Digital plasmonics: from concept to microscopy
Gjonaj, B.

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In this chapter we do not provide new experiments or theory. In this chapter we discuss possible application of the results already presented in the previous chapters. We will describe the potential for the plasmonic microscope along with some other potential applications. Part of the information in this chapter has been filed for a patent.
6.1 Introduction

In this chapter we describe ideas for applications based on amplitude and phase structured plasmonic waves. This chapter is divided into two sections: (1) description of plasmonic microscopy via SPP structured illumination and via raster scanning of a tight plasmonic focus, and (2) description of general concepts and ideas for new plasmonic applications based on the experiments shown in the previous chapters.

6.2 Plasmonic microscopy

Optical microscopes are powerful investigative tools which are widely spread in hospitals, research labs, and industry. One of the most important specifications of an optical microscope is the resolution. The resolution is determined by the diffraction limit of the optical element (the objective lens). We propose here a plasmonic upgrade to an already existing optical microscope. The core of the upgrade is a nanostructured microscope slide which also acts as a plasmonic lens. Because the wavelength of the plasmons is shorter than the wavelength of the plasmon-exciting light, the plasmonic diffraction limit is smaller than the optical one.

A conventional transmission optical microscope is shown in Fig. 6.1a. In any optical microscope we can distinguish: (1) the light source or illumination part, (2) the sample compartment, (3) the optical element or the objective lens, and (4) the detection part. The sample to be imaged is placed on a microscope slide (a flat glass slab with a standard thickness of 180 µm). The glass slide holding the sample is positioned in the sample compartment of the microscope. The sample compartment contains a diaphragm which allows for the illumination of the sample from below (inset of Fig. 6.1a). The scattered light (or the fluorescence) from the sample is collected with an objective lens. Finally the collected light is recorded on a CCD detector.

Since the invention of the microscope, most of its components have been improved to increase the resolution. Improved illumination has resulted in Structured Illumination Microscopy; improved labeling of the samples has resulted in Fluorescence Microscopy; improved objectives have resulted in high numerical aperture immersion microscopy; improved detection has resulted in confocal and multiphoton microscopy. However, there is one component, the microscope slide, which has remained the same since the microscope creation.
6.2. Plasmonic microscopy

Figure 6.1: Conventional microscope and plasmonically upgraded microscope. (a) A conventional transmission optical microscope includes the illumination source, the sample compartment where the microscope slide (in blue) containing the sample (in red) is placed, the collection objective, and the detector. The imaging resolution is given by the diffraction limit of the objective lens. The inset shows a top view of the sample compartment. (b) The plasmonically upgraded microscope includes a light controlling device to shape the wavefront of a coherent laser source. The optical output of the device, the head, is placed in the sample compartment. The ‘golden’ microscope slide is a metallic nanostructure and is positioned on top of the device’s head. Upon properly controlled illumination the ‘golden’ slides becomes a deformable plasmonic lens (the plasmonic condenser) which achieves tight excitation of the sample and thus high imaging resolution.

6.2.1 The slide is the lens

We propose an improvement to the microscope slide based on metallic nanostructures (for example Metal-Insulator-Metal planar waveguides) and plasmonics. This ‘golden’ microscope slide is both the sample holder and a plasmonic lens if properly illuminated. The implementation of this ‘golden’ microscope slide within a conventional microscope is shown in Fig. 6.1b. The head ending of a light controlling device (which contains a Spatial Light Modulator) is fixed on the sample compartment. The nanostructured sample holder (orange slide in the figure) is positioned on top of the device head. The nanostructure supports plasmonic waves which are controlled or focused by the light controlling device. The combined system consisting of the device and of the ‘golden’ microscope slide is the plasmonic lens. The working principle of the plasmonic lens has been presented in chapter 4. By comparison with the original optical microscope which contains only one lens
(the objective), the plasmonic microscope consist of two lenses (the objective and the plasmonic lens). The performance of an Metal-Insulator-Metal plasmonic lens should be better than that of any objective lens.

### 6.2.2 Working modalities: (1) focusing and (2) plasmonic fringes

The plasmonic upgrade kit can be operated in two modalities: (1) plasmonic focusing and scanning, and (2) plasmonic structured illumination. Switching between modalities is done via the computer without any mechanical motion. Both modalities are shown in Fig. 6.2 and include a multiplexed configuration.
supported by the nanostructured microscope slide.

In the first modality, the sample is excited via a tight plasmonic focus which is raster scanned in 2D. The resolution of the microscope is determined by the size of the SPP focus. For a plasmonic lens created from four lines of SPP sources (maximal NA), as shown in Fig. 6.2a, the FWHM of the focus is a quarter of the plasmonic wavelength. The resolution improvement is due to two factors: the short SPP wavelength and the high NA of the plasmonic lens. The plasmonic upgrade kit also includes a feedback approach to focusing in order to compensate for aberrations.

In the second modality, the sample is excited via standing intensity pattern created from two counter propagating SPP waves, as shown in Fig. 6.2b. The final image is achieved, as for optical Structured Illumination Microscope, by processing multiple images taken with shifted and tilted fringe illumination. The resolution is determined by the fringe periodicity which is half the plasmonic wavelength.

