"Investigating the Confinement of Light in Nanometric Domains"

by

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To the blessed memory of my grandfather
Rahamim Mrejen z”l
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Abstract

Over 20 years ago Lewis and coworkers studied the transmission of light through sub-wavelength aperture arrays. A variety of aperture dimensions were studied down to 15 nm and light was detected through even the smallest apertures. Even fluorescence of pyrelene was reported through such aperture arrays.

Lewis and coworkers also introduced single sub-wavelength apertures at the tip of tapered glass structures. These tapered apertured glass structures are prevalent today as the element of choice in near-field optics. Even though such single apertures were coated with the same metal as in the aperture arrays, aluminum or gold, the transmission results were in contrast with the intensities observed in the aperture arrays. Specifically, single apertures resulted in a significant reduction in the intensity of transmission.

In 1998 Ebbesen and coworkers suggested that the extraordinary transmission (EOT) of aperture arrays was due to the excitation of surface plasmons in metals with surface states that could support such plasmonic propagation. In the intervening years since the report of Ebbesen et al there have been numerous studies on the far-field and spectral characteristics of the transmission of these arrays. However, there have been no reports on the nature of the distribution of light in the near-field on the surface of the array and on the alteration of this distribution as a function of distance from the surface. Such characterization is of course crucial for understanding the possible applications for such arrays.

Due to the sub-wavelength dimension of the apertures and the distance between apertures in such arrays there is only one technique that is capable of addressing such a question of light distribution and this is near-field optical microscopy, which was developed by our group as a characterization tool for nanophotonics. In fact, the wide variety of plasmonic structures which are
exemplified by such aperture arrays can be characterized ultimately only with near-field scanning optical microscopy or NSOM. In this work we image the distribution of light in sub-wavelength aperture arrays with EOT using NSOM correlated with on-line atomic force microscopy.

For such an investigation we have used a Focused Ion Beam to fabricate arrays in gold films with an appropriate period to generate surface plasmons. Single holes of the same and larger diameter were also milled apart from the array for on-line comparison purpose. This sample was illuminated with the appropriate wavelength (532 nm) and the near field of the transmitted light was acquired in collection mode using a Nanonics MultiView 2000 NSOM /AFM System. This system has on-line sample and probe scanning and thus a sample can be nanometrically positioned to an incoming light source illuminating the apertures and then nanometrically held in position while a cantilevered fiber optic NSOM probe is scanned across the sample. The atomic force microscopy (AFM) capability of the system gave us the possibility to correlate on-line the surface topography and geometry with the optical near field distribution. The results show strong dependence of the enhanced transmission on the array periodicity, which point to a surface plasmon effect diffusing the localized transmission of the hole along the direction of the surface plasmon excitation. The investigation of the propagation of the light in the near field reveals an effect that can be accounted for by the beaming of the transmitted light, effect that so far has been observed only in the far-field.
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1 Scientific background

1.1 Bethe’s theory of light transmission through sub-wavelength aperture in perfectly conducting film [9]

A hole in a screen is probably the simplest optical element possible, and was an object of curiosity and technological application long before it was scientifically analyzed. It was in the middle of the seventeenth century that Grimaldi first described diffraction from a circular aperture, contributing to the foundation of classical optics. Despite their apparent simplicity and although they were much larger than the wavelength of light, such apertures remained the object of scientific study and debates for centuries thereafter, as an accurate description and experimental characterization of their optics turned out to be extremely difficult. In the twentieth century, the interest naturally shifted to subwavelength holes as the technology evolved towards longer wavelengths of the electromagnetic spectrum. With the rising importance of microwave technology in the war effort of the 1940s, Bethe [2-3] treated the diffractive properties of an idealized subwavelength hole, that is, a hole in a perfectly conducting metal screen of zero thickness. His predictions, notably that the optical transmission would be very weak, became the reference for issues associated with the miniaturization of optical elements and the development of modern characterization tools beyond the diffraction limit, such as the near-field scanning optical microscope (NSOM) [1], which typically has a small aperture in the metal-coated tip as the probing element. When Bethe considered such a system, and thereafter Bouwkamp, they idealized the structure by assuming that the film was infinitely thin and that the metal was a perfect conductor. With these assumptions, they derived a very simple expression for the transmission efficiency $\eta_B$:

$$\eta_B = \frac{64(2\pi \frac{r}{\lambda})^4}{27\pi^2}$$
with r radius of the hole and λ the wavelength of the impinging light. It is immediately apparent that \( n_B \) scales as \( (r/\lambda)^4 \) and that therefore we would expect the optical transmission to drop rapidly as λ becomes larger than r. In addition the transmission efficiency is further attenuated exponentially if the real depth of the hole is taken into account, because it has waveguide properties. The transmission of light through such a guide is very different from the propagation of light in empty space. The confined space of the waveguide essentially modifies the dispersion relation of the electromagnetic field. The lateral dimensions of the waveguide define the wavelength at which light can no longer propagate through the aperture. This wavelength is known as the cutoff wavelength \( \lambda_c \). When the incident wavelength \( \lambda > \lambda_c \) the transmission is exponentially small, characterizing the non-propagating regime (Fig.1.1). With real metals, the cutoff wavelength cannot be sharply defined because one goes continuously from propagative to evanescent regime as the wavelength increases. This exponential dependence reflects the fact that the light cannot propagate through the hole if \( \lambda > 4r \), whereupon the transmission becomes a tunneling process. The cutoff condition \( \lambda > 4r \), is of course a first approximation and in real situation the cutoff occurs at longer wavelengths when the finite conductivity is taken into account. The theory developed by Bethe and Bouwkamp stated also that the diffraction from the hole behaves in a way that is polarization-dependent.

Fig 1.1: Diffraction and exponentially decaying transmission of a subwavelength hole in an idealized conducting screen in the visible regime.
1.2 Surface plasmon theory

Many of the fundamental electronic properties of the solid state can be successfully described by the analogy of single electrons moving in the periodic array of atoms.

Another quite different approach to derive the properties of the solid state starts with the plasma concept: the free electrons of a metal are treated as an electron liquid of high density of about $10^{23}$ cm$^{-3}$, ignoring the lattice in a first approximation.

From this approach, it follows that longitudinal density fluctuations, plasma oscillations, will propagate through the volume of the metal. The quanta of these “volume plasmons” have an energy $\hbar \omega_p = \hbar \sqrt{\frac{4 \pi n e^2}{m_0}}$, where $n$ is the electron density, of the order of 10 eV. They are produced by electrons which are shot into the metal. This exciting phenomenon has been studied in detail theoretically and experimentally with electron-loss spectroscopy.

An important extension of the plasmon physics has been accomplished by the concept of “surface plasmons” (SPs). Maxwell’s theory shows that electromagnetic surface waves can propagate along a metallic surface or on metallic films with a broad spectrum of eigen frequencies from $\omega = 0$ up to $\omega = \omega_p/\sqrt{2}$ depending on the wave vector $k$. Their dispersion relation $\omega(k)$ lies right of the light line which means that the surface plasmons have a longer wave vector than light waves of the same $\hbar \omega$, propagating along the surface, see Fig 1.2. Therefore they are called “nonradiative” surface plasmon, which describe fluctuations of the surface electron density. Their electromagnetic fields decay exponentially into the space perpendicular to the surface and have their maximum in the surface, as is characteristic for surface waves.

