

Jagiellonian University in Krakow

Faculty of Physics, Astronomy
and Applied Computer Science

Aleksandra Sierant

Tailored optical near field potentials for cold atoms

PhD thesis written under supervision of
Dr hab. Tomasz Kawalec

Kraków, 2020

Franciszkowi

Oświadczenie

Ja, niżej podpisana Aleksandra Sierant (nr indeksu: 1061997), doktorantka Wydziału Fizyki, Astronomii i Informatyki Stosowanej Uniwersytetu Jagiellońskiego oświadczam, że przedłożona przeze mnie rozprawa doktorska pt. „Tailored optical near field potentials for cold atoms” jest oryginalna i przedstawia wyniki badań wykonanych przeze mnie osobiście, pod kierunkiem dr hab. Tomasza Kawalca. Pracę napisałam samodzielnie.

Oświadczam, że moja rozprawa doktorska została opracowana zgodnie z Ustawą o prawie autorskim i prawach pokrewnych z dnia 4 lutego 1994 r. (Dziennik Ustaw 1994 nr 24 poz. 83 wraz z późniejszymi zmianami).

Jestem świadoma, że niezgodność niniejszego oświadczenia z prawdą ujawniona w dowolnym czasie, niezależnie od skutków prawnych wynikających z ww. ustawy, może spowodować unieważnienie stopnia nabytego na podstawie tej rozprawy.

data

podpis doktoranta

Streszczenie

Przedmiotem niniejszej rozprawy są bliskie pola optyczne wytwarzane za pomocą polarytonów plazmonów powierzchniowych (z ang. *Surface Plasmon Polaritons* – SPP), do wykorzystania w układach zimnoatomowych i sensorach plazmonowych.

Jedną z metod optycznego wzbudzenia SPP jest użycie specjalnie spreparowanych struktur, w tym metalicznych siatek dyfrakcyjnych. Produkcja siatki dyfrakcyjnej jest procesem złożonym, długotrwałym i wymagającym znacznych nakładów finansowych. Równie efektywną i przy tym tańszą alternatywą jest użycie odpowiednio spreparowanej płyty DVD. Pierwsza część pracy przedstawia okresową strukturę odbiciową powstałą na bazie płyty DVD. Topografia struktury została zbadana przy użyciu mikroskopii sił atomowych, określony również został skład płyty, oraz grubości poszczególnych warstw. Przeprowadzono symulacje numeryczne ścisłą metodą fal sprzężonych (z ang. *Rigorous Coupled Wave Analysis* – RCWA) w celu znalezienia tych warstw płyty, które pozwalają na najbardziej efektywny rezonans plazmonowy. W pracy przedstawiony został szczegółowy opis nowej metody, pozwalającej na przygotowanie odbiciowej struktury plazmonowej na bazie DVD. Na podstawie pomiarów współczynnika odbicia zmierzono efektywność wzbudzenia SPP osiągając 95%. Dzięki przeprowadzonym symulacjom numerycznym metodą RCWA i metodą różnic skończonych w domenie czasowej (z ang. *Finite Difference Time Domain* – FDTD), oszacowano natężenie SPP na 100-200 razy większe niż natężenie wiązki wzbudzającej. Szczegółowo scharakteryzowano również efekty termoplazmoneczne występujące przy wzbudzaniu SPP, ze szczególnym uwzględnieniem promieniowania termicznego. Struktura została z sukcesem wykorzystana w układzie optycznego lustra dipolowego dla zimnych atomów, którego opis kończy część pierwszą.

Część druga opisuje bliskie pole optyczne związane z metaliczną siatką transmisyjną. Przeprowadzono symulacje numeryczne rezonansu plazmonowego metodą RCWA w celu znalezienia optymalnych parametrów siatki dla bliskiej podczerwieni. Opisano proces wytwarzania siatki, oraz zmierzono efektywność wzbudzenia plazmonowego w bliskim i dalekim polu, otrzymując 68% oraz 50-krotne wzmocnienie pola elektromagnetycznego przy powierzchni. Na podstawie porównania wyników ze skaningowego mikroskopu bliskiego pola oraz symulacji numerycznych przeprowadzonych metodą FDTD stworzono ilościowy opis rozkładu pola elektromagnetycznego przy powierzchni. Symulacje numeryczne uwzględniły takie czynniki jak skończony rozmiar siatki, jakość powierzchni oraz obecność igły mikroskopu, stwarzając możliwość pełnego opisu zjawiska, które jest kluczowe przy projektowaniu i produkcji wielu urządzeń plazmonowych, takich jak pułapki powierzchniowe dla zimnych atomów, nanomanipulatory i sensory. Uzyskane wyniki potwierdziły również, że przy pomiarach bliskiego pola jedna ze składowych pola elektromagnetycznego jest znacznie tłumiona przez igłę mikroskopu, co jest wciąż żywo dyskutowanym tematem w mikroskopii bliskiego pola.

Słowa kluczowe: *polarytony plazmonów powierzchniowych, optyczne lustro dipolowe, bliskie pole, metaliczna siatka dyfrakcyjna.*

Abstract

Tailoring of plasmonic near-fields is central to the field of nanophotonics, including the design and fabrication of plasmonic sensors, detectors, nanomanipulators, and atomic devices. The thesis discusses the optical near fields, associated with Surface Plasmon Polaritons (SPPs) mainly in the near-infrared part of the spectrum. One of the methods of optical excitation of SPPs is the use of diffraction grating and other submicron structures.

Usually, preparation of submicron, periodic structures is complicated, time-consuming, and expensive. A cheap and optimal alternative employs the well-known technology of optical discs. First part of the thesis presents the reflective nanostructure, which is based on a modified digital versatile disc (DVD). The topography of the structure was carefully examined under Atomic Force Microscope and the thickness and composition of each layer were thoroughly investigated as well. In order to find the most efficient internal profile for plasmonic excitation, the numerical simulations were performed by Rigorous Coupled Wave Analysis (RCWA) for near-infrared light. The optimized brand new method is proposed to prepare the samples of reflective nanostructures based on the DVDs. The optical properties of the samples are carefully studied via far field zeroth-order reflectivity measurements, compared with numerical simulations performed by RCWA and Finite Difference Time Domain (FDTD) methods. The efficiency of plasmonic coupling is up to 95%, and the intensity of SPPs is 100-200 times the intensity of the excitation beam. The energy loss mechanisms, which unavoidably accompany the SPPs excitation, are thoroughly investigated, and particular attention is devoted to an analysis of thermal radiation. Finally, the usefulness of the DVD based structure is demonstrated by showing that it may be used to create an optical dipole mirror for cold rubidium atoms.

In the second part, a transmissive diffraction grating is considered as another source of SPPs. Unlike the reflective structures, the transmissive grating enables spatial separation between the SPPs and the excitation light. The RCWA numerical optimization of the grating parameters is demonstrated, followed by a brief description of the nanofabrication process. The optical characterization of the grating in far- and near-fields is presented, revealing the coupling efficiency of 68% and the enhancement of the electromagnetic field equal to 50. A fully quantitative comparison of the intensity distributions of the near field measurements by Near Field Scanning Optical Microscope and FDTD numerical calculations are reported. The optimized numerical method allows to take into account the influence of the quality of the gold surface as well as the presence of the NSOM fiber probe. The detailed knowledge of the field distribution is crucial for the design and fabrication of any plasmonic devices. Finally, the obtained data confirmed, that the out of plane component is not coupled to the aperture-type NSOM probe, which is still an investigated topic in near field optics.

Keywords: *Surface Plasmon Polaritons, optical dipole mirror, near field, metallic diffraction grating.*

Acknowledgements

First and foremost, I thank my supervisor, Dr. Tomasz Kawalec, for his constant support, patience, and guidance. I particularly acknowledge introducing me into good lab practices, the encouragement I received through the last 5 years, and always taking time to help me figure things out. I would also like to thank the head of the department, Prof. Jakub Zakrzewski, as well as Prof. Krzysztof Sacha, Dr. Jacek Bieroń, Dr. Bogdan Damski and Dr. Tadeusz Pałasz for all the help I received, and for always answering my questions. I would also like to thank Prof. Jakub Rysz for sharing his expertise on NSOM.

This research would not have happened without my amazing co-workers. I would like to thank Dobrusia Bartoszek-Bober, who taught me which way to turn the screws when I first started, and Romek Panaś for all the MOT adjustments, laughs, and the good time we had in the Lab. I would also like to thank Piotrek Sowa for all the discussions we had during (and off) the tedious measurements of pseudo-momentum.

Furthermore, I would like to thank all of my colleagues from the department: Arek Kosior, Janek and Ewa Major, Tomek Pięta, Andrzej Syrwid, Michał Białończyk, Krzysiek Biedroń, Krzysiek Giergiel, Jakub Janarek, Lutka Mikowska, and all the other members, who were a part of my everyday life in the faculty.

I would also like to thank my collaborators from ICFO. I am incredibly grateful to Prof. Morgan Mitchell, who's unique scientific intuition has motivated me many times, and Vindhya Prakash, for her work ethic, passion for science, and all the fun we had together. I also thank all the Quantum Information with Atoms and Light group: Charikleia Troullinou, Natalia Alves, Lorena Bianchet, Enes Aybar, Chiara Mazzinghi, Michael Tayler, Daniel Benedicto, Stuti Gugnani and Vito-Giovanni Lucivero.

I am indebted to everyone who worked on my experimental apparatus, especially Stanisław Pajka, Janusz Kuźma, and the staff of mechanical workshop. I am grateful to Jacek Fiutowski, Benedykt R. Jany and Michał Włodarczyk for preparing the nanostructures, Paweł Dąbczyński for plasma cleaning and Dominik Wrań for SEM imaging. I acknowledge members of the larger community at the Faculty, including administrators and support staff – especially Monika Król, Małgorzata Nałódka, Agnieszka Golać, Agnieszka Hakenschmidt, Agata Hadasz, Danuta Myrek, and Alicja Mysiek. Special thanks to Karolina and Ania, the amazing ladies from Biuro Promocji, for their invaluable work and constant support.

Outside the lab, I have been fortunate to find many good friends, who always supported me – Karolina and Alfred Mazur, Agnieszka and Sebastian Kukiola, Magda Młotek, Daniela Wybrańczyk, Sabina Gach, and Maria Fabiańska. Thank you for sharing both my triumphs and my struggles. Special thanks to awesome Piotrek Machajek for English corrections of the thesis, and Tomek, Gaba, Maciek, Jacek, and Madzia Kawalec for brightening up my reality in Cracow.

Finally, I would like to thank my husband, Piotrek, for his scientific support and all the encouragement I received to finish the thesis. I also owe my greatest acknowledgement to my mother and my father, who were my first teachers and an example of the true priorities and purpose of life, and to my sisters and my brother, for being the best siblings I can imagine.

List of publications

1. A. Sierant, B. R. Jany, T. Kawalec, *Quantitative near-field characterization of Surface Plasmon Polaritons on nanofabricated transmissive structure*, arXiv e-prints, arXiv:2007.02102 (2020)
2. A. Sierant, R. Panaś, J. Fiutowski, H.-G. Rubahn, T. Kawalec, *Tailoring optical discs for surface plasmon polaritons generation*, Nanotechnology, **31**(2): 025303. doi: 10.1088/1361-6528/ab4688 (2019)
3. T. Kawalec, A. Sierant, R. Panaś, J. Fiutowski, L. Józefowski, H.-G. Rubahn, *Surface Plasmon Polaritons Probed with Cold Atoms*, Plasmonics <https://doi.org/10.1007/s11468-017-0555-8> (2017)
4. T. Kawalec, A. Sierant, *The parametric resonance—from LEGO Mindstorms to cold atoms*, European Journal of Physics, **38**(4), (2017)
5. T. Kawalec, D. Bartoszek-Bober, R. Panaś, J. Fiutowski, A. Pławecka, H.-G. Rubahn, *Optical dipole mirror for cold atoms based on a metallic diffraction grating*, Opt. Lett. **39**(10), 2932 (2014)

Financial Support

The work was supported by Ministry of Science and Higher Education, projects: *Optyczny sensor atomowy* (7150/E-338/M/2016), *Diagnostyka metalicznych struktur periodycznych* (7150/E-338/M/2017), *Sztuczne pola magnetyczne dla zimnych atomów w fali zanikającej* (7150/E-338/M/2018). I would also like to acknowledge support by Faculty of Physics, Astronomy and Applied Computer Science of the Jagiellonian University (pro-quality scholarship). During my fourth year of studies, I was receiving the ETIUDA 6 scholarship (agreement no. 2018/28/T/ST2/00275, project *Nontrivial motion of cold atoms in the optical near fields*) of the National Centre of Science, which I appreciate.

Contents

Streszczenie	7
Abstract	9
Acknowledgements	11
List of Publications	12
List of Abbreviations and Symbols	15
1 Introduction	17
1.1 Background	18
1.2 Atom-light interaction	20
1.3 Surface Plasmon Polaritons	22
1.3.1 SPPs on a metal/dielectric interface	22
1.3.2 Excitation of SPPs at planar interfaces	26
1.4 Optical Dipole Mirror	27
2 Reflective structures	29
2.1 Introduction	29
2.2 Preparation of the plasmonic structure	29
2.2.1 Characterization of optical discs	29
2.2.2 Fabrication of the plasmonic grating	36
2.3 Optical examination of plasmonic resonances	38
2.3.1 Intensity of the electromagnetic field	44
2.4 Energy losses associated with SPPs excitation	44
2.5 Optical Dipole Mirror with SPPs	56
2.5.1 Experimental setup	56
2.5.2 ODM for cold rubidium atoms	62
3 Transmissive structures.	69
3.1 Introduction	69
3.2 Preparation of the structure	70
3.2.1 Optimization	70
3.2.2 Nanofabrication	72
3.3 Numerical simulations of plasmonic excitation	74
3.3.1 Roughness of the surface	75
3.3.2 Rounded edges of the ridges	84
3.3.3 The actual size of the grating	86
3.4 Far Field examination	92

3.5	Near Field examination	95
3.5.1	TM/TE polarization of light	96
3.5.2	Poynting flux calculations	98
3.5.3	Area of the grating	101
3.5.4	Nonoptimal angle of incidence	103
3.5.5	The probe-surface separation	104
3.5.6	Contamination of the surface	104
4	Conclusions	107
	Contribution of the Author	110
	Appendices	
A	Numerical simulations	113
A.1	Rigorous Coupled Wave Analysis	113
A.2	Finite Difference Time Domain	113
A.2.1	EM Explorer script	114
B	Analysis of optical discs	121
B.1	Surface topography	121
B.2	Composition	121
B.3	Plasmonic resonances	121
	Bibliography	130

List of Abbreviations and Symbols

1D One-Dimensional

3D Three-Dimensional

AFM Atomic Force Microscope

AOM Acusto-optic Modulator

BEC Bose-Einstein Condensate

CCD Charge Coupled Device

DVD Digital Versatile Disc

EMCCD Electron Multiplying Charge Coupled Device

FDTD Finite Difference Time Domain

FIB Focused Ion BEAM

FWHM Full width at half maximum

IR Infrared

LSP Localized Surface Plasmon

MOT Magneto Optical Trap

NSOM Near Field Scanning Microscope

ODM Optical Dipole Mirror

OLED Organic Light Emitting Diode

OPLL Optical Phase Locked Loop

PBS Polarization Beam Splitter

PC Polycarbonate

PHD Photodiode

PLL Phase Locked Loop

PMF Polarization Maintaining Fiber

R Reflectivity coefficient

RCWA Rigorous Coupled Wave Analysis

SEM Scanning Electron Microscope

SIMS Secondary Ion Mass Spectrometry

SPP Surface Plasmon Polaritons

TE Transverse Electric

TM Transverse Magnetic

UV Ultraviolet

vdW van der Waals

Chapter 1

Introduction

The thesis is devoted to the study of plasmonic near field potentials for cold atoms. The field of plasmonics is widely used in a broad range of applications, and in recent years, have also started to be attractive for the manipulation, trapping, and positioning of atoms at the micro and nano scales. The accuracy, with which the movement of atoms and simple ions can be controlled is one of the greatest accomplishments of quantum optics. The cloud of atoms can be cooled down to nanokelvin temperatures, fulfilling the quantum degeneracy regime and being trapped in magnetic and optical traps. The smallest spatial resolutions are reported for optical lattices, with a periodicity of half an optical wavelength [1]. Although the typical optical and magnetic traps are limited by the diffraction or technical constraints, the diffraction limit can be bypassed by the use of optical near-fields. A certain kind of plasmonic excitation, Surface Plasmon Polaritons (SPPs), which are associated with an evanescent field, structures the potentials with sub-wavelength resolution [2, 3]. A broad range of scientists take use of plasmonic near fields [4], in the area of optics, spectroscopy [5], data storage [6, 7], photovoltaics [8, 9, 10], sensing and biosensing [11, 12], medicine [13, 14], ultracold atom physics [15, 16], and quantum plasmonics [17]. Of particular interest are plasmonic devices for cold atoms, used for atom trapping and nanomanipulation [15, 18, 19]. The precise control over the atom motion in the subwavelength regime creates number of new possibilities, e.g. the realization of quantum many-body states with topological properties [20] or single-photon applications [21, 22] (these are theoretical proposals so far).

The strength of plasmonic potentials is dependent on the efficiency of the coupling between SPPs and the excitation light. This in turn, depends on the properties of both, the structure and the light (for SPPs excitation by optical methods). Therefore, the studies on the nanostructures are required in order to obtain the most effective plasmonic coupling. The detailed knowledge of the intensity distribution of SPPs is crucial for a design and fabrication of any abovementioned plasmonic devices. Finally, the experimental observation of the interaction between the cold atoms and SPPs is an important step towards creating more complicated atomic surface traps and sensors. The main goal of this thesis is to find the nanostructures providing the most efficient plasmonic coupling, the direct observation of the coupling between the plasmonic structure and cold rubidium atoms, and the detailed characterization of the near field associated with SPPs.

The thesis is organized in the following way. In Chapter 1, a brief introduction is presented, including the description of the dipole potential, Surface Plasmon Polaritons, and the technique of near field imaging. The section introduces a short history of cooling mechanisms in dipole traps, followed by theoretical expressions for atom-light interaction and the definition of SPPs. Then, the basic characteristics and excitation methods of the latter are discussed. The chapter ends with a characterization of an Optical Dipole Mirror.

In chapter 2, the quasi-sinusoidal type of plasmonic grating structure is introduced. The characterization, optimization, and preparation processes are presented for the modified optical discs (DVD $\pm$ R). The measurements of the plasmonic resonance are reported, and compared with numerical calculations performed by two numerical methods: Rigorous Coupled Wave Analysis (RCWA), and Finite Difference Time Domain (FDTD). The studies on energy loss mechanisms, which accompany the SPPs excitation are discussed, i.e. the analysis of the thermal radiation, light scattering and reflection from the grating, and heat convection. Finally, the optical dipole mirror for cold rubidium atoms is demonstrated, with a detailed description of the apparatus, experimental sequence of the mirror, and the obtained results.

In Chapter 3, the transmissive grating is considered. The numerical optimization and nanofabrication of the structure are described, with the detailed calculations of the electromagnetic field intensity. The far field characterization, followed by near field imaging is presented, revealing the efficiency of the plasmonic generation. The fully quantitative description of SPPs excitation is reported, and the comparison between near field experimental observation and FDTD calculations is performed. The processes of build up and propagation of SPPs is shown *in situ*, along with the analysis of plasmonic excitation for different states of polarization, angle of incidence, and the position on the structure.

Appendix A completes the information on RCWA and FDTD numerical simulations, with the enclosed FDTD scripts, used for the calculations. Appendix B complements the studies on modified optical discs, i.e. reveals the measurements of the topography and composition of the discs, and the obtained plasmonic resonances for a number of samples, that were not included in the main part of the thesis.

1.1. Background

The trapping, guiding, and manipulation of cold and ultracold atoms is an actively and widely investigated topic in atomic physics. So far, the trapping has been carried out by using the resonant forces in *radiation-pressure traps*, and/or the forces generated by field gradients acting on magnetic and electric dipole moments of an atom in *dark traps*.

The radiation pressure traps operate with the resonant or near-resonant light, with a typical depth of a few Kelvins. The trapping mechanism acts on atoms in a 'hot' thermal or pre-cooled gas, and reduces the temperature to tens, or several dozens of μ K [23]. The temperature and density limitations are caused by the presence of resonant processes, such as photon recoil and light-assisted inelastic collisions. Likewise, the presence of the resonant light strongly perturbs the internal dynamics of an atom, making it unmeasurable in the experiment. These limitations can be overcome with the elimination of the resonant light in the *dark dipole traps*, which are populated by pre-cooled atoms. The efficient cooling mechanism is crucial to load atoms into any dark trap, since the attainable trap depths are generally below 1 mK. The two most relevant mechanisms are Doppler cooling and polarization-gradient cooling.

The Doppler cooling. First used in [24], requires the light of a frequency slightly detuned from the atomic transition. Due to the Doppler effect, the atoms absorb more photons when moving towards the light source, and significantly fewer photons, if they move in the opposite direction. Each act of absorption leads to the excitation of an atom, followed by spontaneous emission of the photon. The reduced speed is a result of a momentum exchange. The photon is emitted in a random direction, which averaged over the number of events does not change the speed of an atom. Using the counter-propagating beams, the kinetic energy of all atoms is reduced, and so is the temperature. The lowest temperature is called the Doppler temperature,

with the limitation brought about by momentum fluctuations induced by spontaneously emitted photons. Even though the spontaneous emissions are isotropic, and the associated recoil averages to zero for the mean velocity, the mean squared velocity is nonzero, and thus, introducing the heating mechanism to the system [25].

The polarization-gradient cooling, the sub-Doppler cooling. There are two main cooling mechanisms relying on the polarization state of the laser beams. The first one is known as the Sisyphus cooling. It was first noticed by Lett *et al.* [26], that the Doppler limit can be bypassed by using orthogonally polarized counter-propagating laser beams. The counter-propagating waves form a standing wave with spatially varying polarizations, providing a polarization gradient. Atoms moving in the potential of the standing wave, climb up a potential maximum, at which, the optical pumping brings them to a lower energy state. This process causes eventually the loss in kinetic energy. Through the repeated cycles of climbing a potential maximum and optical pumping, the cloud of atoms reaches the temperatures below the Doppler limit. The cooled cloud is called the optical molasses [27], and has been demonstrated for the red- and blue-detuned light [26, 28, 29, 30]. The second mechanism works 'automatically' in common magneto-optical traps due to the use $\sigma^+ - \sigma^-$ configuration. A favourable distribution of probabilities of optical transitions starting at different Zeeman sublevels of the ground state leads to the increase of the cooling forces.

The Raman cooling, the sub-Doppler cooling. The technique is applied to a pre-cooled cloud of atoms of a few μK . Two counter-propagating laser beams transfer atoms from one ground state to another, by means of Raman-like process [31]. During the transition, the atom receives a momentum kick of $2\hbar k$ towards $v = 0$. Subsequently, the third laser beam transfers atoms to an excited state, in order to optically pump the atoms back to the first ground state through the act of spontaneous emission. Each optical-pumping sequence randomizes the atom velocity, so the atoms end up with the velocities around $v = 0$.

Sufficiently cooled atoms are further loaded into dipole traps, *magnetic* or *optical* ones.

The optical dipole traps involve the use of laser light, which is far-detuned from the frequency of atomic transition [1]. The trapping mechanism results from the interaction between the induced electric dipole moment of an atom, and the electromagnetic field. The light-atom interaction is briefly discussed in the next section (Sec. 1.2). Under specific conditions, the trapping mechanism is weakly dependent on the internal state of an atom, and the internal dynamics can be analyzed experimentally. The wide range of available geometries allows to miniaturize the system, which is otherwise complicated when using magnets and/or macroscopic coils in the magnetic dipole traps. It was first considered in 1968 by Letokhov [25] that the optical dipole force acts as a trapping mechanism for neutral atoms. In the paper, Letokhov considers a standing wave, which is produced by far-detuned laser light, which traps atoms at the nodes, or the antinodes, depending on the detuning. Two years later, Ashkin [32] reported the trapping of micron-sized particles, by optical means, being the combination of the radiation pressure, and the optical dipole forces. Later in 1978, he proposed a method of trapping, cooling, and manipulating of atoms with the radiation pressure forces in three dimensions [33]. The same year, the first observation of the dipole force was demonstrated by his group for sodium atoms, with a focused laser light [34]. In 1986, Steven Chu reported the realization of the first dipole-force optical trap for neutral atoms [24]. Since then, a considerable number of techniques have been developed in various areas related to the topic, developing the further cooling techniques, such as evaporative cooling.

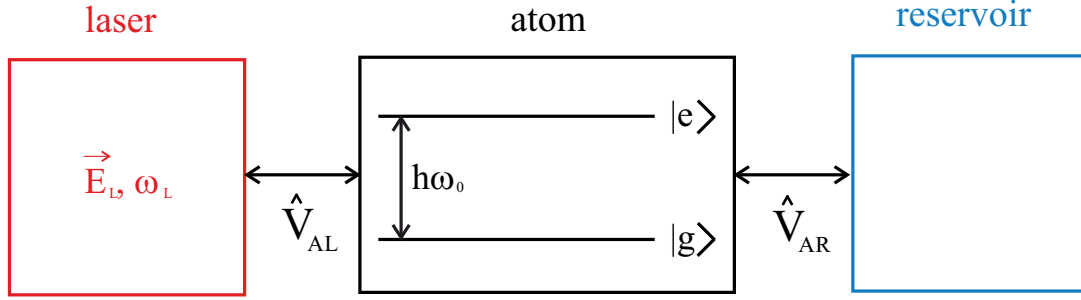


Figure 1.1: The scheme of atom-light interaction. Atom of a ground state $|g\rangle$, and the excited state $|e\rangle$ interacts with an external field $\vec{E}_L$ and reservoir.

The magnetic dipole traps employ inhomogeneous magnetic field, which generates the state-dependent force acting on a magnetic dipole moment of an atom [35]. Whereas the trapping mechanism only holds the atoms together in a given place in space (dipole forces are conservative), the evaporative cooling causes the decrease in the temperature. For the magnetic trap, it is possible to obtain the ultracold regime (hundreds of nanokelvins), which allows one to reach the Bose-Einstein condensate (BEC).

Evaporative cooling. The evaporative cooling was first demonstrated in 1996 by Ketterle and van Druten [36]. The method requires high densities of atomic cloud and a large initial number of atoms. During the cooling process, the hottest atoms are selectively removed from the dark trap by radiofrequency radiation (in magnetic traps) or just by lowering the potential barrier (in optical traps). The thermalization process, if efficient enough, sets the new, lower temperature of the sample. The efficient cooling is achieved by providing the large ratio between the elastic and inelastic collisions (commonly called 'good' and 'bad' collisions). The evaporative cooling is most frequently used as a final stage cooling in Bose-Einstein condensate experiments.

1.2. Atom-light interaction

The atom-light interaction is discussed in detail in [37]. The two-level, non-degenerated atom, of the ground state $|g\rangle$, and the excited state $|e\rangle$ is considered. The levels are distant by $\hbar\omega_0$, the spontaneous decay rate is Γ . The atom interacts with an external field, described by a classical function of time (laser light), and with quantum radiation field (reservoir), assumed to be initially in the vacuum state. The interaction scheme is presented in Fig. 1.1. The Hamiltonian takes the following form:

$$\hat{H} = \hat{H}_A + \hat{H}_R + \hat{V}_{AL} + \hat{V}_{AR}, \quad (1.2.1)$$

where

$$\hat{H}_A = \frac{\hat{p}^2}{2m} + \hbar\omega_0 |e\rangle \langle e|. \quad (1.2.2)$$

The force acting on the atom, in the presence of the laser field is given by:

$$\hat{\vec{F}}(\hat{\vec{R}}) = -\frac{\partial \hat{H}}{\partial \hat{\vec{R}}}. \quad (1.2.3)$$

The interaction $\hat{V}_{AL}$ between the atom and laser light is given by a dipole interaction:

$$\hat{V}_{AL} = -\hat{\vec{d}} \cdot \hat{\vec{E}}_L(\vec{R}, t) = -\vec{d}_{eg}(|e\rangle\langle g| + |g\rangle\langle e|)\vec{e}_L(\vec{R})\epsilon_L(\vec{R})\cos(\omega_L t + \phi(\vec{R})),$$

where $\hat{\vec{d}}$ is the operator of the electric dipole moment of the atom and $\vec{d}_{eg}$ is the respective matrix element. $\vec{E}_L$ is the external field, which is associated with the light wave of polarization $\vec{e}_L(\vec{R})$, amplitude $\epsilon_L(\vec{R})$, frequency ω_L and phase $\phi(\vec{R})$. The Rabi frequency $\Omega(\vec{R})$ is defined as:

$$\epsilon_L(\vec{R})\vec{d}_{eg} \cdot \vec{e}_L(\vec{R}) = \hbar\Omega(\vec{R}). \quad (1.2.4)$$

Applying the long-wave approximation (dipole approximation) and calculating the dynamics of the atomic density matrix, one arrives at the optical Bloch equations [37]. The equations describe the evolution of a two-state quantum system, which interacts with the laser field. Applying the rotating wave approximation, assuming that the internal dynamics of an atom is much faster than the external one and averaging over time, one arrives at force acting on atom given by:

$$\vec{F} = (\vec{e} \cdot \vec{d}_{ge}) \underbrace{(u_{st}\vec{\nabla}\epsilon_L(\vec{R}))}_{\text{optical dipole force}} + \underbrace{v_{st}\epsilon_L(\vec{R})\vec{\nabla}\phi(\vec{R})}_{\text{scattering force}}, \quad (1.2.5)$$

where v_{st} and u_{st} are redefined solutions of optical Bloch equations: $u_{st} = \frac{\Delta}{\Omega} \frac{S}{1+S}$ and $v_{st} = \frac{\Gamma}{2\Omega} \frac{S}{1+S}$, where $\Delta = \omega_L - \omega_0$ is the relative detuning, and $S = \frac{\Omega^2}{\Delta^2 + \frac{\Gamma^2}{4}}$ is the saturation parameter. The force divides into two parts: optical dipole force and spontaneous force, incorporating the field and phase gradients, respectively. The latter one cools atoms down (when used properly), by many absorption-spontaneous emission cycles. The optical dipole force is a reactive force, which provides the trapping mechanism in the dipole traps:

$$\vec{F}_{dip} = -\vec{\nabla}U^{dip} = -\frac{\hbar\Delta}{4} \frac{\vec{\nabla}\Omega^2}{\Delta^2 + \frac{\Gamma^2}{4} + \frac{\Gamma^2}{2}}. \quad (1.2.6)$$

The force is given by the following form of the dipole potential:

$$U^{dip}(\vec{R}) = \frac{\hbar\Delta}{2} \ln \left(1 + \frac{\frac{\Omega^2}{2}}{\Delta^2 + \frac{\Gamma^2}{4}} \right), \quad (1.2.7)$$

which, in the regime of low saturation ($\Omega^2 \ll \Gamma^2 + 4\Delta^2$), simplifies to a form:

$$U^{dip}(\vec{R}) = \frac{\hbar\Omega^2}{4\Delta}. \quad (1.2.8)$$

In order to obtain an efficient trapping mechanism, it is preferred to use the detuned light of a high intensity, and significant intensity gradient. The detuning minimizes the influence of the spontaneous force, and the high intensity provides the strong dipole potential (the spontaneous force saturates with the increasing intensity, the dipole force does not). To achieve the high intensity gradient, most of the optical dipole traps apply the focused Gaussian beams [33, 24, 38, 39, 40], standing waves [41, 42], evanescent waves [43, 44, 45], and **Surface Plasmon Polaritons**. The latter generates a promising plasmonic potentials, which may be structured with subwavelength resolution, unlike the typical optical traps, which are limited by diffraction.

1.3. Surface Plasmon Polaritons

Surface Plasmon Polaritons (SPPs) is a growing research topic, described in detail, in a number of scientific publications [16, 46, 47, 48, 49, 50, 51, 52, 53, 54]. SPPs emerge from a coupling between the photon and collective oscillations of free electrons at a metal surface. The SPPs propagate along the metal-dielectric boundary, with the amplitude of the electromagnetic field exponentially decaying in both media. The nonpropagating form of SPPs, Localized Surface Plasmons (LSP), are found in the vicinity of metallic nanoobjects, e.g. gold nanoparticles [55, 56, 57].

In order to characterize the SPPs, the metal-light interaction is considered. The electromagnetic field is described by macroscopic Maxwell's equations, with proper boundary conditions. The optical properties of metal are characterized by its dielectric function $\epsilon(\omega)$.

1.3.1. SPPs on a metal/dielectric interface

We start with a short review of Maxwell's equations and dielectric function of metals. The Maxwell's equations combine the four macroscopic fields: the dielectric displacement $\vec{D}$, the magnetic field induction $\vec{B}$, the electric field intensity $\vec{E}$, and the magnetic field intensity $\vec{H}$, with an external charge ρ_f and free current density $\vec{j}_f$ [58]:

$$\nabla \cdot \vec{D} = \rho_f, \quad (1.3.1a)$$

$$\nabla \cdot \vec{B} = 0, \quad (1.3.1b)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad (1.3.1c)$$

$$\nabla \times \vec{H} = \vec{j}_f + \frac{\partial \vec{D}}{\partial t}. \quad (1.3.1d)$$

The Maxwell's equations are supplemented by the following relations for electric polarization $\vec{P}$ and magnetization $\vec{M}$. For linear and isotropic media we have:

$$\vec{P} = \epsilon_0 \chi_e \vec{E}, \quad (1.3.2a)$$

$$\vec{M} = \chi_m \vec{H}, \quad (1.3.2b)$$

$$\vec{D} = \epsilon(\omega) \vec{E} = \epsilon_0 \vec{E} + \vec{P}, \quad (1.3.2c)$$

$$\vec{H} = \frac{1}{\mu_0} \vec{B} - \vec{M}, \quad (1.3.2d)$$

where $\epsilon(\omega)$ is the dielectric function, χ_e is electric susceptibility, χ_m is magnetic susceptibility, $\mu = \mu_0(\chi_m + 1)$ is the permeability of the material and μ_0 is the permeability of free space. In general, $\epsilon = \epsilon(\omega)$ is a complex dielectric function of frequency $\epsilon(\omega) = \epsilon'(\omega) + i\epsilon''(\omega)$. Also, $\epsilon(\omega) = \epsilon_0 \epsilon_r(\omega)$, where ϵ_0 is the permittivity of free space and $\epsilon_r(\omega)$ is the relative permittivity.

The electromagnetic wave equations derive from Maxwell's equations 1.3.1 and describe the propagation of electromagnetic waves through a medium. For nonmagnetic media, in the absence of external currents, one gets:

$$\nabla^2 \vec{E} - \mu_0 \epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0, \quad (1.3.3a)$$

$$\nabla^2 \vec{H} - \mu_0 \epsilon \frac{\partial^2 \vec{H}}{\partial t^2} = 0. \quad (1.3.3b)$$

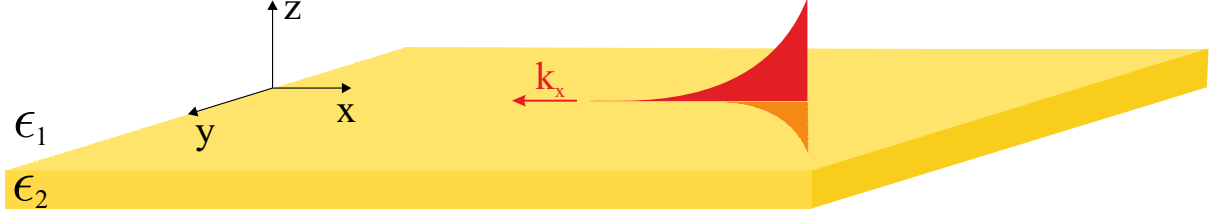


Figure 1.2: Propagation geometry. The SPPs propagate along the x direction.

Let us consider a flat interface between a dielectric and metal, schematically presented in Fig.1.2. The dielectric occupies the area of $z > 0$, with the real, isotropic dielectric constant of $\epsilon_1 > 0$. Here we assume no or weak dependence of ϵ_1 on frequency. For $z < 0$ area, there is a metal layer with a complex dielectric function of $\epsilon_2 = \epsilon_2(\omega) = \epsilon'_2(\omega) + i\epsilon''_2(\omega)$, with $\text{Re}[\epsilon_2] < 0$.

The electromagnetic wave of frequency ω and wavevector $\vec{k}$, propagating in $\vec{r}$ direction, is described by electric and magnetic fields of the following forms:

$$\vec{E}(\vec{r}, t) = \vec{E}_0(\vec{r})e^{-i\omega t}e^{i\vec{k}\cdot\vec{r}}, \quad (1.3.4a)$$

$$\vec{H}(\vec{r}, t) = \vec{H}_0(\vec{r})e^{-i\omega t}e^{i\vec{k}\cdot\vec{r}}. \quad (1.3.4b)$$

According to Fig. 1.2, the wave propagates along the x direction. The wavevector $\vec{k}$ has the following form $\vec{k}_x = (k_x, 0, 0)$, thus the exponent $e^{i\vec{k}\cdot\vec{r}}$ reduces to $e^{ik_x x} = e^{i\beta x}$, where β is the propagation constant (in general, complex). The amplitude of the electric field does not vary along y direction. This results in the following wave equations:

$$\frac{\partial^2 \vec{E}(\vec{r}, t)}{\partial z^2} + (k_0^2 \epsilon_r(z, \omega) - \beta^2) \vec{E}(\vec{r}, t) = 0, \quad (1.3.5a)$$

$$\frac{\partial^2 \vec{H}(\vec{r}, t)}{\partial z^2} + (k_0^2 \epsilon_r(z, \omega) - \beta^2) \vec{H}(\vec{r}, t) = 0. \quad (1.3.5b)$$

The relations between electric and magnetic fields are calculated out of Maxwell's equations 1.3.1 c and d, i.e.:

$$\frac{\partial E^y(\vec{r}, t)}{\partial z} = -i\omega\mu_0 H^x(\vec{r}, t), \quad (1.3.6a)$$

$$\frac{\partial E^x(\vec{r}, t)}{\partial z} - i\beta E^z(\vec{r}, t) = i\omega\mu_0 H^y(\vec{r}, t), \quad (1.3.6b)$$

$$i\beta E^y(\vec{r}, t) = i\omega\mu_0 H^z(\vec{r}, t), \quad (1.3.6c)$$

$$\frac{\partial H^y(\vec{r}, t)}{\partial z} = i\omega\epsilon_0\epsilon_r(z, \omega) E^x(\vec{r}, t), \quad (1.3.6d)$$

$$\frac{\partial H^x(\vec{r}, t)}{\partial z} - i\beta H^z(\vec{r}, t) = -i\omega\epsilon_0\epsilon_r(z, \omega) E^y(\vec{r}, t), \quad (1.3.6e)$$

$$i\beta H^y(\vec{r}, t) = -i\omega\epsilon_0\epsilon_r(z, \omega) E^z(\vec{r}, t). \quad (1.3.6f)$$

The solution of the set of equations 1.3.6 can be specified for two polarization states of light: transverse magnetic (TM) and transverse electric (TE).

Transverse mode The TM mode shows no magnetic field component in the direction of propagation. The nonzero elements are E^x , E^z and H^y . The set of equations 1.3.6 reduces to:

$$E^x(\vec{r}, t) = -i \frac{1}{\omega \epsilon_0 \epsilon_r(z, \omega)} \frac{\partial H^y(\vec{r}, t)}{\partial z}, \quad (1.3.7a)$$

$$E^z(\vec{r}, t) = -\frac{\beta}{\omega \epsilon_0 \epsilon_r(z, \omega)} H^y(\vec{r}, t), \quad (1.3.7b)$$

$$\frac{\partial^2 H^y(\vec{r}, t)}{\partial z^2} + (k_0^2 \epsilon_r(z, \omega) - \beta^2) H^y(\vec{r}, t) = 0. \quad (1.3.7c)$$

The solutions of TM modes are:

- for $z > 0$ (dielectric):

$$\vec{E}(\vec{r}, t) = \vec{E}_1(\vec{r}, t) = A_1 \frac{i}{\omega \epsilon_0 \epsilon_1} (k_1, 0, i\beta) e^{-i\omega t + i\beta x - k_1 z}, \quad (1.3.8a)$$

$$\vec{H}(\vec{r}, t) = \vec{H}_1(\vec{r}, t) = A_1 (0, 1, 0) e^{-i\omega t + i\beta x - k_1 z}, \quad (1.3.8b)$$

- and for $z < 0$ (metal):

$$\vec{E}(\vec{r}, t) = \vec{E}_2(\vec{r}, t) = A_2 \frac{-i}{\omega \epsilon_0 \epsilon_2(\omega)} (k_2, 0, -i\beta) e^{-i\omega t + i\beta x + k_2 z}, \quad (1.3.9a)$$

$$\vec{H}(\vec{r}, t) = \vec{H}_2(\vec{r}, t) = A_2 (0, 1, 0) e^{-i\omega t + i\beta x + k_2 z}, \quad (1.3.9b)$$

where k_1 and k_2 are the z component of the wavevectors in the medium of ϵ_1 and ϵ_2 , perpendicular to the interface between the two media. A_1 and A_2 are the amplitudes of the components of electric and magnetic fields.

The boundary conditions at $z = 0$ require: $H_{y1} = H_{y2}$, $\epsilon_1 E_{z1} = \epsilon_2 E_{z2}$, and $E_{x1} = E_{x2}$. The continuity of components H_y and E_z results in $A_1 = A_2$, and the requirement for E_x gives

$$\frac{k_2}{k_1} = -\frac{\epsilon_2(\omega)}{\epsilon_1}. \quad (1.3.10)$$

For the electromagnetic waves with the amplitude exponentially decaying in both media, $\text{Re}[k_1] > 0$ and $\text{Re}[k_2] > 0$. The dielectric medium of $\epsilon_2 > 0$, requires the medium of $\text{Re}[\epsilon_1(\omega)] < 0$, which proves, that the surface waves exist only on the interface between a dielectric and a metal.

TE mode The TE mode shows no electric field in the direction of propagation. The nonzero elements are H^x , H^z and E^y . The set of equations 1.3.6 reduces to:

$$H^x(\vec{r}, t) = i \frac{1}{\omega \mu_0} \frac{\partial E^y(\vec{r}, t)}{\partial z}, \quad (1.3.11a)$$

$$H^z(\vec{r}, t) = -\frac{\beta}{\omega \mu_0} E^y(\vec{r}, t), \quad (1.3.11b)$$

$$\frac{\partial^2 E^y(\vec{r}, t)}{\partial z^2} + (k_0^2 \epsilon_r(z, \omega) - \beta^2) E^y(\vec{r}, t) = 0. \quad (1.3.11c)$$

The solutions for TE mode are the following:

- for $z > 0$ (dielectric):

$$\vec{E}(\vec{r}, t) = B_1 (0, 1, 0) e^{-i\omega t + i\beta x - k_1 z}, \quad (1.3.12a)$$

$$\vec{H}(\vec{r}, t) = B_1 \frac{-i}{\omega \mu_0} (k_1, 0, i\beta) e^{-i\omega t + i\beta x - k_1 z}, \quad (1.3.12b)$$

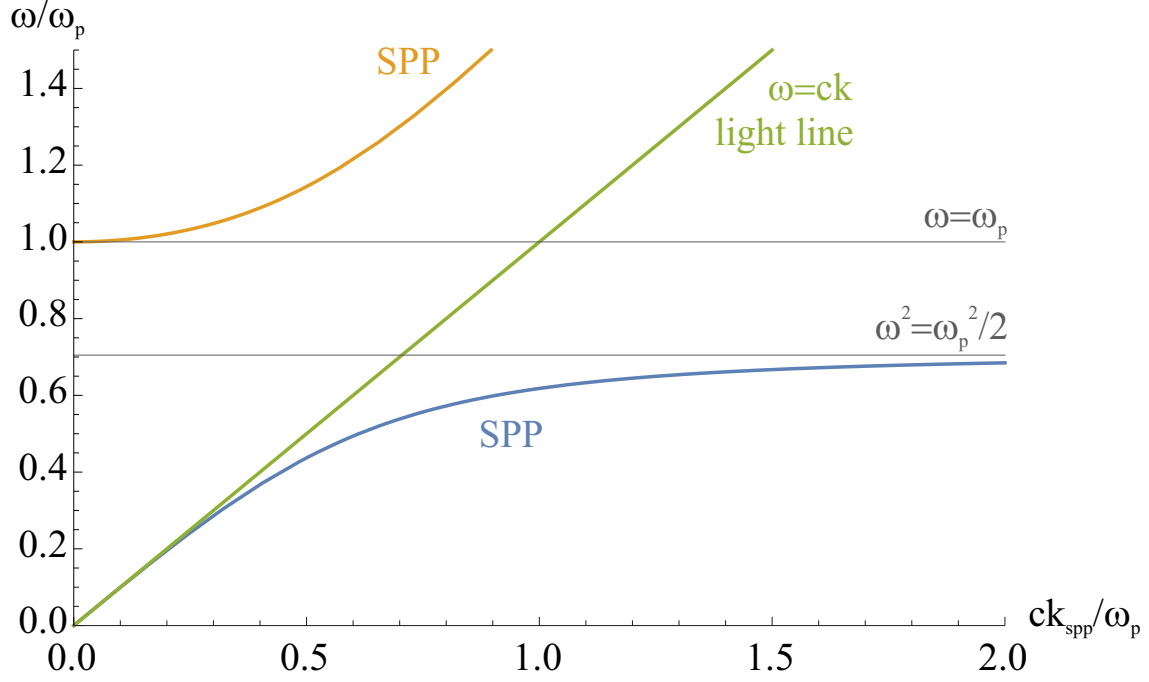


Figure 1.3: Dispersion relation of SPPs at the interface between a metal and dielectric. The frequency ω is normalized to the plasma frequency ω_p . The light line is given as a reference. The calculations are presented for $\epsilon_1 = 1$.

- and for $z < 0$ (metal):

$$\vec{E}(\vec{r}, t) = B_2(0, 1, 0)e^{-i\omega t + i\beta x - k_2 z}, \quad (1.3.13a)$$

$$\vec{H}(\vec{r}, t) = B_2 \frac{i}{\omega \mu_0} (k_2, 0, -i\beta) e^{-i\omega t + i\beta x - k_2 z}. \quad (1.3.13b)$$

The boundary conditions at $z = 0$ require: $H_{z1} = H_{z2}$, $\epsilon_1 E_{y1} = \epsilon_2 E_{y2}$, and $H_{x1} = H_{x2}$. The continuity of H_x requires $B_1 = B_2$, and the continuity of E_y implies $k_1 B_1 + k_2 B_2 = 0$. Then, $B_1(k_1 + k_2) = 0$, and since $\text{Re}[k_1] > 0$ and $\text{Re}[k_2] > 0$, the continuity condition is fulfilled if $B_1 = B_2 = 0$. Thus, Surface Plasmon Polaritons do not exist for TE modes.

Dispersion relation and dielectric function The dispersion relation is calculated from the wave equations 1.3.7c and 1.3.10. The equation for H^y yields:

$$k_1^2 = \beta^2 - k_0^2 \epsilon_1, \quad (1.3.14a)$$

$$k_2^2 = \beta^2 - k_0^2 \epsilon_2(\omega), \quad (1.3.14b)$$

and the dispersion relation of Surface Plasmon Polaritons, of propagation constant β , takes the form:

$$\beta = k_x = k_0 \sqrt{\frac{\epsilon_1 \epsilon_2(\omega)}{\epsilon_1 + \epsilon_2(\omega)}}. \quad (1.3.15)$$

The detailed knowledge about the dispersion relation, and hence about the dielectric function $\epsilon_2(\omega)$, is crucial for the understanding and generation of SPPs. In free electron model of an

electron gas, for an ideal conductor (negligible damping, implying $\text{Im}[\epsilon_2(\omega)] = 0$), the exact form of the dielectric function of metal is [59]:

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}, \quad (1.3.16)$$

where $\omega_p = \sqrt{\frac{ne^2}{\epsilon_0 m}}$ is the plasma frequency, where n is the electron density, e is the charge, and m is the effective mass of the electron. The dispersion relation is plotted in Fig. 1.3. In the plot, the frequency ω is normalized to the plasma frequency ω_p and calculations are performed for $\epsilon_1 = 1$. The orange curve, laying to the left of the light line ($\omega > \omega_p$), describes the regime of radiation, in which the radiation in the metal is observed. For frequencies in the range $\omega_p/\sqrt{2} < \omega < \omega_p$, the wavevector is purely imaginary, thus, no propagation is allowed in this region. The SPPs correspond to the blue curve on the graph, lying to the right of the green light line. At low values of the wavevector (frequency) the SPPs behaves like a photon. In the opposite regime, with the increasing value of the wavevector (frequency), the dispersion relation bends over, reaching an asymptotic limit of $\omega_p/\sqrt{2}$ ($\omega_p/\sqrt{1 + \epsilon_1}$ in general), known as *surface plasmon* frequency.

The above discussion described the case of an ideal conductor. In fact, the Ohmic losses and electron-core interactions introduce damping into the system. Therefore, the dielectric function of the metal is complex $\epsilon_2(\omega) = \epsilon'_2(\omega) + i\epsilon''_2(\omega)$, and with it, also the propagation constant β . For $\epsilon''_2(\omega) < |\epsilon'_2(\omega)|$, we obtain a complex wavevector of the approximated form:

$$\beta = k_x = k'_x + ik''_x, \quad (1.3.17a)$$

$$k'_x = \frac{\omega}{c} \left(\frac{\epsilon'_1 \epsilon_2}{\epsilon'_1 + \epsilon_2} \right)^{1/2}, \quad (1.3.17b)$$

$$k''_x = \frac{\omega}{c} \left(\frac{\epsilon'_1 \epsilon_2}{\epsilon'_1 + \epsilon_2} \right)^{3/2} \frac{\epsilon''_1}{2(\epsilon'_1)^2}. \quad (1.3.17c)$$

Propagation length The propagation length ξ_P is defined as the distance after which the intensity of SPPs decreases by factor of e . The intensity of SPPs propagating along the smooth surface decreases as $e^{-2k''_x x}$. Thus, the propagation length is given by [2]:

$$\xi_P = \frac{1}{2k''_x} = \frac{c}{\omega} \left(\frac{\epsilon'_1 + \epsilon_2}{\epsilon'_1 \epsilon_2} \right)^{3/2} \frac{2(\epsilon'_1)^2}{\epsilon''_1}. \quad (1.3.18)$$

The above formula is valid for a smooth, metallic surface of an infinite thickness. In real metals, the inter-band transitions play a role, and the movement of electrons is suppressed by electron-atom collisions, which increases the temperature of metals (the Ohmic losses). In the presence of thin metallic layers, the radiative losses and Ohmic losses reduce the propagation length ξ_P by two [2, 60]. The presence of the losses modifies the propagation constant into the complex form of $\beta = \beta_1 + i\beta_2$. The imaginary part of the propagation constant causes the damping of SPPs in the direction of propagation. This modifies the dispersion relation of SPPs, which is now a continuous curve and there is no forbidden band gap in the region $\omega_p/\sqrt{2} < \omega < \omega_p$. However, the high imaginary part of β significantly limits the propagation length, which becomes smaller than the wavelength. Therefore, considering SPPs in this region is still unreasonable.

1.3.2. Excitation of SPPs at planar interfaces

SPPs propagate at the dielectric/metal interface. The SPPs dispersion curve lies to the right of the light line $\omega = ck$. Thus, in order to generate the SPPs, the wavevector-matching techniques

must be employed. The most common ones use surface irregularities [61], charged particles [62, 63], highly focused laser beams [64], an evanescent field generated by sub-wavelength aperture [61, 65], or optical phase-matching methods [16]. Among the latter, the first configuration has been proposed by Andreas Otto [66, 67], employing a prism coupling. Shortly after, Kretschmann and Raether proposed another prism based configuration [68]. After that, a number of different variations of the prism coupling were proposed for SPPs excitation.

Grating couplers Beside the prism configuration, the wavevector-matching is achieved by the implementation of the metallic grating coupler [2, 69, 70]. In order to assure the momentum matching, the tangential component of wavevector of incident light $k_{0x} = k_0 \sin \theta$ must be matched with the propagation constant β . Thus, besides providing the TM state of polarization and proper frequency ω , the grating period d must fulfil the following requirement:

$$\beta = k_0 \sin \theta \pm \frac{2\pi m}{d}, \quad (1.3.19)$$

where k_0 is free space wave vector, θ is an angle of the incidence, and $m = 1, 2, \dots$. At this stage, both the transmissive and reflective gratings can be applied. Eq. 1.3.19 is valid for shallow structures. Precise values of the θ angle for the gratings of the height of tens (or more) nm have to be found numerically.

The efficiency of plasmonic excitation is manifested by a decrease in the intensity of the reflected light beam. To precisely characterize the SPPs propagation, the following approaches were employed: near field optical microscopy (NSOM), fluorescence imaging [71], leakage radiation detection [72, 73], and observation of the scattered light [74]. Out of the above, only the NSOM technique provides the sub-wavelength resolution.

1.4. Optical Dipole Mirror

The Optical Dipole Mirror (ODM) is based on the interaction between the atoms and the dipole potential induced by optical methods. The light of a high intensity gradient, which is blue-detuned from the specific transition in atoms, creates the repulsive potential U_{dip} enabling both, an elastic and inelastic reflection of atoms from the surface of the mirror. As mentioned in Sec. 1.2, to avoid the influence of spontaneous force, the far detuned light of a high intensity is used. Figure 1.4a presents the scheme of the ODM. The atoms are trapped in a magneto-optical trap (MOT) a few mm above the metallic grating structure. The SPPs are excited on the top of the structure, creating the repulsive potential for cold atoms. The atoms are released from the trap and fall in the gravitational field towards the mirror surface.

The total potential of ODM consists of the dipole potential U_{dip} coming from SPPs (eq. 1.2.8), van der Waals potential U_{vdW} , and gravitational potential $U_g = mgz$. According to [76], the van der Waals attraction is described by the atom-surface interaction with the following formula

$$U_{vdW} \sim C_3/z^3 f_3(z), \quad (1.4.1)$$

where z is the distance between the atom and a metallic surface, and f_3 is the retardation coefficient. This equation describes the interaction at the distance $z < \lambda_0/2\pi$, where λ_0 corresponds to the dominating transition in an atom (for rubidium, the D_2 transition is 780 nm). For $z > \lambda_0/2\pi$, the Casimir-Polder effect modifies the atom-surface interaction to $U_{CP} \sim -1/z^4$. The total, dipole, and van der Waals potentials are shown in Fig. 1.4b.

