Sub-wavelength structures and applications

Xu, Zhengji

2016

Xu, Z. (2016). Sub-wavelength structures and applications. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/67328>

<https://doi.org/10.32657/10356/67328>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**SUB-WAVELENGTH STRUCTURES AND
APPLICATIONS**

XU ZHENGJI

SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

2016

SUB-WAVELENGTH STRUCTURES AND APPLICATIONS

XU ZHENGJI

SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

A THESIS SUBMITTED TO THE NANYANG TECHNOLOGICAL
UNIVERSITY IN FULFILLMENT OF THE REQUIREMENT FOR THE
DEGREE OF

DOCTOR OF PHILOSOPHY

2016

STATEMENT OF ORIGINALITY

I hereby certify that the content of this thesis is the result of work done by me and has not been submitted for a higher degree to any other University or Institution.

Signature of candidate

Date

ACKNOWLEDGEMENTS

First of all, I would like to express my deepest gratitude to my supervisor, Professor Zhang Dao Hua. I feel fortunate to be supervised by Prof. Zhang who has taught me from undergraduate years to the Ph.D. program. I would like to thank him for his continuous guidance, support and encouragement. What I have learnt from him is not only the in-depth knowledge, but also how to be a good researcher. He was not only the teacher in my study, but also a role model in my life.

During my postgraduate study, I have received invaluable help from many people in Prof. Zhang's research group and in Nanophotonics Laboratory. I have learnt a lot of theoretical, simulation and experimental skills from them. I am very much grateful to them. These include but not limited to: Dr. Yan Changchun, Dr. Landobasa Yosef Mario Alexander Lumban Tobing, Dr. Li Tao, Dr. Lin Jiao, Dr. Li Dongdong, Dr. Xie Yiyang, Dr. Ni Peinan, Dr. Chen Jian, Dr. Tong Jinchao, Mr. Qiu Shupeng, Mr. Aaron David Mueller, Ms. Chen Xizi, Dr. Jin Yunjiang, Dr. Wang Yueke, Dr. Yang Xuefeng, Dr. Qin Fei, Dr. Wang Jun, Dr. Bian Haijiao, Dr. Wang Wenjuan, Dr. Yuan Guanghui, Dr. Wang Qian, Dr. Du Luping, Dr. Ma Jie, Dr. Song Yufeng, Mr. Li Huakai, Mr. Hu Shaogang, Mr. Shao Guodong, Mr. Zhang Jun, Mr. Li Yicen, Mr. Zhang Hui, Dr. Xu Changwen, Dr. Yang Ming, Dr. Ng Tsu Hau, Mr. Chia Keng Yee and Mr. Lim Teng Kheng, Desmond.

I would like to thank Prof. Yu Ting, Dr. Shen Xiaonan, Dr. Qiu Caiyu, Dr. Yang Weihuang, Mr. Cao Bingchen, Mr. Zou Chenji and Dr. Zhang Qing for their help

on experiment facilitations. My gratitude is also extended to the staff and friends in Nanophotonics Laboratory, Characterization Laboratory, Photonics Laboratory I, Photonics Laboratory II and Clean Rooms in Nanyang NanoFabrication Center.

My special thanks will give to my parents, grandparents and my wife Xuehe for their love and great support to my Ph.D. program.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	I
ABSTRACT.....	VI
LIST OF FIGURES	IX
LIST OF TABLES	XV
CHAPTER 1. INTRODUCTION.....	1
1.1 Motivation.....	1
1.2 Objectives	7
1.3 Major contributions.....	8
1.4 Organization of the thesis	11
CHAPTER 2. BACKGROUND.....	13
2.1 Plasmonics Fundamentals.....	13
2.1.1 Optical properties of metals	13
2.1.2 SPP mode equations on a metal-dielectric interface	15
2.1.3 Excitation methods of SPPs	18
2.2 Metamaterials and Metasurfaces.....	22
2.2.1 Metamaterial fundamentals	22
2.2.2 Metasurfaces.....	23
2.3 Experimental methods	27
2.3.1 Electron beam lithography	27
2.3.2 Focused Ion Beams	35
2.3.3 Near-field scanning optical microscopy.....	39
CHAPTER 3. CONCENTRIC CYLINDRICAL METAMATERIALS FOR SUBWAVELENGTH DARK HOLLOW LIGHT CONES	41
3.1 Introduction to dark hollow beam and dark hollow light cone.....	41
3.2 Concentric Cylindrical Metamaterials Structures.....	42
3.3 Effective medium theory for layered structure metamaterials.....	43
3.3.1 CCM covered by a thin layer of chromium (Cr) containing an annulus opening.....	45
3.3.2 CCM covered by a thin layer of chromium (Cr) containing a hole opening	51

3.4 Chapter summary	53
CHAPTER 4. COGWHEELS FOR GENERATION OF SURFACE PLASMON POLARITON VORTEX	54
4.1 Introduction.....	54
4.2 Structure design and principles	55
4.3 Simulation and discussion.....	57
4.4 Chapter summary	62
CHAPTER 5. GROOVE-STRUCTURED METASURFACES FOR MODULATION OF SPP	63
5.1 Introduction.....	63
5.2 Theory and Simulation.....	64
5.2.1 Groove-structure metasurfaces for SPP beam splitting angle modulation	64
5.2.2 Groove-structure metasurfaces for SPP wavelength modulation	67
5.3 Experimental results for SPP wavelength modulation.....	72
5.4 Chapter summary	77
CHAPTER 6. ALUMINUM BASED STRUCTURES FOR MANIPULATING SHORT VISIBLE WAVELENGTH IN-PLANE SPP PROPAGATION	78
6.1 Introduction.....	78
6.2 The principle for wavelength modulation using MIA strucutre.....	79
6.3 The experimental verification of MIA structures.....	86
6.3.1 Fabrication of MIA structures using FIB	86
6.3.2 Near-field imaging of the SPPs with wavelength modulation	87
6.4 Chapter summary	89
CHAPTER 7. SUBWAVELENGTH STRUCTURES FOR VCSELS.....	90
7.1 VCSEL fundamentals.....	90
7.1.1 The brief introduction of VCSEL.....	90
7.1.2 Structure of a VCSEL.....	91
7.2 High Contrast Gratings application to 980nm VCSEL.....	95
7.2.1 Introduction to HCGs in VCSEL	95
7.2.2 Simulation results of GaAs/Al ₂ O ₃ HCGs.....	96
7.2.3 VCSEL and HCG fabrication	100
7.2.4 Measured reflectivity and discussion	101
7.3 SPP generation with VCSELS as the on-chip light source.....	104

7.3.1 VCSELs: The ideal light source for 2D optics and metasurfaces	104
7.3.2 Fabrication of 850nm VCSELs with gold film and gratings.....	105
7.3.3 Near-field imaging of on-chip SPP generation with different injection currents	108
7.4 Chapter summary	115
CHAPTER 8. CONCLUSIONS	116
8.1 Conclusions.....	116
8.2 Recommendations.....	119
AUTHOR’S PUBLICATIONS	121
BIBLIOGRAPHY	124

ABSTRACT

Electromagnetic (EM) wave is currently a major research topic in the modern physics. To quantitatively describe the EM wave, the frequency and wavelength are the two critical parameters used. The frequency is in the time scale, representing the energy of EM wave; while wavelength (or wave number) is in the spatial scale, representing the momentum of the EM wave. Subwavelength optics is based on the light properties and behaviors of subwavelength scaled optical devices. In the visible and near infrared ranges, tens to hundreds nanometers (less than one quarter of the wavelength) subwavelength structures are meaningful to the optical manipulations and extraordinary properties controlling.

The main works done by the candidate are summarized below:

A concentric cylindrical metamaterial (CCM) which can be used for acquiring a dark hollow light cone is designed. The proposed structure consists of a concentric cylindrical silver-dielectric multilayer composite, which is covered by a thin layer of chromium (Cr) containing an annulus or a hole opening for incidence. The simulation results show that an nanometer-level dark hollow light cones with good quality can be formed in the output for circularly polarized incidence and its position can be monitored by choosing different dielectric materials and dimensions of the annular apertures.

A cogwheel structure formed by an air ring and equally distributed air cogs along the ring on a gold film for generation of surface plasmon polariton (SPP) vortex is

proposed. A well-designed cogwheel can generate an optical vortex-like response. The characteristics of such SPP vortex are directly related to cogwheel geometries and can be controlled by adjusting the polarization direction of incident light.

Subwavelength gold groove structure as an alternative metasurface for tuning the wavelength and wavefront of the surface plasmon polariton was designed based on non-resonant mechanism and experimentally demonstrated. Using effective medium theory and finite element method, we calculated the relation between the effective refractive index and the metasurface geometrical parameters. The subwavelength gold groove structures were fabricated using focused ion beam and characterized by near-field scanning optical microscopy. The metasurfaces provide an alternative method for manipulating SPP propagation.

Aluminum based Metal-Insulator-Air (MIA) structures for manipulation of SPP propagation at short visible wavelength range was investigated. The simulation shows that aluminum is a good metal to excite and propagate SPPs with blue light as incidence and that the SPP wavelength can be reduced from about 465 nm to about 265 nm by monitoring the thickness of a coated Si_3N_4 layer deposited on the aluminum film. It is also shown that the damping becomes more significant with the increase of the thickness of the Si_3N_4 layer. The phenomena were experimentally confirmed and can be explained by the variation of effective permittivity. The proposed MIA structures with SPP wavelength tuning ability have potential applications in 2D optics.

High contrast grating (HCG) structures for 980 nm vertical cavity surface emitting lasers (VCSELs) were studied. The new HCG structure is made of GaAs/Al₂O₃. The GaAs layer is generated by direct growth while the Al₂O₃ layer is converted from an epitaxial AlAs layer through oxidation process. The new HCG structures are much easier to be fabricated and have high reliability. The calculated results reveal that the GaAs/Al₂O₃ HCG structures have high reflectance and bandwidth comparable to those of air cavity and the reflectance spectrum shifts towards long wavelength with the increase of periods of gratings. The FIB fabricated HCG structures show that the reflectance values are sensitive to the deviation of the gratings.

Direct SPP excitation using a VCSEL is investigated as it can provide a compact solution for the on-chip SPP generation. In this case, the grating structures were fabricated on surface of the VCSELs by mounting either on a printed circuit board (PCB) or on a copper heat sink to fit the NSOM measurement requirement. It is found that the SPP beam or wave front can be manipulated by varying the VCSEL injection current.

LIST OF FIGURES

Figure 1.1 Jute elements and polarization apparatus setup [4]. © The Royal Society of London.....	3
Figure 1.2 The extraordinary optical refelction spectrum drop.[5] © The Royal Society of London.....	4
Figure 2.1 The dispersion relation, based on the real part of the equation 2.18[21]©IOP	18
Figure 2.2 SPP coupling using Kretschamnn (left) and Otto (right) configurations.....	19
Figure 2.3 Near-field probe (left), and rough metal surface excitation (right) for SPPs ..	20
Figure 2.4 SPP grating coupling configuration.....	21
Figure 2.5 SPP grating coupling dispersion curve.	21
Figure 2.6 Drowning man’s dilemma. A wall with varying height along the seashore will change the optimal route for a lifeguard to reach a drowning man in the sea. [49].....	25
Figure 2.7 Plane of incidence for the subwavelength antenna based metasurfaces [49] ..	26
Figure 2.8 Raith E-Line Electron Beam Lithography workstation in Nanyang Nanofabrication Center.....	28
Figure 2.9 Flow chart of Raith E-line EBL system operation steps.....	29
Figure 2.10 Spin curve of ZEP520A E-beam resist with varies of dilution rate.[55]	31
Figure 2.11 PMMA resist film thickness versus spin speed curves.[56]	32
Figure 2.12 Cross-sectional TEM metrology of gold nanostructures with sub-10 nm gaps fabricated by an HSQ/PMMA bilayer liftoff process.[52] © IOP Publishing	33
Figure 2.13 Flow chart of 50nm linewidth pattern transfer by diluted ZEP520A resist. ..	34
Figure 2.14 Metasurface fabricated by the EBL using ZEP520A electron resist. The gold pattern transfer by lift-off technique.	35
Figure 2.15 Schematic diagram of the 30KeV Ga^{+} ion collision induced sputtered particles and the secondary electrons. R_p and R_l are the projected and lateral range of the Ga^{+} ion. [60] ©MRS	37

Figure 2.16 Zeiss AURIGA® Crossbeam® Focused Ion Beam workstation.	38
Figure 2.17 SEM picture of a metasurface with grating for in-plane SPP fabricated by FIB.	38
Figure 2.18 Schematic of the NSOM measurement set up. The linear polarization incidence is focused by an objective lens in a transmission mode for sample illumination at backside. The light incidence is normal to the sample to excite SPPs on the Au surface. An NSOM probe with aperture operated in collection mode is used to image the near-field electric field distribution.....	40
Figure 3.1 Schematic of the multi-shell concentric cylindrical metamaterial consisting of alternate silver and dielectric shells. The inner and outer radii of the annulus opening are denoted as R_i and R_o with initial values of 80 nm and 130 nm, respectively. W and a are 16 nm and 64 nm, respectively, while the thickness h of the CCM is a variable.....	43
Figure 3.2 Schematic illustration of energy flow in the x - z plane of the CCM.	45
Figure 3.3 Simulated power flow distribution in the x - z plane passing through the central axis of the CCM.	46
Figure 3.4 Simulated power distributions in the x - y planes with (a) $z = 1$ nm, (b) $z = 55$ nm, (c) $z = 100$ nm, and (d) $z = 180$ nm, respectively. Their power distributions along the line across the centre of the planes are shown in (e), (f), (g) and (h), respectively.....	48
Figure 3.5 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 73 nm , and (b) 52 nm. The geometry parameters of the annulus opening are (a) $R_i = 80$ nm, $R_o = 110$ nm, and (b) $R_i = 80$ nm, $R_o = 150$ nm.	49
Figure 3.6 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 43 nm , and (b) 45 nm. The geometry parameters of the annulus opening are (a) $R_i = 50$ nm, $R_o = 100$ nm, and (b) $R_i = 110$ nm, $R_o = 160$ nm.	49
Figure 3.7 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 33 nm and (b) 165 nm, respectively, for the CCMs whose the permittivity of the dielectric is set to 1.8 and 3, respectively.	50

Figure 3.8 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 53 nm, and (b) 52 nm for the CCM with thicknesses of 400 nm and 1000 nm, respectively.	50
Figure 3.9 Simulated power flow distribution in the x - z plane passing through central axis of the CCM when the diameter of the hole is set to (a) 50nm, and (b) 90nm, respectively.	51
Figure 3.10 Simulated power distributions along the line across the centre of the x - y planes with $z =$ 60 nm when the diameter of the hole is set to (a) 50 nm, and (b) 90 nm, respectively.	52
Figure 4.1 Schematic of a typical cogwheel structure consisting of an air ring and a number of circular cogs equally distributed along the outer circle of the ring. The inner radius of the big ring is 1.719 μm , the ring slot is 200 nm wide and the diameters of the cogs are 100 nm.	56
Figure 4.2 Power distributions in the structure surface plane with right circularly polarized incidence for (a) a ring aperture and (b) a cogwheel with 9 equally spaced gears. (c) and (d) are the normalized phase graph for (a) and (b), respectively.	58
Figure 4.3 Characteristics of cogwheel with $q = 18$ under right circularly polarized ($\sigma = +1$) and left circularly polarized ($\sigma = -1$). Power distribution for $\sigma = +1$ (a), and $\sigma = -1$ (b). Phase distribution for $\sigma = +1$ (c), and $\sigma = -1$ (d).	60
Figure 4.4 Power distributions in the structure surface plane with $q = 12$, (a) $\sigma_+ = +1$ or right circularly polarized (RCP) incidence, (b) $\sigma_- = -1$ or left circularly polarized (LCP) incidence, (c) and (d) are normalized phase graph for (a) and (b), respectively.	61
Figure 5.1 (a) Schematic of the meta-surface composed of sub-wavelength groove arrays in gold film on chromium. The period of groove arrays is denoted as P . (b) Perspective view of the metasurface model. The 633nm linearly polarized incidence is illuminated at the back of the substrate.	65

Figure 5.2 Power flow distribution at the surface of the metasurface. The calculated divergence angles shown by black arrows are 45.96, 48.97 and 51.89 degree for period of groove arrays of (a) $P = 110$ nm,(b) $P = 130$ nm and (c) $P = 150$ nm, respectively.	67
Figure 5.3 (a) Schematic of a proposed metasurface formed by an array of $6\ \mu\text{m}$ grooves with a fixed period. On its right is a grating coupler. (b) Simulated electrical field intensity distributions E_z in a set of metasurfaces which are formed by grooves with different periodicities but the same width. The top one is the distribution in a gold film without grooves for comparason. The dashed straight lines indicate the wavefront of SPP in the metasurfaces and the wavelength scaling (or shrinking) with the decreasing period can be easily seen. (c) The SPP wavelengths of the metasurfaces in (b), calculated by EMT (squares) and FEM (triangles).	69
Figure 5.4 Calculated E_z -field distributions inside and outside the metasurface with an array of $P = 110$ nm grooves at the incidence of (a) 532 nm and (b) 775 nm.	72
Figure 5.5 (a) SEM micrograph of the metasurface formed by an array of grooves with $P = 150$ nm and groove width $w = 50$ nm. (b) Schematic diagram of the near field scanning microscope. (c) Measured near-field intensity distribution of the metasurface.	74
Figure 5.6 (a) SEM micrograph of the GRIN metasurface formed by grooves with the period progressively decreasing from 150 nm (at the edge) to 100 nm (at the center). (b) Simulated E_z -field distributions of the GRIN metasurface. (c) Measured field intensity distribution.	76
Figure 6.1 (a) Schematic diagram of an aluminium based MIA structure. (b) Simulated E_z of the MIA structure consisting of 80nm Aluminium film and Air at z-y plane. (c) Simulated E_z of the MIA structure consisting of 80nm Aluminium film, 40nm Si_3N_4 film and Air at z-y plane. (d) E_z distributions in x-y plane at Si_3N_4 /Air interface of the MIA structures with different thicknesses of Si_3N_4 layer above the 80nm Al film. The dashed straight lines are used to indicate the wavefronts of SPPs of the MIA structures.	82

Figure 6.2 (a) Damping of electric field E_z at $\text{Si}_3\text{N}_4/\text{Air}$ interface of the MIA structures consisting of 80nm aluminium film and varied thickness of Si_3N_4 film. (b) SPP wavelength (blue squares) and SPP decay (red circles) rate as a function of thickness of Si_3N_4 film.	84
Figure 6.3 E_z distributions in x-y plane of (a) sample 2's structure with 430 nm gratings period and (b) sample 2's structure with 400 nm gratings period for y polarized incidence. (c) plotting of the fringes electric fields for comparison.	85
Figure 6.4 Schematic diagrams of (a) sample 1: 80nm thick aluminum film on substrate and (b) sample 2: 20nm thick / 80nm aluminum on quartz substrate. SEM images with gratings of (c) sample 1 and (d) sample 2.	87
Figure 6.5 E_z distributions in x-y plane of (a) sample 1 and (b) sample 2 for y polarized incidence. NSOM images of (c) sample 1 and (d) sample 2. The dash arrows in (a) and (b) show the direction of linear polarization.	88
Figure 7.1 Schematic layer structure and operation principle illustration.[138]©Springer	91
Figure 7.2 Current confinement methods for VCSELs. Air-post (left), Proton implanted (middle) and oxide-confined (right). [138]©Springer	92
Figure 7.3 Peak reflectivity of the GaAs-AlAs Bragg reflector versus number of DBR mirror pairs [138]©Springer	94
Figure 7.4 Schematic of the novel HCG-VCSELs in which the Al_2O_3 is the low refractive index layer and the GaAs is the grating layer	97
Figure 7.5 Reflectance spectra of the HCG structure coupled with different refractive index materials.	98
Figure 7.6 Mirror mode loss spectra of the novel HCG-VCSELs with different refractive index materials.	99
Figure 7.7 Reflection spectra of HCG structures with different periods.	100
Figure 7.8 SEM image of the fabricated HCG structure using FIB.	101

Figure 7.9 Reflectance spectra of two HCG structures (I14 and I15), measured with different polarization states of light. The XP, YP and NP are the indications of x polarization (polarized in x direction), y polarization and no polarization.	102
Figure 7.10 Reflectance spectrum of HCG structures as a function of deviation.	103
Figure 7.11 VCSELs and their top electrodes bonded with gold wire on the PCB pads.	106
Figure 7.12 VCSEL array with parallel connection top electrodes on the copper heat sink.	106
Figure 7.13 Light up test for the VCSELs array before wire bonding.	107
Figure 7.14 SEM pictures of FIB milled five slit grating on the gold film of VCSEL. Each grating slit is 250 nm wide and the period is 836 nm.	108
Figure 7.15 Spatial energy distribution for Laguerre-Gaussian modes [171].	109
Figure 7.16 Spatial energy distribution for Hermite-Gaussian modes [172].	110
Figure 7.17 Transverse field distributions of the single VCSEL under different injection currents.	112
Figure 7.18 Farfield image of one VCSEL device in the array at total injection currents of (a) 200 mA, (b) 300 mA and (c) 500 mA.	113
Figure 7.19 NSOM pictures for on-chip generated SPP by parallel connected VCSELs with various currents.	114

LIST OF TABLES

Table 2-1 Four types of E-beam resist and their characters	30
Table 5-1 Calculated maximum SPP beam divergence angles	66
Table 5-2 Summary of effective permittivity $\epsilon_{\text{meta-y}}$, effective refractive index, the decay rate of SPP α_{SPP} , SPP wavelengths calculated from effective medium theory of the metasurfaces formed by arrays of grooves with different periods but the same groove width. The SPP wavelengths simulated using the finite element methods are listed in the last column for comparison.....	71

CHAPTER 1. INTRODUCTION

1.1 Motivation

Understanding and controlling the interactions between light and matters are the long term objective of people. For bulk size materials, people used fine-polished copper plates as mirror from ancient times, which is the most common phenomenon of interaction between light and matters. As for the electromagnetic (EM) waves, light can only be better controlled by subwavelength size structures and optical components. Subwavelength structures have the potential to interact and control with light and other spectra of EM waves in terms of phase, amplitude and polarizations. To manipulate light in the visible to infrared spectrum, the subwavelength structures need to be down scaled to micrometer even nanometer scales. Along with the improvement of the micro/nanofabrication techniques, the subwavelength structures become possible in this wavelength range.

Subwavelength optics is one of current main research areas. It entails design and fabrication of structures with subwavelength sizes; focusing and manipulation of light and, finally, optical characterization with subwavelength resolution. I will begin by introducing two important concepts underlying the structures presented in this thesis: metamaterials, and surface plasmon polaritons.

