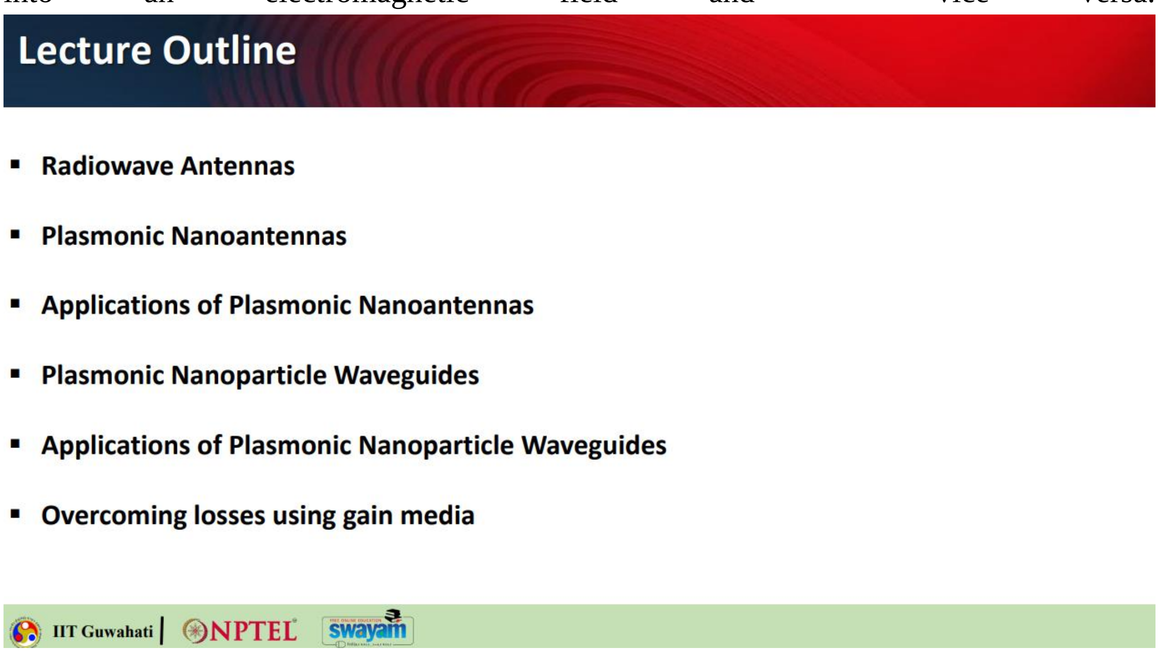
Week-07

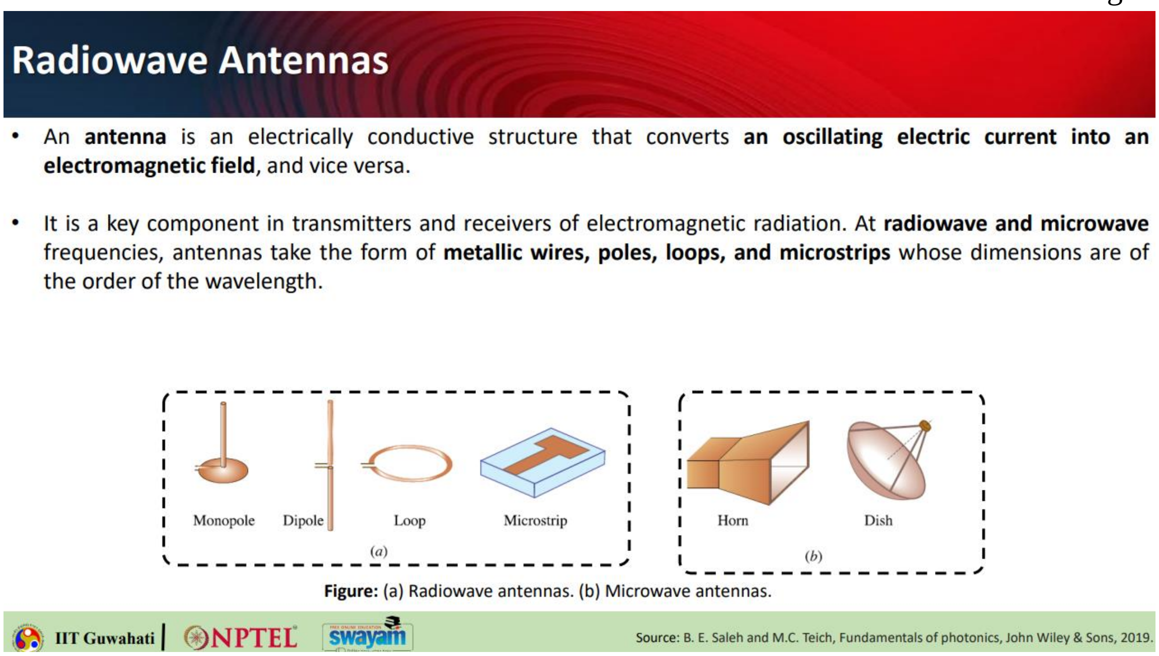
Lecture -20

Hello students, welcome to the 20th lecture of this online course on Nanophotonics, Plasmonics and Metamaterials. Today's lecture will be on Plasmonic Nanoparticles as Antennas and Waveguides. So, here is the lecture outline, we will look into some traditional radio wave and microwave antennas, then we will see how plasmonic nano antennas look like. We will also look into the applications of plasmonic nano antennas, plasmonic nanoparticle wave guides, applications of plasmonic nanoparticle wave guides and how to overcome losses using gain media in this kind of waveguides. So, radio wave antennas are they are in existence for centuries now. So, these antennas are basically an electrically conductive structure that can convert an oscillating current, electric current into an electromagnetic field and vice versa.

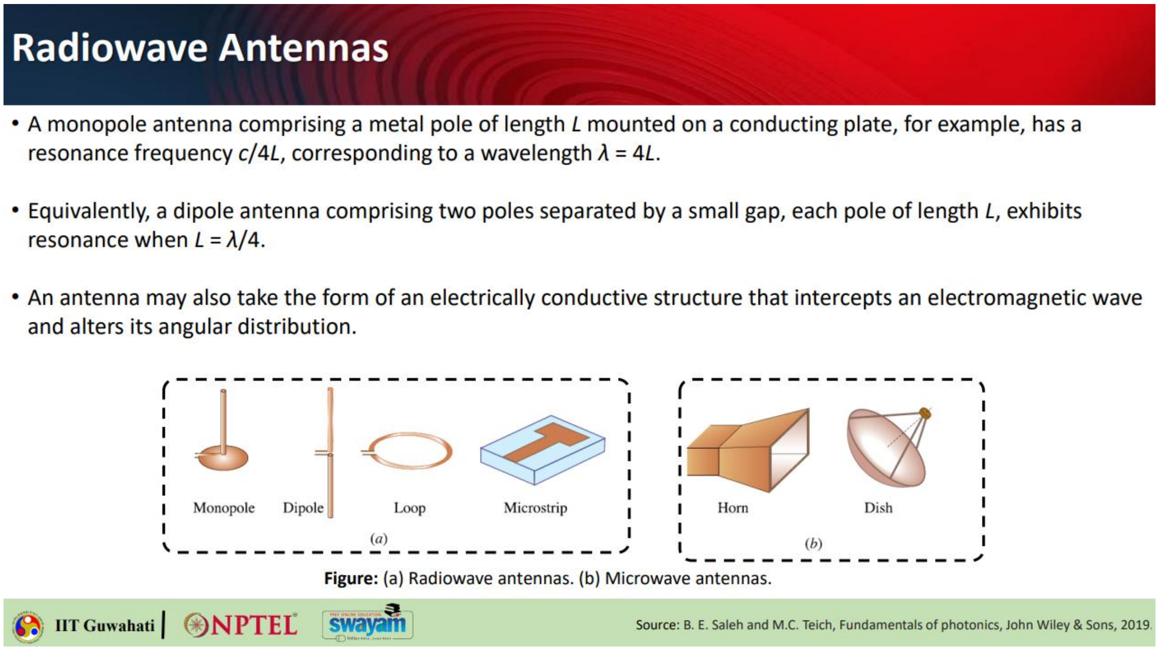


So, a transmitter will be able to convert oscillating electric current into electromagnetic waves or radiation and a receiver antenna should be able to do the opposite of it. So, here are some examples of radio wave antennas and microwave antennas ok, they are put into two buckets. So, it you remember that antennas are key components in transmitters and receivers of electromagnetic radiation And we have seen that at radio wave and microwave frequencies, antennas can take the form of metallic wires, poles, loops, micro strips which are of the dimensions comparable to the wavelength that they are dealing with. Now, if you look into monopole antennas.

