Optical Properties of Plasmonic Ag/Ni Square Nanostructures

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Sammanfattning

I detta projekt har syftet varit att studera optiska egenskaper hos plasmoniska nanostrukturer. Två olika periodiska nanostrukturer på ett multilagematerial av Ag/Ni/Ag har undersömts - en med kvadratiska hål och en med kvadratiska öar. För att undersöka periodicitet och geometri hos nanostrukturerna har mätningar utförts med AFM (Atomic Force Microscope).

Projektet har inneburit mätningar av reflektivitet och transmission med p-polariserat samt s-polariserat ljus i de två proverna. Detta för att förstå hur plasmoner uppkommer i och påverkar plasmoniska nanostrukturer. Nanostrukturerna består av periodiska silveröar och en del av projektet har gått ut på att fördjupa förståelsen av silver som ett plasmoniskt material. Ett stort fokus har lagts på skillnaden på plasmoniska excitationer genom att använda p-polariserat ljus jämfört med s-polariserat ljus samt på att förstå hur plasmonerna påverkas av förändring i det infallande ljusets energi och infallsvinkel.

Nanostrukturerna av silver har uppvisat plasmonresonanser i flera riktningar i materialet. Det har visats att både s- och p-polariserat ljus kan excitera plasmoner, dock i olika riktningar. Resultaten visar även att det är möjligt att kontrollera de plasmoniska gensvaren i en periodisk nanostruktur genom att ändra det infallande ljusets energi eller infallsvinkel.
Abstract

In this work, optical reflectivity and transmission measurements have been carried out in order to investigate the plasmonic properties of samples with periodic nanostructures. The main results for two lattices with square islands and with square holes respectively will be presented and analyzed in order to understand the optical features and how the geometry are related to the plasmonic excitations of the structures. The aim of these measurements is to shed light on the role of material properties of Ag as well as to understand how the plasmonic responses are affected when altering the incident angle and wavelength of the incident light. A large emphasis has been made on the difference between plasmonic excitation from s-polarized versus p-polarized light interacting with the samples. It has been shown that it is possible to manipulate and govern the plasmonic responses of periodic, square nanostructures by this method and that both p- and s-polarized light are capable of exciting surface plasmons, however along different directions in the surface of the nanostructure.
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1 Introduction

The field of plasmonics is a rather new one, with its origin in the beginning of the 1900s. Besides shedding light on long existing phenomena such as the stained glass of churches and castles, the plasmons come with enticements of applications in a wide range of domains from more efficient computer components to cancer treatments and invisible cloaks. A whole new range of possibilities, before only known in the worlds of Harry Potter and science fiction novels, have during the last century been envisioned by scientists all around the globe [1].

When light strikes an interface between a metal and a dielectric, the electric field of the light will start to oscillate the free electrons around the atomic core. These electron oscillations will spread to other atoms, resulting in resonant collective electron oscillations. These are called plasmons. The oscillating atoms, which can now be seen as dipoles, will in turn re-emit radiation. This might seem like a quite simple system, but there is still a lot we do not know about it. Knowing more about plasmons is proving to be favorable in understanding how to govern them, making it possible to use plasmonics in different applications. The question of which materials and which structures that make up the most favorable conditions for launching plasmons is at the center of the scientific concern. Metals are an essential component in order to excite plasmons, which makes a good understanding of the interplay of plasmons with metals very important. A range of different metals have been investigated, but the noble metals are usually of extra interest because of their plasmonic properties. This work has chosen to study the plasmonic properties of the noble metal silver.

The nanostructure of the metals has also shown to be of great importance, since plasmons have been shown not to be able to be launched by the means of just shining optical light on a homogeneous piece of metal. Different nanostructures have been studied, for example circles, ellipses and, as in the case of this work, squares. A multilayer sample of silver, nickel, silver layers with a thickness of 75 Å each has been investigated by optical reflection and transmission measurements in order to deepen the understanding of silver as a plasmonic metal as well as for the square nanostructure. Silver is used to investigate its plasmonic properties, while the layer of nickel is added in between the silver layers because of its magnetic properties. This is done as a means of having the possibility to do magneto-optic measurements and to enable external control of the plasmonic resonances.