Surface Plasmon Polariton (SPP) becomes one of the core topics in the modern physics and involved in many aspects of research areas. These include but not

limited to material science, optics, physical chemistry, biological science and nanotechnology. In the material aspect, SPP is tightly related to the creation of Metamaterials which are “man-made media with electromagnetic properties on demand[1]”. Or more elaborately, “Metamaterial is a man-made media with all sorts of unusual functionalities that can be achieved by artificial structuring smaller than the length scale of the external stimulus”[2]. People use subwavelength sized structures to construct the metamaterials which possess some extraordinary properties which cannot be found in the nature.

The concept of Metamaterials can be date back to 1898[3] when J. C. Bose proposed and experimentally studied the twisted jute elements which can be performed as small molecules with polarization plane twist properties at microwave range[4].

Figure 1.1 Jute elements and polarization apparatus setup [4]. © The Royal Society of London

As shown in the above figure, each of the twisted elements can be treated as one building unit of a large object which possess extraordinary electromagnetic properties. At the late 19th century, this sparkling idea wasn't attracted much of attention. People could not imagine what would be the applications if they could manufacture the subwavelength “molecules” in the visible range. It was also limited by the manufacturing technological in that age. The state of the art techniques were still even not able to fabricate micrometer size fine structures at the time.

In 1902, four years later than J.C. Bose's paper, R. W. Wood studied the “remarkable case of uneven distribution of light in a diffraction grating spectrum[5]” and published in the Proc. Phys. Soc. London. In that paper, Wood

had not explained the extraordinary optical reflection spectrum drop using SPP generation. But people still can mark this paper as the early notice of SPP nature. It is worth to noticing that, the physical phenomenon of both SPP generation and concept of Metamaterials were found or developed more than 100 years ago.

Figure 1.2 The extraordinary optical reflection spectrum drop.[5] © The Royal Society of London

In 1957, R. H. Ritchie systematically studied the plasmonic resonance on the metal thin film[6]. Ritchie noticed when electrons passed through the metal film, the absorption peak appeared at metal plasmon resonance frequency and lower frequency range. In 1959, C.J. Powell and J. B. Swan studied electron energy loss in Aluminum film which confirmed Ritchie's research[7]. In 1960, E.A. Stern and R.A. Ferrell first declared Surface Plasma Oscillation, the physical meaning is exactly the same as so called surface plasmon (SP) today[8]. In 1988, B. Rothenhausler and W. Knoll published a paper in Nature, stated that instead of normal light incidence, they could use the plasmon surface polariton (PSP) field to acquire higher sensitivity and high resolution imaging. The possible microscope technique named surface plasmon microscopy (SPM)[9]. The PSP has the same physical meanings as SPP: With the external light source excitation, if the photon

momentum can be matched with SP momentum, the photon SP coupling will induce the so called surface plasmon polariton (SPP).

The SPP “Rush” started from 1998 when T. Ebbesen found the light extraordinary transmission through the subwavelength metal holes. Soon after that, people studied the SPPs extensively on the effect of transmission enhancement and beam shaping. In 2000, D.R. Smith studied the “composite medium which possesses both negative permittivity and permeability”. Sir J. B. Pendry invented the “perfect lens” using the negative refractive index property.

After 2000, as the improvement of nanofabrication technology, people are able to make finest nanostructures using state-of-the-art facilities. To make the theory into reality, three types of the experiment techniques are mainly required: thin film deposition techniques, nanostructure patterning techniques and characterization techniques. Magnetron sputtering, Electron Beam Evaporation, MBE, MOCVD and PECVD can be used for accurate thin film deposition. Electron Beam Lithography and Focused Ion Beam can be used for nanometer scale patterning and milling. Scanning Electron Microscopy, Atomic Force Microscopy and Near-field Scanning Optical Microscopy are used for nanostructure and devices imaging and characterizations.

Entered into 21st century, researchers have acquired many breakthroughs in the following areas of nanophotonics:

(a) Super Resolution Imaging

In 2004, X. Zhang's group in UC Berkley developed Nanolithography technology based on Surface Plasmon[10]. X. Luo's group used surface Plasmon resonance interference to get subwavelength patterns which can be used for Nanolithography[11]. In 2005, X. Zhang's group used silver thin film to achieve the negative refractive index imaging[12] based on J. B. Pendry's perfect lens theory. Soon after that, several groups demonstrated negative refractive index materials and possible applications in super resolution imaging.

(b) Metasurfaces and 2D optics

As limited by the complexity and difficulty to fabricate 3D metamaterials, people tune to the 2D metamaterials which is easier to be fabricated and possess many useful optical properties. The 2D metamaterials was called metasurface. The milestone paper was published in 2011. F. Capasso's group used 2D array of optical resonators with spatial phase discontinuity to derive generalized laws of refraction and reflection based on Fermat's law [13]. Many works on metasurfaces and 2D optics proved that 2D nanostructures are an ideal playground for physical phenomenon mimicking demonstrations [14-16]. In 2011, L. Li used in-plane diffraction to generate plasmonic Airy beam[17]. In 2012 J. Lin constructed the cosine-gauss plasmon beam which is a long-range non-diffraction surface wave[18]. In 2013, C. Sheng demonstrated the light trapping by gravitational lensing which mimics the general relativity[19]. J. Lin used different polarization light incidence to effectively control the SPP propagation directions[20].

1.2 Objectives

The main objectives of the thesis are to design, simulate and characterize some sub-wavelength structures and explore their possible applications. The subwavelength structures studied include concentric cylindrical metamaterials for generation of dark hollow, cogwheel structures for generation of surface plasmon polariton vortex, gold groove metasurfaces for manipulating SPP propagation, aluminum based metal-insulator-air layered structures for short wavelength SPP, high contrast grating structure for vertical cavity surface emitting lasers, and integration of metasurface and laser diode for enhanced SPP manipulation.

1.3 Major contributions

The main contributions in this thesis are as follows:

1. Designed a concentric cylindrical metamaterial (CCM) which can be used for acquiring a dark hollow light cone. The proposed structure composes of a concentric cylindrical silver-dielectric multilayer composite, which is covered by a thin layer of chromium (Cr) containing an annulus or a hole opening for incidence. The simulation results show that nanometer-level dark hollow light cones with good quality can be formed in the output for circularly polarized incidence and its position can be monitored by choosing different dielectric materials and dimensions of the annular apertures.
2. Proposed a cogwheel structure formed by an air ring and equally distributed air cogs along the ring on a gold film for generation of surface plasmon polariton vortex. A well-designed cogwheel can generate an optical vortex-like response and the characteristics of such SPP vortex are directly related to cogwheel geometries and can be controlled by adjusting the polarization direction of incident light.
3. Proposed and demonstrated an alternative metasurface design based on non-resonant mechanism. Using effective medium theory and finite element calculation, we show the relation between the effective refractive index and the metasurface geometrical parameters, which can be used to

tune the wavelength and wavefront of the surface plasmon polariton (SPP). The experimental studies of the metasurfaces were conducted by near-field scanning of subwavelength gold grooves fabricated by focused ion beam (FIB). The metasurfaces give us an alternative method for manipulating SPP propagation.

4. Investigated aluminum based structures for manipulation of surface plasmon polariton propagation at short visible wavelength. The simulation shows that aluminum is a good metal to excite and propagate SPPs with blue light and that the SPP wavelength can be reduced by monitoring the thickness of a coated Si_3N_4 layer above the aluminum film, which can be explained by the variation of effective permittivity.
5. Designed high contrast grating (HCG) structures for 980 nm vertical cavity surface emitting lasers (VCSELs). The new HCG structure is made of GaAs/ Al_2O_3 . The GaAs layer is directly grown and the Al_2O_3 layer is converted from an epitaxial AlAs layer through oxidation process. The new HCG structures are much easier to fabricate and have high reliability. The calculated results reveal that the GaAs/ Al_2O_3 HCG structures have high reflectance and bandwidth comparable to those of air cavity and the reflectance spectrum shifts towards long wavelength with the increase of periods of gratings. The FIB fabricated HCG structures show that the reflectance values are sensitive to the deviation of the gratings and minimum deviation for high quality HCGs is about 25 nm which is also verified by FDTD simulation.

6. Designed and fabricated the SPP excitation gratings on top of the 850nm wavelength VCSELs. The integrated structures can provide a compact solution for the on-chip SPP excitation and propagation.

1.4 Organization of the thesis

The thesis contains eight chapters and they are organized as the following:

Chapter 1 is the introductory chapter. It introduces the motivation, objectives, main contributions of the Ph.D. program and organization of the thesis.

Chapter 2 is a review chapter. It contains the plasmonics fundamentals, the physics and mechanisms of metamaterials as well as the fabrication and characterization methods of some subwavelength structures which include Electron Beam Lithography, Focused Ion Beam and Near-field Scanning Optical Microscopy.

Chapter 3 presents the study of the concentric cylindrical metamaterials. It starts with the background review of dark hollow beam and optical tweezers. The finite element method (FEM) was used to study this kind of materials.

Chapter 4 describes the design and investigation of the cogwheel structures formed by an air ring and equally distributed air cogs along the ring on a gold film for generation of surface plasmon polariton vortex. Both simulation and experiment works was carried out. In the simulation part, the SPP vortex was generated and can be controlled by adjusting the circular polarization direction of incident light.

Chapter 5 present the study of gold grooved structure metasurfaces designed based on non-resonant mechanism. It contains theoretical calculation using effective medium theory and finite element method, and experimental observation of SPP propagation. Chapter 6 shows the investigation of Aluminum based

subwavelength structures. By designing them into a Metal-Insulator-Air structure, the SPP wavelength can be reduced from about 465 nm to about 265 nm by increasing the thickness of a coated Si_3N_4 layer above the aluminum film for the blue incident light.

In Chapter 7 two major works are presented. One is the GaAs/ Al_2O_3 High Contrast Grating (HCG) application in VCSELs. HCG possesses the very high reflection rate which can be used to replace the top DBR in the VCSEL. This part contains numerically study of the geometrical design of the HCG and experiment fabrication of HCG by FIB. The other is the SPP generation and propagation in the metasurface fabricated directly on the surface of the VCSELs where the SPPs can be generated and manipulated by varying the injection current of the VCSEL.

Chapter 8 is the conclusion chapter. It contains the major contributions of the PhD program and some recommendations for the future works.

CHAPTER 2. BACKGROUND

2.1 Plasmonics Fundamentals

Surface Plasmon Polaritons are a kind of surface wave-like quasi particles propagating along the interface between metal and dielectrics. It possesses the properties of evanescent wave which exponentially decays with the increasing distance from metal-dielectric interface. Starting with the optical properties of metals, the SPP mode equations will be derived and methods of excitations of SPP will be introduced.

2.1.1 Optical properties of metals

The starting point will be the Maxwell's equations which describe the macroscopic electromagnetics:

$$\nabla \cdot \mathbf{D} = \rho_{ext}. \quad (2.1a)$$

$$\nabla \cdot \mathbf{B} = 0. \quad (2.1b)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}. \quad (2.1c)$$

$$\nabla \times \mathbf{H} = \mathbf{J}_{ext} + \frac{\partial \mathbf{D}}{\partial t}. \quad (2.1d)$$

For a dielectric material such as quartz, the conductivity σ is near to zero. For metals such as gold and silver, the conductivity σ can be very high. From Ohm's law, the current density inside the metal $\mathbf{J}_{ext} = \sigma \mathbf{E}$. From equation 2.1d, we have:

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \epsilon_0 \epsilon \frac{\partial \mathbf{E}}{\partial t}. \quad (2.2)$$

For electromagnetic wave with certain frequency, if one takes the harmonic time dependence $\mathbf{E}(t) = \mathbf{E}e^{-i\omega t}$, the equation 2.2 becomes:

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} - i\omega \varepsilon_0 \varepsilon \mathbf{E}. \quad (2.3)$$

Let complex permittivity be

$$\varepsilon = \varepsilon + i \frac{\sigma}{\omega \varepsilon_0}. \quad (2.4)$$

and substitute it into equation 2.3, one has

$$\nabla \times \mathbf{H} = -i\omega \varepsilon_0 \varepsilon \mathbf{E}. \quad (2.5)$$

The complex permittivity can be expressed as two parts. The real part represents the bound charge responding to a driving field, and the imaginary part is the contribution of free electron movements which will induce power loss.

Consider the free electron gas model; the plasma frequency ω_p can be expressed as:

$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 m}. \quad (2.6)$$

The complex permittivity is a function of frequency, described by the Drude model:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}. \quad (2.7)$$

where γ is the collision frequency $\gamma = 1/\tau$, and τ is the relaxation time. At small damping limit, equation 2.7 can be simplified as

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}. \quad (2.8)$$

In most cases, the real part permittivity of a metal is much greater than the imaginary part of the permittivity. To make the problem of SPP propagation simpler in the real applications, it is reasonable to do such approximation. To most of the metals, when $\omega < \omega_p$, the real part of the permittivity is negative. This is the reason why visible light cannot penetrate through the metals but is reflected. The metals with smooth surface can be used as a mirror. When $\omega > \omega_p$, the real part of the permittivity is positive, electromagnetic waves with higher energy such as X-ray or Gamma ray can penetrate through the metals.

2.1.2 SPP mode equations on a metal-dielectric interface

Surface plasmon polaritons are electromagnetic waves confined between a conductor (usually a metal) and dielectric layer which decay evanescently in the perpendicular direction to the interface plane. To find the SPP mode solutions, one can apply the Maxwell's equations 2.1 to the metal-dielectric interface. If there are no external charges and current densities, the equations 2.1c and 2.1d can be combined and expressed as

$$\nabla \times \nabla \times \mathbf{E} = -\mu_0 \frac{\partial^2 \mathbf{D}}{\partial t^2}. \quad (2.9)$$

For harmonic time dependence, $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r})e^{-i\omega t}$, equation 2.9 can be rewritten as the renowned *Helmholtz* equation:

$$\nabla^2 \mathbf{E} + k_0^2 \varepsilon \mathbf{E} = 0. \quad (2.10)$$

If the propagation direction is taken as the x-direction, and x-y plane as the metal-dielectric interface plane, the propagating wave can be described as $\mathbf{E}(x, y, z) = \mathbf{E}(z)e^{i\beta x}$, where β is the propagation constant. Equation 2.10 becomes:

$$\frac{\partial^2 \mathbf{E}(z)}{\partial z^2} + (k_0^2 \varepsilon - \beta^2) \mathbf{E} = 0. \quad (2.11)$$

More explicit expressions are shown as:

$$\frac{\partial E_y}{\partial z} = -i\omega\mu_0 H_x. \quad (2.12a)$$

$$\frac{\partial E_x}{\partial z} - i\beta E_z = i\omega\mu_0 H_y. \quad (2.12b)$$

$$i\beta E_y = i\omega\mu_0 H_z. \quad (2.12c)$$

$$\frac{\partial H_y}{\partial z} = i\omega\varepsilon_0 \varepsilon E_x. \quad (2.12d)$$

$$\frac{\partial H_x}{\partial z} - i\beta H_z = -i\omega\varepsilon_0 \varepsilon E_y. \quad (2.12e)$$

$$i\beta H_y = -i\omega\varepsilon_0 \varepsilon E_z. \quad (2.12f)$$

For the transverse magnetic (TM) mode, equations 2.12 (a-e) can be reduced to:

$$E_x = -i \frac{1}{\omega\varepsilon_0 \varepsilon} \frac{\partial H_y}{\partial z}. \quad (2.13a)$$

$$E_z = -\frac{\beta}{\omega\varepsilon_0 \varepsilon} H_y. \quad (2.13b)$$

The TM wave equation can be expressed as:

$$\frac{\partial^2 E_y}{\partial z^2} + (k_0^2 \varepsilon - \beta^2) H_y = 0. \quad (2.14)$$

Consider equations 2.13 and 2.14, for $z > 0$,

$$H_y(z) = A_d e^{i\beta x} e^{-k_d z}. \quad (2.15a)$$

$$E_x(z) = iA_d \frac{1}{\omega \varepsilon_0 \varepsilon_d} k_d e^{i\beta x} e^{-k_d z}. \quad (2.15b)$$

$$E_z(z) = -A_m \frac{\beta}{\omega \varepsilon_0 \varepsilon_d} e^{i\beta x} e^{-k_d z}. \quad (2.15c)$$

For $z < 0$:

$$H_y(z) = A_m e^{i\beta x} e^{-k_m z}. \quad (2.16a)$$

$$E_x(z) = -iA_m \frac{1}{\omega \varepsilon_0 \varepsilon_m} k_m e^{i\beta x} e^{-k_m z}. \quad (2.16b)$$

$$E_z(z) = -A_m \frac{\beta}{\omega \varepsilon_0 \varepsilon_m} e^{i\beta x} e^{-k_m z}. \quad (2.16c)$$

where A_m and A_d are coefficients to be confirmed, ε_m and ε_d are permittivity of the metal and dielectric, and k_m and k_d are attenuation rates for z -direction. The attenuation rates are real positive numbers. The magnetic field and electric field continuity at the $z=0$ interface requires: $A_m = A_d$ and $\frac{k_d}{k_m} = -\frac{\varepsilon_d}{\varepsilon_m}$,

Combining with the expressions for H_y and fulfilling with wave equation (2.14):

$$k_m^2 = \beta^2 - k_0^2 \varepsilon_m. \quad (2.17a)$$

$$k_d^2 = \beta^2 - k_0^2 \varepsilon_d. \quad (2.17b)$$

We have the dispersion relation at the metal dielectric interface:

$$k_{spp} = \beta = k_0 \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}. \quad (2.18)$$

The SPP dispersion relation is shown in Figure 2.1

Figure 2.1 The dispersion relation, based on the real part of the equation 2.18[21]©IOP

Using the Drude Model equation 2.7, the real permittivity is based on $\omega_p = 1.2 \times 10^{16} \text{ rad/s}$, $\gamma = 1.45 \times 10^{13} \text{ s}^{-1}$.

2.1.3 Excitation methods of SPPs

To confine and generate SPPs propagating along the metal-dielectric interface, the propagation constant $\beta = k_{sp}$ needs to be greater than the wave vector k in the dielectric. The SPP dispersion curve is on the right side of the light line for dielectrics. The wave vector needs to be greater than k to satisfy the phase match conditions.

2.1.3.1 Prism Coupling

The wave vector for surface plasmon polariton k_{sp} must be greater than dielectric light wave vector k to excite the SPP propagation. For smooth metal surfaces, the projection of the light momentum in x direction is always smaller than the SPP propagation wave vector since $k_x = k \sin \theta$.

If one uses a prism to couple the light onto the metal surface, the permittivity of the prism needs to be considered and $k_x = k\sqrt{\epsilon} \sin \theta$ needs to satisfy the SPP excitation conditions. The prism coupling method is also known as the attenuated total internal reflection method. As shown in Figure 2.2, there are two configurations using prism to excite SPPs which were proposed by E. Kretschmann[22] and A. Otto[23] in 1968, respectively. It should be noted that the SPP phase-matching conditions are not fulfilled for the prism/metal interface for both setups. So the SPPs are only generated at the metal/air interfaces.

Figure 2.2 SPP coupling using Kretschmann (left) and Otto (right) configurations

2.1.3.2 Near-field Excitations

Near-field coupling is the most direct excitation method for SPPs. It acts as a point source to generate local excitations. As sketched in Figure 2.3, if one uses a small probe tip with aperture size noted by a , where $a \ll \lambda_0$, the probe needs to be very close to the metal surface to excite the SPP. The metal surface is within the near-field of the probe tip. The diffraction area possesses all the wave vectors, which is able to fulfill the phase matching conditions. As shown in Figure 2.3, when light incidence is scattered by the small particles on the rough metal surface, the scattering light will also possess varied wave vectors, which is able to fulfill the phase matching conditions. Both near-field probe excitation and rough metal surface excitation are the non-resonant schemes of coupling, and they have low efficiency of SPP coupling (only a small portion of the energy can be converted into SPPs).

Figure 2.3 Near-field probe (left), and rough metal surface excitation (right) for SPPs

2.1.3.3 Grating Coupling

To excite the SPP more efficiently, the periodic gratings can be deployed. To fabricate the gratings on the metal surface can satisfy the phase matching conditions. As shown in Figure 2.4,

$$k_{spp} = k_0 \sin \theta \quad (2.19)$$

which is similar to the rough surface excitations. By assistance of the periodic gratings, the dispersion relations can be plotted as Figure 2.5. The light incidence wave vector's x components will be shifted periodically and intersect with the SPP dispersion curve, which can be seen at Figure 2.5, and expressed as[24] :

$$k_{sp} = \frac{\omega}{c} \sin \theta \pm m \frac{2\pi}{\Lambda} \quad (2.20)$$

Figure 2.4 SPP grating coupling configuration.

Figure 2.5 SPP grating coupling dispersion curve.

2.2 Metamaterials and Metasurfaces

2.2.1 Metamaterial fundamentals

Metamaterials are a kind of man-made materials which possess extraordinary macroscopic properties. They contain small units of structures which are smaller than sub-wavelength scale. Metamaterials could generate negative permittivity and permeability, which make the electromagnetic waves propagating direction different from the energy propagating direction. These properties will lead to many new phenomena, such as, reversed Doppler effect[25], reversed Snell refraction[26], reversed Cerenkov Radiation[27] and "perfect lens" to take place.

The electromagnetic properties of a material are usually dependent on two parameters, namely permittivity ϵ and permeability μ . As two parameters appear in the Maxwell's equations, so the ϵ and μ describe the propagation of electromagnetic waves in the material. Normally, $\epsilon(\omega)$ and $\mu(\omega)$ are both positive. But in some frequencies, $\text{Re}(\epsilon)$ and $\text{Re}(\mu)$ can be negative. For example, $\epsilon(\omega)$ is negative below the plasmonic resonance frequency ω_p , $\mu(\omega)$ is negative when a ferromagnetic body nears ferromagnetic resonance frequency. Right-hand material means electric field, magnetic field and propagating directions follow the "right hand rule". When both $\epsilon(\omega)$ and $\mu(\omega)$ are negative, electric field, magnetic field and propagating directions will follow the "left hand rule". Obviously, left-handed materials are all negative index materials (NIMs).

Surface plasmon polaritons are the electromagnetic excitations propagating at the interface between a dielectric and a conductor [28]. The electromagnetic surface waves are confined in the perpendicular direction. The origin of the SPPs is the coupling between the electromagnetic waves and the oscillation of conductor's plasma. The near-field version of the "perfect lens" can be referred to "near-field superlens" (NFSL)[29-32]. This is easier to be achieved because it does not require the optical magnetism. When the surface modes at the NIM interface are satisfied for evanescent wave amplification, the interface between silver and air can support the surface plasmon polaritons, the NFSL condition of $\epsilon = -1$ is satisfied [33].