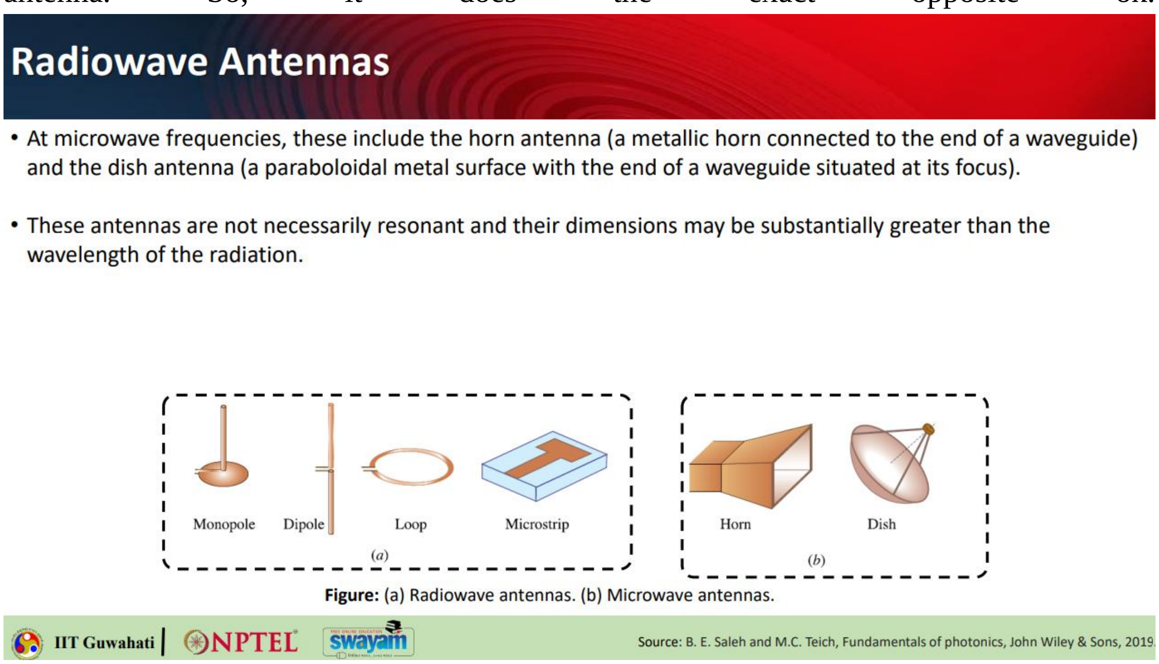
So, these are monopole antennas. So, monopole antennas basically comprise of a single metallic pole which is of length L and it is mounted on a conducting plate and in that case the resonance frequency will be c over 4 L that corresponds to a wavelength of lambda that is equals to 4 L or you can say that the length of the monopole antenna is L which is lambda by 4 ok. So, equivalently you can also have a dipole antenna which comprises of two poles dipole So, there are two poles which are separated by a small gap as you can see here ok and each of these poles are of length L and again L is lambda by 4 when this antenna will show resonance. There are other types of antennas as well loop and micro strip will not go into details of those ok. We are mainly focusing on this dipole kind of thing and monopole because we will see their analog in the plasmonic domain right.



So, an antenna may also take the form of an electromagnetic conductive structure that could intercept an electromagnetic wave and can alter its angular distribution. Now when we come to microwave frequencies. So, these are basically microwave antennas ok and in that case they are looking like a horn. So, this is a metallic horn that will be connected to the end of a waveguide. So, this is where where the waveguide ends and this is the horn kind of metallic horn kind of shape.

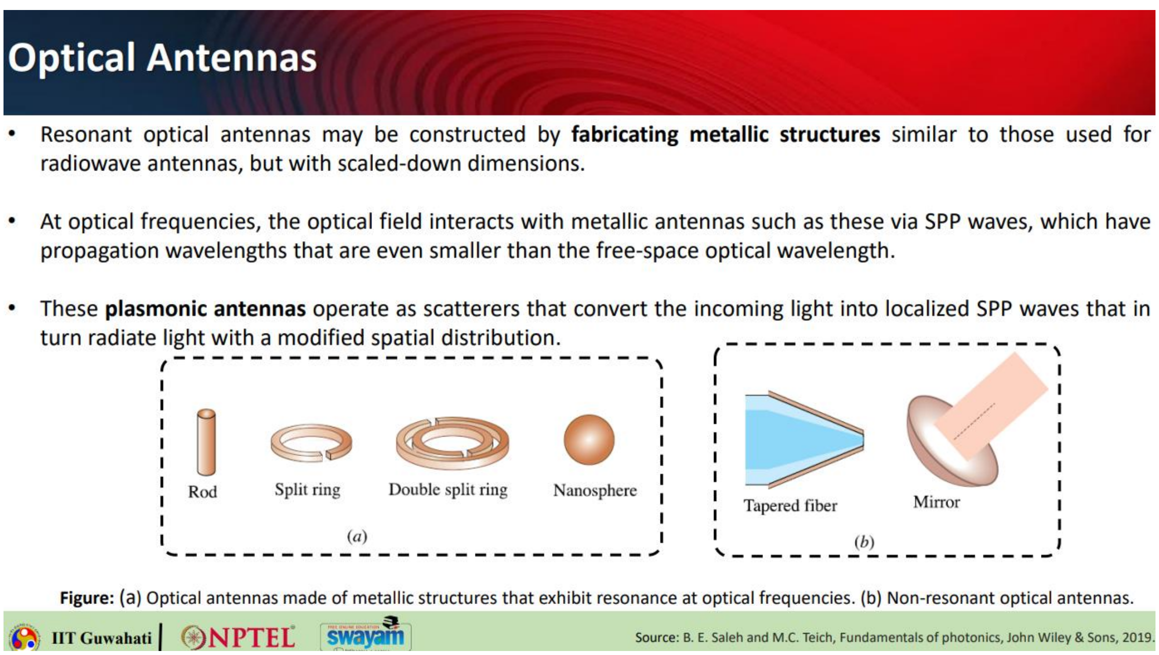


So, this is a horn antenna and you can also have a dish antenna which is I believe everybody has seen dish antenna. This is basically a paraboidal metallic surface that is basically a reflector and the end of the waveguide which is carrying the signal this way or that way ok. If it is a transmitter signal. So, the signal is coming from the waveguide and then it is reflected on the reflector and then it is going out ok and if it is a receiver antenna. So, it does the exact opposite ok.

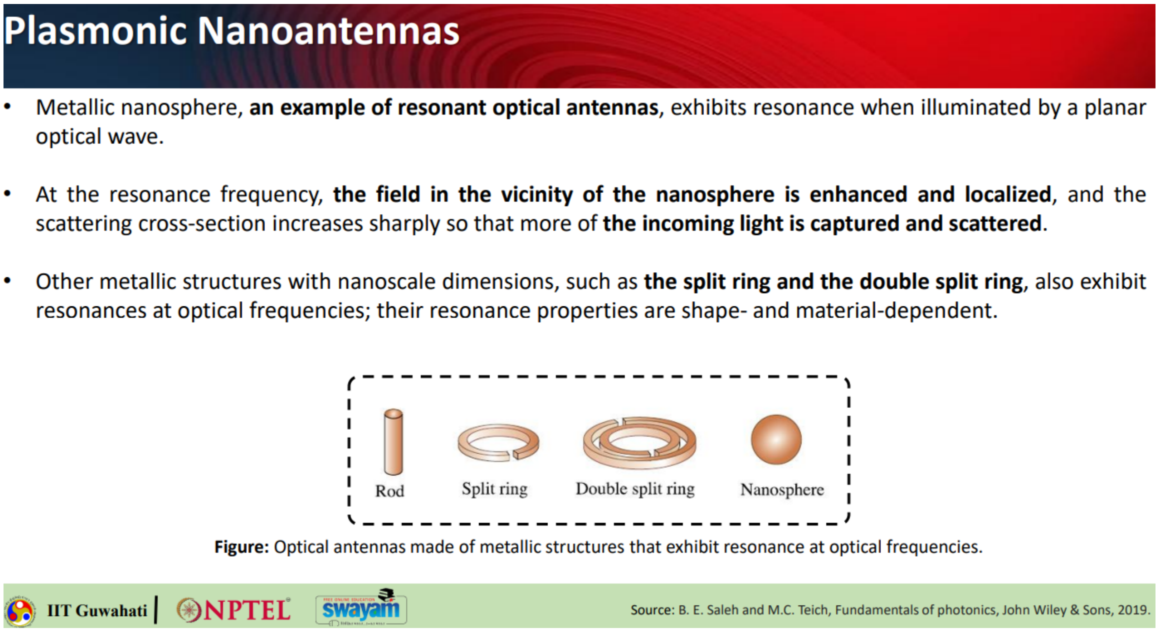


So, in this case the location of the waveguide is exactly at the focus ok. Now these antennas are not necessarily resonant and their dimensions must be substantially greater than the wavelength of the radiation. So, that is the difference between the monopole-dipole antennas that is the radio wave antennas and the microwave antennas ok. Now coming to optical antennas or plasmonic antennas for that matter we will better say optical antennas ok and we will see that resonant optical antennas may be constructed by fabricating metallic structures similar to those of radio wave antennas and here the only important thing is that we have to scale down the dimension because the frequency of optical radiation is much higher than the radio waves. So, the dimension the physical dimension of the elements antenna elements in optical frequency will also be much much smaller ok.

So, here are some examples of optical antennas made of metallic structures that can exhibit resonance at the optical frequencies like rod, split ring, double split ring and nanosphere ok. So, these are the examples of the resonant optical antennas. Now at optical frequencies the optical field interacts with the metallic antennas such as these shown here rod, split ring, double split ring or nanosphere via SPP waves surface plasmon polariton waves which have propagation wavelength much smaller than the free space optical wavelength. So, that is what we have discussed that because the surface plasmons have very large wave number. So, they can actually support very tiny wavelength and that is the reason why they allow you to have that they allow manipulation and guiding of electromagnetic radiation in much much sub wavelength dimension ok.



So, in this case you can also see that the length of the optical quarter wave dipole antenna lies in the nanometer regime right and optical nano antennas are also there which are non resonant. So, in that case you can think of metal coated tapered optical fibre, tip that is used for near field microscopy and also there are paraboidal mirror used in telescopes. So, these two things are also possible. So, these are like non resonant optical antennas and as you understand that the dimension of this optical antennas are typically far greater than the optical wavelength. So, they are very similar to the microwave antennas you can think of and these are very close to sub these are basically sub wavelength antennas.



So, they are basically close to the radio antennas we have seen in the previous slide. So, this plasmonic antennas operate as scatterers that can convert the incoming light into localized surface plasmon polaritons waves that in turn radiate light in with modified spatial distribution. So, you can actually decide the directionality of the light beam being scattered and also you can decide on the spatial distribution of the optical intensity of the reflected or scattered light. Now metallic nanosphere looks pretty simple as an antenna. So, this is basically an example of a resonant optical antenna and it exhibits resonance when it is illuminated by planar optical wave.

Now why I am starting with this because this is nothing, but a plasmonic nanoparticle or you can think of any metallic nanoparticles in optical regime ok. And as we mentioned that you can excite local surface plasmon by direct illumination. So, you can simply shine light on this nano antenna and it will start giving you that kind of characteristics. So, at the resonance frequency so, for gold nanoparticles this rise lies typically around 520 nanometer, for silver nanoparticles it lies typically around 480 nanometer right. So, at the resonance frequency the field in the vicinity of the nanosphere gets enhanced and the field also gets localized.