This report will focus on both of the two plasmon families - Surface Plasmon Polaritons (SPPs) and Localized Surface Plasmons (LSPs). SPPs are plasmons coupling with the electromagnetic field of light and propagates along the metallic-dielectric boundary, trapped in the borderland between them [2]. They carry with them a momentum as they propagate, evanescently decaying in the direction transverse to the propagation direction and will eventually fade out [2]. Since they are able to propagate along a nanostructure the hope is to be able to use them in order to combine the speed of photonics and the versatility of electronics in future optical computer components, using plasmonics as a bridge between optics and electronics. LSPs are surface plasmons that are constricted
in closed surfaces, creating standing waves. These are the plasmons responsible for creating the beautiful colors of stained glass. They are also used in different kinds of sensing applications in biology and chemistry [3].

2 Theory

Understanding the interaction between light and materials, especially metals, is an essential part of this thesis. When the electromagnetic waves of light strikes a metal the molecules of the metal are polarized by the electric field component of light and the free electron clouds are made to oscillate about the nucleus. This produces a dipole moment which causes new waves to be radiated. Some of these new waves will radiate backwards and constitute the reflected light [4].

When the sample has the structure of a grating, part of the light interacting with the sample will be transmitted, while yet another part will be diffracted. The remains of the incident light will be absorbed in the material - and it is this part that is of largest interest in this work, for it is this part that will excite plasmons. Thus, in order to understand how much energy that goes into absorption and excitations of plasmons, it is advantageous to understand how much light goes into the other parts.

The reflection is a surface property and depends on the change in refractive index between the two materials between which the light is traveling. The refractive index in turn depends on material properties as well as the wavelength of the light [4]. To really understand the refractive index and thus reflection, it is of importance to understand where the quantity comes from.

2.1 The Drude Model

One of the great characteristic features of metals is having a large number of free electrons, making the metals conductive. Metals also have very small penetration depths, which is the reason for their opacity. When turned into thin films however, the metals can become partly transparent [5].

Some of the electrons in the oscillating electron clouds are free electrons while some are bound to a specific atom. The free electrons are responsible for the major contributions to the optical properties of the metal [5]. Considering the conduction electrons of the metal as a free electron gas, by neglecting the contributions from the bound electrons, the so-called Drude model is applicable [6] [7]. This model describes the way a metal responds to an electromagnetic field [7] and is quite useful when analyzing the whereabouts of plasmons in angle-wavelength distributions. The Drude model can be used to model an expression for the permittivity, called the complex dielectric function. This gives valuable insight in how the permittivity varies with the frequency of the light [6]. Since the permittivity is a measure of how much an electric field affects and is affected by a dielectric medium it is a very useful tool in reasoning about the surface plasmons.
2.2 Dielectric function and optical constants

The complex dielectric function, $\bar{n}$, is a quantification of the interaction between an electric field and a dielectric medium. It is one of our most useful tools when investigating the basics of plasmonics. It is also known as the permittivity, $\epsilon$, which is given by

$$\epsilon = \epsilon_1(\omega) + i\epsilon_2(\omega).$$  \hspace{1cm} (1)

The square root of the permittivity is the complex refractive index

$$\bar{n} = n(\omega) + ik(\omega).$$  \hspace{1cm} (2)

The two equations are thus also related by

$$\epsilon_1 = n^2 - k^2$$  \hspace{1cm} (3)

$$\epsilon_2 = 2nk$$  \hspace{1cm} (4)

where $n$ is the refractive index and $k$ is the extinction coefficient. These two give us valuable information about the reflection and absorption properties of materials [5].