Optical metamaterials suggest a way to design and modulate optical properties of natural materials by nanofabrication techniques. The ordering of small units in metamaterials is not strict. It means that metamaterials do not need to follow certain periodicity strictly. Optical metamaterials change the way people design optical devices. The metamaterials with negative refractive index can be used for beam splitting [34-36], super-resolution imaging[37] and generating dark hollow light cone(DHLC) [38, 39]. By introducing gain materials into metamaterials, the lasing spaser [40, 41] had been proposed.

2.2.2 Metasurfaces

Metasurface is the design concept of reducing the dimensionality of complex Metamaterials[42]. In order to solve the major obstacles of the classical 3D metamaterials: high loss, fabrication and integration difficulties, Metasurfaces

provide an approach of ultrathin designs with low loss, easy to fabricate and easy to integrate with traditional optoelectronics devices.

The name of “metasurface” is not invented recently. In the microwave to terahertz regime, people use the name of “metafilm” to address the structures of antenna arrays which possess abnormal electromagnetic properties [43, 44]. In the antenna design research, people use “reflectarrays” [45] and “transmitarray”[46] to perform the phase-controlling and radio broadcasting functions. The real challenge came as the wavelength downscale to the infrared and visible spectrum, the size of the “meta atoms” on the metasurface needs to be in the size of micrometers and even nanometers level.

Based on the design principles of current development, metasurfaces can be classified into two categories: antenna scatter based metasurfaces[13], and non-scatter based metasurfaces[47, 48]. Wavefront shaping is the common ability for both types of metasurfaces. The non-scatter based and grooved-structure based metasurfaces will be introduced later in chapter 5.

The principle of the antenna scatter based metasurfaces is introducing an abrupt phase shift associated with reflection, refraction and transmission on the metasurfaces[49]. The major character for antenna based metasurface is the “phase jump”. Richard Feynman’s drowning man’s delimma can explain the traditional optical reflection and refraction. Here we use the explanation by N. Yu et. al, what is the best route for lifeguard to save a drowning man?[49] As shown in Figure 2.6, the lifeguard should run a distance on the land and swim for some distance to reach the man. Which point on the seashore should the lifeguard choose to have shortest time to reach the drowning man? The running speed

v_{run} is faster than swimming speed v_{swim} . The situation is different if we introduce a wall on the seashore. If there is no wall on the seashore, we can express the best route equation:

$$\frac{\sin \theta_i}{v_{run}} - \frac{\sin \theta_t}{v_{swim}} = 0 \quad (2.21)$$

Figure 2.6 Drowning man's dilemma. A wall with varying height along the seashore will change the optimal route for a lifeguard to reach a drowning man in the sea. [49]

This equation has the same form of Snell's Law. If there is a wall along the seashore with constant gradient height, it can be representing the constant gradient phase jump on the metasurfaces. The best route will be modified as[49]:

$$n_t \sin \theta_t - n_i \sin \theta_i = \frac{1}{k_0} \frac{\partial \Phi}{\partial x} \quad (2.22)$$

$$\cos \theta_t \sin \varphi_t = \frac{1}{n_t k_0} \frac{\partial \Phi}{\partial y} \quad (2.23)$$

It is also known as the generalized law of refraction. Similarly, the generalized law of reflection is:

$$\sin \theta_r - \sin \theta_i = \frac{1}{n_i k_0} \frac{\partial \Phi}{\partial x} \quad (2.24)$$

$$\cos \theta_r \sin \varphi_r = \frac{1}{n_r k_0} \frac{\partial \Phi}{\partial y} \quad (2.25)$$

Figure 2.7 Plane of incidence for the subwavelength antenna based metasurfaces [49]

2.3 Experimental methods

The precision and quality of nanophotonics structures and devices are highly dependent on available nanofabrication technology and characterization techniques. For metasurfaces and 2D optics devices in the visible spectrum, three most important experimental techniques are: Thin film deposition, nanopatterning and characterization techniques. In this section, the major experiment methods used in my PhD project are introduced as following.

2.3.1 Electron beam lithography

2.3.1.1 Introduction to electron beam lithography

Electron beam lithography (EBL) is a high-resolution lithographic technique for nanostructure patterning. The fundamental of EBL is using the electrons to expose the electron-sensitive resist. As the electrons can be treated as the de-Broglie wave, the wavelength of the electron can be calculated by equation $\lambda = h/p$, where h is the plank constant and p is the momentum of the electron. The wavelength of the electron beam can reach to deep sub-nanometer scale which is dependent on the acceleration voltage. Besides the acceleration voltage, the resolution of EBL is much dependent on the electron scattering, proximity effect and resists sensitivity. The electron beam writing system was proposed in 1955 based on the scanning electron microscope[50]. It uses the scanning electron beam to write directly on the photoresist and removes or remains the region of exposure.

It can be widely used in photolithography mask fabrication, semiconductor research and nanotechnology.

Figure 2.8 Raith E-Line Electron Beam Lithography workstation in Nanyang Nanofabrication Center

The flowchart of EBL operation for resists such as PMMA and ZEP520A is shown in Figure 2.9. The step of burning point is to make sure that the electron beam was focused well and no much astigmatism for E Beam. The ideal point burned should be less than 30 nm in diameter and the shape is perfect round. The exposure resolution ability is dependent on how small the point one can burn. The diameter of the point represents the single line width or the pixel size of area exposure. If the point burn is not round enough, one needs to repeat the focusing and adjust the step until the perfect round shape is reached. For HSQ resist, one can skip the point burning step because it is not easy to see the burning area on HSQ resist before development.

Figure 2.9 Flow chart of Raith E-line EBL system operation steps

2.3.1.2 Electron beam resists

The most popular types of electron beam (EB) resists are listed in Table 2-1. They can be classified into two categories, positive resists and negative resists. ZEP 520A and Poly-methyl-methacrylate (PMMA) are positive resists. It means that after development, the area of exposure will be removed. Hydrogen silsequioxane (HSQ) and SU8 are negative resist with which after development, the exposed area will remain due to the cross-link reaction. The dose for each resists depends on the radiation energy, resist thickness and development process.

Table 2-1 Four types of E-beam resist and their characters

EBeam Resist	Tone	Manufactory	Resolution	Typical Dose
ZEP 520A	Positive	Zeon	<50 nm[51]	20-50 $\mu\text{C}/\text{cm}^2$
HSQ	Negative	Dow Corning	<10 nm[52]	400-700 $\mu\text{C}/\text{cm}^2$
PMMA	Positive	MicroChem	<10 nm[53]	50-500 $\mu\text{C}/\text{cm}^2$
SU8	Negative	MicroChem	<50 nm[54]	10-100 $\mu\text{C}/\text{cm}^2$

ZEP 520A is the positive resist with properties of high resolution, high sensitivity and high resistance for dry etching. The high resistance property makes ZEP 520A a better choice than PMMA for dry etching pattern transfer. The high sensitivity also makes the ZEP 520A a better choice for its short exposure time. In order to have higher resolution, thinner ZEP520A is required. Anisole is the solvent to dilute the original ZEP520A resist. The spin curve with dilution rate (D.R) is shown in Figure 2.10. The dilution rate is the ratio of the sum of *original resist*+ *solvent* over *original resist*, and the unit is in weight (gram). The typical dose for exposure is only 20-50 $\mu\text{C}/\text{cm}^2$ at 20kv acceleration voltage. The developer for ZEP520A is ZED-N50 which contains n-Amyl acetate.

Figure 2.10 Spin curve of ZEP520A E-beam resist with varies of dilution rate.[55]

PMMA is also a commonly used positive E-beam resist. It has high resolution, but low sensitivity and etching resistance. Compared with ZEP 520A, it is much cheaper and not sensitive to white light, so it has long shelf life and can be stored even longer time in the fridge. There are two solvents for PMMA, namely anisole and chlorobenzene. Based on the molecule weight, PMMA also can be categorized as 950PMMA (with 950k molecule weight) or 495PMMA (495k molecule weight). The 950PMMA A4 resist means 4% 950k molecule weight PMMA in the anisole solvent. The spin curves of the 950PMMA resist with different solvent percentages are shown in Figure 2.11. The developer for PMMA is the mixture of methy-lisobutyl-ketone (MIBK) and IPA.

Figure 2.11 PMMA resist film thickness versus spin speed curves.[56]

HSQ is a very high resolution negative e-beam resist. As declared by the Dow-Corning company, the highest resolution is around 6 nm feature size. The product code is XR-1541. It is made of hydrogen silsequioxane resin in the solvent of MIBK.

The advantage of the HSQ is that after the development, the remaining part will performed as the SiO_x which can be used as the mask of another layer of resist. The developer is Tetramethylammonium hydroxide (TMAH). By using the bilayer (HSQ and PMMA) liftoff technique, the smallest size of pattern transferred can reach below 10 nm [52][[57].

Figure 2.12 Cross-sectional TEM metrology of gold nanostructures with sub-10 nm gaps fabricated by an HSQ/PMMA bilayer liftoff process.[52] © IOP Publishing

SU8 is the negative photoresist which can also be used as E-beam resist. It was developed by IBM and first introduced in 1996. The resist is in the gamma butyrolactone (GBL) solvent and has very high transmission for light incidence above 360 nm wavelength. It can spin coated in the range of 1.5 to 200 μm thickness which is relatively thick. The aspect ratio is very high. The developer can be ethyl lactate and diacetone alcohol. By diluting in cyclopentanone and spin coating at 7000 rpm, the resist thickness can reach 99 nm and minimum feature size can go down to 40 nm[54].

2.3.1.3 Fabrication demonstration of 50 nm line width using diluted ZEP520A

We are using ZEP-A (Anisole) to dilute the ZEP520A in order to get thinner E-beam resist for higher resolution. The dilution rate D.R = 1.7 was chosen. The thickness of the resist is about 130 nm for 1 min 4000rpm spin coating. The flow chart of EBL process is shown in Figure 2.13.

Figure 2.13 Flow chart of 50nm linewidth pattern transfer by diluted ZEP520A resist.

The final transferred gold structure is shown in Figure 2.14. The minimum line width of transferred structure is around 50 nm.

Figure 2.14 Metasurface fabricated by the EBL using ZEP520A electron resist. The gold pattern transfer by lift-off technique.

2.3.2 Focused Ion Beams

Focused ion beam (FIB) is a technique used for both imaging and ablation of materials at the length scale of several nanometers to hundreds micrometers. However, while the SEM uses a focused beam of electrons to image the sample in the chamber, an FIB uses a focused beam of ions for both imaging and milling. Nowadays, most of the commercial FIB workstations use Liquid Metal Ion Source (LMIS) [58, 59]. Among the Ion sources, Gallium was chosen as the best candidate for LMIS because it has low melting temperature (around 30°C), low volatility and low vapor pressure[60]. Based on the above characters, Ga will not react with the FIB emitting needle, and the Ion source is stable. The Ga collision

energy is in the range of 20 -30 KeV which is much larger than the atom binding energy (typically 1 eV)[60]. The collision is non-adiabatic. FIB itself can perform both milling and imaging functions. As shown in the Figure 2.15, the schematic diagram of Ga sputtering effect is demonstrated. The imaging function is performed by the generation of the ion-induced secondary electrons (ISE). Typically, less than 10 electrons were generated by one Ga ion with 5-30KeV energy.

FIB can also be incorporated into a system with both electron and ion beam columns, allowing the same feature to be investigated using either of the beams. Figure 2.16 is the due-beam FIB system from Zeiss company.

Figure 2.15 Schematic diagram of the 30KeV Ga^+ ion collision induced sputtered particles and the secondary electrons. R_p and R_l are the projected and lateral range of the Ga^+ ion. [60]
©MRS

Figure 2.16 Zeiss AURIGA® Crossbeam® Focused Ion Beam workstation.

An example of a sample whose fabrication utilizes FIB milling to ablate structures on gold films is shown in Figure 2.17. FIB milling was used to fabricate the nanostructure presented in Chapters 5, 6 and 7 of this thesis.

Figure 2.17 SEM picture of a metasurface with grating for in-plane SPP fabricated by FIB.

2.3.3 Near-field scanning optical microscopy

Near-field scanning optical microscopy (NSOM), also known as scanning near-field optical microscopy (SNOM), is a microscopic technique for surface feature investigation that breaks through the far-field diffraction limit by utilizing probe much close to the specimen surface for excitation or collection of diffraction in the near-field. The idea of employing near-field optics to achieve images beyond the diffraction limit was first discussed in 1928 by E. H. Synge[61]. Several decades later, Pohl and Lewis introduced the usage of a subwavelength metal coated optical tip and a feedback mechanism to achieve resolution as low as 25 nm. In the NSOM system, the resolution is limited by the aperture size of the detectors instead of the wavelength of the illuminating light. NSOM is a powerful technique for studying nanoscale optical interactions. There are three basic NOSM operational modes: illumination mode, reflection mode and collection mode. In illumination mode operation, the light is coupled into the optical probe as the source to illuminate a sample in the near-field. A high numerical aperture objective lens is positioned under the sample to collect the transmitted light and focus it into a photodetector. Reflection mode operation has the similar principle as illumination mode except that the photodetector is set to collect the light reflected from the opaque sample surface. In collection mode operation, the light is coupled into an objective lens to illuminate the sample. The NSOM probe collects the electromagnetic field on the sample surface and delivers it to the photodetector through the fiber. The optical image of sample surface is collected point to point by scanning either the probe or the sample stage. The scanning routine can either work at a constant height or regulated height by using a feedback mechanism. Tuning fork shear-force feedback technique is used to

control the distance between NSOM probe and sample surface. Then, light propagating through the fiber is directed to a sensitive detector, such as photomultiplier tubes (PMT). After that, the PMT signal is transmitted to the computer where image processing is employed to obtain the final optical image.

Figure 2.18 Schematic of the NSOM measurement set up. The linear polarization incidence is focused by an objective lens in a transmission mode for sample illumination at backside. The light incidence is normal to the sample to excite SPPs on the Au surface. An NSOM probe with aperture operated in collection mode is used to image the near-field electric field distribution

CHAPTER 3. CONCENTRIC CYLINDRICAL METAMATERIALS FOR SUBWAVELENGTH DARK HOLLOW LIGHT CONES

There are many methods to generate dark hollow beam or dark hollow cones, such as Fraunhofer diffraction but the size of the dark hollows cannot be downscaled to subwavelength size due to diffraction limit. In this chapter, we propose and simulate a subwavelength structure, concentric cylindrical metamaterial (CCM), for dark hollows which can have subwavelength size.

3.1 Introduction to dark hollow beam and dark hollow light cone

A dark hollow beam (DHB) is a doughnut-shaped laser beam with zero central intensity. It has broad applications in laser optics, biology, chemistry and atom optics as it can be used to manipulate neutral atoms, molecules and even living samples [62-67]. Compared with a solid beam, the DHB possesses many advantages. For example, it can reduce laser power and heat generation which gives less risk of damaging living samples [68], and has also an ability to levitate spheres with relative refractive index less than one [69]. There have been many methods to generate the DHB so far, including a geometric method [70], a transverse-mode method [71], a hollow fiber method [72] and a computer generated hologram method [73]. In general, the dark spots generated by these methods are usually more than half a wavelength in size.

Over the last decades, great efforts have been put in this field in order to break the diffraction limit and some novel ideals have been proposed [74-76]. The recent research on metamaterials opened a new field for fundamental studies and practical applications in the realm of optics[77]. The metamaterials with negative refractive index can be used for super-resolution imaging [78, 79], cloaking [80], and beam splitting [81]. Recently, our group reported nanorod-based metamaterials for beam splitting and dark hollow light cone (DHLC) [82]. In this chapter, a high-quality subwavelength DHLC formed by a concentric cylindrical metal-dielectric structure will be introduced and such DHLC has high potential for handling nanoscale objects.

3.2 Concentric Cylindrical Metamaterials Structures

The structure of the concentric cylindrical metamaterial (CCM) is shown in Figure 3.1. It consists of silver/dielectric concentric cylindrical metal-dielectric multishells whose top surface is covered by a 50 nm thick chromium (Cr) layer with an annulus opening. The annulus opening is centered on the axis of the CCM and designed for the incident beam to pass through. The outmost radius of the structure is set to $8p$, where p is the period, defined as $p = a + w$ with a being the dielectric layer thickness and w the silver layer thickness in one period.

The structure is simulated using a finite element method. In the simulations, a 632 nm circularly-polarized plane wave with an electric field of 1 V/m is assumed to be the normal incident source. The permittivities of silver and Cr used are from the reference [83, 84]. The permittivity of the dielectric is varied and its effect on

the performance of the CCM is then investigated. The maximum mesh sizes for the silver layers, dielectric layers, chromium layer, annulus and output region are set to 16 nm, 50 nm, 50 nm, 50 nm and 40 nm, respectively. The generalized minimal residual method (GMRES) is selected for our simulations because of its rapid convergence and short calculation time.

Figure 3.1 Schematic of the multi-shell concentric cylindrical metamaterial consisting of alternate silver and dielectric shells. The inner and outer radii of the annulus opening are denoted as R_i and R_o with initial values of 80 nm and 130 nm, respectively. W and a are 16 nm and 64 nm, respectively, while the thickness h of the CCM is a variable.

3.3 Effective medium theory for layered structure metamaterials

From the effective medium theory (EMT), the effective permittivity of the layered structure can be expressed as [85]:

$$\varepsilon_r = \frac{N\varepsilon_m P + (1-N)\varepsilon_d}{NP + (1-N)} = \varepsilon_{\perp}, \quad (3.1)$$

$$\varepsilon_z = N\varepsilon_m + (1-N)\varepsilon_d = \varepsilon_g = \varepsilon_{\parallel}, \quad (3.2)$$

where $P=2\varepsilon_d/(\varepsilon_m+\varepsilon_d)$, and N is the metal filling ratio. When $\varepsilon_z < 0$ and $\varepsilon_r > 0$, the dispersion equation can be expressed as:

$$k_z^2 + \frac{\varepsilon_r}{\varepsilon_z} k_r^2 = k_0^2 \varepsilon_r, \quad (3.3)$$

where $k_0 = \omega/c$, and k_z and k_r are the wave vectors along the z and radial directions, respectively.

EMT is used as a guide for designing the negative refractive index CCM. Using Formula 3.1 and 3.2, the anisotropy permittivities in the perpendicular and parallel direction of the CCM can be predicted. For the CCM with the ring width of $a=64$ nm for the dielectric and $w=16$ nm for silver, the calculated ε_z and ε_r are -1.28 and 4.18, respectively, which satisfy the negative refraction condition.

Figure 3.2 shows the cross section of the CCM. The arrows denote the energy flow in the structure. When a light wave reaches the sub-wavelength annulus opening, it will produce high spatial frequency waves which excite surface plasmon polaritons (SPPs) on the surfaces of silver layers near the annulus opening. The SPPs couple to sideways along the ways shown in the figure (namely, beam 1 and beam 2). Meanwhile, the structure has a negative refraction property. The waves out of the CCM refract towards the central axis, and they interfere each other and diffract, leading to a dark hollow formed in region 3. A circularly polarized light is chosen in order to acquire a three-dimensional concentrically symmetric DHLHC.

Figure 3.2 Schematic illustration of energy flow in the x-z plane of the CCM.

3.3.1 CCM covered by a thin layer of chromium (Cr) containing an annulus opening

We first investigate the power flow distribution in the CCM with a thickness h of 668 nm. The permittivity of dielectric is set to 2.4. As shown in Figure 3.3, the beam propagates through the CCM into air and a distinguished DHLC is generated in the near field. A cone-shaped power flow distribution is formed in the metal/dielectric region.

Figure 3.3 Simulated power flow distribution in the x - z plane passing through the central axis of the CCM.

Figures 3.4(a)-(h) show the power flow distributions in different cross sections at different z positions and the power intensities in the planes along their diameter lines. In the plane of 55 nm below the CCM, the dark hollow (DH) exists and the power intensity at the center of the plane is the lowest (Figures 3.4(b) and (e)). In the plane of 100 nm below the CCM, the DH becomes bigger but the power intensity at the center of the plane is also increased to about half of the maximum intensity (Figures 3.4(c) and (f)). At $z = 180$ nm, the DH almost disappears (Figures 3.4(d) and (g)). If we define the position at which the power intensity

becomes half of the maximum intensity of the light cone as the edge of the DH, the diameter of the DH at $z = 55$ nm is about 38 nm. It increases to 70 nm at $z = 100$ nm and becomes zero at $z = 180$ nm. These results indicate the formation of the DHLHC which ends at about 180 nm below the CCM.

Next, the size of the annulus opening is varied and the corresponding effects on the position of the minimum power intensity are studied. In the simulations, the inner and outer radii for the annulus opening are set to $R_i = 80$ nm, $R_o = 110$ nm; $R_i = 80$ nm, $R_o = 150$ nm; $R_i = 50$ nm, $R_o = 100$ nm and $R_i = 100$ nm, $R_o = 160$ nm, respectively. The corresponding power flow distributions are shown in Figures 3.5(a), (b), 3.6(a) and (b), respectively. The DHLHCs' center positions where the light intensity is the lowest for the CCM described in Figures 3.5 (a) and (b) are located at 73 nm and 52 nm below the CCM, while they are located at 43 nm and 45 nm below the CCM described in Figures 3.6(a) and (b), respectively. It is also found that the diameter of the DHLHCs does not change significantly with the change of radius of the annulus opening but the light intensity does as the change in radius directly affects the intensity of the incidence.

Figure 3.4 Simulated power distributions in the x - y planes with (a) $z = 1$ nm, (b) $z = 55$ nm, (c) $z = 100$ nm, and (d) $z = 180$ nm, respectively. Their power distributions along the line across the centre of the planes are shown in (e), (f), (g) and (h), respectively.

Figure 3.5 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 73 nm , and (b) 52 nm. The geometry parameters of the annulus opening are (a) $R_i = 80$ nm, $R_o = 110$ nm, and (b) $R_i = 80$ nm, $R_o = 150$ nm.

Figure 3.6 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 43 nm , and (b) 45 nm. The geometry parameters of the annulus opening are (a) $R_i = 50$ nm, $R_o = 100$ nm, and (b) $R_i = 110$ nm, $R_o = 160$ nm.

For the CCM with fixed thickness, the position of the DHLC can be controlled by varying the permittivity of dielectric in the CCM. We simulated the power distributions for the CCMs with dielectric constants varied from 1.8 to 3. It is found that for the permittivity of 1.8, the DHLC's center is located at 33 nm below the CMM. When the permittivity is increased to 3, the DHLC's center extends to 165 nm, as shown in Figure 3.7. In addition, the diameter of the DHLC also increases from 33 nm to 85 nm although the light intensity is decreased when the permittivity is increased from 1.8 to 3. Evidently, the position, size and light intensity of the DHLC can be monitored by choosing different dielectric materials.