So, it is very strong just around the nanoparticle and that also gives rise to the scattering cross section. So, the scattered the amount of scattering by this nanoparticle at resonance become much larger than its geometrical cross section and that is how they can actually work as an antenna. The other metallic nanostructures also possible which have got nanoscale dimensions such as this kind of split ring structure or double split ring structure. They also can be designed in a way to have resonance at optical frequencies and mind that their properties the resonant properties are basically shape and material dependent. So, you can get tunability in terms of the resonant frequency where you want your antennas to operate based on the design and the material of the antenna.

Plasmonic Nanoantennas

- Resonant optical nanoantennas may be used **to localize and couple light into small absorbers**, such as single molecules.
  - In the near-field microscopy arrangement, for example, a metal rod on a conducting pedestal may be placed at the end of a tapered optical fiber to create a monopole antenna.
- A nanosphere at the end of a pointed glass tip, carries out a similar function.
- In general, a resonant optical nanoantenna placed between an emitter and an absorber can serve **to enhance their interaction by facilitating the processes of radiation and detection**.

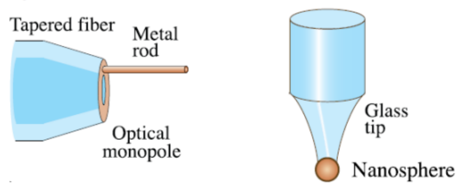
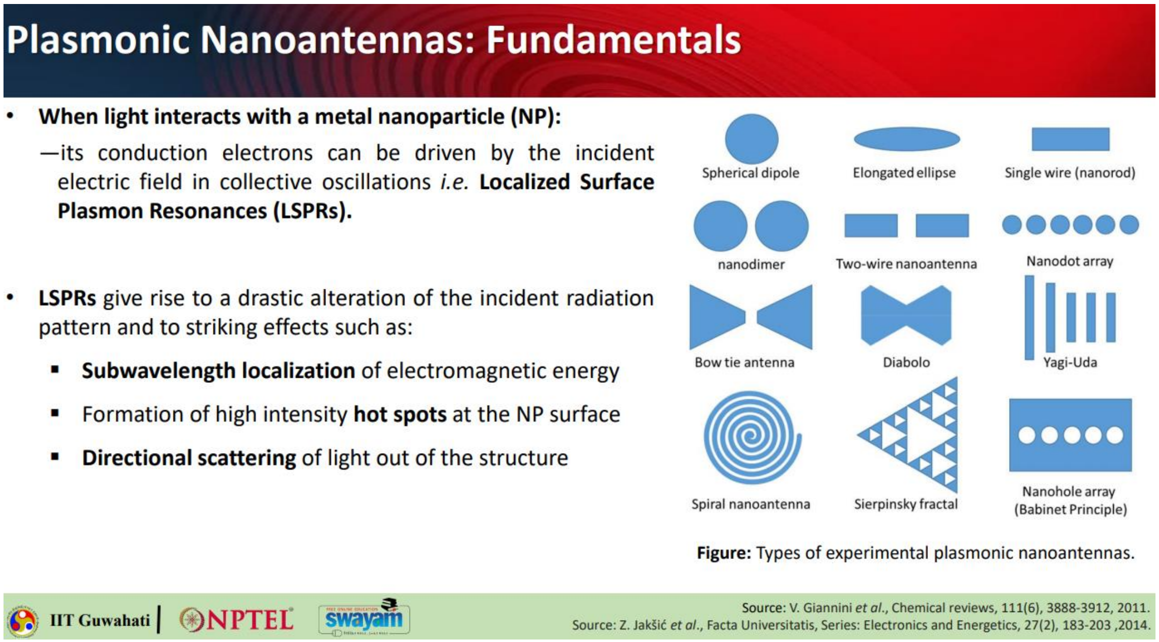


Figure: Optical antennas used to localize light in near-field microscopy. (a) Monopole antenna at the end of a tapered fiber. (b) Nanosphere antenna at the end of a glass tip.

Source: B. E. Saleh and M.C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.

We have also seen till now the discussion was on this resonant optical nano antennas which are useful to localize and couple light into small absorbers. So, you can also think of this kind of structures ok they are able to localize and couple light into small absorbers such as single molecule. Now, in the case of near field microscopy arrangement where you have a metal rod like this on a conducting conducting pedestal and that may be placed at a tapered end of an optical fiber and this can create a monopole antenna right. So, this will be useful for near field microscopy and you can also think of another arrangement where a nanosphere is placed at the end of a pointed glass tip that also carries out in a carries out a similar function of localizing and coupling light to small absorbers like molecules and all these things. So, in general resonant optical antenna placed between an emitter and an absorber can enhance so these are the resonant optical antenna they are not these are the resonant optical antennas this one and this one.



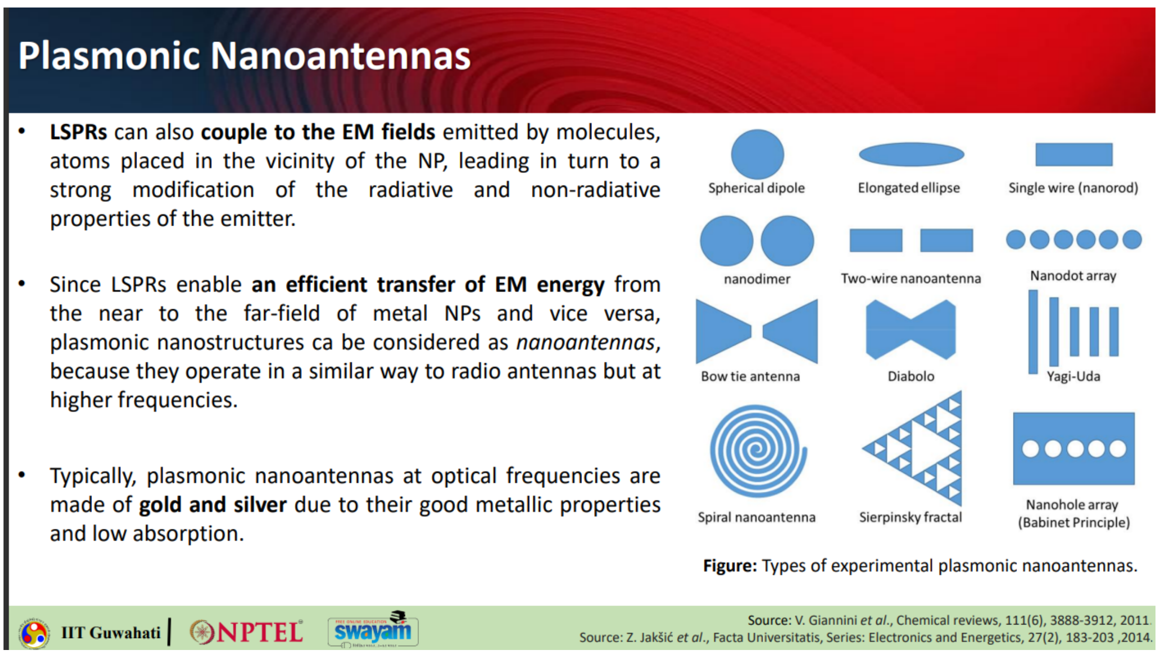
So, they are placed between an emitter and an absorber. So, here the emitter is that molecule ok and you can that will emit the light and this will be the absorber that will catch the light or it will gather the light you can say or collect the light. So, they this kind of interaction between the emitter and the absorber can serve to enhance the interaction by facilitating the process of radiation and detection. So, these are some examples of resonant antennas in near field microscopy right. Now, let us go back quickly to the basics of what happens when plasmonic nano antennas or metallic nano antennas or you can say metallic nanoparticles they interact with light.

So, if you remember from our previous couple of lectures that metallic nanoparticles have abundance of surface electrons and which now naturally oval like a piece of jelly. So, when there is an impinging light or in light falls on them the electric field of the light oscillates at a particular frequency that is the frequency of the light right that you have chosen. Now, when the frequency of the light matches the natural frequency of oscillation of the electrons on that metallic nanoparticle there will be resonance. So, that resonance we call as localized surface plasmon resonance. Now, LSPRs give rise to a drastic alteration of the incident radiation pattern and to striking effects such as sub wavelength localization of electromagnetic energy which we already discussed that using by converting photons to you are basically transferring the energy from photons to plasmons right.

And by doing that you are able to because plasmons have wavelength which are deep sub wavelength you are able to have sub wavelength localization of electromagnetic energy. You are also able to have high intensity hot spots. Hot spots means the places where there are high huge concentration of electric fields ok. So, these are called electric field hot spots and you can also find or achieve directional scattering. It means you will not scatter in all the direction rather your scattering will be only focused in one particular direction.

So, that is directional scattering of light ok. So, here are some of the examples of typical plasmonic nano antennas that have been fabricated till now. So, you can think of spherical dipole, you can think of elongated ellipse. So, these are like nano these are like these are ellipsoidal shape. You can think of single wire which is basically a nanorod, you can think of dimers mean there are two particles two spherical particles.

