Digital plasmonics: from concept to microscopy

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Here we demonstrate a novel Surface Plasmon Polariton (SPP) microscope which is capable of imaging below the optical diffraction limit. A plasmonic lens, generated through phase structured illumination, focusses SPP’s down to the their diffraction limit and scans the focus with steps as small as 10 nm. This plasmonic lens is implemented on a metallic nanostructure consisting of alternated hole array gratings and bare metal arenas. The nanostructure has two uses: its hole gratings provide the light-to-SPP coupling while the bare metal arenas provide the focusing/scanning area of the plasmons. The resolution is determined with scattering holes on the bare metal arenas. Because the propagation of SPPs on bare gold is non radiative, only light from the scattering holes is recorded thus allowing us to determine their relative location on the nanostructure. The resolution is determined by the scanning SPP focus, independent of the detection optics. This novel technique has potential for biomedical imaging microscopy, surface biology and functionalization chemistry.
4.1 Introduction

Optical microscopy provides images of a specimen via its interaction with light. The smallest features resolved with conventional microscopy are at best in the range of the optical wavelength $\lambda$ and subject to the diffraction limit of the optics. To reveal the underlying information inside $\lambda^3$ volumes, a number of techniques have been proposed [115, 116]. Near-field microscopy employs scanning nanoprobes either in collection or scattering mode to achieve better resolution [3, 117, 118]. In [119] fluorescence microscopy the improvement exploits special qualities of the labels like fluorescence saturation [120, 121] or stochastic emission [122, 123]. Because most of the interactions and exchanges between living cells and the surrounding environment happen at the surface, surface specific microscopy is of crucial importance for biology and medicine as well as for nanotechnology. Total internal reflection microscopy (TIRFM) is a widely used technique that uses evanescent waves to achieve surface-only imaging [124].

Plasmonic microscopy is a novel concept of microscopy [77, 108, 109] via the excitation of evanescent waves on metallic nanostructures. Surface Plasmon Polaritons (SPP) are surface waves bound to metal-dielectric interfaces. The major advantage of SPPs is that, for a fixed light frequency, the wavelength of these waves is shorter than that of free propagating photons in the same dielectric [41, 44, 43]. Thus, plasmonic microscopy offers not only evanescent out-of-plane resolution (similarly to TIRFM), but also offers large potential for in-plane super resolution.

The main barrier for plasmonic microscopy is the impossibility to use plasmon optics [125] for detection: the read out is always optical. Wide-field plasmonic excitation from a SPP plane wave yields an image that is limited in resolution by the detection optics.

Super resolution is achievable provided that plasmon optics are used to provide tightly confined excitation (e.g. SPP diffraction limited focus) in a scannable way. Advances in nanofabrication allow for the use of nanostructures to manipulate SPPs [82, 83, 84]. But these methods have tiny fields of view, and are thus more suitable for sensing than for microscopy. Recent theoretical [104, 105, 87] and experimental [111, 112] developments have shown the potential of plasmonic phase structuring for 2D surface microscopy. Nevertheless, due to intrinsic problems of these techniques (resolution, field of view or speed), super resolution plasmonic microscopy still has to be implemented.
4.1.1 Our contribution

We demonstrate here the first plasmonic microscope performing at the SPP diffraction limit by imaging scatterers on top of a metallic microscope slide. Specifically, we show that by using phase-structured illumination from a spatial light modulator (SLM) we can both focus and scan SPP’s below the optical diffraction limit. The size of the SPP focus is given by the plasmonic diffraction limit which, for a fixed photon frequency, is smaller than the optical diffraction limit. The combined system of the nanostructure with the phase-structured illumination can be thought of as a deformable plasmonic lens. Due to the simplicity of our metallic microscope slide we can calculate the required phase profile for focusing of our plasmonic lens without the necessity of feedback loops. This deterministic approach allows for fast scanning with steps as small as 10 nanometers, and thus microscopy. The imaging resolution is determined by the SPP wavelength supported by our metallic microscope slide. Upgrading the microscope slide, for example by using a multilayered metal-insulator-metal film, opens up potential for a new range of high resolution imaging. Furthermore, because fast SLM devices with megapixels have recently become available, parallel processing of multiple foci might be achievable at video rate and without any resolution loss.