These surface plasmons have also been studied with electron-loss spectroscopy and with light extensively. The excitation with light needs special light plasmon couplers (grating coupler, prism coupler), since the dispersion relation lies right of the light line.
Dispersion relation

The electron charges on a metal boundary can perform coherent fluctuations which are called surface plasma oscillations. The frequency $\omega$ of these longitudinal oscillations is tied to its wave vector $k_x$ by a dispersion relation $\omega(k_x)$. These charge fluctuations are accompanied by a mixed transversal and longitudinal electromagnetic field which disappears at $|z| \to \infty$ (Fig. 1.2), and has its maximum in the surface $z=0$, typical for surface waves. This explains their sensitivity to surface properties. The field is described by

$$E = E_0 e^{i(k_x x + k_z z - \omega t)}$$

with $+$ for $z \geq 0$, $-$ for $z \leq 0$, and with imaginary $k_z$, which causes the exponential decay of the field in $E_z$. The wave vector $k_z$ lies parallel to the $x$ direction; $k_z=2\pi/\lambda_p$, where $\lambda_p$ is the wavelength of the plasma oscillation. Maxwell’s equations yield the retarded dispersion relation for the plane surface of a semi-infinite metal with the dielectric function ($\epsilon_m = \epsilon'_m + i\epsilon''_m$), adjacent to a dielectric medium $\epsilon_d$ as air or vacuum:

$$D_0 = \frac{k_{z,m}}{\epsilon_m} + \frac{k_{z,d}}{\epsilon_d} = 0$$

together with

$$\epsilon_d \left(\frac{\omega}{c}\right)^2 = k_x^2 + k_{z,d}^2$$

or
\[ k_{z,i} = \left[ \varepsilon_i \left( \frac{\omega}{c} \right)^2 - k_x^2 \right]^{1/2}, \ i = m, d. \]

The wave vector \( k_x \) is continuous through the interface. Then the dispersion relation can be written as:

\[ k_x = \frac{\omega}{c} \left( \frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} \right)^{1/2} \quad (1.1) \]

If we assume besides a real \( \omega \) and \( \varepsilon_d \) that \( \varepsilon'_m < |\varepsilon'_m| \), we obtain a complex \( k_x = k'_x + i k''_x \) with

\[ k'_x = \frac{\omega}{c} \left( \frac{\varepsilon'_m \varepsilon_d}{\varepsilon'_m + \varepsilon_d} \right)^{1/2} \quad (1.2) \]

\[ k''_x = \frac{\omega}{c} \left( \frac{\varepsilon'_m \varepsilon_d}{\varepsilon'_m + \varepsilon_d} \right)^{3/2} \frac{\varepsilon''_m}{2\varepsilon'_d^2} \quad (1.3) \]

for real \( k'_x \) one needs \( \varepsilon'_m < 0 \) and \( |\varepsilon'_m| > \varepsilon_d \), which can be fulfilled in a metal; \( k''_x \) determines the internal absorption. In the following we write \( k_x \) in general instead of \( k'_x \).

**Spatial extension and propagation length of the Surface Plasmon fields.**

Wave vectors \( k_{z,m} \) and \( k_{z,d} \) are imaginary due to the relation \( \omega/c < k_x \) and \( \varepsilon'_m < 0 \), so that, as mentioned above, the field amplitude of the Surface Plasmons decreases exponentially as \( \exp[-|k_{z,m}| |z|] \), normal to the surface. The value of the skin depth at which the field falls to \( 1/e \), becomes

\[ \hat{z}_d = \frac{1}{|k_{z,d}|} \quad \text{or} \]

in the medium with \( \varepsilon_d \):

\[ \hat{z}_d = \frac{\lambda}{2\pi} \left( \frac{\varepsilon'_m + \varepsilon_d}{\varepsilon'_d^2} \right)^{1/2} \]

in the metal with \( \varepsilon_m \):

\[ \hat{z}_m = \frac{\lambda}{2\pi} \left( \frac{\varepsilon'_m + \varepsilon_d}{\varepsilon''_m^2} \right)^{1/2} \]
the intensity of SPs propagating along a smooth surface decreases as \( \exp[-2 k''_x x] \) with \( k''_x \) from (1.3). The length \( L_i \) after which the intensity decreases to 1/e is given by

\[
L_i = (2k''_x)^{-1} \quad (1.4)
\]

**Excitation by light**

The application of photons to excite surface plasmons meets the difficulty that the dispersion relation lies right from the light line (\( k_x > \omega/c \)). At a given photon energy \( h\omega \) the wave vector \( h\omega/c \) has to be increased by a \( \Delta k_x \) value in order to transform the photons into SPs. The method of interest here is what one calls the “Grating Coupler”. In this method if light (\( k=\omega/c \)) hits a grating with a grating constant \( a \) at an angle \( \theta_0 \) its component in the surface can have wave vectors \( (\omega/c) \sin \theta_0 \pm \lambda j \) with \( j \) an integer and \( \lambda = 2\pi/a \). The dispersion relation (1.1) can be then fulfilled

\[
k_x = \frac{\omega}{c} \sin \theta_0 \pm j\lambda = \frac{\omega}{c} \left( \frac{\varepsilon_m' \varepsilon_d}{\varepsilon_m' + \varepsilon_d} \right)^{1/2} = k_{sp} \quad (1.5)
\]

This can be seen as a resonance condition and this resonance is observed as a minimum of the reflected light.

The reverse process takes place too: SPs propagating along a grating or a rough surface can reduce their wave vector \( k_x \) by so that the SP is transformed into light. This light emission, a consequence of the photon-SP coupling via roughness, plays an important role.

1.3 **Role of surface plasmon in enhanced light transmission in subwavelength structures**
The coupling of light to SPs through periodic structures opens up interesting opportunities, especially when it comes to transmission of light through subwavelength apertures. As described above, the transmission through nano apertures is very inefficient but the lack of efficiency can be circumvented with the coupling to SPs. Extraordinary Optical Transmission (EOT) through nano-holes arrays has been reported [4] where a $10^3$ enhancement is achieved in comparison to the Bethe’s theory. The EOT is thought to be a plasmonic phenomena and the mechanism involving SPs is described below.

The method used is that of “grating coupler” cited above. In this case, the grating is in fact a periodic structure of nano holes. By tailoring properly the period, one can achieve resonance and then couple the incoming light to SPs. The SPs generated propagate along the interface between the dielectric and the metal; tunnel through the holes to other side of the metallic film and through the periodicity existing in this side the SPs couple back into light. This mechanism yields significant transmission enhancement.

Consider a 2D square lattice of nano-holes see Fig. 1.3.

For 2D grating, (1.4) can be written

$$\tilde{k}_{sp} = \tilde{k}_0 \pm i\tilde{G}_x \pm j\tilde{G}_y$$  \hspace{1cm} (1.6)
For normal incident light of wavelength $\lambda$ we have $\theta_0=0$, $i$ and $j$ are integers $\vec{G}_x, \vec{G}_y$ are the reciprocal lattice vectors. For square lattice we have

$$\left| \vec{G}_x \right| = \left| \vec{G}_y \right| = \Lambda = 2\pi / a_0 \quad (1.7)$$

with

$$\left| \vec{k}_{sp} \right| = \frac{2\pi}{\lambda} \sqrt{\frac{\varepsilon_{d,l} \varepsilon_m}{\varepsilon_{d,l} + \varepsilon_m}} \quad \text{with } l=1,2. \quad (1.8)$$

Combining (1.6) with (1.7) and (1.8) yields

$$\frac{2\pi}{\lambda} \sqrt{\frac{\varepsilon_{d,l} \varepsilon_m}{\varepsilon_{d,l} + \varepsilon_m}} = \frac{2\pi}{a_0} \sqrt{i^2 + j^2} \iff a_0 = \lambda \sqrt{\frac{(i^2 + j^2) (\varepsilon_{d,l} + \varepsilon_m)}{\varepsilon_{d,l} \varepsilon_m}} \quad (1.9)$$

This is the expression of the period that gives rise to the surface plasmon resonance. It is important to stress the meaning of $i$ and $j$. They represent the different directions of propagation of the surface plasmons. Each set $(i,j)$ can be view as a mode of propagation of the SP.