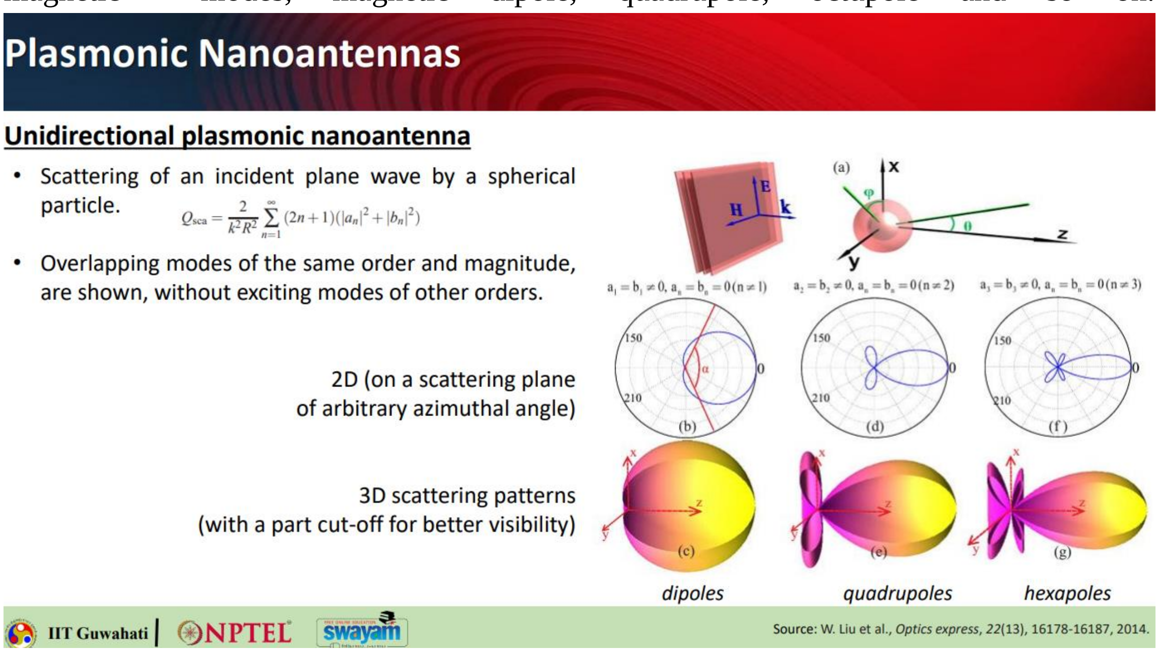
You can think of two wire nano antenna is like this this single wire this is two wire. You can also have nano dot array. So, where you place this dipoles in a linear chain. You can have bow tie shape antennas. Here there will be very strong confinement of electric field.



You can also have diabolo kind of shape, you can have nanorods patterned or placed as yagi uda kind of antenna shape. You can think of spiral nano antennas, you can think of fractal design, you can also think of nano hole array which are from the babinet principle. So, these all different shapes have been tried and tested for different applications typically they all have resonance in close to visible range. So, invisible and near infrared range ok. So, that was the entire motivation behind studying this kind of structures because LSPR can also couple the electromagnetic fields emitted by the molecules atoms placed in the vicinity of nanoparticles leading in turn to a strong modification of the radiative and non radiative properties of the emitter.

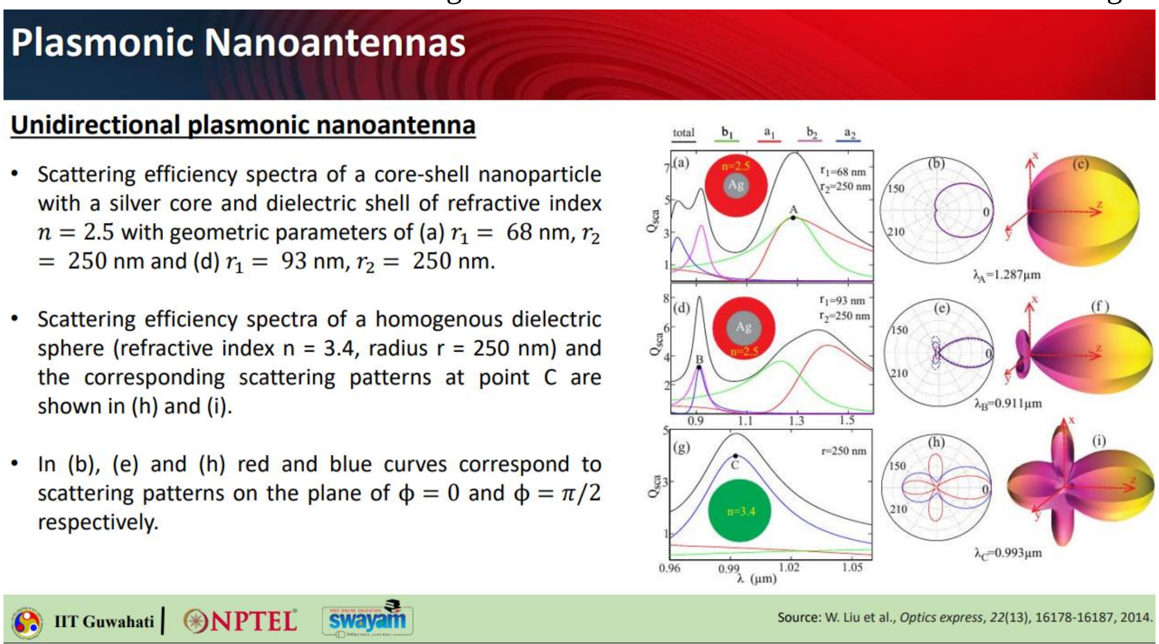
So, you can actually probe a single molecule or a atom using this kind of small dipole antennas. Now, since LSPR enables an efficient transfer of electromagnetic energy from the near to the far field of the metallic nanoparticles and vice versa. They can be considered as antennas because they are able to transfer energy both ways ok. And they work in a similar way as the radio antennas, but the only difference is that this nano nano antennas work at much higher frequency range right. So, what are the materials as I already discussed that these are plasmonic nano antennas when they are operating at the optical frequencies the material we choose are of gold and silver because of their good metallic properties and low absorption in this particular frequency range.

So, here is an example of plasmonic nano antennas for unidirectional scattering. So, when we see scattering you can think of a silver nanoparticle coated with some kind of dielectric layer ok. Now, why we require two of these to get a unidirectional scattering? Now, the reason is that you can think of this metallic nanoparticles to have the electric dipole because you can have the electron cloud moving on top and top and bottom it can wobble depending on the electric field right. But the charges will always remain on the surface of this metal right that is the fundamental physics that we know from school days. But then when we have a coating of a dielectric layer around this one there can be a polarization current in this coating and this circular current will give rise to different magnetic modes, magnetic dipole, quadrupole, octupole and so on.



Similarly here also on the electric on the metallic surface you can get electric dipole, electric quadrupole, electric octupole depending on the charge distribution of the oscillation that is taking place. Now, if you remember from the Mie scattering theory we are able to calculate the scattering cross section of any spherical particle of radius r ok. If we know this coefficients which is a n and b n these are the Mie scattering coefficients right. So, a n is the electric nth order or nth mode electric coefficient and b n is basically the nth mode or nth order mode magnetic coefficient. So, if you think of making it unidirectional the first important thing is that you have to ensure that you are getting a overlap of the same order of the electric and magnetic modes and they are also of the same magnitude right.

So, that is the reason that is how you will get a unidirectional scattering. So, this is one example of that. So, here a 1 b 1 are nonzero remaining all are zeros all higher order modes are zeros ok. It means you are only able to excite in this case electric dipole and magnetic dipole and if you make them perfectly overlap you are basically getting a unidirectional scattering. It means you see the scattering lobe is only in the forward direction there is nothing in the backward direction right.

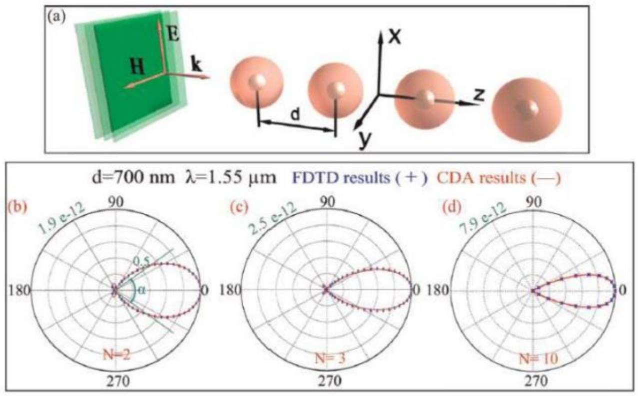


So, this is a unidirectional scattering. Only problem is that the beam width alpha is much wider. Now, look at this one here only a 2 and b 2 are nonzero remaining ones are 0. It means you are only able to excite quadrupoles ok. So, when you excite only the quadrupoles and make them completely overlap the electric quadrupole and magnetic quadrupole completely overlap and they are same in magnitude you actually come up with this kind of a front lobe. So, you see this is much more directional because the beam width is much narrower in this case, but it comes with some additional side lobes.

What are these? These are basically the 3D scattering pattern which are cut or sliced ok for better visibility. Now, when you go to higher order modes like hexapoles or octopoles ok. So, you are able to that is a 3 b 3 are nonzero remaining all are 0 ok. In that case you see you can actually make it more directional, but there will be some scattering losses because the side lobes come out ok. So, this tells us that there is possibility of achieving unidirectional scattering if you are able to do that.

Plasmonic Nanoantennas

Unidirectional plasmonic nanoantenna: Yagi-Uda design

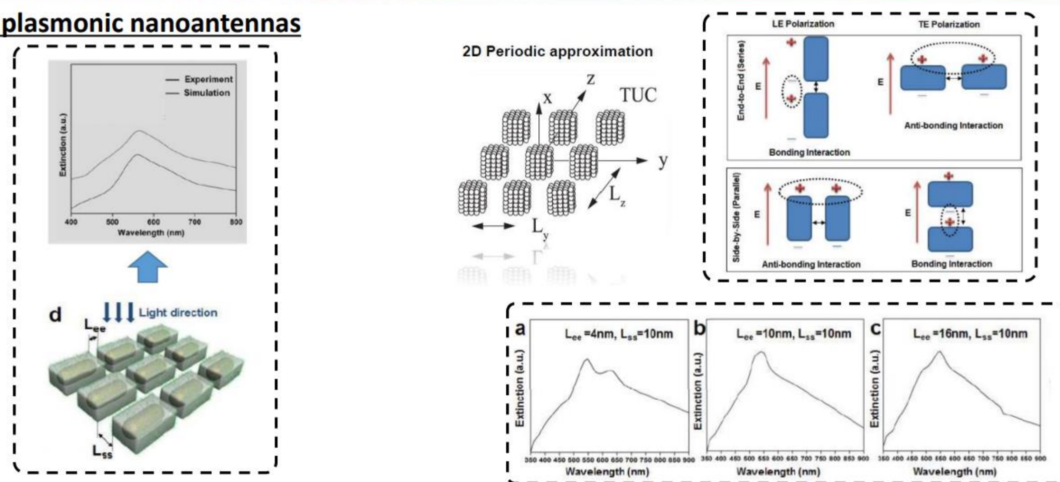


Source: L. Wang, Advanced Functional Materials, 30(51), 2005400, 2020.
Source: V. Giannini *et al.*, Chemical reviews, 111(6), 3888-3912, 2011.