It has already been explained how the electric field component of light polarizes the atoms, causing the electrons to oscillate about the nucleus. The real part of the complex refractive index, $n$, is a measure of this polarization [2] and also of how fast the light waves travel in the medium. The oscillating system can be viewed as a dipole, which radiates new waves [4], and this process takes some time. A greater $n$ means a greater polarization and the greater the polarization, and thus the oscillation of the atoms, the longer time it will take for the electromagnetic waves to be absorbed and re-radiated by the dipoles. The phase velocity of the traveling light waves will thus be lower in a material than in vacuum.

The refractive index, $n$, is given by

$$n = \frac{c}{v}$$  \hspace{1cm} (5)

where $c$ is the speed of light in vacuum and $v$ is the phase velocity of the traveling wave. The extinction coefficient, $k$, describes the medium’s optical absorption of light, i.e. how much of the light that will be absorbed in the material. The larger extinction coefficient, the larger the absorption [2].

The amount of light reflected at a surface depends in this model on the imaginary part of the permittivity [2], which contains both the real part of the complex dielectric function - the refractive index - as well as the imaginary part - the extinction coefficient. If the light is traveling from air into a material, a large imaginary part of the dielectric function would imply a high reflection. This means that a large extinction coefficient, $k$, not only implies a high absorption but also implies a high reflection. A material with good absorbing properties will thus also have good reflecting properties. An effective absorber will ironically
thus not need to absorb that much light at all. As mentioned once before, the reflection and the absorption goes hand in hand. Metals usually have large values of $k$, which explains their high reflectivity of optical light and gives them their shiny appearance

Knowing the optical properties of a material, one can easily extract valuable information about the reflection and transmission. Using the Fresnel Equations one can calculate how much of the incident light will be reflected versus transmitted. According to the Fresnel equations the reflectivity and transmission of a material depend on three things; the wavelength of the incident light, the complex refractive index $\bar{n}$ and the incident angle. The Fresnel equations can be found in several books on optics, for example in Optics by Hecht. They are however only accurate for homogeneous metal surfaces without absorption.

In order to understand reflection and transmission in situations with periodic nanostructures supporting plasmons, something else is needed.

2.3 Surface Plasmons

Surface plasmons are usually divided into two families, the first being Surface Plasmon Polaritons and the second one being Localized Surface Plasmons. Really, there is no physical difference between the plasmon part of the SPPs and the LSPs but the distinction is made rather because of the difference in the boundary conditions of the two.

In order to do quantitative evaluations of the plasmons, the propagation length and propagation constant are introduced. The propagation length is a measure of how long the surface plasmons can travel without fading out. The propagation constant, $\beta$, is defined to be the distance over which the electric field amplitude decays by $\frac{1}{e}$. A plasmonic material that can support surface plasmons to travel longer distances without fading will have long propagation lengths.

2.3.1 Surface Plasmon Polaritons

Surface Plasmons Polaritons (SPPs) can be described as electron density waves, propagating on the surface of a metal, trapped in the boundary of the metal and a dielectric. The analogy of a stone being thrown in the water and thus creating ripples in the water is often used. However, instead of waves in water the surface plasmons are waves in the sea of free electrons. Just like the ripples on the surface of the lake, the plasmons cannot escape the surface of the electron sea but are trapped on the surface of the metal.

The SPPs are surface plasmons coupled to the electromagnetic waves of light on the dielectric side. They will propagate in the boundary of the metal and the dielectric, until they fade away due to energy losses.

The electron density waves can propagate through the film and couple to light on the other side, causing a radiation from the surface. This is the cause for the very interesting phenomenon called extraordinary transmission. Imagine a nanostructure with a surface coverage of 70% metal. The rest of the 30%
Figure 1: SPPs always propagate in the interface between a metal and a dielectric.

are a dielectric material with negligible absorption. Now, if light is shone on this nanostructure one might expect that 30\% of the incident light would be transmitted. However, it has been shown that the transmission can be larger than 30\%. This is due to the propagation of plasmons to the other side, where the surface plasmons will emit light [2].