The use of an evanescent field in an atomic mirror was first suggested by Cook and Hill in 1982 [77]. The first experimental realization was made five years later by Balykin *et al.* [78],

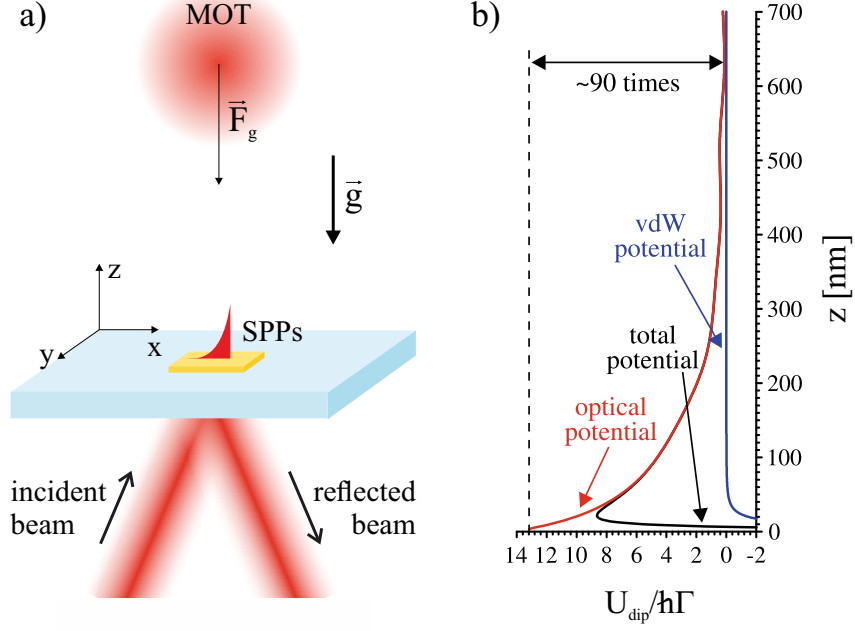


Figure 1.4: a) The scheme of the ODM. The cloud of atoms, which is trapped in a magneto-optical trap (MOT), falls under gravity onto the surface of ODM. The repulsive potential is generated by SPPs on a diffraction grating. b) 1D cut of the total potential of ODM above the grating structure. The plot is taken from [75].

for an atomic beam and an evanescent wave. In 1990, Kasevich *et al.* reported the dipole mirror for cold atoms [79]. Since then, many experiments have been performed [80]. Apart from the evanescent wave, also the near field of Surface Plasmon Polaritons was employed in few experiments, based on a Kretschmann configuration [81, 82, 83]. In all these experiments, the evanescent field was excited by a laser undergoing total internal reflection at a dielectric prism. An alternative is to use a metallic grating coupler for SPPs excitation, which leads to significant miniaturization of the system [84, 75].

The dipole mirrors can be used for the construction of surface traps and precise nanomanipulators for cold atoms [85, 21, 86, 87, 15, 19]. Especially, the plasmonic potentials, which are tailored with subwavelength resolution, offer a wide range of possibilities in the topic. Besides, the atomic mirrors serve as a platform for the research on atom-surface or atom-plasmons interaction [18, 75].

Chapter 2

Reflective structures

2.1. Introduction

In this chapter, the optical near fields associated with reflective structures are discussed. The structures are based on the modified optical discs, providing the quasi-sinusoidal gratings suitable for plasmonic excitation. It was first shown by Kaplan *et al.* [88], that Digital Versatile Discs (DVD) enable the efficient excitation of Surface Plasmon Polaritons for infrared light. Thus, commercially available optical discs can be considered as a promising alternative for reflective gratings, which is (unlike the lab-produced gratings) cost effective and provides large and homogeneous area. The main implementations, presented up to this time, make the use of the discs either in an unmodified version, or fine tuned by means of chemical and physical processes [89, 90, 88], both using only the transparent (not labelled), polycarbonate disc out of two discs forming the common DVD plate.

In the new method, presented here, the other one (labelled) component disc is used, after covering it with a thin layer of gold. This method is the easiest and at the same time the best regarding SPPs generation efficiency and resonance quality among solutions published so far. This chapter presents the full characterization of optical discs of various companies, including the examination of the internal structures. The several dozens of samples have been investigated with atomic force microscopy in a search for plasmon-friendly internal shapes and sizes. Each sample has been optically tested with goniometric far field measurements, revealing the efficiency of the plasmonic resonance. The numerical simulations have been performed for the comparison, namely the Rigorous Coupled Wave Analysis (RCWA) and Finite Difference Time Domain (FDTD) techniques. Using the modified optical discs, the energy loss mechanisms associated with SPPs excitation were investigated, with the particular emphasis on thermal radiation. The end of the chapter is devoted to the description of an optical dipole mirror for cold rubidium atoms, based on a modified optical disc.

2.2. Preparation of the plasmonic structure

2.2.1. Characterization of optical discs

The recordable Digital Versatile Discs (DVD) are multilayer, quasi-sinusoidal (in the cross-sections), periodic structures, produced in two types: write-once (DVD+ and DVD-R), and rewritable (DVD+RW and DVD-RW). Each optical disc consists of two *protective* layers, with *adhesive*, *recording* and *metallic* layers in between. The characteristics of the respective layers have been examined with an advanced apparatus, including the measurements of the composition, thickness, shape, and dimensions.

Disc company	period _{AFM}	height _{AFM}	period _{diffraction}
SK _{DVD+R}	745 nm	70-90 nm	735 nm
TDK _{DVD+R}	742 nm	80-100 nm	736 nm
SONY _{DVD+R}	743 nm	90-110 nm	738 nm
EMTEC _{DVD+R}	750 nm	100-120 nm	741 nm
Verbatim _{DVD+R}	741 nm	100-120 nm	736 nm
Platinum _{DVD+R}	748 nm	90-100 nm	737 nm
GIGA MASTER _{DVD+R}	745 nm	100-120 nm	737 nm
Kaufland _{DVD+RW}	745 nm	20-40 nm	737 nm

Table 2.1: The list of parameters, examined by AFM (period_{AFM} and height_{AFM}) and in optical diffraction measurements (period_{diffraction}) for various brands.

- The topography, i.e. grating period, height and the profile shape, were scanned with x-y calibrated Atomic Force Microscope (AFM) Nanosurf FlexAFM in contact mode.
- The thickness was measured with Scanning Electron Microscope (SEM) Quanta 3D at the University of Southern Denmark¹.
- The composition was determined by Secondary Ion Mass Spectrometry (SIMS) TOF-SIMS 5 (ION-TOF GmbH) system².

The examination included several dozens of write-once and rewritable discs, of the following companies: Platinum, Verbatim, TDK, Omega, EMTEC, Sony, Kaufland, SK, Giga Master. The AFM measurements revealed that there is no significant difference in the topographies, which were obtained within one company (see appendix B.1 for details). The scans were taken for physically different discs, types of discs (+R/-R and +RW/-RW), and various areas of a given sample, showing the same grating period, height and shape of the grating profile. The small discrepancies occur between the optical discs produced by different brands. The profile and grating period of the specific layers remain alike, however, the height varies by several dozens of nm. The measured values of the grating parameters (period_{AFM} and height_{AFM}) are collected in Table 2.1, together with the grating period period_{diffraction} determined by optical diffraction measurements, at 632.8 nm. The comparison between period_{diffraction} and period_{AFM} proves 2% of accuracy in the period determination. The AFM, SEM, and SIMS examinations allow one to characterize each layer of the disc, as described in the following paragraphs. To make the description easier to understand, the construction schemes of the optical discs are presented in Fig. 2.1 for DVD+R, and 2.2 for DVD-RW.

Protective layer. The optical discs consist of two protective layers, 0.6 mm thick, made of polycarbonate (PC). The top protective layer is labelled, and the bottom one is transparent. The top layer is a flat substrate, which is not directly suitable for plasmonic purposes, dissatisfying the momentum matching condition for SPPs excitation. The bottom layer possesses quasi-sinusoidal grooves, covering the entire surface. The grating period is close to 740 nm, the height of the ridges is dependent on the disc class, varying between 130-190 nm for DVD±R and 20-40 nm for DVD±RW.

Recording layer. The recording layer covers the grooves of the bottom, PC layer. For the recordable discs (DVD+R and DVD-R), the recording material is made of an organic dye, most

¹The measurements were performed by Dr. Jacek Fiutowski.

²The measurements were performed by Dr. Paweł Dąbczyński.

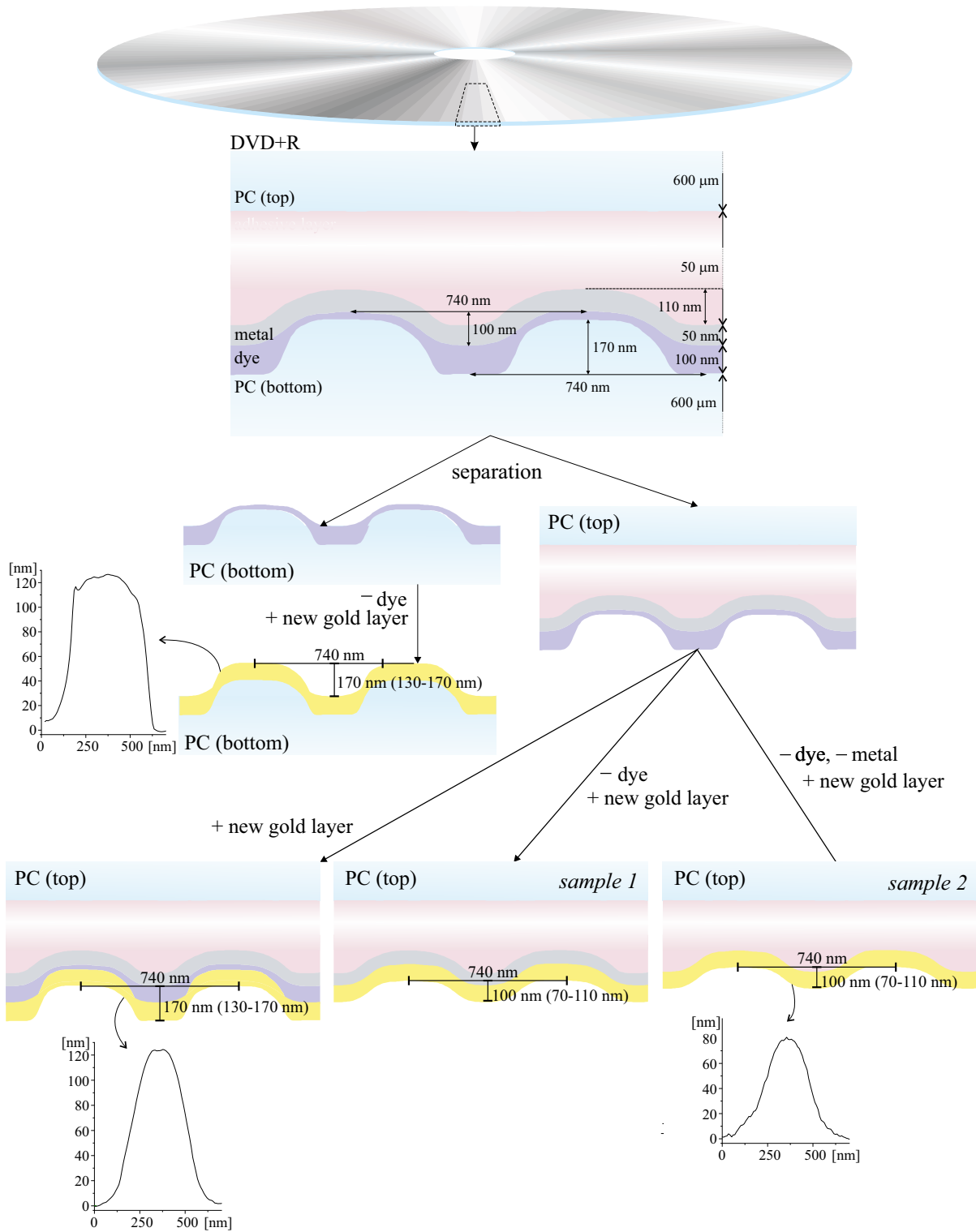


Figure 2.1: The schematic diagram of the specific layers of DVD+R, based on the investigation with AFM and SEM techniques. Beneath: the different ways of the possible preparation processes with the AFM topographies of one grating period. '-' means removal of a given layer, whereas '+' means addition of a new layer. PC stands for polycarbonate.

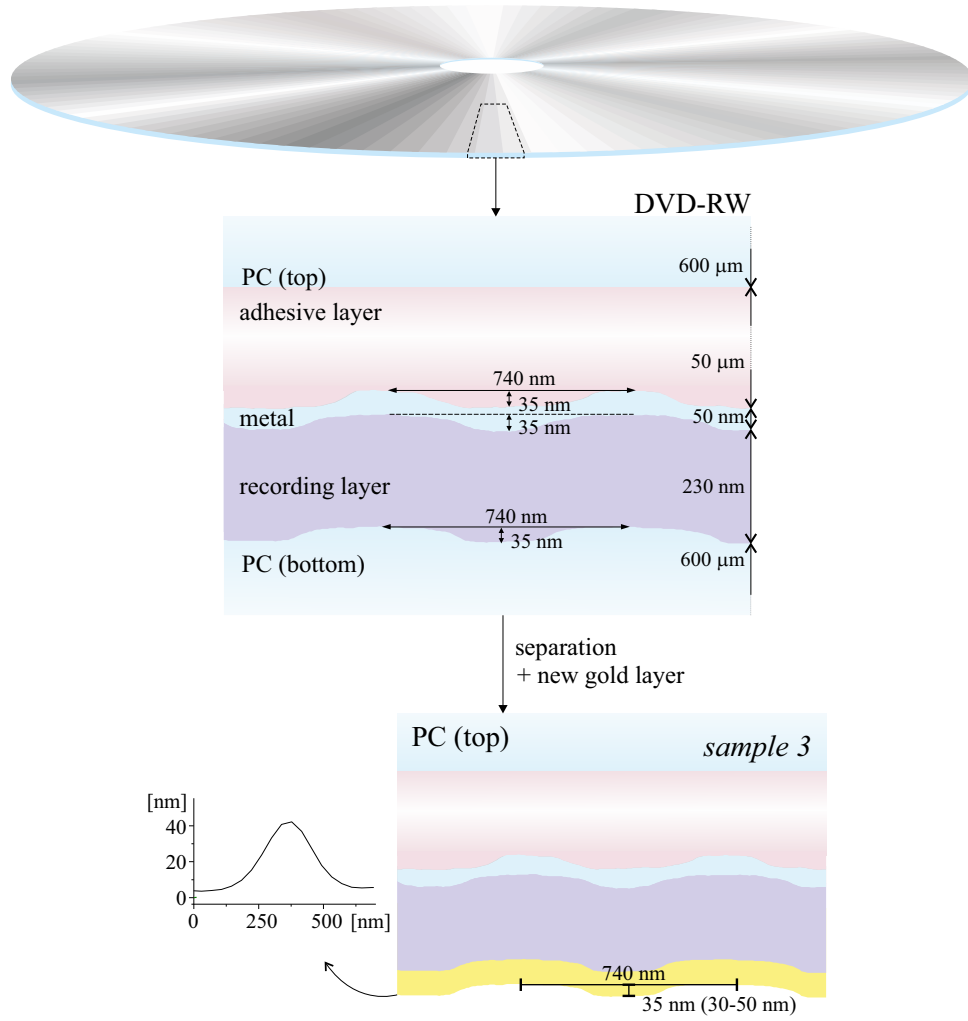


Figure 2.2: The schematic diagram of the specific layers of DVD-RW, based on the investigation with AFM and SEM techniques. Beneath: the scheme of the preparation process, with the AFM topography of one grating period. '-' means removal of a given layer, whereas '+' means addition of a new layer. PC stands for polycarbonate.

often of cyanine, phthalocyanine or metal azo [91] with a thickness of around 100 nm. After the separation process, the recording layer can cover bottom or top PC layer. The height of the recording layer is 80-120 nm, if combined with bottom PC, or 130-190 nm, if combined with the top PC. In the case of rewritable discs (DVD+RW and DVD-RW), the recording layer consists of the phase changing layer (AgInSbTb), surrounded by two dielectric layers (ZnS, SiO₂), with the total thickness of 200-250 nm. The height of the ridges is 20-40 nm, regardless of being combined with the bottom, or the top PC.

Reflective (metallic) layer. The metallic layer coats the top of the recording layer, recreating the periodic structure, with a thickness of 50 nm. The reflective part of the DVD±R is mostly made of silver, aluminium or aluminium alloy, with the grating height of 60-120 nm. For the DVD±RW case, the gold, silver, or silver alloy are usually used (see also Appendix B.2 for details), with grating depth of 20-40 nm. The collected data with specific heights can be found in table 2.1.

Adhesive. The adhesive bonds the bottom and the top layers. The thickness of the adhesive is varying between 40-70 μm . The adhesive recreates the periodic structure with the height of about 60-120 nm for recordable discs, and 20-40 nm for rewritable ones.

For plasmon-associated experiments, e.g. plasmonic mirrors and surface traps for cold atoms, or sensing devices, the efficient excitation of SPPs is crucial. To maximize the efficiency of the process, the numerical calculations for near-infrared light at 785 nm, and the AFM-based profiles were employed. The in-depth calculations of the reflectivity coefficient R were performed for each layer of different optical discs by RCWA method, looking for a narrow and deep resonances. The parameters were: grating period of 740 nm, grating heights 40-130 nm, and profile shapes: sinusoidal, slim quasi-sinusoidal, and wide quasi-sinusoidal, as found in real samples. The calculated plasmonic resonances are presented in Fig. 2.3, with the quasi-sinusoidal profiles depicted in (g). To keep the graphs transparent, and to show some tendency between low/high and wide/slim ridges, the results are presented for three grating heights: 40, 80, and 100 nm. The conclusion is as follows:

- for the gratings of a *slim quasi-sinusoidal shape*, the required height is around several dozens of nm (see Fig. 2.3a),
- for the gratings of a *sinusoidal shape*, the grating is most effective with heights up to 60 nm, (see Fig. 2.3b)
- for the gratings of a *wide quasi-sinusoidal shape*, the shallow ridges are required, around 40 nm (see Fig. 2.3c).

To give the main points in the other words: the sinusoidal shapes work better with lower heights, the 'slimmer' profiles require larger heights, and the 'wider' structures are preferable for very shallow grating grooves.

The typical results of the AFM-based topography are presented in Fig. 2.4, for DVD+R type. The profile shape of the bottom PC layer resembles the wide quasi-sinusoidal profile, 120 nm high. The top PC layer corresponds to the slim quasi-sinusoidal profile, 80 nm high. The dye and metallic layers, which cover the top PC substrate, are sinusoidal gratings, with the height of 120 and 80 nm, respectively. From the above, only the bottom PC layer clearly does not favour the plasmonic excitation (very high and wide quasi-sinusoidal profile). However, if one applies the additional preparation process, such as chemical etching, it is possible (as claimed by

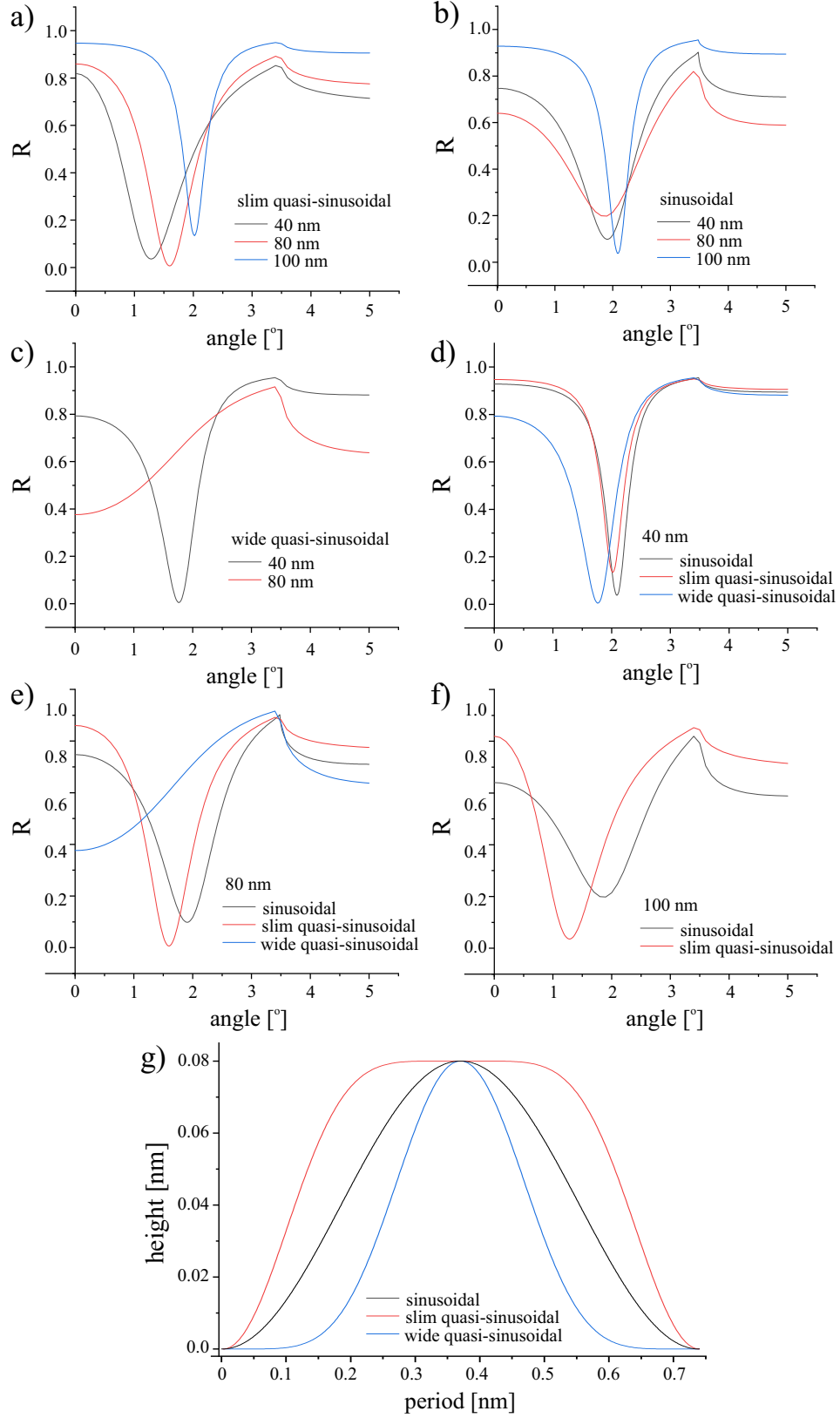


Figure 2.3: (a)-(f) The reflectivity coefficient R , calculated by RCWA method, for TM polarized and 785 nm laser light, for various grating profiles, as depicted in (g), and three grating heights: 40, 80 and 100 nm.

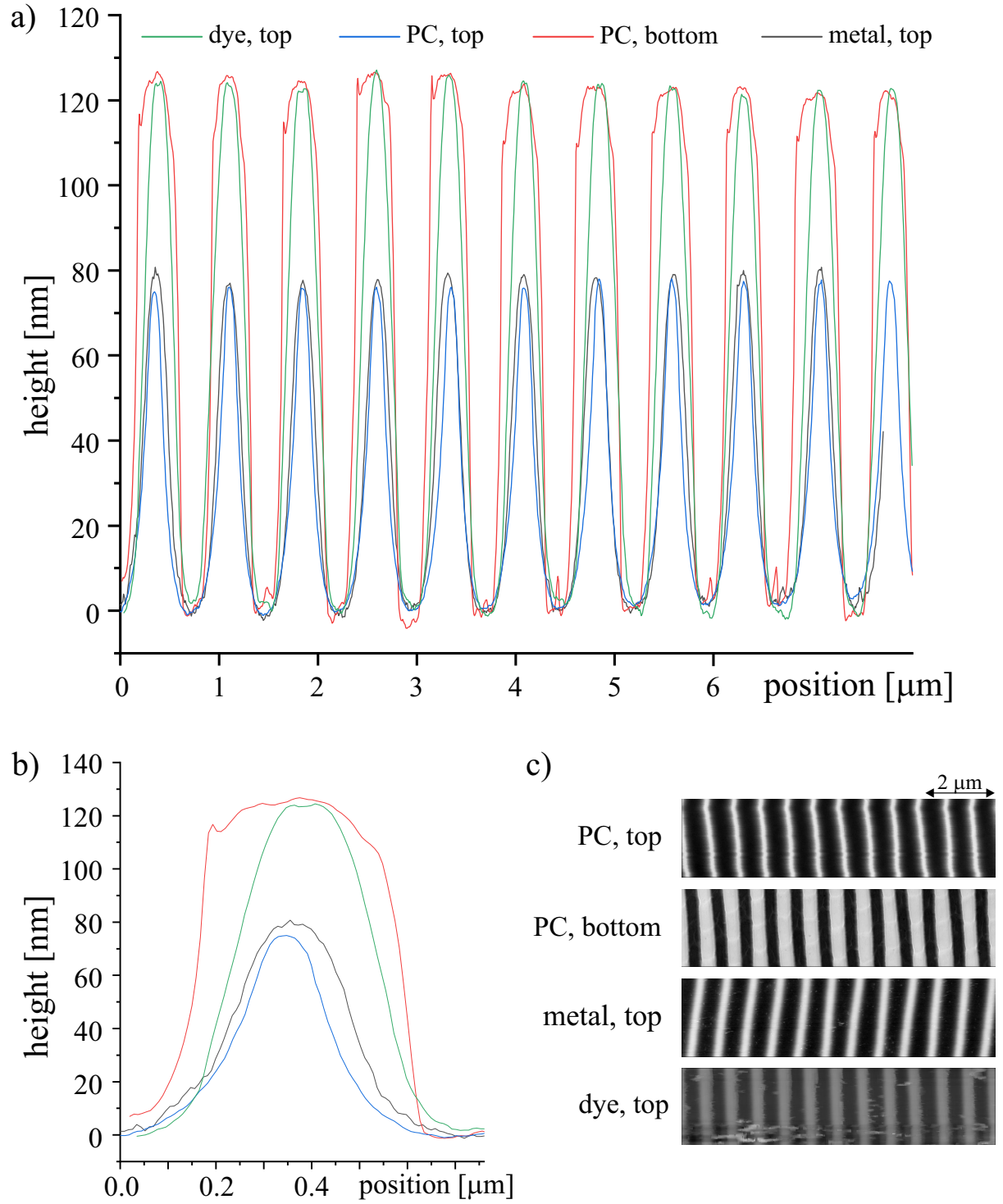


Figure 2.4: AFM-based topographies of different layers of the optical disc, measured among one disc company (SK DVD+R). The respective layers are denoted in the graph. a) The shape of the profile for eleven grating periods. b) Close up view on one grating period. c) AFM images of the topographies of respective layers.

authors) to use the wider, bottom structure with a high groove as well [88]. These conclusions are consistent with the results reported for the grating of a rectangular shape [92, 93]. As for the DVD $\pm$ RW, the wide quasi-sinusoidal shape of the bottom PC is combined with the heights up to 40 nm. This should result in an efficient plasmonic resonance.

The detailed characterization of the specific layers reveals the most suitable structures for plasmonic excitation, based on recordable and rewritable discs. Those are:

- for recordable discs: top PC layer, optionally covered with original metal or dye,
- for rewritable discs: bottom PC layer, covered with original metal.

. The selected ones, are further subjected to the fabrication process.

2.2.2. Fabrication of the plasmonic grating

The proper modification of the optical disc is crucial for the creation of the plasmonic grating. At first, the disc was manually split into two pieces with a drawing pin. After the separation, both polycarbonate substrates are covered with the original metallic and dye layers, in different proportions. The process of splitting is completely uncontrollable – a variety of configurations occurs, and one has to choose the preferable one.

DVD+R and DVD-R The preparation scheme is presented in Fig. 2.1. Over a hundred of DVD+R, and DVD-R probes have been investigated for the construction of a plasmonic grating. The difficulties in the delamination process have caused that only several dozens of samples have proceeded for the final fabrication. The PC bottom-based structures are not considered due to the undesired combination of wide quasi-sinusoidal profile and grating height³. The top PC substrate, which is always combined with an adhesive, and usually covered with the metal and/or organic dye, results in the following possibilities:

1. *The top PC layer with adhesive, metal and dye.* Although the quasi-sinusoidal shape and the grating depth seems to show an efficient plasmonic resonance, the presence of an unknown organic dye prevents using this combination in the further experiments, i.e. in ultrahigh vacuum, due to possible evaporation of the dye. One must be aware of the fact that the dye layer is not chemically stable over longer periods (some months) when exposed to ambient air.
2. *The top PC layer with adhesive and metal.* The structure possesses quasi-sinusoidal profile with depths of 60-120 nm. For the preparation, the dye layer is removed by a stream of ethanol, followed by a blow of dry nitrogen. Throughout the thesis, this class of a samples is referred to as *sample 1*.
3. *The top PC layer with adhesive.* The structure shows the same dimensions as *sample 1*. This class is identified as *sample 2* through the thesis.

DVD+RW and DVD-RW The preparation scheme is presented in Fig. 2.2. Over a dozen DVD+RW and DVD-RW samples were investigated. The possibilities for a plasmonic grating are as follows:

³For the sake of completeness, we note, that we have investigated the bottom PC treated by chemical etching process. The obtained shape of the etched structure was not optimal for SPPs excitation and the attempts were not continued.

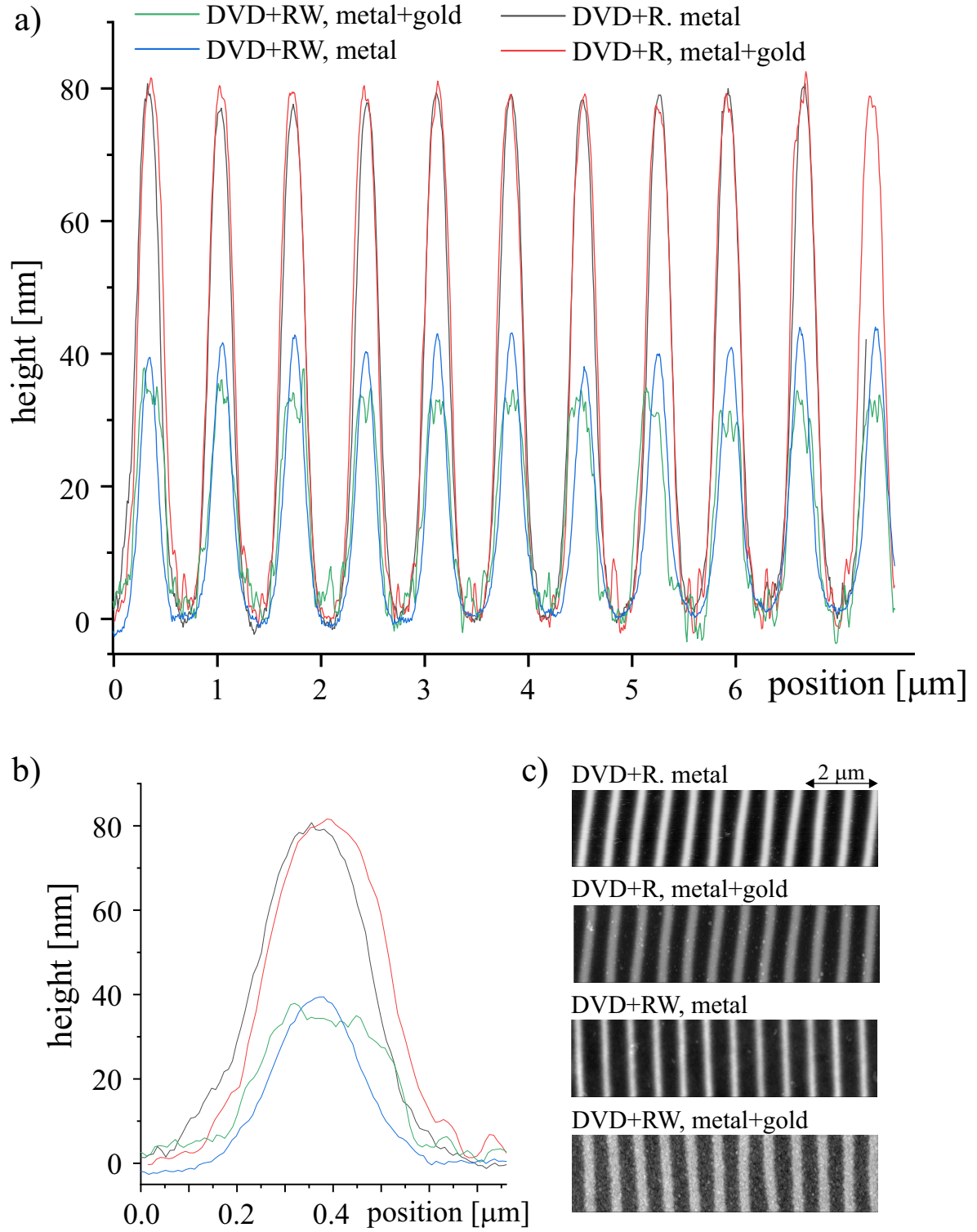


Figure 2.5: AFM-based topographies of the top, metallic layer, of recordable SK DVD+R, and rewritable Kaufland DVD+RW, performed with AFM, before and after covering the samples with gold. a) The shape of the profile for eleven grating periods. b) Close up view on one grating period. c) AFM images of the topographies of the respective structures.

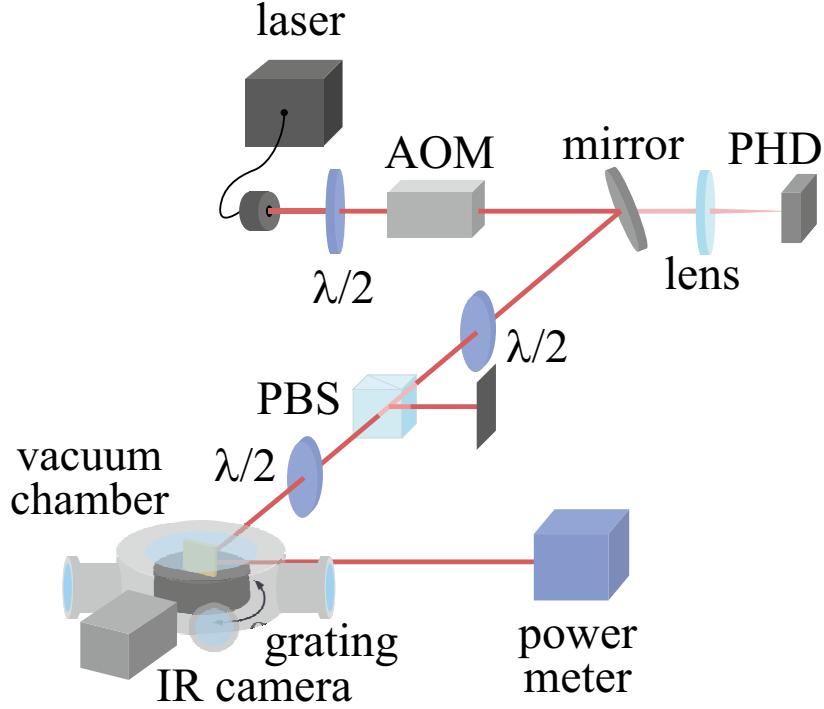


Figure 2.6: Generic scheme of the experimental setup used for SPPs excitation on disc-based gold nanostructures. Laser beam of a controlled polarization and power stabilization illuminates the grating. The power of the reflected light is measured by a power meter. Optionally, the temperature map is recorded by an infrared camera. AOM – acousto-optic modulator, PBS – polarizing beam splitter, PHD – photodiode for power stabilization, $\lambda/2$ – half waveplate.

1. *The top PC-based structure, with adhesive, metallic and recording layers.* The structure possesses wide quasi-sinusoidal profile of 20-40 nm high ridges. This class of the samples is denoted as *sample 3* through the thesis.
2. *The bottom PC-based structure.* The structure gives similar results as *sample 3*.

The preferable combination of layers is cleaned with an ethanol bath. Subsequently, the selected sample is coated with 3 nm of titanium wetting layer and 120-150 nm of gold in vapor deposition system Cryofox Explorer 600 (Polyteknin A/S, University of southern Denmark), at a rate of 0.5 Å/s. The gold coating is optimal for the excitation of SPPs by infrared light, and is chemically stable (as opposed to silver, which is certainly preferable for plasmonic purposes, but strongly chemically reactive [94]). After the preparation process, the topographies of the samples are once again measured under the AFM, to compare with the data taken before deposition of the gold. The before/after comparison is shown in Fig.2.5. The images prove that the metallic coating reproduces the profile of the substrate. Maintaining the chosen shape and height of the substrate as before is crucial – any change in one of the dimensions, significantly deteriorates the grating properties.

2.3. Optical examination of plasmonic resonances

The quality of the SPPs excitation was indirectly measured by goniometric far field zeroth-order reflectivity measurements, with the setup presented in Fig. 2.6. The setup was used for the examination of plasmonic resonances and the energy losses, which are associated with

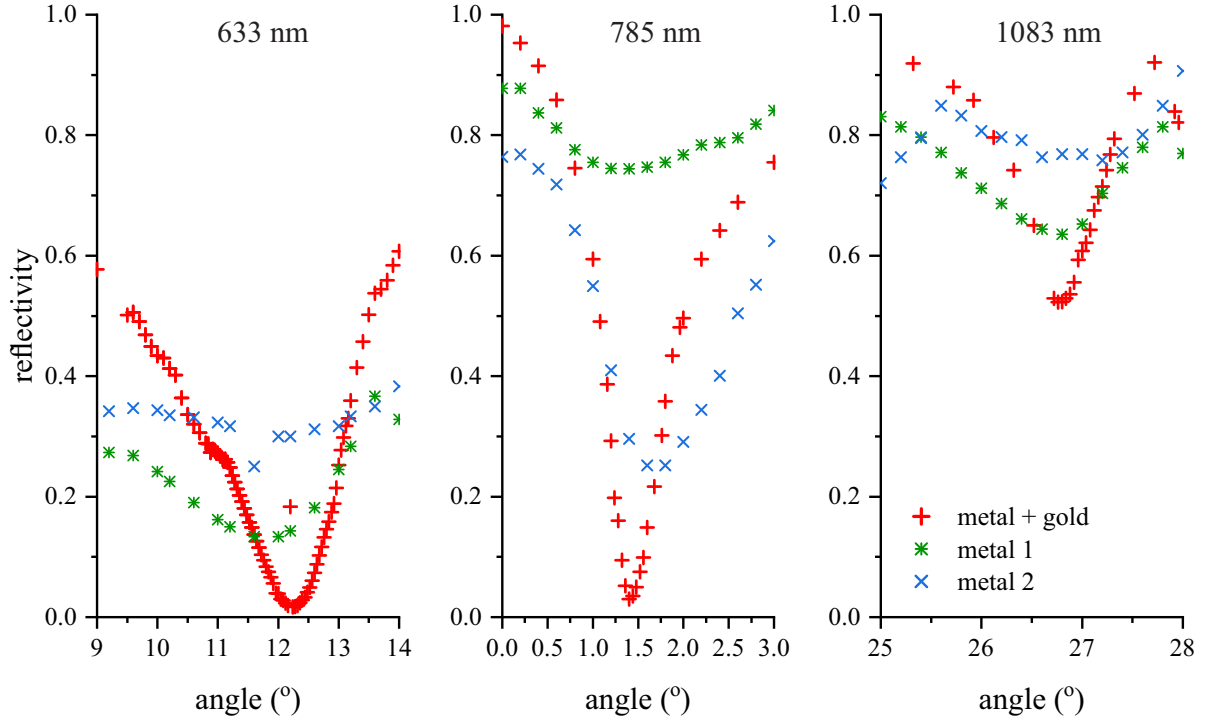


Figure 2.7: The comparison between the plasmonic resonances measured for 633, 785 and 1083 nm laser light, performed for the uncoated (metal 1 and metal 2), and gold-coated (metal+gold) disc-based structures.

the excitation of SPPs (see Sec. 2.4). The laser beam passes through the optical setup and illuminates the disc-based grating. The laser power is stabilized by a chain of acousto-optical modulator and a photodiode in a closed loop circuit. The polarization of light is controlled by polarizing beam splitter cube, and a half waveplate. Plasmonic grating is placed on a manual rotation stage, which provides a smooth change of angle of incidence/reflection. Optionally, the grating is placed in the vacuum chamber, and the temperature map is recorded by an infrared camera as described later. The power of the reflected light is detected by a power meter. The presence of SPPs is manifested by low reflectivity coefficient at a proper angle of incidence. The reflectivity is calculated as a ratio of the power of the incoming light, to the power of the reflected light. The most efficient plasmonic excitation corresponds to the lowest reflectivity coefficient. The measurements were performed for the laser wavelengths of 633 nm, 785 nm and 1083 nm, for each angle of incidence in the range 0-80°, for TM and TE states of polarization. The setup was used for the investigation of gold-coated, and uncoated disc-based structures.

The comparison between the resonances obtained for the uncoated (referred to as metal 1 and metal 2), and gold-coated samples (referred to as metal + gold), is presented in Fig. 2.7. The metal 1 (green stars) and metal 2 (blue x-es) correspond to the structures made of top, PC layer, combined with an original metallic layer of the DVD+R disc, of no additional preparation, except the cleaning with ethanol. The observed efficiency of the plasmonic excitation is rather low (high value of reflectivity coefficient) for the uncoated samples. For the wavelength of 633 nm, the presence of the first diffraction order decreases the overall level of reflectivity coefficient, in comparison to the wavelengths 785 and 1083 nm, where only zeroth order exists for the considered angles of incidence. This shows that the excitation of SPPs on the unmodified optical disc is possible, but not efficient. The metal+gold case shows the significantly improved excitation for each wavelength, with narrow and deep resonance curves, compared to the uncoated case. Thus,

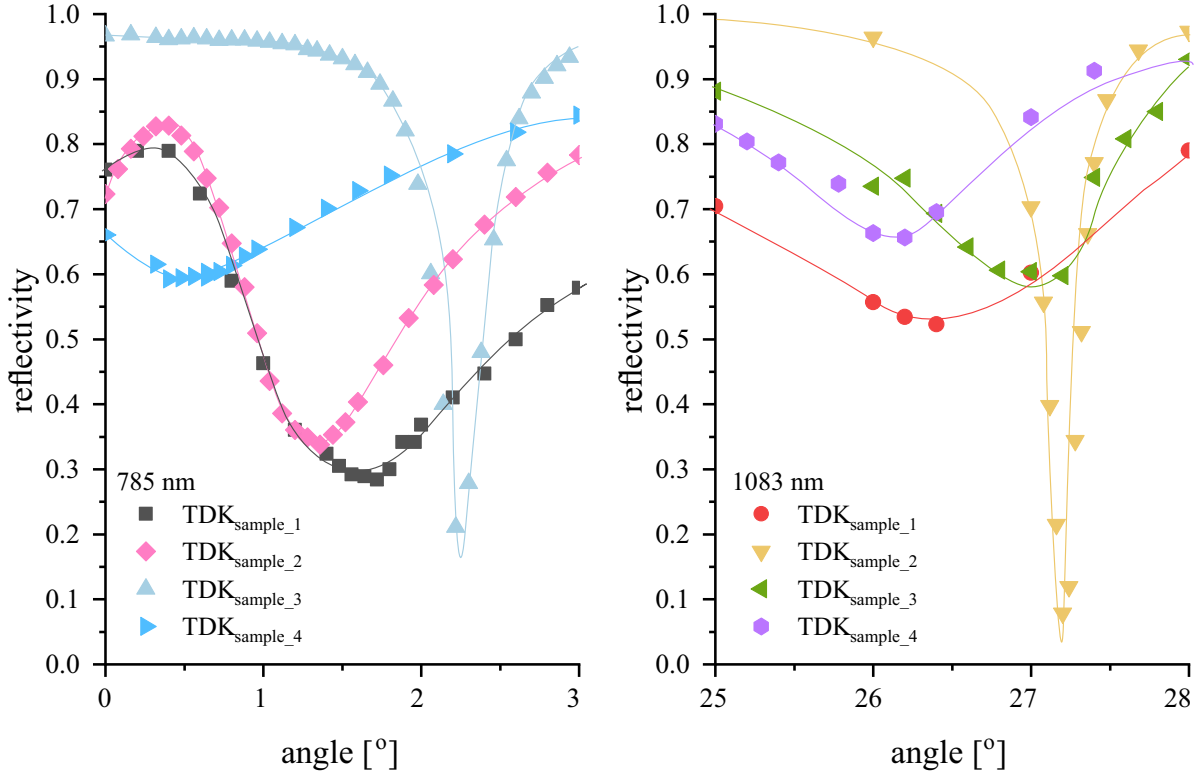


Figure 2.8: Plasmonic resonances measured for TM polarized laser light of 785 and 1083 nm wavelengths. The measurements were taken for four samples of the TDK DVD+R disc (top PC + metallic layer + gold). The curves are added to guide an eye.

it is definitely advised to implement the gold coating, instead of using the original metallic layer.

The AFM measurements show the same topography of the discs among samples from one company, yet, sometimes it does not result in the same quality of plasmonic resonance, as presented in Fig. 2.8. The figure shows the reflectivity curves, measured for four samples based on four different TDK DVD+R optical discs. The resonances were measured with TM polarized, 785 and 1083 nm laser light. The graphs reveal four different qualities of the SPPs excitation, indicating that the same disc structure can result in different plasmonic resonances. The observed differences are presumably caused by the storing conditions of the gold-coated samples. It has been observed, that the quality of gold can be easily degraded, even in the clean lab conditions. As a side effect, the microscopic and optical examination facilitates the deposition of unwanted particles on the gold surface, which has an impact on the quality of resonance. Also, the details of the quasi-sinusoidal profile substantially affect the plasmonic resonance. In order to find the effective plasmonic grating, the following steps are suggested:

1. The significant number of samples should be prepared. The optimal parameters, suggested by numerical simulations should be taken into account.
2. Each sample should be optically investigated to find the quality of the plasmonic resonance.
3. The chosen samples should be kept in vacuum or a closed container, before further application.

To complement the measured resonances, the numerical simulations were performed for each structure, with two independent techniques: Rigorous Coupled Wave Analysis (RCWA) and Finite Difference Time Domain (FDTD). The brief description of the methods is presented in

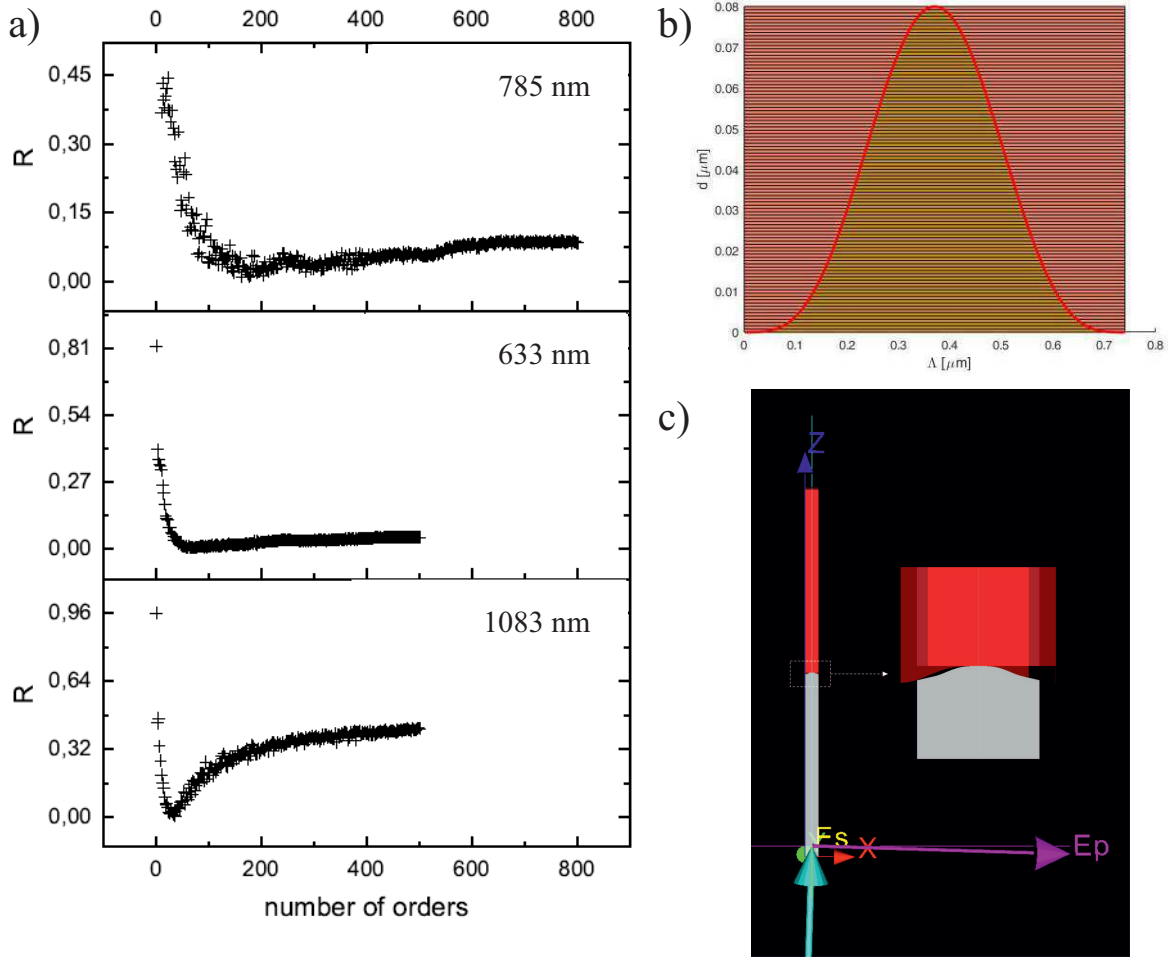


Figure 2.9: a) RCWA simulations: reflectivity dependence on number of orders, which were taken into account in the calculations, performed for 633, 785 and 1083 nm wavelengths, for *sample 2*. Note the different scales. b) The modelled profile shape of *sample 1*, implemented in rcwa-1d (RCWA) and c) EM Explorer (FDTD) initial setup.

Appendix A. For the RCWA simulations, to determine the number of orders (technical parameter of RCWA method), which guarantees the convergent results, the calculations of the dependency between the reflectivity coefficient and the number of orders, have been performed. The results obtained for *sample 2* at each wavelength, are presented in Fig. 2.9. The required number of orders was determined to be: 700 orders at 785 nm calculations, 300 orders at 633 nm calculations, and 400 orders at 1083 nm calculations. These values remain for any further calculations presented in the thesis. The model of the profile shape of the grating is based on AFM-imaged topographies. *Sample 1* is presented as an example in Fig. 2.9b. The resolution of the generated quasi-sinusoidal shape is 0.8 nm. Exactly the same quasi-sinusoidal shape, was implemented in FDTD simulations. The size of a Yee cell, which determines the resolution of the calculations, was limited to 5 nm.

The complete examination of SPPs excitation have been performed for at least 30 samples, including the optical and numerical characterizations. In the thesis, only a few selected cases are reported. The names of the samples, which are analyzed, are introduced in paragraph 2.2.2. Figure 2.10 shows typical comparison between the measured values of the reflectivity coefficient

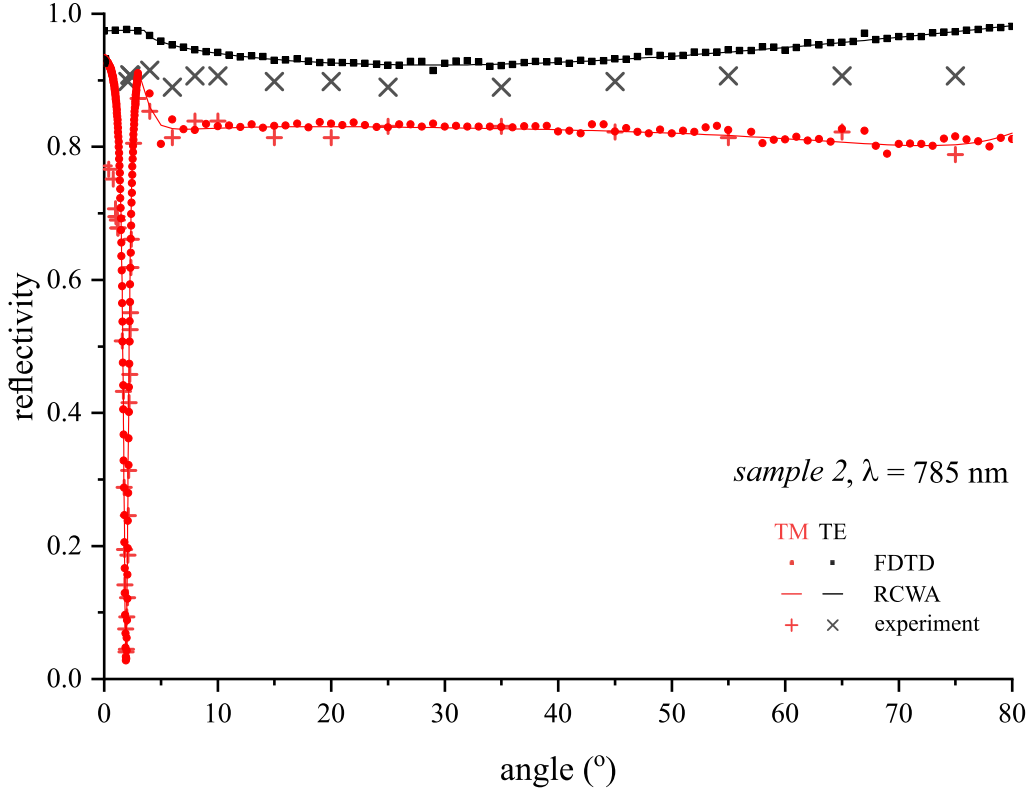


Figure 2.10: The reflection coefficients as a function of angle of incidence. The investigation is performed for 785 nm of TM (red) and TE (black) polarized laser beam, for *sample 2*.

(denoted as 'experiment'), and numerical simulations (denoted as 'FDTD' and 'RCWA', depending on the method), presented for the full angle dependence 0° - 80° . Figure 2.11 shows the plasmonic resonances for each wavelength and sample, near the optimal angle of incidence. To see the full angle dependence, see Appendix B.3. The determined optimal angles of incidence roughly fulfil the dispersion relation for the shallow gratings (eq. 1.3.19).

633 nm For the red light, the resonance is observed around 11° - 12° , with the lowest reflection coefficients equal 0.02 for *samples 1*, 0.02 for *sample 2*, and 0.36 for *sample 3*. Slight discrepancies between the measured and calculated values are observed for the positions of the resonance curves, while the width and the depth of the resonance are almost identical.

785 nm For the near-infrared light, the maximum efficiency of SPPs excitation occurs around 1° - 2° , with the lowest reflection coefficients equal 0.05 for *samples 1*, 0.04 for *sample 2*, and 0.21 for *sample 3*. The comparison between the numerically calculated, and optically measured values of the reflectivity coefficient reveals a very good agreement for the case of 785 nm laser beam.

This proves, that the 633 and 785 nm light is suitable for the high and slim quasi-sinusoidal profiles (*samples 1-2*), and low and wide-quasisinusoidal shapes (*sample 3*).