Now, if you take a practical example of silver nanosphere coated with n equals 2.5 kind of material and there if you try to see that this is the scattering only from the electric and magnetic dipoles and you are able to match them here exactly and this is what you will get. You will get a very very much unidirectional scattering pattern that we have seen before at this particular wavelength right. Now, if you consider these are the radius of r 1 is the radius for the silver nanosphere and r 2 is the radius for this coating the or the shell ok. If you choose a different set of parameters you will be able to get a match between electric quadrupole and magnetic quadrupole these are all described here ok.

Plasmonic Nanoantennas

2D plasmonic nanoantennas



Source: L. Wang, Advanced Functional Materials, 30(51), 2005400, 2020.
Source: V. Giannini *et al.*, Chemical reviews, 111(6), 3888-3912, 2011.

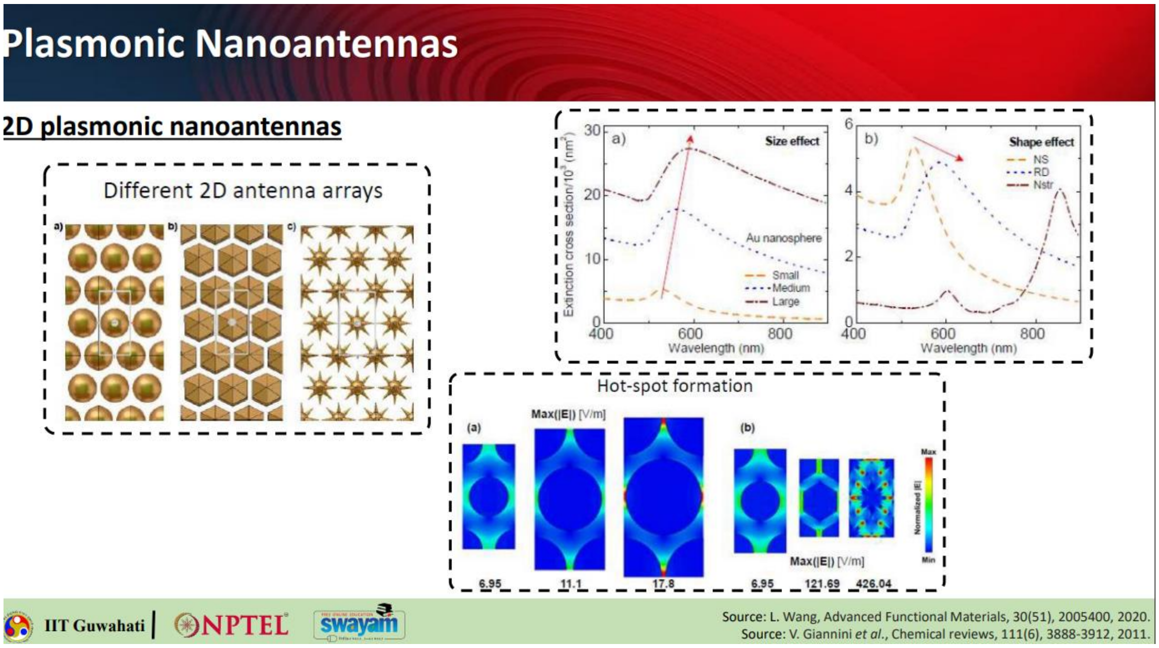
And if you see that you are actually getting a kind of much narrower one, but then theta equals 0 and theta equals 5 they are not exactly matching because there is slight mismatch between the two things, but that they are very close to each other ok. And if you compare this with a uniform sphere of dielectric material ok. So, if you take a uniform sphere like this of refractive index n equal 3.4 you will see that you are only So, getting this kind of mode ok and the scattering pattern is actually not unidirectional. you have scattering in the forward direction you have scattering in the backward direction.

So, what is this red and the blue thing? So, the red one shows the plot along phi equals 0 and phi equals 90 is shown is along this axis phi 0 is this one horizontal and the vertical cuts you can say and you can see here that the red and the blue are not overlapping. So, there is a perfect overlap here there is a little bit of mismatch here and this one is a complete mismatch ok because it is not symmetrical as you would say symmetrical ok. So, you can also make this kind of nanoparticles line up to make a kind of design. So, what you can see here that when you just have two nanoparticles this is a particular this is the beam width and you have got tiny side lobes which are not so good and you see this maximum radiation intensity is 1.

2 e to the power minus 12 ok. This is a cross section basically in meter square and when you make n equals 3 you see the side lobes are getting narrower because you are kind of this overlaps are kind of making this constructive interference and then your beam lobes are getting narrower. So, this happens with n equals 3 also the intensity of the beam is also increasing. When you go for n equals 10 that means, you have lined up 10 such nanoparticles. So, you are working at 1550 nanometer or 1.55 micrometer the d is the gap between them that is taken as 700 nanometer here.

So, when you take 10 such nanoparticles and you shine light from here you see a very very good unidirectional antenna. So, the maximum scattering cross section has also increased 7.9 e to the power minus 12 and there is no back scattering. So, that is also perfectly good. So, these are simulation results as well as so FDTD simulation finite difference time domain method simulation results are shown here along with CDA that is coupled dipole approximation.

I will not have time to go through the, but these are like different analytical techniques this one to find out the scattering calculations. So, they are showing that the simulation results are good match to the theory it means the way it is been calculated is correct. You can also have 2D plasmonic nano antennas like this ok. So, you can have 2D plasmonic nano antenna something like you have a gold nano rod in a silver nano cuboid ok and you can line them up as in kind of array 2D array. So, there also you can calculate what is the scattering cross section theoretical and simulation you can find it out.

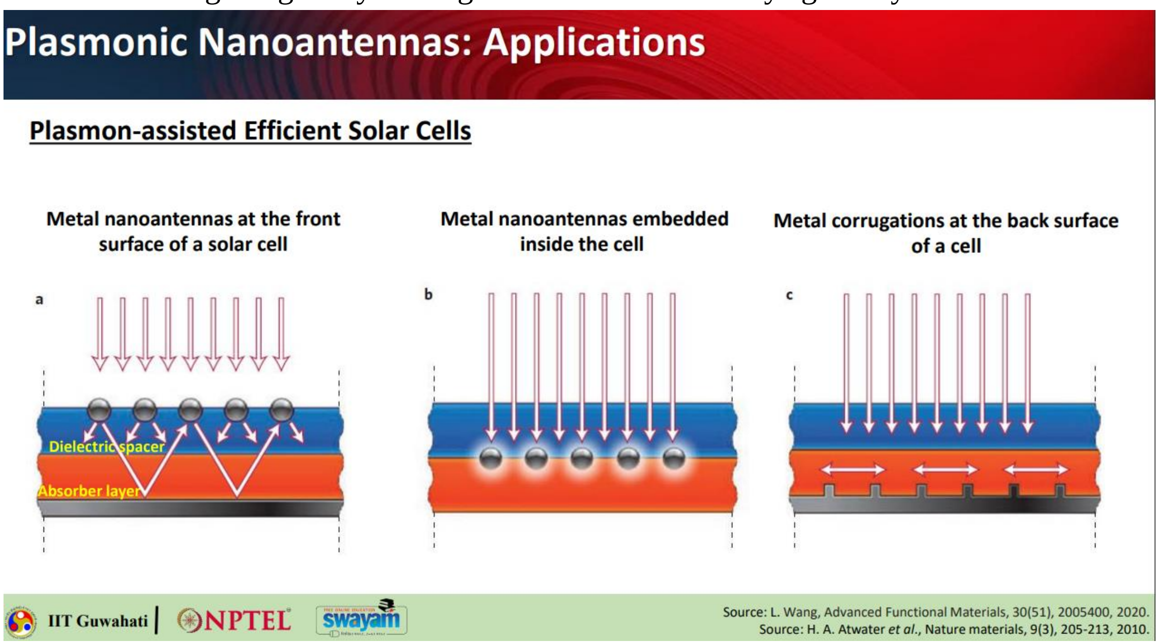


Here the reason to show this one is that different elements can be also. So, each of these particles can be actually modeled as tiny dipoles which are all interacting with each other and this overall particle is also interacting with another particle ok. So, if you look into this 2 particles ok you can think of these 2 particles lined up here. Now depending on the electric field direction.

So, if the electric field direction is this one. So, we call this as L e that is longitudinal edge polarization it means the polarization is along the longitudinal edge you will have dipoles created like this plus minus plus minus and you will have a kind of bonding type of interaction. So, when this kind of interaction happens the energy will lower and it will red shift. You can also have the other type of interaction when the nanoparticles are placed side by side and or you can say nano antenna is placed side by side and the electric field is along the transverse direction you have plus minus plus minus and this positive charges they are closer to each other now or the negative charges they are closer to each other. So, they will experience a repulsive force and that will actually increase the energy and you will see a blue shift in the resonance peak. Anti-bonding type of interaction is also seen when you have electric field in this kind of orientation or in this kind of orientation.