Figure 3.7 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 33 nm and (b) 165 nm, respectively, for the CCMs whose the permittivity of the dielectric is set to 1.8 and 3, respectively.

We also studied the effect of the CCM thickness on the DHLC. Figures 3.8(a) and (b) show the power distributions in the cross sections passing through the DHLC centre for the CCM of 400 nm and 1000 nm thick, respectively. The DHLC center positions are located at 53 nm and 52 nm and their diameters are 30 nm and 33 nm for the CCM with thicknesses of 400 nm and 1000 nm, respectively. This observation indicates that the thickness of the CCM does not affect the center position and the size of the DHLC. However, as shown in the figure, thinner CCM will provide a light cone with higher intensity.

Figure 3.8 Simulated power distributions along the line across the centre of the x - y planes with $z =$ (a) 53 nm, and (b) 52 nm for the CCM with thicknesses of 400 nm and 1000 nm, respectively.

3.3.2 CCM covered by a thin layer of chromium (Cr) containing a hole opening

In this section, we study the DHLC of the CCM with a hole rather than an annulus opening in the cover layer. Figures 3.9(a) and (b) show the power distributions in the x - z planes across the central axis for the CCM with hole radii of 25 nm and 45 nm, respectively. It is found that when the hole radius in the chromium cover layer is increased, more light is transmitted through the CCM due to the increase of the incident power. However, the two positions of the DHLCs for the two different hole radii are about 60 nm below the CCMs.

Figure 3.9 Simulated power flow distribution in the x - z plane passing through central axis of the CCM when the diameter of the hole is set to (a) 50nm, and (b) 90nm, respectively.

Figures 3.10(a) and (b) show the power distributions in the x - y plane at $z = 60$ nm for the CCMs with two different diameters, respectively. It is clearly seen that the diameters and depths of the two DHLCs are almost the same while the light intensity of the CCM with larger hole opening is greater.

Figure 3.10 Simulated power distributions along the line across the centre of the x - y planes with $z = 60$ nm when the diameter of the hole is set to (a) 50 nm, and (b) 90 nm, respectively.

3.4 Chapter summary

In this chapter, a concentric cylindrical metamaterial (CCM) consisting of alternative silver-dielectric multi-shells covered by a 50 nm-thick chromium layer containing an annulus or a hole opening was proposed. By simulating the power flow distributions of the CCM with different annulus sizes, dielectric permittivities and thicknesses of the composite, we find that a dark hollow light cone (DHLC) of sub-wavelength size can be formed in the output side of the CCM. The position of the DHLC is almost independent of the thickness of the CCM but highly sensitive to the dielectric material used in the CCM and the dimension of the annular aperture. It is believed that such CCMs have potential applications in manipulating atoms and molecules.

CHAPTER 4. COGWHEELS FOR GENERATION OF SURFACE PLASMON POLARITON VORTEX

In this chapter, the subwavelength scale cogwheels were designed and simulated. By changing the direction of circular polarization, SPP propagation can be manipulated.

4.1 Introduction

The ability for confining light at deep subwavelength scale has made surface plasmon polaritons (SPPs) attractive for metamaterial studies [47-49, 86-88], super-resolution imaging [89, 90], optical trapping [91], and transformation plasmonics [92, 93]. The propagation of SPPs can be controlled by monitoring polarization of the incident light [20]. Meanwhile, whispering gallery modes (WGMs) have been used to monitor light in various aspects, such as realizing compact laser [94], detecting light orbital angular momentum [95], and generating optical vortex beams [96]. It is believed that whispering gallery mode for surface plasmon polaritons should also be able to provide more flexibility for light manipulation. This chapter presents the design and study of cogwheel structures that can generate SPP vortex beam and the direction of the vortex beam can be controlled by varying the circular polarization of incident light.

4.2 Structure design and principles

Figure 4.1 shows the schematic of a cogwheel structure which consists of an air ring and some equally distributed air cogs along the outer circle of the ring formed on a metal film. The air cogs are also in circular aperture. With the addition of the cogs to the ring, angular perturbation is introduced and excitation of SPP whispering gallery modes in the structure becomes possible. As the cogs are equally distributed along the ring aperture, the distance between two neighboring cogs and the radius of the ring are closely related to the coupling condition between the free-space incident light and the in-plane SPP waves, while the circumference of the ring is related to the resonance condition of the WGMs. For a ring with inner radius R and assuming SPP propagation constant β_{SPP} , and an azimuthal mode number p , the resonance condition for the WGMs can be written as

$$\nu_{WGM} = \beta_{spp} R = p. \quad (4.1)$$

While the angular phase matching condition is

$$\nu_{rad} = \nu_{WGM} - gq = 0, \quad (4.2)$$

where q is the number of cogs, and g is an integer denoting the grating order that satisfies the phase match condition. ν_{WGM} is the azimuthal propagation constant. The SPP propagation constant in a metal slot is denoted by $\beta_{SPP} = 2\pi/\lambda_{SPP}$, where λ_{SPP} is the SPP wavelength. For a circularly polarized beam of $\lambda = 633$ nm normally incident from the bottom of 200-nm thick gold film, the SPP wavelength

is found to be $\lambda_{\text{SPP}} \sim 600$ nm. If the azimuthal mode order p is taken as 18, the corresponding to a ring radius of $R = p\lambda_{\text{SPP}}/(2\pi) \sim 1.719$ μm .

Figure 4.1 Schematic of a typical cogwheel structure consisting of an air ring and a number of circular cogs equally distributed along the outer circle of the ring. The inner radius of the big ring is 1.719 μm , the ring slot is 200 nm wide and the diameters of the cogs are 100 nm.

Let us consider three cogwheel structures with $q = 9$, $q = 18$ and $q=12$, respectively, for the fixed p of 18. For the first two structures, the angular phase matching conditions are satisfied with $g = 2$ (for $q = 9$) and $g = 1$ (for $q = 18$), respectively. In these two cases, SPP whispering gallery waves are excited in clockwise and counter clockwise directions, which is similar to the excitation of counter propagating SPP waves when light is normally incident on a grating. However, if the cogwheel structure is designed in such a way that no integer g can satisfy the phase matching condition, such as in the third structure where $q = 12$ (which corresponds to $g = 3/2$), the propagation characteristics of SPP WGM would depend strongly on the polarization of incidence. The left/right circularly

polarized light can also be denoted as positive or negative spin angular momentum (SAM) or spin state [97, 98]: $|\sigma_{\pm}\rangle$, $\sigma_{+}=+1$ for the right circularly polarization (RCP), and $\sigma_{-}=-1$ for the left circular polarization (LCP).

4.3 Simulation and discussion

Numerical simulations were carried out by using Finite Element Method (COMSOL Multiphysics), where permittivities of gold is taken as $\epsilon_{Au} = -9.586 + 1.18i$ (at $\lambda=632.8$ nm) [83], and both the slot width and gold film thickness are set to 200 nm. The scattering boundary condition was used due to its accuracy and efficiency. The generalized minimal residual method (GMRES) is chosen for matrix inversion due to its rapid convergence and short calculation time.

Figure 4.2 shows the power distributions and phase responses of a ring (a) and (c), and a cogwheel with 9 equally distributed cogs (b) and (d), when they are illuminated with right circularly polarized light (RCP) at normal incidence. Here, the phase response (θ) is used to illustrate the wave front of the excited SPPs, which is obtained from the phase response of longitudinal electric field (E_z), i.e., $\theta = \arg(E_z)$. As expected from the circular symmetry of the ring aperture, the radial counter-propagating SPP waves are excited [Figure. 4.2(a) and Figure 4.2(c)]. It is interesting to note that the wave front is of spiral shape. This is attributed to the circular polarization of the incident beam that excites SPP at different direction at different delays, causing the wave front to lag along with the ring circumference. Thus, it stands to reason that changing the direction of the circular polarization

should change the phase spiral direction, as will be shown later in Figure 4.3. The spiraling is clearly seen at the inner side of the ring aperture while it is less prominent at the outer side where the SPP waves appear more as radial waves. It should be noted that the spiral phase response resembles the phase of optical vortex beam [96]. In terms of power distribution [Figure 4.2(a)], most of the light is confined in the slot, while some are localized at the center of the ring due to standing wave patterns.

Figure 4.2 Power distributions in the structure surface plane with right circularly polarized incidence for (a) a ring aperture and (b) a cogwheel with 9 equally spaced gears. (c) and (d) are the normalized phase graph for (a) and (b), respectively.

The characteristics of such optical vortex-like response can be changed by introducing angular perturbations. In the cogwheel with $q = 9$, when angular grating is introduced into the ring aperture, There will be the excitation of azimuthal SPP waves with resonance condition dependent on the cog pitch. The interference between radial waves (from ring aperture) and azimuthal waves (from the cogs) gives rise to azimuthal lobes, as shown in Figure 4.2(b). There are 18 azimuthal lobes from both power distribution and phase response, confirming that the SPP WGM is of the mode number of $p = 18$, as expected from our design ($R=1.719 \mu\text{m}$). The resonance condition for $q = 9$ is satisfied at $g = 2$ (see equation 4.2), which denotes the grating order of 2. The efficiency can be further increased by decreasing the grating order, for example by having 18 cogs ($q = 18$) such that the resonance condition at the first grating order ($g = 1$). Fig. 4.3 shows the power distribution and the phase response of cogwheel structure ($q = 18 = p$) excited under two circularly polarized light. The azimuthal lobes are clearly stronger than those in Figure 4.2(b). In addition, the phase responses (of both circular polarizations) show that the SPP WGM extends more outward compared to the case of $q = 9$, where the spiraling direction directly depends on whether the light is right circularly polarized (RCP) or left circularly polarized (LCP).

We now look at the case when the grating order is not an integer. Figure 4.4 shows the power distribution and phase responses of the cogwheel structure with $q = 12$, where the resonance condition is satisfied when $g = 3/2$. The number of SPP lobes is increased to 24, double the number of cogs. When the g is an integer, the excited SPP waves from cogs constructively interfere with each other along the circumference of the ring aperture, making SPP whispering gallery modes. This is in agreement with the fact that the number of SPP lobes is the same as the mode

number ($p = 18$). Since the SPP propagation direction depends on the direction of the longitudinal electric fields, each cog excites SPP waves with direction dependent on incident polarization.

Figure 4.3 Characteristics of cogwheel with $q = 18$ under right circularly polarized ($\sigma = +1$) and left circularly polarized ($\sigma = -1$). Power distribution for $\sigma = +1$ (a), and $\sigma = -1$ (b). Phase distribution for $\sigma = +1$ (c), and $\sigma = -1$ (d).

Thus, for integer g , the constructive interference is dominant along the ring aperture, while for non-integer g , the constructive interference is satisfied outside the ring aperture. Figure 4.4(a) and Figure 4.4(b) show a rather skewed SPP lobes distribution in contrast to radially symmetric SPP lobes in integer g (Figure 4.2 and Figure 4.3). It is also expected to see that the skew of the SPP lobes is

dependent on the circular polarizations of the incident light. The normalized phase plots for RCP and LCP light are shown in Figure 4.4(c) and Figure 4.4(d), respectively. The direction of SPP vortex is clearly seen both along the ring slot and at the center of the cogwheel structure. For both RCP and LCP incidence, the direction of the SPP vortex is the same as that of the incident circular polarization at the center of the cogwheel, while it is the opposite in the ring slot.

Figure 4.4 Power distributions in the structure surface plane with $q = 12$, (a) $\sigma_+ = +1$ or right circularly polarized (RCP) incidence, (b) $\sigma_- = -1$ or left circularly polarized (LCP) incidence, (c) and (d) are normalized phase graph for (a) and (b), respectively.

4.4 Chapter summary

In this chapter, cogwheel structures were proposed and theoretically studied for SPP vortex generation. The characteristics of the excited SPP waves can be changed by controlling the interference between the radial and azimuthal SPP waves, which are respectively contributed by the ring slot and the angular grating of the cogs. Furthermore, the spiral phase response resembles the properties of an optical vortex, which are controllable by the incident circular polarization. We believe that the cogwheels presented here can provide additional flexibility in light manipulation and be of potential application in photonics devices such as high speed optical switch, plasmonic circuit integration and optical tweezer.

CHAPTER 5. GROOVE-STRUCTURED METASURFACES FOR MODULATION OF SPP

In this chapter, subwavelength groove structured metasurfaces for non-resonant mode of SPP manipulation are designed, simulated and fabricated. It comes with the discussion of the maximum SPP divergence angles first, and then the study of SPP wave-front manipulation.

5.1 Introduction

Surface plasmon polaritons (SPPs) have gained significant interest for their potential applications in nanophotonic integration [14, 99, 100], sensing [101, 102], biology detections [87, 103, 104] and so on. To date, SPP manipulations using well-defined metallic nanostructures [17, 105-110] have achieved remarkable successes in beam splitting [34, 36], super-resolution imaging [109], the generation of hollow beam [86, 111], and subwavelength-sized optical devices [112, 113]. Recently, there is a growing interest in controlling light by a so-called metasurface [13] which refers to a kind of two-dimensional metamaterials consisting of subwavelength resonant elements. Such metasurface has shown unique abilities in manipulating light refraction [13, 42], reflection [114] and even in photonic spin Hall effect with local phase discontinuities which are considered to beat the conventional Snell's law [115]. Although similar idea has been proposed to realize the conversion between radiation wave and surface wave [47, 116], little experiment was reported in manipulation of in-plane SPP propagation

in optical region. One possible reason is that the metasurface designs are generally resonance-based, which is expected to be highly susceptible to loss and have narrow bandwidth. Therefore, for realizing device performances that are insensitive to loss within broad bandwidth, one would need metasurface designs based on non-resonance mechanism.

The concept of non-resonant metasurface was initially proposed by Pendry et al. [117], where artificial electromagnetic surface modes can be supported in structured perfect conductor surfaces. This strategy can be extended to the real plasmonic regime, where the SPP property can be tuned without resonant processes. Instead of employing spoof SPP based on hole arrays [117], in this chapter, metasurfaces designed based on subwavelength grooves in a metal film will be presented. Effective medium theory (EMT) is then employed to derive dispersion relation, which also serves as our design framework for SPP beam splitting angle and wavelength modulation. Our numerical simulation shows that the SPP wavelength modulation is related to the structural parameters of the metasurfaces, which is verified experimentally by the near field scanning optical microscopy (NSOM) measurements.

5.2 Theory and Simulation

5.2.1 Groove-structure metasurfaces for SPP beam splitting angle modulation

The structure of the metasurface is shown in Figure 5.1. It is composed of the sub-wavelength groove arrays and 3-slits grating etched from a 150nm thick gold film which was deposited on 60nm Cr layer. The whole structure of simulated area is

$5\mu\text{m} \times 10\mu\text{m}$ in size of x and y directions. The 3-slit grating grooves are $1\mu\text{m}$ long, 150nm wide and 210nm deep. The distance between the centres of neighbouring slits is 610 nm . SPPs are launched by the light penetrating through the grating and they propagate to both directions perpendicular to the slits. The sub-wavelength groove arrays are 150nm deep. Each groove is 50 nm wide and $3\mu\text{m}$ long. The period of groove arrays is a variable P which are chosen as 110 nm , 130 nm and 150 nm . Fig. 1(b) shows the perspective view of our model.

Figure 5.1 (a) Schematic of the meta-surface composed of sub-wavelength groove arrays in gold film on chromium. The period of groove arrays is denoted as P . (b) Perspective view of the metasurface model. The 633nm linearly polarized incidence is illuminated at the back of the substrate.

Using effective medium theory of nanowire arrays [118], the effective permittivity of the metasurface can then be expressed as

$$\epsilon'_{\text{meta-x}} = \frac{N\epsilon'_m Q + (1-N)\epsilon_d}{NQ + (1-N)} \quad (5.1)$$

$$\epsilon'_{\text{meta-y}} = N\epsilon'_m + (1-N)\epsilon_d \quad (5.2)$$

where $\epsilon'_{\text{meta-x}}$ and $\epsilon'_{\text{meta-y}}$ are the effective permittivity for the electrical field x and y directions, respectively, which also coincide with the propagation direction of the SPPs. ϵ_d is the permittivity of the dielectric, ϵ'_m is the real permittivity of the

metal, $Q = 2\varepsilon_d/(\varepsilon_m' + \varepsilon_d)$, and $N = (P - w)/P$ is the metal filling ratio for grooves with periodicity P and width w .

When $\varepsilon'_{\text{meta-x}} < 0$, $\varepsilon'_{\text{meta-y}} > 0$ and $k_0 = \omega/c$, the dispersion equation can be expressed as:

$$k_y^2 + \frac{\varepsilon'_{\text{meta-x}}}{\varepsilon'_{\text{meta-y}}} k_x^2 = k_0^2 \varepsilon'_{\text{meta-x}} \quad (5.3)$$

where k_y and k_x are wave vectors along the y and x directions. Based on the EMT and dispersion relation we calculated the effective permittivity. It is shown that the maximum beam divergence angle in the beam propagation direction is related to the angle between the asymptotes of the hyperbola and k_x/k_0 axis.

The maximum SPP beam divergence angle on the meta-surface can be expressed as[119]:

$$\tan\theta = \sqrt{\frac{\varepsilon'_{\text{meta-x}}}{|\varepsilon'_{\text{meta-y}}|}} \quad (5.4)$$

Using Eq. (5.4), we calculated the divergence angles for dielectric permittivity of $P = 110$ nm, $P = 130$ nm and $P = 150$ nm and they are 45.96° , 48.97° , 51.89° , respectively. As shown in Figure 5.2, the divergence angle follows the trend of the period of groove arrays and the calculated results are matched with the simulation results very well. The calculation data is listed in Table 5-1.

Table 5-1 Calculated maximum SPP beam divergence angles

$P(\text{nm})$	N	$\varepsilon'_{\text{meta-x}}$	$\varepsilon'_{\text{meta-y}}$	$\tan\theta$	θ
110	0.545	5.098	-4.769	1.034	45.96
130	0.615	7.276	-5.51	1.149	48.97
150	0.667	9.74	-5.987	1.275	51.89

Figure 5.2 Power flow distribution at the surface of the metasurface. The calculated divergence angles shown by black arrows are 45.96, 48.97 and 51.89 degree for period of groove arrays of (a) $P = 110$ nm, (b) $P = 130$ nm and (c) $P = 150$ nm, respectively.

When the SPPs start propagating on the grooves, the edge of groove bridges the momentum gap for the SPP modes. High frequency components are created and they are supported by the anisotropic gold dielectric multi-groove structure. The calculation results show that dispersion relation of the meta-surface structure has hyperbolic shape which is similar to stratified metal-dielectric composite metamaterials. That is why the excited SPP beam diverges to two directions inside the designed metasurface structure.

5.2.2 Groove-structure metasurfaces for SPP wavelength modulation

The proposed metasurface for SPP wavelength modulation is schematically shown in Figure 5.3(a). It consists of subwavelength grooves perpendicular to the grating coupler used to couple the light from free-space to in-plane SPP waves. As the electric field does not extend in the z -direction, and is tightly confined to the

metal's surface, the metasurface resembles a case of one-dimensional nanowire arrays.

Assuming the groove depth is larger than the SPP penetration depth ($h > \delta_{\text{meta}}$) for the incident light with a wavelength λ_0 , one can thus infer the SPP wavelength from a typical SPP dispersion relation [21]

$$\lambda_{\text{spp}} \cong \lambda_0 \sqrt{\frac{\epsilon_d + \epsilon_{\text{meta-y}}'}{\epsilon_d \epsilon_{\text{meta-y}}'}} \quad (5.5)$$

where the permittivity of metal (ϵ_m) is replaced by $\epsilon_{\text{meta-y}}'$ for SPP propagating in y-direction (corresponds to the electric fields E_y). By substituting Eq. (5.2) into Eq. (5.5), the SPP wavelength in a metasurface can be expressed as

$$\lambda_{\text{spp}} \cong \lambda_0 \sqrt{\frac{(2-N)\epsilon_d + N\epsilon_m'}{N\epsilon_d \epsilon_m' + (1-N)\epsilon_d^2}} \equiv \lambda_0 \alpha \quad (5.6)$$

where α denotes the wavelength scaling factor and is equal to the inverse of the effective index ($\alpha = 1/n_{\text{eff}}$). Table 5.2 shows the effective permittivity ($\epsilon_{\text{meta-y}}'$), effective refractive indices (n_{eff}) and SPP wavelength ($\lambda_{\text{SPP-EMT}}$) derived from the effective medium theory for the metasurfaces on a gold film, with groove periodicity varied from $P = 100$ nm to $P = 150$ nm and groove width fixed to $w = 50$ nm, at $\lambda_0 = 633$ nm incidence wavelength.

Figure 5.3 (a) Schematic of a proposed metasurface formed by an array of $6 \mu\text{m}$ grooves with a fixed period. On its right is a grating coupler. (b) Simulated electrical field intensity distributions E_z in a set of metasurfaces which are formed by grooves with different periodicities but the same width. The top one is the distribution in a gold film without grooves for comparison. The dashed straight lines indicate the wavefront of SPP in the metasurfaces and the wavelength scaling (or shrinking) with the decreasing period can be easily seen. (c) The SPP wavelengths of the metasurfaces in (b), calculated by EMT (squares) and FEM (triangles).

As a comparison, the E_z -field distributions of metasurfaces with the same groove periodicities and groove depth ($h = 50$ nm) were also calculated by finite element method (FEM) using COMSOL commercial software. The input of the incident electric field is 1 Vm^{-1} , and the permittivities are $\epsilon_{Au} = -9.586 + 1.18i$ (for gold) and $\epsilon_{Air} = 1$ (for air) for $\lambda_0=632.8$ nm incident wavelength[83]. The penetration depth is found to be in $\delta \sim 30$ nm range, which validates the assumption that the groove depth ($h = 50$ nm) is larger than the SPP penetration depth. The E_z field distribution in a unit cell is shown in Figure 5.3(b), where a periodic boundary condition was used and the sparse matrix was solved by using UMFPACK algorithm. On the other hand, for the large-scale simulations shown in Figure 5.4 and Figure 5.6(b), the scattering boundary condition was used in order to reduce artificial reflections and GMRES algorithm was used to solve the sparse matrix for its rapid convergence. The SPP wavelengths based on FEM calculation are also shown in Table 5-2. The difference between the EMT and FEM wavelength is because of the depth of the groove is set to 50 nm. The difference between these two wavelengths can be reduced by increasing the groove depth.