In order to excite surface plasmons, there are some criteria that must be satisfied. A detailed explanation of this will be given in section 2.4.

2.3.2 Localized Surface Plasmons

Localized Surface Plasmons (LSPs) are surface plasmons that are stuck on a closed surface. They can be viewed as an excitation of the conduction electrons of a metal particle. The surface waves on the closed surface will compose a standing wave. Therefore it will, in contrast to the SPPs, be non-propagating [2]. The LSPs are the origin of the beautiful colors in the stained glass of churches.

Figure 2: An electric field is exciting an LSP on a metal particle.

They will there absorb some wavelengths, making the window transmit only some specific colors. The LSPs are surface plasmons on the closed surface of metallic nanoparticles mixed in with the glass. Different metals and sizes creates different conditions for the plasmons and thus creates different colors [8] [9].
2.4 Exciting Surface Plasmons

As mentioned in the introduction, it requires a bit more than just shining optical light on a homogeneous piece of plasmonic metal to successfully launch surface plasmons. A homogeneous piece of metal will not be able to support any surface plasmons without some tricks being applied. The reason for this incapability of the homogeneous plasmonic metals to carry surface plasmons is a momentum mismatch. At all times, the momentum and energy of a system need to be conserved. However, in this system the momentum of the photon will always be lower than that needed for the plasmons to be excited. To excite surface plasmons, the photon momentum thus needs to be increased. [10]

Below, some of the tricks commonly used to shift the photons to higher momentum in order to launch surface plasmons are presented.

2.4.1 Otto Configuration

One way to excite surface plasmons is by the Otto configuration. It has the aim to, with the help of a prism, by-pass the difficulty of the mismatch between the incident light momentum to that of the surface plasmon by the means of increasing the photon momentum with the help of a higher refractive index dielectric. Letting the incident light first propagate through the higher index material, then couple evanescently though a lower index dielectric thin film it would at last excite the surface plasmon at the interface between the metal and the dielectric. [8]

![Figure 3: Schematic of the Otto Configuration.](image)

The disadvantage of the Otto Configuration is the practical difficulties of the delicate adjustment of the thin dielectric film required, making it a less popular alternative compared to other configurations [5].

2.4.2 Kretschmann-Raether Configuration

Another configuration for exciting surface plasmons is the Kretschmann-Raether configuration, which is also a prism-based method. However, it is much more popular than the Otto configuration. In this configuration, the light will propagate through a prism, just as in Otto configuration, but here the metal and dielectric has been reversed. The light is refracted through a prism, before it is
incident on a thin metal film and at the bottom surface of this metal film, in
the interface of the metal and a dielectric, surface plasmons are launched. [8]

![Figure 4: Schematic of the Kretschmann-Raether Configuration.](image)

### 2.4.3 Diffraction Grating

A third method for exciting surface plasmons, and the method used in this
particular work, is the use of a diffraction grating. To really understand the
way the light behaves while interacting with the grating, it is first necessary
to have a clear image of what diffraction is. A good point to start is by the
Huygens-Fresnel Principle, in Hecht stated as "every unobstructed point of a
wavefront will itself serve as a source of spherical secondary wavelets" [5].