4.2 The working principle

The requirements for a SPP microscope are: (1) to control the amplitude and phase of SPPs locally on the surface of the sample, (2) to create and 2D raster scan a plasmonic focus without feedback, and (3) to provide a consistent and reproducible image of the sample surface.

4.2.1 Experimental configuration

To satisfy our first goal we image 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. The imaging system and its design have already been reported in chapter 2. Amplitude and phase control of the SLM is achieved by grouping pixels into superpixels. We independently control amplitude and phase of $32 \times 32$ superpixels. The image of each superpixel (nearly 450 nm with a 650 times demagnifying imaging system) locally excites surface plasmon waves due to periodic corrugations on the
sample [126]. These waves propagate along the surface of the sample and emit photons when encountering scatterers (like nanoparticles or fluorescent molecules). Finally, the surface of the sample is imaged onto the sensor of a CCD camera revealing these ejected photons.

Figure 4.1: Working principle of the SPP microscope. The Spatial Light Modulator (SLM) is illuminated with a large laser beam (the translucent red circle) and is imaged onto the surface of a nanostructure metallic film. The nanostructure, imaged onto a CCD, is a hole array grating with arenas. The arenas consist of bare metal with few scatterers (the circles). Only two pixel lines of the SLM have nonzero amplitude (amplitude profile). These bright pixels, when imaged onto the grating lines adjacent to the arena, locally generate SPPs that propagate into the middle arena. The arena’s flatness allows us to predict the phase profile for SPP focusing (dashed lines) without the necessity of a feedback loop. Photons are detected only when the SPP hit a scatterer, thus locating the scatterer. A raster scan (2D) of the focus provides a full SPP resolution image of scatterers.

4.2.2 Deterministic SPP focusing and scanning

To achieve SPP focusing at a chosen location we combined our ability to structure the incident illumination (in this case a He:Ne laser was used)
with a specially designed nanostructure. This configuration is schematically depicted in Fig. 4.1. Two parallel lines of bright pixels (non zero amplitude) are imaged on a specially designed nanohole array to launch SPP waves. These lines, each comprised of 13 superpixels, are our SPP sources. The area between the source lines, which we will call the arena, is free of the grating: it is bare metal with a few scatterers to test the properties of the microscope. The SPP waves inside the arena in which they propagate freely in two dimensions can be described by the well known Hankel function (the equivalent of a spherical wave in 2D). The analytical expression of the Hankel function is known. This knowledge allows us to determine the phases for SPP focusing at any target point inside the arena by evaluating the relative distances target-sources. Furthermore, these SPP waves cannot couple to the far field; only when a scatterer is encountered photons are emitted thus imaging the scatterers. More lines of sources can be used to create multiple foci for parallel imaging of many arenas without any increase in the acquisition time, thus allowing multiplexing.

### 4.2.3 Hole array with structured arenas

The nanostructure is a metallic nanohole array with a rich electromagnetic behavior [85]. Subwavelength gratings offer potential for super-resolution either for dielectric [86] or metal-dielectric [87, 91] configuration. On the grating, the electromagnetic behavior can be described in terms of a hybrid wave [88] arising from SPPs (majority) and quasi-cylindrical waves [89] (minority). The propagation of quasi-cylindrical waves on bare metal is very short(wavelength). Our samples have been designed so that only SPP waves are observed.

Our substrate is composed of a 200 nm of gold film deposited on top of 1 mm BK7 glass substrate. The array covers an area of $30 \times 30 \, \mu m^2$ and the hole period ($a_0$) is 450 nm. Square holes were milled using a focused ion beam with sides of 177 nm. The nanostructure includes four square arenas ($5 \, \mu m \times 5 \, \mu m$), each different from the other and all surrounded by the hole array, as shown in Fig. 4.2.