1083 nm For the infrared light, the resonance occurs around 26° - 27° , with the lowest reflection coefficients equal 0.53 for *samples 1*, 0.42 for *sample 2*, and 0.06 for *sample 3*. The comparison between the RCWA, FDTD calculations and optically measured values of the reflectivity coefficient reveals very good agreement for *sample 3*, and slightly less consistent for *samples 1-2*. This

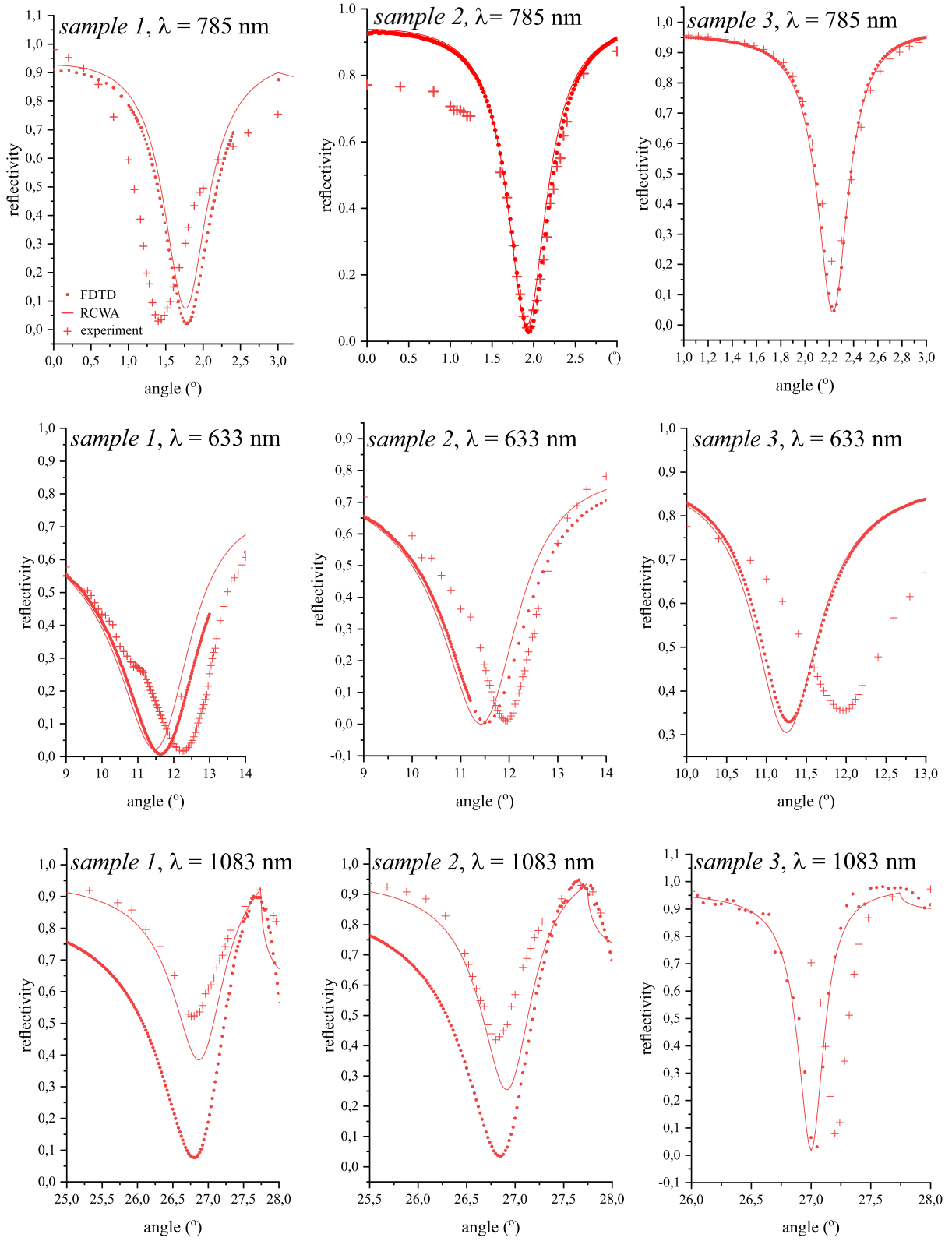


Figure 2.11: The reflection coefficients as a function of angle of incidence. The investigation is performed for 633, 785, and 1083 nm of TM (red) and TE (black) polarized laser beam, for *samples 1-3*.

proves, that the 1083 nm light is most efficient with wide quasisinusoidal and shallow shapes (*sample 3*).

The explanation of the discrepancies, which emerge between the numerics and the optically measured resonances, lies in the model of the structure, and the applied values of refractive indices. The modelled structure, which is used in the calculations, is a single grating period, based on the AFM-imaged topography. The periodic boundary conditions make the grating an infinite structure of such a single grating periods. For the real grating, the profile shape varies among the periods. Moreover, the calculations implement the refractive index of gold, which is measured with some uncertainty especially in the case of thin layers [95]. Both of these are a possible explanation of the differences between the numerics and the optically tested resonances.

2.3.1. Intensity of the electromagnetic field

The consistency between the numerical simulations and far field goniometric measurements proves the high accuracy of the implemented numerical model. The correct model provides the opportunity to investigate the distribution of the electromagnetic field, which is associated with SPPs excitation. The detailed understanding of the distribution is crucial for the design of e.g. plasmonic sensors, nanomanipulators, plasmonic traps and other atomic devices. The knowledge of the electromagnetic field enhancement is also essential for the construction of atomic dipole mirrors.

The electromagnetic field distributions were calculated as a I/I_0 ratio, where I_0 is the intensity of the incident light. The calculations implement the optimal angle of incidence (taken from reflectivity calculations) and TM polarized light. Figure 2.12 shows the calculations performed for one grating period of *sample 2*, for 785 nm light, via RCWA and FDTD methods. The comparison reveals the identical distributions for both techniques. In the thesis, the further intensity maps are shown only for the FDTD method.

Figures 2.13-2.15 present the electromagnetic field distributions obtained for *samples 1-3*, respectively. For the 633 nm light, the highest intensity of electromagnetic field reaches 50–60 times the intensity of the incident laser beam, for each sample. For the 785 nm light, the ratio grows up to 200-220 for *samples 1-2*, and up to 180 for *sample 3*. For the 1083 nm light, the intensity enhancement varies between 80 for *samples 1-2*, and 160 for *sample 3*. The strongest field enhancement is obtained for the excitation with 785 nm light, as expected. The low (in comparison to other wavelengths) enhancement obtained for 633 nm light, is a result of the presence of other than zero diffraction orders. For 633 nm light, part of the energy is transferred into the first diffraction order, which leads to a less effective plasmonic coupling.

As shown above, the most efficient wavelength for plasmonic coupling on disc-based structures is near-infrared. Yet, the use of other wavelengths is possible and results in deep and narrow resonances, with the possible implementation in plasmonic sensors. Likewise, the electromagnetic field enhancement at 633 and 1083 nm is strong enough to be employed for the creation of complicated potentials for cold potassium and cesium atoms.

2.4. Energy losses associated with SPPs excitation

This section describes the energy losses associated with generation of SPPs on optical discs. Thermoplasmonic effects are an unavoidable consequence of plasmonic excitation, which have been extensively reported in the case of localized plasmons [96, 97, 98, 99]. The detailed knowl-

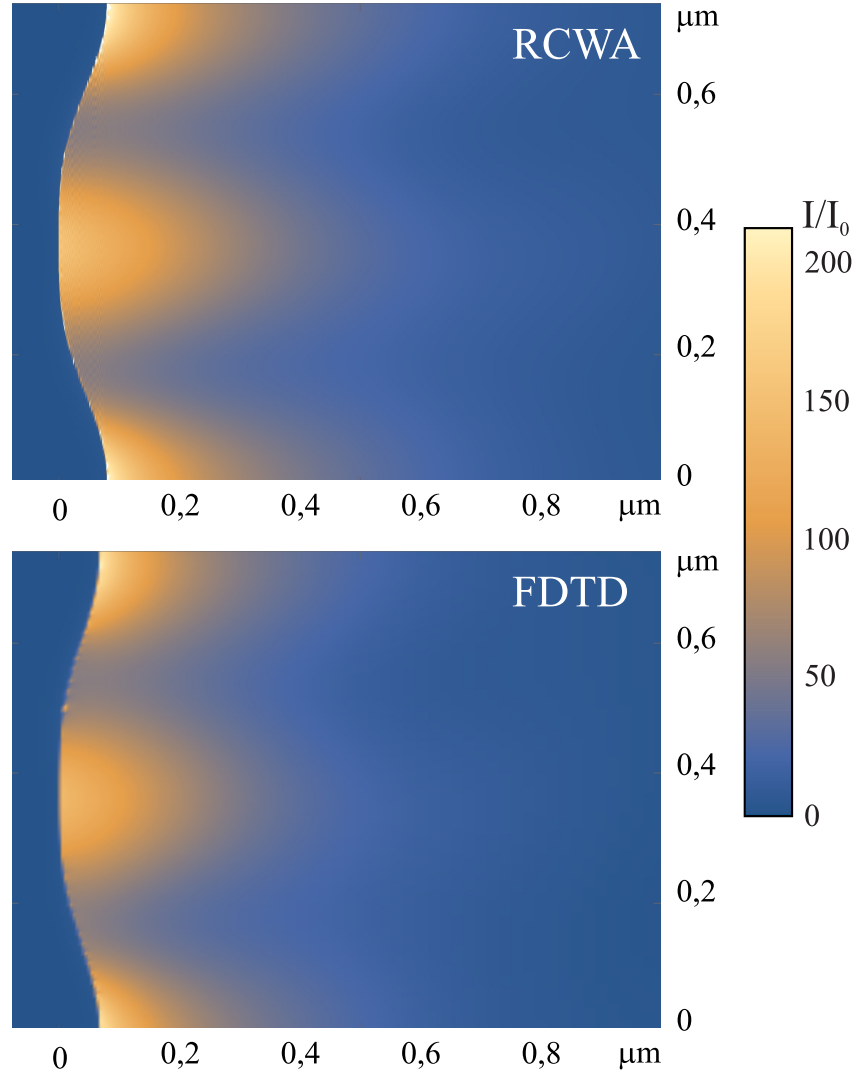


Figure 2.12: The comparison between the distribution of electromagnetic field I/I_0 calculated by RCWA and FDTD methods. The calculations are performed for *sample 2*, 785 nm and TM polarized light, and one grating period. The horizontal axis shows the distance from the grating surface.

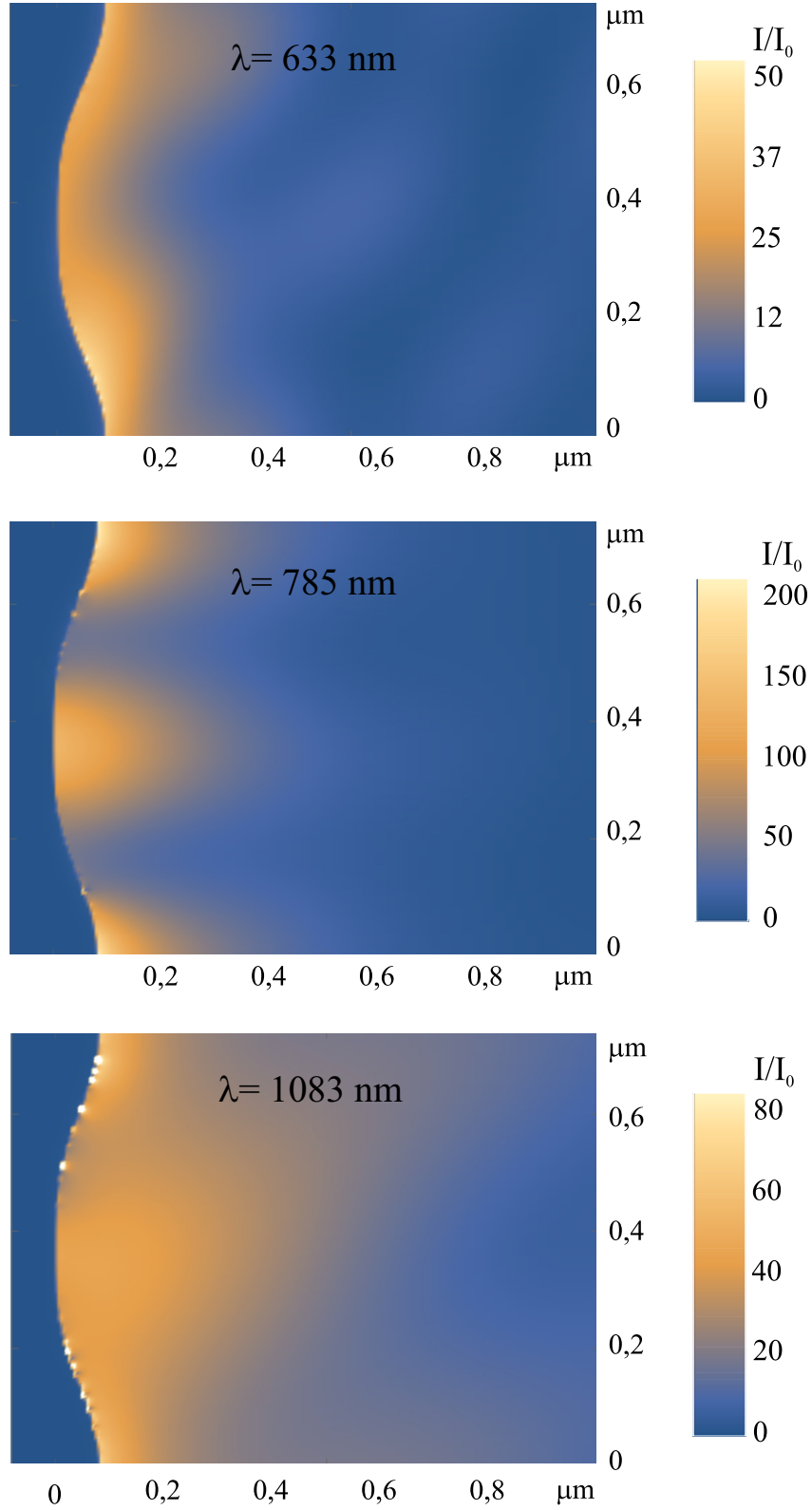


Figure 2.13: FDTD calculations of the relative intensity I/I_0 distribution above one grating period. The calculations are performed for *sample 1* and laser light of 633, 785 and 1083 nm. The horizontal axis shows the distance from the grating surface.

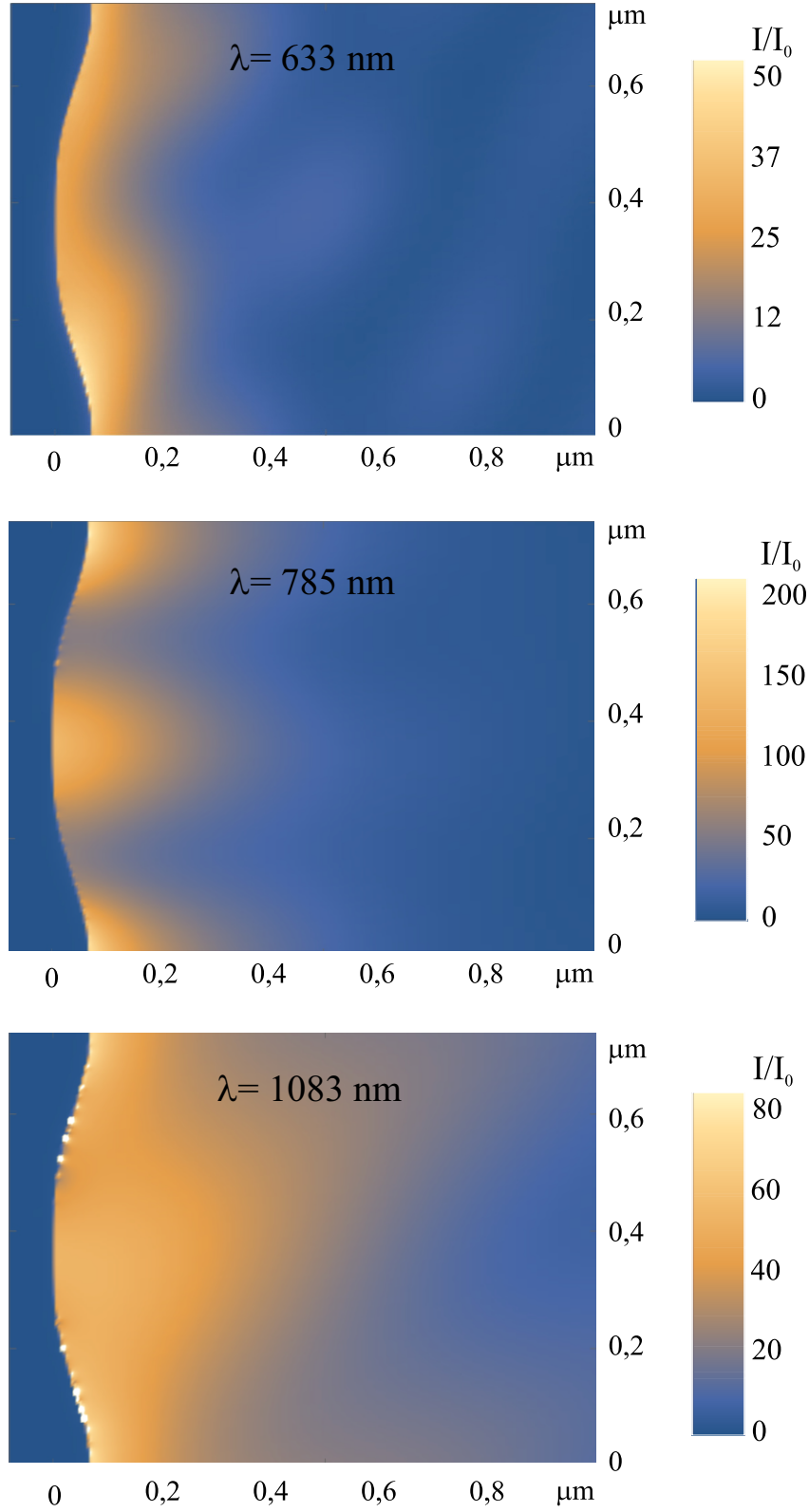


Figure 2.14: FDTD calculations of the relative intensity I/I_0 distribution above one grating period. The calculations are performed for *sample 2* and laser light of 633, 785 and 1083 nm. The horizontal axis shows the distance from the grating surface.

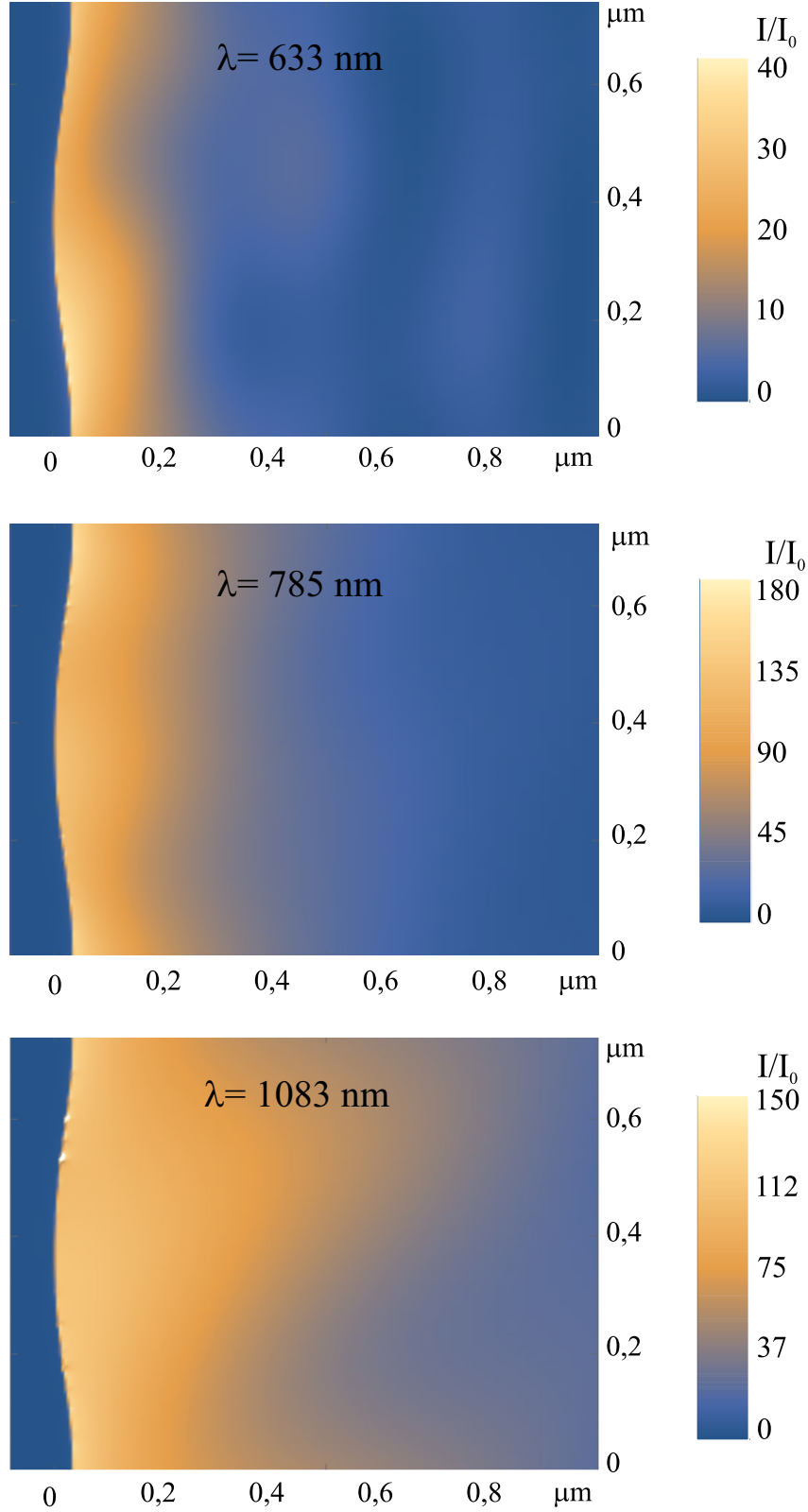


Figure 2.15: FDTD calculations of the relative intensity I/I_0 distribution above one grating period. The calculations are performed for *sample 3* and laser light of 633, 785 and 1083 nm. The horizontal axis shows the distance from the grating surface.

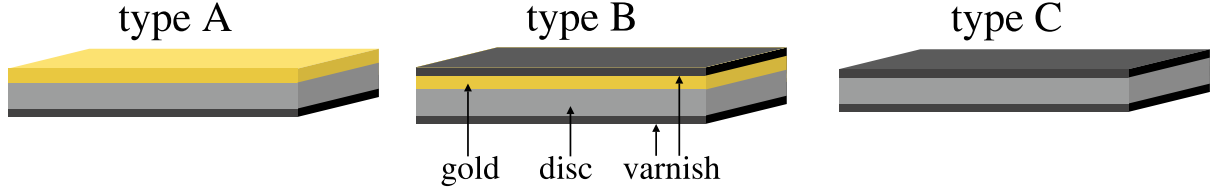


Figure 2.16: Scheme of the probes used for thermoplasmonic examination. Type A refers to *samples 1-3*, characterized in the previous section and covered with black, matt varnish on the bottom side. Type B corresponds to type A, which is covered with black varnish on both sides. Type C is the optical disc, which is covered with the black, matt varnish on both sides (no gold layer).

edge about the topic is crucial for further application of the structure, e.g. in cold atom experiments or plasmonic sensors.

The major concern is the heating mechanism, which leads to the irreversible modification of the grating structure and subsequent loss of plasmonic coupling. The heating is a consequence of thermal scattering of plasmonic energy [90], combined with poor thermal conductivity of the polycarbonate layer. Besides the heat transfer, the reflection and scattering of incident laser light are taken into account in our approach.

The thermoplasmonic measurements were conducted with the setup presented earlier in Fig. 2.6. The laser beam of a controlled polarization and possible wavelengths equal 633, 785 or 1083 nm excites SPPs on a gold grating for different laser powers and polarizations. The grating is placed either in the air or inside a vacuum chamber with a residual pressure of 10^{-3} - 10^{-5} mbar. One of the glass vacuum viewports was replaced with ZnSe Torr Scientific anti-reflection coated vievport⁴, with maximal transmission range between 8 and 14 μm , which covers the thermal radiation spectrum for 20-100°C. The temperature distribution was recorded with FLIR i60 infrared camera, with thermal sensitivity $< 0.1^\circ\text{C}$ and spectral range 7.5-13 μm . The measurements were performed for both, continuous and quasi-pulsed laser operation, at the optimal, and close to optimal angles of incidence, for both light polarizations and different laser powers.

In order to obtain full understanding of the topic, several dozens of samples have been investigated. The examined structures can be divided into three types, through the thesis referred to as *type A*, *B* and *C*. The characterization of each kind is the following:

- *Type A* corresponds to structures, which were previously used for plasmonic measurements. The metallic part of the optical disc is covered with gold, and additionally, coated with black matt varnish on the bottom part of the sample, as shown in Fig. 2.16 (left). *Type A* corresponds to *sample 1*, *sample 2* and *sample 3*, according to section 2.2.2.
- *Type B* describes the the samples of *type A*, which are covered with additional, top, varnish layer, as shown in Fig. 2.16 (middle). The absence of gold layer prevents any plasmonic excitation.
- *Type C* describes the original optical disc with black, matt, varnish surrounding the probe from each side, as shown in Fig. 2.16 (right).

The use of the black matt varnish provides the homogeneous area of relatively high emissivity coefficient (reaching almost 1), which is desirable for infrared camera recordings. The *type B*

⁴The thermal infrared region is strongly absorbed by the original glass vacuum viewport.

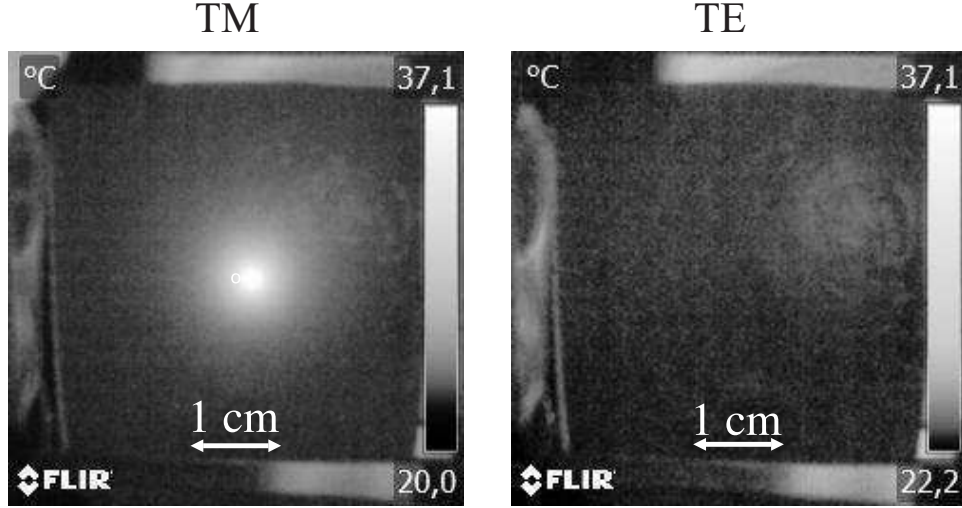


Figure 2.17: Temperature distribution recorded by infrared camera under continuous operation of 785 nm laser light, TM and TE polarized, and the optimal angle of plasmonic excitation.

and *type C*, which are totally covered with the varnish, imitate the 'blackbodies', serving as a reference for the thermoplasmonic measurements.

The reflection of the incident light

The light reflected from the structure has been measured by a power meter for near-infrared light of TM and TE polarizations. For *type A*, the power of the reflected light depends on the efficiency of plasmonic coupling. For the TM polarized light, the reflected power is from a few, up to 25% of the incident power. For the TE polarized light, the reflection increases to 90%. *Types B* and *C* show no plasmonic coupling, the power of the reflected light is around 5% of the incident power, regardless of the polarization.

The scattering of the incident light

The scattering of light on the structure was measured by goniometric measurements with a power meter. The scattered light is 2.5(0.5)% of the total power, for each type of the structure.

Thermal radiation and heat convection

The thermal radiation of the structure was investigated with infrared camera, which mapped the temperature distribution in a stationary state. The laser light of 785 nm operated in the continuous regime, at the optimal angle of plasmonic excitation, for laser powers of 10-60 mW. The typical maps are presented in Fig. 2.17, for the structure of *type A* and TE and TM polarizations. The absence of SPPs excitation for TE polarized light serves as the background data, which eliminates the contributions from the room temperature radiation and the residual radiation emitted by the camera sensor. The image of camera sensor, which is reflected from the surface of the structure, can be seen in the top right corner of the TE image. The markers, which were added on the edges of the sample, allow us to precisely calibrate the dimensions of the measured area. Figure 2.18 shows the cross-sections of the temperature distributions, obtained for different laser powers. The maximum temperature increases with the growing laser

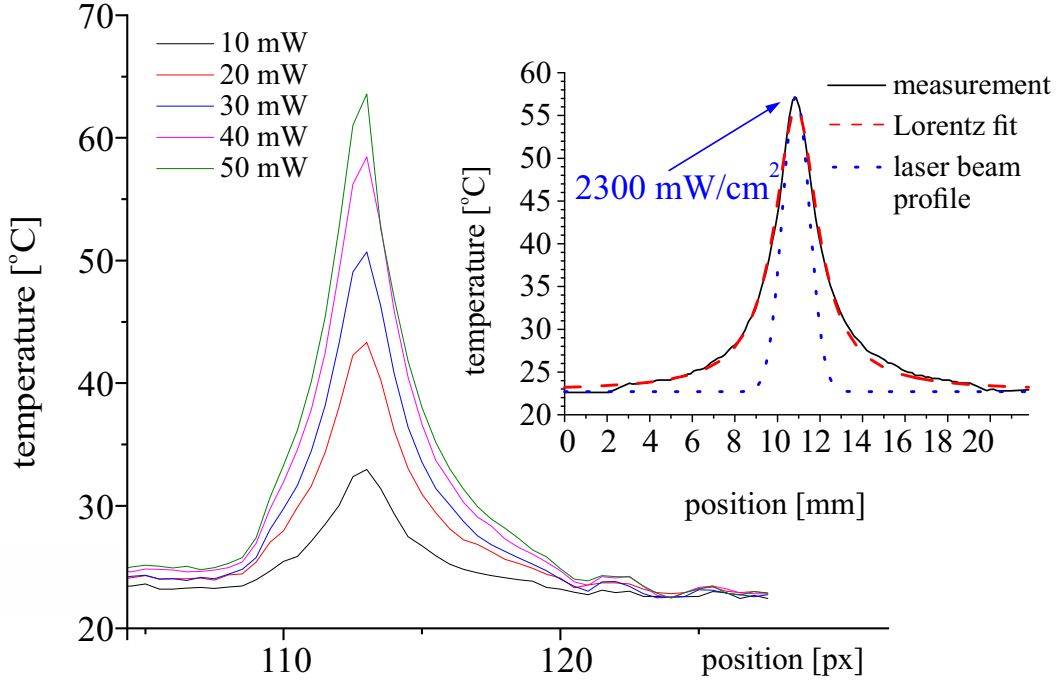


Figure 2.18: Cross-section of the temperature map taken for different laser powers (785 nm, TM polarized). Inset: the selected distribution combined with laser beam profile and fitted Lorentz function, presented for 60 mW of the incoming laser beam.

power, from 33° at 30 mW, up to 65° at 50 mW. The Lorentz fit matches the profile of the cross-section, with the calculated FWHM equal to 2.5 mm. The comparison between the temperature distribution and the Gaussian beam profile (Gaussian radius type e^{-2} of 1.3 mm) is presented in the inset of Figure 2.18.

The influence of the heat convection was investigated by comparing the temperature maps recorded in the air and vacuum, at first under residual pressure of 10^{-3} mbar. Figure 2.19 presents the temperature cross-section for 40 and 50 mW laser powers, recorded in air and in vacuum. The temperature distributions indicate small differences between the images recorded in air/vacuum. However, other measurements for various laser powers gave ambiguous results.

Calculation of the radiated power

To calculate the power radiated from the grating surface, the following steps are:

1. The temperature map was recorded by the infrared camera and imported to Wolfram Mathematica software, revealing the value of the temperature at each position.
2. The original pixels were converted to meters, based on the known length of the markers (see Fig. 2.17).
3. The temperature distribution was interpolated with the built-in Hermite method. Figure 2.20 shows the comparison between the original data, and the interpolated function.
4. The power, which radiates from the surface of the grating is given by Stefan-Boltzman law. The interpolating function was integrated over the sample's area, for both polarizations.

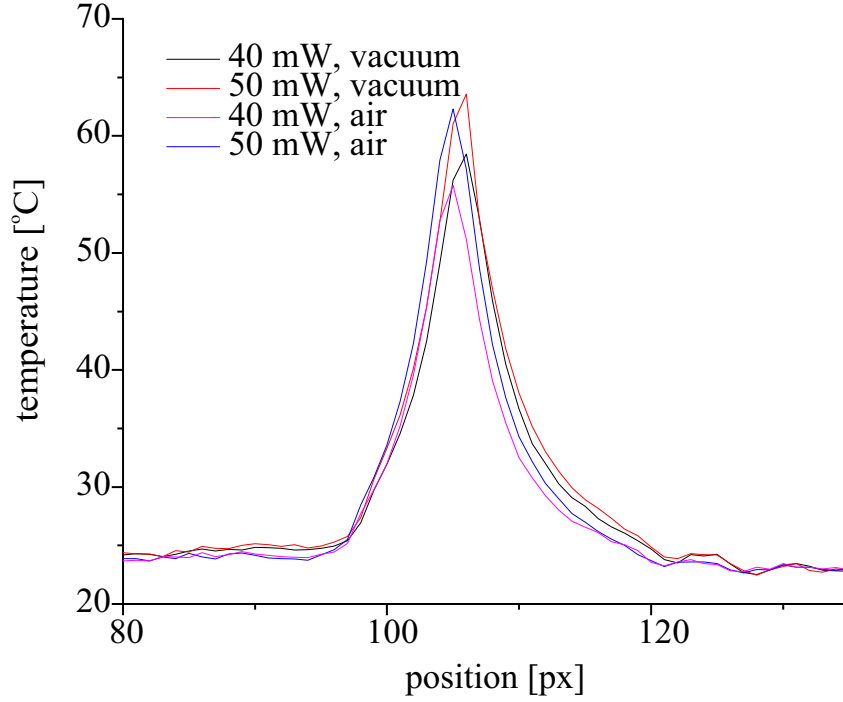


Figure 2.19: The comparison between the measurements taken in the air and in vacuum for the structure of *type A*: the temperature cross-section, recorded for 785 nm, TM polarized beam of 40 and 50 mW of laser power.

5. The calculations for TE polarization serve as a background for *type A* probes. The total radiated power, associated with SPPs excitation is a result of the subtraction of the powers obtained for TM and TE cases, measured on the black side of the structure (almost no power is radiated through the gold layer).
6. For the structures of *type B* and *C*, the background data is recorded in the absence of the laser light, and subtracted from the case with the laser beam presence. The total radiated power is a sum of the measurements taken for both sides of the structure.

Figure 2.21 shows the results for the structure of *type A*. The gold plasmonic grating with black varnish on the bottom is based on the DVD+R (*sample 1* and *2*, according to Sec.2.2.2), or DVD+RW (*sample 3*). The figure presents the thermally radiated power, and the ratio of the radiated to incident power. The results are presented for each *sample* separately, for different laser powers in the range of 10-50 mW. The energy losses, resulting from the thermal radiation, are about 10-15% of the incoming laser power. For *types B* and *C*, the ratio is 70-80%. The energy losses, which are caused by reflection and scattering of light, vary between a few, up to 27.5(1.5)% of the incident power. The data are collected in Table 2.2. The system is in the stationary state and all the energy loss mechanisms are taken into account in the analysis, but the results are inconsistent with the expectations. The expected value of the re-emitted power is 100% of the power, which is pumped into the system. The total re-emitted and reflected power of gold samples is 22% for *samples 1* and *2*, and 40.5% for *sample 3*. The difference is presumably caused by the efficiency of the plasmonic coupling (additional 20% is due to reflection for *sample 3*). Likewise, the 'blackbodies' of *types B* and *C* do not re-emit 100% of the supplied energy, which proves the method incorrectness. The explanation was found in [100, 101]. The thermal conductivity of the air stays almost constant at a certain level with the decreasing pressure from the atmospheric pressure down to 10^{-5} mbar. Thus, to fully eliminate the heat convection, the

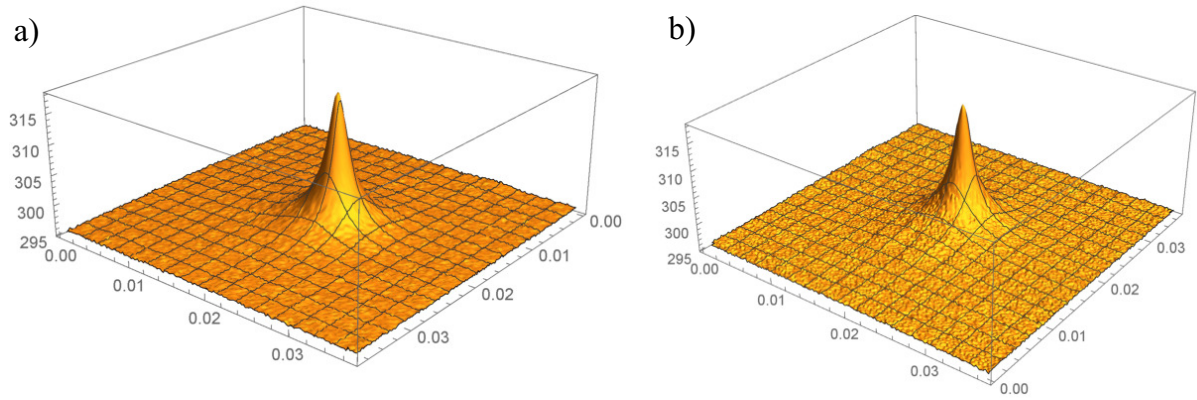


Figure 2.20: a) The temperature distribution imported from the infrared camera and b) the data interpolation performed in Wolfram Mathematica, with the built-in Hermite method.

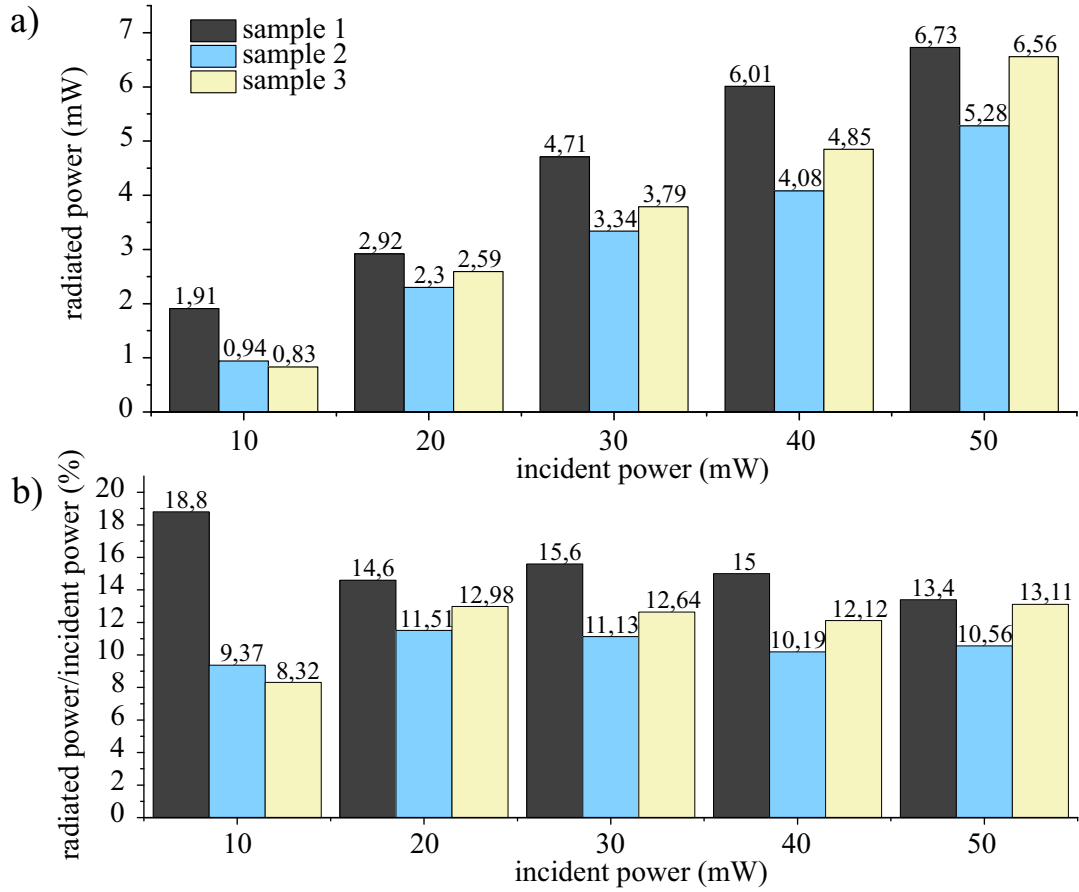


Figure 2.21: The thermal radiation of plasmonic grating. a) The calculated power, which radiates from the surface of the structure. b) The calculated ratio of the radiated power to the incident power. Measurements were performed for *samples 1-3* of *type A*, for 785 nm, TM polarized laser beam, and different laser powers.

probe type	A_{+R}	A_{+RW}	B	C
reflection [%]	4.5(0.5)	25(1)	5(0.5)	5(0.5)
scattering [%]	2.5(0.5)	2.5(0.5)	2.5(0.5)	2.5(0.5)
convection [%]	0 (?)	0 (?)	0 (?)	0 (?)
radiation [%]	15(4.0)	13.0(3.0)	70(8.0)	80(6.0)
total [%]	22(5)	40.5(8.5)	77.5(9)	87.5(7)

Table 2.2: The respective contributions of the re-emitted energy, measured for structure of *type* A , B and C , performed in the vacuum of the order of 10^{-3} mbar.

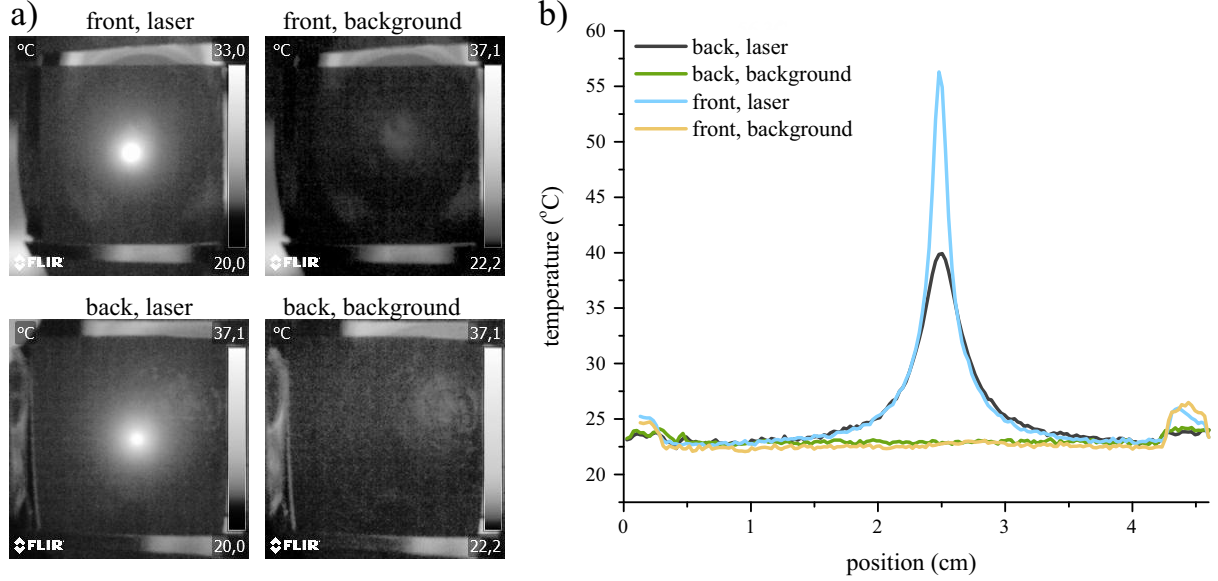


Figure 2.22: a) Temperature distribution recorded by infrared camera for the structure of *type* C (the 'blackbody'). The maps are shown for continuous operation of 785 nm laser light (front/back laser), and for the absence of light (front/back, background), which serves as a background data. The measurements were performed for both sides of the structure. b) The cross-sections of the temperature distribution.

further investigation were performed in a vacuum chamber of a residual pressure of 10^{-5} mbar.

Figure 2.22 presents the temperature distribution of the structure of *type* C . The front and the back of the structure are imaged under continuous operation of 785 nm light, and for the absence of light. The later provides the background data. The power, which radiates from each side of the structure, adds up to roughly 100% of the delivered power, as expected. The result confirms the assumed thermal coefficient of air [100, 101] and allows to conduct further measurements with a reliable method. The results for plasmonic gratings are presented in Fig. 2.23, showing the changes of the temperature with time and laser power. The first plot reveals the dramatic increase of the temperature – 75°C is reached for 90 mW, for 785 nm light of a continuous operation. The long lasting exposition leading to a high temperature causes the irreversible macroscopic changes in the disc structures, significantly worsening the plasmonic resonance quality. The second plot shows the increase in the maximum temperature, which is raised to the 4th power, versus laser power, for *samples 2* and *3*, which were illuminated with 785 nm and 1083 nm light, respectively. The fourth power of temperature does not grow linearly with the increasing laser power, which indirectly confirms the adverse modification of the

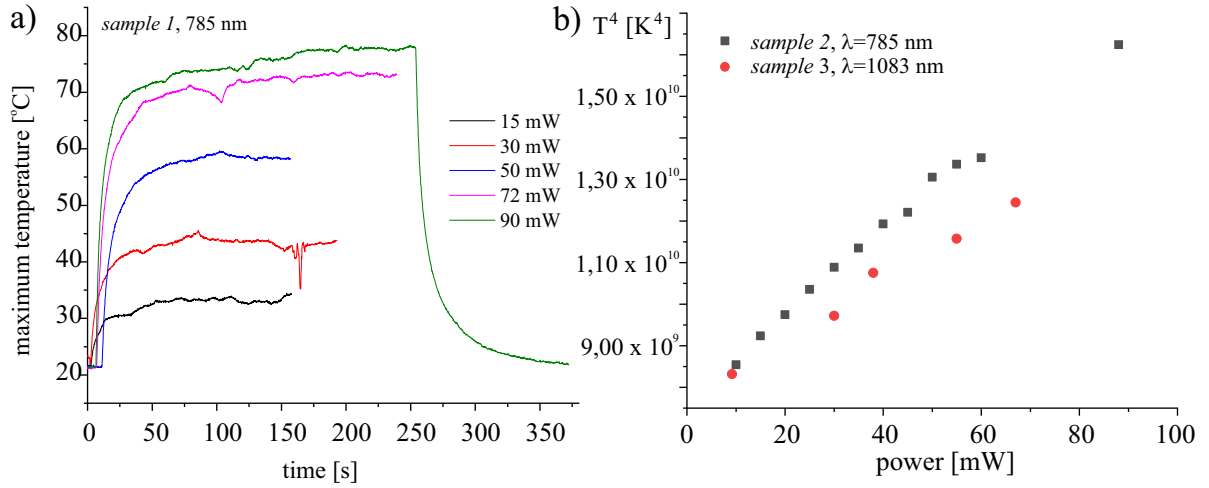


Figure 2.23: The maximum temperature of the structure recorded in time and for different laser powers. The temperature was measured for *sample 1* (a), *samples 2* and *3* (b) at 785 nm and TM polarized laser light for different laser powers.

probe type	A_{+R}	A_{+RW}	B	C
reflection [%]	4.5(0.5)	25(1)	5(0.5)	5(0.5)
scattering [%]	2.5(0.5)	2.5(0.5)	2.5(0.5)	2.5(0.5)
convection [%]	0	0	0	0
radiation [%]	53.5(6.0)	53.0(8.0)	102(8.0)	98(6.0)
total [%]	61(7)	81(10)	110(9)	106(7)

Table 2.3: The respective contributions of re-emitted energy, measured for structure of *type A*, *B* and *C*, performed in the high vacuum of the order of 10^{-5} mbar.

structure caused by thermal damage of the grating. For the sake of completeness, the changes of the temperature were also measured for 633 nm at 11 mW (maximum available power) giving 30°C of the maximal temperature for *samples 1-3*. Regardless the laser wavelength and power, no rise in the temperature is observed for TE polarized light.

Finally, to properly examine the energy losses balance associated with plasmonic excitation, the thermal radiation was calculated once again for the high-vacuum measurements. The data are collected in Table 2.3. The given uncertainties for the radiation contribution were estimated based on the reproducibility of the separate measurements. The main conclusions are as follows:

- The reflected and the scattered light account for a few % of the energy losses, as long as the quality of the resonance is high in the case of plasmonic gratings (*type A*).
- The heat convection is eliminated by applying high vacuum chamber, with the residual pressure of at least 10^{-5} mbar.
- The thermal radiation from the structures of *type A* gives half of a contribution of the supplied energy. This makes the total re-emitted power being 60-80% of the total supplied power.
- There is an unknown energy loss mechanism associated with SPPs excitation on a gold-coated optical disc, representing 20% of the losses. The unknown losses remain an open question. One of the possible explanations is Lorentz friction, as described in [102, 103].

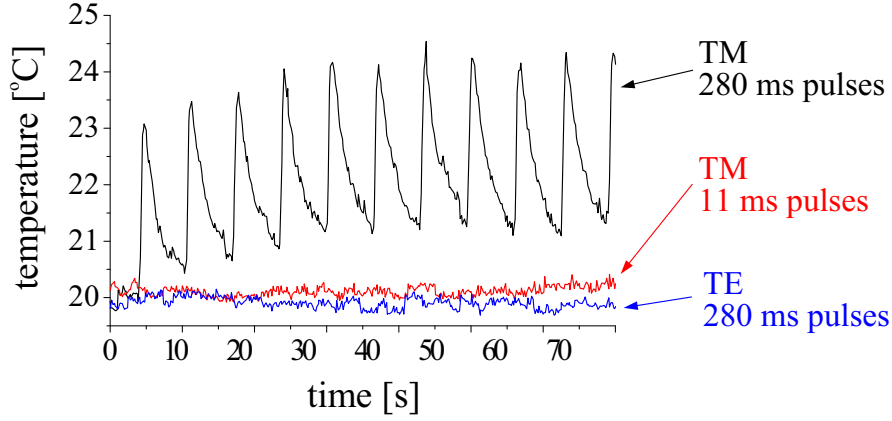


Figure 2.24: The maximum temperature of the structure recorded in time. The temperature was measured for *sample 1*, 785 nm and TM polarized laser light, operating under pulsed illumination.

- For the 'blackbody' samples (*types B and C*), the re-emitted energy is over 100% of the total. Exceeding 100% is caused by a systematic error of the infrared camera readouts.

The half of the laser beam power is transformed to the heat. For laser powers greater than several milliwatts, the grating structure is damaged, leading to the deterioration of the plasmonic coupling. Thus, the increase of the temperature prevents the application of the structure in any atomic or plasmonic devices. To solve the problem, the pulsed operation of the light is investigated. Figure 2.24 reveals the changes of the temperature for 60 mW of 785 nm light, for different pulse duration and light polarization. The small temperature increase of 4°C is observed for the 280 ms long pulses of TM polarized light, whereas the same pulses of TE polarization show no changes in temperature. For the pulse duration of 11 ms no temperature rise is observed, regardless the polarization state.

In summary, to avoid the temperature increase, it is possible to implement the pulsed operation. On the other hand, it is possible to take an advantage of the heating effect, either for bacteria sterilization [104], or for rubidium desorption in optical dipole mirror for cold atoms [75].

2.5. Optical Dipole Mirror with SPPs

In this section, the realization of an Optical Dipole Mirror (ODM) for cold rubidium atoms is reported. The basis of the mirror is discussed in the Introduction in Sec. 1.4.

The cold rubidium atoms, source of which are rubidium dispensers, are trapped in MOT. The ODM reflects the atoms from the surface of the grating, by means of strong, repulsive, dipole potential generated by SPPs. The plasmonic grating, which is described in Sec. 2.2.2, serves as a platform for the excitation of SPPs with blue-detuned light. The electromagnetic field is significantly enhanced above the surface of the structure with the amplitude of the field exponentially decaying with the growing distance from the surface. The large intensity gradient provides the required plasmonic potential.

2.5.1. Experimental setup

The ODM is a complex system composed of many subsystems, which e.g. provides vacuum or prepares the laser beams for trapping. The employed apparatus is briefly described in the following points.

1. Vacuum system

The ultrahigh vacuum is provided by three vacuum pumps and the vacuum chamber, produced by PreVac company. The initial vacuum is supported by the rotational (TRIVAC E2) and turbomolecular pumps (TURBOVAC MAG), up to the pressure of 10^{-9} mbar. The ion pump (PCHYSICAL ELECTRONICS) reaches the residual pressure of 6×10^{-10} mbar, and remains in operation during the ODM experiment.

2. Rubidium dispensers

The pair of rubidium dispensers supply the rubidium atoms to the vacuum chamber. The rubidium partial pressure is controlled by the electric current, in the range of 3-5 A.

3. Helmholtz and compensation coils

The Helmholtz coils provide the necessary magnetic fields, required for the MOT operation. The current of the coils is digitally controlled via LabVIEW program, which enables rapid changes of magnetic field. The typical currents vary between 2.5 and 3.5 A. The compensation of the magnetic field of Earth is done by three pairs of compensation coils, controlled by regulated power supplies.

4. Lasers

Two of TOPTICA DL 100 lasers were used for trapping and repumping processes and the TOPTICA TA PRO was employed for SPPs excitation. Both lasers are tunable diode lasers, operating at 780 nm. The DL 100 reaches 100 mW of the power, whereas the maximum power of TA PRO is 2 W, including the tapered amplifier.

5. Imaging system

The detection of atoms was carried out with fluorescent imaging, employing the Electron Multiplying CCD (EMCCD) camera. Andor iXon^{EM}+ camera has the resolution of 1004×1002 pixels of $8 \mu\text{m} \times 8 \mu\text{m}$ each, and the advanced cooling mechanisms down to -100°C .

6. Software

The experimental sequences were controlled via *sterBEC* program (LabVIEW software), written by Dobrosława Bartoszek-Bober [105].

The heart of the experiment is a background pressure loaded, magneto-optical trap for ^{87}Rb . The MOT requires at least one trapping laser light and a repumper laser. The lasers need to be stabilized in terms of frequency to an atomic transition, by using e.g. absorption spectroscopy. For the ODM experiment, the MOT is constructed with 3 pairs of counter-propagating beams of trapping light (Master DL100) overlapped with the repumping beam (Repumper DL100). Another laser light, which is blue-detuned from the rubidium transition, is used for SPPs excitation (TA PRO). The laser beams are prepared in the laser park on an optical table, which is spatially divided into 'level 0', 'level 1' and 'level 2' (see Figure 2.25).