If plane waves of light are allowed to travel through a slit, one can observe
that the light after leaving the slit will start to propagate in circular waves.
Positioning a screen, which will serve as a plane of observation, at a distance
much larger than the slit size makes it possible to observe a phenomenon called
interference. Due to superposition of the circular wavelets from the different
points, the waves will start to alternately add up contra cancel each other out
in so called constructive and destructive interference, respectively. This phe-

omenon will create a pattern on the plane of observation, called a diffusion
pattern or interference pattern. [5]

If one instead allows light to be reflected at a nanosurface with a grating,
one will be able to make similar observations with only a slight difference which
is due to the fact that different wavelengths will be reflected in different angles
from the incidence light. This grating will cause the light to be divided into
different wavelengths traveling in different directions along the surface of the
nanostructure, causing the excitations of surface plasmons. Diffraction wise,
there is no difference between using a hole nanostructure or an island nano-
structure if the two have the same dimensions. [8]

As mentioned before, the reason for the difficulty in exciting surface plas-
mons is a momentum mismatch between the photon and the surface plasmon.
According to the laws of nature, the energy and momentum of a system must
at all times be conserved. However, the part of the momentum vector of the
photon that is parallel to the surface does not add up to the momentum needed
to excite a surface plasmon with the same energy as the photon [10]. Thus, the
photon needs some help on the way in order to excite the surface plasmon. This
is where the grating comes to the rescue. The momentum of the SPP is given by

\[ |\vec{k}_{spp}| = \frac{\omega}{c} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \] (6)

where \( \omega \) is the angular frequency, \( c \) is the speed of light in vacuum and \( \epsilon_m \) is the permittivity of the metal and \( \epsilon_d \) is the permittivity of the dielectric \([10]\), while the momentum of the photon is given by

\[ |\vec{k}_p| = \frac{\omega}{c} \] (7)

and these two does not add up. In order to fix this problem, a grating is used to produce a momentum

\[ \vec{k} = \vec{k}_p + \vec{G} \] (8)

which does add up to the momentum of the SPP \([10]\). The \( \vec{G} \) is the reciprocal lattice vector, indicating that it is important to use a grating with suitable proportions.

Figure 5: Illustration of the momentum mismatch between the photon and the SPP, which can be made up for by using a grating.
3 Experiment and Analysis

The structures of the samples were investigated with an Atomic Force Microscope. The reflection and transmission measurements were then made using a simple arrangement described below. The data collected during the experiment are illustrated in reflectivity and transmission maps. To be able to analyze the results further, the reflectivity and transmission maps are plotted with the dispersion relations for three different directions in the sample. All of these analysis methods and experimental setups are described below.

3.1 Nanostructures

In this work, the samples measured are arrays of square nanoparticles, called islands, or anti-nanoparticles, called holes. The material is made of a silver, nickel, silver multilayer. Each layer has a thickness of 75 Å. These layers are placed upon a glass substrate with a thin layer of ITO in between. Fig. 6 shows a schematic of the structures.

Figure 6: a) Schematic of one island seen from the side, b) schematic of the hole structure seen from above and a c) schematic of the island structure seen from above. This figure also shows the miller indices defining the directions in these structures.
3.2 Atomic Force Microscopy

The Atomic Force Microscope (AFM) is a technique that allows scientists to see structures far beyond the diffraction limit. This makes it possible to investigate thoroughly the nanostructure of the sample on an almost atomic scale.

A laser generates a beam of light that strikes a cantilever. The beam of light is reflected and the reflected light is then collected by a photodiode. The cantilever is carried over the sample, scanning the surface. When the cantilever is displaced due to the interactions with the surface, so will the beam on the photodiode be. Thus, by reading the changes on the photodiode one is able to get an image and map the features of the sample structure [11].

3.3 Reflection and Transmission Measurements

Fig. 7 shows a schematic of the setup used for reflectivity and transmission measurements in this work. Monochromatic light is generated by a super con-

![Figure 7: a) Top view schematic of the setup.](image)

tinuum laser and is allowed to pass through a polarizer. The light generated in the laser has electric field vectors pointing in all different directions and can be seen as a superposition of s-polarized light with electric field vectors only perpendicular to the scattering plane and p-polarized light with the electric field vectors parallel to the scattering plane, as can be seen in fig. 8. The polarizer shuts out either the s- or the p-polarized light and when the light then interacts with the sample, it is thus either s- or p-polarized.

