Digital Plasmonics

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I. MANUSCRIPT

The field of plasmonics[1] offers a route to control light fields with metallic nanostructures through the excitation of Surface Plasmon Polaritons (SPPs)[2,3]. These surface waves, bound to a metal dielectric interface, tightly confine electromagnetic energy[4]. Active control over SPPs has potential for applications in sensing[5], photovoltaics[6], quantum communication[7], nano circuitry[8,9], metamaterials[10,11] and super-resolution microscopy[12]. We achieve here a new level of control of plasmonic fields using a digital spatial light modulator. Optimizing the plasmonic phases via feedback we focus SPPs at a freely pre-chosen point on the surface of a nanohole array with high resolution. Digital addressing and scanning of SPPs without mechanical motion will enable novel interdisciplinary applications of advanced plasmonic devices in cell microscopy, optical data storage and sensing.

Positioning and focusing waves in transparent media requires fine tuning of the phase profile so that waves converge and constructively interfere at a point. A conventional lens uses refraction to redirect the waves to the focus and a well-designed lens shape to align the phase vectors of these waves. Due to the fixed geometric shape of the lens, the position of the focus can only be controlled by mechanically moving the lens or changing the angle of incidence of the incident beam. Focusing and controlling the position where waves constructively interfere in complex structures require new methods that are more versatile. Optical wavefront shaping has become a popular method that allows to focus light even inside completely disordered materials[13,14].

Positioning and focusing SPP waves in a controlled way is important for nanophotonic applications. To date plasmonics offers only a limited flexibility in the control of light fields: as with the conventional lens the geometry is typically fixed, so for a given optical frequency the locations of optical field enhancement are also fixed. Recently, some breakthroughs have been made on active control in which the intensity of the light fields is influenced in time, either through pump-probe[15,16] or through coherent control[17]. Only in specific cases this control also leads to spatial selectivity[18,20]. However, in the experiments the spatial selectivity is limited to a few modes predefined by the sample structure.

We demonstrate here a new level of control of SPP wavefronts. This control allows us to tune any SPP interference phenomenon with unprecedented flexibility. Specifically, we show that we can generate, focus SPPs and scan the focus on a nanohole array with an electronically controlled spatial light modulator and standard helium neon laser. Because the light-to-SPP conversion process is coherent, the structured optical wavefront is projected onto the SPP wavefront. This conversion gives us full phase control of the SPPs, allowing us to shape the SPP wavefronts digitally. Because we use optimization loops to determine the necessary wavefront, our method is applicable to any plasmonic structure. Such flexible and digital control of SPPs is a large step forward towards interdisciplinary applications of advanced plasmonics.

The sample is a nanohole array, similar to those used typically for Enhanced Optical Transmission (EOT) experiments[21,22] and recently suggested for super-resolution[23]. Our sample is composed of a 200 nm of gold film deposited on top of 1 mm BK7 glass substrate. The array covers an area of 30 x 30 μm² and the hole period is 450 nm. Square holes were milled with sides of 177 nm. The SPP wavelength at the gold-air interface from incident radiation of \( \lambda_0 = 633 \text{ nm} \) is given by

\[
\lambda_S = \lambda_0 \text{Re}\sqrt{\frac{\varepsilon_m + \varepsilon_d}{\varepsilon_m \varepsilon_d}},
\]

with \( \varepsilon_m \) and \( \varepsilon_d \) the dielectric constants of gold and air, respectively. Using tabulated bulk values for \( \varepsilon_m \) we found \( \lambda_S = 600 \text{ nm} \).

Our aim is to digitally control the amplitude and phase of SPPs locally on the surface of the sample. This control is achieved by imaging a Spatial Light Modulator (SLM) onto the surface of the sample thus mapping each unit cell (pixel) of the SLM to a corresponding area on the sample. Amplitude and phase control of the SLM is achieved via the 4-pixel technique[24] where four adjacent pixels are grouped into a superpixel. We apply to the SLM a 32 x 32 superpixel division and we independently control amplitude and phase of each superpixel.

A diagram of the setup is given in Fig. 1. Based on SPP momentum conservation we designed the imaging...
electricity and magnetism (EM) interact with matter at length scales near the electromagnetic wavelength. This interaction is magnified when the length scales are comparable to the wavelength, resulting in enhanced EM fields, which can be utilized in plasmonic devices. These devices are gaining traction in a variety of applications such as sensing, imaging, and information storage. In this work, we introduce a novel method for focusing Surface Plasmon Polaritons (SPPs) with a Spatial Light Modulator (SLM). The approach offers improved control over SPPs compared to previous techniques, such as spatial light modulators.

