Sub-diffraction Imaging via Surface Plasmon Decompression

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Abstract: We theoretically propose a novel scheme for sub-diffraction imaging based on a process of adiabatic decompression of the local wavelength of a surface plasmon polariton supported by two adjoining curved metal surfaces.

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Conventional optical elements such as lenses or mirrors cannot image sub-wavelength features [1]. This limitation greatly affects many important applications ranging from lithography to microscopy. The difficulty to improve the resolution beyond the diffraction limit stems from the inability of conventional optics to access the optical near field [2,3]. Accessing and controlling light in the near-field remains a central challenge in nano-engineering.

Early attempts to retrieve these evanescent components culminated with the invention of the near-field scanning optical microscopes (NSOM)[2,4,5]. Such instruments offer sub-diffraction resolution, however they are inherently slow since the image is reconstructed by means of a time-consuming raster scan of the sample. Metamaterials research has provided a new perspective based on the synthesis of artificial media with electromagnetic properties not found in nature. This has enabled unprecedented control over light propagation and has led to novel strategies to achieve sub-diffraction resolution. Far-field super-resolution has been demonstrated by utilizing conformal multi-layer structures with hyperbolic dispersion[6-9]. These structures, however, are complex and often pose challenges in the fabrication. Here, we propose to access the optical near field by adiabatically decompressing the local wavelength of a surface plasmon polariton, and to form an image by exploiting the intrinsic curvature of the interface supporting such surface wave.

A tapered metallic wave-guide can gradually slow down and asymptotically stop light at its tip to efficiently deliver optical energy to the nanoscale [10]. During this adiabatic slowdown, the wavelength of light decreases by several orders of magnitude from micrometers to nanometers. Moreover, the wavelength decreases smoothly, and there is no discontinuity in the phase along the path of propagation [10]. We propose to reverse this process. The reduction in the local wavelength can be in fact exploited to probe features of an object that would be sub-diffraction in free space. A tapered metallic waveguide could efficiently extract the near field information of a source placed in proximity of the region of minimum modal wavelength, where the light nearly stops. The waveguide could capture the sub-wavelength evanescent modes from the light source, which would be otherwise lost, and convey them to the far field through the reverse adiabatic process. Because this adiabatic slowdown ensures no discontinuity in the phase of the light, in this reverse process, the position of the light source, which is encoded in the phase, can now be accessed from far field with nanoscale resolution.

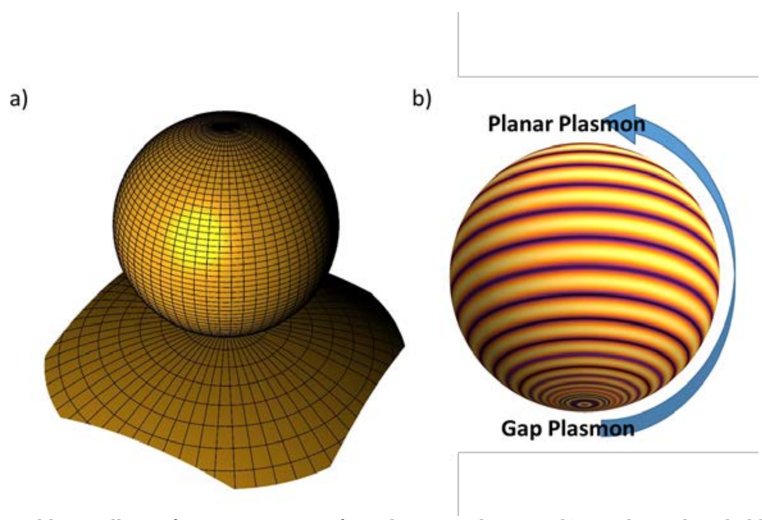

Figure 1. (a) Double metallic surface supporting Surface Plasmon Polaritons. (b) Local wavelength dilation.

In Fig.1(a) we show the layout of the proposed scheme. A metallic sphere is brought in close proximity of a second metallic interface. Considering the region close to the lower hemisphere and the bottom surface, if the radius of the sphere is large compared to the wavelength of light, the relative distance between the two interfaces is a slowly varying function of the position on the spherical surface. As a consequence also the local effective index of the surface plasmon polaritons supported by the sphere is a slowly varying function of the position. Under these conditions the supported modes of the structure are adiabatically transformed from high index gap plasmons to nearly planar plasmons on the top hemisphere (Fig1(b)).

The object to be imaged is placed in the gap between the sphere and the bottom surface, where it is efficiently probed by the local high index gap plasmons. The intrinsic curvature of the spherical surface supporting these surface waves causes the field to refocus and to form an image at the top hemisphere, as shown in Fig.2 for a point source. Because of the local wavelength dilation caused by the adiabatic decompression of the plasmon polaritons in going from the lower to the upper hemisphere, the image produced is a pre-magnified version of the object that could be scattered out to be resolved with a conventional imaging system, thereby providing sub-diffraction resolution.

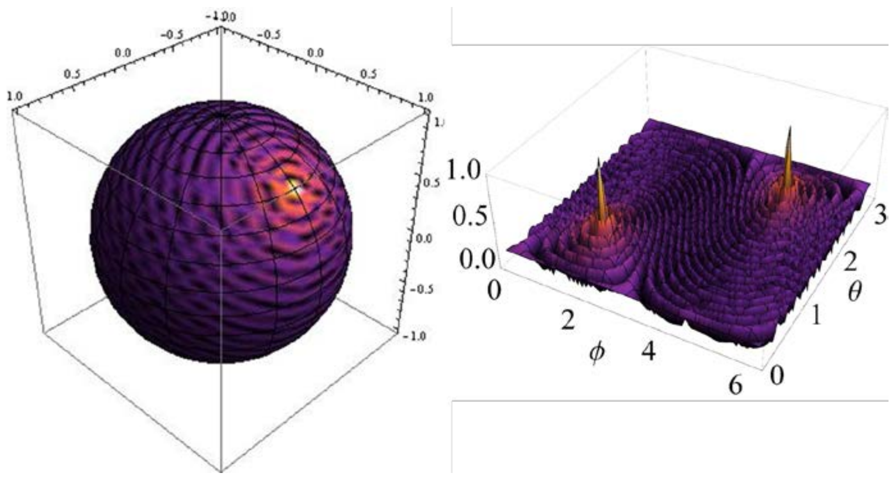

Figure 2. Image Formation on a spherical surface.

We have developed an analytical model describing this process of image formation and we have confirmed its validity through extensive full-wave numerical simulations. According to our model the proposed imaging scheme is able to deliver sub-diffraction images with resolution on the order of $\lambda / 20$, limited only by the propagation losses experienced by the surface plasmon polaritons on the the spherical surface, and by the width of the gap between the two surfaces .

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