Another fact of importance is that that treatment is neglecting the size of the holes and the finite size of a real array. Those parameters give rise to effects that we will reveal experimentally.

### 1.4 Review of existing Near-Field measurements related to the Extraordinary Optical Transmission

First reported work involving sub-wavelength holes arrays in metallic film is found in [1]. There, already in 1986, Lewis and co-workers investigate transmission properties of such apertures for the development of the NSOM.
In this early work, they notice relatively strong transmission but they do not look further into this interesting effect.

Since Ebbesen’s paper [4] in 1998, where a 3 orders of magnitude enhancement is reported, nano-holes arrays have induced extensive research works both theoretically and experimentally in order to get an insight of the physics involved in the Extraordinary Optical Transmission (EOT) [5-9].

It’s worthy to note that the enhancement claimed is in comparison to the theoretical efficiency as calculated in the Bethe’s treatement of diffraction from small holes. All the works investigated the behavior of these structures in the far-field. Few of them have investigated them in the near-field [8-10], despite the major role of the near-field in the enhancement process.

A theoretical study of the near-field of nano-holes arrays in silver film can be found in [10]. Intensity distributions at different planes above the surface are calculated in this paper.

In [11] the authors present NSOM images. Singles holes are studied with illumination mode NSOM, so the surface plasmons involved in the transmission process are localized and the effects due to the periodicity of a structure like arrays are not investigated in this paper.

An investigation of the Near-field of periodic structures is presented in [12]. The structure studied is an array of sub-wavelength annular apertures but here also the excitation of the surface plasmons is localized so the contribution of the periodicity to the surface plasmons generation is in fact not studied.

None of the two last papers has dealt with the propagation of the light from the nano structures studied. Moreover the original Ebbesen’s experiment has not been carried out and measured in the near-field. Another point is that there is no near field comparison of the transmission of single nano-hole and nano-holes array.
2 Research method

In this work we want to address the points that in our opinion are lacking in the different works cited above. First, non-localized excitation of the surface plasmons in arrays like in the Ebbesen's experiment has not been reproduced for near field experiment. Such excitation will enable near field investigation study of structure-linked effects. Second, comparison in the same experiment of the transmission of single nano-holes and arrays. This gives a more reliable enhancement factor than the comparison to the theoretical and idealized Bethe efficiency. Last, we want to carry out profiling of the light intensity at different planes above the surface in the near field in order to look for irregular or unexpected diffraction behavior as claimed in the literature.

In this chapter we will first describe the general layout of the sample that has to be fabricated to achieve our goals. This includes calculation of the parameters of the arrays and single holes. Next, the techniques used to fabricate the sample is exposed, along with the optimization of process parameters in order to minimize unwanted effects. And finally, the unique experimental setup that enable near field characterization of the samples is introduced.

2.1 Sample Design

In order to begin with the design considerations let’s, for the moment, present the general process used to fabricate the sample, with emphasis on the steps relevant to the design process. First, a coverslide is thin-film coated with gold while monitoring the thickness. The coated coverslide is inserted into a Focused Ion Beam that mills through the film patterns that has been designed. We will describe in more details the fabrication process afterwards. The guiding lines in the design of the sample were:
• The holes to be milled have to be sub-wavelength. At the same time, too small holes will be difficult to characterize especially those not included in arrays.

• It has to include a square array of nano-holes, which parameters will fulfill the resonance condition derived in Eq. 1.9.

• Close to this array, single holes should be milled in order to “catch” in the same experiment both array and single holes. Here the trade off is the distance between the array and the single holes. Too close will mean that SPs generated by the array can reach the single holes and enhance the transmission through it. But too far will make the measurement more difficult.

• Once the patterns milled, one should find the area of interest in easy way keeping in mind that all the dimensions are far beyond the resolving power of human naked eyes.

Let address each of these points.

The lightwave source that is available in the laboratory is a Nd:YAG laser with a wavelength of 532 nm (doubled). The power it provides is labeled as 20 mW. For a hole to be considered sub-wavelength, its radius should not excess \( \lambda/4 \) (see section 1.1) i.e. 133 nm. A 65 nm radius is chosen. The holes will be really sub-wavelength but still detectable when positioned alone as the transmission given by Bethe’s theory is \( T \sim (r/\lambda)^4 \sim 2.23 \times 10^{-4} \). For our 20 mW laser, the power after the nano-hole will be about 4 \( \mu \)W and after the collecting near field probe we will use in the experiment, the power will be about 4 nW; power still detectable with modern Avalanche Photo Diode (APD) or Photomultiplier (PMT).

Let us consider in more details Eq. 1.9:

\[
a_0 = \lambda \sqrt{\frac{(i^2 + j^2)(\varepsilon_{d,l} + \varepsilon_m)}{\varepsilon_{d,l} \varepsilon_m}}
\]

Obviously, the determining parameters of the periodicity \( a_0 \) the dielectric constants of the materials used, and \( \lambda \) the wavelength used. \( \lambda \) has already been chosen (532 nm). The materials involved are (see Fig. 1.3): glass (cover
slide), gold (film) and air is surrounding the sample. For the two dielectrics (air and glass) we consider a real and constant dielectric constant. The gold case is different. The concept of dielectric function is more adapted as it changes with the wavelength. Furthermore it is a complex function where the imaginary part is reflecting losses. The reference [14] provides data for gold in the visible range. But it is in the form of the complex index of refraction \( \bar{n} = n + ik \). For the data to be useful in our case we first convert it to the form \( \epsilon = \epsilon' + i\epsilon'' \) using the relation \( \epsilon = n^2 \). The data is given with increment in \( \lambda \) of 10 nm. In order to get more accurate results a fit to the experimental data is needed. This fit is achieved by a Least-Squares Cubic Spline Fit. The result of this first step calculation toward computing of Eq. 1.9 is showed in Fig 2.1. The original data can be found in Appendix A.

Fig. 2.1 Comparison of the experimental data for the dielectric function of gold to the fit
Once the dielectric function of gold is known in a range encompassing the wavelength of interest (532 nm), the period given by Eq. 1.9 can be calculated for both interfaces Glass-Gold and Gold-Air. The dielectric constants taken are $\varepsilon_{\text{Air}} = 1$, $\varepsilon_{\text{Glass}} = n^2 = 1.44^2 = 2.07$. The results for few sets of $(i,j)$ are plotted in Fig. 2.2.

![Gold-Air interface: Resonance period vs max lambda](image)

![Glass-Gold interface: Resonance period vs max lambda](image)

Fig. 2.2: Plot of the period as it is calculated from the resonance condition for SPs. Glass-Gold and Gold-Air interfaces are depicted. Few sets of $(i,j)$ are also plotted.
In fact, the interface of importance in the incoming light coupling to the SPs is the Glass-Gold interface. The question that has to be answered now is which set of \((i,j)\) will be chosen. Reference [10] can provide the answer. We reproduce here the data needed.