The SPP wavelength at the gold-air interface from incident radiation of $\lambda_0 = 633 \, nm$ is given by

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

(4.1)

with $\varepsilon_m$ and $\varepsilon_d$ the dielectric constants of gold and air, respectively. Using tabulated bulk values for $\varepsilon_m$[53] we found $\lambda_S = 590 \, nm$ (for $\lambda_0 = 633nm$).
SPP waves are launched from the hole array grating and propagate on the arena. Each arena will be used separately.

4.2.4 Test samples

To test our microscope’s imaging ability, two arenas with known structures were prepared. Each arena includes eight scatterers which are nanoholes identical to the ones of the hole array. SEM images of these arenas are shown in Fig. 4.3a-b. The arena of Fig. 4.3a includes randomly positioned holes to test our 2D scanning ability.

The line arena of Fig. 4.3b consists of bare gold with a line of holes. The profile of the line is shown in Fig. 4.3c. The spacing between the holes, defined as the width of the metal stripe between them, is

\[ l_i = i \cdot 100 \text{ nm}, \quad \forall i \in 1...7. \]  

(4.2)

We will use the varying hole spacing in the line arena to determine the resolution of our microscope: if we focus in the space between the holes and if the SPP focus is smaller than the hole spacing, then no photons should be detected.
4.3 Calibration and implementation

Both arenas have a large margin of bare gold between the scatterers and the grating so that only SPP waves are observed (no quasi-cylindrical waves).

4.3 Calibration and implementation

Here we will present reference experiments obtained from a wide field plasmonic microscopy (plane wave SPP illumination). We will show that, because we are using plane wave SPP illumination (no focusing), the imaging resolution is still photon-like diffraction limited. Finally we will conduce preparations for implementing our deformable plasmonic lens, like initializing the SPP sources and calculating their phase for focusing.

4.3.1 Plasmonic plane wave microscopy

Here we image the structure of the line arena using a plane wave SPP illumination. The phase of all superpixels are set to the same value yielding a SPP wave propagating on the arena. The scatterers are excited from this SPP plane wave (wide field illumination). The scattered light is recorded on
a single CCD image (single-shot) determining the location of the scatterers. Results from this wide field SPP illumination (which will be later used as a reference) are shown in Fig. 4.4. Two lines of SPP sources with flat phase are placed on the opposite sides of the arena. The SPP plane wave propagating inside the arena is invisible (it cannot radiate) except for when it is scattered by the holes. In such a way the single-shot image of the holes, Fig. 4.4, is taken. The imaging resolution of this wide field SPP microscope is still photon-like diffraction limited: because the SPP illumination is not focused the resolution of such an image is fully determined by the detection optics and the photon wavelength. In principle the image remains unchanged for any given SPP wavelength, no matter how small. The resolution can improve depending on the SPP wavelength only by using plasmonic optics, thus by creating and scanning a focus.

4.3.2 Initializing the SPP sources

To calculate the required phases for focusing at a chosen target point, the distance of all sources from the target must be known. In order to find
these distances we define a coordination system based on the CCD’s pixels coordinates. Because of the magnification of our detecting system, each pixel corresponds to 64 nm on the sample. To determine the location of the sources we load them (turn them ”on”) one by one, as illustrated in Fig. 4.5a-c for three sources. For this figure, extra white light illumination is used to observe the arena (but not for the initialization process).

Once a single source \((S_n)\) is loaded, we associate its position with the maxima of the CCD image: the source location, \(r_n\), is the maxima’s position. We iterate this initialization procedure for all the 26 sources (2 lines of 13) of the amplitude mask.