The sample is mounted on a goniometer, which rotates through precise angular positions. This to be able to measure the reflection and transmission at different incident angles and thus acquiring an understanding of the dependence of said angle. The light is incident on the sample in the [10]-angle in the
The incident angle is varied through a range of 4 to 30 degrees, according to the optical convention, with a resolution of one degree. This procedure is repeated for different frequencies of the light, from 1.65 eV to 3.15 eV with a resolution of 0.1 eV.

At the sample, part of the light will be transmitted, part will be reflected, some of the light will be diffracted and some of the light will be absorbed in the material. The last of these are the part we are most interested in, since it is this part of the light that will contribute to creating plasmons. It is to understand how much of the light that is absorbed one wishes to record the amount of light that is transmitted versus reflected.

The reflectivity and transmission measurements are made separately, for both s- and p-polarized light. The reflected and transmitted light is collected in a photodetector. A single measurement of the direct beam of every frequency is also measured in order to be able to calculate the relative intensity of the light in percent instead of the absolute intensity in Volt.

### 3.4 Maps and Dispersion Relation Curves

Color maps are a suitable way of presenting the data collected in the reflection and transmission measurements. In these maps, the occurrence of plasmons can be spotted if they exist in the material. The maps show the energy of the light on the y-axis and the incident angle distribution on the x-axis. The intensity of the collected light in percent is shown in a color scale, ranging between percentage values best suited to see the plasmon features. Some parts have a multiplication factor in order to get a better contrast.

The maps are plotted together with the dispersion relation curves for the $[10]$-, $[0\pm1]$- and $[-10]$-direction of the sample structure. The physical meaning of these dispersion relation curves are the critical limit where the momentum vector
k of the diffracted light start to point into the metal, matching the momentum to that of the surface plasmons and thus allowing the excitation of surface plasmons in the direction in question. The [10] dispersion curve is thus the critical limit for launching plasmons in that direction, below which it is possible while above it is not. The dispersion curves are given by

\[ E = \frac{hc}{a} \frac{(i^2 + j^2)}{\sqrt{(i^2 + j^2) - j^2\sin^2\theta - isin\theta}} \] (9)

where \( i \) and \( j \) are miller indices, \( \theta \) is the incident angle of the light, \( h \) is the Planck constant, \( c \) is the speed of light and \( a \) is the periodicity of the lattice, defined in fig. 9.

In order to see where the plasmons are created, one must look for intensity drops over these dispersion curves. If the silver surface would have a constant reflection with respect to the incident angle, the intensity drop would be proportional to the energy which is exciting the plasmons. This is however a simplification of the current case and in order to be completely truthful, one should compare the color maps to those made for a homogeneous piece of silver. It is however possible to do approximate estimations about the plasmon resonances without that comparison. A plasmon resonance is calculated by

\[ 100 - \frac{R(-)}{R(+)} \times 100 \] (10)

where \( R(+) \) is the maximum value before the drop and \( R(-) \) is the minimum value after the drop. In this work, this is done for the reflectivity maps of the hole structure.
4 Results and Discussion

4.1 Atomic Force Microscopy Pictures

Investigation of the structure using AFM was carried out for both the two samples looked at in this work. The idea of the samples was that they should consist of periodic square elements - square holes and square islands.

![AFM pictures of the island structure. The black is the substrate and white is the top of the structure at 22.5 nm.](image)

The AFM pictures of the islands show a highly periodic structure. Although, as can be noticed looking at fig 10 b), the islands are not really square. The geometrical form as well as the periodicity of the islands are however quite regular. The periodicity of the islands are estimated to about 510 nm and the width of the islands is estimated to 420 nm.
The AFM picture of the hole structures also show a highly regular periodicity and the holes seem to be quite square, although the question is if the holes are equally deep everywhere. The periodicity of the hole structure is estimated to 511 nm and the width of one hole is estimated to 250 nm. This makes the amount of metal in the island and hole structures to be 68 % and 76 % respectively, assuming perfectly square structures.
4.2 Reflection and Transmission Maps

Figure 12: Reflection map of the hole structure. Notice the scaling factor in the upper right corners which shows the multiplication factor of the data. This is used to highlight certain features otherwise difficult to see because of the large variations in intensity.

