Digital plasmonics: from concept to microscopy

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What are Surface Plasmon Polaritons?
Surface Plasmon Polaritons are surface waves at the interface between a conductor (metal) and an insulator (dielectric). In an insulator the electrons are strongly bound to the nuclei and they are not free to move around. In a metal, instead, the electrons are free to move around. The collective oscillations of the free electrons (the electron sea) are known as plasmons (bulk plasmons). The collective oscillation of only the free electrons adjacent to the surface of a metal give rise to a surface wave: the Surface Plasmon. Away from the surface, the intensity of this wave decreases exponentially with the distance from the surface.

Let us consider the unperturbed surface of a lake. When a leaf falls in the lake, it will locally generate a surface wave that propagates along the surface. In this intuitive picture the leaf is the source of the perturbation which creates the surface wave. Similarly, when the free electron sea of a metal is perturbed than a surface charge density wave is launched and propagates along the surface (the interface with the insulator). Typically the perturbation of the metallic electrons is done with photons or with electrons.

Why are Surface Plasmon Polaritons important?
Surface Plasmon Polaritons can tightly confine or focus electromagnetic energy. The length scale to which a wave can be focused is proportional to the wavelength. The shorter the wavelength the better the focusing. Surface Plasmons Polaritons can be excited via light. For a fixed light frequency, the wavelength of the excited Surface Plasmon is shorter than the wavelength
Overview

of the exciting light. Thus plasmonic confinement is better than optical
confinement. One way to harvest the high confinement of Surface Plasmon
Polaritons is by using these waves for imaging.

What is plasmonic imaging or a plasmonic microscope?
When a wave is incident on a sample, the wave is scattered, reflected or
absorbed by the sample. The wave scattered (or reflected or absorbed)
from the sample is recorded on a detector because it contains information
regarding the sample and can be used to create an image of the sample.
Different waves can be used for different imaging techniques: for example in
radiography X-ray waves are used; in echography ultrasound waves are used;
in optical microscopy light waves are used; in electron microscopy electron
waves are used. The resolution of the imaging technique is determined by
the way we detected the scattered wave and the ultimate resolution is given
by the wavelength of the wave used to create the image. In plasmonic mi-
croscopy (part of optical microscopy) plasmonic waves are used because of
their shorter wavelengths compared to light.

How does a plasmonic microscope work?
Surface Plasmons are surface waves propagating on a metallic surface and
are excited from incident light. The sample to be imaged is placed on top of
this metallic surface. Propagating Surface Plasmons are optically invisible
(you cannot see them propagating), but when these waves encounter the
sample plasmons are locally scattered by the sample into light emitted in
all directions. This light scattered out of the metallic surface is recorded on
an normal optical detector (a camera). The optical image recorded on the
detector is the image of the sample which was excited by Surface plasmons.
Because the image is created using light and standard lenses, the resolution
does not depend on the plasmonic wavelength and is ultimately determined
by the quality of the lens used and by the wavelength of detected light. Nev-
ertheless, even by using the same light, the same lens and the same detection
camera, there is a way to create an image of the sample which depends on
the plasmonic wavelength (thus improved resolution): the plasmonic excita-
tion of the sample has to be tightly focused. In other words, to improve the
resolution, a plasmonic lens has to be used for focusing the plasmons and
for scanting the focus.

How do you make a plasmonic lens?
Plasmonic lenses, as well as plasmonic sources and detectors are not avail-
able. The plasmonic lens is created by using synchronized light beams. We use many light beams to create as many plasmonic sources: this is similar with many leaves falling on the surface of the lake. The circular surface waves originating from every leaf (source) will propagate and interfere with each other. If the leaves fall at the same exact time and next to each other in space to form a line, then the interference of the surface waves is a line wave similar to the ocean waves. If the leaves fall not all at the same time but each with a time delay, then the interference pattern of the surface waves can be tuned to create a focus at any desired location by controlling the relative time delays. The relative time delays are tuned so that at the exact desired locations all waves coming from each leaf are in phase with each other and thus interfere constructively.

Similarly, we use many light beams incident on a metallic nanostructure to generate surface plasmon waves. The relative time delay of the light beams are tuned via a spatial light modulator. This pixelated device changes the phase (and the amplitude) of light passing through it. When light passing through this device impinges on the surface of the metallic structure it will originate many plasmonic circular waves, one for each pixel. The phase of the incident light (the incident wavefront) can be tuned to focus the plasmonic waves at any desired location on the metallic surface. This way a plasmonic lens is created which can focus Surface Plasmons and scan this focus.