![Figure 4.5: Determination of source’s positions. Each source is loaded separately in absence of the other ones. The maxima of the picture (it’s position) locates the source. (a)-(c) Three sources loaded in series. For showing the relative position of the sources in respect to the arena, the arena is also illuminated with white light.](image)

### 4.3.3 Calculation of the phases for focusing

After the initialization procedure, we have located all sources at positions (CCD coordinates)

\[
r_n = (x_n, y_n) \quad \forall n \in 1...26.
\]

With these source positions we calculate the required phases \(\tilde{\phi}(r_n, r_0)\) for focusing the SPPs at an arbitrary target point at position \(r_0 = (x_0, y_0)\). The Green’s function connecting the source to the target, \(g(r_0, r_n)\), is given by the Hankel function \(H_0^{(1)}(K_Sr)\) with \(K_S (K_S = k_S + i2/L_S)\) the complex valued SPP momentum
This Green’s function is fully determined once the source-target distance \((R_{0,n})\) is known. For focusing, the fields from different sources have to be in phase with each other at the target location. To achieve this phase alignment, the loaded phase (via the SLM) of any source must compensate the phase delay introduced by the relative Green’s function
\[
\tilde{\phi}(r_n, r_0) = -\arg[g(r_0, r_n)] = -k_S r_{0,n} = -\frac{2\pi}{\lambda_S} r_{0,n}.
\]

The phase \(-\pi/4\) in the exponent of the right side of eq. 4.4, constant for all sources, is removed from Eq. (4.5) as part of a global phase offset (only phase differences are relevant).

### 4.4 SPP microscopy via focusing and scanning

To implement the scanning of the focus (required for imaging) we repeat the calculation for a 2D grid of target point. A typical grid of 100 \(\times\) 100 target points, while covering the entire 5 \(\mu m\) \(\times\) 5 \(\mu m\) arena, provides a step-scan resolution of 50 nm. This series of simple calculations allows us to separately focus SPPs at points which are up to few nanometers far from each other.

#### 4.4.1 2D imaging of the random arena

Our main result, two dimensional imaging using the new scanning plasmon microscope, is shown in Fig. 4.6a. A single point of the image is acquired by focussing SPP at the target point having coordinates \((x_0, y_0)\) and reading out only the CCD intensity of the pixel corresponding to the same coordinates. The full image is acquired by raster scanning the focus: the fast axis along the focal line (focal plane in 3D). The scan step is 16 nm. For comparison, an image of the same structure obtained with white light illumination is shown in Fig. 4.6b. At first glance it is already clear that the plasmonic image of the structure is sharper and better resolved than the white light one.

The overlap between the SEM image (transparent) of the structure and the plasmonic image is shown in Fig. 4.6c: the two images match correctly.
Figure 4.6: Imaging the nanostructured arena. (a) Accumulative 2D image of the arena achieved via scanning the SPP focus. Only when the SPP focus encounters a scatterer photons are detected. (b) Arena imaged with white light illumination. (c) Comparison between (a) and the SEM image of the structure (Fig. 4.3a).
There are few deviations (upper left corner). One reason for deviations is that two nearby scatterers screen each other from the plasmon sources (left and right of the image). Nevertheless, those two scatterers are better resolved than in the white light image. To estimate the focal size of the SPP spot we fitted a gaussian to the line cut of the collected intensity of best resolved holes (Fig. 4.7). The geometrical size of the hole is known from the SEM image. The optical profile (lateral cut) is the result of a convolution of the geometrical profile of the hole with our gaussian SPP focus. From the fit we determined for the SPP focus a FWHM (full width at half maximum) of $280 \pm 30 \text{ nm}$, in agreement with the SPP diffraction limit ($\lambda_S/2$). The optical diffraction limit of our objective lens is $430 \text{ nm}$ for the HeNe wavelength ($\lambda_0 = 633 \text{ nm}$). In principle the SPP numerical aperture can be improved to include all possible angles by using four lines of sources in square geometry.