**System Description**

The system consists of a Spatial Light Modulator (SLM), a He-Ne laser, a beam splitter, a camera, two lenses (L1 and L2), and a sample hole array. The SLM is used to control the amplitude and phase of the incoming light. The He-Ne laser provides the illumination source. The beam splitter divides the light into two paths: one that passes through the SLM and another that acts as a reference. The light is then imaged onto the sample, which consists of a nanohole array. The sample is placed between the two lenses, which further magnify the focused SPPs.

**Experiment Setup**

In Fig. 1, the experimental setup is shown. The SLM is imaging the sample through the two-lens system L1 and L2. The demagnification is 650 times. Every image point on the sample is formed by three pixels. The amplitude and phase of each pixel are controlled independently with a computer. The sample is a nanohole array engraved on a gold film. The blue arrows illustrate the propagation of Surface Plasmon Polaritons (SPPs) launched from two pixels of the SLM. The resulting illuminated areas are visible in Fig. 2a. The overall phase is constant. Any intensity detected inside the arena is purely plasmonic. The designed amplitude profile defines four bright plasmon-launching areas and one central dark arena. This setup ensures that no photons enter the “off” areas. The observed contrast is nearly three orders of magnitude, indicating that no photons enter the “off” areas.

**Amplitude Projection**

To separate plasmonic from optical effects, the system is designed to control amplitude and phase. In Fig. 2b, the sample is illuminated by the structured amplitude profile and the light reflected from the sample is imaged on the camera. In each sample point, the bright rectangles are the illuminated (amplitude=1) SPP launching areas. The SPPs are observed in the dark (amplitude=0) central SPP arena.

**Phase Control**

The phase of the incident light and the laser light are controlled with a computer. When the designed amplitude profile is projected onto the sample, SPPs are launched toward the center of the detector. This light includes both the direct reflection of the illuminating beam and the scattered light from plasmonic features. Thus, the resulting image is a combination of both the SLM amplitude pattern and the generated SPPs.

**Amplitude Optimization**

To demonstrate this, experiments with different amplitude profiles are conducted. In Fig. 2a, the sample is illuminated by the structured amplitude profile and an additional white light source, revealing both the hole array grating itself and the laser light. The figure also demonstrates the optical resolution of the setup: sufficient to resolve the presence of the hole array pattern but not the shape of the holes.

When two counterpropagating SPP waves interfere, a standing wave pattern of intensity is created. The observed period of the fringe pattern is clearly not half the SPP wavelength, as expected for SPPs propagating on an ideally smooth and non-corrugated sample. The measured fringe period is 1±0.05 µm. We attribute the fringe pattern to a Moiré effect between the true standing SPP wave and the periodicity of the arrays.

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Now we present experiments of SPP focusing with digital phase control. The achieved SPP focusing is shown in Fig. 3a. We use a phase optimization loop to focus SPPs at a pre-chosen target. This loop yields the optimal phase (φ) for each superpixel as well as the relative contribution (C) to focus. The amplitude profile is the same as for the bare gold case with four launching areas and a central dark area where only SPPs can propagate. The incident polarization is diagonal with the grating lines so as to have all available angles (2π range) contributing to the focus, thereby maximizing the NA and resolution.
Successful focusing at center of the SPP arena is shown in Fig. 3a. The structured SPP wavefront produces an intensity in the designated target that is at least 20 times higher than the average SPP background of an unstructured wavefront. The measured size of the plasmonic focus is 420 nm, consistent with the diffraction limit of the detecting optics.

We interpret SPP focusing in terms of Green’s functions connecting the electric fields at any two points. We idealize every “on” superpixel in the SPP arena without any mechanical motion to controlled positions in the plasmonic arena. Thus the superpixels of the SLM effectively behave as amplitude and phase sensitive detectors. These results are valid for any Green’s function or nanostructure and can be extended to the time domain and the transfer matrix approach.

For a perfectly smooth sample with no corrugations the SPP Green’s function is simply a cylindrical wave in two dimensions (the Hankel function $H_0^{(1)}(Kr)$ with $K$ the complex-valued SPP momentum). Our digitally measured Green’s function includes the light-to-SPP coupling and therefore presents much more complexity. With digital plasmonics we demonstrate the first “black-box” with nanoscale SPP outputs and text file inputs. Specifically, we focus SPPs on hole arrays and locally scan the focus freely over a field-of-view (SPP arena) without any mechanical translation. In achieving such dynamic focusing we recorded amplitude and phase.
Green’s functions. These digital records, which contain the full complexity of the Green’s function, are used as self-calibrated inputs. The method can be extended to any plasmonic structure and to the time domain. This digital plasmonic workbench is anticipated to enable interdisciplinary applications in microscopy, optical data storage and in bio-sensing.

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