- *Level 0* corresponds to the main part of the laser park, with the power and frequency stabilization system, shutters and beam size and propagation controllers. The detailed scheme is presented in Fig. 2.26.
- *Level 1* forms the final stage of the MOT construction, the fluorescent imaging, and the vacuum system. Level 1 is shown in Fig. 2.27.
- *Level 2* prepares the blue-detuned light for SPPs excitation. Level 2 is shown in Fig. 2.27.

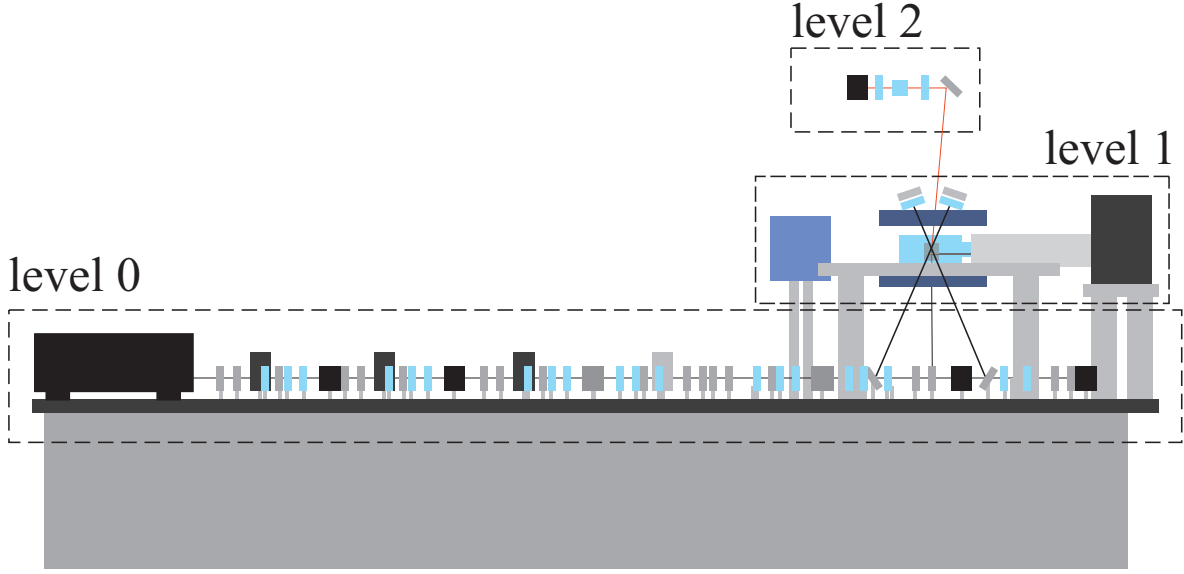


Figure 2.25: Scheme of the experimental setup. The respective layers are shown in detail in figures 2.26 and 2.27.

The details of the laser park are described in the following paragraphs, for each laser light separately.

Master DL100 Master DL100 serves as a trapping laser beam, marked with black line in the schemes in Fig. 2.26 and 2.27. The laser beam is divided into two orthogonal directions on the first PBS (Polarization Beam Splitter) cube (see Fig. 2.26).

1. For the *side-reflected beam*, the small amount of laser power is used for stabilization of the frequency. The size of the beam is reduced with the Galilean telescope and passes through the acousto-optical modulator (AOM), operating at the frequency 91.67 MHz, in single-pass, and +1 diffraction order, which shifts the frequency towards the lower frequencies (AOM precedes the saturation spectroscopy setup). The stabilization is provided by saturation spectroscopy for ^{87}Rb , at the transition between the state $5^2S_{1/2} |F = 2\rangle$, and the crossover resonance *co23*.
2. (a) For the *straight-through beam*, the main part of the light is steered through another polarizing beam splitters and a Galilean telescope, to reduce the diameter of the beam towards the second AOM. The AOM operates at the frequency of 107.70 MHz, in a double-pass, at +1 diffraction order at each pass, shifting the frequency towards the higher frequencies. Finally, the total detuning of the light from the transition $5^2S_{1/2} |F = 2\rangle$ to $5^3P_{3/2} |F' = 3\rangle$ is 9.6 MHz (towards lower frequencies).
- (b) The master laser beam is further combined with the repumping beam, at the next PBS cube. Both beams enter the telescope, which increases the diameter of the beams for the trapping stage. During the experimental sequence, the MOT beams are switched off by the respective AOMs. However, the residual light leaking through the AOMs is still present. The mechanical shutter (commonly called click-clack) is installed at the position of the waist of the telescope, to remove the remains of the beam, if needed. For the MOT stage, the beams are distributed into 3 orthogonal directions and guided to level 1 (the level of the vacuum chamber). Each beam is of the same laser power.

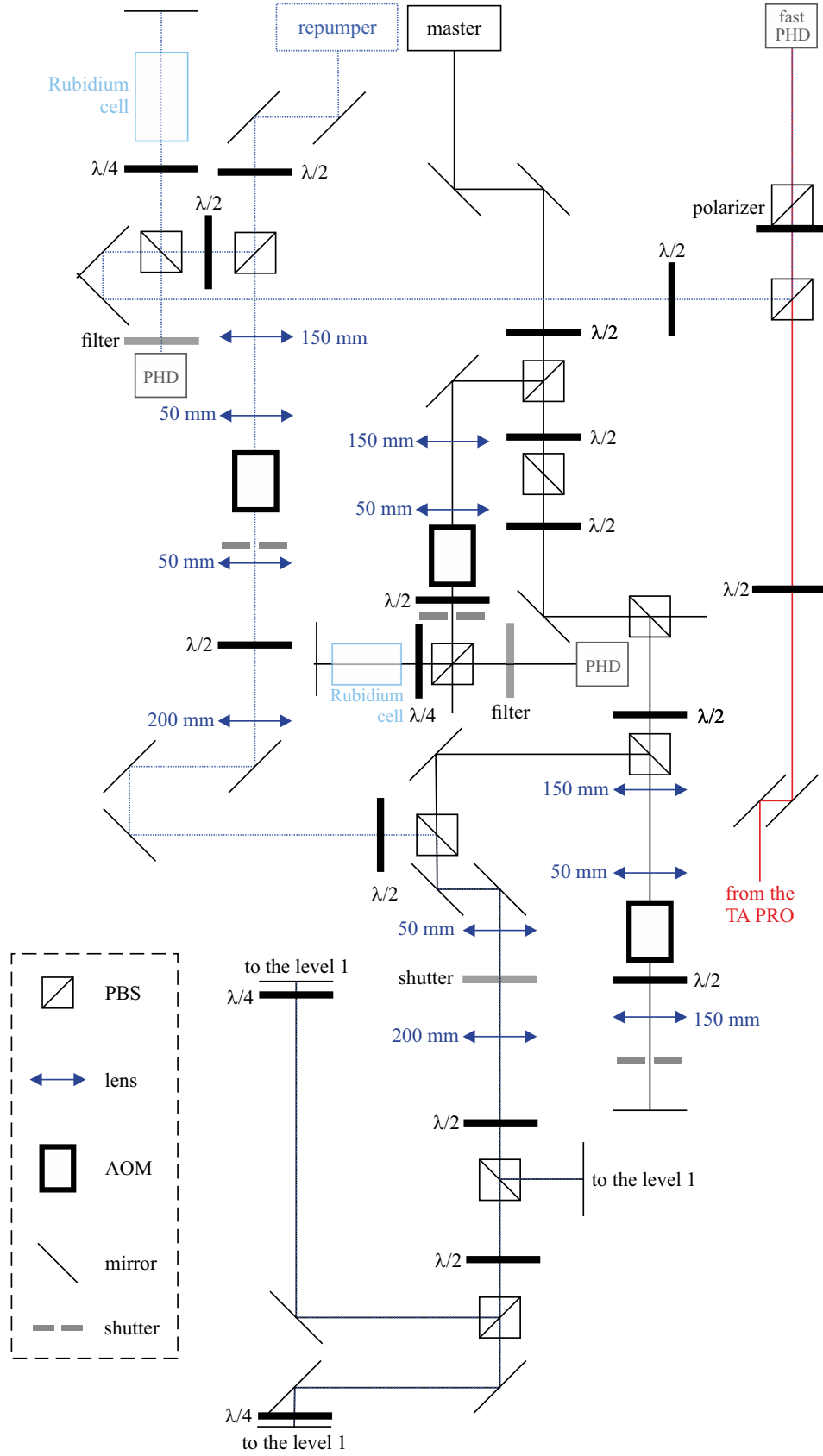


Figure 2.26: Detailed scheme of the experimental setup for level 0 (see Fig.2.25). AOM is acousto-optical modulator, PBS is polarization beam splitter, PHD is photodiode, $\lambda/2$ and $\lambda/4$ are half- and quarter-wave plates, respectively. See the text for details.

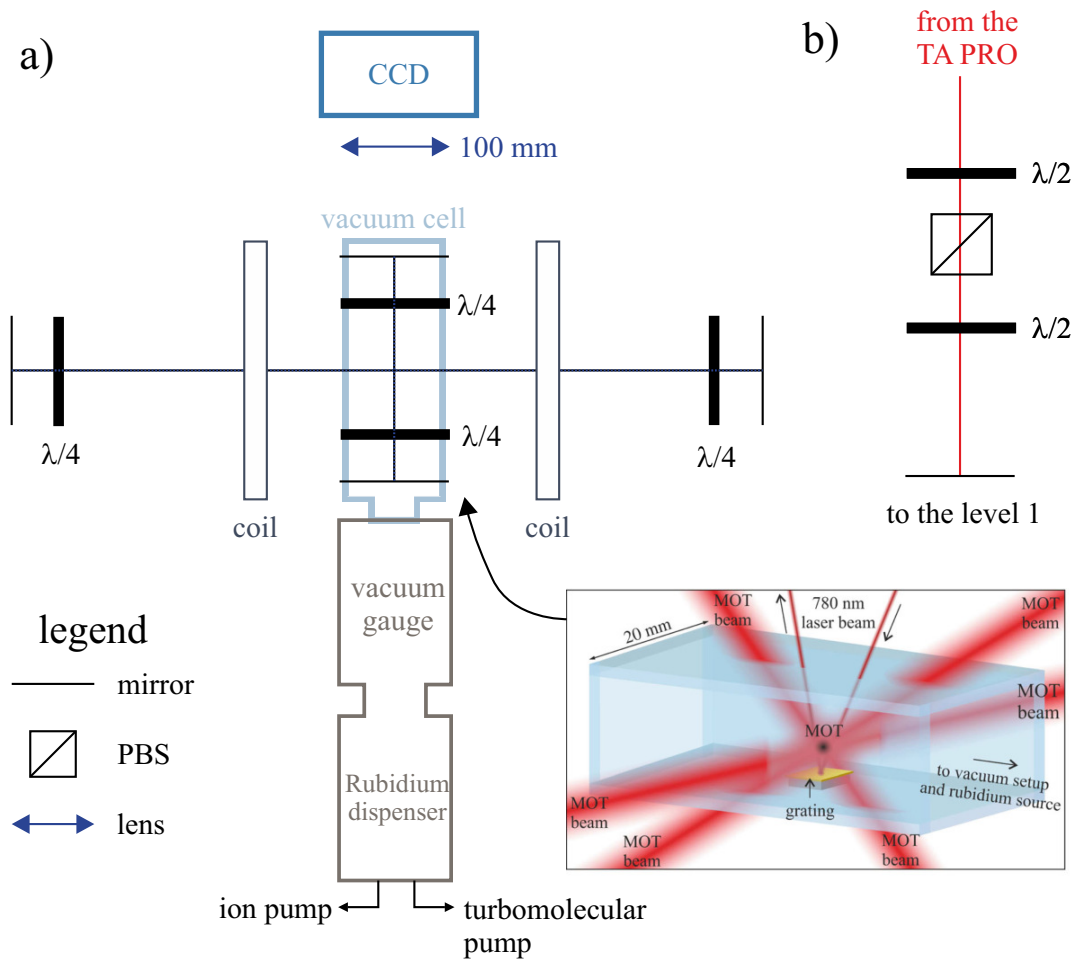


Figure 2.27: Detailed scheme of the experimental setup for level 1 (a) and level 2(b) as indicated in Fig.2.25. PBS is polarization beam splitter, $\lambda/2$ and $\lambda/4$ are half- and quarter-wave plates, respectively. See the text for details.

- (c) At level 1 (see Fig. 2.27), the beams are transmitted through the quarter-wave plate and reach the vacuum chamber. Then, the beams go through another quarter-wave plate, followed by the reflection from the dielectric mirrors, after which the reflected and the incident beams are overlapped. The incident and the reflected beams are circularly polarized with the opposite handednesses. The three pairs of counter-propagating beams intersect at a right angle, in the middle of the vacuum chamber. The trapping mechanism is provided by the gradient of magnetic field, which is provided by coils in the anti-Helmholtz configuration.

Repumper DL100 The repumper beam provides the pumping process, between the hyperfine states of $|F = 1\rangle$ and $|F = 2\rangle$. The beam is marked by a blue line on the schemes in Fig. 2.26 and 2.27.

Part of the laser beam is guided through the PBS to the saturation spectroscopy setup. The repumper is stabilized at the transition from the state $5^2S_{1/2} |F = 1\rangle$ to the crossover resonance *co12*, detuned by 6489 MHz from the transition $5^2S_{1/2} |F = 2\rangle$ to $5^3P_{3/2} |F' = 3\rangle$. The rest of the repumping light is separated again, and guided to the frequency locking system of TA PRO laser. The other part passes through Galilean telescope, followed by AOM, which shifts the frequency by 79.22 MHz towards the higher frequencies (+1 diffraction order, single-pass). Then, the diameter of the beam is magnified by another Galilean telescope, and the light is combined with the laser beam of the master and directed towards MOT, as described in the paragraph above.

TA PRO The TA PRO laser beam is responsible for SPPs excitation, marked with red line in Fig. 2.26 and 2.27.

The TA PRO laser is mounted on the external optical table. The light from the seed laser and the amplifier is guided to the main experiment via single mode, polarization-maintaining fibers. The first beam is used for laser frequency stabilization (level 0, see Fig. 2.26) and the second one for SPPs excitation (level 2, see Fig. 2.27).

1. The frequency stabilization of TA PRO is provided by the Optical Phase Locked Loop (OPPL) technique, which uses the repumper laser as a reference. The TA PRO and repumper beams are combined on a PBS cube and guided to the polarizer. The polarizer changes the ratio between the intensities of the beams (the beams possess orthogonal polarizations). The ultrafast photodiode (Alphas UPD-200-UP) captures the beat signal, which is amplified and send to the phase locked loop (PLL), where the frequency is divided by 32. The relative frequency and the phase of the repumper-TA PRO signal are stabilized to the reference signal, which is provided by external digital generator (Hewlett-Packard 8647A). The reference frequency is 93 MHz. The total detuning, which results from OPPL is $32 \times 93\text{MHz} = 2976\text{ MHz}$. The locking mechanism is reported in details in [106, 107]. The detuning of the TA PRO laser is 9546 MHz (from the transition $5^2S_{1/2} |F = 2\rangle$ to $5^3P_{3/2} |F' = 3\rangle$), which is a sum of the detuning of repumper and OPPL. The high value of the detuning minimizes the incoherent photon scattering, and allows to neglect the excited hyperfine structure, which simplifies the calculations of the dipole potential.
2. The second TA PRO beam is delivered for SPPs excitation (see Fig. 2.27). The power and the polarization of light are controlled by the half-wave plates and PBS cube. The light is guided to the plasmonic grating, which is placed in the vacuum chamber. The angle of incidence is set to be optimal for plasmonic excitation.

Apart from the laser operation, the imaging technique, the SPPs excitation, and the optimized experimental sequence is crucial for ODM experiment.

Fluorescent imaging The fluorescent imaging [108] is an imaging technique, which was used for the detection of rubidium atoms in the experiment. The atoms were excited by the MOT beams shifted in frequency to the atomic resonance. The two-dimensional Gaussian function was fitted to the CCD-image, revealing the number of atoms in the cloud. The temperature of the cloud was calculated with the time of flight method (TOF) [109]. The details of calculations (number of atoms and the temperature) are discussed in [110].

SPPs excitation The SPPs were excited on the gold-coated internal layer of the optical disc (type DVD+R). The disc was cropped to the size of $6 \times 4 \text{ mm}^2$, and glued to a 3 mm high platform (see the inset in Fig. 2.27). The SPPs were generated by TA PRO laser beam with a Gaussian radius of 1.3 mm and laser power of 30-120 mW. The beam was directed at an angle of 1.5° , which results in most efficient plasmonic coupling. The thermoplasmonic effects (discussed in sec. 2.4) were taken into account. The possible damages were limited by the quasi-pulsed operation of TA PRO light.

Software The experiment was controlled by *National Instruments* computer, with two PXIe 6259 cards controlled by LabVIEW software. The steering program *sterBEC* was written by Dr. Dobrosława Bartoszek-Bober [105]. The ODM experimental sequence is divided into five stages. Each stage is divided into specific columns, with the option of setting the respective parameters, e.g. the value of the voltage or current, which is applied to the apparatus. For each process, the 64 TTL and 8 analogue signals are generated, either as a constant value, or a ramp signal, if needed. The experimental sequence (not described here) was optimized during the experiment, to obtain a large number of cold atoms. Figure 2.28 presents the controlling and action panels of *sterBEC* program.

2.5.2. ODM for cold rubidium atoms

A typical experimental sequence of ODM consists of the following stages:

- Six seconds of loading the MOT with rubidium atoms. Typically 3×10^6 atoms are collected.
- The cloud is trapped 5 mm above the plasmonic grating with the typical temperature of $30 \text{ } \mu\text{K}$. The atoms are prepared in $F=2$ ground hyperfine state (the repumper beam is on for the whole sequence).
- The atoms are released from the MOT and fall under gravity towards the ODM for 32 ms on average.
- As the atoms approach the surface, the TA PRO laser is switched on for 11 ms. The TM polarized light excites SPPs, which generate the repulsive potential for cold atoms. The short pulse of light reduces the dramatic temperature increase and prevents the damage of the disc, as well as limits the radiation pressure force acting on atoms.
- The cloud of atoms is reflected from the surface of the mirror and imaged after the reflection off the structure. The fluorescent imaging technique is applied to detect the cloud of atoms. The images are taken 0.2 - 20 ms after the reflection. The imaging time is 1 ms.
- Each measurement is repeated 40 times in a row. The final result is averaged over the 40 experimental runs.

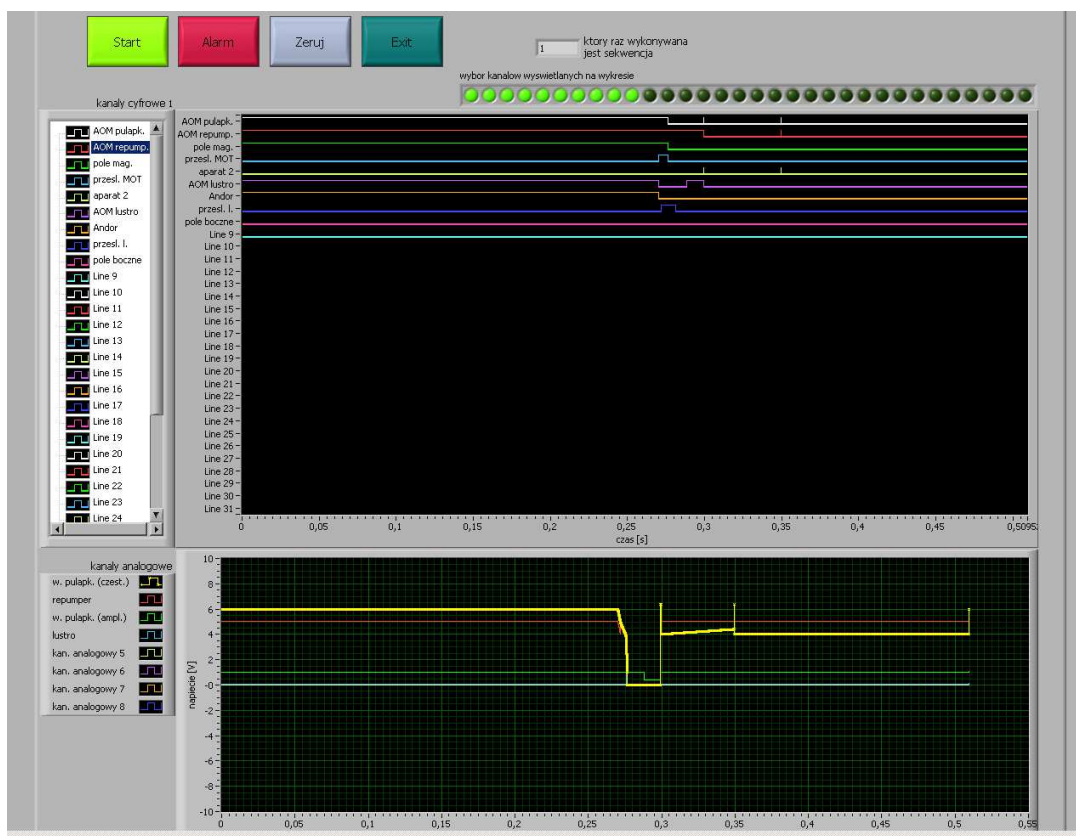
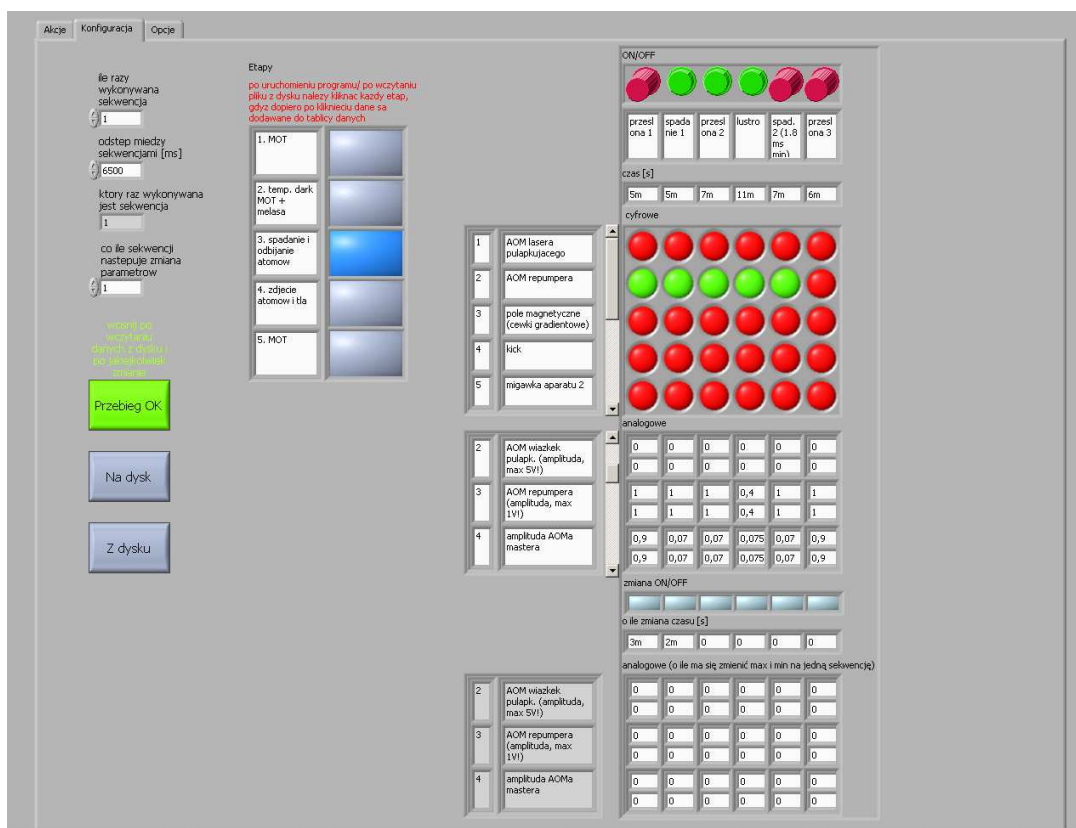


Figure 2.28: The screenshot of the controlling panel (up) and the action panel (bottom) of *sterBEC* program.

- The area of the ODM is determined by the diameter of the laser beam (Gaussian beam diameter is 2.58 mm). However, the horizontal size of the atom cloud is significantly larger than the size of the ODM. The atoms, which fall outside the area of mirror, form the undesired background. To remove the background, the measurements for the TE polarized light are taken, and subtracted from the respective TM image.

During the experiment, the rubidium adsorption on the grating surface was observed. The contamination of the surface significantly deteriorates the quality of plasmonic coupling. To reduce the rubidium adsorption, the 280 ms pulses of 1300 mW per cm^2 were employed (see Fig. 2.24). The technique significantly improves the plasmonic resonance: the efficiency of plasmonic coupling increased from 70% up to 84%.

The ODM results are supplemented with numerical simulations, described in the next paragraphs. The calculations take into account the initial position of atoms, velocity spread of atoms, the imaging geometry, time sequence, and the distribution of electromagnetic field based on RCWA simulations. Figure 2.29 presents the reflection of the atom cloud, imaged 1-5 ms after the bounce. Based on the recorded fluorescent images, the detailed analysis of atom distribution and the influence of laser power on ODM are presented below.

Atom distribution In the vicinity of the plasmonic structure, the atoms experience the gravity force, the repulsive dipole force, and the attractive van der Waals force. The simulations concerning the van der Waals attraction and atom distribution were performed by Dr. Roman Panaś (see [110] for details).

Figure 2.30a presents the calculated 1D cut of the total potential, which is seen by atoms, revealing the gain of 90 between the intensity of the excitation beam and the intensity of SPPs. The distribution of atoms, which is measured 17 ms after the bounce, is compared with the numerical simulations in Fig. 2.30b. The calculated atomic distribution matches the data obtained by fluorescent imaging. The agreement concerns both, the position and the overall shape of the distribution. The consistent results prove the numerically calculated intensity of SPPs, reaching 90 times the intensity of the excitation laser beam.

Fraction of reflected atoms versus the laser power In 1996 Landragin shown that the fraction of the reflected atoms grows exponentially with the increasing laser power, for the mirrors of a Gaussian-type intensity profile [111]. Figure 2.31 shows the fraction η of the reflected atoms, normalized to the number of the falling ones, versus power of light. The η is calculated for 25, 30 and 35 μK of MOT temperature due to the difficulty in its precise determination. The numerical simulations are marked with solid lines in the figure. The grey area between the red and the blue lines denotes the most probable numerical results. The experimentally determined value of η is represented by crosses. According to [111], η grows linearly on semi-logarithmic scale of laser power. Indeed, the dependency is linear for a certain range of powers. For lower intensities, the initial conditions (the size and the non-zero temperature of MOT) come into play and cause a smooth decrease to $\eta = 0$, due to the spread of mechanical energy of the atoms. The fraction of the reflected atoms strongly depends on the size of the MOT, which determines the number of atoms, which have a potential chance to be reflected. Likewise, the results are dependent on the temperature of the atom cloud. The cloud spreads faster for the higher temperatures, providing less atoms, which hit the active part of the ODM. The total measured fraction of the reflected atoms is 1-4%, depending on the laser power. Due to the differences between the size of the atom cloud and ODM, only a few percent of atoms can be reflected. Amongst them, almost each atom is reflected, and the mirror efficiency is estimated to be 100%.

The correspondence between the experimentally measured η and the simulations proves the correctness of the calculation model. This applies to all the calculations, which are presented in

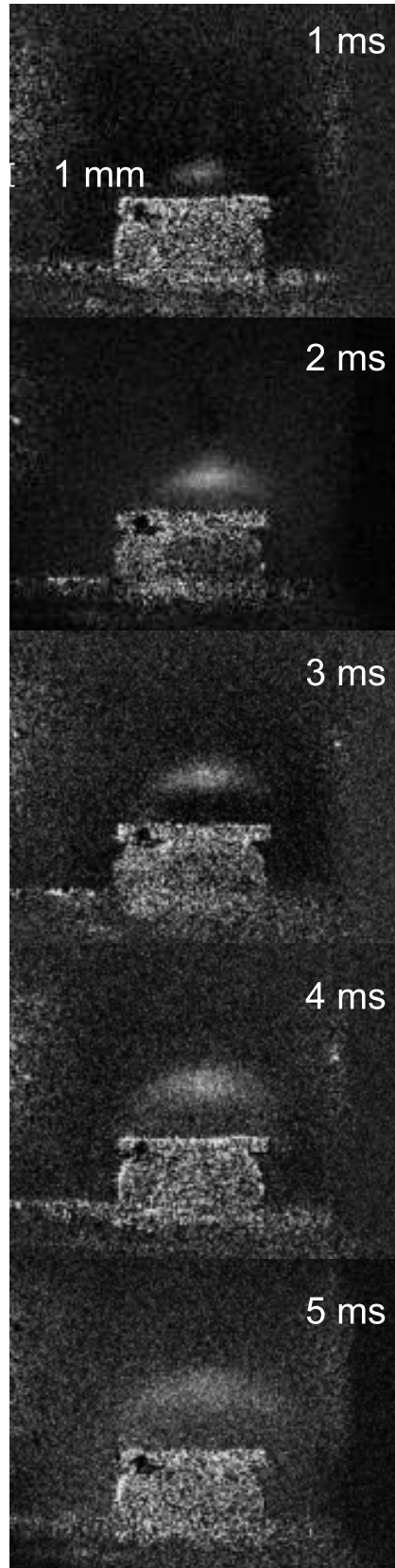


Figure 2.29: The reflection from the ODM of rubidium atoms after 1-5 ms after the reflection, as indicated in the respective pictures. The CCD integration time was 1 ms. Each image is averaged over 40 experimental runs.

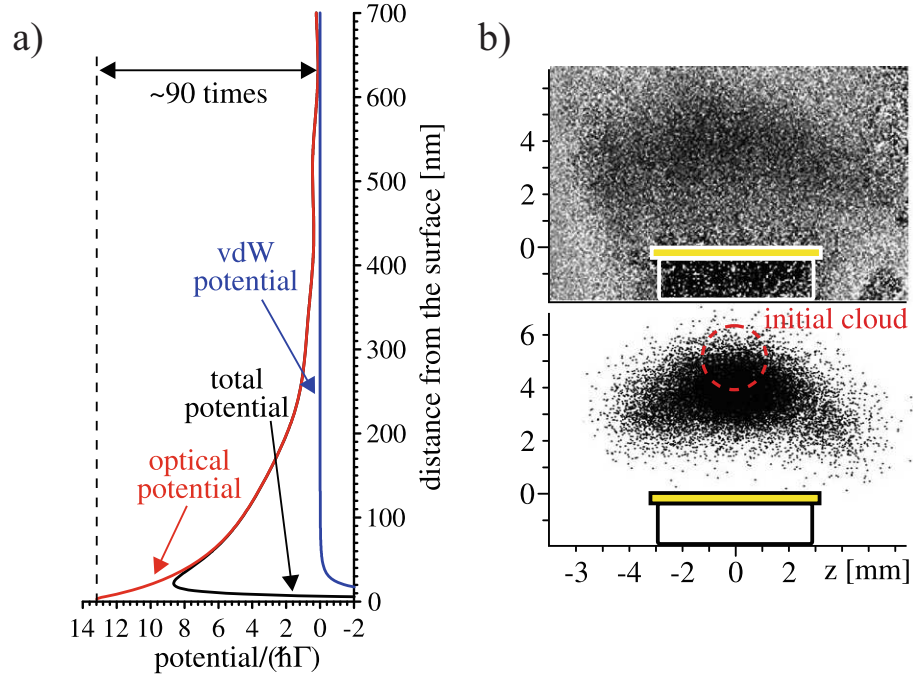


Figure 2.30: a) 1D cut of the total potential above the grating structure. b) The CCD image (top) and numerical calculations (bottom) of the reflected cloud. The images show 10^5 of atoms, 17 ms after the bounce. The position of the grating is marked with the white and the black lines. The initial size of the atom cloud is shown with red, dotted circle. The figure is taken from [75].

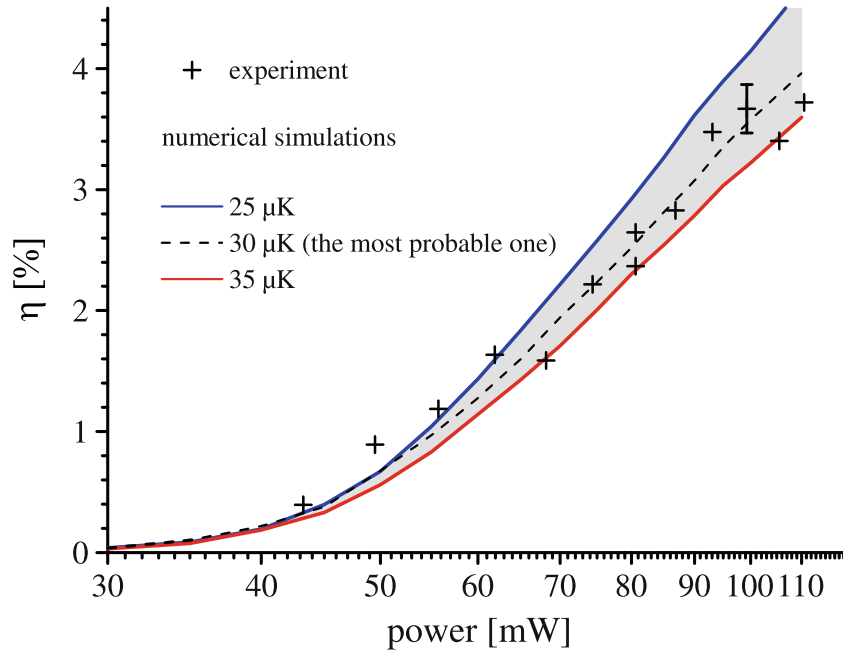


Figure 2.31: Fraction η of the initial atom cloud, which is reflected from the surface of the mirror, for different laser power and temperature of the MOT. A typical experimental uncertainty for the reflectivity is shown at 100 mW. Note the logarithmic horizontal scale. The figure is taken from [75].

Sec. 2.3.1, including the respective distributions of electromagnetic field, and indirectly proves the intensity of SPPs reaching 220 times the intensity of the excitation beam.

Chapter 3

Transmissive structures.

3.1. Introduction

In this chapter, the near fields associated with SPPs excitation on a transmissive structure are discussed. The transmissive structures have been widely employed in a broad range of experiments, including OLED light outcoupling of plasmonic cavity with subwavelength hole-array [112] and plasmonic nanoresonators for high resolution color filtering [113]. Besides it, the transmissive grating is a promising tool for the construction of ultrasensitive plasmonic sensors [11], biosensors and nanofabricated atomic devices [15, 19, 75, 84]. Likewise, the structure enables the direct observation of SPPs via scanning near-field optical microscopy (NSOM) [114, 115, 116, 117, 118, 60, 119].

The main difference between transmissive and reflective gratings is the way the structure is illuminated. In a transmissive grating the light passes through the structure, whereas for reflective grating, the light is reflected by the grating surface. For the transmissive structure, it is possible to generate the SPP on both, glass-gold and gold-air boundaries. The latter is advantageous for cold atom experiments and NSOM imaging. For the atomic mirrors based on the reflective grating, the presence of excitation light on the gold-air side leads to unwanted atom-photon scattering. Likewise, it would be detected by the probe, disturbing the direct NSOM characterisation of electromagnetic field, which is generated by SPPs. The detailed knowledge of the field distribution is crucial for a design and fabrication of plasmonic sensors [5, 11], detectors, photovoltaics, plasmon-based circuits [120], nanomanipulators [121, 122], electrooptic plasmonic modulators [123] and atomic devices [124, 15, 19, 75, 84].

The chapter presents the full description of the transmissive structure and of the SPPs associated near field. The parameters of the grating were numerically optimized with RCWA method for near-infrared light. On this basis, the nanofabrication process was performed with the FIB technique, followed by SEM examination. The plasmonic resonance of the structure was tested with goniometric far field measurements. The direct measurements of the intensity of SPPs were performed with NSOM and compared with FDTD simulations, providing the fully quantitative description. The numerical calculations took into account the exact size of the grating and the surface corrugation. The processes of build up and propagation of SPPs were observed with NSOM technique, as well as the respective components of the electric field were analyzed in detail.

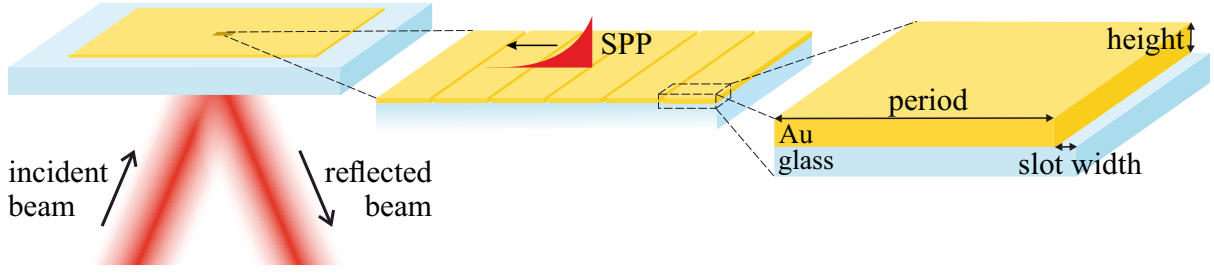


Figure 3.1: Scheme of the modelled, gold transmissive grating, with one grating period magnified, used for numerical optimization.

3.2. Preparation of the structure

3.2.1. Optimization

To maximize the efficiency of plasmonic coupling, the parameters of the structure have been optimized with RCWA method, with particular emphasis on narrow-width slots, as proposed in [125]. The modelled grating geometry is presented in Fig. 3.1. The optimized structure consists of gold, rectangular ridges, separated by slots of the width s . The grating period is d , and grating height is h . The aim of the calculations was to maximize the efficiency of the excitation process for near-infrared light and further application in a plasmonic sensor and/or atomic mirror. The main requirements are the following:

- a narrow and deep plasmonic resonance,
- a strong electromagnetic field enhancement,
- the grating period smaller than 780 nm, to avoid the dispersion of light into diffraction orders other than the zeroth one.

Due to the technically demanding process, the final parameters should be determined so that the production error of a few nm barely affects the plasmonic coupling. The calculations were performed for 780 nm laser light and the following range of scanned parameters: grating periods of 400-760 nm, slot widths of 30-140 nm, and grating heights of 20-80 nm. The periodic boundary conditions, which are imposed by the method, make the grating to be virtually an *infinite* structure. The optimization involved two types of calculated quantities: the reflectivity coefficient R , and the electromagnetic field intensity I/I_0 , where I_0 is the intensity of the incident light. The more detailed calculations are presented in [105].

The most effective plasmonic coupling is obtained for grating period equal to 550 nm. Figure 3.2 presents the reflectivity map and the plasmonic resonances obtained for the optimal grating period. The reflectivity coefficient is minimized for slot widths of the range 100-140 nm and grating heights of 40 nm and up, reaching $R = 0.02 - 0.04\%$. However, for 100-140 nm wide slots, the shape and the width of plasmonic resonances are much below expectations, preventing the application in ultrasensitive plasmonic sensors. The respective intensity of SPPs is shown in Fig. 3.3, for the same range of parameters. The strongest intensities are obtained for 55-65 nm of grating height and 30-40 nm of slot width, reaching 60 times the intensity of the excitation beam.

Finally, 550 nm of the grating period, 55 nm of the grating height and 40 nm of slot width have been accepted for the fabrication. Figure 3.4 presents the electromagnetic field distribution calculated for the optimal set of parameters, for one grating period, performed by FDTD method

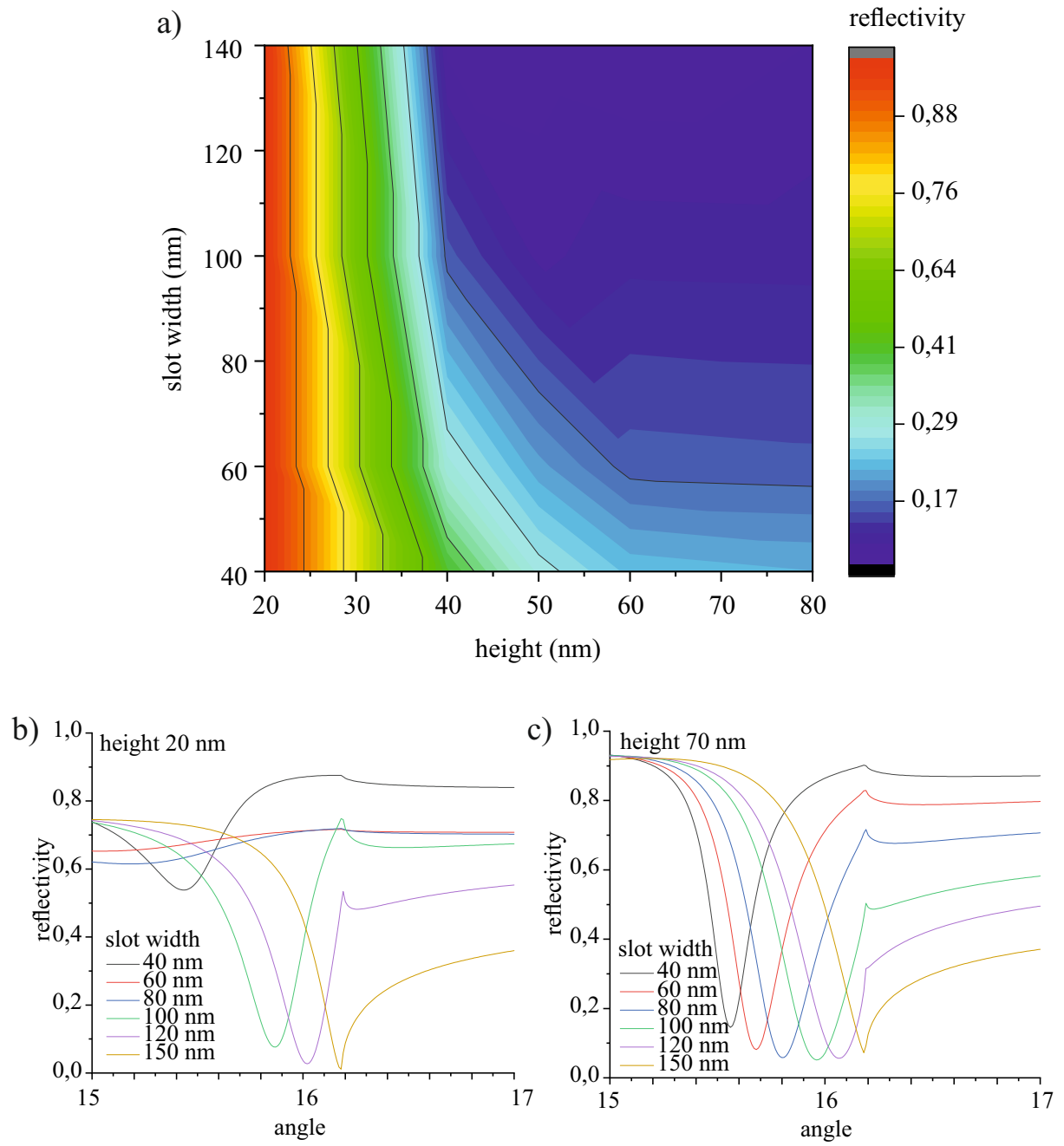


Figure 3.2: Optimization performed by RCWA method for the grating of 550 nm period and various slot widths and grating heights. a) Reflectivity map and the plasmonic resonances calculated for grating heights of b) 20 and c) 70 nm.

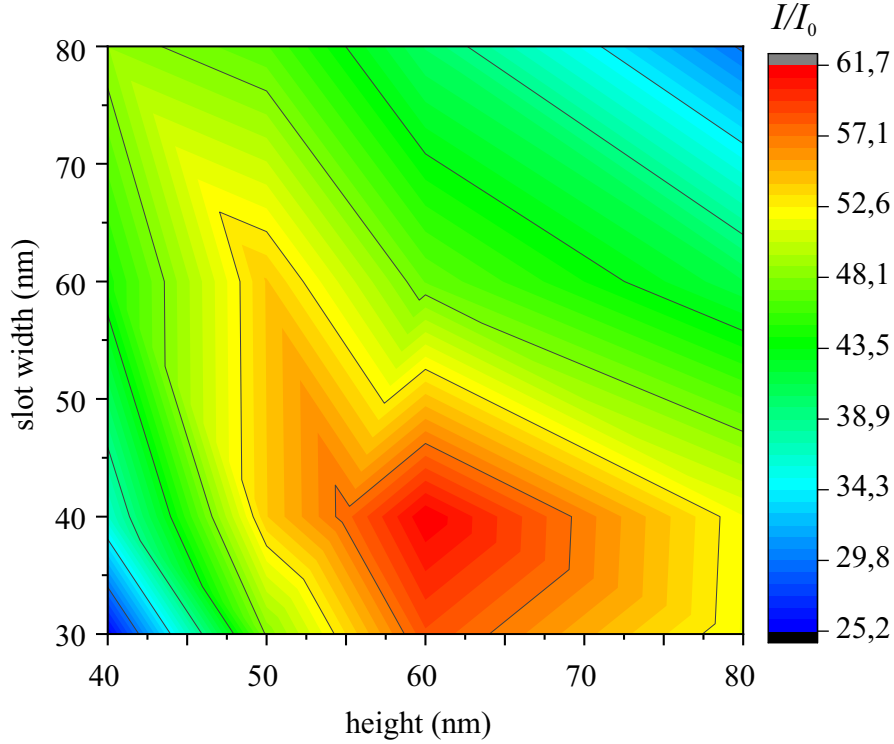


Figure 3.3: Optimization performed by RCWA method for the grating of 550 nm period and various slot widths and grating heights: intensity map of SPPs I/I_0 , where I_0 is the intensity of the incident light.

with a high accuracy. The grating structure is marked with dashed, white rectangle. The exciting beam comes from the bottom side of the figure, whereas the SPPs are excited above the gold surface (see Fig. 3.1 for the geometry). The electromagnetic field distribution reveals the exponential decay of the amplitude of the electric field, with an increasing distance from the surface. The regions of the highest intensity are located in the middle of the gold ridge and in the vicinity of sharp edges of the structure. The lowest enhancement is expected to be in the groove area. The highest enhancement reaches more than 100 times the intensity of the exciting light. The significant difference between this value, and the value taken from the intensity map in Fig. 3.3 (RCWA simulations) is caused by the higher resolution and better accuracy, which were used for FDTD simulations.

3.2.2. Nanofabrication

The structure was nanofabricated by Focused Ion Beam (FIB) milling technique on a gold-glass substrate. The preparation was a two-stage process of the substrate preparation, followed by FIB nanopatterning.

Glass-gold substrate The glass-gold substrate consists of $1 \times 15 \times 15$ mm glass substrate and 55 nm thick gold layer, which was evaporated by electron beam deposition, supported by 3 nm of titanium adhesion layer. The glass-gold substrates was prepared with UV lithography by Dr. Jacek Fiutowski, from University of Southern Denmark. The process is briefly described in the following steps.

1. The glass substrate is cleaned in order to remove any contaminations from the surface.

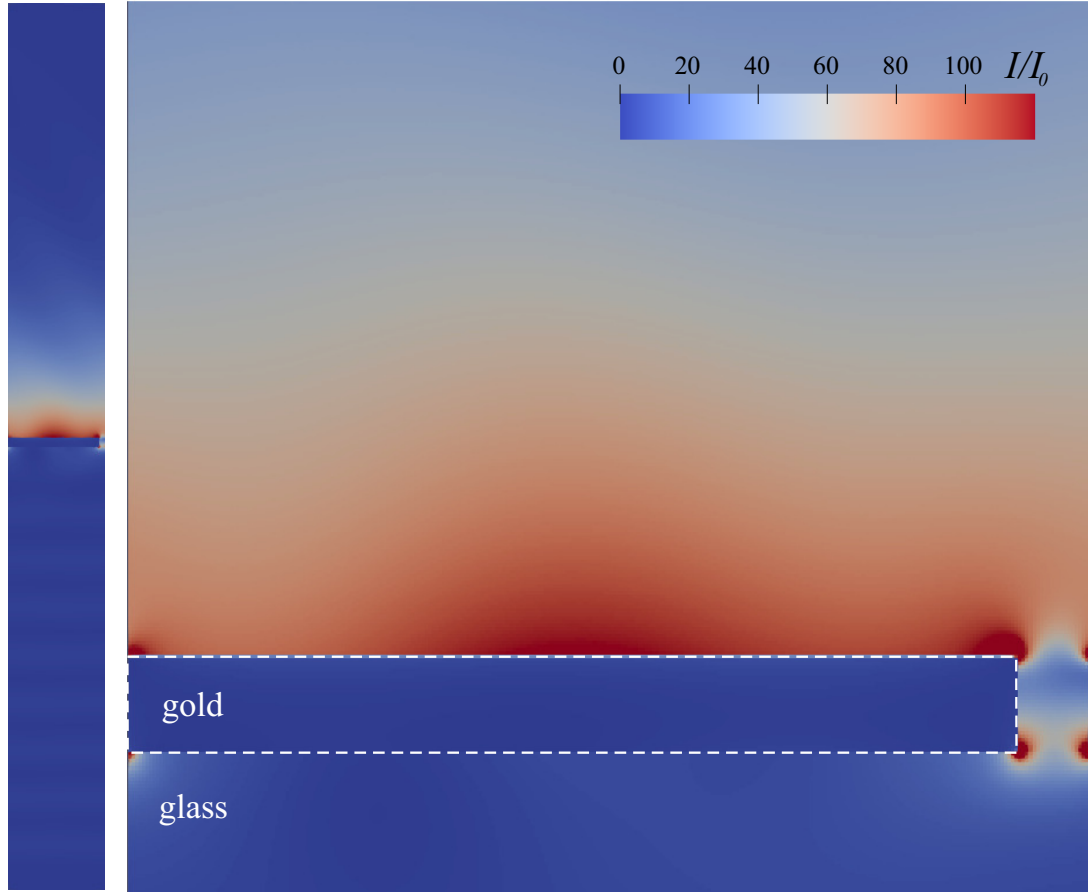


Figure 3.4: FDTD calculations of the electromagnetic field distribution of gold transmissive grating: simulated distribution I/I_0 , where I_0 is the intensity of the incident laser beam, for 780 nm laser light, TM polarized. The grating structure is marked with white, dotted line, of 550 nm of period, 55 nm of grating height and 40 nm of slot width.

2. The clean surface is covered with photoresist material by spin coating method, leaving a flat layer of the resist.
3. The photomask, which blocks light in some areas and passes in others, is placed onto the photoresist. The mask is a $1\text{ mm} \times 1\text{ mm}$ opaque square.
4. The photomask is illuminated with the UV light. As a result, the whole photoresist is exposed to UV light, except the black square.
5. The structure (glass+photoresist) is placed in the chemical solution of the developer. The part of the photoresist, which was not exposed to UV, is removed,¹ producing $1\text{ mm} \times 1\text{ mm}$ square in the middle of the photoresist.
6. The structure is covered with 3 nm titanium adhesion layer, followed by the evaporation of 55 nm of gold.
7. The remaining photoresist is removed with acetone, leaving the titanium/gold square in the middle of the glass substrate.

Grating structure The transmissive structure was nanofabricated with FIB milling technique by Dr. Benedykt R. Jany from the Department of Solid State Physics, Jagiellonian University in Krakow. The Dual Beam SEM/FIB Quanta 3D FEG microscope by FEI (USA) used gallium ions of 30 keV energy to mill the 38 nm wide grooves, continuously repeated every 550 nm, on the area of $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$. The electron fluid gun charge neutralizer was used to prevent charging of the sample during FIB nanopatterning. Directly after the process of milling, the structure was imaged with Scanning Electron Microscope (SEM) at 5 keV energy in the same apparatus. Figure 3.5 presents SEM images of the grating. The detailed SEM analysis of Fig. 3.5a revealed the 550 nm of grating period and 38 nm of slot width. The SEM micrograph in Fig. 3.5b shows the magnified gold surface of the transmissive grating. The magnification exposed the presence of grains of a spherical like shapes, which cover the gold surface. The radius of the grain is estimated to be less than 15 nm and the height is up to 6 nm. The modification of the flat surface is significant and will be included in the further numerical simulations.

3.3. Numerical simulations of plasmonic excitation

The numerical simulations are crucial for the design and fabrication of plasmonic sensors and structured plasmonic potentials for atoms. The direct observation of SPPs via near field microscopy, together with the correct numerical model provide the fully quantitative description of near fields, necessary for the construction of many plasmonic devices. To perform a comparison between the numerical calculations and the near field observation, many factors are taken into account for the calculations. The model, which is presented in sec. 3.2.1, consists of the rectangular, gold ridge of a perfectly flat surface. In this section, the calculated model is extended by the following factors:

- roughness of the surface,
- rounded edges of the ridges,
- finite size of the grating, which is surrounded by flat, gold surface.

¹This kind of photoresist is known as the *negative* type of the photoresist. The *positive* photoresist is soluble in the area, which was exposed to UV.

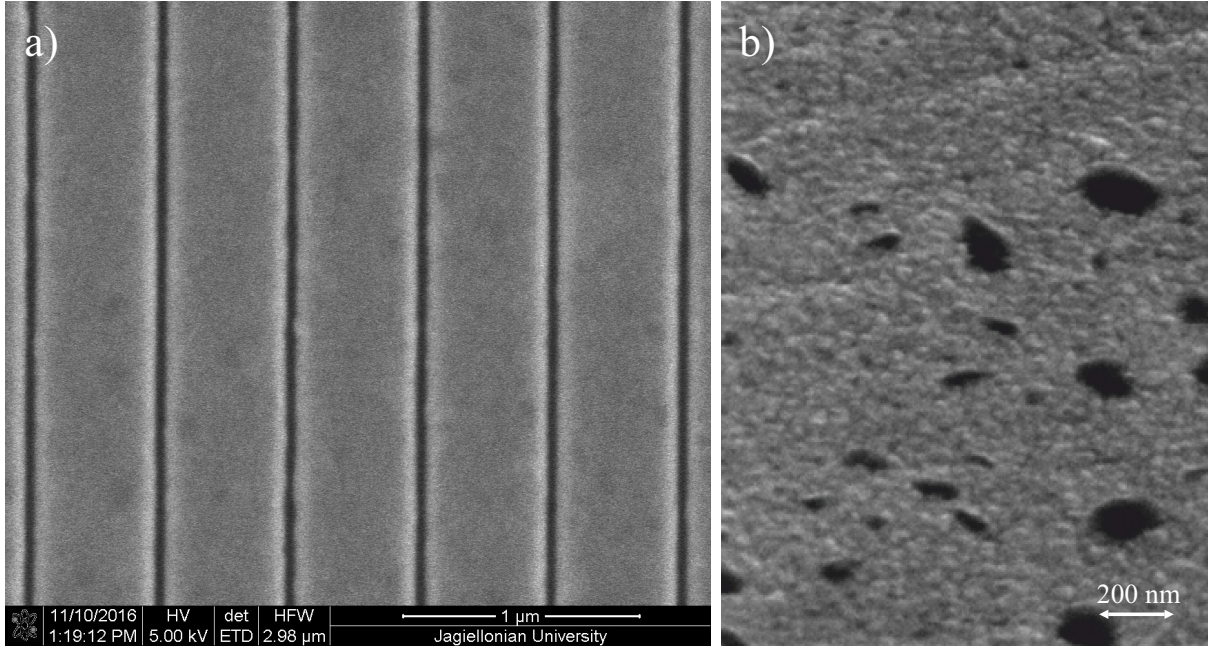


Figure 3.5: SEM images taken during nanopatterning by Dr. Benedykt Jany. a) The micrograph of 5 grating periods, and b) the detailed view on corrugation of the surface.