The comparison between FEM and EMT is shown in Figure 5.3 (c), with the case of un-patterned gold film ($N = 1$) is also shown for reference. It can be seen that the EMT results are in qualitative agreement with FEM results. In general, EMT is more accurate when the structural dimensions are in the deep subwavelength regime ($< \lambda/10$). However, in this work the groove periodicity of metasurface is $\sim \lambda/6$, which may be the reason for the apparent differences between EMT and FEM results. The second factor contributing to the difference is the fact that only

the real part of gold permittivity is considered in EMT, in contrast to the FEM case which takes into account the complex gold permittivity values.

Table 5-2 Summary of effective permittivity $\epsilon_{\text{meta-y}}$, effective refractive index, the decay rate of SPP α_{SPP} , SPP wavelengths calculated from effective medium theory of the metasurfaces formed by arrays of grooves with different periods but the same groove width. The SPP wavelengths simulated using the finite element methods are listed in the last column for comparison.

$P(\text{nm})$	N	$\epsilon_{\text{meta-y}}$	n_{eff}	$\alpha_{\text{SPP}} (1/\mu\text{m})$	$\lambda_{\text{SPP-EMT}} (\text{nm})$	$\lambda_{\text{SPP-FEM}} (\text{nm})$
	1	-9.586	1	0.2351	599	605.75
150	0.667	-5.987	1.033	0.2519	578.4	586.12
140	0.643	-5.807	1.036	0.2469	575.92	584.98
130	0.615	-5.510	1.04	0.2622	572.69	582.27
120	0.583	-5.172	1.054	0.2829	568.52	574.61
110	0.545	-4.769	1.064	0.2866	562.74	569.37
100	0.5	-4.293	1.077	0.2985	554.39	562.53

Figure 5.3 (c) shows the geometrical dependency of SPP wavelength, where the SPP wavelength is shorter for decreasing groove periodicity. This also indicates that the effective refractive index can be increased by decreasing the groove periodicity. This provides us a framework to design gradient index (GRIN) metasurface for SPP focusing, as will be shown in the next section.

In order to investigate this, we simulated electric field distributions of metasurface illuminated by different wavelengths of light, as shown in Figure 5.4. It is evident that both $\lambda_0 = 532 \text{ nm}$ [Figure 5.4 (a)] and $\lambda_0 = 775 \text{ nm}$ [Figure 5.4 (b)] incident wavelengths result in SPP wavelength scaling, although the scaling factors are

rather different (α is higher for smaller λ_0). This indicates that the metasurface operates under certain bandwidth, in contrast to the ideal condition where the metasurface characteristics is supposed to be wavelength-independent. This is, we believe, due to the fact that the metasurface is treated as a uniform anisotropic medium under EMT framework, which is valid only if the structures are in deep subwavelength regime.

Figure 5.4 Calculated E_z -field distributions inside and outside the metasurface with an array of $P = 110$ nm grooves at the incidence of (a) 532 nm and (b) 775 nm.

5.3 Experimental results for SPP wavelength modulation

The metasurface fabrication was carried out by first depositing 210 nm thick gold film (with 2 nm thick Cr adhesion layer) on glass substrate by sputtering, followed by metasurface patterning by focused ion beam (FIB) with Ga ion with 30keV beam energy. The beam current used for patterning the grating coupler and metasurface were 20 pA and 120 pA, respectively. Figure 5.5(a) shows the

fabricated metasurface with $L = 6 \text{ }\mu\text{m}$, $w = 50 \text{ nm}$, $h = 50 \text{ nm}$, and $P = 150 \text{ nm}$. The coupling from free-space into in-plane SPPs is facilitated by grating coupler [the left grating structure in Figure 5.5(a)], which comprises slit grating with 15- μm slit-length and 150-nm slit-width.

The electric field distributions were characterized using a near field scanning optical microscope (NSOM). The characterization setup is schematically shown in Figure 5.5 (b). The linearly polarized He-Ne laser ($\lambda = 632.8 \text{ nm}$) is normal incident beam from the bottom of the glass substrate through objective lens (Olympus UPlanFLN 10 $\times$, NA=0.3). Meanwhile, the aluminium-coated NSOM tip (less than 100 nm in diameter) was positioned about 10 nm from the sample to collect near field information which was then amplified by photomultiplier tube (PMT). The NSOM characterization of the metasurface (for $P = 150 \text{ nm}$) is shown in Figure 5.5 (c).

Note that there are fringes in NSOM results, which can be attributed to the interference between directly transmitted incident beam and in-plane surface plasmon polariton[20, 120], where the bright (dark) fringes correspond to constructive (destructive) interference situation. Thus, the SPP wavelengths (λ_{SPP}) can be deduced by measuring the distances between the fringes, i.e., $\lambda_{\text{SPP}}=d/(q-1)$, where d is the distance between q fringes. The measured SPP wavelengths are $\lambda_{\text{SPP}} \sim 605 \text{ nm}$ ($d = 1210 \text{ nm}$ for $q = 3$) for the un-patterned gold film, and $\lambda_{\text{SPP}} \sim 586.7 \text{ nm}$ ($d = 1760 \text{ nm}$ for $q = 4$) for the patterned gold film (metasurface). In comparison to our numerical results (see Table 5-2), the measured λ_{SPP} outside the metasurface ($\lambda_{\text{SPP}} \sim 605 \text{ nm}$) is very close to that from FEM calculation ($\lambda_{\text{SPP-FEM}}$

~ 605.75 nm).

Figure 5.5 (a) SEM micrograph of the metasurface formed by an array of grooves with $P = 150$ nm and groove width $w = 50$ nm. (b) Schematic diagram of the near field scanning microscope. (c) Measured near-field intensity distribution of the metasurface.

The measured λ_{SPP} inside the metasurface ($\lambda_{\text{SPP}} \sim 586.7$ nm) is also close to the simulated ($\lambda_{\text{SPP-FEM}} \sim 586.12$ nm for $P = 150$ nm). The scaling factor can then be deduced by $\alpha = \lambda_{\text{SPP,out}}/\lambda_{\text{SPP,in}}$, where $\lambda_{\text{SPP,in}}$ ($\lambda_{\text{SPP,out}}$) is the SPP wavelength inside (outside) the metasurface. Note that the contraction of in-plane SPP wave can be experimentally observed from the mismatch between inside and outside fringes in Figure 5.5(c), thereby validating the theoretical calculation. This also shows, at least indirectly, the tuning of effective index by introducing subwavelength grooves in a gold film. Therefore, it is possible to mimic the phase shift in a lens by introducing different effective indices in the lateral direction. This principle is employed to design GRIN metasurface for in-line SPP focusing. For a fixed groove width, since shorter groove periodicity gives higher effective index [see Figure 5.3 (c)], the metasurface can approximate phase response of a lens when the groove periodicity progressively increases from the center to the edge of the metasurface. The fabricated GRIN metasurface is shown in Figure 5.6(a). It consists of 56 grooves with periodicity changed from $P = 150$ nm (at the edge) to $P = 100$ nm (at the center). The groove width is fixed to 50 nm, while the groove periodicity is decreased consecutively for every 2 periods by 5 nm towards the center on the metasurface. The FEM calculation and NSOM results are presented in Figure 5.6 (b) and Figure 5.6 (c), respectively, where the focusing action can be seen in both cases, showing excellent agreement between them. This is further verified by the fact that the wavefront in Figure 5.6(c) is curved instead of straight as in Figure 5.5 (c), demonstrating that the SPP wave goes into a lens-like medium. Although such fringes are not phase-resolved as in the FEM calculations shown in Figure 5.6 (b), we nevertheless have shown a proof-of-concept of SPP focusing by using GRIN metasurface. Furthermore, we also note that the focusing

action in Figure 5.6 (c) is still considerably weak. Stronger focusing action can be achieved by fabricating denser grooves at the center so as to make the lens exhibiting ‘stronger index contrast’, and thus giving shorter focal length.

Figure 5.6 (a) SEM micrograph of the GRIN metasurface formed by grooves with the period progressively decreasing from 150 nm (at the edge) to 100 nm (at the center). (b) Simulated E_z -field distributions of the GRIN metasurface. (c) Measured field intensity distribution.

5.4 Chapter summary

In this chapter, metasurfaces consisting of sub-wavelength groove arrays in a gold film were proposed and demonstrated. They show the capability of SPP beam splitting, wavelength modulation and wavefront engineering. The effective medium theory employed in our device design has a good agreement with FEM calculations and has been verified by NSOM measurements. In particular, the subwavelength gold grooves with locally varying periodicity has been fabricated and characterized, where SPP wavelength shrinking and in-plane SPP focusing have been experimentally observed. It is believed that the proposed metasurface can be potentially used for wavefront engineering, nanophotonics and metadevices.

CHAPTER 6. ALUMINUM BASED STRUCTURES FOR MANIPULATING SHORT VISIBLE WAVELENGTH IN-PLANE SPP PROPAGATION

Metals are the major concerns in plasmonic research and application. As a low cost metal, aluminum has good plasmonic property in the short visible wavelength range. In this chapter, Aluminum based subwavelength structures were studied and SPP wave-front modulation was demonstrated by the design structures.

6.1 Introduction

Confining light into a deep subwavelength scale has made surface plasmon polaritons (SPPs) attractive to the fields of modern optics, particularly in metamaterial studies [47-49, 88, 121], super-resolution imaging [89, 90, 122], optical trapping [91, 111], and transformation plasmonics [35, 93]. The propagation of SPPs can be controlled by monitoring polarization of the incident light [20, 123, 124]. As quasi particles, SPPs also play an important role in the area of sub-wavelength optics and 2D optics [17, 125]. However, in general, the widely used noble metals, e.g., gold and silver, do not perform well in the short visible wavelength as compared to longer visible and infrared wavelength. This is mainly attributed to the interband transitions in the visible spectrum, which gives higher damping constant. For this reason, aluminum is often proposed as an alternative material for plasmonics due to its lower damping constant in the UV to visible spectrum. However, the drawback for aluminum is its native oxidation that changes its surface property [126].

Theoretical studies of aluminum showed the capacity of this non-noble metal for plasmonics applications [127, 128]. Langhammer *et al.* studied localized surface plasmon resonance (LSPR) of the aluminum nanodisks with varies of diameters in UV-vis-NIR spectrum[129]. Taguchi *et al.* demonstrated size tunable aluminum nanostructure for deep-UV LSPR[130]. Zhu *et al.* demonstrated Al/SiO₂ waveguide integrated circuits at 1550nm[131]. Gjonaj *et al.* used silver-nitride-air structure to get sub-100nm focusing in the near-field [125]. To the best of our knowledge, little experimental work has been done for in-plane SPP propagation based aluminum. In this chapter, we propose a metal-insulator-air (MIA) structure to accommodate SPP propagation at short visible wavelength, and study the effect of the dielectric layer in the Al/Si₃N₄/air structures on the SPP wavelength and propagation length.

6.2 The principle for wavelength modulation using MIA strucutre

In the near field optics, the propagation of surface plasmon polaritons (SPPs) is characterized by surface plasmon wavelength (λ_{SPP}). For an incident light of wavelength λ_0 , the dispersion relation of SPPs along the metal-dielectric interface is given by [21]

$$\lambda_{spp} \cong \lambda_0 \sqrt{\frac{\epsilon_d + \epsilon_m'}{\epsilon_d \epsilon_m'}}, \quad (6.1)$$

where ϵ_m' and ϵ_d are the real permittivity of the metal and dielectric, respectively.

In the case where the metal is highly plasmonic, $|\epsilon_m'| \gg \epsilon_d$, Eq. 1 can be simplified as

$$\lambda_{\text{SPP}} \approx \lambda_0(\epsilon_d)^{-1/2} \quad (6.2)$$

which suggests that changing dielectric permittivity can readily tune the SPP wavelength. However, the dielectric permittivity as perceived by the propagating SPP is not always the bulk permittivity of the dielectric, particularly when the dielectric thickness is smaller than the SPP penetration depth in the dielectric ($t < \delta_d$). This is expected as the SPP electric field overlaps with both dielectric and air, which gives an averaged permittivity according to its overlap integral. The SPP penetration depth in the metal (δ_m) and dielectric (δ_d) are expressed respectively as [21]

$$\delta_m = \frac{1}{k_0} \left| \frac{\epsilon_m' + \epsilon_d}{\epsilon_m'^2} \right|^{\frac{1}{2}}, \quad \delta_d = \frac{1}{k_0} \left| \frac{\epsilon_m' + \epsilon_d}{\epsilon_d^2} \right|^{\frac{1}{2}} \quad (6.3)$$

which, in highly plasmonic metal (such as Al), can be further simplified into the following

$$\delta_m \cong \frac{1}{k_0} \frac{\sqrt{\epsilon_d}}{|\epsilon_m'|}, \quad \delta_d \cong \frac{1}{k_0} \frac{\sqrt{|\epsilon_m'|}}{\epsilon_d} \quad (6.4)$$

where k_0 is the wave vector of the incident light in vacuum.

It is clear that if the dielectric film is thicker than the penetration depth of SPP δ_d , the SPP wavelength can be predicted by the Equation 6.1 accurately. If it is

thinner than the penetration depth δ_d , however, the SPP wavelength will be smaller than the value calculated from equation 6.1. The loss and damping property will also change as the film thickness is changed. As the leakage increases from the insulator-air interface, the direct measurement becomes possible. In this work, Silicon Nitride (Si_3N_4) was chosen for the dielectric layer. The calculated SPP penetration depth of $\delta(\text{Si}_3\text{N}_4)$ is ~ 90 nm on Al film for the incidence of 473 nm light. Figure 6.1(a) shows the schematic of the Al/ Si_3N_4 /air structures with 80 nm thick aluminum and varied thickness of the Si_3N_4 layer.

Figure 6.1(b) and (c) show the simulated electric field distributions in z-y plane of the Al-Air structure (80 nm Al) and a typical MIA structure (80 nm Al and 40 nm Si_3N_4), respectively. The SPPs are excited by linearly polarized light of 473 nm at normal incidence through a slot opening which is about 100 nm wide. The input of the incident electric field is 1 Vm^{-1} , and the permittivities are $-30.498 + 7.727i$ for Al, 4.17 for Si_3N_4 and 1 for air at the incident wavelength of $\lambda_0=473$ nm [132, 133]. As shown from the figures, the SPPs excited by the incident light from the air slit propagate along the y and $-y$ directions symmetrically and the field intensity decay along the propagation directions. It is also seen that for the structure with the 40 nm Si_3N_4 layer, the SPP field distribution and wavelength are different from those of the structure without the Si_3N_4 layer. To study the effects of the dielectric layer above the aluminium film, the E_z field distributions of the Al/ Si_3N_4 /air structures with same Al thickness (80 nm) but varied thickness of the Si_3N_4 layers from 20 nm to 60 nm are calculated and plotted in Figure 6.1(d), where the vertical dash lines are used to indicate the wave fronts of these SPPs. It

is clearly seen that the SPP wavelength shrinks with the increase of Si_3N_4 thickness, which is accompanied by the increasing propagation loss.

Figure 6.1 (a) Schematic diagram of an aluminium based MIA structure. (b) Simulated E_z of the MIA structure consisting of 80nm Aluminium film and Air at z-y plane. (c) Simulated E_z of the MIA structure consisting of 80nm Aluminium film, 40nm Si_3N_4 film and Air at z-y plane. (d) E_z distributions in x-y plane at Si_3N_4 /Air interface of the MIA structures with different thicknesses of Si_3N_4 layer above the 80nm Al film. The dashed straight lines are used to indicate the wavefronts of SPPs of the MIA structures.

In order to see more details for the SPP propagation loss in the MIA structures, Figure 2(a) shows damping of E_z fields of four structures with different thicknesses of the Si_3N_4 layer. As seen from the figures, for all the MIA structures

studied, E_z field decays in intensity with the increasing propagation distance and the decay or damping is not so significant for the MIA structures without or with a very thin Si_3N_4 layer of 20 nm, but becomes more and more significant for structures with a thicker Si_3N_4 layer. Such observations are consistent with Equation 6.4 that describes the relation between permittivity and the SPP penetration depth. Assuming that the Si_3N_4 is well below its skin depth ($t < 90$ nm) where the effective permittivity depends on the film thickness, one can see that increasing Si_3N_4 thickness gives higher effective Si_3N_4 permittivity, which according to Equation 6.4 leads to the increase (decrease) of δ_m (δ_d). Thus, more overlapping with metal will naturally give higher propagation loss. On the other hand, if the decrease of Si_3N_4 thickness give a decrease in effective Si_3N_4 permittivity, leading to a decrease (increase) of δ_m (δ_d). Thus, the SPP overlaps less with the metal, which consequently gives lower propagation loss. To have quantitative description for the decay, the SPP propagation can be expressed as [134]:

$$E_z(y) = E_{z0} e^{ik'_y y} e^{-k''_y y} = E_{z0} e^{ik'_y y} e^{\alpha_{SPP} y} \quad (6.5)$$

where α_{SPP} is the electric field decay rate of SPPs propagating in y direction.

The SPP wavelength as a function of Si_3N_4 thickness is presented in Figure 6.2(b), where the wavelength has shrunk from 430 nm to 265 nm as the Si_3N_4 thickness is increased from 20 nm to 60 nm. This can also be attributed to the increase of the effective refractive index of the dielectric materials which is consistent to Equation 6.2.

Figure 6.2 (a) Damping of electric field E_z at $\text{Si}_3\text{N}_4/\text{Air}$ interface of the MIA structures consisting of 80nm aluminium film and varied thickness of Si_3N_4 film. (b) SPP wavelength (blue squares) and SPP decay (red circles) rate as a function of thickness of Si_3N_4 film.

To better illustrate the tolerance of the gratings' periodicity, the structures with $p=430$ nm and $p=400$ nm but with other parameters the same are simulated. The numerical simulation results are shown in Figure 6.3.

Figure 6.3 E_z distributions in x-y plane of (a) sample 2's structure with 430 nm gratings period and (b) sample 2's structure with 400 nm gratings period for y polarized incidence. (c) plotting of the fringes electric fields for comparison.

From the figure, we can see that the periods of the SPP fringes from the two structures are both 430 nm although their grating periodicities are different. This observation indicates that the period of fringes, which is the SPP wavelength propagating in both directions of the structures, has nothing to do with the period of the gratings. It is also seen that the intensity of the electric field decreases along both propagation directions and the values of the intensity from the two structures

are different. For example, the values of the third peak from the right edge of the gratings are 0.815 V/m and 0.628 V/m, respectively, for the structures with periods of 430 nm and 400 nm, respectively, which is due to the difference in excitation efficiency. Nevertheless, the coupled SPP is still strong enough to be measured by the NSOM measurement, which allows some tolerances in sample fabrication.

6.3 The experimental verification of MIA structures

6.3.1 Fabrication of MIA structures using FIB

To experimentally verify the SPP propagation, the thickness of Si_3N_4 film cannot be made too thick as it will weaken the field signal on the top Si_3N_4 surface and make measurement difficult. For the above reason, we fabricated two structures, one of which has only 80 nm Al (sample 1) and the other has 80nm Al covered by a 20nm Si_3N_4 layer (sample 2) and both structures were on quartz substrate, as illustrated in Figures 6.4(a) and (b), respectively. The top views of the two structures with fabricated gratings are shown in Figure 6.4(c) and (d).

The Al deposition was carried out with 30W DC power and 6.4 sccm Argon gas, while the Si_3N_4 deposition was performed with 80W RF power and 5.5 sccm Argon gas. High vacuum is maintained in continuous state during aluminium and Si_3N_4 layer deposition to minimize oxidation. The thicknesses of both layers were verified by a surface profiler. The gratings were fabricated using a Carl Zeiss AURIGA crossbeam (FIB-SEM) workstation. The ion source is Gallium (Ga) beam with energy of 30 keV. The milling of the grating structures were performed at a beam current of 120 pA. There are five slits in the grating in each sample.

Each grating slit is 100 nm wide and the periods are 470 nm and 400 nm for sample 1 and sample 2, respectively. Note that the number of periodic gratings only affects the intensity of the SPP but not wavelength.

Figure 6.4 Schematic diagrams of (a) sample 1: 80nm thick aluminum film on substrate and (b) sample 2: 20nm thick / 80nm aluminum on quartz substrate. SEM images with gratings of (c) sample 1 and (d) sample 2.

6.3.2 Near-field imaging of the SPPs with wavelength modulation

The electric field distributions were measured using a near-field scanning optical microscope (NSOM). The linearly polarized 473nm laser was the normal incident beam from the bottom of the quartz substrate. A photomultiplier tube (PMT) is used for signal detection and amplification. The NSOM probe tip (aluminium-coated) is less than 100 nm in diameter and it is positioned about 10 nm above the sample surface, based on shear-force feedback mechanism.

The SPP near field patterns are shown in Figure 6.5, which results from the interference between the in-plane SPP fields and the transmitted out-of-plane incident beam [20, 120]. The SPP wavelengths can be deduced as the distance between the fringes, $\lambda_{spp} = d/(q - 1)$, where d is the distance between q fringes. The SPP wavelengths in Figure 6.5(c) and Figure 6.5(d) are about 465 ± 5 nm for the sample with 80nm Aluminum only and about 430 ± 5 nm for the sample with 80nm Aluminum film and 20nm Si_3N_4 coating. The FEM simulation and NSOM results are also presented in Figure 6.5(a) and (b), where the fringing can be seen for each condition, showing excellent agreement between the measured values and simulation. The experimental results are also in excellent agreement with the simulations shown in Figure 6.2(b).

Figure 6.5 E_z distributions in x-y plane of (a) sample 1 and (b) sample 2 for y polarized incidence. NSOM images of (c) sample 1 and (d) sample 2. The dash arrows in (a) and (b) show the direction of linear polarization.

6.4 Chapter summary

The aluminum based MIA structures are proposed and SPP propagation characteristics in the structures are studied theoretically and experimentally. Such structures can be used to excite and propagate SPPs of wavelengths from 465 nm to about 265 nm by varying the thickness of a coated Si_3N_4 layer up to 60 nm, which provides an alternative way to manipulate in-plane SPPs. In addition, with a coated thin Si_3N_4 layer, the oxidation of Al can be prevented to a certain extent. We believe that the presented aluminum based MIA structures have potential applications in nanophotonics, such as super-resolution focusing and 2D optics.

CHAPTER 7. SUBWAVELENGTH STRUCTURES FOR VCSELS

Light sources are core components in optical systems. In the nanophotonics era, VCSELs will play an important role for optical integrations. In this chapter, two types of subwavelength grating structures were studied. One is the high contrast grating structure which is used to replace the top distribute Bragg reflector of a VCSEL; The other is metallic grating structure directly fabricated on the top of a VCSEL for SPP generation and propagation.

7.1 VCSEL fundamentals

7.1.1 The brief introduction of VCSEL

Vertical-cavity surface-emitting lasers (VCSEL) are semiconductor devices which emit light vertically from their surface. Compared with the edge-emitting semiconductor lasers, it has more applications in the fields of on-chip light communications, all-light computation and nanophotonics.