From this data it is clearly seen that the main peak occurs at the metal/glass interface and for the \((0,1)\) set i.e. for \(i^2 + j^2 = 1\). From Fig. 2.2 the resonant period \(a_0\) for Glass-Gold interface, provided \(i^2 + j^2 = 1\), is \(a_0 \approx 280\) nm. The actual period retained for the sample is larger. The reason is that, as written above, the treatment developed in section 1.3 is assuming an infinite 2D array, and is neglecting the finite size of the holes themselves. Those two facts influence the choice of the right period \(a_0\). One numerical method may be useful in this case and an attempt to simulate our structure with it has been made. The method is the Finite-Domain Time Difference (FDTD).

An FDTD attempt

The FDTD algorithm models the propagation of light by discretizing Maxwell’s equations both in time and space coordinates. Although many variants exist, in the basic Yee algorithm each node contains 3 E-field and 3 H-field components. Both the spatial positions as well as the temporal update of these components are offset (“leap-frogged”) to improve the estimation of the derivatives. This method has been used extensively for very different applications in electromagnetics [15] and has been proven to be very accurate if appropriate use of all the parameters is made (appropriate 3D meshing,
time step ensuring numerical stability etc.). A plus of this method is that surface plasmons effects can be simulated by modeling the permittivity through Lorentz-Drude model or Debye model for permittivity. The difficulty we encountered using this method is a technical one rather than fundamental. As said above, the method yields good results only if right parameters are used. In our case, in the region of the metallic film the grid has to be very dense to sample properly the fields as the wavelength inside the metal drops drastically. Moreover, in order to cancel numerical reflections at the boundaries of the computational domain, they need to be placed far away from the holes. To satisfy those two points for our structure, huge amount of memory is required as one can find only in super-computers, which were not available for this study. For a structure of 3 µm side length, provided that a meshing of 0.5 nm is required [16], a rough approximation gives a requirement of 2000 Gb (!) of memory. Yet we were able to simulate propagation of light through a 150 nm hole milled in gold film sitting on glass substrate. The results are believed to be accurate as they meet the transmission efficiency as predicted by Bethe for such a hole (Fig. 2.3).

Fig. 2.3: FDTD calculation for a single 130 nm hole milled in a gold film of 200 nm thickness. The field depicted is Ex.
The scale is to be compared to an input of 1 used for the simulation.

Fig. 2.3 clearly shows the evanescent property of the light after the sub-wavelength hole. According to the colorbar the transmission is about $10^{-4}$ in agreement with Bethe’s calculation.

In any case, the FDTD has not been really helpful in determining the period to be used for our array. We therefore refer to the Ebbesen’s paper [4]. An allusion for what the period should be, is given in Figure 2(a) in that paper which is reproduced below.

![Graph showing transmission as a function of wavelength/period](image)

The solid line refers to Ag, dashed line to Au, and doted-dashed line to Cr. The transmission is given as a function of $\lambda / a_0$ and according to the graph the peak occurs at a ratio of $\sim 1.61$ for gold. Provided our wavelength of 532 nm, the period $a_0$ is choosen to be 330 nm.

The last parameter to be determined is the distance where the single hole should be placed in order not to be influenced by the SPs generated at the array. A first approximation can be calculated from Eq. 1.4:

$$L_i = (2k_x^p)^{-1} \quad \text{with} \quad k_x^p = \frac{2\pi}{\lambda} \left( \frac{\varepsilon_m^' \varepsilon_d^'}{\varepsilon_m^' + \varepsilon_d^'} \right)^{3/2} \frac{\varepsilon_m^''}{2\varepsilon_m^' \varepsilon_m^''}$$

Here again, the use of the interpolated dielectric function of gold as calculated above is needed. Same dielectric constants for glass and air are used. Fig 2.4 presents the results.
Fig. 2.4: Extinction Length $L_p$ of Surface plasmons at different interfaces. For each of them, length calculated for 532 nm is specified.

Those graphs, as first approximation, give a lower bound for the distance where the single holes should be placed from the holes array and from one to another. 545 nm is this lower bound. For the sample, we opt for a conservative value of 2 μm.

Let’s write in condensed the parameters calculated for the sample:

- Diameter of the holes: 150 nm.
- Period of the array: $a_0 = 330$ nm.
- Distance between holes: $L_p = 2$ μm.
- Thickness of the gold film: $h \sim 300$ nm.

The thickness of the film has not been found to be a parameter in the
expressions describing the processes. Nonetheless, one could say that it should be more than the skin depth of gold film which is about 30 nm but less than the extinction length of SPs which has been calculated to be ~600 nm. We chose a thickness $h \approx 250-300$ nm because of apparatus constraints.

Finally, the general layout of the sample is depicted in Fig 2.5. It contains a 9x9 holes array, several distanced singles holes of same diameters as in the array, and at some distance a larger hole (400 nm in diameter) is positioned. This hole is for alignment and ease of experiment purpose.

Fig. 2.5: General layout of the sample to be fabricated. The dimensions are not scaled.

### 2.2 Sample Fabrication

With the parameters calculated above, we proceed to the sample fabrication. The first step is the gold coating of the cover slide. This is done with a thermal evaporation process. The vacuum thermal evaporation deposition technique consists in heating until evaporation of the material to be deposited. The material vapor finally condenses in form of thin film on the cold substrate surface and on the vacuum chamber walls. Usually low pressures are used, about 10⁻⁶ or 10⁻⁵ Torr, to avoid reaction between the vapor and atmosphere. At these low pressures, the mean free path of vapor atoms is the same order as the vacuum chamber dimensions, so these particles travel in straight lines from the evaporation source towards the substrate (Fig. 2.6). The thickness of the film being deposited is monitored by a quartz crystal microbalance.
A quartz crystal microbalance measures mass by measuring the change in frequency of a piezoelectric quartz crystal when it is disturbed by the addition of a small mass. If the dimension of the substrate as well as the atomic mass of the material being deposited are known the change in the mass can be converted into film thickness.

The process is stopped when a thickness of 300 nm is reached. The thickness will be checked in the next step.

Once the cover slide is coated, the designed pattern has to be milled. This is achieved with a Focus Ion Beam (FIB). In the FIB, high-energy Gallium ions bombard the sample and eject the target atoms into the vacuum. Due to its very small spot size (~5 nm), it is used to mill through materials on a nanometric scale. The FIB we used is the FEI Strata 400-STEM (Fig. 2.7) available at the Technion’s Microelectronic Center in Haifa. It combines a Scanning Electron Microscope (SEM) enabling visualization of the process.

Fig. 2.6: Thermal Evaporation Principle.

Fig. 2.7: the FEI Strata 400-STEM
Using the FIB ability to mill the thin film of gold, we ran the designed pattern. By sectioning a line of holes, it has been found that the exposure time of the beam is a critical parameter. A long exposure time causes the glass substrate to be milled (Fig 2.8). We therefore tried to reduce the exposure time to minimize the milling in the glass. We found the optimal time that provides minimal milling in the glass while keeping the beam stable (see Fig 2.8). The sectioning ability of the FIB is also used to check the thickness of the film.

![Fig. 2.8: Investigating the exposure time influence on the hole’s depth. (Left) typical depth achieved with non-optimized exposure time. (Right) Best result achieved from both depth and beam stability point of view.](image)

From Fig. 2.8 one can see that the depth of the hole, after optimization, is less than a wavelength (~400 nm), so the hole does not act as a waveguide. This is an important fact if one wants the transmission through the hole to be influenced only by SPs. Another point is that the sectioning gives us an accurate measure of the depth, which matches the depth determined in the evaporation process.