The near field distributions and plasmonic resonances were calculated by FDTD. The TM-polarized light of 780 nm and the grating parameters of 550 nm of grating period, 55 nm of grating height, and 40 nm of slot width were implemented in all calculations discussed in this section. Note, that the calculations impose periodic boundary conditions, making the modelled structure to be virtually an *infinite* structure. The numerical calculations of the transmissive structures were time consuming, taking from a few hours up to few days.

3.3.1. Roughness of the surface

The *roughness of the surface* refers to the presence of grains, which were observed under SEM investigation. The *roughness* is taken into account by modifying the numerical model of the grating. The basic model of the structure is presented in Fig. 3.1, consisting of a perfectly flat cuboid. The modification involves the implementation of additional gold forms, which imitate the grains. The size of the irregularities matches the outcome from SEM analysis, indicating the maximum height as 6 nm and maximum diameter as 14 nm. The distribution of the roughness is randomly generated by Wolfram Mathematica (RandomReal function). The grains cover the entire surface of the structure, both the ridges and the grooves. The later corresponds to the presence of residual gold at the bottom of the groove.

The size of the roughness The influence of the size of the roughness on a plasmonic resonance was calculated for seven numerical models. The models differ in size of the irregularities, imposed by the maximum height and length of the grain. The range of the respective dimensions are gathered in Table 3.1. The maximum height is marked with "h", reaching 1, 3, or 5 nm. The maximum length of 5 or 10 nm is marked with "l". For example, the numerical model h5nm_l10nm corresponds to the transmissive grating, which is covered with the grains of different sizes, not exceeding 5 nm in height and 10 nm in length. The model h0nm_l1nm serves as a reference, corresponding to the basic cuboid grating (no irregularities). The respec-

Name	Maximum height of the grain	Maximum length of the grain
h0nml1nm	0 nm	1 nm
h1nml5nm	1 nm	5 nm
h1nml10nm	1 nm	10 nm
h3nml5nm	3 nm	5 nm
h3nml10nm	3 nm	10 nm
h5nml5nm	5 nm	5 nm
h5nml10nm	5 nm	10 nm

Table 3.1: The parameters used in the calculations involving surface corrugations: maximum height of the grain is marked with "h", and its maximum length is marked with "l".

tive numerical models of the grating profile is presented in figure 3.6. The distribution of the irregularities is random.

The plasmonic resonance and intensity distribution have been calculated for each numerical model, to determine the influence of the size of the roughness on plasmonic coupling. Numerical calculations are time-consuming and require large computing power. For these reasons, the primary calculations were performed with the resolution of 10 nm, followed by the calculations with accuracy of 1-2 nm in the vicinity of the resonance. Figure 3.7 presents the calculations of the reflectivity coefficient R , performed at different angles of incidence of the excitation beam. The minimum located around 5° corresponds to the SPPs excited on the glass-gold boundary. The second one, located around 15° , results from the SPPs generated on the gold-air interface, which is shown in more detail in the vicinity of the resonance. From now on, only the gold-air excitation is discussed. The efficiency of plasmonic coupling varies from $R=0.23$ to $R=0.53$, depending on the numerical model, and so changes the optimal angle of incidence. As expected, the most effective excitation is observed for the perfectly flat grating h0nm_1nm with the lowest R equal to 0.23. Surprisingly, the second lowest R is observed for the structure h5nm_10nm, corresponding to the most corrugated surface. Then, the lowest reflectivity coefficient is obtained for the grains of 1 nm of height, followed by the rest of models.

Figures 3.8 and 3.9 present the electromagnetic field distribution, which is calculated for the optimal angle of incidence of the excitation beam. The distribution is shown as a ratio I/I_0 , where I_0 is the intensity of the incident light. Figure 3.8 reveals the detailed distribution in the vicinity of the surface, whereas figure 3.9 presents a more general view. The distribution for a perfectly flat grating is presented in Fig. 3.4. The calculations revealed two separate contributions, which constitute the total intensity distribution. The overall enhancement of the electromagnetic field, which is also observed for the perfectly flat grating, comes from the excitation of SPPs on a periodic structure. The other contribution is caused by the excitations on grains, resulting in high local field intensity, which is most clearly seen for h5nm_10nm in Fig. 3.8. If the size of the roughness is smaller than the excitation wavelength, it is possible to generate the SPPs on the surface defects [126]. Although the local enhancements generate strong field, the interaction range is limited to a few nanometers, which is far from the region of reflection of atoms in dipole mirrors. Nevertheless, the quality of the surface should be controlled. The distribution of energy into local plasmonic excitation on grains prevents the efficient plasmonic coupling on a grating. This results in a low reflectivity coefficient, but weak electromagnetic field, as observed for numerical model h5nm_10nm.

Figure 3.10 presents the quantitative comparison between the intensities, obtained for the numerical models. The figure shows the cross-section of the intensity profile, which was taken in the middle of the ridge, perpendicularly to the surface. The maximum enhancement varies between 70 and 120, depending on the size of the grains. The highest intensity is observed for

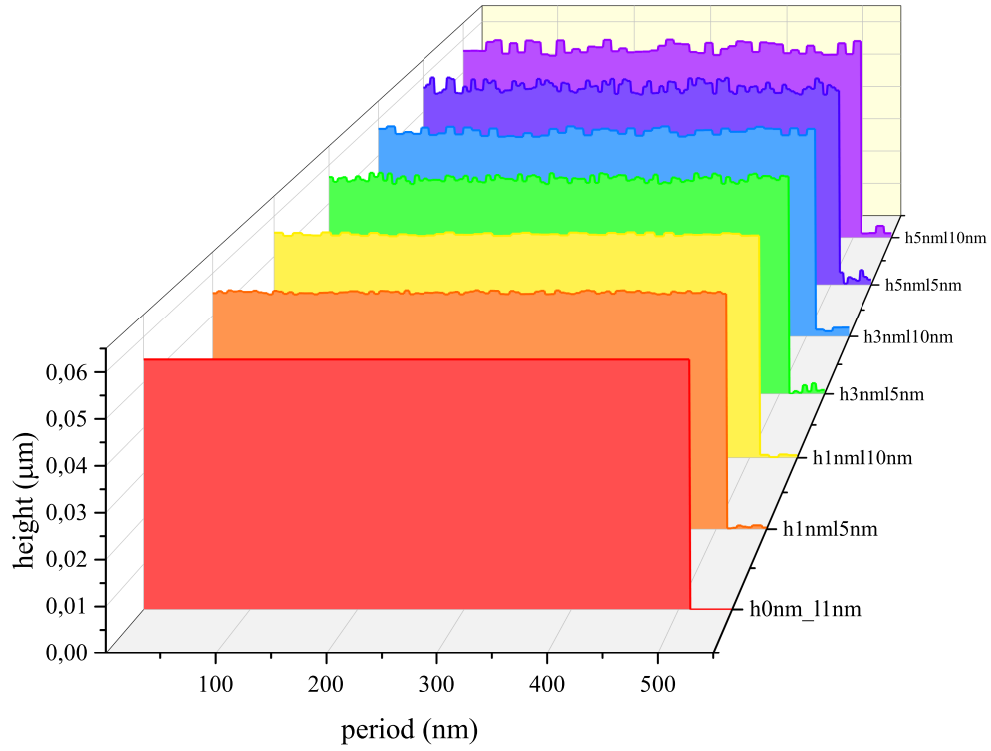


Figure 3.6: Scheme of the modelled, single grating periods, which were used in numerical calculations. The distribution of the irregularities is random. The 'h' and 'l' indicate the maximum height and length of the grain, respectively (see Tab. 3.1 for more details).

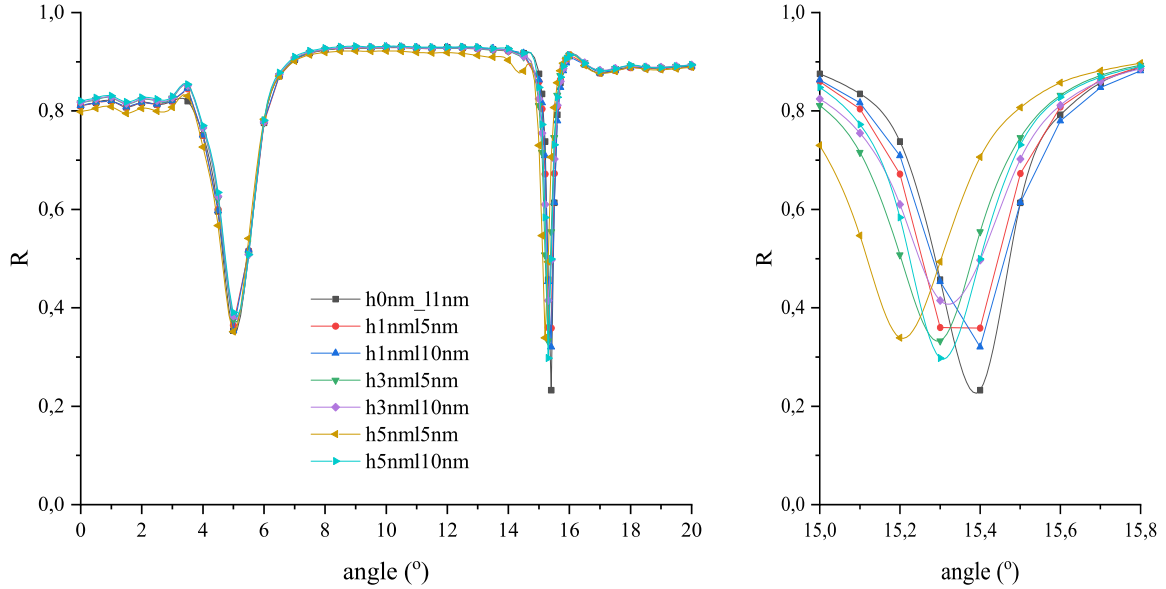


Figure 3.7: The reflectivity coefficient R versus angle of incidence of excitation beam, calculated by FDTD method for different numerical models, which differ in size of the roughness (see Tab. 3.1 for details). The curve is added to guide an eye.

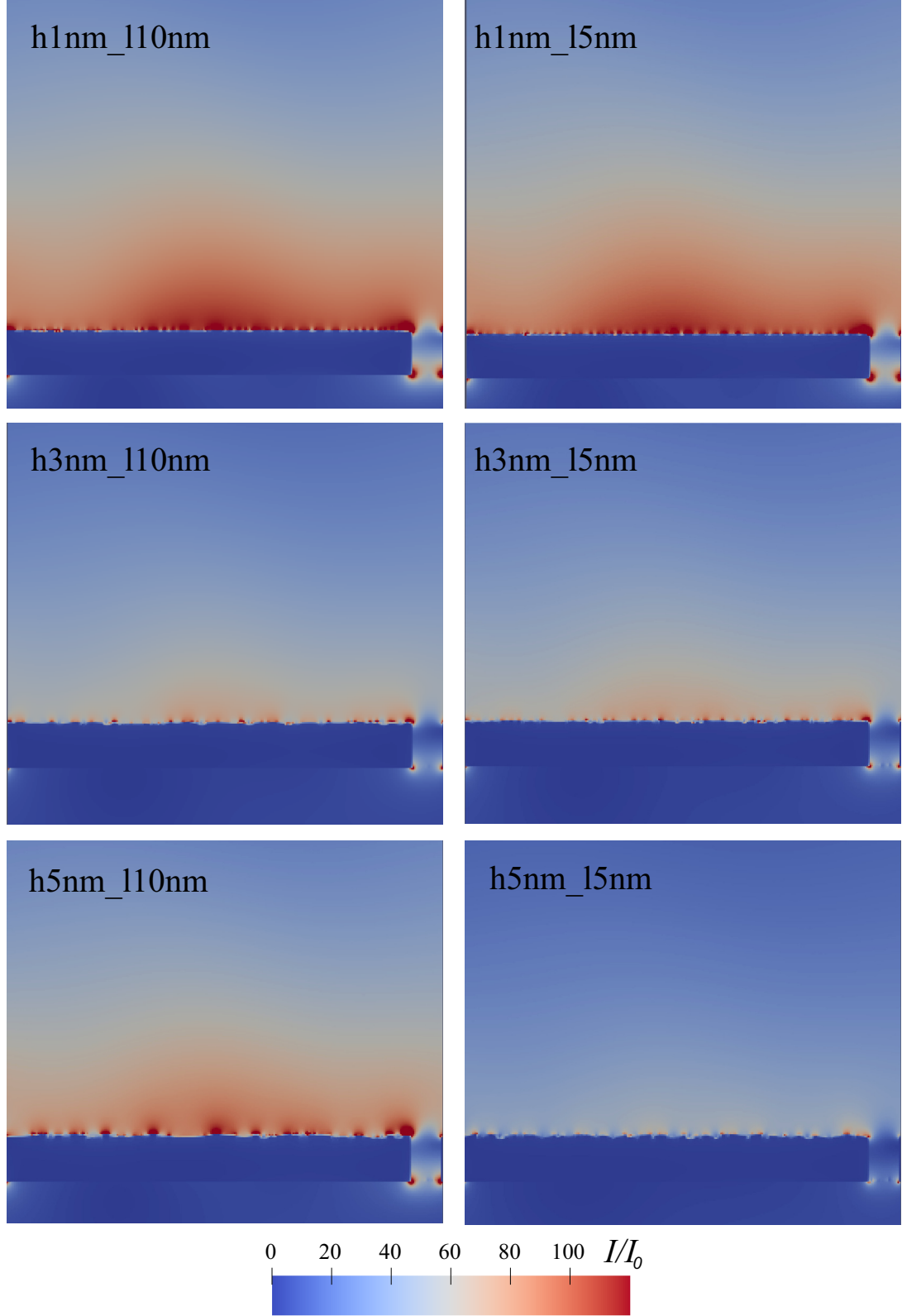


Figure 3.8: FDTD calculations of the I/I_0 electromagnetic field distribution above the grating surface. The simulations are performed for different numerical models (see Tab. 3.1 for details), for optimal angle of incidence of excitation light, of the intensity I_0 . The figure presents one period of the grating.

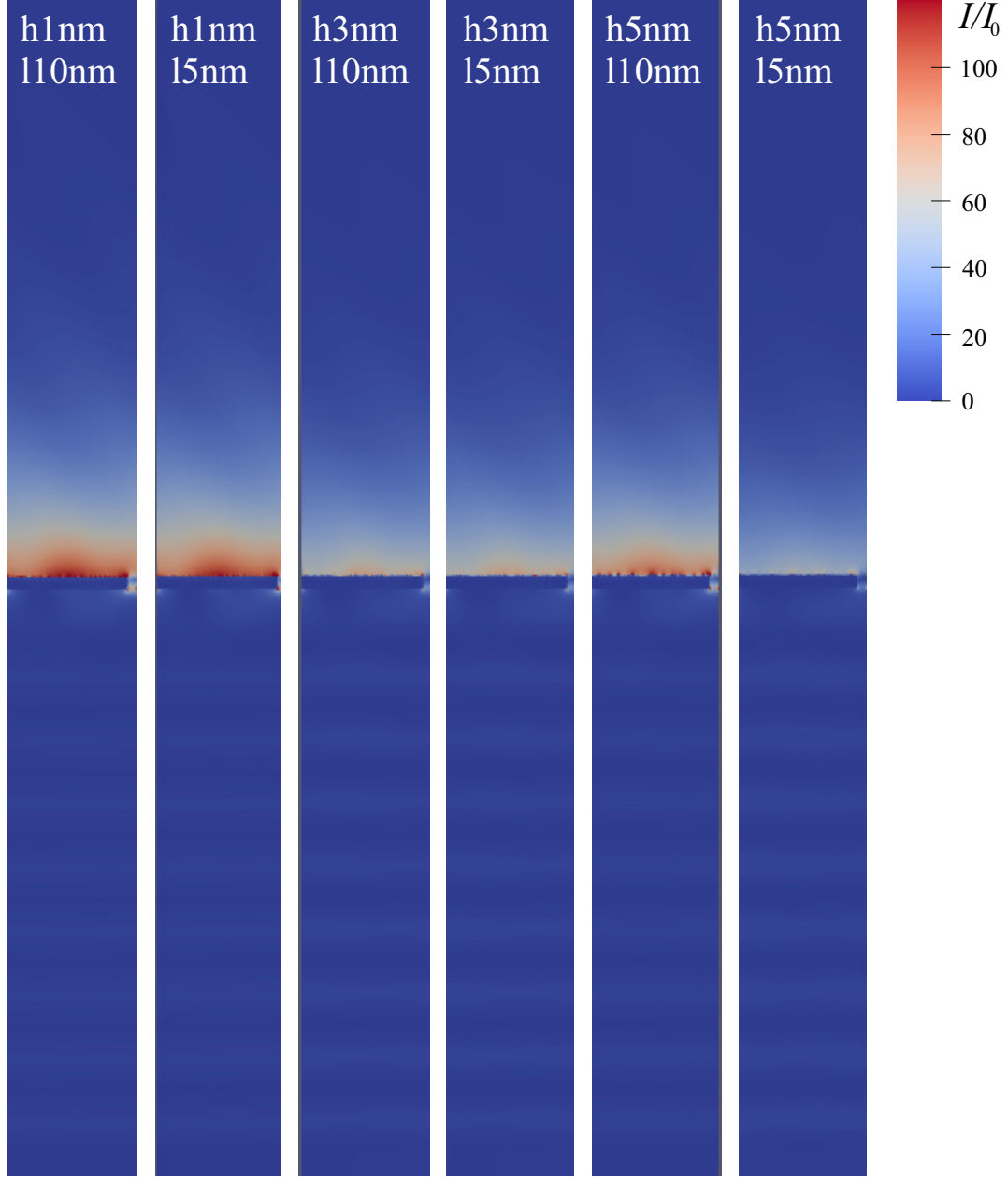


Figure 3.9: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for different numerical models (see Tab. 3.6 for details), for optimal angle of incidence of excitation light. The figure presents one period of the grating.

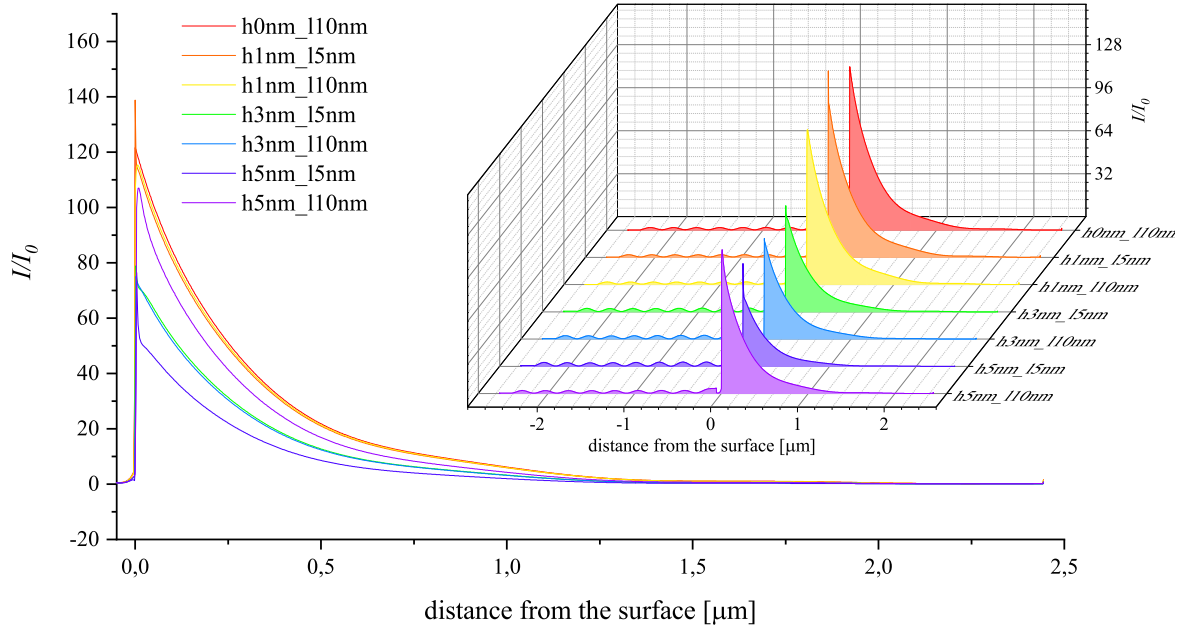


Figure 3.10: FDTD calculations of the I/I_0 electromagnetic field. Cross-section through the field distribution, taken in the middle of the ridge. The simulations are performed for different numerical models (see Tab. 3.1 for detail), for optimal angle of incidence of excitation light.

the least corrugated surfaces, with the height of the grains up to 1 nm. Although the analysis indicates, that the size of the grains determines the quality of plasmonic resonance, the problem is more complex. The comparison between the models of maximum heights of 3 and 5 nm shows that in certain models the stronger field is observed for the more rough surface. The possible explanation is the particular distribution of grain, which is studied in the next paragraph.

The distribution of the roughness The influence of the distribution of the grains is analyzed for seven numerical models, referred to as 'model 1', 'model 2' and so on. Each model is designed with the same maximum height (3 nm) and length (10 nm) of the irregularities. The distribution of the grains was generated by Wolfram Mathematica (RandomReal function). Figure 3.11 presents the modelled profiles of the grating structure.

The plasmonic resonances, which were calculated for each of the models, are shown in Fig. 3.12. The lowest reflectivity coefficient varies between 0.3 and 0.4, showing a smaller spread than previously seen for the calculations, which took into account different sizes of the grains. The intensity of the electromagnetic field I/I_0 is presented in Fig. 3.13 in the vicinity of the grating, and in Fig. 3.14 for the overall distribution, for models 1-6. Model 7 corresponds to the numerical model h3nm_110nm, introduced in the previous paragraph (see Fig. 3.8 and 3.9 for the intensity distribution). The intensity distribution is calculated for the optimal angle of incidence of the excitation beam of the intensity I_0 . The local enhancement associated with grains and the overall gain resulting from plasmonic coupling on a grating are clearly visible. The differences between the intensities, which are observed for the respective models are significant. Figure 3.15 shows the straightforward analysis of the field distribution, presenting the cross-sections of the intensity profile. The cut goes through the middle of the ridge. The maximum enhancement I/I_0 varies between 60-75 for models 1,2,3,5, and between 120-130 for models 4,6,7. Note, that model 6 reaches the gain of 155 according to the graph, however, this

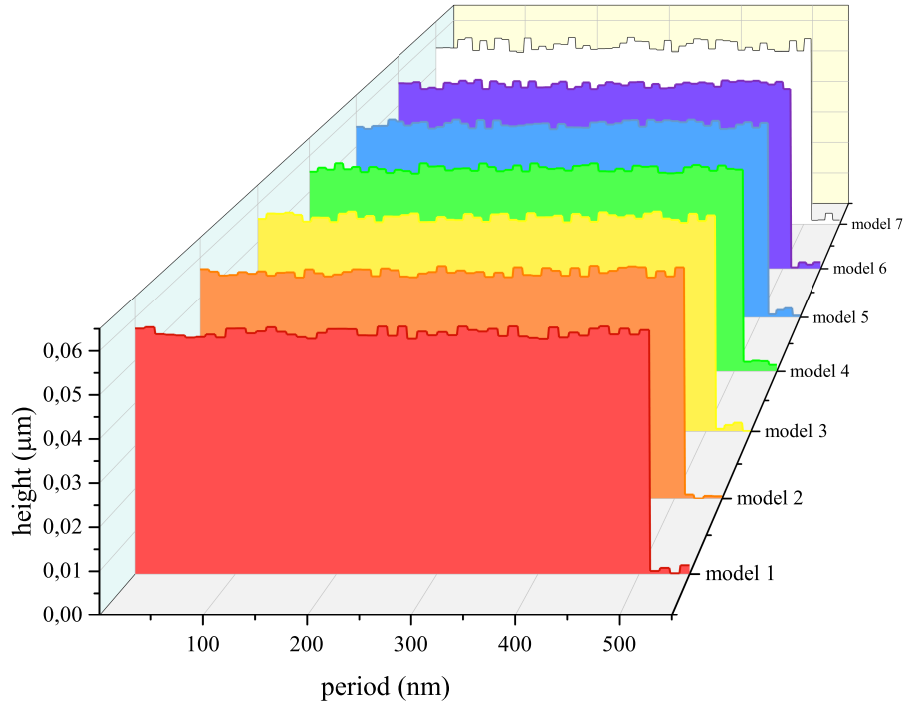


Figure 3.11: Scheme of the modelled, single grating periods, which were used in numerical calculations. The distribution of the irregularities is random, but the maximum height and length are the same.

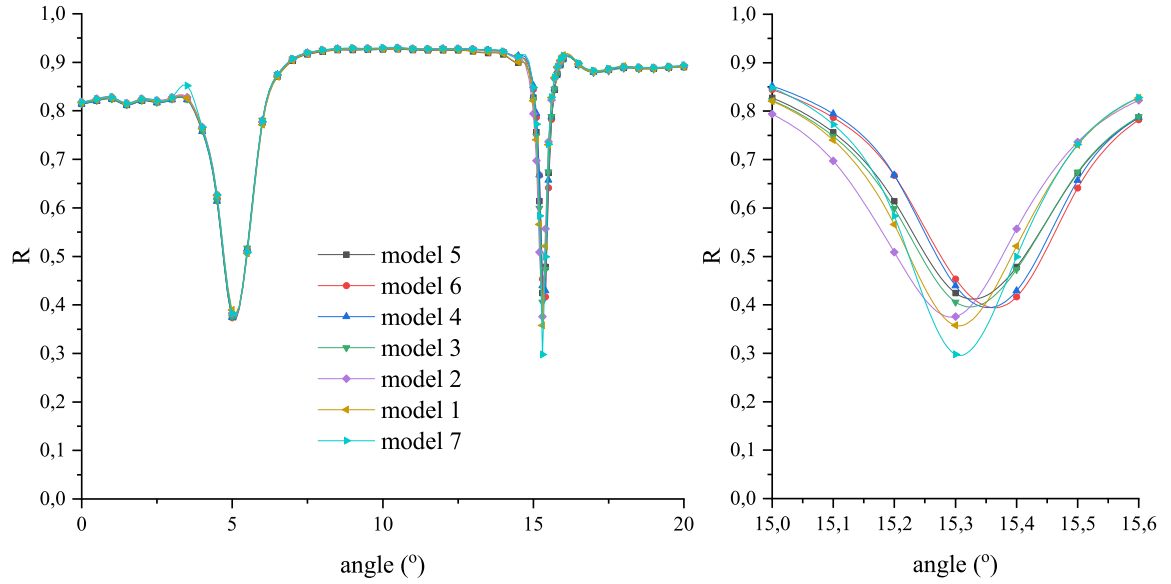


Figure 3.12: The reflectivity coefficient R versus angle of incidence of excitation beam, calculated by FDTD method for different numerical models, which differ in the distribution of the roughness (see Fig. 3.11 for details). The maximum height of the irregularity is 3 nm and the maximum length is 10 nm. The curve is added to guide an eye.

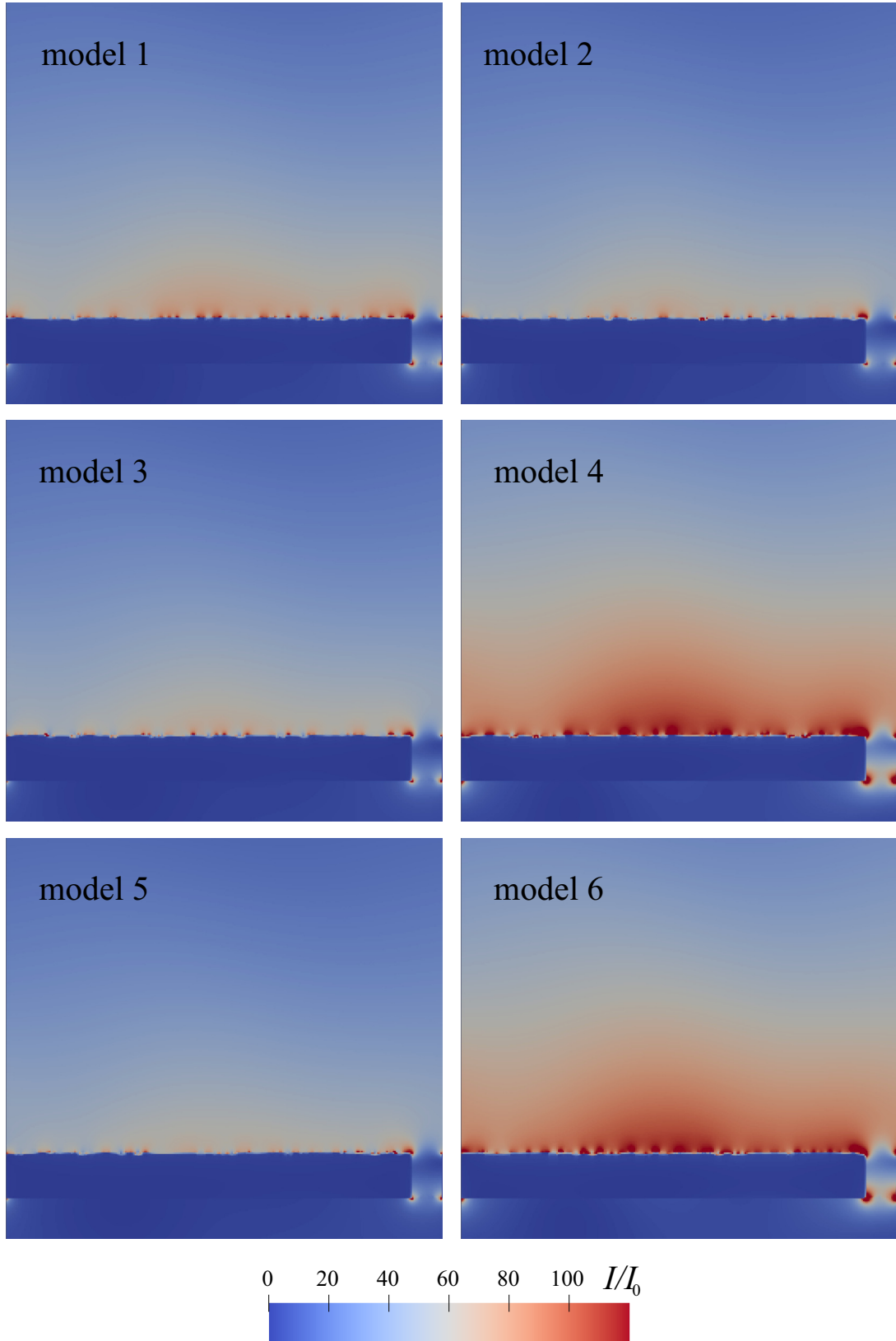


Figure 3.13: FDTD calculations of the I/I_0 electromagnetic field distribution above the grating surface. The simulations are performed for different numerical models (see Fig. 3.11 for details), for optimal angle of incidence of excitation light. The figure presents one period of the grating.

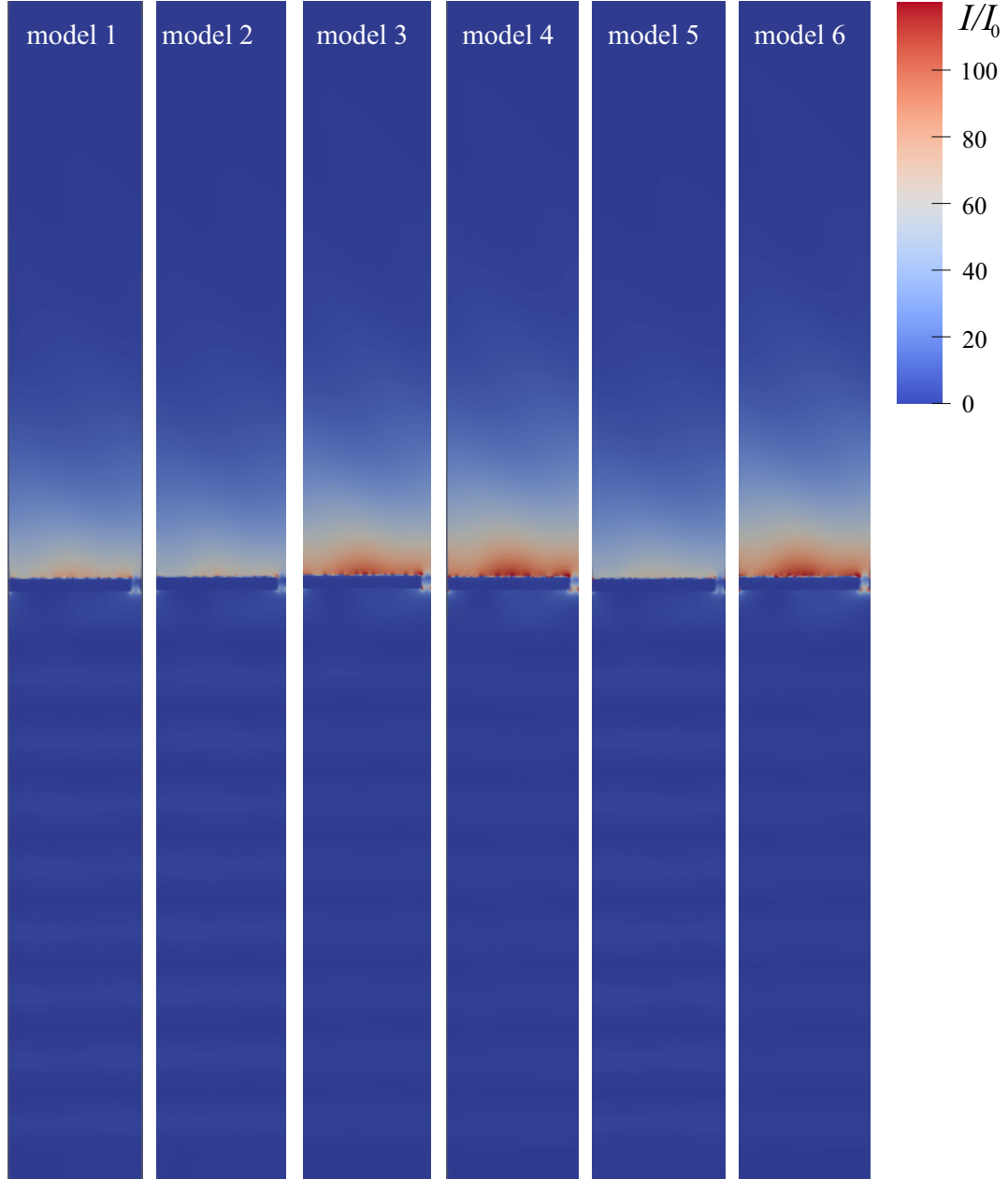


Figure 3.14: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for different numerical models (see Fig. 3.11 for details), for optimal angle of incidence of excitation light. The figure presents one period of the grating.

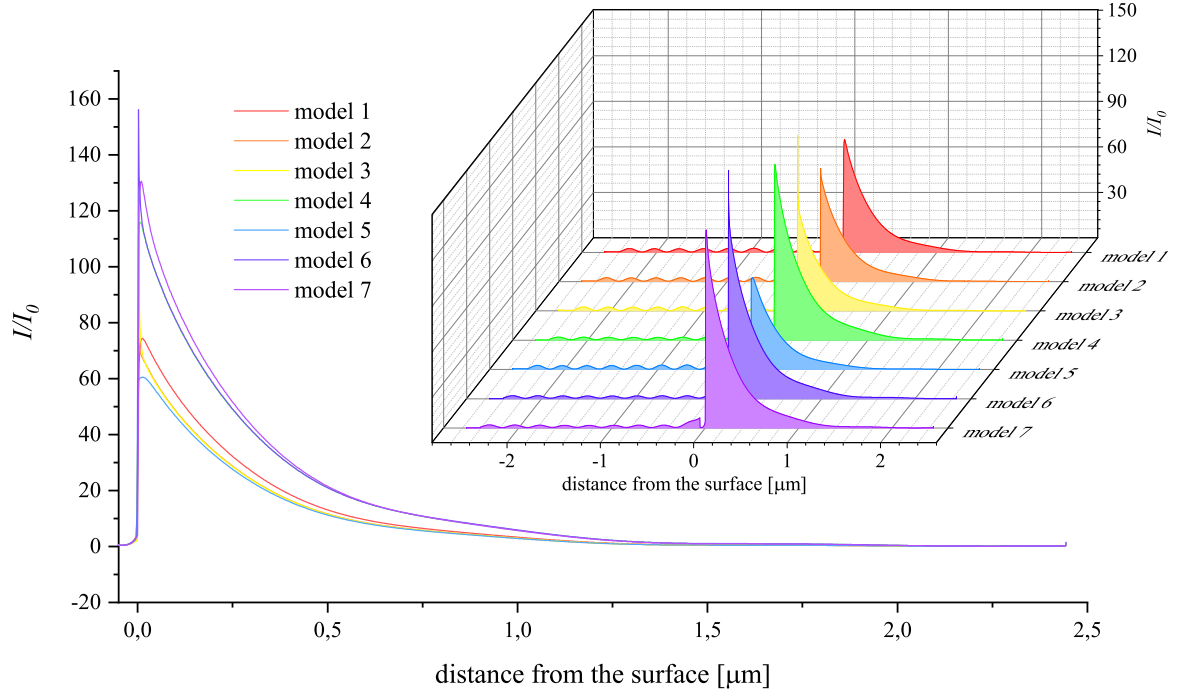


Figure 3.15: FDTD calculations of the I/I_0 electromagnetic field. Cross-section through the field distribution, taken in the middle of the ridge. The simulations are performed for different numerical models (see Fig. 3.11 for details), for optimal angle of incidence.

is due to the local enhancement, which is not included in the comparison.

The significant discrepancies between the intensities of SPPs indicates that the plasmonic coupling is very sensitive to surface roughness. The differences are caused by both, the grains of a different size and various distributions. Based on the calculations, it is impossible to determine which factor is more important. The periodic boundary conditions play a key role for the explanation of the observed differences. Each numerical model of one grating period is repeated infinitely, forming an unrealistic structure with the same profile on each of the ridges. The more plasmon-friendly profile results in a strong enhancement, and the less plasmon-friendly shape shows low intensity of SPPs. In the actual grating, the profiles between the individual ridges differ from each other. This points to the need for more complex calculations of the actual structure, which will be implemented in the numerical model.

For certain, the results indicate the importance of the precise nanofabrication of the transmissive grating. A gold substrate of a high quality and the accurate nanopatterning are required to minimize the granulation of the structure, providing the efficient plasmonic coupling.

3.3.2. Rounded edges of the ridges

So far, each numerical model of the grating was based on the perfect cuboid. The sharp edges of the ridge are a source of a strong, local plasmonic field, as shown in Fig. 3.4 for the perfectly flat cuboid. In this paragraph, the origin of the local field is examined, by calculating the modelled grating with rounded edges. Figure 3.16 presents two models used for the calculations. Model 2 corresponds to the grating with rounded edges and a flat surface, whereas model 1 takes into account the irregularities of the surface. Figure 3.17 shows the intensity distribution, which was calculated for each model. The two distributions are very much alike, except for the small

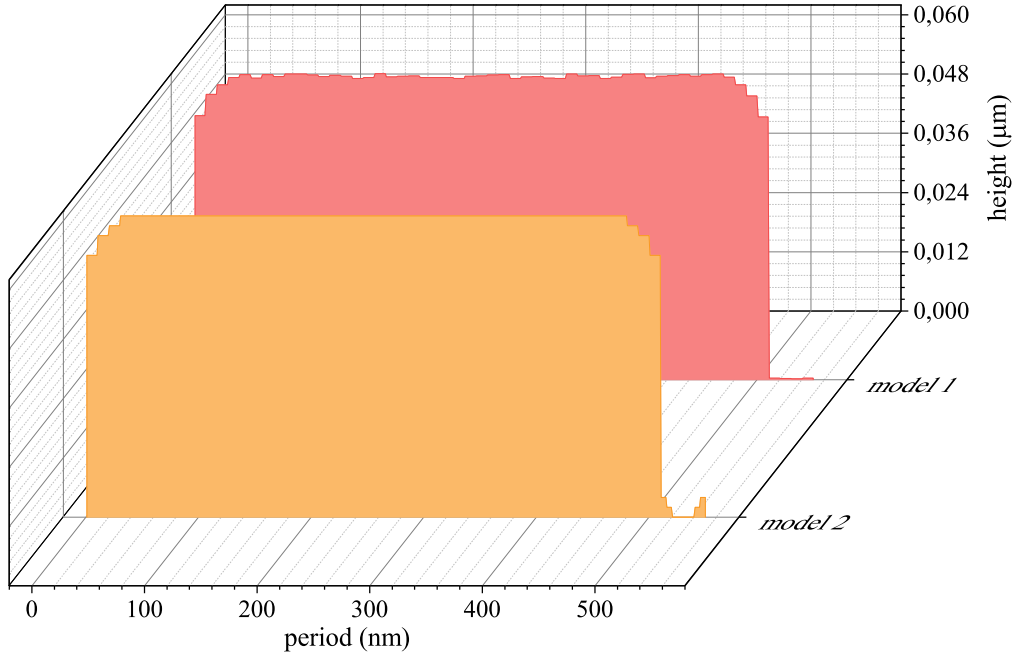


Figure 3.16: Scheme of the modelled grating periods, which were used in numerical calculations for the grating with rounded edges. Model 2 describes the flat ridge and model 1 takes into account the roughness of the grating surface.

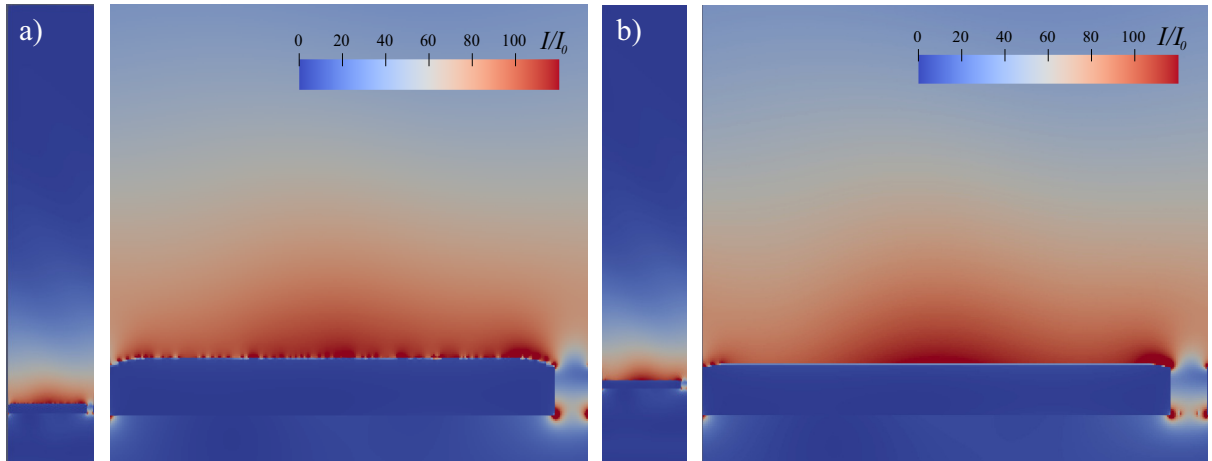


Figure 3.17: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for optimal angle of incidence of excitation light. The results are presented for two types of the grating of the rounded edges: a) model 1 and b) model 2.

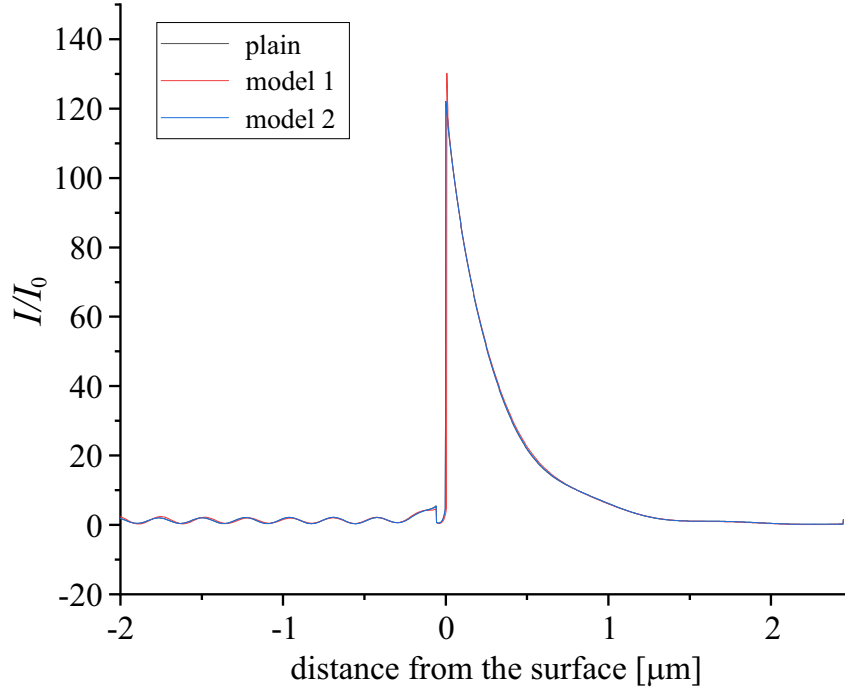


Figure 3.18: FDTD calculations of the I/I_0 electromagnetic field. Cross-section through the field distribution, taken in the middle of the ridge. The simulations are performed for optimal angle of incidence of excitation light. The results are presented for two types of the grating of the rounded edges ('model 1' and 'model 2'), and the rectangular grating, which serves as a reference ('plain').

local excitation resulting from the presence of grains. The enhancement, which is observed in the vicinity of the sharp edge for the modelled perfect cuboid, is also present for the grating of the rounded edges. The quantitative analysis of the intensity of the rounded grating is presented in Fig. 3.18. The figure compares the cross-section of the intensity I/I_0 of the rounded gratings of model 1 and model 2 with the intensity of perfectly flat, rectangular grating, marked as 'plain'. The rectangular and the rounded grating of a flat surface shows the exactly same cross-section, reaching the enhancement of 130 times the intensity of incident light. The slight discrepancy is seen in comparison to the rounded grating with an introduced roughness, which is caused by the modification of the surface, not the roundness of the edges. Due to the very good agreement in terms of intensity distribution between the rounded and the rectangular gratings, the further calculations are performed for the rectangular grating, taking into account the roughness of the surface.

3.3.3. The actual size of the grating

The actual grating consisted of 183 grating periods, covering the area of $100 \mu\text{m} \times 100 \mu\text{m}$, surrounded by a plain gold surface ('plain' corresponds to the area, which is continuous and uninterrupted by the slits of the grating). Up to this point, all the calculations have been performed for the modelled profile of a single grating period. Due to the boundary conditions, the given period was repeated infinitely, creating the numerical model of a *infinite* grating. The calculations, which are introduced in this section, deal with the actual size of the grating, hereinafter refereed to as a *finite* grating.

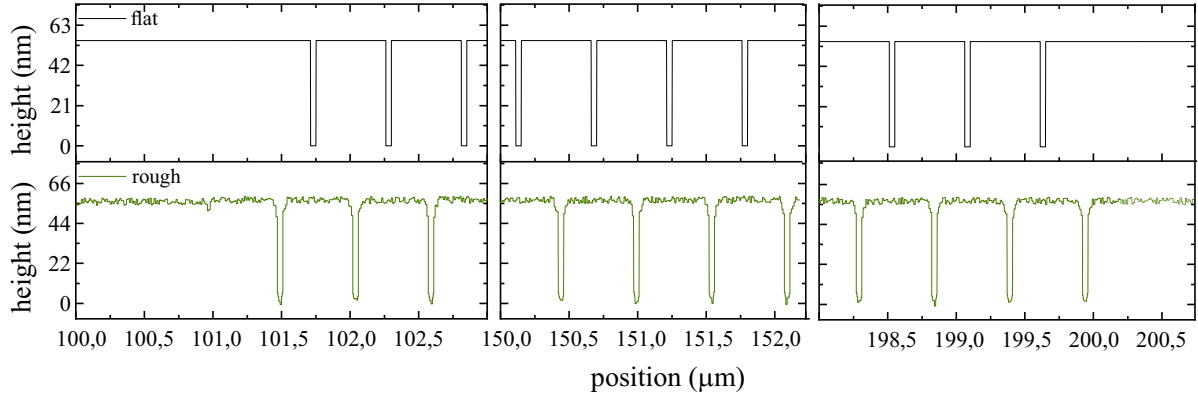


Figure 3.19: Scheme of the modelled grating, which were used in numerical calculations, presented for the middle, the left and the right edges of the grating. Model 'flat' describes the perfectly flat, rectangular grating, whereas model 'rough' takes into account the roughness of the surface.

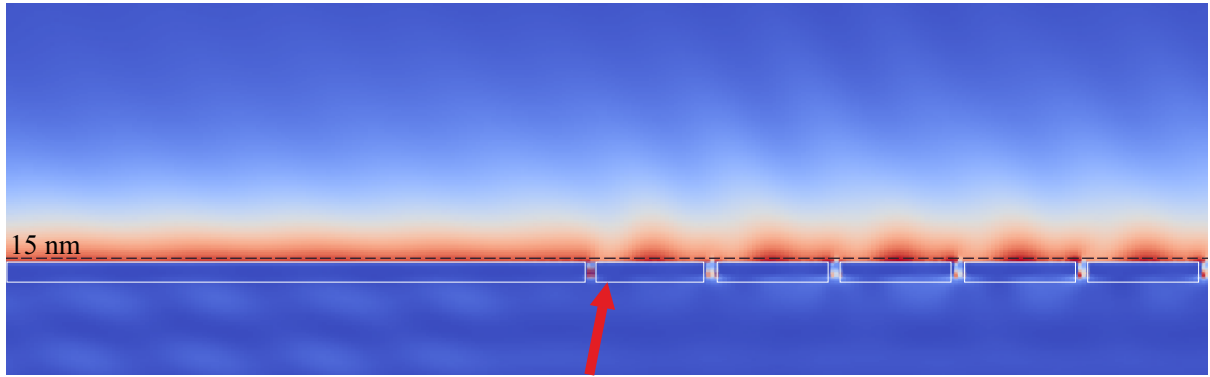


Figure 3.20: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for optimal angle of incidence of excitation light, of the intensity I_0 . The intensity distribution is presented for left edge of the perfectly flat finite grating. The five grating periods and the area of plane gold are marked with white, solid lines. The cut through the intensity distribution was taken 15 nm above the grating surface, indicated in the picture with black, dashed line. The red arrow indicates the direction of the 780 nm excitation beam.

Two numerical models of the finite grating are considered. The models consist of 183 grating periods, surrounded by 100 μm of flat gold on each side. Figure 3.19 presents the middle, the left and the right edges of the modelled gratings. First model describes the rectangular grating of a perfectly flat surface refereed to as 'flat', whereas the second model takes into account the irregularities of the surface, indicated as 'rough'. The maximum height and length of the irregularities are 3 and 10 nm, respectively.

The periodic boundary conditions are imposed in the FDTD method. The presence of plain gold separates the neighbouring gratings by 200 μm . This distance seems to be large enough to remove any residual plasmonic coupling between subsequent virtual gratings. This way the SPPs behavior is calculated on a truly isolated, finite grating. The total numerical model of a finite grating is therefore 300 μm long. Figure 3.20 presents the intensity distribution above the left edge of the finite, perfectly flat, rectangular grating. The transmissive grating and the plain gold, which surrounds the structure, are marked with white, solid lines. The obtained electromagnetic field was used to compare the intensity distribution with the geometry of the

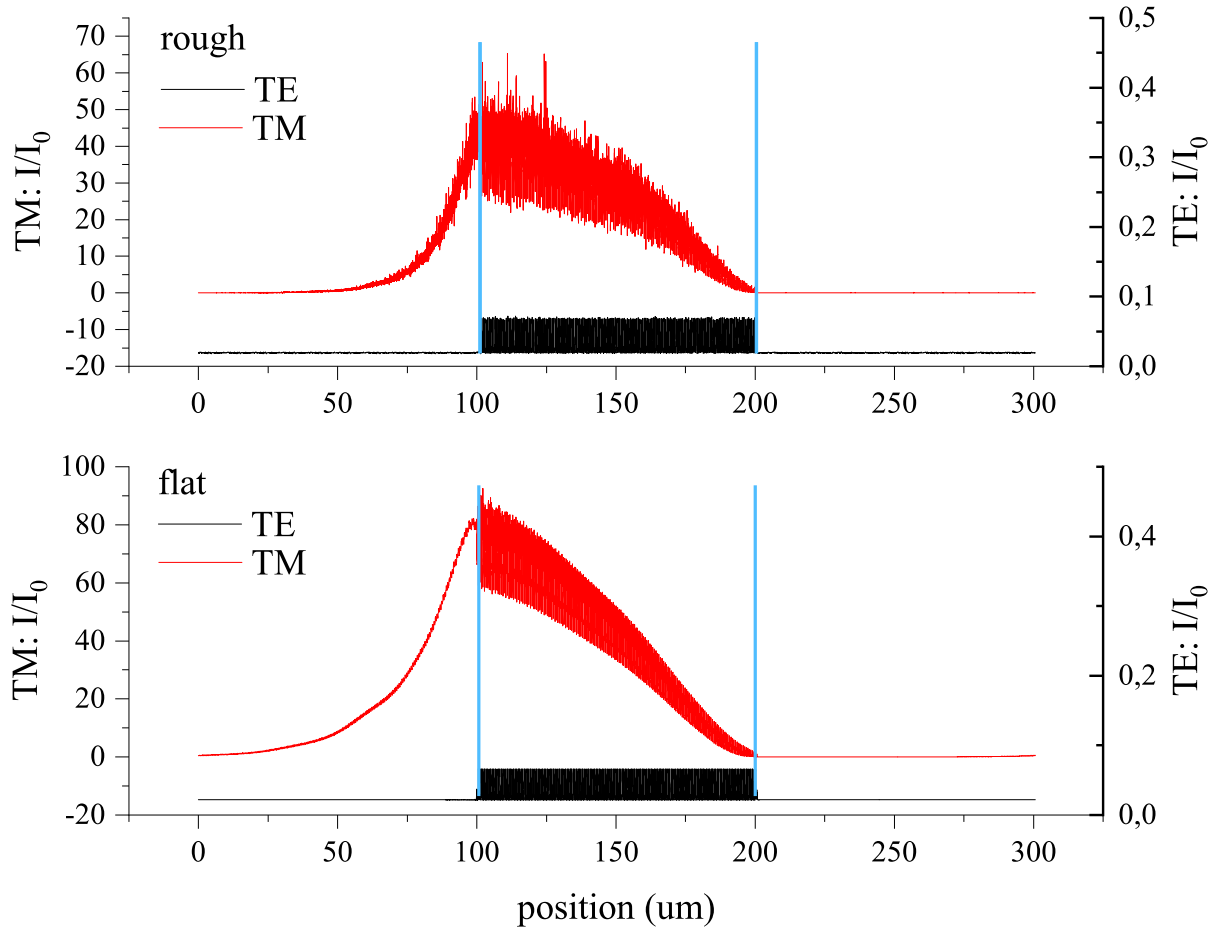


Figure 3.21: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for optimal angle of incidence of excitation light, for TE and TM polarizations. The intensity distribution is presented for both, the rough and perfectly flat finite gratings (see the corresponding descriptions). The two edges of the grating are denoted by blue, vertical lines, given as a reference. Note the separate scales for TM and TE polarizations and upper and lower graphs..

transmissive grating, for TE and TM polarizations. The intensity profile was determined by a cross-section, taken 15 nm above the surface of the structure, as indicated with the black, dashed line in Fig. 3.20. The distance of 15 nm corresponds to the commonly accepted value of the separation between the grating surface and the NSOM probe during the measurements on plasmonic near fields.