The concept of VCSEL was firstly proposed by Kenichi Iga in 1977 and published in 1979[135]. Before that, the longitudinal plasmonics laser at 5.2 μm lasing wavelength at InSb substrate was proposed by Ivars Melngailis in 1965 [136]. As declared by Prof. Kenichi Iga, the VCSEL has following major advantages but not limited to[137]: 1) Monolithic and high yield fabrication. 2) Extremely low threshold and small power consumption. 3) High-speed modulation at low driving current. 4) Easy packaging. After more than 35 years' development, VCSELs now

have the second largest production volume in the semiconductor lasers market. They are commercially used as the light sources for millions of optical mice and high speed data transmission devices based on multimode-fiber interconnects[138].

Using the high contrast gratings (HCGs) to replace the top distribute Bragg reflector (DBR) which will make the VCSEL structure more compact, easier to be fabricated and even be able to control the lasing polarization directions. Secondly, we will explore the possibility of using VCSELs as the on-chip light source to excite SPP for in-plane propagation.

7.1.2 Structure of a VCSEL

Figure 7.1 Schematic layer structure and operation principle illustration.[138]©Springer

The typical layout is illustrated in the Figure 7.1. The VCSEL is normally designed for the emitting wavelength of 850nm to 980nm which require 8-10 μ m epitaxial growth material. There are several quantum wells embedded inside the epitaxial materials performed as the inner cavity and active layers. The p-type on n-type doping arrangement is preferred because the n-type substrate normally has lower defects.

Figure 7.2 Current confinement methods for VCSELs. Air-post (left), Proton implanted (middle) and oxide-confined (right). [138]©Springer

Confining the current inside the active region is a critical requirement of VCSEL operation. As illustrated in the Figure 7.2, there are three major methods used to achieve the current confinement. The air-post method is also named mesa etching method [139, 140], the problems for this method are the active region exposure to the air and light scattering losses. The proton implantation method is used for the first commercialized VCSEL which is high reliable and producible [141, 142]. The selective oxidation method made the VCSEL fabrication a leap in low-loss lasing, light confinement and performance [143-146]. In this work, the selective wet oxidation method is performed to get better current confinement and light quality.

The mirror of the VCSEL is formed by the DBR. It consists of alternating high and low refractive index materials. Each pair of DBR's thickness is one fourth of the lasing effective wavelength. To calculate the reflection index of DBRs, the following equations can be applied [138, 147]:

$$R_{top,bottom} = \left(\frac{1-b_{top,bottom}}{1+b_{top,bottom}} \right)^2 \quad (7.1)$$

$$b_{top} = \frac{n_{air}}{n_c} \left(\frac{n_{B1}}{n_{B2}} \right)^{2M_{top}} \quad (7.2)$$

$$b_{bottom} = \frac{n_{B1}^2}{n_c n_s} \left(\frac{n_{B1}}{n_{B2}} \right)^{2M_{bottom}} \quad (7.3)$$

where n_{B1} , n_{B2} are refractive indexes of two alternating materials of Bragg reflectors. n_{air} , n_s and n_c are refractive indexes of air, substrate and cladding layer, respectively. $R_{top,bottom}$ is the top or bottom DBRs' peak reflectivity with the M_{top} or M_{bottom} layers of alternating high index contrast materials. As shown in Figure 7.3, the GaAs-AlAs top lossless mirror needs to have at least 21 pairs to get the 99.9% peak reflectivity. From the Figure 7.1, we can see that the DBR layers is much thicker than the active region. In practice, the DBR of the laser emitting side needs to reach at least 99.5% reflectivity by 21-25 pairs of reflector, while the other side of the DBR needs to reach 99.99% reflectivity with more than 30 pairs of DBRs.

Figure 7.3 Peak reflectivity of the GaAs-AlAs Bragg reflector versus number of DBR mirror pairs [138]©Springer

7.2 High Contrast Gratings application to 980nm VCSEL

7.2.1 Introduction to HCGs in VCSEL

High contrast grating (HCG) is a subwavelength scale nanostructure, which can supply high reflectance and larger reflectivity bandwidth about four times of the distribute Bragg reflectors (DBRs) [148-150]. It is considered to be the ideal reflector of the vertical cavity surface emitting lasers (VCSELs) to replace the top DBR [149-155]. Many works have been done for the HCGs in VCSELs [149-151], and they have been proven being one of the best reliable and useful ways to control the mode and polarization states of the VCSELs [150-167]. A new HCG-VCSEL consisting of air cavity and suspension grating was first produced by Chang's group [150]. The device operates at a single fundamental mode and the stable polarization and the orthogonal polarization suppression ratio (OPSR) is more than 40 dB. The output power of the devices is more than 1 mW and the side mode suppression rate (SMSRs) is more than 45 dB. Although remarkable results of the HCG-VCSELs have been obtained, this type of devices is difficult to fabricate and the device reliability is easily disturbed if the working condition is changed [150-153]. In order to improve the characteristics of the devices, a new HCG structure which uses SiO_2 as the low refractive index layer and amorphous silicon as the grating layer was proposed [153]. However, such HCG structure can only be used in short wavelength VCSELs. For 980 nm VCSELs, we proposed a GaAs/ Al_2O_3 HCG structure. In the HCG, the AlAs layer is used to generate an Al_2O_3 layer by wet oxidation which functions as the low refractive index layer, and a GaAs layer is used as the grating layer. Both (AlAs and GaAs) layers can be

obtained by epitaxial method, which greatly reduces the process difficulties and enhances the characteristics of the VCSELs. We first design the HCG structures and calculate the mode loss using Finite Difference Time Domain (FDTD). The designed structures were fabricated using the Focused Ion Beam (FIB) and then characterized using a reflectance test system under different polarizations of light.

7.2.2 Simulation results of GaAs/Al₂O₃ HCGs

Figure 7.4 shows the cross-sectional schematic of the new HCG-VCSEL structure in which the GaAs layer in the HCG is the high refractive index grating layer and the Al₂O₃ is LRI layer. The refractive index of the Al₂O₃ is about 1.6. Moreover, the Al₂O₃ layer has better mechanical stability than air, which will obviously make fabrication process of the HCGs much easier and benefit the device reliability. In addition, the P contact of the VCSELs is much closer to the active region, which will reduce the series resistance and self-heating.

Figure 7.4 Schematic of the novel HCG-VCSELs in which the Al_2O_3 is the low refractive index layer and the GaAs is the grating layer

In order to analyze the effect of the LRI layer, the reflectance spectra for different LRI materials in the HCGs were calculated and the results are shown in Figure 7.5. As seen in the figure, the high reflectance bandwidth in the spectra of the LRI layers are slightly smaller than that of air, and the highest reflectance values are also slightly lower. However, the reflectance of the coupled structure is 99.5%, which is good enough for the VCSEL to emit. The mode losses of these HCG-VCSELs were calculated by using the equation of $\alpha_m = 1/L(\ln(1/(R_{top} * R_{down})^{1/2}))$ [157, 159] where L is the effective cavity length (about $1 \mu\text{m}$); R_{top} and R_{down} are the reflectance of the top and bottom reflector of the devices. In the calculation, the bottom reflectance was assumed to be 1 as the mirror mode loss and also the devices mode loss are mainly determined by the top

reflector reflectance. As shown in Figure 7.6, a little reflectance change will result in a big mode loss in the device, implying a higher threshold current operation.

Figure 7.5 Reflectance spectra of the HCG structure coupled with different refractive index materials

Figure 7.6 Mirror mode loss spectra of the novel HCG-VCSELs with different refractive index materials

According to the simulation results, replacing air with Al_2O_3 LRI layer in the HCG-VCSEL can offer an approach for producing low cost and high reliability VCSELs. To further increase the reflectance of the coupled HCG structure, the period of gratings of the proposed structure was also simulated using the FDTD method. Figure 7.7 shows the reflectance of the HCG as a function of grating period. As shown in the figure, the high reflectance bandwidth of all the considered periods can cover the wavelength of 980 nm and the bandwidth shifts to longer wavelength side as the period increases from 360 to 460 nm. The best periods at which the reflectance is the highest for 980 emissions are in the range of 380 nm to 420 nm. We therefore chose the period of 410 nm in our HCG-VCSELs and the air slit of 150 nm was adopted in our experiments.

Figure 7.7 Reflection spectra of HCG structures with different periods.

7.2.3 VCSEL and HCG fabrication

The HCG-VCSEL wafers were grown by MOCVD. The n-type bottom DBRs consisting of 36.5-pairs of $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$ layers were first grown on a n-type GaAs substrate, followed by the active region of three GaInAs/GaAs quantum wells for 980 nm emission wavelength, a 30-nm $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ oxidation layer, and a 215 nm p-type GaAs as contact layer. To form the HCG structure, a 158 nm AlAs and 230 nm GaAs layers were then grown. The HCG-VCSELs were fabricated by the following steps. First, small mesas were etched down to the P contact layer, and then the big mesas down to the active region. The mesas were all formed by inductively coupled plasma reaction ion etching (ICP-RIE) using SiO_2 as mask for etching. Then the $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layer and the AlAs layer were selectively oxidized to form the needed oxide aperture and the needed Al_2O_3 layer. Top ohmic (Ti/Au) ring contacts were patterned and bottom ohmic (Au/Ge/Ni/Au)

contacts were formed. Then, the devices were annealed by rapid thermal annealing at 430 °C for 35 seconds. The HCG structures were patterned and transferred into GaAs using FIB and EBL techniques. The etching conditions were optimized with the least etching damage. The HCG structure has a period of 410 nm, an air slit width of 150 nm, and a thickness of 230 nm. Figure 7.8 shows the top view of two typical fabricated HCG-VCSELs.

Figure 7.8 SEM image of the fabricated HCG structure using FIB

7.2.4 Measured reflectivity and discussion

After fabrication, the devices were tested using a reflectance test system. Figure 7.9 shows the reflectance spectra of two samples. It is found that the measured

reflectance spectrum shapes are different from the simulation ones. There is an abnormal valley in the reflectance spectrum, when the spectrum wavelength is less than 870 nm. It is likely due to the absorption of the GaAs material. There is also a valley in the spectrum at the wavelength of 980 nm, which is caused by the splice between two automatic photodetectors in the measurement system. From the measured results, it is obvious that the reflectance for the light polarization orthogonal with the gratings (Y direction) is the highest among all polarizations. However, the measured reflectance values are not as high as the simulated ones. By comparing the data from the two device samples, the reflectance values of sample I14 are about 10% more than those of sample I15. To know the reason, we compared the quality of the gratings in the two samples. From the SEM images shown in Figure 7.7, the gratings in I14 are more sharp and uniform than those in I15 due to the optimization of the FIB dose density, while I15 was a little bit over-milling, which may be the main factor for the reflectance difference.

Figure 7.9 Reflectance spectra of two HCG structures (I14 and I15), measured with different polarization states of light. The XP, YP and NP are the indications of x polarization (polarized in x direction), y polarization and no polarization.

Figure 7.10 Reflectance spectrum of HCG structures as a function of deviation.

To verify this conclusion, I have simulated the effect of the deviation in the gratings (defined in the insert of Figure 7.10) on the reflectance of the devices and the results are shown in Figure 7.10. It is seen that as the deviation increases, the bandwidth of the high reflectance decreases quickly and it disappears when the deviation is as big as the width of the air slits. However, if the deviation is 25 nm, the reflectance at the wavelength 980 nm is close to 99.5%, indicating that the deviation must be ≤ 25 nm in order to achieve resonance in the cavity and emission of a HCG-VCSEL. The low reflectance also causes high mirror mode loss in VCSELs. The mirror mode loss of sample I14 is about 526 cm^{-1} which is about 53 times of that of the double DBRs VCSEL (10 cm^{-1}), and 21 times of that of the device with a reflectance of 99.5% (25 cm^{-1}). It is important to reduce the deviation in order to obtain higher quality HCG-VCSELs.

7.3 SPP generation with VCSELs as the on-chip light source

7.3.1 VCSELs: The ideal light source for 2D optics and metasurfaces

Excitation of surface plasmon polaritons on the metal surface is an essential task for the experimental plasmonics studies. Usually, the light source for 2D optics and metasurfaces research needs to be coherent to satisfy the requirements of monochromatic, accurate phase information and good collimation. Laser is the best light source with above characters for SPP generation. Meanwhile, coupling light into the subwavelength structures still remains as the most challenging part of experiment. In the past, people used prism or gratings to couple the light from a separate laser into nanostructures. The compactness of the nanophotonics devices was compromised while alignment and adjustment of the light path always made the measurements difficult.

The VCSEL is an ideal light source for 2D optics and metasurfaces. Firstly, it is a coherence light source. Compared with sole quantum dots, quantum wells or light emitting diodes (LEDs), VCSEL is the only one which can provide stable coherent light emitting. Secondly, the VCSEL is vertically emitting light source which is compatible with the grating SPP generation method for 2D optics and metasurfaces. Thirdly, the VCSEL is able to be integrated with the current semiconductor fabrication process. The phase, wavefront and SPP wavelength can be manipulated by using various layers of metals, dielectrics and metasurfaces, and VCSEL will be the real platform of nanophotonics laboratory on a chip. Last

but not the least; the VCSEL is the most economical light source for SPP experiment. It will not only save a lot of time and money for optical path setups, but also the cheapest laser for SPP generation once VCSELs can be manufactured in batch production.

7.3.2 Fabrication of 850nm VCSELs with gold film and gratings

The 850nm VCSELs with full DBRs adopted oxidization layer confined aperture technique. To my knowledge, only two groups reported the SPP generation and propagation on the VCSEL [168, 169]. They both used grating coupling to measure the far field image, rather than direct near-field measurements for in-plane SPP propagation. In order to be able to directly measure the near field SPP propagation, we fabricated the 850nm VCSELs, deposited gold film on the VCSELs and made gratings on the gold film. They were mounted either on a PCB or a copper heat sink for characterization. Figure 7.11 shows the SEM pictures of eight VCSEL devices separately arranged and six of them were wire bonded on the PCB. Figure 7.12 shows the VCSELs top electrodes array parallel connected to five gold wires to support current injection for all the VCSEL devices.

Figure 7.11 VCSELs and their top electrodes bonded with gold wire on the PCB pads.

Figure 7.12 VCSEL array with parallel connection top electrodes on the copper heat sink.

After the VCSELs were fabricated, they were tested, as shown in Figure 7.13. Then, a 120nm gold film was deposited on top of the VCSEL array. The hardmask was applied to avoid the short circuit connection by gold coating. The gratings were then fabricated using a Carl Zeiss AURIGA crossbeam (FIB-SEM) workstation and the top view is shown in Figure 7.14. The ion source is Gallium (Ga) beam with energy of 30 keV. The milling of the grating structures was performed at a beam current of 120 pA. There are five slits in the grating on the gold film. Each grating slit is 250 nm wide and the period is 836 nm.

Figure 7.13 Light up test for the VCSELs array before wire bonding

Figure 7.14 SEM pictures of FIB milled five slit grating on the gold film of VCSEL. Each grating slit is 250 nm wide and the period is 836 nm.

7.3.3 Near-field imaging of on-chip SPP generation with different injection currents

There are two types of the laser transverse modes commonly existing in the VCSEL operations, namely Laguerre-Gaussian(LG) mode and Hermite-Gaussian(HG) modes. The expressions of these modes are shown below[170].

Laguerre-Gaussian modes:

$$u_{pl}(r, \phi, z) = \frac{C}{\left(1 + \frac{z^2}{z_R^2}\right)^{\frac{1}{2}}} \left(\frac{r\sqrt{2}}{w(z)}\right) L_p^l \left(\frac{2r^2}{w^2(z)}\right) \times e^{\left(\frac{-r^2}{w^2(z)}\right)} e^{\left(\frac{-ikr^2z}{2(z^2+z_R^2)}\right)} e^{(-il\phi)}$$

$$\times e^{(i(2p+l+1) \tan^{-1} \frac{z}{z_R})}, \quad (7.4)$$

where z_R is the Rayleigh range, $w(z)$ is the radius of the beam, L_p^l is the Laguerre polynomial, and C is a constant and the beam waist is at $z = 0$. Figure 7.15 shows the spatial energy distribution of the Laguerre-Gaussian modes.

Figure 7.15 Spatial energy distribution for Laguerre-Gaussian modes [171].

Hermite-Gaussian modes:

$$u_{mn}(x, y, z) = CH_m(\sqrt{2} \frac{x}{w(z)})H_n(\sqrt{2} \frac{y}{w(z)})e^{-(x^2+y^2)/w^2(z)}e^{(i\phi z)}, \quad (7.5)$$

where H_m and H_n are the Hermite polynomial, ϕ is the phase of the beam. Figure 7.16 shows the spatial energy distribution of the Hermite-Gaussian modes.

Figure 7.16 Spatial energy distribution for Hermite-Gaussian modes [172].

The Laguerre-Gaussian modes are the cylindrically symmetric solution of the paraxial approximation. The Hermite-Gaussian modes are generated when the VCSEL cavity design is not radially symmetric. For VCSEL injection current confined by wet oxidation process, the cavity will be a slightly asymmetric due to the wet oxidation gas turbulence.

In order to find the current injection influence, the transverse field distributions of the VCSEL without any gold coating and gratings were measured under different injection currents first. These distributions can also tell the light emitting positions on top of the VCSEL apertures. From Figure 7.17, we can see that the transverse field becomes more complex as the injection current is increased. We use the decomposition of the Hermite-Gaussian modes HG_{mn} to express the transverse field, where m and n represent mode number in the x and y direction, respectively. For the working conditions at the injection currents of 0.5 mA, 1mA and 1.5 mA, the transverse field distributions can be represented by HG_{00} , HG_{10} and

combination of HG_{01+10} , respectively. When the current is increased to 2 mA, 3 mA and 10 mA, the transverse field distributions likely perform as combination of strong mode HG_{01} and weak higher order HG modes. However, it is interesting to note that when the injection current becomes 3 mA and more, the single cycle-like dark hollow is developed into two cycle-like hollows. The potential combination is the strong HG_{01} mode and weak HG_{20} mode.

To study the SPP generation and the correlation between the SPP propagation and the transverse field induced by different injection currents, the 91 VCSELs were parallel-connected. Among the 91 VCSELs some were deposited with 200 nm thick gold film and 5 slits grating for observing SPP generation and some have no gold film and grating for observing the laser mode under the same injection current. Figure 7.18 shows the far-field images taken by an optical microscope for the lasers emitted at 200 mA, 300 mA and 500 mA, respectively. It is seen that when the VCSEL array total injection current are 200 mA to 300 mA, the transverse field distribution can be attributing to strong HG_{01} and weak HG_{10} modes, and when the current is increased to 500 mA, the transverse field intensity shows combination of strong HG_{02} and weak HG_{10} modes. It is noted that the laser modes from the VCSELs in the array are different from those observed in the discrete VCSELs introduced in the last section. It is mainly due to the fabrication process which results in more asymmetry for the oxidation aperture of the VCSELs in the array.

Figure 7.17 Transverse field distributions of the single VCSEL under different injection currents.

Figure 7.18 Farfield image of one VCSEL device in the array at total injection currents of (a) 200 mA, (b) 300 mA and (c) 500 mA.

The SPP distributions of the VCSELs under 3 different injection currents are shown in the Figure 7.19. With the injection currents of 200 mA and 300 mA, two SPP beams were observed and they propagate towards two opposite directions. It is because the transverse field distributions are concentrated at two peak areas of the HG_{01} mode. The energy distributions between the two peaks are not exactly same due to the asymmetric shape of the VCSEL aperture. When the injection current increased to 500 mA, it is clearly shown at Figure 7.19(c) that three SPP beams are generated and they also propagate to opposite directions. This is consistent with the Figure 7.18(c) that high-order HG_{02} mode became dominant in this situation. From the above experiments, it is approved that the number of the SPP beams or the wave front of the SPP can be controlled by varying the VCSEL injection current.

Figure 7.19 NSOM pictures for on-chip generated SPP by parallel connected VCSELs with various currents

7.4 Chapter summary

In this chapter, the new HCG structure consists of GaAs/Al₂O₃ were proposed and fabricated. The Al₂O₃ layer is converted from an epitaxial AlAs layer through oxidation process. The new HCG structures are much easier to fabricate and have high reliability. The calculated results reveal that the GaAs/Al₂O₃ HCG structures have high reflectance and bandwidth comparable to those of air cavity and the reflectance spectrum shifts towards long wavelength with the increase of periods of gratings. The FIB fabricated HCG structures show that the reflectance values are sensitive to the deviation of the gratings and minimum deviation for high quality HCGs is about 25 nm which is also confirmed by FDTD simulation.

By utilizing the 850nm VCSEL, the SPP can be excited on a direct light source which can provide a compact solution for the on-chip SPP generation. The SPP beam or wave front can be manipulated by varying the VCSEL injection current. The VCSEL was either mounted on the Print Circuit Boards (PCBs) or parallel connected and mounted on the copper heat sinks to fit the NSOM measurement requirement. The near-field images were measured by the NSOM with different amount of current supplying. It is believed that the SPP on-chip light source will be useful in the areas of subwavelength super focusing, optical tweezers, SPP optics demonstration and biochemical sensors.

CHAPTER 8. CONCLUSIONS

In this chapter, the works done in my PhD program are concluded and recommendations for future work are proposed. Last but not the least, the potential applications of these results obtained are also given in the outlook part.

8.1 Conclusions

In my PhD project, some subwavelength structures and possible applications were investigated as they are important for new photonics technology. The first work is on concentric cylindrical metamaterial (CCM) for acquiring a dark hollow light cone. The proposed structures were designed and simulated using finite element method- COMSOL. The structure composes of concentric cylindrical silver-dielectric multilayer composites with the top surface covered by a thin layer of chromium (Cr) containing an annulus or a hole opening for incidence. The simulation results show that nanometer-level dark hollow light cones with good quality can be formed in the output for circularly polarized incidence and its position can be monitored by choosing different dielectric materials and varying the dimensions of the annular apertures.

The cogwheel structure consists of an air ring and equally distributed air cogs along the ring on a gold film for generation of surface plasmon polariton vortex. A well-designed cogwheel can generate an optical vortex-like response and the characteristics of such SPP vortex are directly related to cogwheel geometries and can be controlled by adjusting the polarization direction of incident light. With the

q number of 18, the left (right) circularly polarized incidence induces clockwise (anticlockwise) direction of SPP vortex.

Subwavelength gold groove structure as an alternative metasurface for tuning the wavelength and wavefront of the surface plasmon polaritons was proposed and designed based on non-resonant mechanism. The structures were fabricated using focused ion beam and characterized by a near-field scanning optical microscopy. The SPP wavelength can be tuned from 606 nm to 562 nm on the metasurface by varying the grooves period for the 633 nm He-Ne laser incidence. Using effective medium theory and finite element calculation, the relation between the effective refractive index and the metasurface geometrical parameters was calculated. The predicated SPP focusing effect was varified experimentally.