The optimal exposure time being defined, the pattern can finally be milled. For experimental purpose, we milled many identical patterns few microns apart. The resulting sample is shown in Fig. 2.9 with the dimensions achieved.
It is clearly seen that a region of ~6-7 μm side length includes an array of holes and at least one, if not two, single holes. This fact is of great importance when considering the one the goal we set at the beginning i.e to be able to measure during the same experiment transmission of light through the holes in an array and through single holes. Uniform illumination of an area of 6-7 μm² can be achieved relatively easily as we will show in the description of the experimental setup we used.
2.3 Experimental setup

Our experimental setup is based on a NSOM head combined with a dual optical microscope. The optical microscope is used to illuminate the sample and to align the light with respect to the probe and area of interest in sample. The NSOM is used to collect the light in the near field. To that purpose, the NSOM is combined with an Atomic force microscope (AFM) sensing and feedback. In the experiment we want to carry out, we shine light on the sample from the bottom and the NSOM probe gets into contact with the sample and collects the light while being kept in the near field by the AFM. In most of the AFM, the sample is doing the raster scanning. In our configuration, this is not possible as the spot is aligned to the right place on the sample. For that reason we must have a probe scanning ability. The Probe scanning feature is challenging for standard AFM sensing & Feedback method because the regular sensing method is based on the beam-bounce scheme (Fig. 2.10)

![Fig. 2.10: Schematic of a beam-bounce AFM](image)

In this scheme the sensing is achieved by shining a laser spot on the cantilever of the probe. Any change in the force is translated by a deflection of the spot on a detector. We can already see that this scheme does not enable probe scanning. Thus an alternate method is used that enables “portable” sensing of the force while the probe is scanning over the sample. This method is based
on the resonance of a tuning fork. In this method, the probe is mounted on one of the prong of the tuning fork (Fig. 2.12). When oscillated, this system can resonate at a certain frequency given by

$$\text{resonant frequency} = \frac{1}{2\pi} \sqrt{\frac{\text{spring constant}}{\text{mass}}}$$

The frequency dependence of the amplitude of this system is described by a lorentzian-shaped bell (Fig. 2.11).

![Resonance Curve](image)

**Fig. 2.11:** typical resonance curve for a probe-tuning fork system

The meaning of this shape is that a little change in the frequency is strongly reflected in the amplitude. As it can be seen the frequency is mass dependent. Thus a tuning-fork-probe system driven at its resonance frequency can sense very accurately changes in the frequency that occurs when the effective mass of the system is changed by the interactions with a sample while in contact.

![Tuning Fork-Probe Assembly](image)

**Fig. 2.12:** tuning fork-probe assembly. Left: the shear-force is sensed and used for the feedback loop; Right: Actual probe used for the experiment (Normal Force).
Thus, this method provides the “portable” sensing needed for the probe scanning AFM scheme.

In the AFM-NSOM system we used (Nanonics Imaging Multiview 2000/4000), the nanometric movement is done by a set of four piezo-tubes. In fact both the probe and the sample are mounted on separated piezotubes scanners, providing high flexibility and very convenient positioning of the sample and the probe one with respect to the other. The Nanonics’ scanner is flat and enables movement in x, y and z (Fig. 2.13). In this flat geometry the optical axis is opened from the below the sample and above the tip.

The probes used are fiber-optic based probe (Supertips Ltd., Jerusalem, Israel). They are heated and pulled in a controlled fashion that produce very sharp tip at the end. In the case of NSOM probes, the tip is eventually coated with a metallic film to ensure light confinement at the very tip and to make a well-defined subwavelength aperture (Fig. 2.14). Typically, the aperture diameter used in our collection NSOM experiment is about 200 nm. This kind of diameter ensures relatively high NSOM resolution while providing fair AFM images and detectable collected-light signals.
The NSOM head is placed in a dual optical microscope (see Fig. 2.15). Thanks to the flat scanners, the optical axis is completely free enabling optical access to the sample from below and above.
Using the lower microscope the sample is illuminated. As we described above, the region to be illuminated uniformly is about 6-7 μm² (Fig 2.16 present a schematic of the experiment).

![Diagram of the experiment](image)

**Fig. 2.16: Schematic of the experiment.**

This relatively large uniform spot is achieved using in the inverted microscope an Olympus X10 objective with a numerical aperture (NA) of 0.25. In the upper microscope, the visualization of the alignment is done through an Olympus X50 objective, NA=0.45, which provides sufficient magnification (Fig 2.17).

Another important point is the polarization direction. A polarizer is inserted between the objective and the sample to ensure proper polarization direction. The polarization is chosen to be in the x direction i.e. co-linear with the singles holes direction. This direction is depicted in by the green array in Fig. 2.17(b). This is an important parameter as the pattern is designed to give maximum enhancement in the y direction i.e. perpendicular to the polarization axis. This expected feature will be discussed in the results section.

Finally, the ability of the upper scanner to move with nanometric resolution in z as well enables us to investigate the propagation of the transmitted light through the array. Once the tip is in contact the feedback loop is turned off and the tip is gradually retracted from the surface. At each step (100 nm in z), the light is collected by scanning the probe at this height. In this way, the light intensity is sampled in x, y and z, providing a 3d data of the propagating light. We chose to “slice” the light intensity within one wavelength ~600 nm: it is in this range that the most interesting near field phenomena occur.
Fig. 2.17: Optical images of the sample obtained with the upper microscope with X50 objectives.

In Fig. 2.17 (a) a general view of the sample is presented. The arrays are clearly seen and the singles are barely distinguished. Each array is roughly 3 \( \mu \)m square. Fig. 2.17 (b) shows the alignment of the NSOM tip near the area of interest. Using the positioning ability of the tip scanner offsets the tip. Green light is illuminating the sample from below and a bright green spot can be seen already in (b). This is the light transmitted by the large 400nm hole. In Fig. 2.17(c), the white light illumination is turned off, and the transmitted light through the different structures is seen. The orange arrow shows the 400 nm hole, and the red arrow is pointing at the array. No transmitted light from the 150 nm single holes is detected in this far field visualization.
3 Results and discussion

In this section we present results obtained in two types of experiments. The first set of results is obtained while the probe is in contact with the surface. This experiment shows the enhancement the array enables, the strong dependence of this enhancement on the periodicity and the features linked to the polarization. The second experiment is intended to map the light intensity in the propagation direction (z).

3.1 Near-field distribution at the surface.

Enhancement and periodicity-linked features

In order to show a relative enhancement, an area including both an array and single holes is scanned. As we are in contact, the online AFM provides data on the topography enabling correlation between the NSOM data and the topography of the area scanned. The results are shown below in Fig. 3.1.

Fig. 3.1: (a) online AFM; (b) NSOM

Fig. 3.1 shows the NSOM and the AFM acquired at the same time of an area of 7 μm square. The angle in the pictures is due to the probe scanning with 45
degree relative to the sample. In the AFM picture the holes are clearly
distinguishable. The array, two single holes and on the right the 400 nm hole
can be seen. However, on the NSOM picture only the array and the 400 nm
hole are seen. The 400 nm hole gives a bright spot which is expected due to its
large diameter. The single holes are not seen in the NSOM image because of
the very low transmission through them as expected and because the scale is
adjusted to the whole image. A line profile reveals them as it is depicted in
Fig 3.2.

Fig. 3.2: line profile of the NSOM signal over the two single holes (the yellow line
show the line being plotted).

The signal level is about 17 Hz. Compared to the maximum signal (1.85 KHz),
it is clear that the color map cannot render such a small signal level.
We can readily observe that the array of nano holes is giving rise to an
enhancement of the transmission compared to the transmission of similar but
isolated nano holes. In order to quantify the enhancement we plot a line
profile over the array (Fig. 3.3).