**How to determine the relative time delays for focusing?**

Determining the required optical wavefront (the phase delays of the light beams) for focusing is the most important part of the plasmonic lens. We have used two methods to determine the optical wavefront: (1) experimental measurements and (2) theoretical calculations. The experimental method consist of trying all possible combinations of possible time delays and selecting among all these combination only the one which provides the largest intensity in the desired focal spot. This method can be applied in a smart way by using a feedback algorithm to maximize the resultant interference from all sources at the desired spot. In applying this experimental method no assumptions have to be made regarding the metallic nanostructure. The theoretical calculation is possible only when the Surface Plasmons propagate along a flat metallic surface (no corrugations). When this condition is satisfied then the time delay for each source is easily determined by the distance between the source and the desired focal point.

Intuitively when leaves fall in a lake and there is nothing to perturb the propagation of the surface waves (like floating wood), then it is predictable
that for focusing at a target the time delays are determined by the source-target distance. If the waves are also scattered by floating wood pieces, then the time delays are not determined by the source-target distance and another approach to determine the time delays has to be used.

Because we can fabricate the metallic nanostructure with any desired pattern, we know in advance which method to use for determining the time delays. For plasmonic microscopy, a flat metallic film is preferable because on such structure plasmonic focusing and scanning can be done faster and with high resolution.

**Why are focusing and scanning needed for plasmonic microscopy?** We have created the plasmonic lense which can create a smaller focus than an optical lens because the plasmonic wavelength is shorter than the optical wavelength. Nevertheless the plasmonic lens can not be used as a detection lens because there are no plasmonic detectors: the read out of the plasmonic microscope is optical (light detected). To create the image of the sample with plasmonic resolution the sample is excited by the plasmonic focus. When we focus Surface Plasmons on one point all the light comes only from a portion of the sample which is as small as the size of the plasmonic focus. The total intensity of the outgoing light from that portion of the sample constitutes one point of the final image of the plasmonic microscope(in correspondence of the position of the plasmonic focus). The adjacent point is added to the final image by: focusing plasmons to the adjacent spot to excite the adjacent portion of the sample and by integrating the intensity of the outgoing light from this new portion of the sample. Thus by scanning the plasmonic focus we can create an image of the entire sample and the resolution of this image is given by the size of the plasmonic focus.

**What is the actual performance of the plasmon microscope?** Some of the main characteristic of a microscope are: (1) the resolution or the ability to resolve nearby points, (2) the field-of-view or the largest size of the sample that can be imaged, and (3) the acquisition time or the time needed to create the image. We used our plasmonic microscope to image scatterers positioned on top of a metallic nanostructure. The actual imaging resolution achieved with our plasmonic microscope is dependent on the plasmonic wavelength and is 10 – 20% better than conventional optical microscopy. This increase in resolution is due to a shorter plasmonic wavelength (as compared to the incident light wavelength). The field-of-view and the acquisition time are inversely proportional to each other because the image
is created via scanning: the further you scan the larger the field-of-view but also the longer the acquisition time.

**Can the performance of the plasmon microscope be improved?**
With the actual microscope we have successfully proved the principle of a plasmonic microscope. The performance of the microscope can be improved by nearly one order of magnitude. The resolution can be improved by using better nanostructures: the plasmonic wavelength experimentally reported for the best planar metal nanostructures is 10 times shorter than the wavelength of the incident light meaning that the plasmonic focus can be made 10 times smaller than the actual one. The field-of-view can be improved by without any increase in acquisition time via parallel processing of multiple plasmonic foci; thus multiplexing. The acquisition time can be improved by using high speed spatial light modulator devices for faster scanning.

The optimal performance of the plasmonic microscope is achieved by using the latest spatial light modulators in combination with an optimal nanostructure and a multiplexed configuration. With this optimized plasmonic microscope we can achieve in the near future video rate imaging of millimetric-size samples with a resolution of 50 nm.

**Who is going to use the plasmon microscope?**
A plasmonic microscope can provide high resolution imaging of the surface of a sample. The surface of the sample has to in contact with the metallic nanostructure which is also the plasmonic lens. For biologist the surface of a cell is probably the most investigated part of the cell. All the exchange of material and information between the living cell and the external environment happens at the cell boundaries. Due to this large interest in surface biology various optical microscopes have been used. Because our plasmonic microscope can provide better imaging of living cells without any fluorescent labeling, we think that biologist and medical doctors will largely benefit from this new microscopy.