To seek an economical material with better performance, aluminum based structures were investigated, aiming for manipulation of surface plasmon polaritons (SPPs) at short visible wavelength and UV. The simulation shows that aluminum is a good metal for exciting SPPs with blue light and that the SPP wavelength can be reduced from about 465 nm to about 265 nm by increasing the thickness of a coated Si_3N_4 layer above the aluminum film. It is also shown that the damping becomes more significant with the increase of the thickness of the Si_3N_4 layer. Experimentally confirmed and the observations can be explained by the variation of effective permittivity. The proposed Metal-Insulator-Air (MIA) structures with SPP wavelength tuning ability have potential applications in 2D optics.

In order to have a more compact design of VCSEL, high contrast grating (HCG) structure for 980 nm vertical cavity surface emitting lasers (VCSELs) was designed and fabricated. The new HCG structure is made of GaAs/Al₂O₃. The GaAs layer is directly grown and the Al₂O₃ layer is converted from an epitaxial AlAs layer through oxidation process. The new HCG structures are much easier to fabricate and have high reliability. The calculated results reveal that the GaAs/Al₂O₃ HCG structures have high reflectance and bandwidth comparable to those of air cavity and the reflectance spectrum shifts towards long wavelength with the increase of periods of gratings. The FIB fabricated HCG structures show that the reflectance values are sensitive to the deviation of the gratings.

Finally, direct excitation of SPPs by the VCSEL light source was investigated. The structure is a 91-device array. Each device has a 5 slit grating formed on the gold film deposited on the top surface of a VCSEL. The structures were mounted either on a Print Circuit Boards (PCBs) or on copper heat sinks to fit the NSOM measurement requirement. The near-field images were measured by the NSOM with varies of current supplying. It is observed that SPPs can be well excited and the SPP beam or wave front can be manipulated by varying the VCSEL injection current.

8.2 Recommendations

The numerical simulations are very powerful tools for theoretical design and simulation for subwavelength structures. Converting ideas from simulation to reality is currently one of the main research approaches. Aiming at the experimental demonstration and real applications, the designs must be practical and achievable from the beginning of the research. With the assistance of state of the arts nanofabrication techniques, the structures can be made smaller and finer than ever before. From the results of this thesis, recommendations for further work are the followings:

1. The MIA structures with different metal and dielectric combinations. In this thesis, the Al-Si₃N₄-Air structure was proposed. The thickness of the dielectric layer (Si₃N₄) was set to 20nm. There is a tradeoff between loss and wavelength modulation abilities. In the future, we will explore higher index materials such as TiO₂. With the assistance of accurate deposition and measurement facilities, the thickness of high index material can be even thinner but still possess high modulation ability and low loss. Beside the material exploring aspect, we will search the deeper visible-UV wavelength SPP excitation ability for the Al and Al based MIA structures.
2. The integrated nanophotonics devices with on-chip SPP generation ability. To further study the VCSEL's characters relationship between current injection and transverse mode. We will design and control the transvers

field distribution under different current injections. With proper design of the nanostructure and devices on the VCSEL, polarization of the light will be able to achieve. The SPP propagation can be controlled and manipulated more precisely.

3. With well-designed subwavelength structures capable for direct excitation, manipulation and propagation of SPPs, integration of them into compact systems should be carried out. It is believed that the integrated systems with required functions can serve better for new generation photonics technology.

AUTHOR'S PUBLICATIONS

Journal papers:

Thesis related works

1. Z. Xu, Y. Xie, et al, "On-chip manipulating SPP in-plane propagation with VCSEL light source", in preparation.
2. Z. Xu, L. Y. M. Tobing, Y. Xie, J. Tong, P. Ni, S. Qiu, T. Yu and, D.-H. Zhang, "Aluminum based structures for manipulating short visible wavelength in-plane surface plasmon polariton propagation." Opt. Express 23, 22883-22889 (2015).
3. Z. Xu, L. Y. M. Tobing, D. Zhang and D.-H. Zhang, "Cogwheels for generation of surface plasmon polariton vortex." Int. J. Nanotechnology 12, 10/11/12, 909-916 (2015)
4. Z. Xu, T. Li, D.-H. Zhang, C. Yan, D. Li, L. Y. M. Tobing, F. Qin, Y. Wang, X. Shen, and T. Yu, "Groove-structured metasurfaces for modulation of surface plasmon propagation," Appl. Phys. Express 7, 052001 (2014).
5. Z. Xu, D. H. Zhang, C. Yan, D. Li, and Y. Wang, "Concentric cylindrical metamaterials for subwavelength dark hollow light cones," J. Opt. **14**, 114014 (2012).
6. Y. Xie, Z. Xu, W. Fan, Q. Wang, D.-H. Zhang, M. Gębski, M. Dems, T. Czyszanowski, Q. Kan and H.-D. Chen, "New High-Contrast gratings Vertical Cavity Surface Emitting Lasers. " Submitted to Int. J. Nanotechnology.

Collabration Works

7. J.-B. Tian, C.-C. Yan, C. Wang, Y. Han, R.-Y. Zou, D.-D. Li, Z. Xu, and D.-H. Zhang, "Actively tunable Fano resonances based on colossal magneto-resistant metamaterials," *Opt. Lett.* **40**, 1286-1289 (2015).
8. M. Gębski, O. Kuzior, M. Dems, M. Wasiak, Y. Y. Xie, Z. Xu, Q. J. Wang, D. H. Zhang, and T. Czystzanowski, "Transverse mode control in high-contrast grating VCSELs," *Opt. Express* **22**, 20954-20963 (2014).
9. A. Yang, C.-C. Yan, J. Tian, C. Wang, Y. Han, D. Zhang, D. Li, and Z. Xu, "A sensitive sensor with a double U-shaped ring-based metamaterial," *Appl. Phys. A*, 1-4 (2014).
10. D. Li, D.-H. Zhang, C.-C. Yan, and Z. Xu, "Figure of Merit for Optimization of Metal-Dielectric Multilayer Lenses," *IEEE Trans. Nanotechnology* **13**, 452-457 (2014).
11. D. Li, D. H. Zhang, C. Yan, T. Li, Y. Wang, Z. Xu, J. Wang, and F. Qin, "Unidirectional surface plasmon-polariton excitation by a compact slot partially filled with dielectric," *Opt. Express* **21**, 5949-5956 (2013).
12. X. Yang, D. H. Zhang, Z. Xu, Y. Wang, and J. Wang, "Designing arbitrary nanoscale patterns by a nanocavity waveguide with omnidirectional illumination," *Appl. Phys. B* **109**, 215-219 (2012).
13. C. C. Yan, D. H. Zhang, Z. Xu, D. D. Li, and A. Yang, "A multi-layered split ring metamaterial for a multiwavelength and tunable lasing spaser," *J. Opt.* **14**, 045101 (2012).
14. Y. Wang, D. H. Zhang, J. Wang, M. Yang, D. Li, and Z. Xu, "Beam splitting with subwavelength resolution using combined metallodielectric films," *J. Opt.* **14**, 015103 (2012).

15. Y. Wang, D. H. Zhang, C. Yan, D. Li, and Z. Xu, "Efficient and wide spectrum half-cylindrical hyperlens with symmetrical metallodielectric structure," *App. Phys. A* **107**, 31-34 (2012).
16. C. Yan, D. H. Zhang, D. Li, H. Bian, Z. Xu, and Y. Wang, "Metal nanorod-based metamaterials for beam splitting and a subdiffraction-limited dark hollow light cone," *J. Opt.* **13**, 085102 (2011).
17. Y. Wang, D. H. Zhang, J. Wang, X. Yang, D. Li, and Z. Xu, "Waveguide devices with homogeneous complementary media," *Opt. Lett.* **36**, 3855-3857 (2011).

Conference paper:

1. Z. Xu, D. H. Zhang, T. Li, C. Yan, D. Li, Y. Wang, and F. Qin, "Manipulating Surface Plasmon Polaritons on the meta-surface," in *Nanoelectronics Conference (INEC), 2013 IEEE 5th International*(2013), pp. 446-448.

BIBLIOGRAPHY

1. N. I. Zheludev, and Y. S. Kivshar, "From metamaterials to metadevices," *Nat Mater* **11**, 917-924 (2012).
2. N. I. Zheludev, "What diffraction limit?," *Nat Mater* **7**, 420-422 (2008).
3. W. Martin, and I. Z. Nikolay, "Artificial chiral materials," *Journal of Optics A: Pure and Applied Optics* **11**, 070201 (2009).
4. J. C. Bose, "On the Rotation of Plane of Polarisation of Electric Waves by a Twisted Structure," *Proceedings of the Royal Society of London* **63**, 146-152 (1898).
5. R. W. Wood, "On a Remarkable Case of Uneven Distribution of Light in a Diffraction Grating Spectrum," *Proceedings of the Physical Society of London* **18**, 269 (1902).
6. R. H. Ritchie, "Plasma Losses by Fast Electrons in Thin Films," *Physical Review* **106**, 874-881 (1957).
7. C. J. Powell, and J. B. Swan, "Origin of the Characteristic Electron Energy Losses in Aluminum," *Physical Review* **115**, 869-875 (1959).
8. E. A. Stern, and R. A. Ferrell, "Surface Plasma Oscillations of a Degenerate Electron Gas," *Physical Review* **120**, 130-136 (1960).
9. B. Rothenhausler, and W. Knoll, "Surface-plasmon microscopy," *Nature* **332**, 615-617 (1988).
10. W. Srituravanich, N. Fang, C. Sun, Q. Luo, and X. Zhang, "Plasmonic Nanolithography," *Nano Letters* **4**, 1085-1088 (2004).

11. X. Luo, and T. Ishihara, "Surface plasmon resonant interference nanolithography technique," *Applied Physics Letters* **84**, 4780-4782 (2004).
12. Z.-W. Liu, Q.-H. Wei, and X. Zhang, "Surface Plasmon Interference Nanolithography," *Nano Letters* **5**, 957-961 (2005).
13. N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, "Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction," *Science* **334**, 333-337 (2011).
14. Y. Fu, X. Hu, C. Lu, S. Yue, H. Yang, and Q. Gong, "All-Optical Logic Gates Based on Nanoscale Plasmonic Slot Waveguides," *Nano Lett.* **12**, 5784-5790 (2012).
15. F. Aieta, P. Genevet, M. A. Kats, N. Yu, R. Blanchard, Z. Gaburro, and F. Capasso, "Aberration-Free Ultrathin Flat Lenses and Axicons at Telecom Wavelengths Based on Plasmonic Metasurfaces," *Nano Letters* **12**, 4932-4936 (2012).
16. N. Yu, F. Aieta, P. Genevet, M. A. Kats, Z. Gaburro, and F. Capasso, "A Broadband, Background-Free Quarter-Wave Plate Based on Plasmonic Metasurfaces," *Nano Letters* **12**, 6328-6333 (2012).
17. L. Li, T. Li, S. M. Wang, C. Zhang, and S. N. Zhu, "Plasmonic Airy Beam Generated by In-Plane Diffraction," *Phys. Rev. Lett.* **107**, 126804 (2011).
18. J. Lin, J. Dellinger, P. Genevet, B. Cluzel, F. de Fornel, and F. Capasso, "Cosine-Gauss Plasmon Beam: A Localized Long-Range Nondiffracting Surface Wave," *Physical Review Letters* **109**, 093904 (2012).
19. ShengC, LiuH, WangY, S. N. Zhu, and D. A. Genov, "Trapping light by mimicking gravitational lensing," *Nat Photon* **7**, 902-906 (2013).

20. J. Lin, J. B. Mueller, Q. Wang, G. Yuan, N. Antoniou, X.-C. Yuan, and F. Capasso, "Polarization-Controlled Tunable Directional Coupling of Surface Plasmon Polaritons," *Science* **340**, 331-334 (2013).
21. L. B. William, "Surface plasmon–polariton length scales: a route to sub-wavelength optics," *J. Opt. A: Pure Appl. Opt.* **8**, S87 (2006).
22. E. Kretschmann, and H. Raether, "Notizen: Radiative Decay of Non Radiative Surface Plasmons Excited by Light," in *Zeitschrift für Naturforschung A*(1968), p. 2135.
23. A. Otto, "Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection," *Z. Physik* **216**, 398-410 (1968).
24. "Surface plasmons on gratings," in *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*(Springer Berlin Heidelberg, 1988), pp. 91-116.
25. J. Chen, Y. Wang, B. Jia, T. Geng, X. Li, L. Feng, W. Qian, B. Liang, X. Zhang, M. Gu, and S. Zhuang, "Observation of the inverse Doppler effect in negative-index materials at optical frequencies," *Nat Photon* **5**.
26. J. B. Pendry, and D. R. Smith, "Reversing Light With Negative Refraction," *Physics Today* **57**, 37-43 (2004).
27. S. Xi, H. Chen, T. Jiang, L. Ran, J. Huangfu, B.-I. Wu, J. A. Kong, and M. Chen, "Experimental Verification of Reversed Cherenkov Radiation in Left-Handed Metamaterial," *Physical Review Letters* **103**, 194801 (2009).
28. S. A. Maier, *Plasmonics: Fundamentals and Applications* (Springer, 2007).

29. Z. Liu, N. Fang, T.-J. Yen, and X. Zhang, "Rapid growth of evanescent wave by a silver superlens," *Applied Physics Letters* **83**, 5184-5186 (2003).
30. D. Melville, and R. Blaikie, "Super-resolution imaging through a planar silver layer," *Opt. Express* **13**, 2127-2134 (2005).
31. L. Hyesog, X. Yi, F. Nicholas, S. Werayut, D. Stephane, A. Muralidhar, S. Cheng, and Z. Xiang, "Realization of optical superlens imaging below the diffraction limit," *New Journal of Physics* **7**, 255 (2005).
32. T. Taubner, D. Korobkin, Y. Urzhumov, G. Shvets, and R. Hillenbrand, "Near-Field Microscopy Through a SiC Superlens," *Science* **313**, 1595 (2006).
33. N. Fang, H. Lee, C. Sun, and X. Zhang, "Sub Diffraction-Limited Optical Imaging with a Silver Superlens," *Science* **308**, 534-537 (2005).
34. C. C. Yan, D. H. Zhang, Y. Zhang, D. D. Li, and M. A. Fiddy, "Metal-dielectric composites for beam splitting and far-field deep sub-wavelength resolution for visible wavelengths," *Opt. Express* **18**, 14794-14801 (2010).
35. Y. Wang, D. H. Zhang, J. Wang, X. Yang, D. Li, and Z. Xu, "Waveguide devices with homogeneous complementary media," *Opt. Lett.* **36**, 3855-3857 (2011).
36. Y. Wang, D. H. Zhang, J. Wang, M. Yang, D. Li, and Z. Xu, "Beam splitting with subwavelength resolution using combined metallodielectric films," *J. Opt.* **14**, 015103 (2012).
37. Y. K. Wang, D. H. Zhang, C. C. Yan, D. D. Li, and Z. J. Xu, "Efficient and wide spectrum half-cylindrical hyperlens with symmetrical metallodielectric structure," *Appl. Phys. A* **107**, 31-34 (2012).

38. C. C. Yan, D. H. Zhang, D. D. Li, H. J. Bian, Z. J. Xu, and Y. K. Wang, "Metal nanorod-based metamaterials for beam splitting and a subdiffraction-limited dark hollow light cone," *Journal of Optics* **13**, 085102 (2011).
39. Z. Xu, D. H. Zhang, C. C. Yan, D. D. Li, and Y. K. Wang, "Concentric cylindrical metamaterials for subwavelength dark hollow light cones," *J. Opt.* **14**, 114014 (2012).
40. N. I. Zheludev, S. L. Prosvirnin, N. Papasimakis, and V. A. Fedotov, "Lasing spaser," *Nat Photon* **2**, 351-354 (2008).
41. C. C. Yan, D. H. Zhang, Z. J. Xu, D. D. Li, and A. Yang, "A multi-layered split ring metamaterial for a multiwavelength and tunable lasing spaser," *J. Opt.* **14**, 045101 (2012).
42. A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, "Planar Photonics with Metasurfaces," *Science* **339** (2013).
43. E. F. Kuester, M. A. Mohamed, M. Piket-May, and C. L. Holloway, "Averaged transition conditions for electromagnetic fields at a metafilm," *Antennas and Propagation, IEEE Transactions on* **51**, 2641-2651 (2003).
44. C. L. Holloway, M. A. Mohamed, E. F. Kuester, and A. Dienstfrey, "Reflection and transmission properties of a metafilm: with an application to a controllable surface composed of resonant particles," *Electromagnetic Compatibility, IEEE Transactions on* **47**, 853-865 (2005).
45. D. M. Pozar, S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *Antennas and Propagation, IEEE Transactions on* **45**, 287-296 (1997).

46. C. G. M. Ryan, M. R. Chaharmir, J. Shaker, J. R. Bray, Y. M. M. Antar, and A. Ittipiboon, "A Wideband Transmitarray Using Dual-Resonant Double Square Rings," *Antennas and Propagation, IEEE Transactions on* **58**, 1486-1493 (2010).
47. Y. Liu, and X. Zhang, "Metasurfaces for manipulating surface plasmons," *Appl. Phys. Lett.* **103**, 141101 (2013).
48. Z. Xu, T. Li, D. H. Zhang, C. Yan, D. Li, L. Y. M. Tobing, F. Qin, Y. Wang, X. Shen, and T. Yu, "Groove-structured metasurfaces for modulation of surface plasmon propagation," *Appl. Phys. Express* **7**, 052001 (2014).
49. N. Yu, and F. Capasso, "Flat optics with designer metasurfaces," *Nat. Mater.* **13**, 139-150 (2014).
50. K. C. A. Smith, and C. W. Oatley, "The scanning electron microscope and its fields of application," *British Journal of Applied Physics* **6**, 391 (1955).
51. B. Shokouhi, Z. Jian, and C. Bo, "Very high sensitivity ZEP resist using MEK:MIBK developer," *Micro & Nano Letters, IET* **6**, 992-994 (2011).
52. D. Huigao, H. Hailong, H. Hui Kim, S. Zexiang, and K. W. Y. Joel, "Free-standing sub-10 nm nanostencils for the definition of gaps in plasmonic antennas," *Nanotechnology* **24**, 185301 (2013).
53. W. Hu, K. Sarveswaran, M. Lieberman, and G. H. Bernstein, "Sub-10 nm electron beam lithography using cold development of poly(methylmethacrylate)," *Journal of Vacuum Science & Technology B* **22**, 1711-1716 (2004).
54. B. Bilenberg, S. Jacobsen, M. S. Schmidt, L. H. D. Skjolding, P. Shi, P. Bøggild, J. O. Tegenfeldt, and A. Kristensen, "High resolution 100kV

- electron beam lithography in SU-8," *Microelectronic Engineering* **83**, 1609-1612 (2006).
55. "ZEP 520A," <http://www.zeon.co.jp/>.
 56. "PMMA Data Sheet," <http://www.microchem.com/>.
 57. M. Rommel, B. Nilsson, P. Jedrasik, V. Bonanni, A. Dmitriev, and J. Weis, "Sub-100nm resolution after lift-off using HSQ/PMMA double layer resist," *Microelectronic Engineering* **110**, 123-125 (2013).
 58. J. C. Vickerman, "Secondary ion mass spectrometry—basic concepts, instrumental aspects, applications and trends. A. BENNINGHOVEN, F. G. RUDENAUER and H. W. WERNER, Wiley, New York, 1987, 1277 pages," *Surface and Interface Analysis* **10**, 435-435 (1987).
 59. R. J. Young, "P. D. Prewett and G. L. R. Mair Focused Ion Beams from Liquid Metal Ion Sources Research Studies Press. 344pp; Price £52.50; \$108.70. ISBN 0863 80120X, Wiley 0471 930881. (1991)," *Surface and Interface Analysis* **18**, 377-377 (1992).
 60. C. A. Volkert, and A. M. Minor, "Focused Ion Beam Microscopy and Micromachining," *MRS Bulletin* **32**, 389-399 (2007).
 61. E. H. Synge, "XXXVIII. A suggested method for extending microscopic resolution into the ultra-microscopic region," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **6**, 356-362 (1928).
 62. J. Yin, W. Gao, and Y. Zhu, "Chapter 3 Generation of dark hollow beams and their applications," in *Progress in Optics*(Elsevier, 2003), pp. 119-204.
 63. M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, "Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor," *Science* **269**, 198-201 (1995).

64. G. M. Gallatin, and P. L. Gould, "Laser focusing of atomic beams," *Journal of the Optical Society of America B* **8**, 502-508 (1991).
65. J. J. McClelland, and M. R. Scheinfein, "Laser focusing of atoms: a particle-optics approach," *Journal of the Optical Society of America B* **8**, 1974-1986 (1991).
66. X. Xu, V. G. Minogin, K. Lee, Y. Wang, and W. Jhe, "Guiding cold atoms in a hollow laser beam," *Physical Review A* **60**, 4796-4804 (1999).
67. Y. Song, D. Milam, and W. T. Hill Iii, "Long, narrow all-light atom guide," *Optics Letters* **24**, 1805-1807 (1999).
68. N. B. Simpson, D. McGloin, K. Dholakia, L. Allen, and M. J. Padgett, "Optical tweezers with increased axial trapping efficiency," *Journal of Modern Optics* **45**, 1943-1949 (1998).
69. R. C. Gauthier, and S. Wallace, "Optical levitation of spheres: analytical development and numerical computations of the force equations," *Journal of the Optical Society of America B* **12**, 1680-1686 (1995).
70. R. M. Herman, and T. A. Wiggins, "Production and uses of diffractionless beams," *Journal of the Optical Society of America* **8**, 932 (1991).
71. X. Wang, and M. G. Littman, "Laser cavity for generation of variable-radius rings of light," *Optics Letters* **18**, 767 (1993).
72. J. P. Yin, H. R. Noh, K. I. Lee, K. H. Kim, and Y. Z. Wang, "Generation of a dark hollow beam by a small hollow fiber," *Optics Communications* **138**, 287 (1997).
73. C. Paterson, and R. Smith, "Higher-order Bessel waves produced by axicon-type computer-generated holograms," *Optics Communications* **124**, 121 (1996).