Fig. 3.3: line profile of the NSOM signal over one of the row in the array (yellow
line).
The maximum intensity in the single holes profile is 19 Hz and in the array profile it yields 770 Hz. The ratio gives a relative enhancement of 40.52. It is important to stress that this enhancement is obtained by comparing intensities acquired at the same time of an array and a single nano hole illuminated under the same conditions. This is important because Ebbesen’s first paper [4] claimed enhancement of $10^3$ but it was compared to the theoretical transmission ratio given by Bethe. On the another hand, relative enhancement of 7 was claimed [17] but there the model explaining the phenomenon is not SP based. This is not the case here, as we will see afterwards. The explanation we can provide for the lower enhancement than expected is the dimensions of the array. The finite size of the array is a parameter of importance in the SP-based enhancement process [18]. We used a 9x9 holes array for practical reasons, but it yields a fair enhancement and can exhibit the SP nature of the phenomenon, as we will see later on.

Another striking feature appearing in Fig. 3.1 is the fact that the light intensity over the array itself is not uniform. As we will see in the next section this fact is inherent to the array as we designed it. But yet an interesting fact can be learned from Fig. 3.1. As we saw in the theory of SPs, light is converted into SPs and inversely through the periodicity of a structure. Here it can clearly be seen from the AFM that the structure periodicity is locally altered and thus the transmission in this area is not enhanced. This local damage can also be responsible for the lower enhancement measured. For further investigation of the SP-based phenomena occurring in this structure we choose to focus on an array that has not been damaged.

**Polarization and symmetry effects**

The sample is moved using the lower scanner till an intact array is found. In this method, the probe remains aligned with respect to the illumination and further alignments are not required, keeping the experimental conditions uniform from one scan to another. Especially, the polarization remains in the x direction.
Fig. 3.4 shows results obtained for the undamaged array close-up.

There are two striking facts arising from the NSOM of the array we want to discuss.

The first one is the non-uniformity of the light distribution over the array. This non-uniformity is a product of two facts as described in [18]. One would expect a uniform and symmetric distribution because the structure is symmetric. The break in this symmetry is induced by the polarization of the light. The polarized light creates a “preferred” direction and makes the structure behaving in different ways in x and in y and being sensitive to the angle of incidence of the exciting light. The other parameter that causes the non-uniformity in the finite size of the array or in other words the edges of the array. The edges are a break in the periodicity of the array and though at these edges the SPs stop to be generated, can be reflected giving rise to interference phenomena inside the array between propagating SPs and reflected ones. An interesting correlation between the results presented in Fig. 3.4(b) and Fig. 2 in [18] (reproduced below in 3.5) has been observed. It should be stressed that the results presented in Fig. 2 of [18] are observed in the far-field, fact that emphasizes the uniqueness of the results and method used here. Furthermore the size of the array is 31x31 while our array is 9x9,
this can explain the non-uniformity observed in our results in the y direction as well.

Fig. 3.5: reproduction of the fig. 2 in [18]. The legend there says: Demonstration of the strong sensitivity of emission patterns to the incident angle. Left panels: Experimental emissivity. Right panels: Theoretical Transmission per hole. Patterns are obtained at resonance for a 31 \times 31 hole array illuminated by p-polarized light using the same colour scale. The results for three different values of $\theta$ are shown: a,b correspond to $\theta = 0^\circ$, c,d to $\theta = 2^\circ$ and e,f to $\theta = 5^\circ$.

The correlation between the Fig 3.5(e) and 3.4(b) in the x direction has to be noted. That means that the illumination in our system is not completely perpendicular to the plane of the array, the angle of incidence according to [18] is $5^\circ$. The angle of $5^\circ$ can be accounted for by the way the sample is mounted into the AFM/NSOM head.

The second point, which can be learnt from Fig 3.4(b), is linked to the SPs preferred propagation direction induced by the structure and its design. Let’s have a look at two line profiles: one taken in the X direction and one taken in the Y direction (Fig. 3.6). It is clearly seen that in the y direction the spots arising from the holes are less distinguishable than the spots in the X direction. To quantify this difference, we chose to use here the concept of contrast defined as [19]:

$$C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$
The contrast is bounded between 0 and 1, when \( C \rightarrow 1 \) means high contrast and, in our case, spots well defined and distinguishable.

Fig. 3.6: (a) line profile over the array taken in the x direction. (b) line profile over the array taken in the y direction. (The white line indicates where the profile is taken)

Based on these line profiles, the C parameter is calculated with the parameters gathered in the table below for both x direction and y direction.

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<th>( I_{\text{min}} ) [KHz]</th>
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<td>X direction (fig. 3.6(a))</td>
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<tr>
<td>Y direction (fig. 3.6(b))</td>
<td>2.25</td>
<td>1.95</td>
<td>( C_y=0.07 )</td>
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As we can see from the comparison of $C_x$ to $C_y$, on a scale from 0 to 1 the holes in x direction exhibit much higher contrast than in the y direction. One can think that this is due to the non-negligible size of the NSOM aperture collecting the light which gives rise to some convolution effects as can be seen from the simulation below (see Appendix C for the code):

The result obtained from the convolution seems similar to the NSOM image displayed in Fig. 3.4(b) in the sense that in the image obtained the holes are less distinguishable than in the original image. The problem is that this explanation does not account for the difference observed between the x and the y direction, a difference that according the table above cannot be neglected. To our opinion this difference is an expression of the Surface-Plasmon based effects that take place in the sample. The sample, as we designed it, was chosen to support the (0,1) SP mode of propagation (see section 2.1). This mode means that the SPs generated propagate in the y direction. What we observe in Fig 3.6(b) is this preferred propagation direction (y direction) for the SPs generated. Along this direction more SPs propagate than in the x direction, giving rise to more light in the y direction. Obviously, a combination of the two effects described here (convolution and SPs preferred direction) is more likely to be the source of what is observed but it should be stressed that the convolution alone does not account for the asymmetry between x and y directions.

Once the behavior of the array has been investigated at the surface, we turn
now to the investigation of the propagation properties of the light after it exits the nano holes array.

3.2 Propagation of the light after the nano holes array

The propagation of the light after the array is investigated by sectioning the light field at different heights within a distance of one wavelength from the surface. To do so the NSOM probe is brought into contact with the surface and retracted gradually with the help of the upper piezos scanner. At each step (100 nm) a scan is run, and the \( (x,y) \) light distribution is obtained at each specific \( z \) (height) distance. We chose to study the light propagation within one wavelength i.e. \(~600 \text{ nm}\); a total of six slices are thus collected.

![Schematic of the experiment conducted.](image)

In this experiment, the light is kept with a polarization in the \( x \)-direction. We present the set of images obtained in Fig. 3.8.
Fig. 3.8 (a) to (f): sections at different distances from the sample. The color map depicted in (a) is common to all the six images. Arrows in (e) and (f) point at light coming from the 400 nm aperture.