Figure 3.21 presents the total intensity distribution above the transmissive grating and the plain gold. The distribution is shown for TM (red line) and TE (black line) polarizations of the exciting beam. The process of SPPs' build up takes place at the right side of the grating, demonstrated by the very low intensity for TM polarized light. Then, in the middle of the grating, the signal becomes stronger. The SPPs propagate outside the left edge of the grating, and the enhancement of intensity reaches 50 for the rough model and 90 for perfectly flat grating. The structure was illuminated from the left side of the grating (see Fig. 3.20), proving the SPPs propagates backwards. Due to the plasmonic excitation, the TM polarization shows much higher intensity than the TE case, reaching the TM/TE ratio equal 1000 for rough and 1800 for flat gratings. The precise analysis of the intensity distribution with respect to the geometry of the

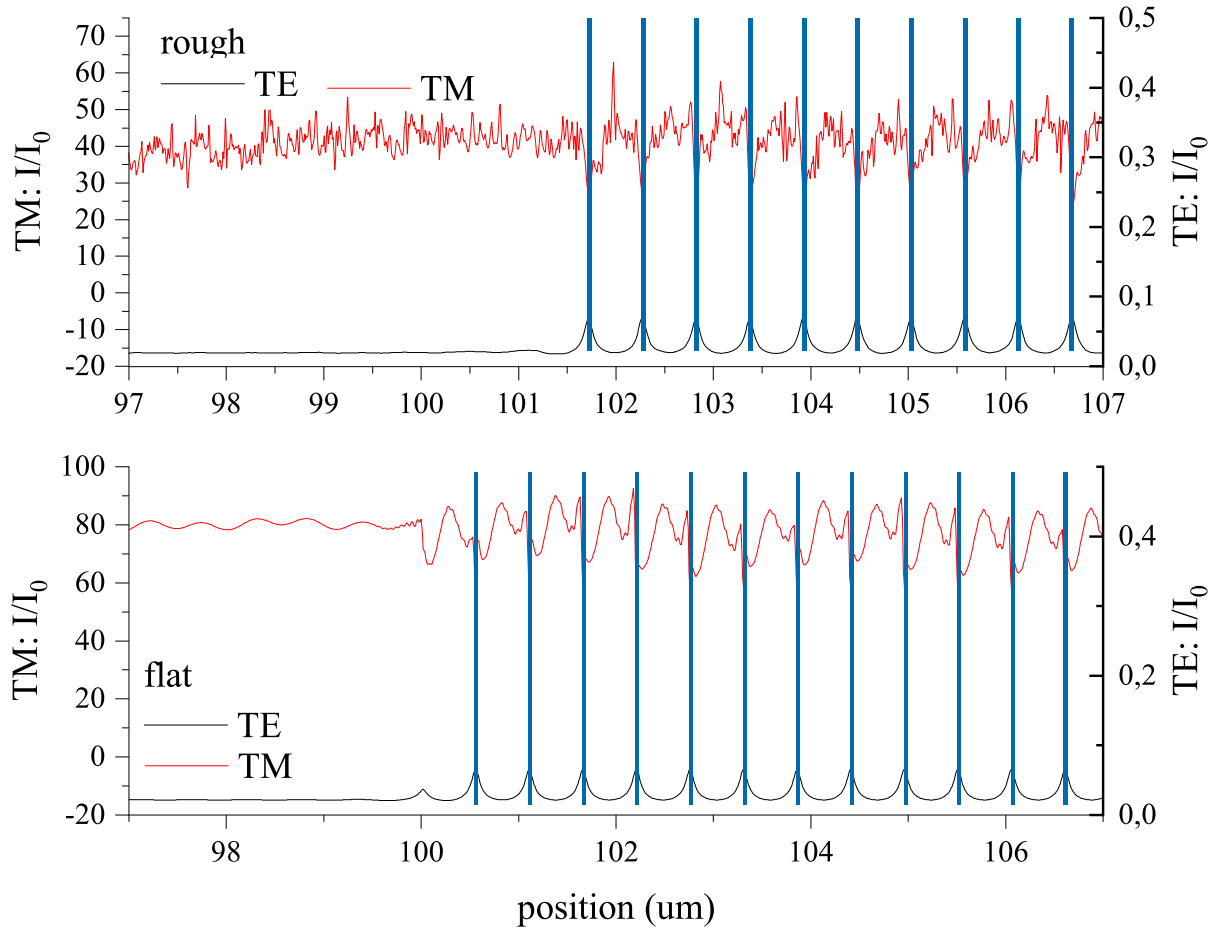


Figure 3.22: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for optimal angle of incidence of excitation light, for TE and TM polarizations. The intensity distribution is presented for both, the rough and perfectly flat finite gratings (see the corresponding descriptions), calculated at the left edge of the grating. The position of the grooves of the grating is denoted by blue, vertical lines, given as a reference. Note the separate vertical scales.

grating is impossible in the range of $300\ \mu\text{m}$ due to resource demanding calculations. Therefore, the separate results are presented for the center, the left and the right edges of the grating structure in Figs. 3.22 – 3.24. The analysis demonstrates the position of minima and maxima with respect to grating's ridges and grooves. The TM signal possesses minima in the groove and maxima in the middle of the ridge. The TE signal presents the reversed order. For the sake of completeness, the intensity distribution above 3 grating periods and the respective cross-section are presented in Fig. 3.25, revealing the exponential decay from the surface for TM polarization.

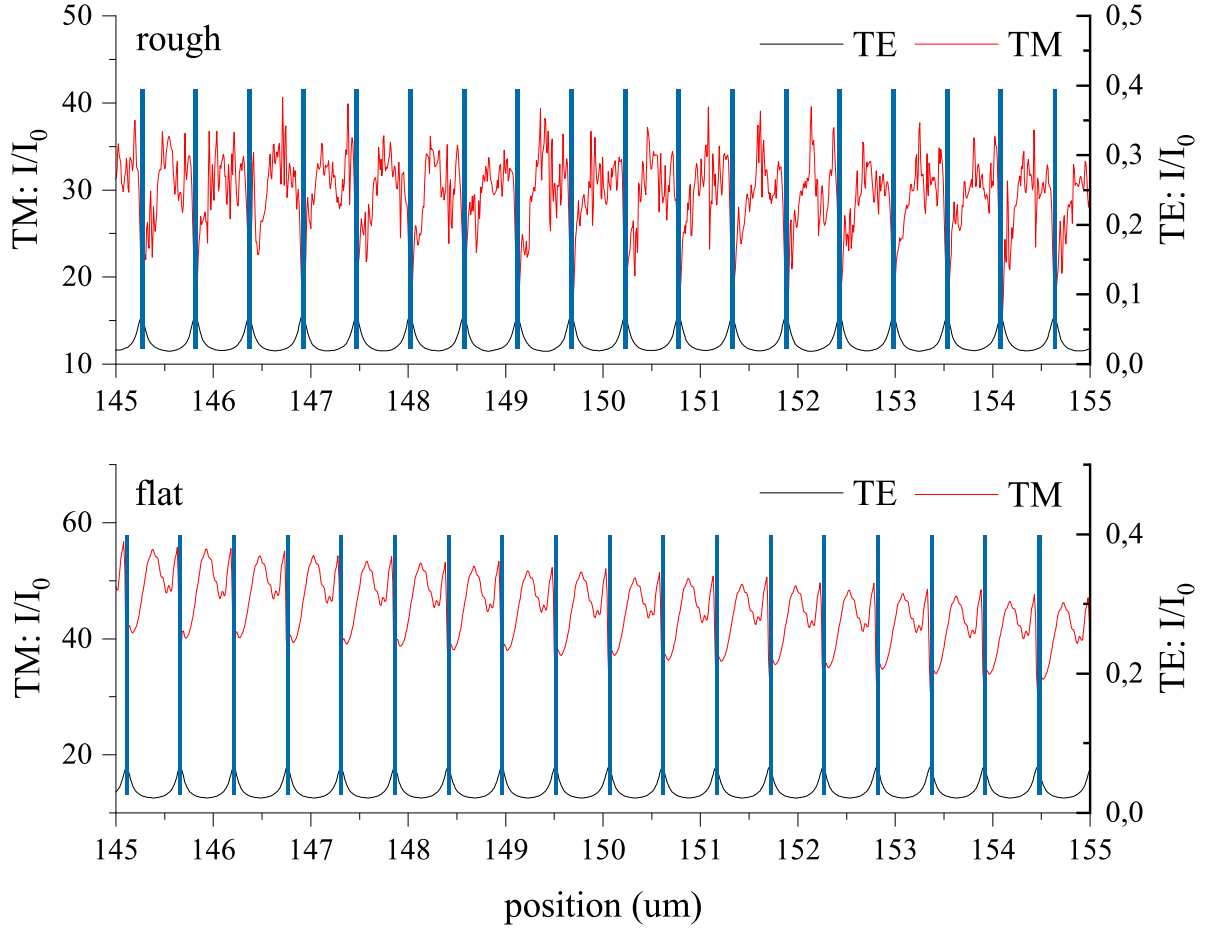


Figure 3.23: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for optimal angle of incidence of excitation light, for TE and TM polarizations. The intensity distribution is presented for both, the rough and perfectly flat finite gratings (see the corresponding descriptions), calculated at the center of the grating. The position of the grooves of the grating is denoted by blue, vertical lines, given as a reference. Note the separate vertical scales.

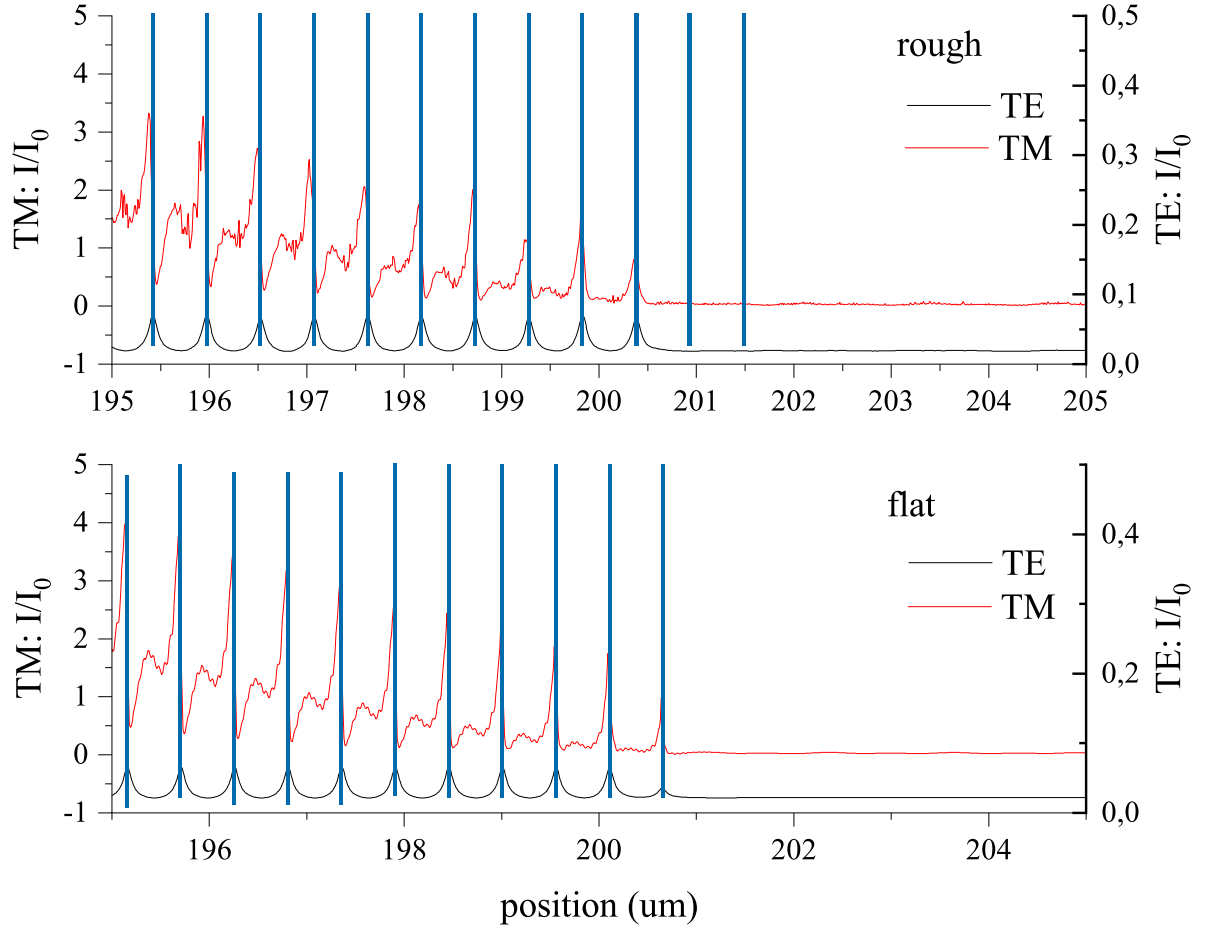


Figure 3.24: FDTD calculations of the I/I_0 electromagnetic field distribution. The simulations are performed for optimal angle of incidence of excitation light, for TE and TM polarizations. The intensity distribution is presented for both, the rough and perfectly flat finite gratings (see the corresponding descriptions), calculated at the right edge of the grating. The position of the grooves of the grating is denoted by blue, vertical lines, given as a reference. Note the separate vertical scales.

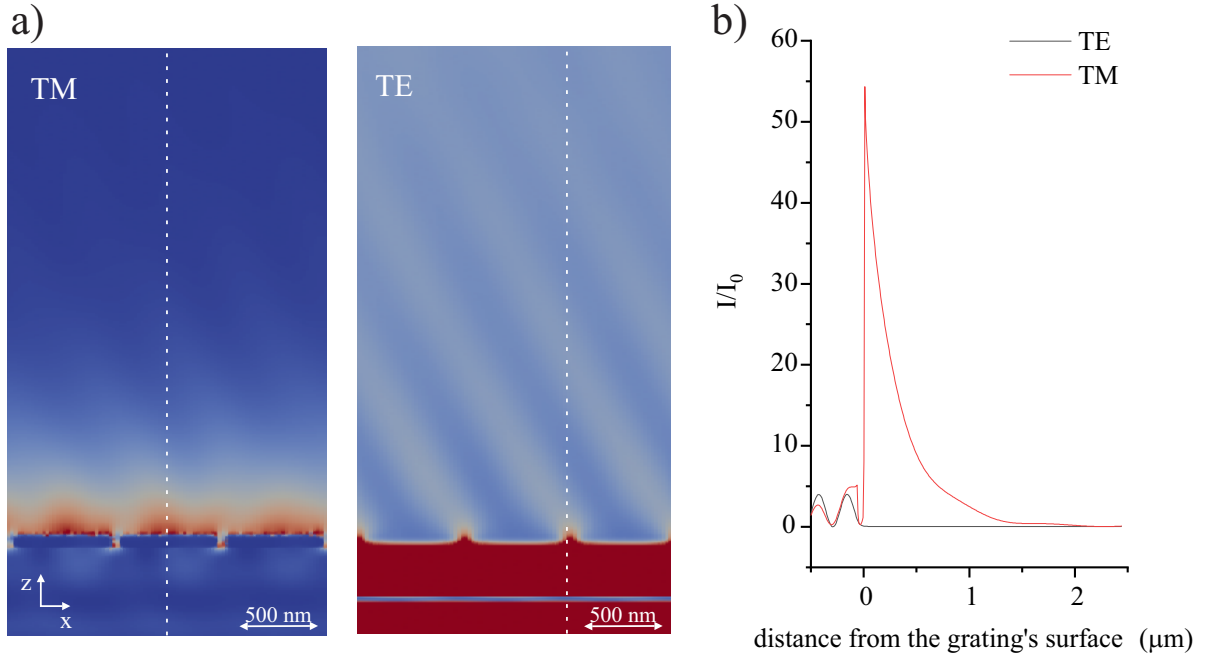


Figure 3.25: a) FDTD calculations of the I/I_0 electromagnetic field distribution over a rough grating. The simulations are performed for optimal angle of incidence of excitation light, for TE and TM polarizations. b) Cross-section in z direction (see the corresponding dashed lines) for TE and TM polarizations of light.

3.4. Far Field examination

The quality of the nanofabricated transmissive grating is determined by far and near field optical responses of the structure. Far field characteristics were provided by goniometric measurements of plasmonic resonance, whereas the near field analysis was performed by NSOM investigation, revealing the intensity of SPPs. Figure 3.26a presents the experimental setup, which was used to carry out the measurements of the optical response. The combined system of the NSOM and optical setup enables the simultaneous measurements of the plasmonic resonance and intensity.

The procedure of the far field measurements is the following: the 780 nm laser beam (Toptica DLX100) of a controlled power and polarization was directed to the polarization maintaining fiber, followed by the second polarizing set up. The beam was reflected from the dielectric mirror, up to the bottom (air-glass) side of the transmissive grating. The SPPs were excited on the top (gold-air boundary) side of the grating. The transversal intensity distribution of the reflected light was monitored on a CCD camera. The presence of SPPs is demonstrated through an extinction in the reflected light intensity, caused by a phase difference between specularly reflected and radiated light. The CCD images recorded for TE and TM polarizations are shown in Fig. 3.26b, together with the respective cross-sections. The reflectivity coefficient was calculated as a ratio of the intensity of the light at the grating to the intensity of the light reflected from the plain gold. The setup was modified to perform goniometric measurements in the full range of angles. The full angle dependency was measured without the simultaneous near field observations.

The plasmonic resonance for a full range of angles was measured with the following steps:

- The light of a TM polarization was illuminating the grating at a given angle (the grating

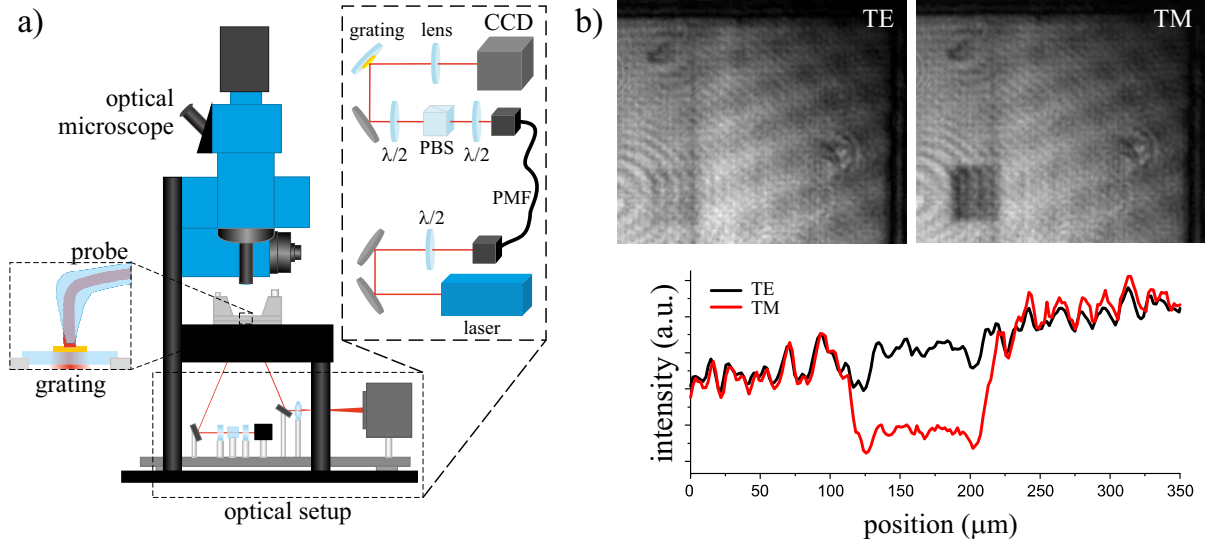


Figure 3.26: a) Schematic of the experimental setup, which was used for SPPs observation. The system consists of the NSOM, and the optical setup. $\lambda/2$ is a half waveplate, PBS is polarization beam splitter. b) The photos of the reflected beam for the optimum angle of incidence for TE i TM polarized light, taken by a CCD camera, with the respective cross-sections.

was mounted on a precision rotational stage).

- The lens and the CCD camera were positioned to record an enlarged and sharp image of the grating structure.
- The photo was taken by the default camera software EHDGrab. The typical picture is presented in inset in Fig. 3.26b).
- The same procedure was repeated for the light of TE polarization and for 0-20° angles of incidence.

Figure 3.27 compares the plasmonic resonances, which were measured via optical examination and numerically calculated by RCWA and FDTD methods. The modelled structure of RCWA assumed a perfectly flat, rectangular grating, whereas the FDTD incorporated the irregularities of the gold surface. The model assumes a plane wave for SPPs excitation. For that reason, the calculations of reflectivity coefficient cannot be applied for *finite* gratings, because a significant part of the plane wave is reflected from the flat, gold surface, affecting the final result. Therefore, both methods have employed the *infinite* type of structure.

The first minimum is located around 3° (glass-gold excitation), with experimentally achieved reflectivity equal to 0.28, unimportant due to the location of the SPPs inside the sample. The second minimum is located around 16° (gold-air excitation), reaching the coupling efficiency 68%, i.e. reflectivity equal to 0.32. The narrow and deep resonance indicates the excitation of SPPs of a high efficiency. A very good agreement between the simulations performed by FDTD and RCWA methods is observed, with a slight discrepancy between the reflectivity coefficient calculated at the optimal angle of incidence ($R_{RCWA} = 0.26$ and $R_{FDTD} = 0.39$). The difference quantifies the degree to which the plasmonic coupling is determined by the imperfections of the surface. The discrepancy between the numerical calculations and the experimental points is most visible at the position of resonances, caused by the implemented numerical model of the grating (the infinite type structure, whereas the actual grating is of a finite type).

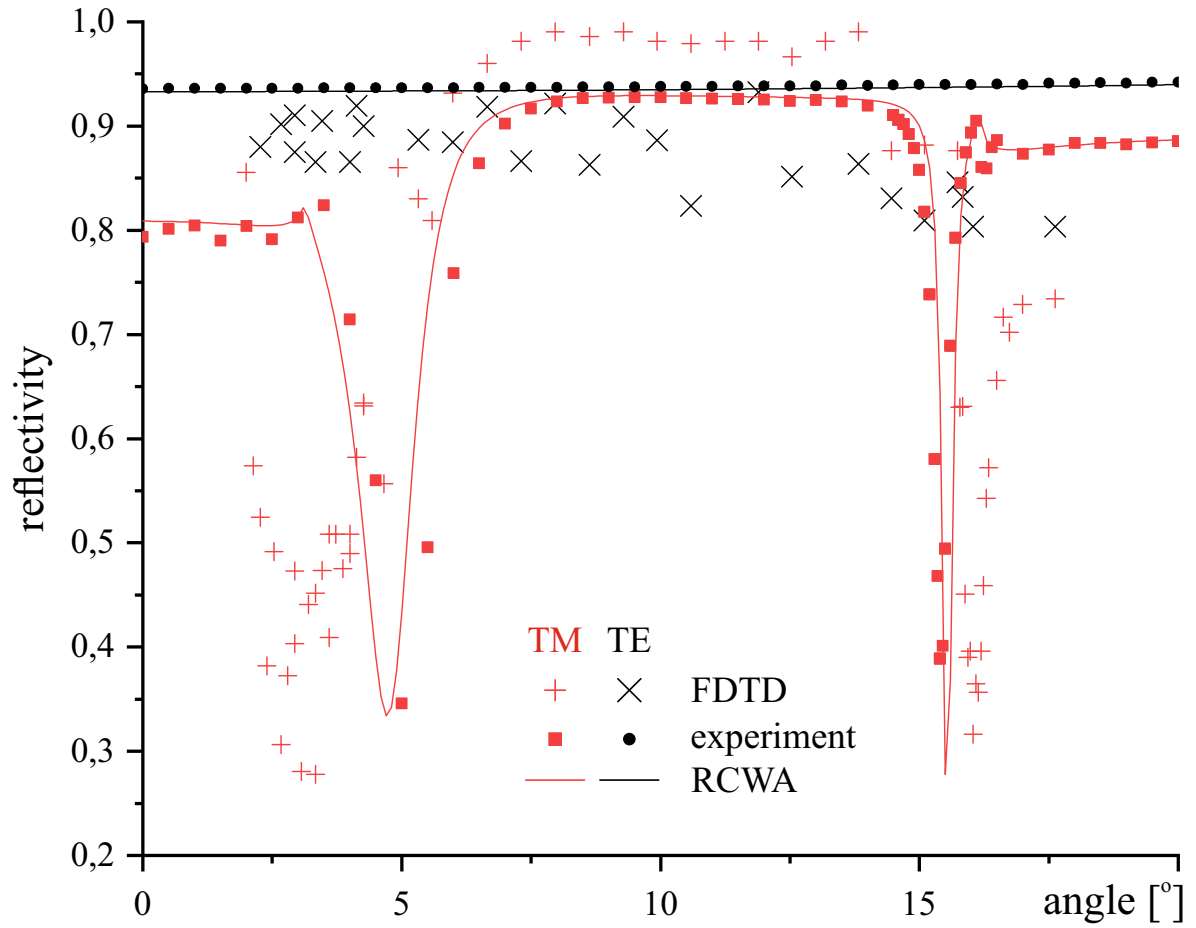


Figure 3.27: Angle dependent zeroth order reflectivity of the 780 nm laser beam. Numerical calculations performed by FDTD method are denoted by squares and circles. Solid lines indicate the results simulated by RCWA technique. The far field measurements of the reflectivity coefficient are presented by crosses and pluses. Black and red colours denote the TE and TM polarizations of light, respectively.

3.5. Near Field examination

The near-field techniques enable observation of the electromagnetic field in the vicinity of nanofabricated structures [127]. The near-field scanning optical microscopy (NSOM) was developed to provide insight into electromagnetic field extending up to tens, or hundreds of nm in the direction perpendicular to the surface, for visible and near-infrared light [128, 129, 130]. The near-field measurements provide an opportunity to investigate the physical processes, such as extraordinary optical transmission of light on periodically patterned structures [131, 132], light propagation in photonic crystal waveguides [133, 134] and dynamics of plasmonic nanoantennas [135, 136]. The knowledge about the near field distribution is crucial for the design of a number of devices, e.g. nanomanipulators [121, 122], sensors based on surface enhanced Raman spectroscopy [5], plasmonic sensors [11], surface plasmons-based circuits [120], electro-optic plasmonic modulators [123], and chip-scale atomic devices [124]. The understanding of near fields is also necessary for the construction of structured optical potentials for cold atoms, e.g. atom mirrors and plasmonic surface traps [15, 19, 75, 84].

The SPPs are a common object of study by near-field techniques, both, the localized and propagating SPPs [3, and references therein]. First near-field observation of SPPs was performed on a flat, silver film [137, 138, 139, 140]. Other studies include mapping the near field associated with metallic waveguides based on: stripes [141, 142], nanowires [143, 144, 145, 146], cavities [147], nanoparticles [148, 149], or gold film surface covered with randomly positioned scatterers [150, 151]. The plasmonic modes were also imaged in gold nanorods [152], gratings [117, 118, 60, 119], slits [114, 115, 116], metallic discontinuities [153], Au-Al heterostructure [154, 155], and nanoholes [156, 157, 158]. Using NSOM imaging of inhomogeneous nanoscale structures, the dependence on the handedness of the circularly polarized incident light was revealed [159]. Apart from localized and propagating SPPs, also the standing waves of SPPs, have been observed by NSOM technique for a variety of structures [160, and references therein], including a set of nanoslits [161, 162]. The propagation length has been widely studied with NSOM technique, e.g. for prism configuration [140, 163], metallic discontinuities [153], nanowires [145] and gratings [60, 119]. The enhancement in the propagation length for a buried diffraction grating in comparison to the usual one, is described in [117].

So far, only the qualitative analysis of the intensity distribution have been studied. In this section, the direct observation of SPPs is presented with a fully quantitative description of the excitation of SPPs on a nanofabricated transmissive structure.

Figure 3.26 presents the experimental setup for near field measurements, with simultaneous control of plasmon resonance in far field. The near field distributions were imaged by Nanonics MultiView 1000 Scanning Near Field Microscopy, integrated with an optical microscope. The entire structure was scanned, including the grating and tens of μm beyond, with a single scan size of $20\ \mu\text{m} \times 20\ \mu\text{m}$. The scanned area was observed in real time via optical microscope. The structure was imaged with multimode, Cr-Au coated fibers of two diameters: 50 and 100 nm, operating in contact, in a collection mode. The signal was collected through NSOM aperture, and detected with a photomultiplier, revealing the intensity of the electromagnetic field. The topography of the surface was measured with the same NSOM probe, working as an atomic force microscope (AFM).

The various parameters are taken into account during the near field studies, such as polarization of light, angle of incidence and the effective separation between the NSOM aperture and the grating surface. For each NSOM measurement the corresponding FDTD simulations have been performed, taking into account the finite size of the grating. The modelled structure consisted of $100\ \mu\text{m}$ of grating periods, surrounded by plain, gold surface of $100\ \mu\text{m}$ on each side of the grating.

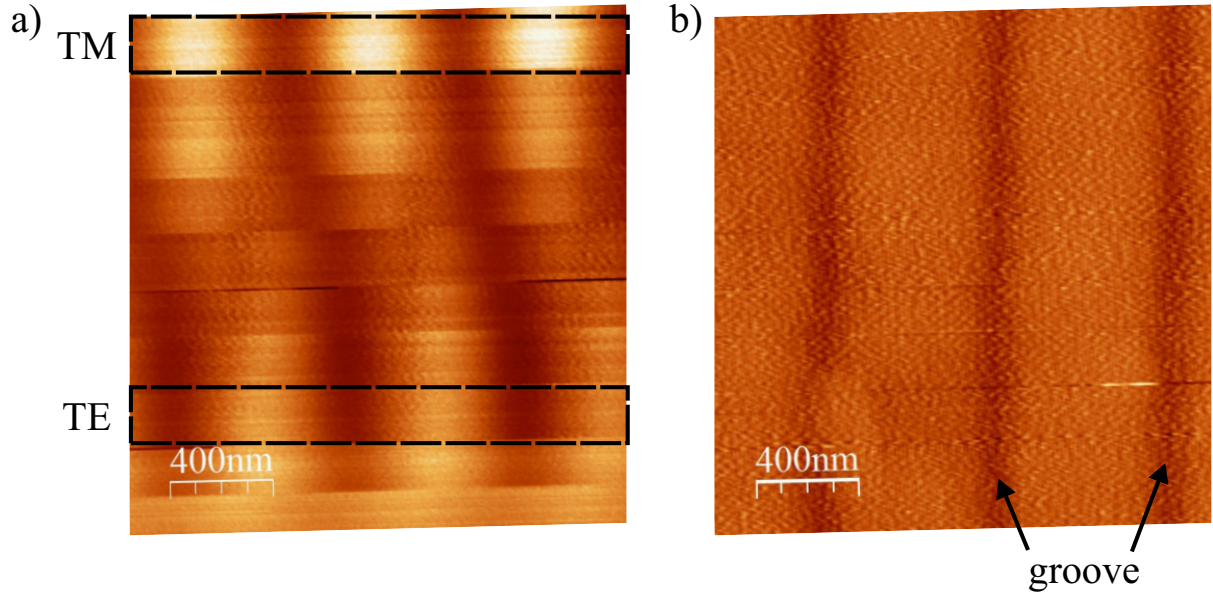


Figure 3.28: Electromagnetic field enhancement above the transmissive diffraction grating and topography of the surface measured by NSOM (AFM part). a) Qualitative comparison for polarization of light varying gradually between TE and TM. The polarization was varied within a single measurement cycle. b) Topography of the surface.

3.5.1. TM/TE polarization of light

Figure 3.28 presents the intensity distributions, and the corresponding topography of the surface, taken at the center of the grating for different states of polarization. The state of polarization was varied from TM to TE polarization, by the rotation of the orientation of the polarization plane with the half-wave plate, with the step of 7.5° . Different polarizations of light were investigated in a single NSOM cycle in order to obtain a reliable comparison. The near field distribution has significantly changed due to the rotation of the polarization plane. The minima and maxima switch their positions between TM and TE cases. Likewise, the strength of the signal decreases with the vanishing excitation of SPPs (this is, from TM to TE).

More thorough analysis is introduced in Fig. 3.29. Figure 3.29a presents the signal, which was by detected by NSOM at the center of the grating. The image of the intensity distribution and the respective cross-section are presented for TM and TE polarized light. The red colour on the graphs denotes the TM polarized light, whereas the black describes the TE polarization. The numbers expressed in kHz denote the quantity, which is proportional to photon counts. To compare the intensity distribution with the geometry of the grating, two of the grating slots are denoted by black, dashed line in the plot. The results of numerical simulations are shown in Fig. 3.29b, taking into account the irregularities of the surface for a finite grating (the figure presents only 13 grating periods periods out of 183 for comparison). The position of maxima and mainima with respect to grating's geometry are well matched for the simulations and experiment. The maxima of the TM polarized light occur in the middle of the ridge, whereas the maxima of TE case can be found in the vicinity of the groove. The diameter of the fiber aperture is 50 nm, excluding the Cr-Au cladding, and the width of the slot is 40 nm. The spatial integration of the collected signal over the probe diameter slightly widens the recorded maxima in comparison to the FDTD simulated signal. For both, calculations and experiment, the TM case gives stronger signal than the TE. Quantitatively, a typical TM/TE ratio measured by NSOM is 10, and the highest recorded ratio was 40. According to the FDTD calculations, the TM/TE ratio is

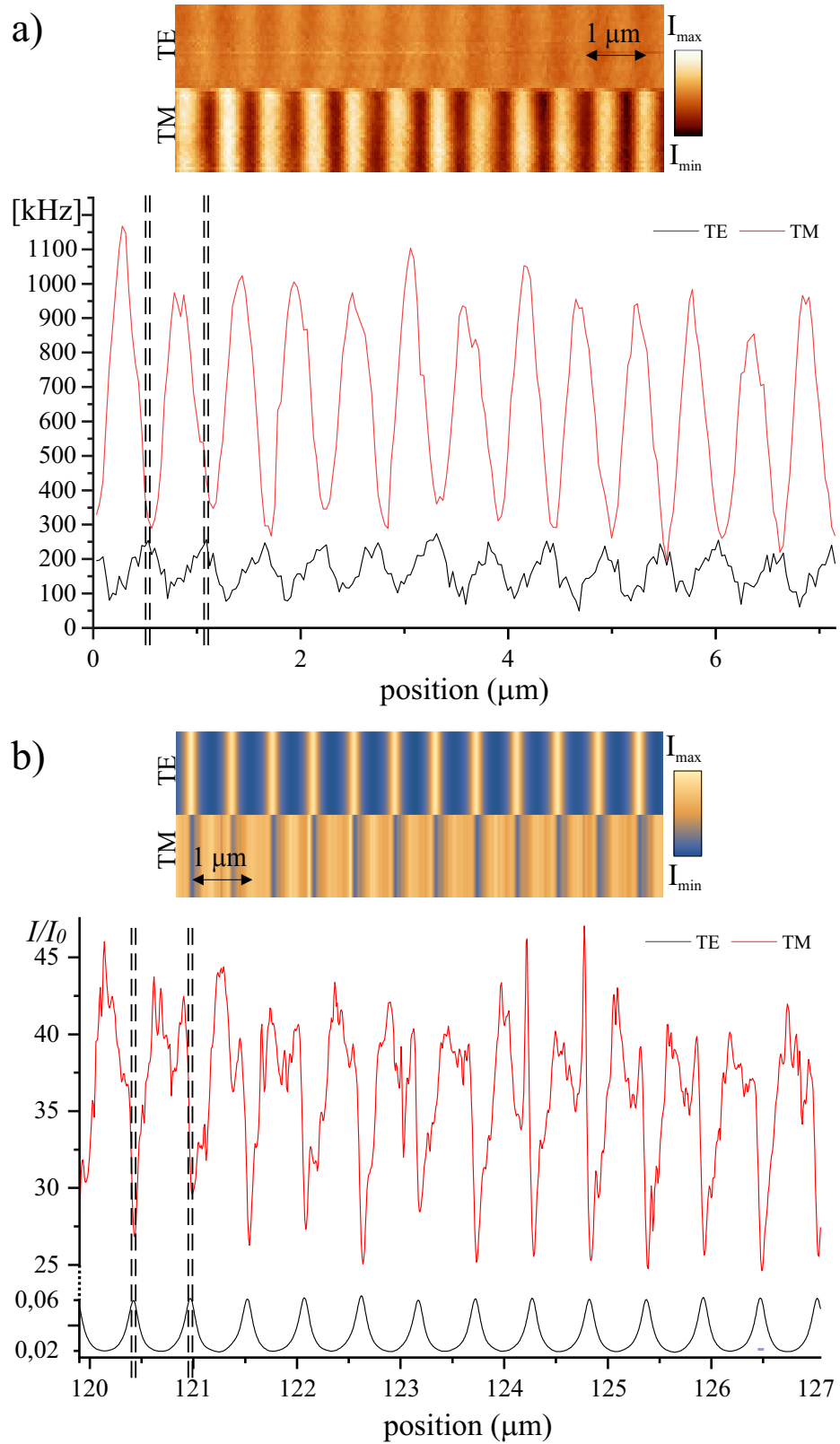


Figure 3.29: Electromagnetic field intensity above the transmissive diffraction grating imaged by NSOM (a) and calculated with FDTD method (b) for TE and TM polarized light. Quantitative analysis of the respective cross-sections, obtained for TM and TE polarizations of light is presented underneath. Two of the grating slots, based on the AFM topography, are denoted by black dashed lines. Note the break in the vertical axis.

expected to be more than 500. The disagreement of a factor of 10 can be readily explained by the operation method of NSOM.

The signal, which is measured by NSOM, comes from the *out of plane* and *in plane* electric field components. The *out of plane* component corresponds to the direction perpendicular to the surface of the structure, whereas the *in plane* is parallel to the surface. For the aperture-type probes, the out of plane component is greatly suppressed in NSOM detection, as shown in [127].

The electric field of SPPs possesses the following nonzero components:

- For TM polarization of light: E_x (in plane) and E_z (out of plane).
- For TE polarization of light: E_y (in plane).

Therefore, the total electric field of TE polarized light is detected by NSOM, whereas for the TM polarization, the E_z component is weakly detected by the probe. Figure 3.30 shows the contribution of the respective components of the TM polarization of light. A quantitative comparison in Fig. 3.30a determines the E_z^2 component being the main contribution to the total intensity, 20 times stronger than the E_x^2 component. Thus, the plasmonic enhancement is mostly caused by E_z component, not detected by NSOM, which qualitatively explains the differences between the TM/TE ratios obtained for NSOM detection and calculations.

For the sake of completeness, the presence of the interference pattern in glass in Fig. 3.30b is due to the interference between the leakage radiation [164] and incident and reflected plasmonic beams. The angle of incidence of the excitation beam is 15.4° and the calculated angle of leakage radiation is 43° , both measured in glass.

3.5.2. Poynting flux calculations

In order to quantitatively examine the discrepancy between FDTD intensity distribution and NSOM results, the presence of the fiber probe has been taken into account in the calculations. The modelled structure is presented Fig. 3.31a. The numerical model consisted of 20 μm long set of grating periods, modified by the irregularities corresponding to the topography measurement. Note, that this is the *infinite* type of the structure; the calculations on the *finite* case were infeasible due to the required computing power and time. The NSOM probe consisted of a trapezoid-like, glass structure of a 50 nm diameter, covered with 100 nm of gold coating, placed 15 nm above the grating structure. The typical results obtained for TM and TE polarization of light are shown in Fig. 3.31b. The power transmitted through the aperture into the probe is calculated by integrating the Poynting vector over the cross-section of the core. The Poynting flux has been calculated with the built-in *flux* function, 5 μm above the tip apex. After calculating the flux in one position, the simulations have been repeated, scanning more than one period in total, with a step of 50 nm. Figure 3.31c presents the quantitative comparison between the Poynting flux and the intensity distribution I/I_0 , calculated without the NSOM presence, for TE and TM polarizations of light. The compared values agree on shape of the intensity distribution for both polarizations, therefore, it matches also the NSOM signal. The TM to TE ratio determined by I/I_0 equals 2000, whereas the one driven by Poynting flux gives factor of 200, reducing the no-probe ratio ten times, giving the previously missing factor of 10. This proves, that the out of plane component of electric field is greatly suppressed in NSOM detection, and shows that our quantitative comparison between NSOM measurement and FDTD simulations is correct.

The analysis suggests that for the calculations of the TM/TE ratio, it is more reliable to calculate the Poynting flux instead of the intensity distribution I/I_0 . However, these calculations are unrealizable for the finite gratings, and since the Poynting flux reproduces the shape of the distribution of I/I_0 , all the following simulations are carried out for the numerical model without the NSOM probe. In addition, for any further experiments, i.e. plasmonic sensor or atomic

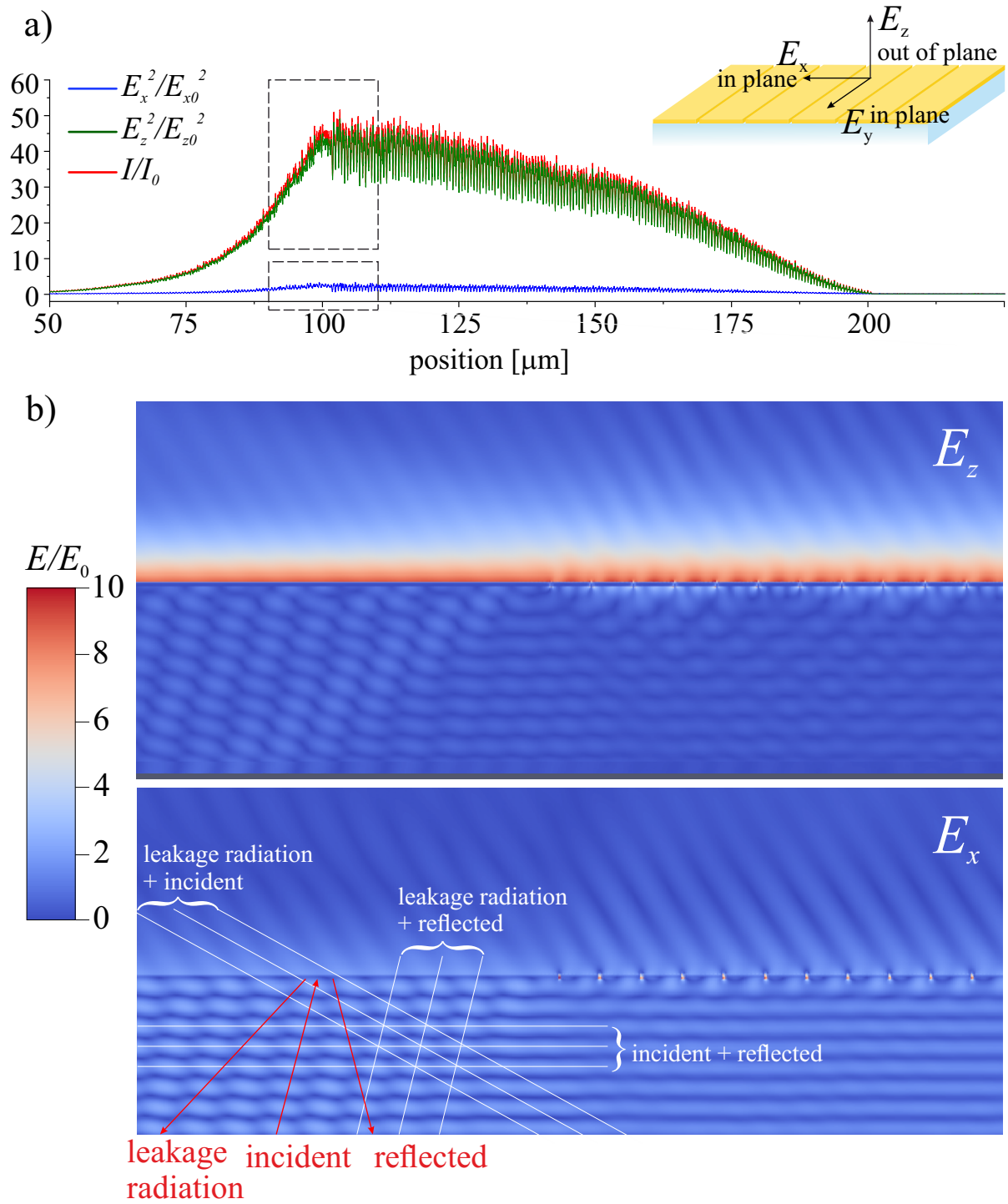


Figure 3.30: FDTD simulations of electromagnetic field enhancement above the transmissive diffraction grating for TM polarization of light. a) The comparison between the total intensity I/I_0 and the corresponding electric field components E_x (in plane) and E_z (out of plane). b) Amplitudes of E_x and E_z on the left edge of the grating. The maxima of interference pattern, resulting from interference between the incident and reflected light and leakage radiation, are schematically marked with white lines.

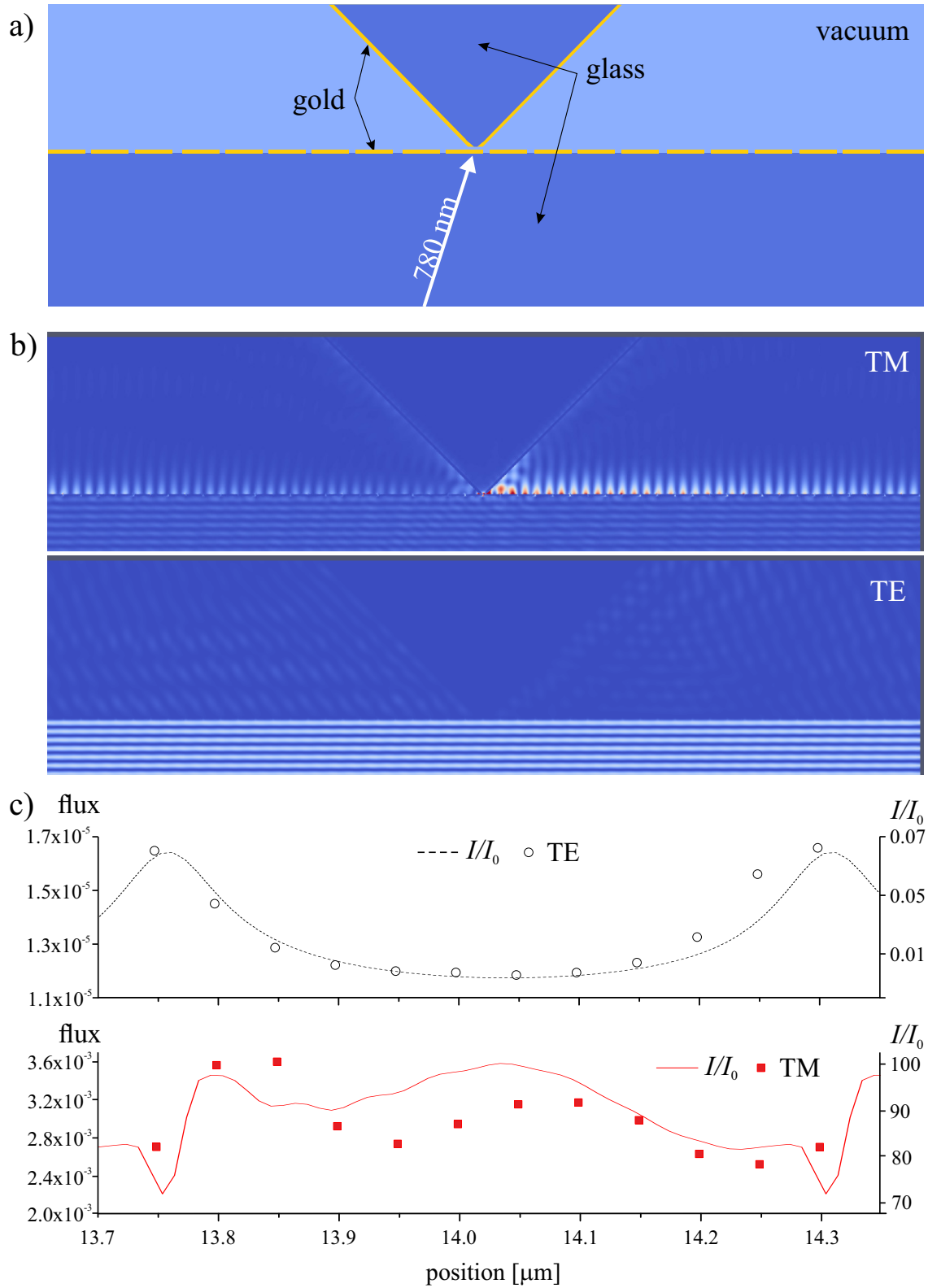


Figure 3.31: FDTD simulations of electromagnetic field enhancement above the transmissive grating. a) Scheme of the modelled structure with a NSOM probe. b) The respective intensity distributions for TE and TM polarization of light. c) Poynting flux calculated for TM (red squares) and TE (black circles) polarization of light, compared with the intensity distribution I/I_0 , calculated without the NSOM presence (solid and dashed lines).

mirror, the knowledge of the actual field distribution is crucial (the field, which is not affected by the probe).

3.5.3. Area of the grating

The intensity distribution was measured for the entire sample's area, with a single scan size up to $20\ \mu\text{m} \times 20\ \mu\text{m}$. The following areas are distinguished: *the right edge*, *the center*, *the left edge*, and *outside the left edge* (the excitation beam illuminated the structure from the left side). Figure 3.32 presents the specified areas, which are marked with white squares, in relation to the grating structure (black, dotted square). The real-time scanning area was observed through the optical microscope — the relevant images are included on the left side of the figure. The picture of the scanned area is completed with FDTD simulations and the NSOM measurements for TE and TM polarization of light, imaged together in a single measurement cycle. The quantitative comparison is shown in Fig. 3.33 for the SPPs excitation on a grating.

Right edge of the grating The intensity of the TM polarized light is very low at the right edge of the grating. This proves the process of SPPs build-up, reaching the enhancement of 10 at $15\ \mu\text{m}$ from the right edge.

The center of the grating The center of the grating was extensively discussed in the previous section, i.e. Sec. 3.5.1. Both, the signal and the contrast become stronger, in comparison to the right edge of the grating for TM polarization.

Left edge of the grating The signal observed for TM polarization of light is significantly stronger than the signal obtained for TE case, reaching the enhancement of 40 times the intensity of the incident light.

Outside the left edge of the grating Although there are no grooves outside the grating area, the presence of interference fringes is observed for the TM polarization of light, revealing the fringes of a high contrast and high intensity. The presence of the fringes is due to the interference between the propagating SPPs, and the incident beam, which leaks through the gold layer. For the TE case there is only a residual amplitude of the fringes outside the grating.

The comparison between the numerical simulations and the intensity distribution measured by NSOM is very accurate throughout entire grating area. The analysis shows, that the SPPs propagate backwards, as expected (it results directly from the dispersion relation for SPPs excited on the grating, for our set of parameters). The propagation length ξ_P is given by eq. 1.3.18, valid for a flat surface of an infinite thickness. The length describes the distance, at which the intensity of SPPs decreases e times, giving for a flat gold $\xi_P^{flat} = 43\ \mu\text{m}$. As mentioned in the Introduction, the propagation length in the case of the thin layers decreases by a factor of 2 due to the leakage radiation. This is confirmed by the numerical simulations for a perfectly flat grating (i.e. no irregularities on the surface). The exponential function $\sim \exp(-x/\xi_P)$ has been fitted to the intensity distribution calculated for a perfectly flat grating, revealing $\xi_P^{perf} = 21\ \mu\text{m}$, which is half of the analytical calculations. Likewise, the same function has been fitted to the intensity distributions, which correspond to the actual grating (Fig. 3.33), for both, FDTD simulations of the rough grating, and the NSOM signal. The numerically calculated propagation length is $\xi_P^{FDTD} = 12.9(0.1)\ \mu\text{m}$ and is consistent with the experimentally measured value $\xi_P^{EXP} = 11.5(2.0)\ \mu\text{m}$. In addition, the presented intensity distribution allows one to quantitatively describe the SPPs build up. The numerical and experimental intensity

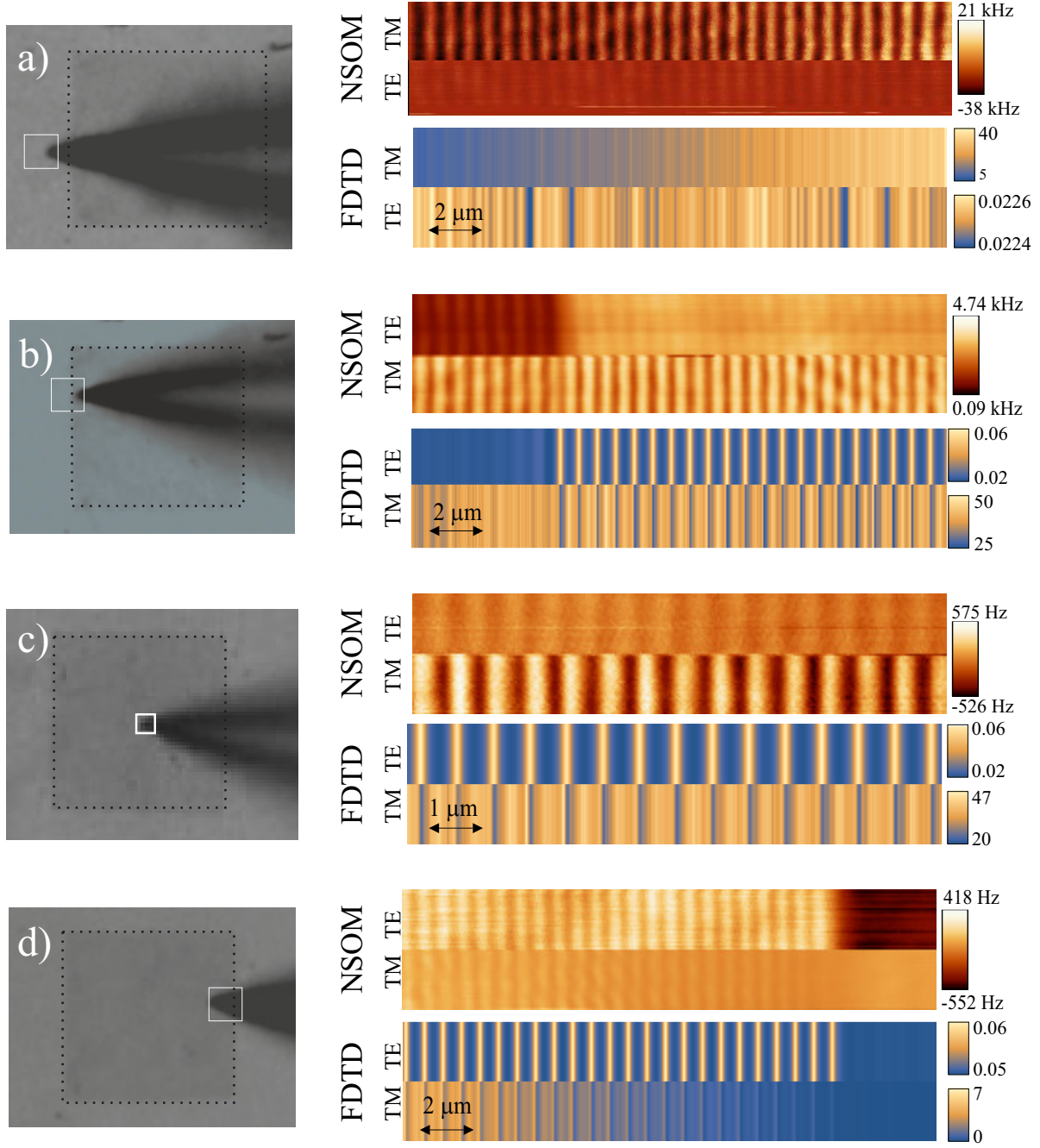


Figure 3.32: Electromagnetic field intensity above the transmissive diffraction grating measured by NSOM and calculated by FDTD method for TE and TM polarizations of light. The comparison is shown a) outside the left edge, b) on the left edge, c) in the center, d) on the right edge of the grating. The respective area is marked in the images taken by optical microscope. The white square corresponds to the scanning area, whereas the black, dotted square indicates the grating.