- 74. J. B. Pendry, "Negative Refraction Makes a Perfect Lens," *Physical Review Letters* **85**, 3966 (2000).
- 75. L. Zhao, and T. J. Cui, "Super-resolution imaging of dielectric objects using a slab of left-handed material," *Applied Physics Letters* **89**, 141904-141903 (2006).
- 76. C. C. Yan, D. H. Zhang, and D. D. Li, "Spherical metallic nanoparticle arrays for super-resolution imaging," *Journal of Applied Physics* **109**, 063105-063105 (2011).
- 77. W. Cai, and V. Shalaev, *Optical Metamaterials* (Springer, 2010).
- 78. Z. Liu, H. Lee, Y. Xiong, C. Sun, and X. Zhang, "Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects," *Science* **315**, 1686 (2007).
- 79. N. Fang, H. Lee, C. Sun, and X. Zhang, "Sub-Diffraction-Limited Optical Imaging with a Silver Superlens," *Science* **308**, 534-537 (2005).
- 80. J. B. Pendry, D. Schurig, and D. R. Smith, "Controlling Electromagnetic Fields," *Science* **312**, 1780-1782 (2006).
- 81. C. C. Yan, D. H. Zhang, Y. Zhang, D. D. Li, and M. A. Fiddy, "Metal-dielectric composites for beam splitting and far-field deep sub-wavelength resolution for visible wavelengths," *Optics Express* **18**, 14794-14801 (2010).
- 82. C. C. Yan, D. H. Zhang, D. D. Li, H. J. Bian, Z. J. Xu, and Y. K. Wang, "Metal nanorod-based metamaterials for beam splitting and a subdiffraction-limited dark hollow light cone," *Journal of Optics* **13**, 085102 (2011).
- 83. E. D. Palik, "Handbook of Optical Constants of Solids," (Elsevier, 1985).

84. P. B. Johnson, and R. W. Christy, "Optical Constants of the Noble Metals," *Physical Review B* **6**, 4370 (1972).
85. Z. D. H. L. D. D. Yan C C, and Y. Zhang, "Dual refractions in metal nanorod-based metamaterials," *Journal of Optics* **12**, 065102 (2010).
86. Z. Xu, D. H. Zhang, C. Yan, D. Li, and Y. Wang, "Concentric cylindrical metamaterials for subwavelength dark hollow light cones," *J. Opt.* **14**, 114014 (2012).
87. L. Y. M. Tobing, L. Tjahjana, D. H. Zhang, Q. Zhang, and Q. Xiong, "Deep subwavelength fourfold rotationally symmetric split-ring-resonator metamaterials for highly sensitive and robust biosensing platform," *Sci. Rep.* **3**, 2437 (2013).
88. L. Y. M. Tobing, L. Tjahjana, D. H. Zhang, Q. Zhang, and Q. Xiong, "Sub-100-nm Sized Silver Split Ring Resonator Metamaterials with Fundamental Magnetic Resonance in the Middle Visible Spectrum," *Adv. Opt. Mater.* **2**, 280-285 (2014).
89. X. Zhang, and Z. Liu, "Superlenses to overcome the diffraction limit," *Nat. Mater.* **7**, 435-441 (2008).
90. X. Yang, D. H. Zhang, Z. Xu, Y. Wang, and J. Wang, "Designing arbitrary nanoscale patterns by a nanocavity waveguide with omnidirectional illumination," *Appl. Phys. B* **109**, 215-219 (2012).
91. C. Min, Z. Shen, J. Shen, Y. Zhang, H. Fang, G. Yuan, L. Du, S. Zhu, T. Lei, and X. Yuan, "Focused plasmonic trapping of metallic particles," *Nat. Commun.* **4** (2013).

-
92. Y. Wang, D. Zhang, J. Wang, F. Qin, D. Li, and Z. Xu, "Design of sharp bends with transformation plasmonics," *Appl. Phys. A* **112**, 549-553 (2013).
 93. Y. Luo, D. Y. Lei, S. A. Maier, and J. B. Pendry, "Transformation-Optics Description of Plasmonic Nanostructures Containing Blunt Edges/Corners: From Symmetric to Asymmetric Edge Rounding," *ACS Nano* **6**, 6492-6506 (2012).
 94. R. Chen, V. D. Ta, and H. Sun, "Bending-Induced Bidirectional Tuning of Whispering Gallery Mode Lasing from Flexible Polymer Fibers," *ACS Photonics* **1**, 11-16 (2014).
 95. P. Genevet, J. Lin, M. A. Kats, and F. Capasso, "Holographic detection of the orbital angular momentum of light with plasmonic photodiodes," *Nat. Commun.* **3**, 1278 (2012).
 96. X. Cai, J. Wang, M. J. Strain, B. Johnson-Morris, J. Zhu, M. Sorel, J. L. O'Brien, M. G. Thompson, and S. Yu, "Integrated Compact Optical Vortex Beam Emitters," *Science* **338**, 363-366 (2012).
 97. S.-W. Cho, J. Park, S.-Y. Lee, H. Kim, and B. Lee, "Coupling of spin and angular momentum of light in plasmonic vortex," *Opt. Express* **20**, 10083-10094 (2012).
 98. Y. Gorodetski, A. Niv, V. Kleiner, and E. Hasman, "Observation of the Spin-Based Plasmonic Effect in Nanoscale Structures," *Phys. Rev. Lett.* **101**, 043903 (2008).
 99. D. K. Gramotnev, and S. I. Bozhevolnyi, "Plasmonics beyond the diffraction limit," *Nat. Photonics* **4**, 83-91 (2010).

100. P. Fan, C. Colombo, K. C. Y. Huang, P. Krogstrup, J. Nygård, A. Fontcuberta i Morral, and M. L. Brongersma, "An Electrically-Driven GaAs Nanowire Surface Plasmon Source," *Nano Letters* **12**, 4943-4947 (2012).
101. K. A. Tetz, L. Pang, and Y. Fainman, "High-resolution surface plasmon resonance sensor based on linewidth-optimized nanohole array transmittance," *Opt. Lett.* **31**, 1528-1530 (2006).
102. L. Pang, G. M. Hwang, B. Slutsky, and Y. Fainman, "Spectral sensitivity of two-dimensional nanohole array surface plasmon polariton resonance sensor," *Appl. Phys. Lett.* **91**, 123112-123113 (2007).
103. J. Lakowicz, "Plasmonics in Biology and Plasmon-Controlled Fluorescence," *Plasmonics* **1**, 5-33 (2006).
104. W. Lukosz, "Principles and sensitivities of integrated optical and surface plasmon sensors for direct affinity sensing and immunosensing," *Biosens. Bioelectron.* **6**, 215-225 (1991).
105. L. Yin, V. K. Vlasko-Vlasov, J. Pearson, J. M. Hiller, J. Hua, U. Welp, D. E. Brown, and C. W. Kimball, "Subwavelength Focusing and Guiding of Surface Plasmons," *Nano Lett.* **5**, 1399-1402 (2005).
106. X. Liu, Y. Wang, and E. O. Potma, "A dual-color plasmonic focus for surface-selective four-wave mixing," *Appl. Phys. Lett.* **101**, 081116-081114 (2012).
107. Y. Luo, J. B. Pendry, and A. Aubry, "Surface Plasmons and Singularities," *Nano Lett.* **10**, 4186-4191 (2010).

-
108. D. Li, D. H. Zhang, C. Yan, T. Li, Y. Wang, Z. Xu, J. Wang, and F. Qin, "Unidirectional surface plasmon-polariton excitation by a compact slot partially filled with dielectric," *Opt. Express* **21**, 5949-5956 (2013).
 109. L. Li, T. Li, S. Wang, S. Zhu, and X. Zhang, "Broad Band Focusing and Demultiplexing of In-Plane Propagating Surface Plasmons," *Nano Lett.* **11**, 4357-4361 (2011).
 110. N. Anttu, Z. Q. Guan, U. Hakanson, H. X. Xu, and H. Q. Xu, "Excitations of surface plasmon polaritons in double layer metal grating structures," *Appl. Phys. Lett.* **100**, 091111-091113 (2012).
 111. C. Yan, D. H. Zhang, D. Li, H. Bian, Z. Xu, and Y. Wang, "Metal nanorod-based metamaterials for beam splitting and a subdiffraction-limited dark hollow light cone," *J. Opt.* **13**, 085102 (2011).
 112. G. Rui, W. Chen, D. C. Abeysinghe, R. L. Nelson, and Q. Zhan, "Beaming circularly polarized photons from quantum dots coupled with plasmonic spiral antenna," *Opt. Express* **20**, 19297-19304 (2012).
 113. S. Kéna-Cohen, P. N. Stavrinou, D. D. C. Bradley, and S. A. Maier, "Confined Surface Plasmon–Polariton Amplifiers," *Nano Lett.* **13**, 1323-1329 (2013).
 114. S. Sun, K.-Y. Yang, C.-M. Wang, T.-K. Juan, W. T. Chen, C. Y. Liao, Q. He, S. Xiao, W.-T. Kung, G.-Y. Guo, L. Zhou, and D. P. Tsai, "High-Efficiency Broadband Anomalous Reflection by Gradient Meta-Surfaces," *Nano Lett.* **12**, 6223-6229 (2012).
 115. X. Yin, Z. Ye, J. Rho, Y. Wang, and X. Zhang, "Photonic Spin Hall Effect at Metasurfaces," *Science* **339**, 1405-1407 (2013).

116. X. Li, S. Xiao, B. Cai, Q. He, T. J. Cui, and L. Zhou, "Flat metasurfaces to focus electromagnetic waves in reflection geometry," *Opt. Lett.* **37**, 4940-4942 (2012).
117. J. B. Pendry, L. Martín-Moreno, and F. J. Garcia-Vidal, "Mimicking Surface Plasmons with Structured Surfaces," *Science* **305**, 847-848 (2004).
118. R. Wangberg, J. Elser, E. E. Narimanov, and V. A. Podolskiy, "Nonmagnetic nanocomposites for optical and infrared negative-refractive-index media," *J. Opt. Soc. Am. B* **23**, 498-505 (2006).
119. Z. Jacob, L. V. Alekseyev, and E. Narimanov, "Semiclassical theory of the hyperlens," *J. Opt. Soc. Am. A* **24**, A52-A59 (2007).
120. L. Yin, V. K. Vlasko-Vlasov, A. Rydh, J. Pearson, U. Welp, S.-H. Chang, S. K. Gray, G. C. Schatz, D. B. Brown, and C. W. Kimball, "Surface plasmons at single nanoholes in Au films," *Appl. Phys. Lett.* **85**, 467-469 (2004).
121. L. Y. M. Tobing, L. Tjahjana, D. H. Zhang, Q. Zhang, and Q. Xiong, "Deep subwavelength fourfold rotationally symmetric split-ring-resonator metamaterials for highly sensitive and robust biosensing platform," *Sci. Rep.* **3** (2013).
122. J. Wang, F. Qin, D. Hua Zhang, D. Li, Y. Wang, X. Shen, T. Yu, and J. Teng, "Subwavelength superfocusing with a dipole-wave-reciprocal binary zone plate," *Appl. Phys. Lett.* **102**, 061103 (2013).
123. L. Huang, X. Chen, B. Bai, Q. Tan, G. Jin, T. Zentgraf, and S. Zhang, "Helicity dependent directional surface plasmon polariton excitation using a metasurface with interfacial phase discontinuity," *Light: Sci. Appl.* **2**, e70 (2013).

124. Q. Wang, J. Bu, and X. C. Yuan, "High-resolution 2D plasmonic fan-out realized by subwavelength slit arrays," *Opt. Express* **18**, 2662-2667 (2010).
125. B. Gjonaj, A. David, Y. Blau, G. Spektor, M. Orenstein, S. Dolev, and G. Bartal, "Sub-100 nm Focusing of Short Wavelength Plasmons in Homogeneous 2D Space," *Nano Lett.* **14**, 5598-5602 (2014).
126. G. Maidecchi, G. Gonella, R. Proietti Zaccaria, R. Moroni, L. Anghinolfi, A. Giglia, S. Nannarone, L. Mattera, H.-L. Dai, M. Canepa, and F. Bisio, "Deep Ultraviolet Plasmon Resonance in Aluminum Nanoparticle Arrays," *ACS Nano* **7**, 5834-5841 (2013).
127. W. Su, G. Zheng, and X. Li, "Design of a highly sensitive surface plasmon resonance sensor using aluminum-based diffraction grating," *Opt. Commun.* **285**, 4603-4607 (2012).
128. K.-H. Lee, and K. J. Chang, "First-principles study of the optical properties and the dielectric response of Al," *Phys. Rev. B* **49**, 2362-2367 (1994).
129. C. Langhammer, M. Schwind, B. Kasemo, and I. Zorić, "Localized Surface Plasmon Resonances in Aluminum Nanodisks," *Nano Lett.* **8**, 1461-1471 (2008).
130. A. Taguchi, Y. Saito, K. Watanabe, S. Yijian, and S. Kawata, "Tailoring plasmon resonances in the deep-ultraviolet by size-tunable fabrication of aluminum nanostructures," *Appl. Phys. Lett.* **101**, 081110 (2012).
131. S. Zhu, T. Y. Liow, G. Q. Lo, and D. L. Kwong, "Fully complementary metal-oxide-semiconductor compatible nanoplasmonic slot waveguides for

- silicon electronic photonic integrated circuits," *Appl. Phys. Lett.* **98**, 021107 (2011).
132. A. D. Rakic, A. B. Djurisic, J. M. Elazar, and M. L. Majewski, "Optical properties of metallic films for vertical-cavity optoelectronic devices," *Appl. Opt.* **37**, 5271-5283 (1998).
133. H. R. Philipp, "Optical Properties of Silicon Nitride," *J. Electrochem. Soc.* **120**, 295-300 (1973).
134. V. Z. Anatoly, and I. S. Igor, "Near-field photonics: surface plasmon polaritons and localized surface plasmons," *J. Opt. A: Pure Appl. Opt.* **5**, S16 (2003).
135. S. Haruhisa, I. Ken-ichi, K. Chiyuki, and S. Yasuharu, "GaInAsP/InP Surface Emitting Injection Lasers," *Japanese Journal of Applied Physics* **18**, 2329 (1979).
136. I. Melngailis, "LONGITUDINAL INJECTION-PLASMA LASER OF InSb," *Applied Physics Letters* **6**, 59-60 (1965).
137. *Vertical-Cavity Surface-Emitting Laser Devices* (Springer, 2003).
138. *VCSELs Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers* (Springer-Verlag Berlin Heidelberg, 2013).
139. J. L. Jewell, Y. H. Lee, S. Walker, A. Scherer, J. P. Harbison, L. T. Florez, and S. L. McCall, "Low-threshold electrically pumped vertical-cavity surface-emitting microlasers," in *Electronics Letters* (Institution of Engineering and Technology, 1989), pp. 1123-1124.
140. R. S. Geels, S. W. Corzine, J. W. Scott, D. B. Young, and L. A. Coldren, "Low threshold planarized vertical-cavity surface-emitting lasers," *Photonics Technology Letters, IEEE* **2**, 234-236 (1990).

141. J. K. Guenter, R. A. Hawthorne III, D. N. Granville, M. K. Hibbs-Brenner, and R. A. Morgan, "Reliability of proton-implanted VCSELs for data communications," (1996), pp. 102-113.
142. K. D. Choquette, and H. Q. Hou, "Vertical-cavity surface emitting lasers: moving from research to manufacturing," *Proceedings of the IEEE* **85**, 1730-1739 (1997).
143. K. L. Lear, K. D. Choquette, R. P. Schneider, S. P. Kilcoyne, and K. M. Geib, "Selectively oxidised vertical cavity surface emitting lasers with 50% power conversion efficiency," *Electronics Letters* **31**, 208-209 (1995).
144. B. Weigl, M. Grabherr, C. Jung, R. Jäger, G. Reiner, R. Michalzik, D. Sowada, and K. J. Ebeling, "High-performance oxide-confined GaAs VCSELs," *Selected Topics in Quantum Electronics, IEEE Journal of* **3**, 409-415 (1997).
145. J.-F. Seurin, C. L. Ghosh, V. Khalfin, A. Miglo, G. Xu, J. D. Wynn, P. Pradhan, and L. A. D'Asaro, "High-power high-efficiency 2D VCSEL arrays," (2008), pp. 690808-690808-690814.
146. K. Takaki, N. Iwai, S. Kamiya, H. Shimizu, K. Hiraiwa, S. Imai, Y. Kawakita, T. Takagi, T. Ishikawa, N. Tsukiji, and A. Kasukawa, "Experimental demonstration of low jitter performance and high reliable 1060nm VCSEL arrays for 10Gbpsx12ch optical interconnection," (2010), pp. 761502-761502-761508.
147. S. W. Corzine, R. H. Yan, and L. A. Coldren, "A tanh substitution technique for the analysis of abrupt and graded interface multilayer dielectric stacks," *Quantum Electronics, IEEE Journal of* **27**, 2086-2090 (1991).

148. C. F. R. Mateus, M. C. Y. Huang, D. Yunfei, A. R. Neureuther, and C. J. Chang-Hasnain, "Ultrabroadband mirror using low-index cladded subwavelength grating," *Photonics Technology Letters, IEEE* **16**, 518-520 (2004).
149. M. Gębski, O. Kuzior, M. Dems, M. Wasiak, Y. Y. Xie, Z. J. Xu, Q. J. Wang, D. H. Zhang, and T. Czyszanowski, "Transverse mode control in high-contrast grating VCSELs," *Optics Express* **22**, 20954-20963 (2014).
150. M. C. Y. Huang, Y. Zhou, and C. J. Chang-Hasnain, "A surface-emitting laser incorporating a high-index-contrast subwavelength grating," *Nat Photon* **1**, 119-122 (2007).
151. C. J. Chang-Hasnain, Z. Ye, M. Huang, and C. Chase, "High-Contrast Grating VCSELs," *Selected Topics in Quantum Electronics, IEEE Journal of* **15**, 869-878 (2009).
152. M. C. Y. Huang, Y. Zhou, and C. J. Chang-Hasnain, "A nanoelectromechanical tunable laser," *Nat Photon* **2**, 180-184 (2008).
153. W. Hofmann, C. Chase, Mu, x, M. Iler, R. Yi, C. Grasse, Bo, x, G. hm, M.-C. Amann, and C. J. Chang-Hasnain, "Long-Wavelength High-Contrast Grating Vertical-Cavity Surface-Emitting Laser," *Photonics Journal, IEEE* **2**, 415-422 (2010).
154. M. Gębski, M. Dems, C. Jian, W. Qijie, Z. Dao Hua, and T. Czyszanowski, "Optical Properties of GaAs/AlO_x High Contrast Gratings Designed for 980-nm VCSELs," *Nanotechnology, IEEE Transactions on* **13**, 418-424 (2014).
155. M. Gębski, M. Dems, J. Chen, Q. J. Wang, D. H. Zhang, and T. Czyszanowski, "The Influence of Imperfections and Absorption on the

- Performance of a GaAs/AlO_x High-Contrast Grating for Monolithic Integration With 980 nm GaAs-Based VCSELs," *Lightwave Technology, Journal of* **31**, 3853-3858 (2013).
156. J. Chen, W. J. Fan, Q. J. Wang, M. Gebiski, M. Dems, T. Czystanowski, And D. H. Zhang, "Optical Gain And Energy Band Structure Of Photonic Crystal Vcsels With High-Index-Contrast Subwavelength Gratings," *Journal Of Molecular And Engineering Materials* **02**, 1440014 (2014).
157. K. Iga, "Surface-emitting laser-its birth and generation of new optoelectronics field," *Selected Topics in Quantum Electronics, IEEE Journal of* **6**, 1201-1215 (2000).
158. C. Jung, R. Jager, M. Grabherr, P. Schnitzer, R. Michalzik, B. Weigl, S. Muller, and K. J. Ebeling, "4.8 mW singlemode oxide confined top-surface emitting vertical-cavity laser diodes," *Electronics Letters* **33**, 1790-1791 (1997).
159. N. Ueki, A. Sakamoto, T. Nakamura, H. Nakayama, J. Sakurai, H. Otoma, Y. Miyamoto, M. Yoshikawa, and M. Fuse, "Single-transverse-mode 3.4-mW emission of oxide-confined 780-nm VCSELs," *Photonics Technology Letters, IEEE* **11**, 1539-1541 (1999).
160. Z. Delai, and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *Quantum Electronics, IEEE Journal of* **38**, 1599-1606 (2002).
161. A. Kroner, F. Rinaldi, J. M. Ostermann, and R. Michalzik, "High-performance single fundamental mode AlGaAs VCSELs with mode-selective mirror reflectivities," *Optics Communications* **270**, 332-335 (2007).

162. X. Yi-Yang, K. Qiang, X. Chen, Z. Yan-Xu, W. Chun-xia, and C. Hong-Da, "Low Threshold Current Single-Fundamental-Mode Photonic Crystal VCSELs," *Photonics Technology Letters, IEEE* **24**, 464-466 (2012).
163. Y.-Y. Xie, C. Xu, Q. Kan, C.-X. Wang, and H.-D. Chen, "Multi-point defect single-fundamental-mode photonic crystal vertical cavity surface emitting laser," *Optics & Laser Technology* **50**, 130-133 (2013).
164. J. W. Shi, C. C. Chen, Y. S. Wu, S. H. Guol, K. Chihping, and Y. Ying-Jay, "High-Power and High-Speed Zn-Diffusion Single Fundamental-Mode Vertical-Cavity Surface-Emitting Lasers at 850-nm Wavelength," *Photonics Technology Letters, IEEE* **20**, 1121-1123 (2008).
165. A. Liu, M. Xing, H. Qu, W. Chen, W. Zhou, and W. Zheng, "Reduced divergence angle of photonic crystal vertical-cavity surface-emitting laser," *Applied Physics Letters* **94**, 191105 (2009).
166. D.-S. Song, Y.-J. Lee, H.-W. Choi, and Y.-H. Lee, "Polarization-controlled, single-transverse-mode, photonic-crystal, vertical-cavity, surface-emitting lasers," *Applied Physics Letters* **82**, 3182-3184 (2003).
167. T. Cao, C. Xu, Y.-Y. Xie, Q. Kan, S.-M. Wei, M.-M. Mao, and H.-D. Chen, "Vertical cavity surface emitting laser transverse mode and polarization control by elliptical hole photonic crystal," *Chinese Physics B* **22**, 024205 (2013).
168. J. M. Lamy, J. Justice, G. Lvque, and B. Corbett, "Monolithic excitation and manipulation of surface plasmon polaritons on a vertical cavity surface emitting laser," *Appl. Phys. A* **103**, 665-667 (2011).
169. P. A. Porta, J. Justice, G. Leveque, and B. Corbett, "Vertical-Cavity Surface-Emitting Lasers With Integrated Excitation of Surface Plasmon

- Polariton Modes," *Photonics Technology Letters, IEEE* **21**, 221-223 (2009).
170. L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, "Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes," *Physical Review A* **45**, 8185-8189 (1992).
171. http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_14.html.
172. http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_13.html.