The spot pointed by the yellow arrow in 3.8 (a) &(b) is arising from a single 130 nm diameter hole. The first interesting feature seen from those results is
that while the single isolated is detected only in the two first images ((a) and (b)), the array is well seen on all the six images and keeps the same overall dimensions. This observation is difficult to explain. It could be thought that as the tip moves away from the array, at one given point it collects diffracted light from more and more holes. When the tip is contact, it collects light exclusively from the hole it is going over but when it retracts from the surface, surrounding holes are contributing to the intensity the tip feels. According to this explanation, one expects that the overall dimensions of the “array”, or more precisely the pattern formed by the light diffracted from the nano holes constituting the array, should grow with a peak intensity that continuously decreases. It is obviously not the case here. The light arising from the isolated nano hole ((a) & (b)) disappears after 200 nm, which can be predicted from the sub-wavelength nature of the hole giving rise mostly to evanescent waves that disappear within one wavelength. However, diffracted light from the array, constituted by exactly the same nano holes as the isolated one, is well observed over all the range. We suggest that a possible explanation of this effect could be accounted for by what is called beaming effect. It has been shown [20,21] that plasmonics devices of the kind that we are treating here i.e. apertures with periodical structures surrounding them, transmit light in a particular way that is not obeying classical diffraction theory. Propagating light transmitted through sub wavelength apertures becomes evanescent and disappears exponentially. The fact that propagating light transmitted by sub-wavelength apertures can be observed is viewed as a beaming process i.e. the light behaves like a beam, which has high directionality. The beaming arises from the surface plasmon processes involved in the transmission. Although the classical diffraction explanation given above might be valid in our case, it is likely in this case that, as noted by previous workers, the array supports surface plasmon effects. Thus our results could be taken to support this suggestion of surface plasmon.
4 Conclusion

In this work we have reported first near-field investigation of the Extraordinary Optical Transmission (EOT) property of nano holes arrays. The work included special sample design that has enabled in-depth study of the properties of such arrays. The properties that have been studied were the surface plasmons assisted relative enhancement of transmitted light, the array’s sensitivity to the polarization of incident light and propagation of transmitted light. Effects like beaming or polarization sensitivity that, so far, have been observed in the far-field, were observed in the near-field thanks to a unique NSOM setup.

The applications that plasmonics devices like the one studied here offer are very exciting. As it has been shown through this work, plasmonics devices enable manipulation of the light on a nanometric scale. As electronics components shrink and reach their physical limits, photonics is thought to be the next candidate. It is imperative that in this case photonics reaches the dimensionalities that have been achieved with electronic systems. For this to effectively take place new methods of manipulating light at nanometric dimensions are needed. One of these approaches is the use of plasmonic structures that are showing unique capabilities both in terms of the confinement and the intensity of light. Our study focused on one such structure and discovered that in the near-field polarization dependent effects were observable that confined light along particular directions. The behavior of such light as it propagated from such nanometric confinement hinted to non-classical optical phenomena that were a result of the plasmonic nature of the confinement. Our study clearly demonstrates the great utility of near-field optics as an important method of characterizing such nanophotonic advances.
Bibliography


5 Appendices

5.1 Appendix A: Gold Dielectric function (adapted from [14])

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5.2 Appendix B: MATLAB code used for sample design (2.1)

```matlab
close all;
lambda=490:1:820;
Epsilontag=interp1(Epsilon(:,1),Epsilon(:,2),lambda,'pchip');
Epsilontt=interp1(Epsilon(:,1),Epsilon(:,3),lambda,'pchip');
figure
plotyy(Epsilon(:,1),Epsilon(:,2),lambda,Epsilontag);
xlabel('wavelength in nm');
title('comparison of Re(epsilon) data for Gold (left) to fit (right)');
figure
plotyy(Epsilon(:,1),Epsilon(:,3),lambda,Epsilontt);
xlabel('wavelength in nm');
title('comparison of Im(epsilon) data for Gold (left) to fit (right)');
epsilonGlass=1.44^2;
epsilonAir=1;
periodGl_Au1=lambda./sqrt(epsilonGlass*Epsilontag./(Epsilontag+epsilonGlass));
periodGl_Au2=sqrt(2)*lambda./sqrt(epsilonGlass*Epsilontag./(Epsilontag+epsilonGlass));
figure
hold on
plot(lambda,periodGl_Au1,'red');
plot(lambda,periodGl_Au2);
plot(lambda(43),periodGl_Au1(43),'+');
plot(lambda(43),periodGl_Au2(43),'*');
h=legend('$i^2+j^2=1$','$i^2+j^2=2$','[$\lambda=532 nm,a_0=$',num2str(periodGl_Au1(43)), 'nm'],
['$\lambda=532 nm,a_0=$',num2str(periodGl_Au2(43)), 'nm'],'Location','NorthWest');
set(h,'Interpreter','latex');
LEGEND BOXOFF ;
xlabel('wavelength in nm');
ylabel('resonance period in nm');
title('Glass-Gold interface: Resonance period vs max lambda')
periodAu_Air1=lambda./sqrt(epsilonAir*Epsilontag./(Epsilontag+epsilonAir));
periodAu_Air2=sqrt(2)*lambda./sqrt(epsilonAir*Epsilontag./(Epsilontag+epsilonAir));
figure
hold on
plot(lambda,periodAu_Air1,'red');
plot(lambda,periodAu_Air2);
plot(lambda(43),periodAu_Air1(43),'+');
plot(lambda(43),periodAu_Air2(43),'*');
h=legend('$i^2+j^2=1$','$i^2+j^2=2$','[$\lambda=532 nm,a_0=$',num2str(periodAu_Air1(43)), 'nm'],
['$\lambda=532 nm,a_0=$',num2str(periodAu_Air2(43)), 'nm'],'Location','NorthWest');
set(h,'Interpreter','latex');
LEGEND BOXOFF ;
xlabel('wavelength in nm');
ylabel('resonance period in nm');
```

```matlab
% Gold-Air interface: Resonance period vs max lambda
a = 2*2*pi./lambda;
b = (epsilonGlass*Epsilontag./(Epsilontag+epsilonGlass)).^(3/2);
c = Epsilontt./(2*Epsilontag.^2);
LengthGlass_Au = 1./(1000*(a.*b.*c));
figure
hold on
plot(lambda,LengthGlass_Au);
plot(lambda(43),LengthGlass_Au(43), '*');
h = legend('length versus wavelength in microns', ['$\lambda=532 nm, L_p=$', num2str(LengthGlass_Au(43)), ' microns'], 'Location', 'NorthWest');
set(h,'Interpreter','latex');
LEGEND BOXOFF;
xlabel('wavelength in nm');
ylabel('length of plasmons propagation in microns');
title('Glass-Gold interface: length of plasmons propagation vs lambda');

b2 = (epsilonAir*Epsilontag./(Epsilontag+epsilonAir)).^(3/2);
c2 = Epsilontt./(2*Epsilontag.^2);
LengthAu_Air = 1./(1000*(a.*b2.*c2));
figure
hold on
plot(lambda,LengthAu_Air);
plot(lambda(43),LengthAu_Air(43), '*');
h = legend('length versus wavelength in microns', ['$\lambda=532 nm, L_p=$', num2str(LengthAu_Air(43)), ' microns'], 'Location', 'NorthWest');
set(h,'Interpreter','latex');
LEGEND BOXOFF;
xlabel('wavelength in nm');
ylabel('length of plasmons propagation in microns');
title('Gold-Air interface: length of plasmons propagation vs lambda');
```
5.3 Appendix C: MATLAB code used for section 3.1