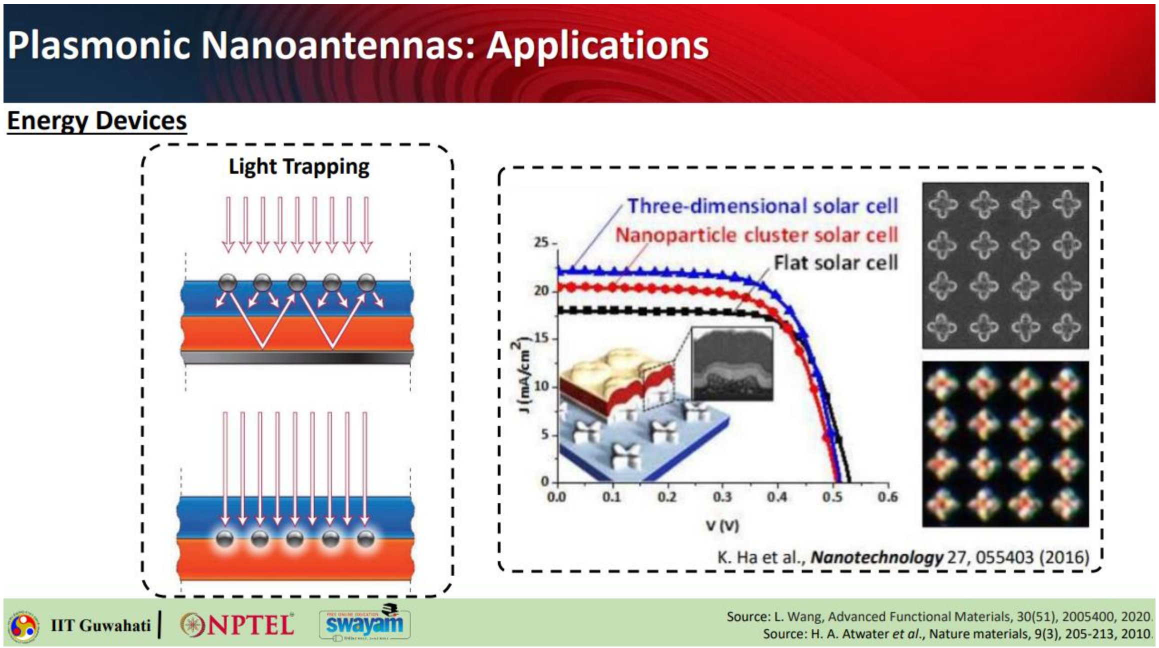
So, here also you can see that what is happening these are side by side and electric field is along the longitudinal edge. So, you can have anti-bonding interaction here and this is where they are next to each other and electric field is along the transverse edge. So, for different gap L x and L y this L x and this is L y you can actually find out what is the well there is the typo here this has to be z this is x ok. So, you can also find out. So, L e is nothing, but edge to edge separation S s is side by side to side separation.

So, for different dimensions you see the resonance peak looks different there may be new other peaks coming up, but overall they all look like a having a resonant wavelength. So, that is how this can work as 2D plasmonic antennas. There are other types of 2D plasmonic antennas possible like you can have 2D array of gold nanoparticles spherical gold nanoparticles or you can have them in other shapes like spikes and so on dodecahedron ok. So, this shape is called rhombic dodecahedron these are different shapes, but they all actually serve a different purpose here as you can see. So, if you just think of gold nanospheres this one and then if you keep on increasing the size of the spheres keeping the lattice constant same you will see that the resonance is getting red shifted in wavelength that is happening because as you keep on increasing the size of the nanospheres the nanospheres are getting very close to each other their interaction is getting very stronger and that actually gives you this red shift.



And when you change the shape from spherical to rhombic dodecahedron to spikes the spikes will have much more electric field concentration along the spikes because of this lightning rod effect and you can see that they are able to interact much strongly with each other and that is why the resonance for the spike one is much red shifted as compared to the nanosphere arrays ok. You can also have different applications of this plasmonic nano antennas one more most prominent application is in the field of making solar cells more efficient. So, you can use this metallic nano antennas at the front surface of the solar cell to absorb light as well as they can scatter light into the absorber layer. So, here the main application is not as absorber rather forward scatterer. So, they actually allowing the light to actually go into this absorber layer and whatever is getting reflected that is again reflected backed by this nanoparticle layer.

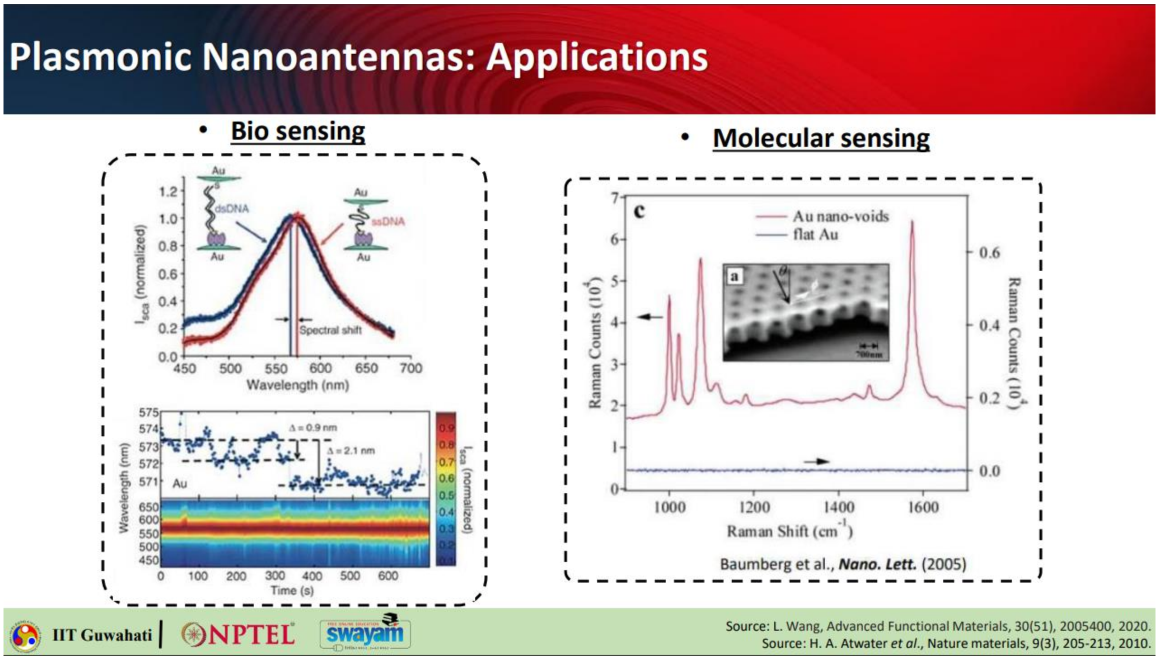
So, that it gets a chance to get absorbed. So, that is how the efficiency of the solar cell can be improved. You can also have nano antennas embedded inside the solar cell. So, here they will be acting as absorbers at the resonance wavelength and they will help you generate more hot electrons. You can also have metal corrugation at the back surface of a cell and if they are sub wavelength and these are metallic ones.



So, they also give rise to plasmonics. So, they will allow you to absorb more efficiently. So, these are the different methods of improving the light trapping efficiency or light conversion efficiency. So, here is an example that with 3 dimensional solar cell as compared to the nano particle cluster solar cell or the flat solar cell. The 3 dimensional solar cell like this with nanoparticles they are actually having the highest efficiency. So, these are the 3D solar cells what people have try to make and they have got the highest efficiency.

So, that that is a work reported in 2016. Now, things have also improved further there people are able to go even further efficiency in solar technology. We can also use plasmonic nano antennas for sensing applications. So, how it works like you have 2 gold nano spheres maybe and you see that they are you are going to sense single strand DNA or double strand DNA. So, single strand DNA's are flexible.

So, they allows this nanoparticles to come closer to each other. When the nanoparticles come closer to each other your resonance peak will get red shifted, but if it is a double strand DNA that gets attached between the nanoparticles they are much stronger or stiffer you must say. So, the gap between the nanoparticles are larger. So, it will be a much blue shifted one. So, the spectral shift allows you to do the sensing and tell you whether it is a double stranded or a single stranded DNA. You can also do molecular sensing using the plasmonic hotspots that we have decide discussed like plasmonic nano antennas will have a lot of electric field hotspots in between.



So, there if you have some sensing molecules and you try to do the surface enhanced Raman scattering experiments you will get much enhanced effects out of this. So, these are also applications of plasmonic nano antennas. They are basically serving as test beds for SERS ok or you can say they are SERS substrate SERS ok. You can also think of waveguides. So, another novel concept of guiding electromagnetic radiation with transverse confinement that is below the diffraction limit and it is based on the near field coupling between closely spaced metallic nanoparticles.

So, if you think of one dimensional particle array like this they can exhibit coupled modes due to near field interactions between adjacent nanoparticles. And we have to make sure that the particle diameter is much much smaller than lambda and in that case the light matter interactions could lead to oscillating homogeneous polarization of the nanoparticle volume and that results in a oscillating dipole field. So, one particle will excite the another particle, this will act as a source for the next particle and that is how the oscillation will keep on propagating along the length unless it is decay because there is some loss associated with each of this particles. So, there will be damping loss is damping. So, that is where it it will propagate to a certain distance and then it will die off.

Plasmonic Nanoparticle Waveguides

- One of the **novel concept for guiding electromagnetic waves** with a transverse confinement below the diffraction limit is based on near-field coupling **between closely spaced metallic nanoparticles**.
- One-dimensional particle array can exhibit coupled modes due to near-field interactions between adjacent nanoparticles.
- For a particle with a diameter D $\ll \lambda$, the light-matter interactions lead to an oscillating homogeneous polarization of the nanoparticle volume, resulting in an oscillating dipole field. For spherical Au and Ag nanoparticles in air, the dipole plasmon resonance frequencies lie in the visible part of the spectrum.

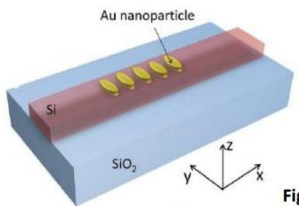
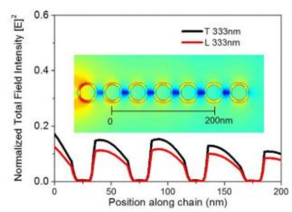


Figure: Au nanoparticles as waveguide.



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Source: S. A. Maier *et al.*, Physical Review B, 67(20), 205402, 2003.
Source: M. Février *et al.*, Optics express, 20(16), 17402-17409, 2012.

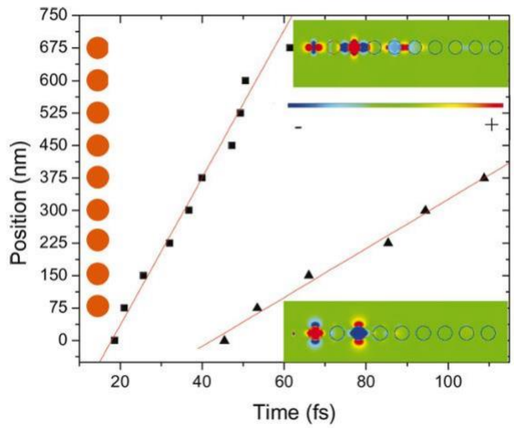
So, here you can see this is basically a linear chain of spherical nanoparticles. So, here you can see that the electric field density normalized total field density is been intensity is measured here at different positions along this chain. So, gradually the peak position peak is actually getting lower ok. So, you have high low high low high low and so on and that is how it has been measured.