Figure 13: Transmission map of the hole structure.

The silver nanostructures show plasmon resonances which can be observed in both low and high angles. Plasmons in the [10]- and [-10]-directions can be observed in the p-polarized measurements of both the island and the hole structures, while there are no traces of plasmons in the [0±1]-direction.
Figure 14: Reflectivity map of the hole array structure. Notice the features close to the [0±1] dispersion curve.

Figure 15: Transmission map of the hole array structure.

In the results for the s-polarized light there are no traces of plasmons in the [10]- and [-10]-directions while the results show sharp signs of plasmons excited in the [0±1]-direction.

The metal density of the hole structure leaves 24 % of surface where the light can make it through without interacting with the metal. If the metal would have been opaque, a transmission intensity of 24 % would be expected if the incident angle were zero degrees. In this case, the lowest incident angle is four degrees and thus the transmission would be even less than 24 %, if we neglect light that fails to be absorbed in the metal. It could be calculated by
the Beer-Lambert law, however this has been let out of this thesis as it will only make small changes for the relevant regions of analysis. The transmission of p-polarized light in this thin film surface is however about 30% in the area where we find plasmons, indicating extraordinary transmission of the p-polarized light. For the s-polarized light, however, a transmission of about 20-25% is observed, which is about the same as the expected value for an opaque film.

Figure 16: Reflectivity map of the island structure. This measurement was done with p-polarized light. Notice the scaling factor in the upper right corners which shows the multiplication factor of the data. This is used to highlight certain features otherwise difficult to see because of the large variations in intensity.

In fig. 16, the upper part of the map has been magnified in strength in order for clearer observations of the features. Plasmon features are observed in the (10)- and (-10)-direction, however not in the (0±1)-direction.
Figure 17: Transmission map of the island structure. This measurement was done with p-polarized light. The measurements at 2.75 eV are considered unphysical.

The dark blue spots in fig. 17 look suspicious and are considered to be unphysical and due to fluctuations in the measuring technique. There is still possible to see traces of plasmons in the [10]- and [-10]-direction, which agrees with observations from the reflectivity. There are no traces of plasmons in the [0±1]-direction.

Figure 18: Reflectivity map of the island structure. This measurement was done with s-polarized light.

In the reflectivity map in fig. 18 plasmon features are observed in the [0±1]-direction but not in any other direction. The same is true for the transmission
in fig. 19 however not as clearly as in the reflection.

In the case of the island structure, the metal density is of about 68% leaving 32% for the light to travel directly through without interacting with the metal. The transmission for the p-polarized light is measured to be about 55% below the [10]-curve and over 55% in the [-10]-direction. For the s-polarized light, the transmission is measured to be about 40% below the [0±1]-curve, indicating extraordinary transmission here as well.

To be noticed is that in both the hole structure and the island structure, the s-polarized light only excite surface plasmons in the [0±1]-direction, which is the same direction as the electric field vector of s-polarized light is oriented along. Similarly, the p-polarized light only excite surface plasmons in the [10] and [-10]-direction, which is the same directions as the orientation for the electric field of the p-polarized light.

Figure 19: Transmission map of the island structure. This measurement was done with s-polarized light.
4.3 Plasmonic Resonances

Figure 20: Reflectivity (% of total incident light) versus incident angle for specific wavelengths. Figures a-c shows the reflectivity for measurements with p-polarized light while figures d-f shows reflectivity for measurements with s-polarized light. 3.05 eV, 2.55 eV and 1.95 eV corresponds to 406.6 nm, 486.3 nm and 635.9 nm respectively. The orange circles mark chosen maximum and minimum reflectivity points around the dispersion curve in measurements where plasmons are observed while the green squares mark the points at angles taken from the orange circles in the corresponding figure. The dashed line shows where the dispersion curve is.