6.3 General ideas for applications

Here we provide qualitative descriptions of these other potential applications. The ideas presented here are based on the results of chapter 2 which are valid for any plasmonic nanostructure because feedback is used to create the desired effect.

6.3.1 Maskless plasmonic lithography

The fabrication of a microchip involves many steps. Lithography is one of these steps and is used for patterning the surface of the chip. The bulk silicon wafer of the chip is coated with a photoresist layer. When the photoresist material is locally exposed to light of short wavelength, typically UV light, the chemical properties of the exposed areas of the photoresist are changed. A chemical bath which specifically binds only to the UV exposed photoresist material, is used to wash away the exposed photoresist from the chip. The empty spaces left after the chemical bath are filled with a new material. The pattern of photoresist exposed to light is controlled by a designed metallic mask, as shown in Fig. 6.3a. The resolution of the pattern is dependent on the wavelength of light: excimer laser at wavelengths of 193 nm are the standard in current technology.

We suggest to use a focused plasmonic beam to imprint the desired pattern in the photoresist with improved resolution. The wafer covered with
Figure 6.3: Standard lithography and plasmonic lithography principles. (a) The wafer is covered with a photoresist layer. Using a metallic mask, only a portion of the photoresist is illuminated with UV light. After developing the resist with a chemical bath, the exposed portion is washed out. The size of the removed portion is proportional to the UV wavelength. (b) The covered wafer is positioned on top of an aluminium film. UV light incident on the film will launch SPP waves of shorter wavelength than the original UV light. A sharp SPP focus is impressed in the photoresist yielding higher resolution than the direct UV lithography.

the photoresist is placed on top of metallic film with the metal in photoresist side towards the metal. To use the same UV light (wavelength = 193 nm), metals with very high plasma frequency (short plasma wavelength) have to be used, for example aluminium (Al). The wavelength of Surface Plasmons at the interface between aluminium and the photoresist (n=1.5) excited from UV light (wavelength = 193 nm) is nearly 90 nm, thus four times shorter than the incident wavelength. The resolution of the pattern imprinted in the photoresist with a focused SPP wave of such short wavelength is higher than by the standard UV lithography, as illustrated in Fig. 6.3b.
6.3.2 Focused plasmons for electron-source generation

Using electron beams to generate Surface Plasmons is a well established technique. These electron generated SPPs propagate and radiate light when encountering scatterers or gratings. Thus electrons generate plasmons which generate light. We propose the inverse configuration: high power light pulses couples into SPPs pulses which, if tightly focused in space and time, will locally generate electrons via the photoelectric effect. This inverse configuration is described in Fig. 6.4a.

**Figure 6.4:** Electron generation from focused SPP waves. (a) Light incident on a metallic nanostructure (grey rectangle) will locally generate SPP waves (the five blue stars) of controllable wavefront. Tightly focused SPP will generate electrons (red circle) at the excamb focus position. (b) Creating multiple SPP foci (from more SPP sources) will result in multiple electron sources. We assume that these are coherent sources. The wavefront of all these electron emitters is controlled via the SPP wavefront which is in turn controlled by the incident optical wavefront. Electron focusing via wavefront shaping is an interesting consequence.

Because we can focus SPPs at any desired point, we can locate an electron source at any desired point. The size of this electron source is the size of our SPP focus, thus smaller than the size of a focused light beam of the same wavelength. The principle of an electron source via focused SPPs can be extended to multiple sources (from multiple SPP foci) yielding the possibility of electronic Wavefront Shaping, as shown in Fig. 6.4b, if the electron emission is a coherent process.
Figure 6.5: Writing a plasmonic byte of information. Light incident on the gold structure will locally induce plasmonic sources (the stars). The phase of all the plasmonic sources as well as their amplitude is controlled via the incident optical wavefront. The optical wavefront is controlled via a computer. Five plasmonic sources are grouped into a SPP pixel which can either create a SPP focus or not. The foci positions coincide with the inputs (nanowires or nanogrooves) of the plasmonic processor. The processor is assumed to be a black box. By tuning the plasmonic pixels “on” or “off” it is possible to communicate a byte to the processor.

6.3.3 Writing an plasmonic byte

Optical computing is the discipline that studies the possibility to use coherent light for computers. The calculating time of an optical computer, based on the principles of quantum optics, is exponentially faster than that of the standard computer. The core of a standard computer is the processor. We The information to/from the processor is transmitted via electrical contacts (wires). The core of an optical computer is the optical chip. The information to/from the optical chip is transmitted via optical contacts (waveguides). An important category of optical computers is based on plasmonics nanostructures that benefit from the good waveguiding properties of surface plasmons (channel plasmons).

We do not propose an improvement of the plasmonic processor which we consider as a working black box. We propose one way to communicate
with a plasmonic chip using a computer. Thus we propose an interface between electronics, optics and plasmonics. The principle of writing one plasmonic byte is shown in Fig. 6.5. A plasmonic processor is connected to a gold platform via metallic nanowires (or grooves). Light incident on the gold platform will excite plasmons sources. These SPP sources can be tuned to create multiple foci (any desired configuration) in correspondence of the nanowire inputs of the processor. The plasmons propagate along the nanowire waveguide and communicate the information to the processor.