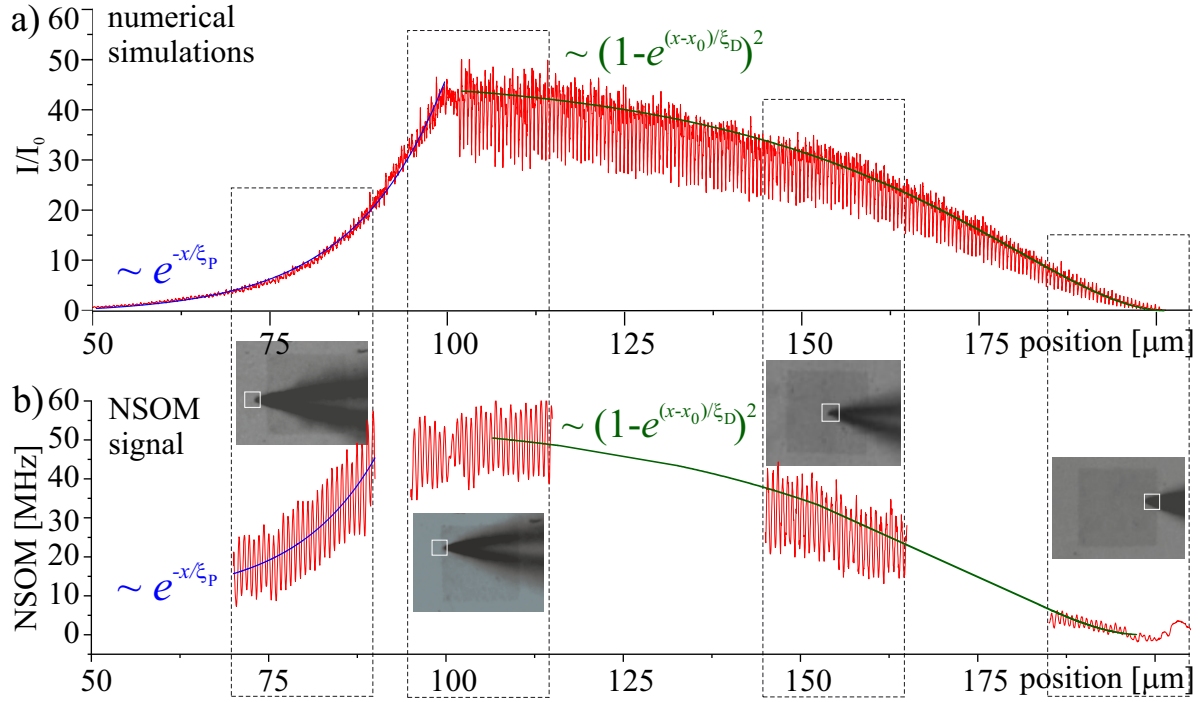


Figure 3.33: Electromagnetic field intensity distribution above the transmissive diffraction grating calculated by FDTD method (a) and measured by NSOM (b) for TM polarized light. The particular areas of the grating are shown by images taken with the optical microscope.

profiles are very accurately characterized by an analytic formula $I/I_0 \sim (1 - \exp((x - x_0)/\xi_D))^2$, where ξ_D is the amplitude decay length [165]. The calculated values of the decay length are $\xi_D^{FDTD} = 30.3(0.1)$ and $\xi_D^{EXP} = 31(2) \mu\text{m}$, for FDTD simulations and NSOM observation, respectively.

Corners of the grating For the sake of completeness, the plasmonic excitation on the corner of the grating is presented in Fig. 3.34. The observation of SPPs on the corners confirms that the SPPs build-up on the right edge of the grating, and propagate outside the left edge. The intensity of the TE signal is equal on both edges, whereas the TM signal shows a significant variation in the detected intensity between the edges.

3.5.4. Nonoptimal angle of incidence

The near field distribution was also measured for the nonoptimal angles of incidence of the excitation beam. The measurements have been performed for TM and TE polarization of light and four angles of incidence. The angle is given as a deviation from the optimal angle, i.e. 0° , 0.3° , 0.8° and 1.1° . The NSOM images are presented in Fig. 3.35, together with the respective cross-sections of the intensity distributions. The strongest plasmonic signal is observed for the optimal angle of incidence, as expected. Then, the contrast weakens with the increasing deviation from the optimal angle. The same measurements, performed for TE polarized light, show no differences between various angles of incidence.

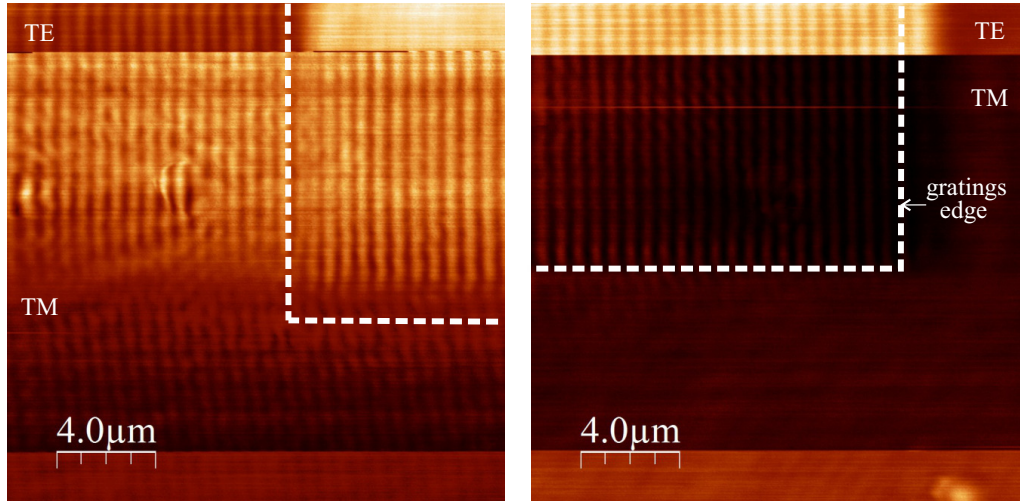


Figure 3.34: Electromagnetic field enhancement above the transmissive diffraction grating measured by NSOM for TE and TM polarized light, taken during one measurement cycle on the bottom corners of the grating.

3.5.5. The probe-surface separation

The amplitude of SPPs decays exponentially in the direction perpendicular to the surface, which can be precisely examined by the NSOM technique. However, in Nanonics MultiView 1000 SNOM the position of the probe with respect to the level of the structure is not known when the probe leaves the contact mode (in the AFM sense). Therefore, only the qualitative measurements on the probe-surface separation were performed. The change of the separation was controlled by option 'withdrawn', provided by the software, which vertically shifted the probe from the surface by a unknown distance.

Figure 3.36 presents the intensity imaged by NSOM for three different positions of the probe, with the respective cross-sections. The first position, marked as 'in contact', corresponds to the contact position between the probe and the surface. The positions 'withdrawn (1 step)' and 'withdrawn (2 steps)', describes the probe which is shifted vertically with 1 and 2 steps, respectively. The results reflect the nature of SPPs, showing the strongest signal for the measurement taken in contact, and significant weakening of the intensity with the growing distance from the surface.

3.5.6. Contamination of the surface

Figure 3.37a presents the peculiar shapes, which emerged on the grating structure after two days of the NSOM investigation. The double-like fringe structure is observed due to microscopic contamination of the gold surface. All the near field measurements were carried out in air (i.e. no under vacuum). Although many precautions have been taken, the sample has been exposed to organic contaminants from air conditioning and other unwanted factors, which deteriorate the quality of the surface. The grating was successfully decontaminated by Dr. Paweł Dąbczynski in a plasma cleaner, recovering the proper plasmonic resonance (see Fig. 3.37b). Thus, it is highly suggested to keep the sample in a vacuum after the fabrication process until it is applied in further experiment.

As a side effect, an extraordinary sensitivity of the structure to the contamination is confirmed, making this grating a promising structure for plasmonic sensors.

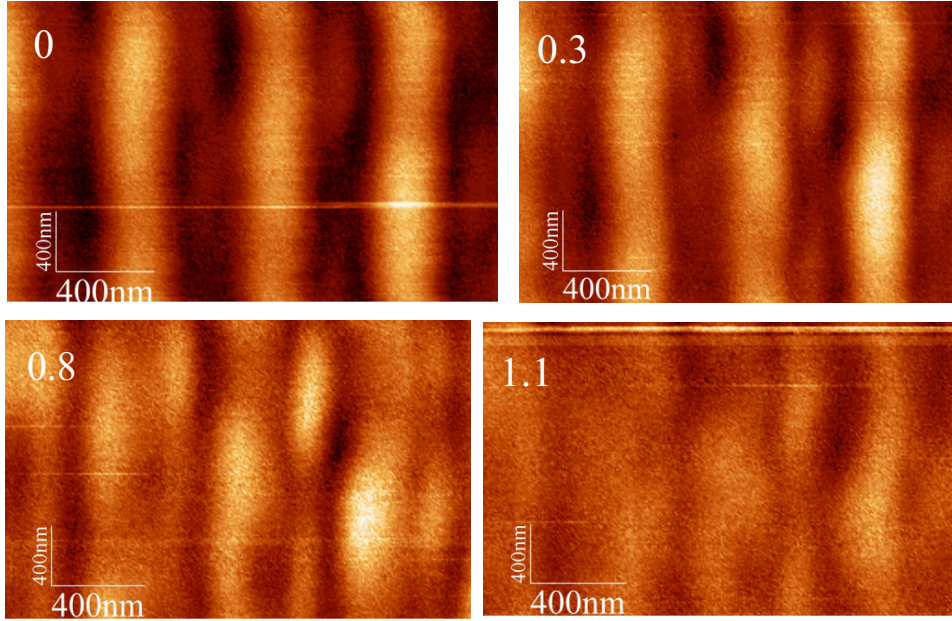
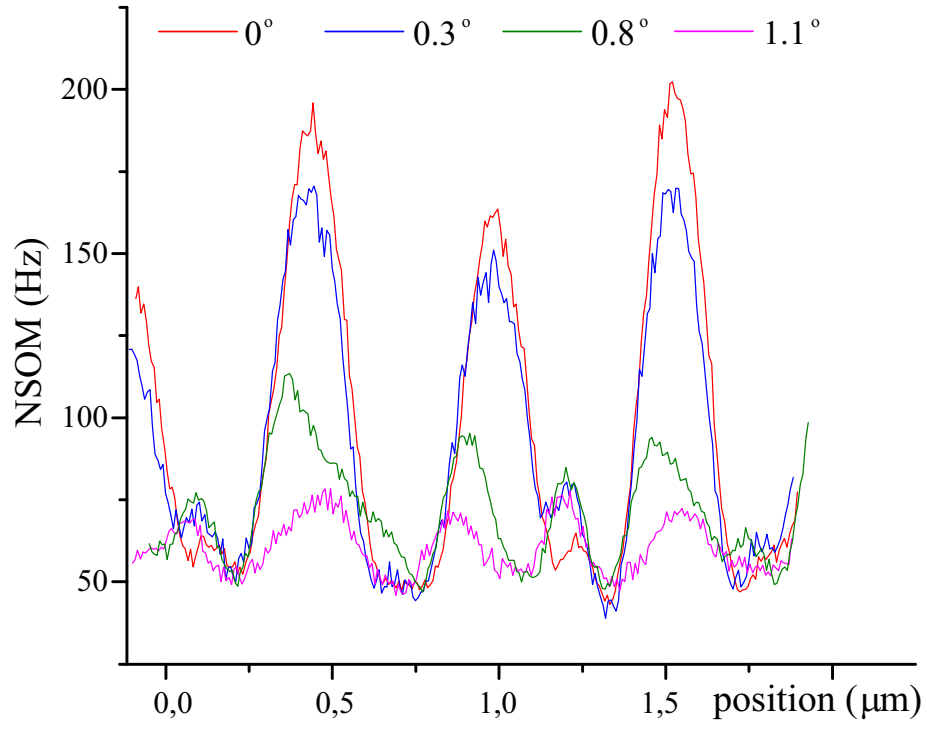


Figure 3.35: Electromagnetic field enhancement above the transmissive diffraction grating measured by NSOM for TM polarized light, taken for different angles of incidence. 0° corresponds to the optimal angle of plasmonic excitation, angles $0.3^\circ - 1.1^\circ$ are a measure of deviation from the optimal angle.

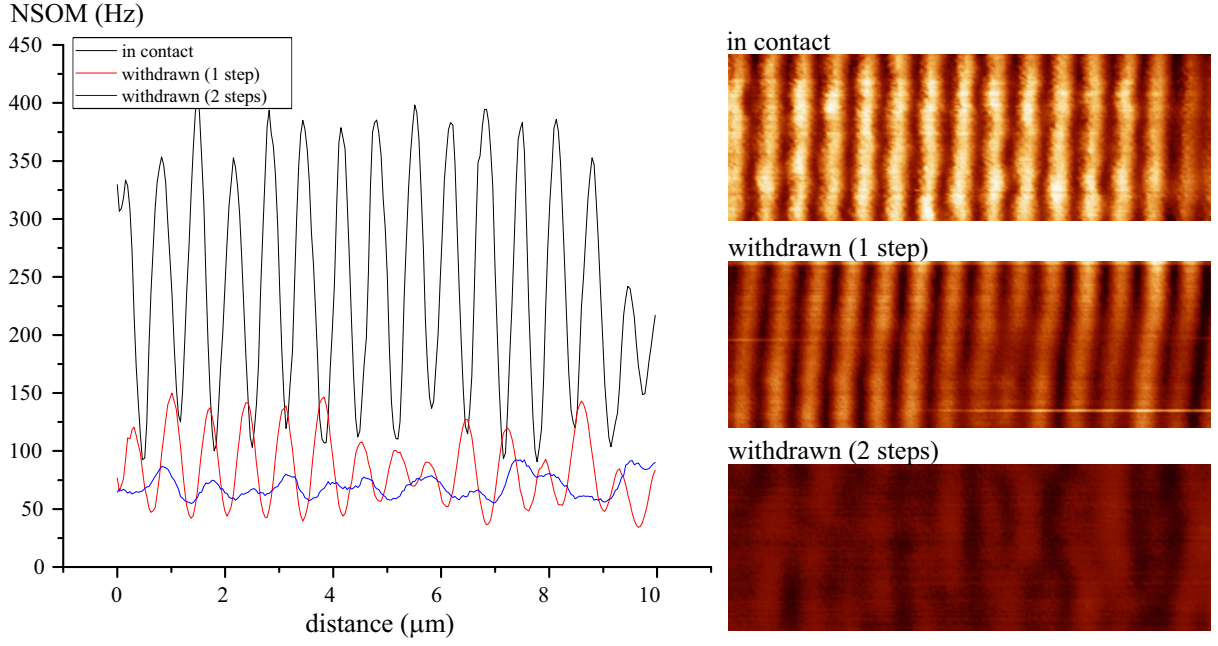


Figure 3.36: Electromagnetic field enhancement above the transmissive diffraction grating measured by NSOM for TM polarized light, taken for different separations between the probe and the surface of the grating. *In contact* corresponds to the position of the probe being in contact with the surface, *withdrawn (1 step)* describes the position of the probe, which is vertically shifted for one step, and *withdrawn (2 steps)* for two steps.

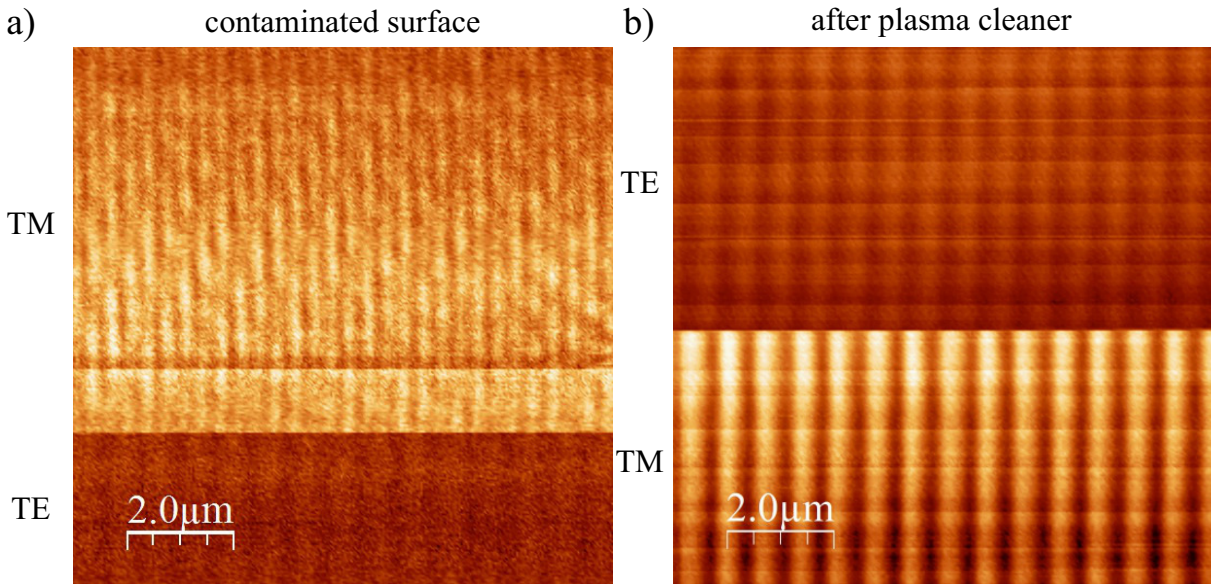


Figure 3.37: Electromagnetic field enhancement above the transmissive diffraction grating measured by NSOM for TM and TE polarized light, taken during one measurement cycle. a) The NSOM observation of a transmissive grating with contaminated surface. b) The same grating structure, after plasma cleaning.

Chapter 4

Conclusions

This thesis discusses the plasmonic near field potentials for plasmonics, sensors and cold atoms. The near fields are associated with Surface Plasmon Polaritons in the vicinity of the metallic reflective and transmissive grating structures. The use of SPPs enables the design and fabrication of complicated dipole potentials, which are tailored with subwavelength resolution, unlike the typical magnetic or optical potentials, in which spatial resolution is limited by technology and diffraction. Therefore, the plasmonic potentials are a promising platform for nanomanipulation, ultrasensitive detection and surface trapping of cold atoms.

The thesis discusses two types of plasmonic structures: reflective and transmissive grating couplers. The main observations and findings, which are reported in the thesis, are summarized below.

1. Reflective structures and Optical Dipole Mirror, published in [75].
 - The widely available optical discs: DVD±R and DVD±RW can be successfully used as very efficient plasmonic couplers.
 - The AFM examination of optical discs revealed the topography of the internal layers of DVDs, which was later included in numerical simulations.
 - The RCWA simulations showed the most effective plasmonic resonance of recordable optical discs for the top (labelled) polycarbonate layer. The rewritable optical discs provide the most effective plasmonic coupling for the bottom (transparent) layer.
 - The RCWA and FDTD simulations showed that the DVD based structures are most effective for near-infrared light (780 nm) [105] However, other wavelengths such as 633 nm and 1083 nm can be used as well, especially with potassium and caesium atoms.
 - The described method of optical discs modification provides sharp plasmonic resonances with 95% coupling efficiency.
 - The goniometric far field zeroth-order reflectivity measurements confirmed the high quality of plasmonic resonances.
 - The DVD based structure was successfully implemented in ODM for cold rubidium atoms, with the mirror efficiency of 100% (based on the comparison between the measurements and numerical simulations). The ODM experiment indirectly proved the intensity of SPPs reaching 90 times the intensity of the excitation beam for a particular structure. See also [110].
 - The most effective DVD based structure revealed the calculated enhancement of 220 with respect to the intensity of the excitation beam.

2. Reflective structures and thermal plasmonic effects, published in [75, 166].

- The SPPs excitation on DVD based structures is accompanied by thermoplasmonic effects.
- The increase of the temperature on a plasmonic grating is significant at laser powers greater than several milliwatts. The high temperatures cause the thermal damage of the grating and prompt deterioration of plasmonic coupling efficiency.
- The thermal plasmonic effects can be limited by introducing the quasi-pulsed excitation regime in the ODM experiment. Slightly stronger pulses can be employed to reduce the rubidium adsorption of the gold surface
- The measurements of energy conversion revealed the unknown mechanism of SPPs energy dissipation.

3. Transmissive structures, written up in a preprint [167].

- The RCWA numerical calculations of the parameters of the transmissive grating at 780 nm revealed the optimum grating period of 550 nm, the grating height of 55 nm, and a slot width of 40 nm.
- The FDTD numerical simulations of intensity distribution proved the importance of surface quality. The strongest SPPs intensity is observed for perfectly flat surface. However, the microscopic analysis of the structure showed that the presence of spherical-like shaped grains is inevitable.
- For the calculations of SPPs intensity, the numerical model must take into account the corrugation of the flat surface and finite size of the grating.
- The goniometric far field zeroth-order reflectivity measurements confirmed the narrow and deep plasmonic resonance, reaching the coupling efficiency of 68%.
- The direct near field observation of SPPs intensity by NSOM showed the processes of the build-up and propagation of SPPs. The propagation length equals to $11.5 \mu\text{m}$ (outside the grating), and the build up rate, which characterizes the growth rate is $31 \mu\text{m}$ (within the grating). The values are consistent with FDTD calculations and prove, that the presence of the surface corrugations reduces the propagation length in comparison to the perfectly flat surface, roughly by half.
- The generated field builds up along the grating, so the effective area of the plasmonic field appears smaller than the grating size. On the other hand, the SPPs propagate also outside of the grating. Both features are crucial in the design of nanostructures for cold atoms.
- The different intensity distributions are observed for TM and TE polarized light, both in NSOM imaging and FDTD calculations. The maxima of the TM polarization occur in the middle of the ridges, whereas the maxima for TE case were found in the vicinity of the grooves.
- The NSOM analysis compared with FDTD calculations revealed that the aperture-type probe does not couple the out of plane component of the electric field. The results confirm the widespread notion shown in [127]. However, there are works, which anticipate that the two field components contribute to the detected signal equally [161]. The findings of this thesis throw a new light on the matter, revealing the quantitative analysis, in favour of the findings presented in [127].

- Only the numerical model which takes into account the presence of the surface corrugations and finite size of the grating gives consistent results with near field observation. The fully quantitative comparison between the NSOM observation and FDTD calculations requires calculating Poynting flux. The SPPs intensity is 50 times greater than the intensity of the excitation beam.

These findings indicate that both, reflective and transmissive gratings studied here are effective plasmonic structures. The efficient plasmonic coupling makes the structures a promising tool for cold atoms experiments and ultrasensitive plasmonic sensing. With the experience gathered in Sec. 2.5, the construction of ODM based on the transmissive grating is being currently realized in the Laboratory. The implementation of transmissive grating separates the excitation beam from the magneto-optical trap, preventing the unwanted photon scattering. The ODM can be further used for construction of surface trap for cold atoms, as proposed in [85, 21, 86, 87], as well as in other atomic devices [15, 19].

The narrow and deep resonances, which were observed with far field goniometric measurements, prove that the investigated types of gratings are an effective base for ultrasensitive plasmonic sensing [11, 5]. This is also confirmed by the high sensitivity to any contaminations. The thermoplasmonic effects, discussed in Sec. 2.4, can be effectively used in biophysics for bacteria sterilization [168].

The numerical simulations presented in Sec. A provided the fully quantitative description of SPPs intensity, proving the numerical method to be correct. The numerical analysis can be further used to calculate the near field distribution, which is crucial for the design of a number of devices, e.g. nanomanipulators [121, 122], surface plasmons-based circuits [120], electro-optic plasmonic modulators [123], chip-scale atomic devices [124], and the aforementioned sensors [11, 5] and atomic devices [15, 19, 75, 84].

Contribution of the Author

The cold atom experiments often require a team of people to operate and advance the experiment. The magneto-optical trap was constructed by the Author and Roman Panaś (PhD student at that time). Similar applies to the investigation of the MOT operation, the procedure of optimization and measurements during ODM experiment (the mirror based on a reflective grating). The results, obtained together with Roman Panaś, are presented in Fig. 2.29. The numerical simulations presented in Fig. 2.30 and Fig. 2.31 were performed by Roman Panaś, excluding the RCWA simulations of the intensity distribution, which were carried out by the Author. The entire experimental setup was rebuilt for another type of ODM (mirror based on a transmissive grating), in a cooperation between the Author and Piotr Sowa (current PhD student).

All other measurements, calculations, data processing, and analysis, which are presented in the thesis, were made entirely by the Author. This includes the full characterization of optical discs, AFM investigations, thermoplasmonic measurements and calculations, RCWA and FDTD numerical simulations of plasmonic resonances and intensity distributions, optical characterization of reflective and transmissive structures, and near field measurements.

Appendices

Appendix A

Numerical simulations

In the thesis, the two numerical methods have been used for calculations of the plasmonic structures: Rigorous Coupled Wave Analysis and Finite Difference Time Domain.

The calculations for plasmonic structures require the knowledge of the dielectric constant of gold, or any other dielectric/metal, which is implemented in the simulations. The dielectric constant is determined by theoretical models, or measured in the experiment [169, 170, 171, 172, 173]. In the thesis, the refractive indices of gold are:

- $0.18344 + 3.4332i$ at 633 nm,
- $0.14737 + 4.7414i$ at 780 nm,
- $0.14891 + 4.7830i$ at 785 nm,
- $0.26760 + 7.1115i$ at 1083 nm.

The numerical calculations were run on a 4-core computer with 32 GB RAM.

A.1. Rigorous Coupled Wave Analysis

The *Rigorous Coupled Wave Analysis (RCWA)* is a computational method, which solves scattering problems, and is mostly used for periodic structures [174]. In the method, the structure is divided into the layers, uniform in the direction perpendicular to the surface of the planar structure, with the two additional layers, which surround the structure. In the area of the structure, the periodic permittivity function is expanded in the Fourier series, and the respective components of the TM/TE electromagnetic field are written via the plane wave expansion. The Maxwell equations are turned into the set of differential equations, and with the proper boundary conditions, expanded into Floquet functions and transformed into algebraic equations.

The RCWA calculations were carried out via Matlab-based `rcwa-1d` script, created by Pawel Kwiecien from Optical Physics Group, University in Prague. The script was modified for near-infrared plasmonic grating optimization firstly by Dobrosława Bartoszek-Bober [105] and then by the Author.

A.2. Finite Difference Time Domain

The *Finite Difference Time Domain (FDTD)* is a class of grid-based numerical methods, which solve time-dependent Maxwell's equations in a partial differential form. Based on the equations, every alteration in the electric field in time ($\partial E/\partial t$) affects the value of the magnetic

field in space ($\nabla \times H$), and conversely. In the FDTD methods, the changed value of E (or H) in time, affects the stored value of the field, and the numerical curl of the H (or E) field in space. In 1966, Kane Yee's proposed a method, which discretizes the equations through finite volume cubic cells [175], covering the total calculated area. The electric E and H fields are determined over each cell. The vector components are distributed in such a way, that each electric field component is located midway between a pair of magnetic field components, and vice versa. The boundary conditions around the calculated area minimize the reflection and provide the maximal absorption of electromagnetic waves. The material constants of each cell are specified, e.g. permeability, permittivity, and conductivity.

The FDTD calculations were performed using commercially available EM Explorer, employing the built in script *Surface Plasmon Resonance (SPR) Produced by Grating*. The original script has been modified a number of times, as needed. The calculations of the structures with any geometry were introduced, by implementing the structure parameters from an external file. This way a random surface roughness and other features were taken into account. Also, the multiple loops were used, enabling the automatic scanning of many parameters.

A.2.1. EM Explorer script

The rectangular structure

The script has been used to calculate the diffraction efficiency and the intensity of the electromagnetic field, for the rectangular transmissive grating, for any given number of grating periods and length of the flat surface outside the grating.

```
# Material properties
set L 0.78
set n_GL 1.51
set n_VAC 1.0
set k_GL 0.0
set k_VAC 0.0

# Grating properties
set PITCH 0.55
set WIDTH 0.0
set HEIGHT 0.055

set NP 183; # number of grating pitches
set W 100.0; # grating-free region size

# Yee cell size
set GRIDSIZE 0.01; #0.005; # user should try a smaller gridsize for better accuracy

# Simulation domain size
set LX [expr $PITCH * $NP + 2.0 * $W]
set LY $GRIDSIZE
set LZ 5.0

set OUTFILE [open "filename.txt" w]
puts $OUTFILE " theta R"
close $OUTFILE

# Number of Yee cells
set NX [expr int($LX/$GRIDSIZE+0.5)]
set NY [expr int($LY/$GRIDSIZE+0.5)]
set NZ [expr int($LZ/$GRIDSIZE+0.5)]

for {set THETA 15.4} {$THETA <15.8} {set THETA [expr $THETA+0.6]} {
```

```

set ID $THETA
### Setup FDTD grid
emxp::grid lx=[expr 1*$LX] ly=$LY lz=$LZ nx=$NX ny=$NY nz=$NZ n0=$n_GL k0=$k_GL

### Setup FDTD geoemtry
set n_Au [expr -0.27830938+0.85820907*$L-0.58519103*$L*$L+0.23758361*$L*$L*$L]
set k_Au [expr -1.62161159+8.00501576*$L]
#

set XC [expr 0.5*$LX]
set YC [expr 0.5*$LY]
set ZC [expr 0.5*$LZ]
set XW $LX
set YW 1.0
set ZW $HEIGHT
emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_VAC k=$k_VAC

for {set i 0} {$i < $NP} {incr i} {
    set XC [expr 0.5*$W]; #podklad zloty z lewej
    set ZC [expr 0.5*$LZ]
    set XW [expr $W]
    set ZW $HEIGHT
    emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au
}

for {set i 0} {$i < $NP} {incr i} {
    set XC [expr 1.5*$W+$NP*$PITCH]; #podklad zloty z prawej
    set ZC [expr 0.5*$LZ]
    set XW [expr $W]
    set ZW $HEIGHT
    emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au
}

for {set i 0} {$i < $NP} {incr i} {
    set XC [expr $W + $PITCH * ($i + 0.5)]; #cokolik zloty
    set ZC [expr 0.5*$LZ]
    set XW [expr $PITCH-$WIDTH]
    set ZW $HEIGHT
    emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au
}

#vacuum
set XC [expr 0.5*$LX];#obszar nad siatka
set YC [expr 0.5*$LY]
set ZC [expr 0.5*$LZ+0.5*$HEIGHT+0.5*($LZ-(0.5*$LZ+0.5*$HEIGHT))]
set XW $LX
set YW 1.0
set ZW [expr $LZ-(0.5*$LZ+0.5*$HEIGHT)]
emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_VAC k=$k_VAC

### Setup FDTD incident field (i.e., p-polarized planewave)
emxp::planewave2 wavelength=$L z_source=[expr 0.03*$LZ] theta=$THETA phi=0
ep_amp=1 es_amp=0 ep_phz=0.0 es_phz=0.0

### Setup FDTD convergence monitor
emxp::convergence i=[expr $NX/2] j=0 k=0 samples_per_cycle=0.1 sample_size=10
tolerance=0.001

#emxp::snapshot property=intensity file=I_filename imin=0 imax=$NX jmin=0 jmax=0

```

```

kmin=0 kmax=$NZ;

### Run FDTD solver
emxp::run n_cycles=1000

set R00 [emxp::diffraction_efficiency field=reflected type=individual m=0 n=0]

emxp::output property=intensity imin=0 imax=$NX jmin=0 jmax=0 kmin=0 kmax=$NZ
file=I_filename.vtk

# Save data to file
set OUTFILE [open "filename.txt" a]
puts $OUTFILE " $THETA $R00"
close $OUTFILE

### Reset FDTD solver before next loop
emxp::reset
}; # THETA loop

exit

```

The structure *from file*

The script has been used to calculate the diffraction efficiency and the intensity of the electromagnetic field, for the rectangular transmissive grating, for a structure profile given by the external files. The calculations of the script are time-consuming, taking from a few hours up to few days to calculate the intensity distributions and plasmonic resonances.

```

# Material properties
set L 0.78
set n_GL 1.51
set n_VAC 1.0
set k_GL 0.0
set k_VAC 0.0

# Grating properties
set PITCH 0.55
set WIDTH 0.04
set HEIGHT 0.055

set NP 50; # number of grating pitches
set W 0.0; # grating-free region size
# Read data from file
set dx 0.01

set FILENAME "profile.txt"
set FILE [open $FILENAME "r"]
set TEXT [read $FILE]
close $FILE
set LINES [split $TEXT "\n"]
set profile [list]
foreach LINE $LINES {
    if {$LINE == ""} {continue}
    lappend profile [expr double($LINE)]
}
set npts [llength $profile]
puts "$npts points read"

# Post-process the profile to compact the data
set profile2 [list]

```

```

set x1 0.0
set p1 [lindex $profile 0]
set x 0.0
foreach p $profile {
    set x [expr $x+$dx]
    if {$p != $p1} {
        lappend profile2 [expr $x - $x1]
        lappend profile2 $p1
        set x1 $x
        set p1 $p
    }
}
lappend profile2 [expr $x - $x1]
lappend profile2 $p1

set FILENAMEa "filename.txt"
set FILEa [open $FILENAMEa "r"]
set TEXTa [read $FILEa]
close $FILEa
set LINESa [split $TEXTa "\n"]
set profilea [list]
foreach LINEa $LINESa {
    if {$LINEa == ""} {continue}
    lappend profilea [expr double($LINEa)]
}
set nptsa [llength $profilea]
puts "$nptsa points read"

# Post-process the profile to compact the data
set profile2a [list]
set x1a 0.0
set p1a [lindex $profilea 0]
set xa 0.0
foreach pa $profilea {
    set xa [expr $xa+$dx]
    if {$pa != $p1a} {
        lappend profile2a [expr $xa - $x1a]
        lappend profile2a $p1a
        set x1a $xa
        set p1a $pa
    }
}
lappend profile2a [expr $xa - $x1a]
lappend profile2a $p1a

# Yee cell size

set GRIDSIZE 0.01; #0.005; # user should try a smaller gridsize for better accuracy

# Simulation domain size
set LX [expr $PITCH * $NP + 2.0 * $W]
set LY $GRIDSIZE
set LZ 9.9

# Number of Yee cells
set NX [expr int($LX/$GRIDSIZE+0.5)]
set NY [expr int($LY/$GRIDSIZE+0.5)]
set NZ [expr int($LZ/$GRIDSIZE+0.5)]

```

```

for {set THETA 15.4} {$THETA <=15.4} {set THETA [expr $THETA+0.4]} {

set ID $THETA
### Setup FDTD grid
emxp::grid lx=[expr 1*$LX] ly=$LY lz=$LZ nx=$NX ny=$NY nz=$NZ n0=$n_GL k0=$k_GL

### Setup FDTD geoemtry
set n_Au [expr -0.27830938+0.85820907*$L-0.58519103*$L*$L+0.23758361*$L*$L*$L]
set k_Au [expr -1.62161159+8.00501576*$L]
#

set XC [expr 0.5*$LX]
set YC [expr 0.5*$LY]
set ZC [expr 0.5*$LZ]
set XW $LX
set YW 1.0
set ZW $HEIGHT
emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_VAC k=$k_VAC

#vacuum->glass
set XC [expr 0.5*$LX];#obszar nad siatka
set YC [expr 0.5*$LY]
set ZC [expr 0.5*$LZ+0.5*$HEIGHT+0.5*($LZ-(0.5*$LZ+0.5*$HEIGHT))]
set XW $LX
set YW 1.0
set ZW [expr $LZ-(0.5*$LZ+0.5*$HEIGHT)]
emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_GL k=$k_GL

set position [expr 0.5*$LX-0.6]

# surface glass
set x 0.0
foreach {w p} $profile2 {
    set XC [expr $x+0.5*$w]
    set YC [expr 0.5*$LY]
    set ZC [expr 0.5*$LZ+0.5*$p]
    set XW $w
    set YW 1.0
    set ZW $p
    if {$p < [expr 0.5*$HEIGHT]} {
        emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au
    } else {
        emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au
    }
    set x [expr $x+$w]
}

#surface au

set xa 0.0
foreach {wa pa} $profile2a {
    set XC [expr $xa+0.5*$wa]
    set YC [expr 0.5*$LY]
    set ZC [expr 0.5*$LZ+0.5*$pa]
    set XW $wa
    set YW 1.0
    set ZW $pa
    if {$pa < [expr 0.5*$HEIGHT]} {
        emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_VAC k=$k_VAC
    }
}

```

```

    } else {
        emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_VAC k=$k_VAC
    }
    set xa [expr $xa+$wa]
}

for {set i 0} {$i < $NP} {incr i} {
    set XC [expr $W + $PITCH * ($i + 0.5)]; #cokolik zloty
    set ZC [expr 0.5*$LZ]
    set XW [expr $PITCH-$WIDTH]
    set ZW $HEIGHT
    emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au
}

#Au
# set XC [expr $position-0.075];#obszar nad siatka
# set YC [expr 0.5*$LY]
# set ZC [expr 0.75*$LZ+0.03]
# set XW 0.1
# set YW 1.0
# set ZW [expr 4.97]
# emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au

#fiber
# set XC $position;#obszar nad siatka
# set YC [expr 0.5*$LY]
# set ZC [expr 0.75*$LZ-0.47]
# set XW 0.05
# set YW 1.0
# set ZW [expr 3.97]
# emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_GL k=$k_GL

#Au
#set XC [expr $position+0.075];#obszar nad siatka
#set YC [expr 0.5*$LY]
#set ZC [expr 0.75*$LZ+0.03]
#set XW 0.1
#set YW 1.0
#set ZW [expr 4.97]
#emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_Au k=$k_Au

#set XC [expr $PITCH-0.5*($LX-$WIDTH1)]
#set YC [expr 0.5*$LY]
#set ZC [expr 0.5*$LZ+0.5*$HEIGHT+0.5*$TH]
#set XW [expr $PITCH-$WIDTH1]
#set YW 1.0
#set ZW $TH
#emxp::solid shape=box xc=$XC yc=$YC zc=$ZC xw=$XW yw=$YW zw=$ZW n=$n_VAC k=$k_VAC

### Setup FDTD incident field (i.e., p-polarized planewave)
emxp::planewave2 wavelength=$L z_source=[expr 0.03*$LZ] theta=$THETA phi=0
ep_amp=1 es_amp=0 ep_phz=0.0 es_phz=0.0

### Setup FDTD convergence monitor
emxp::convergence i=[expr $NX/2] j=0 k=0 samples_per_cycle=0.1 sample_size=10 tolerance=0.001

#emxp::snapshot property=intensity file=intensity_${ID} imin=0 imax=$NX jmin=0 jmax=0
kmin=0 kmax=$NZ;

### Run FDTD solver

```

```

    emxp::run n_cycles=100

set flux88 [emxp::poynting_flux xc=$position yc=[expr 0.5*$LY] zc=8.8 xw=6.0 yw=$LY zw=0]
set flux98 [emxp::poynting_flux xc=$position yc=[expr 0.5*$LY] zc=9.8 xw=8.0 yw=$LY zw=0]

set R00 [emxp::diffraction_efficiency field=reflected type=individual m=0 n=0]

emxp::output property=intensity imin=0 imax=$NX jmin=0 jmax=0 kmin=0 kmax=$NZ file=I_filename.vtk

# Save data to file
set OUTFILE [open "filename.txt" a]
puts $OUTFILE " $THETA $flux88 $flux98 $R00 $position"
close $OUTFILE

### Reset FDTD solver before next loop
emxp::reset
}; # THETA loop

exit

```

Appendix B

Analysis of optical discs

B.1. Surface topography

To compare the shape and dimensions between different optical discs, it is crucial to know the repeatability of the parameters among one disc type. Figure B.1 presents the AFM-based topographies of the disc, performed for SK DVD+R. The comparison applies to the following:

1. In order to investigate the repeatability of the AFM measurements, the disc topography has been imaged in two consecutive measurements at the same place, revealing the exactly same profile.
2. To confirm the homogeneity of the disc, four approaches to different regions of one disc have been performed. All profiles match each other.
3. To confirm the homogeneity within one company, two different discs of SK DVD+R have been examined, revealing good consistency.

Figure B.2 shows the AFM-based topographies of optical discs for three different brands, from which +R/-R and +RW/-RW pairs have been tested. The measurements show the same grating period, height and shape of the grating profile among the respective pairs, revealing no difference in the construction of the structure for +R/-R and +RW/-RW.

Figure B.3 presents the AFM-based topographies of the disc, performed for five optical discs of different companies. The grating period and the shape of the profile remains the same for different brands, whereas the height varies by several dozens of nm.

B.2. Composition

The composition of the respective layers of optical disc was examined with Secondary Ion Mass Spectroscopy (SIMS), by Dr. Paweł Dąbczyński. Figures B.4 and B.5 show the composition of metallic layer of recordable and rewritable discs, respectively. The recordable metallic layer consists of silver, with a low carbon content, whereas the rewritable metallic layer is made of silver (mostly), carbon, zinc, sulfur and silicone.

B.3. Plasmonic resonances

The full angle dependence of the zeroth order reflectivity is presented in Fig. B.6-B.8, for the measured and calculated values, for 633, 785 and 1083 nm laser light. The red and black

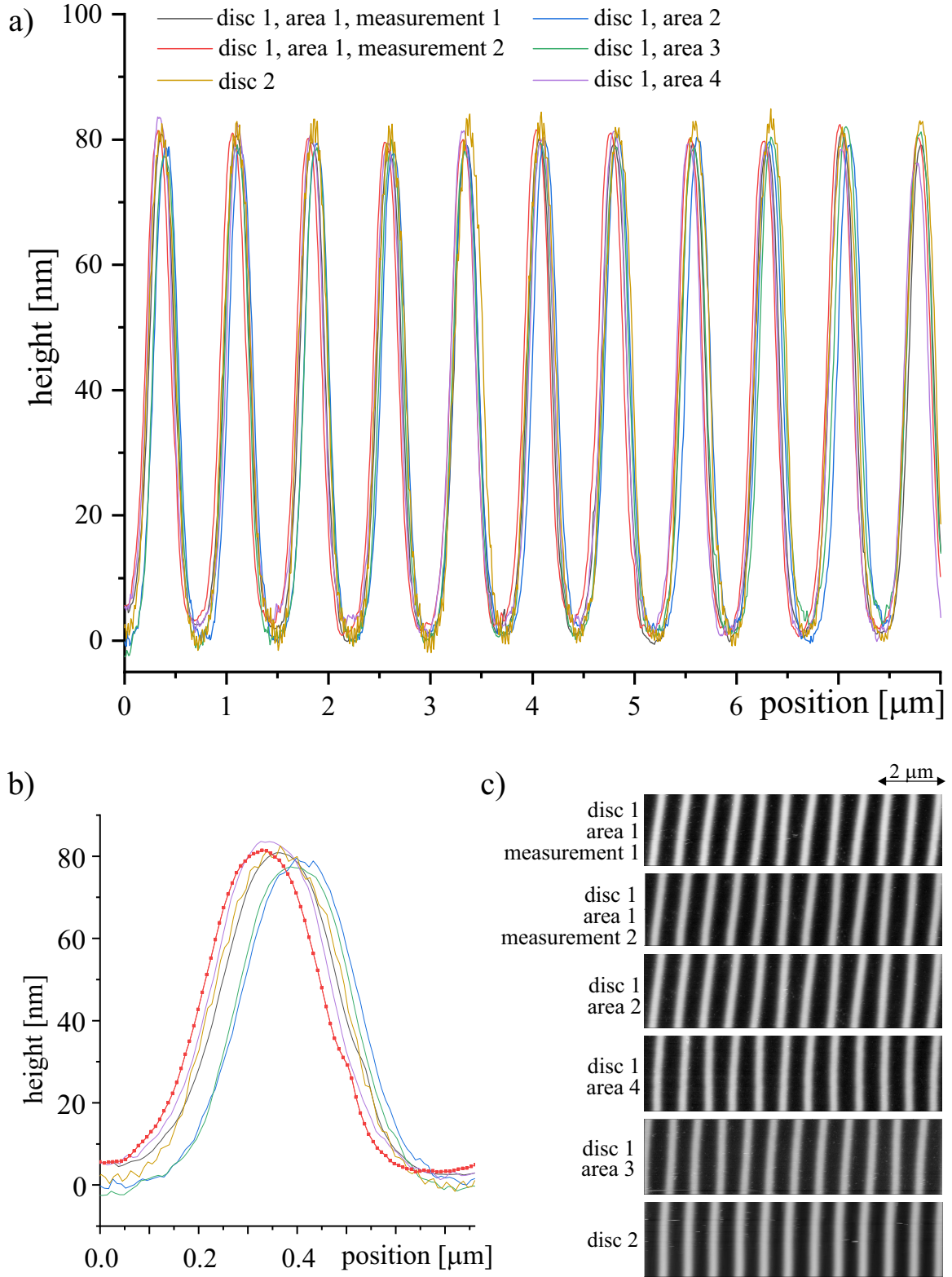


Figure B.1: AFM-based topographies of the top, metallic layer of SK DVD+R optical disc. The comparison between two separate measurements of one spot ('disc 1 area 1, measurement 1' and 'disc 1 area 1, measurement 2'), two different spots on one disc ('disc 1, area 1', 'disc 1, area 2', 'disc 1, area 13' and 'disc 1, area 4'), and two different discs of the company ('disc 1' and 'disc 2'). a) The shape of the profile for eleven grating periods. b) Close up view on one grating period. The resolution of the scan is marked with red squares. c) AFM images of topographies of the respective measurements.

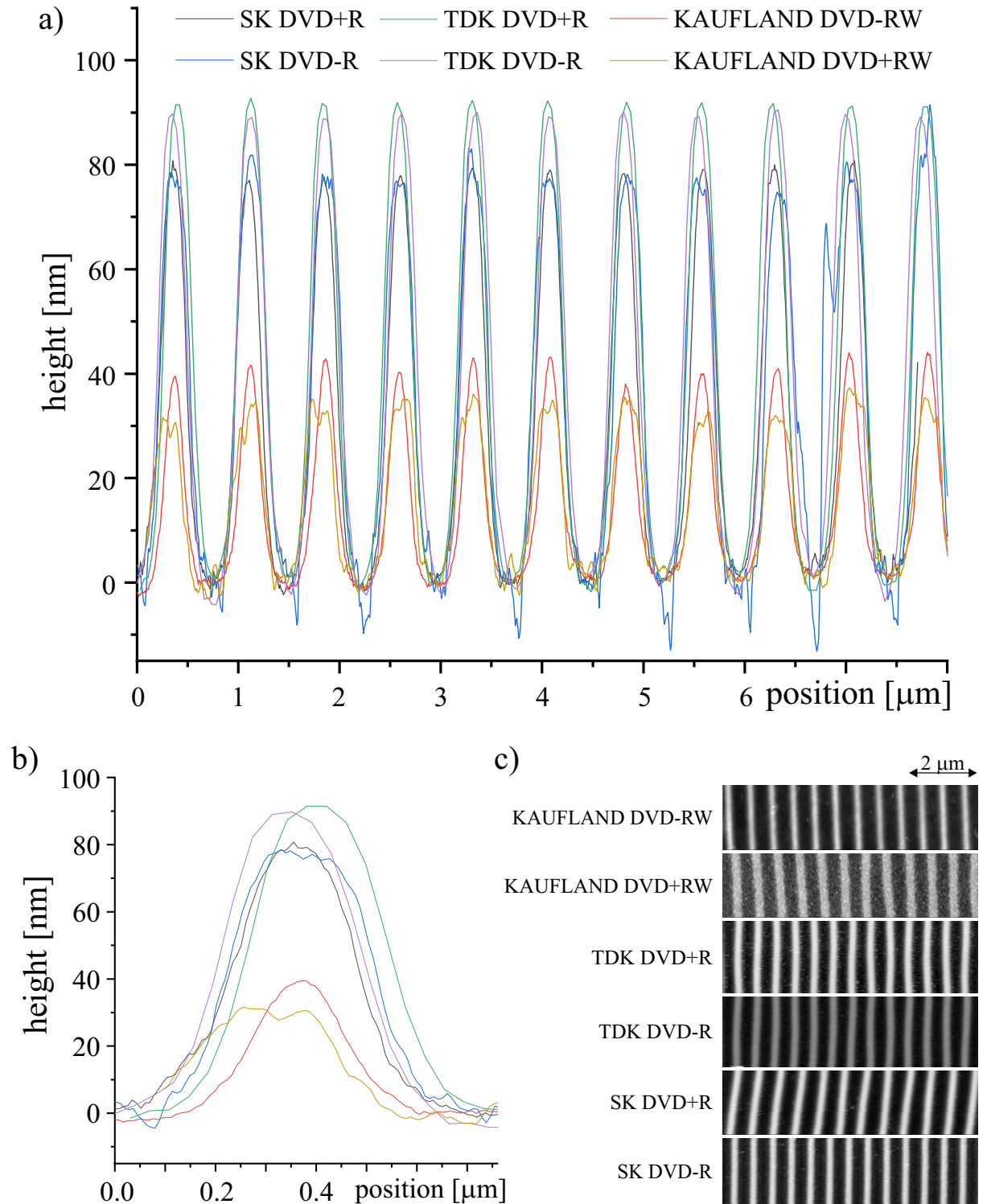


Figure B.2: AFM-based topographies of the top metallic layer performed for discs fabricated by different companies: SK, TDK, OMEGA, Giga Master and Kaufland. a) A few periods of profile shapes obtained for each of the measurements. b) Close up view on one grating period. c) AFM topographies of the respective measurements.

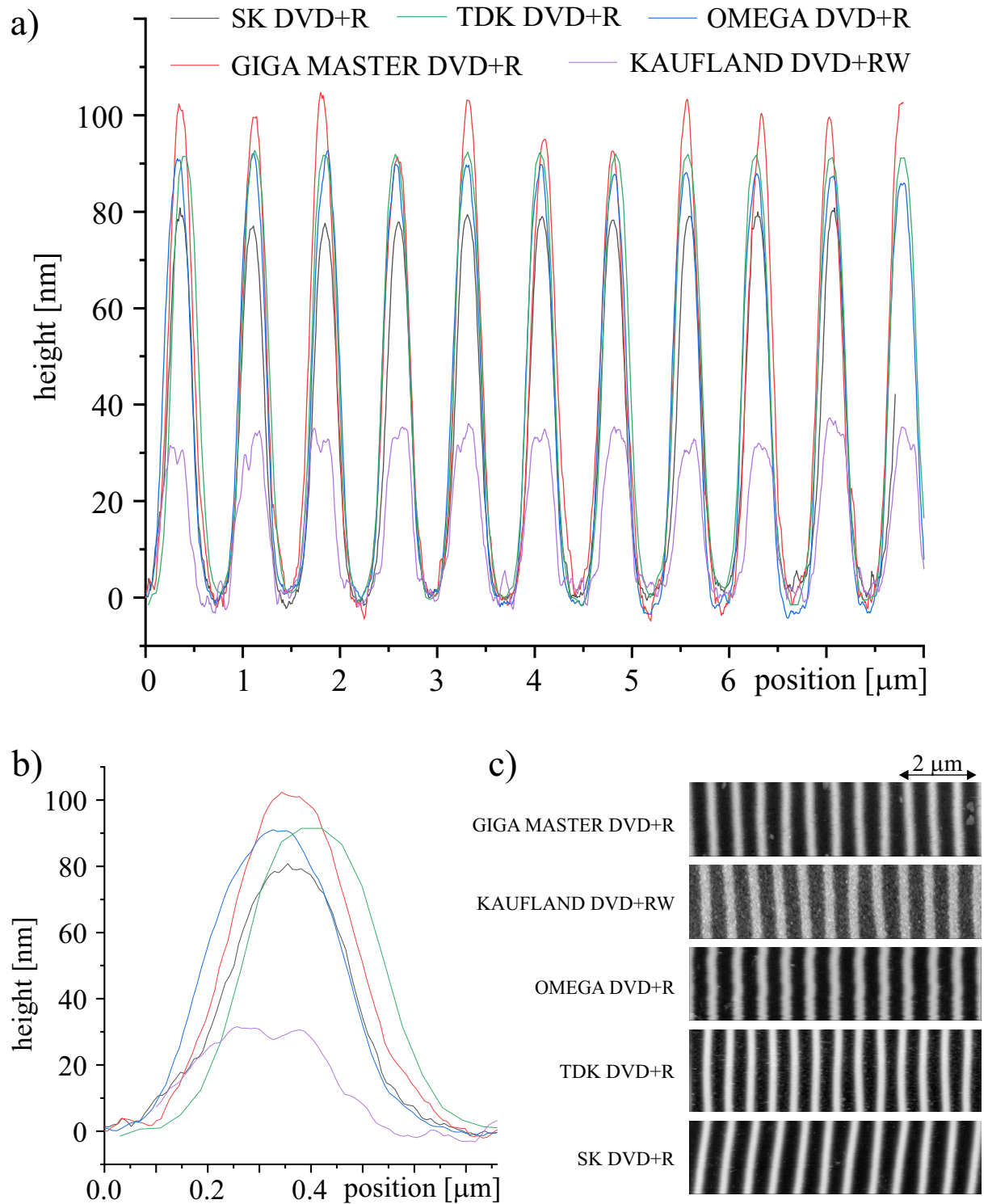


Figure B.3: AFM-based topographies of the top metallic layer: comparison between +R and -R as well as +RW and -RW on the example of 3 companies: SK, TDK and Kaufland. a) A few periods of profile shapes obtained for each of the measurements. b) Close up view on one grating period. c) AFM topographies of the respective measurements.