Figure 20 shows the intensity of the light (in percentage of total incident light) reflected from the hole structure plotted to the incident angles for specific energies of the light. The energies are chosen to correspond to places where plasmons are observed, according to the reflectivity maps. The purpose of these figures is to illustrate the existence and quantify the strength of plasmon resonances. Since these only occur around the dispersion curves, the behavior of the curves around the dashed lines (corresponding to the dispersion curves) is important. In the reflectivity and transmission maps, plasmon features were observed for directions corresponding to fig. 20 a, c and e. In these figures, the maximum $R(\pm)$ and minimum $R(\mp)$ values around the dispersion curve are marked with circles. In the figures corresponding to events where no plasmons were observed, b, d and f, the squares mark the points at the angles correspond-
The plasmon resonances for the energies in fig. 20 are calculated according to eq. 10 and are displayed in the table below.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Polarization</th>
<th>p-</th>
<th>s-</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.05 eV</td>
<td></td>
<td>27.16</td>
<td>-37.50</td>
</tr>
<tr>
<td>2.55 eV</td>
<td></td>
<td>10.34</td>
<td>19.16</td>
</tr>
<tr>
<td>1.95 eV</td>
<td></td>
<td>24.76</td>
<td>9.12</td>
</tr>
</tbody>
</table>

Table 1: The table shows plasmonic resonance strengths expressed in relative percentage for different energies and polarizations of the light. Energies of the light 3.05 eV, 2.55 eV and 1.95 eV correspond to the [10]-, [0±1]- and [-10]- direction in the surface, respectively.

Notice that the table agrees very well with observations from the reflectivity and transmission maps. The highest plasmon resonance strengths occurs for the same directions as the ones with the observed plasmon features in the maps. The negative value of the S 3.05 eV is a nice example of a consequence of the non-homogeneous reflectivity of silver and how the background reflectivity can dominate the calculations.

5 Conclusions and Outlook

In this work, properties of the reflectivity and transmission of square Ag/Ni/Ag plasmonic nanostructures have been investigated. This has been done in order to deepen the understanding of silver as a plasmonic material as well as to understand how the plasmons affect the reflectivity and transmission of a periodic nanostructure with square elements.

The nanostructures consisted of periodic arrays of square holes or square islands. The periodicity and geometry of these were investigated with AFM measurements. The reflectivity and transmission were measured and illustrated in color maps.

By altering the polarization, the incident angle or the wavelength of the incident light, it is possible to manipulate and govern the plasmonic responses of the periodic, square nanostructures.
Figure 21: Plasmons are excited in the direction of the electric field vector, $E$.

Both p- and s-polarized light are capable of exciting surface plasmons, however only along different directions in the surface of the nanostructure. The p-polarized light excite surface plasmons in the [10]- and [-10]-direction, which are in the same plane as the electric field vector for p-polarized light. The same is true for s-polarized light. The surface plasmons excited by the s-polarized light in the $[0\pm1]$-directions are in the same plane as the electric field vector for the s-polarized light. This is illustrated in fig. 21. The conclusion is that surface plasmons are excited along the direction parallel to the electric field vector of the light.

The geometry of the structures used in this work were not perfectly square. If they were, it would be easier to compare the results for the islands to that of the holes. As an extension of this, one could also look at square islands and holes of several different periodicities in order to deepen the understanding of how the surface plasmons depend on the periodicity. Another step that would be interesting to take is to investigate the magneto-optic properties of the structures by looking at an effect called TMOKE. This would allow further focus to be applied on the plasmon excitations as well as how these can be enhanced by the presence of an external magnetic field.

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References