So, it has been also measured along the transverse and longitudinal direction. So, the transverse one is this one when the excitation is along the transverse direction. So, that is the black curve. So, in that case it propagates further and longitudinal excitation is this one when the polarization is along the length of the chain ok. So, in that case it propagates a shorter distance ok. So, there are examples to prove that people have done the or finite difference time domain simulation to show all these things.

So, consider a chain of gold nanospheres these are 50 nanometer gold nanospheres and they are separated by a center to center distance of 75 nanometer and there is air in between nothing else. And these are the calculations of the pulse peak position over time ok.In this plasmonic waveguide consisting consisting of the spherical nanoparticles for the longitudinal. So, this is the longitudinal polarization this black squares and the transverse one is this one when the polarization is along the transverse direction.

Plasmonic Nanoparticle Waveguides

- Examples of the electric field distribution of the guided modes, which depicts results from FDTD simulations of pulse propagation through a chain of 50 nm gold spheres separated by a center-to-center distance of 75 nm in air.
- **Pulse peak positions** over time in a plasmon waveguide consisting of **spherical particles** for both longitudinal (black squares) and transverse (black triangles) polarization.
- The spheres along the coordinate indicate the position of the Au nanoparticles.
- Snapshots of the x(y) component of the electric field in the xy plane for **longitudinal (transverse)** polarization are shown in the **upper (lower)** inset.



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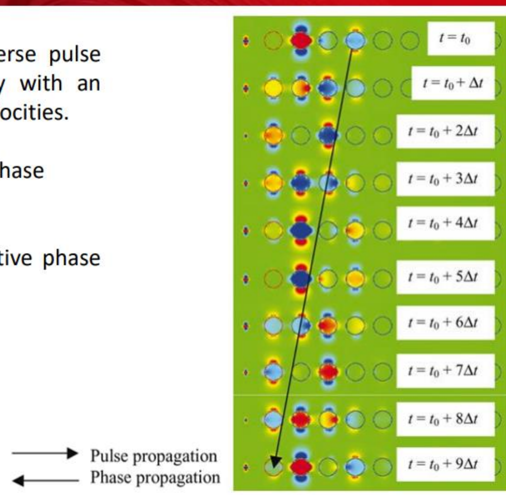
Source: S. A. Maier, Plasmonics: fundamentals and applications, 1, 245, New York: Springer, 2007.
Source: M. Février *et al.*, Optics express, 20(16), 17402-17409, 2012.

So, this is this one. So, you can see this can actually sustain much longer ok and these are the snapshots. So, this as you can see these are basically the propagation along the longitudinal direction and this is when it is along the transverse one. Here also another set of simulation is shown. So, these are basically time snapshots of the electric field for transverse pulse propagation showing a negative phase delay with an anti parallel observation of the phase and group velocities. So, this has been done at different different time steps starting from t equals t naught then you added a delay with it that delta t 2 delta t 3 delta t and so on ok.

Plasmonic Nanoparticle Waveguides

- Time snapshots of the electric field for transverse pulse propagation showing a negative phase velocity with an antiparallel orientation of the phase and group velocities.
- The arrow denotes the movement of a particular phase front.
- These simulations have also confirmed the negative phase velocity of transverse modes



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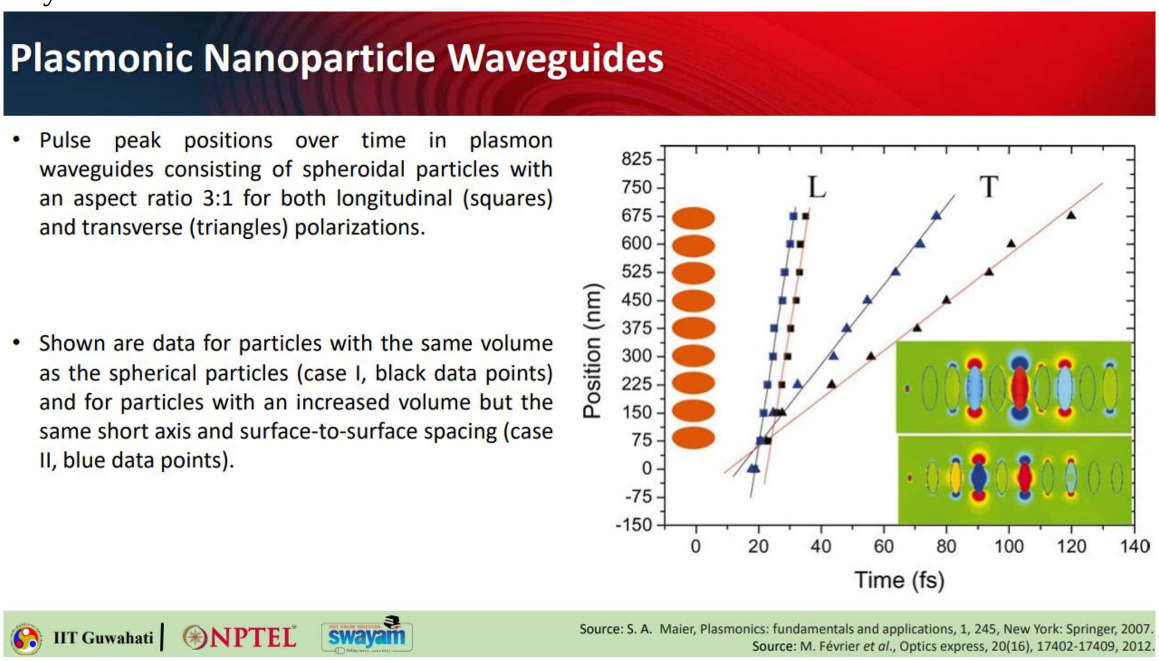
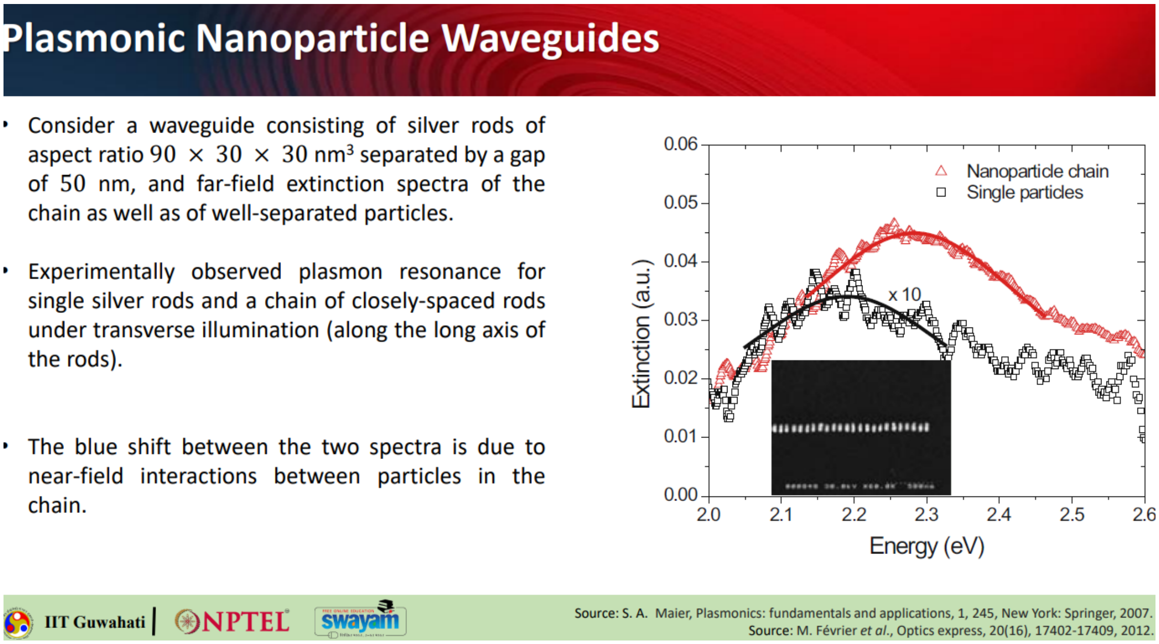
Source: M. Février *et al.*, Optics express, 20(16), 17402-17409, 2012.

So, you are able to see the particular the arrow is showing the movement of the particular phase front and this simulations though it is not clearly visible here unless it is an animation ok. This simulations also confirmed a negative phase velocity of the transverse modes ok. And when you change the shape of the particles from spherical to ellipsoid there are also changes in the transverse and the longitudinal modes those are propagating along this waveguides ok. So, the pulse peak positions over time in a plasmonic waveguides consisting of spheroidal particles like this one.

So, here the aspect ratio of the particle is taken as 3 is to 1 ok. So, we are showing the longitudinal as squares ok and transverse as the triangles ones and we are comparing this with the spherical particles. So, consider this case the black data points. So, the black data points are basically case 1 where the particles the spherical spheroidal particles are having the same volume as that of the spherical particles ok. So, that is the case of this one the black squares and you can see the other one that is the case 2 there is a blue ones the blue ones are basically those cases when the particles with an increased volume, but they have same short axis.