**Figure 4.7:** Evaluation of the SPP focus size. The data are a cut of Fig. 4.6a restricted to a single hole. This observation is the convolution of a gaussian SPP focus with the hole profile (known by design). We fitted the data with a fixed hole profile to determine the SPP gaussian spot (FWHM of $280 \text{ nm}$)
4.4. SPP microscopy via focusing and scanning

**Figure 4.8:** 2D imaging of the line arena. (a) Image acquired with our new method. (b) SEM fragment of the arena shows that all scatters are resolved except for the two closest ones. (c) Cut of image (a) and comparison with a cut achieved without SPP focusing (Fig. 4.4). The holes separated by 100 nm gold are unresolved, while the shoulder next to the high peak resolves the ones separated by 200 nm gold (only for the focusing and scanning image). This shoulder is indicated by the pointer.
4.4.2 Imaging the line arena

To better characterize the resolving power of our plasmonic scanning microscope we imaged with a 64 nm step scan (corresponding to one CCD pixel) the structure of the line arena. Because for this arena the line of scatterers is parallel to the source lines, two nearby scatterers cannot screen each other. In other words: SPPs propagating along the lines that connect the sources to a scatterer do not encounter any other scatterer. Thus, for this arena, screening or shadowing among scatterers is avoided.

Results for this structure are shown in Fig. 4.8. The 2D SPP focusing image, shown in Fig. 4.8a, perfectly matches the structure of the arena. In Fig. 4.8b we show for comparison the SEM image of the same structure. Our focusing and scanning image is sharper than the image obtained with plane wave plasmon illumination (Fig. 4.4). The fundamental difference between these two images is that, even though both of them are detected with the same optics, Fig. 4.4 is photon-like diffraction limited and Fig. 4.8a is plasmon-like diffraction limited.

For quantitative comparison of these two images we plot in Fig. 4.8b one dimensional line cuts along the line of holes. Because the SPP wavelength ($\lambda_s = 590 \text{ nm}$) is only few percent shorter than the vacuum wavelength ($\lambda_0 = 633 \text{ nm}$), the cuts seem similar at first glance. The two holes separated by 100 nm gold are unresolved with both methods, as seen by the high central peak. A separation of 200 nm is still not fully resolved. However, the shoulder right of the main peak is a clear indication of the higher resolving power of our novel microscope. Such shoulder is unresolved by the Rayleigh criterion (standard diffraction limit) but is considered resolved by the Sparrow criterion which requires a local minima.

4.5 Interpretation and discussions

Now we will show calculations related to the point spread function (psf) of our 2D imaging technique and how this psf depends on the read out method. Different readout methods will be compared theoretically and our experimental readout method will be justified as the best method. Finally we will calculate the intensity distribution in the arena and will test the robustness and consistency of the microscope.
4.5. Interpretation and discussions

4.5.1 Point spread function (psf)

A microscope’s resolution is fully characterized by its point spread function. The psf is the image created by an ideal point source. For a standard objective lens the psf at the focal plane $h(\mathbf{r})$ is an Airy disk, which can be approximated by a 2D gaussian profile. The FWHM is determined by the optical numerical aperture of the lens. Our detection objective has a NA=0.9 yielding a diffraction limit of 430 nm ($\lambda_0 = 633nm$).

For the SPP microscope the psf, $h_S(\mathbf{r})$, is a combination of the SPP excitation $f(\mathbf{r})$ and detection $h(\mathbf{r})$ point spread functions. A point source $\delta(\mathbf{r})$ in the origin of the coordinates is illuminated with SPP excitation $f(\mathbf{r}-\mathbf{r}_0)$ focused at $\mathbf{r}_0$. Optical detection yields for the full CCD intensity

$$I_{CCD}^0(\mathbf{r}) = [f(\mathbf{r}-\mathbf{r}_0)\delta(\mathbf{r})] \otimes h(\mathbf{r}) = f(-\mathbf{r}_0)h(\mathbf{r}). \quad (4.6)$$

Here we consider three relevant experimental means of plasmon illumination and optical detection. Each of these combinations gives different values for the SPP microscope point spread function $h_S(\mathbf{r})$ and thus the resolution. These three are (1) wide field plasmon illumination with single shot optical imaging, (2) scanning focused plasmon illumination with integrated intensity optical collection, and (3) scanning focused plasmon illumination with optical collection at the expected focus. We will call these readouts: single shot (1), integrated intensity (2), and pixel intensity at the SPP focus (3). The experiments shown before were performed using the pixel intensity at the SPP focus.