clear all
close all
a=zeros(79);
d=zeros(79);
for i=8:8:72
    for j=8:8:72;
        a(i,j)=1;
    end
end
d(40,40)=1;
b=[0 1 1 0;1 1 1 1;1 1 1 1;0 1 1 0];
c=[0 0 0 1 0 0 0;0 0 1 1 1 0 0;0 1 1 1 1 0 0;1 1 1 1 1 1 1;1 1 1 1 1 1 1;0 1 1 1 1 1 0;0 0 1 1 1 0 0];
orig=conv2(a,b);
conv=conv2(orig,c);
tip=conv2(d,c);
figure
colormap('gray');
imagesc(a);
figure
colormap('gray');
imagesc(b);
figure
colormap('gray');
imagesc(orig);
figure
colormap('gray');
imagesc(c);
figure
colormap('gray');
imagesc(conv);
figure
colormap('gray');
imagesc(tip);
סקנרשיה מסיעת והפרובה בקריאית הלまるית והפרובה במגע. בלול הז לשל
הנ隹יה ההטאות שתיתכן: שנדניחת האור דרכ הɦוים במעבר פי 40 לעמות.
העונצאה הממידת במכיול דרכ הɦוים בדידים, קשאי של יבג יזון וההמווריו.
ב뇨ור המערר דרכ המיאש את המקור הפולימיני של התופעה. הՁע בוח היא איפו
ה降幅אצף האור שהשבה עבואר את הח稌ים הנכוסריים. איפור זה נשענethylene ואיתו
מערך ינאי כהור הסקנרש העילוי מתחר באנק מברק למращת הממד בדוי.
משוער אוועצמא האור. שלו�ו ולאנחנו יבעاعتماد את עצנט את האור יקושייכר שוניג
בכוכית ה降幅אצף. חור חזרנה לכ 100 נמגdeer למרחק של 600 נמ"ש (שור 6 דרגות).
שיה מגוריה היא גב איה ובמקימייההתופעה של פיתוח הקור. מצודת אול
נמצא שאר העגור דרכ הɦוים במערו ממד דע המתקמד הכי גדול בוש האור.
הכלליות של האלומת (בודגל הכללי לשכת) מפורמת. לעמעת את אור העגור דרכ הור
בוד צפה קר דע 200 נמ"ש אכיל במרך הז כתום ממסק לתחתרב. באומן
משמעוני. הטבר לו יגוי החלמה באס ממידה או חזרביי גו יבלי חבר
הממידות של פולימוני במעגונים העגור דרכ הɦוים הממסדועים במער. איכריעה
נמדד בשדה הרוחות ממערה שבאלומת האור המסהשת ממדע נいただいて
וחת ביןגלת האור הקלאסיות של עקפה. ממצאות של יאנוש מרגים או יבלי להוות
תצפית אלוושנה של אותרת תופעה בשדה הקור.
ב авгון בשוב החליניג החברות כקר תופעת פולימוני. אלא כי בניסיון של שדה
דחיית האור הנמדדされている. דבר שלוח ה الاثنين בדר לשמעה של האור ברכיב
הפוטונים בעדות.
בעובדה, אנו מאפשרים את התפלה לעור בחרים בהדרגה על עורם של…andית אוכר עד לשדרמה קיים
העבורה שתייה. דוגמ(“ד”) לע ידי mikroskopifית השדה הקורוב משולבים עם mikroskopifית
הዶות האטומיים
לשם כ בבעcade ולא יציראת המ ogl המכיל תורים של חורים של yan והגד_solve שבבה מתכתית
דקה המותאמת על וכובץ לבין שאר באורר של 532 נמ_ שוערジェקוטים משشعورים. דבר
יה מושג את התפלה החדרית התמריץ של ווד גולונח החרום הממדים שעבקש בלבל היא
וסת התמרי התחרים במעד: 33 נמ_ לקוות התחרים: 130 נמ_ כמ_ לשוזואהת
חרום בעיל ממדים שונים של מאוזדים תבונון ברקבי התמריץ. מתך мнווניל בון
העפר והחרום הבנדיום חוסב. חוץ שבל הת nephew שב הריווור בע"י שימשו
באלומת ממוקדת של ויוו. בשייתו זו אולמה של ויוו גלויות מופקת על המישוע
המתכתית (בֶּל הכתמ_ 5 נמ_ הקדחת את החקרו בחתם לתכות). על מנת להם את
ידים גואודי הקורוב השמתונית במעבר המגוני הגמואר באיר. 1. לניסוי יש הדמ_ מאור
מלטפת כ ש yatv אחדת יאדו מקוור החרום. ידיג מון על סקר מובסס
גביש פיני-אלקטרים,דבר המאפר ייוו כיוון מדף על של החרום במדל האופטי
האורה הממעבר דרכו החרום יאסף בשדה הקורוב לע ידי סיב אופטי משך ומוכפף עם קוטר
shall 200 נמ_ בקביצה המאפר. הקצץ השתי של הסיב מתחבר לגלילאי אור מסור דזרד
ממדל המודד את האור הנאסף וחמור דרכו הסיב. הפורב הזה מונק על עז
המשטח ונומר במעע עד שע ידי שישת mikroskopifית של הכח DARK האטומיים

איור 1: סכמת של מועד הניסוי

X30, NA=0.45
Probe scanner

Sample scanner

Polarizer

X10, NA=0.20

NaYAG laser

Detector
לקני יתיר מעשהím שגיה ליאו ישותפי חקר את העברת האור דרכ מטריצים של חורים בלווי
ממידים תתי-אירונ גל ב곽 שיבת דקה שלמתכת. מנוג על גלונים חקרה, את 15 נומר.
יאור נמד אפול דרכ החורים הקטנים בינה. כמ קי צה על פוליאורוכנס של פילר דרכ.
יאור חורים קצני ממידים
ליאת שות שיגה תורי תתי-אירונ גל ליידיס בקצחו של סיב אופי מושק. חורים אלה
מרומים כים מרכיב מרכיב בקצחו של אנטייקת השדה הקורוב. לומרות השימוע בצי
有效性 מאמות סוג הנמצע במערכים המתקנים עלי, העברת האור דרכ החוריםบทדיס
היתכה הקטנה ביאופ ממעניוניה ממח שנעפה קודה לכנ חורים יאולים ממידים אנלב.
מיאורגנס בןנה מערקית
ב 1998 אבוס ישותפי הציעה@Slfבעת האור היצאת יום הנפעת דרדרעיכים, ולאמקורה
בורור שלפלמומגנויות משטחיים ובשכבה המתקנות השדה. פלמומגנONENTרגים התאונותורקליתיה
האיר על המתקת מתפתשים דרכ המשטח שרמות הממישית מתכת-דילינטירזיו. אופז
ה karşıים התאונות מים הז הניש לאימונ הממישת העברה מנוגבת של אור דרכ חורים
הっぽישות מוארכ הגלなくなる כשאימונינぷוררמאつき בחרת מאמ סומית. בҤזימ שיבור את
ה같ה נאורה הגל על עונג של יאדי של שות, העברת רום הקורד לשון הקורוב בחרת השדה הקורוב
ב❥וספליוס הסופטילית. אולב, ואופמס מפדע. לע דווה על בורח החולות השדה השדיתשוד
האיר והפלולוגמה תמרוגות בחרת הקורד אחור שיו ננה עגור דרכ יאמ תמעך שול
נוגוור
בגלל האופי התאורה גל של אומת חורים ורמות הקורד בינה. כיימ קב שית
יאת המאפרשות אירופ הנשידה הקורוב נפגנס כל באח מיקורוספיקית השדה הקורוב
שפתה עי, קבוצת בניו של בחרת כל ליופי ני פוטוני. בפעז השול ויה מחרז הט 초 מקוד
שופמי כיולק מנכנימ פלמומגניר יומת המגריצים הקורוב בעבודה.
טכניון ע"ש הונקר

"חקור הגבלת האור בממדים ננומטריים"  
מאית מייכל מרגן  
בהנחיית של פרופ' אהרון לואיס  
עבודת מונוגשת לשם קבלת תואר מוסמך למדעים

אביר תשא"ז