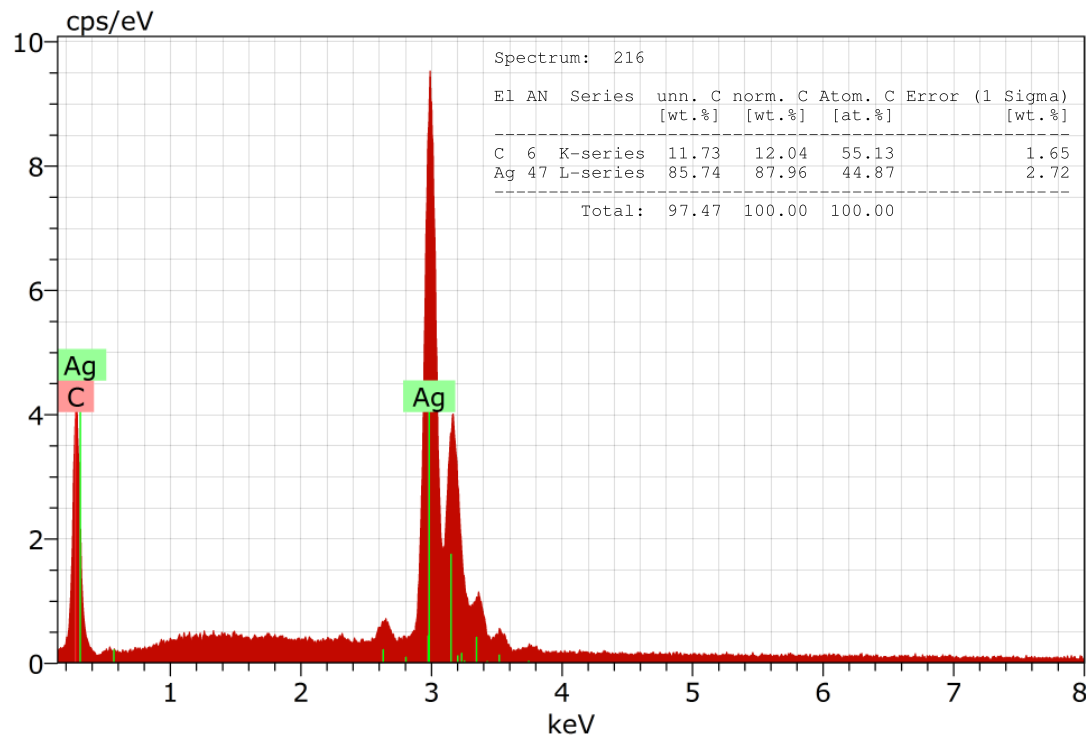


Figure B.4: SIMS measurements. Composition of metallic layer of SK DVD+R. Measurement performed by Dr. Paweł Dąbczyński.

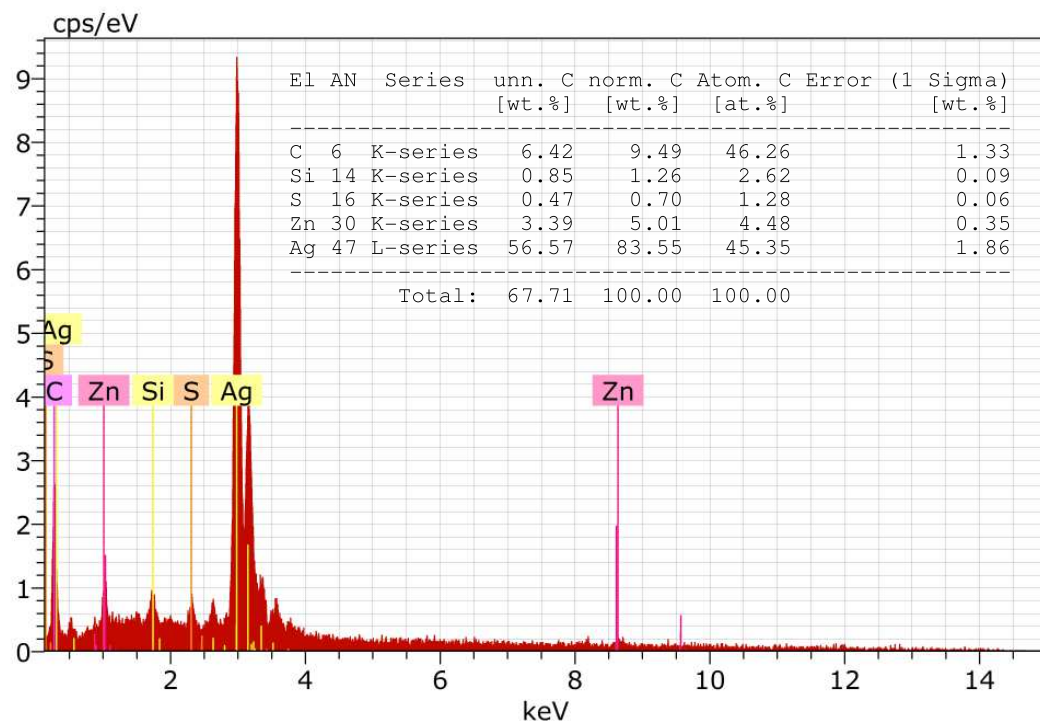


Figure B.5: SIMS measurements. Composition of metallic layer of Kaufland DVD+RW. Measurement performed by Dr. Paweł Dąbczyński.

colors indicate the TM and TE polarized light, respectively. RCWA calculations are marked with solid and dashed lines, and the results of far-field goniometric measurements are denoted by crosses.

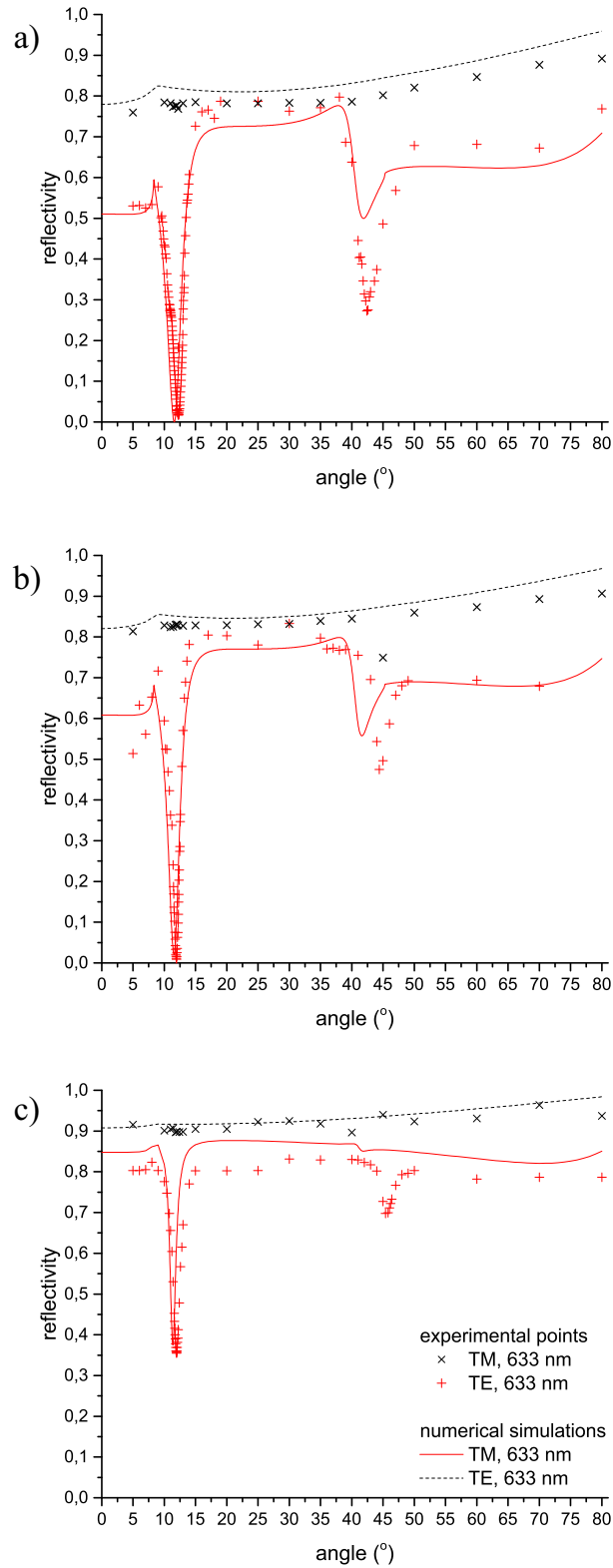


Figure B.6: The reflection coefficients as a function of angle of incidence. The investigation is performed for 633 nm of TM (red) and TE (black) polarized laser beam, for a) *sample 1*, b) *sample 2* and c) *sample 3*.

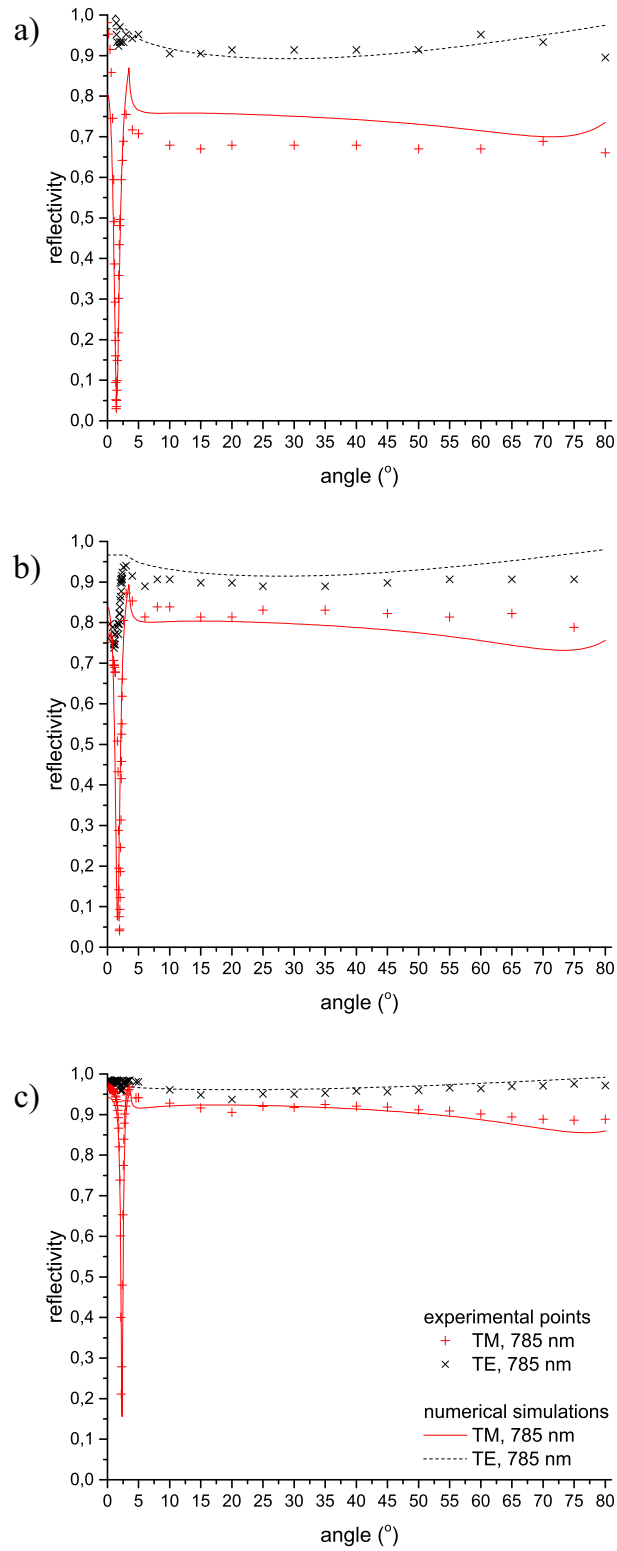


Figure B.7: The reflection coefficients as a function of angle of incidence. The investigation is performed for 785 nm of TM (red) and TE (black) polarized laser beam, for a) *sample 1*, b) *sample 2* and c) *sample 3*.

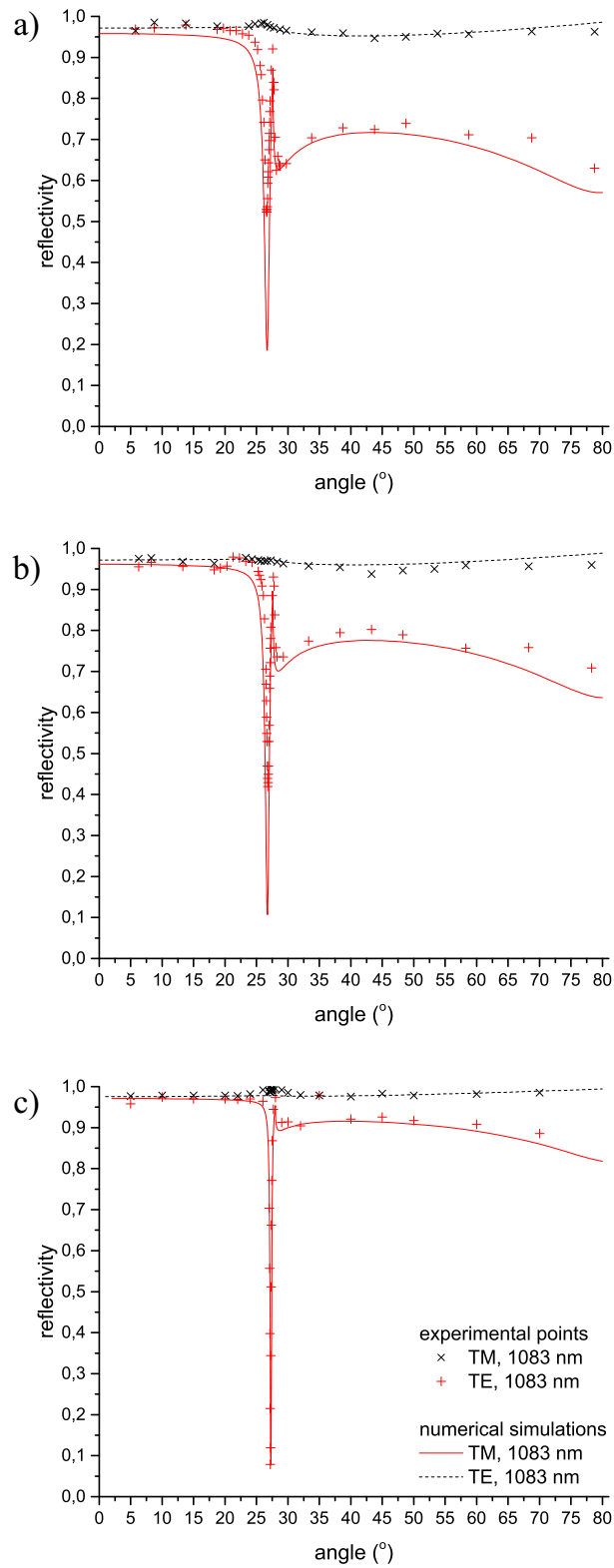


Figure B.8: The reflection coefficients as a function of angle of incidence. The investigation is performed for 1083 nm of TM (red) and TE (black) polarized laser beam, for a) *sample 1*, b) *sample 2* and c) *sample 3*.

Bibliography

- [1] Rudolf Grimm, Matthias Weidemüller, and Yurii B Ovchinnikov. Optical dipole traps for neutral atoms. In *Advances in atomic, molecular, and optical physics*, volume 42, pages 95–170. Elsevier, 2000.
- [2] Heinz Raether. Surface plasmons. *Springer tracts in modern physics*, 111:1, 1988.
- [3] William L Barnes, Alain Dereux, and Thomas W Ebbesen. Surface plasmon subwavelength optics. *Nature*, 424(6950):824–830, 2003.
- [4] Junxi Zhang, Lide Zhang, and Wei Xu. Surface Plasmon Polaritons: physics and applications. *Journal of Physics D: Applied Physics*, 45(11):113001, 2012.
- [5] Jian Feng Li, Yi Fan Huang, Yong Ding, Zhi Lin Yang, Song Bo Li, Xiao Shun Zhou, Feng Ru Fan, Wei Zhang, Zhi You Zhou, Bin Ren, et al. Shell-isolated nanoparticle-enhanced Raman spectroscopy. *Nature*, 464(7287):392–395, 2010.
- [6] Mark H Kryder, Edward C Gage, Terry W McDaniel, William A Challener, Robert E Rottmayer, Ganping Ju, Yiao-Tee Hsia, and M Fatih Erden. Heat assisted magnetic recording. *Proceedings of the IEEE*, 96(11):1810–1835, 2008.
- [7] Peter Zijlstra, James WM Chon, and Min Gu. Five-dimensional optical recording mediated by surface plasmons in gold nanorods. *Nature*, 459(7245):410–413, 2009.
- [8] O Stenzel, A Stendal, K Voigtsberger, and C Von Borczyskowski. Enhancement of the photovoltaic conversion efficiency of copper phthalocyanine thin film devices by incorporation of metal clusters. *Solar Energy Materials and Solar Cells*, 37(3-4):337–348, 1995.
- [9] Vivian E Ferry, Luke A Sweatlock, Domenico Pacifici, and Harry A Atwater. Plasmonic nanostructure design for efficient light coupling into solar cells. *Nano Letters*, 8(12):4391–4397, 2008.
- [10] Michael D Brown, Teeraporn Suteewong, R Sai Santosh Kumar, Valerio D’Innocenzo, Annamaria Petrozza, Michael M Lee, Ulrich Wiesner, and Henry J Snaith. Plasmonic dye-sensitized solar cells using core-shell metal-insulator nanoparticles. *Nano Letters*, 11(2):438–445, 2011.
- [11] Alexandre Brolo. Plasmonics for future biosensors. *Nature Photonics*, 6:709–713, 11 2012.
- [12] Jiř Homola, Sinclair S Yee, and Günter Gauglitz. Surface plasmon resonance sensors. *Sensors and Actuators B: Chemical*, 54(1-2):3–15, 1999.
- [13] Leon R Hirsch, R Jason Stafford, James A Bankson, Scott R Sershen, B Rivera, RE Price, John D Hazle, Naomi J Halas, and Jennifer L West. Nanoshell-mediated near-infrared thermal therapy of tumors under magnetic resonance guidance. *Proceedings of the National Academy of Sciences*, 100(23):13549–13554, 2003.

- [14] Prashant K Jain, Ivan H El-Sayed, and Mostafa A El-Sayed. Au nanoparticles target cancer. *Nano Today*, 2(1):18–29, 2007.
- [15] Christian Stehle, Helmar Bender, Claus Zimmermann, Dieter Kern, Monika Fleischer, and Sebastian Slama. Plasmonically tailored micropotentials for ultracold atoms. *Nature Photonics*, 5(8):494, 2011.
- [16] Stefan Alexander Maier. *Plasmonics: fundamentals and applications*. Springer Science & Business Media, 2007.
- [17] Mark S Tame, KR McEnery, ŞK Özdemir, Jinhyoung Lee, Stefan A Maier, and MS Kim. Quantum plasmonics. *Nature Physics*, 9(6):329–340, 2013.
- [18] Christian Stehle, Claus Zimmermann, and Sebastian Slama. Cooperative coupling of ultracold atoms and surface plasmons. *Nature Physics*, 10(12):937–942, 2014.
- [19] Matthias Mildner, Andreas Horrer, Monika Fleischer, Claus Zimmermann, and Sebastian Slama. Plasmonic trapping potentials for cold atoms. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 51(13):135005, 2018.
- [20] B Juliá-Díaz, T Graß, O Dutta, DE Chang, and M Lewenstein. Engineering p-wave interactions in ultracold atoms using nanoplasmonic traps. *Nature Communications*, 4(1):1–7, 2013.
- [21] DE Chang, JD Thompson, H Park, V Vuletić, AS Zibrov, P Zoller, and MD Lukin. Trapping and manipulation of isolated atoms using nanoscale plasmonic structures. *Physical Review Letters*, 103(12):123004, 2009.
- [22] M Gullans, TG Tiecke, DE Chang, J Feist, JD Thompson, J Ignacio Cirac, P Zoller, and Mikhail D Lukin. Nanoplasmonic lattices for ultracold atoms. *Physical Review Letters*, 109(23):235309, 2012.
- [23] E. L. Raab, M. Prentiss, Alex Cable, Steven Chu, and D. E. Pritchard. Trapping of neutral sodium atoms with radiation pressure. *Phys. Rev. Lett.*, 59:2631–2634, Dec 1987.
- [24] Steven Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable. Experimental observation of optically trapped atoms. *Phys. Rev. Lett.*, 57:314–317, Jul 1986.
- [25] Vladimir Georgievich Minogin and Vladilen Stepanovich Letokhov. *Laser light pressure on atoms*. CRC Press, 1987.
- [26] Paul D. Lett, Richard N. Watts, Christoph I. Westbrook, William D. Phillips, Phillip L. Gould, and Harold J. Metcalf. Observation of atoms laser cooled below the Doppler limit. *Phys. Rev. Lett.*, 61:169–172, Jul 1988.
- [27] J. Dalibard and C. Cohen-Tannoudji. Laser cooling below the Doppler limit by polarization gradients: simple theoretical models. *J. Opt. Soc. Am. B*, 6(11):2023–2045, Nov 1989.
- [28] C Salomon, J Dalibard, W. D Phillips, A Clairon, and S Guellati. Laser cooling of Cesium atoms below 3 μ k. *Europhysics Letters (EPL)*, 12(8):683–688, aug 1990.
- [29] D. Boiron, C. Triché, D. R. Meacher, P. Verkerk, and G. Grynberg. Three-dimensional cooling of cesium atoms in four-beam gray optical molasses. *Phys. Rev. A*, 52:R3425–R3428, Nov 1995.

- [30] A. Hemmerich, M. Weidemüller, T. Esslinger, C. Zimmermann, and T. Hänsch. Trapping atoms in a dark optical lattice. *Phys. Rev. Lett.*, 75:37–40, Jul 1995.
- [31] Mark Kasevich and Steven Chu. Laser cooling below a photon recoil with three-level atoms. *Phys. Rev. Lett.*, 69:1741–1744, Sep 1992.
- [32] A. Ashkin. Acceleration and trapping of particles by radiation pressure. *Phys. Rev. Lett.*, 24:156–159, Jan 1970.
- [33] A. Ashkin. Trapping of atoms by resonance radiation pressure. *Phys. Rev. Lett.*, 40:729–732, Mar 1978.
- [34] J. E. Bjorkholm, R. R. Freeman, A. Ashkin, and D. B. Pearson. Observation of focusing of neutral atoms by the dipole forces of resonance-radiation pressure. *Phys. Rev. Lett.*, 41:1361–1364, Nov 1978.
- [35] Alan L. Migdall, John V. Prodan, William D. Phillips, Thomas H. Bergeman, and Harold J. Metcalf. First observation of magnetically trapped neutral atoms. *Phys. Rev. Lett.*, 54:2596–2599, Jun 1985.
- [36] Wolfgang Ketterle and N. J. van Druten. Bose-Einstein condensation of a finite number of particles trapped in one or three dimensions. *Phys. Rev. A*, 54:656–660, Jul 1996.
- [37] Claude Cohen-Tannoudji, Jacques Dupont-Roc, and Gilbert Grynberg. Atom-photon interactions: basic processes and applications. *Atom-Photon Interactions: Basic Processes and Applications*, by Claude Cohen-Tannoudji, Jacques Dupont-Roc, Gilbert Grynberg, pp. 678. ISBN 0-471-29336-9. Wiley-VCH, March 1998., page 678, 1998.
- [38] JD Miller, RA Cline, and Daniel J Heinzen. Far-off-resonance optical trapping of atoms. *Physical Review A*, 47(6):R4567, 1993.
- [39] D Boiron, A Michaud, JM Fournier, L Simard, M Sprenger, G Grynberg, and C Salomon. Cold and dense cesium clouds in far-detuned dipole traps. *Physical Review A*, 57(6):R4106, 1998.
- [40] S Inouye, MR Andrews, J Stenger, H-J Miesner, DM Stamper-Kurn, and W Ketterle. Observation of feshbach resonances in a Bose-Einstein condensate. *Nature*, 392(6672):151–154, 1998.
- [41] Vladan Vuletić, Cheng Chin, Andrew J Kerman, and Steven Chu. Degenerate Raman sideband cooling of trapped cesium atoms at very high atomic densities. *Physical Review Letters*, 81(26):5768, 1998.
- [42] S Friebe, Cosimo D’Andrea, J Walz, M Weitz, and TW Hänsch. Co₂ laser optical lattice with cold rubidium atoms. *Physical Review A*, 57(1):R20, 1998.
- [43] CG Aminoff, AM Steane, P Bouyer, P Desbiolles, J Dalibard, and C Cohen-Tannoudji. Cesium atoms bouncing in a stable gravitational cavity. *Physical Review Letters*, 71(19):3083, 1993.
- [44] Yu B Ovchinnikov, I Manek, and R Grimm. Surface trap for cs atoms based on evanescent-wave cooling. *Physical Review Letters*, 79(12):2225, 1997.
- [45] Jacek Fiutowski, Dobrosława Bartoszek-Bober, Tomasz Dohnalik, and Tomasz Kawalec. Evanescent wave mirror for cold atoms—a quasi-resonant case. *Optics Communications*, 297:59–64, 2013.

- [46] Anatoly Zayats, Igor Smolyaninov, and Alexei Maradudin. Nano-optics of Surface Plasmon Polaritons. *Physics Reports*, 408(2011):131–314, 03 2005.
- [47] Lin Li. *Manipulation of near field propagation and far field radiation of surface plasmon polariton*. Springer, 2017.
- [48] JM Pitarke, VM Silkin, EV Chulkov, and PM Echenique. Theory of surface plasmons and surface-plasmon polaritons. *Reports on Progress in Physics*, 70(1):1, 2006.
- [49] Anatoly V Zayats and Igor I Smolyaninov. Near-field photonics: Surface Plasmon Polaritons and localized surface plasmons. *Journal of Optics A: Pure and Applied Optics*, 5(4):S16, 2003.
- [50] William L Barnes, W Andrew Murray, J Dintinger, E Devaux, and TW Ebbesen. Surface Plasmon Polaritons and their role in the enhanced transmission of light through periodic arrays of subwavelength holes in a metal film. *Physical Review Letters*, 92(10):107401, 2004.
- [51] P Törmä and William L Barnes. Strong coupling between Surface Plasmon Polaritons and emitters: a review. *Reports on Progress in Physics*, 78(1):013901, 2014.
- [52] Satoshi Kawata, Motoichi Ohtsu, and Masahiro Irie. *Near-field optics and Surface Plasmon Polaritons*, volume 81. Springer Science & Business Media, 2001.
- [53] Pierre Berini. Long-range Surface Plasmon Polaritons. *Advances in Optics and Photonics*, 1(3):484–588, 2009.
- [54] Harald Ditlbacher, Joachim R Krenn, Gerburg Schider, Alfred Leitner, and Franz R Aussenegg. Two-dimensional optics with Surface Plasmon Polaritons. *Applied Physics Letters*, 81(10):1762–1764, 2002.
- [55] Eliza Hutter and Janos H Fendler. Exploitation of localized surface plasmon resonance. *Advanced Materials*, 16(19):1685–1706, 2004.
- [56] Eleonora Petryayeva and Ulrich J Krull. Localized surface plasmon resonance: Nanostructures, bioassays and biosensing—a review. *Analytica Chimica Acta*, 706(1):8–24, 2011.
- [57] Catherine Louis and Olivier Pluchery. *Gold nanoparticles for physics, chemistry and biology*. World Scientific, 2012.
- [58] David J Griffiths. Introduction to electrodynamics, 2005.
- [59] Charles Kittel, Paul McEuen, and Paul McEuen. *Introduction to solid state physics*, volume 8. Wiley New York, 1996.
- [60] Tahir Iqbal. Propagation length of Surface Plasmon Polaritons excited by a 1d plasmonic grating. *Current Applied Physics*, 15(11):1445–1452, 2015.
- [61] Anatoly V Zayats, Igor I Smolyaninov, and Alexei A Maradudin. Nano-optics of Surface Plasmon Polaritons. *Physics Reports*, 408(3-4):131–314, 2005.
- [62] R Vincent and J Silcox. Dispersion of radiative surface plasmons in aluminum films by electron scattering. *Physical Review Letters*, 31(25):1487, 1973.
- [63] RB Pettit, J Silcox, and R Vincent. Measurement of surface-plasmon dispersion in oxidized aluminum films. *Physical Review B*, 11(8):3116, 1975.

- [64] Hiroshi Kano, Seiji Mizuguchi, and Satoshi Kawata. Excitation of surface-plasmon polaritons by a focused laser beam. *JOSA B*, 15(4):1381–1386, 1998.
- [65] Dror Sarid and William A Challener. *Modern introduction to surface plasmons: theory, Mathematica modeling, and applications*. Cambridge University Press, 2010.
- [66] Andreas Otto. Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection. *Zeitschrift für Physik A Hadrons and nuclei*, 216(4):398–410, 1968.
- [67] A Otto. A new method for exciting non-radioactive surface plasma oscillations. *Phys. Stat. Sol.*, 26:K99–K101, 1968.
- [68] Erwin Kretschmann and Heinz Raether. Radiative decay of non radiative surface plasmons excited by light. *Zeitschrift für Naturforschung A*, 23(12):2135–2136, 1968.
- [69] EL Wood, JR Sambles, NP Cotter, and SC Kitson. Diffraction grating characterization using multiple-wavelength excitation of Surface Plasmon Polaritons. *Journal of Modern Optics*, 42(6):1343–1349, 1995.
- [70] Richard A Watts, Trevor W Preist, and J Roy Sambles. Sharp surface-plasmon resonances on deep diffraction gratings. *Physical Review Letters*, 79(20):3978, 1997.
- [71] Harald Ditlbacher, Joachim R Krenn, Nordin Félidj, B Lamprecht, Gerburg Schider, Marco Salerno, Alfred Leitner, and Franz R Aussenegg. Fluorescence imaging of surface plasmon fields. *Applied Physics Letters*, 80(3):404–406, 2002.
- [72] Aurélien Drezet, Andreas Hohenau, Daniel Koller, Andrey Stepanov, H Ditlbacher, Bernhard Steinberger, Franz Rembert Aussenegg, Alfred Leitner, and Joachim Rudolf Krenn. Leakage radiation microscopy of Surface Plasmon Polaritons. *Materials Science and Engineering: B*, 149(3):220–229, 2008.
- [73] Armando Giannattasio and William L Barnes. Direct observation of surface plasmon-polariton dispersion. *Optics Express*, 13(2):428–434, 2005.
- [74] Ricardo A Depine and Silvia Ledesma. Direct visualization of surface-plasmon bandgaps in the diffuse background of metallic gratings. *Optics Letters*, 29(19):2216–2218, 2004.
- [75] Tomasz Kawalec, Aleksandra Sierant, Roman Panaś, Jacek Fiutowski, Dobrosława Bartoszek-Bober, Leszek Jozefowski, and Horst-Gunter Rubahn. Surface Plasmon Polaritons probed with cold atoms. *Plasmonics*, 13, 03 2017.
- [76] Bindia Arora and B. K. Sahoo. Van der Waals coefficients for alkali-metal atoms in material media. *Phys. Rev. A*, 89:022511, Feb 2014.
- [77] Richard J Cook and Richard K Hill. An electromagnetic mirror for neutral atoms. *Optics Communications*, 43(4):258–260, 1982.
- [78] VI Balykin and VS Letokhov. Atomic cavity with light-induced mirrors. *Applied Physics B*, 48(6):517–523, 1989.
- [79] Mark A Kasevich, David S Weiss, and Steven Chu. Normal-incidence reflection of slow atoms from an optical evanescent wave. *Optics Letters*, 15(11):607–609, 1990.

- [80] Jonathan P Dowling and Julio Gea-Banacloche. Evanescent light-wave atom mirrors, resonators, waveguides, and traps. In *Advances in Atomic, Molecular, and Optical Physics*, volume 37, pages 1–94. Elsevier, 1996.
- [81] Tilman Esslinger, Matthias Weidemüller, Andreas Hemmerich, and Theodor W Hänsch. Surface-plasmon mirror for atoms. *Optics Letters*, 18(6):450–452, 1993.
- [82] S Feron, J Reinhardt, S Le Boiteux, O Gorceix, J Baudon, M Ducloy, J Robert, Ch Miniatura, S Nic Chormaic, H Haberland, et al. Reflection of metastable neon atoms by a surface plasmon wave. *Optics Communications*, 102(1-2):83–88, 1993.
- [83] H Gauck, M Hartl, D Schneble, H Schnitzler, T Pfau, and J Mlynek. Quasi-2d gas of laser cooled atoms in a planar matter waveguide. *Physical Review Letters*, 81(24):5298, 1998.
- [84] Tomasz Kawalec, Dobrosława Bartoszek-Bober, Roman Panaś, Jacek Fiutowski, Aleksandra Pławicka, and Horst-Günter Rubahn. Optical dipole mirror for cold atoms based on a metallic diffraction grating. *Opt. Lett.*, 39(10):2932–2935, 2014.
- [85] C Garcia-Segundo, H Yan, and MS Zhan. Atom trap with surface plasmon and evanescent field. *Physical Review A*, 75(3):030902, 2007.
- [86] Zhao Chen, Fan Zhang, Qi Zhang, Juanjuan Ren, He Hao, Xueke Duan, Pengfei Zhang, Tiancai Zhang, Ying Gu, and Qihuang Gong. Blue-detuned optical atom trapping in a compact plasmonic structure. *Photonics Research*, 5(5):436–440, 2017.
- [87] NT Phuong Lan, DT Thuy Nga, and Nguyen Ai Viet. Trapping cold atoms using surface plasmons with phase singularities generated by evanescent Bessel beams. In *J Phys Conf Ser*, volume 627, pages 0–8, 2015.
- [88] Burkan Kaplan, Hasan Güner, Ozlem Senlik, Kemal Gurel, Mehmet Bayindir, and Aykutlu Dâna. Tuning optical discs for plasmonic applications. *Plasmonics*, 4:237–243, 09 2009.
- [89] K. Chakraborty, N. Kumawat, Sabiha Sultana, and M.M. Varma. Enhancing the quality factor of grating coupled plasmon resonance in optical recording media. *Sensors and Actuators A: Physical*, 244:50–55, 2016.
- [90] Xuan Dou, Pei-Yu Chung, Peng Jiang, and Jianli Dai. Surface plasmon resonance and surface-enhanced Raman scattering sensing enabled by digital versatile discs. *Applied Physics Letters*, 100:041116, 2012.
- [91] Yuki Suzuki, Yuuko Okamoto, Yutaka Kurose, and Shuuichi Maeda. High-speed recording performance of metal azo dye containing digital video disc-recordable discs. *Japanese Journal of Applied Physics*, 38:1669–1674, 03 1999.
- [92] Gaëtan Lévêque and Olivier J. F. Martin. Optimization of finite diffraction gratings for the excitation of surface plasmons. *Journal of Applied Physics*, 100(12):124301, 2006.
- [93] Armando Giannattasio, Ian R. Hooper, and William L. Barnes. Dependence on surface profile in grating-assisted coupling of light to surface plasmon-polaritons. *Optics Communications*, 261(2):291 – 295, 2006.
- [94] Gowri Manickam, Ram Gandhiraman, Rajani K Vijayaraghavan, Laura Kerr, Colin Doyle, David Williams, and Stephen Daniels. Protection and functionalisation of silver as an optical sensing platform for highly sensitive SPR based analysis. *The Analyst*, 137:5265–71, 10 2012.

- [95] P. B. Johnson and R. W. Christy. Optical constants of the noble metals. *Phys. Rev. B*, 6:4370–4379, Dec 1972.
- [96] Luciano De Sio, Tiziana Placido, Roberto Comparelli, M Curri, Marinella Striccoli, Nelson Tabiryan, and Timothy J. Bunning. Next-generation thermo-plasmonic technologies and plasmonic nanoparticles in optoelectronics. *Progress in Quantum Electronics*, 41:23–70, 03 2015.
- [97] Daniel Tordera, Dan Zhao, Anton V. Volkov, Xavier Crispin, and Magnus P. Jonsson. Thermoplasmonic semitransparent nanohole electrodes. *Nano Letters*, 17(5):3145–3151, 2017. PMID: 28441500.
- [98] Guillaume Baffou and Romain Quidant. Thermo-plasmonics: using metallic nanostructures as nano-sources of heat. *Laser & Photonics Reviews*, 7(2):171–187, 2013.
- [99] Xiaohua Huang, Prashant K. Jain, Ivan H. El-Sayed, and Mostafa A. El-Sayed. Plasmonic photothermal therapy (PPTT) using gold nanoparticles. *Lasers in Medical Science*, 23(3):217, Aug 2007.
- [100] Huilai wu, Semen Grabarnik, A Emadi, G Graaf, and R F Wolffenbuttel. Characterization of thermal cross-talk in a MEMS-based thermopile detector array. *Journal of Micromechanics and Microengineering*, 19:074022, 06 2009.
- [101] Deepak Ganta, Elijah Dale, J P Rezac, and Albert Rosenberger. Optical method for measuring thermal accommodation coefficients using a whispering-gallery microresonator. *The Journal of Chemical Physics*, 135:084313, 08 2011.
- [102] W. Jacak. Size-dependence of the lorentz friction for surface plasmons in metallic nanosphere. *Opt. Expr.*, 23:4472–4481, 2015.
- [103] De Sio L *et al.* Next-generation thermo-plasmonic technologies and plasmonic nanoparticles in optoelectronics. *Progress in Quantum Electronics*, 41:23–70, 2015.
- [104] Xuan Dou, Pei-Yu Chung, Peng Jiang, and Jianli Dai. Surface plasmon resonance-enabled antibacterial digital versatile discs. *Applied Physics Letters*, 100(6):063702, 2012.
- [105] Dobrosława Bartoszek-Bober. *Manipulowanie atomami przy powierzchniach za pomocą potencjałów optycznych i magnetycznych*. PhD thesis, Jagiellonian University in Krakow, 2013.
- [106] Tomasz Kawalec and Dobrosława Bartoszek-Bober. Construction and performance of an optical phase and frequency lock of diode lasers. *Optical Engineering*, 52:126105, 12 2013.
- [107] Tomasz Kawalec and Dobrosława Bartoszek-Bober. Two-laser interference visible to the naked eye. *European Journal of Physics*, 33:85–90, 01 2012.
- [108] Isabelle Serre, Laurence Pruvost, and Hong Tuan Duong. Fluorescence imaging efficiency of cold atoms in free fall. *Appl. Opt.*, 37(6):1016–1021, Feb 1998.
- [109] Paul D. Lett, Richard N. Watts, Christoph I. Westbrook, William D. Phillips, Phillip L. Gould, and Harold J. Metcalf. Observation of atoms laser cooled below the Doppler limit. *Phys. Rev. Lett.*, 61:169–172, Jul 1988.
- [110] Roman Panaś. *Zimne atomy w bliskim polu optycznym*. PhD thesis, Jagiellonian University in Krakow, 2019.

- [111] A. Landragin, J.-Y. Courtois, G. Labeyrie, N. Vansteenkiste, C. I. Westbrook, and A. Aspect. Measurement of the van der Waals force in an atomic mirror. *Phys. Rev. Lett.*, 77:1464–1467, 1996.
- [112] Wei Ding, Yuxuan Wang, Hao Chen, and Stephen Y. Chou. Plasmonic nanocavity organic light-emitting diode with significantly enhanced light extraction, contrast, viewing angle, brightness, and low-glare. *Advanced Functional Materials*, 24(40):6329–6339, 2014.
- [113] Ting Xu, Yi-Kuei Wu, Xiangang Luo, and L. Jay Guo. Plasmonic nanoresonators for high-resolution colour filtering and spectral imaging. *Nature Communications*, 1(59), 2010.
- [114] HW Kihm, Kwang Geol Lee, DS Kim, JH Kang, and Q-Han Park. Control of surface plasmon generation efficiency by slit-width tuning. *Applied Physics Letters*, 92(5):051115, 2008.
- [115] Prabhu K Venuthurumilli, Xiaolei Wen, Vasudevan Iyer, Yong P Chen, and Xianfan Xu. Near-field imaging of surface plasmons from the bulk and surface state of topological insulator $\text{Bi}_2\text{Te}_2\text{Se}$. *ACS Photonics*, 6(10):2492–2498, 2019.
- [116] D Costantini, L Greusard, A Bousseksou, R Rungsawang, TP Zhang, Ségolène Callard, J Decobert, F Lelarge, G-H Duan, Y De Wilde, et al. In situ generation of Surface Plasmon Polaritons using a near-infrared laser diode. *Nano Letters*, 12(9):4693–4697, 2012.
- [117] J Jose, Franciscus B Segerink, Jeroen P Korterik, Alberto Gomez-Casado, Jurriaan Huskens, Jennifer Lynn Herek, and Herman L Offerhaus. Enhanced surface plasmon polariton propagation length using a buried metal grating. *Journal of Applied Physics*, 109(6):064906, 2011.
- [118] Tahir Iqbal. Coupling efficiency of Surface Plasmon Polaritons: far-and near-field analyses. *Plasmonics*, 12(1):215–221, 2017.
- [119] Mena N Gadalla, Kundan Chaudhary, Christine M Zgrabik, Federico Capasso, and Evelyn L Hu. Imaging of Surface Plasmon Polaritons in low-loss highly metallic titanium nitride thin films in visible and infrared regimes. *Optics Express*, 28(10):14536–14546, 2020.
- [120] Ekmel Ozbay. Plasmonics: Merging photonics and electronics at nanoscale dimensions. *Science*, 311(5758):189–193, 2006.
- [121] Alexander Minovich, Angela E Klein, Norik Janunts, Thomas Pertsch, Dragomir N Neshev, and Yuri S Kivshar. Generation and near-field imaging of Airy surface plasmons. *Physical Review Letters*, 107(11):116802, 2011.
- [122] Mathieu L Juan, Maurizio Righini, and Romain Quidant. Plasmon nano-optical tweezers. *Nature Photonics*, 5(6):349, 2011.
- [123] Wenshan Cai, Justin S. White, and Mark L. Brongersma. Compact, high-speed and power-efficient electrooptic plasmonic modulators. *Nano Letters*, 9(12):4403–4411, 2009. PMID: 19827771.
- [124] John Kitching. Chip-scale atomic devices. *Applied Physics Reviews*, 5(3):031302, 2018.
- [125] Kyung Hun Yoon, Michael L. Shuler, and Sung June Kim. Design optimization of nano-grating surface plasmon resonance sensors. *Opt. Express*, 14(11):4842–4849, 2006.

- [126] Anatoly V. Zayats, Igor I. Smolyaninov, and Alexei A. Maradudin. Nano-optics of Surface Plasmon Polaritons. *Physics Reports*, 408(3):131–314, 2005.
- [127] N Rotenberg and L Kuipers. Mapping nanoscale light fields. *Nature Photonics*, 8(12):919, 2014.
- [128] D. W. Pohl, W. Denk, and M. Lanz. Optical stethoscopy: Image recording with resolution $\lambda/20$. *Applied Physics Letters*, 44(7):651–653, 1984.
- [129] U. Durig, D. W. Pohl, and F. Rohner. Near-field optical-scanning microscopy. *Journal of Applied Physics*, 59(10):3318–3327, 1986.
- [130] E. Betzig, M. Isaacson, and A. Lewis. Collection mode near-field scanning optical microscopy. *Applied Physics Letters*, 51(25):2088–2090, 1987.
- [131] Ph Lalanne and JP Hugonin. Interaction between optical nano-objects at metallo-dielectric interfaces. *Nature Physics*, 2(8):551–556, 2006.
- [132] G Gay, O Alloschery, B Viaris De Lesegno, Colm O’Dwyer, J Weiner, and HJ Lezec. The optical response of nanostructured surfaces and the composite diffracted evanescent wave model. *Nature Physics*, 2(4):262–267, 2006.
- [133] H Gersen, TJ Karle, RJP Engelen, Wim Bogaerts, Jeroen P Korterik, NF Van Hulst, TF Krauss, and L Kuipers. Real-space observation of ultraslow light in photonic crystal waveguides. *Physical Review Letters*, 94(7):073903, 2005.
- [134] Sergey I Bozhevolnyi, Valentyn S Volkov, Thomas Søndergaard, Alexandra Boltasseva, Peter I Borel, and Martin Kristensen. Near-field imaging of light propagation in photonic crystal waveguides: Explicit role of bloch harmonics. *Physical Review B*, 66(23):235204, 2002.
- [135] Jens Dorfmueller, Daniel Dregely, Moritz Esslinger, Worawut Khunsin, Ralf Vogelgesang, Klaus Kern, and Harald Giessen. Near-field dynamics of optical Yagi-Uda nanoantennas. *Nano Letters*, 11(7):2819–2824, 2011.
- [136] M Schnell, A Garcia-Etxarri, AJ Huber, K Crozier, J Aizpurua, and R Hillenbrand. Controlling the near-field oscillations of loaded plasmonic nanoantennas. *Nature Photonics*, 3(5):287, 2009.
- [137] U Ch Fischer and DW Pohl. Observation of single-particle plasmons by near-field optical microscopy. *Physical Review Letters*, 62(4):458, 1989.
- [138] P. M. Adam, L. Salomon, F. de Fornel, and J. P. Goudonnet. Determination of the spatial extension of the surface-plasmon evanescent field of a silver film with a photon scanning tunneling microscope. *Phys. Rev. B*, 48:2680–2683, Jul 1993.
- [139] Othmar Marti, Hartmut Bielefeld, Bert Hecht, Stephan Herminghaus, Paul Leiderer, and Jürgen Mlynek. Near-field optical measurement of the surface plasmon field. *Optics Communications*, 96(4-6):225–228, 1993.
- [140] Paul Dawson, Frédérique De Fornel, and Jean-Pierre Goudonnet. Imaging of surface plasmon propagation and edge interaction using a photon scanning tunneling microscope. *Physical Review Letters*, 72(18):2927, 1994.

- [141] J-C Weeber, Joachim R Krenn, Alain Dereux, B Lamprecht, Yvon Lacroute, and Jean-Pierre Goudonnet. Near-field observation of surface plasmon polariton propagation on thin metal stripes. *Physical Review B*, 64(4):045411, 2001.
- [142] Ramona Dallapiccola, C Dubois, A Gopinath, Francesco Stellacci, and L Dal Negro. Near-field excitation and near-field detection of propagating Surface Plasmon Polaritons on au waveguide structures. *Applied Physics Letters*, 94(24):243118, 2009.
- [143] Jörg P Kottmann, Olivier JF Martin, David R Smith, and Sheldon Schultz. Plasmon resonances of silver nanowires with a nonregular cross section. *Physical Review B*, 64(23):235402, 2001.
- [144] Jean-Claude Weeber, Alain Dereux, Christian Girard, Joachim R Krenn, and Jean-Pierre Goudonnet. Plasmon polaritons of metallic nanowires for controlling submicron propagation of light. *Physical Review B*, 60(12):9061, 1999.
- [145] Joachim R Krenn, B Lamprecht, Harald Ditlbacher, Gerburg Schider, Marco Salerno, Alfred Leitner, and Franz R Aussenegg. Non-diffraction-limited light transport by gold nanowires. *EPL (Europhysics Letters)*, 60(5):663, 2002.
- [146] Matthias M Wiecha, Shihab Al-Daffaie, Andrey Bogdanov, Mark D Thomson, Oktay Yilmazoglu, Franko Kuppens, Amin Soltani, and Hartmut G Roskos. Direct near-field observation of Surface Plasmon Polaritons on silver nanowires. *ACS Omega*, 2019.
- [147] Sinan Balci, Ertugrul Karademir, Coskun Kocabas, and Atilla Aydinli. Direct imaging of localized Surface Plasmon Polaritons. *Optics Letters*, 36(17):3401–3403, 2011.
- [148] Joachim R Krenn, Alain Dereux, Jean-Claude Weeber, E Bourillot, Y Lacroute, Jean-Pierre Goudonnet, Gerburg Schider, W Gotschy, Alfred Leitner, Franz R Aussenegg, et al. Squeezing the optical near-field zone by plasmon coupling of metallic nanoparticles. *Physical Review Letters*, 82(12):2590, 1999.
- [149] Stefan A Maier, Pieter G Kik, Harry A Atwater, Sheffer Meltzer, Elad Harel, Bruce E Koel, and Ari AG Requicha. Local detection of electromagnetic energy transport below the diffraction limit in metal nanoparticle plasmon waveguides. *Nature Materials*, 2(4):229–232, 2003.
- [150] Sergey I Bozhevolnyi, Valentyn S Volkov, and Kristjan Leosson. Localization and waveguiding of Surface Plasmon Polaritons in random nanostructures. *Physical Review Letters*, 89(18):186801, 2002.
- [151] Sergey I Bozhevolnyi, Valentyn S Volkov, Alexandra Boltasseva, and Kristjan Leosson. Local excitation of Surface Plasmon Polaritons in random surface nanostructures. *Optics Communications*, 223(1-3):25–29, 2003.
- [152] Kohei Imura, Tetsuhiko Nagahara, and Hiromi Okamoto. Near-field optical imaging of plasmon modes in gold nanorods. *The Journal of Chemical Physics*, 122(15):154701, 2005.
- [153] L Salomon, G Bassou, H Aourag, JP Dufour, F De Fornel, F Carcenac, and AV Zayats. Local excitation of Surface Plasmon Polaritons at discontinuities of a metal film: Theoretical analysis and optical near-field measurements. *Physical Review B*, 65(12):125409, 2002.

- [154] Tazuko Kitazawa, Shintaro Miyanishi, Yoshiteru Murakami, Kunio Kojima, and Akira Takahashi. Snom observations of Surface Plasmon Polaritons on metal heterostructures. *Chinese Physics Letters*, 24(10):2827, 2007.
- [155] Tazuko Kitazawa, Shintaro Miyanishi, Yoshiteru Murakami, Kunio Kojima, and Akira Takahashi. Refraction of surface plasmon-polaritons at au-al boundaries observed by scanning near-field optical microscopy. *Physical Review B*, 77(19):193404, 2008.
- [156] L Yin, VK Vlasko-Vlasov, A Rydh, J Pearson, U Welp, S-H Chang, SK Gray, George C Schatz, DB Brown, and C Wl Kimball. Surface plasmons at single nanoholes in au films. *Applied Physics Letters*, 85(3):467–469, 2004.
- [157] Rongjing He, Xiuli Zhou, Yongqi Fu, and Yiwei Zhang. Near-field optical experimental investigation of gold nanohole array. *Plasmonics*, 6(1):171–176, 2011.
- [158] Shih-Hui Chang, Stephen K Gray, and George C Schatz. Surface plasmon generation and light transmission by isolated nanoholes and arrays of nanoholes in thin metal films. *Optics Express*, 13(8):3150–3165, 2005.
- [159] Y Gorodetski, A Niv, V Kleiner, and E Hasman. Observation of the spin-based plasmonic effect in nanoscale structures. *Physical Review Letters*, 101(4):043903, 2008.
- [160] Fan Ye, Juan M Merlo, Michael J Burns, and Michael J Naughton. Optical and electrical mappings of surface plasmon cavity modes. *Nanophotonics*, 3(1-2):33–49, 2014.
- [161] Petr Dvořák, Tomáš Neuman, Lukáš Břínek, Tomáš Šamořil, Radek Kalousek, Petr Dub, Peter Varga, and Tomáš Šikola. Control and near-field detection of surface plasmon interference patterns. *Nano Letters*, 13(6):2558–2563, 2013.
- [162] Petr Dvořák, Zoltán Édes, Michal Kvapil, Tomáš Šamořil, Filip Ligmajer, Martin Hrtoň, Radek Kalousek, Vlastimil Křápek, Petr Dub, Jiří Spousta, Peter Varga, and Tomáš Šikola. Imaging of near-field interference patterns by aperture-type SNOM; influence of illumination wavelength and polarization state. *Opt. Express*, 25(14):16560–16573, Jul 2017.
- [163] P Dawson, BAF Puygranier, and JP Goudonnet. Surface plasmon polariton propagation length: A direct comparison using photon scanning tunneling microscopy and attenuated total reflection. *Physical Review B*, 63(20):205410, 2001.
- [164] Oksana Kostiučenko, Jacek Fiutowski, Tomasz Kawalec, Vladimir Bordo, Horst-Günter Rubahn, and Leszek Jozefowski. Surface plasmon polariton dispersion relation at organic/dielectric/metal interfaces. *Optics Communications*, 331:77–81, 2014.
- [165] Stephan T Koev, Amit Agrawal, Henri J Lezec, and Vladimir A Aksyuk. An efficient large-area grating coupler for Surface Plasmon Polaritons. *Plasmonics*, 7(2):269–277, 2012.
- [166] Aleksandra Sierant, Roman Panaś, Jacek Fiutowski, Horst-Günter Rubahn, and Tomasz Kawalec. Tailoring optical discs for Surface Plasmon Polaritons generation. *Nanotechnology*, 31(2):025303, 2019.
- [167] Aleksandra Sierant, Benedykt R. Jany, and Tomasz Kawalec. Quantitative near-field characterization of Surface Plasmon Polaritons on nanofabricated transmission structure. *arXiv e-prints*, arXiv:190.00357, 2020.

- [168] Xuan Dou, Pei-Yu Chung, Peng Jiang, and Jianli Dai. Surface plasmon resonance-enabled antibacterial digital versatile discs. *Applied Physics Letters*, 100(6):063702, 2012.
- [169] JR Sambles, GW Bradbery, and Fuzi Yang. Optical excitation of surface plasmons: an introduction. *Contemporary Physics*, 32(3):173–183, 1991.
- [170] Glenn D Boreman, Timothy Johnson, Andrew C Jones, Sang-Hyun Oh, Robert L Olmon, Markus B Raschke, David Shelton, and Brian Slovick. Broadband electrical permittivity of gold for plasmonics and nano-optics applications. In *Quantum Electronics and Laser Science Conference*, page QTuL3. Optical Society of America, 2011.
- [171] Peter B Johnson and R. W. Christy. Optical constants of the noble metals. *Physical Review B*, 6(12):4370, 1972.
- [172] Bora Ung and Yunlong Sheng. Interference of surface waves in a metallic nanoslit. *Optics Express*, 15(3):1182–1190, 2007.
- [173] Edward D Palik. *Handbook of optical constants of solids*, volume 3. Academic Press, 1998.
- [174] MG Moharam, Eric B Grann, Drew A Pommet, and TK Gaylord. Formulation for stable and efficient implementation of the rigorous coupled-wave analysis of binary gratings. *JOSA A*, 12(5):1068–1076, 1995.
- [175] Kane Yee. Numerical solution of initial boundary value problems involving Maxwell’s equations in isotropic media. *IEEE Transactions on Antennas and Propagation*, 14(3):302–307, 1966.