The psf for single shot imaging is given by Eqs. (4.7a-b). The psf of this single shot read out is the detection psf which is independent of the plasmonic illumination wavelength. This read out does not improve the resolution beyond the detection optics as was shown experimentally in Fig. 4.4.

$$I_{S,1}(\mathbf{r}) \equiv I_{CCD}^0(\mathbf{r}) = f(-\mathbf{r}_0)h(\mathbf{r}); \quad \forall \mathbf{r}, \quad (4.7a)$$

$$\Rightarrow h_{S,1} = h. \quad (4.7b)$$

The integrated intensity read out is described in Eqs. (4.8a-b). For every position of the focus we integrate the full CCD intensity. The psf of this read out is the plasmonic psf, $f(\mathbf{r})$, which gives improved resolution along the SPP focal line.

$$I_{S,2}(\mathbf{r}_0) \equiv \int I_{CCD}^0(\mathbf{r})d\mathbf{r} = f(-\mathbf{r}_0)\int h(\mathbf{r})d\mathbf{r}; \quad \forall \mathbf{r}_0, \quad (4.8a)$$

$$\Rightarrow h_{S,2} = f. \quad (4.8b)$$
Figure 4.9: Point spread functions for different read outs. (a) The single shot read out yields the same psf as the detection optics. (b) The integrated intensity read out yields a psf given by the shape of the SPP focus (assumed here to be an ellipse as for a single line of sources). (c) The pixel intensity at the SPP focus yields the optimal read out. The psf is the product of detection and excitation ones.

The optimal read out method is the pixel intensity at the SPP focus. The psf of this read out is the product of the excitation and detection point spread functions. This psf is the smallest possible.

\[ I_{S,3}(r_0) \equiv I_{CCD}^0(r_0) = f(-r_0)h(r_0); \quad \forall r_0, \quad (4.9a) \]
\[ h_{S,3} = f \cdot h. \quad (4.9b) \]

A cartoon describing the differences of the read out methods is shown in Fig. 4.9. For any given detection and excitation point spread functions, the best achievable combination is the product. For our SPP microscope, such combination is provided via the pixel intensity at the SPP focus read out.

4.5.2 Consistency test with a different intensity read out

The pixel intensity at the SPP focus method was used to obtain (via scanning) the images of the arenas as presented in Figs. 4.6 and 4.8. To form these images, we focused SPPs at one target and acquired only the target pixel intensity \( I_{CCD}(x_0,y_0) \). From every CCD picture only one pixel value was acquired. Thus the imaging quality of the technique strongly depends on creating the focus exactly at the target.

Here we test if the focus is exactly created at the target location. The principle behind this test is the fact that the plasmonic intensity is maximal at the exact focus location. Thus to run the test we will compare the maximal intensity value (only along the focal line) with the intensity value at the presumed focus. If these two values are equal than the test is successful.
Figure 4.10: Line arena imaged with the maxima read out. (a) The image is acquired by focusing at a target and reading the maximal intensity along the focal line. (b) Cuts from the maxima read out (black line) and the pixel read out (red line). The pixel read out provides sharper and more correct imaging. The blue line is the location of the maxima: the plateaus are the scatterers.

meaning that the presumed location and the real location of the focus coincide. Otherwise, phase offsets have to be used to compensate for deviations of the focus location.