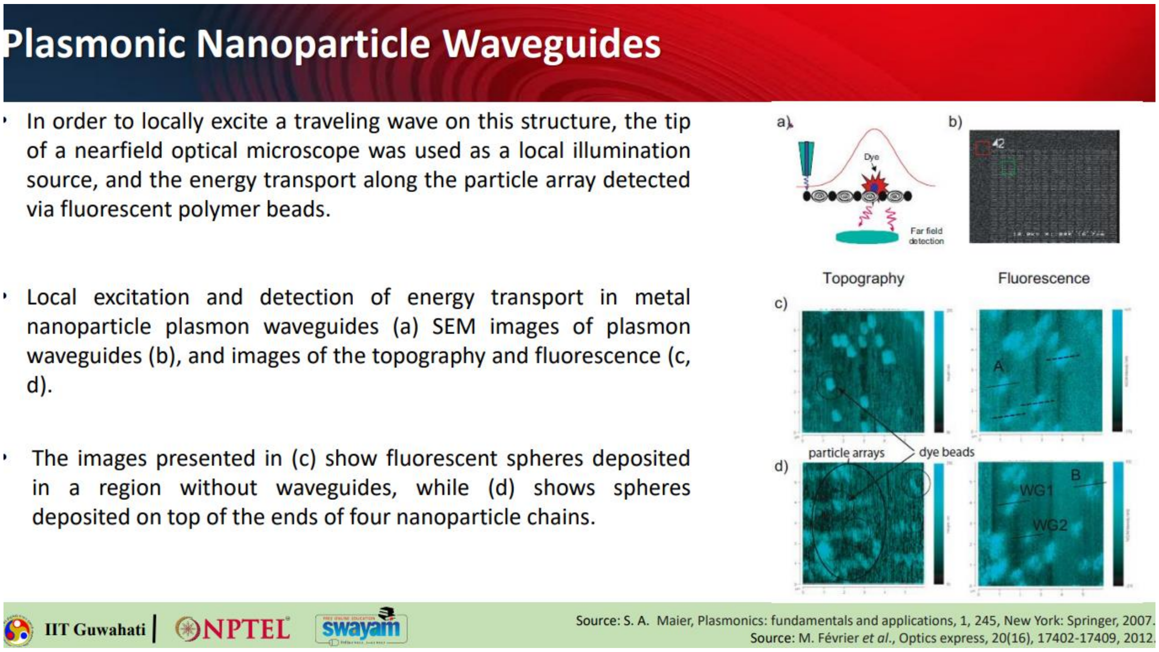


So, in that case the surface to surface spacing is also maintained. So, they are having a larger volume, but the same short axis and surface to surface spacing. So, that is the blue points. So, this also provides a comparison that when you change the size and shape of this plasmonic nano antennas to form a waveguide you can actually control the propagation characteristics along the transverse mode or along the longitudinal mode that also you can decide. So, all these things tell you about the excitation which excitation you should use to propagate longer and which kind of particles you should take. So, this is an experimental demonstration of a silver nanorod which has got an aspect ratio of 90 is to 30 is to 30 ok and there is a gap of 50 nanometer in between them and this is a far field excitation spectra of this kind of chain of particles ok.

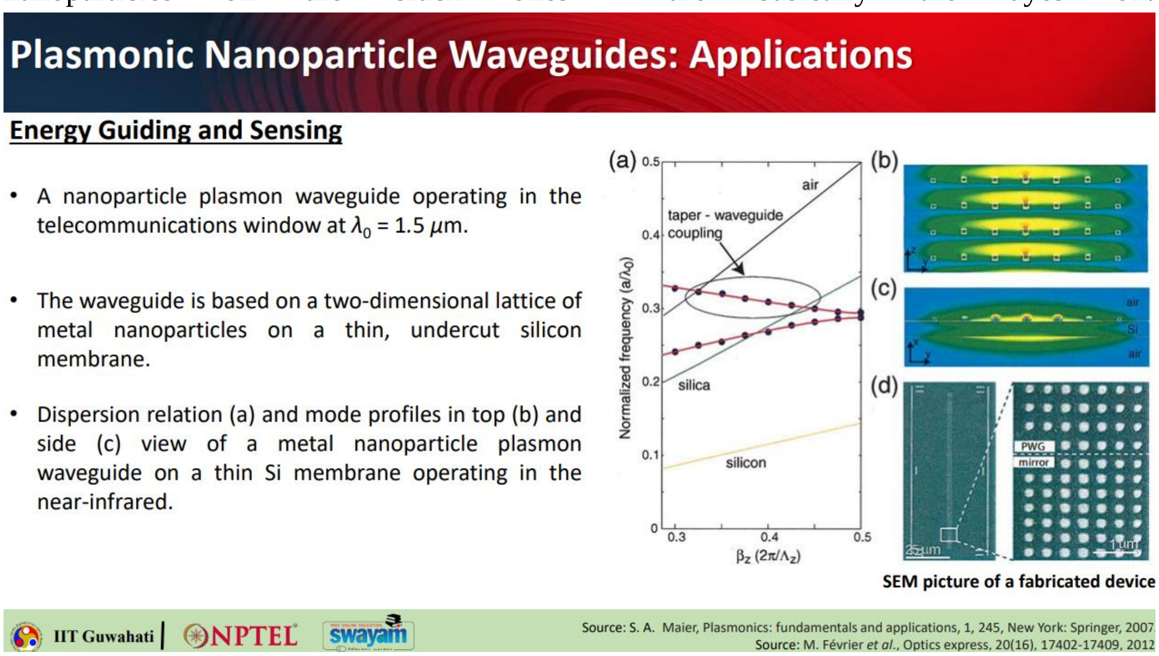


So, the square one is basically the result from single particles and the triangle ones are basically from the nanoparticle chain. So, you see there is a definite change in the resonance wavelength for this kind of linear chain right and the experimentally observed surface plasmon resonance for the single silver rods shown here and the chain of this same nanorods in a close pack kind of chain arrangement for the transverse illumination. So, in this case the transverse means they are the orient electric field orientation is in this direction and that is the difference you can actually see the excitation wavelengths or energy are different. So, there is a blue shift between the two spectra and that results from the near field interaction between the particles in the chain and this you can actually understand from those kind of what is happening when the two particles are next to each other and they have a electric field along this way ok.

So, you can actually analyze the kind of interactions from that kind of analogy. You can also see or visualize this kind of plasmonic wave propagation along a nanoparticle waveguide by introducing some kind of dye ok. So, in order to locally excite a travelling wave on this structure the tip of the near field optical microscope like this ok can be used as a local illumination source. So, this you are only exciting one particular nanoparticle ok and then the energy is basically transported along this and then if you put some kind of dye here ok that is able to do some extra like there are some scattering from this and that can be detected in the far field and which is shown here right. So, you are able to do some local excitation you are able to do the energy transport because there is no energy directly illuminating this one the energy was illuminated here and it has been transported along this chain by this coupling ok. So, this black dots are basically the particles this is where the coupling takes place ok and this is where you have put a dye and you can that energy in the dye will allow you to have some fluorescence and that can be measured.



So, local excitation this is the SEM image of the plasmonic waveguide ok and these are basically the images of the topography and the fluorescence that you can see. So, the image that is shown in this one c show the fluorescence spheres ok deposited in the region without waveguides and here you can actually see the spheres deposited on top of the ends of the 4 nanoparticle chain. So, 1, 2, 3, 4 ok. So, this is the 4 nanoparticle chain this is the illumination source ok and that is how you can actually see the local excitation and scattering. Well, I think they have pictorially shown these as the nanoparticles ok the black ones are basically the dyes ok.



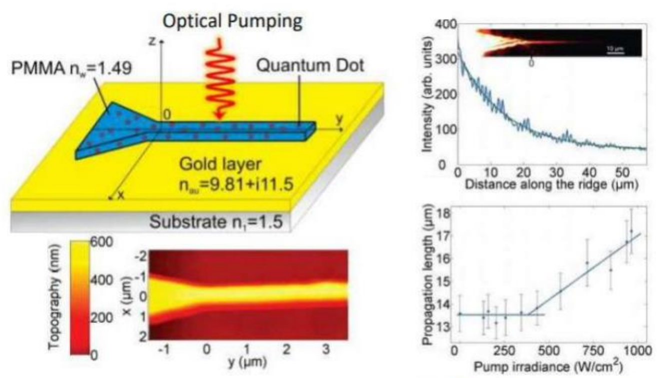
You can also see energy guiding and sensing on plasmonic waveguides which are operating at telecom window at 155 nanometer. So, this this kind of waveguide is based on a 2 dimensional lattice of nanopart metallic nanoparticles on the thin undercut silicon membrane. So, you can see the SEM image of a fabricated device here. So, the dispersion relation will not go into the calculation of this, but then for this periodic arrangement you can actually find out the dispersion relation and this is the dispersion relation and the mode profile from the top view and the side view of this device is shown here and this is basically nothing, but a plasmon waveguide on a thin silicon membrane which operates at in the near infrared window that is 1550 nanometer. We have also understood that this metallic nanoparticles they have they are lossy in visible wavelength.

Overcoming losses using gain media

- Ohmic losses in metal can be compensated by using optical gain media ($Im\{\varepsilon\} < 0$).
- Field confinement also increases with optical gain.

$$\beta = k_0\sqrt{\frac{\epsilon_m\epsilon_d}{\epsilon_m+\epsilon_d}}$$

The presence of gain can lead to a complete vanishing of the denominator



Grandidier et al., ***Nano Lett.*** (2009)

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So, the propagation of plasmons will not happen infinitely they will gradually decay they will lose energy. So, ohmic losses in metal are responsible for the decay of the plasmons when they are propagating through them. So, you can actually compensate for this losses by using some kind of gain media. So, you can think of some quantum dots as a gain media where you can optically pump them and based on that they will be able to provide you some gain and allow longer propagation of plasmon along this gold nanoparticle layer ok.

So, sorry it is a gold layer which has got quantum dots through this PMMA. So, there is a PMMA slab which has got this quantum dots. So, you are putting optical pump on this. So, that is how you can increase the propagation length of plasmons propagating on this gold layer fine. So, you can see the intensity profile along the ridge and this is how it decays.

So, you can also see the propagation length how it increases with the pump irradiance. So, when there is pump it can actually go to a very long distance like up to 17 micron ok. In other case it actually dies down much faster. So, you can actually use optical gain media to overcome the losses and allow surface plasmon wave to propagate much longer. So, optical field confinement also increases with optical gain and the presence of the gain can lead to a complete vanishing of the denominator and you will get a very very large propagation constant ok. So, with that we will stop here today and in the next class we will see plasmonic nanoparticles in other applications.

So, if you have got any queries or doubts on this particular lecture you can drop an email to this email address mentioning MOOC on the subject line. Thank you. .