The test is experimentally run by acquiring an image of the line arena with a new read out, the maximal intensity read out. When focusing at \( r_0 = (x_0, y_0) \) with the sources along the \( x \) axis, the new read out associates to the point \( r_0 \) the maxima of intensity along the focal line \( (y = y_0) \). Mathematically, this maximal intensity read out \( I_S(r_0) \) is

\[
I_S(x_0, y_0) \equiv \max \{ I_{CCD}(x, y) \} \bigg|_{y = y_0}. \tag{4.10}
\]

Results from this readout are shown in Fig. 4.10a. With this read out
we can test if the calculated focus is really focusing at the target location. In Fig. 4.10b we compare the absolute intensities (cuts) of the maximal read out with the pixel intensity at the focus read out. These cuts nearly coincide in their highest absolute intensity. Thus the test is successful and confirms that, at least for the central holes, focusing is happening at the target location with very high precision.

For holes close to the arena border there are deviations. These deviations are possible border effects due to the structure of the scatterers. The borders of the hole scatter more than the center and thus the maxima always coincides with a border even though the center of the focus might well be on bare gold. The deviations are up to the hole size.

For clarity, the pixel read out is the one that maps the structure with correct dimensions.

### 4.5.3 Calculated intensity distribution in the arena

Here we will numerically calculate the theoretical intensity distribution in the arena when focusing, thus the SPP point-spread-function. We will use the fact that each source emits spherical waves and the phases of these waves are set to focus at a random point of the arena. Finally, other source geometries that can improve the focusing will be discussed.

The intensity distribution for focusing with the real experimental parameters (two lines of sources) is shown in Fig. 4.11a. As expected, a standing pattern of roughly circular fringes is created with $\lambda_S/2$ spacing. Cuts for the created focus are shown in Fig. 4.11c. The axial resolution is as expected $\lambda_S/4 = 150 \text{ nm}$, or half the fringe spacing. The lateral resolution is nearly $\lambda_S/2 = 300 \text{ nm}$. This lateral resolution depends on the numerical aperture used to create the focus.

Better focusing can be achieved if we increase the numerical aperture (NA) by adding more sources. For example, in Fig. 4.11b we simulate focusing with four lines of sources in a square geometry. This configuration provides the sharpest focus possible with both axial and lateral resolutions equal to $\lambda_S/4$. By choosing the pixel readout, it is possible to isolate the central peak from the side lobes.

To test the robustness of the focusing procedure, we added phase noise to the intensity distribution Fig. 4.11d. We add a large amount of random noise, $\pm 20\% \cdot 2\pi$, to the ideal phase. The distortions are well contained (comparison with Fig. 4.11a) and the aberrations are minimal confirming that the imaging technique is robust against errors.
Figure 4.11: The images are calculated intensity distributions inside an empty arena. The source lines are next to the arena. (a) Two vertical lines of sources create a focus. The lateral and axial resolutions are different. (b) Focusing with four lines of sources results in a sharper focus. The better focussing (FWHM=150 nm; lateral and axial) is due to a maximized numerical aperture (2π). (c) Axial (along x) and lateral cuts of the focus created with two lines of sources (figure a). The axial (lateral) FWHM is 150 (300) nm. (d) In repeating the two line focusing, random phase noise was added (up to 30% of 2π). The focusing is barely distorted yielding that the method is very robust.
4.6 Conclusions

We show the first imaging technique based on surface plasmon polaritons that provides resolution beyond optical diffraction without near field probing. The technique, demonstrated on single-interface SPPs, is implementable to metal-insulator-metal SPPs that achieve wavelengths ten times shorter than the vacuum one.

The novelty of the method is the use of deformable plasmon optics for 2D imaging, which in contrast to previous attempts on SPP microscopy with far field detection, provides resolution dependent on the SPP wavelength. To create the plasmonic lens we use phase structured illumination from a spatial light modulator (SLM) and deterministic (without feedback) calculation of the phases for focusing and step scanning with nanometer precision. Because we use a megapixel SLM, parallel processing of multiple foci is possible.

This new technique offers the potential to revolutionize microscopy, surface biology, and in-vivo medical imaging: Extending the technique with fast spatial light modulators (100 KHz) and short wavelength MIM plasmons enables video rate imaging of millimetric samples with nanoscale resolution.

4.7 Acknowledgments

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